TeV Gamma-ray Observations and the Origin of Cosmic Rays

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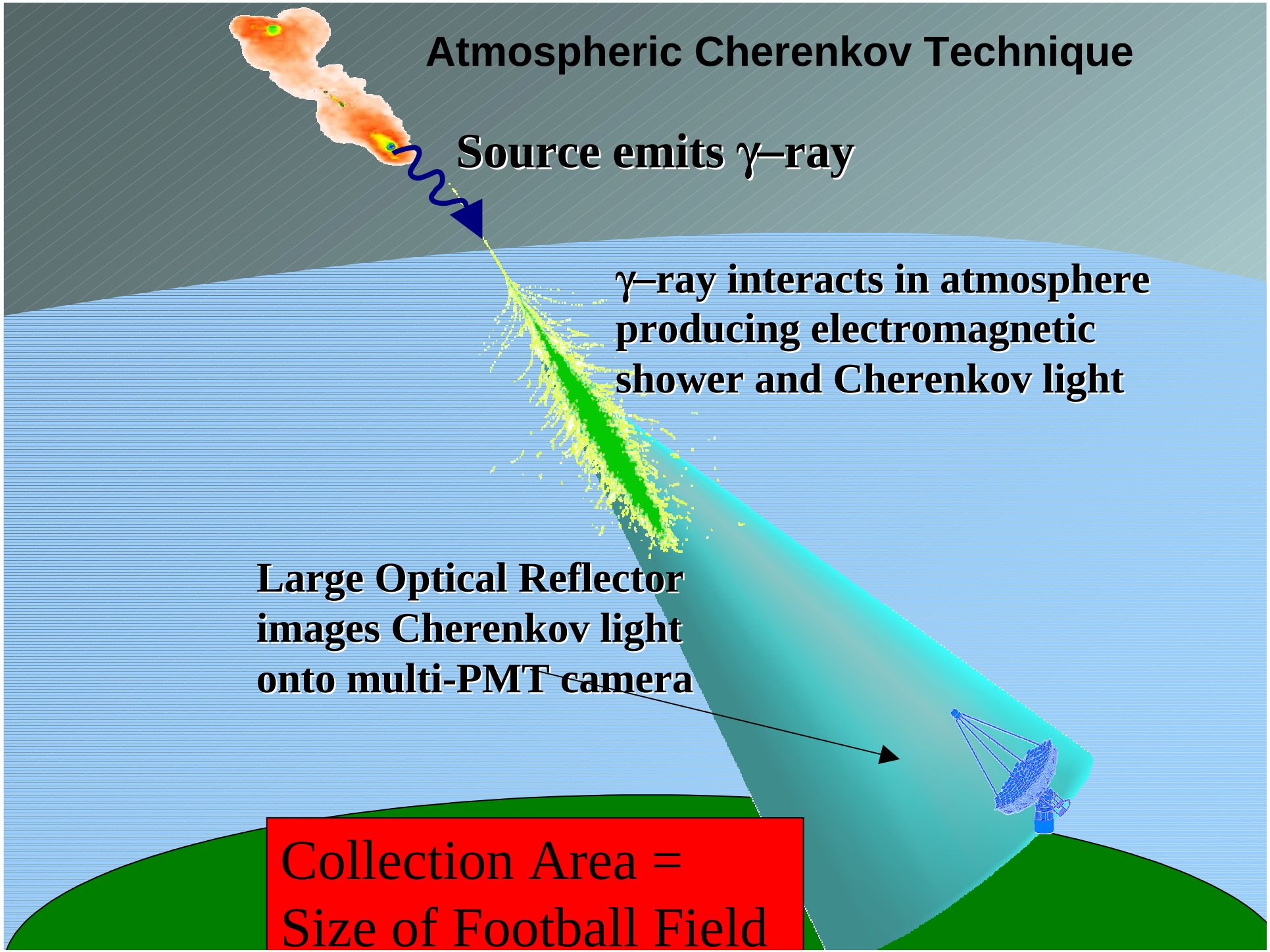
Why do we study TeV Gamma-rays?

Why go to such high energies?

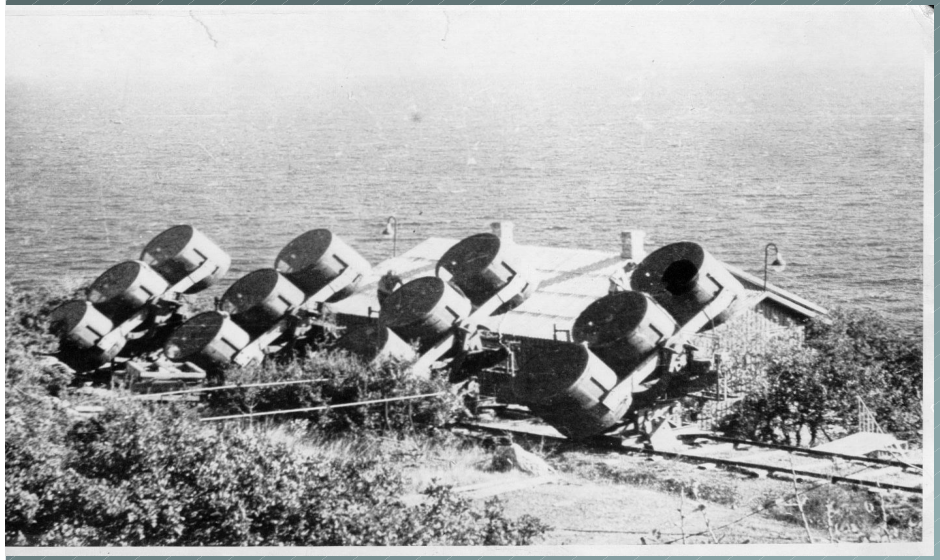
Why do we study elephants when mosquitoes are easier and more plentiful?

Elephants and TeV gamma-rays are more interesting!

To find the Origin of the Cosmic Radiation (the Holy Grail of cosmic ray studies!)


Atmospheric Cherenkov Technique
Source emits γ–ray
γ–ray interacts in atmosphere producing electromagnetic shower and Cherenkov light
Large Optical Reflector images Cherenkov light onto multi-PMT camera
Collection Area = Size of Football Field

Brief History of Cherenkov Technique

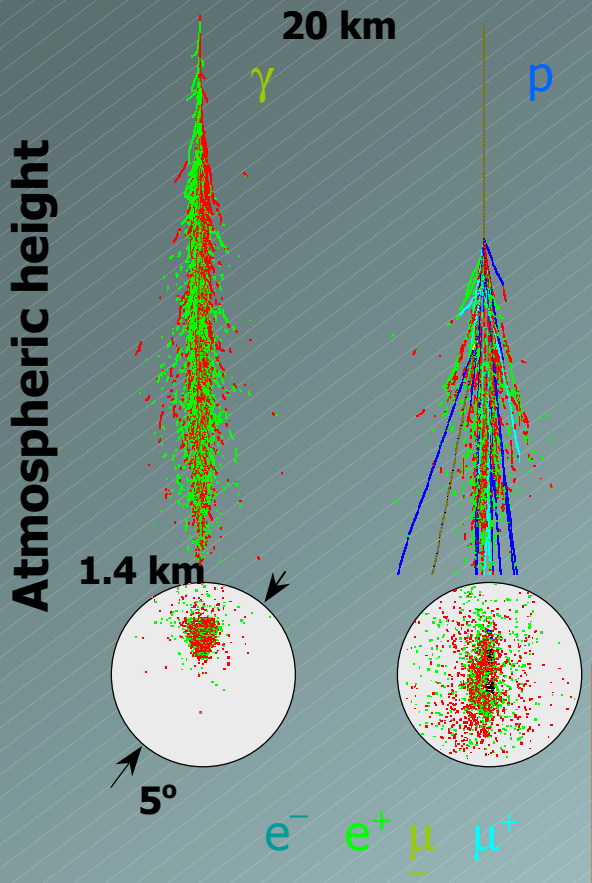


Crimea Experiment
1960-1965

Whipple 10 Gamma Ray Telescope, 1968 -

- First Generation Systems 1960
- No Sources Detected 1960-1977
- Phantom Detection of Binary Sources 1977-1984
- Imaging Technique proposed 1977

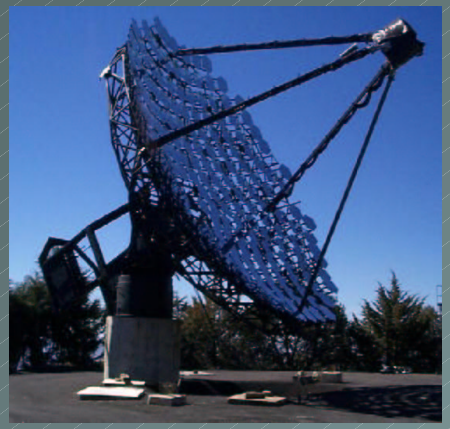
Atmospheric Cherenkov Imaging



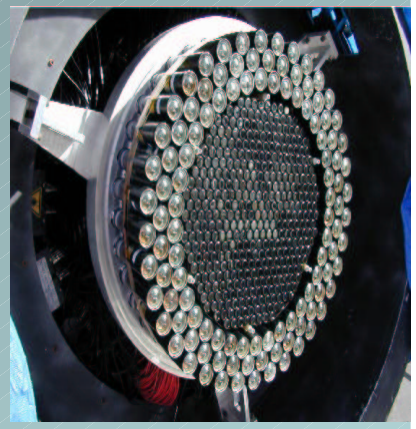
Cherenkov Imaging gives the ability to distinguish compact images of gamma-ray showers from more irregular images from hadron shower

*Imaging systems came into operation 1984 -
*First Galactic Source detected (Crab Nebula/ Whipple Observatory) 1989
*First Extragalactic Source detected (Mrk 421/Whipple Observatory) 1992
*HEGRA array of imaging detectors 1995 -

Development of Third Generation Telescopes

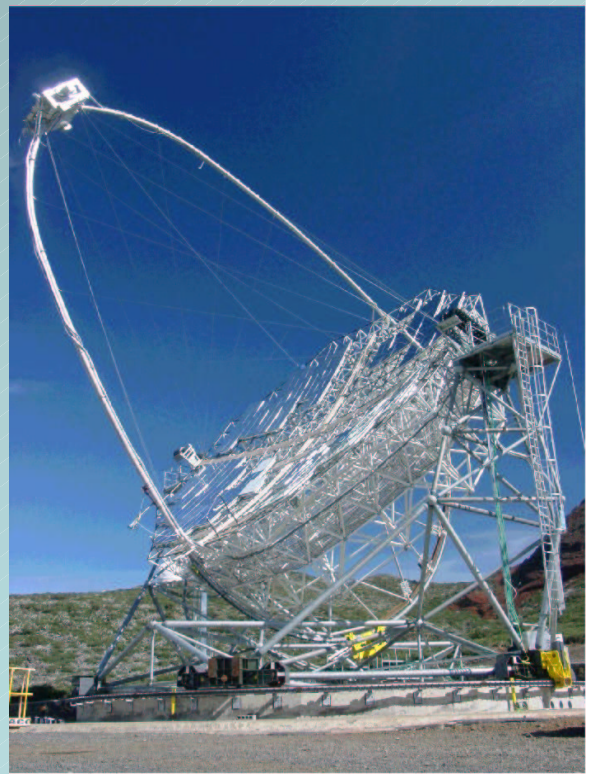


Second-generation imaging systems large optical reflectors, many pixel cameras at dark locations, have served us well.



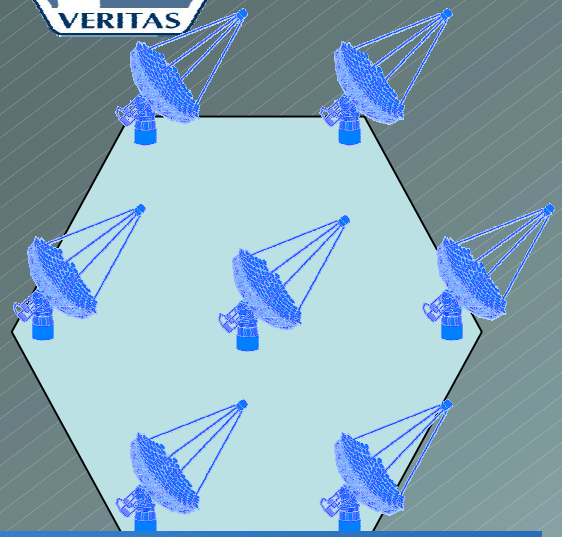
- Justification for more development to achieve
  - Better Flux Sensitivity
  - Lower Energy for good GLAST Overlap

MAGIC Telescope on La Palma (Oct.,2003) 17 aperture, new technology telescope



NEXT GENERATION TELESCOPES

Arrays of Imaging Telescopes



Philosophy

- Improve Flux Sensitivity
- Reduce Energy Threshold
- Multiple 10/12 m telescopes
- New Technology where appropriate.

VERITAS
first telescope

Now under construction:
CANGAROO III
HESS
VERITAS

World Picture of Future sub-TeV Observatories

Four Major Observatories ideally distributed to give maximum coverage

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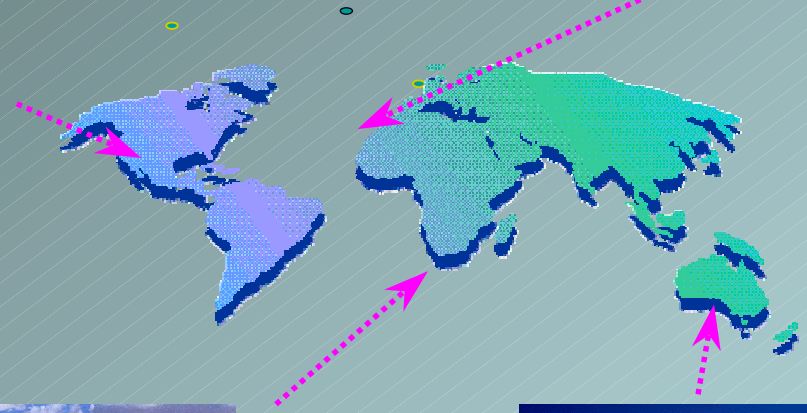

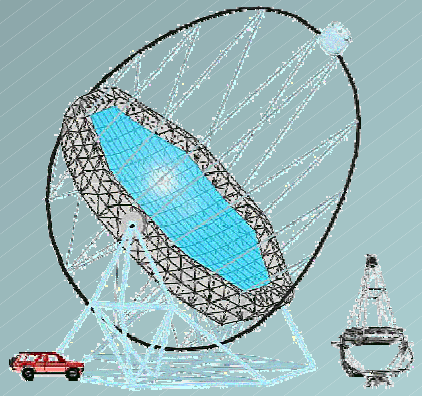

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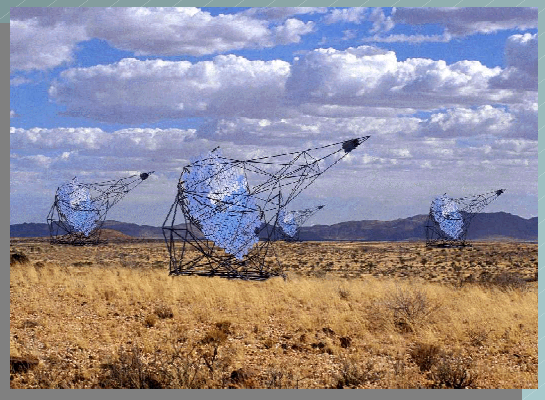

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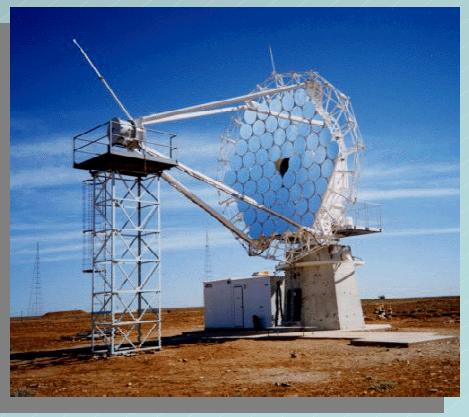

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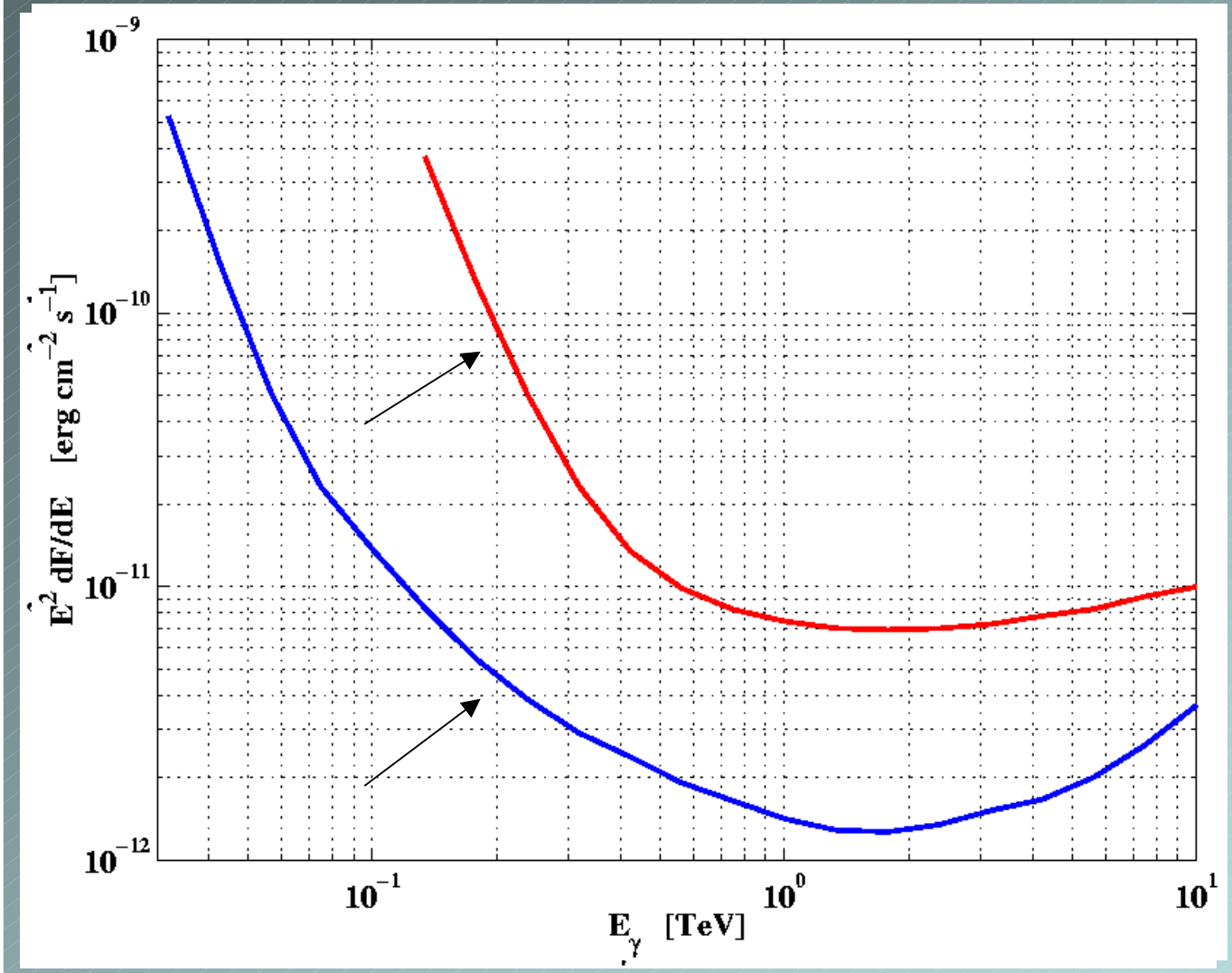
Differential Flux Sensitivity



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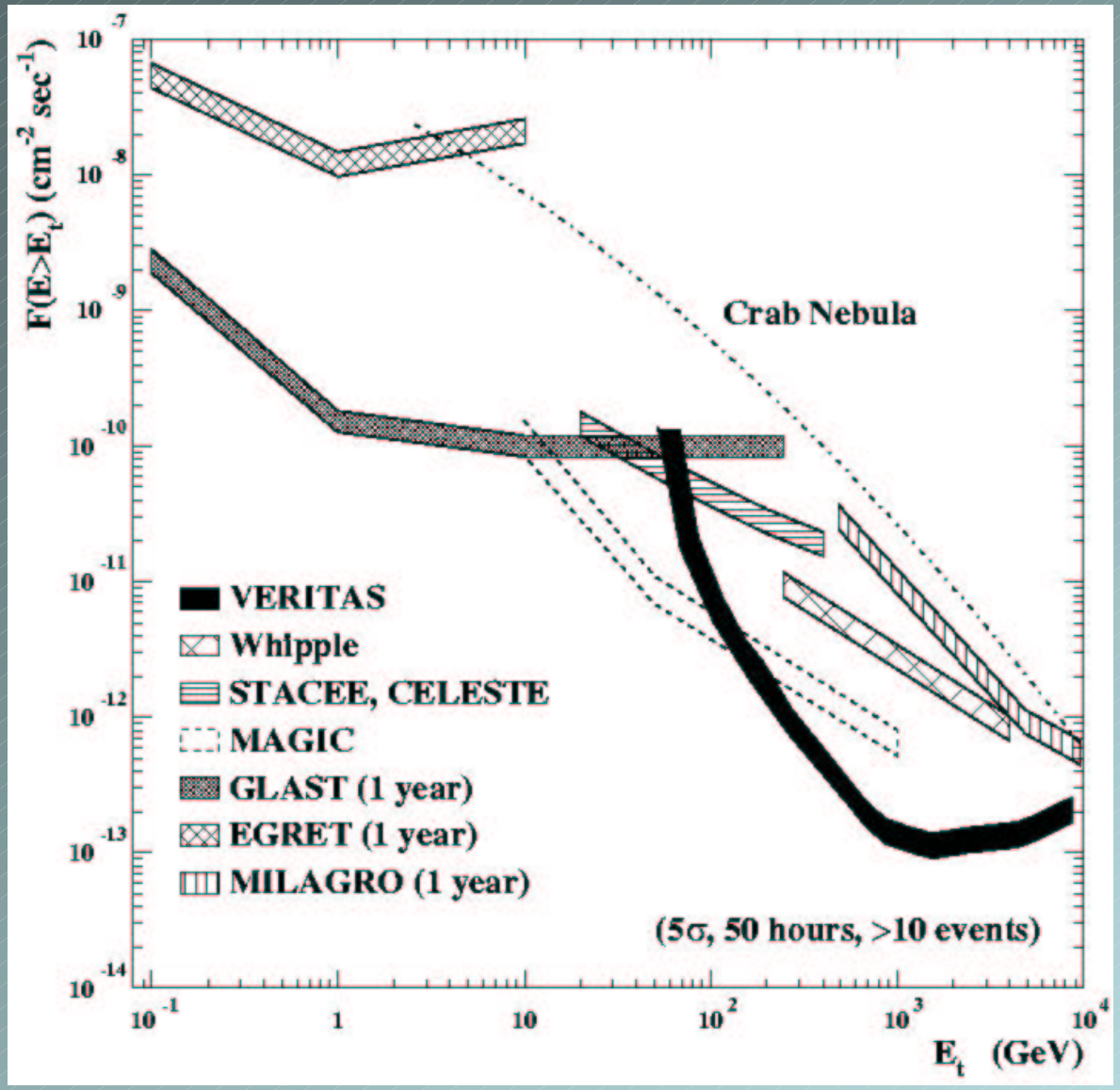
Compare Sensitivity at 200 GeV

Integral Flux Sensitivity



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Early Expectations of TeV Gamma-ray Astronomy

Find the Origin of the Cosmic Radiation:

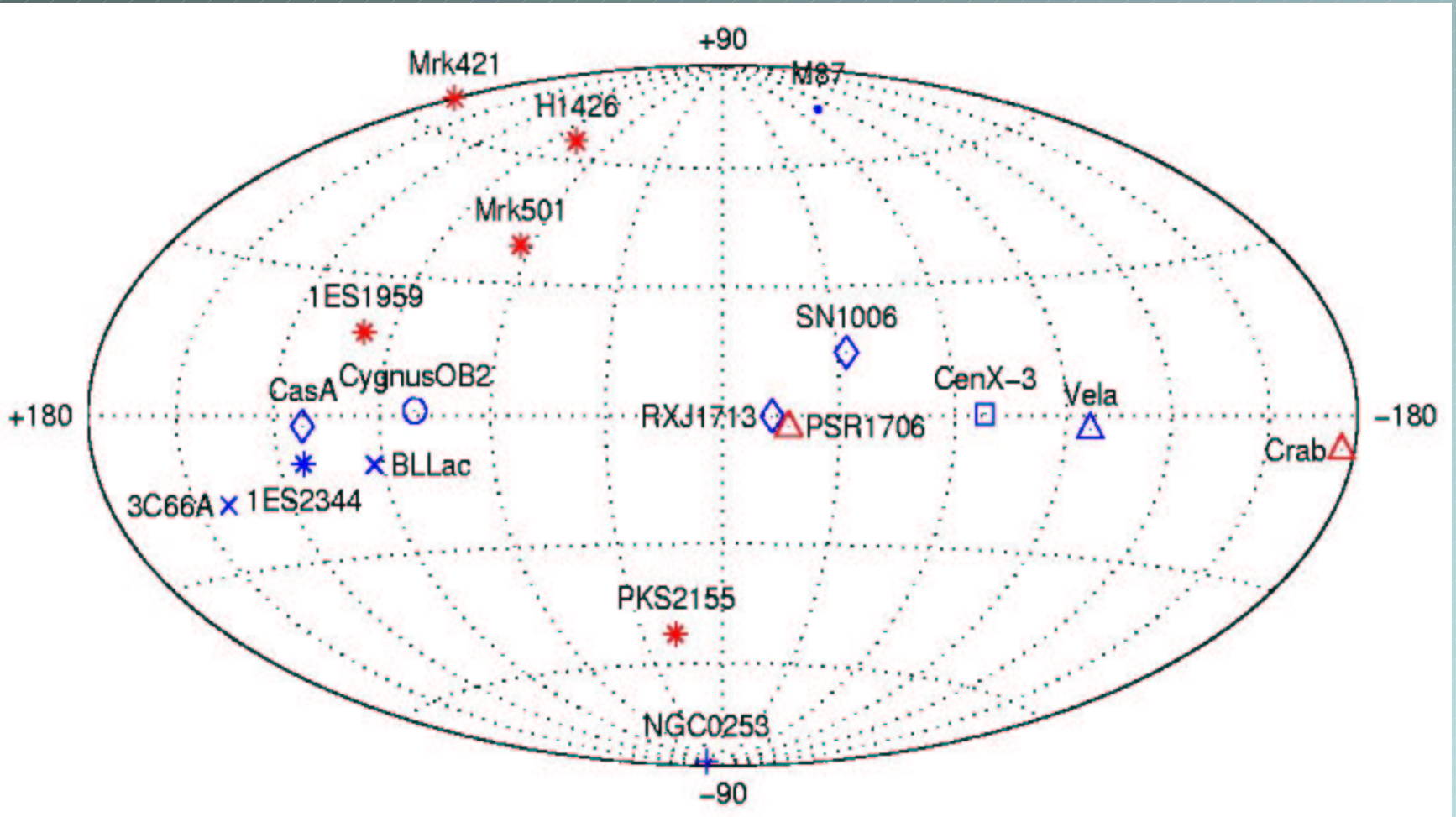
* Single source or class of sources
* Unambiguous detection of the 70 MeV bump in the spectrum
* Source(s) would be in the Galaxy

Locate the "Smoking Gun" of Cosmic Ray Origins!

The reality has been quite different!

* Many different sources
* No unambiguous hadron source detection
* More sources are Extragalactic

Tev Gamma-ray Sky Status c.2003



18 Sources reported in literature prior to this ICRC;
10 are Extragalactic, 8 are Galactic

Catalog Name	Source	Type	Date/Group	EGRET	Grade
TeV 0047-2518	NGC 253	Starburst	2003/CANG.	no	B
TeV 0219+4248	3C66A	Blazar	1998/Crimea	yes	C-
TeV 0535+2200	Crab Nebula	SNR	1989/Whipple	yes	A
TeV 0834-4500	Vela	SNR	1997/CANG.	yes	C
TeV 1121-6037	Cen X-3	Binary	1999/Durham	yes	C
TeV 1104+3813	Mrk 421	Blazar	1992/Whipple	yes	A
TeV 1231+1224	M87	Radio Gal.	2003/HEGRA	no	C
TeV 1429+4240	H1426+428	Blazar	2002/Whipple	no	A
TeV 1503-4157	SN1006	SNR	1997/CANG.	no	B
TeV 1654+3946	Mrk 501	Blazar	1995/Whipple	no	A
TeV 1710-2229	PSR 1706-44	SNR	1995/CANG.	no	A
TeV 1712-3932	RXJ1713-39	SNR	1999/CANG.	no	B+
TeV 2000+6509	1ES1959+650	Blazar	1999/TA	no	A
TeV 2032+4131	CygOB2?	OB Assoc.	2002/HEGRA	yes?	C
TeV 2159-3014	PKS2155-304	Blazar	1999/Durham	yes	A
TeV 2203+4217	BL Lacertae	Blazar	2001/Crimea	yes	C
TeV 2323+5849	Cas A	SNR	1999/HEGRA	no	B
TeV 2347+5142	1ES2344+514	Blazar	1997/Whipple	no	C

TeV Gamma-ray Observation Status

At least half of these sources have been seen at > 5 sigma by two groups.
Large information content in well-detected sources.

- Catalog of Sources expanding every year!
- Almost all TeV sources are identified …unlike the 100 MeV EGRET sources
- Diverse classes of object in TeV Catalog:
  - AGN
  - Radio Galaxy
  - Starburst Galaxy
  - Supernova Remnants
  - Binary Source
  - OB Association

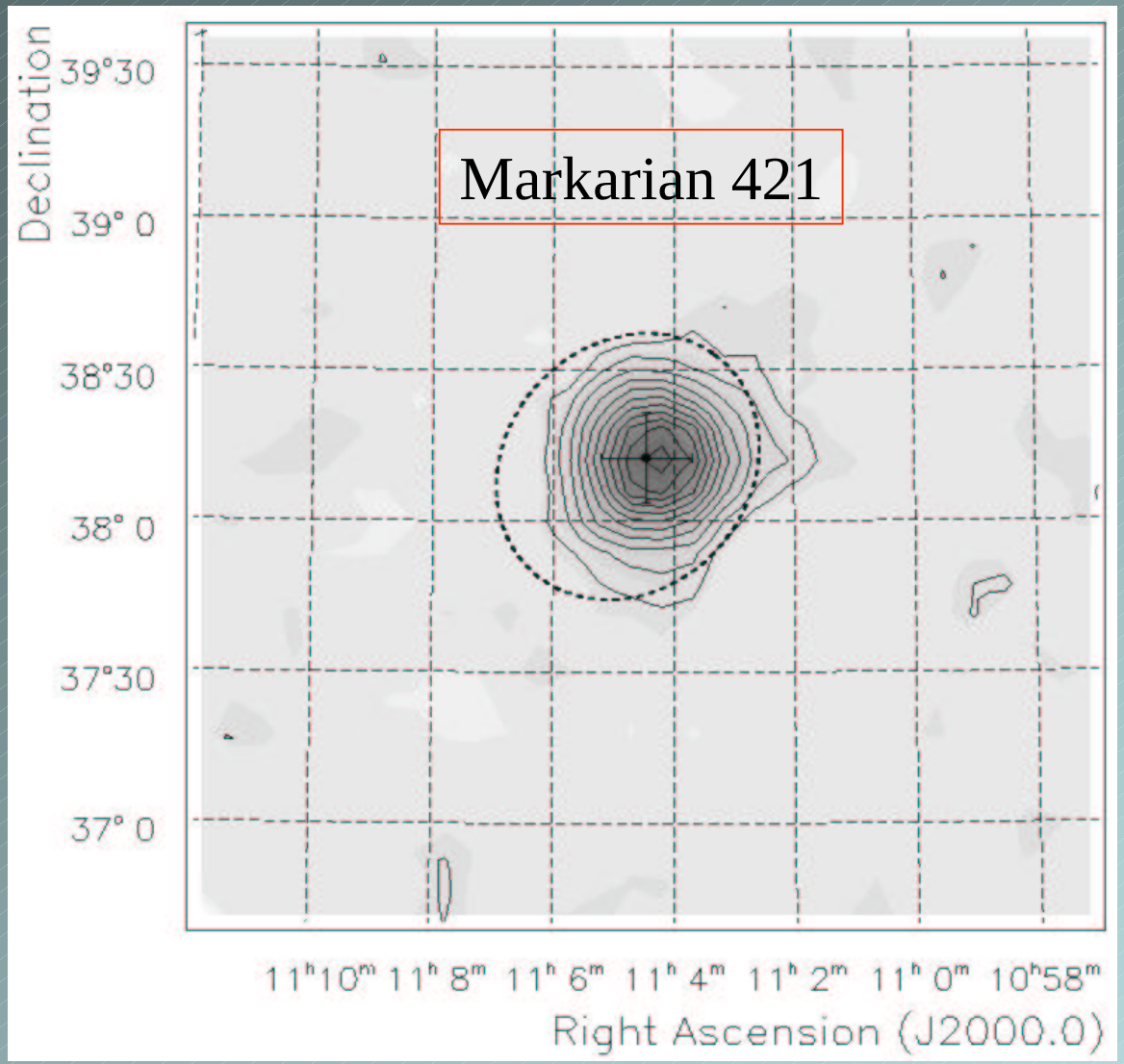
TeV Catalog of AGN

Catalog Name	Source	Date/Group	Type	Redshift
TeV 0219+4248	3C66A	1998/Crimea	LBL	0.444
TeV 1104+3813	Mrk 421	1992/Whipple	HBL	0.031
TeV 1429+4240	H1426+428	2002/Whipple	HBL	0.129
TeV 1654+3946	Mrk 501	1995/Whipple	HBL	0.033
TeV 2000+6509	1ES1959+650	1999/TA	HBL	0.048
TeV 2159-3014	PKS2155-304	1999/Durham	HBL	0.116
TeV 2203+4217	BL Lacertae	2001/Crimea	LBL	0.069
TeV 2347+5142	1ES2344+514	1997/Whipple	HBL	0.044

HBL = High frequency BL Lac

Horan, Weekes, 2003

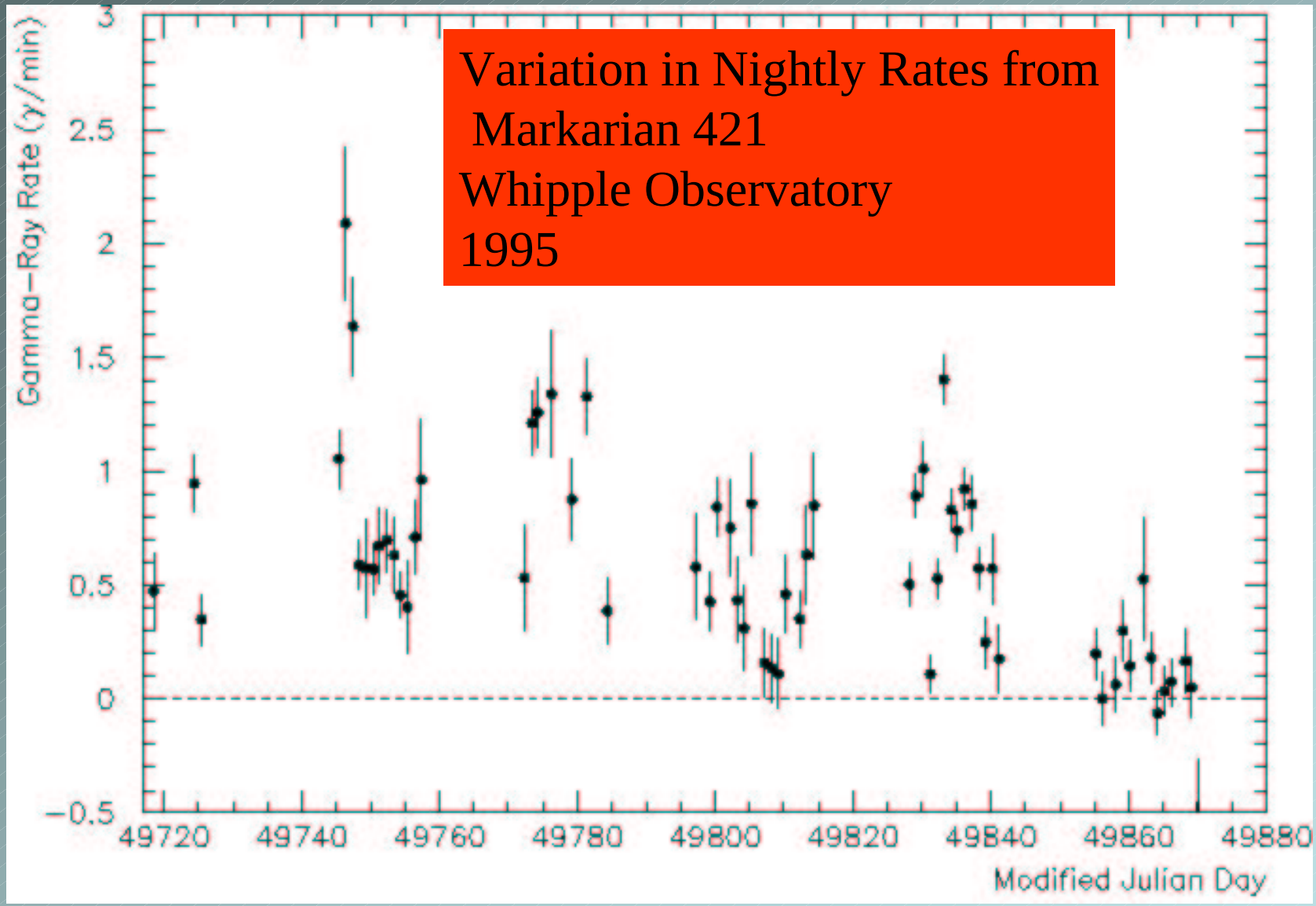
Location of TeV Gamma-ray Sources



Strong Sources can be located to a few arc-min

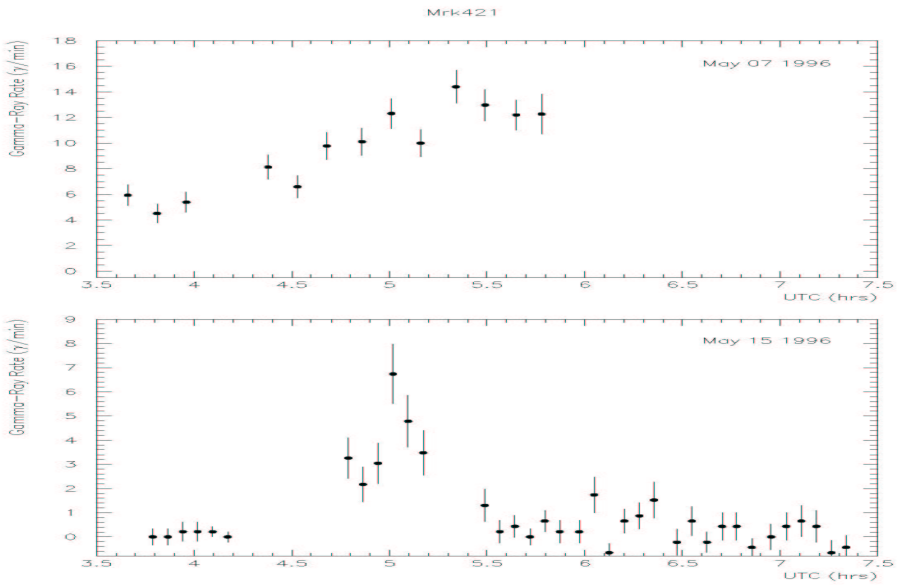
Cross = X-ray source
Dotted line : EGRET error circle
Contours: TeV source intensity

Time Variability: AGN Light Curves

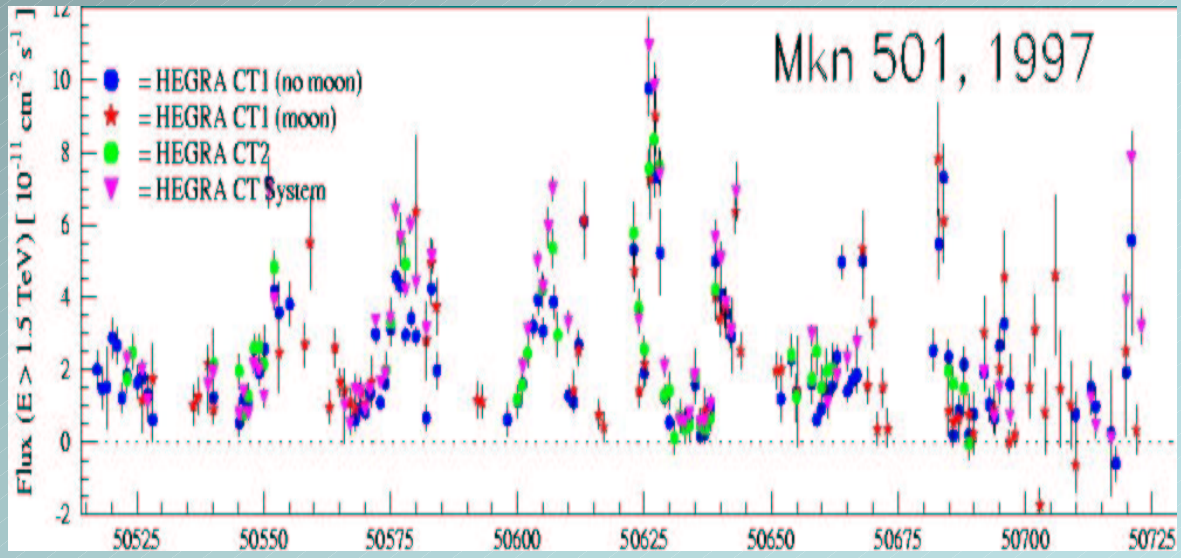


Buckley et al. 1996

Variations Seen on Many Time-scales

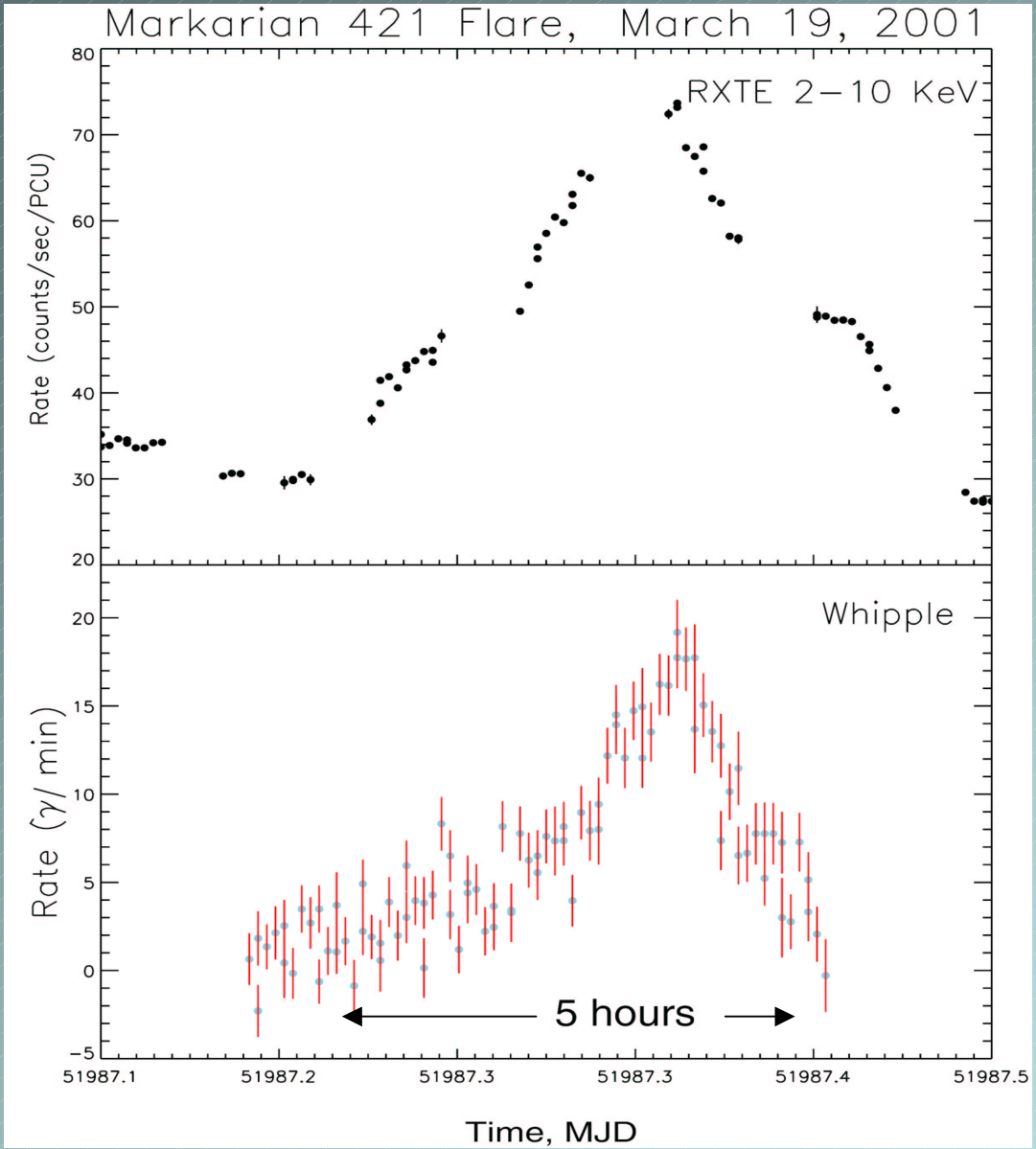


Markarian 421
Whipple Observatory
Hours - minutes

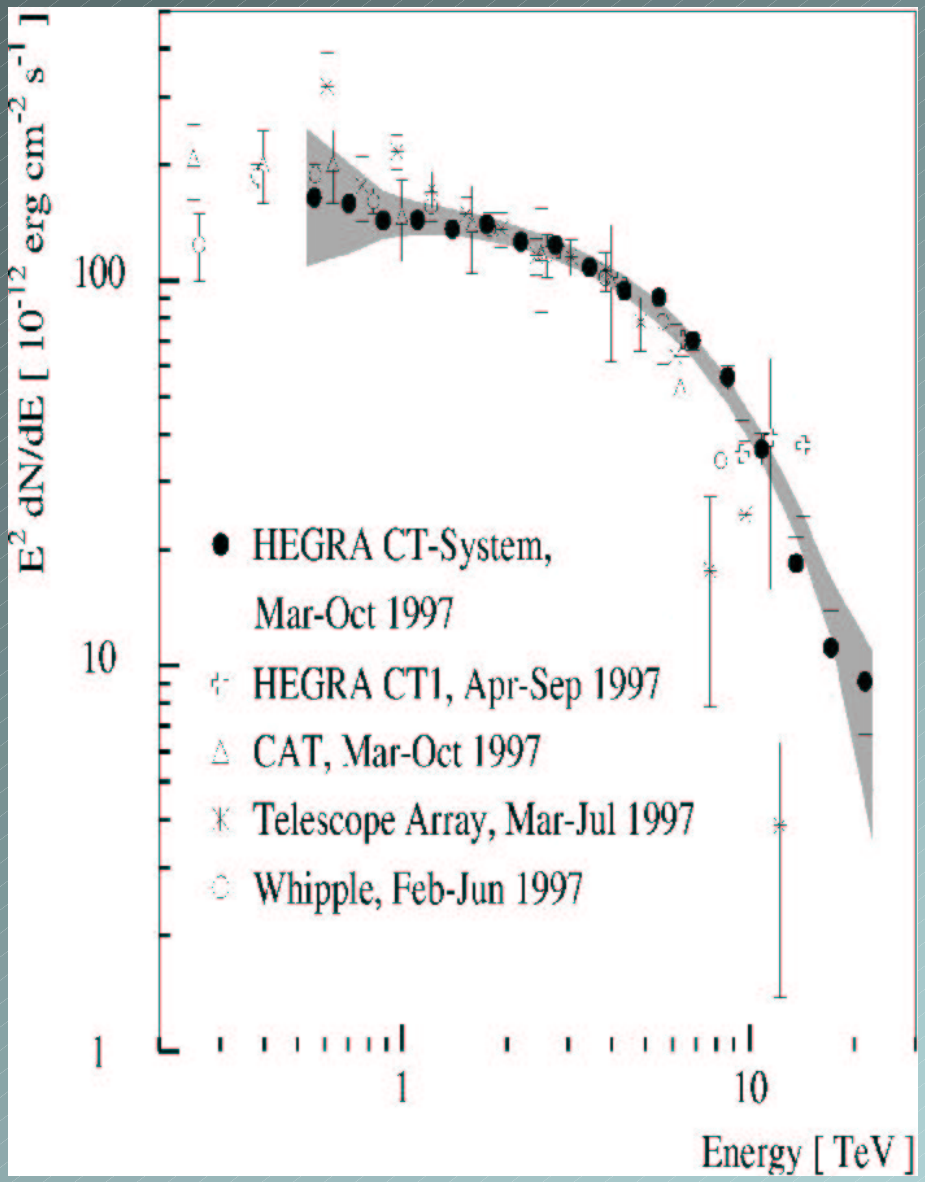


Markarian 501
HEGRA
Days-months

Correlation with X-ray Band



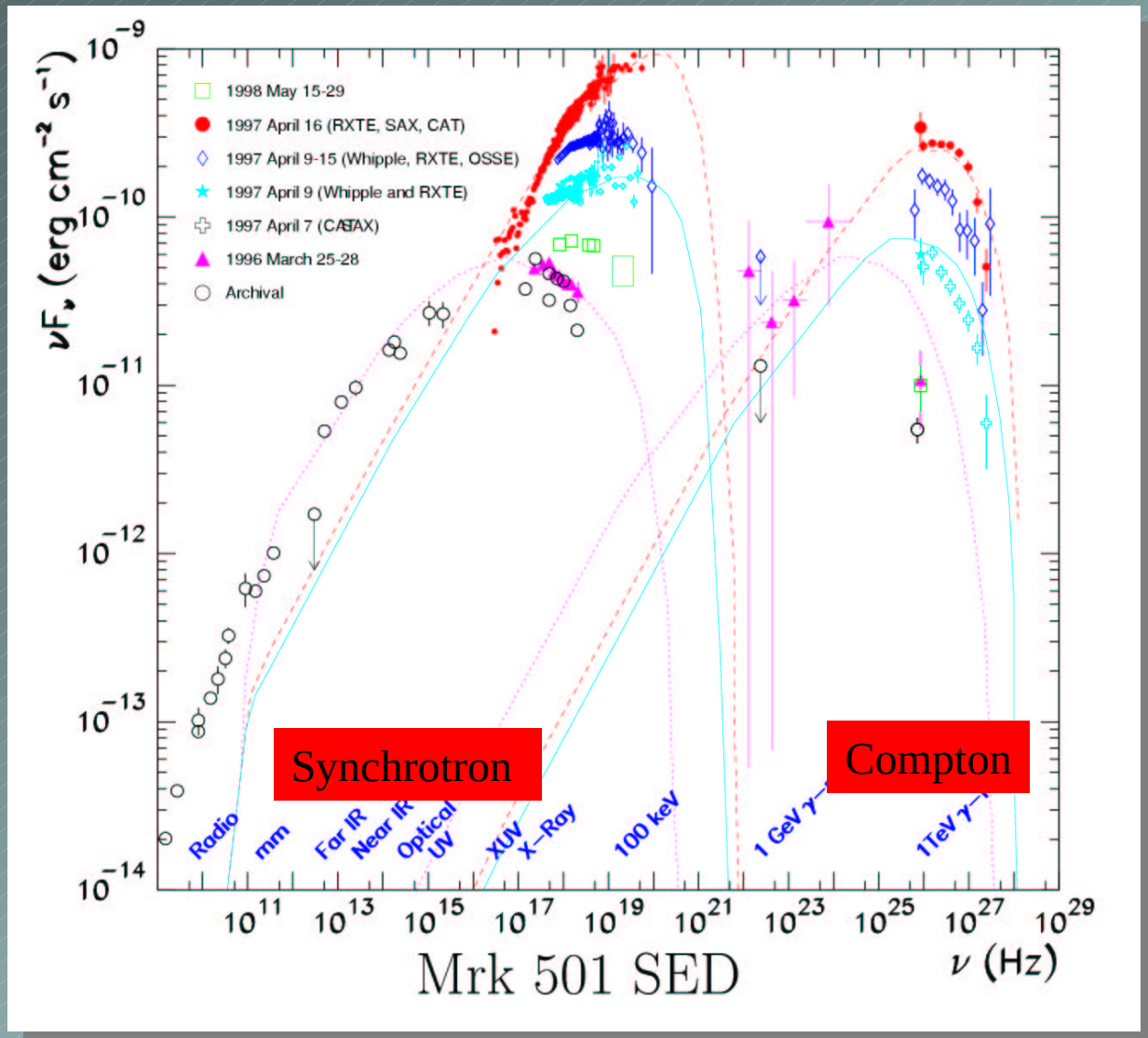
Spectral Measurements: Mrk 501



Composite spectrum of Markarian 501 showing consistency of measurements by several telescopes and detection of structure in shape of spectrum…power law plus exponential cutoff.

Aharonian et al. 1999

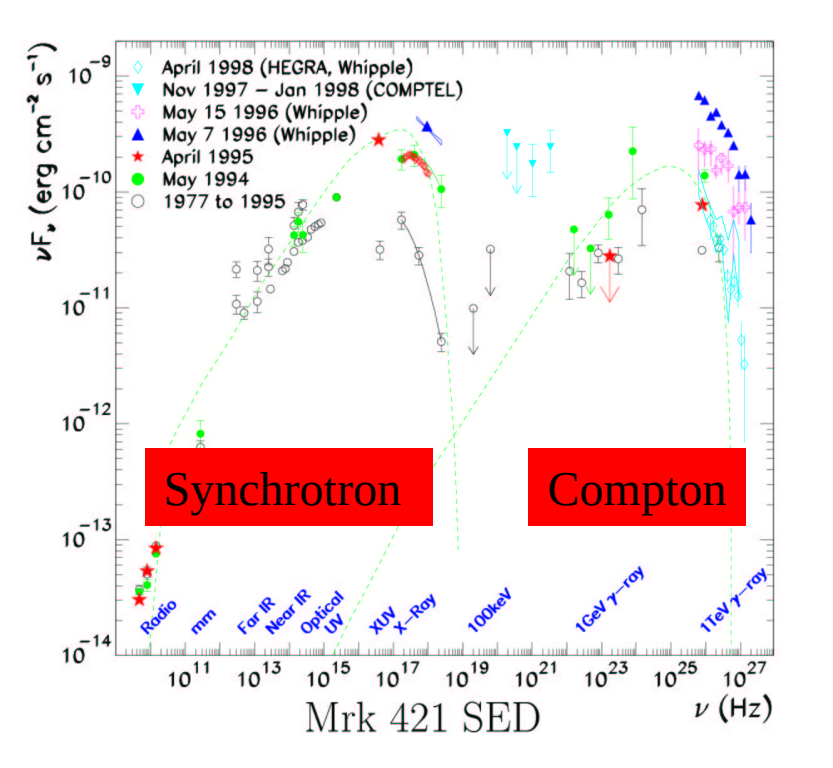
Multiwavelength Results: Power Spectra



Mrk 501

Similar double peaked Power Spectra seen in other AGN

Multiwavelength Results: Power Spectra



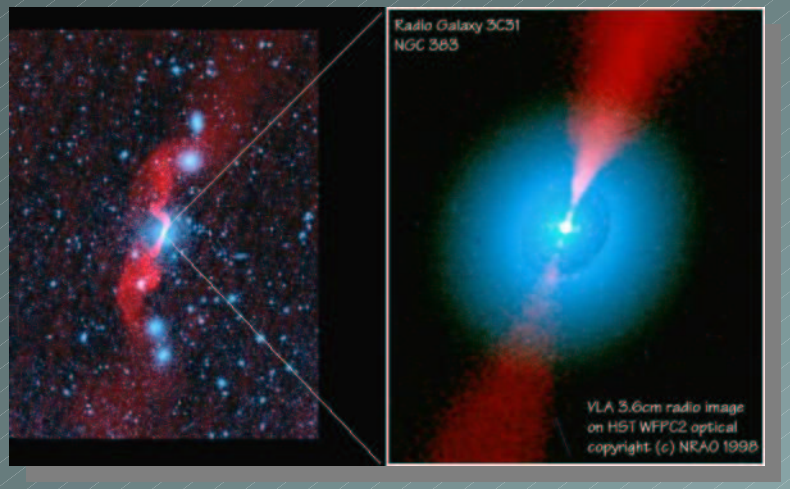
Mrk 421

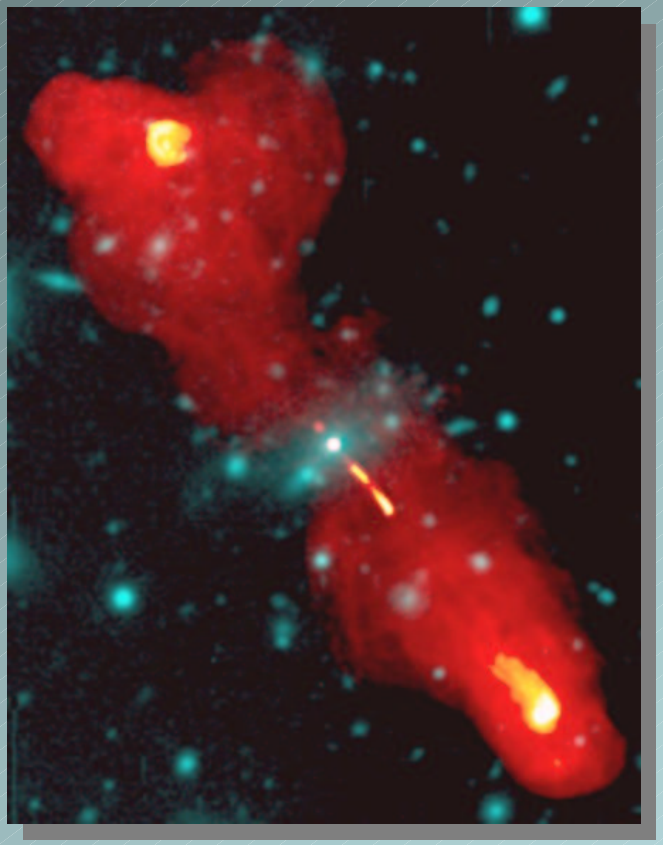
Gamma-ray luminosity is comparable with X-ray luminosity…much power at highest energies.

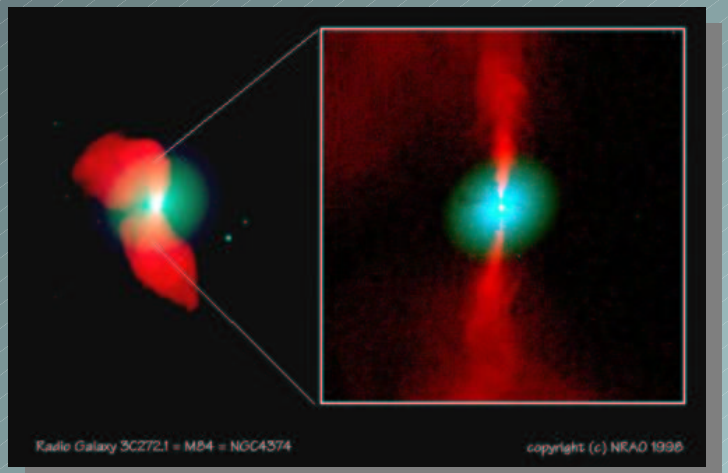
Gamma-ray luminosity is so high and time variations so short, that it is difficult to model the TeV emission if the emitting source is isotropic.

Luminosity is reduced by factor of 1,000-10,000
if Relativistic Beaming in Jets assumed.
Size of Emitting Region, Maximum Particle Energy also relieved.

AGNs: Relativistic Jets



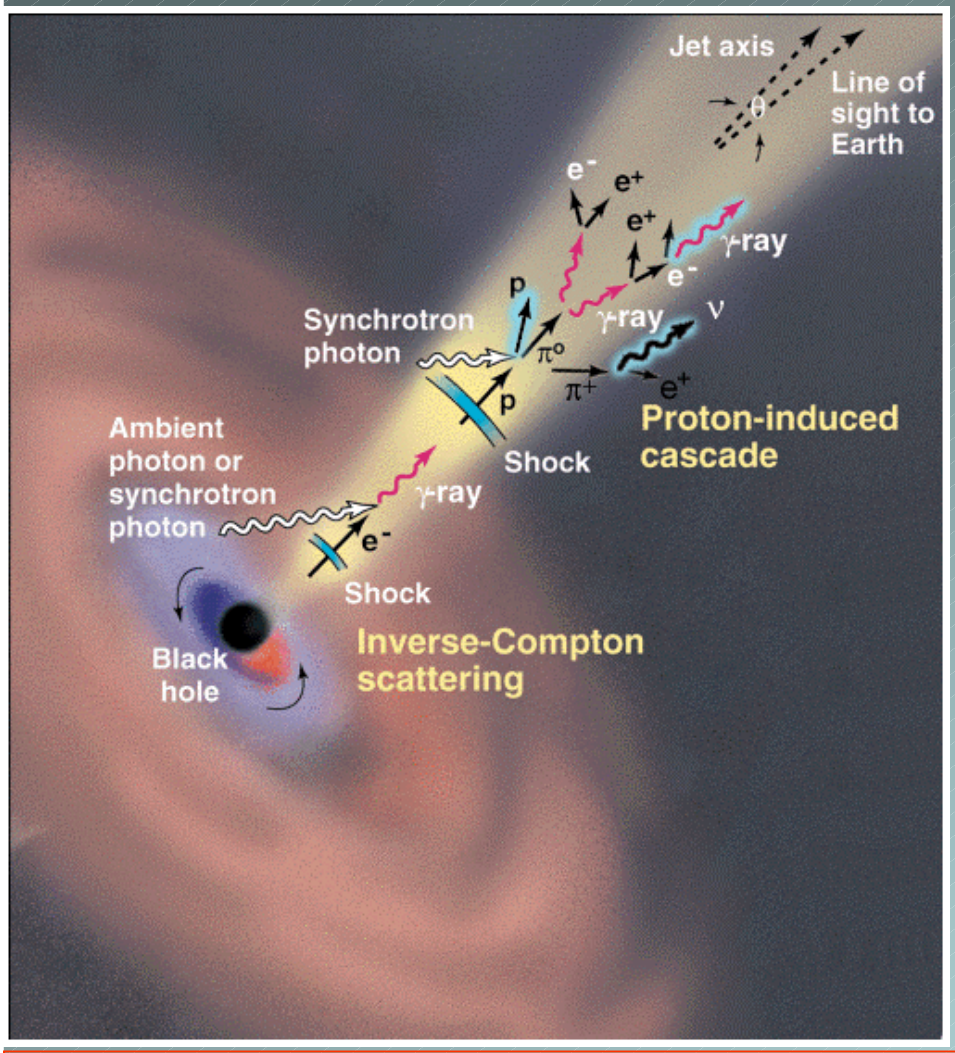




$$\Gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}} \lesssim 10 \quad \text{or} \quad v = 99.5\% \text{ of } c$$

Looking down the Barrel of a Cosmic Cannon

AGN Jet Emission Mechanisms



Electron Progenitors:

- Synchrotron Self Compton
- External Compton

Proton Progenitors:

- Proton Cascades
- Proton Synchrotron

Electron Synchrotron Self Compton Models most consistent with TeV AGN…..but observations are complex and require more sophisticated Modelling of Jets.

Extragalactic TeV Gamma-ray Astronomy

New Developments:

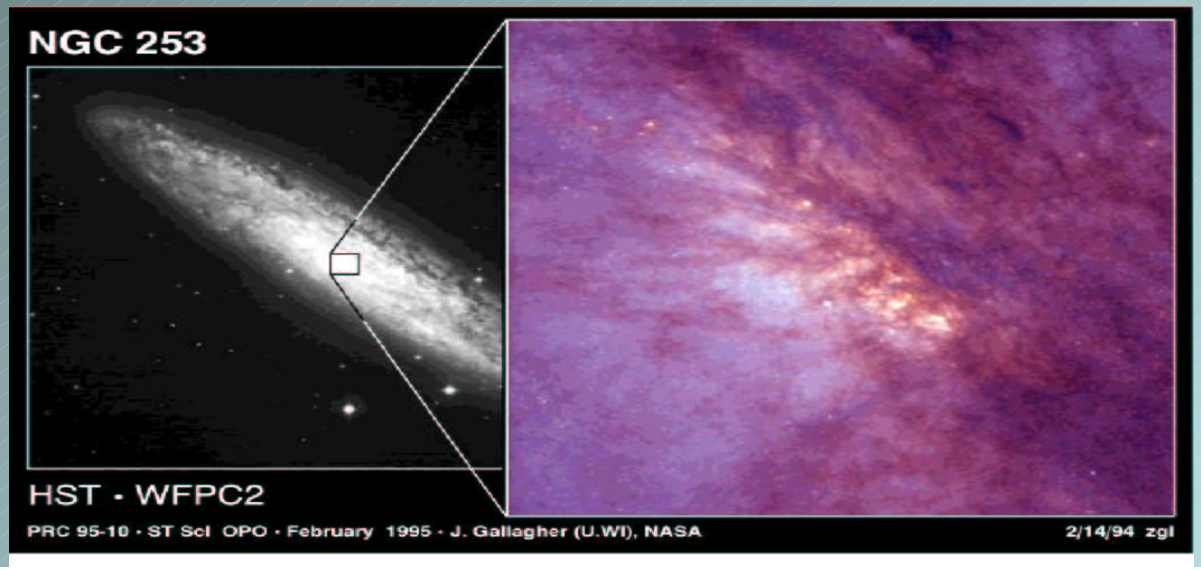
Detection of Starburst Galaxy, NGC253

Detection of Radio Galaxy, M87

Spectral Variability in Mrk 421

Detection of Starburst Galaxy, NGC 253

* CANGAROO Detection, 2003
- Nearby Starburst Galaxy
- High Rate of Supernova Explosions
- 11 sigma detection
- Very steep spectrum
- Not a jet source; new class of object
- Extended



Itoh et al. 2003

Detection of Radio Galaxy, M87

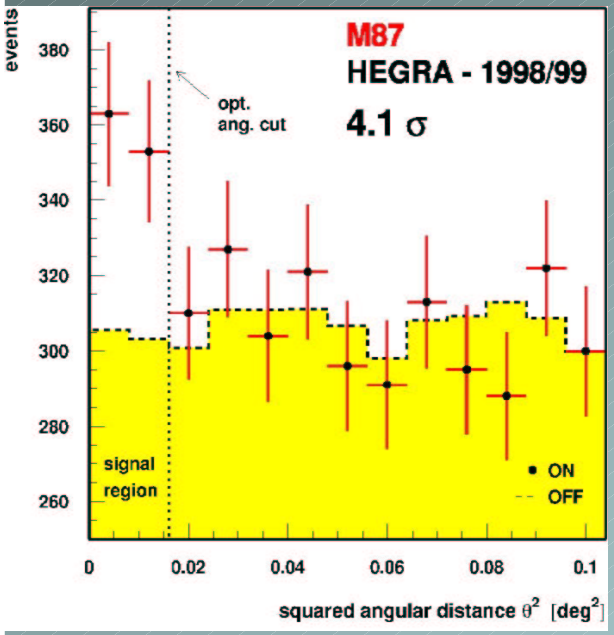
Nearby Radio Galaxy (Virgo A)

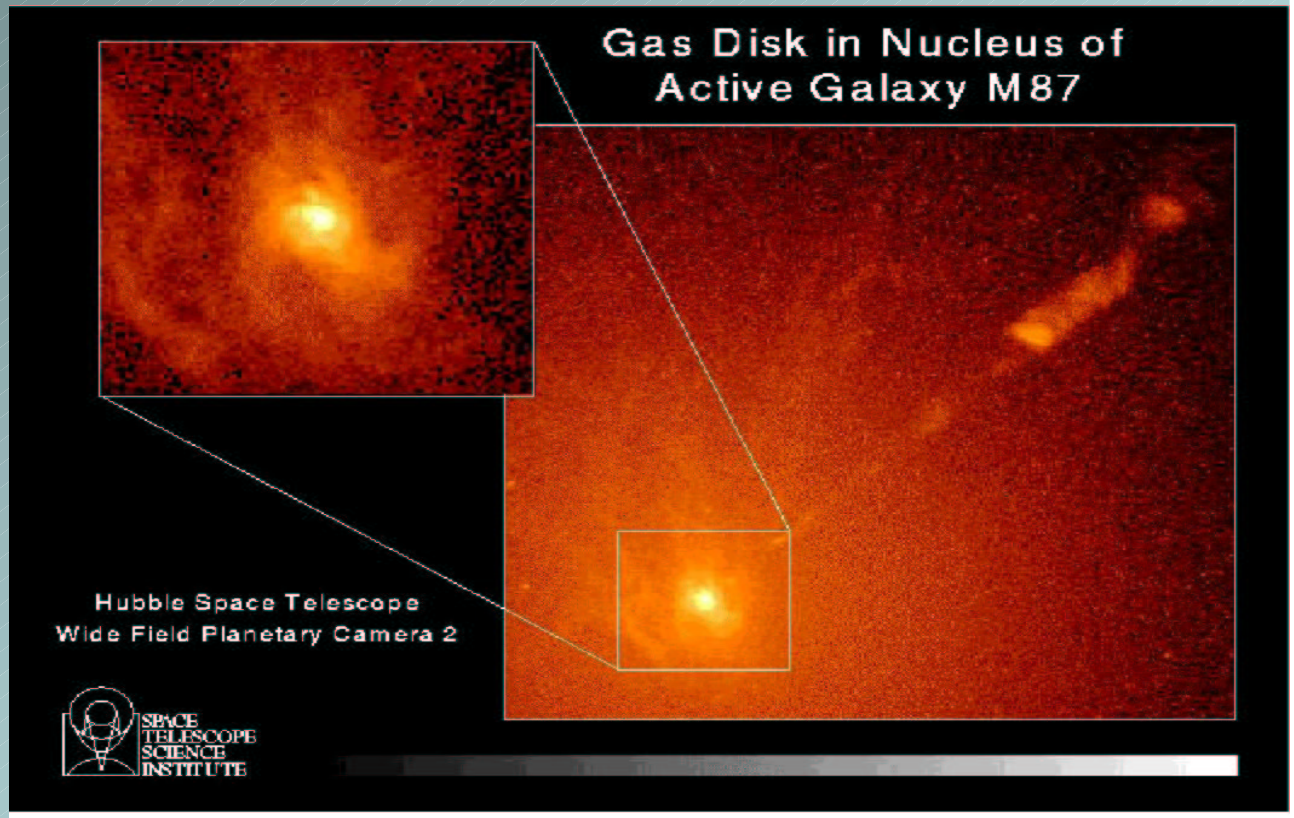
Off axis jet source

HEGRA Group

4.1 sigma detection

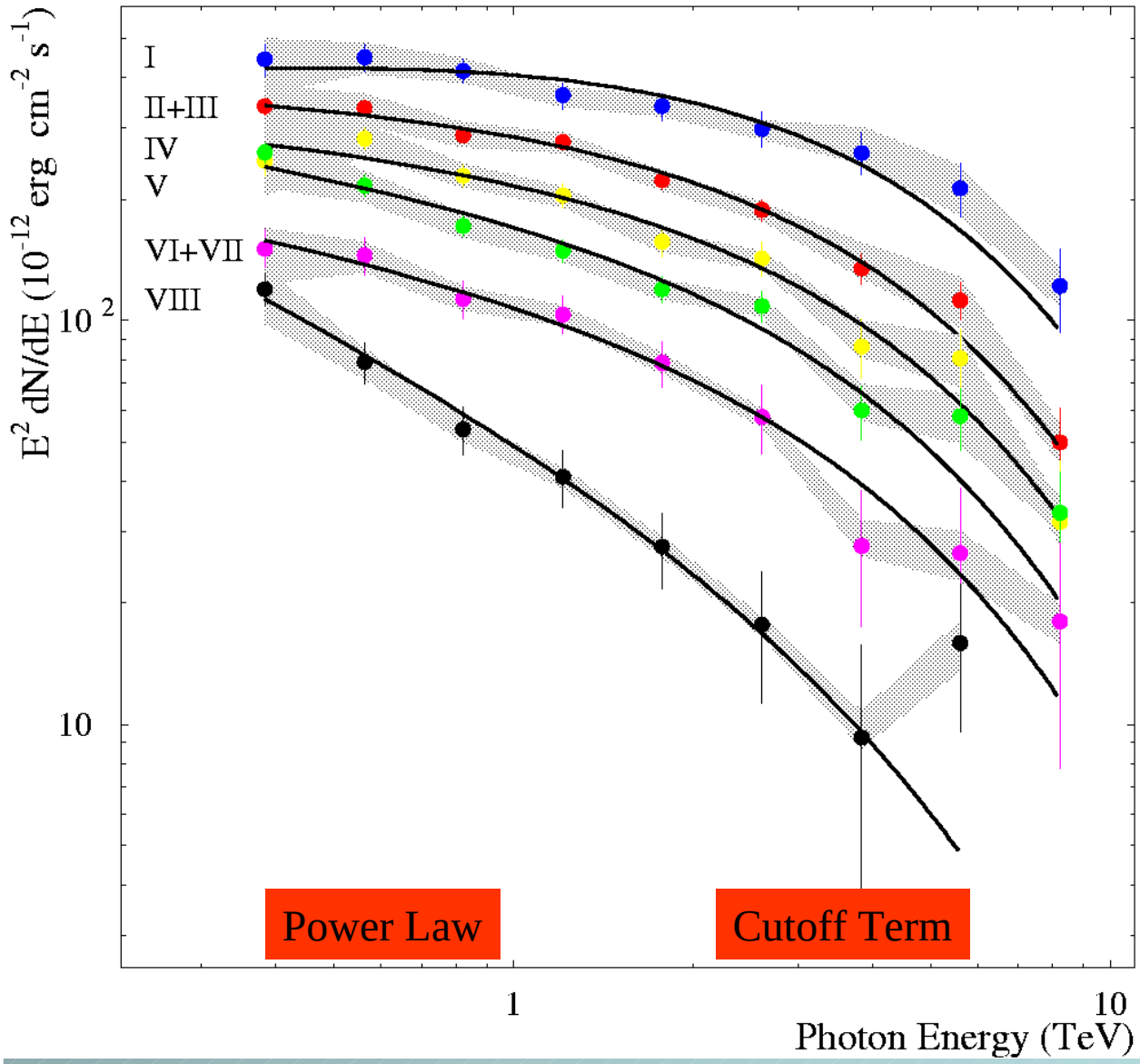
Weak source but important





Aharonian et al. 2003

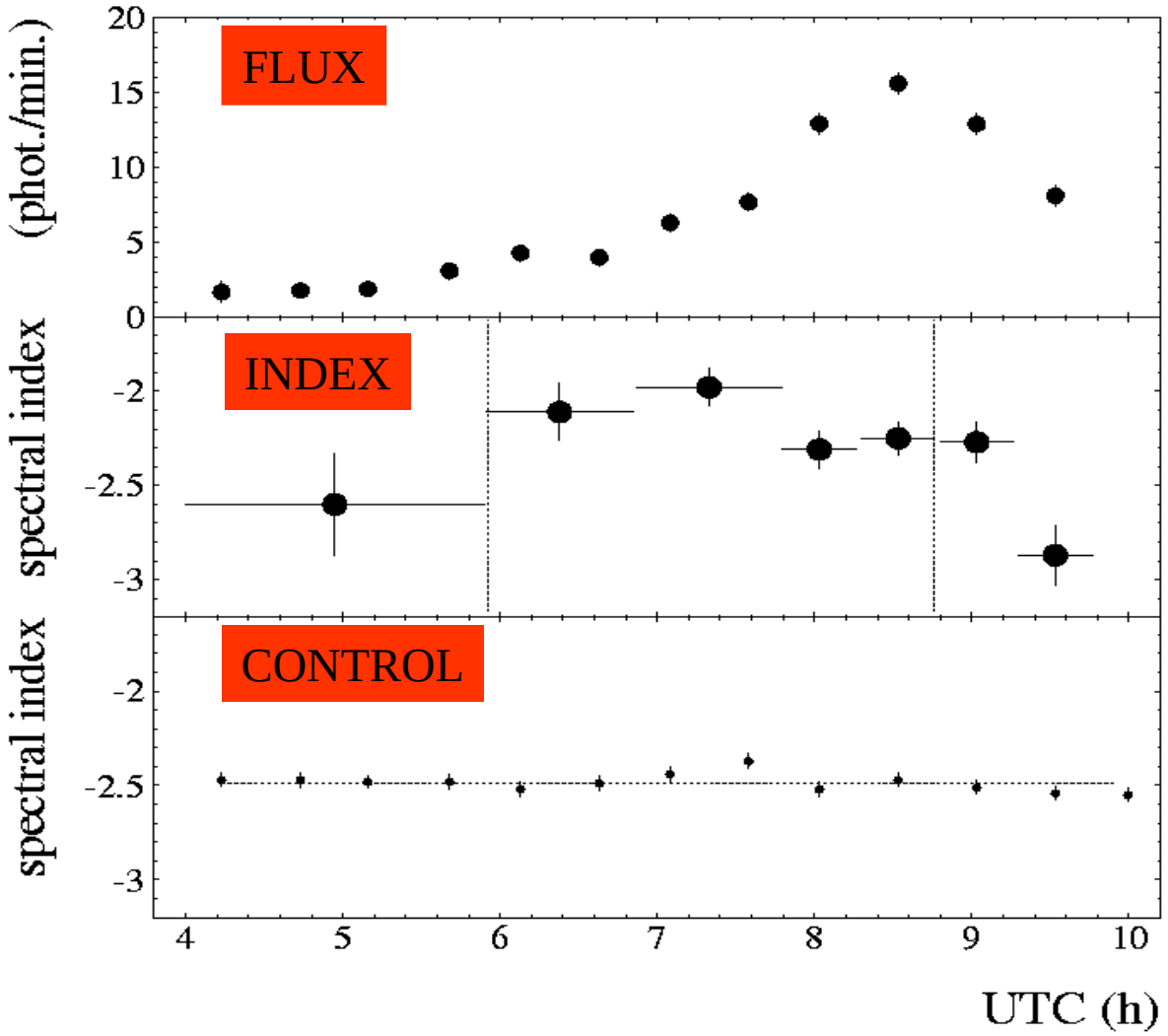
Mrk421 Spectral Variability



Exponent of Power Law Changes with Total Intensity. Cutoff Term Remains the Same

Krennrich et al. 2003

Short-term Spectral Variability : I



Mrk 421, Flare

March 19, 2001

Clear change of power law spectral index during flare

Krennrich et al.
OG2.3, 2-P-071

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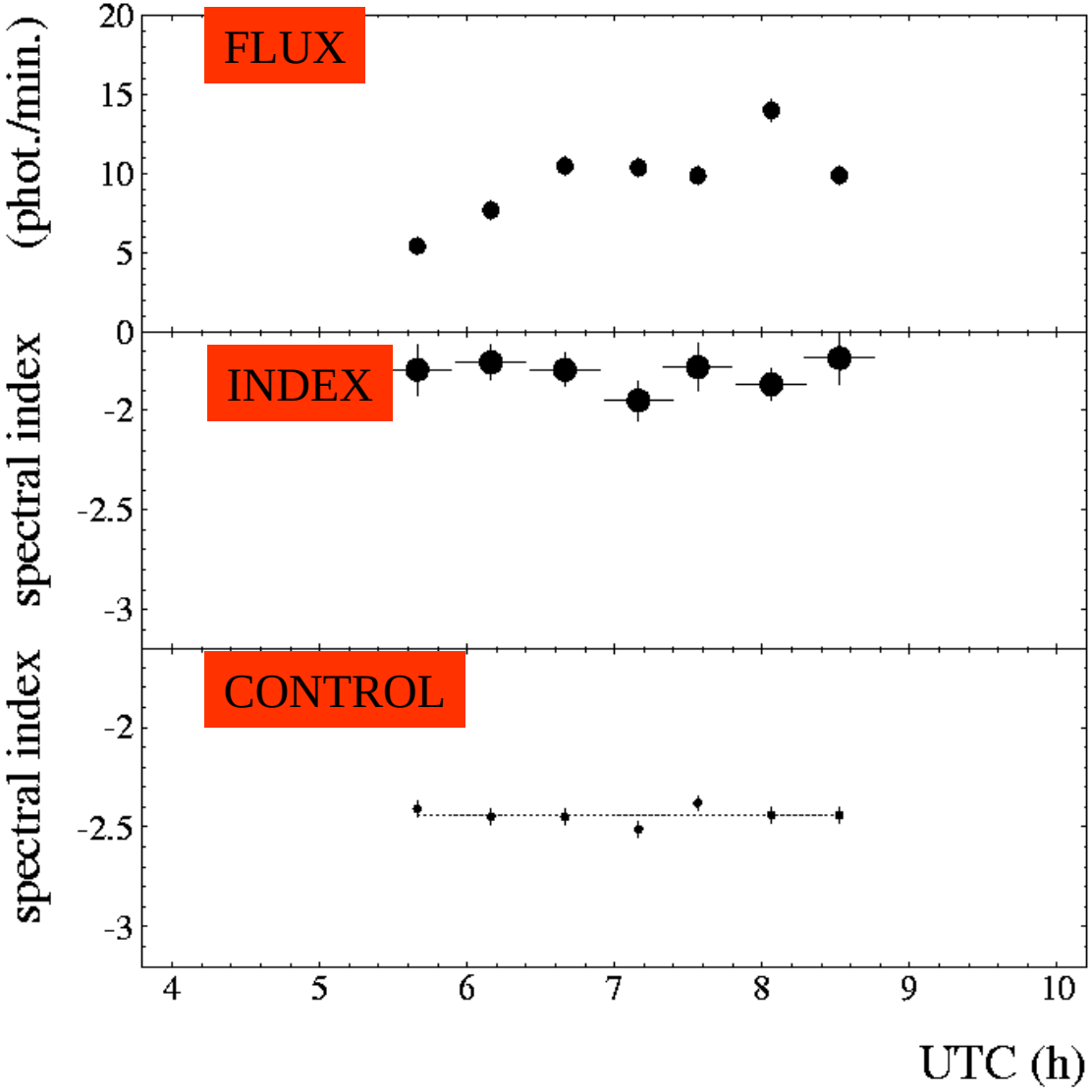
Short-term Spectral Variability : II



Mrk 421

March 25, 2001

No change in spectral index during flare.

Krennrich et al.
OG2.3, 2-P-071

Extragalactic TeV Gamma-ray Sources are making a real contribution to Astrophysics

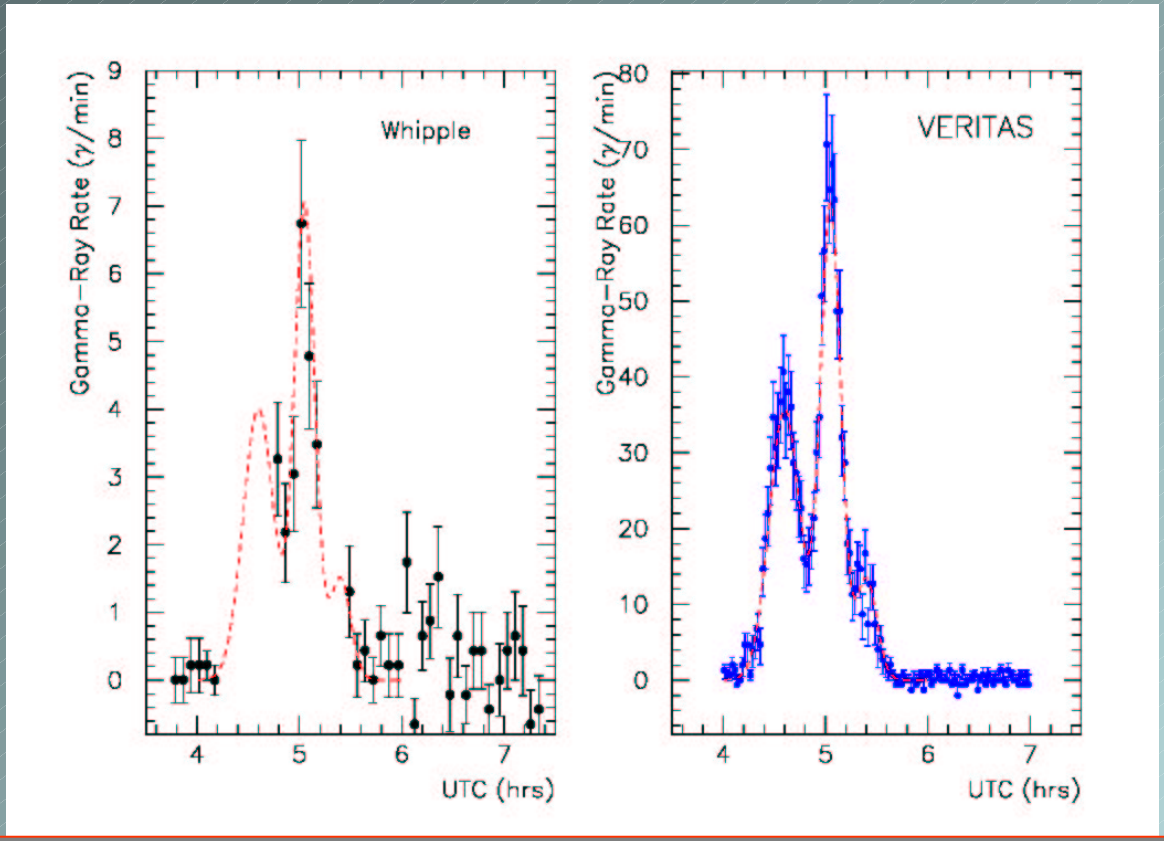
The Study of TeV gamma-ray sources is more than a sub-section of OG Cosmic Rays.

It has become a New Astronomical Discipline with interest from astronomers in many wavebands.

The New Generation of Telescopes has impressive abilities for:

Location of Sources	Angular Res. ~ 0.05 deg.
Measurement of Spectra	Energy Res. ~ 10-15 %
Monitoring of Time Variability	Minutes – Years
Correlations with other bands	GLAST, ARGOS, EXIST optical, infrared, radio

Ability to detect transients



Data points are from Whipple telescope detection of very short flare from Markarian 421 in 1996.

Red dotted line is possible (undetected) substructure in flare.

Data points on right are calculated data points as it would be detected by CANGAROO-III, HESS or VERITAS

Conclusions: Extragalactic TeV Sources

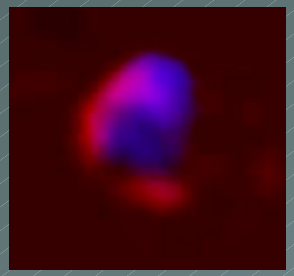
No Smoking Gun for Origin of the Cosmic Radiation …but a Fascinating View of Particle Acceleration in Distant Sources

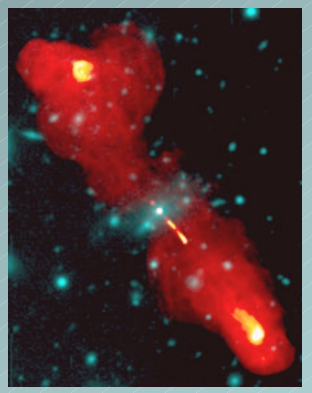
Diverse Extragalactic Sources of TeV Gamma-rays suggest Particle Acceleration is Ubiquitous; hence there may be many Extragalactic Cosmic Ray Sources.

There may be common features between TeV Gamma-ray Sources, Gamma-ray Burst Sources and Sources of UHE Cosmic Rays.

TeV Gamma-ray Astronomy established as New Astronomical Discipline.

The Wonder of TeV Gamma-ray Astronomy





- We should never forget the extraordinary nature of TeV sources
- Even the detection of a single source is an astrophysical marvel!
- Every source is evidence for a **Cosmic Particle Accelerator**
- Techniques are simple, ground-based and relatively inexpensive