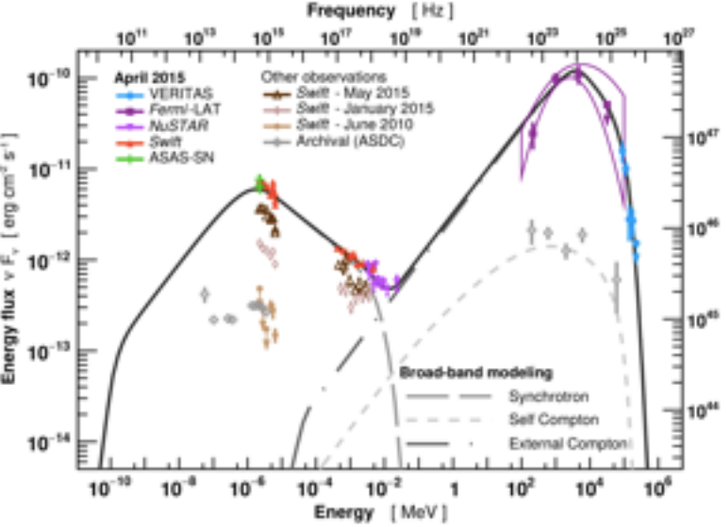
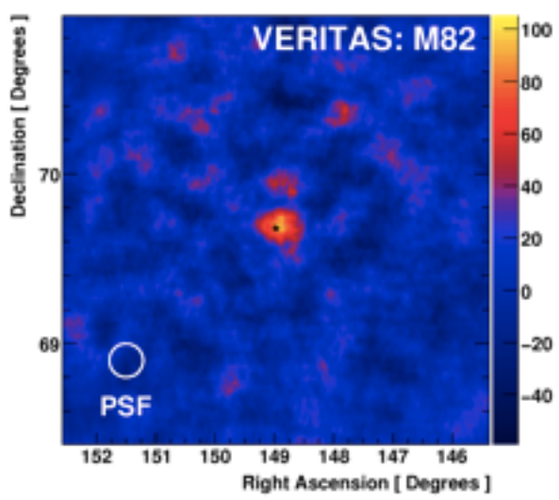
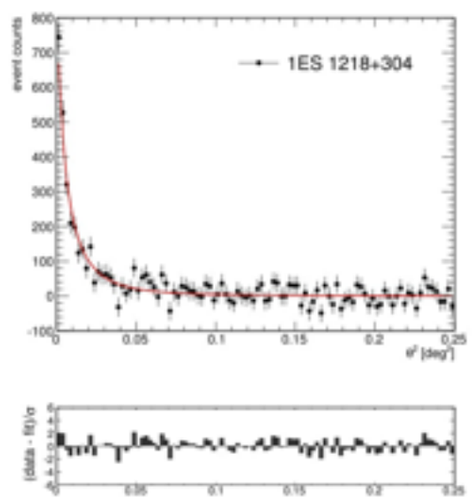
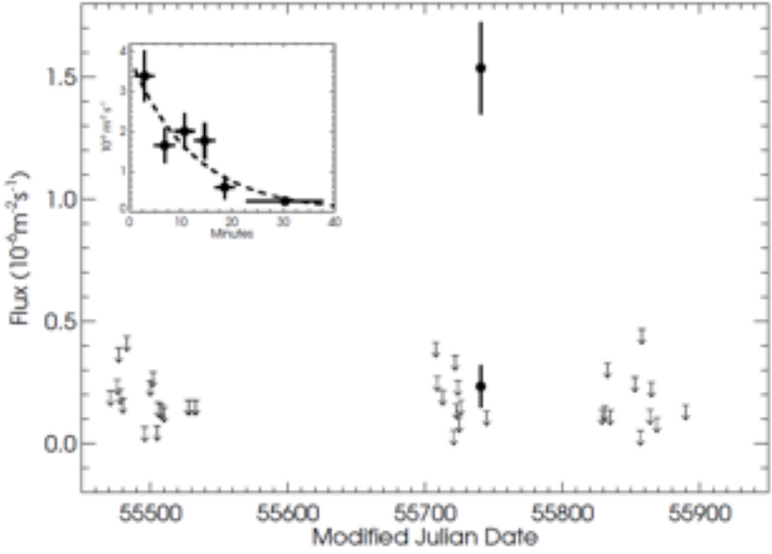
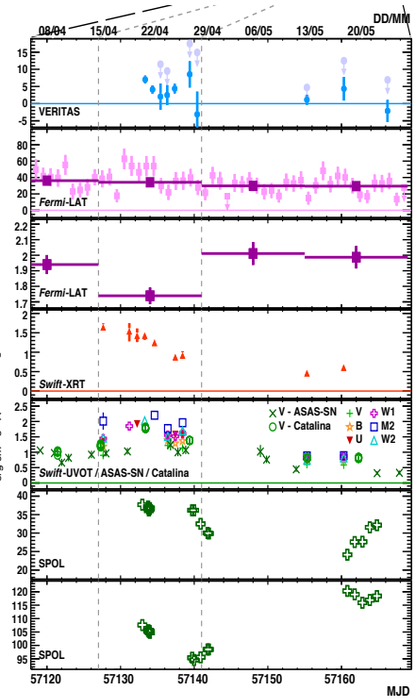


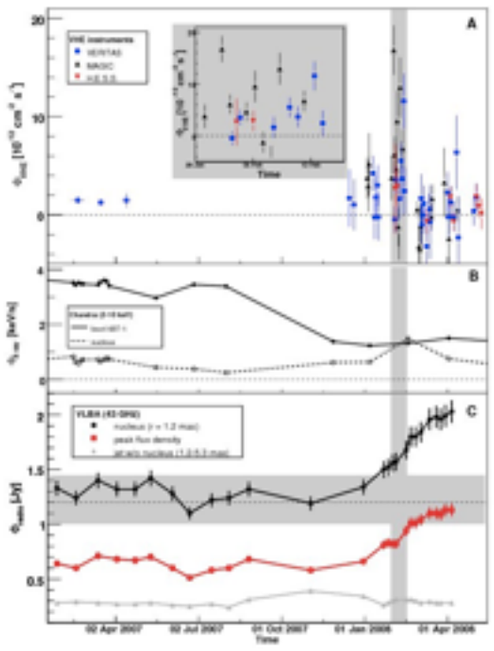


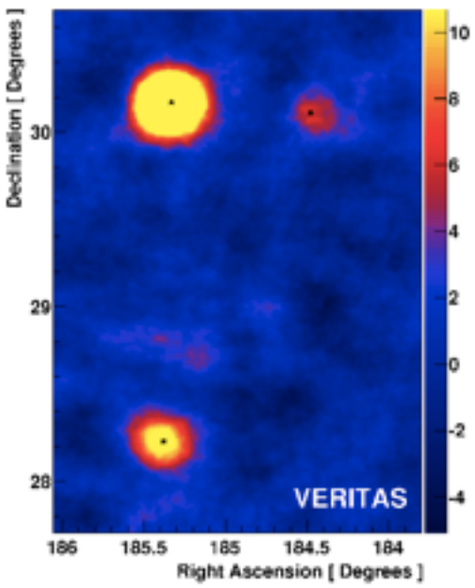


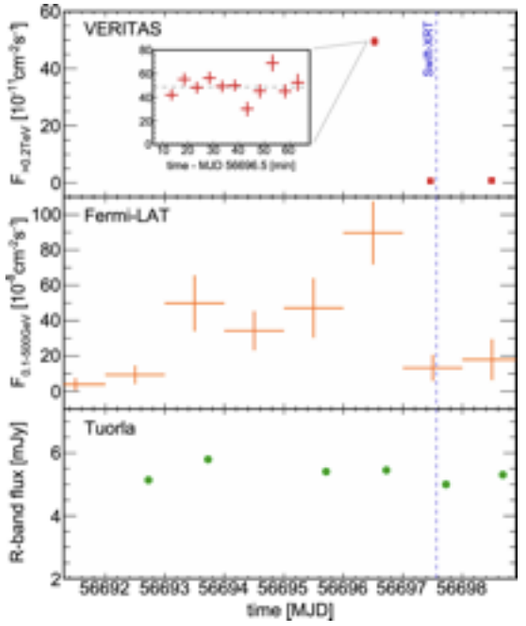


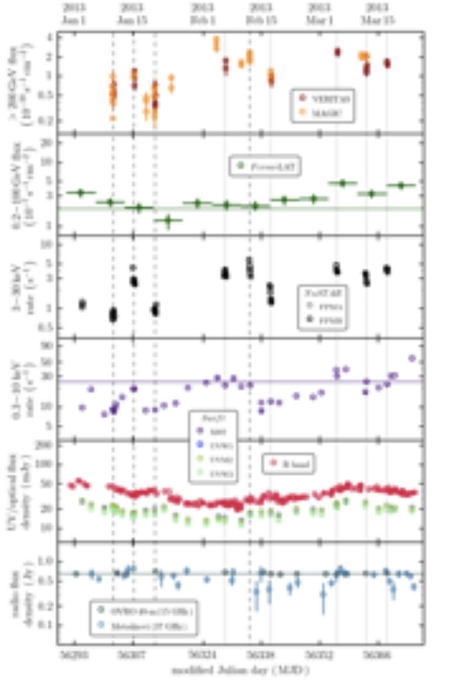
10 Years of TeV Extragalactic Science with VERITAS





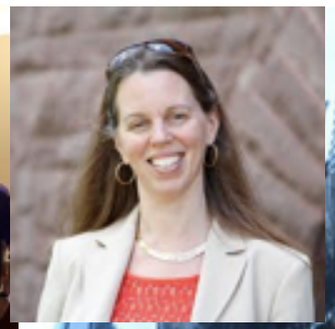
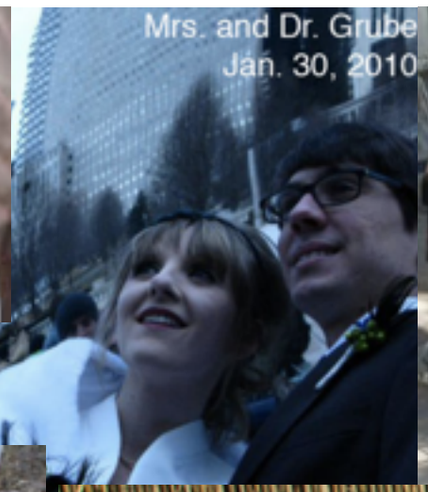




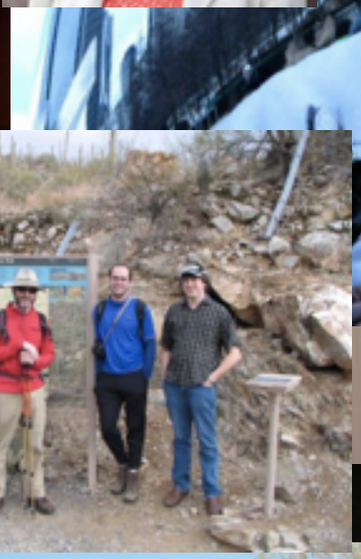


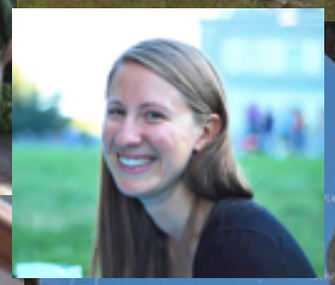
Amy Furniss
California State University East Bay

An unsolicited observation....











An unsolicited observation....

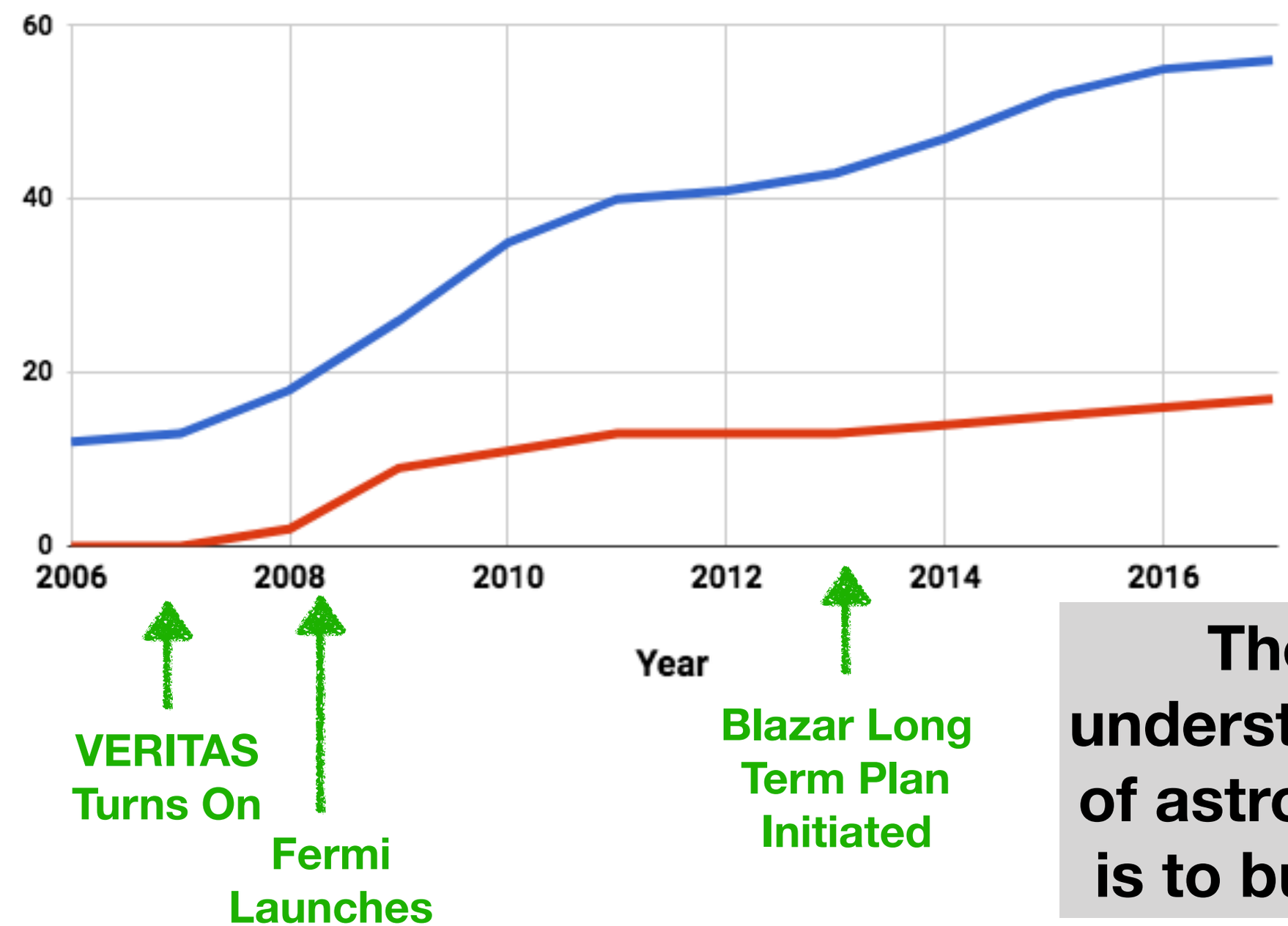
I look forward to continuing this study as more statistics become available

The Ever Present Question: Why Observe Extragalactic Sources with VERITAS?

- Particle Physics and Fundamental Laws
  - Particle processes at the highest energies
  - Lorentz invariance violation
  - Origin of ultra high energy cosmic rays
  - Exotic physics - e.g. evidence for axions
- Cosmology
  - Extragalactic background light density
  - Magnitude of the intergalactic magnetic field
- Black holes
  - Supermassive black holes
  - Jet physics
  - Evolution

VERITAS Discoveries

VERITAS has discovered gamma-ray emission from nearly 20 extragalactic sources in 10 years

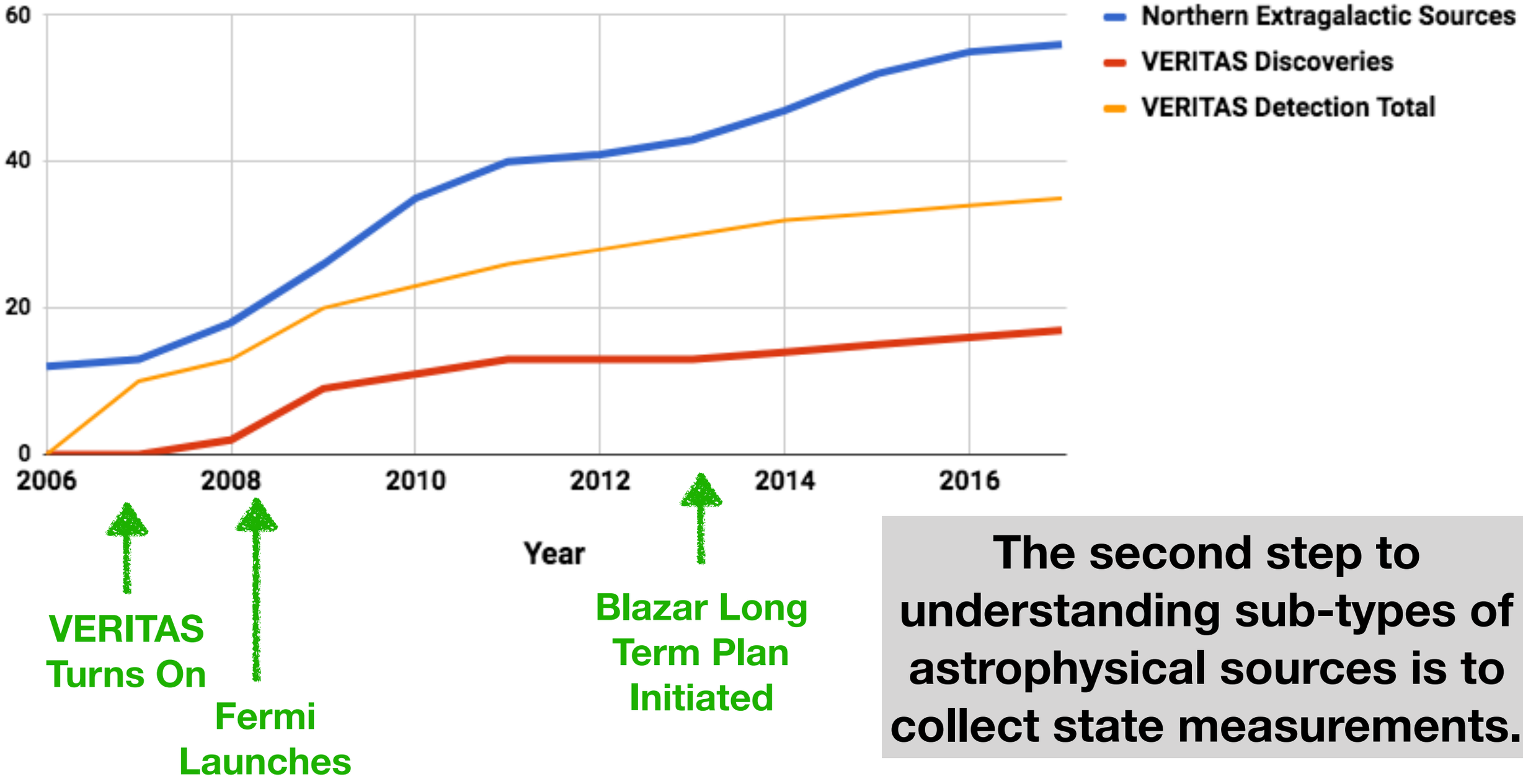


The first step to understanding sub-types of astrophysical sources is to build a population.

VERITAS Detections ✓✓✓✓✓

VERITAS collects data on all visible gamma-ray detected galaxies every year, providing a vast dataset on sources in both low and high emission states

VERITAS Discoveries versus Northern Extragalactic TeV Detections



The second step to understanding sub-types of astrophysical sources is to collect state measurements.

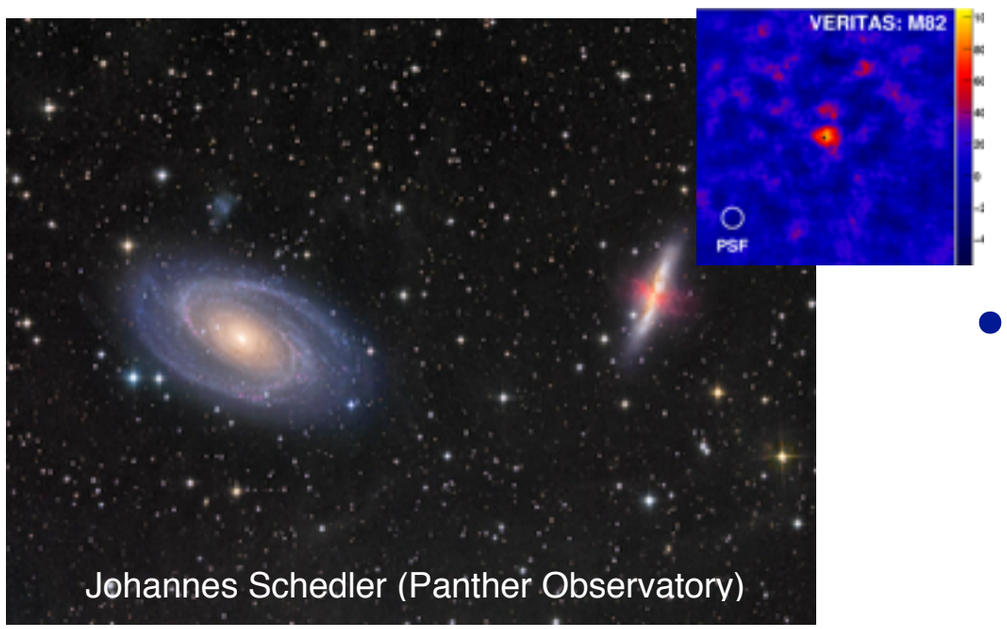
10 Years to Address Fundamental Questions

- What types of galaxies produce gamma-ray emission?
- Where does the gamma-ray emission originate within radio galaxies and blazars?
- How is the gamma-ray emission produced within these sources?
- Is there any pattern or mode to the variability of the gamma-ray emission from these sources?
- How is the gamma-ray emission related to the lower-energy emission emerging from these sources?
- How do the spectral signatures of these sources change as the sources evolve?
- What is the astrophysical origin of ultra-high-energy cosmic rays?
- What secondary interactions do gamma rays undergo as they travel extragalactic distances?
- What is the density of the low redshift optical/IR light produced by stars and galaxies?
- What is the magnitude (and origin) or the intergalactic magnetic field?

What type of galaxies produce gamma-ray emission?

The Starburst Galaxy M82

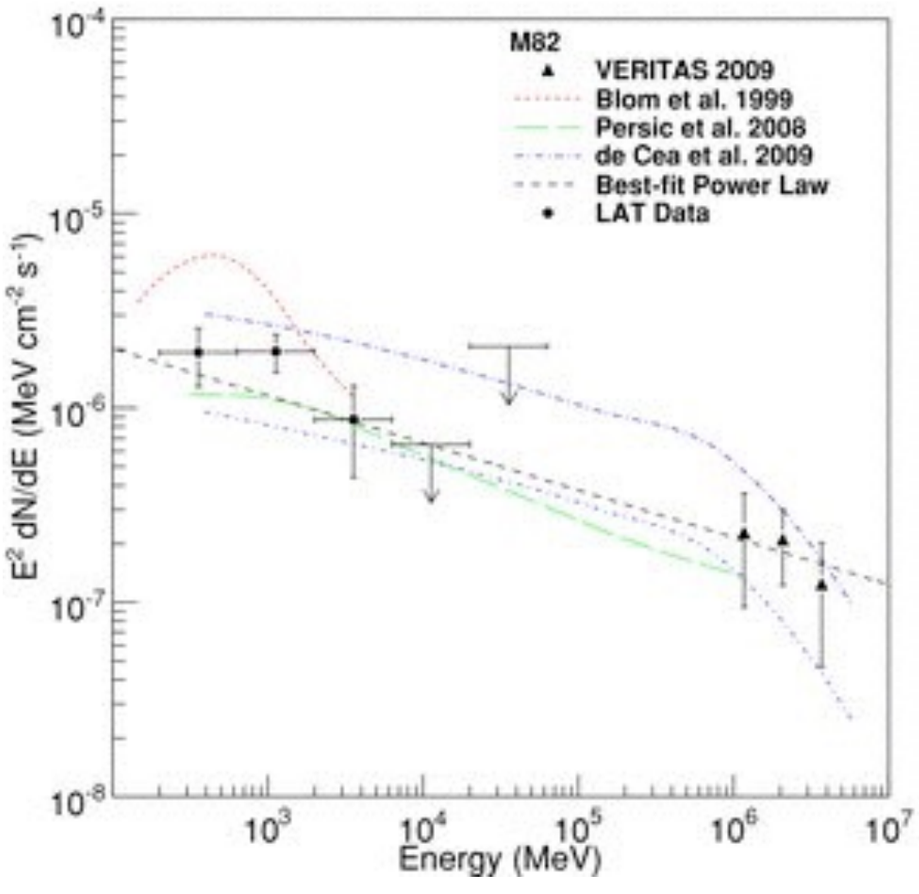
V. A. Acciari et al., Nature, volume 472, 770-772, 2009



CR hadrons + gas => pions => γ-rays

CR e^- + ambient photons => γ-rays

- M 82 is a prototypical starburst galaxy
  - D = ~3.9 Mpc toward Ursa Major: EBL a non-issue
  - Diameter ~1' => Point-like for VHE γ-ray studies
  - Central SMBH: < 3 x 10^7 M_{sun}; No evidence of an AGN
  - Starburst region
- Tidal forces => Active starburst region
  - Diameter ~ 1000 light years
  - HST => Contains >200 massive star clusters
- High star formation rate: ~10x Milky Way
- High supernova rate: ~0.1 to ~0.3 / year
- VERITAS (2007-09): ~137 h live time
- E_{th} ~ 700 GeV; Sensitivity less at elevation ~ 39°
- Nice agreement with Fermi-LAT detection, Γ = 2.5

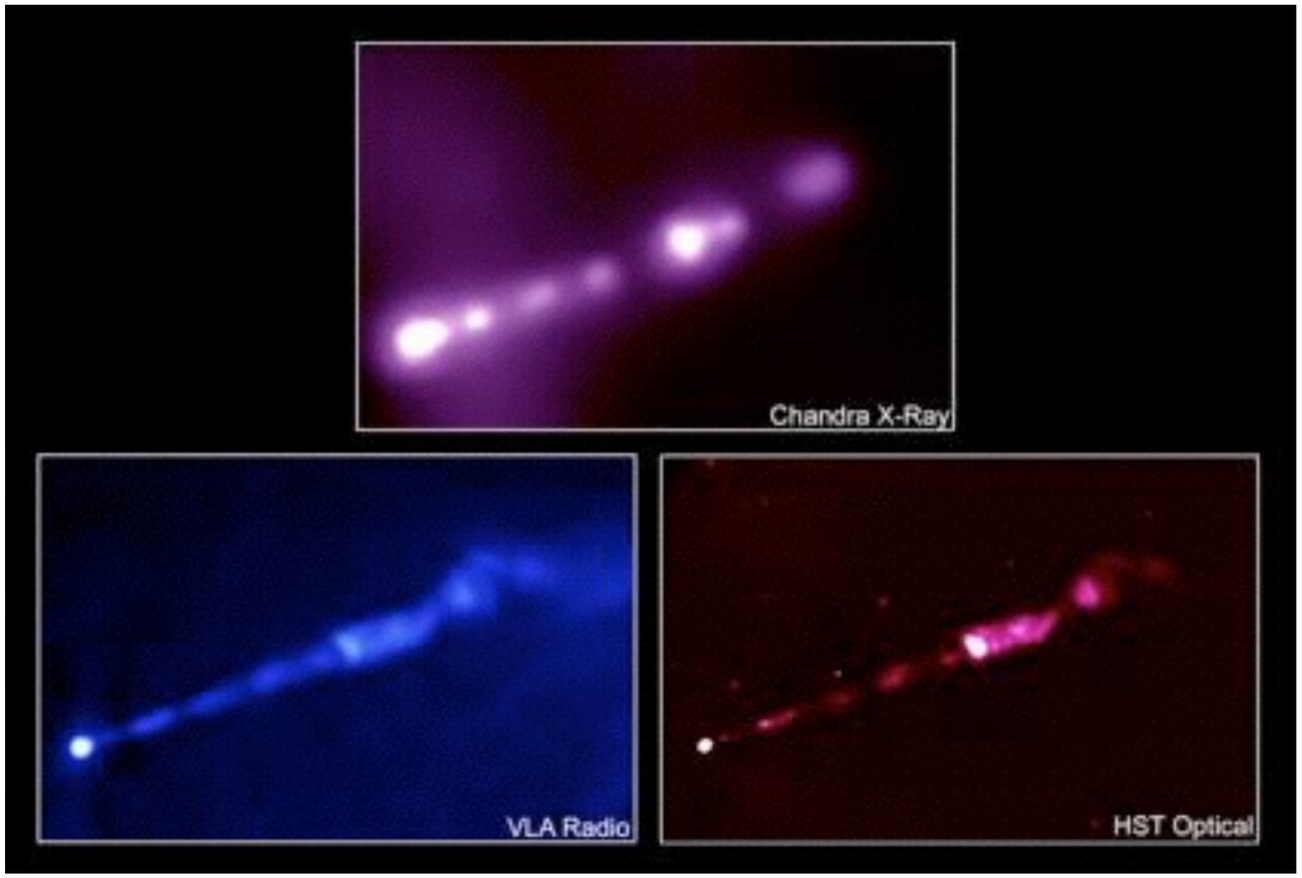


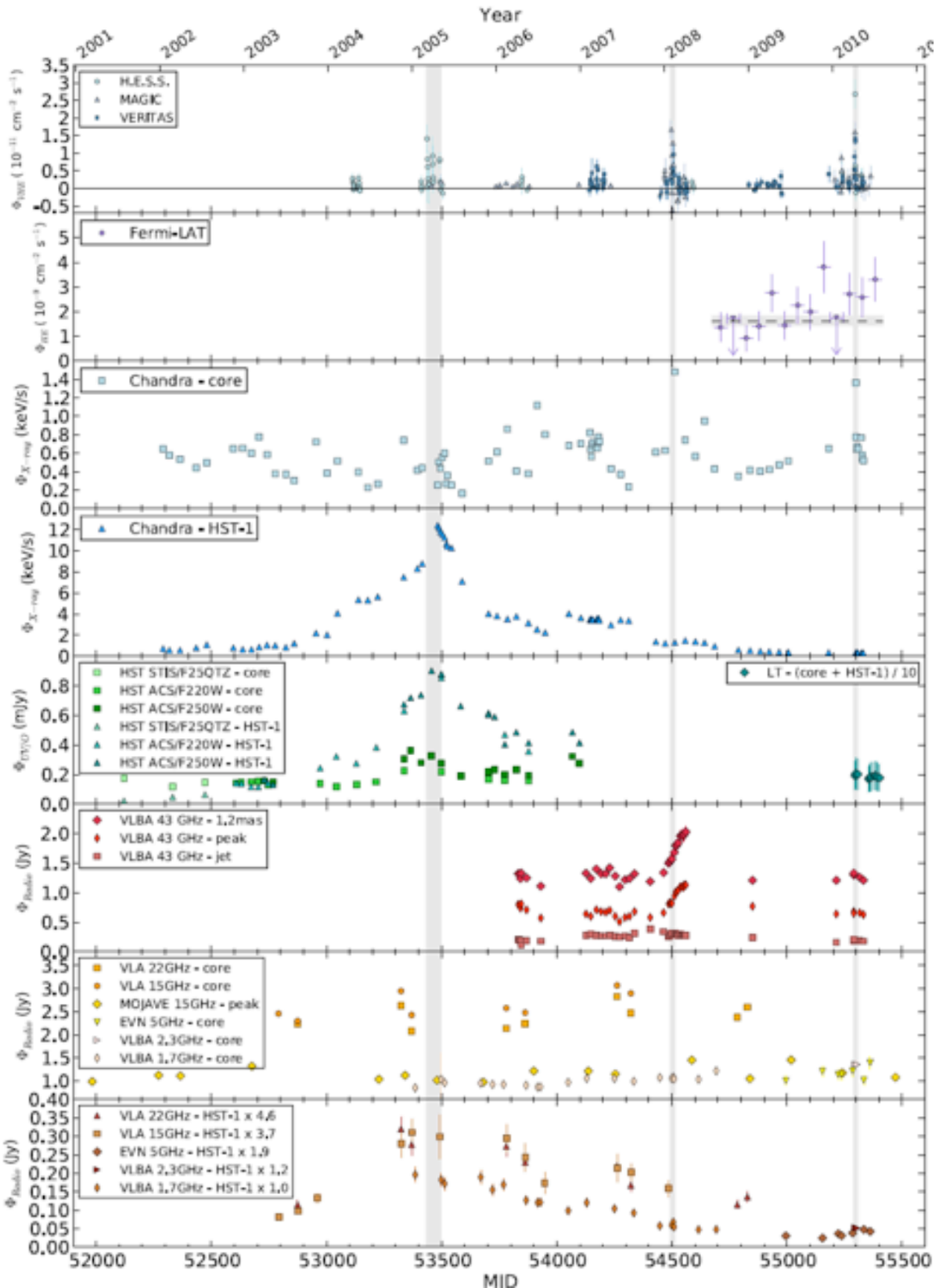
Where does the gamma-ray emission originate within radio galaxies and blazars?

The Radio Galaxy M87

A. Abramowski et al. (The VERITAS Collaboration, with HESS, MAGIC, Fermi, Chandra, HST and others), Astrophysical Journal 746: 151, 2011

- Unique laboratory for the jet and substructure studies
- Big MWL γ-ray, X-ray and Radio campaign between 2008-2011 (VERITAS/MAGIC/ HESS/VLBA/Chandra)
- Location of VHE emission region still uncertain despite apparent correlations in MWL data



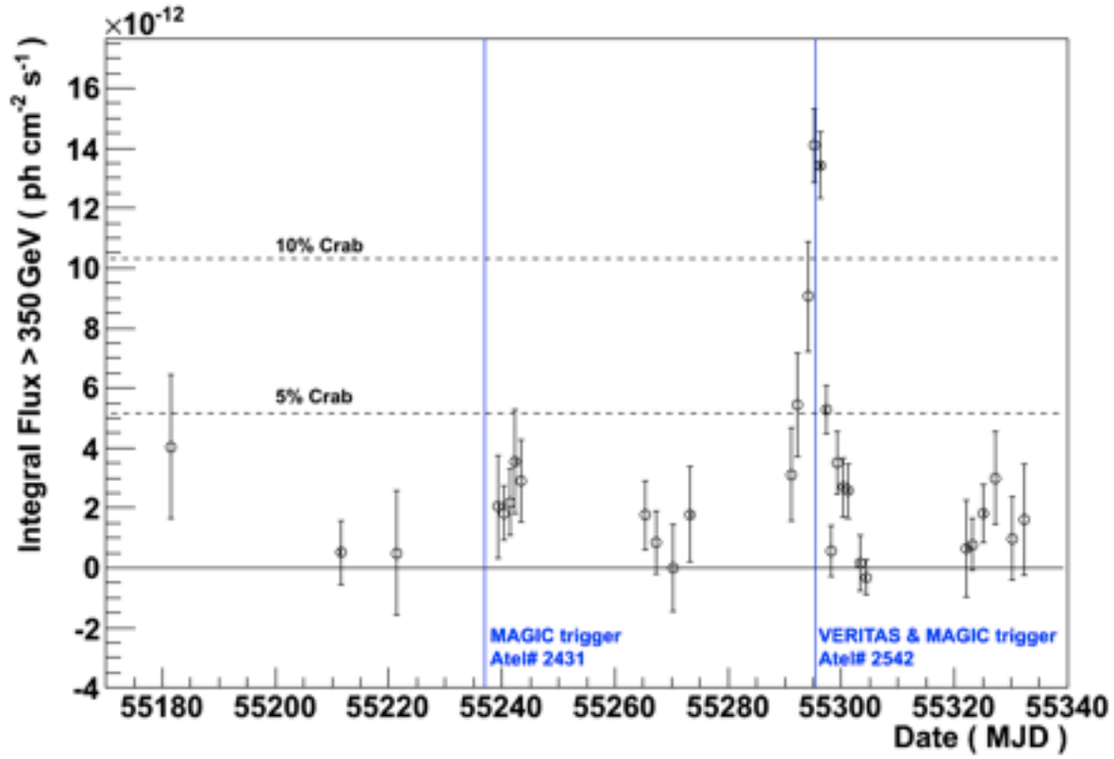


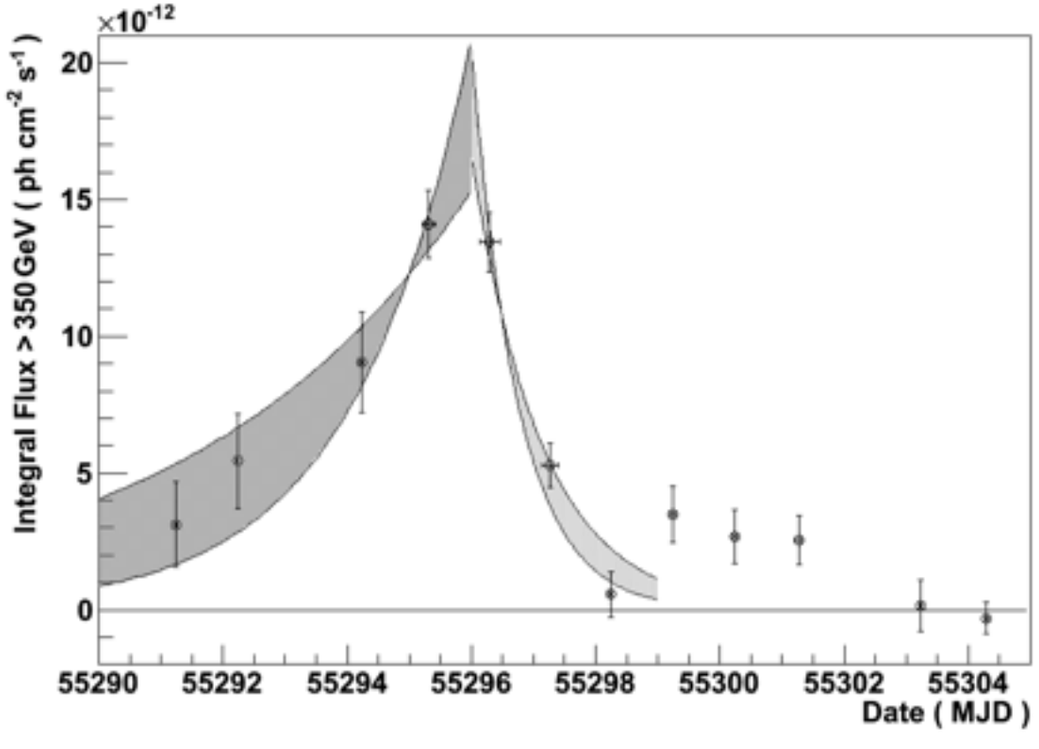
Where does the gamma-ray emission originate within radio galaxies and blazars?

The Radio Galaxy M87

E. Aliu et al. (The VERITAS Collaboration), Astrophysical Journal 746: 141, 2012

- Coordination continues between the IACT instruments when observing this source
- The exponential timescale is ~3 days for the rising side of the flare, and ~1 day for the falling side of the flare
- The spectra and timescales derived from this dataset favor the predictions by leptonic models over those of hadronic or large scale models
- Through causality, the timescale of the enhanced TeV emission implies an emission region size of $R \leq 5 \times 10_{15}\, \delta$ cm
- Both the core and HST-1 are still viable candidates for VHE gamma-ray emission following these observations

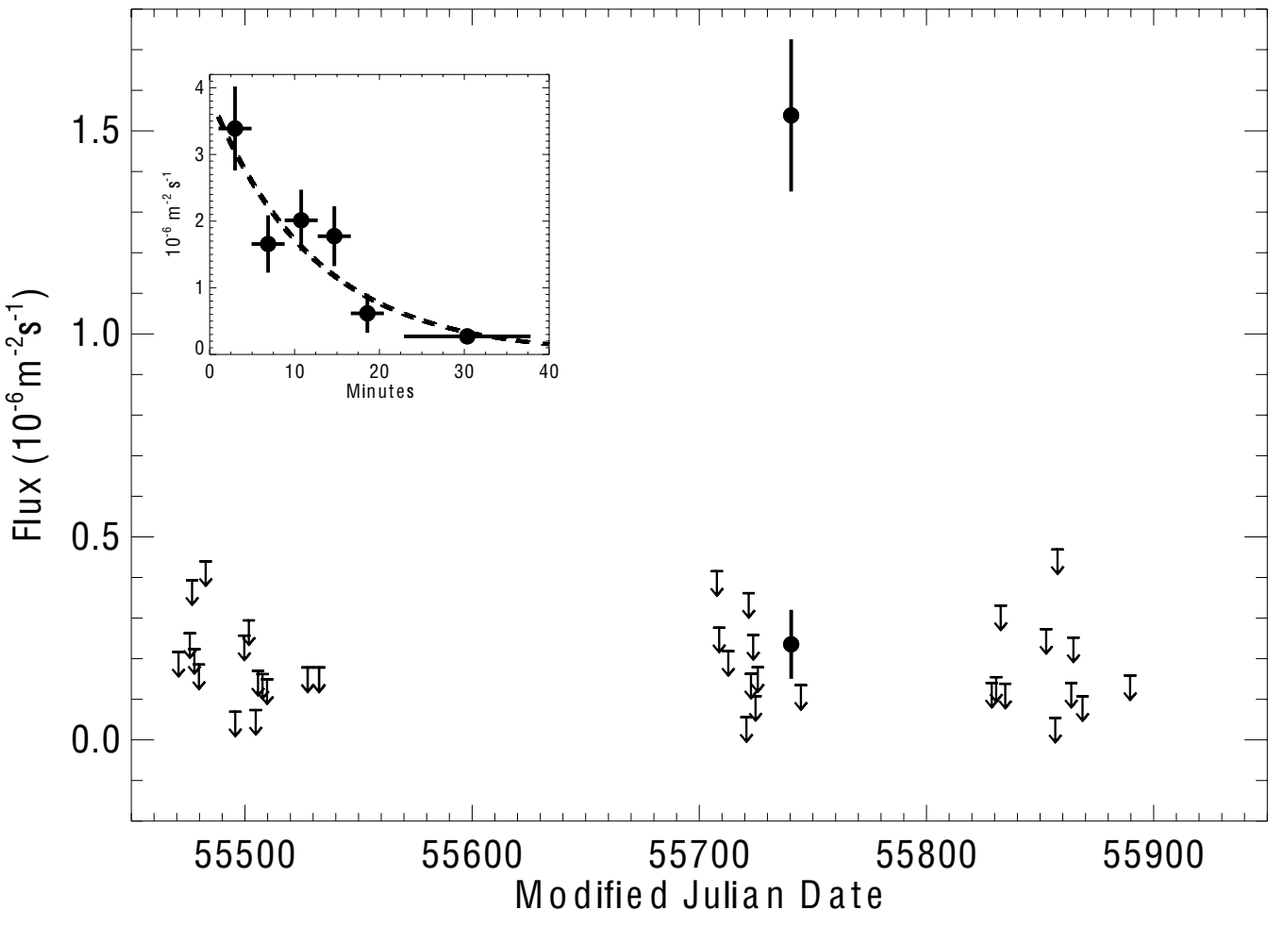




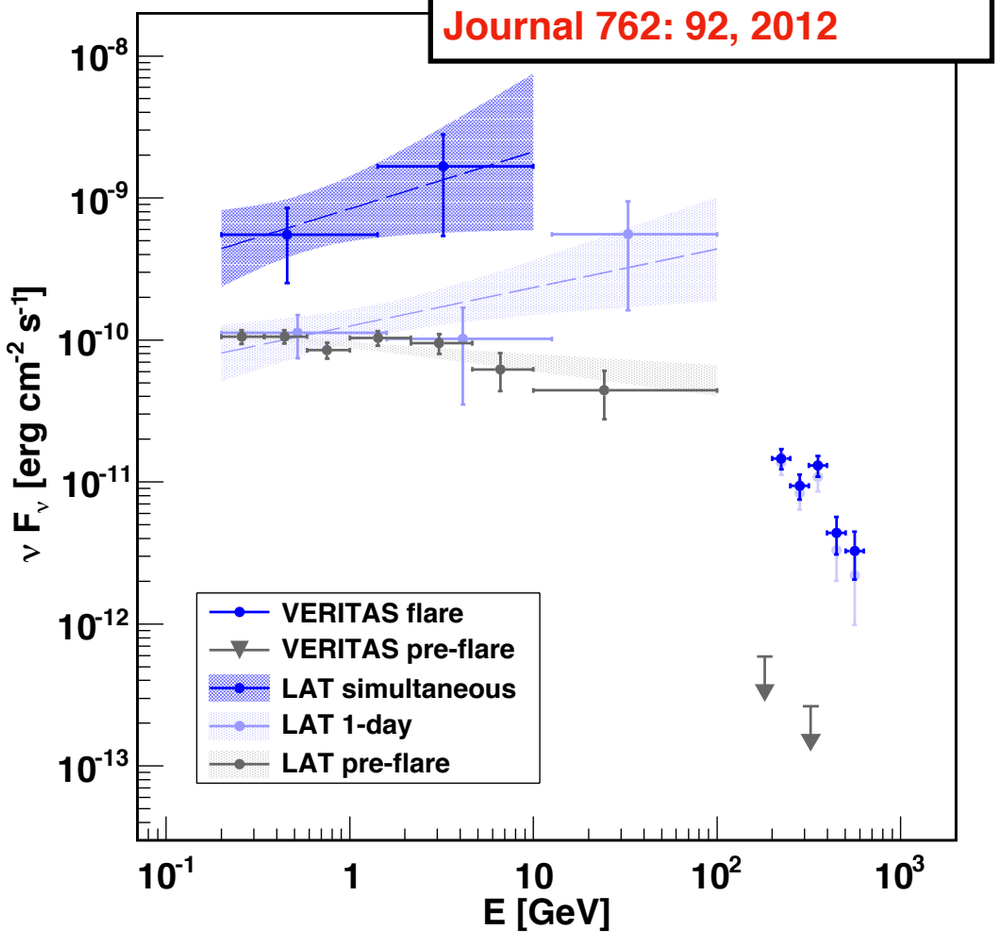
Is there any pattern or mode to the variability of the gamma-ray emission from these sources?

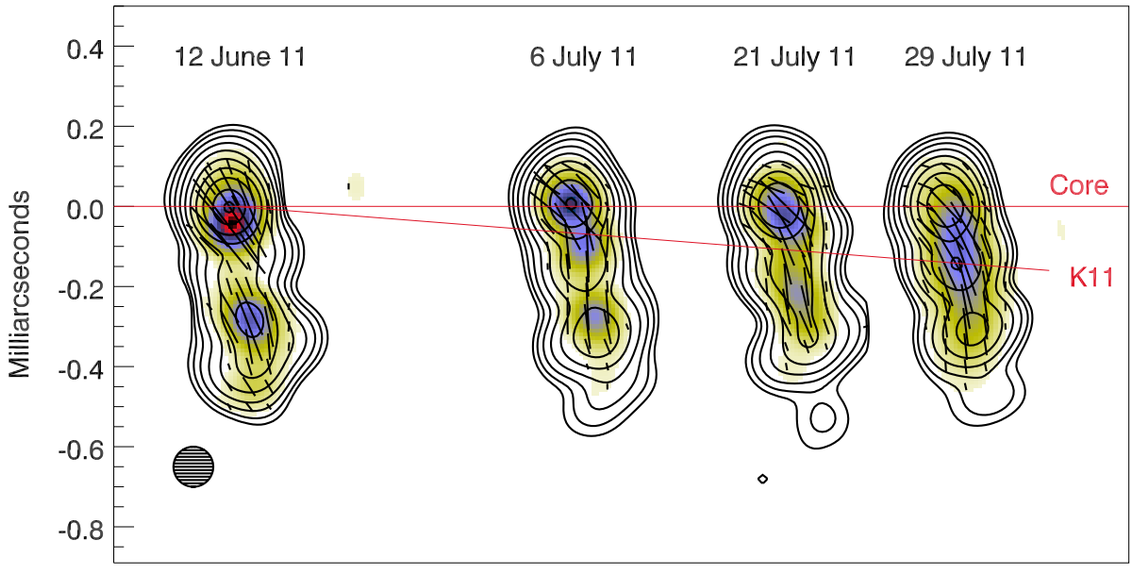
Initial Insight from BL Lacertae

- MAGIC discovered TeV-blazar (2005)
- VERITAS non-detection 2010 < 3% Crab
- Many reports of MWL activity (May 2011)
- June 28th 2011 VERITAS (3T, twilight) observed a flare in a 40 min observation
- Soft spectrum $\Gamma = 3.6 \pm 0.4$ at ~125% Crab



T. Arlen et al., Astrophysical Journal 762: 92, 2012

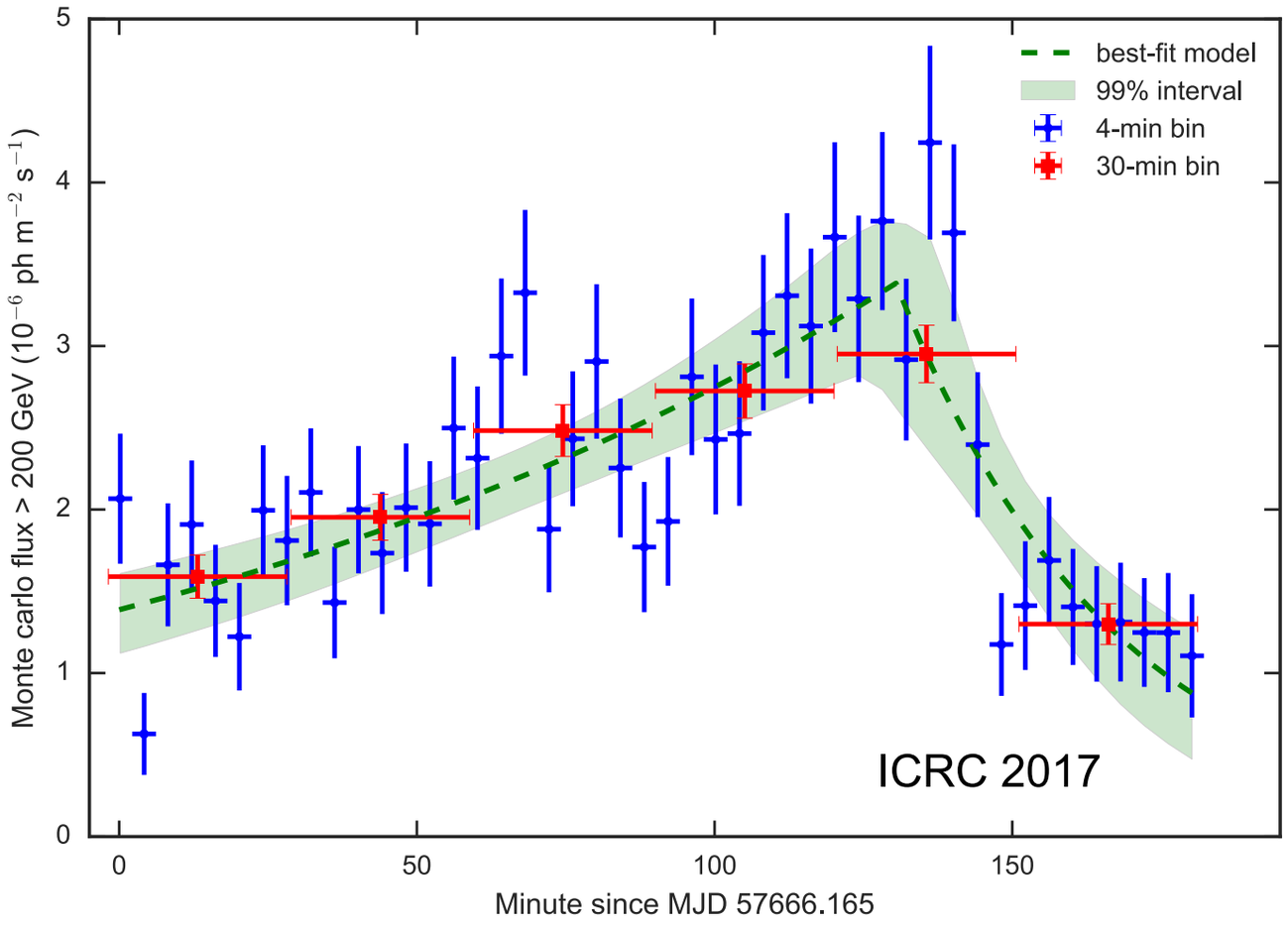




Is there any pattern or mode to the variability of the gamma-ray emission from these sources?

Additional Insight from BL Lac

Observations in October 2016



- VERITAS detected a fast flare from BL Lac, reaching a flux of ~180% Crab
- The decay time is of order ~30 minutes, and faster than the rise time
- This constrains the size of the emitting region to be less than 12 Schwarzchild radii
- Observation of a correlated, albeit slower, GeV/optical flare at the time of the TeV flare
- Changes in polarization observed in both R band and radio frequencies
- VLBA 43 GHz images consistent with a superluminal radio knot passing the core around the time of the TeV flare (but the interpretation is not unique).

Where and how is the gamma-ray emission produced within these sources?

The VERITAS Detection of OJ 287

The Astronomer's Telegram

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25 Jun 2017; 17:53 UT

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VERITAS Detection of VHE Emission from OJ 287

ATel #10051; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on 5 Feb 2017; 02:02 UT
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

We report the detection of VHE emission (>100 GeV) from OJ 287 with VERITAS. The source was observed by VERITAS between 1 February and 4 February 2017 (UTC), for a total exposure of 13.0 hours. OJ 287 is an optically bright quasar, known to display quasi-periodicity with roughly 12-year optical cycles (Shi et al., Ap&SS 310, 59, 2007), and is believed to host a binary supermassive black hole (Valtonen et al., ApJ, 643L, 9, 2006). The VERITAS observations were carried out in response to a rising X-ray flux, noted in the X-ray light curve measured by Swift-XRT; see http://www.swift.psu.edu/monitoring/source.php?source=OJ287 (Stroh & Falcone, ApJS, 207, 28, 2013). A preliminary analysis of the VERITAS observations yields an excess of 141 events above the background at the position of the blazar, corresponding to a statistical significance of 5.7 standard deviations. The corresponding flux observed above 100 GeV is (18 +/- 3) x 10^-12 cm^-2 s^-1, or 3% of the Crab Nebula flux above the same threshold. VERITAS measurements of possible enhanced gamma-ray activity on 2017 Feb 1, led to Swift observations on Feb 2 and 3, which showed the source to be in a remarkably high X-ray state at, or near, the same time (Grupe et al., ATel 10043). VERITAS will continue to observe OJ 287; multi-wavelength observations are encouraged. Questions regarding the VERITAS observations should be directed to Reshmi Mukherjee (muk@astro.columbia.edu). Contemporaneous target-of-opportunity observations with the Swift satellite have also been scheduled. VERITAS (Very Energetic Radiation Imaging Telescope Array System) is located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, and is most sensitive to gamma rays between ~85 GeV and ~30 TeV (http://veritas.sao.arizona.edu).

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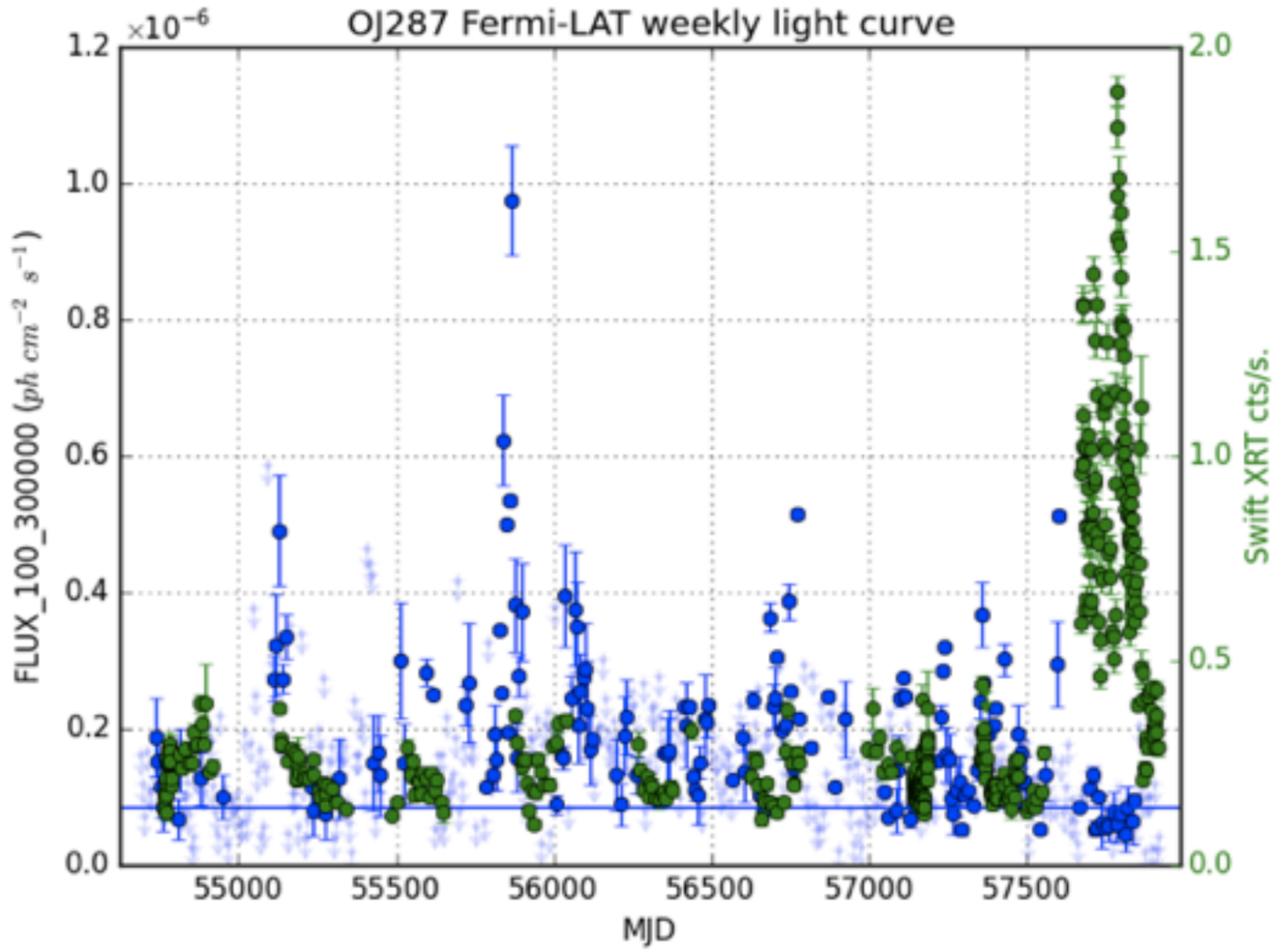
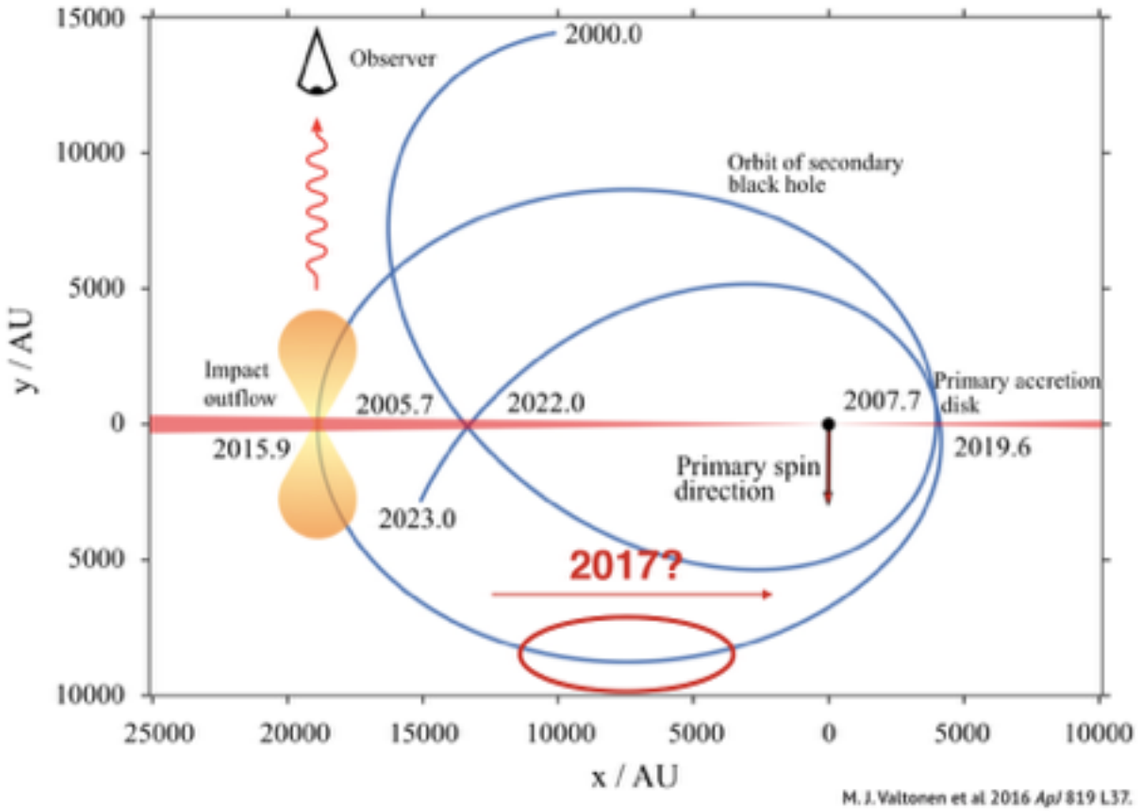


- OJ 287 is a blazar around z~0.3
- Proposed as a source with a binary supermassive black hole system
- Detected during high X-ray activity/low *Fermi*-band activity
- Not inline with predicted high state according to optical modulation

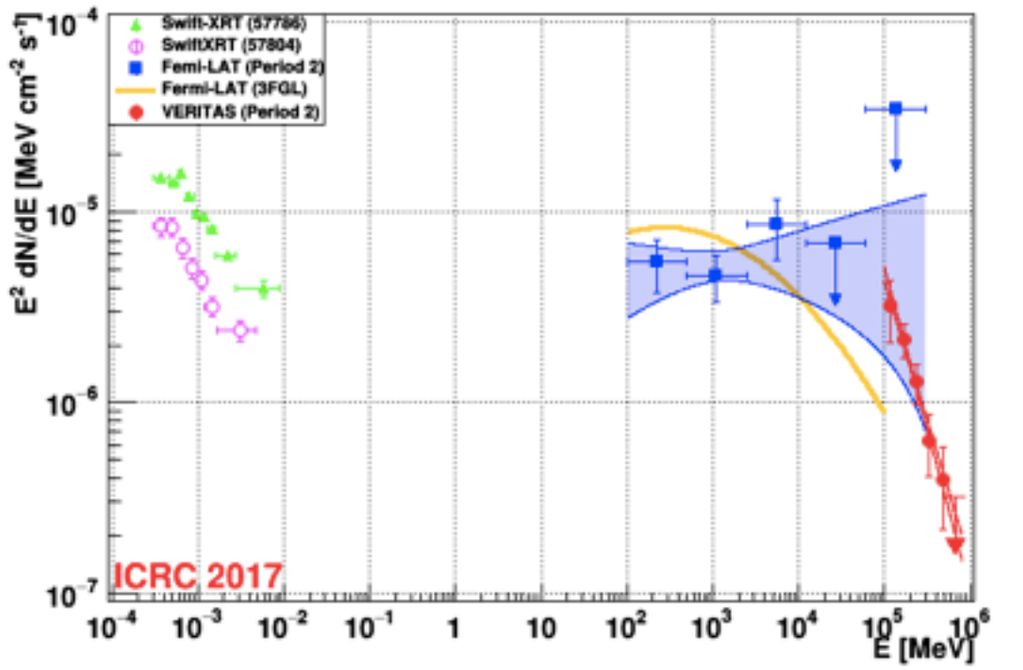
Where and how is the gamma-ray emission produced within these sources?

The VERITAS Detection of OJ 287

- Observed more than 400 times with *Swift*
- Great simultaneous *Swift* coverage over last VERITAS observations
- Variability observed by VERITAS over the last 10 years
- New detections lead to new questions!
  - Is this gamma-ray activity due to standard BL Lac emission?
  - Is the gamma-ray emission due to the location of the secondary black hole within the system?
  - What does the long term LAT gamma-ray emission tell us about the relative state of the source and how is this related to what was(n't) observed by VERITAS over the last decade?



M. J. Valtonen et al. 2016 *ApJ* 819 L37.



How to the spectral signatures of these sources change as the sources evolve?

PSK 1441+25: Broadband View of a Distant Gamma-ray Source

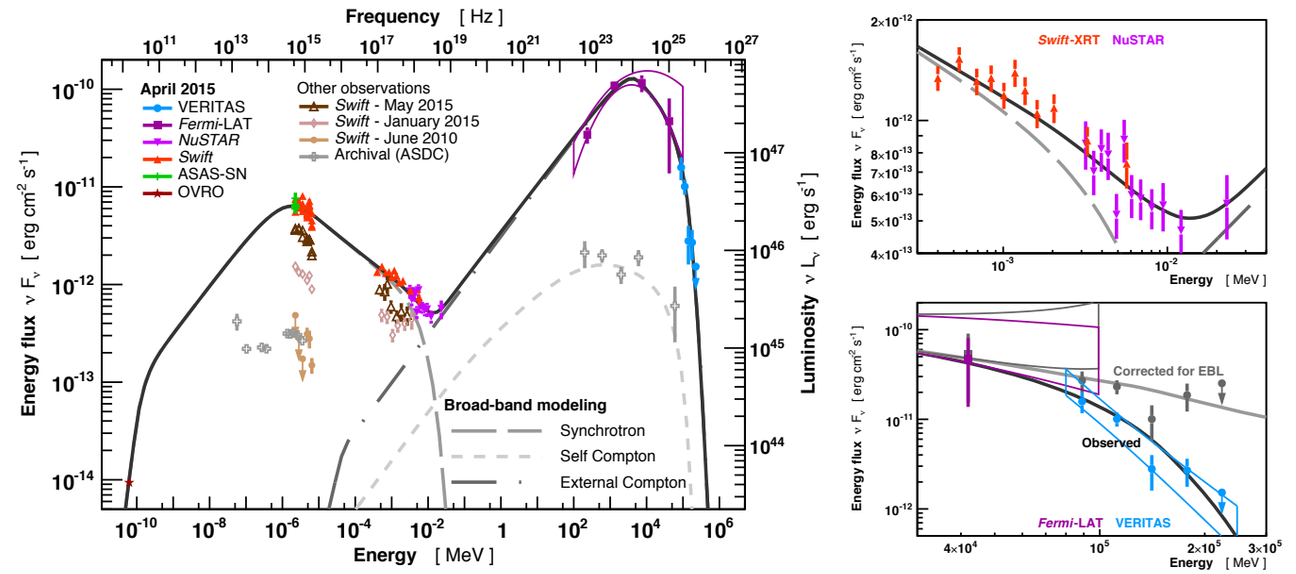
What is the density of the low redshift optical/IR light produced by stars and galaxies?

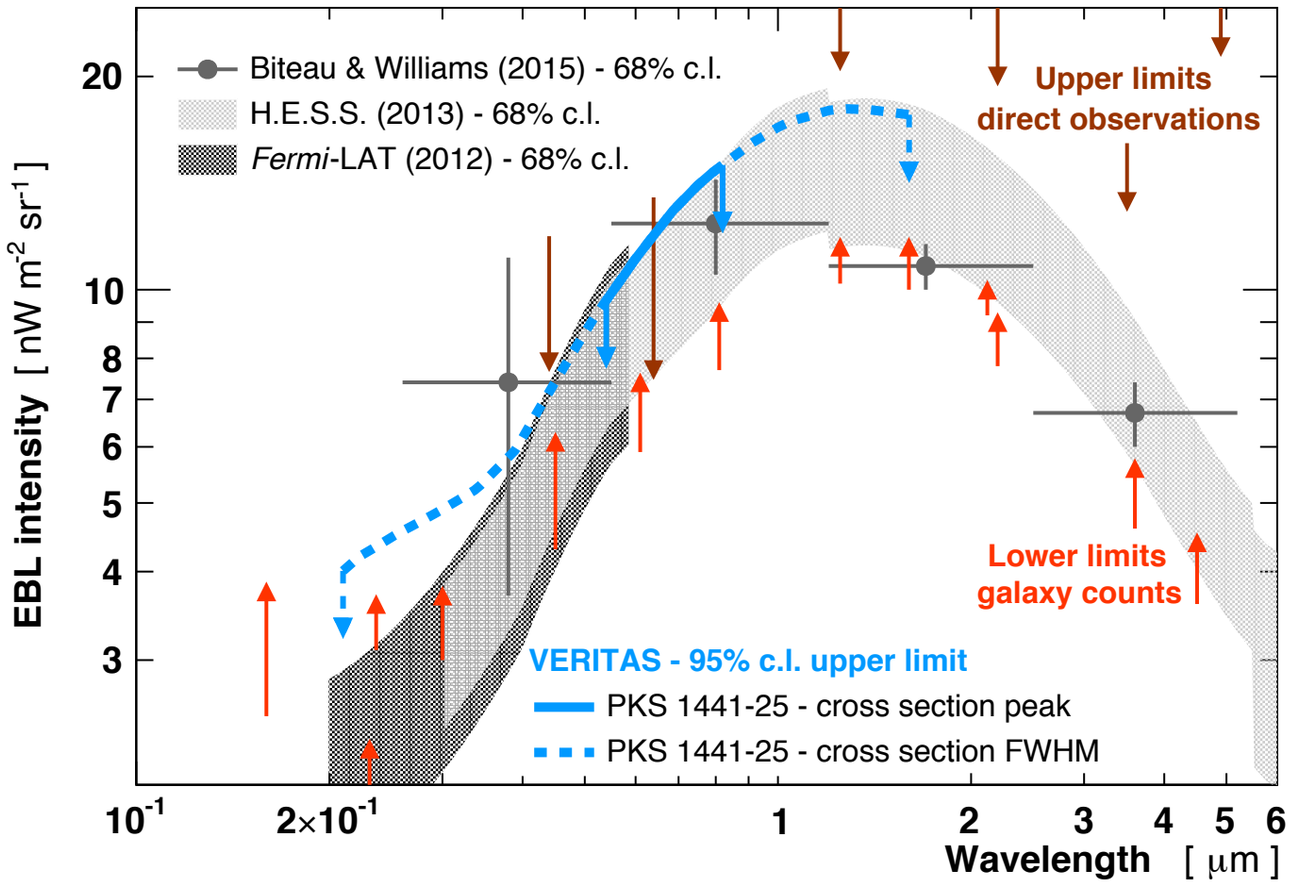
PKS 1441+25: Broadband View of a Distant Gamma-ray Source

- Detection by *Fermi* LAT, MAGIC and VERITAS motivated a extraordinary MWL campaign on the source, allowing the full broadband view

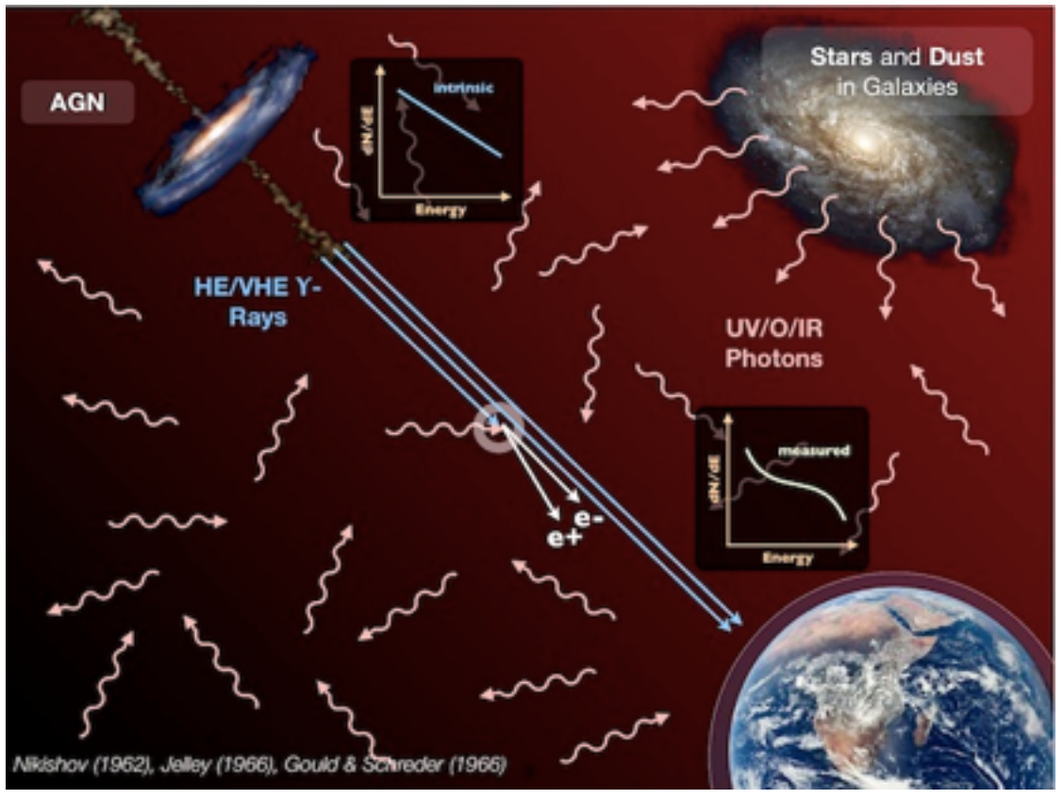
- The model parameters consistent with the emission are close to FSRQ characteristics

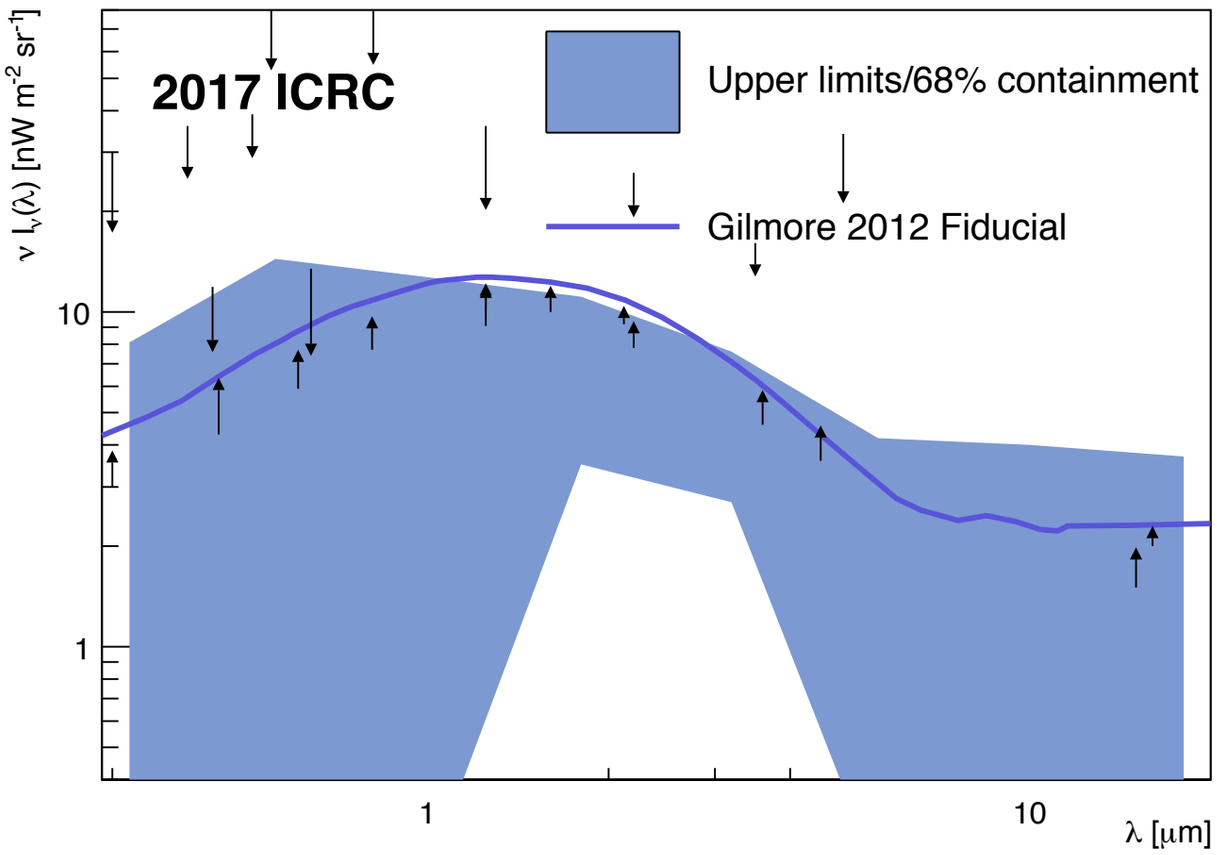
- Combination and continuity of Fermi-LAT & VERITAS data allows constraint on the EBL from ~0.2-2.0 μm which is constant with constraints from previous studies





What is the density of the low redshift optical/ IR light produced by stars and galaxies?

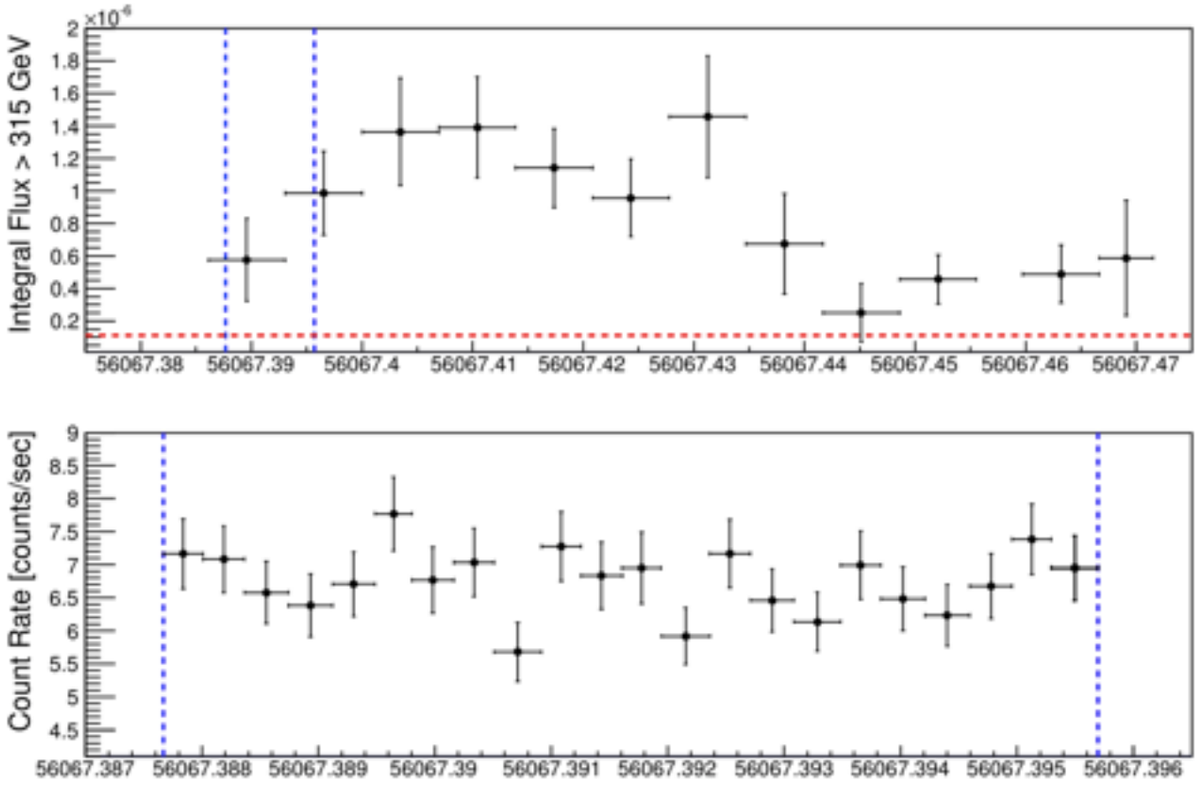


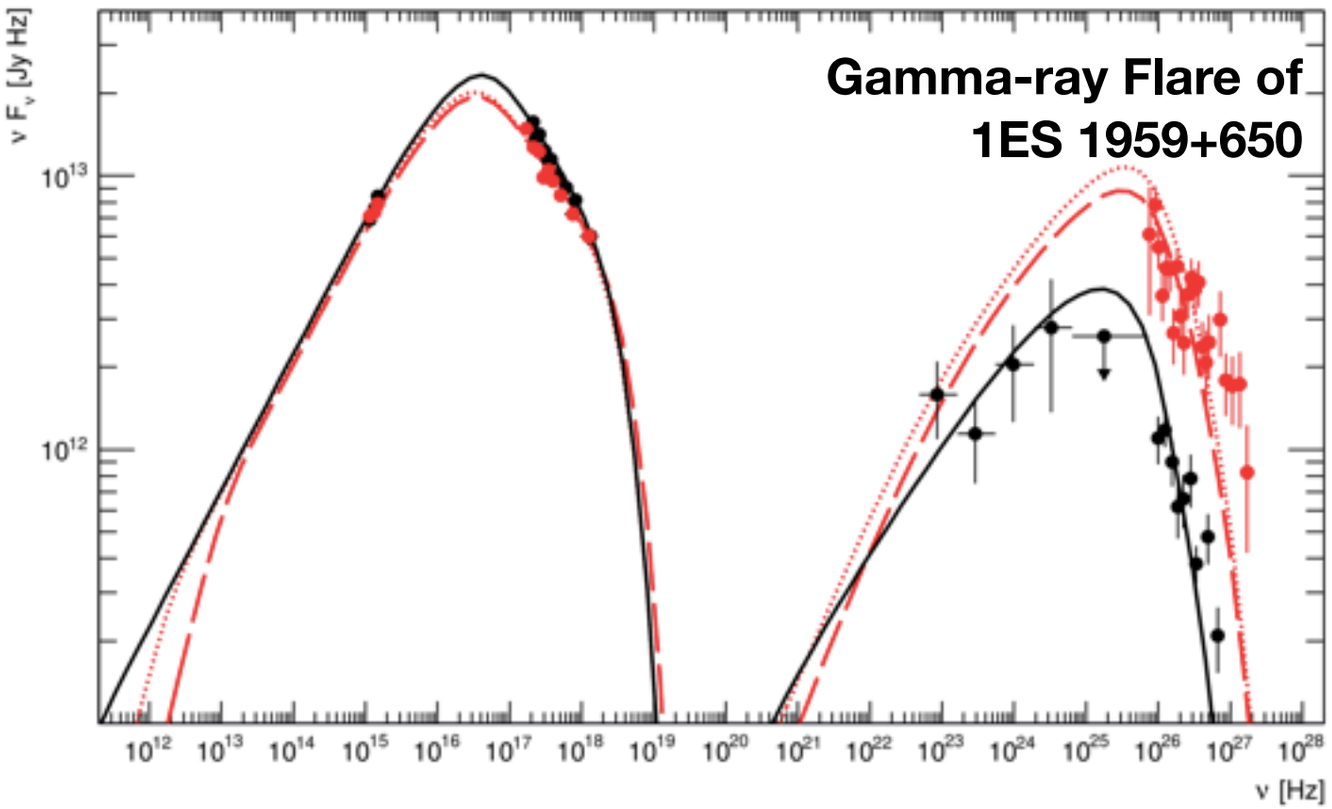


- Interaction of EBL-VHE photons results in the observation of attenuated spectra above 100 GeV
- Making ~500000 EBL shapes and extracting the opacity values then deabsorbing the VERITAS spectral points for multiple TeV blazers and comparing them to Fermi LAT spectra provides a model independent constraint on the EBL density can be produced as a function of wavelength
- The energy across which the TeV blazer is detected by VERITAS translates to the wavelength range of the EBL that can be constrained by that source
- Constraint region is consistent with galaxy count lower limits and current model-dependent EBL density profiles

How is the gamma-ray emission related to the lower-energy emission emerging from these sources?

Insight from *Swift* XRT and UVOT



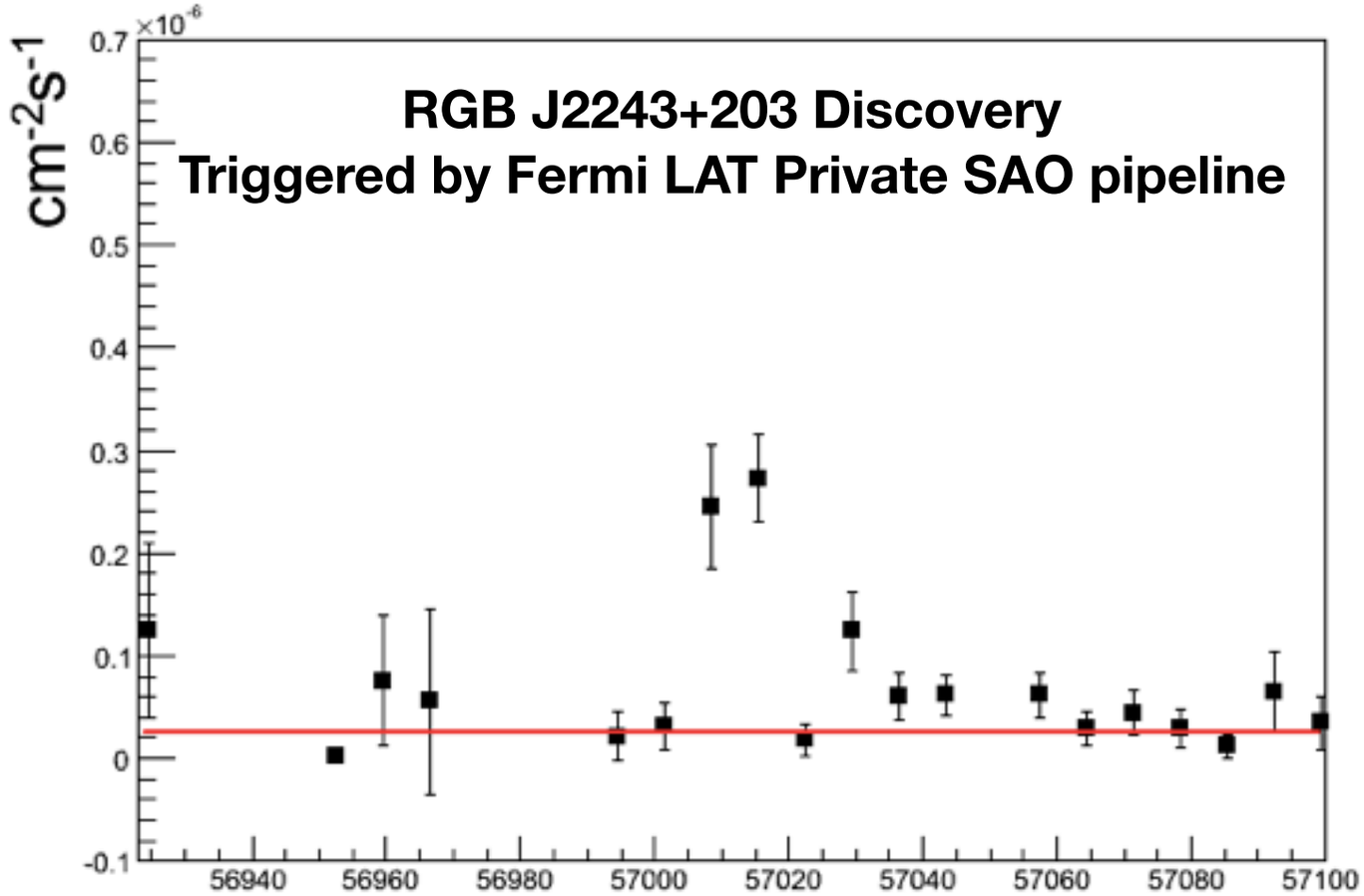


- Information on emission mechanisms possible through broadband view
- Moved from **contemporaneous** to **simultaneous** observation method
- *Swift* provides critical constraint with XRT and UVOT simultaneous shots
- Coordination of observation windows for many TeV blazars
- Trigger on high X-ray states to build understanding of source variability

How is the gamma-ray emission related to the lower-energy emission emerging from these sources?

Quasi-continuous Insight from *Fermi* LAT

- Fermi LAT allows full picture of gamma-ray emission characteristics
- Open lines of communication to flaring sources allow fast response to flaring sources
- Triggering observations based on private communication, Astronomer's Telegrams, public light curves and private rapid analysis pipelines



VERITAS Discovery of VHE Emission from RGB J2056+496

ATel #9721; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on 6 Nov 2016; 20:55 UT
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

Subjects: Gamma Ray, >GeV, TeV, VHE, AGN, Blazar

Tweet Recommend 50

We report the first detection of VHE emission from RGB J2056+496. This blazar, of unknown redshift, was targeted by VERITAS due to its favorable properties above 50 GeV, as described in the Fermi-LAT 2FHL catalog (M. Ackermann, et al., ApJS, Vol. 222, No. 1 (2016).Â The blazar is also an XMM-Newton source and a Swift-BAT source. It was observed for 4.2 h of good-quality live time between October 10, 2016 and November 6, 2016.Â A preliminary analysis of these observations yields an excess of 70 events above the background at the position of the blazar, corresponding to a statistical significance of 5.2 standard deviations.Â We interpret this excess as the discovery of VHE gamma-ray emission from the blazar.Â The corresponding flux observed above 200 GeV is (9.4 +/- 2.2) x10^-12 cm^-2 s^-1, or 4.0% of the Crab Nebula flux above the same threshold. We note that the blazar is 13 arc-seconds distant from the micro-quasar candidate LS III +49 13, and the two objects are effectively co-located for VERITAS. VERITAS will continue to observe RGB J2056+496 and multi-wavelength observations are encouraged. Questions regarding the VERITAS observations should be directed to Reshmi Mukherjee (muk@astro.columbia.edu).Â Contemporaneous target-of-opportunity observations with the Swift satellite have also been scheduled. VERITAS (Very Energetic Radiation Imaging Telescope Array System) is located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, and is most sensitive to gamma rays between ~85 GeV and ~30 TeV (http://veritas.sao.arizona.edu).

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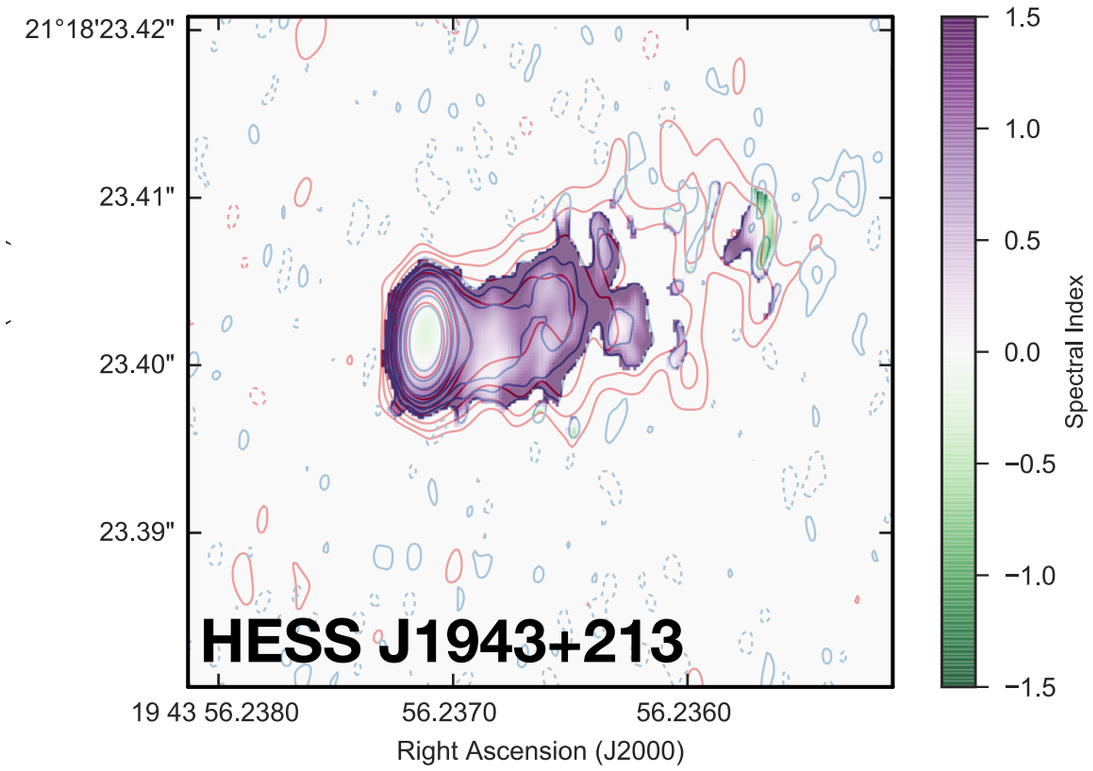
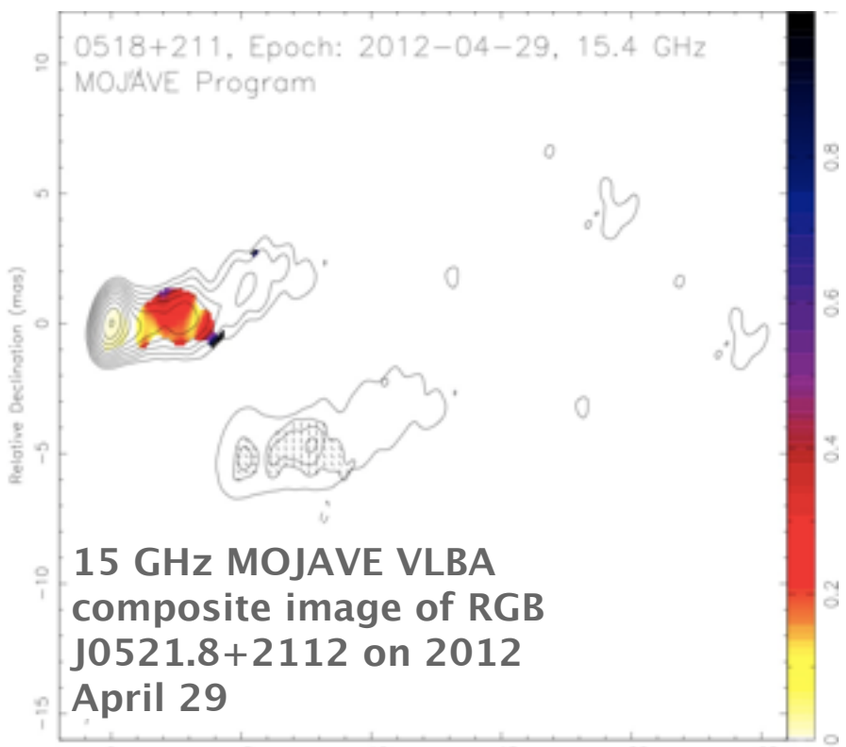
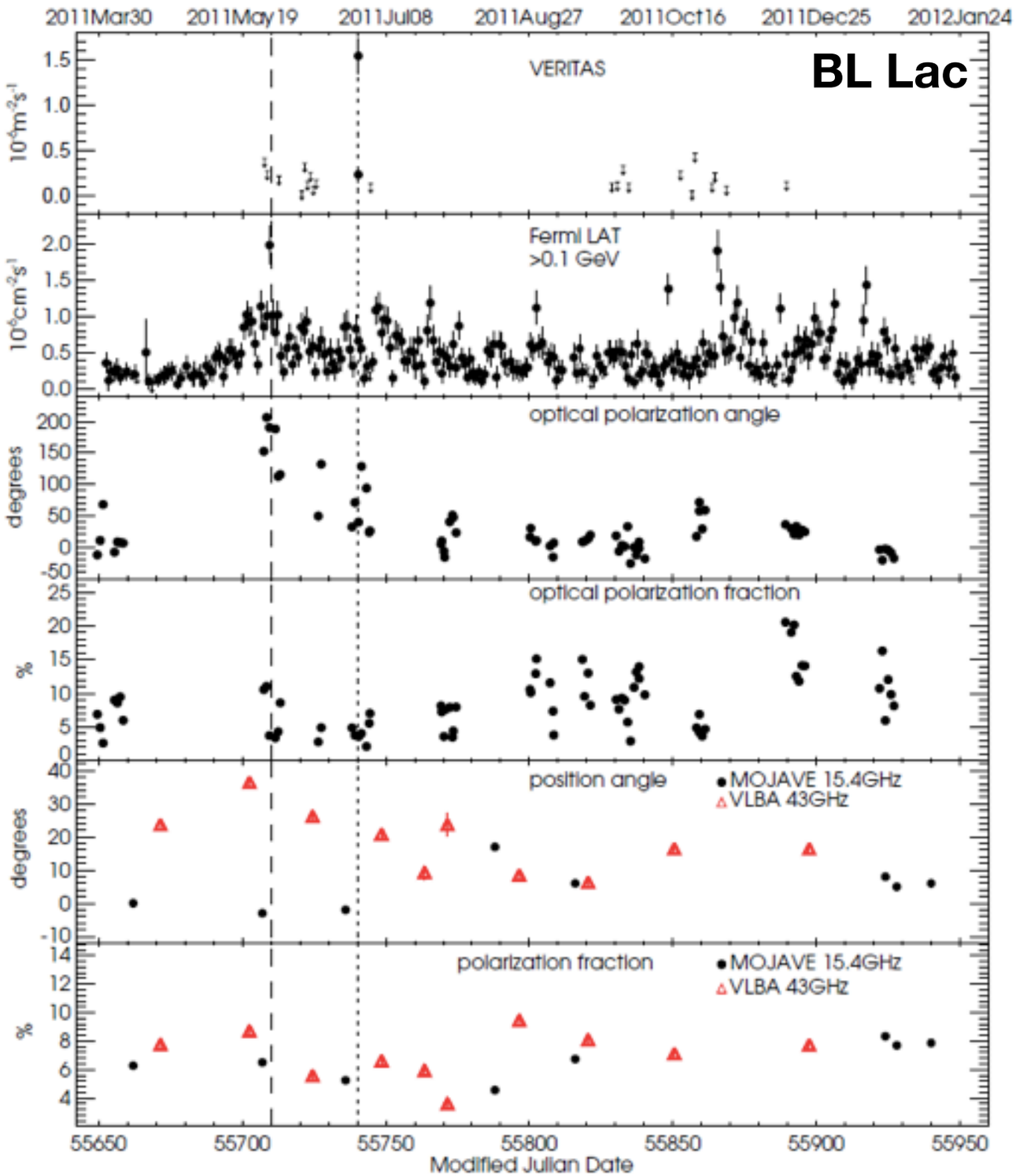
How is the gamma-ray emission related to the lower-energy emission emerging from these sources?

Evidence of Jet Structure from Radio and Polarimetry Measurements

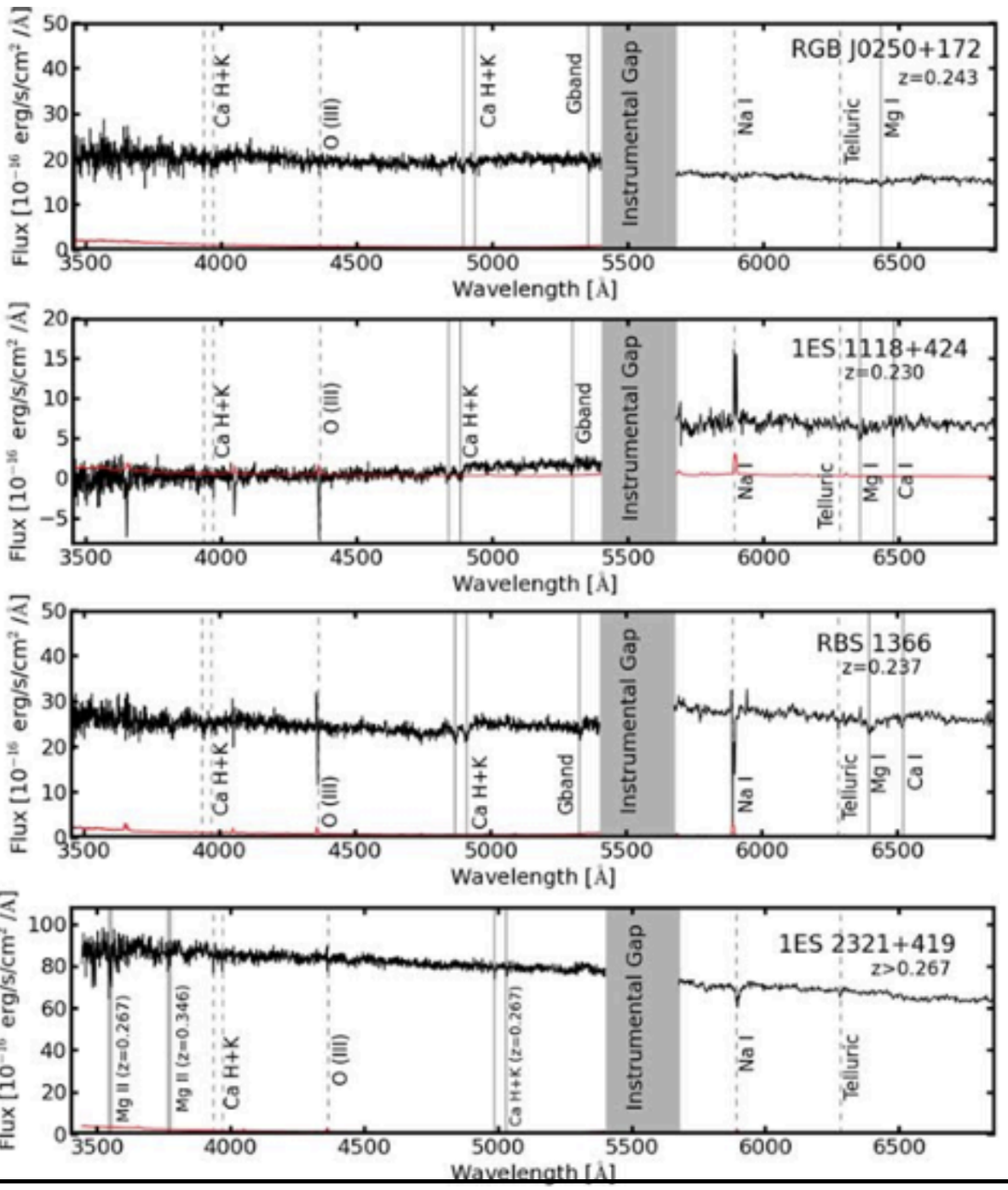






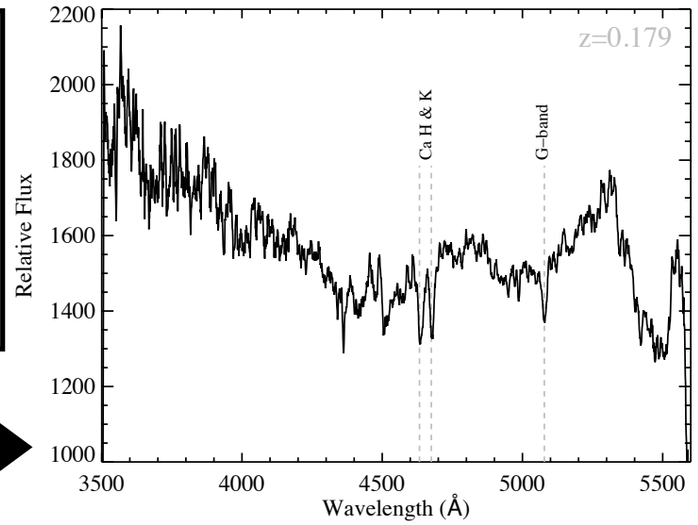
What secondary interactions do gamma-rays undergo as they travel extragalactic distances?

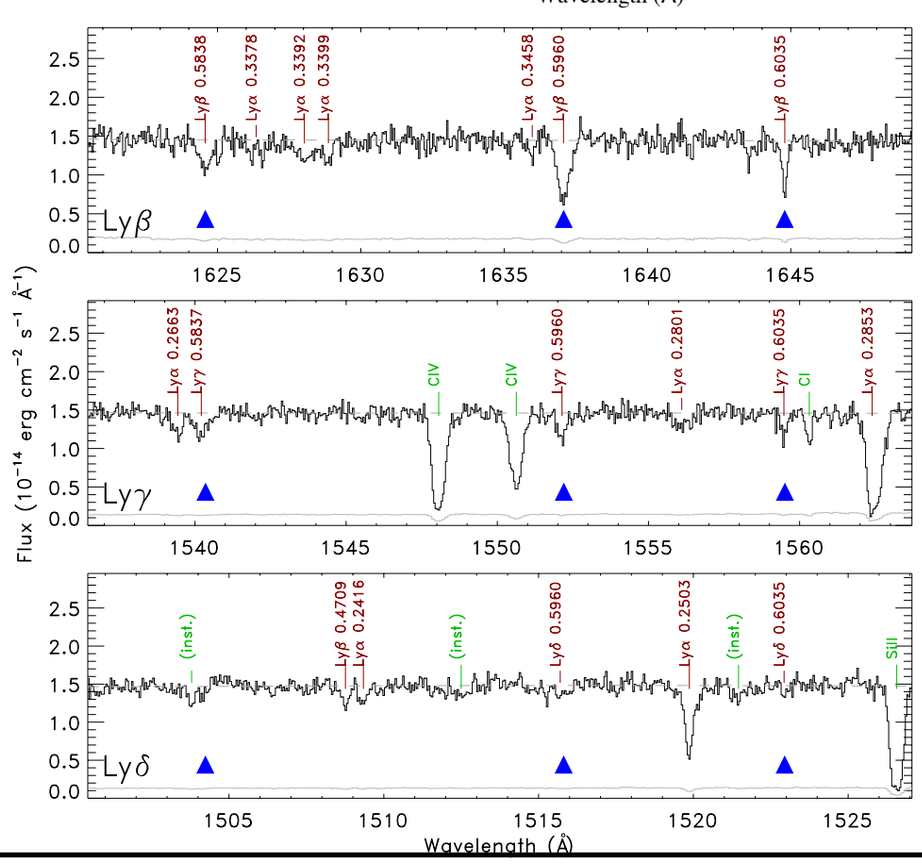
Motivating Spectral Redshift Measurements



Lick Observations of Various Non-detected VHE Candidates

Fermi LAT Bright Source List Target RX J0648.5+1516 Keck Spectrum z=0.179





PKS 1424+240 HST Observations (z>0.60)

The Search Continues

- What types of galaxies produce gamma-ray emission?
- Where does the gamma-ray emission originate within radio galaxies and blazars?
- How is the gamma-ray emission produced within these sources?
- Is there any pattern or mode to the variability of the gamma-ray emission from these sources?
- How is the gamma-ray emission related to the lower-energy emission emerging from these sources?
- How do the spectral signatures of these sources change as the sources evolve?
- What is the astrophysical origin of ultra-high-energy cosmic rays?
- What secondary interactions do gamma rays undergo as they travel extragalactic distances?
- What is the density of the low redshift optical/IR light produced by stars and galaxies?
- What is the magnitude (and origin) or the intergalactic magnetic field?

Opportunities Abound

- More than 50 accepted papers on VERITAS observations of extragalactic gamma-ray galaxies
- The potential for new and unexpected discoveries persists, and now we have a 10 years of observations to lead us in the right directions
- I am optimistic about the prospect for VERITAS observations of extragalactic sources to motivate new investigative techniques, and enable the definitive closure of persistent debates
- With our experience we can continue to prepare a strong foundation on which to continue ground-based gamma-ray astronomy well into the future