Particle acceleration in relativistic jets: Results from VERITAS

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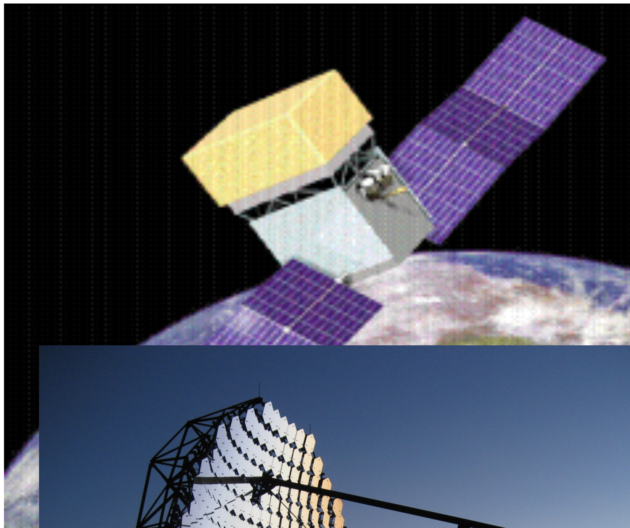
VERITAS

- Sensitivity improvement: 1% Crab in ~25 hr
- Sensitive energy range: 100 GeV to 30 TeV
- Spectral reconstruction: begins at ~150GeV.
- Energy resolution: ~15% - 20%
- Angular resolution: < 0.1º at 1 TeV, 0.14º at 200 GeV (68% values)

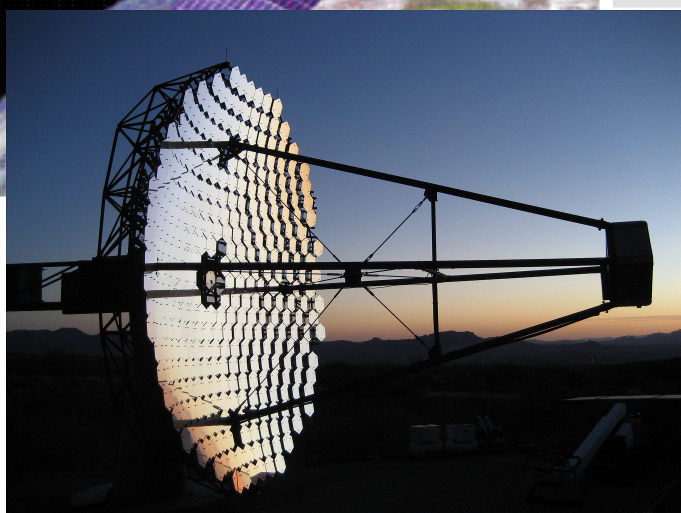
VERITAS in Context



Low-energy threshold: AGILE, Fermi
(~10s MeV - 300 GeV)

Space-based (small effective area), background -free, large duty cycle, large aperture

Sky survey < 10 GeV, transients



High sensitivity: HESS, MAGIC, VERITAS

(~100 GeV - 30 TeV)

Ground-based, large effective area, excellent background rejection, low duty cycle, small aperture

Survey limited regions of the sky, high resolution energy spectra

Large Aperture: MILAGRO/ HAWC
(>20 TeV)

Large duty cycle, good background rejection, limited angular resolution

Unbiased sky survey, extended sources, transients

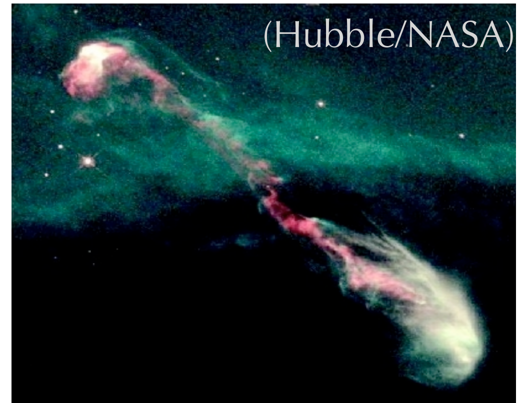
Relativistic Jet Phenomenology

Jets are ubiquitous in nature. Relativistic jets are extremely powerful outflows of collimated plasma that occur in a variety of objects of different mass scales.

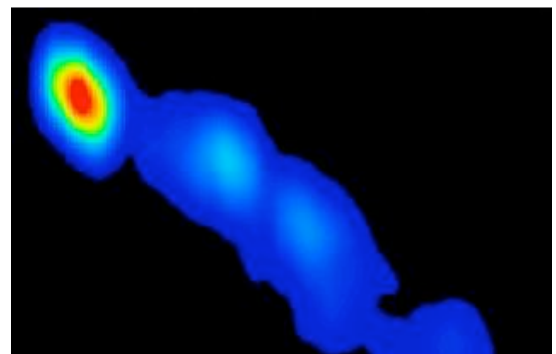
- In addition to AGNs with central SMBHs, relativistic jets also appear in stellar-mass black holes in X-ray binaries and GRBs – These are scaled-down versions of the jets seen in AGNs.

- Observations of different black hole systems over eight orders of magnitude in black hole mass have shown a very tight correlation between the rate of accretion of matter into the central black hole, the jet luminosity, and the black hole mass (e.g. Merloni et al. 2003). Common physical origin.

- Study of astrophysical leptonic jets now possible in the laboratory? (see Sarri et al. 2013, laser-based table top accelerator).
- Key outstanding issues: acceleration, collimation and stability/propagation of observed jets.



Protostellar Jet HH 47: Three-Trillion-Mile-Long



kpc scale radio jet of 3C 273 (VLBA)

Galactic Jets

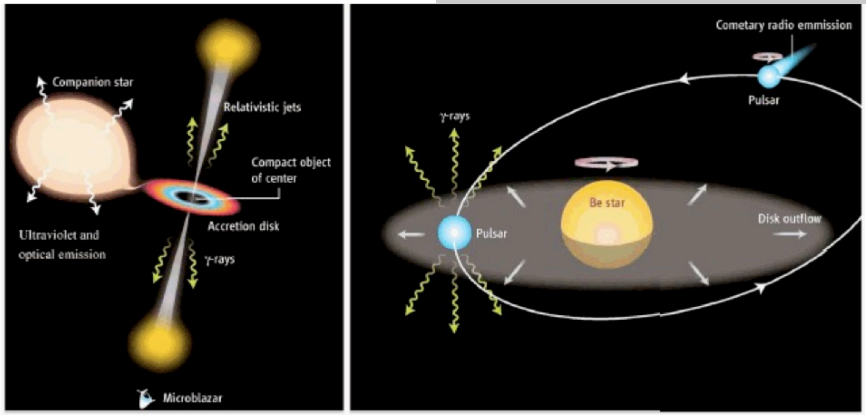
Galactic sources of HE relativistic outflows

- 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.
  - Two Scenarios: *Microquasar:* γ-rays are produced in a radio-emitting jet.
  - *Pulsar Binary*: particles accelerated in the shock produced by the interaction of the pulsar wind and the wind of the stellar companion.
  - X-ray binaries believed to be excellent targets for TeV emission – evidence of relativistic particle acceleration.

- Only 4 TeV binary detections to date (LS I+61° 303, LS 5039, PSR B1259-63, HESS J0632+057).

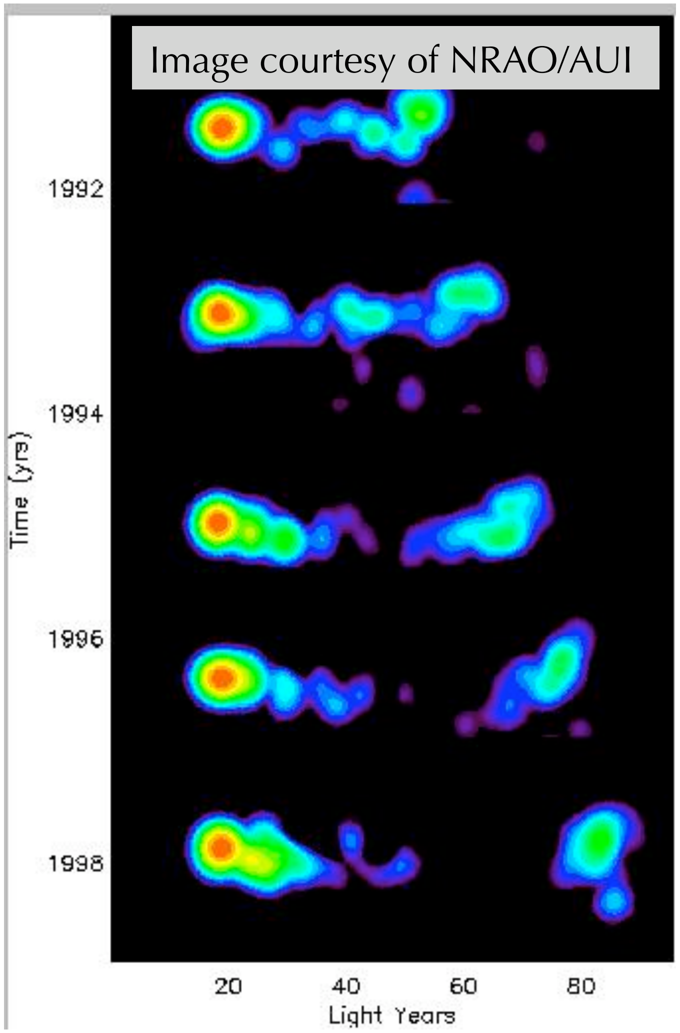
- High-mass XRBs like Cygnus X-3 and GRS 1915+105 not detected at TeV energies.

Mirabel 2006 Science



Extragalactic Jets

Blazar Characteristics



Most extreme active galactic nuclei:

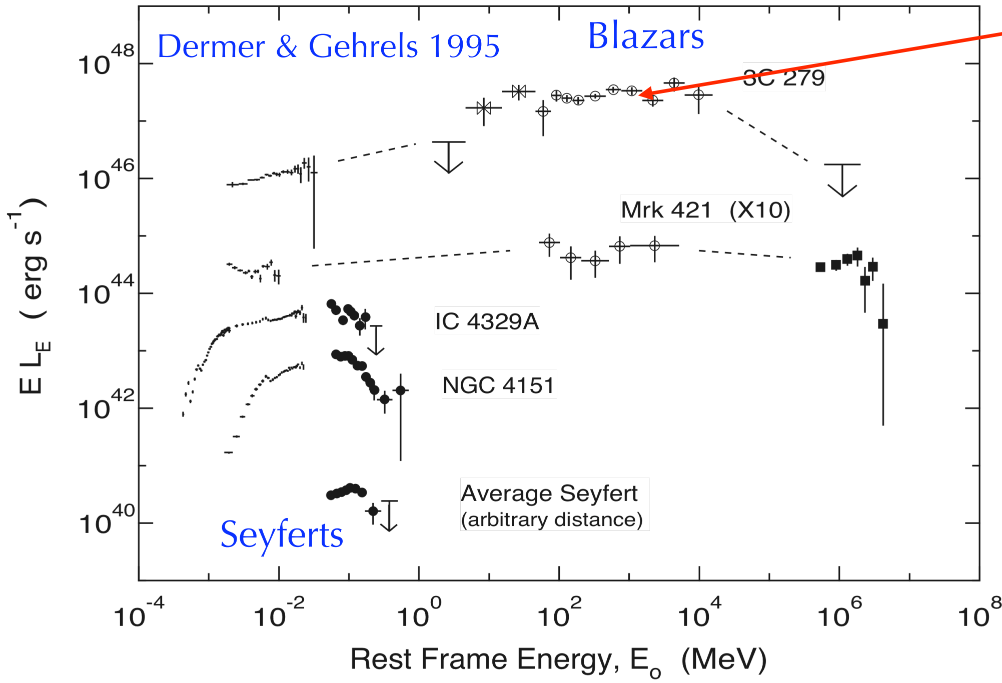
-Almost all AGN seen at high energies are blazars – radio loud AGN viewed directly along the jet axis. – (The small viewing angle of the jet makes it possible to observe strong relativistic effects).

-Accreting SMBH, oppositely directed plasma jets at superluminal speeds

- Jets propelled by magnetic fields twisted by differential rotation by the BH's accretion disk (e.g. Blandford & Znajek 1977; Meier et al. 2001)

- Particle acceleration outward along the jet in an acceleration and collimation zone containing a coiled magnetic field (e.g.Vlahakis & Konigl 2004). Energy transported as bulk motion of electrons, protons & magnetic field.

Relativistic Beaming in Blazars



High isotropic γ-ray luminosity ~ 10^{48}erg/s

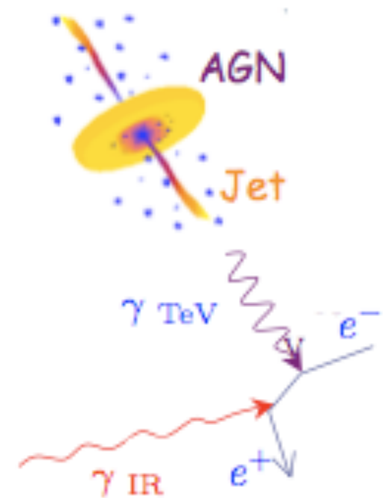
Non-thermal, continuum spectra. *Dramatic peak at γ-ray energies*. Emission extends to GeV-TeV band.

Absence of intrinsic γγ pair absorption ---> beaming in blazars.
High luminosity → optical depth >> 1, γ-ray emission originates in strongly beamed sources.
Tests of beaming – Elliot-Shapiro relation:
-For a spherically symmetric source in a steady state, $L < L_{Edd} < 1.3X10^{38}(M/M_O)$ ergs/s. Min. intrinsic time scale of variation: $\Delta t > R_S/c = 10^{-5}M/M_O$)

Why study TeV blazars?

In addition to jet physics and properties of SMBHs and their environments….

- Particle acceleration and emission mechanisms?
  - General picture of jet structure & jet formation, acceleration & collimation?
  - Specific location of blazar outbursts?
  - TeV origin – particle content leptonic or hadronic?
  - Black hole – jet connection

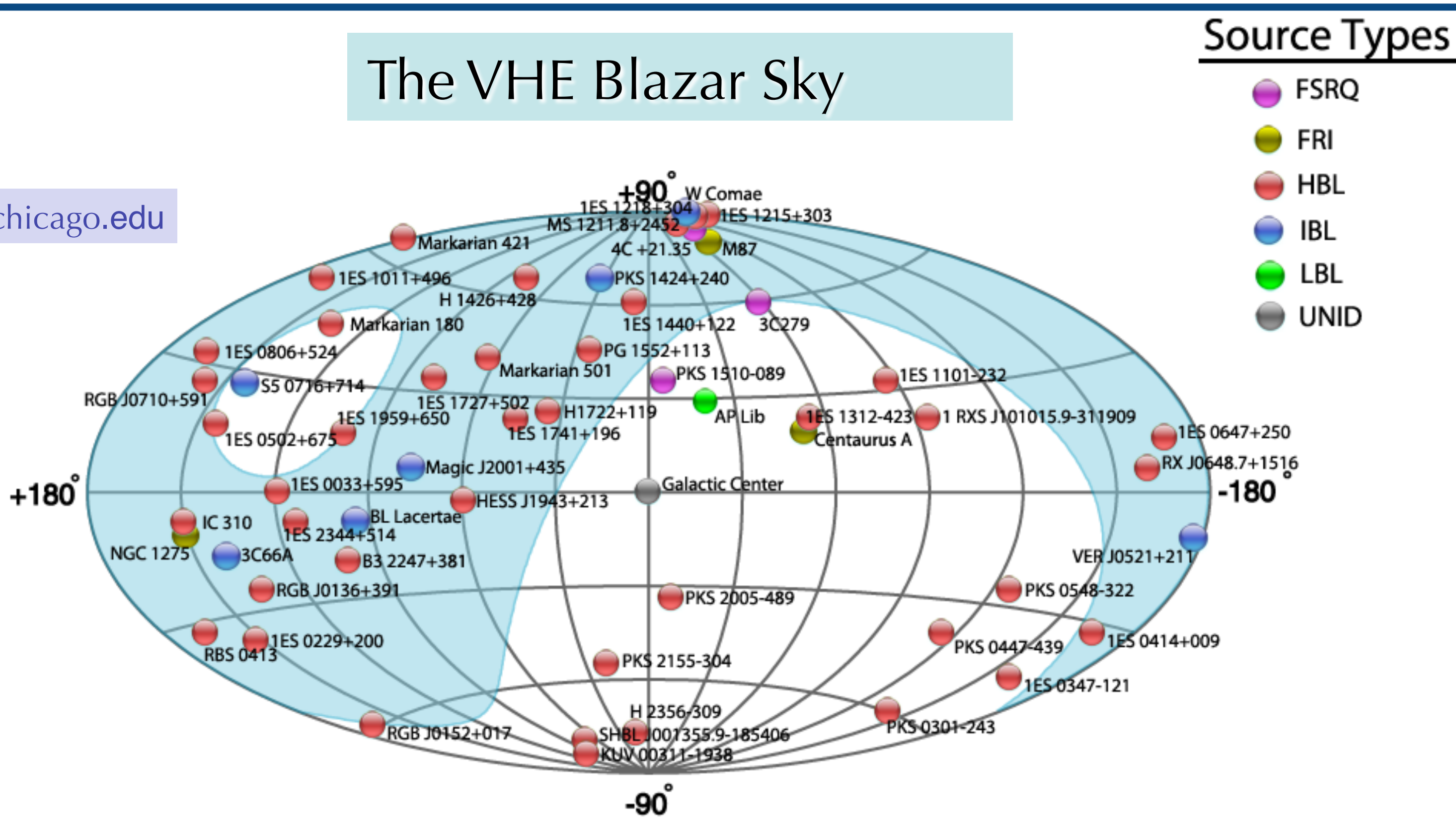


- Best extragalactic probes of the EBL via its interaction with TeV photons traveling cosmological distances.
- Better constrain the IGMF.

- Test the validity of the Lorentz Invariance principle at high energies.
- Particle acceleration to extreme energies - origin of UHE cosmic rays (E>10^{18} eV)?

Gamma Ray Observations of Relativistic Jets

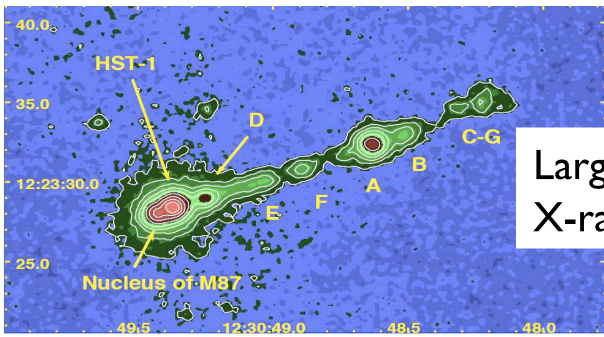
tevcat.uchicago.edu



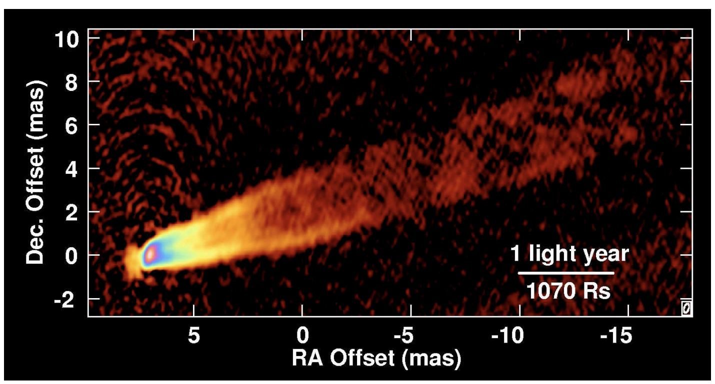
- Current generation of IACTs (H.E.S.S., MAGIC and VERITAS) has detected γ-ray emission from ~ 50 AGNs. Redshift range from 0.03 to > 0.6035.
- Population is largely dominated by high-frequency peaked BL Lacs (~80%), but also includes low-frequency peaked objects (~20%), flat spectrum radio quasars (3), and radio galaxies (3).

Radio Galaxies: M 87 - A very close AGN

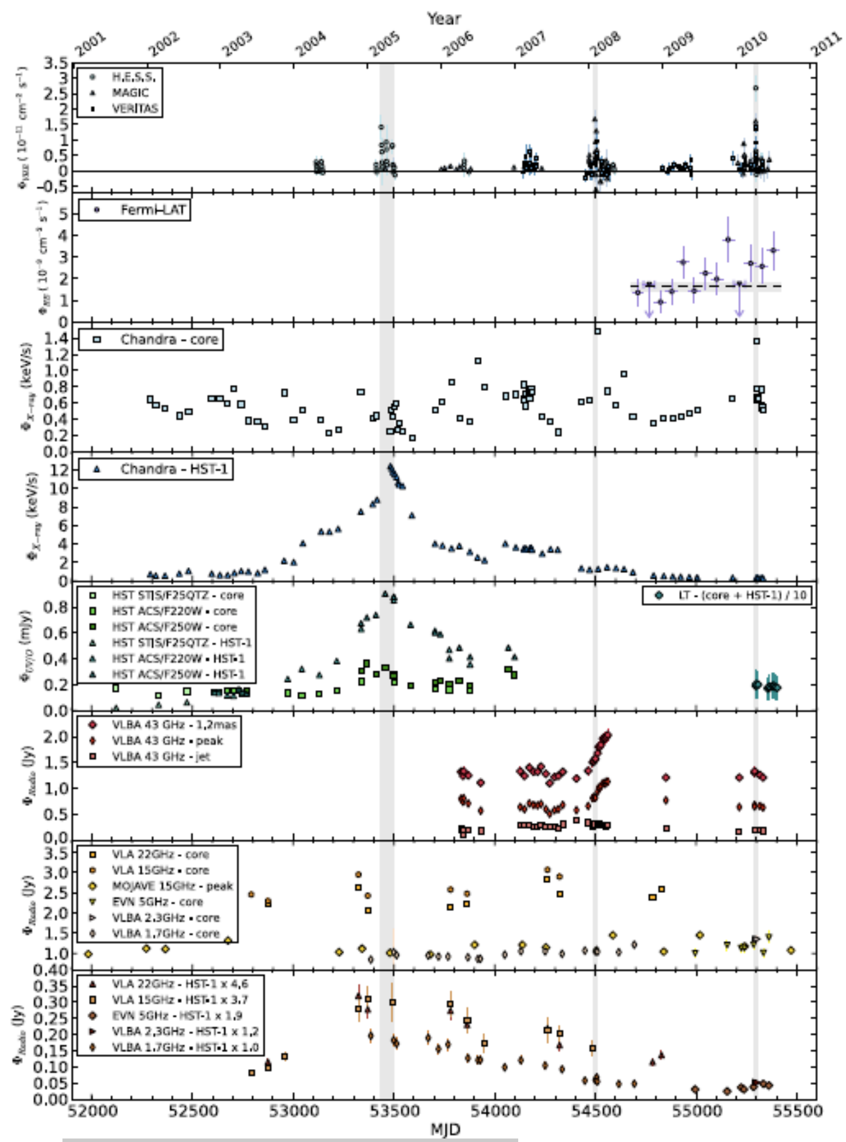
- Location of the emission region ----
- M 87 is one of the closest AGNs (20 Mpc). The jet is oriented at ~ 20°
- VHE studies are likely to contribute to a better understanding of AGN unification schemes



Large scale jet in X-ray (Chandra)

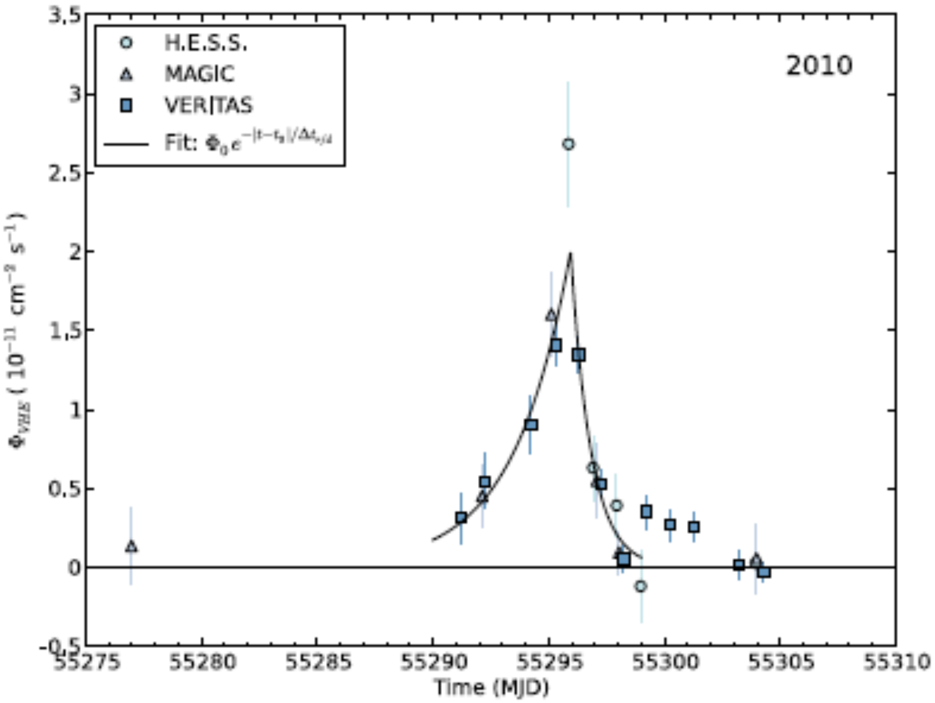


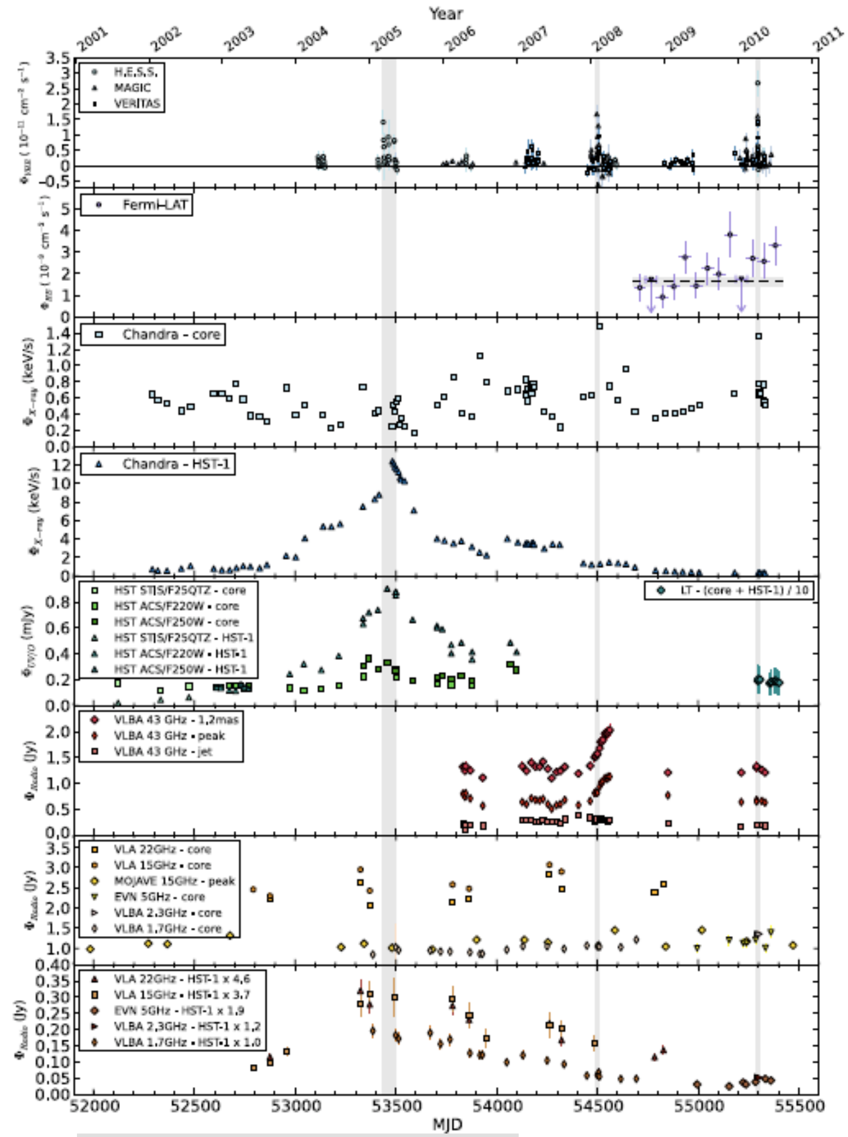
Inner jet in radio (43GHz, VLBA).



Abramowski et al. 2012

Radio Galaxies - M 87 - A very close AGN



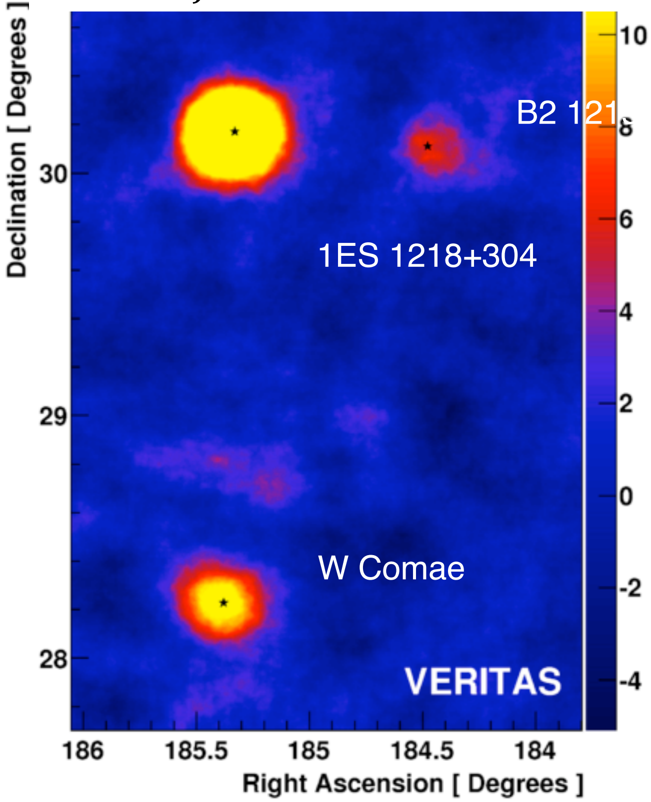


Abramowski et al. 2012

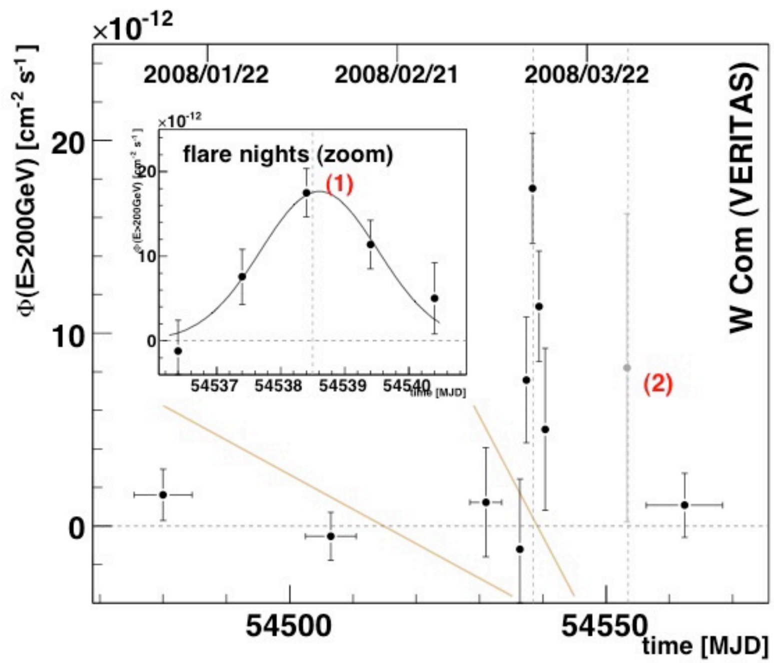
- VHE light curve of M 87 zoomed on the 201 flare.
- VHE temporal behavior characterized – τ_{rise} = ~1.7 days and τ_{decay}= ~0.61 days

VERITAS: Typical Blazar Luminosities

- Blazars detected as point sources at TeV
- Variable sources; variability could be ~ day-scale or sub-hour
- VHE γ rays during W Comae flare ~ 25% of the flux of the Crab Nebula (> 200 GeV). Luminosity ~10^{45} ergs/s. Only a very small fraction of the blazar jet (<10%) accounts for this luminosity.



Benbow et al. ICRC 2011

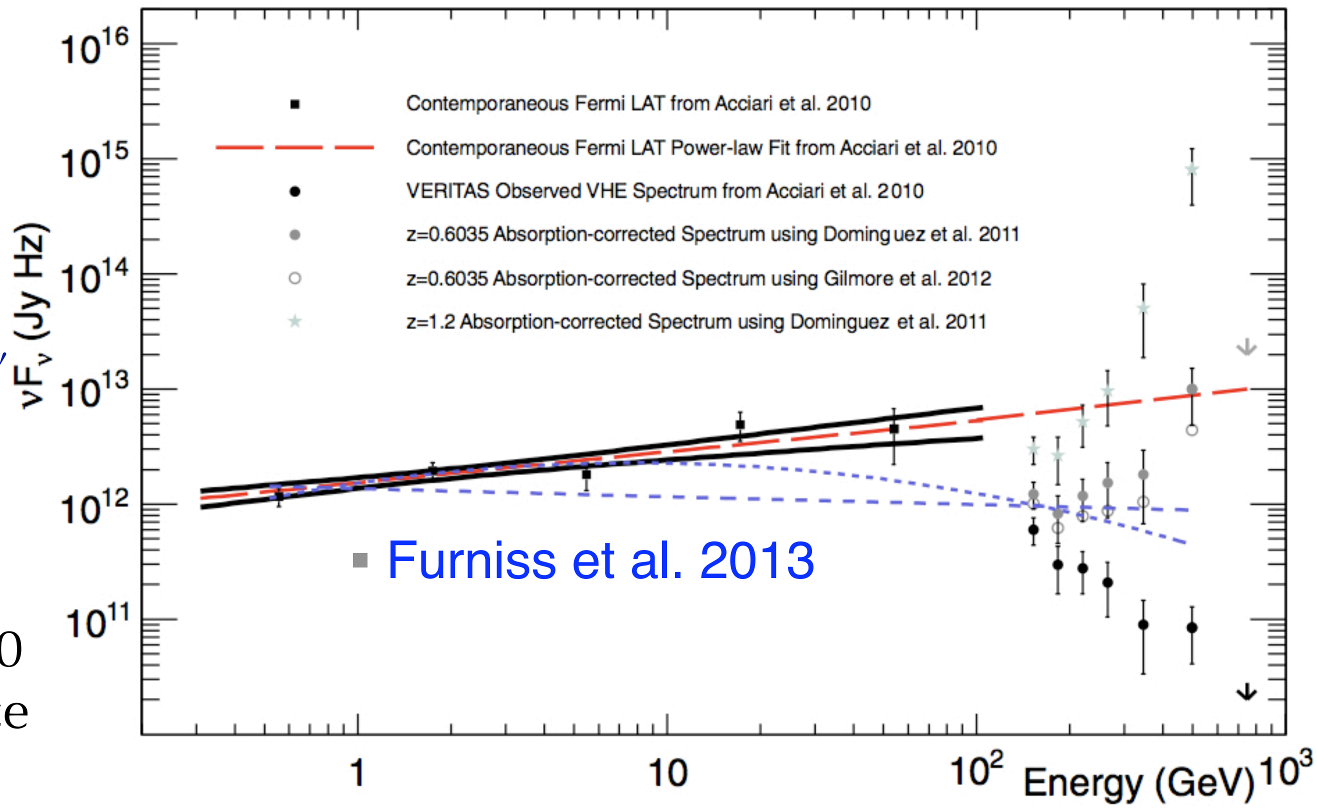


Acciari et al. 2008 ApJ 690, L73

- 70% of excess from 4-night flare in 2008 March
- 275γ, 8.6σ; τ ≈1.3 ± 0.3 days, 9% CU

PKS 1424+240

- Detected at VHE by VERITAS in 2010
- New HST/COS obs. : z >0.6035 (Furniss et al., 2013)
- *Most distant BL Lac*
- Deep campaign: >100 hours of new data since 2010

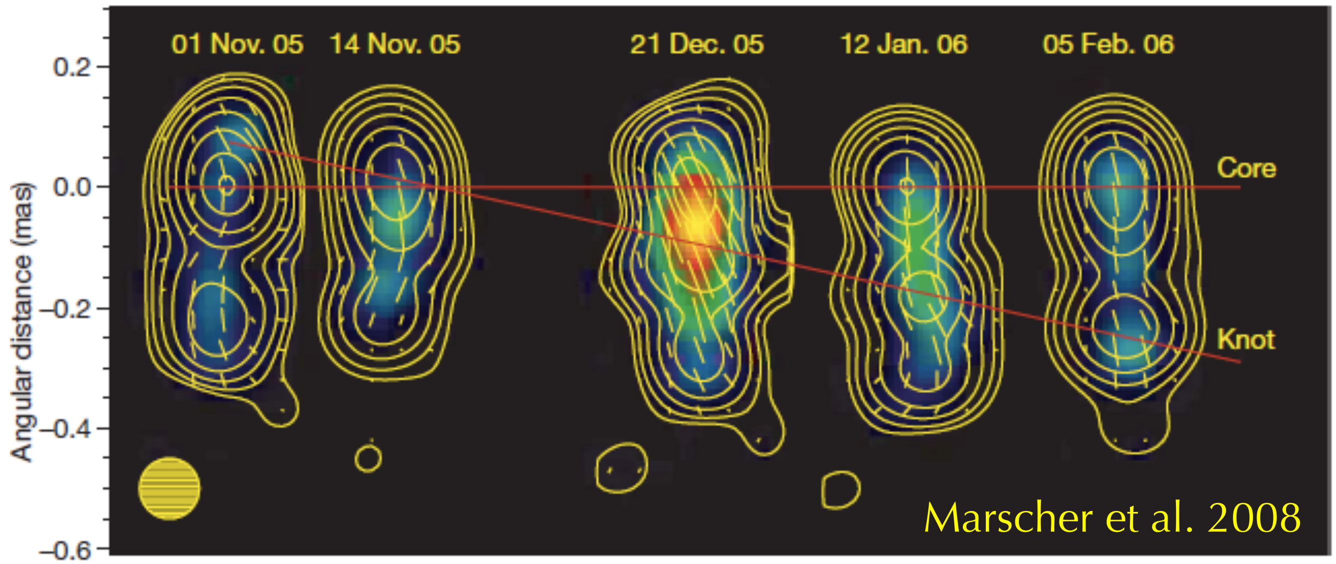


- Furniss et al. 2013

- VERITAS spectral measurements probe the EBL for large optical depths (~ τ > 4, for minimal EBL models)
- VERITAS spectrum is lower than expected from a smooth extrapolation of the Fermi-LAT spectrum.

Locating the Emission Region in the Jet

The jet of BL Lac - Sequence of VLBA images at a λ of 7mm (43 GHz).



- Blazar at a redshift of 0.069 (291 Mpc)

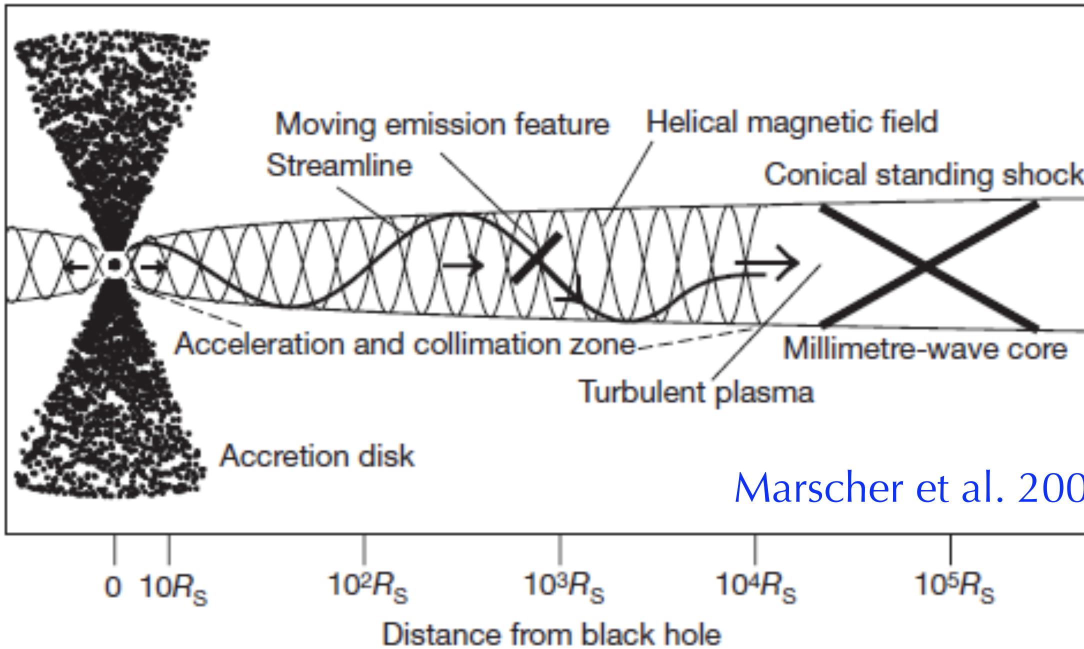
-VHE emission detected by MAGIC in 2005

- Angle of BL Lac jet to our line of sight: 6–10^{o}. Flow speed: of 0.981–0.994c. Corresponding Lorentz factor: ~7 (Jorstad et al. 2005)

-Relativistic aberration and the Doppler effect strongly beam the radiation, high apparent luminosity.

- Knot's observed proper motion of 1.2 mas/yr (~5.0c) (Marscher et al. 2008)

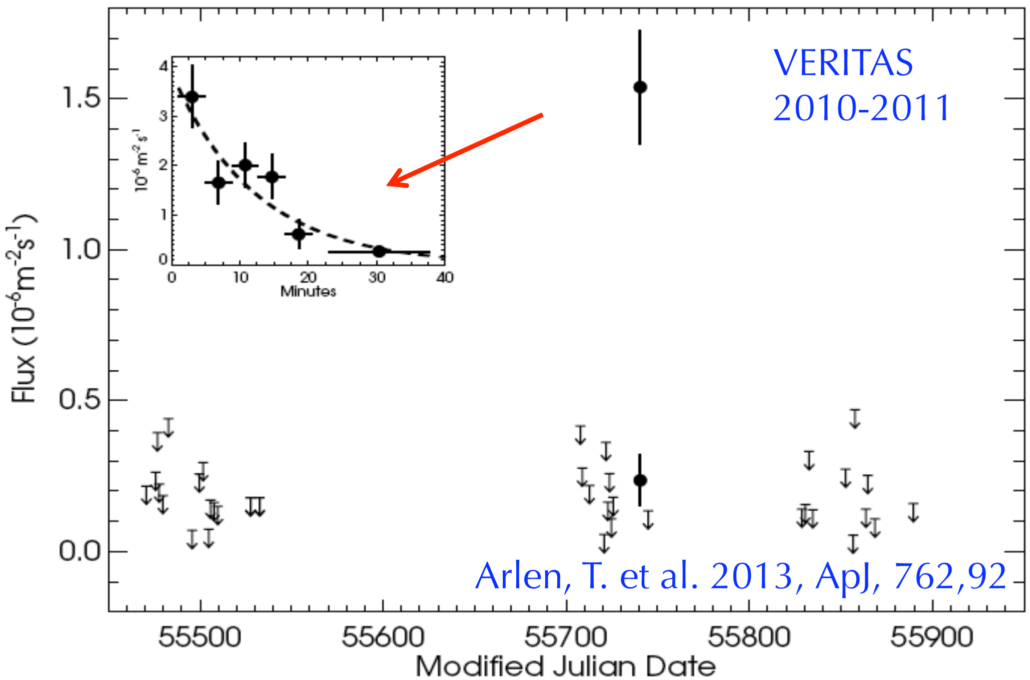
A Proposed Model of the Inner Jet



Marscher et al. 2008

- Where is the energy dissipated in the jet? What fraction of the jet is responsible for the observed luminosity?
- Data from radio + TeV γ-ray flare seem to indicate that the core is a standing shock located well downstream of the BH.
- Radiating plasma follows a helical magnetic field configuration upstream of the radio core (Marscher et al. 2008).
- Radio observations probe outer regions of the jet (pc scale). TeV γ-ray observations powerful tool for probing inner regions of jets.

BL Lac: TeV Flare and Rapid Variability

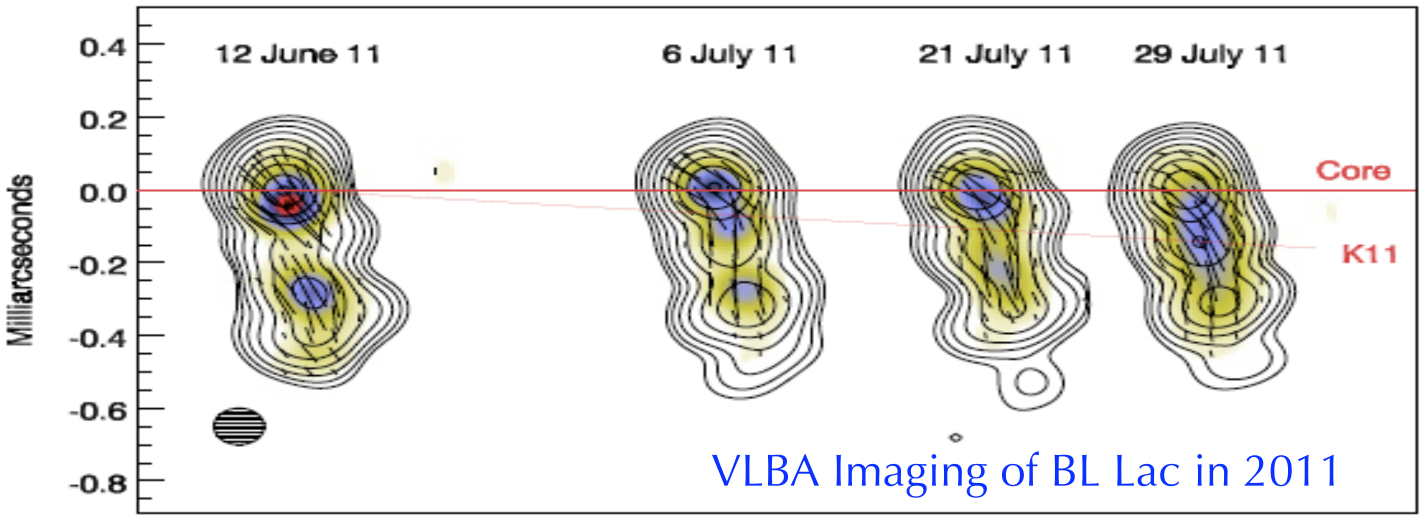


- First detection of minute-scale variability in low-synch peaked object.
- Rapid variability in blazars poses serious challenges to the theoretical understanding of γ-ray production in blazars.

- Flare on June 28, 2011 picked up by VERITAS monitoring; 4-min bins; 125% Crab flux (> 200 GeV); $\Gamma = 3.8 \pm 0.3$; good MWL coverage.
- Flux decayed by factor of 10 in $\tau = 13 \pm 4$ min => Strongly constrains size of emission region ($R < c\tau\delta/(1+z) \sim 2.2\mathrm{X}10^{13}\delta$ cm) (independent of any model).

Probing the Inner Region in the Jet

- Detailed multi-wavelength observations of blazar outbursts can be used to probe the emission region.
- New SL component near core (43 GHz) - new knot K11, shows a different polarization position angle (20^o compared with 44^o for the core).

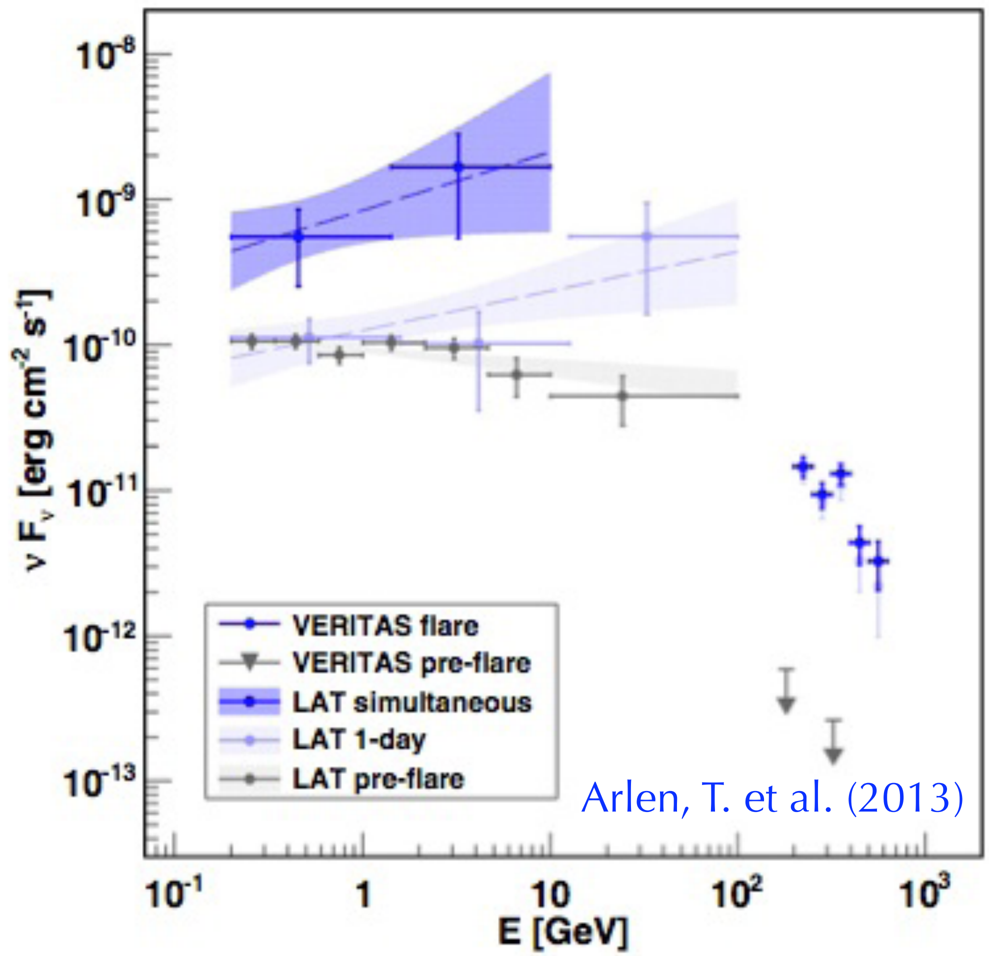


VLBA Imaging of BL Lac in 2011

Emergence of a radio linked to the γ-ray flare.

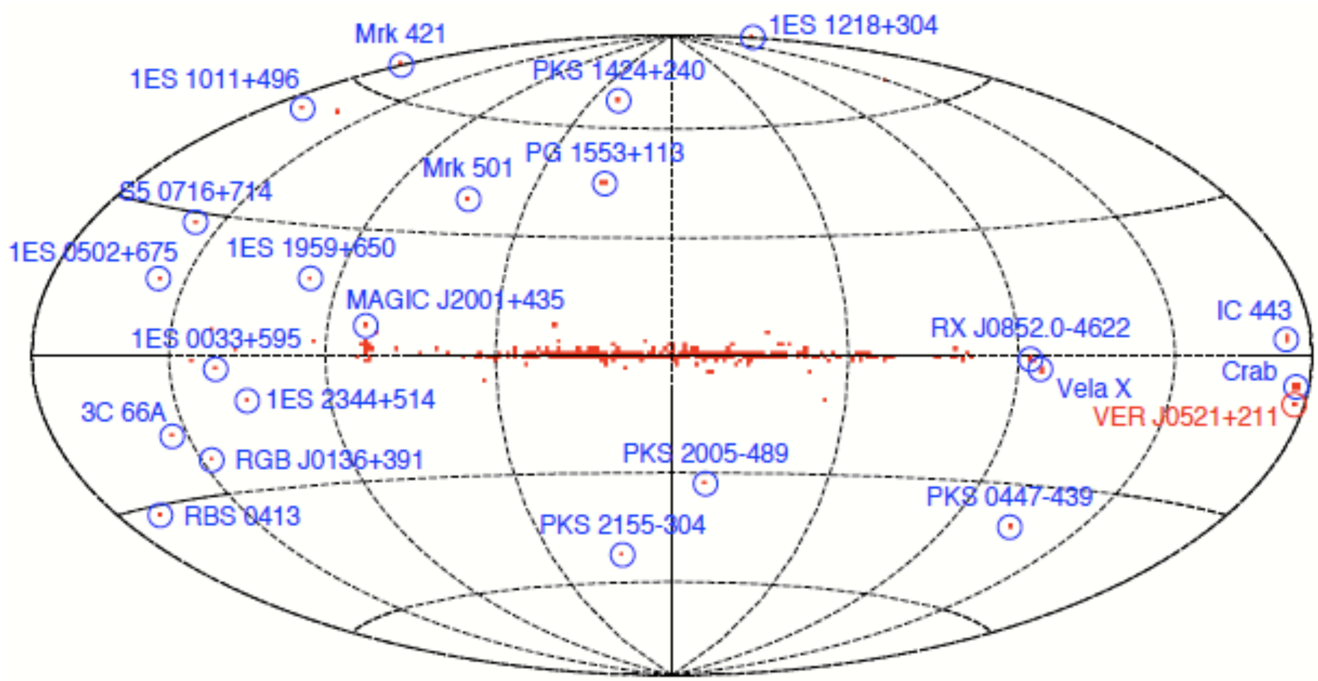
BL Lacertae flare & pre-flare SED

- TeV flare occurred when source was active & variable in GeV band. γ-ray SED peak lies ~ 10-100 GeV.
- LAT data shows evidence for spectral hardening during the VERITAS flare.
- Sharp break at TeV energies – Klein-Nishina effects ($h\nu_0 \geq mc^2/4\gamma_{KN}$ - electron cooling rate is substantially reduced)



Arlen, T. et al. (2013)

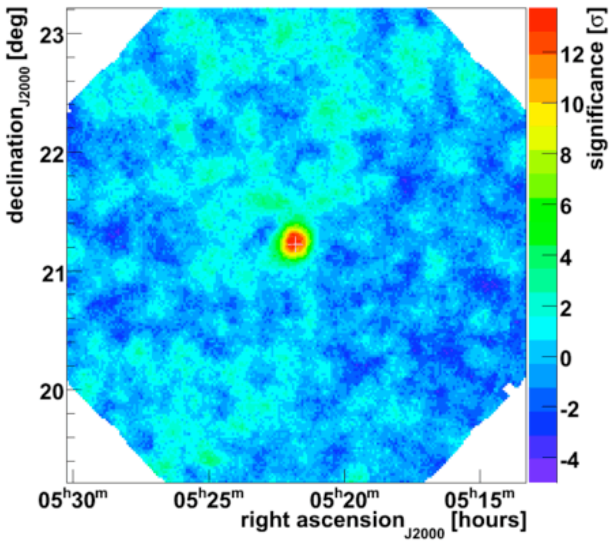
VERITAS Discoveries: Finding new blazars (Follow up of Fermi Sources)



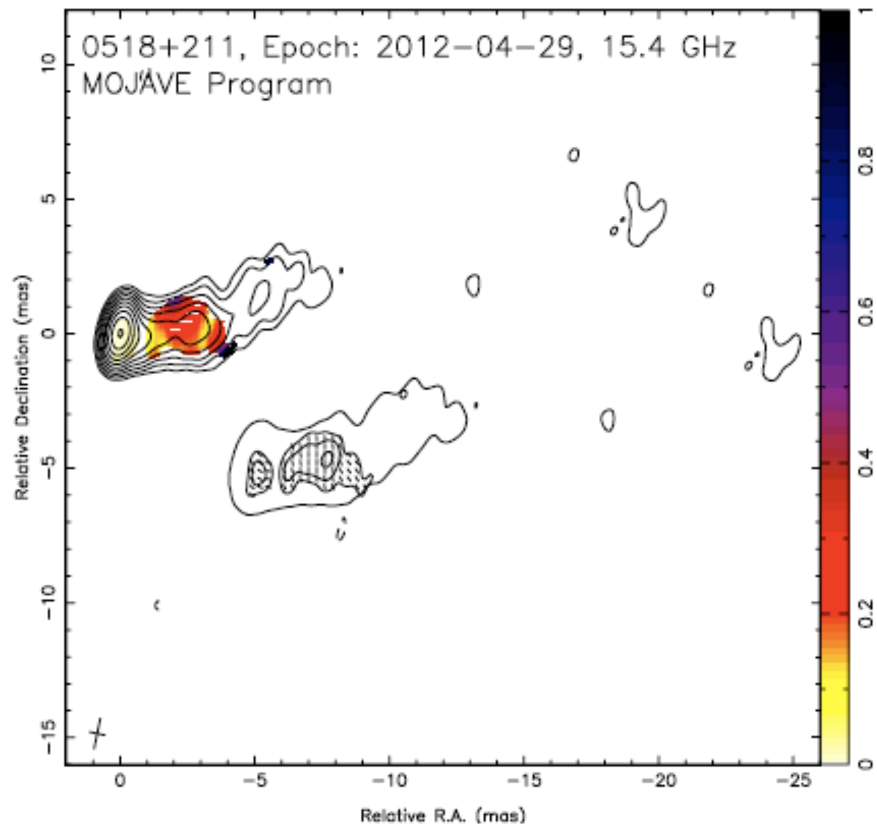
- A number of unidentified Fermi sources are expected to be blazars behind the Galactic plane.
- VHE telescopes are a good tool for identifying blazars at low latitudes (better localization, higher sensitivity to flux variability).

Blazars behind the Galactic plane

VER J0521+211

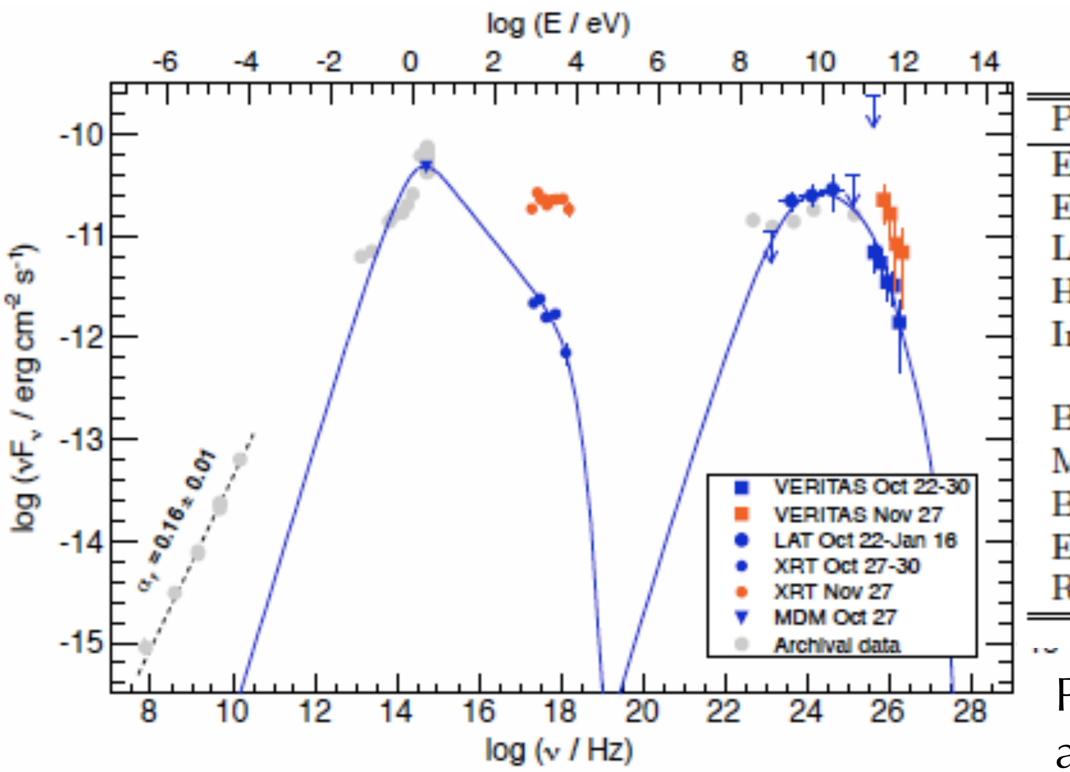


- Discovered in 2009. Flare detected ~10% Crab in 2012.
- Strongly variable from optical to TeV bands, with a peak flux corresponding to ~ 0.3 time bands the steady Crab (at TeV energies).
- Recent optical spectroscopy - typical of BL Lacs, z~0.108



15 GHz MOJAVE VLBA image of RGB J0521.8+2112 on 2012 April 29. The radio morphology consists of a bright radio core + apparent one-sided jet that extends for ~20 mas to the west

SED of VER J0521+211



Archaumbault *et al*. 2013 (sub.)

Parameter	Symbol	Value
Electron distribution		
Electron power	L_e [erg s^{-1}]	7.7×10^{44}
Low-energy cutoff	γ_{min}	3.5×10^{4}
High-energy cutoff	γ_{max}	2.0×10^{6}
Injection index	q_e	3.0
Blob radius	R_b [cm]	4.0×10^{17}
Magnetic field	B [G]	0.0025
Bulk Lorentz factor	Γ	30
Escape parameter	η_{esc}	300
Redshift (assumed)	z	0.10

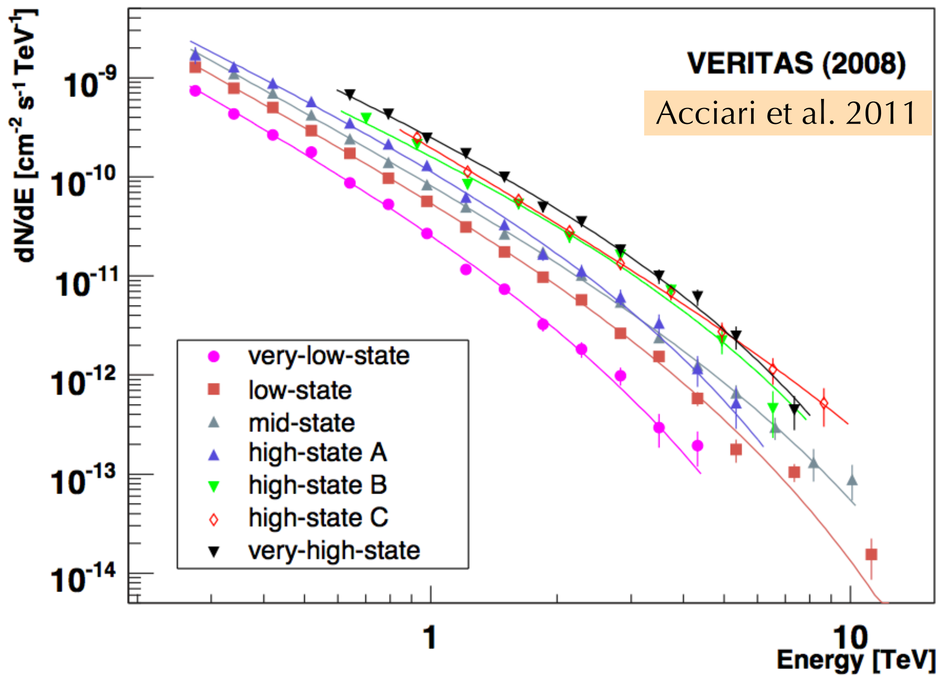
- Shift in VHE power not as dramatic - Could be from onset of KN suppression ($h\nu \sim m_e c^2$ in e^- rest frame)
- Min value of Doppler factor: $\delta \sim 30$
- Energy budget: $u_e/u_b < 0.01$

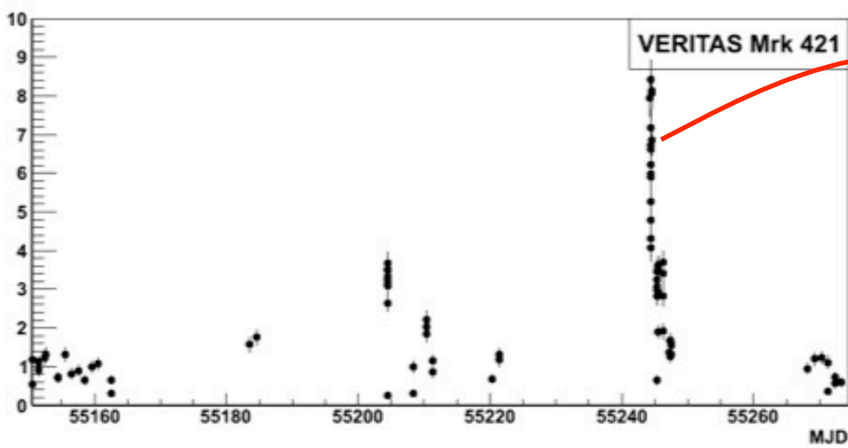
Peak in the γ-ray band, between 10 and 200 GeV -- leptonic one-zone SSC emission model.

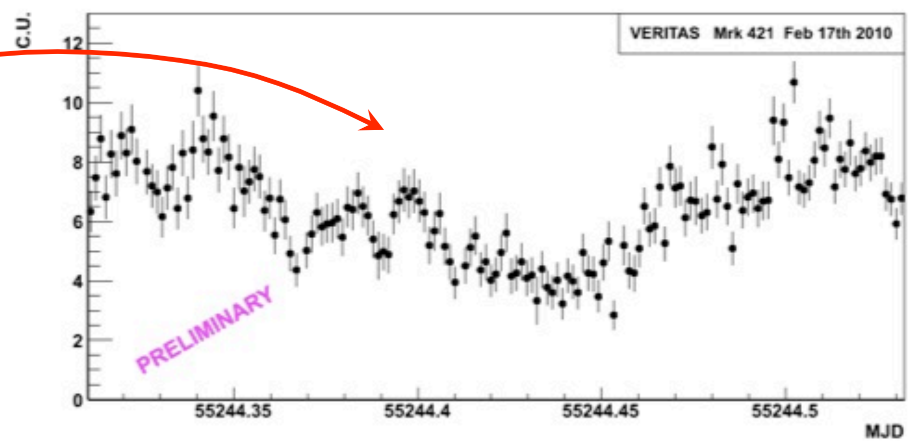
Model parameters indicate a relatively weak magnetic field of ~ 0.01 G and a particle dominated jet.

Characterizing the brightest TeV Blazars: Mrk 421

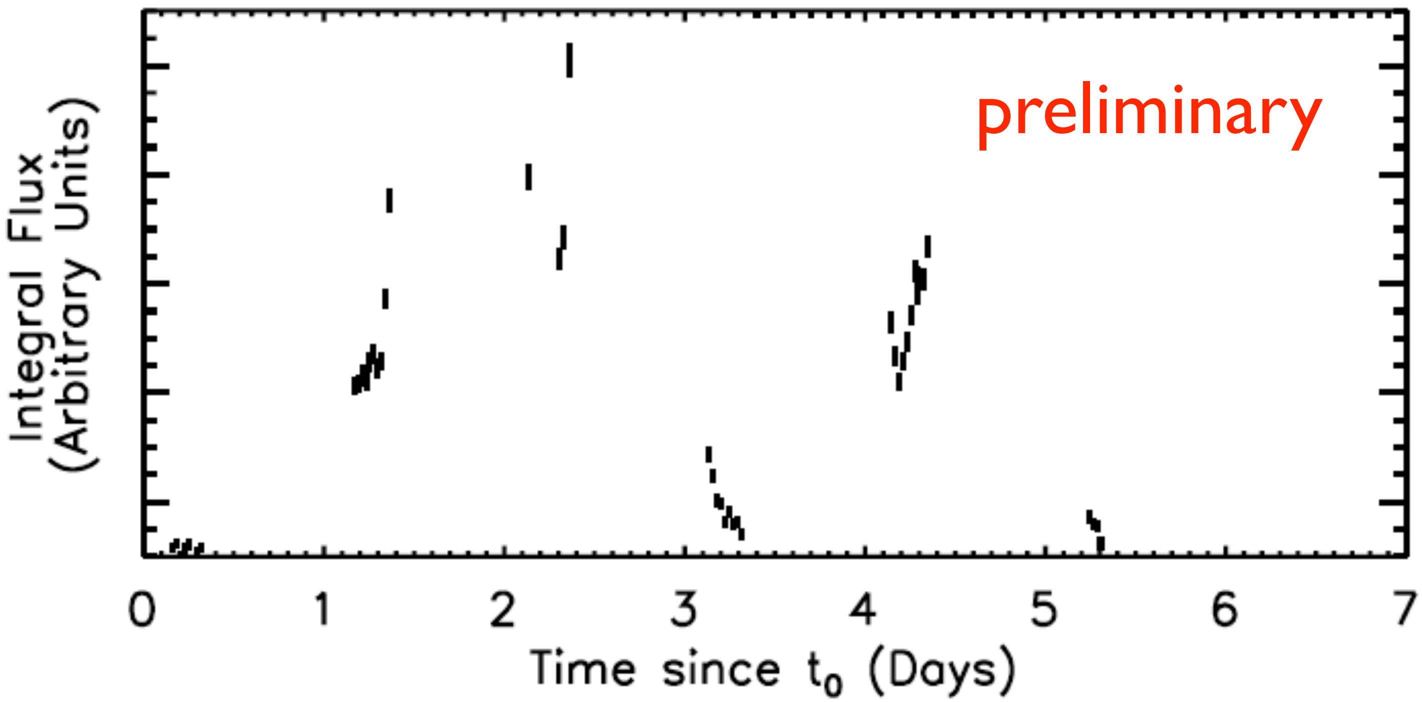
- Long-term monitoring program
- Major flares in 2008 & 2010
  - initiated large MWL efforts
  - spectral hardening with increasing flux
- Huge flare on Feb 17th 2010
  - ~8 Crab Nebula flux
  - variability on 5-10 min time scales
  - >10 σ per 2 minute bin







Mrk 421 Flare in 2013



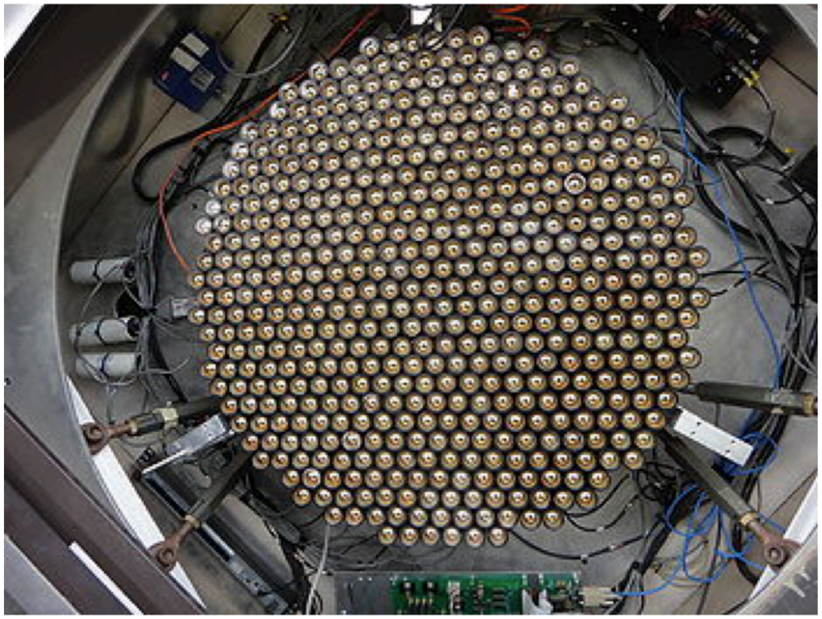
- Flaring detected in April 2013, during a MWL campaign with NuSTAR and Swift.
- Detected by both VERITAS and MAGIC. Flaring at > 11 Crab Nebula flux. (Low state flux ~ 0.5 Crab). ~30 photons/min (~few nights)
- Maintained its bright state above 1 C.U. for five days – Strong intra-night variability.

VERITAS Results: Improved Instrument – New Detections

- VERITAS camera upgrade in 2012 summer. Better sensitivity to weak blazars.
- Initial tests of event rates, bias curves, and observations of the Crab show ~ 30% decrease in triggering threshold of cosmic and γ-ray events
- ~ 2.5 times increase in raw rates

New blazar detections:

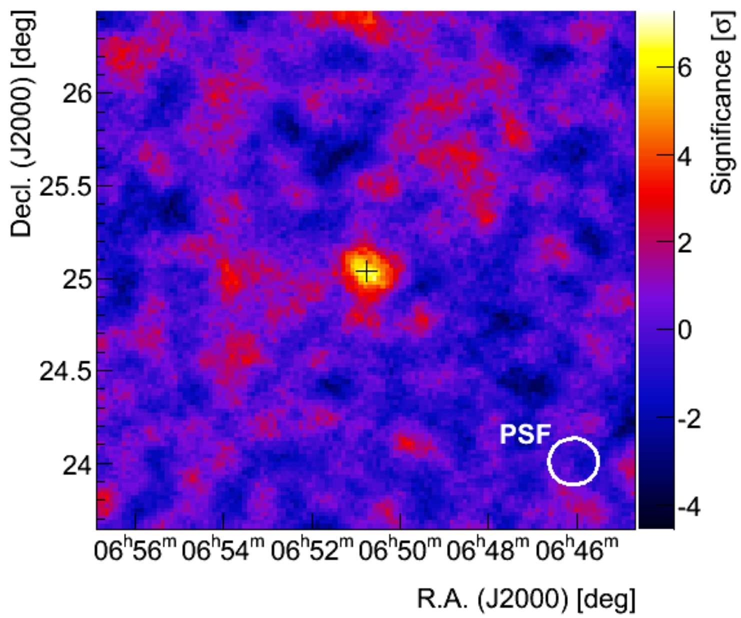
- 1ES 1011+496
- 1ES 0647+250



New high-QE PMTS(R10560-100-20 MOD Hamamatsu) installed in the VERITAS Cameras (July 2012)

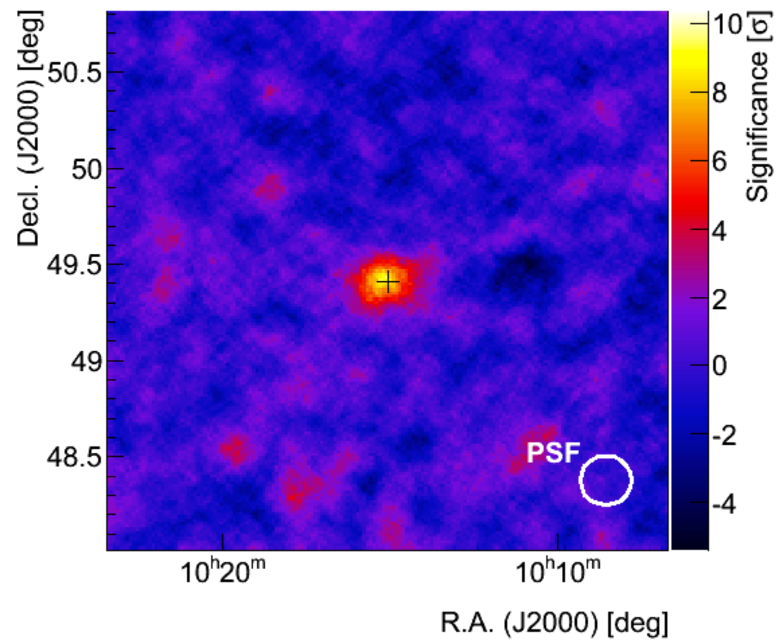
New Blazar Detections

1ES 0647+250



- Fermi Γ = 1.59, promising VHE target
- VERITAS partial moonlight observations – 6.2σ detection, 2.9% Crab (>140 GeV) – confirms MAGIC detection in 2011

1ES 1011+496



- VERITAS ~ 6.3% C.U. (> 150 GeV), in rough agreement with the MAGIC detection in 2007.
- VERITAS observations carried out in partial moonlight

Summary & Future Outlook

- Cherenkov Telescope Array (CTA) has one order of magnitude better sensitivity than the current generation of γ-ray telescopes. That will allow the detection of γ-ray emission from the various particle acceleration regions in nearby radio galaxies, and with much greater time resolution than before from blazars.

-Observations with CTA will further constrain the structure and make-up of jets, and thus, test models of jet formation, acceleration, and collimation.

- Detailed studies of the spectral evolution of bright blazars during flares will be possible with CTA, helping to discriminate between particle injection, particle acceleration, or beaming effects as the cause for the flaring events. The ability to produce light curves with significantly shorter time binning will give access to measure shorter variability timescales, deriving tighter constraints to the size and location of the gamma-ray emitting region.

Extras….