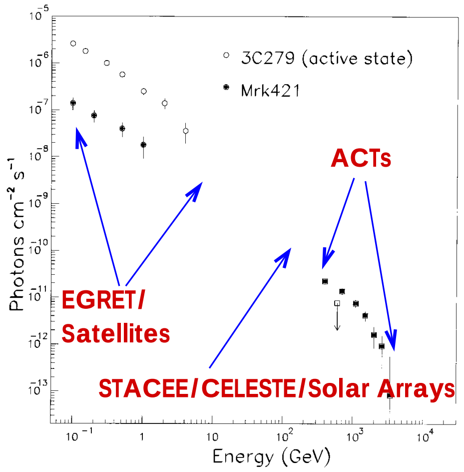
BLAZARS – Observational Aspects

Recent Results

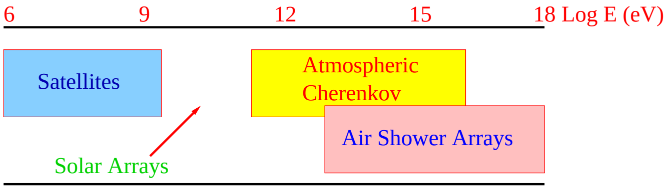
Reshmi Mukherjee, Barnard College, Columbia University

Integral Photon Spectrum of Blazars



Gamma Ray spectrum of blazars covers 6 decades in energy

Observational Techniques

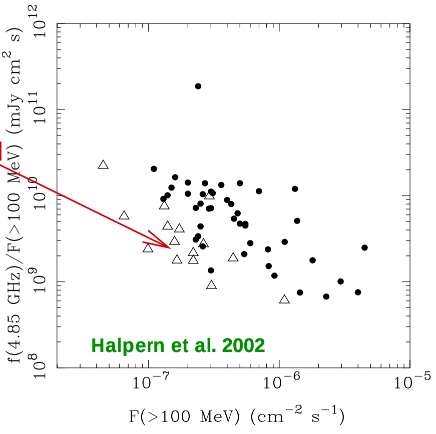


- **30 MeV – 10 GeV:** **68 Blazar detections by EGRET**
- **> 300 GeV:** **5 Blazars detections by ground–based ACTs**
- **50 GeV – 250 GeV:** **New low–threshold ACTs, e.g. STACEE, CELESTE, Solar II.**

EGRET BLAZARS

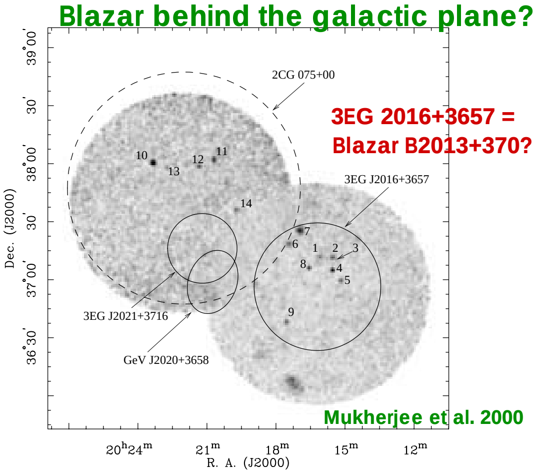
- **Important advancement in HE astro – detection by EGRET of 271 persistent sources.**
- **While most of the sources are unidentified – the majority of the ID–ed are blazars.**
- **The principle method of identification – find positional coincidences between EGRET & flat–spectrum radio/mm sources. This relies on the statistical evidence that blazars are the dominant population.**
- **Most EGRET blazars are associated with radio sources with 5GHz fluxes of > 500 mJy. However, it is likely that many of the unidentified 3EG sources are blazars with lower radio fluxes.**

Newly–identified optical counter–parts to EGRET blazars



Halpern et al. 2002

Blazar behind the galactic plane?

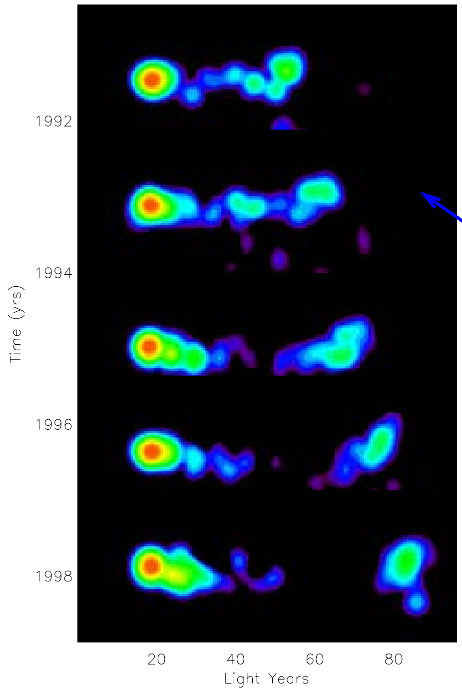


3EG 2016+3657 = Blazar B2013+370?

Mukherjee et al. 2000

EGRET BLAZARS – General Characteristics

- Almost all AGN seen by EGRET are blazars –– radio loud AGN viewed directly along the jet axis.



- High fraction of EGRET blazars are superluminal –– (Evidence from VLBI)

→ Blobs move relativistically

→ Trajectory must be inclined at small angles

Long term high frequency VLBI monitoring of the relativistic jet in 3C 279 at 22 GHz.

1991 – 1997 (18 epochs)

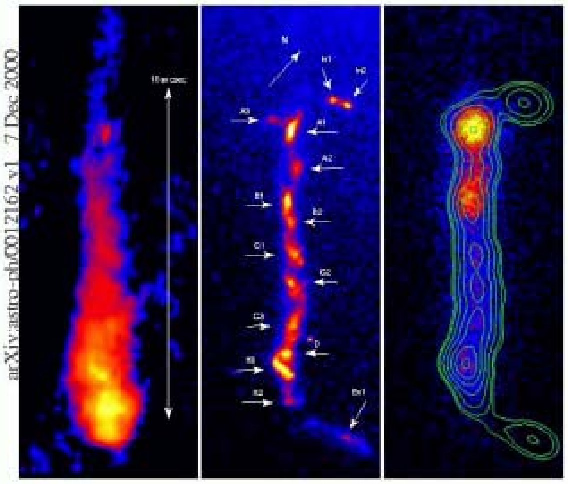
Bright, compact VLBI core, and jet components

Apparent speeds measured for 6 superluminal components range from 4.8c to 7.5c.

Wehrle et al. ApJ, astro–ph/0048458

EGRET BLAZARS – Jets at X–ray Energies

- Recently one–sided jet structures have also been resolved in blazars at X–ray energies through observations by the Chandra X–ray satellite.



1.647 GHz (Merlin) Hubble Chandra Image

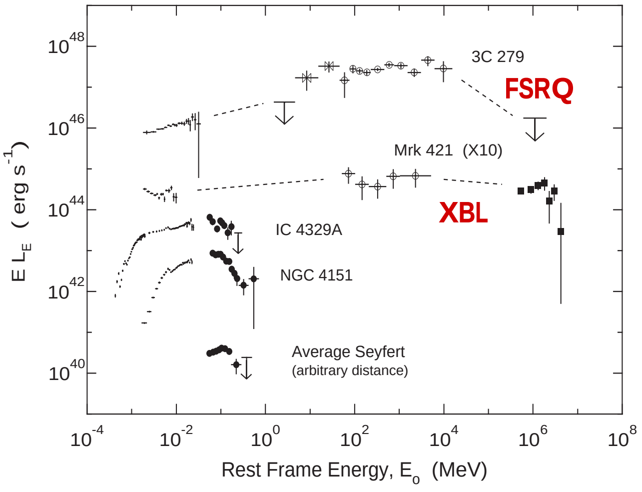
The overall shapes of the X–ray & optical jets are remarkably similar in shape and curvature – but the X–ray jet fades towards the end of the jet.

X–ray emission is seen from the inner jet, within 5–10" from the core.

Marshall et al. (2000)

EGRET BLAZARS – General Characteristics

Multiwavelength power spectra of typical AGN
Comparison of radiated energies



Dermer & Gehrels 1995

Unlike Seyfert galaxies that have thermal spectra, blazars have non−thermal continuum spectrum, with peak at gamma−ray energies.

Non−thermal emission extends to GeV and sometimes TeV energies.

High γ−ray luminosity −−> Isotropic luminosity (EGRET) ~ 10^{48} erg/s

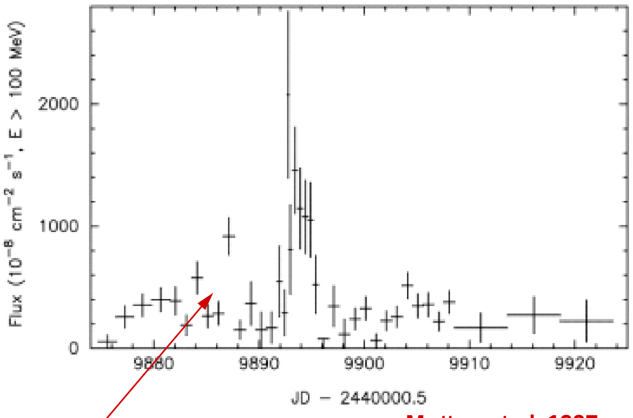
- For isotropic emission from a uniform spherical source at rest, and intrinsic $L > 10^{48}$ erg/s → optical depth >> 1
- Absence of intrinsic $\gamma\gamma$ pair absorption → beaming in blazars
  Gamma−ray emission originates in strongly beamed sources.

Temporal Variability in EGRET BLAZARS

- Blazar emission is seen to change significantly on short time scales (~days or less)

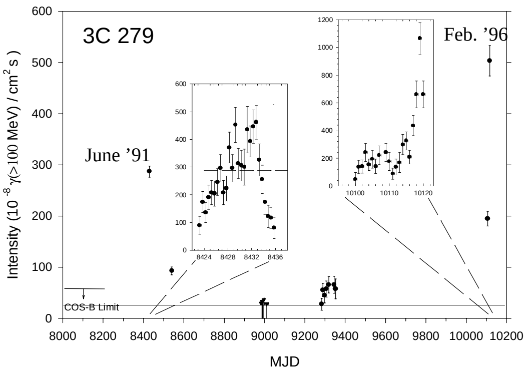
→ Short term variability points to small sizes of the emission regions which are consistent with the bright nuclei

Estimated emission region: $r < c\,\Delta t\,/\,(1+z)$



Mattox et al. 1997

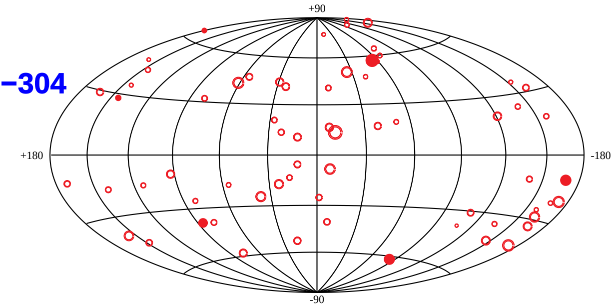
"Doubling" time ~ 3.8 hr

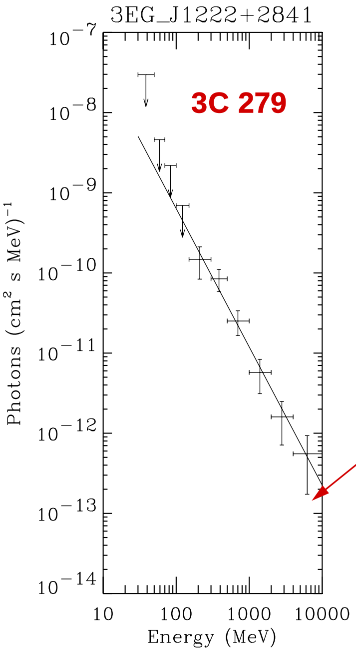


Short term variability in 3C 279 –
Doubling time ~ 8 hr

Blazars Detected at > 100 MeV

Majority are FSRQs
~ 25% are BL Lac objects
3 are XBLs: Mrk 421, Mrk 501 & PKS 2155−304





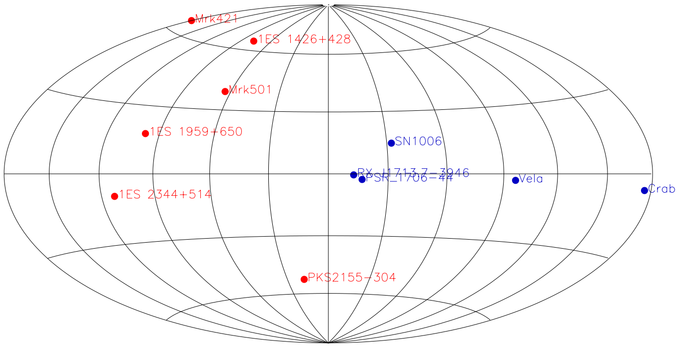
Power−law spectra in the energy range 30 MeV − 10 GeV

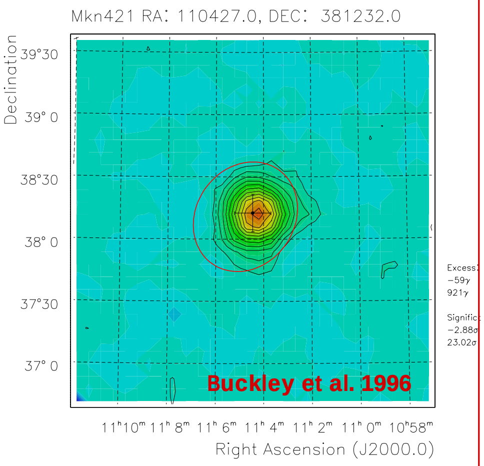
No evidence of spectral cutoff below 10 GeV

Steeply falling photon spectra −
− Poor statistics above ~ 10 GeV

At very high energies blazar studies are carried out
by ground−based ACTs − large collecting areas

Blazars Detected at > 300 MeV





Buckley et al. 1996

Imaging Atmospheric Cherenkov Telescopes

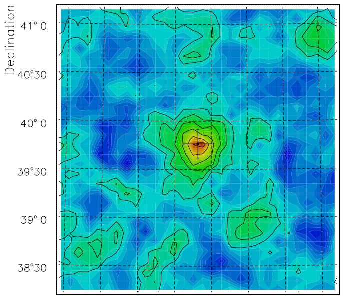
Experiment	Location	Telescope(s)	E_{th} (TeV)
Whipple	Arizona	10 m	0.25
Crimea	Crimea	6×2.4 m	1.0
SHALON	Tien Shan	4 m	1.0
CANGAROO	Woomera	10 m	0.5
HEGRA	La Palma	6×3 m	0.5
CAT	Pyrenees	4.5 m	0.25
TACTIC	Mt. Abu	10	0.3

1992 − First TeV detection of
an AGN − Mrk 421 − by
Whipple.

z = 0.031 − closest BL Lac object
− Flare: ~ 10 Crab
− Quiescent ~ 0.3 Crab

Adapted from Weekes (2000)

Other "TeV" Blazars



Catanese & Weekes 1999

- **Markarian 501**

2nd closest BL Lac (z = 0.034), first to be "discovered" at TeV energies.

Detected by Whipple, HEGRA, CAT, TAP, TACTIC.

TeV Flux: Flare ~ 6 Crab
Quiescent ~ 0.1 – 1.4 Crab

- **H 1426+428**

z = 0.129 –– Highest redshift of all TeV blazars – interesting for spectral studies.
Not an EGRET source, but predicted to be a TeV source based on its synchrotron peak location at ~ 100 keV.

Monitored from 1995–2001by TeV telescopes.
Strongest TeV signal detected in 2000–2001 (~ 5σ)

(Horan et al. 2002, Aharonian et al. 2002, Djannati–Atai et al. 2002)

- **1ES 2344+514**

z = 0.044
Not an EGRET source.
TeV Flux: Flare ~ 0.63 Crab (6.0 σ), Quiescent < 0.11 Crab (4.0σ)

(Catanese et al. 1997)

Extragalactic TeV Sources – Summary

- **PKS 2155–304**

z = 0.116
EGRET source
TeV flux: 1997 – 0.48 Crab (6.8σ) – During X–ray high state
TeV flux: 1998 – < 0.32 Crab – During X–ray low state

- **1ES 1959+650**

z = 0.048
Not an EGRET Source
TeV Flux: 1998 – < 3 Crab
2002: Strong TeV signal detected by VERITAS 10 m (Peak GeV/TeV flux 2.5 Crab (13σ) Dowdall et al. 2002

From Horan et al. 2002, Catanese & Weekes 1999

Extragalactic TeV Sources

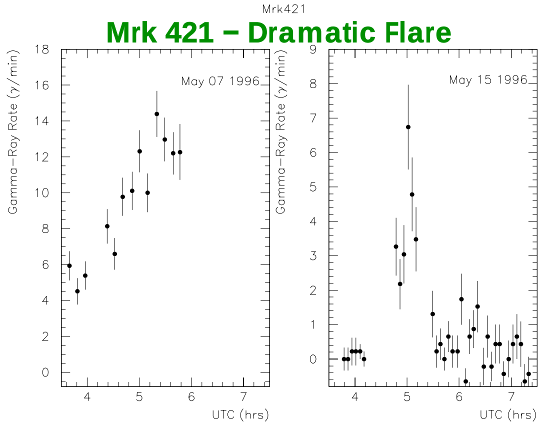
Source	Type	z	Discovery	Group	Ref	EGRET
Markarian 421	HBL	0.031	1992	Whipple	Punch et al. 1992	Yes
Markarian 501	HBL	0.034	1995	Whipple	Quinn et al. 1996	Yes
1ES 2344+514	HBL	0.044	1997	Whipple	Catanese et al. 1998	No
1ES 1959+650	HBL	0.048	1999	TA	Nishiyama et al. 2000	No
PKS 2155-304	HBL	0.116	1999	Durham	Chadwick et al. 1999	Yes
H 1426+4284	HBL	0.129	2001	Whipple	Horan et al. 2000	No
3C 66A	LBL	0.444	1998	Crimea	Neshpor et al. 1998	Yes
BL Lacertae	LBL	0.069	2001	Crimea	Neshpor et al. 2001	Yes

Sources that await confirmation

Variability in Blazars – IACTs

- IACTs have the ability to study very short time scale variability in blazars.

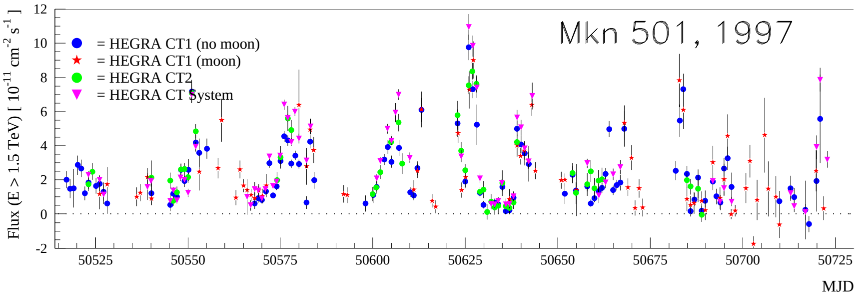
Mrk 421 – Dramatic Flare



- Rapid: < 15 min variability time scale
- Entire flare lasted ~ 30 min.
- Fastest time scale variability seen in any blazar to date.

Observations indicate a compact emission region of ~ 1−10 light hours diameter− 10 Schwarzschild radius of a $10^8 M_\odot$ BH.

Gaidos et al. (1996)

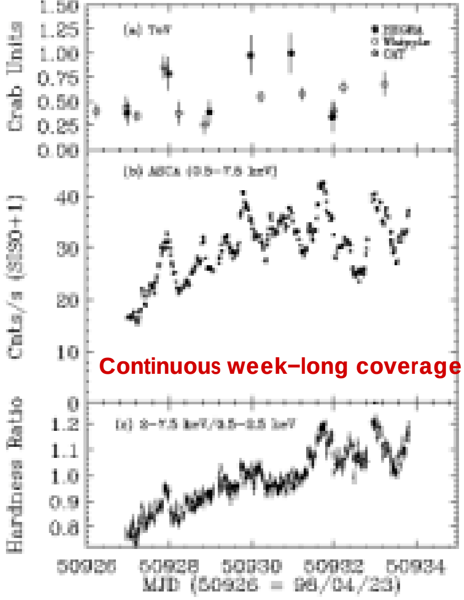


Demonstrates the ability of IACTs to carry out long term monitoring of blazars.

Kranich et al. (1999)

Multiwavelength Variability in Blazars

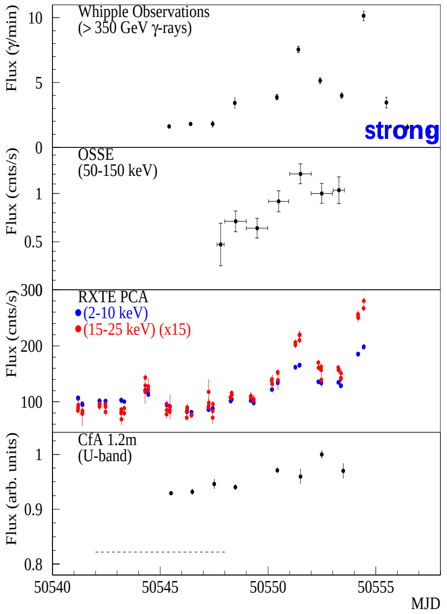
TeV & ASCA Campaign
Markarian 421



Continuous week−long coverage

Takahashi et al. 1998

Markarian 501



strong OSSE flux

April 1997 flare

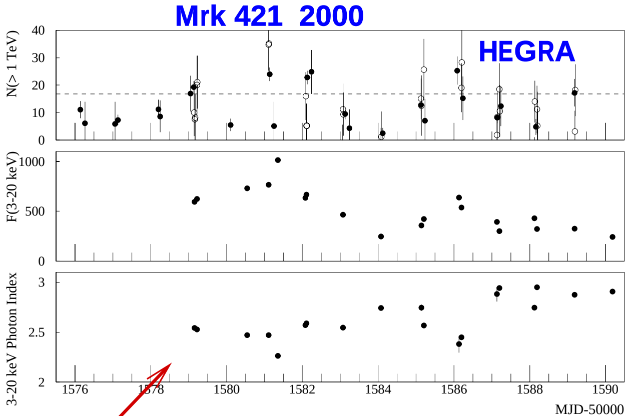
Catanese et al. 1997

- TeV flaring activity coincides with X−ray flares

Spectrum between X−rays & TeV emission needs to be measured on shot time scales − as short as the variability time scales − in order to constrain emission mechanisms.

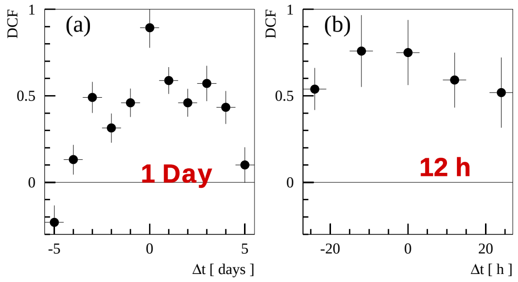
Multiwavelength Variability in Blazars

Mrk 421 2000



Krawczynski et al. 2001

Mrk 501 1997 Flare



Krawczynski et al. 1999

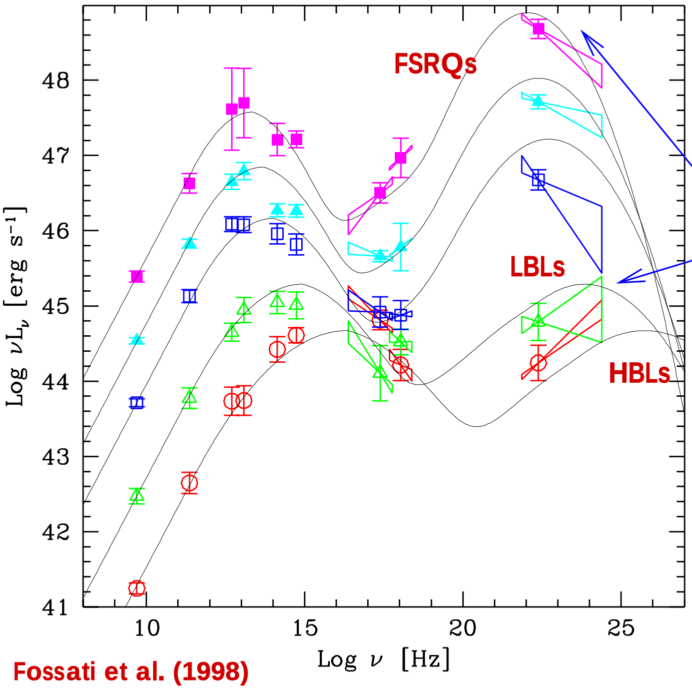
Correlation of RXTE (25 keV) and HEGRA (2 TeV) flux – TeV flux is seen to lag the X-ray flux.

TeV flux variability seen on 30 min time-scales. "e-folding" times of ~ 1hr at TeV energies & ~ 5hr at X-ray energies.

The different variability time scales seen at X-ray and TeV energies indicate that a more detailed analysis involving inhomogeneous models with several emission regions may be needed.

Blazar Unification

Spectral Energy Distribution of Blazars



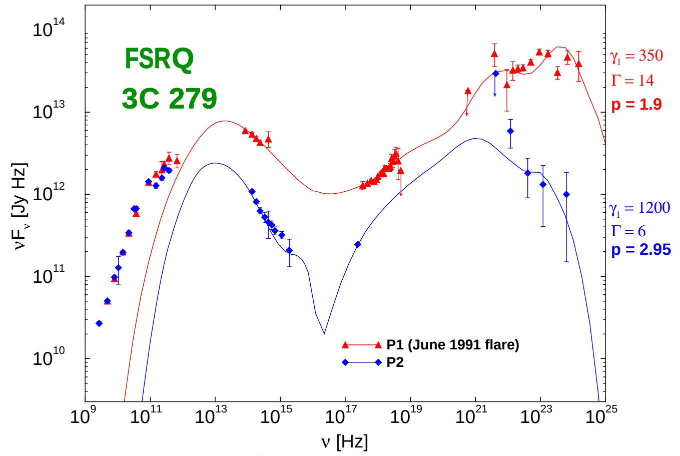
Fossati et al. (1998)

- Non-thermal emission – consists of at least two distinct, broad spectral components.
- A sequence of sub-classes of blazars can be defined through the peak frequencies and the relative νF_ν peak fluxes of those components.
- Blazars detected by EGRET are mostly FSRQs and low-frequency peaked BL Lacs.
- No FSRQ has been detected by ground-based ACTs > 100 GeV

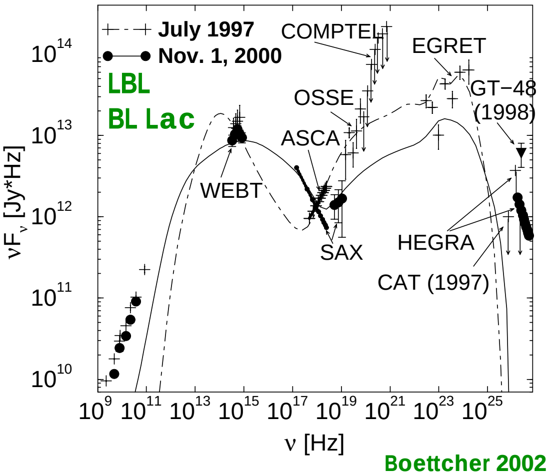
- The lack of sufficient number of GeV-TeV blazars limits our understanding of the gamma ray emission, and our ability to extrapolate results to the larger population of radio sources.

Broadband Spectra of Blazars

Each object shown at two different epochs at two different activity states.



Hartman & Boettcher 2000



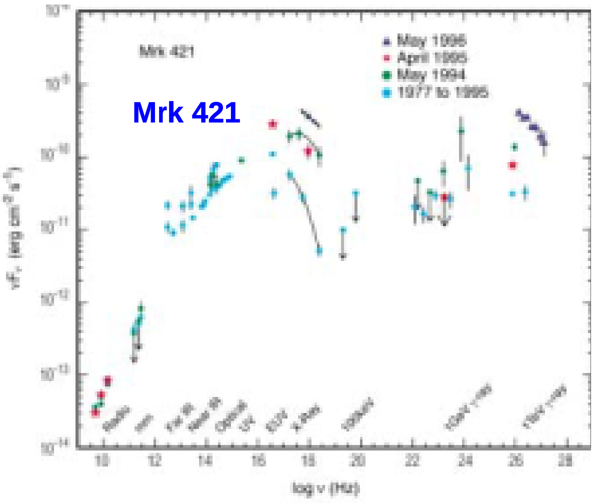
Boettcher 2002

- In flaring states the gamma−ray peak flux of FSRQs dominates over the low−frequency emission by ~ 1 order of magnitude.

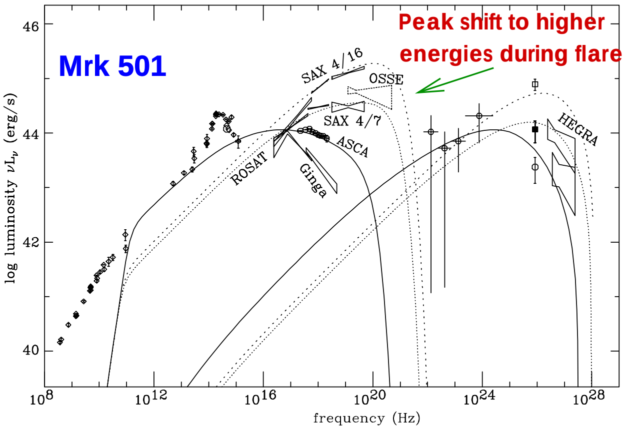
- LBLs are apparently intermediate between the FSRQs and the HBLs.
  The peak of their low−frequency component is typically located at IR or optical wavelengths.

  For LBLs the high frequency component peaks typically at ~ several GeV

Broadband Spectra of Blazars – XBLs



Catanese & Weekes 1999



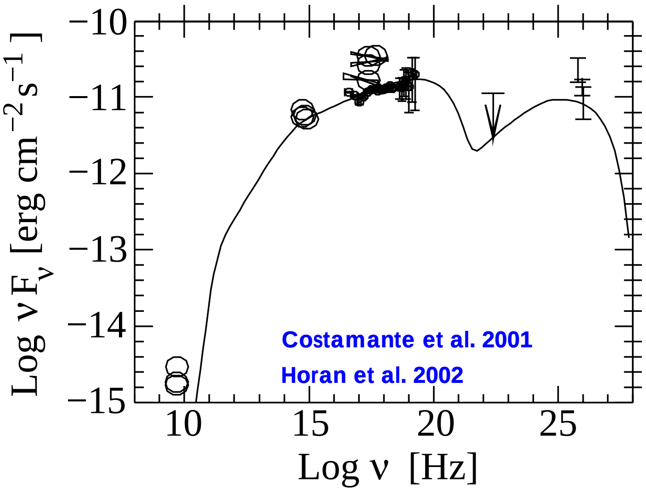
Kataoka et al. 1999

- All blazars detected at VHE gamma−ray energies to date are HBLs.

In spite of extending to extremely high photon energies, the peak flux (SED) of the gamma ray component of HBLs is generally at most comparable to the spectral output in the low−frequency component.

- In terms of their overall bolometric luminosity, FSRQs appear to be several orders of magnitude more powerful sources than HBLs.

XBL H1426+428 – Predicted TeV Source



Costamante et al. 2001

Horan et al. 2002

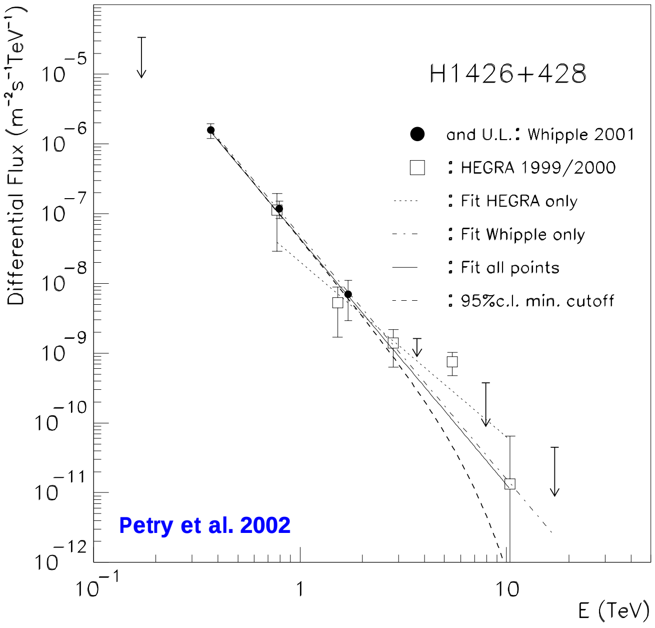
1426+428 -- "Extreme BL Lac"

Synchrotron Peak at ~ 100 keV

Predicted to be one of the best candidates for TeV emission based on SSC models.

SED similar to Mrk 421 & Mrk 501 -- extremely high synchrotron peak frequencies, TeV gammas.

The TeV Spectrum of H 1426+428



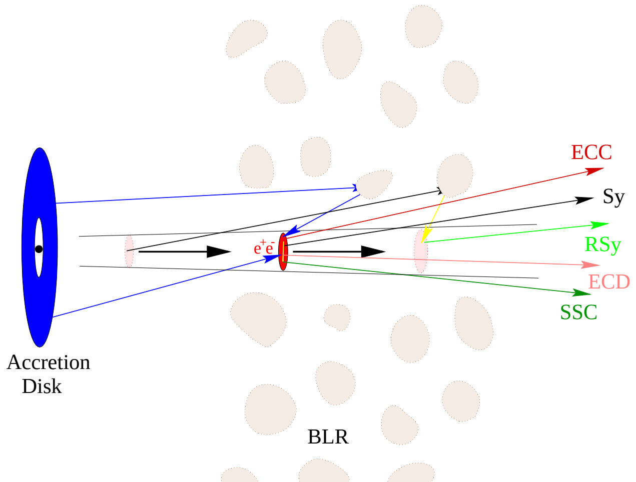
Petry et al. 2002

2001 spectrum of H 1426+428 – measured by HEGRA & Whipple.

Spectrum below 800 GeV is steeper than any other TeV blazar.

Could this be due to IR absorption?

Blazar Models



Boettcher 1999

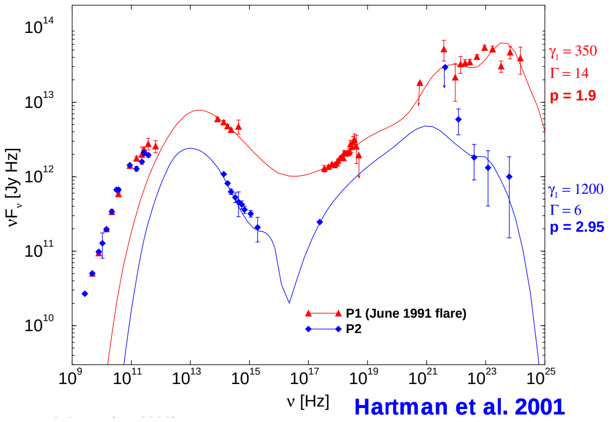
Assumptions:

- **Central supermassive BH – surrounded by accretion disk and possibly a gas and dust torus.**
- **Accretion energy powers a beamed jet of material with bulk Lorentz factor Γ**
- **Relativistic particles are injected at a certain rate**
- **Model follows the time evolution of relativistic particles – various cooling mechanisms are at work**

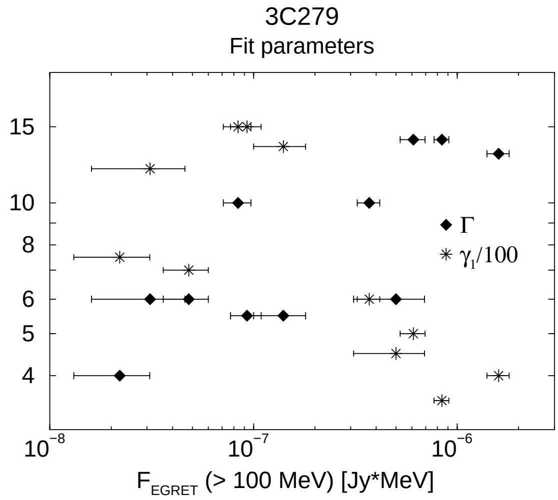
ECC: External Compton of accretion disk radiation scattered in clouds
ECD: External Compton of direct accretion disk radiation
SSC: Synchrotron Self Compton
RSy: Synchrotron Mirror

Multi Epoch SED of 3C 279 – Leptonic Jet Models

Time−averaged modelling of 3C 279



Hartman et al. 2001



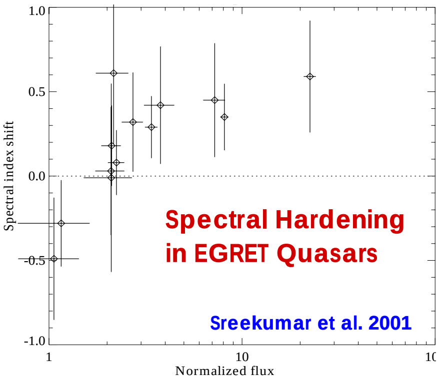
Long term variability of 3C 279 is reasonably well−reproduced with a higher bulk Lorentz factor Γ and lower low−energy cutoff of the electron distribution, during higher gamma ray states.

This bears striking similarity to the trend between different blazar sub−classes −−>Higher gamma−ray luminosity indicates a stronger contribution from Comptonization of external radiation.

The analogy is mediated by the stronger Γ dependence of the ERC component compared to the SSC component (Dermer 1995).

Modelling Spectral Variability in Blazars

- Spectral variability in HBLs are generally well−understood in the framework of SSC models (e.g. Takahashi et al. 1996; Kataoka et al. 2000; Li & Kusunose 2000)
- A detailed analysis of the rapid variability in quasars is generally more challenging (lack of consistent variability patterns, larger number of parameters entering into multi−component high energy spectral calculations ...)
- For quasars, which have their IC peak in the GeV region, it is difficult to obtain time−dependent spectral information near the gamma−ray peak.
- A time−dependent shock−in−jet model was recently applied to the quasar PKS 1406−076 −− A promising first step (Sikora et al. 2001)



Spectral Hardening in EGRET Quasars

Sreekumar et al. 2001

Clear evidence of spectral hardening in quasars when source transitions from low to high state.

Changes in the gamma−ray spectrum could arise from either changes in the charged particle spectrum or the soft photon distribution

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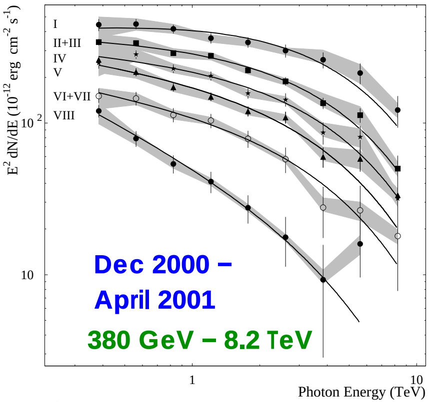
Spectral Variability in Markarian 421

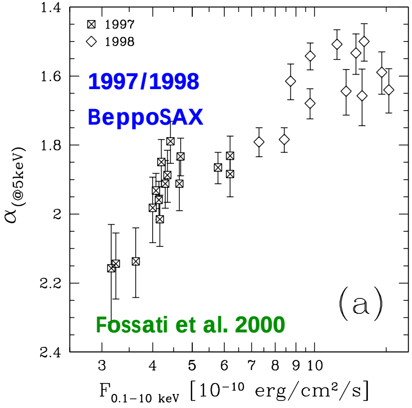
Mrk 421 Spectral variability averaged over a 4.5 month period

Krennrich et al. 2002



Dec 2000 − April 2001

380 GeV − 8.2 TeV



1997/1998 BeppoSAX

Fossati et al. 2000

- Observations with Whipple revealed strong & long−lasting flaring activity
- Flaring levels of 0.4 − 13 times Crab flux − Hence, detailed spectral studies possible.
- Spectra well−described by power−law plus exponential cutoff
- 2000/2001 spectra consistent with cutoff at ~ 4.3 TeV − no evidence of variation of the cutoff energy with flux.

Spectral index varies between 1.89 (high) to 2.72 (low).

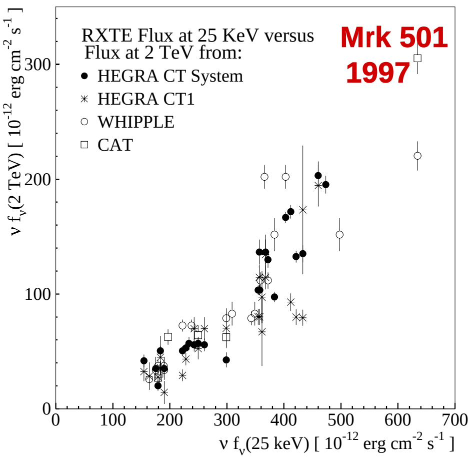
Spectral hardening also observed for Mrk 421 at X−ray energies − (BeppoSAX)−−

Interpreted as the shift of synchrotron peak to higher frequencies

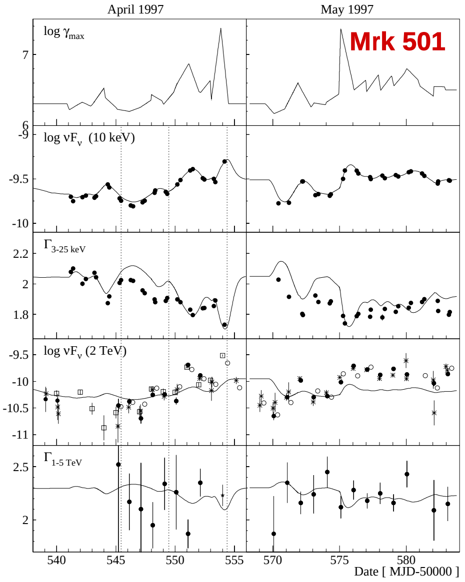
Further studies of spectral variability over shorter time scales needed.

Time Dependent Modelling of Mrk 501

Time dependent modelling presented by Krawczynski, Coppi & Aharonian (2002)



Correlation between X−ray & TeV flux

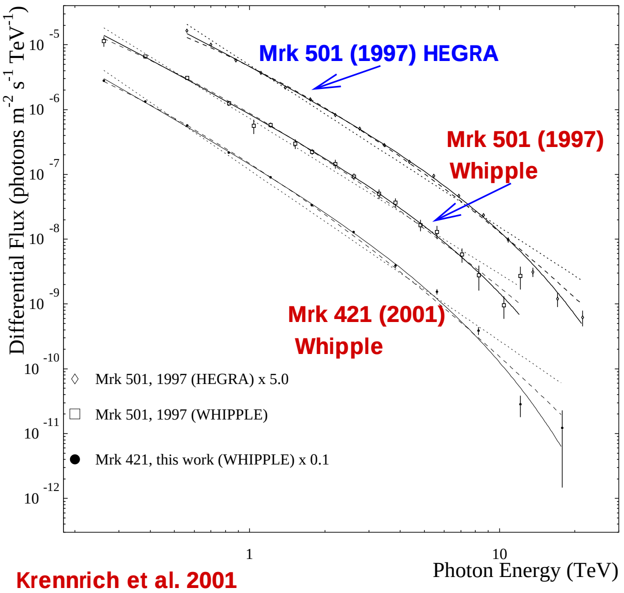


Model with soft steady X−ray component plus a variable SSC component describes the data well.

- If the high energy emission from TeV blazars is produced by SSC mechanism, simultaneous X−ray & gamma−ray observations are a powerful probe of the electron (and/or positron) populations responsible for the emission.

It's important to measure the lag between X−ray & TeV gamma−ray flux variability.

Spectral Cutoffs in Blazars



Krennrich et al. 2001

2001 flare of Mrk 421 was strong enough that the spectra could be determined precisely.

Spectrum over the 250 GeV − 17 TeV energy range shows an exponential cutoff at 3−6 TeV.

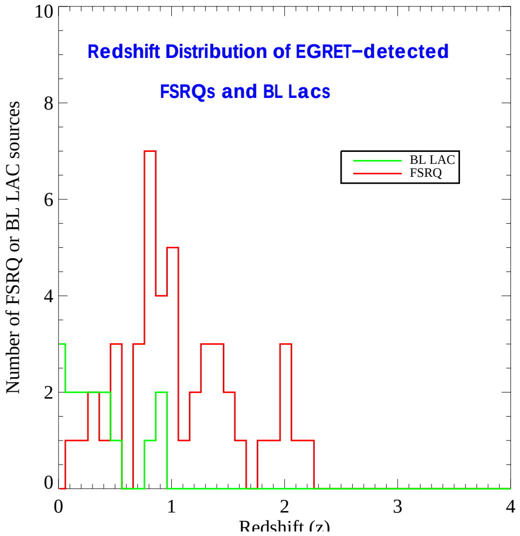
Similar cutoff observed in Mrk 501 by both HEGRA & Whipple in 1997.

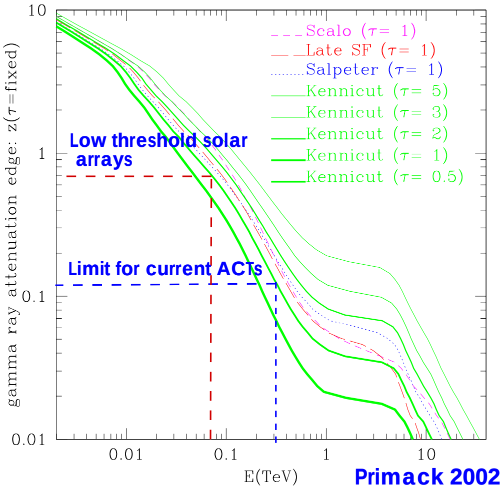
The occurrence of cutoffs at similar energy in two nearly equally distant quasars could imply that cutoff is due to IR background radiation.

Further studies of blazars at high energies over a range of redshifts is required to probe IR radiation fields.

Visibility of Gamma−Ray Sources

- EGRET has seen many blazars out to a redshift of 2.7.



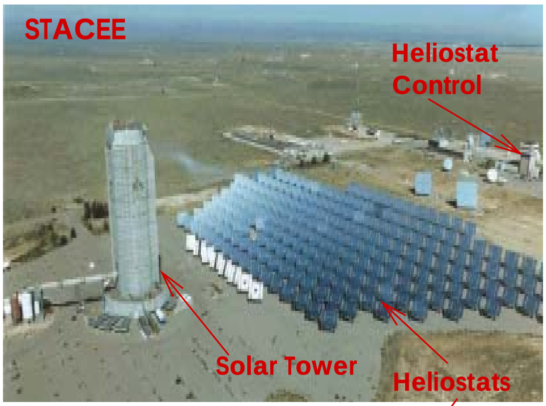


Primack 2002

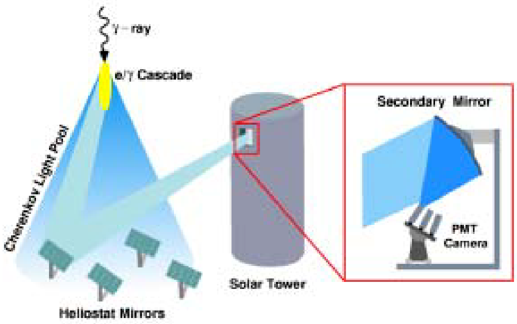
Gamma−ray horizon plot defining relation between z and cutoff energy: $\tau\_\gamma\gamma$ (z,E)

- Low threshold ACTs have the potential for exploring a deeper redshift range than current TeV telescopes.

Solar Arrays − Low Threshold ACTs



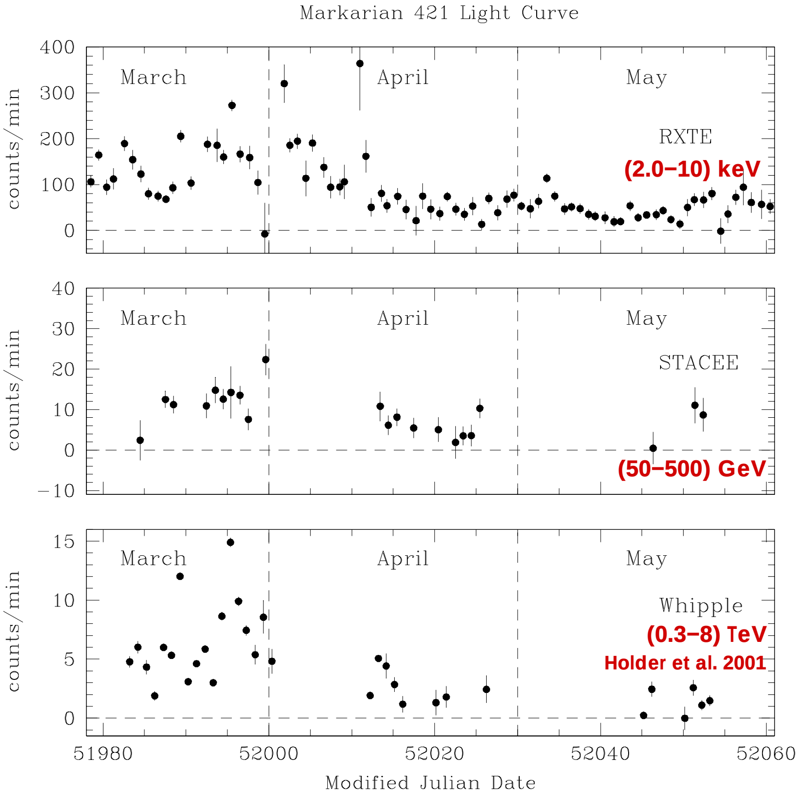
STACEE Concept



STACEE uses 64 heliostats to achieve 2500 m^2 collecting area.

Very large areas allow solar arrays to probe a lower energy regime.

Detection of Mrk 421 by STACEE in 2001



Boone et al. 2002

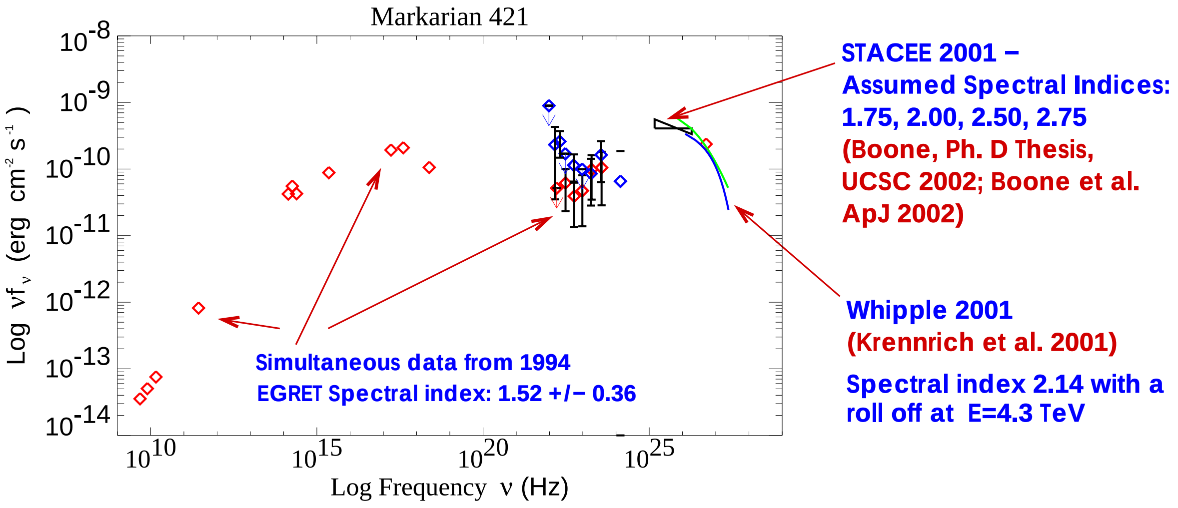
Substantial outburst of Mrk 421 detected in early 2001.

STACEE observed γ rays in the 50–500 GeV regime.

Integral flux measured by STACEE:

(8.0 +/− 0.7 +/− 1.5) X 10^{-10} / cm^2/s above 140 GeV

Mrk 421 Spectral Energy Distribution



STACEE 2001 –
Assumed Spectral Indices: 1.75, 2.00, 2.50, 2.75
(Boone, Ph. D Thesis, UCSC 2002; Boone et al. ApJ 2002)

Simultaneous data from 1994
EGRET Spectral index: 1.52 +/− 0.36

Whipple 2001
(Krennrich et al. 2001)

Spectral index 2.14 with a roll off at E=4.3 TeV

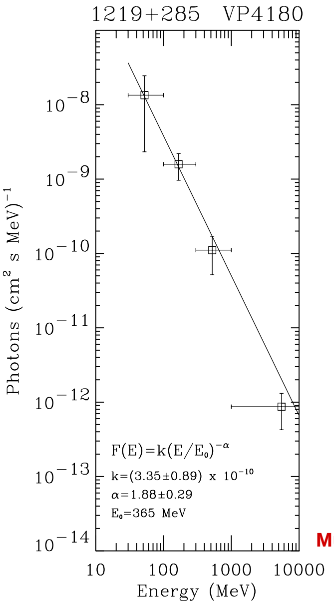
- **SED is characterized by a synchrotron peak at X-ray energies, typical of TeV-detected XBLs. Note that the high energy IC peak is in the 50–300 GeV range.**
- **STACEE data occupy an important energy range in the SED of Mrk 421.**
- **Spectral information from STACEE will be important for constraining SSC models in the future.**

STACEE−32 Observations of W Comae

- STACEE observed W Comae in Spring 1999 with 32 heliostats.
  W Comae was also observed in Spring 2002 with a 64−channel sysyem.

Choice of W Comae as a STACEE target: Characteristics of the source:

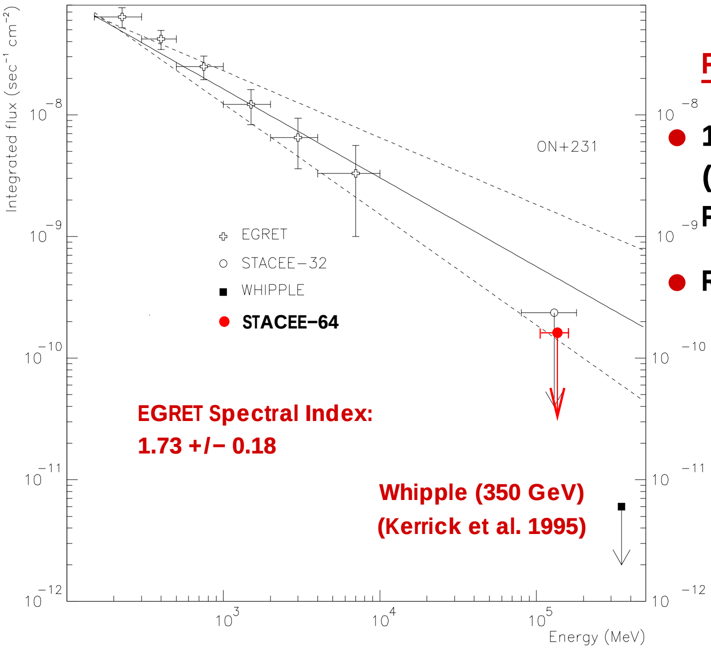
- Low−frequency peaked BL Lac object. Not detected by Whipple & others above 250 GeV.



Mukherjee et al. 2001

- Attractive Redshift: 0.102. Significant external absorption likely.
- Hard EGRET spectrum: 1.73 +/− 0.18. No cut−off seen at high energies. Detected as a strong source at > 1 GeV.
  27.3 GeV photon detected by EGRET (Dingus & Bertsch 2001).
- Predicted to be a likely TeV source (e.g. Mannheim 1995).
- Naive extrapolation of EGRET spectrum predicts strong flux > 50 GeV.

STACEE−32 Observations of W Comae
W Comae or 1219+285



EGRET Spectral Index:
1.73 +/− 0.18

Whipple (350 GeV)
(Kerrick et al. 1995)

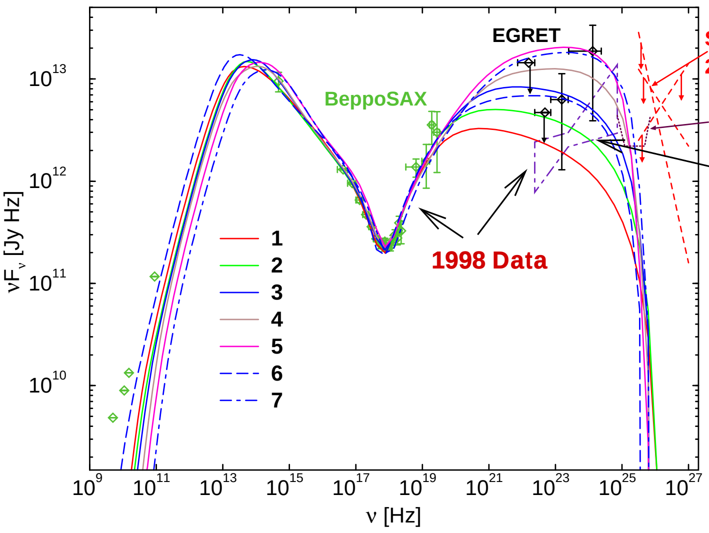
Theoret (Thesis; McGill 2001)

Preliminary Results

- 17 on−off pairs after initial run cuts.
  (46.8 hours)
  Final pairs after L1 rate cuts : 14
- Results consistent with no detection.

The Spectrum of W Comae

Pure SSC model



STACEE
2σ UL

(2 sigma UL for a possible range of spectral indices 3.75 − 1.5)

(Theoret thesis, McGill 2001)

STACEE

Average EGRET spectrum: 1.73 +/− 0.18

Richest & most detailed portion of SED:
SAX LECS + MECS + PDS spectrum in
0.1−100 keV range. (Tagliaferri 2000)

Low energy synchrotron spectrum goes
out to ~ 4 keV, significant variability
on t< 10 hr timescales.
Onset of HE component beyond 4 keV.

(Boettcher, Mukherjee & Reimer 2002)

1998 Beppo SAX spectrum is inconsistent with EGRET spectrum and STACEE UL for pur SSC models.

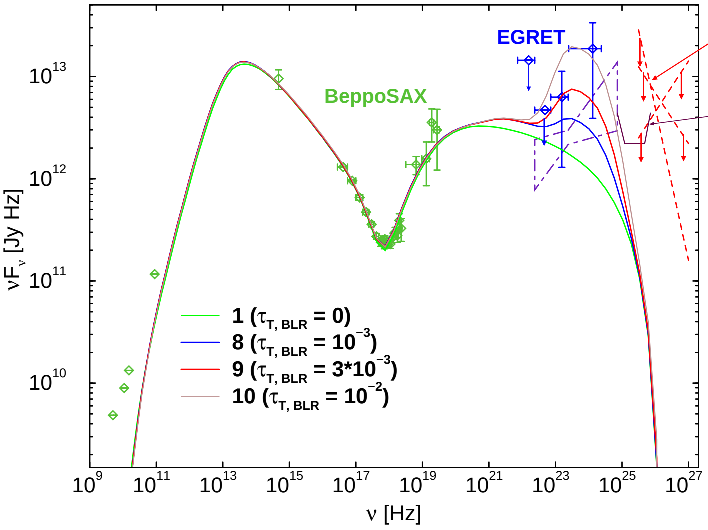
For SSC models, X−ray spectrum in 0.1−100 keV range predicts very low fluxes at STACEE energies.

External radiation components needed?

- STACEE detection or upper limit could help to resolve model uncertainties.

The Predicted High Energy Spectrum of W Comae

SSC + ERC model fit to the 1998 optical + X−ray spectrum of W Comae



STACEE
2σ UL

(Theoret thesis, McGill 2001)
(Preliminary)

STACEE

1998 optical + X−ray spectrum provides
accurate guidelines for the hard X−ray
SSC emission of W Comae in the
framework of leptonic models.

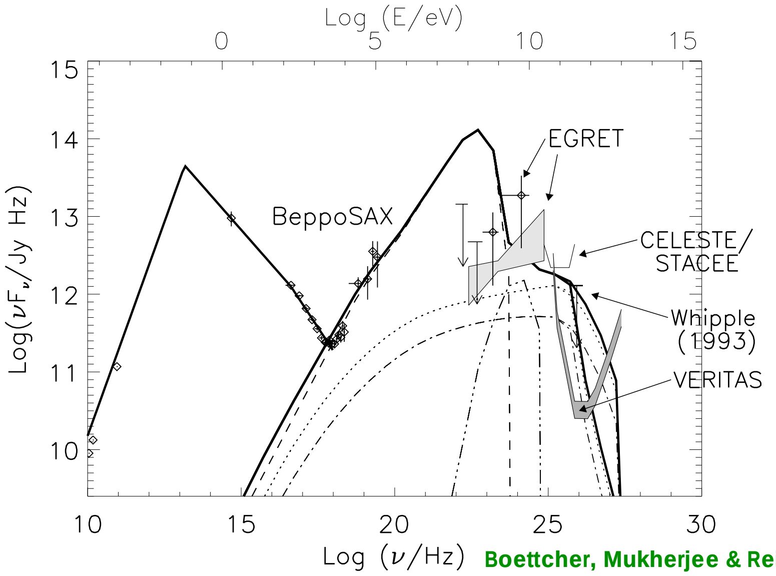
Various leptonic jet models allow for a
large uncertainty in the > 40 GeV flux.

(Boettcher, Mukherjee & Reimer 2002)

- Including information contained in the X−ray variability measured by BeppoSAX, one can narrow down the range of possible leptonic model parameters to predict > 40 GeV fluxes of ~ (0.5 − 1) X 10^{-10} ph/cm^2/s
- However, all acceptable leptonic model fits cut off at ~ 100 GeV.

Hadronic Models for W Comae?

Hadronic synchrotron proton blazar model (SPB) – Muecke et al. 2002.



Boettcher, Mukherjee & Reimer 2002

A likely SPB model is inconsistent with EGRET spectra – but predicts emission beyond 1 TeV ––

A promising candidate for VERITAS?

In general, leptonic and hadronic jet model fits to W Comae make drastically different predictions with respect to the emission beyond ~ 100 GeV.

- A detection of W Comae at energies > 100 GeV by future ACTs would pose a serious challenge to leptonic jet models and favor hadronic models instead.

- W Comae could be a promising target to distinguish between jet models.