



# *TEV GAMMA-RAY ASTRONOMY WITH VERITAS*

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on behalf of the VERITAS Collaboration



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# *The VERITAS Collaboration*

4 Countries, > 20 Institutions, 90 members, 6 Funding Agencies.

- Smithsonian Astrophysical Observatory, AZ
- Adler Planetarium, IL
- Argonne National Laboratory, IL
- Purdue University, IN
- Columbia University, NY
- Iowa State University, IA
- University of Iowa, IA
- DePauw University, IN
- Washington University, St. Louis, MO
- Grinnell College, IA
- University of Chicago, IL
- University of California, Santa Cruz, CA
- University of Utah, UI
- University of Massachusetts, Amherst, MA
- University of Delaware, DE
- University of California, Los Angeles, CA
- Penn State University, PA
- Cork Institute of Technology, Ireland
- McGill University, Montreal, Canada
- Galway-Mayo Institute of Technology, Ireland
- National University of Ireland, Dublin, Ireland
- National University of Ireland, Galway
- University of Leeds, UK
- Associate Members

Project office: Whipple observatory SAO, AZ

Funding: NSF, DOE, Smithsonian, PPARC, SFI, NSERC.

# VERITAS at F.L. Whipple Observatory in Amado, Arizona



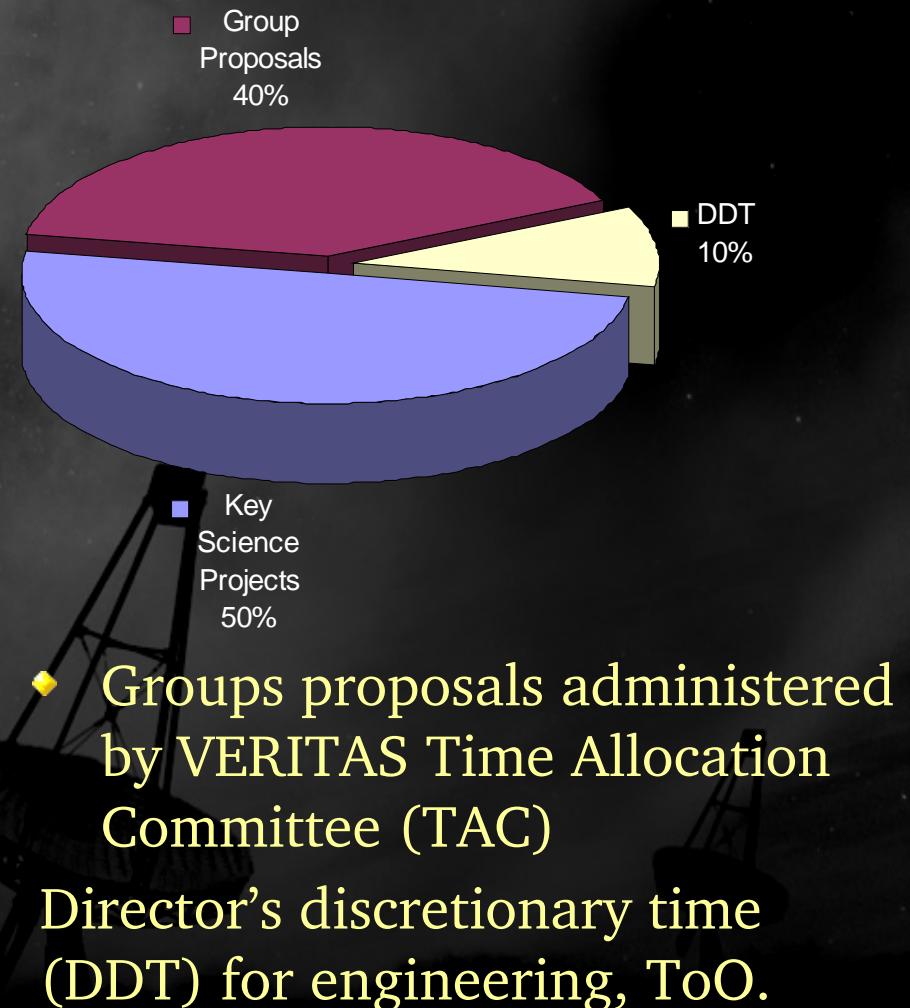
- ◆ Geographic Location:  $31^{\circ} 40'$  North,  $110^{\circ} 57'$  West, Altitude: 1268 masl.
- ◆ First stereo observations started in January 2006.
- ◆ Stays at this site to at least end of 2010.

# VERITAS TIME ALLOCATION

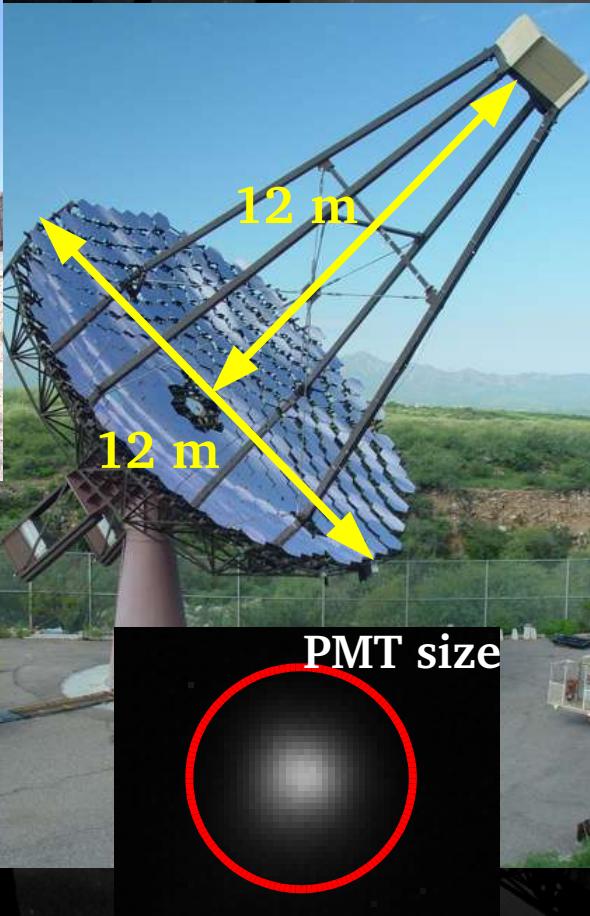
- ◆ About 800 hours allocated for science observations and  $\sim 90$  hours for engineering per year.

- ◆ Key Science Projects

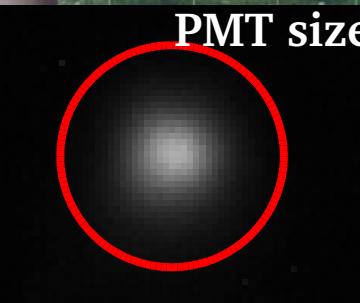
- ◆ Sky Survey (Preliminary scan and follow up observations)
  - ◆ Dark Matter (Deep observations of selected candidate sources)
  - ◆ Supernova Remnants (Intensive observations, search for new sources)
  - ◆ Blazars (MWL campaign for large flare, intensive observation of some AGN, search for new blazars)



# The Telescope Design

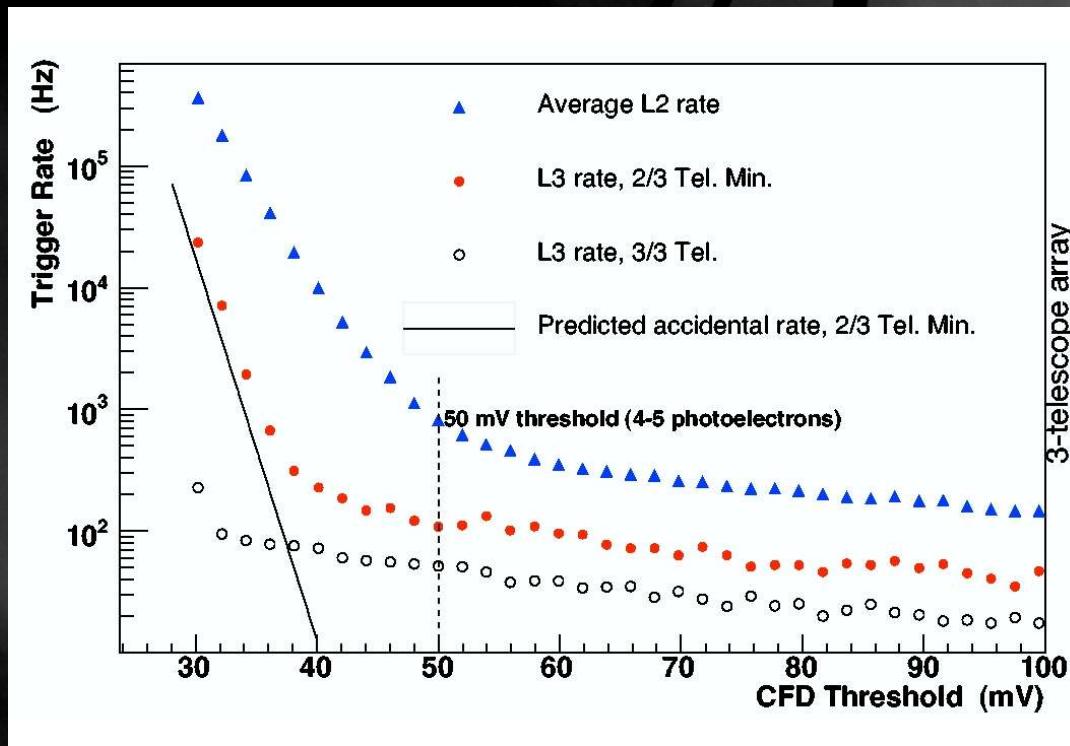


PSF:  $\sim 0.06^\circ$  FWHM measured at Polaris (elevation  $31^\circ$ )



- ◆ Mirror Area:  $110 \text{ m}^2$
- ◆ Mirror Reflectivity: (at 320 nm)  $> 90 \%$
- ◆ Light Collector Reflectivity: (at 260 nm)  $> 85 \%$
- ◆ Tracking Accuracy:  $0.02^\circ$
- ◆ Camera Pixel Spacing:  $0.15^\circ$
- ◆ Energy Threshold:  $\sim 100 \text{ GeV}$

# The Trigger System



500 Mega-sample/s flash ADC on each channel

- ◆ Array Trigger Rate:  $\sim 150 - 230$  Hz
- ◆ Dead time: 7 – 11 %

- ◆ 1<sup>st</sup> level (CFD): Determines how many photoelectrons should trigger each PMT. Helps eliminate night sky background noise (100-200 Hz).
- ◆ 2<sup>nd</sup> level (L2): Sets the CFD pulse width that fixes the resolving time and sets the pixel multiplicity condition.
- ◆ 3<sup>rd</sup> level (L3): Sets hardware multi telescope multiplicity.

# Calibration

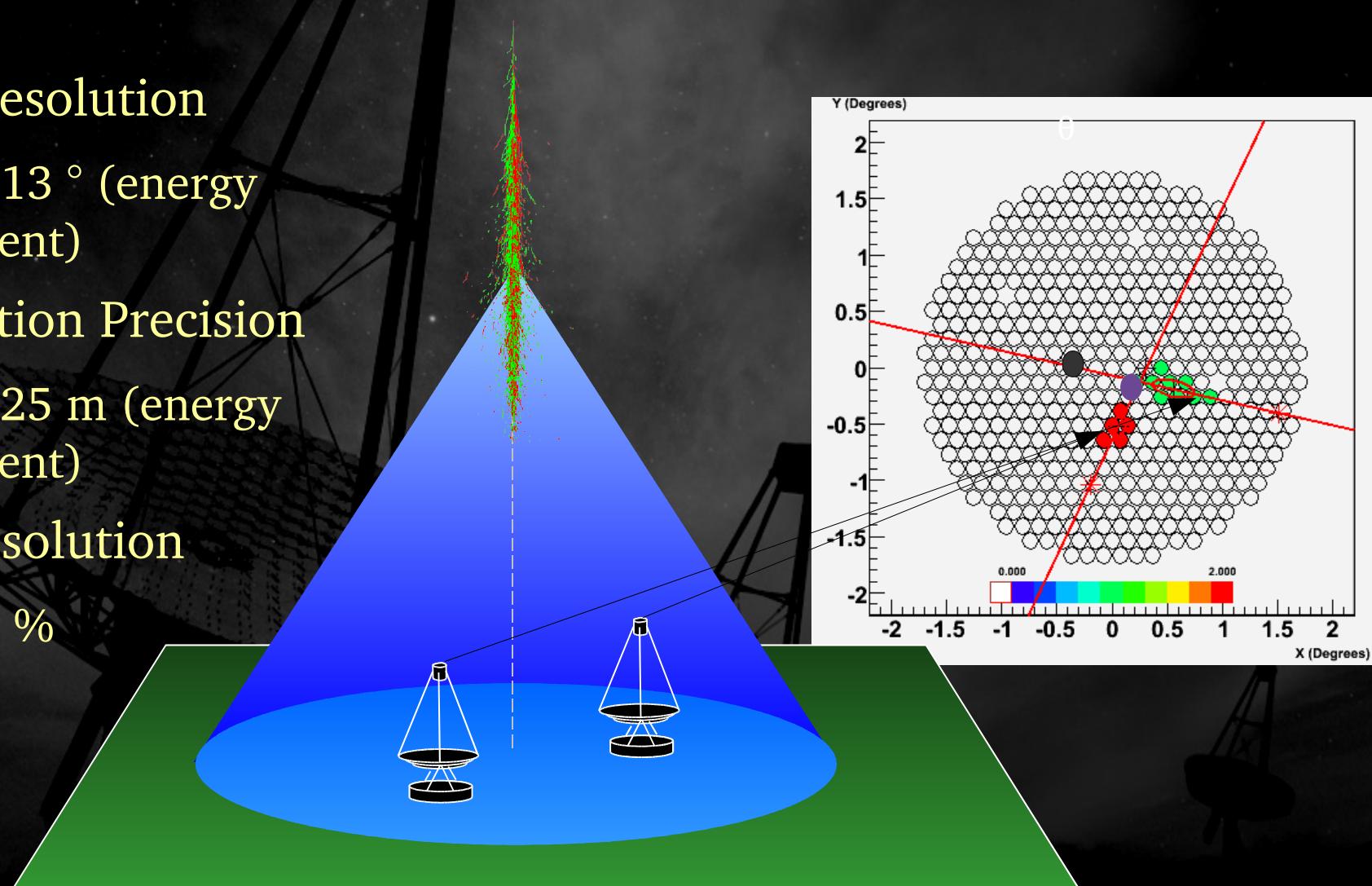
- ◆ Laser measurements
  - ◆ flat fielding cameras using 5 min run laser runs each night
    - ◆ laser placed 4 m away from the camera pulses every 4 ns in ultraviolet (337 nm)
  - ◆ Direct measurement of single-electron peak
  - ◆ Measurement of the muon rings
    - ◆ used to measure throughput of the telescope

# *Analysis Chain*

- ◆ Official Analysis Package VEGAS consists of 6 analysis stages
  - ◆ Stage 1 : calculation of calibration coefficients
  - ◆ Stage 2: application of the calibration coefficients
  - ◆ Stage3: image parameterization
  - ◆ Stage4: stereoscopic reconstruction of shower parameters
  - ◆ Stage5: application of gamma-hadron separation cuts
  - ◆ Stage6: background subtraction, mapping, signal extraction, spectrum determination
- ◆ Fully documented, backed up in the CVS repository, released to the collaboration

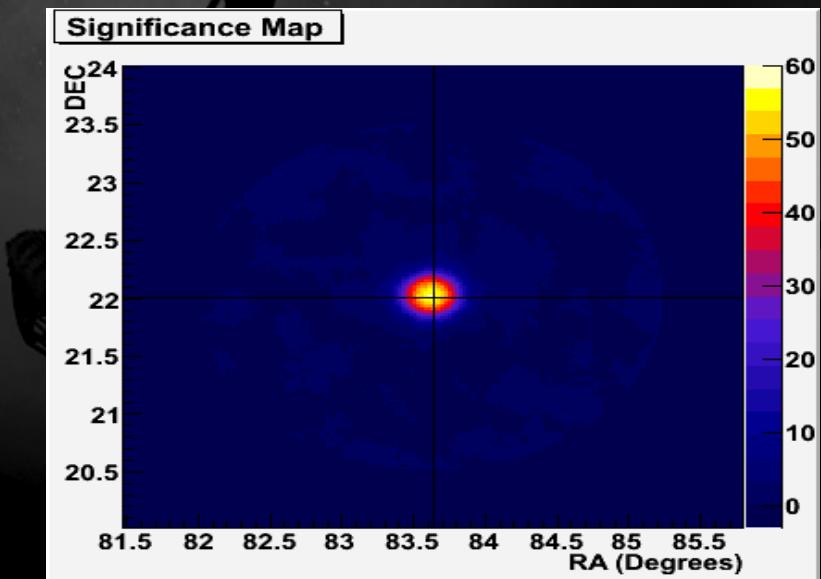
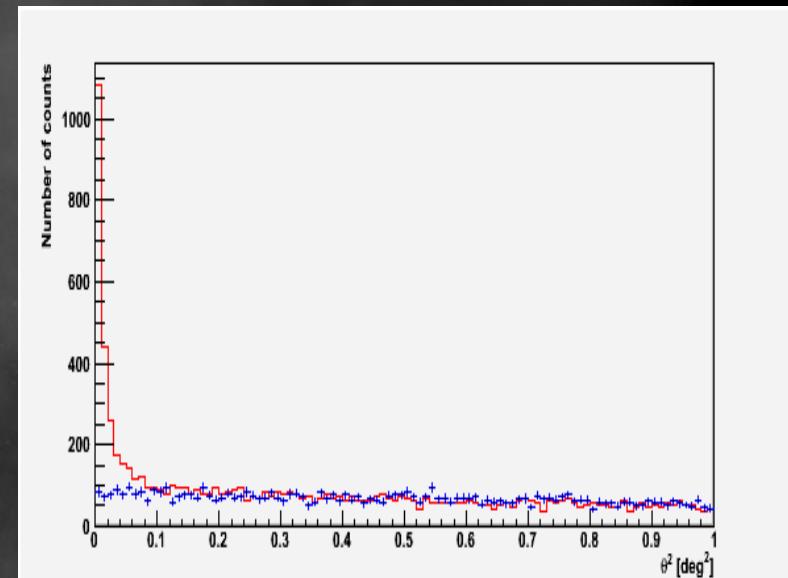
# Stereoscopic Reconstruction

- ◆ Angular Resolution
  - ◆  $0.1 - 0.13^\circ$  (energy dependent)
- ◆ Core Location Precision
  - ◆  $\sim 15 - 25 \text{ m}$  (energy dependent)
- ◆ Energy Resolution
  - ◆  $15 - 20 \%$



# The Crab Nebula

- ◆ 3 telescope data from January-February 2007
  - ◆ Significance:  $59.8 \sigma$
  - ◆ Sensitivity:  $31.29 \sigma / \sqrt{\text{hrs}}$
  - ◆ Gamma-ray rate:  $7.02 \gamma/\text{min}$
  - ◆ Background rate:  $0.94 \text{ bkg}/\text{min}$
- ◆ 2 telescope data from Fall 2006
  - ◆ Sensitivity:  $20.64 \sigma / \sqrt{\text{hrs}}$
  - ◆ Gamma-ray rate:  $3.51 \gamma/\text{min}$
  - ◆ Background rate:  $0.64 \text{ bkg}/\text{min}$



# VERITAS Performance

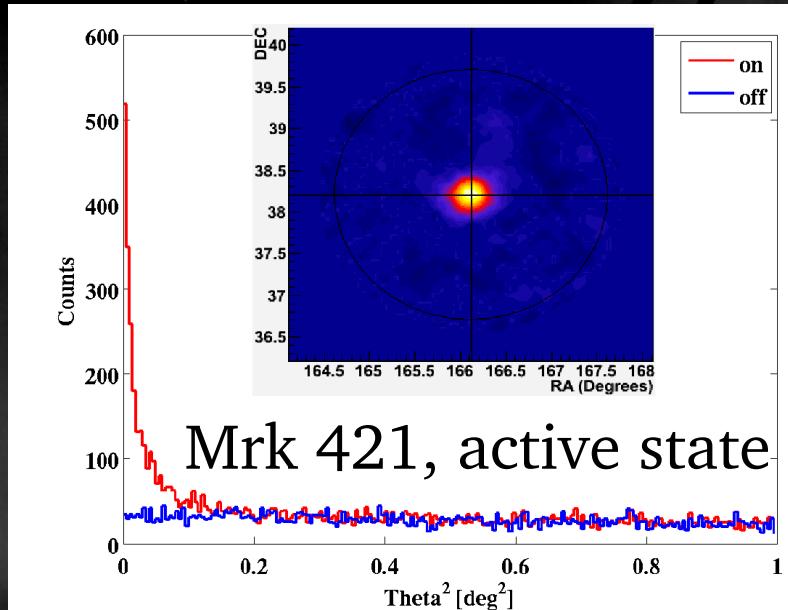
- ◆ Effective Area:  $10^4 - 10^5 \text{ m}^2$
- ◆ Flux of the Crab Nebula (3 telescopes)

$$\frac{d\phi}{dE} = \phi_0 \cdot \left(\frac{E}{E_0}\right)^\alpha \quad \text{where} \quad E_0 = 1 \text{ TeV}$$

- ◆  $\phi_0 = (3.63 \pm 0.15^{\text{stat}}) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$
- ◆  $\alpha = -2.54 \pm 0.05^{\text{stat}}$
- ◆  $\phi (> 1 \text{ TeV}) = (2.35 \pm 0.12^{\text{stat}}) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1}$
- ◆ Analysis Energy Threshold:  $\sim 200 \text{ GeV}$

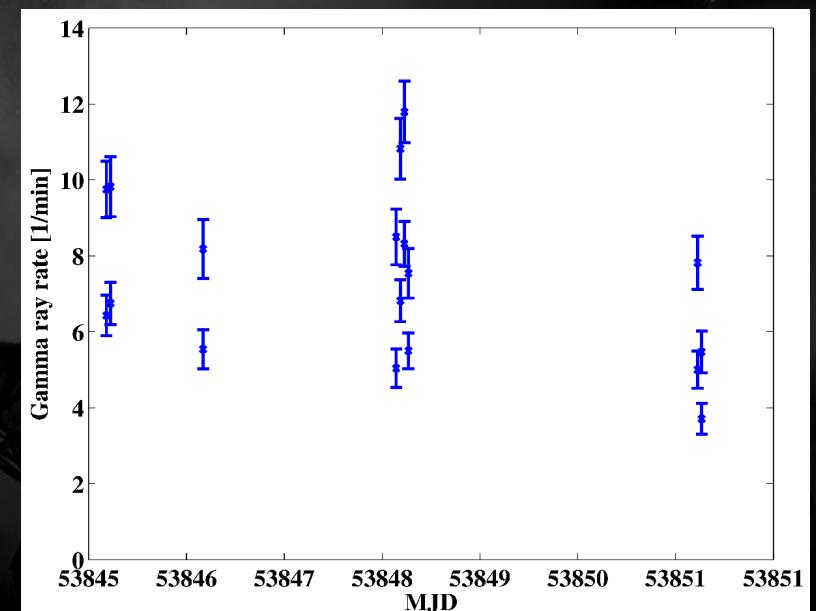
- ◆ Sensitivity
  - ◆ Crab Nebula detected ( $5\sigma$ ) with 3 telescopes in 1.9 minutes.
  - ◆ For  $5\sigma$  detection of a source having 10 % of the Crab Nebula flux
    - 3.3 hours (2 telescopes)
    - 1.2 hours (3 telescopes)
    - <1 hours (4 telescopes)

# AGN Observations: Mrk 421

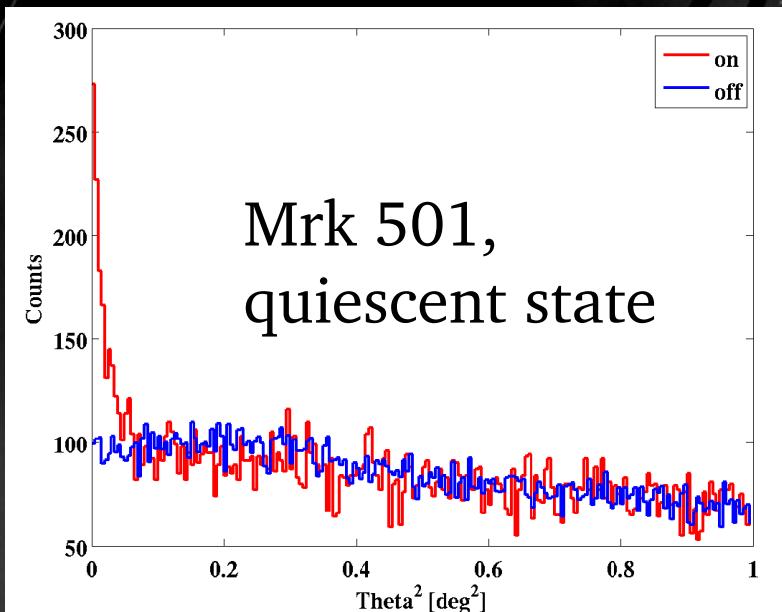


- ◆ VERITAS: Spring 2006 (2 telescopes)
- ◆ 4.5 hours
- ◆ Significance:  $35 \sigma$
- ◆ Gamma-ray rate:  $5.6 \gamma/\text{min}$

- ◆ Detected by Whipple 10 m.
- ◆ This BL Lac is one of the first extragalactic gamma-ray source detected.

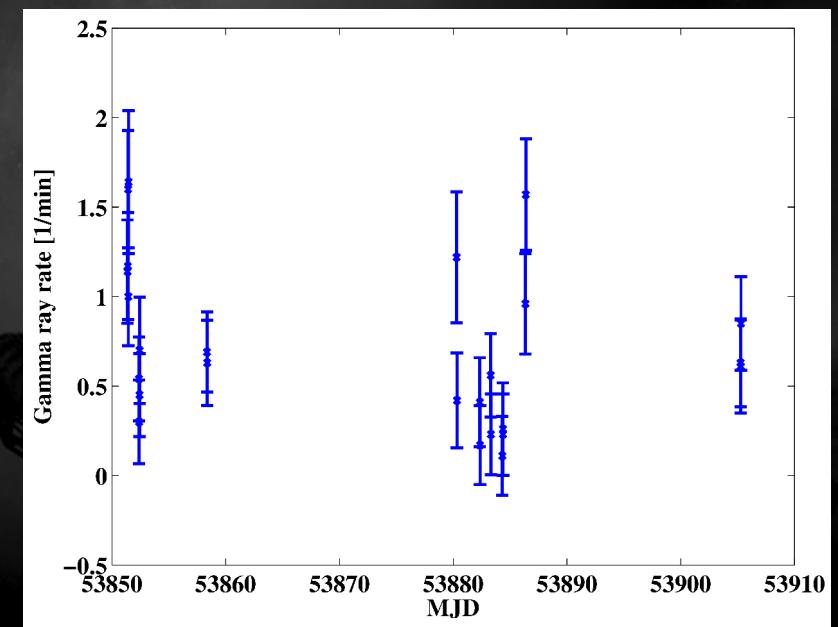


# AGN Observations: Mrk 501



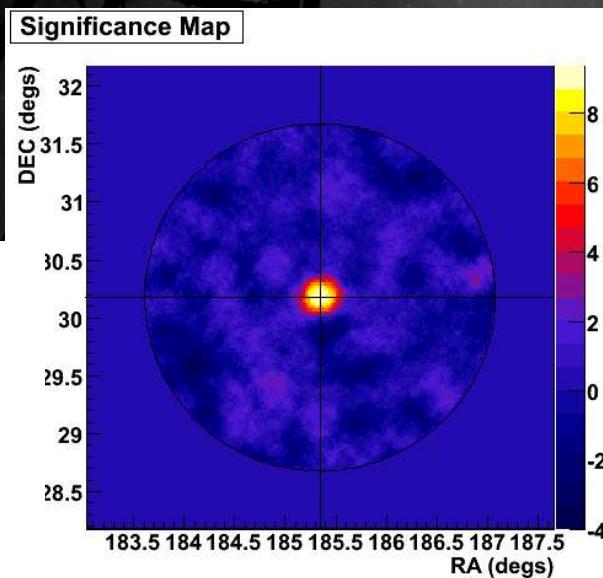
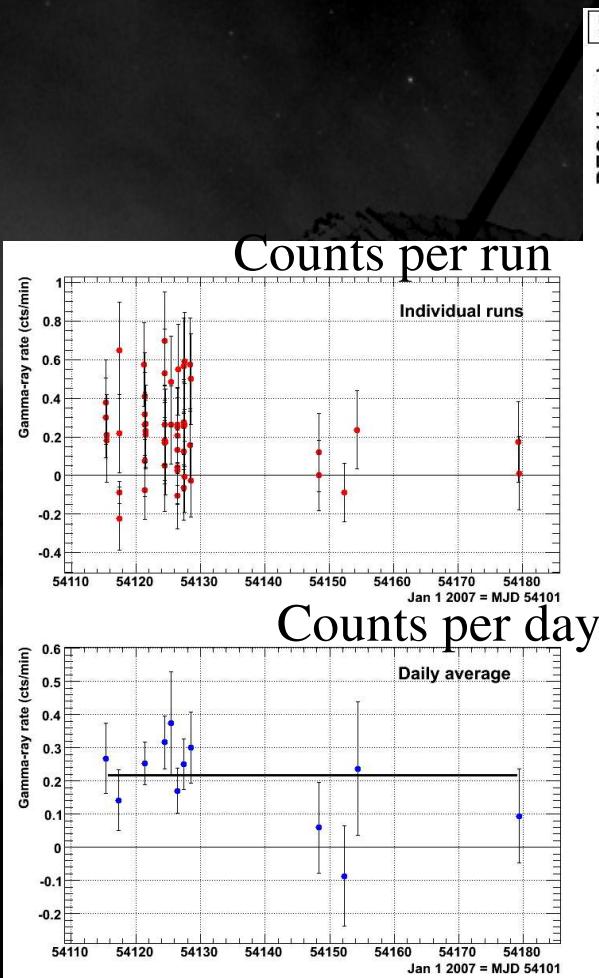
- VERITAS: Spring 2006 (2 telescopes)
- 12.5 hours
  - Significance:  $16 \sigma$
  - Gamma-ray rate:  $0.8 \gamma/\text{min}$

- Detected by Whipple 10 m.
- This BL Lac is one of the first extragalactic gamma-ray source detected.



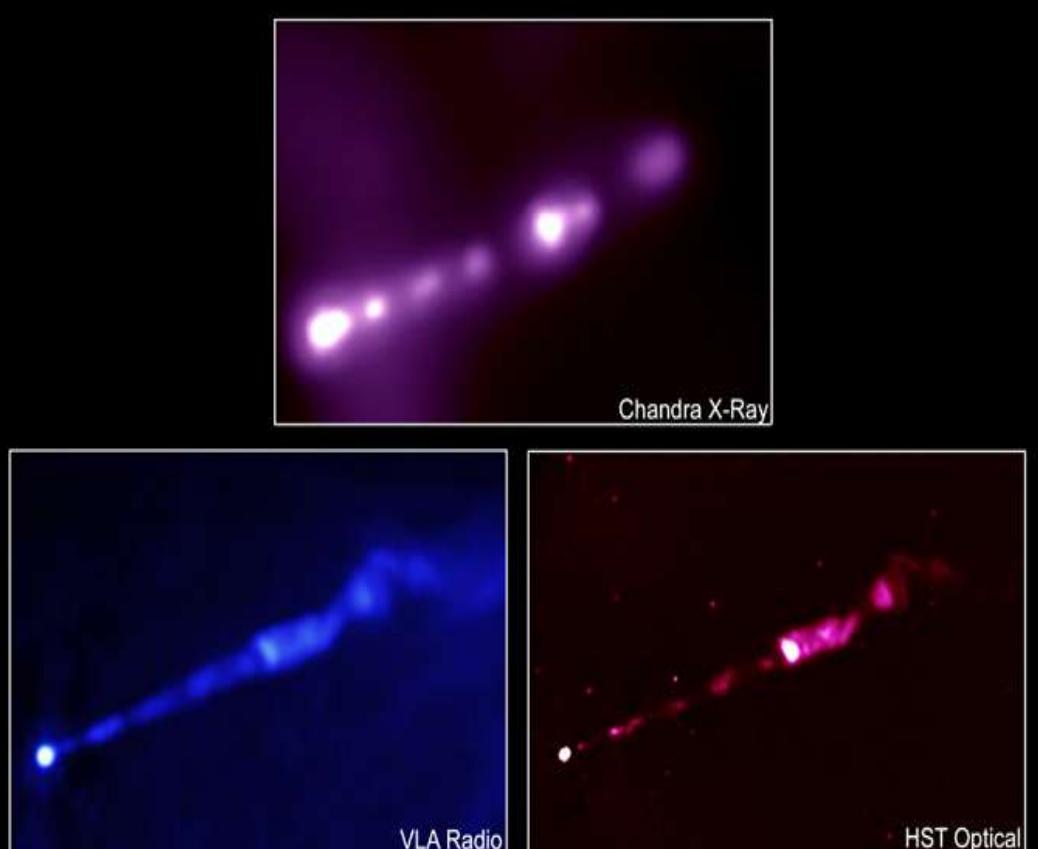
# AGN Observations: 1ES 1218

- 1ES 1218 high-frequency peaked BL Lac at high red shift ( $z=0.182$ )



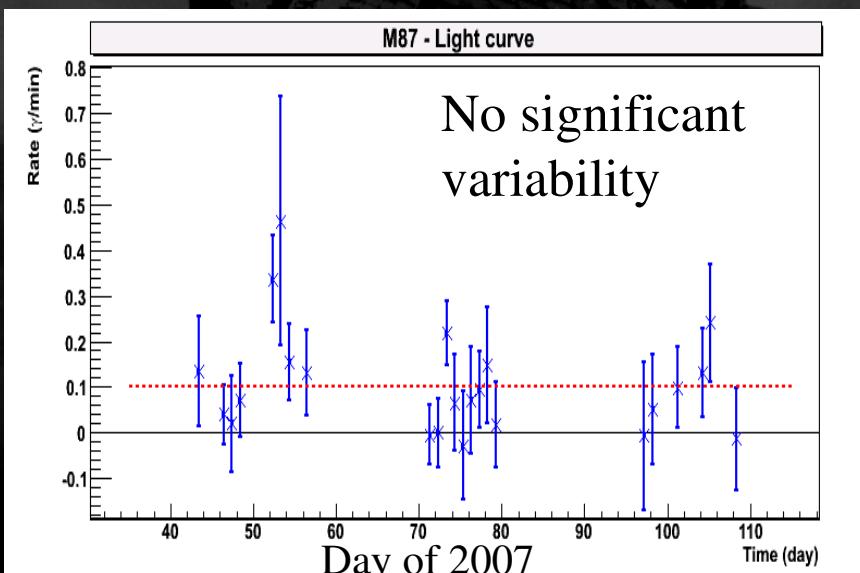
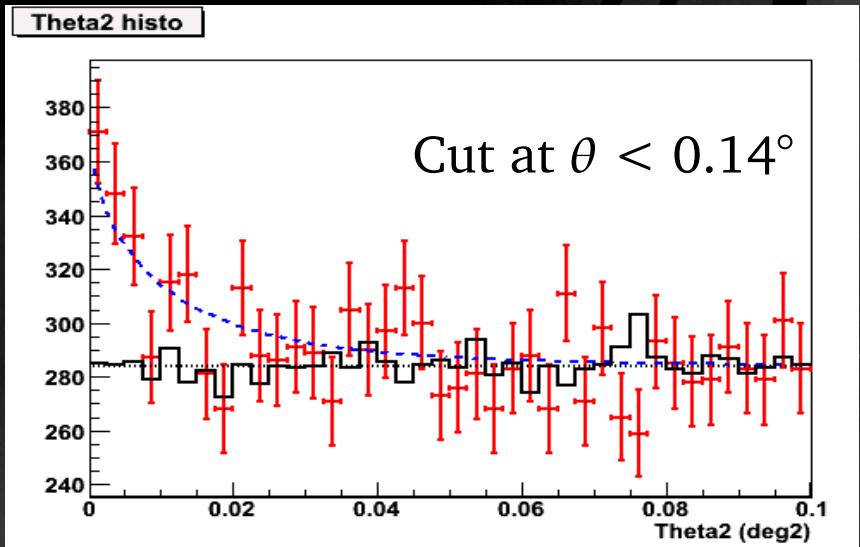
- MAGIC detection: 8.2 hours,  $6.4 \sigma$ ,  $E > 120$  GeV
- VERITAS : December 2006 – March 2007
- 17.4 hours (2 and 3 telescopes)
- Significance:  $10.2 \sigma$
- Gamma-ray rate:  $0.23 \gamma/\text{min}$
- Point-like gamma-ray emission.

# AGN Observations: M87



- Giant radio galaxy at a distance of 16 Mpc
- Center of M87 is a black hole of mass  $3.2 \times 10^9 M_{\odot}$
- Jet-structure seen in optical, radio and X-ray
- The only non-blazar extragalactic TeV gamma-ray source

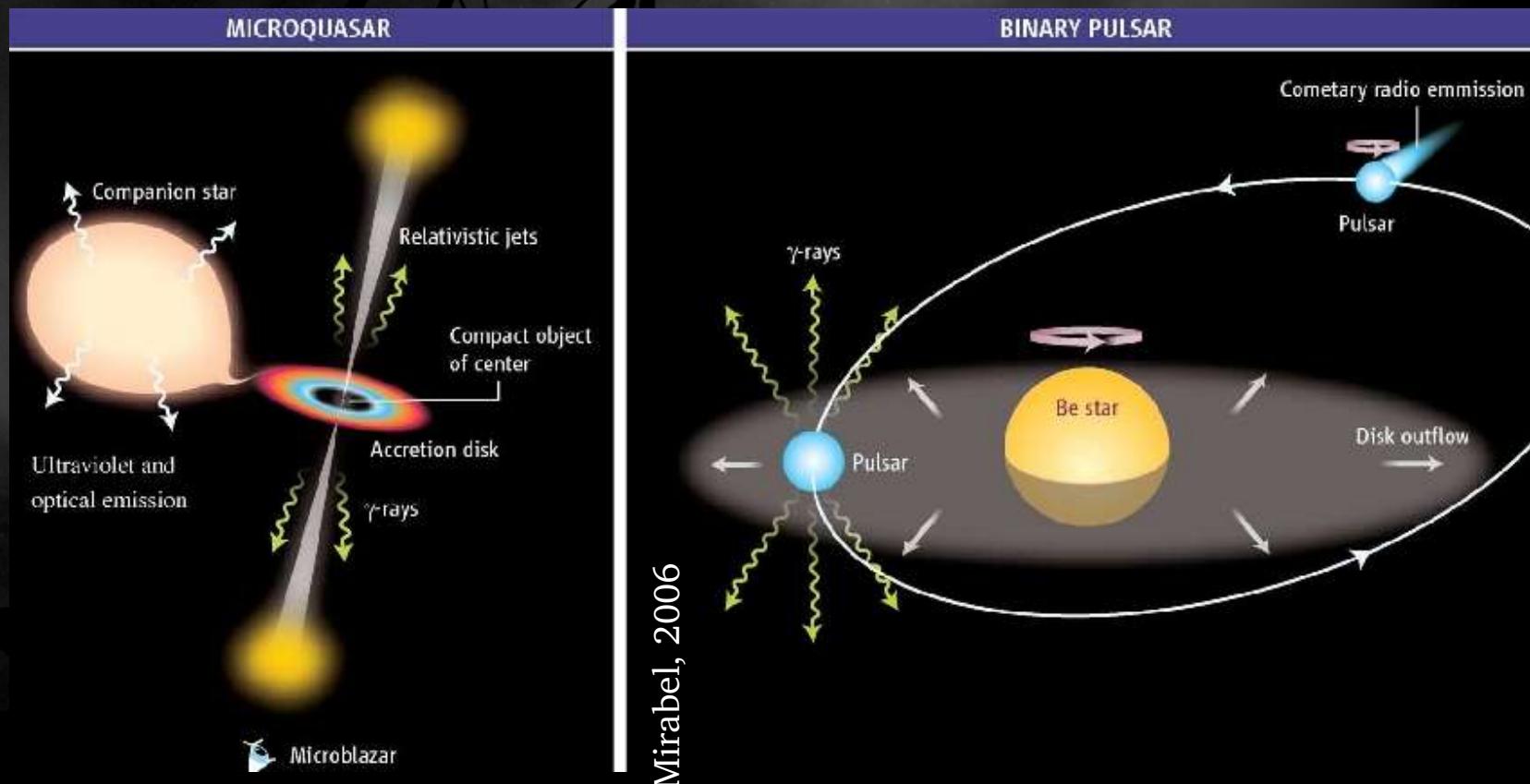
# M87



- ◆ Previous detections
  - ◆ HEGRA at  $4.5 \sigma$  (1998-1999)
  - ◆ H.E.S.S. at  $13 \sigma$  (2003-2006)
- ◆ VERITAS
  - ◆ February – April 2007
  - ◆ 51 hours (3 telescopes)
  - ◆ Significance:  $5 \sigma$
  - ◆ Gamma-ray rate:  $0.1 \gamma/\text{min}$
  - ◆ Gamma-ray emission: point-like
  - ◆ Flux ( $> 250 \text{ GeV}$ ) is 1.7 % of the flux of the Crab Nebula.

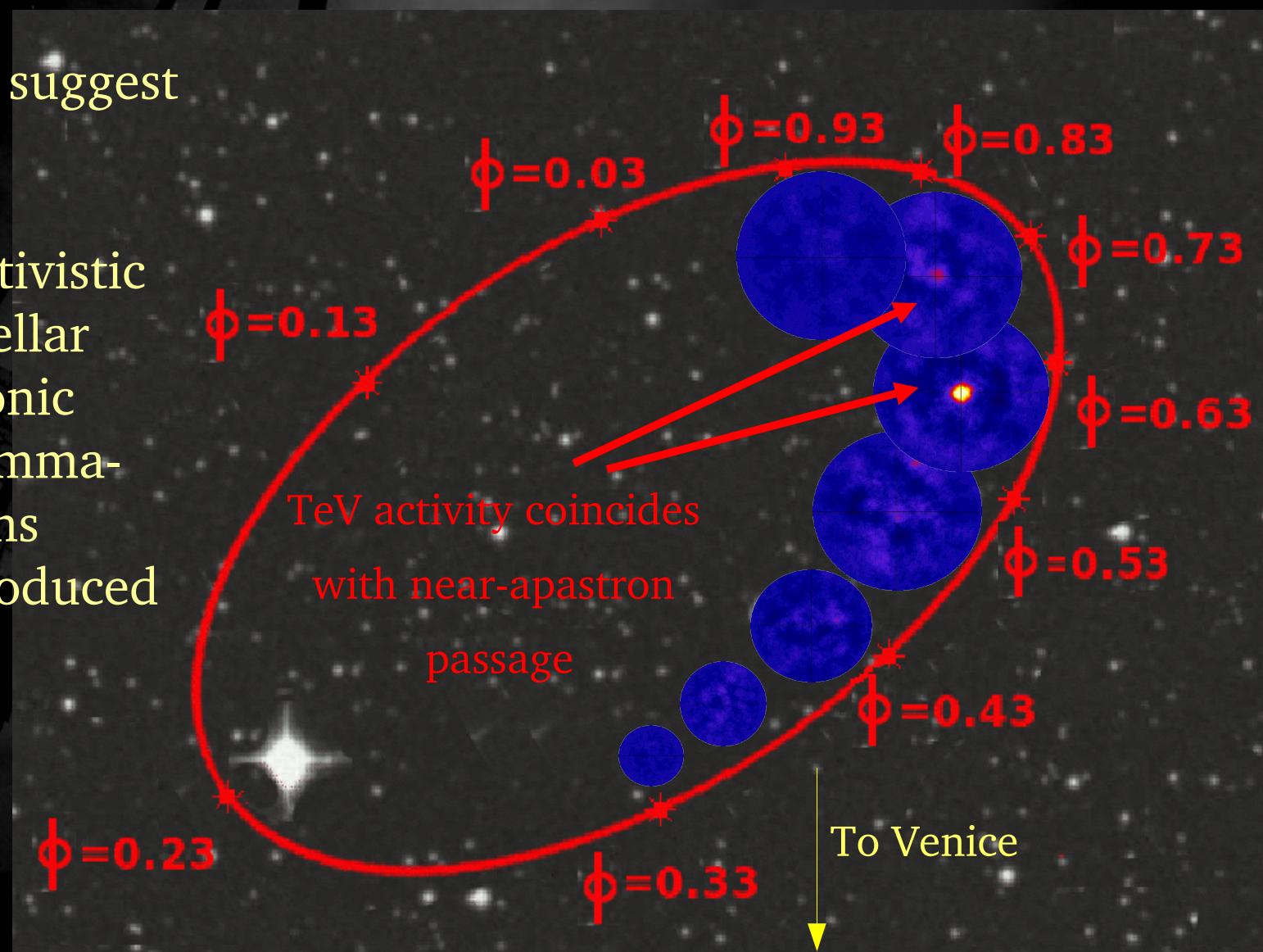
# *LSI +61° 303*

- ◆ High-mass X-ray Binary
- ◆ System consists of pulsar or black hole orbiting Be star companion
- ◆ Period: 26.5 days

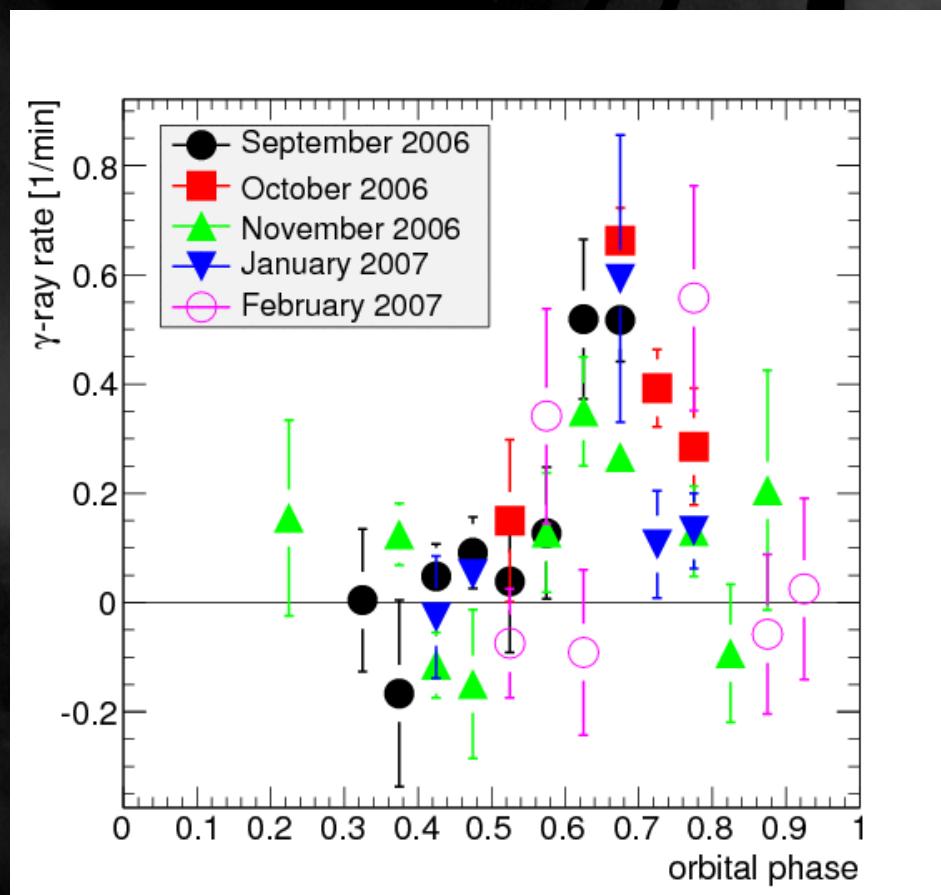


# Galactic Sources: LSI +61° 303

- ◆ Emission models suggest VHE gamma-ray emission from IC scattering of relativistic electrons with stellar photons or hadronic production of gamma-rays through pions which may be produced in the proton interactions.

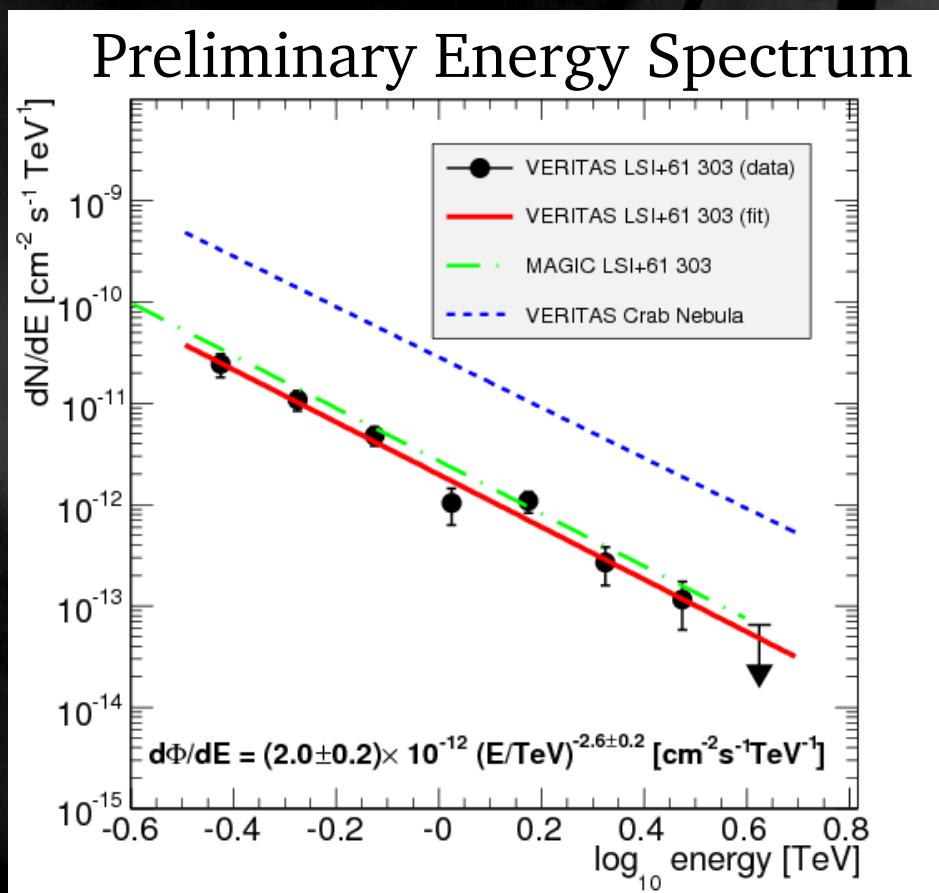


# *LSI +61° 303*



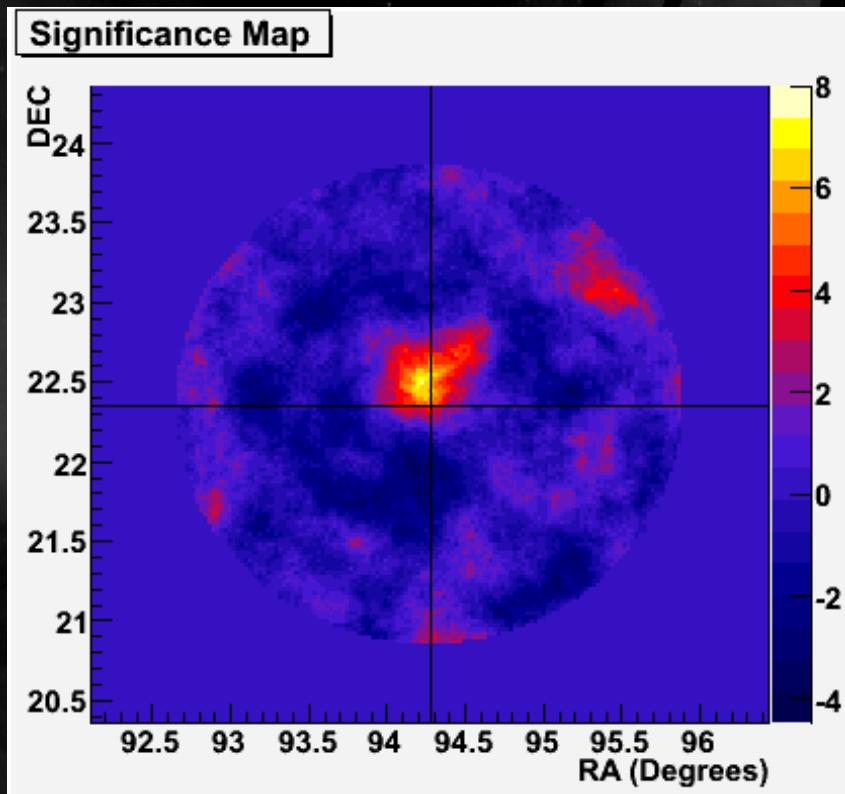
- ◆ MAGIC detection
  - ◆ 54 hours, 9  $\sigma$ ,  $E > 200$  GeV
- ◆ VERITAS observations
  - ◆ September 2006 – February 2007
  - ◆ 44 hours, 8.8  $\sigma$ ,  $E > 350$  GeV
  - ◆ Point-like gamma-ray emission.
  - ◆ Phase-dependent variable emission

# *LSI +61° 303*



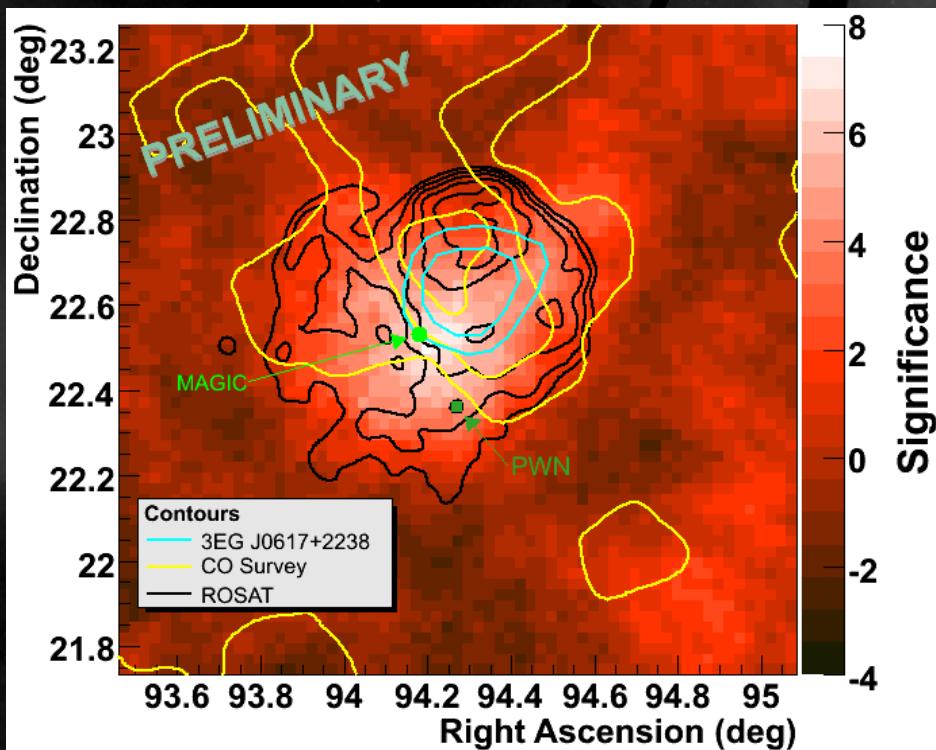
- ◆ Crab like flux
  - ◆ Flux < 3 % of Crab flux in low-flux phase bins
  - ◆ Flux > 10 % of Crab flux in high-flux phase bins
- ◆ Flux consistent with MAGIC results

# Galactic Sources: IC 443



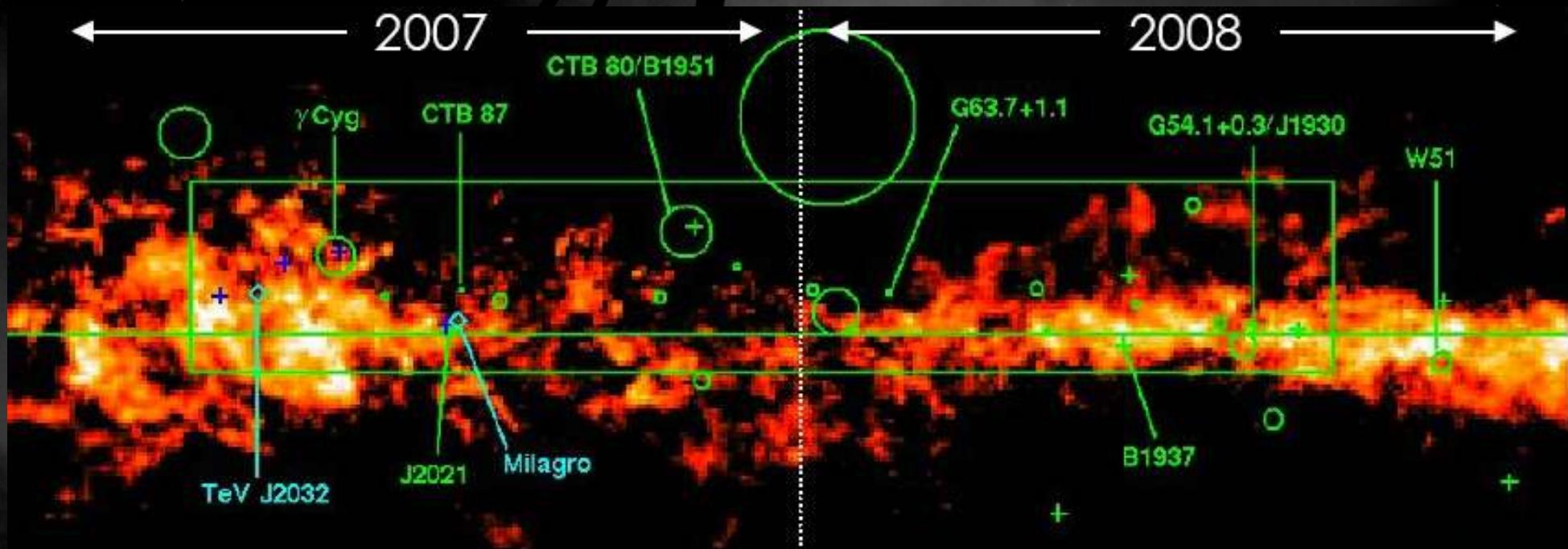
- ◆ An SNR associated with molecular cloud interactions
- ◆ 3 telescope data from February - March 2007
  - ◆ Significance:  $7.4 \sigma$
  - ◆ Sensitivity:  $1.76 \sigma / \sqrt{\text{hrs}}$
  - ◆ Gamma-ray rate:  $0.24 \gamma/\text{min}$
  - ◆ Background rate:  $0.92 \text{ bkg}/\text{min}$
  - ◆ Flux( $>200 \text{ GeV}$ ) is 3 % of the Crab Nebula

# IC 443



- ◆ Spatial overlap between the peak of the gamma-ray excess and the CO map.
- ◆ VERITAS detected gamma-ray excess region overlaps with MAGIC gamma-ray signal.
- ◆ Models of gamma ray production
  - ◆ by pion decay that is a product of proton interactions.
  - ◆ by interactions of relativistic electrons from the SNR with the ambient photons.

# VERITAS Sky Survey



Cygnus Region:  $52 < l < 82$ ,  $-1 < b < 4$  ,  
130 hours per year is allocated

Currently data is being analyzed!

# Conclusion

- ◆ The VERITAS experiment is fully operational since 2007 and is producing exciting results.
  - ◆ Sensitivity of 10 % of the flux of the Crab Nebula in less than 1 hour is achieved.
- ◆ VERITAS has detected many gamma-ray sources like a binary system, SNR interacting with a molecular cloud and AGN.
  - ◆ The details on the analysis of each of these sources and more contributions of VERITAS can be found in the ICRC 2007, Merida proceedings.