OBSERVATIONS OF VERY HIGH ENERGY GAMMA RAYS FROM M87 BY VERITAS

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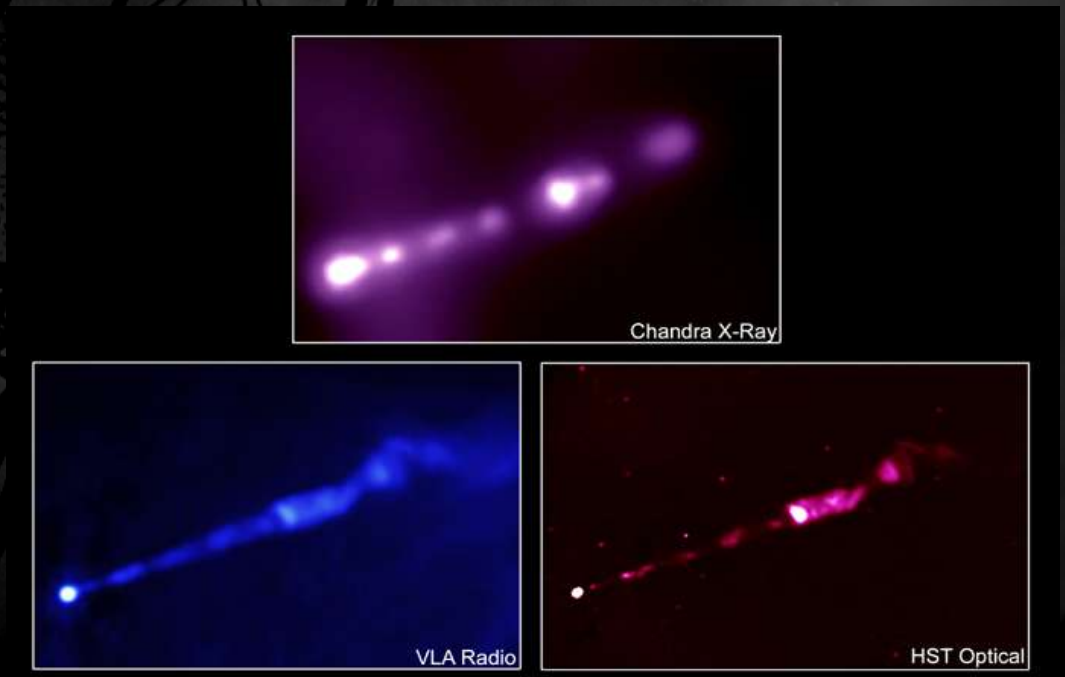
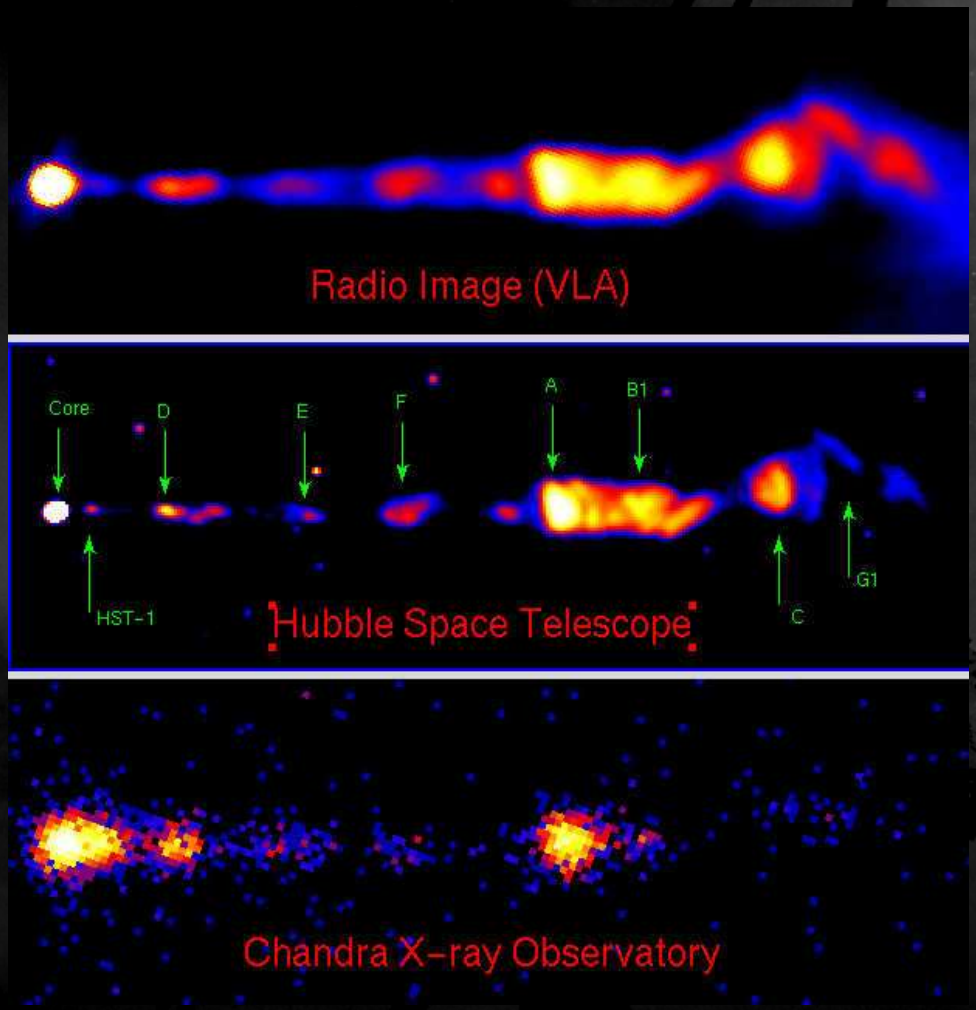
on behalf of the VERITAS Collaboration
(http://veritas.sao.arizona.edu)



APOD , 2004 December 11

M87: A Non-blazar AGN



Credit: X-ray: NASA/CXC/MIT/H.Marshall et al., Radio: F.Zhou, F.Owen (NRAO), J.Biretta (STScI), Optical: NASA/STScI/UMBC/E.Perlman et al.

- Giant elliptical radio galaxy at a distance of 16 Mpc
  - z = 0.004
- Center of M87 is a black hole of mass 3.2 x10^9 $M_\odot$
- Jet-structure seen in optical, radio and X-ray
  - Jet orientation typically 30° - 35°
- The only non-blazar extragalactic TeV gamma-ray source

Models of TeV Gamma-ray Emission in M87: Source of the Gamma Rays

- Leptonic Emission (Blazar-type) Models: Synchrotron radiation from high-energy electrons from the jet (or core) interact through inverse-Compton scattering with the same electrons in the jet (Stawarz et al. 2003) or in the core (Georganopoulos et al. 2005)
- Synchrotron Proton Emission Model: including protons in the production of TeV gamma rays, (Reimer et al. 2004)
- Alternative Models: TeV emission from ultra-high-energy cosmic rays through photo-pion production or by proton and muon synchrotron radiation (Biermann el al. 2001), dark matter annihilation (Baltz et al. 2000), and the black hole magnetosphere and curvature model (Rieger & Aharonian 2008).

Models of TeV Gamma-ray Emission in M87: Location of the Gamma Rays

- The Core Region (Georganopoulos et al. 2005, Reimer et al. 2004, Ghisellini et al. 2005, Neronov & Aharonian 2007, Lenain et al. 2007)
- The HST-1 Knot (Stawarz et al. 2006)
- Large Scale Jet (Stawarz et al. 2006) Has large extended structure, and turbulent nature. Candidate site for acceleration of cosmic ray particles

AGN Unification Models

- According to the Unified Scheme of AGN (Urry & Padovani 1995), the TeV emission of M87 is categorized into FRI, where the jet doesn't point along the line of sight, like blazars. Rapid variability observed in radio, optical and X-ray.
  - Short time variability of the TeV emission of M87 correlated with X-rays might prove the unification scheme of BL Lacs and FRIs.

Recent Most Sensitive Imaging Atmospheric Cherenkov Telescope (IACT) Systems

Imaging Technique of the Air-showers

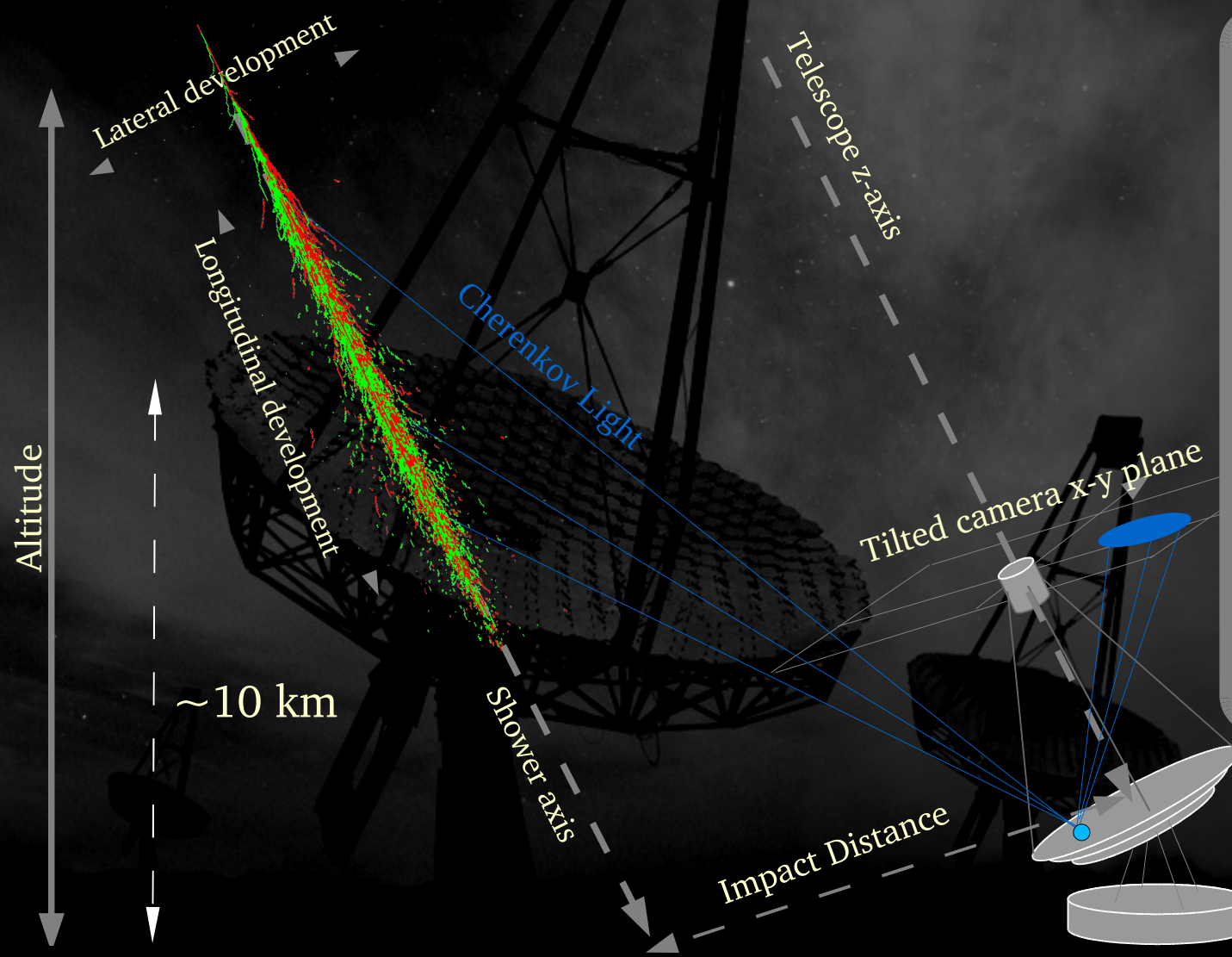
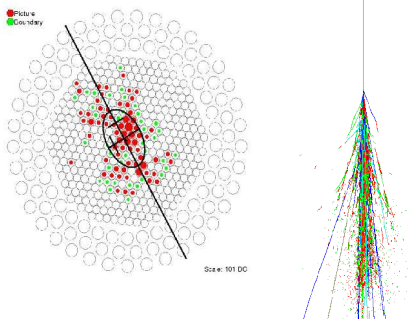
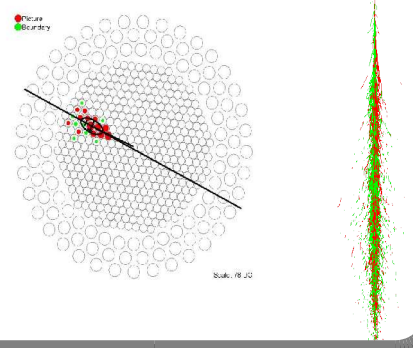


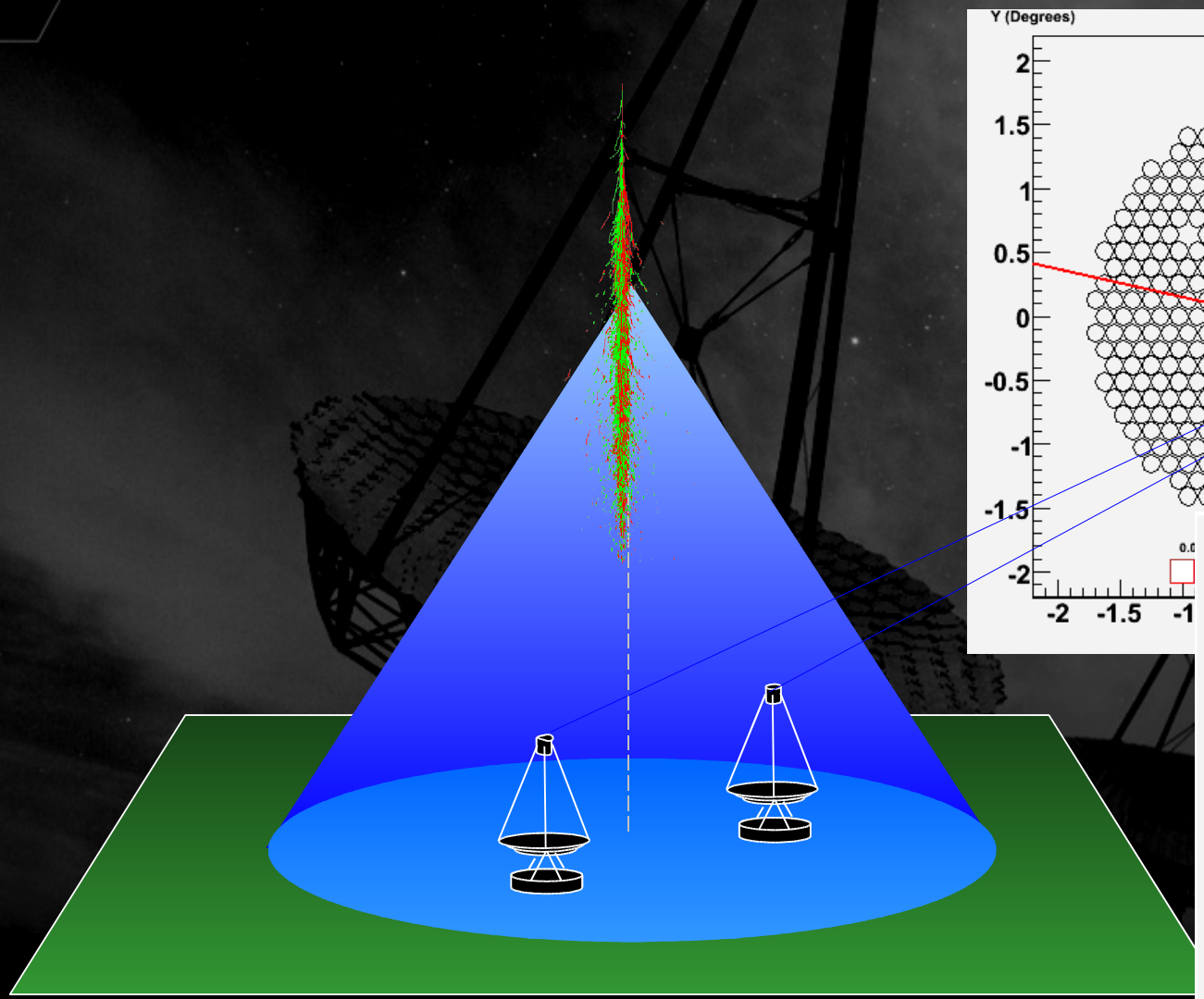
Image of Hadronic Shower

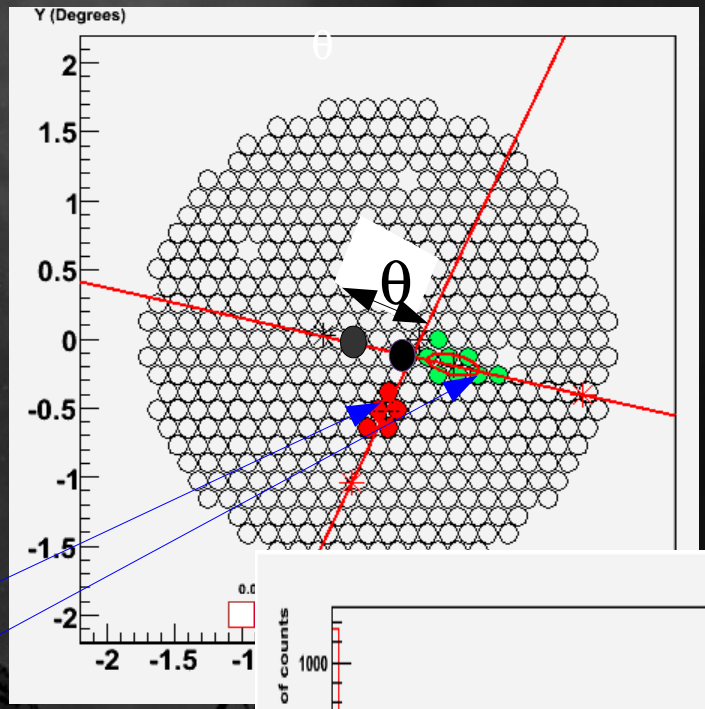


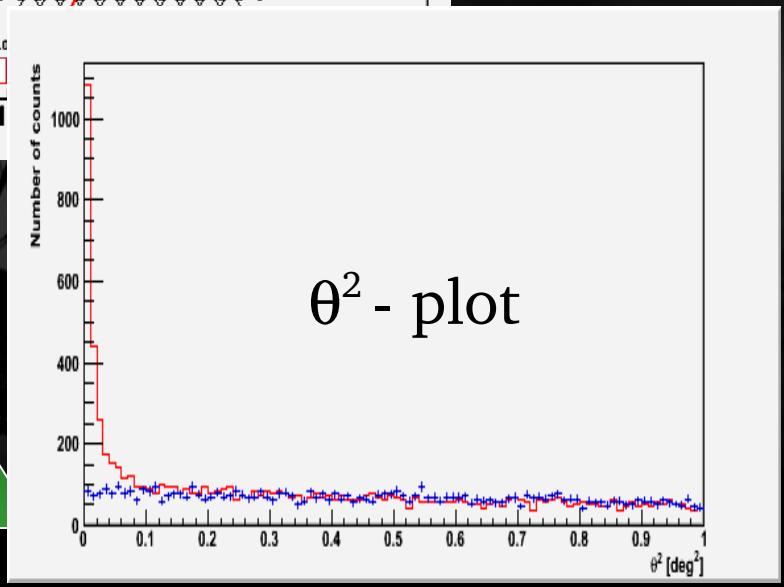
Gamma-ray Shower Image



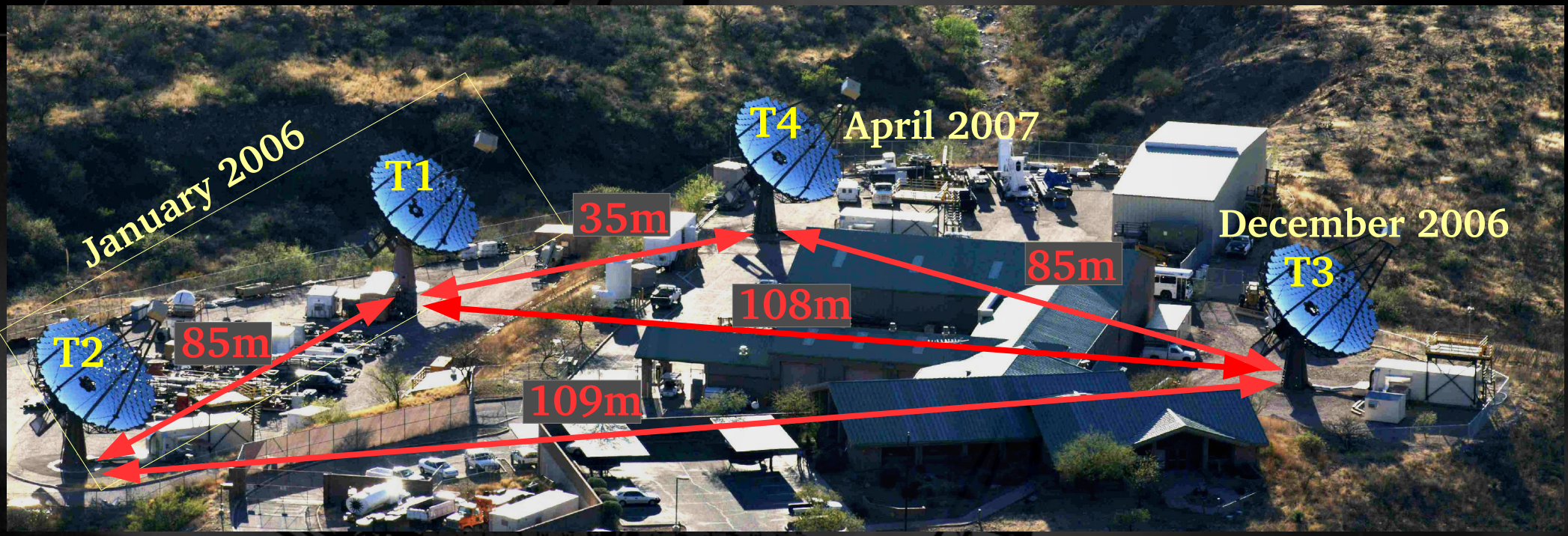
The Reconstruction of the Direction of the Gamma Rays







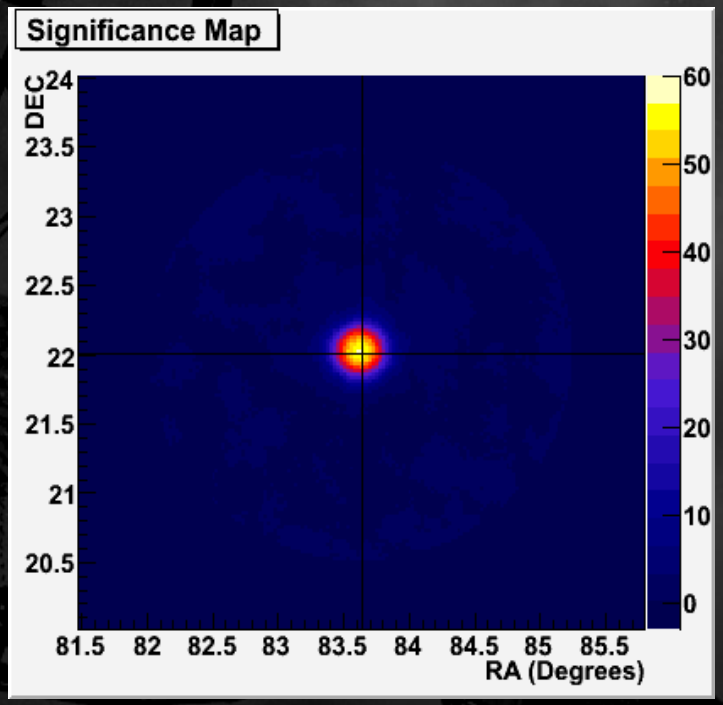
VERITAS at F.L. Whipple Observatory in Amado, Arizona



- Geographic Location: 31° 40´ North, 110° 57´ West, Altitude: 1268 masl.
- Telescope's FoV: 3.5°
- Energy Range: 100 GeV - 30 TeV

The Crab Nebula: A Plerion as Standard Candle

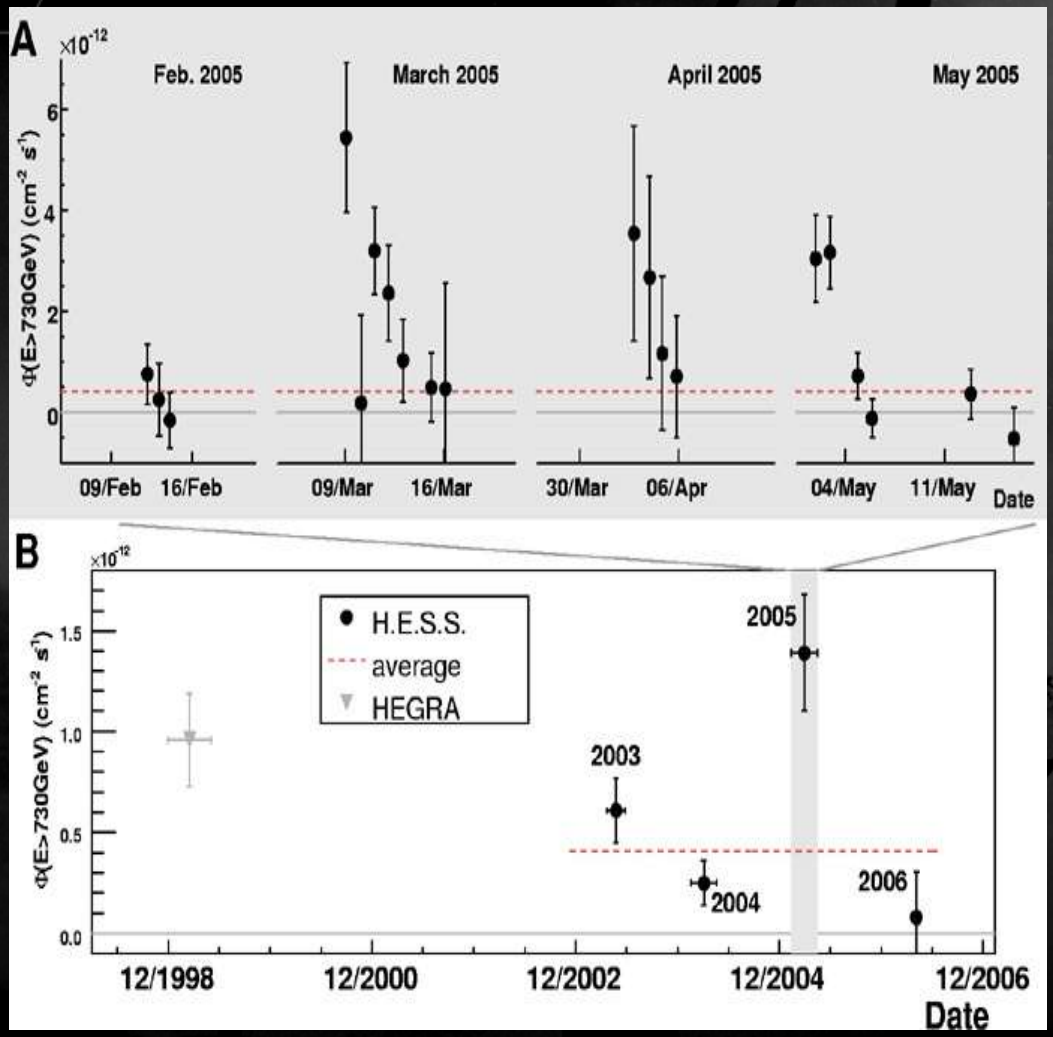
Point-like gamma-ray emission, $\sigma = 0.07^\circ \pm 0.01^\circ$



Point-source Sensitivity:

1% of the Crab Nebula detected at 5σ in $\leq$ 50 hours at 20° zenith

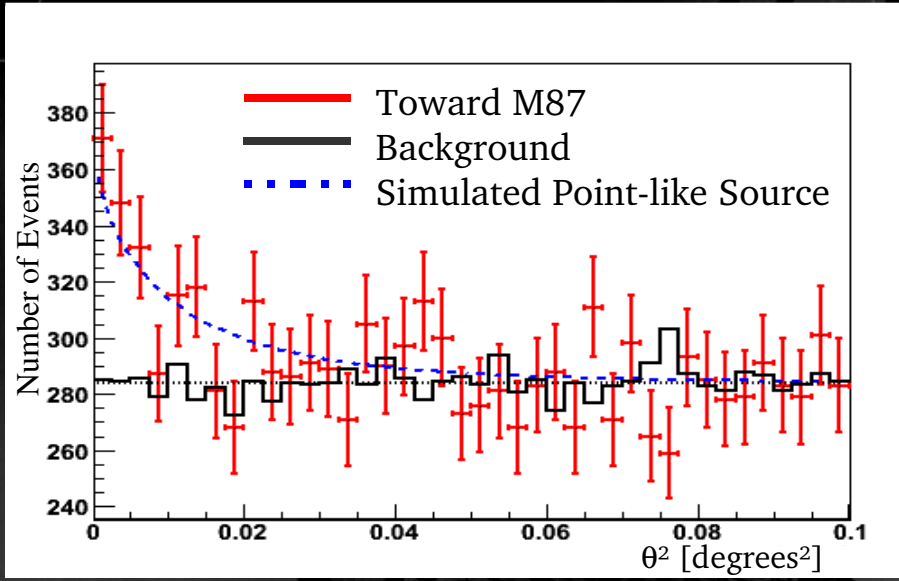
History of the TeV Gamma-ray Observations of M87

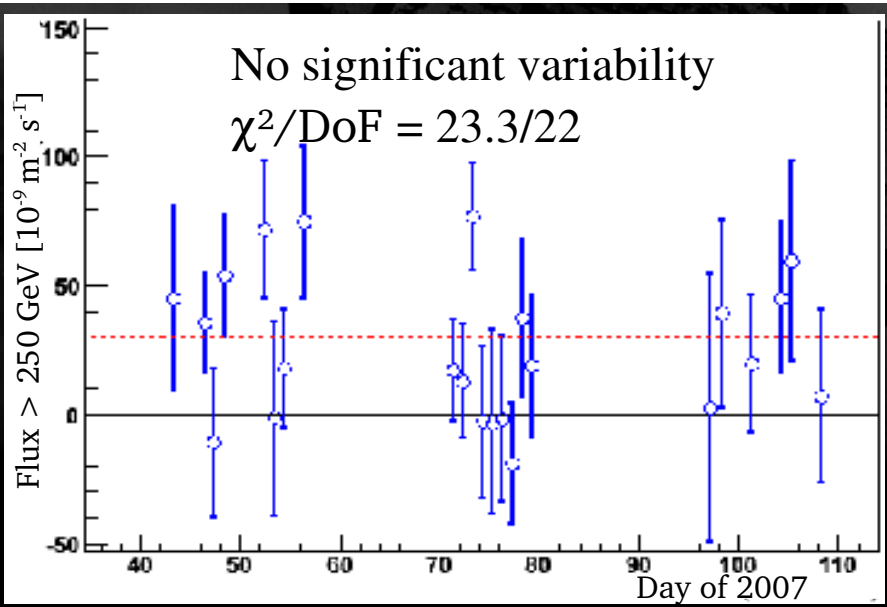


- HEGRA at 4.5 σ (1998-1999)
- Whipple upper limit (2000-2003)
- H.E.S.S. at 13 σ (2003-2006)
  - Year-scale variability in gamma-ray flux
  - Day-scale variability during high state activity in 2005 constraining the emission region
  - Hard spectral index (2.2) in 2005

F.Aharonian et al., Science, Vol. 314, 1424 (2006)

M87 2007 Observations with VERITAS

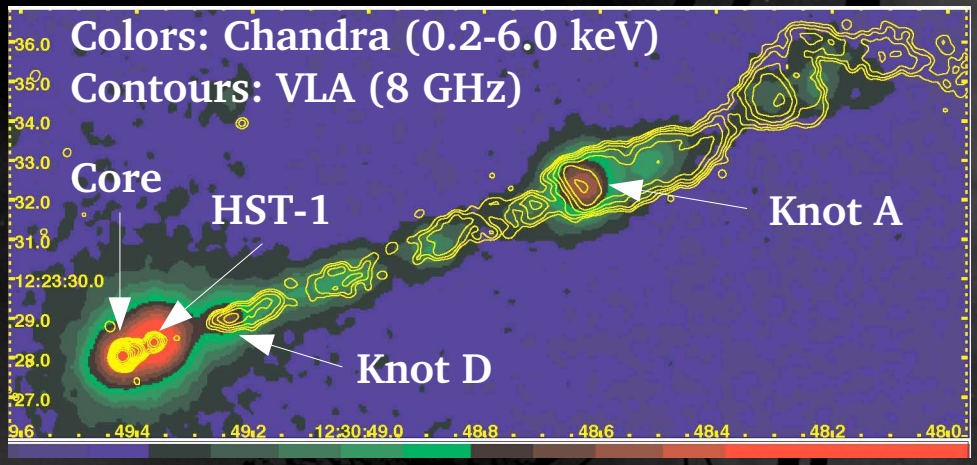




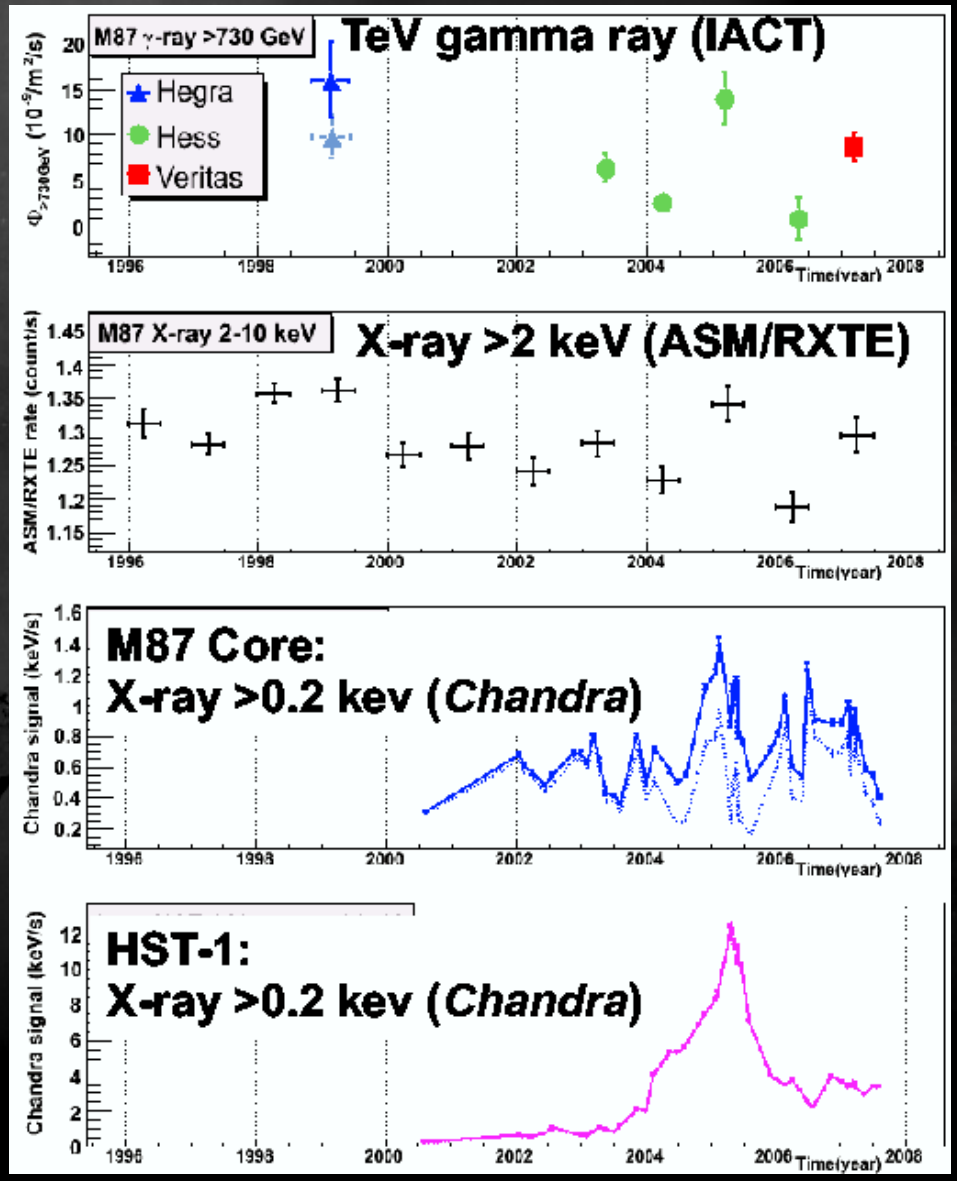
- Observations:
  - February - April 2007 (mostly with 3 telescopes)
- Analysis Results:
  - Exposure: 51 hours (only 44 hours of good data used for analysis)
  - Zenith of Observations: 19° - 35°
  - Significance: 5.9 σ
  - Gamma-ray rate: 0.1 γ /min
  - Flux (> 250 GeV) is 1.9 % of the flux of the Crab Nebula.

V.A. Acciari, Ap.J., Vol. 679, 397 (2008)

Correlation between VHE Gamma-ray and X-ray Measurements

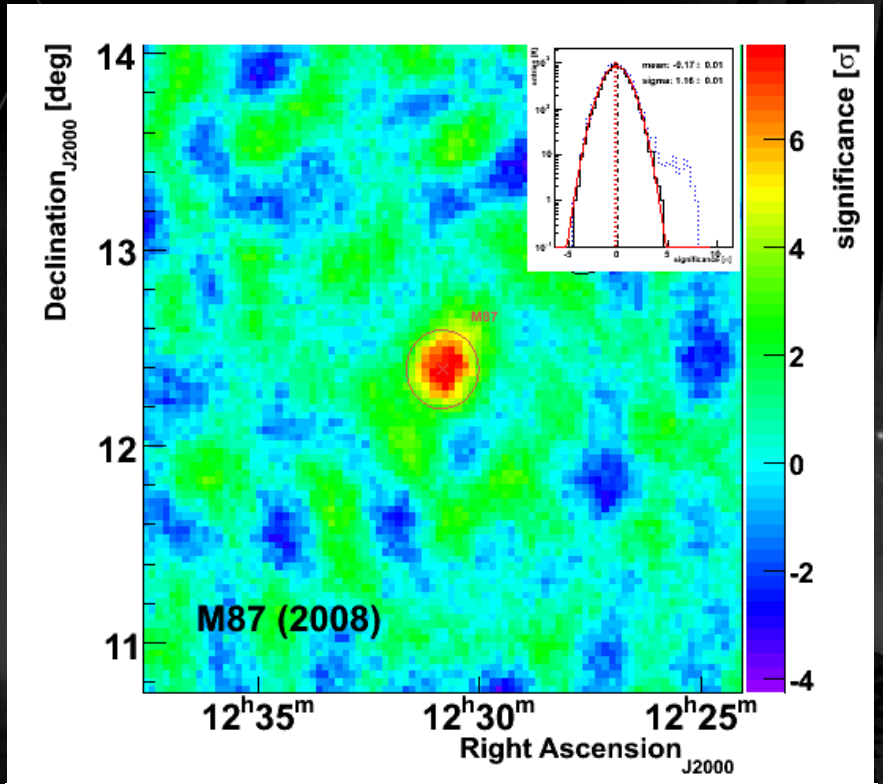


- H.E.S.S. 2005 flare happened during an X-ray outburst in the HST-1 knot on the jet
- VERITAS 2007 measurements correlate with ASM/RXTE, but during this time interval no main outburst was seen from the Core or HST-1 regions by Chandra



V.A. Acciari, Ap.J., Vol. 679, 397 (2008)

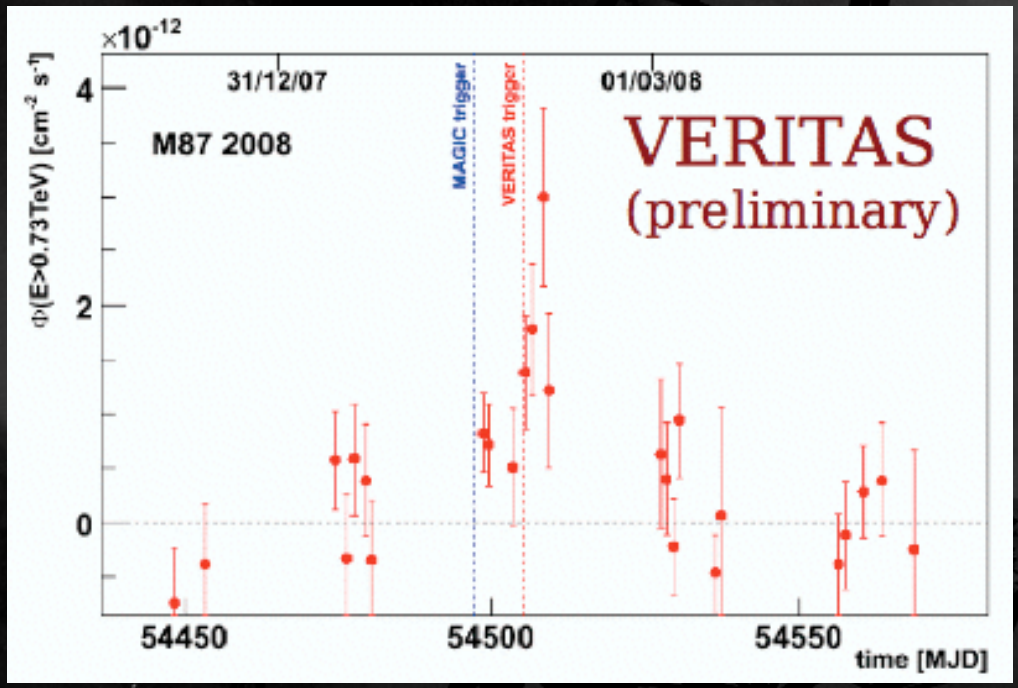
M87 2008 Observations with VERITAS



- Observations:
  - December 2007 (4 telescopes)
  - January – May 2008 (4 telescopes)
- Analysis Results
  - Exposure: 41 hours
  - Zenith of Observations: 19° - 36°
  - Significance: 7.1 σ
  - Gamma-ray rate: 0.14 γ /min
  - Background rate: 0.75 bkg/min
  - Flux (> 250 GeV) is 2.0 % of the flux of the Crab Nebula.

M. Beilicke, M. Hui

2008 H.E.S.S./VERITAS/MAGIC Observation Campaign

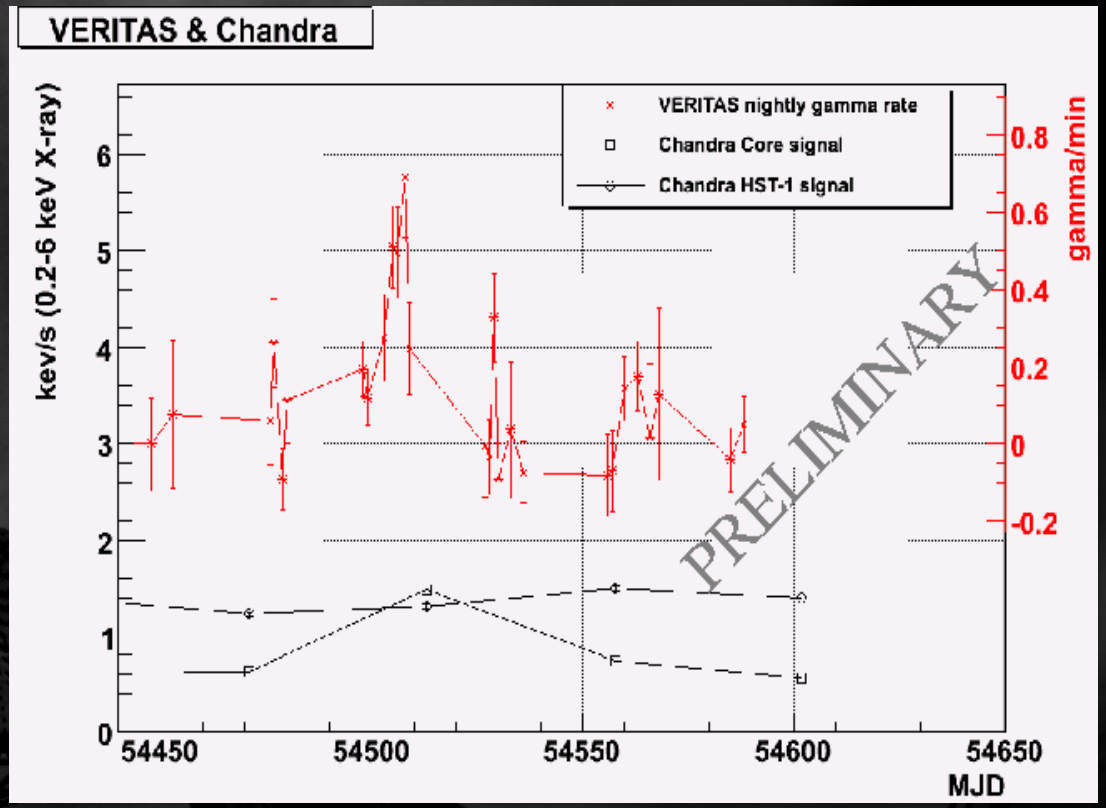


M. Beilicke

- During an X-ray low state of HST-1, MAGIC observed a gamma-ray outburst in February 2008
- MAGIC alerted VERITAS and H.E.S.S.
- About a week after MAGIC trigger, VERITAS detected another flare
  - Confirms short term variability

Correlation Studies

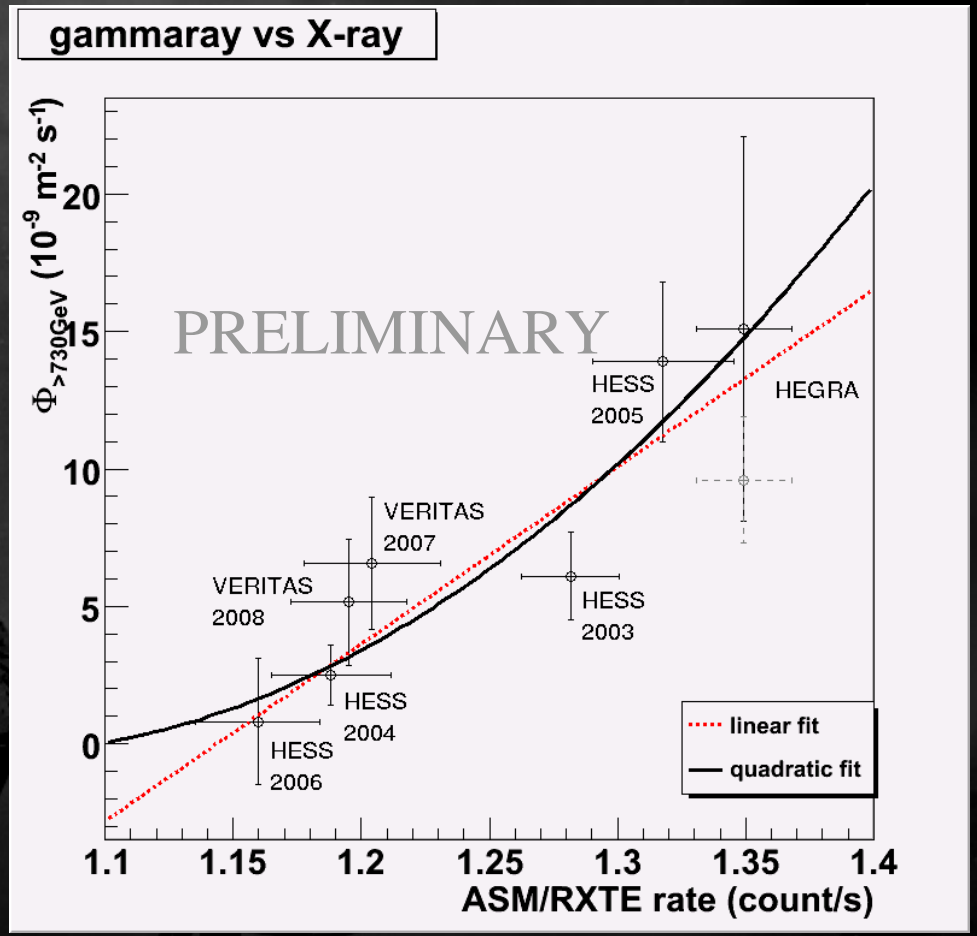
- Possible correlation between the higher X-ray flux measured by Chandra from the Core region and the gamma-ray flux measured by VERITAS during the H.E.S.S./VERITAS/MAGIC observation campaign
- Flux from the HST-1 region is at X-ray low state during this time



M. Hui, D. Harris

Year Scale Correlation with ASM/RXTE

- The year scale correlation between VHE gamma-ray flux (> 730 GeV) measured by the IACTs in the last 10 years and the X-ray rate monitored in the range of 2-10 keV by ASM/RXTE is strong. Good fits with both linear and quadratic functions.



(5 Month Average)
M. Hui, the ASM-RXTE Team

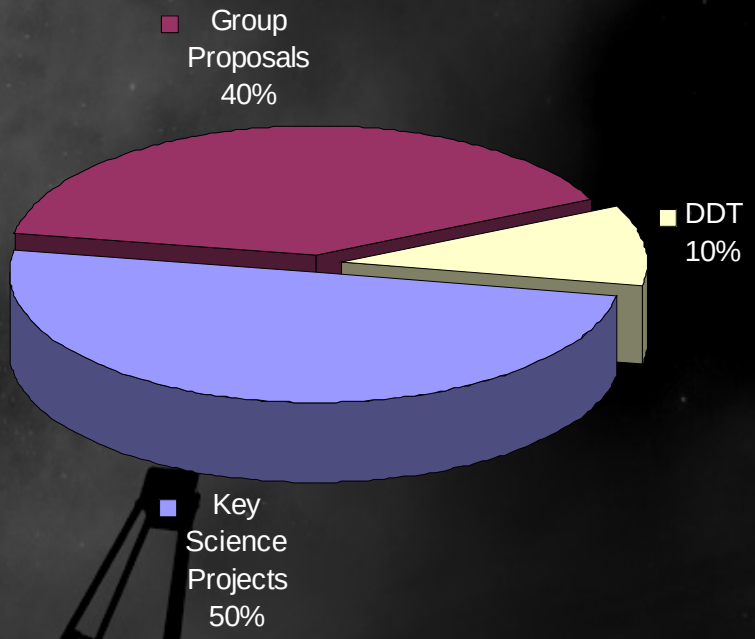
Conclusion

- M87 gives us the unique opportunity to study the mechanism and location of the production of the VHE gamma rays in AGN.
- During Spring 2008 VERITAS observed a gamma-ray flare from M87 with a significance of 7.1 σ .
- The results of the joint VERITAS/H.E.S.S./MAGIC campaign during February 2008 together with the Chandra observations show the gamma-ray flare coinciding with the increased X-ray activity in the Core region of M87.
- Short term variability is observed and it rules out the dark matter models and of gamma-ray production and large scale jet emission model.

From Here On Back-up Slides

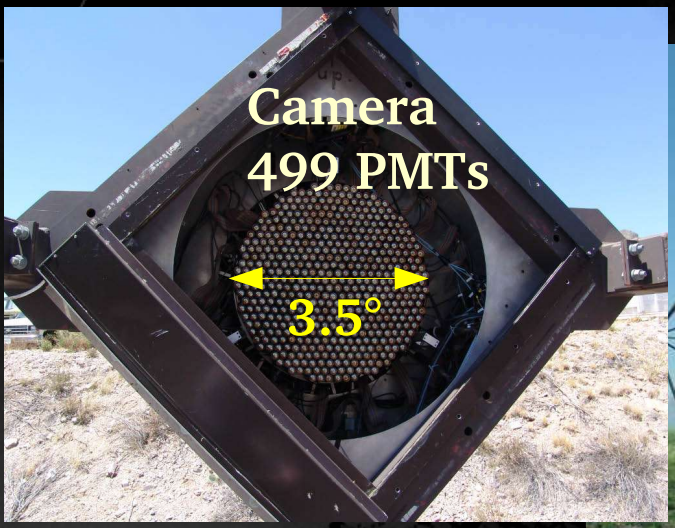
VERITAS Time Allocation

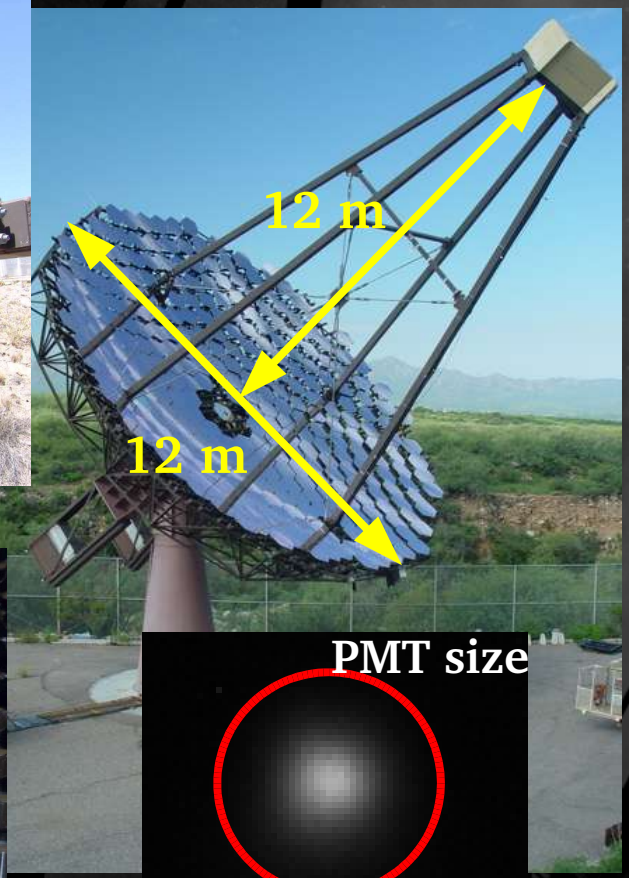
- About 800 hours allocated for science observations and ~ 90 hours for engineering per year.

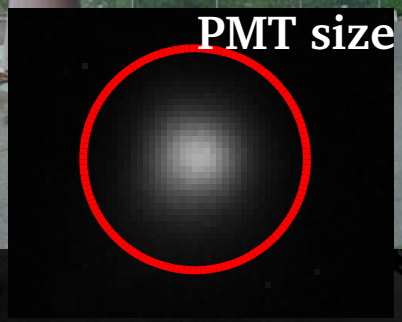


- Key Science Projects
  - Sky Survey (Preliminary scan and follow up observations)
  - Dark Matter (Deep observations of selected candidate sources)
  - Supernova Remnants (Intensive observations, search for new sources)
  - Blazars (MWL campaign for large flare, intensive observation of some AGN, search for new blazars)
- Groups proposals administered by VERITAS Time Allocation Committee (TAC)
- Director's discretionary time (DDT) for engineering, ToO.

The Telescope Design







- Mirror Area: 110 m^2
- Tracking Accuracy: 0.02°
- Angular Resolution : 0.1 – 0.13 ° (energy dependent)
- Energy Resolution: 15 – 20 %

PSF: ~ 0.06° FWHM measured at Polaris (elevation 31°)