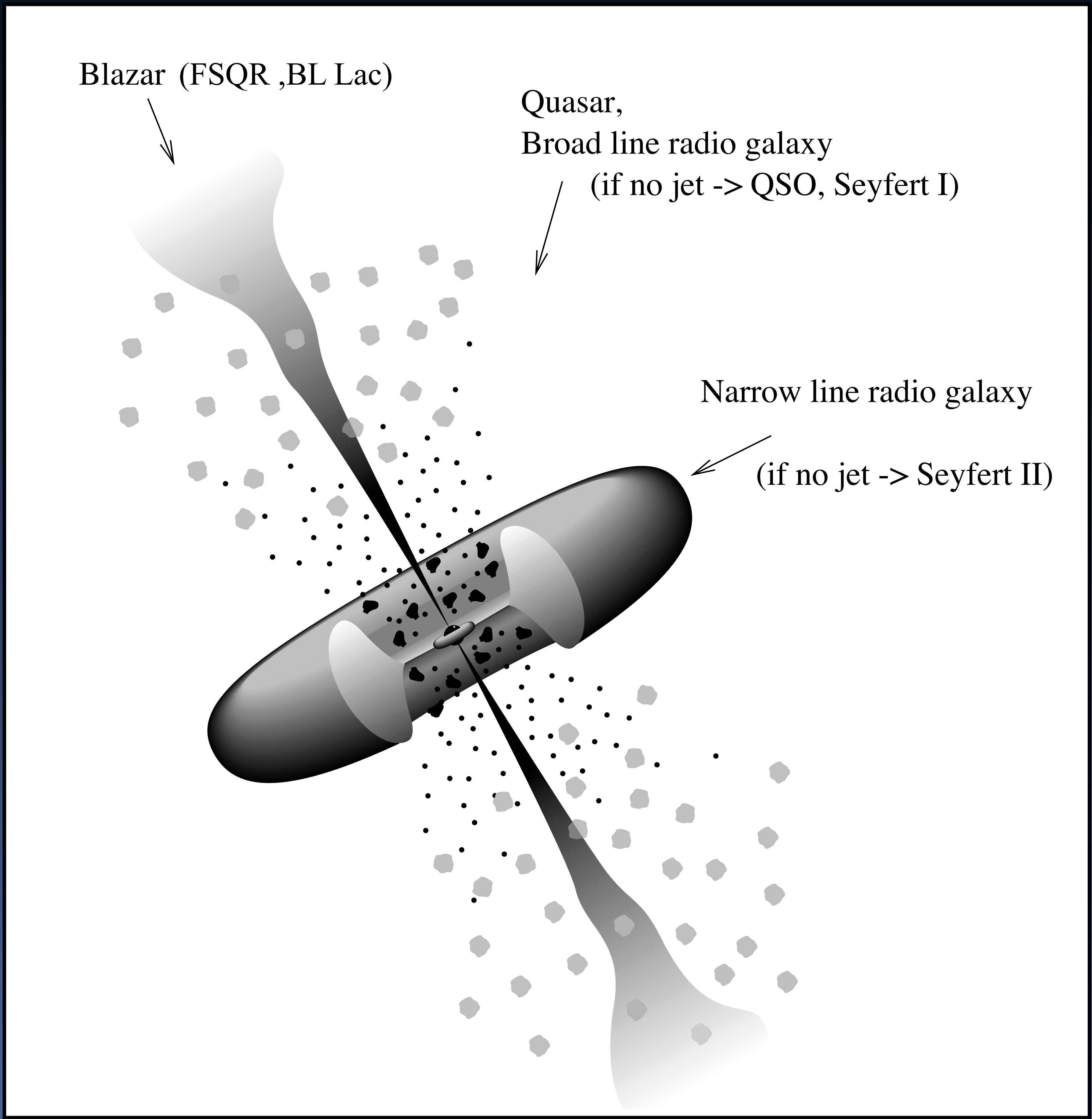
The Whipple AGN Era

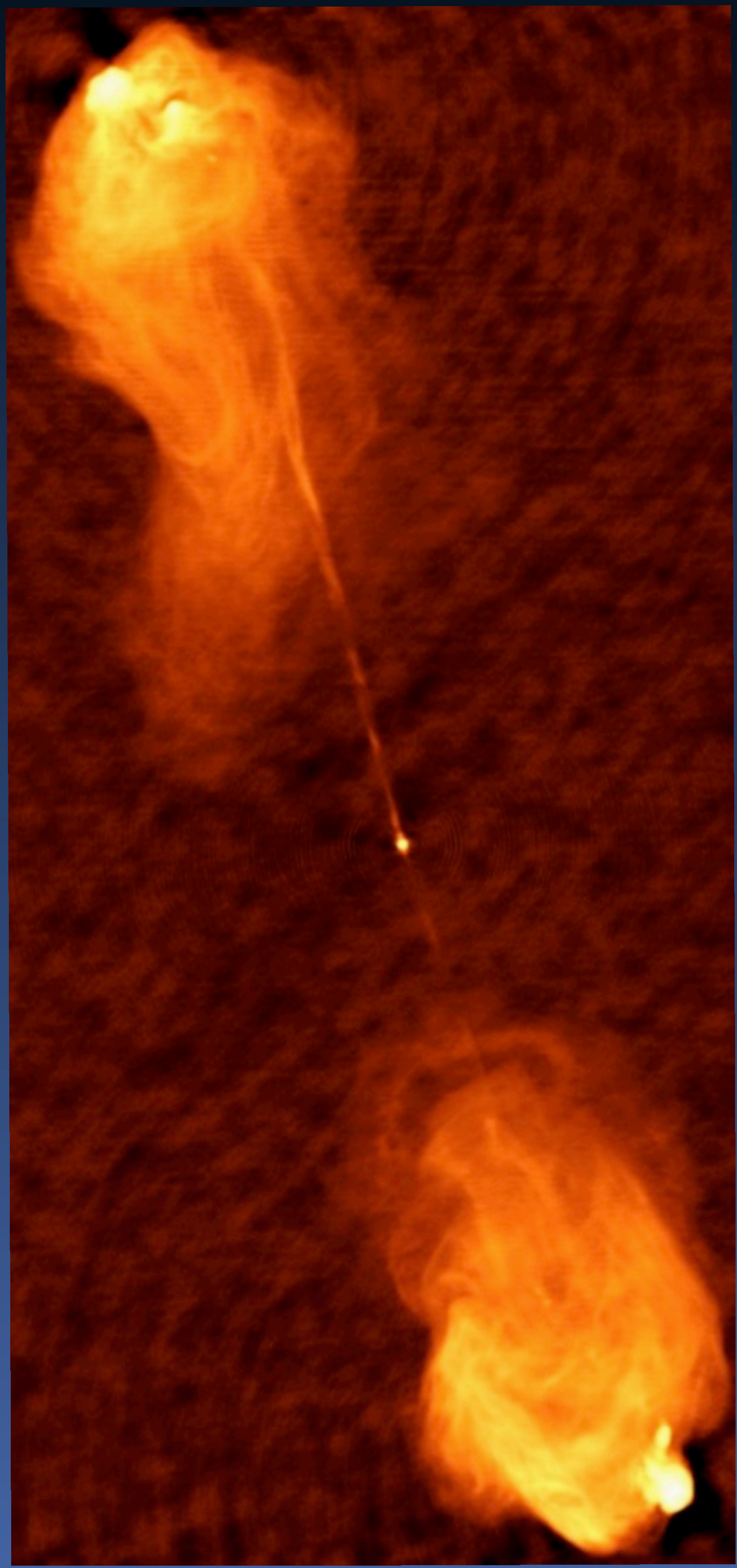
John Quinn

UCD DUBLIN

Active Galactic Nuclei



Urry & Padovani, 1995



Cygnus A, (NRAO)

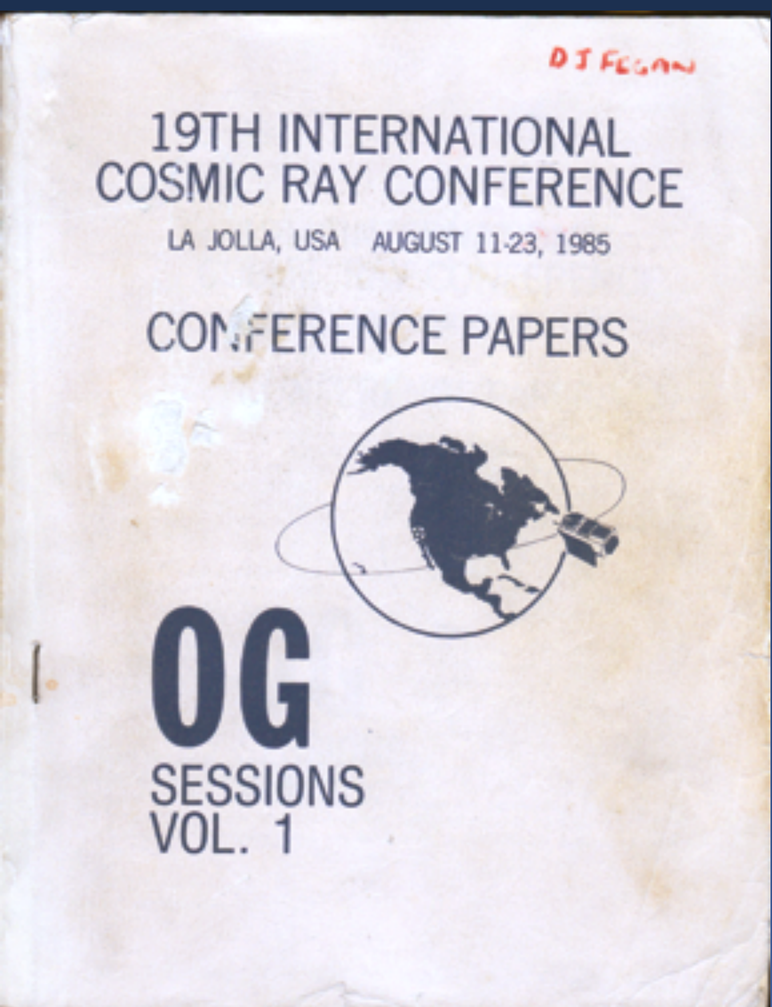
Early Targets

OGG 2.7-3

264

Search for γ-rays from M31
and other extragalactic objects

M.F. Cawley[1], D.J. Fegan[1], K. Gibbs[2], P.W. Gorham[3], R.C. Lamb[4],
D.F. Liebing[4], N.A. Porter[1], V.J. Stenger[3], T.C. Weekes[2]



37-pixel camera

TABLE 1.

Object	RA	Dec	Class	z	limit (A)	limit(B)
NGC1275	03 19	+41 25	SEYFERT	.017	1.2E-9	9.5E-11
PKS0735+17	07 35	+17 49	BL LAC	.424	1.7E-10	6.9E-11
PKS0736+01	07 36	+01 44	BL LAC		1.3E-11	1.5E-10
OJ287	08 52	+20 18	BL LAC	.306	4.8E-10	1.2E-10
PKS0906+01	09 06	+01 34	BL LAC		3.1E-10	7.1E-11
OK222	09 13	+29 50	BL LAC		3.7E-10	1.3E-10
3C232	09 55	+32 38	QSO	.53	1.3E-10	1.3E-10
X1052+607	10 52	+60 42	BL LAC		3.6E-12	9.2E-11
MK421	11 01	+38	BL LAC	.030	2.3E-10	6.3E-11
NGC4151	12 09	+39 30	SEYFERT	.003	3.0E-10	1.9E-10
ON325	12 17	+30 12	BL LAC		4.0E-10	1.1E-10
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3C273	12 28	+02 09	QSO	.158	3.6E-10	1.7E-10
M87	12 30	+12 29	NORMAL	.003	6.0E-10	8.3E-11
3C279	12 53	-05 31	QSO	.538	4.6E-10	2.0E-10
OQ208	14 05	+28 41	SEYFERT		2.4E-10	7.7E-11
MK501	16 52	+39 48	BL LAC	.034	2.5E-10	1.8E-10
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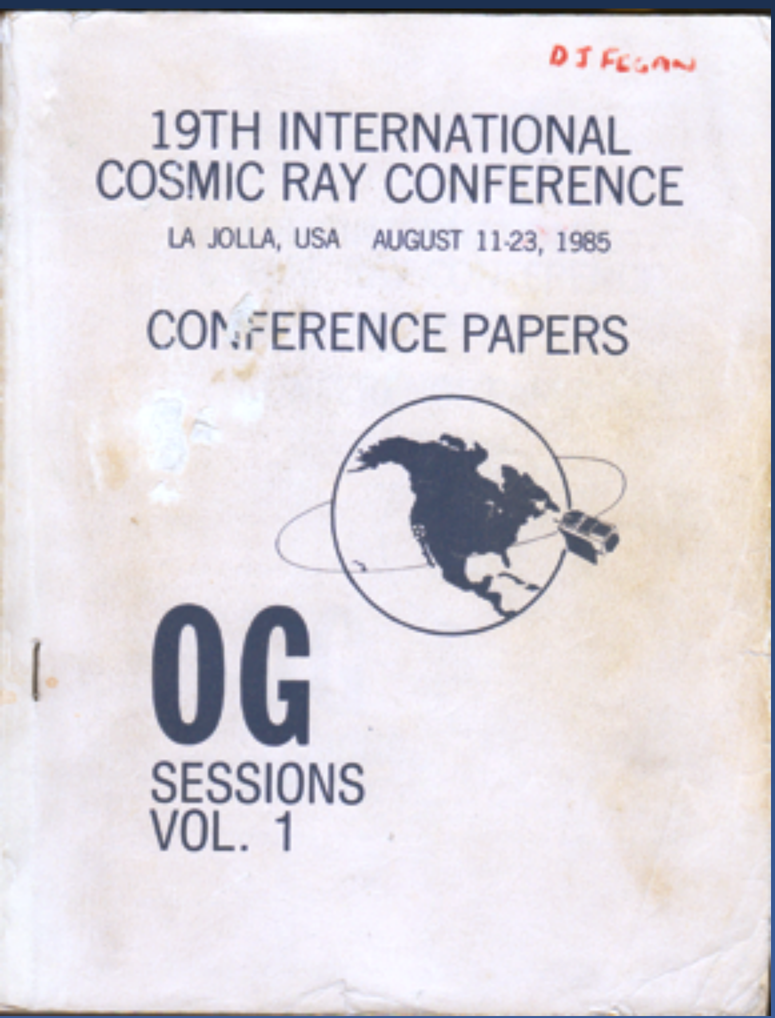

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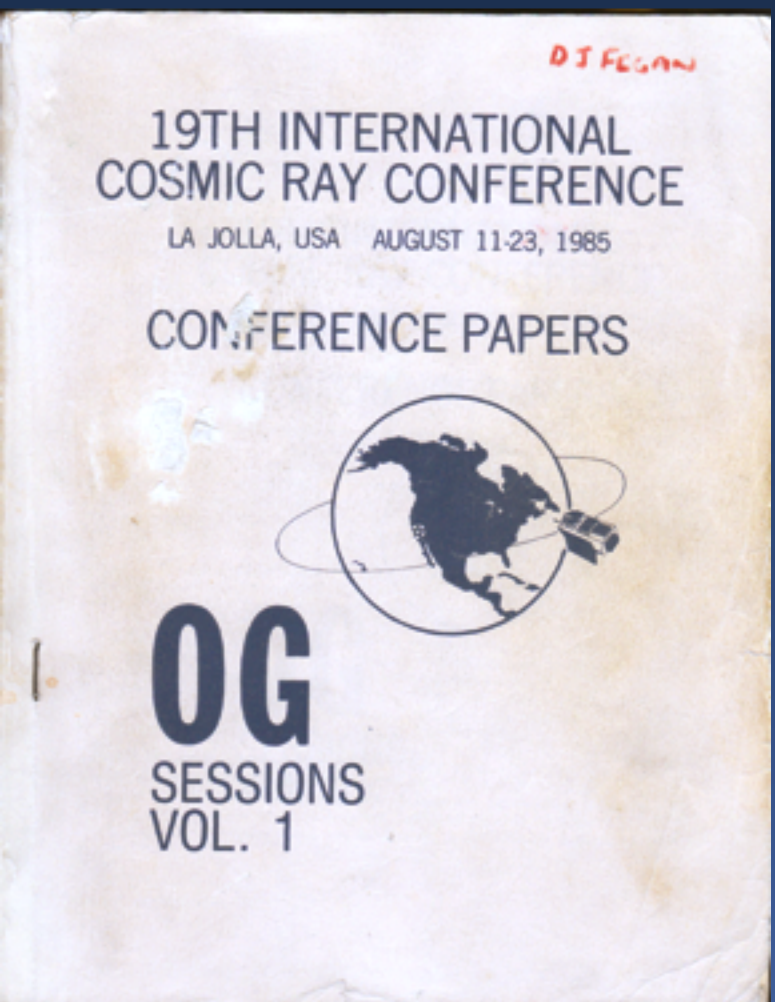

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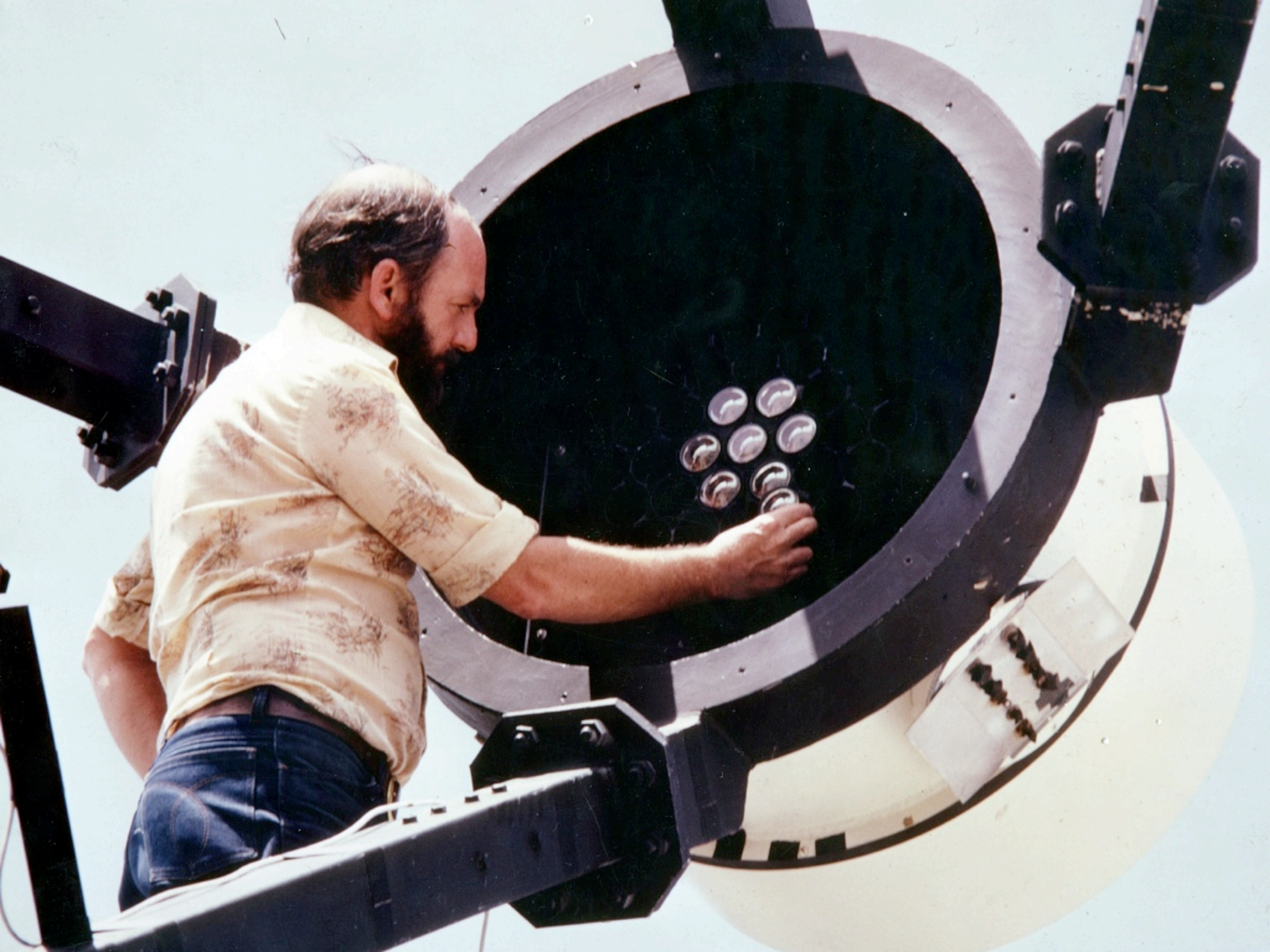
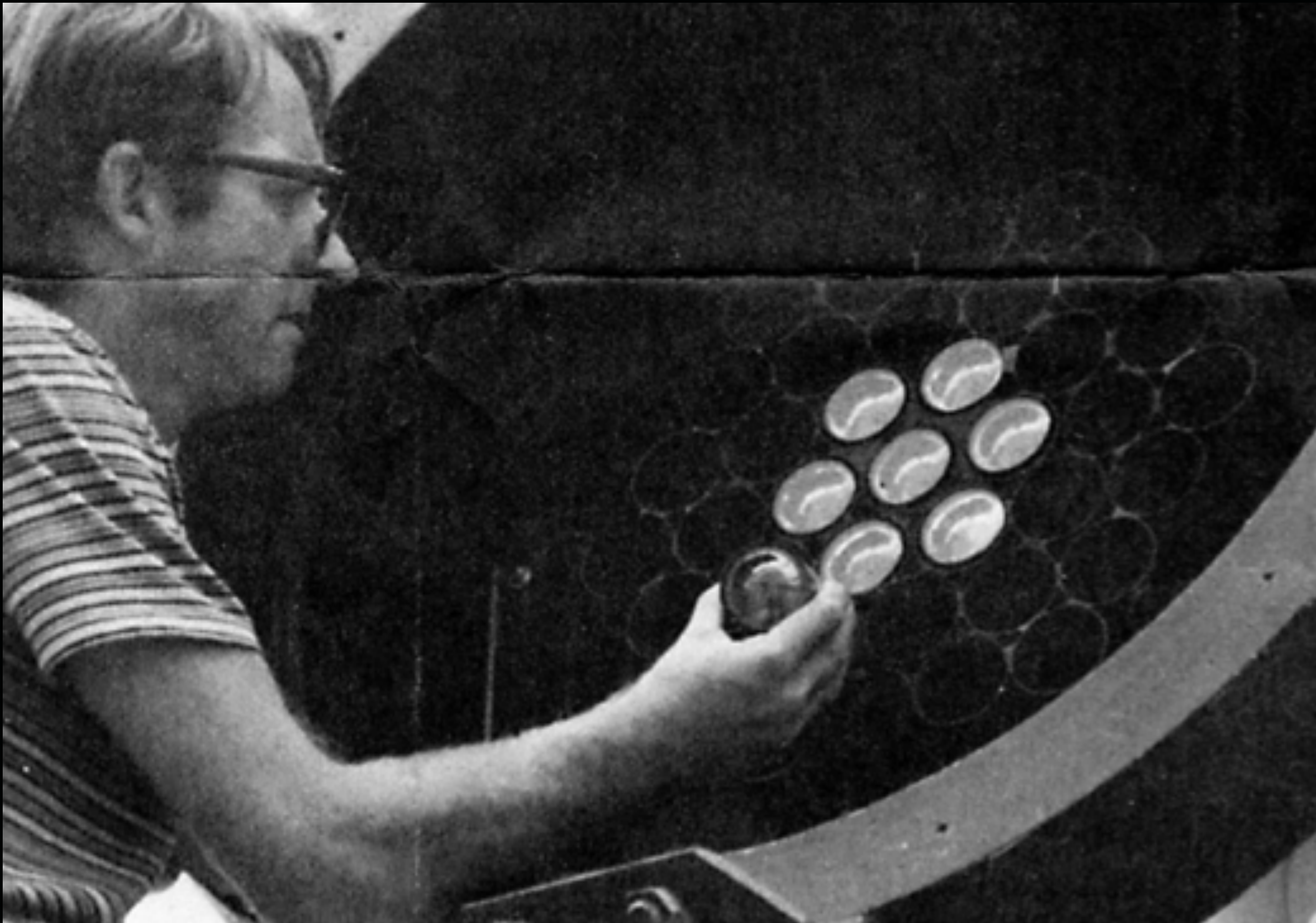
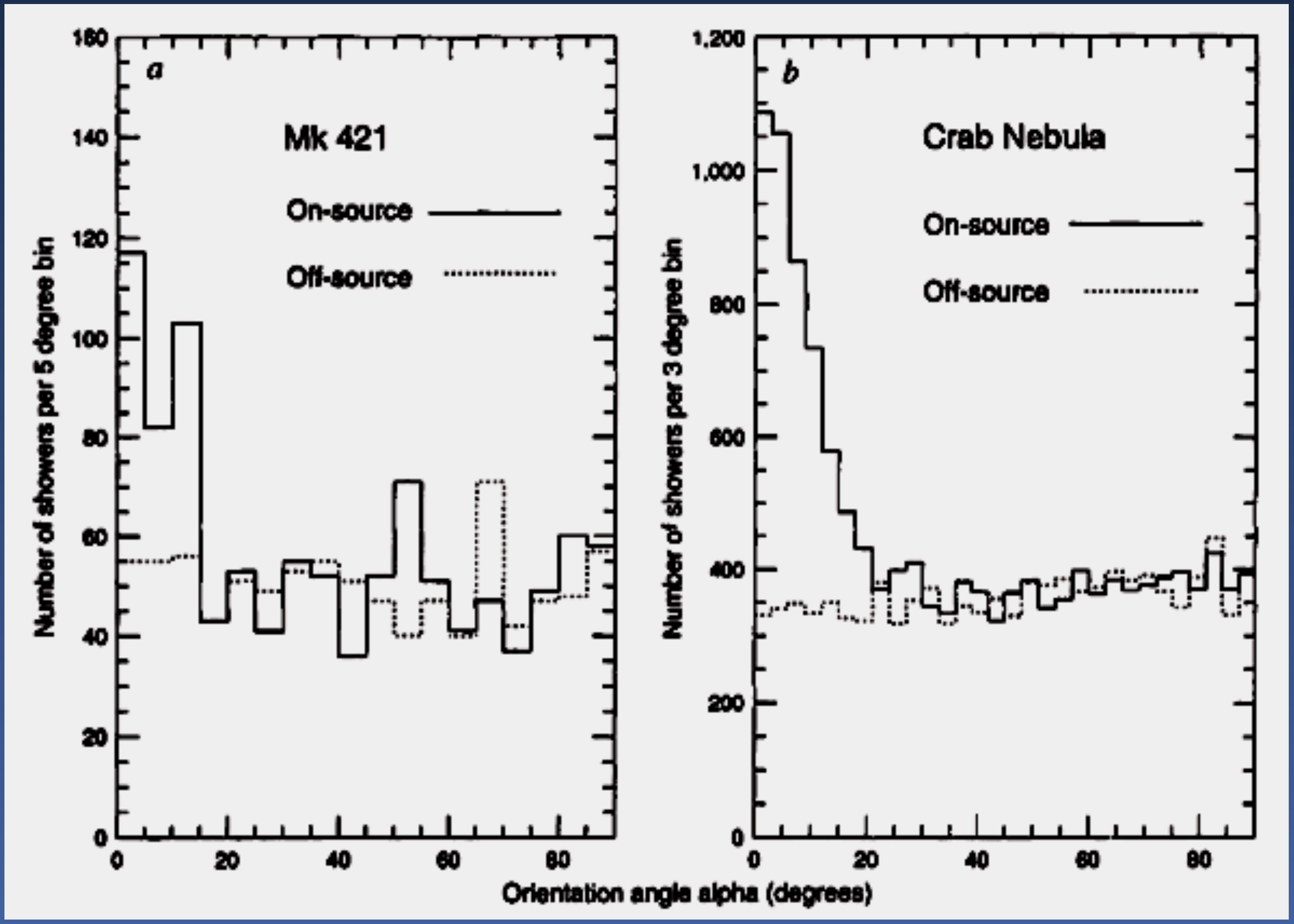




1992: Markarian 421

- 109-pixel camera
- 2nd TeV source and first extragalactic TeV source detected with the IACT.
- 7.5 hrs of observations between March and June yielded a 6.3σ detection.
- Flux 0.3 times that of Crab Nebula - incredible luminosity if isotropic.



Punch et al., 1992

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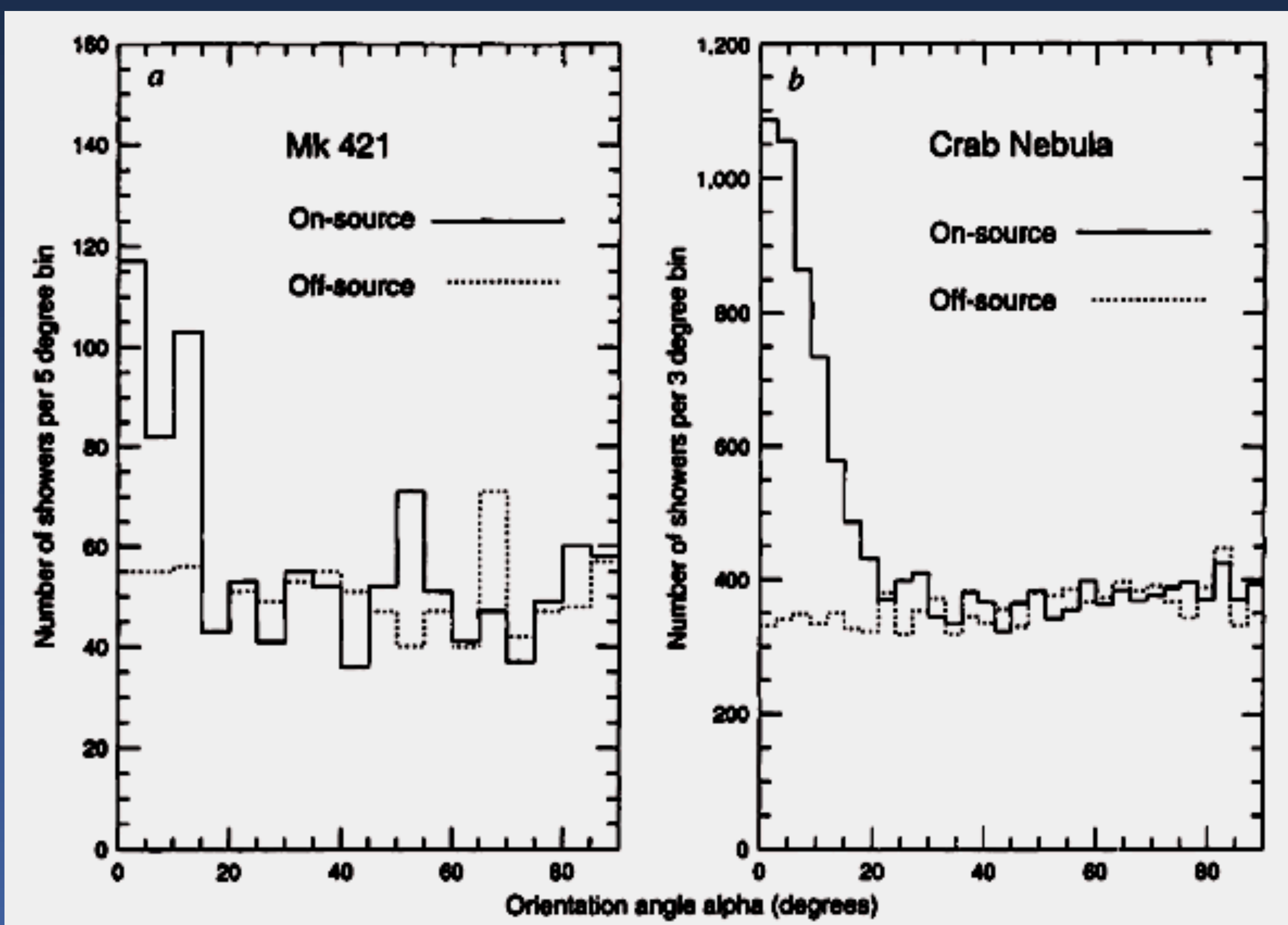
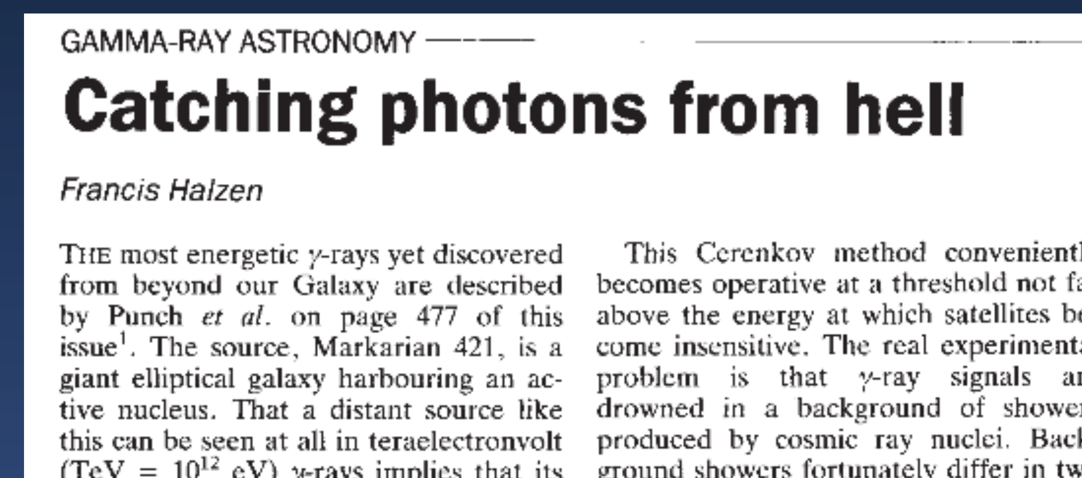


Punch et al., 1992



GAMMA-RAY ASTRONOMY

Catching photons from hell

Francis Halzen

THE most energetic γ-rays yet discovered from beyond our Galaxy are described by Punch *et al.* on page 477 of this issue[1]. The source, Markarian 421, is a giant elliptical galaxy harbouring an active nucleus. That a distant source like this can be seen at all in teraelectronvolt (TeV = 10^{12} eV) γ-rays implies that its

This Cerenkov method conveniently becomes operative at a threshold not far above the energy at which satellites become insensitive. The real experimental problem is that γ-ray signals are drowned in a background of showers produced by cosmic ray nuclei. Background showers fortunately differ in two

Halzen, 1992

EGRET AGN

NASA's Compton Gamma-Ray Observatory, April 1991 - June 2000

EGRET (100 MeV to ~1 GeV) onboard CGRO ultimately detected 93 AGN.

IAU Circular in March 1992 announcing detection of Mrk 421 with EGRET (Michelson et al., 1992)

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- **Whipple detection of Markarian 421 significant because:**
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  - Markarian 421 is a very bright X-ray source.
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  - Markarian 421 is the closest blazar.

- 1992-1995 Whipple Collaboration targeted 35 AGN, 15 of which had EGRET detections, but with no new detections (e.g. Kerrick et al.,1995).

1993: Markarian 421?

1992

Out of the Darkness

Discovery of Markarian 421

Who:

Whipple

Punch et al. 1992, Nature, 358, 477

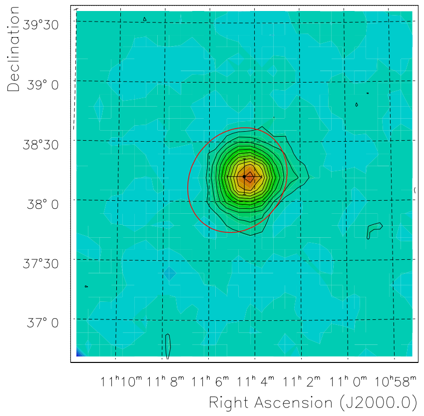
What:

Flux at E>500 GeV ≈ 0.3 Crab

EGRET source

X-ray selected BL Lac Object

$z = 0.031$ (closest BL Lac)



Slides courtesy Mike Catanese

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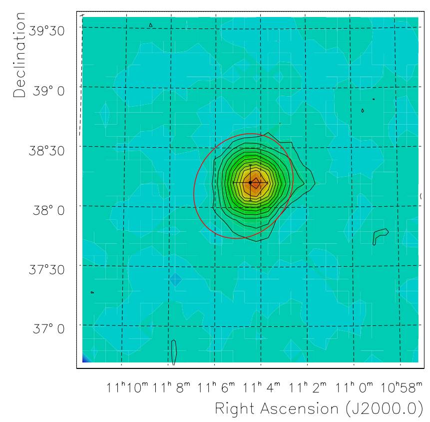


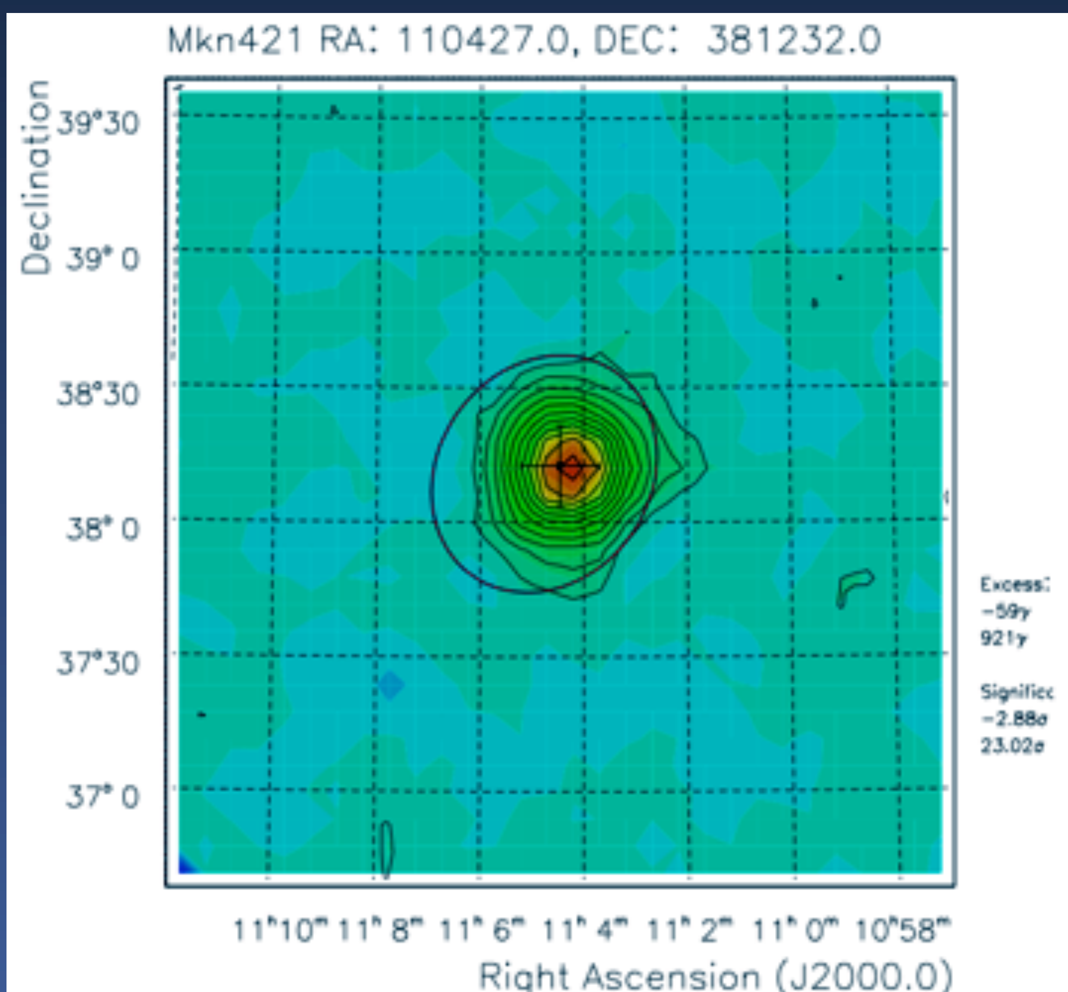
1993

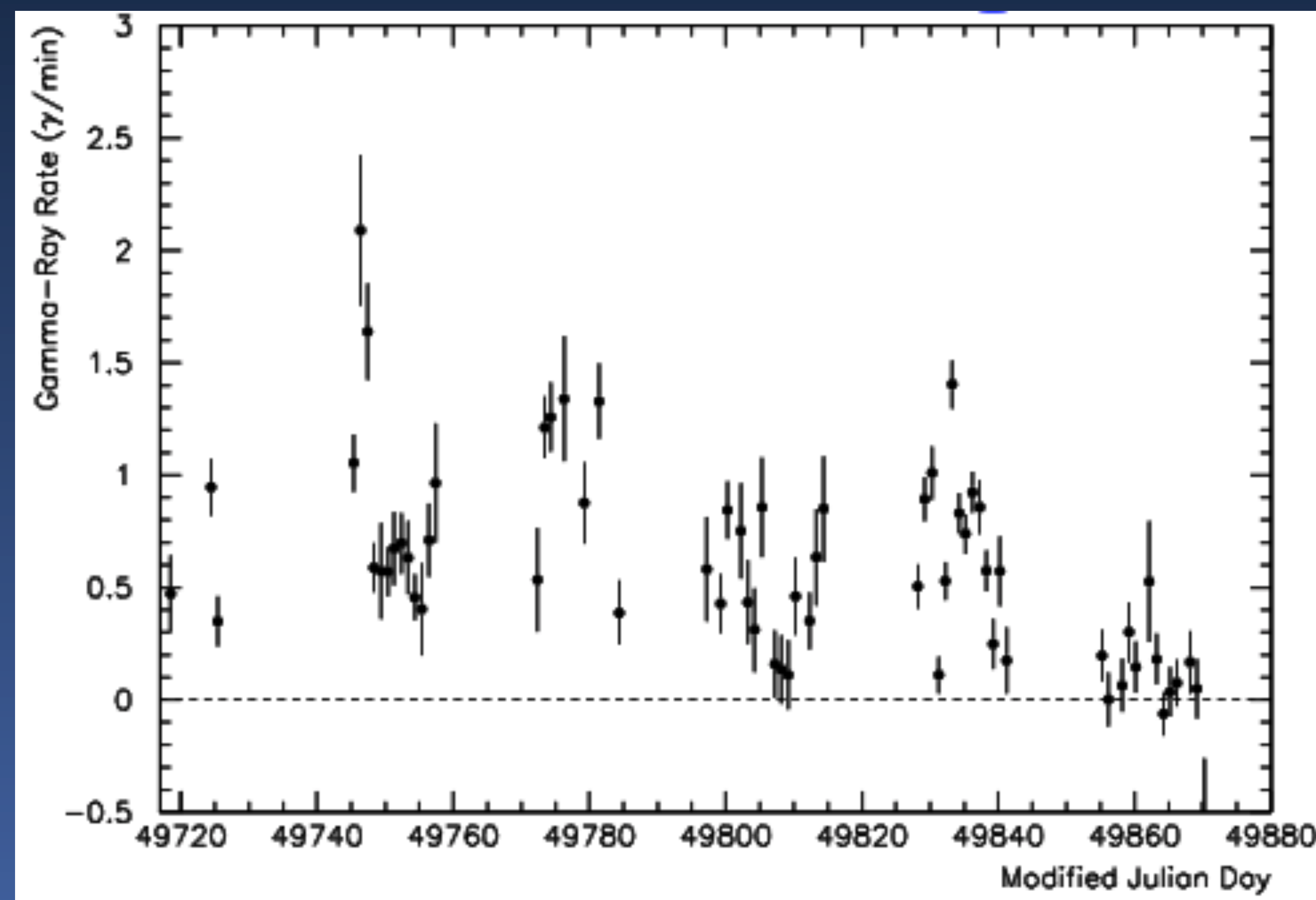
The Valley of Despair

Slides courtesy Mike Catanese

1994-1995: Markarian 421

- Markarian 421 detected again.
- Confirmation of TeV emission by HEGRA (Petry et al., 1996)
- Highly variable emission: day-scale flares and periods below the sensitivity of the telescope.

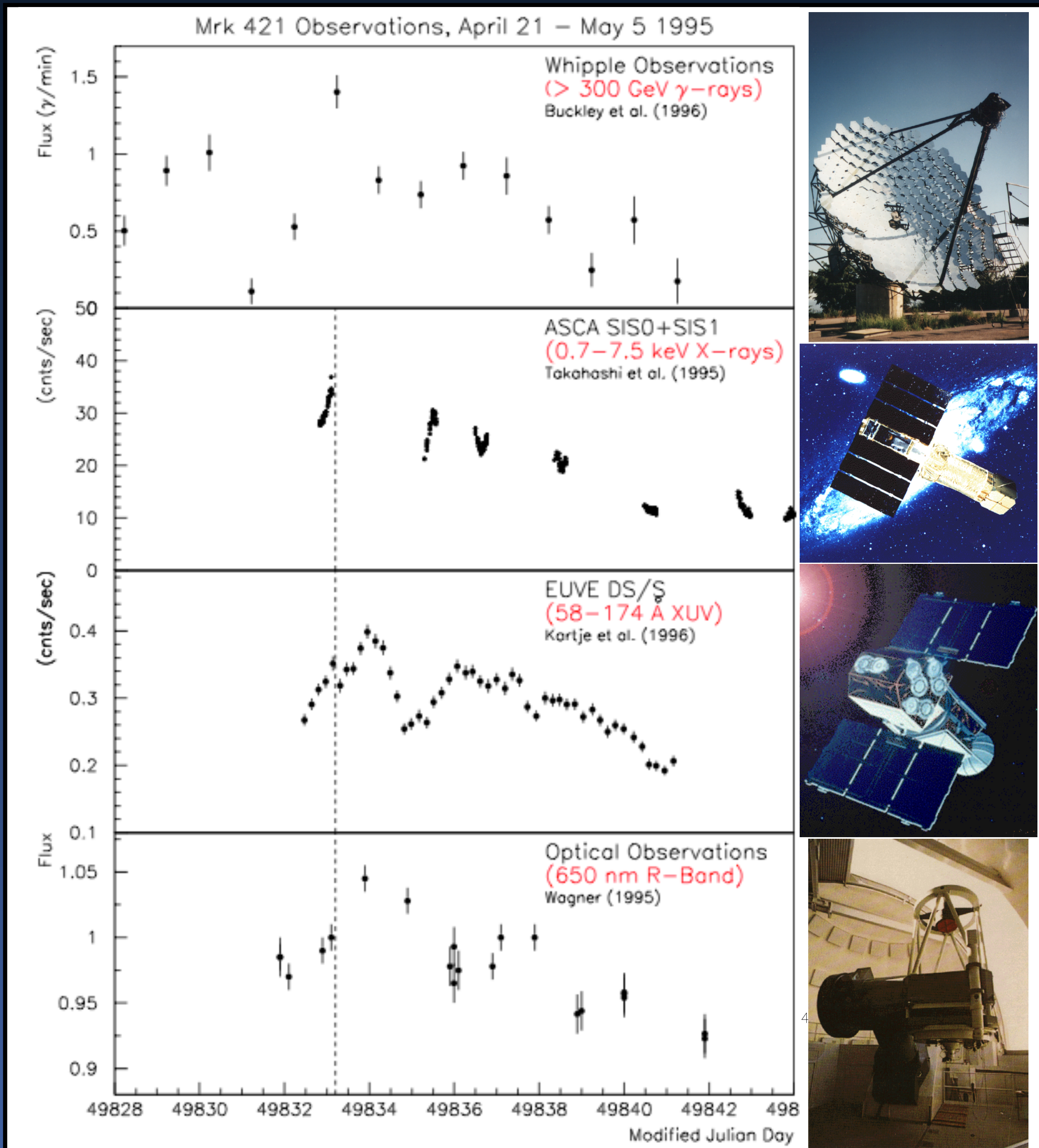




Buckley, et al., 1996

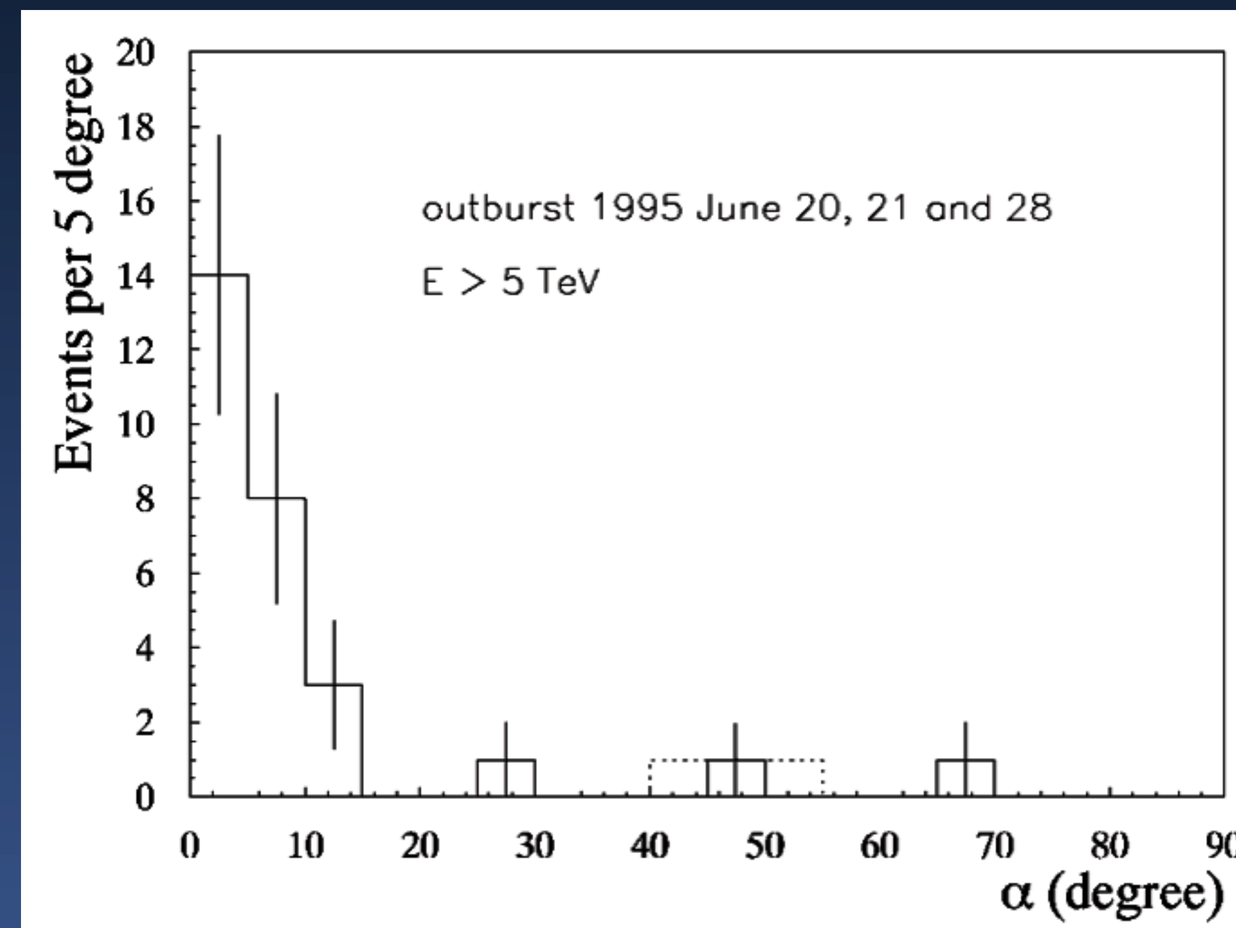
1994-1995: Markarian 421

First multi-wavelength campaigns...



Buckley, et al., 1996

Use of Large Zenith Angle technique to extend the spectral range beyond 5 TeV.



Krennrich, et al., 1997

1995: Markarian 501 through the drizzle

- Observing program expanded to target nearby, X-ray bright blazars not necessarily detected by EGRET

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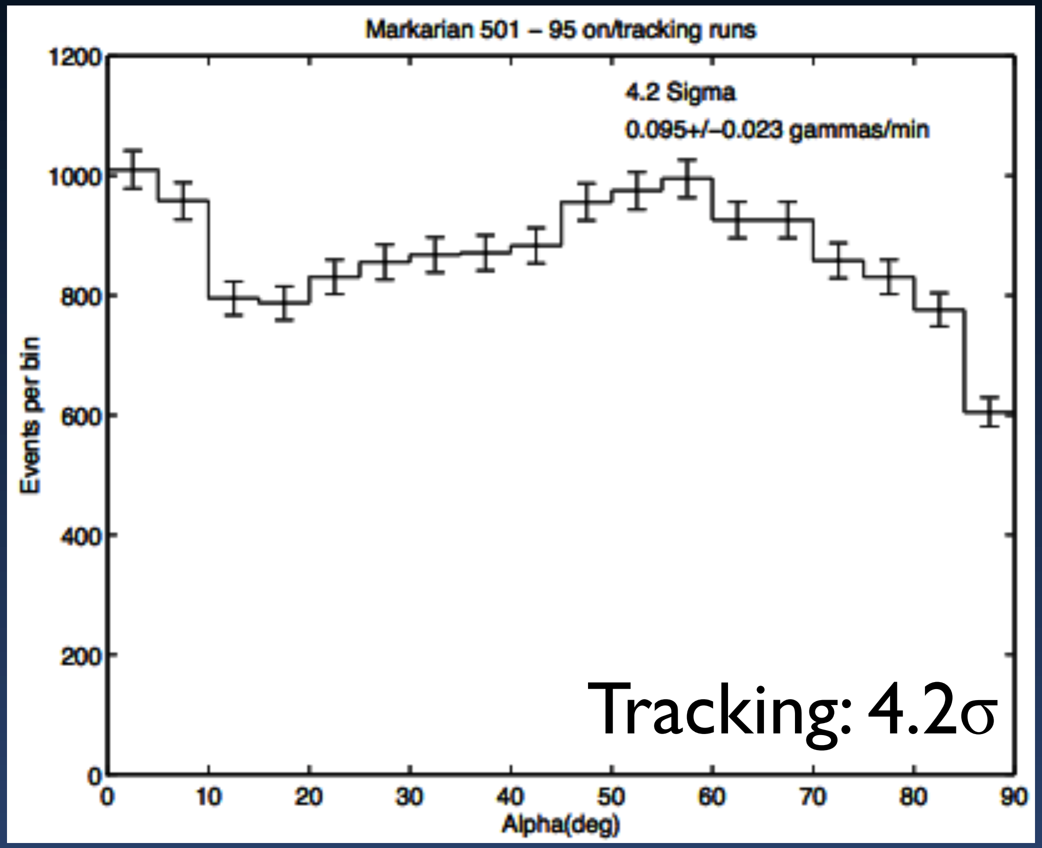
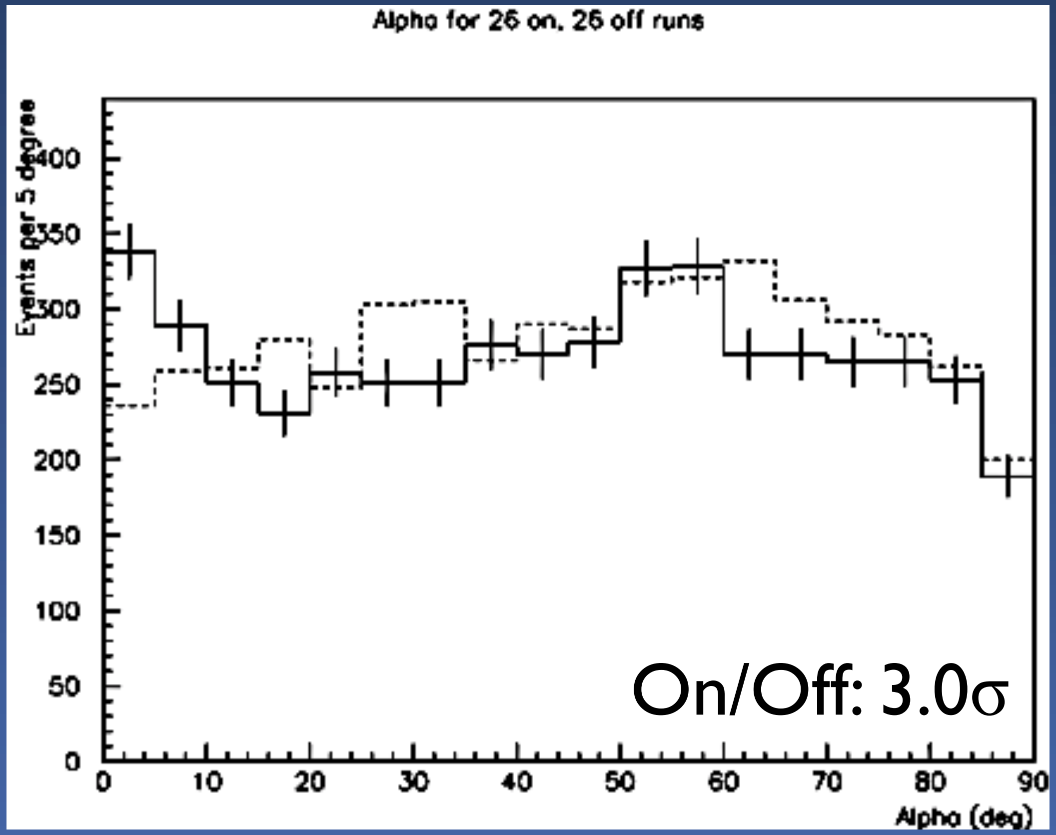
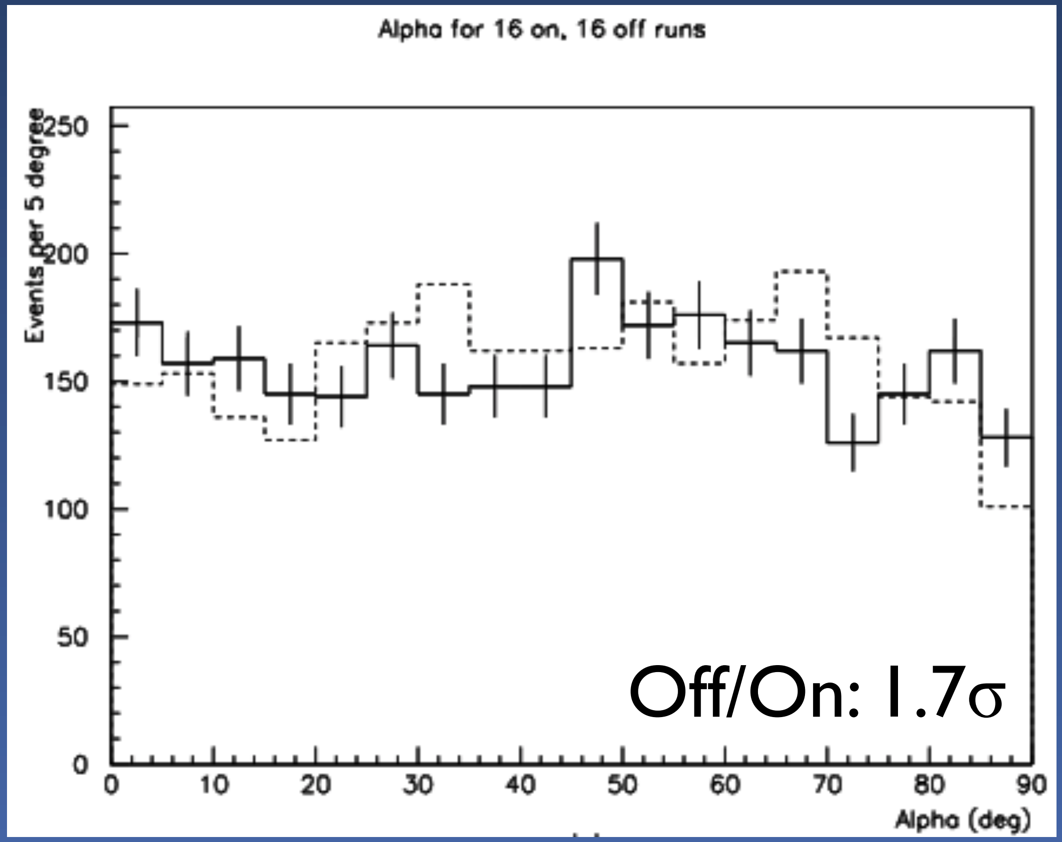






1995: Markarian 501 detected

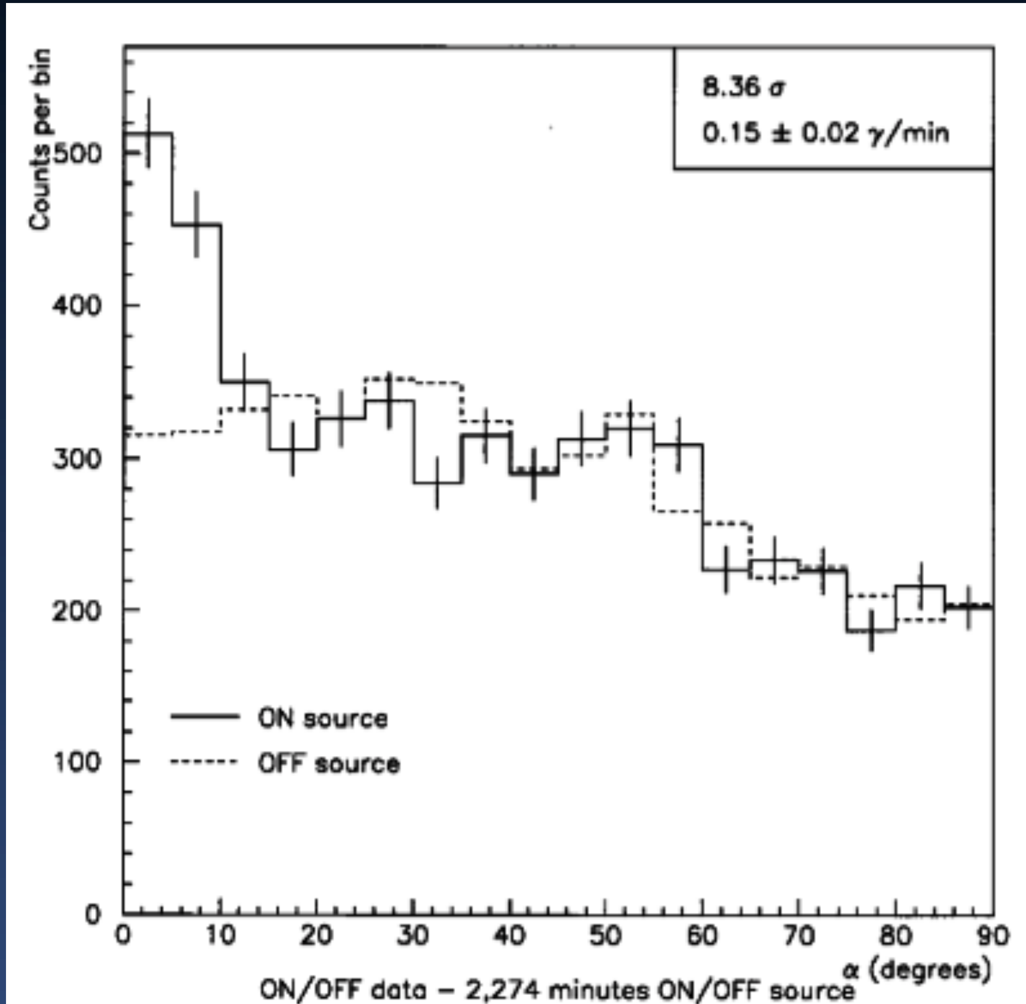


FIG. 2.—α plot of 37.9 hr of ON and OFF data on Mrk 501

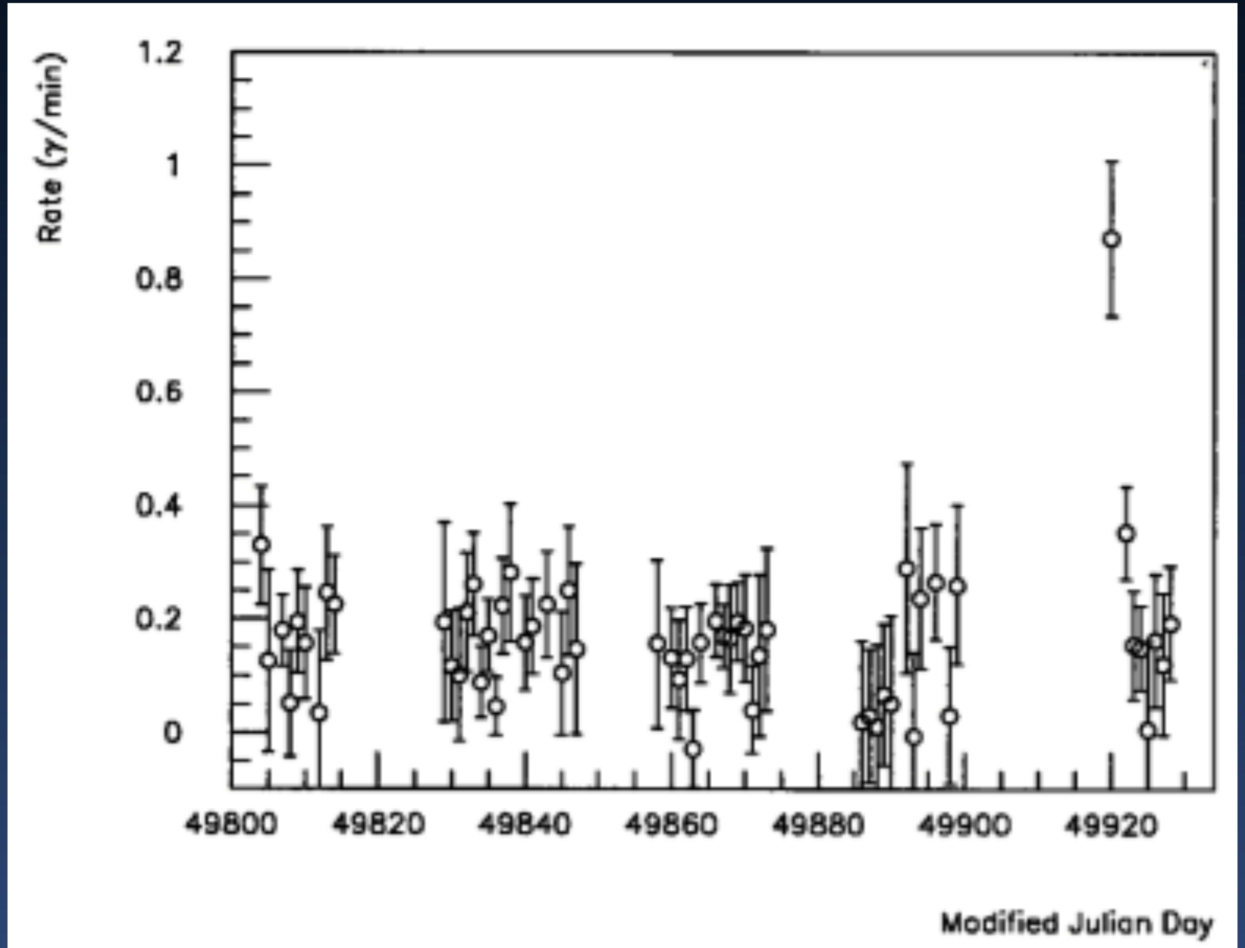
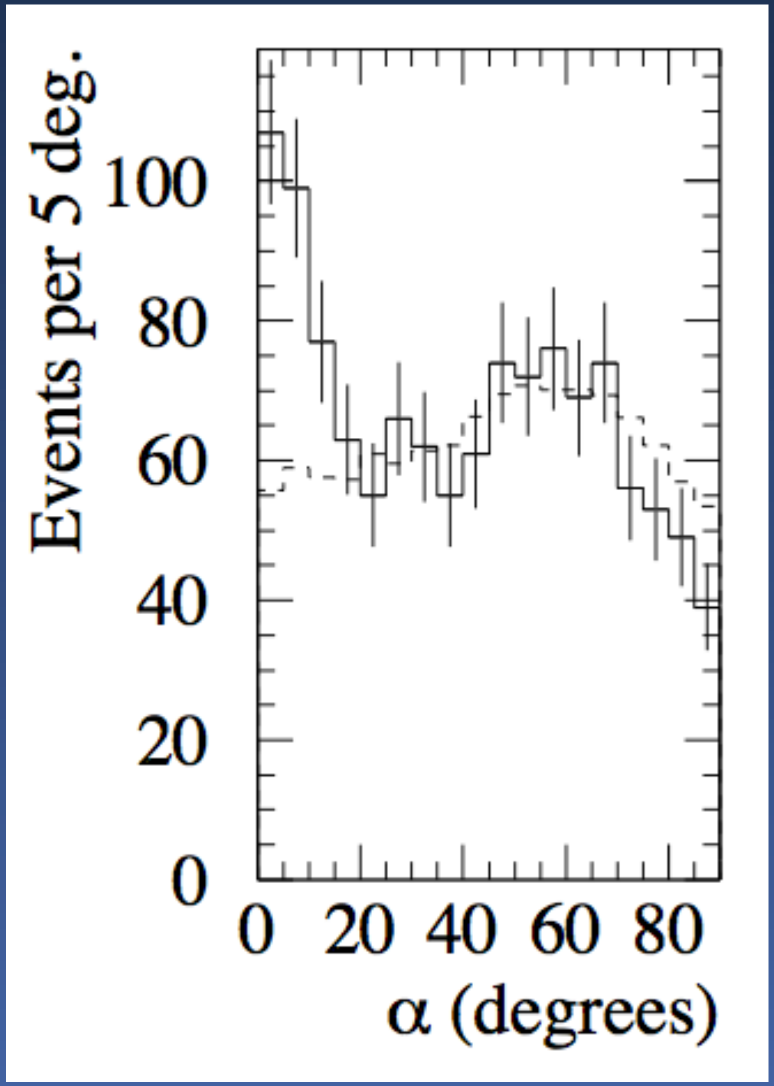


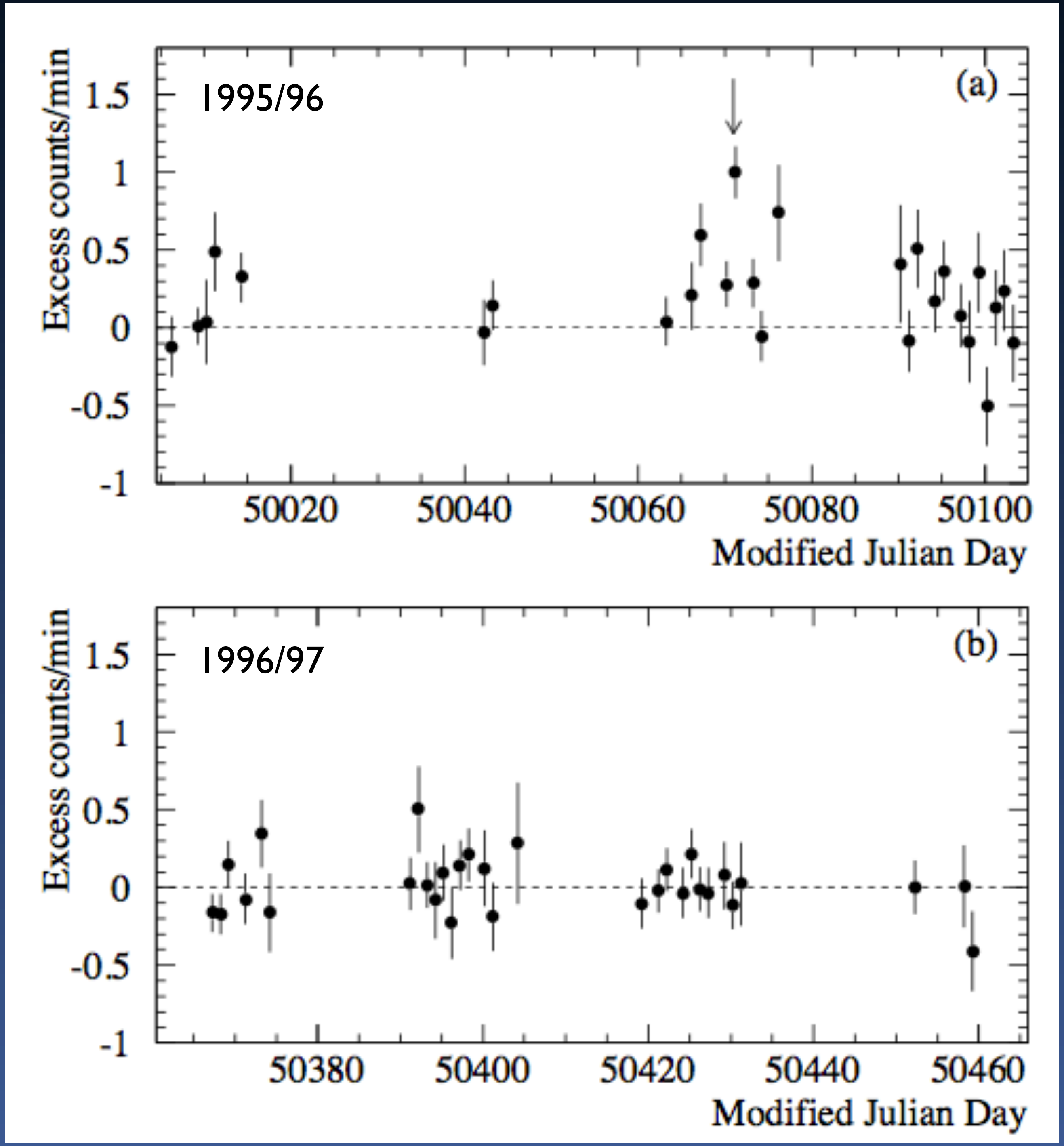
FIG. 3.—Daily gamma-ray rates from Mrk 501; all rates are based on the ON or tracking observations only, and the error bars are increased accordingly.

- Detected at 8σ (*On/Off,* 38 hr) and 9σ (*Tracking,* 31 hr) (Quinn et al., 1996)
- Steady (average flux ~8% that of the Crab nebula) - apart from one night.
- 2nd closest BL Lac.
- Not an EGRET source at the time - detection came later (Kataoka et al., 1999)
  - first extragalactic gamma-ray source discovered from the ground.
- Confirmation by HEGRA (Bradbury et al., 1996)

1995-1997: 1ES 2344+514

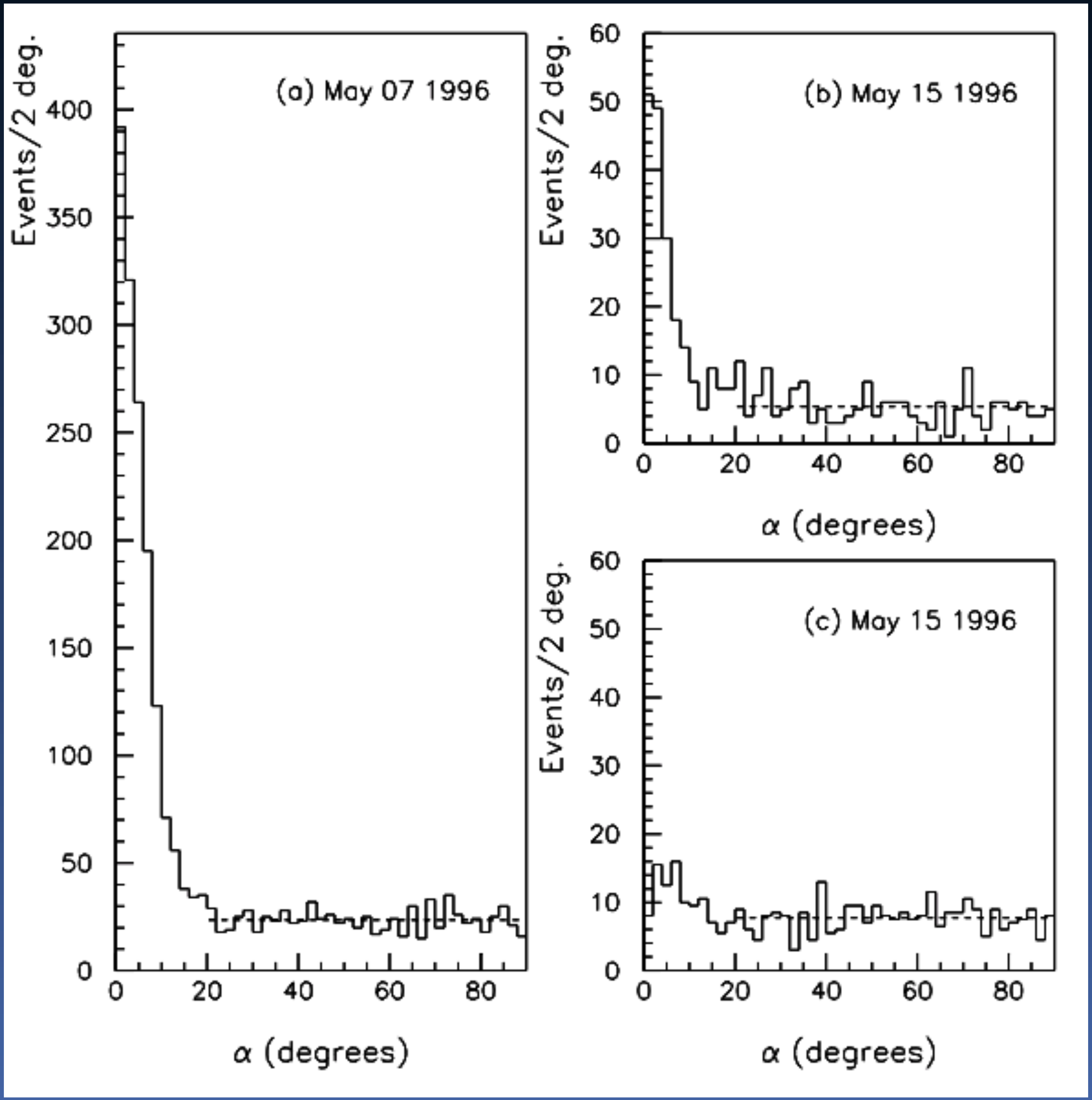
- 2nd success of new strategy
- Not an EGRET source
- Signal primarily from one flare night. (6σ, 60% Crab flux)
- 3rd closest blazar.





Catanese et al., 1998

1996: The Most Violent Place in the Universe

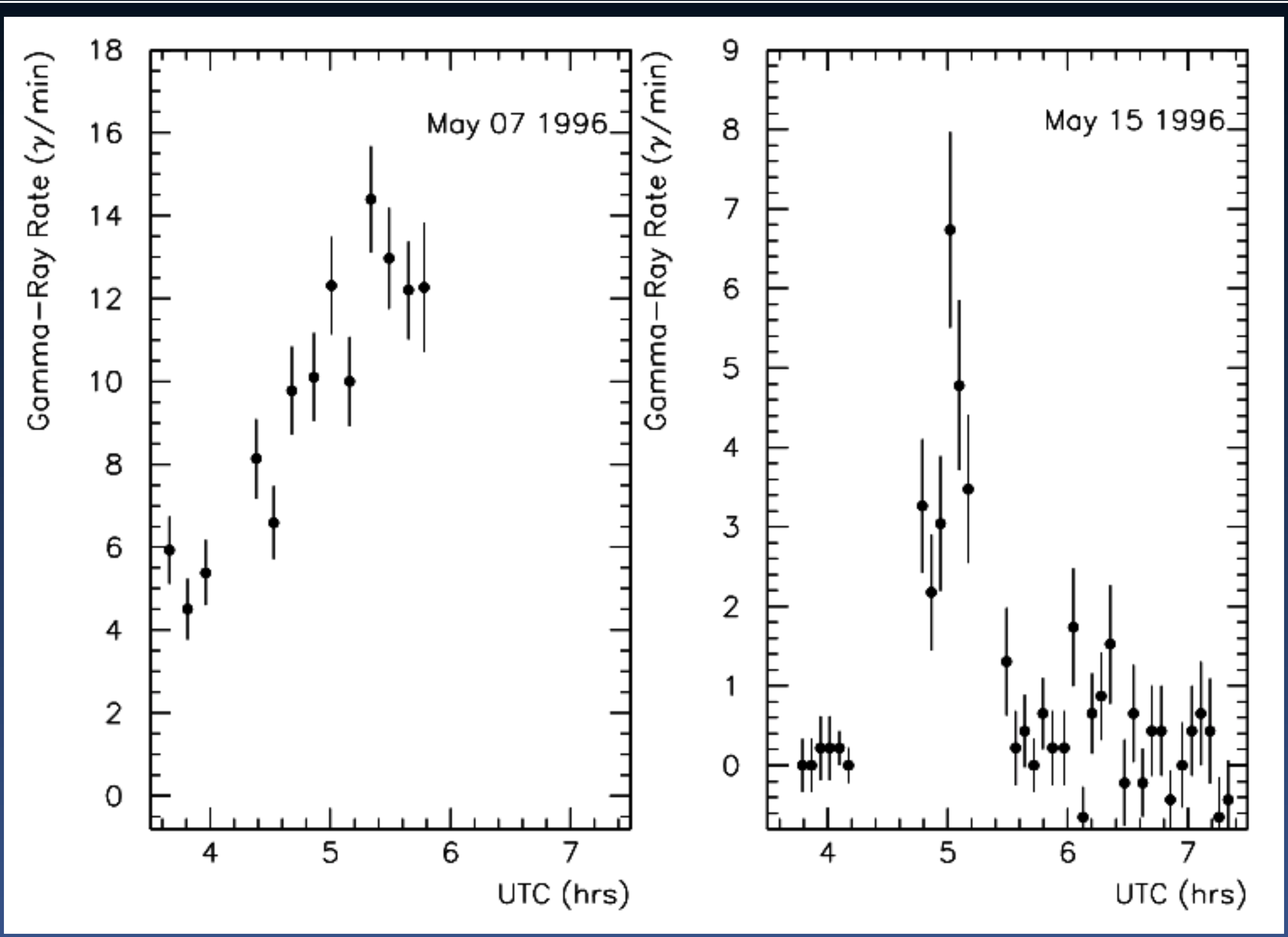


Markarian 421 extreme flares:

- May 7th:
  - flux reaches 10 Crab
  - 56σ in 2hrs
- May 15th:
  - flux reaches 5 Crab.

Gaidos et al., 1996

1996: The Most Violent Place in the Universe



Gaidos et al., 1996

- May 7th - doubles in ~30 mins (peak at 50x its quiescent state)
- May 15th - from 0 to 25x its quiescent state and back again in 30 mins.
- Implication: relativistically boosted (δ>10) and compact emission region (<10 light hours)
- May 7th flare witnessed by distinguished guests...

1996: The Most Violent Place in the Universe

Eur. Phys. J. H **37**, 459–513 (2012)
DOI: 10.1140/epjh/e2012-30016-x

THE EUROPEAN PHYSICAL JOURNAL H

Very-high energy gamma-ray astronomy

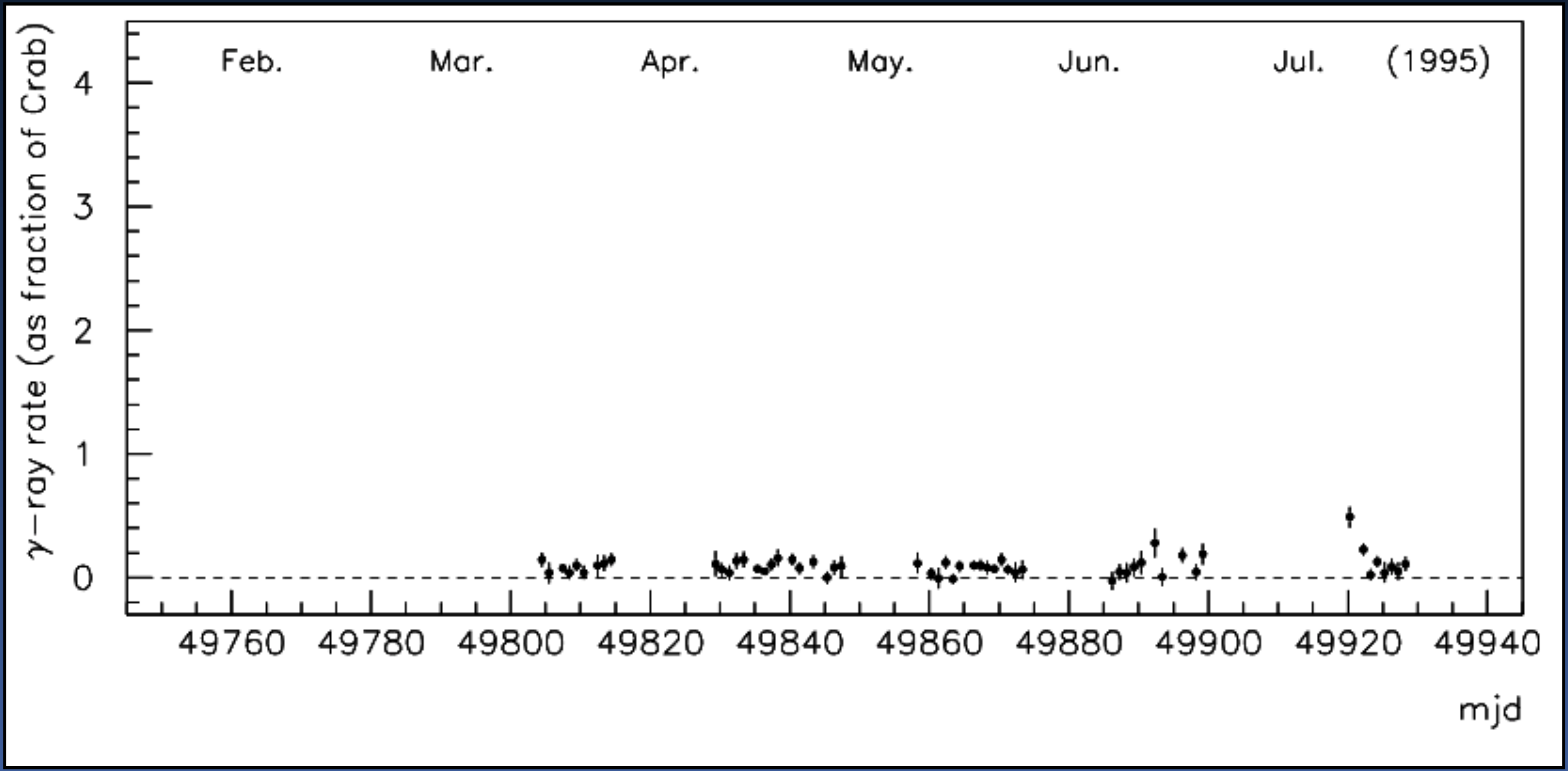
A 23-year success story in high-energy astroparticle physics

E. Lorenz[1] and R. Wagner[1,2,a]

5.6 A huge flare from Markarian 421 – a personal episode

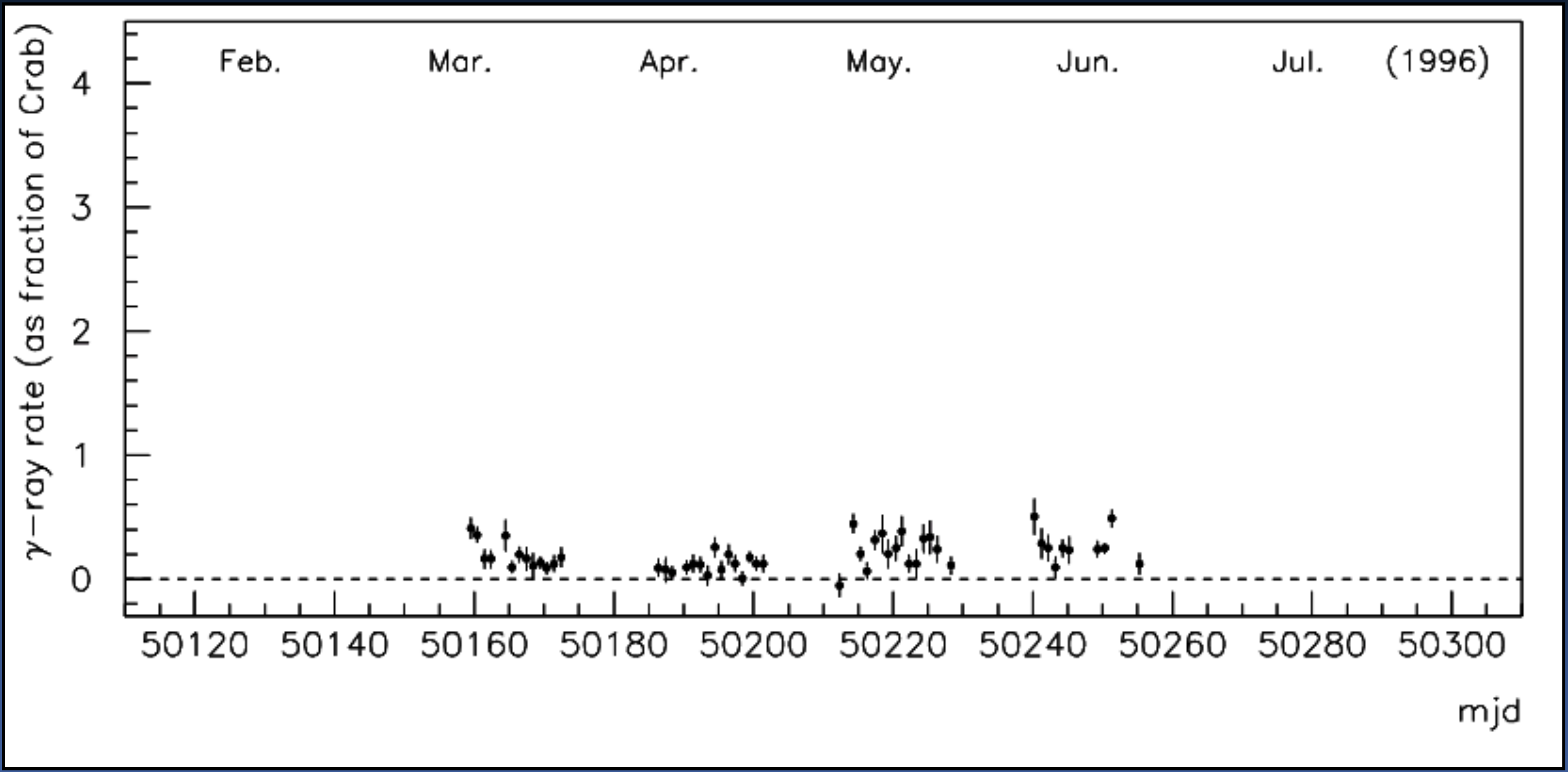
In spring 1996, one of us (E.L.) participated in the meeting of the High-Energy Astrophysics Division of the American Astronomical Society in San Diego. Also, Tadashi Kifune was attending. We both asked Trevor Weekes if we could visit the Whipple telescope and see it in operation on our way back after the conference. On May 7 we were at the site. As it was nearly full moon only about one hour of observation time was possible. The students were not very excited to switch on all the necessary instruments for such a short observation time. Nevertheless, Trevor convinced his team to start observations with the telescope, which was then pointed towards Mkn 421. Very surprisingly, the online display events looked mostly like perfect and clean γ-showers occurring at high rate. Normally one would expect that nearly all events to be from hadronic showers, zipping across the camera in all directions, but nearly never pointing to the reference position of Mkn 421 in the camera. I even suspected that the students had decided to show the visitors just Monte-Carlo events of gamma-showers. In order to clarify the situation the data were transmitted via computer link to Ireland and immediately processed. A few minutes later the so-called ALPHA plot (cf. Fig. 9) was sent back showing a huge signal of more than 10-σ excess for 20 minutes of

1995 - 1997: Markarian 501



Quinn et al., 1999

1995 - 1997: Markarian 501



Quinn et al., 1999

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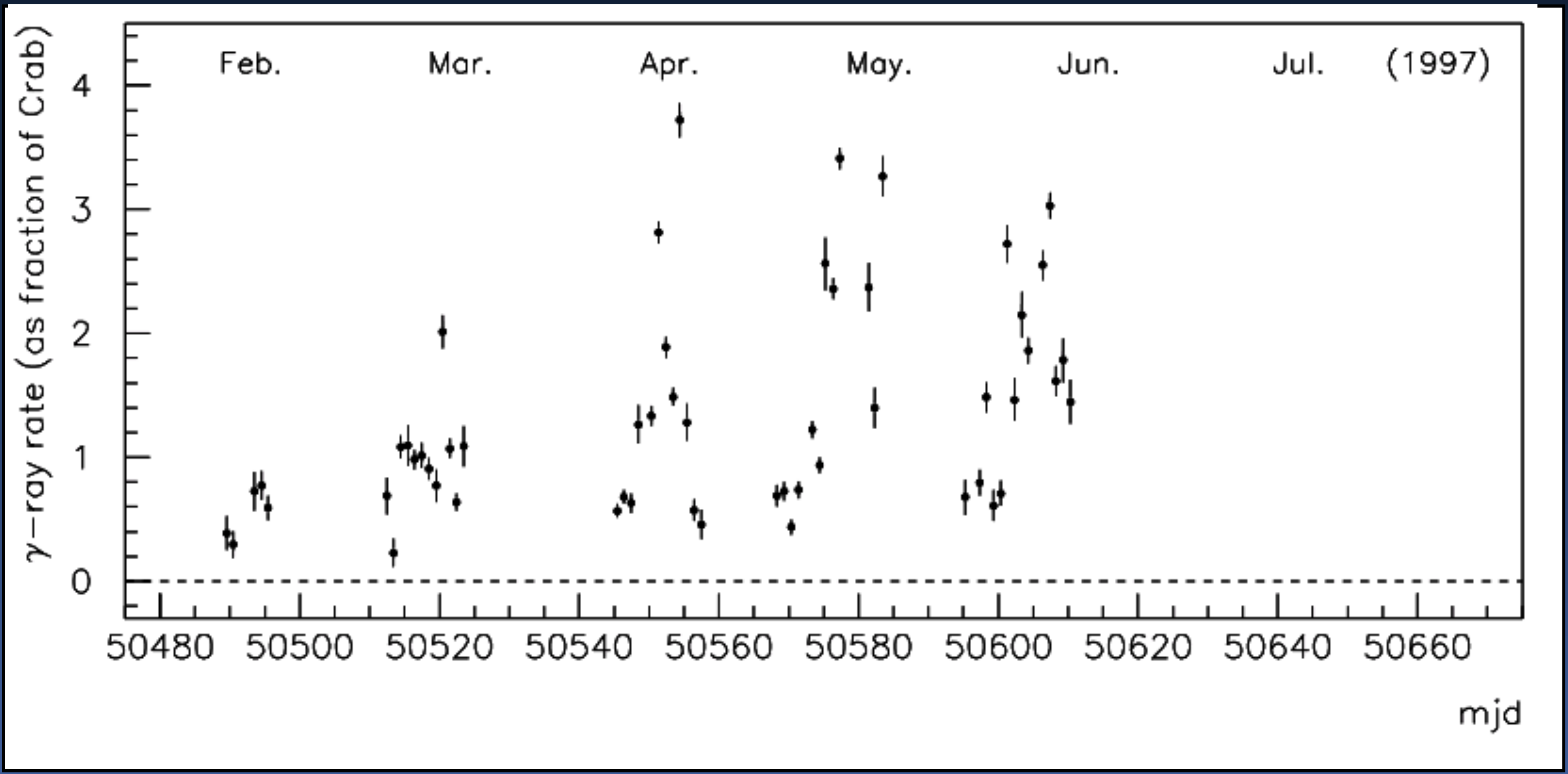

Quinn et al., 1999

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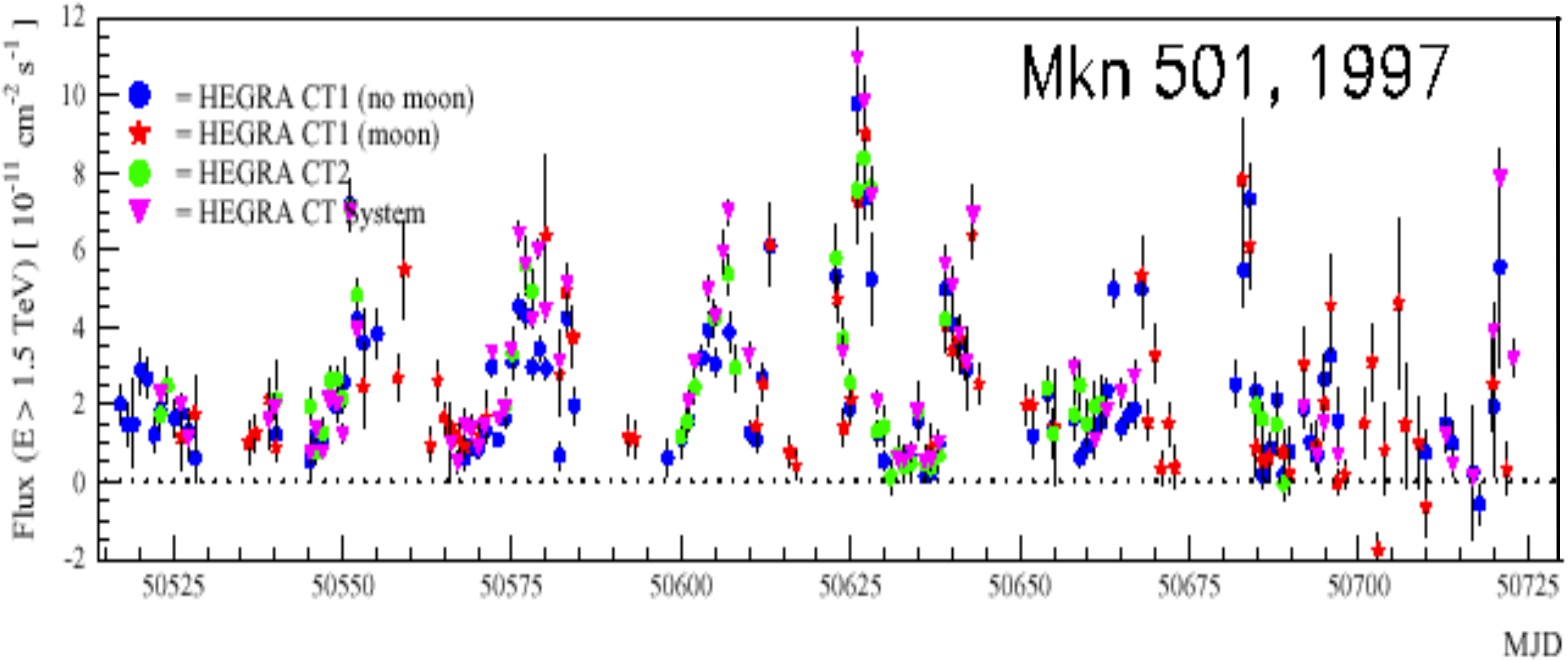
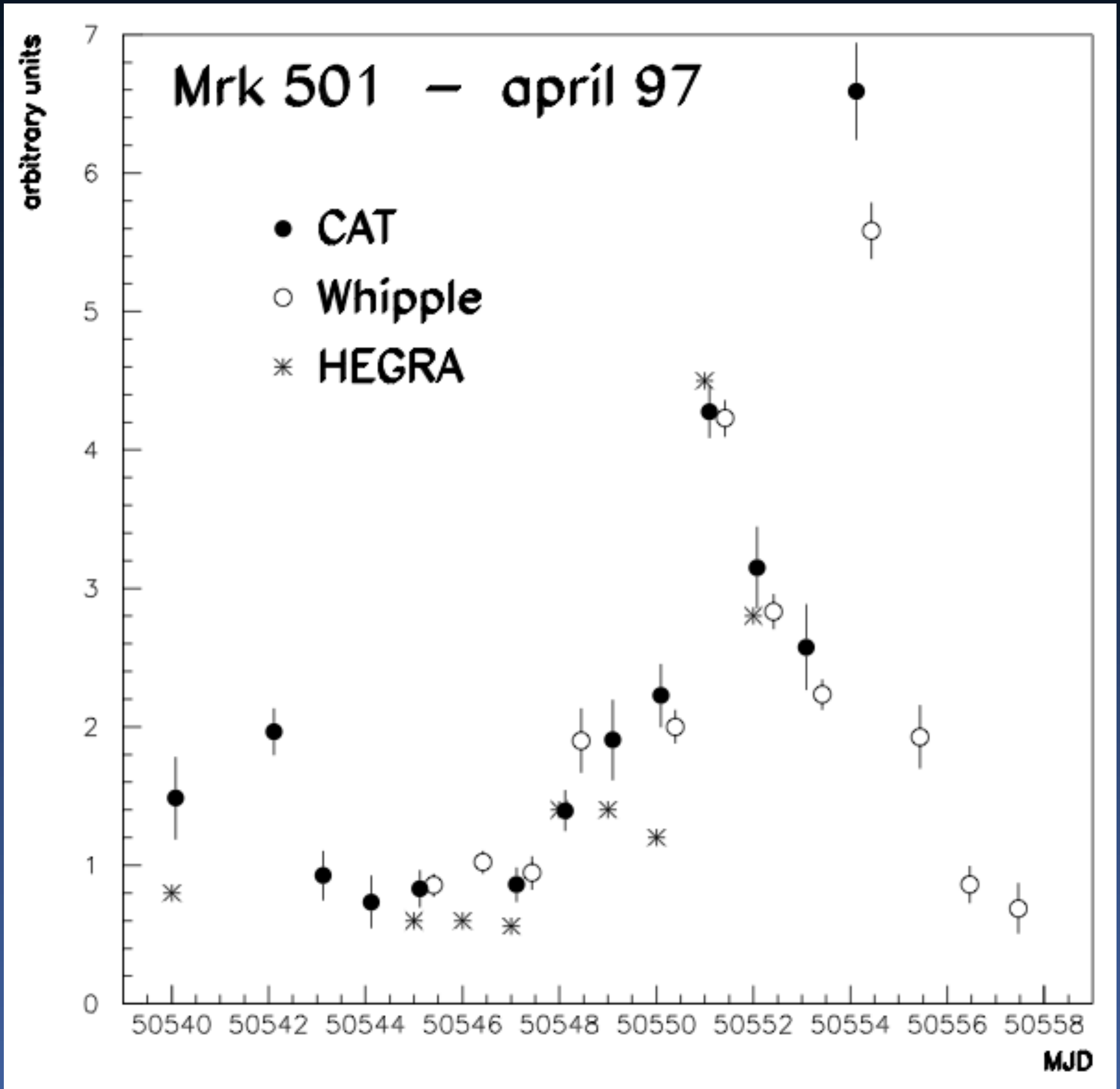


Markarian 501,
(Kranich et al., 1999)

1997: Markarian 501



Protheroe et al., 1997

Detections by:

- CAT (Punch, 1997)
- the Telescope Array Project (Hayashida et al. , 1998)
- TACTIC (Bhat, 1997)

1997: Markarian 501

- Spectrum to >10 TeV

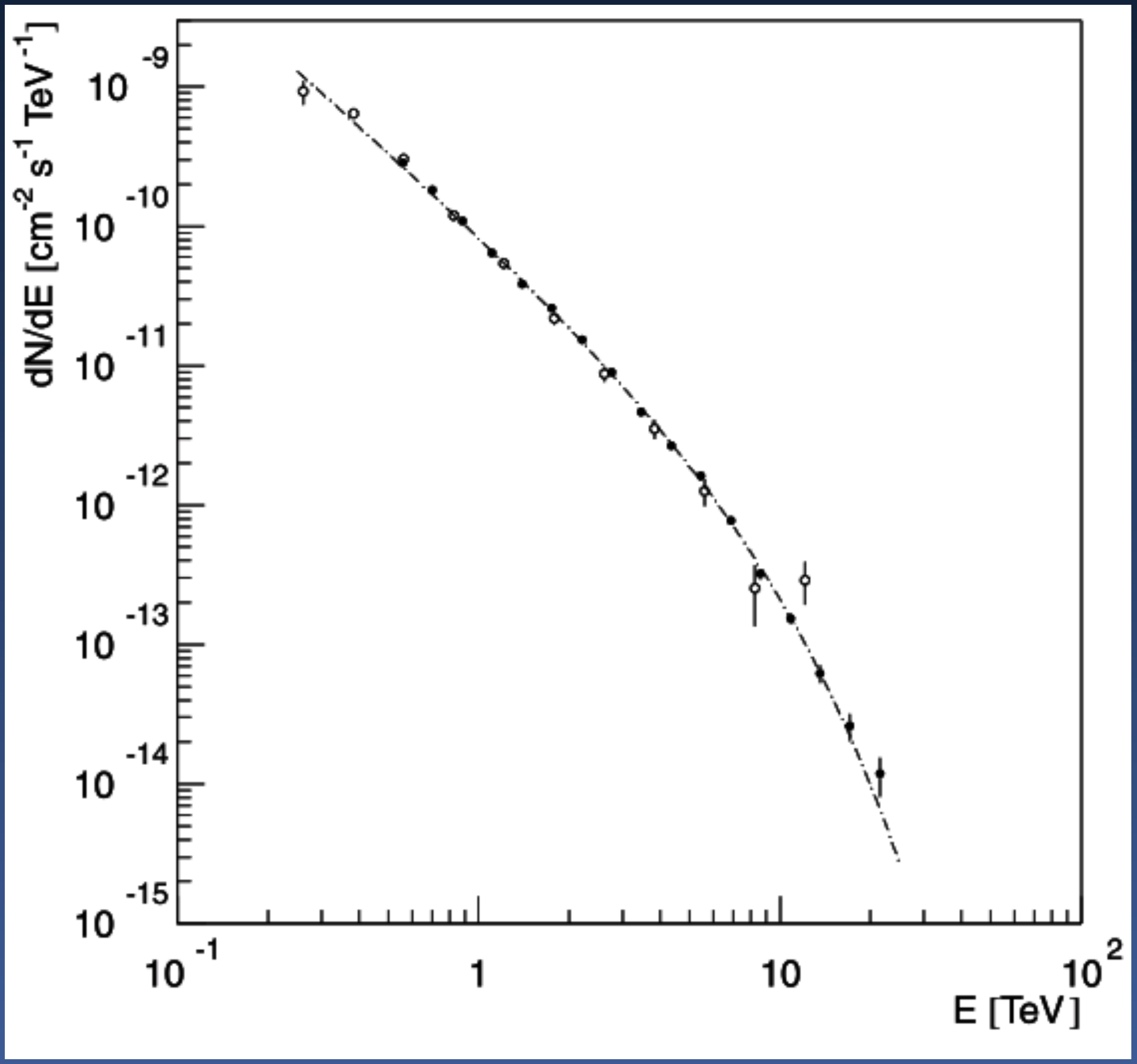
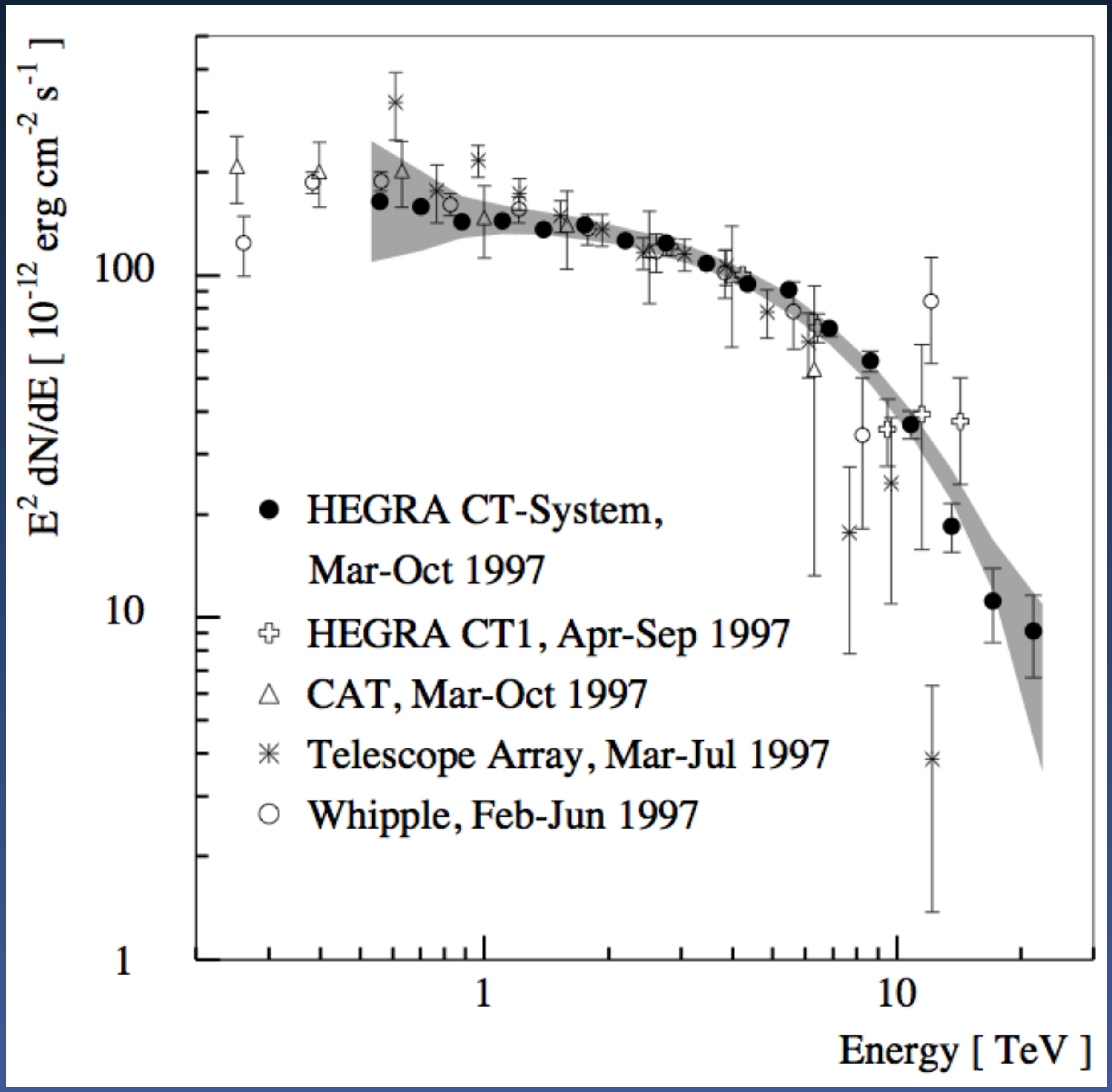
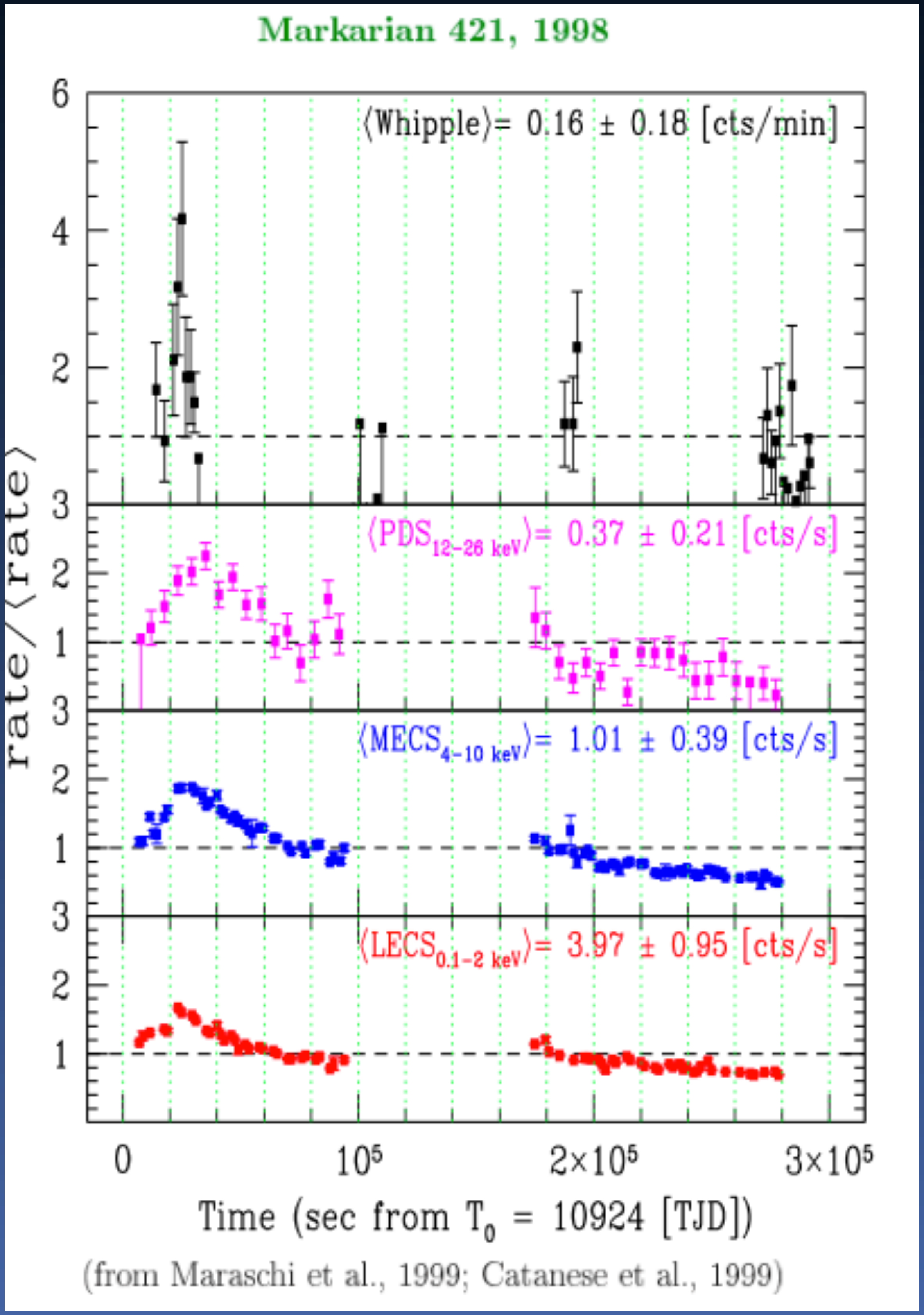


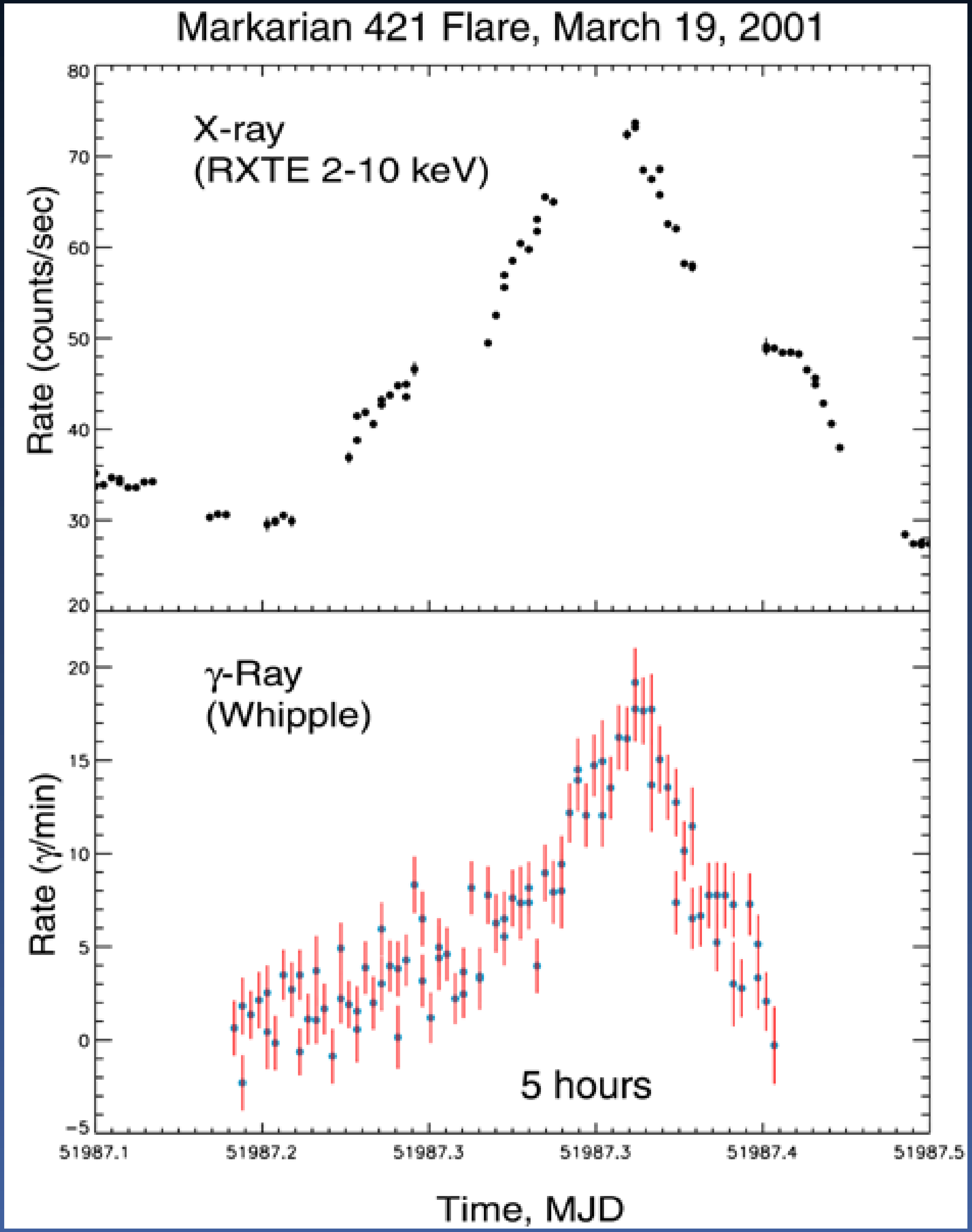
figure from Konopelko, 1999:
• Whipple points (open circles) from Krennrich et al, 1999,
• HEGRA points (filled circles)



Aharonian et al, 1999

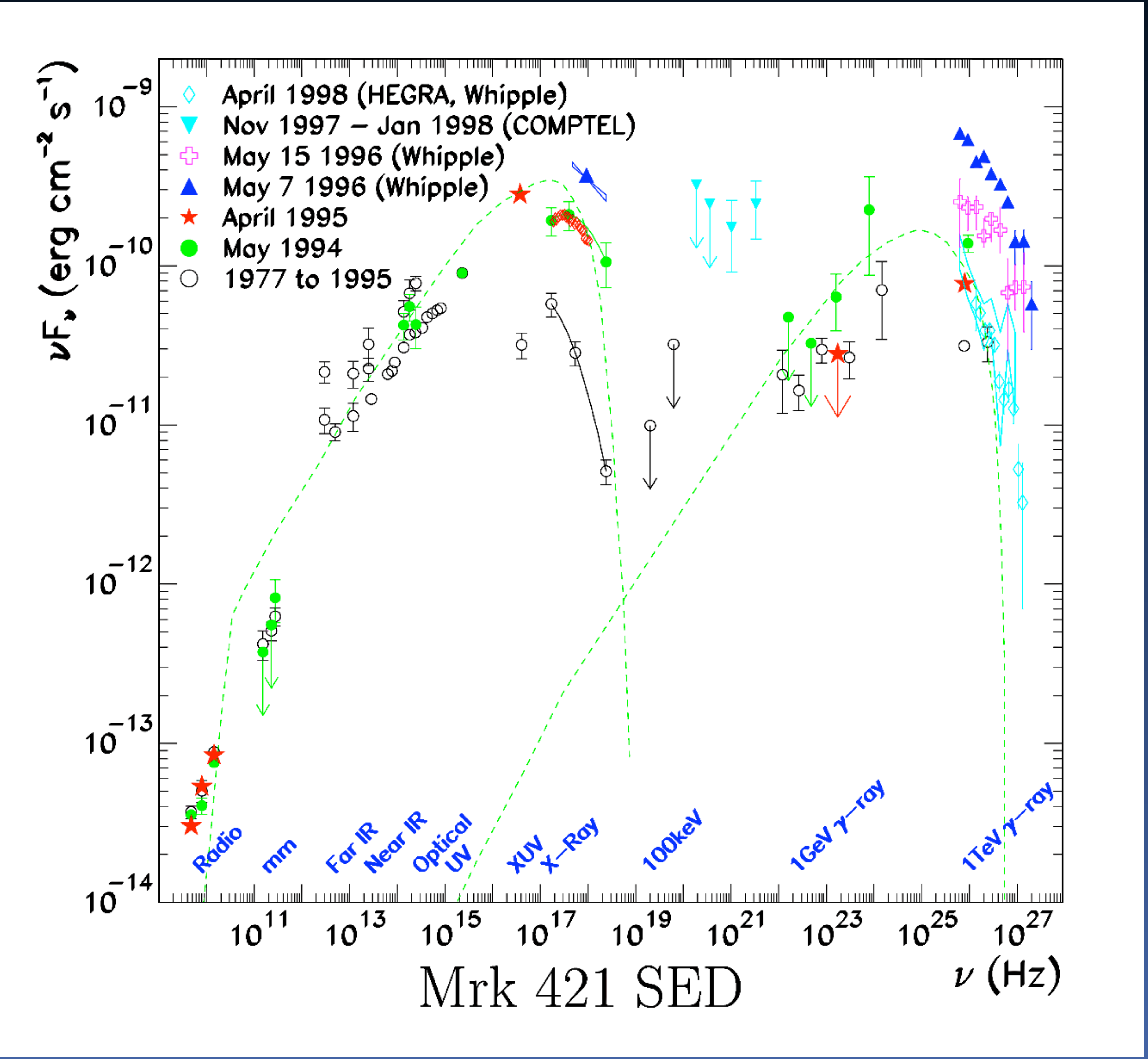
Markarian 421: Multiwavelength Variability



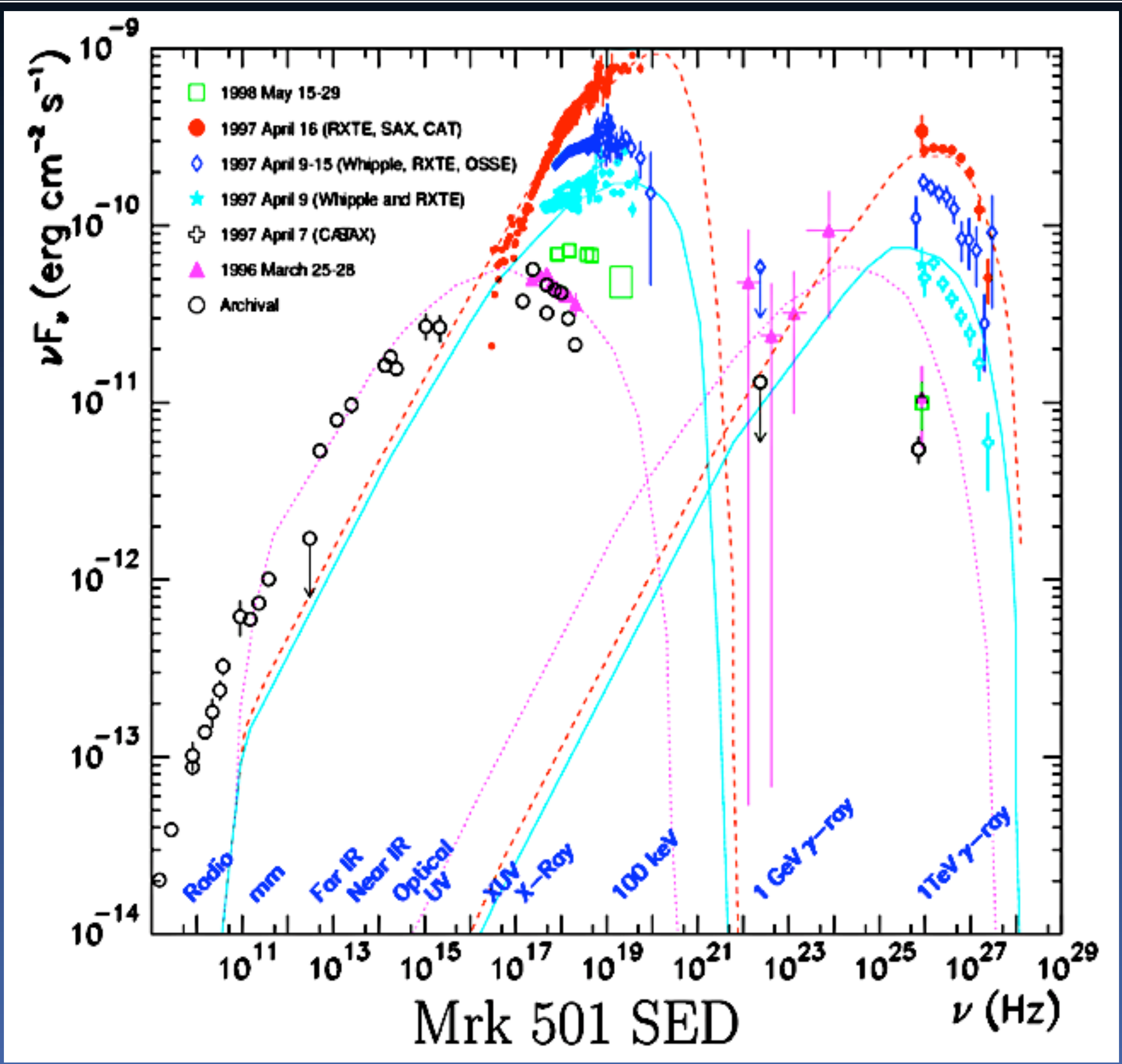


Jordan et al. ,2001

Markarian 421: Spectal Energy Distribution

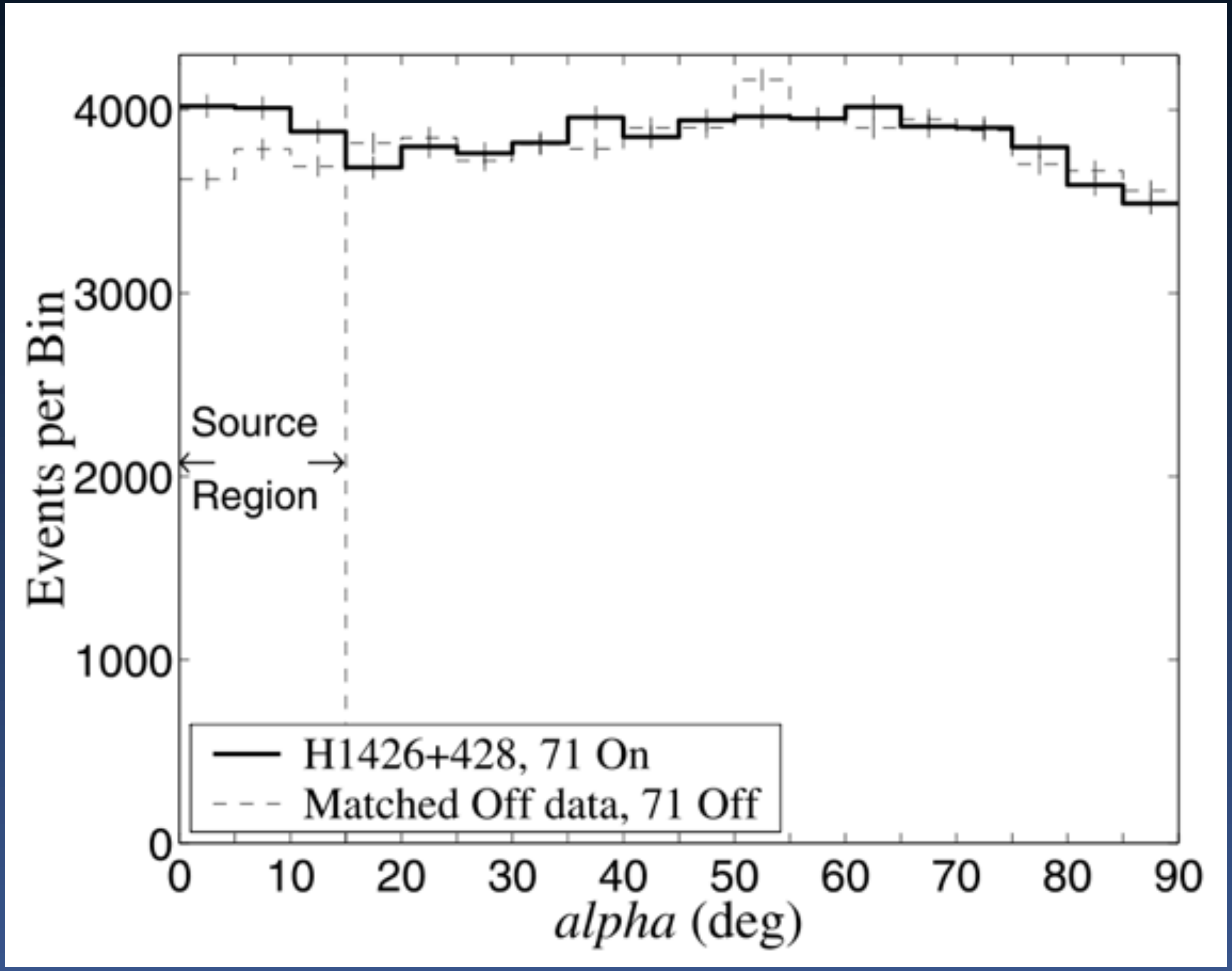


Markarian 501: SED - An Extreme Blazar



H1426+428

- Multi-year observations yielded small, consistently positive excess.
- 2000/2001 Whipple Observations motivated by Beppo-Sax X-ray observations that found 4 more Extreme Blazars (Costamante et al., 2000, 2001)
- Whipple detections at 3.3σ (2000) and 5.5σ (2001) levels.
- Flux max. at ~10% Crab.
- Spectrum steeper than Crab
- z=0.129: furthest yet.



Horan et al, 2002

The TeV Blazars c. 2002

TABLE 6

EXTRAGALACTIC TeV SOURCES (CATANESE & WEEKES 1999)

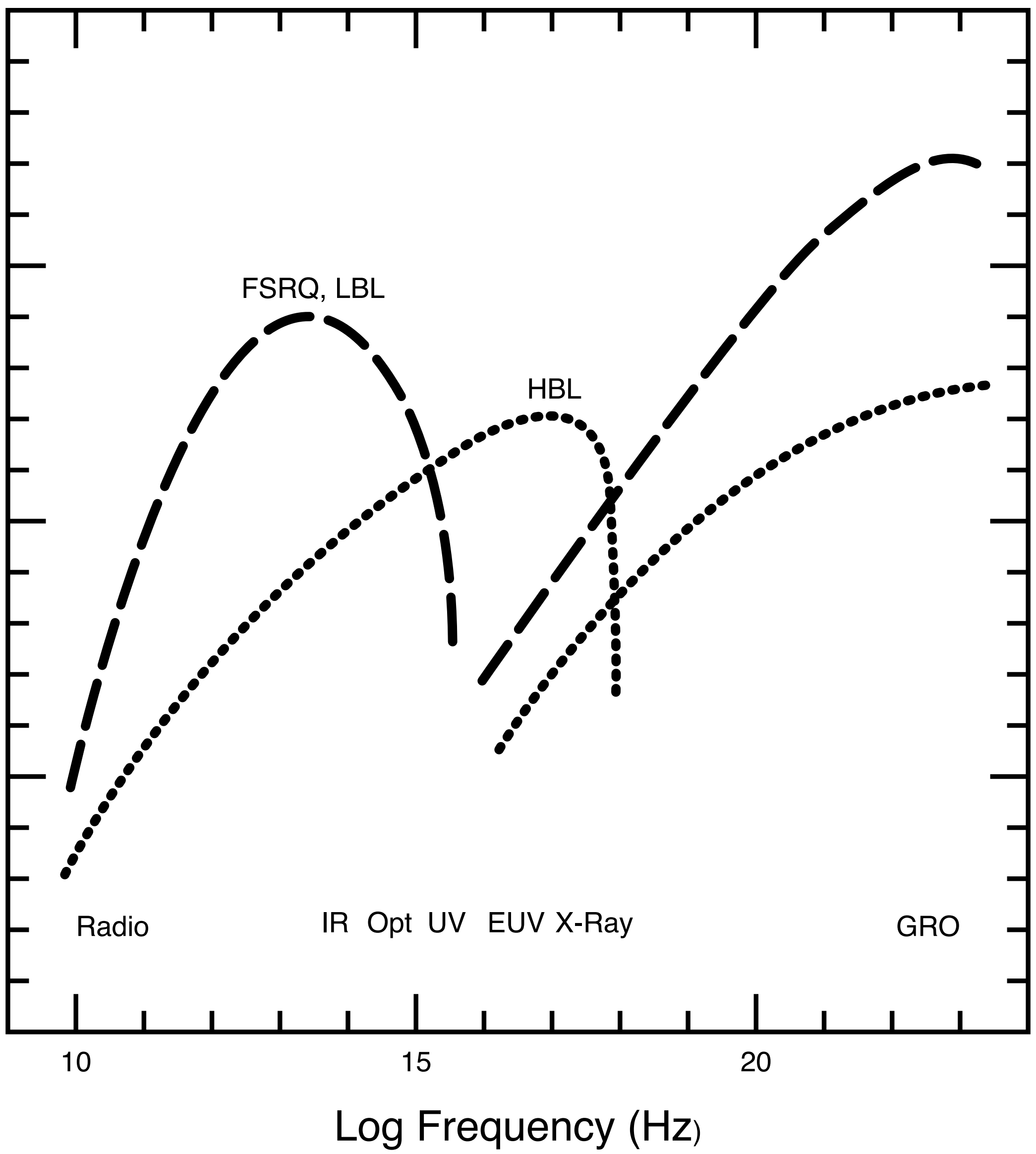
Source	Type	z	Discovery	Group	EGRET
Mrk 421	HBL	0.031	1992	Whipple[a]	yes
Mrk 501	HBL	0.034	1995	Whipple[b]	yes
1ES 2344 + 514	HBL	0.044	1997	Whipple[c]	no
1ES 1959 + 650	HBL	0.048	1999	Telescope Array[d]	no
PKS 2155-304	HBL	0.116	1999	Durham[e]	yes
H1426 + 428	HBL	0.129	2001	Whipple[f]	no
3C 66A..................	LBL	0.444	1998	Crimea[g]	yes
BL Lacertae	LBL	0.069	2001	Crimea[h]	yes

[a] Punch et al. 1992.
[b] Quinn et al. 1996.
[c] Catanese et al. 1998.
[d] Nishiyama et al. 2000.
[e] Chadwick et al. 1999.
[f] Horan et al. 2000, 2001a, 2001b.
[g] Neshpor et al. 1998.
[h] Neshpor et al. 2001.

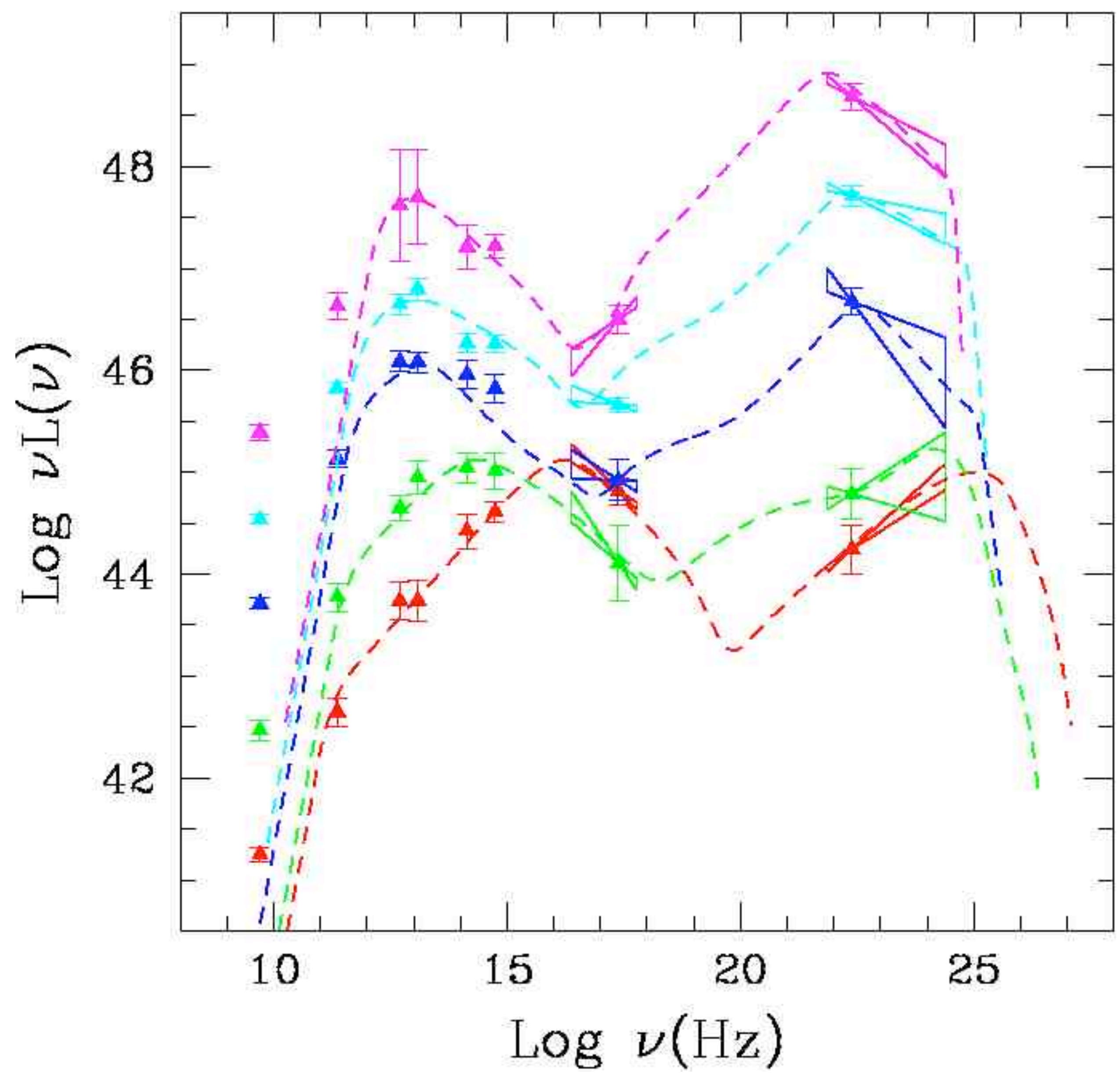
Horan (2002)

Blazar Classification

Two Types of Blazars?



SEDs of Blazars form a continuum

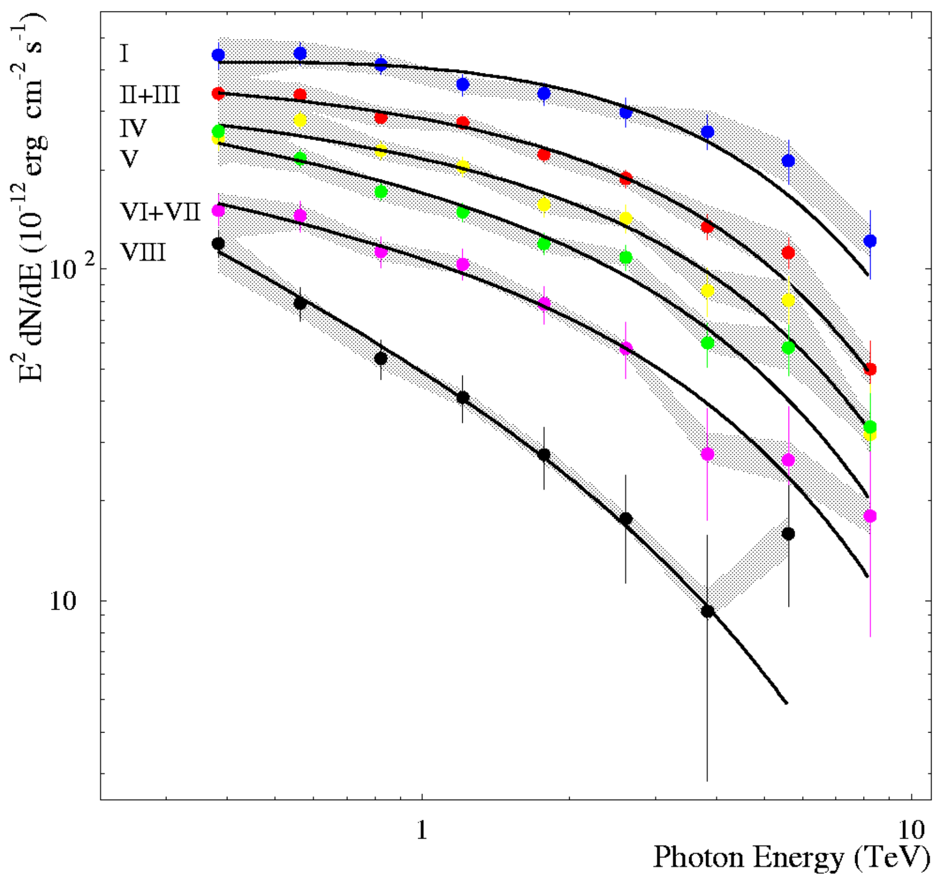


Urry, 1996

Donato et al., 2001

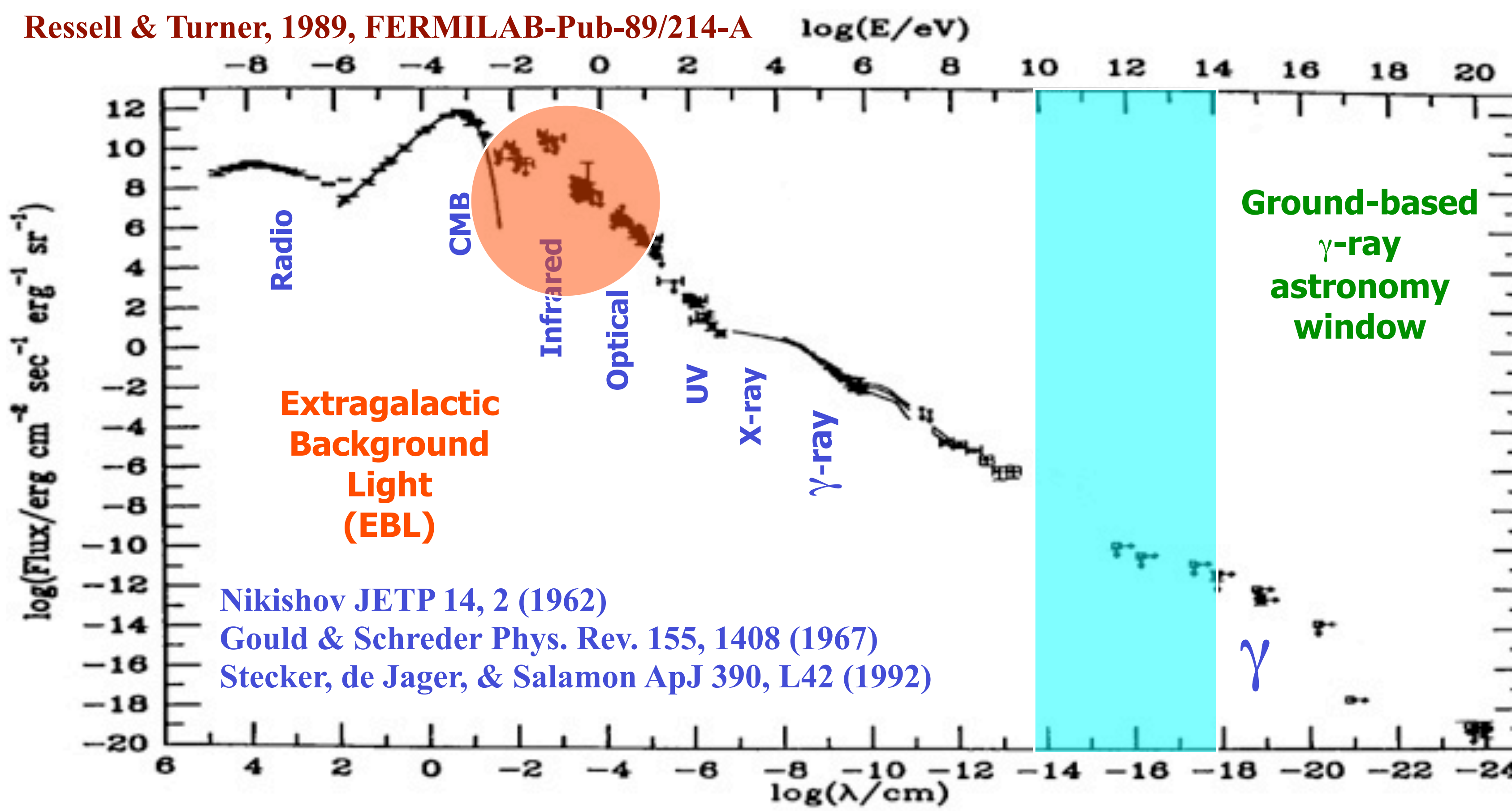
Science from TeV Blazar Detections

Spectral Variability & Cutoffs (e.g. Markarian 421, Krennrich et al., 2003)



Extragalactic Background Light: TeV - EBL Coupling

$$\gamma_{TeV} + \gamma_{IR} \rightarrow e^+ + e^- \qquad J_{Obs}(E_\gamma) = J_0(E_\gamma)e^{-\tau_{\gamma\gamma}(E_\gamma, z)}$$



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Limits to Quantum Gravity Effects on Energy Dependence of the Speed of Light from Observations of TeV Flares in Active Galaxies

S. D. Biller,[1] A. C. Breslin,[2] J. Buckley,[3] M. Catanese,[4] M. Carson,[2] D. A. Carter-Lewis,[4] M. F. Cawley,[5] D. J. Fegan,[2] J. P. Finley,[6] J. A. Gaidos,[6] A. M. Hillas,[7] F. Krennrich,[4] R. C. Lamb,[8] R. Lessard,[6] C. Masterson,[2] J. E. McEnery,[9] B. McKernan,[2] P. Moriarty,[10] J. Quinn,[11] H. J. Rose,[7] F. Samuelson,[4] G. Sembroski,[6] P. Skelton,[7] and T. C. Weekes[11]

Conclusions

- The discovery by Whipple of TeV gamma-ray emission from blazars opened a new window on the extragalactic universe and revitalised AGN science.
- The Whipple discoveries were instrumental in establishing TeV astronomy as a viable and important branch of astronomy.
- It was incredibly exciting and a privilege to be at the Whipple observatory during the 1990s.
- Trevor's drive, leadership, encouragement, optimism and support were critical to the successes that were achieved.

The 10m as a Blazar Monitor

- Once VERITAS operational the 10m used to monitor the classical TeV Blazars.
- Markarian 421: 16 years (October 1995 to May 2011) monthly averages: