The CANGAROO Project and Observation of AGNs at TeV Energies

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THE CHARLENE HEISLER WORKSHOP 2001
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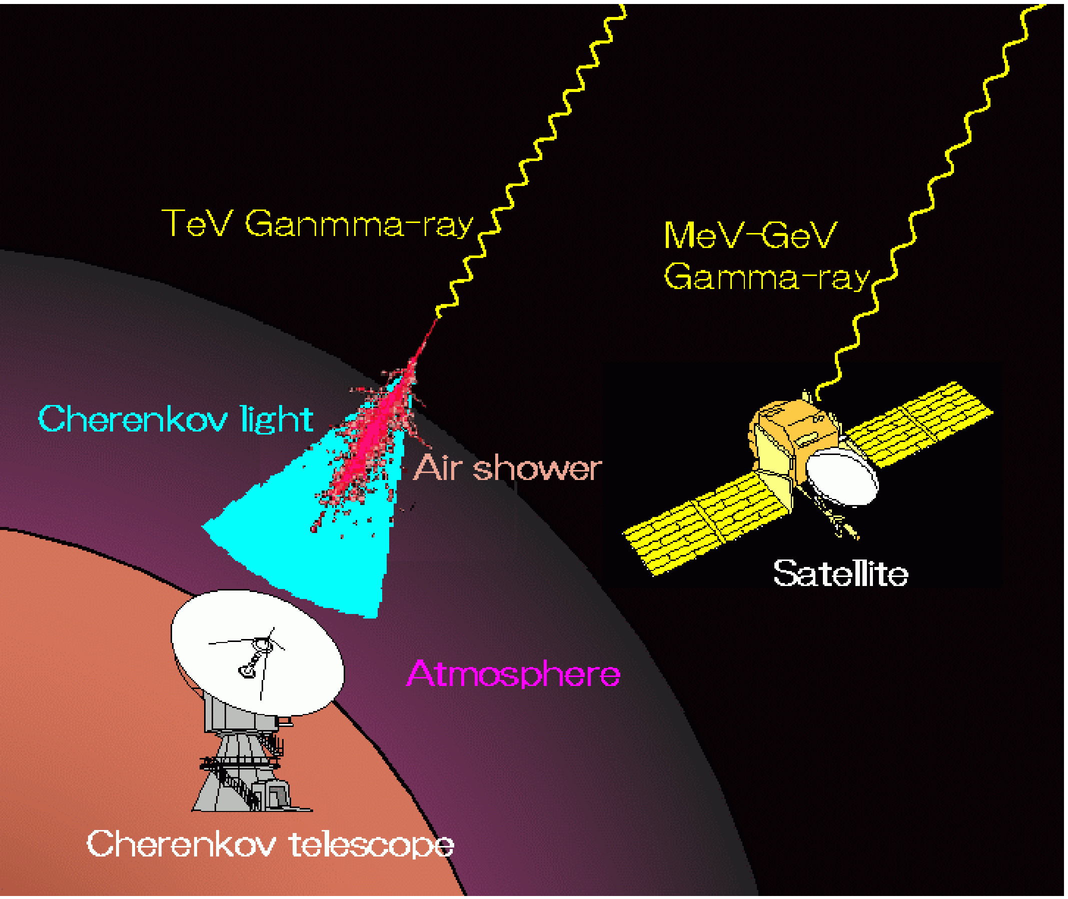
CANGAROO collaboration

Collaboration of **A**ustralia and **N**ippon for a **GA**mma **R**ay **O**bservatory in the **O**utback

CANGAROO III

- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectual University
- Kanagawa University
- Konan University
- Kyoto University
- Nagoya University
- National Astronomical Observatory of Japan
- Osaka city University
- Institute of Physical and Chemical Research
- Shinshu University
- Institute for Space and Aeronautical Science
- Tokai University
- University of Tokyo
- Tokyo Institute of Tehnology
- Yamagata University
- Yamanashi Gakuin University

Observation of gamma-rays



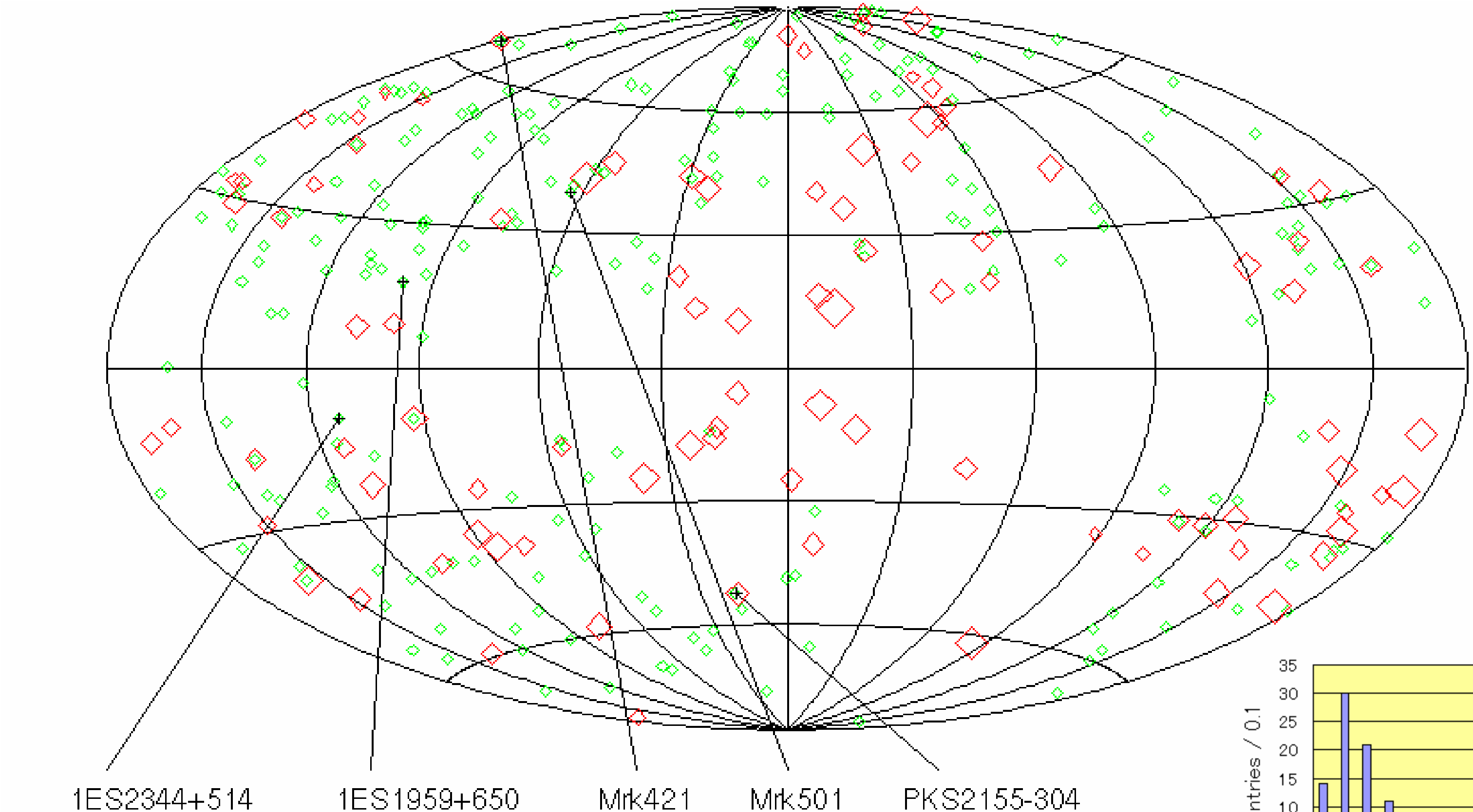
Base	Satellite	Ground
Gamma-ray detection	Direct (pair creation)	Indirect (atmospheric Cherenkov)
Energy	< 30 GeV (→ 100 GeV)	>300 GeV (→ 50 GeV)
Pros	High S/N Large FOV	Large area Good $\Delta\theta$
Cons	Small area High cost	Low S/N (CR bkgd.) *(but imaging overcomes this!)* Small FOV

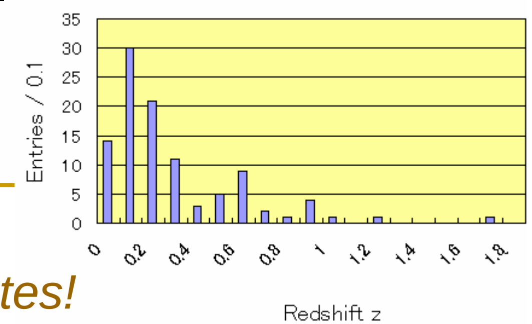
Gamma-ray AGNs

≈ Blazars (Mostly FSRQ and BL Lac's)

RED EGRET 3rd catalog AGNs

Green Padovani & Giommi MN 1995





TeV *Whipple, HEGRA, CAT, 7TA, Durham*

Nearby blazars are TeV emitter candidates!

TeV gamma-ray absorption by IR background

$\gamma_{TeV} + \gamma_{IR} \rightarrow e^+ + e^-$

Summary of extragalactic background light measurements

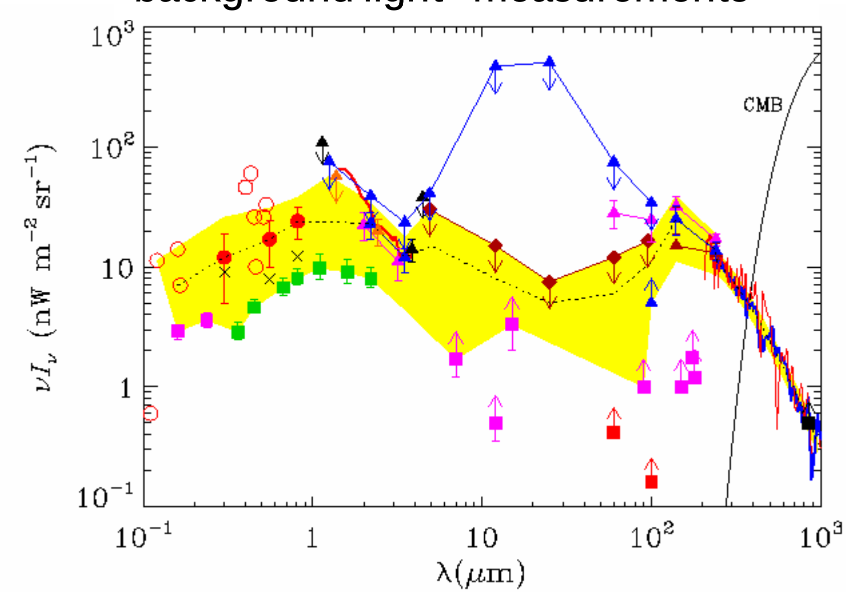


Figure 5. Summary of extragalactic background light (EBL) measurements and limits. Error bars for detections are 1σ. Square symbols show lower limits obtained by integrating the light of detected sources. X's show 2σ lower limits on integrated resolved sources from Bernstein (1999). Diamonds show upper limits from fluctuation measurements. All other symbols show absolute background measurements (1σ error bars) or limits (2σ). The shaded region represents current observational limits for the EBL spectrum, and the dotted line shows nominal values (see § 3.10 for discussion). The black line (CMB) shows the cosmic microwave background radiation.

Mean free path for e^+e^- pair production

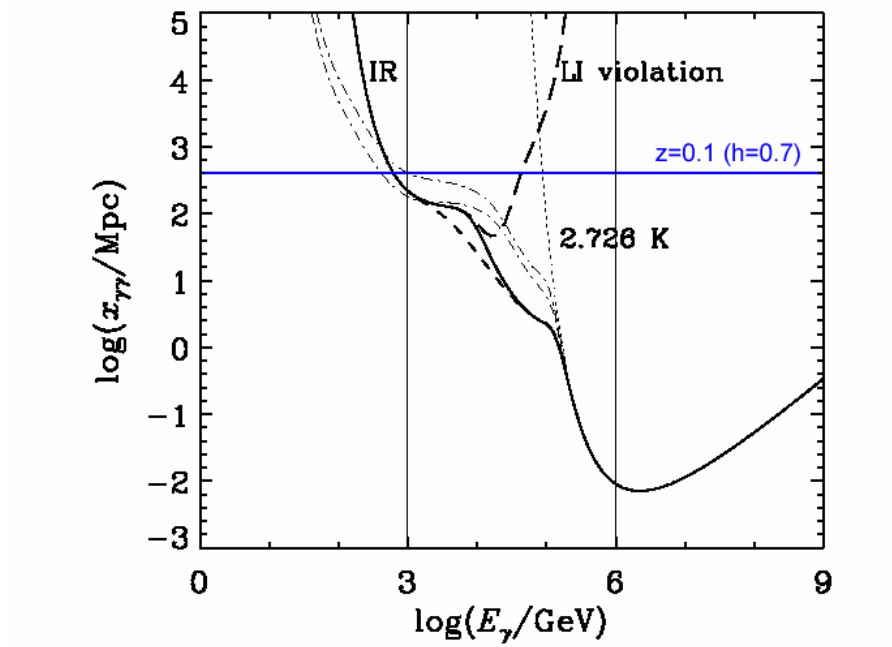


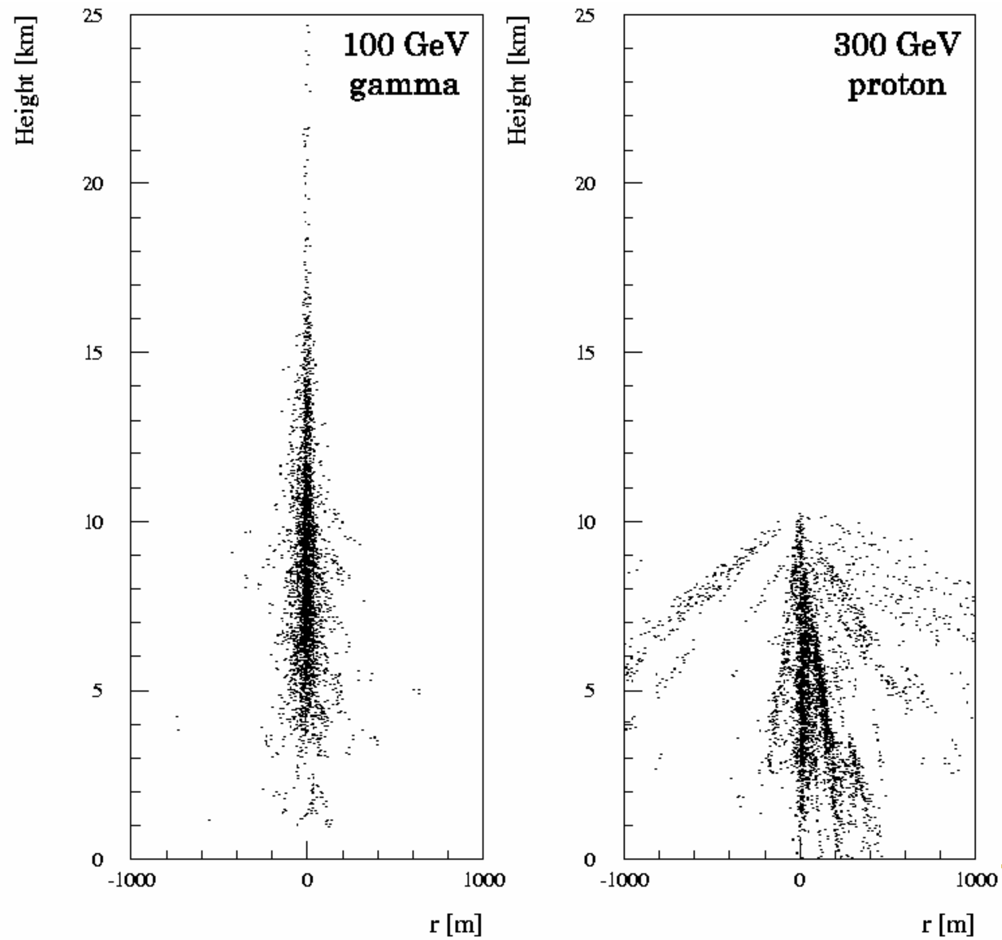
Figure 2: Mean free path for photon-photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz Invariance violation discussed in Section 4 is shown by the long dashed curve.

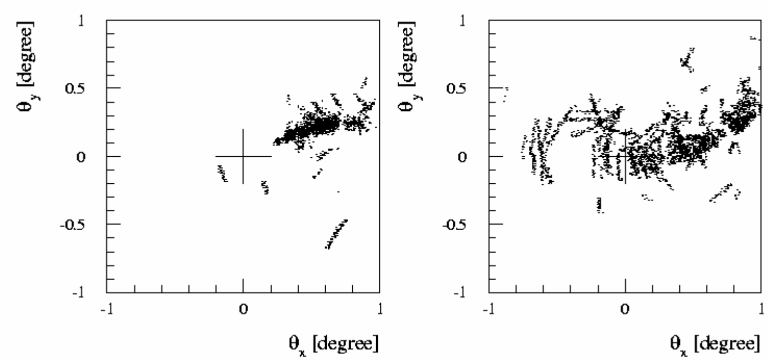
Hauser and Dwek astro-ph/0105539

Protheroe et al. astro-ph/0005349

Imaging Cherenkov technique

- Differentiate gamma-rays from cosmic-ray nuclei by utilizing difference in Cherenkov light image





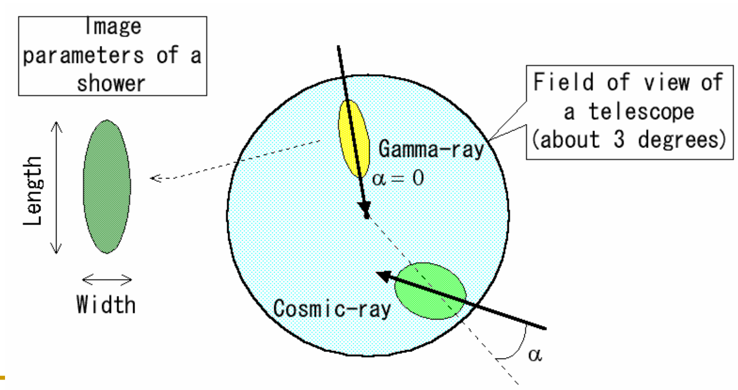
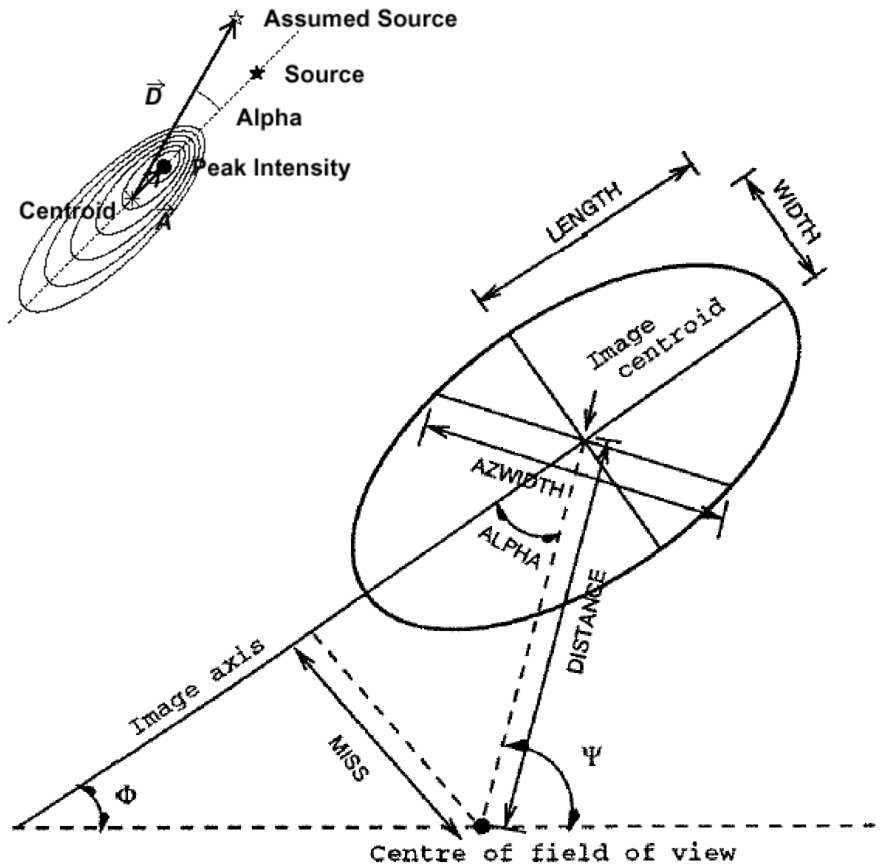
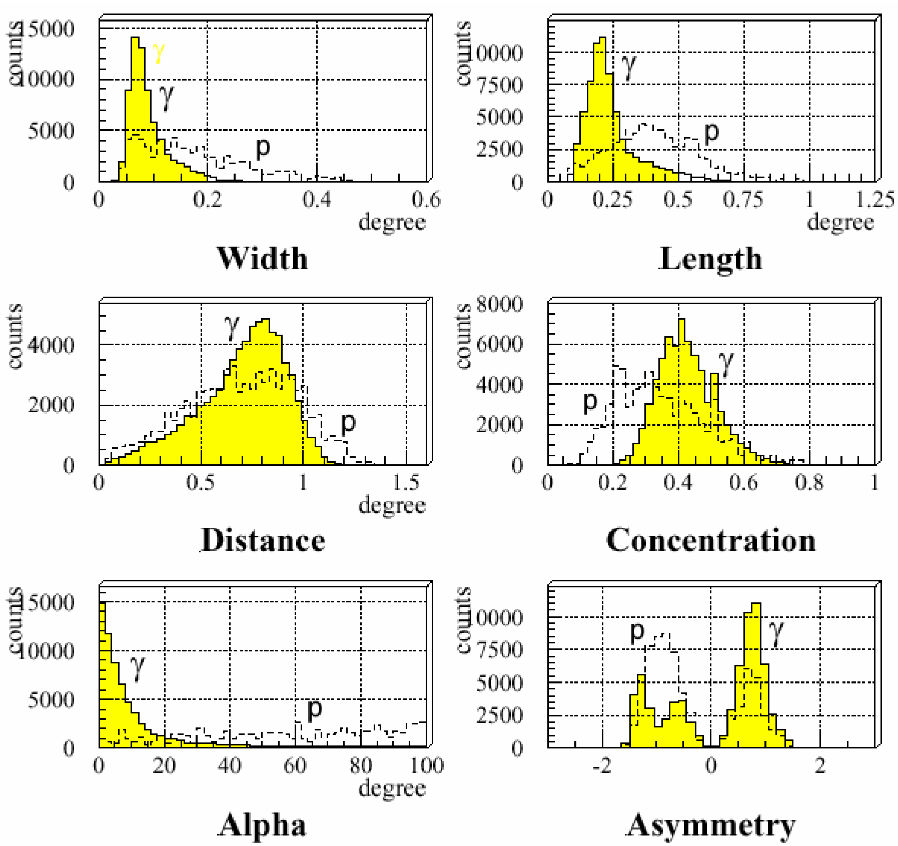


Image parameters *Hillas 1985 ICRC*





D.J. Fegan, J.Phys.G, 1997

(Simulation)

TeV observations of AGNs

Source	Energy (GeV)	Flux ($\times 10^{-11} cm^{-2} s^{-1}$)	Group	EGRET source
Blazars: XBL				
Markarian 421	260	variable	Whipple, HEGRA, CAT	yes
z = 0.031				
Markarian 501	260	variable	Whipple, HEGRA, CAT, TA	no
z = 0.034				
1ES2344+514	300	variable	Whipple	no
z = 0.044				
PKS2155-304	300	variable	Durham	yes
z = 0.116				
1ES1959+650	600	variable	TA	no
z = 0.048				
Blazars: RBL				
3C66A	900	variable	Crimea	yes
z = 0.44				

(Detection of 1ES1426+428 (z=0.13) is claimed by Whipple but not published yet)

Krennrich, astro-ph/0101120

TeV flares

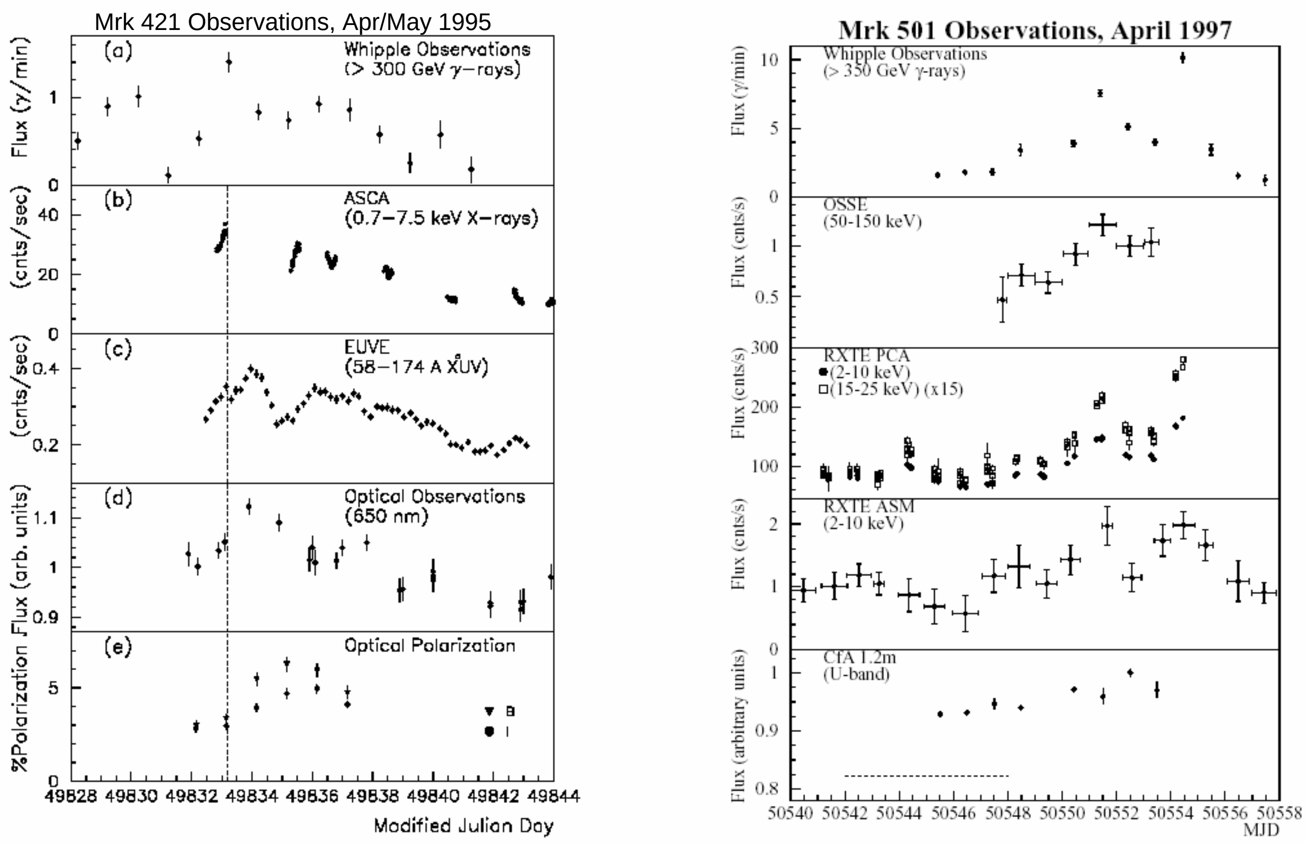


Fig. 6. (Left): Multi-wavelength observations of Mrk 421 [19]: (a) VHE γ-ray, (b) X-ray, (c) extreme UV, and (d) optical lightcurves taken during the period 1995 April–May (April 26 corresponds to MJD 49833). (Right) Multi-wavelength observations of Mrk 501 [17]): (a) γ-ray, (b) hard X-ray, (c) soft X-ray, (d) U-band optical taken during the period 1997 April 2–20 (April 2 corresponds to MJD 50540). The dashed line in (d) indicates the optical flux in 1997 March.

fast variability at day scale; correlation with X-rays

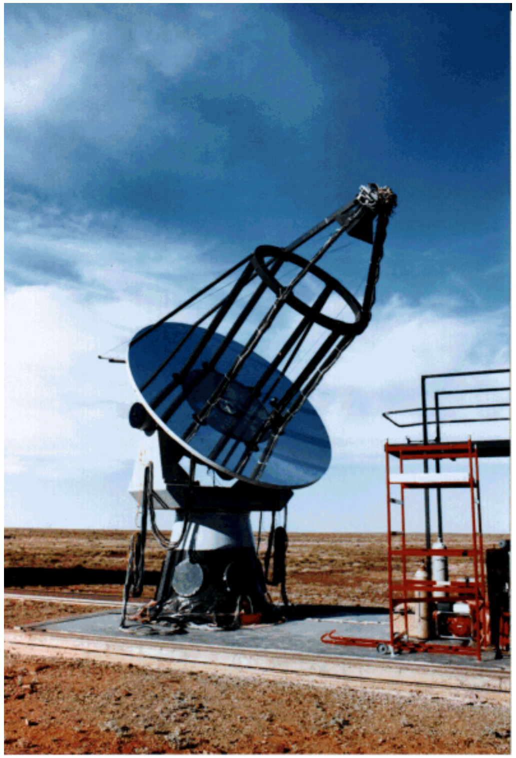
Buckley, Astropart. Phys. 11 (1999)

Cherenkov observation at Woomera

- Southern sky - good for galactic objects
- Observation only on moonless, clear nights
- Less humidity and rain
- Infrastructure (electricity, access road, people)
- Protection (prohibited area)

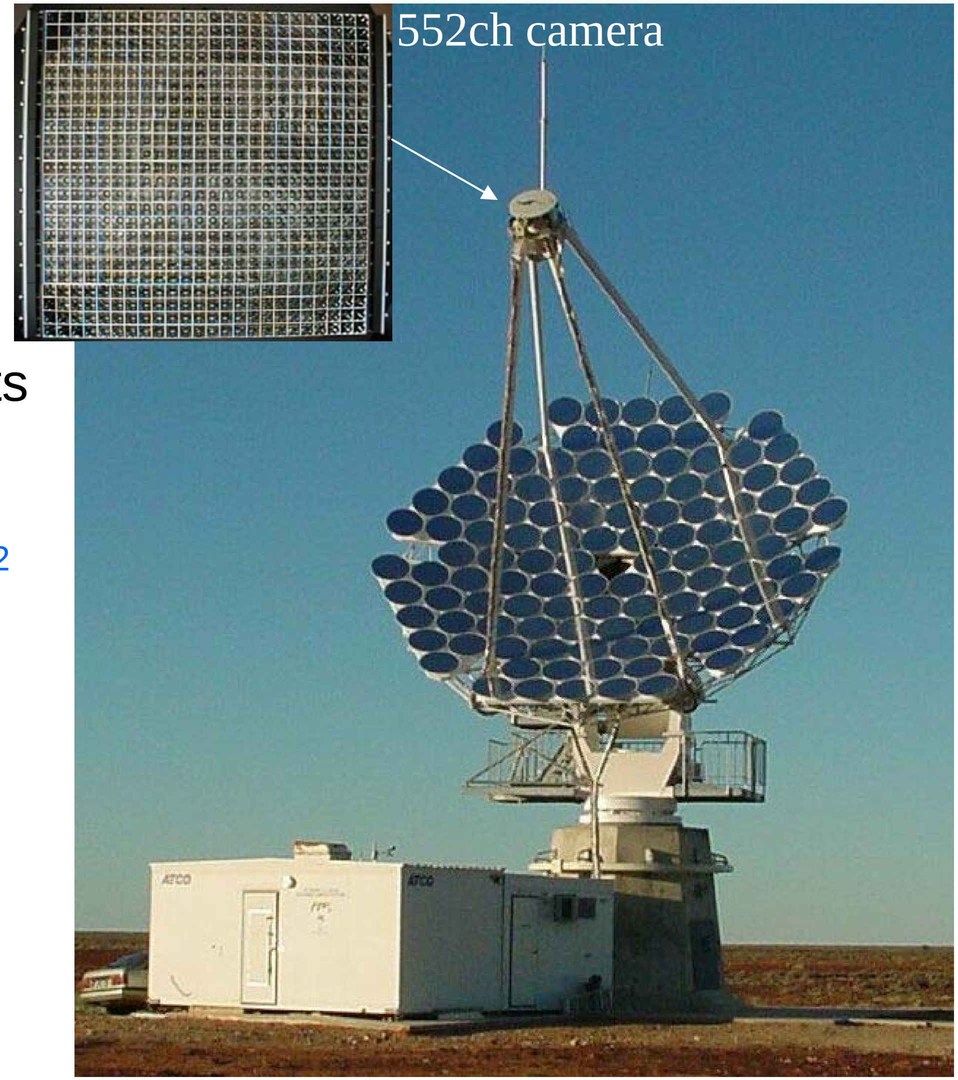
latitude:31º06'S,
longitude:136º47'E,
160 m a.s.l.

History of CANGAROO telescopes



Diameter	3.8m	7m	10m
Focal length	3.8m	8m	8m
Number of pixels	256	512	552
Point image size (FWHM)	0.1°	0.15°	0.20°
Operation	1992-1998	May1999-Feb2000	Mar2000-

CANGAROO-II 10m telescope



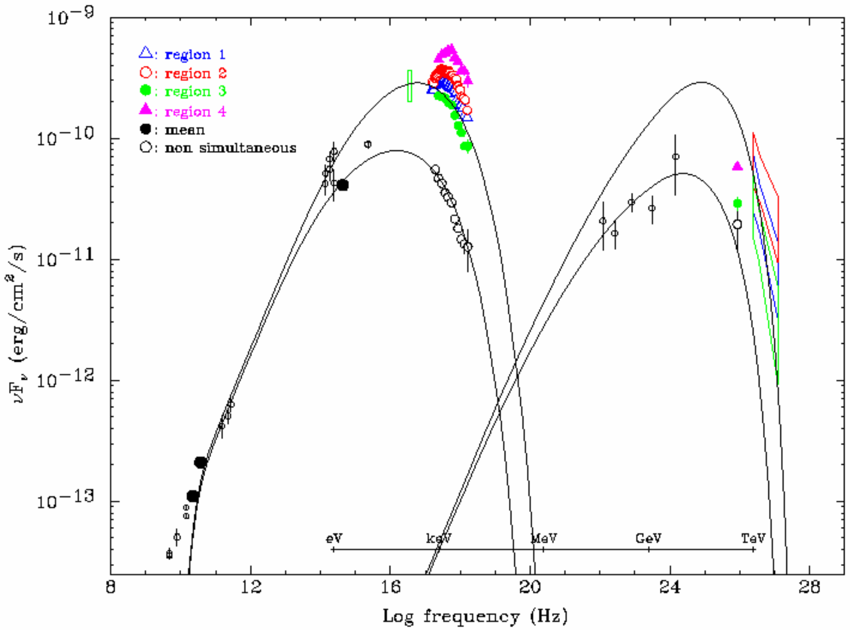
- Alt-azimuth mount
- Reflector
  - tessellated parabola with 114 spherical mirror facets (made of CFRP, 0.8 m in diameter)
  - light collection area: $57 m^2$
  - focal length: 8m
- Camera (prime focus)
  - field of view: ~3°
  - PMT pixel size: $0.115° \times 0.115°$
  - number of pixels: 552

Summary of AGN observations

Target	z	Year	Time(hrs)	E(TeV)	Telescope
EXO0423.4-0840	0.039	'96	20	2.0	3.8
PKS0521-365	0.055	'95/'96	89	2.0	3.8
PKS0548-322	0.069	'97	26	1.5	3.8
		'99	16.6	1.0	7
		'00	2.6		10
PKS2005-489	0.071	'93/'94/'97	58	2.0/1.5	3.8
		'99	26.2	1.1	7
		'00	32.6	0.45	10
PKS2155-304	0.116	'97	18	2.5/1.5	3.8
		'99	58.5	0.96	7
		'00	35.6	0.40	10
PKS2316-423	0.055	'96	26	2.0	3.8
Cen A	3.5Mpc	'95	23	1.5	3.8
Mrk421	0.031	'01	14.4	9.3	10

Mrk 421

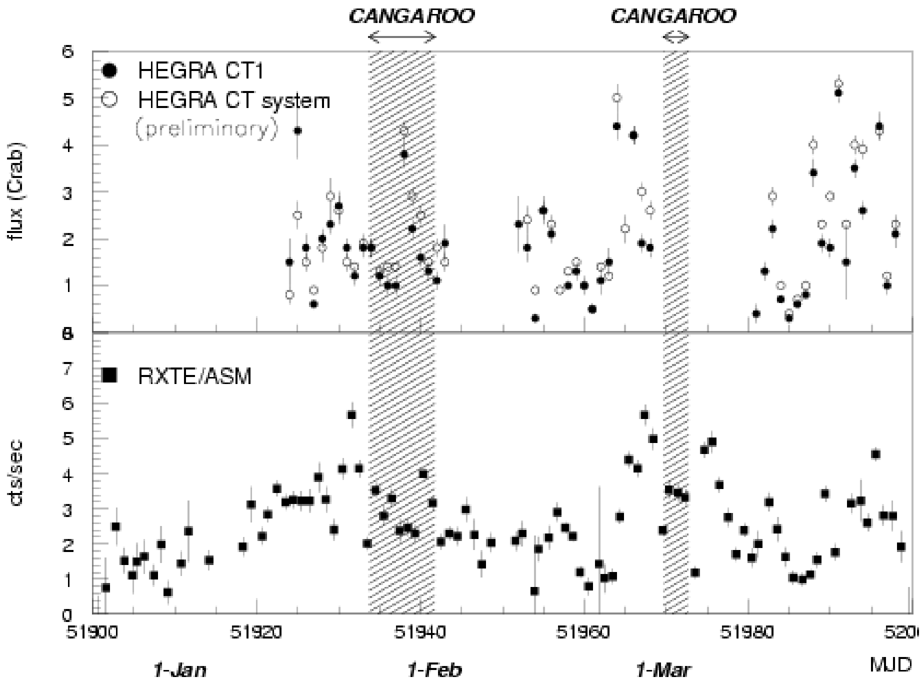
- Nearby XBL (z=0.031)
- The first extragalactic source at TeV energies reported by Whipple group in 1992
- Extensive measurements in the TeV region
- Several multiwavelength campaigns
- TeV gamma radiation can be explained by SSC (synchrotron self-Compton) mechanism



Takahashi et al. ApJ. 542, 2000

CANGAROO observation of Mrk 421 in Feb/Mar 2001

- Jan.24 – Feb.1, Mar.1 – 4, 2001
  - 10 nights, 14.4 hours (on)
- Average zenith angle :
  69.8 degree
  (large zenith angle observation – higher threshold but larger effective area)
- Energy threshold :
  ~10 TeV
- Average effective area :
  $\sim 8 \times 10^9 \mathrm{cm}^2$



Large zenith angle observations

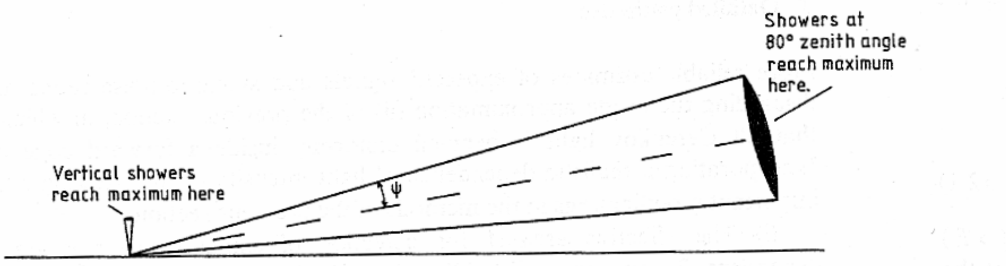
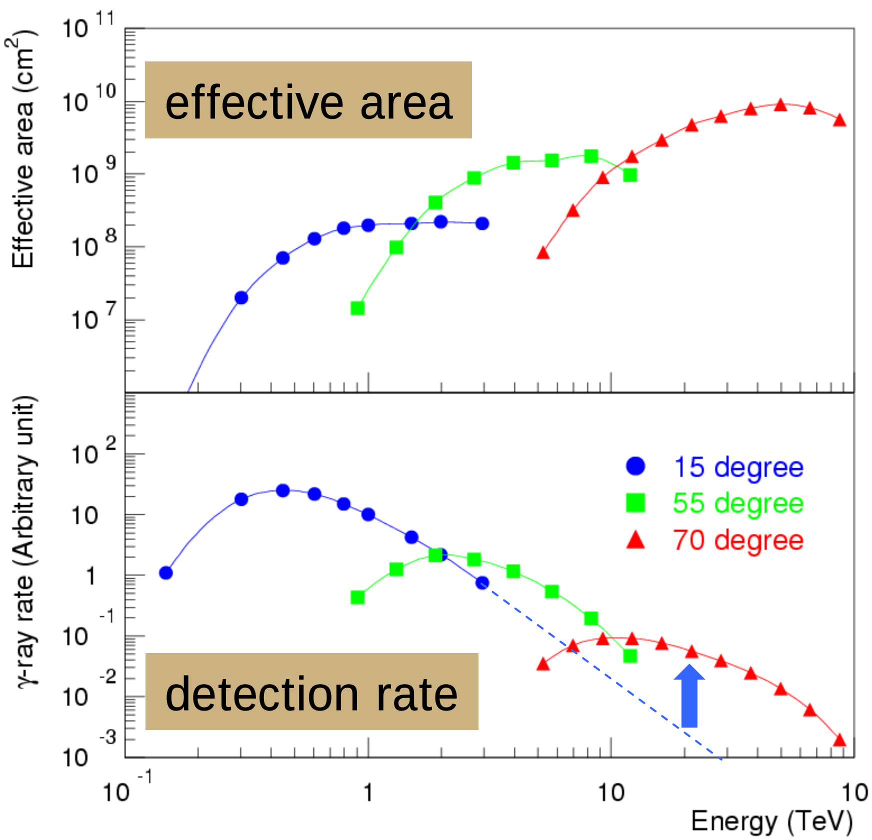


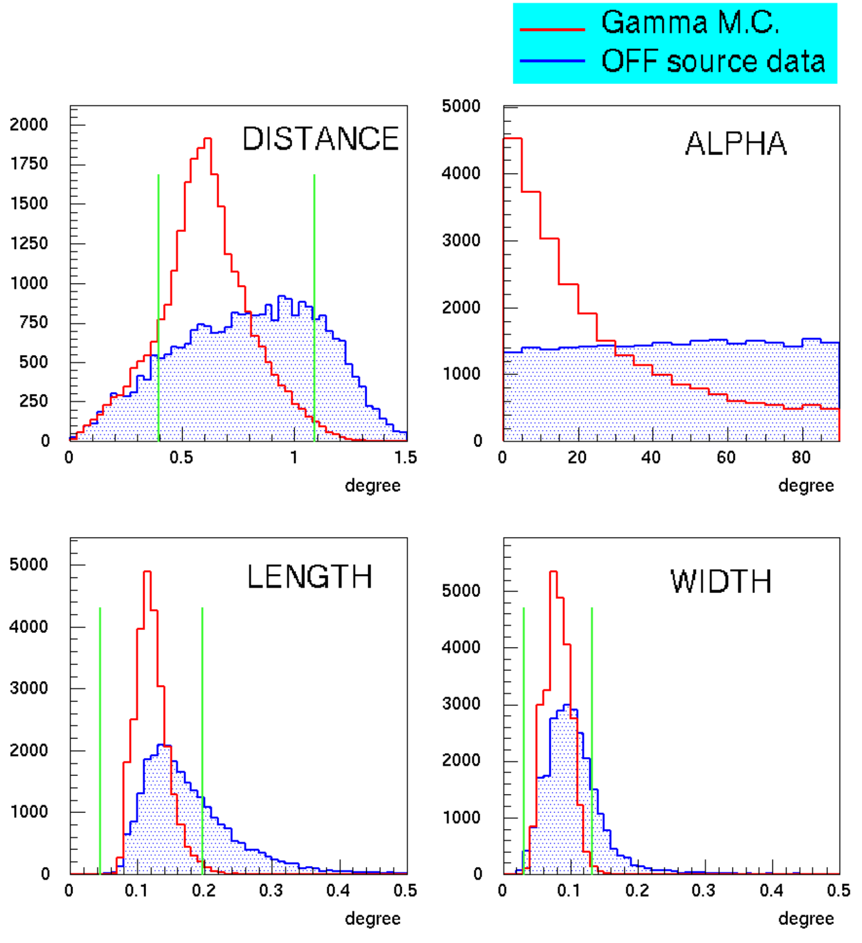
Figure 1. A detector which accepts light within a cone of half-angle ψ can be pointed vertically or at large zenith angle. The shaded regions represent the effective detection areas in the two cases.

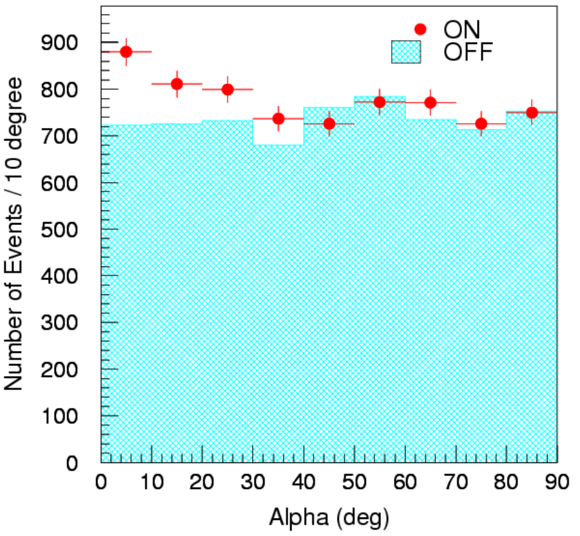
Sommers and Elbert, J.Phys.G13 (1987)

Simulation: spectral index $\gamma = -2.5$



Imaging analysis (square cut)

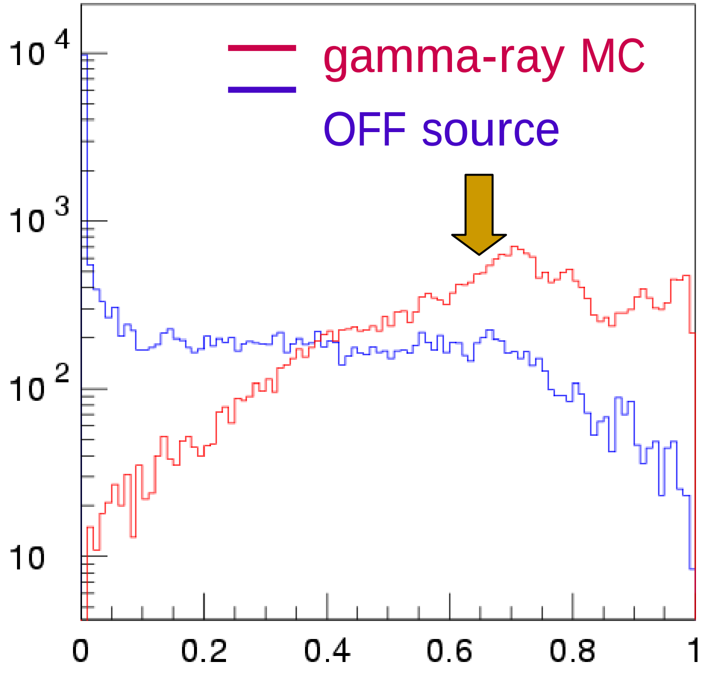




- event selection by
- 0.40º<DIS<1.1º
- 0.05º<LENGTH<0.2º
- 0.03º<WIDTH<0.13º
- ALPHA<20º
- Excess of 258±56 events (4.6 σ) detected

Imaging analysis (likelihood method)

- Powerful and non-artificial method
- Product probability of DISTANCE, LENGTH and WIDTH parameter
  Prob = P(DIS)･P(LENGTH)･P(WIDTH)
- Energy dependence considered
- Cut by Likelihood Ratio, R>0.63

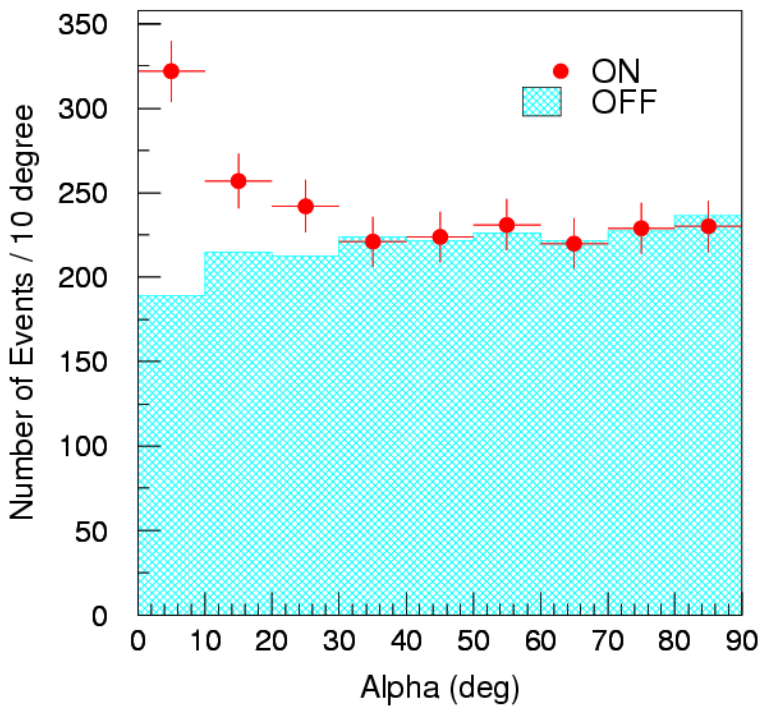


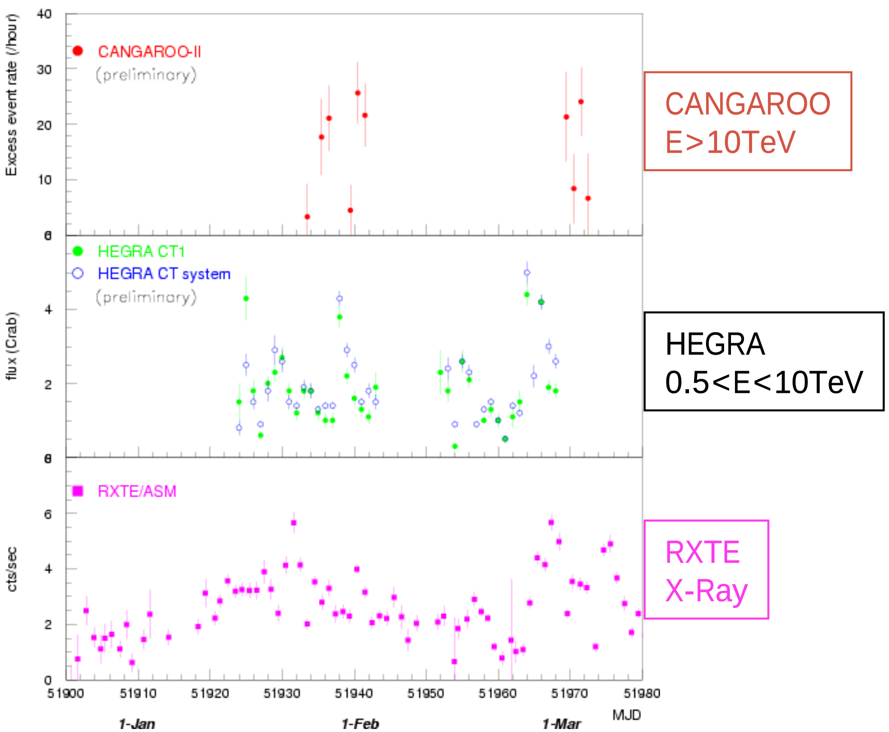
Likelihood ratio, R

$$R = \frac{Prob_{\gamma}}{Prob_{\gamma} + Prob_{B.G.}}$$

$Prob_{\gamma}$: probability for gamma-rays
$Prob_{B.G.}$: probability for background

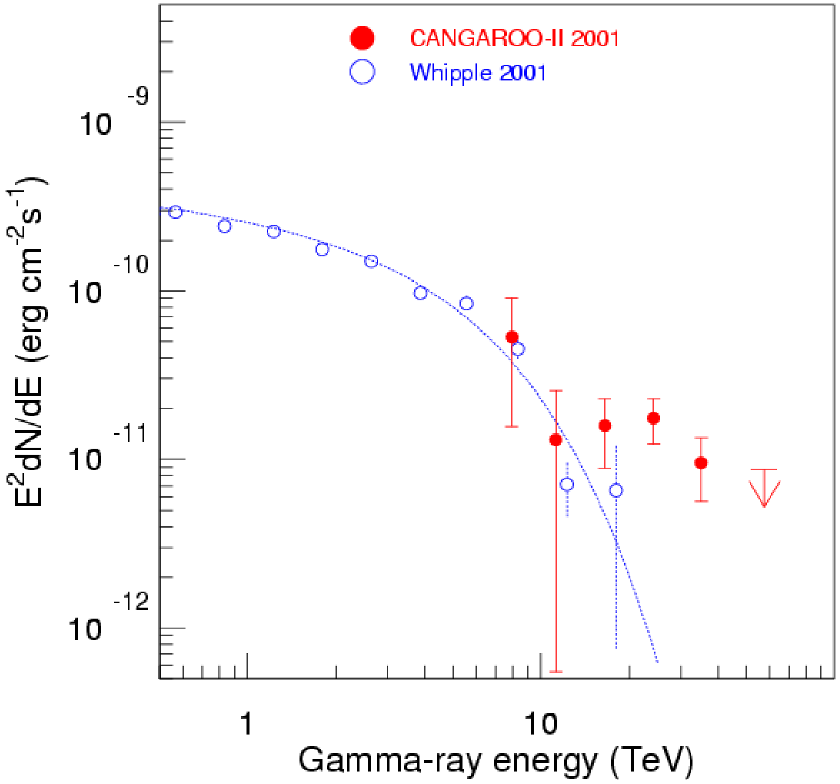
Alpha distribution and light curve

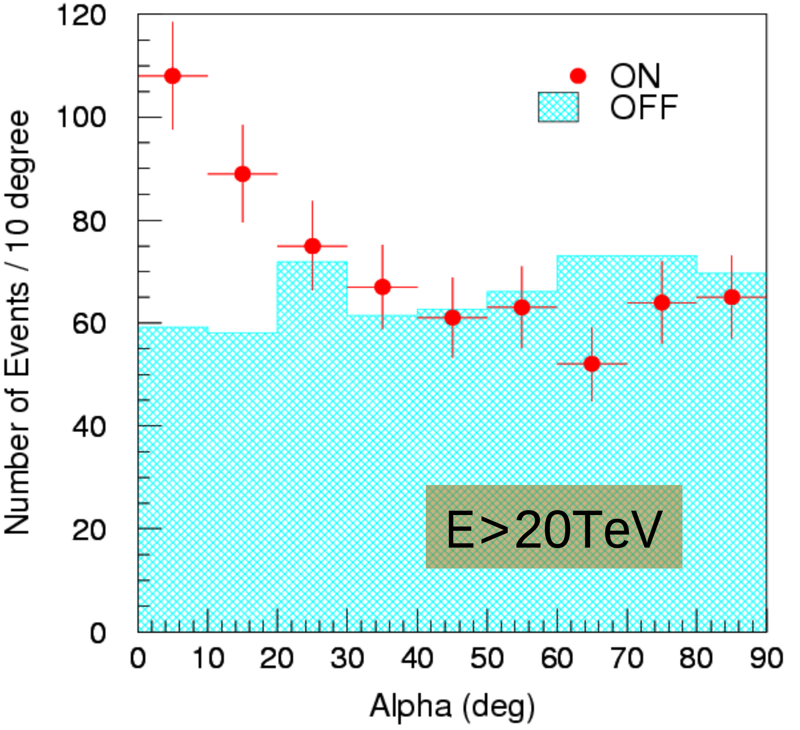




- 175±32 events (5.4σ) detected
- possible variability observed for E>10TeV
- χ^2 test with flat hypothesis
  15.7/9 d.o.f. (7.3%)

Energy spectrum





- Spectrum extends over 20 TeV [80±18 events (4.4σ)]

TeV crisis?

- Strong attenuation due to IR photons expected above 20 TeV
  - intrinsic spectrum diverge?!
- Possible explanation
  - fewer infrared photons ?
  - unknown gamma-ray radiation mechanism ?
  - gamma-ray halo ?
  - Lorentz invariance breaking ?

Mrk501

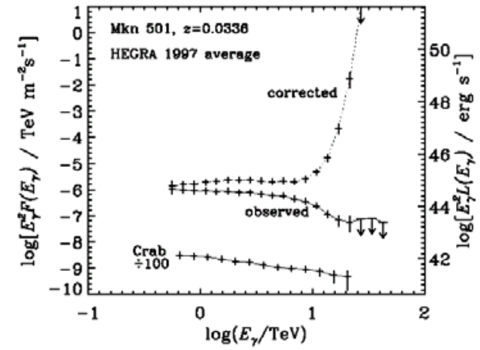
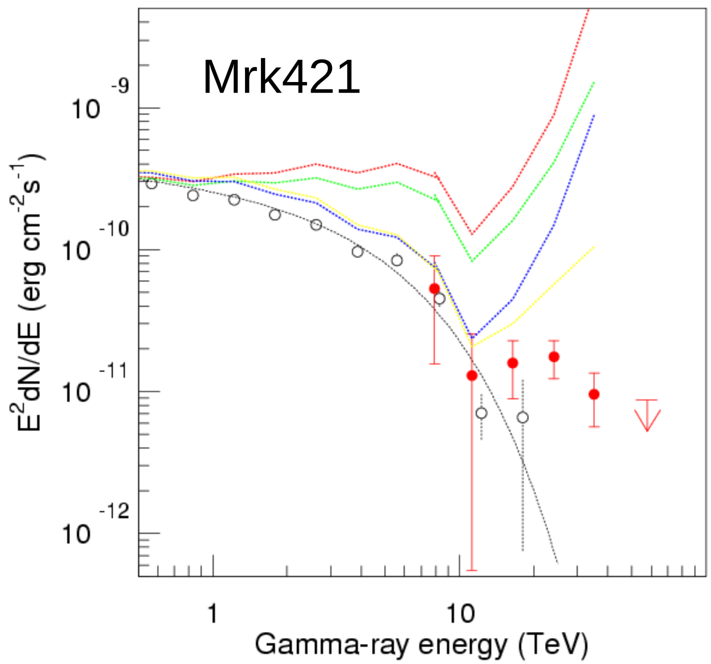


Figure 3: The time-averaged spectrum of gamma-rays from Markarian 501 observed in 1997[18] is compared with the spectrum of the Crab Nebula observed in 1997–8[21, 22]. The spectrum of Markarian 501 after correction for absorption in the infrared background is also shown assuming $H_0 = 65$ km s^{-1} Mpc^{-1}. The right hand scale shows the luminosity for Markarian 501.

Protheroe et al. astro-ph/0005349



PKS2005-489 (z=0.071, XBL)

- No evidence for gamma-ray steady emission
- Flux upper limits (2σ)
  - CANGAROO-I 3.8 m
    - Aug 1993, Aug/Sep 1994

      $F(>2\mathrm{TeV}) < 1.1 \times 10^{-12} \mathrm{cm^{-2} s^{-1}}$ (Roberts et al.(1998) A&A 337, 25)
    - Aug/Sep 1997

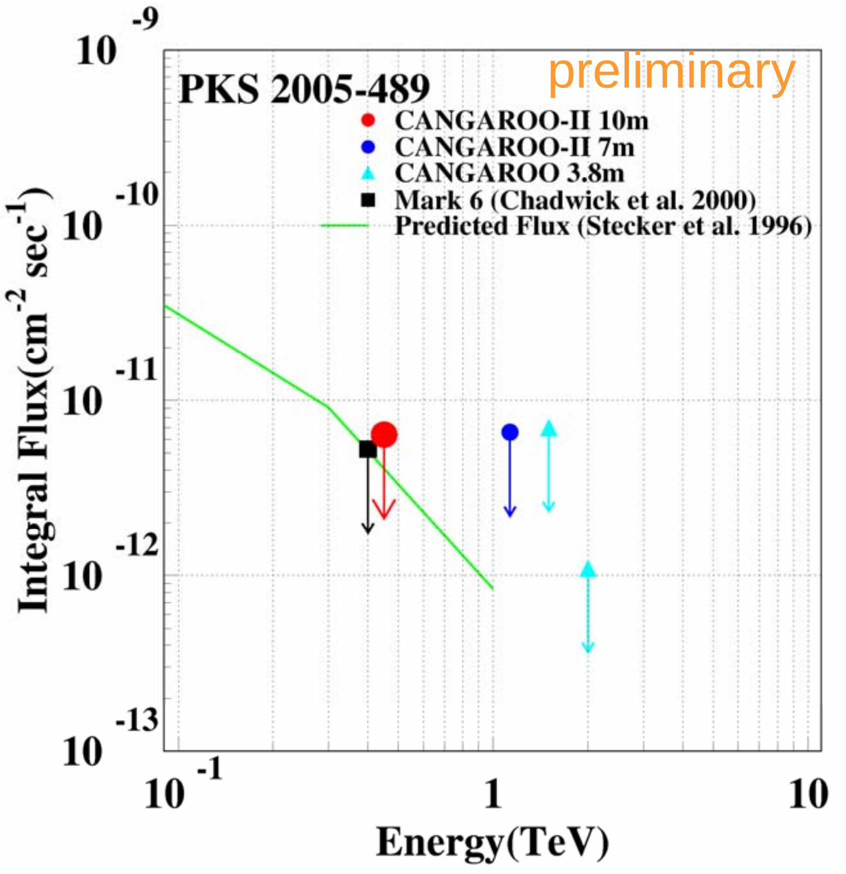
      $F(>1.5\mathrm{TeV}) < 7.0 \times 10^{-12} \mathrm{cm^{-2} s^{-1}}$ (Roberts et al.(1998) A&A 343, 691)
  - CANGAROO-II 7 m
    - Aug 1999

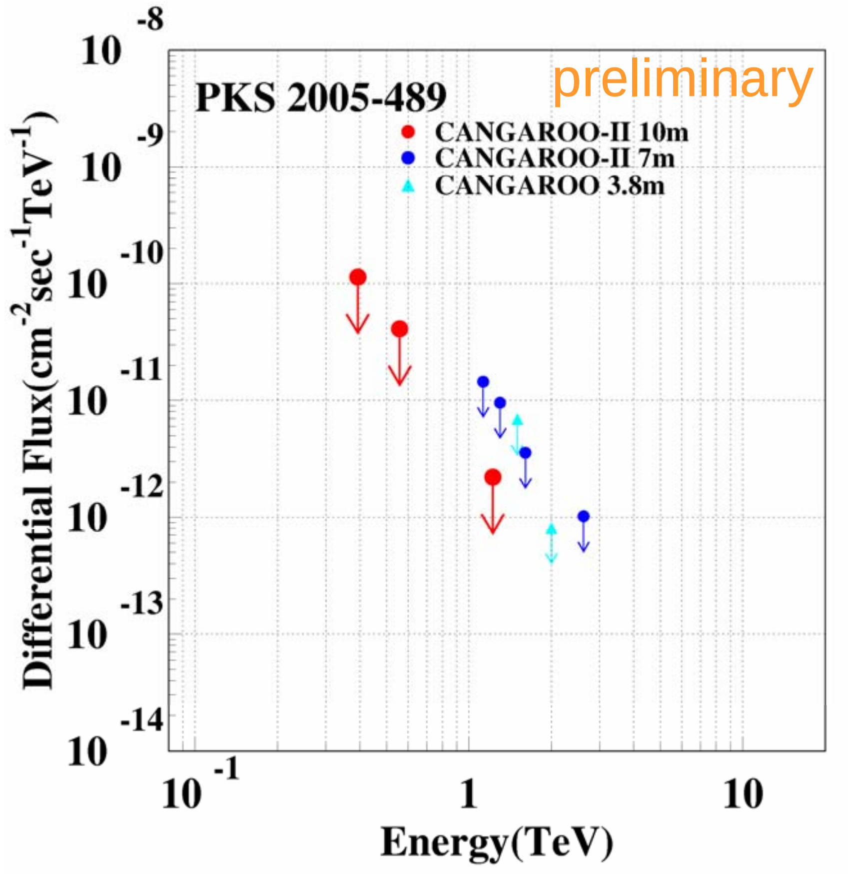
      $F(>1.1\mathrm{TeV}) < 6.6 \times 10^{-12} \mathrm{cm^{-2} s^{-1}}$ (preliminary)
  - CANGAROO-II 10 m
    - July/Aug/Sep 2000

      campaign:July 28 - Aug.1, Aug. 25 - Sep. 3 with RXTE and others

      $F(>0.45\mathrm{TeV}) < 6.4 \times 10^{-12} \mathrm{cm^{-2} s^{-1}}$ (preliminary)

PKS 2005-489: spectrum

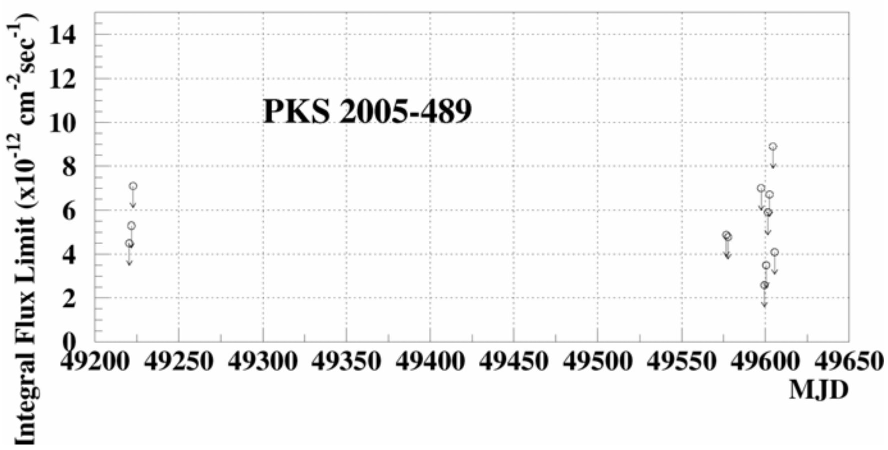




PKS 2005-489: light curve

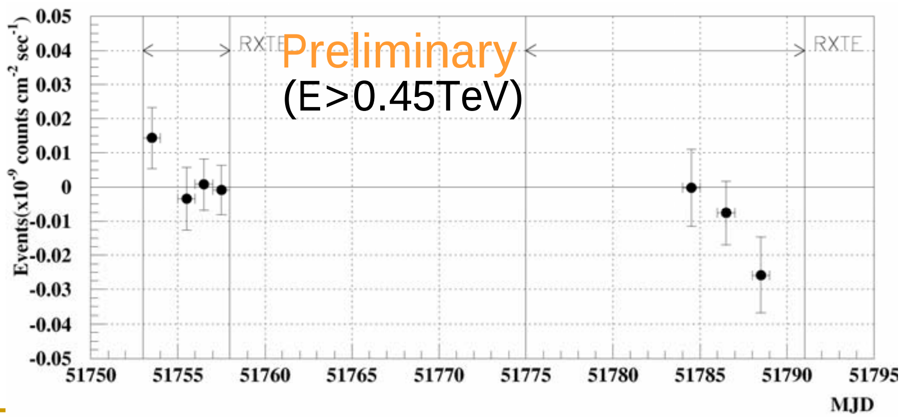
- No evidence for gamma-ray flare emission
  - CANGAROO-I 3.8 m
    - Aug 1993, 1994

      (Roberts, M.D. et al.(1998) A&A 337, 25)



  - CANGAROO-II 10 m
    - July/Aug/Sep 2000

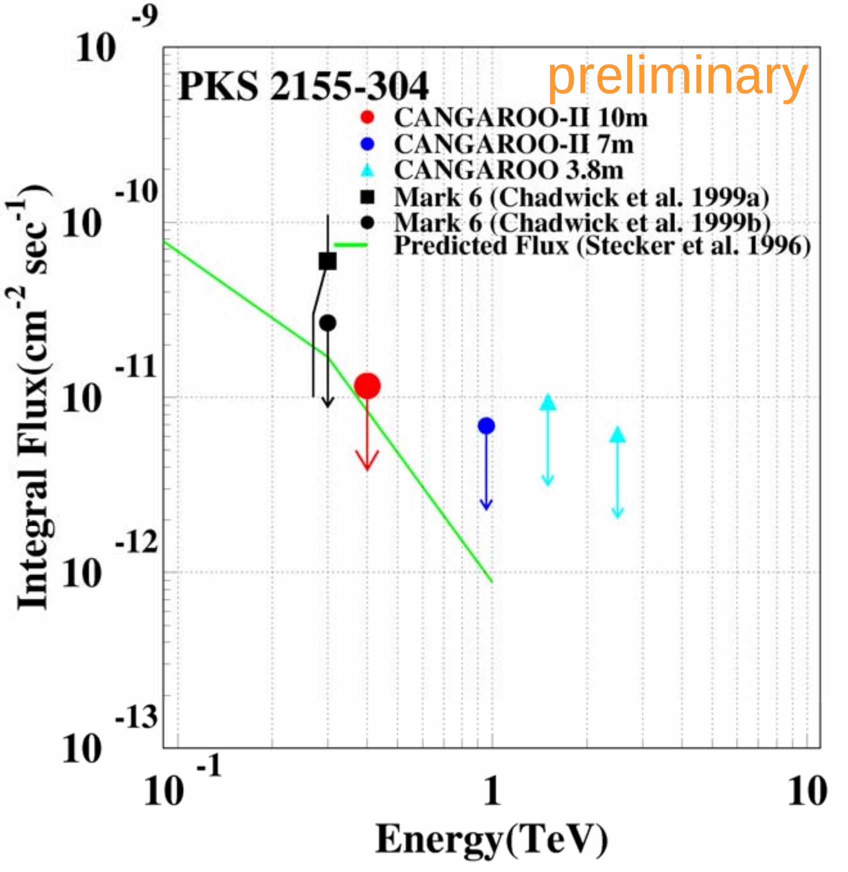
      (preliminary)

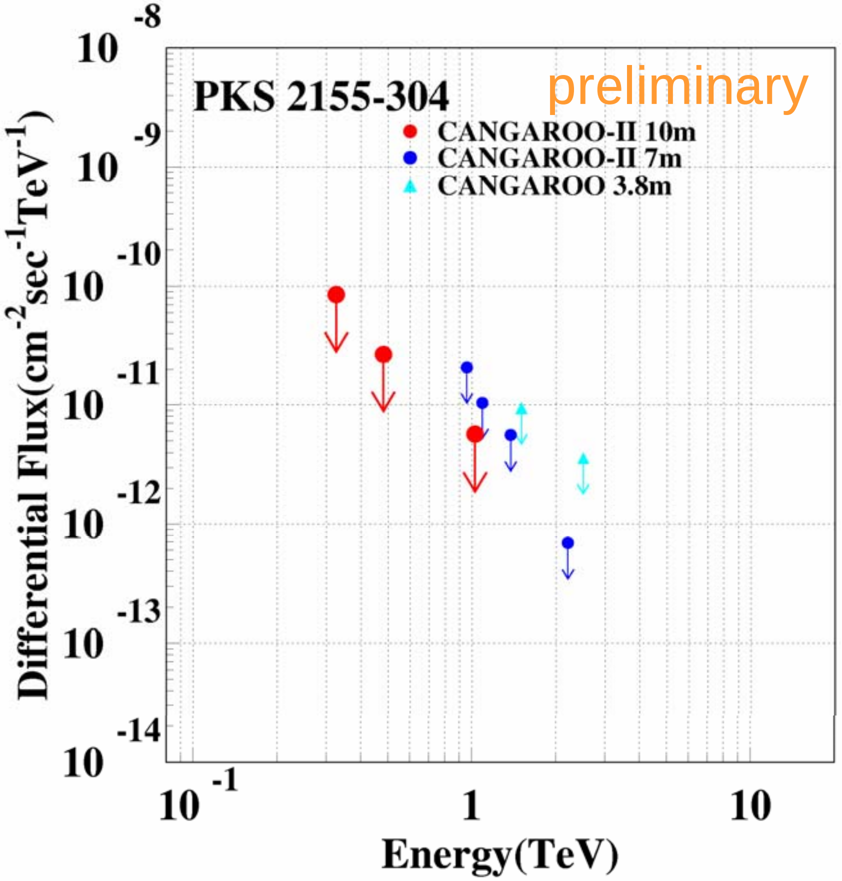


PKS2155-304 (z=0.116, XBL)

- Detection of VHE gamma-rays correlated with a strong X-ray flare in 1997 is reported.
  (Durham Mark6 telescope: Chadwick, P.M., et al.(1999) ApJ 513, 161)
- No evidence for gamma-ray steady emission
- Flux upper limits (2σ)
  - CANGAROO-I 3.8 m
    - Sep/Oct/Nov/Dec 1997
      $F(>1.5\text{TeV}) < 9.5 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$ (Roberts et al. (1998) A&A 343, 691)
  - CANGAROO-II 7 m
    - Sep/Oct 1999
      $F(>0.96\text{TeV}) < 6.9 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$ (preliminary)
  - CANGAROO-II 10 m
    - Aug/Sep/Oct 2000
      campaign:Aug. 27 – Aug. 31 with RXTE
      $F(>0.40\text{TeV}) < 1.2 \times 10^{-11}\text{cm}^{-2}\text{s}^{-1}$ (preliminary)

PKS 2155-304: spectrum

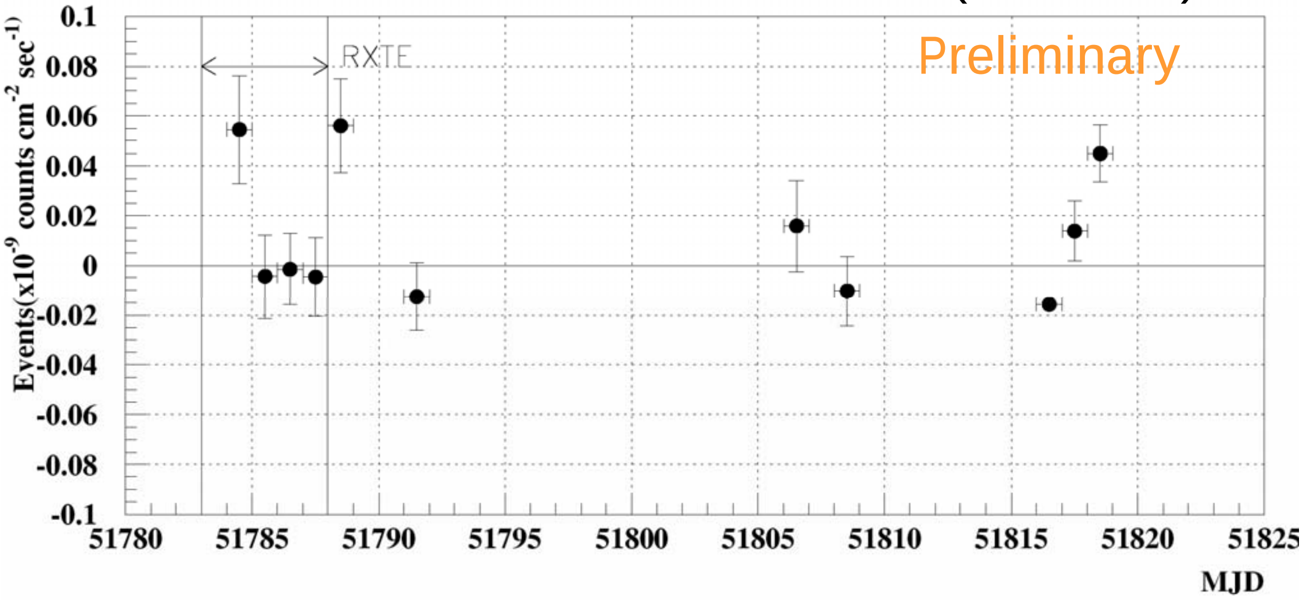




PKS 2155-304: light curve

- No evidence for short-term emission

(E>0.4TeV)



Other AGNs

- No evidence for long-term or short-term emission of gamma-rays
- Flux upper limits (2σ)
  - CANGAROO-I 3.8 m
    - PKS0521-365('95,'96) : $F(>2TeV) < 1.0 \times 10^{-12} cm^{-2} s^{-1}$ (I)
    - EXO0423.4-0840('96) : $F(>2TeV) < 1.1 \times 10^{-12} cm^{-2} s^{-1}$ (I)
    - PKS2316-423('96) : $F(>2TeV) < 1.2 \times 10^{-12} cm^{-2} s^{-1}$ (I)
    - PKS0548-322('97) : $F(>1.5TeV) < 4.3 \times 10^{-12} cm^{-2} s^{-1}$ (II)
    - Cen A('95) : $F(>1.5TeV) < 5.5 \times 10^{-12} cm^{-2} s^{-1}$ (III)

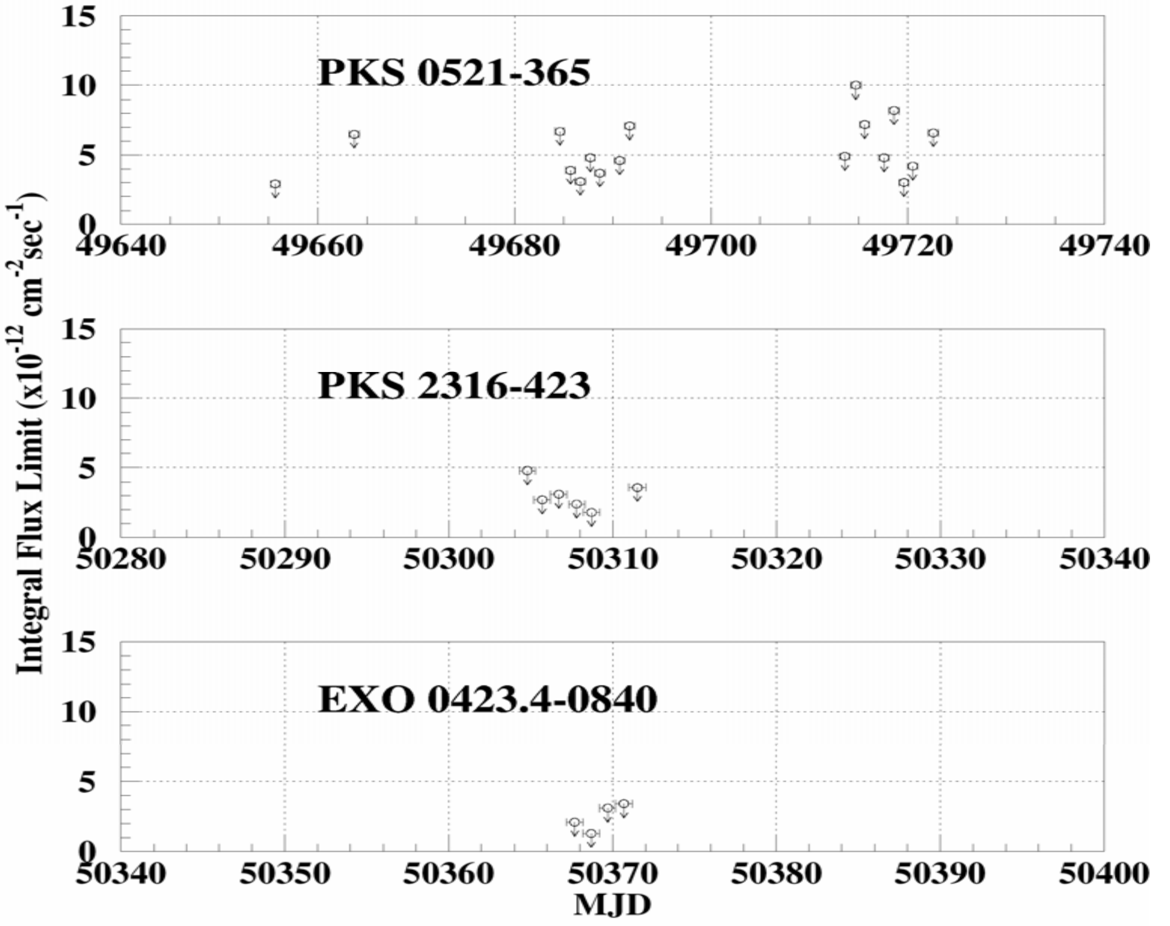
      I : Roberts, M.D. et al.(1998) A&A 337, 25

      II : Roberts, M.D. et al.(1998) A&A 343, 691

      III: Rowell, G.P. et al.(1999) Astropart. Phys.11, 217)
  - CANGAROO-II 7 m
    - PKS0548-322('99) : $F(>1.5TeV) < 1.0 \times 10^{-11} cm^{-2} s^{-1}$ (preliminary)

Other AGNs: light curve

- Night by night flux upper limits



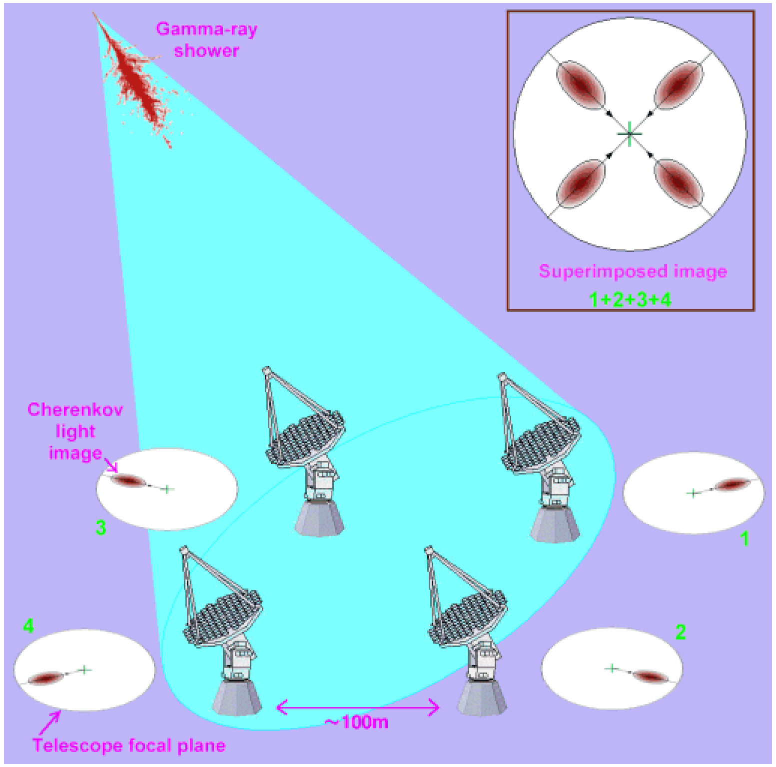
Summary of AGN observations

Table 1: AGN observation summary. Present work including preliminary results with the CANGAROO-II 7/10 m telescope is indicated by c in the last column. Other data are taken from a: Roberts et al. 1998a, b: Roberts et al. 1998b and d: Rowell et al. 1999 which are all obtained with 3.8 m telescope

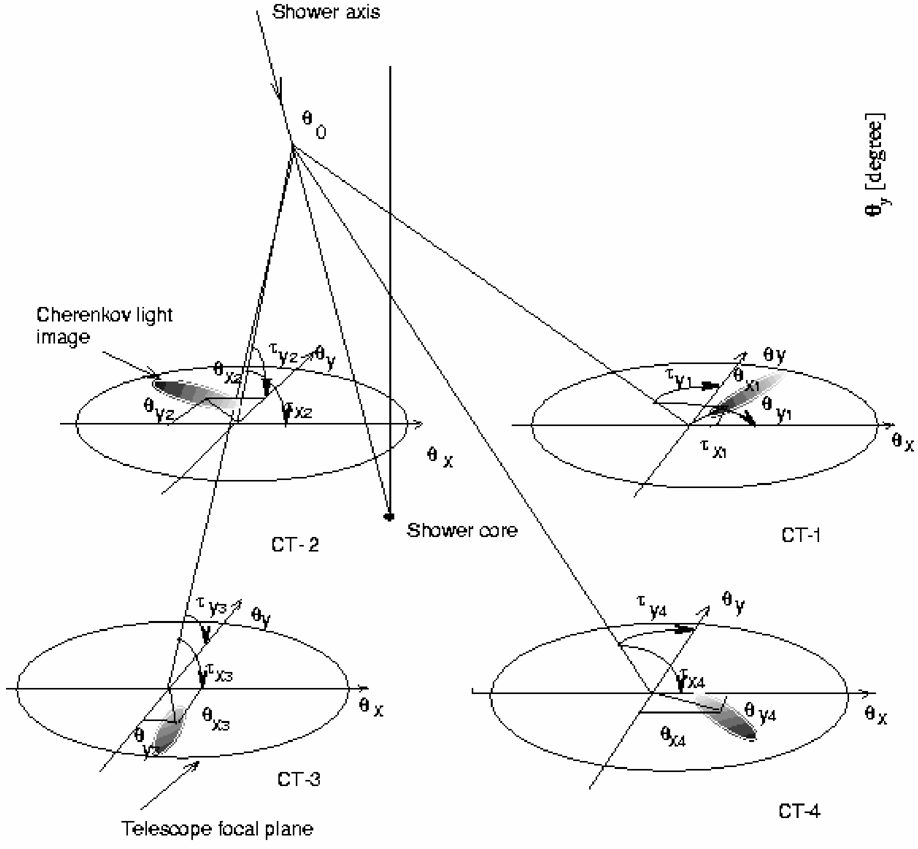
Target	z	Year	Time (hr)	E (TeV)	Flux ($cm^{-2}s^{-1}$)	Ref
EXO 0423.4–0840	0.039	1996	20	2.0	$< 1.1 \times 10^{-12}$	a
PKS 0521–365	0.055	1995–96	89	2.0	$< 1.0 \times 10^{-12}$	a
PKS 0548–322	0.069	1997	26	1.5	$< 4.3 \times 10^{-12}$	b
		1999	16.6	1.0	$< 1.0 \times 10^{-11}$	c
		2000	2.6			
PKS 2005–489	0.071	1993–94	41	2.0	$< 1.1 \times 10^{-12}$	a
		1997	17	1.5	$< 7.0 \times 10^{-12}$	b
		1999	26.2	1.1	$< 6.6 \times 10^{-12}$	c
		2000	32.6	0.45	$< 6.4 \times 10^{-12}$	c
PKS 2155–304	0.116	1997	18	1.5	$< 9.5 \times 10^{-12}$	b
		1999	58.5	0.96	$< 6.9 \times 10^{-12}$	c
		2000	35.6	0.40	$< 1.2 \times 10^{-11}$	c
PKS 2316–423	0.055	1996	26	2.0	$< 1.2 \times 10^{-12}$	a
Cen A	3.5 Mpc	1995	23	1.5	$< 5.5 \times 10^{-12}$	d
Mrk 421	0.031	2001	14.4	9.3		c

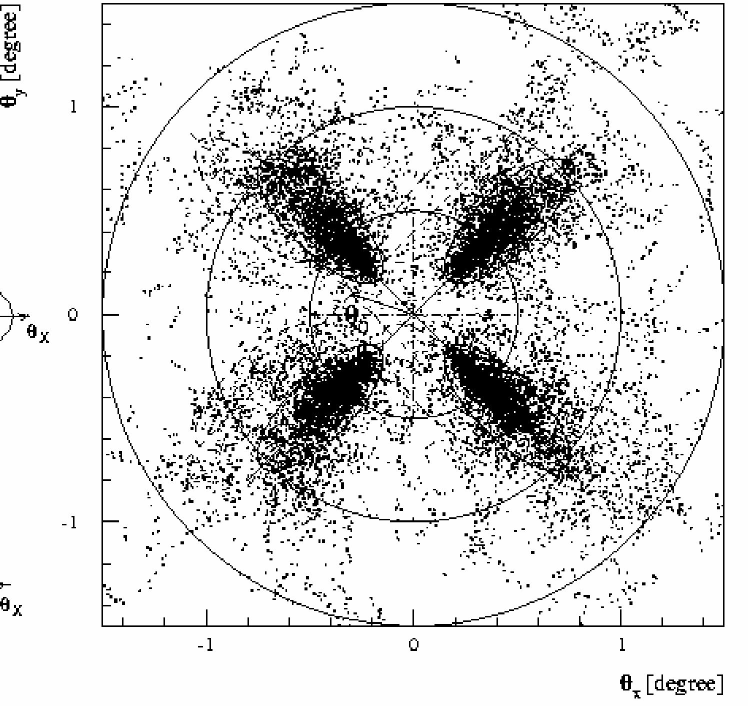
CANGAROO-III project

- Stereoscopic observation of Cherenkov images
  - Better $\Delta\theta$, better ΔE
- An array of four 10 m imaging Cherenkov telescopes will be completed in early 2004



Stereo reconstruction of Cherenkov images





Improvement for CANGAROO-III

- Refinement of mirror optical quality
- Wider FOV camera with individually HV-controlled PMTs
- Front-end electronics in VME-9U
- Faster data readout
- Pattern trigger circuit using PLD
- Flexible, centralized telescope control
- Total monitor system (calibration light source, environment etc.)

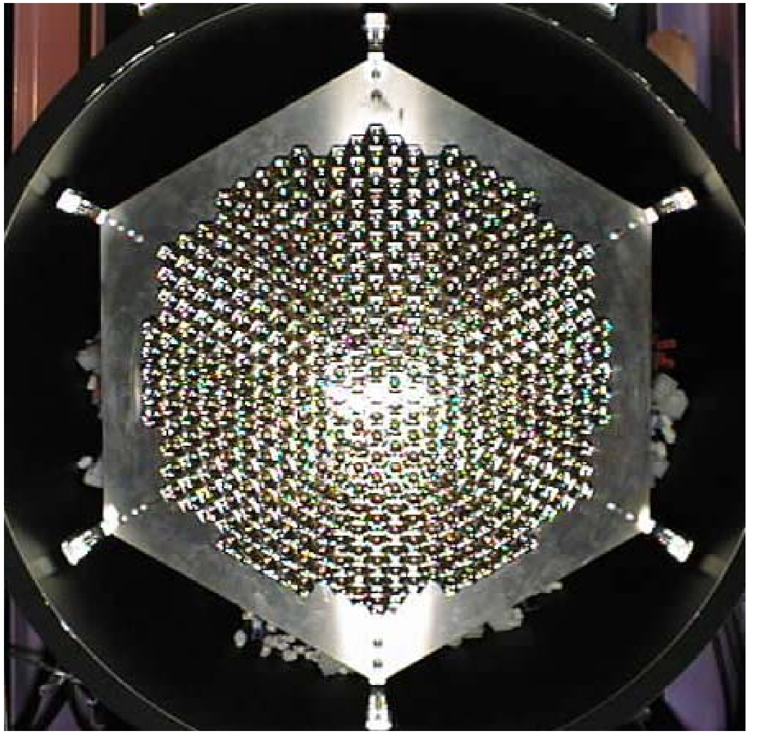
Optical reflector

- 114 x 80cmϕ segmented mirrors ($57m^2$)
- Further development from 1st telescope
  - Carbon Fiber Reinforced Plastic (CFRP) ⇒ GFRP (Glass Fiber)
  - Improved manufacturing accuracy (mirror surface, curvature radius)
  - Increased yield rate (~80%)
- Light weight (~6.7kg/mirror)
  - gravitational deformations is negligible
- Robust and durable for outdoor usage
  - tested with 1st telescope

A.Kawachi et al
Astropart. Phys. 14 261 (2000)

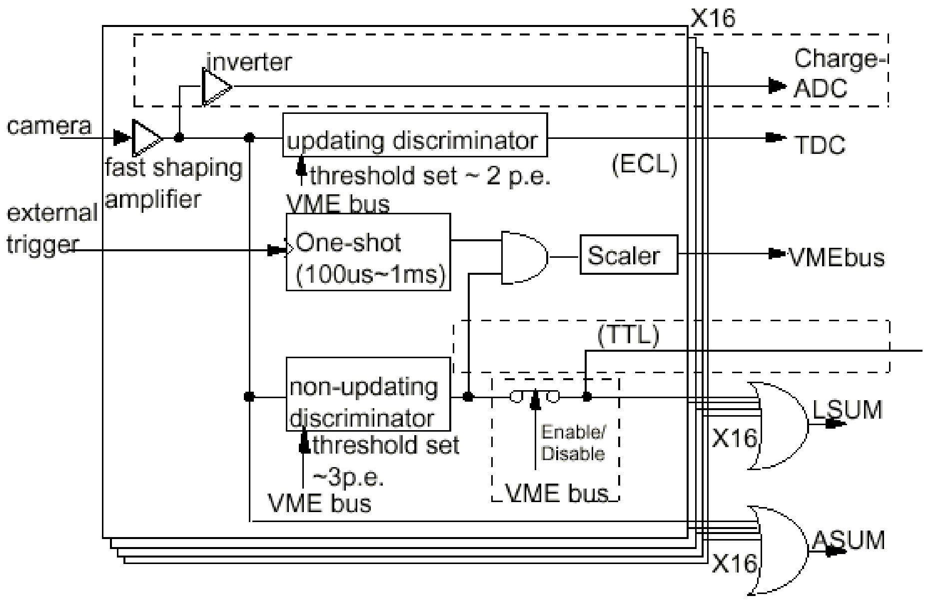
New imaging camera

- 427 PMTs（3/4”）arranged in hexagonal shape
- 0.17° pixel
- FOV ~4°
- Light weight (<100kg)



New electronics

- VME-based module
  - Frontend (Discriminator and summing) module
  - Charge ADC
    - 16bit ADC chip for each channel
    - 150ns internal delay
  - TDC
    - 1nsec resolution
    - 256nsec window
- Electronics hut on telescope verandah
  - remote controllable



Schedule

- FY2000: production of the 2nd telescope
- FY2001: installation of the 2nd telescope / start of stereo observation / production of the 3rd telescope
- FY2002: installation of the 3rd telescope / production of the 4th telescope
- FY2003: installation of the 4th telescope / start of observation by the full array

（Japanese FY: April to March)

Summary

- CANGAROO telescope is watching the TeV gamma-ray sky from Woomera, SA.
- We have observed eight AGNs since 1993.
- Preliminary results imply the detection of gamma-ray emission from Mrk421 in the energy range above 10 TeV in Feb/Mar 2001.
- There is no evidence of gamma-ray emission from any other AGNs during our observations up to now.
- An array of four 10m imaging telescopes will be ready in 2003-4 for high sensitivity observation.