VERITAS Observations of Relativistic Jets

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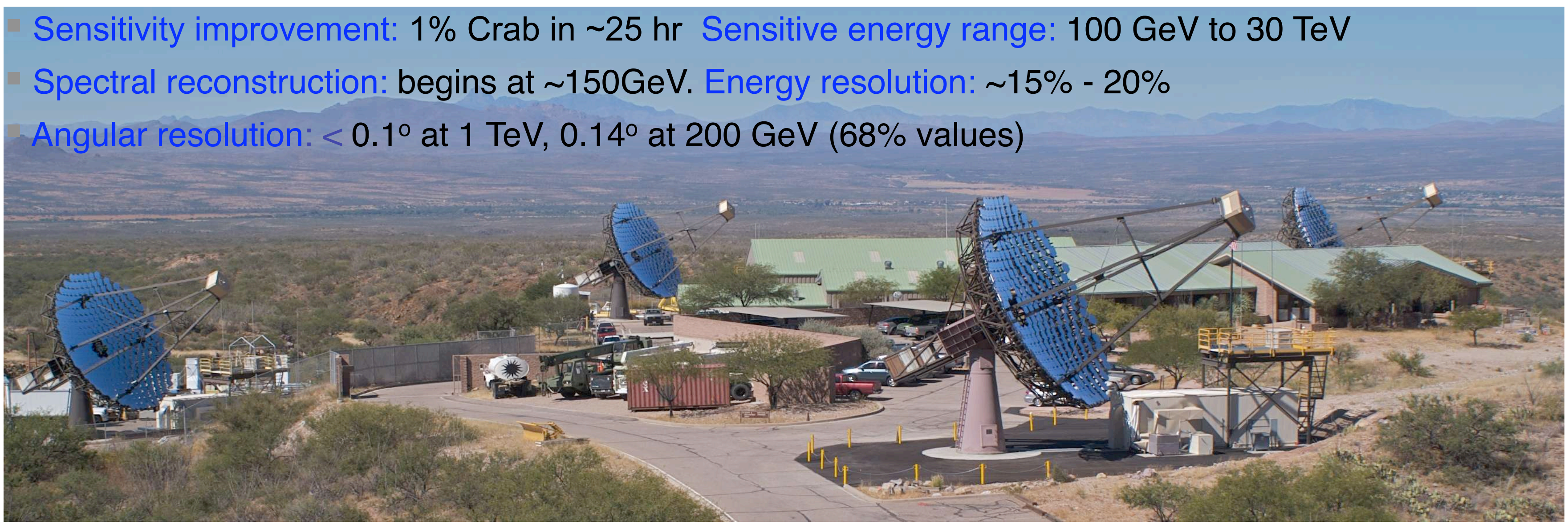


Relativistic Jet Phenomenology

Relativistic jets are extremely powerful outflows of collimated plasma that appear in active galactic nuclei , gamma-ray bursts, and X-ray binaries.

- 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).

- The observed similarity (in morphology and spectrum) of jets from black holes of different mass suggests that they share a common physical origin.

Outline of talk

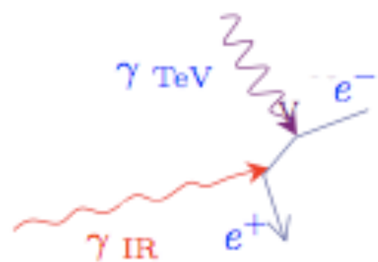
- Highlights from the VERITAS Extragalactic Program
  - TeV Blazar Sample
  - Spectral Energy Distributions of VHE Blazars
- Galactic sources of HE relativistic outflows
  - Gamma-ray binaries

Why study TeV blazars?

Opportunity to explore a large range of scientific questions ….

- Properties of SMBHs and their environments

- Particle acceleration and emission mechanisms?
  - Jet structure & jet formation, acceleration & collimation?
  - TeV origin – leptonic or hadronic?
  - Black hole – jet connection

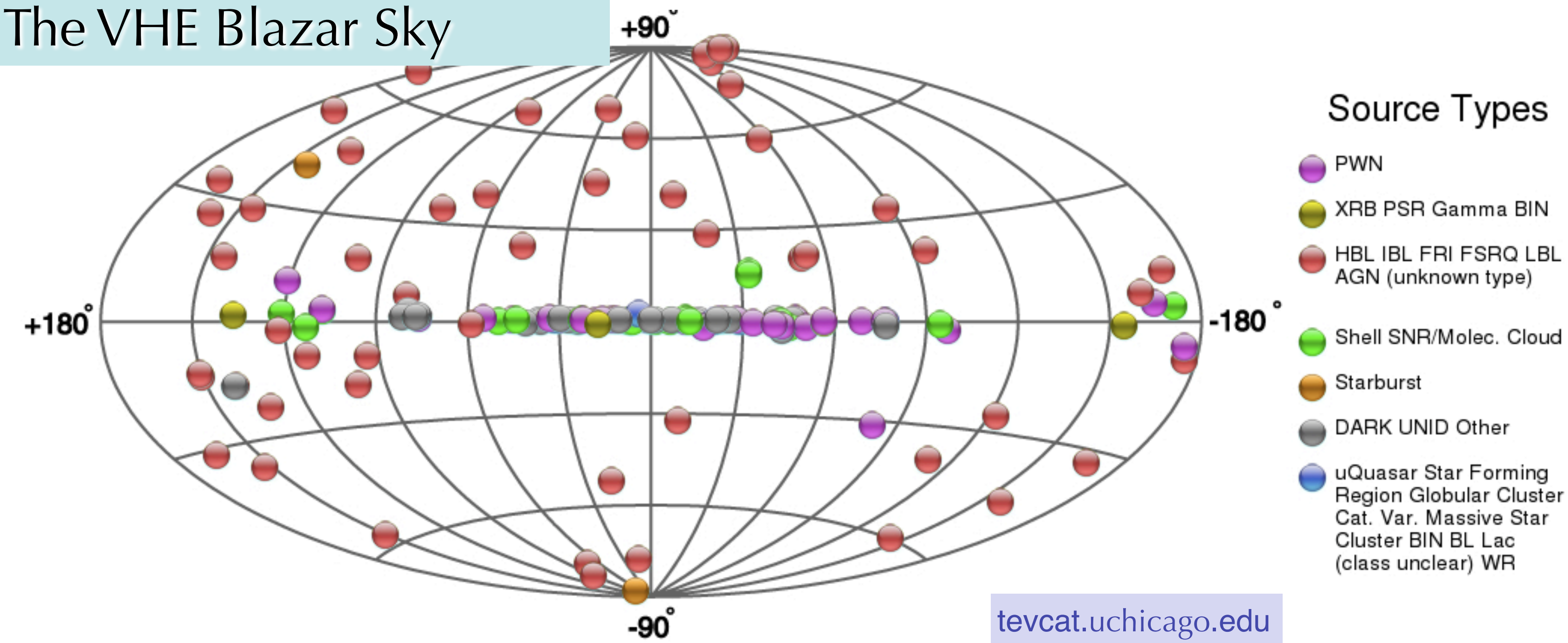


- Best extragalactic probes of the EBL via its interaction with TeV photons traveling cosmological distances.
- Better constrain the IGMF e.g. see #40, Menzler
- Test the validity of the Lorentz Invariance principle at high energies.

- Particle acceleration to extreme energies - origin of UHE cosmic rays (E>10^{18} eV)?

Gamma Ray Observations of Relativistic Jets

The VHE Blazar Sky

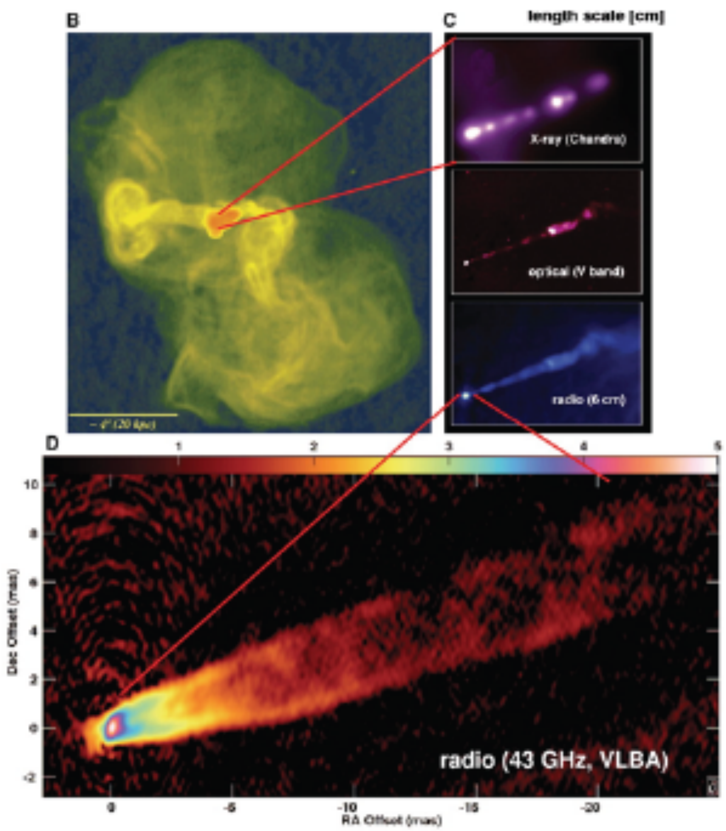


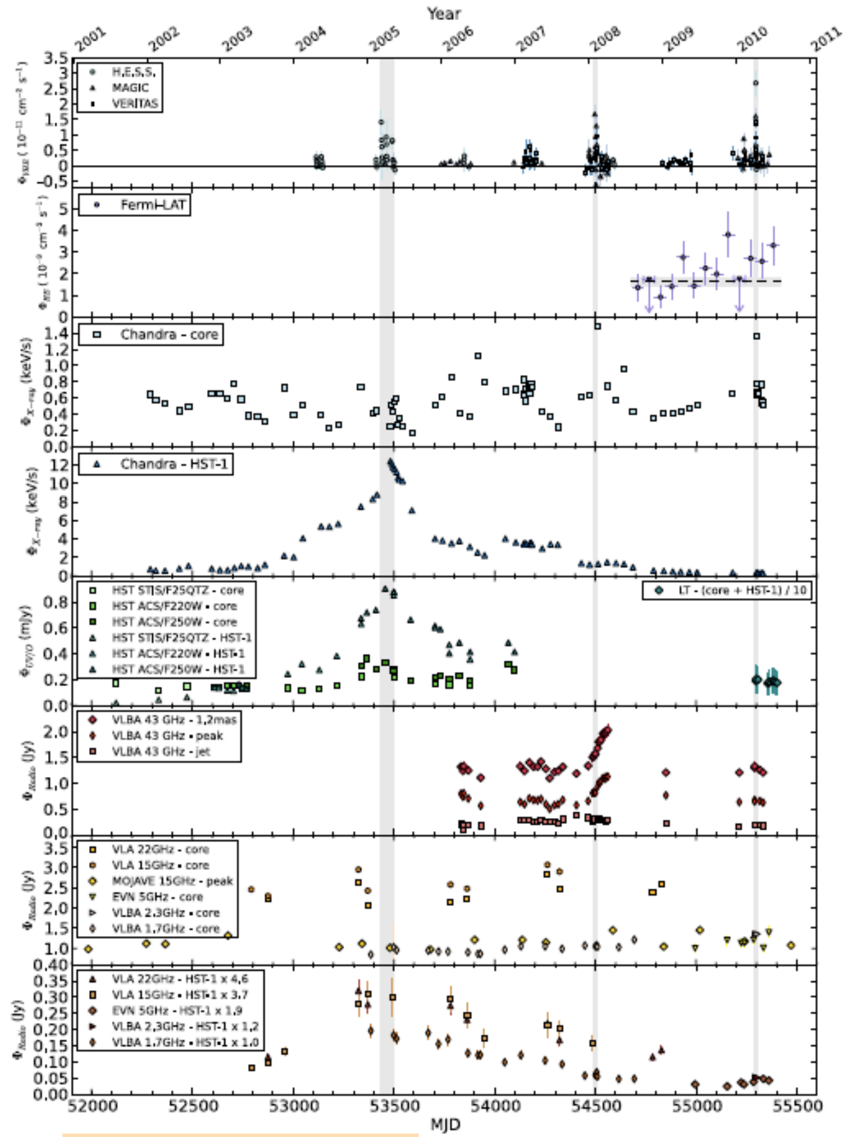
Also see #38, Kaufmann

- Current generation of IACTs (H.E.S.S., MAGIC and VERITAS) has detected γ-ray emission from ~ 50 AGNs.
- 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

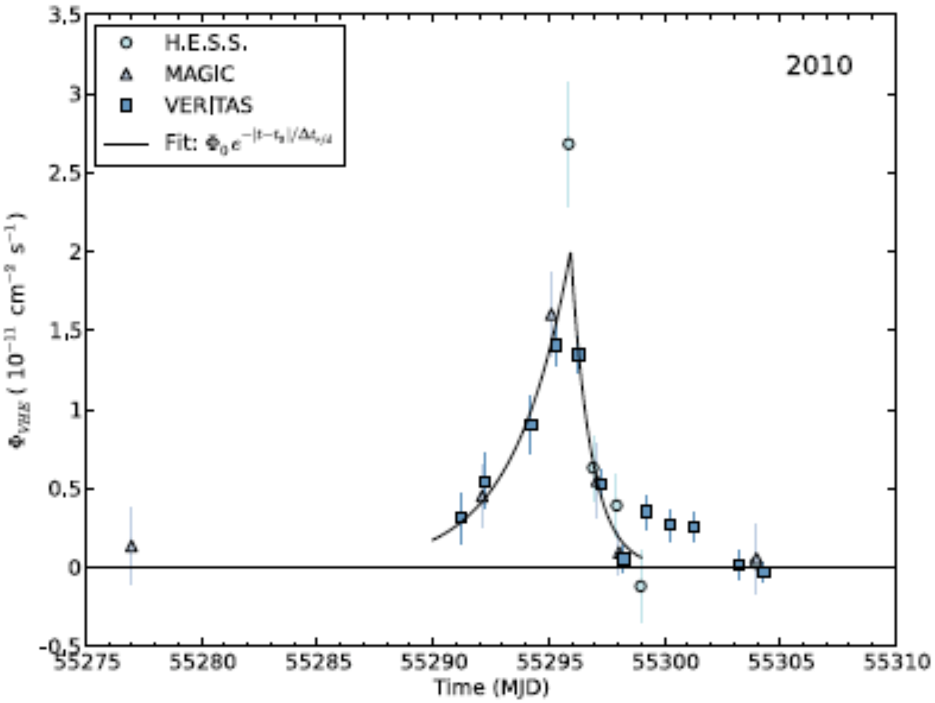
- Location of the emission region ----
- M 87 is one of the closest AGNs (20 Mpc). The jet is oriented at ~ 20°
- VHE studies are likely to contribute to a better understanding of AGN unification schemes

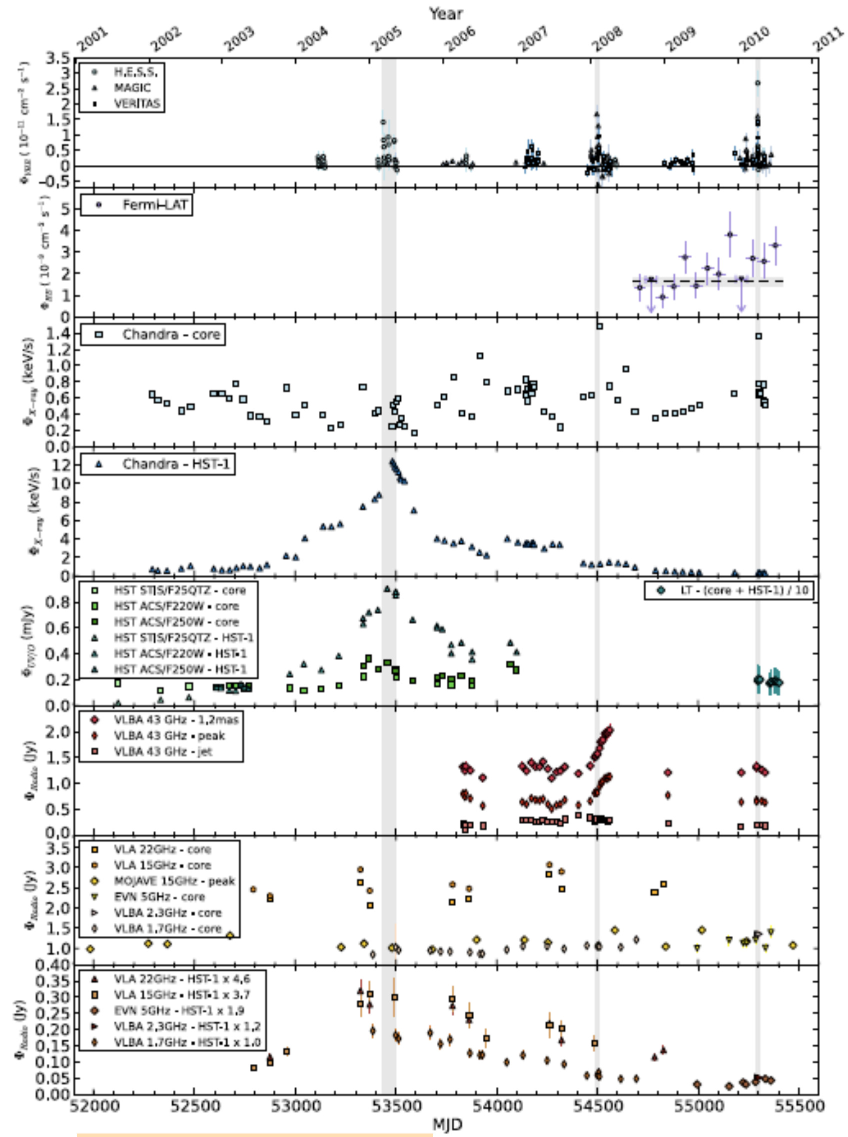




Abramowski et al. 2012

Radio Galaxies - M 87 - A very close AGN

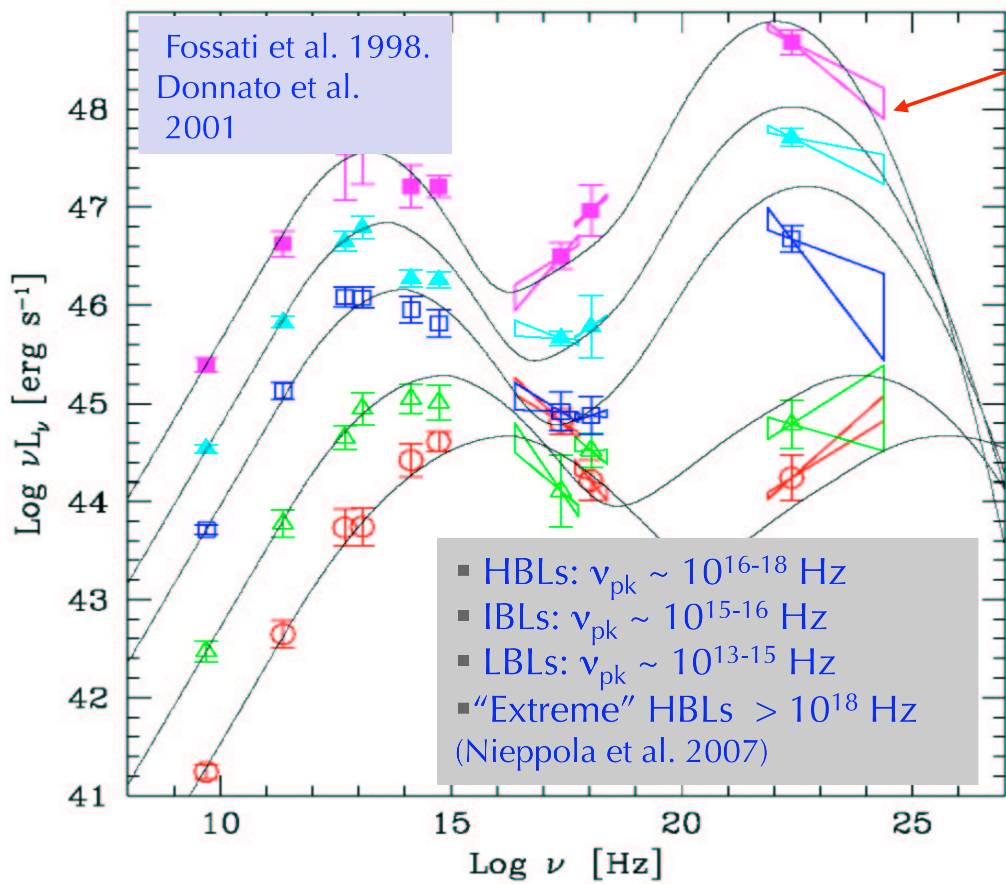




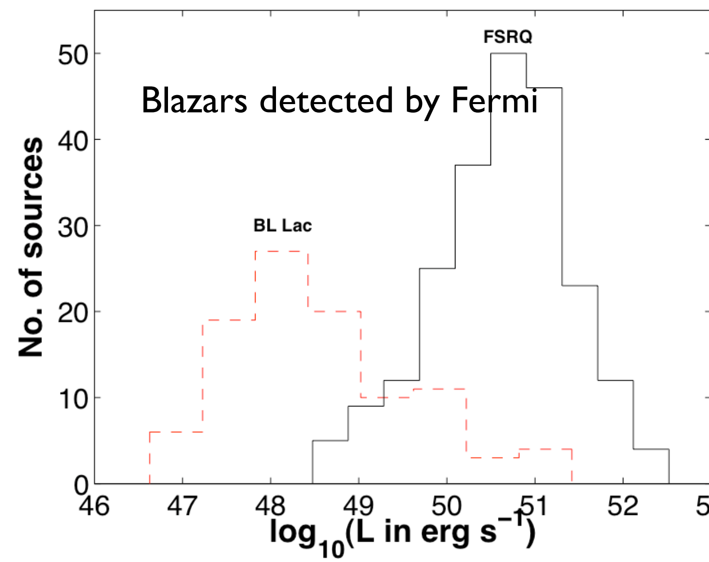
Abramowski et al. 2012

- 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

Blazar sequence – expanding on TeV source classes



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



Absence of intrinsic γγ pair absorption → beaming in blazars.
High isotropic γ-ray luminosity ~ 10^{48}erg/s→ Optical depth >> 1
→ γ-ray emission originates in strongly beamed sources.

Blazars Detected by VERITAS

Key Science Project: Discovery,
MWL & ToO observations
~400 hr/yr including moonlight data

- 26 detections
  - 10 discoveries
  - 1 radio-galaxy : Messier 87
  - 1 LSP : BL Lacertae
  - 6 ISP
  - 18 HSP
- Predominately nearby
  - VHE horizon (z = 0.03 to at least 0.6035) (Furniss et al. 2013 arXiv:1304.4859)
- Target selection
  - Mostly X-ray candidates
  - Now – Fermi-LAT motivated

AGN	Type	z
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
1ES 1727+502	HBL	0.055
BL Lac	LBL	0.069
W Comae	IBL	0.102
VER J0521+211	IBL/HBL	0.108
RGB J0710+591*	HBL	0.125
H 1426+428	HBL	0.129
B21215+303	IBL/HBL	0.130?
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.139
1ES 1440+122	IBL/HBL	0.162
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 1011+496	HBL	0.212
1ES 0414+009	HBL	0.287
1ES 0502+675	HBL	0.341?
1ES 0647+250	HBL	~ 0.45
PG 1553+113	HBL	0.43 < z < 0.47
3C 66A	IBL	0.444 ?
PKS 1424+240	IBL/HBL	>0.6035

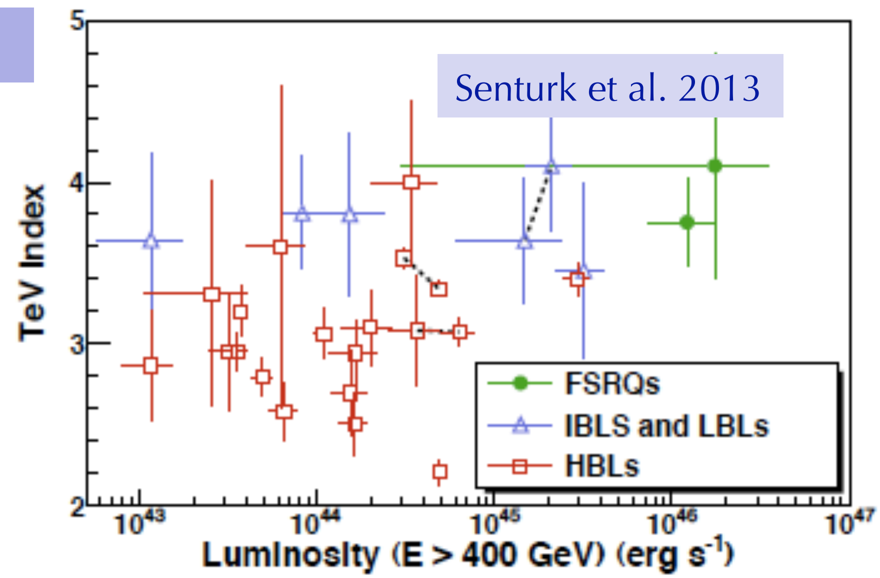
VERITAS Results: Low Synchrotron Peak Objects

With better sensitivities, LSP blazars are becoming more common in TeV catalogs.

Average properties of VHE-detected blazars

	Γ	low state	t_{var}
HBL	harder	detectable	~3 min
IBL		weak	1 day
LBL		not seen	~15min
FSRQ	softer	not seen	~10min

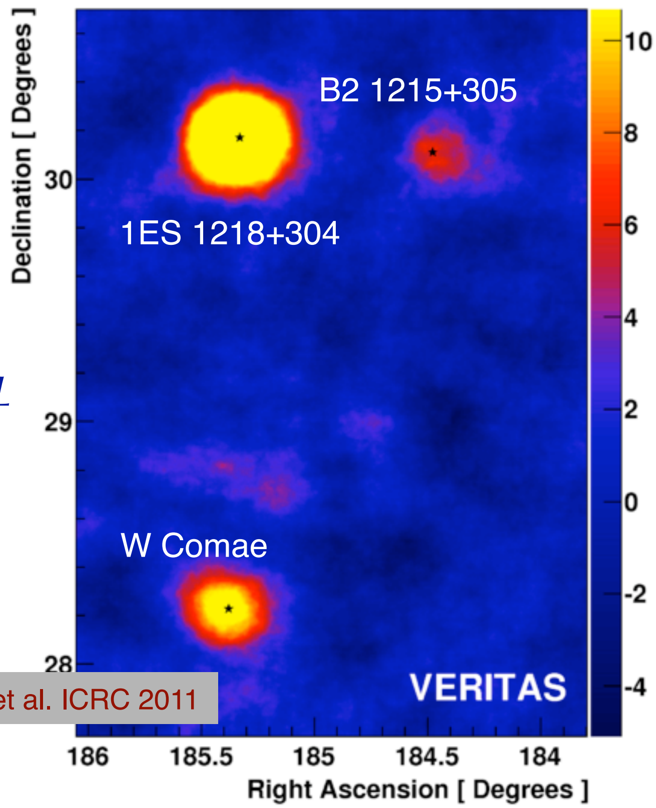
Errando et al. arXiv: 1205.006



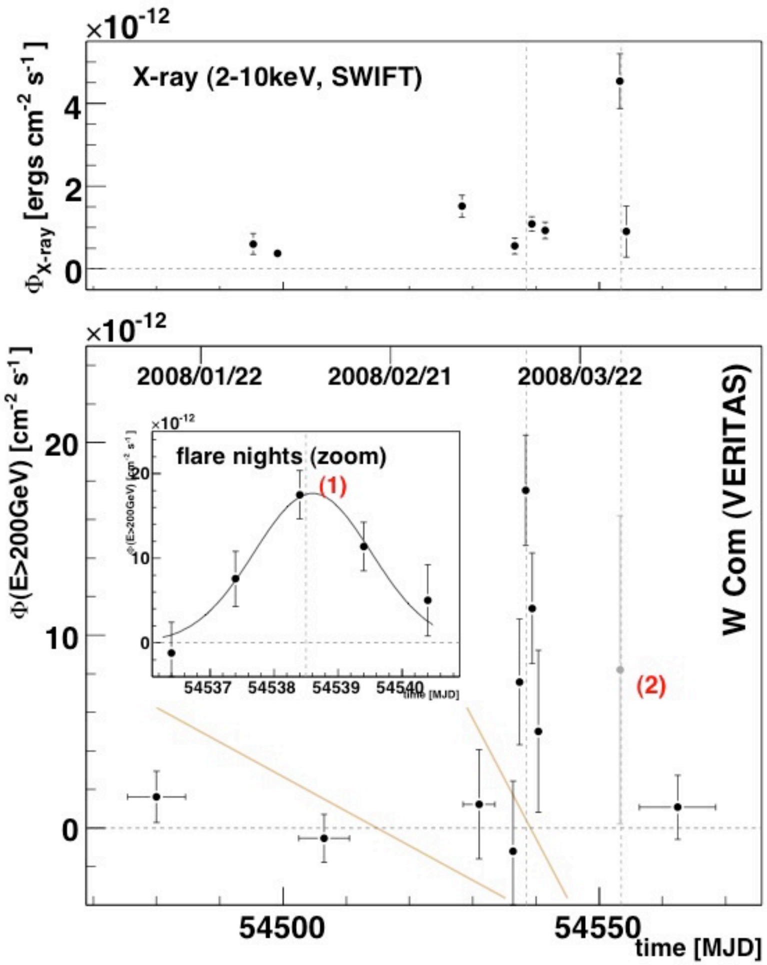
IBLs: VERITAS Discovery of W Com

- Intermediate-peaked (IBL).
- First IBL to be detected > 200 GeV
- Strong flare 2008 March (ATel 1422)
- 2008 Jan – Apr: ~5 σ in ~40 hr observations

FOV shows HBL/IBL/LBL



Benbow et al. ICRC 2011

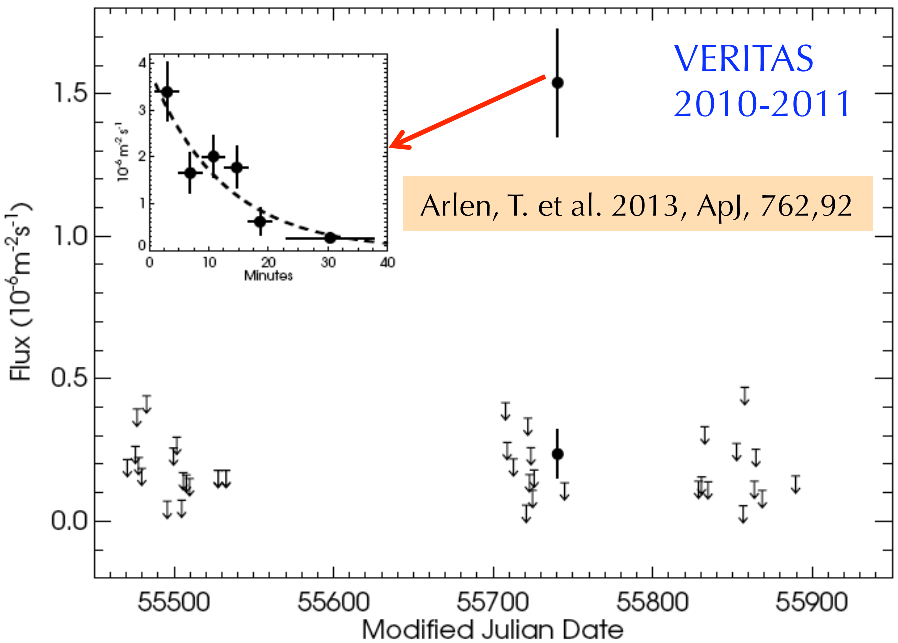


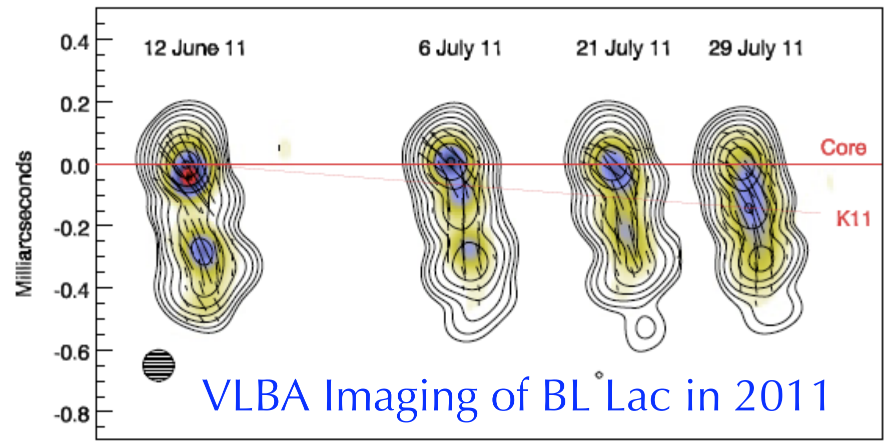
Acciari et al. 2008 ApJ 690, L73

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

BL Lacertae Flare and Rapid Variability

Locating the Emission Region in the Jet





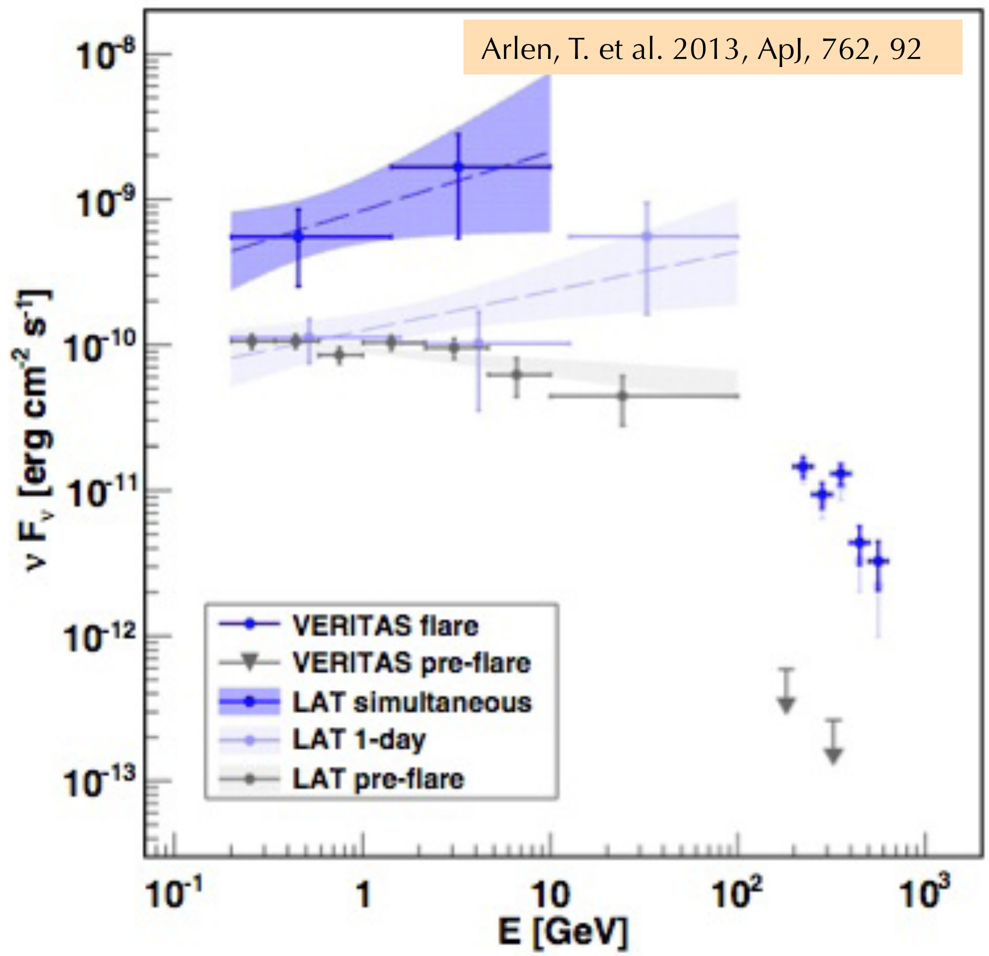
New superluminal component near core (43 GHz) – emergence of radio knot linked to γ ray flare.

- Flare on June 28, 2011 picked up by VERITAS monitoring; 125% Crab flux (> 200 GeV); $\Gamma = 3.8\pm0.3$; good MWL coverage.
- Flux decayed by factor of 10 in $\tau = 13 \pm 4$ min => Strongly constrains size of emission region ($R < c\tau\delta/(1+z) \sim 2.2\times10^{13}\delta$ cm).
- Simultaneous changes in optical polarization, X-ray, optical and UV flux + new radio feature: Enables location of emission region.

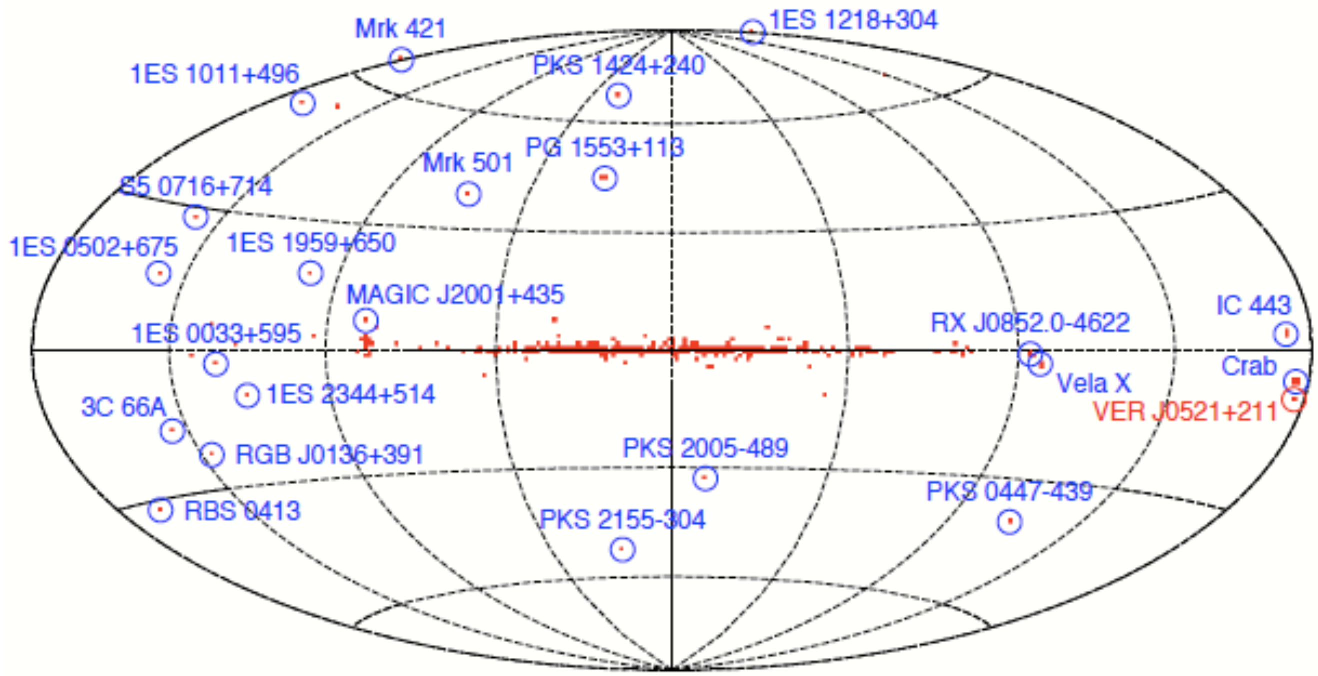
BL Lacertae flare & pre-flare SED

- TeV flare occurred when source was active & variable in GeV γ rays
- Simultaneous VERITAS and LAT spectra show that the γ-ray SED peak lies ~ 10 and 100 GeV.
- LAT data shows evidence for spectral hardening during the VERITAS flare.

Also see #37, Errando



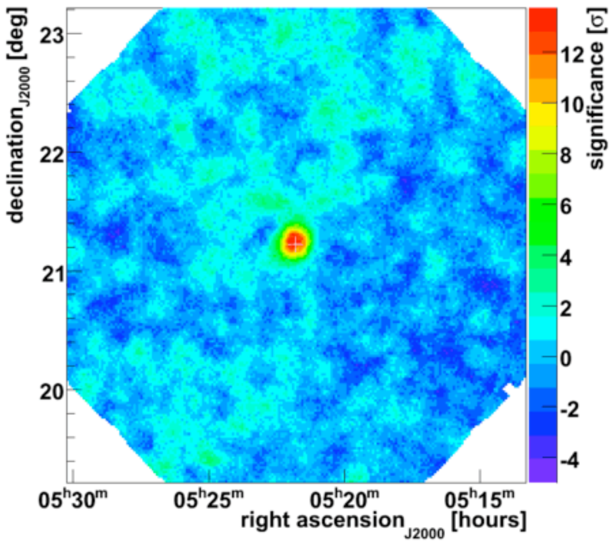
VERITAS Results: Finding new blazars (Follow up of Fermi Sources)

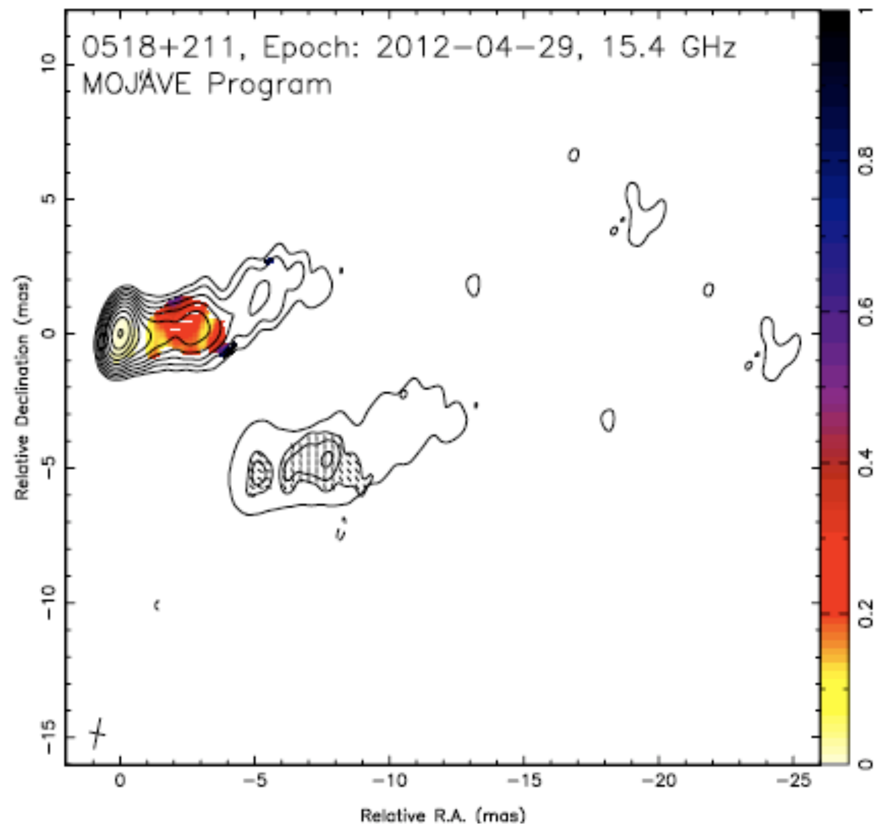


- A number of unidentified Fermi sources are expected to be blazars behind the Galactic plane.
- VHE telescopes are a good tool for identifying blazars at low latitudes (better localization, higher sensitivity to flux variability).

Blazars behind the Galactic plane

VER J0521+211



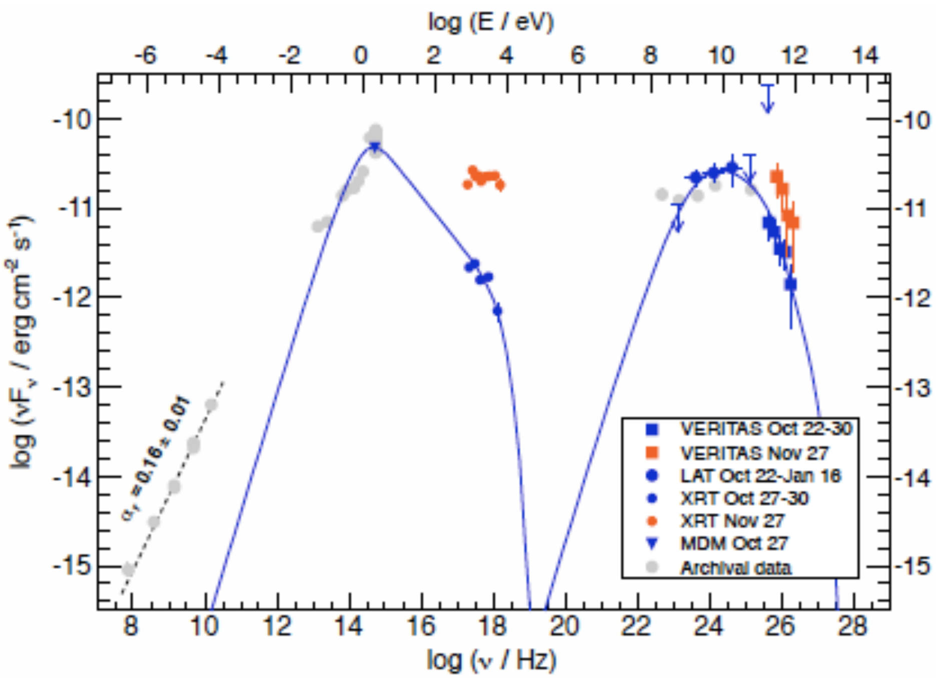


- Discovered in 2009. Flare detected ~10% Crab in 2012.
- Strongly variable from optical to TeV bands, with a peak flux corresponding to ~ 0.3 time bands the steady Crab (at TeV energies).
- Recent optical spectroscopy - typical of BL Lacs, z~0.108

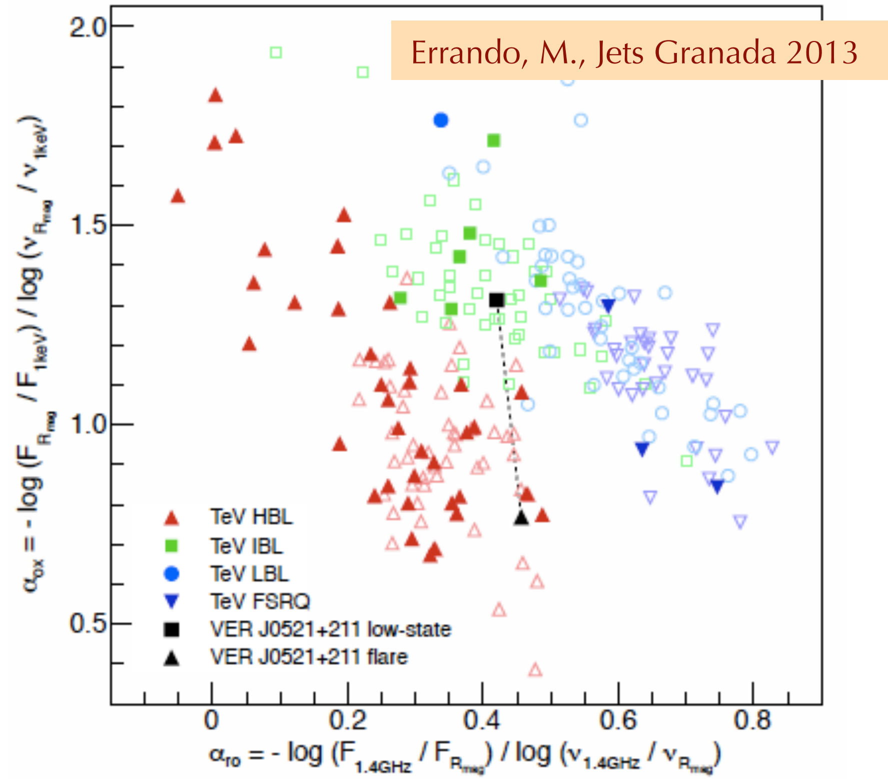
Errando, M., Jets Granada 2013

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

Spectral Properties of VER J0521+211



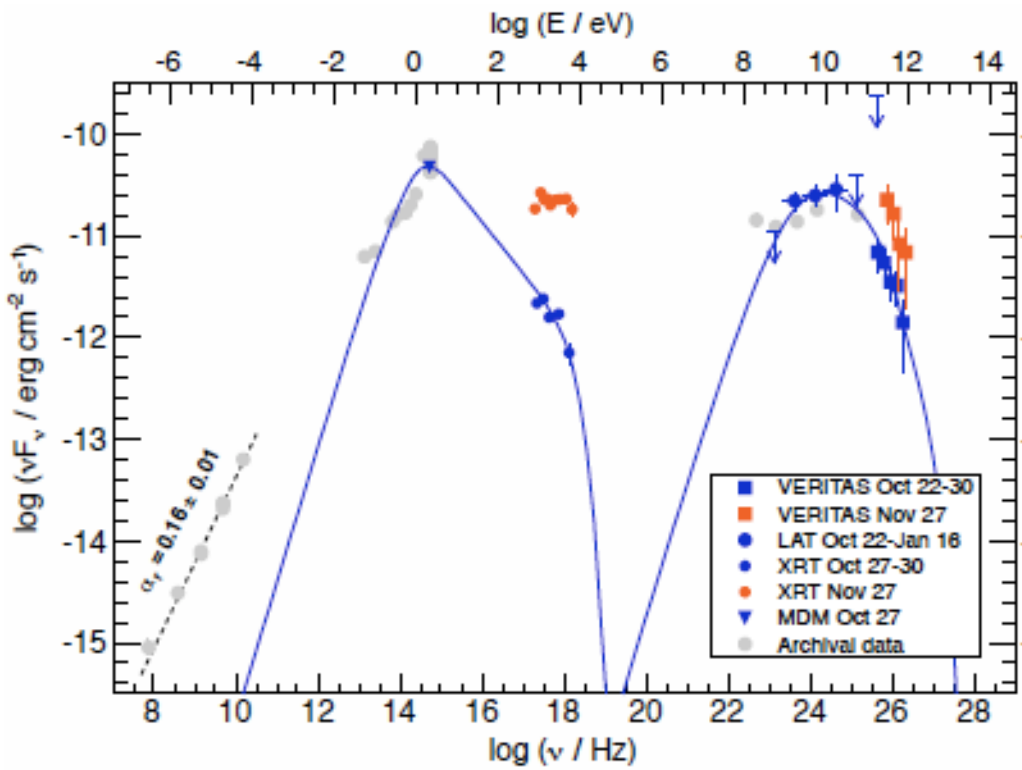
Spectral energy distribution of VER J 0521+211 during the VERITAS detection in 2009



IBL or HBL? Synchrotron properties similar to IBLs, however, synchrotron component shows HBL-like properties during the X-ray and TeV flare of 2009 November

SED of VER J0521+211

E. Aliu *et al*. 2013, in prep.



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

Gamma-ray spectra:

Γ_{HE} = 1.7 ± 0.1

Γ_{VHE} = 2.9 ± 0.3 (low), 3.3 ± 0.7 (high)

X-ray photon index:

Γ_{Xray} = 2.5 ± 0.1 (low), 2.0 ± 0.1 (high)

The high-energy emission from VER J0521+211 peaks in the γ-ray band, between 10 and 200 GeV, and can be described with a leptonic one-zone SSC emission model.
Model parameters indicate a relatively weak magnetic field of ~ 0.01 G and a particle dominated jet.

VERITAS Results: High-Synchrotron Peak Objects (HBL)

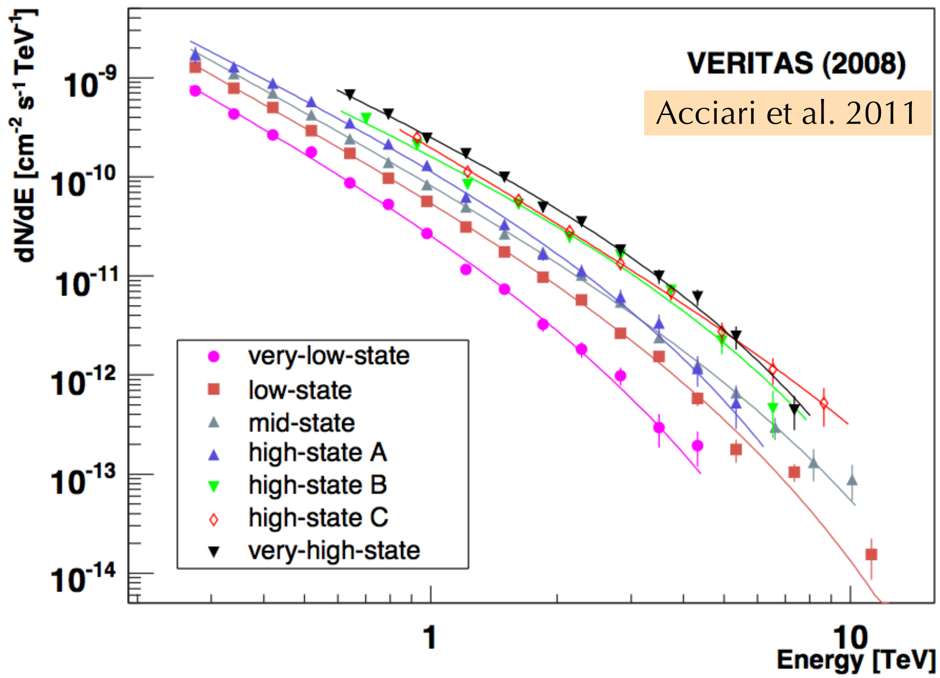
Majority of VERITAS blazars are HBL

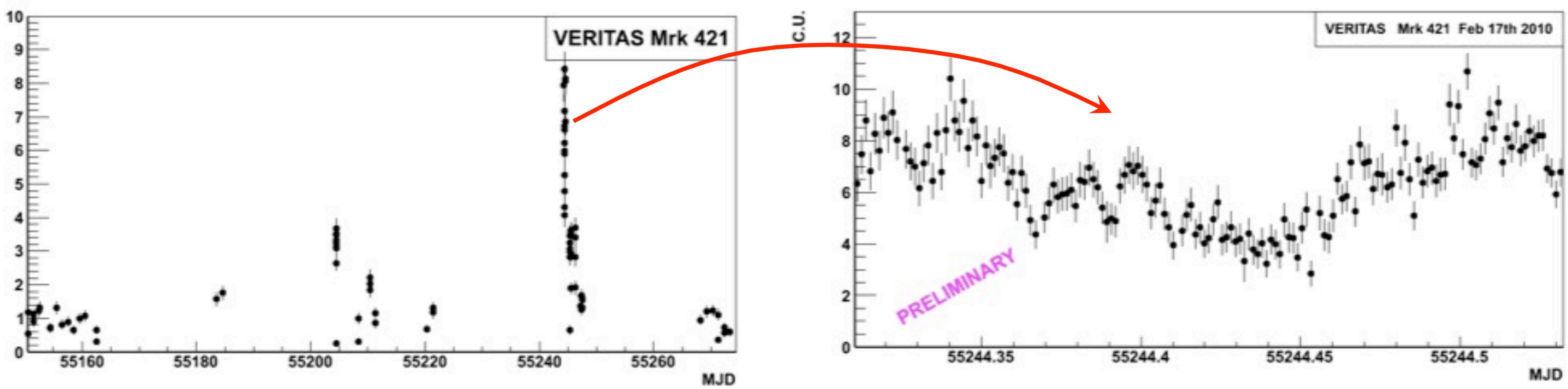
Some highlights:

- Long term study of 1ES 0229+200
- Mrk 421 flare

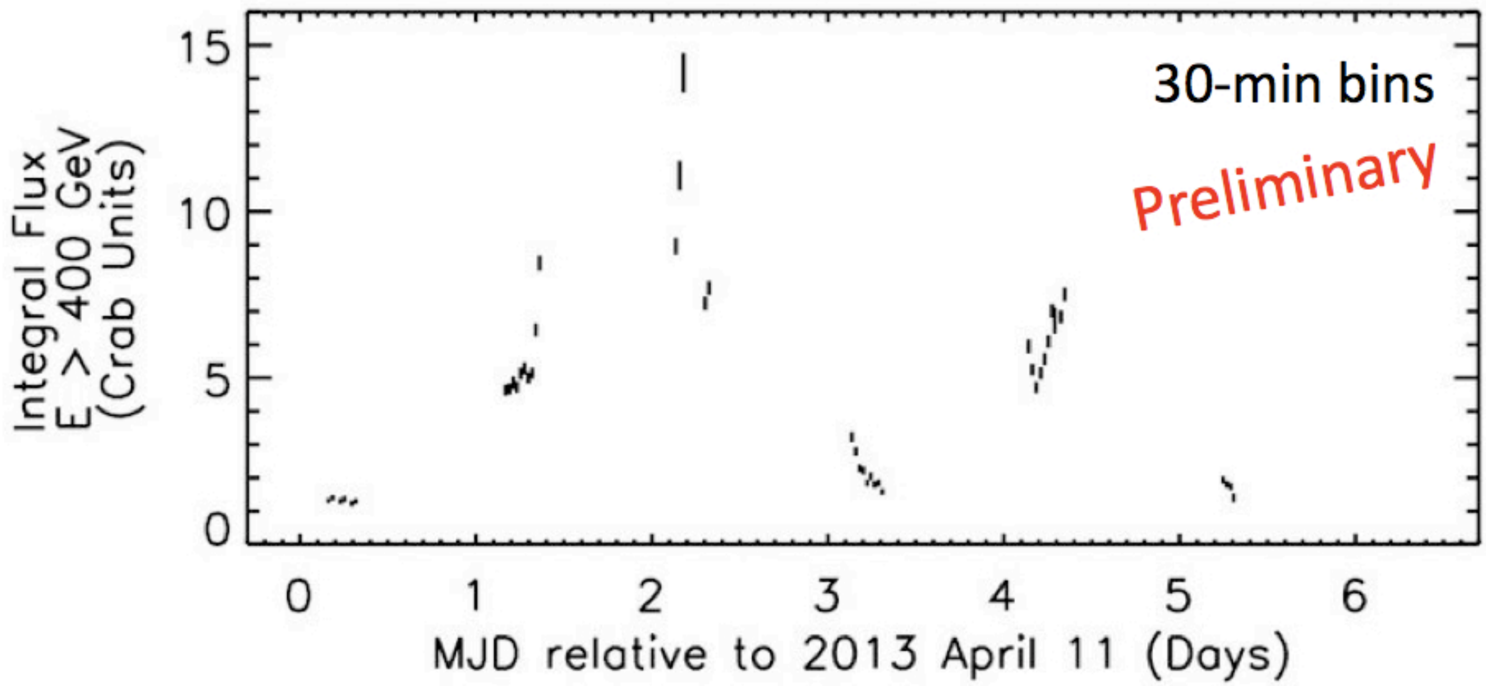
TeV Blazar: Mrk 421

- long-term monitoring program
- major flares in 2008 & 2010
  - initiated large MWL efforts
  - spectral hardening with increasing flux
- high in VHE & X-ray since 11/09
  - 35 h of data; ~400 σ
- huge flare on Feb 17th 2010
  - ~8 Crab
  - variability on 5-10 min time scales
  - >10 σ per 2 minute bin





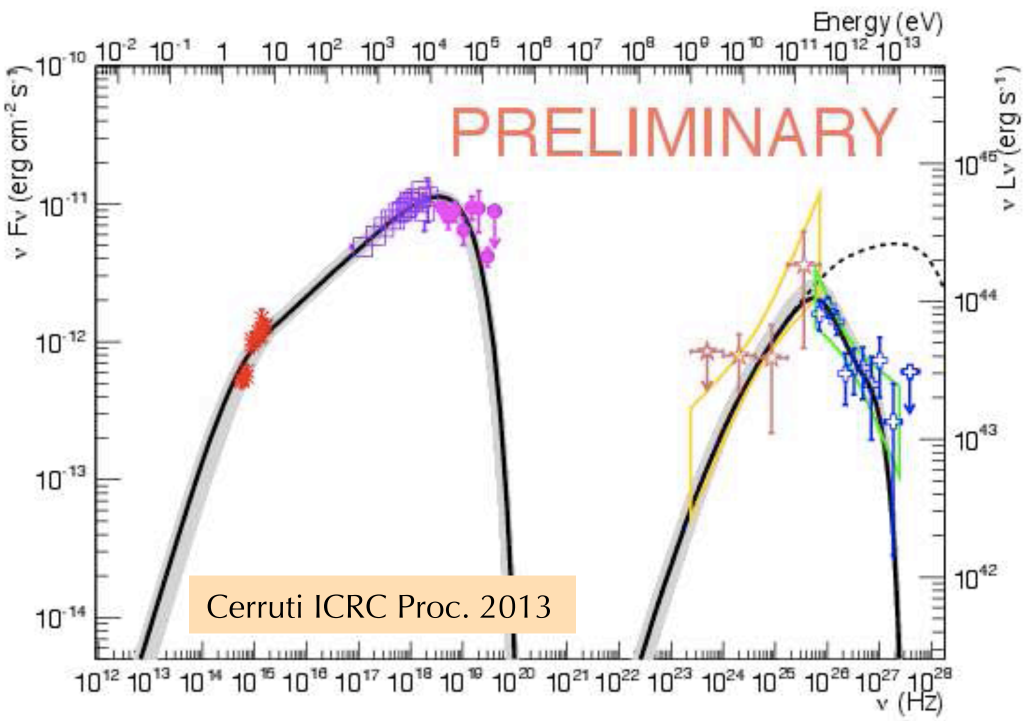
Mrk 421 Flare in 2013



Also see #28, Balokovic

- 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)
- Maintained its bright state above 1 C.U. for five days – Strong intra-night variability

1ES 0229+200 - Long term VERITAS monitor



- Most detailed VHE SED to date
- Synch Peak ~ 10 keV

- Min value of Doppler factor: δ > 56 (higher than commonly assumed in SSC modeling of HBLs)

- Energy budget - magnetic/ particle energy density: $u_e/u_b \sim 10^5$ – significantly out of equipartiton.

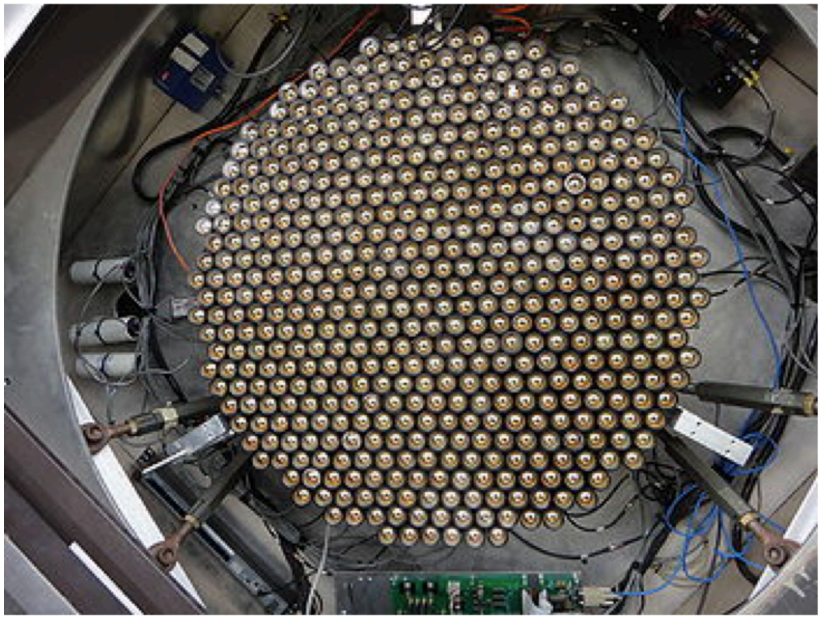
- Hard spectrum at TeV energies: Γ ~ 2.5, flux ~ 2% Crab (> 300 GeV)
- 3 years of VERITAS data indicates a variable source
- Candidate for intergalactic magnetic field (IGMF) & EBL studies

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:

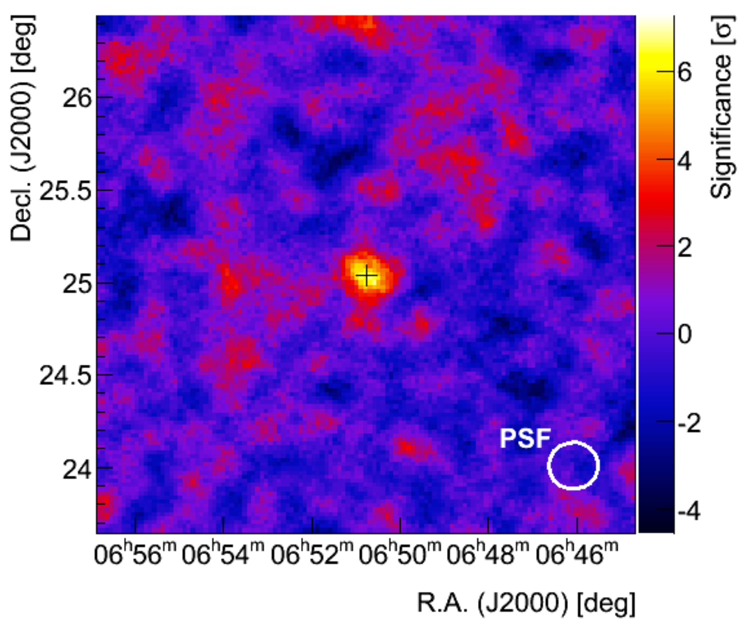
- 1ES 1011+496
- 1ES 0647+250



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

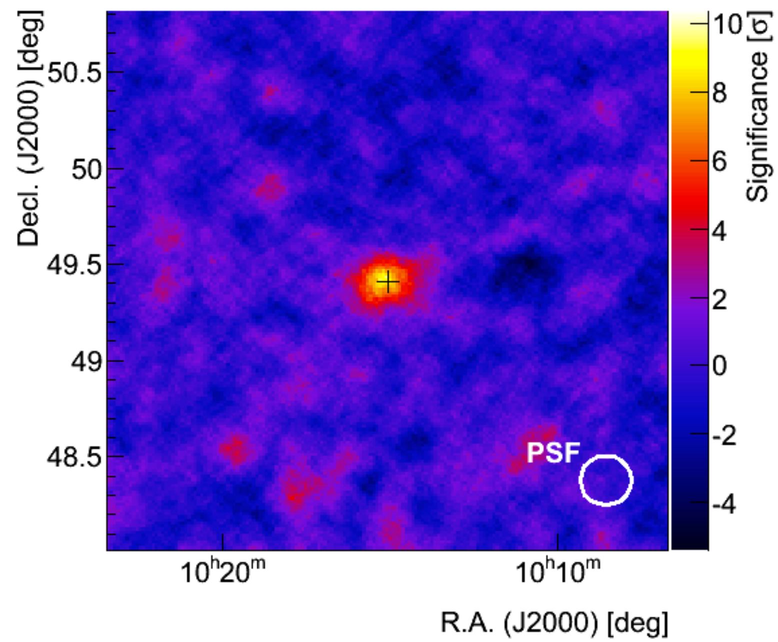
New Blazar Detections

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

Outline

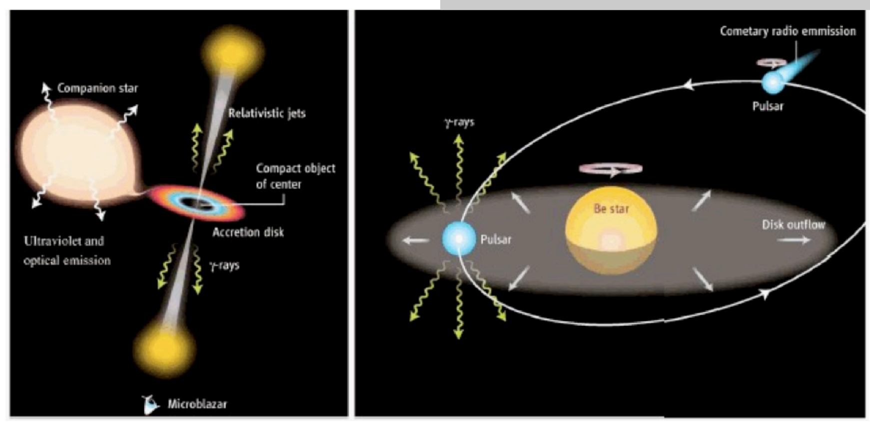
- (Quick) introduction to VERITAS
- Highlights from the Extragalactic Program
  - TeV Blazar Sample
  - Modeling blazar SEDs
- Galactic sources of HE relativistic outflows
  - Gamma-ray binaries

Galactic sources of HE relativistic outflows

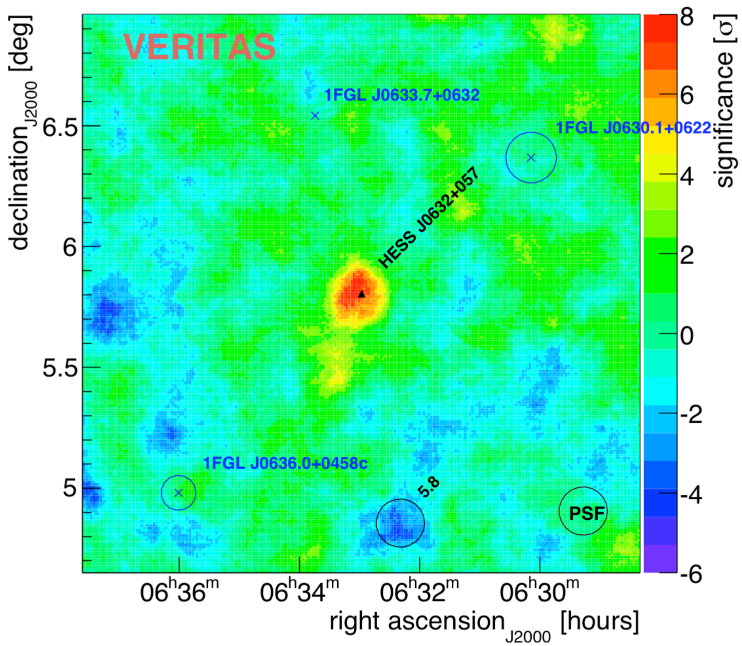
- TeV observations of binaries:
  - X-ray binaries believed to be excellent targets for TeV emission – evidence of relativistic particle acceleration
  - Binaries are the *only* variable Galactic TeV sources.
  - TeV emission probes the highest energy particles accelerated. May provide the keys to an understanding of astrophysical jets.
  - Two Scenarios: *Microquasar:* gamma-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 companion

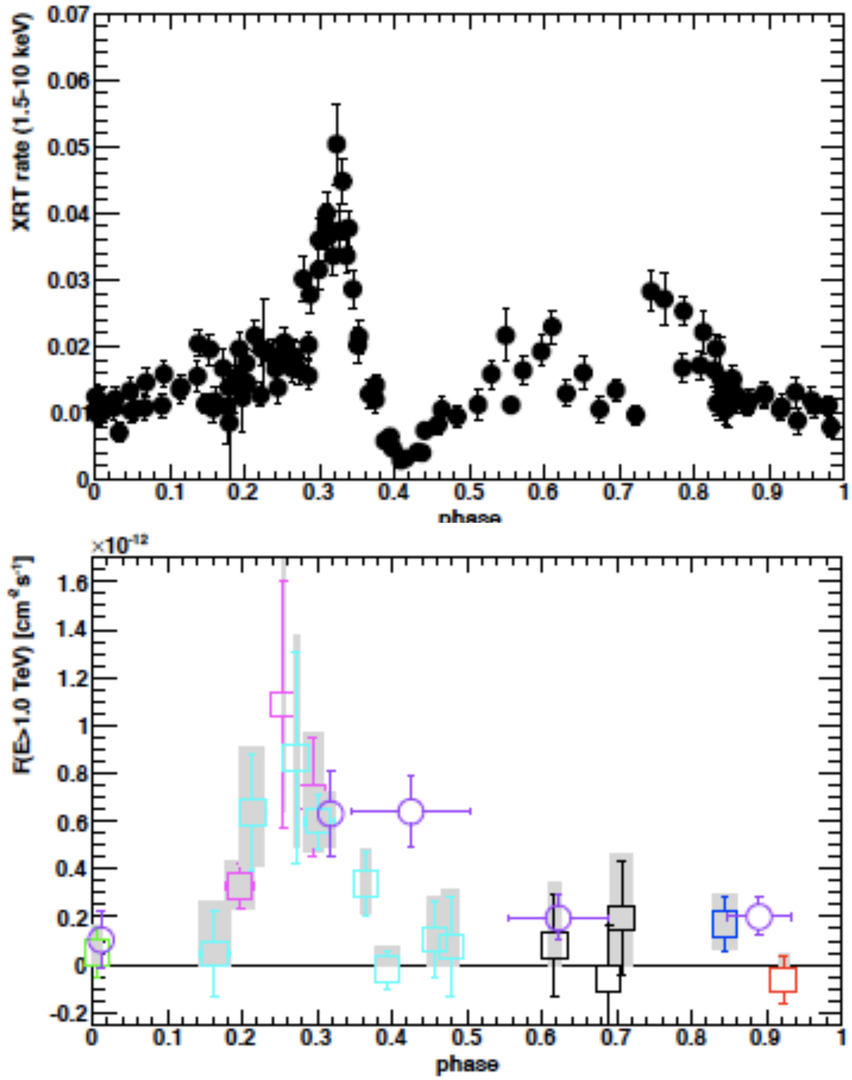
- Only 4 TeV binary detections to date (LS I+61° 303, LS 5039, PSR B1259-63, HESS J0632+057)
- HESS J0632+057 identified as a binary with follow up VERITAS & X-ray observations

Mirabel 2006 Science



Galactic sources of HE relativistic outflows





- HESS J0632+057: unidentified γ-ray source located in the Monoceros region
- Associated with massive Be star MWC 148.
- VHE & Swift X-ray data indicate that the source is a binary period of 321 days.

Maier & Skilton, 2011 ICRC, arXiv: 1111.2155

Summary

- Population of VHE blazars is growing – starting to understand their collective observational properties. Long term monitoring of a sample of northern VHE blazars – study spectral and flux variability. Goals are to-
    - catch fast flares (size of the emission region, Lorentz Invariance).
    - measure SEDs of very bright blazars and increase sensitivity to weak sources (study of emission mechanisms).
    - radio galaxies, M87 (location of the emission region).
    - detect new blazars, soft-spectrum sources may be accessible with upgraded camera (blazar population studies).
- VERITAS has carried out in-depth characterization of the TeV binaries LS I +61 303 and HESS J0632+057. Need to carry out further investigation of this fascinating source class. Outstanding questions --
    - what are the fundamental similarities between the known TeV binary systems? How do they differ from other HMXBs that have not been detected at TeV energies such as Cygnus X-3 and GRS 1915+105?

Extras….