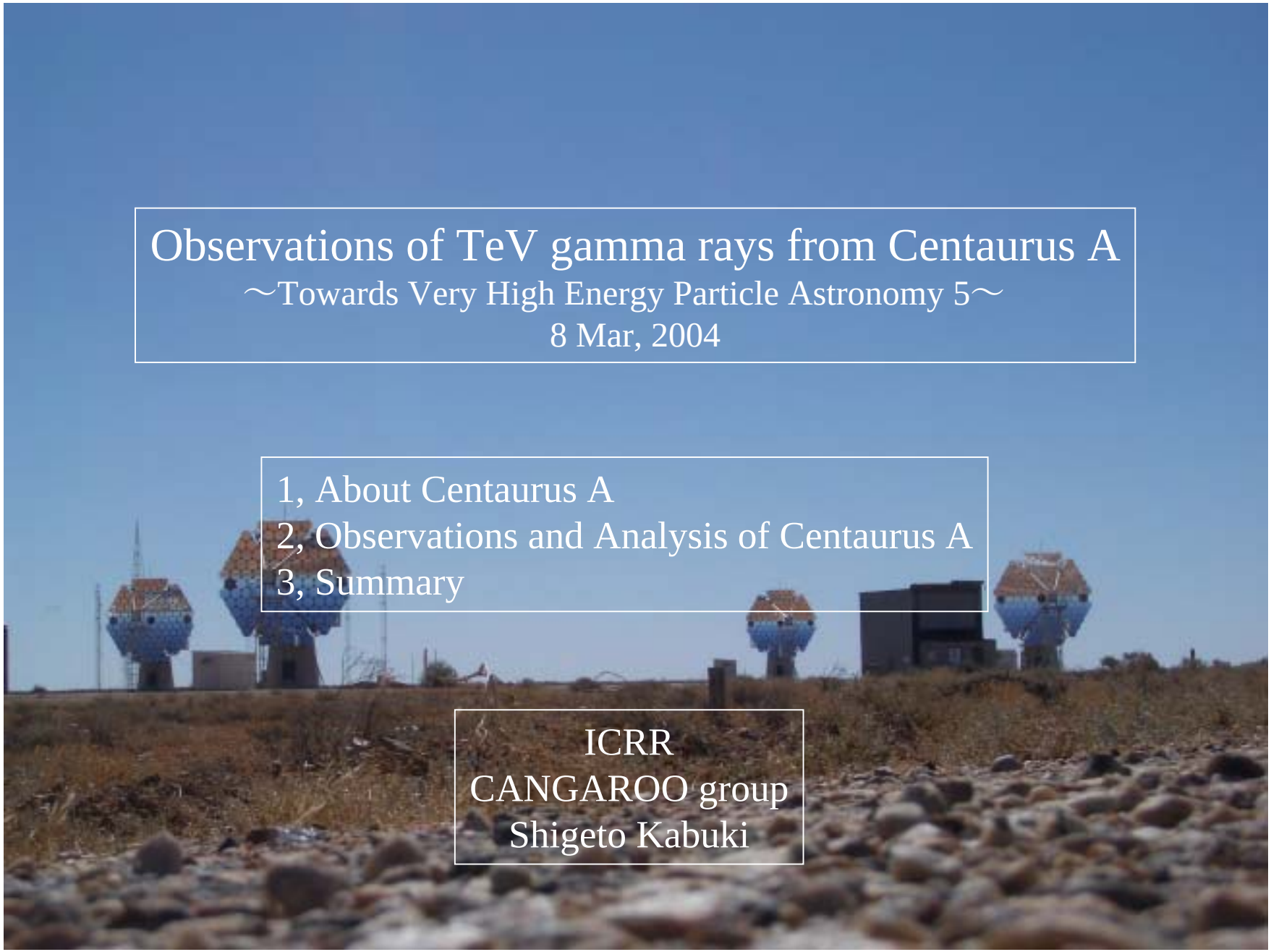


Observations of TeV gamma rays from Centaurus A

～Towards Very High Energy Particle Astronomy 5～

8 Mar, 2004

1, About Centaurus A
2, Observations and Analysis of Centaurus A
3, Summary

ICRR
CANGAROO group
Shigeto Kabuki

Active Galactic Nuclei (AGN)

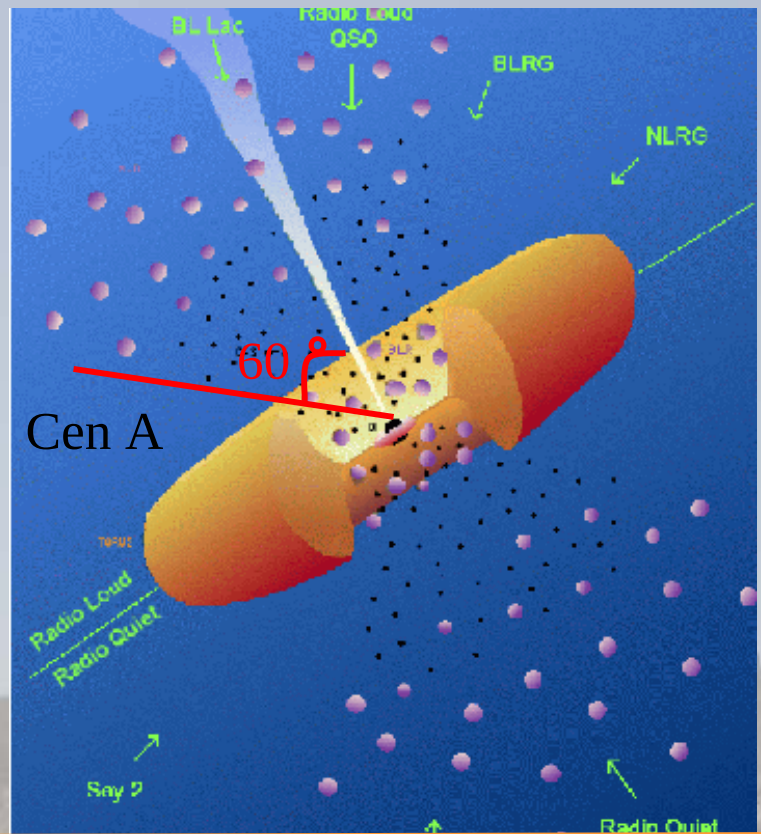
Galaxy 10% ⇒ AGN

AGN - Time variation (1000sec)
- It is 100 or more times brighter than the star of the whole galaxy.
- A massive black hole (MBH) is in a nucleus.

AGN 10% ⇒ Jet (Blazer)

Jet - Radio lobe
- Hot spot
- Knot

AGN unification model



This model is accepted below the X-ray energy region.
How is it in TeV energy?

Active Galaxy Centaurus A

About Centaurus A

Elliptical
Radio galaxy
Fanaroff-Riley type I
Misaligned BL Lac (~ 60^{o})
Distance 3.5 Mpc
First source of AGN
in the TeV region

Parameter	value
α(J2000)	201^{o}.3650633
δ(J2000)	-43^{o}.0191125
Galaxy Size	18 × 14 arcmin
Radio Source size	8 × 4 degrees
Distance	3.5 Mpc
Apparent Magnitude	7.96 mag
Total galaxy mass	(4±1) × 10^{11} M
Outer radio lobe	250 kpc
Inner radio lobe	5 kpc
Inner radio jet	1.35 kpc
Relativistic nuclear jet	1.65 pc
Radio core	0.008 pc
Dust lane radius	7 kpc

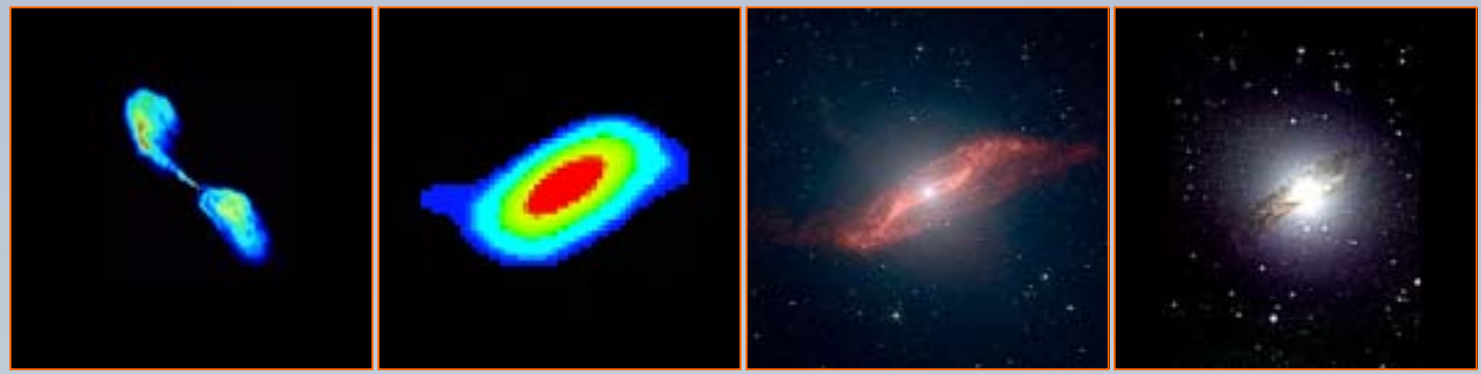
The Optical image of Centaurus A
(ESO/MPG 2.2-m telescope with WFI)

Multiwave images

Image Size = 15 × 14 arcmin

（We have observed the center region this time.）

0.25°



Radio
VLA(6cm)
4.9GHz

Far infrared
IRAS
60-100μm

Mid infrared
Spitzer
3.6 to 8μm

Near infrared
2MASS
1.2-2.17μm

One event resolution

CANGAROO-III
Angular resolution

Gamma

X-ray
Chandra
1-3 KeV

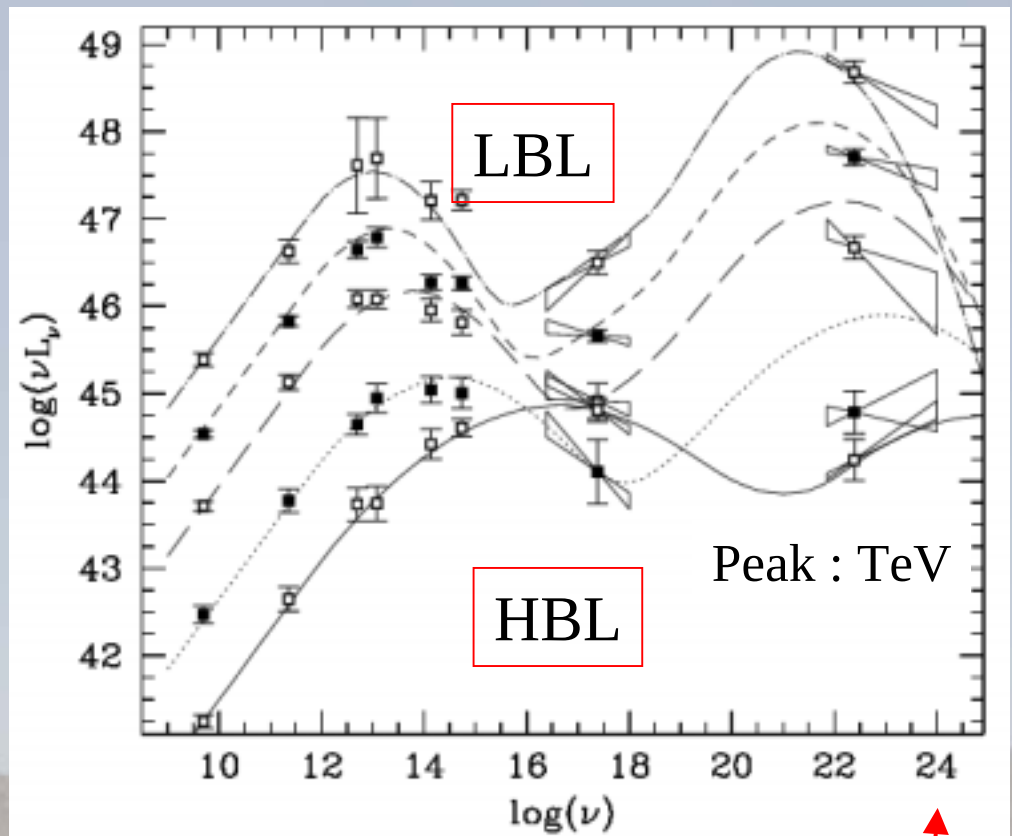
Ultraviolet
GALEX
130-300nm

Visible
DSS
405-645nm

Synchrotron self-Compton model

- Double-peaked structure
  = synchrotron
  + inverse Compton
  (Synchrotron Self Compton model)

$$\frac{L_{sync}}{L_{IC}} \sim 1$$



Observation

Observation by two telescope mode was performed this time.

← The 4th telescope was constricted in March 2004.

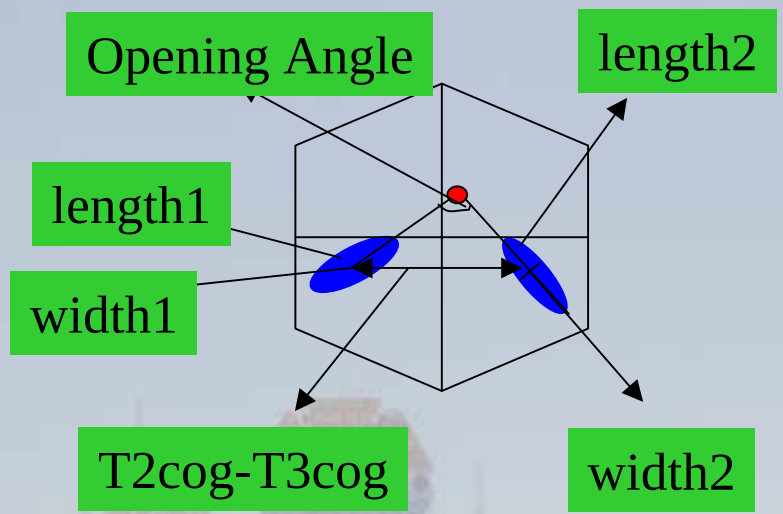
Three fold coincidence mode was not performed.

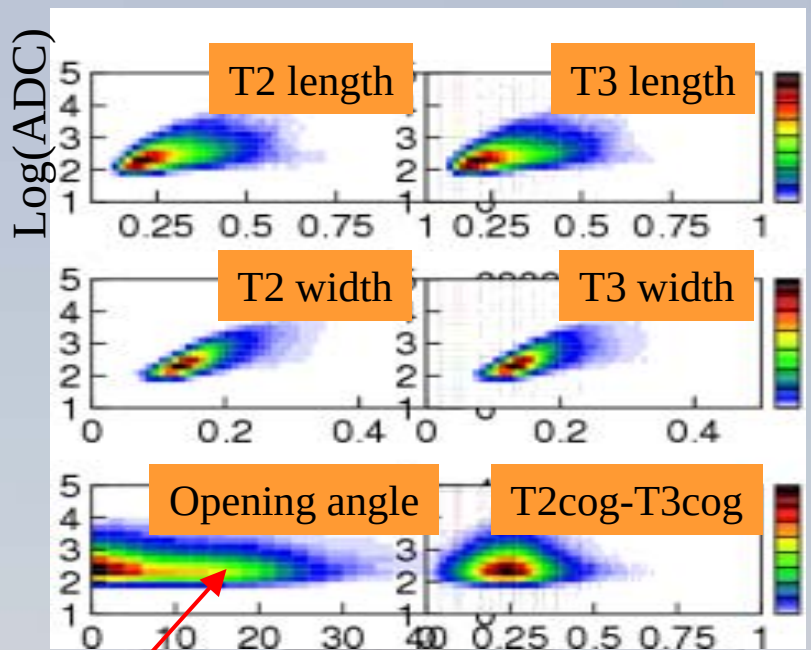
The stereo events were selected in the offline analysis.

Centaurus A

Observation term	Observation time (T2-T3)	Observation time (T2-T4)	Average zenith angle
15 – 28 Mar 2004	603 min	414 min	17 degree
15 – 28 Apr 2004	444 min	468 min	17 degree
Total	1047 min	882 min	

Analysis method : Likelihood cut





Probability density function (PDF)

→ Gamma ray

→ Proton

PDF of normalization is unsuitable.

↓

Quantity like probability

Likelihood analysis

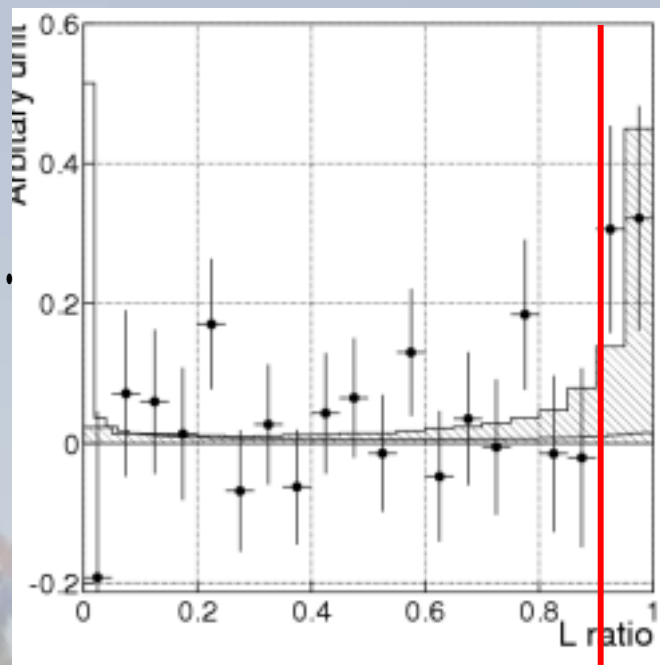
Likelihood parameters

L(gamma-ray)=PDF(length1(g))*PDF(width1(g))
*PDF(length2(g))*PDF(width2(g)) ・・・
L(proton)= PDF(length1(p))*PDF(width1(p))
*PDF(length2(p))*PDF(length2(p)) ・・・

L ratio

$$Lratio = \frac{L(gamma-ray)}{L(gamma-ray)+L(proton)}$$

L ratio distribution of Crab

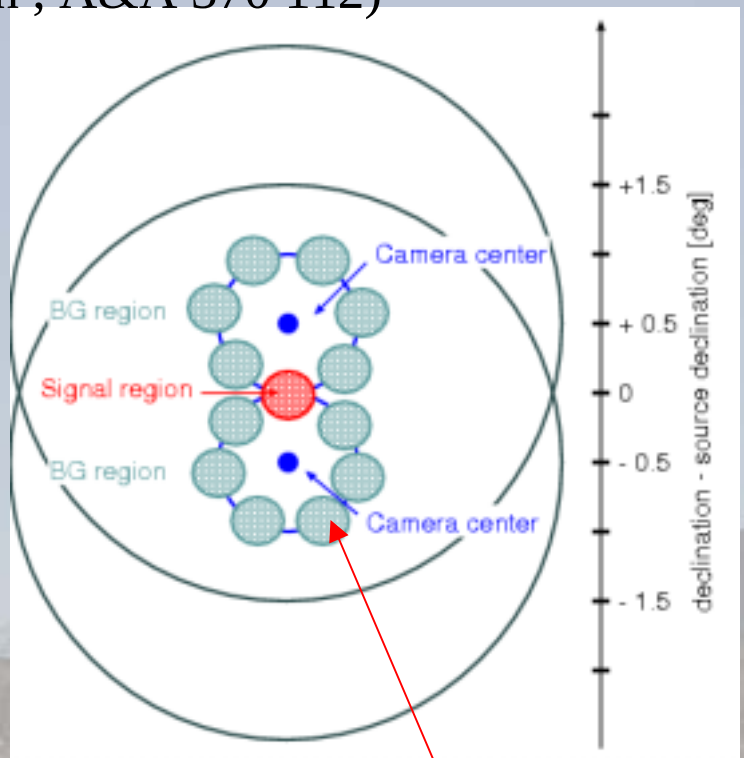


0.9

Hatched : MC (gamma ray)
Blank : OFF
Points : ON (square cut)

BG region selection

Wobble mode
(HEGRA Aharonian , A&A 370 112)



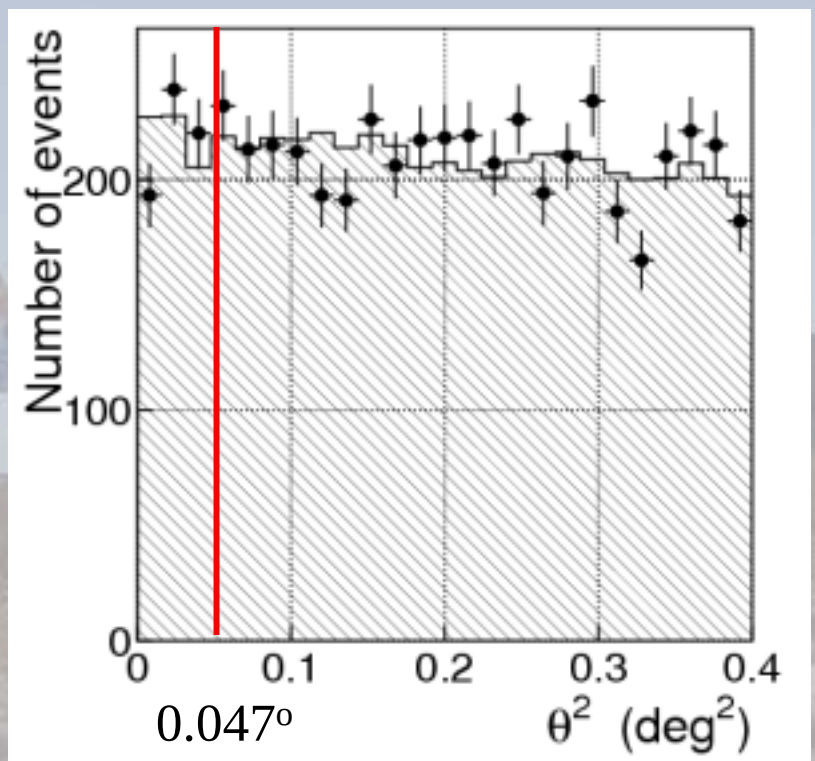
Number of BG region is 6.

We can gain 6 times as many as statistics.

These circle radius:
0.217^{o} deg (θ^2=0.047)

Centaurus A result

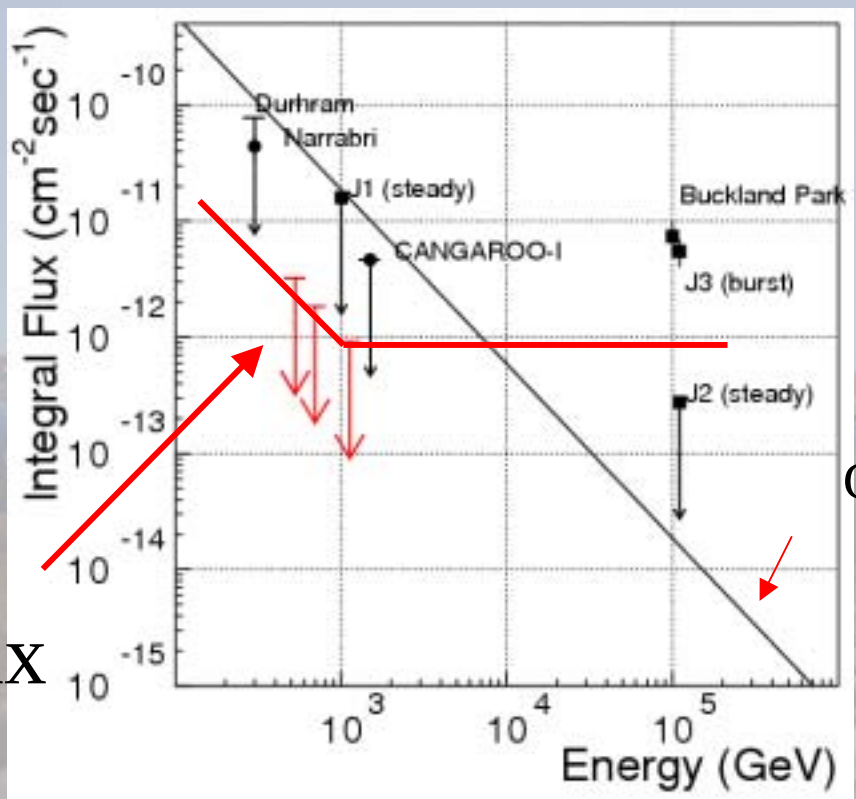
θ^2 distribution



Hatched : OFF
Points : ON

Comparison with the past data

Energy bin (GeV)	530	700	1120
2 σ upper limit flux ($\times 10^{-12}$cm^{-2}sec^{-1})	3.2	1.8	0.9



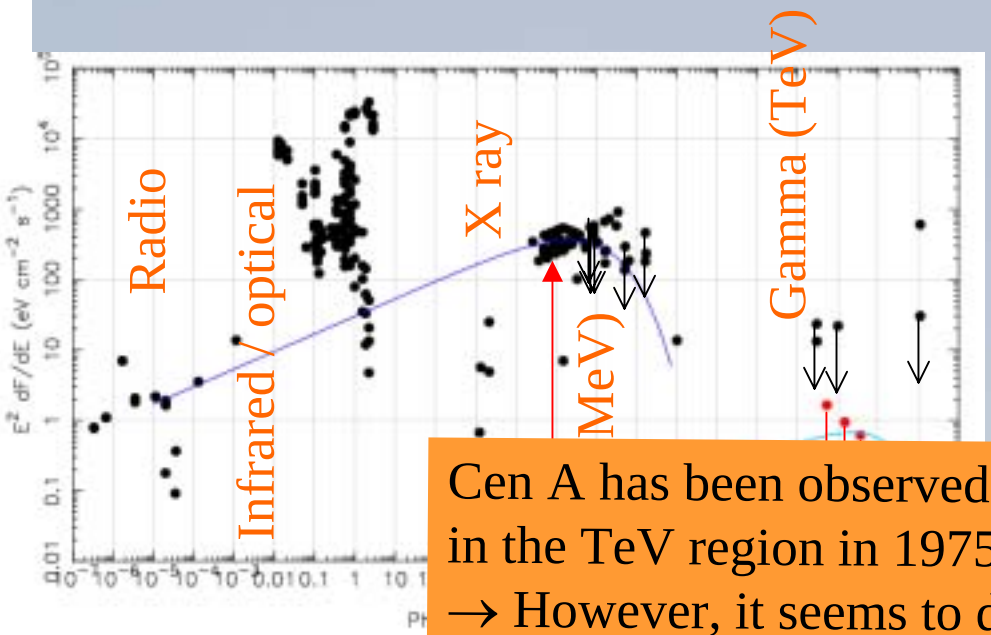
7% Crab Flux

Crab flux

0.1 Flux

Our limits are 10 times lower flux than previous result.

Possibility on HBL assumption



Cen A has been observed for the first time in the TeV region in 1975.
→ However, it seems to differ from typical AGN.

peak

IC peak

Typical AGN model

$\nu_{ssc} / \nu_{sync} \sim 10^{8}$

$L_{ssc} / L_{sync} \sim 1$

But Cen A…

$1/400 << 1$

$U_{sync} \sim 6eV/cc$

$U_B > 400 U_{sync} = 2400 eV/cc$

$U_B = 1/8\pi B^2$

$B > 210\mu G \times (R/12kpc)^{-1}$

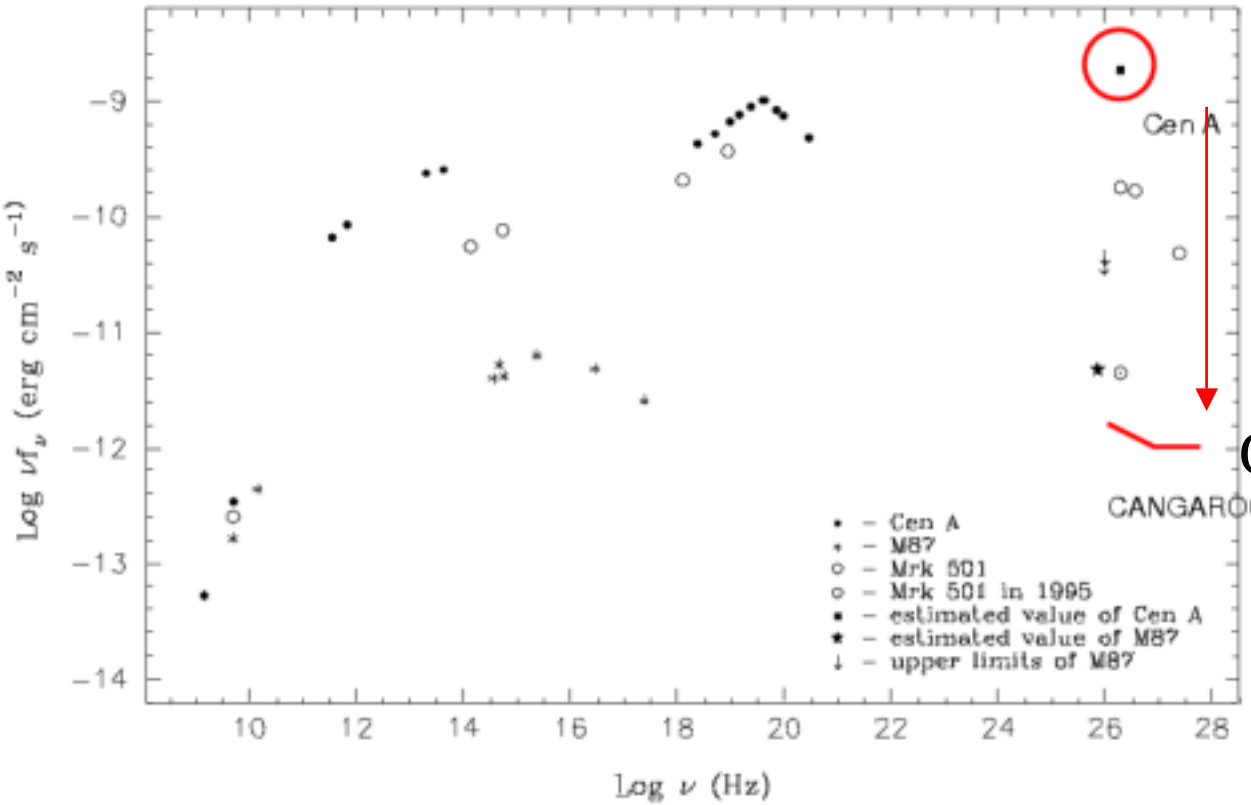
R ~ pc (acceleration region size)

→ B ~ G

$$\frac{L_{ssc}}{L_{sync}} = \frac{U_{sync}}{U_B}$$

$$U_{sync} = 4\pi R^2 c \delta^4 U_{sync}$$

Estimation of Flux



Bai estimation

1000 times lower than estimation

CANGAROO-III

Bai, J.M. et al 1999

F(0.25-30TeV)=6.4×10^{-9}erg cm^{-2} s^{-1} : Bai

F(530GeV<) =2.6×10^{-12} erg cm^{-2} s^{-1} : CANGAROO-III

Upper limit on density of CDM

Cen A → Giant Galaxy
3.5 Mpc

The annihilation rate of the CDM can be written,

$$< \sigma v > B_{q\bar{q}} n^2$$

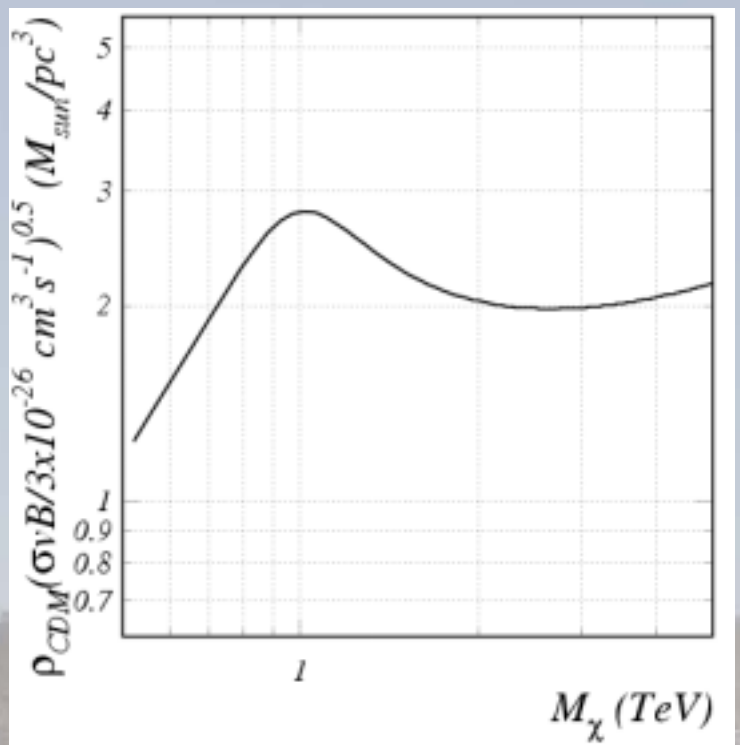
The accelerator measurement on the fragmentation function

$$\frac{1}{\sigma_h}\frac{d\sigma}{dE / M_\chi}$$

is limited to lower energy of such as 100 MeV.

Gamma-ray flux is written

$$\left[\frac{dF}{dE}\right] = \frac{< \sigma v B_{q\bar{q}} > \rho_{CDM}^2 \left[V/(4\pi d^2)\right]}{M_\chi^3} \cdot \left[\frac{1}{\sigma_h} \cdot \frac{d\sigma}{d(E/M_\chi)}\right]$$



The limit of Cen A CDM is 100 times bigger than our galaxy.

Conclusion

- In CANGAROO-III, three telescopes were extended and stereo observation started.
  In this result, the energy threshold is 500GeV and angular resolution is 0.16^{o}.
- The significant signal were not detected using 2-dimensional Likelihood.
  The upper limit of 2σ of $0.32\times10^{-11}cm^{-2}sec^{-1}$ was given by the observation of 1050 minutes.
  Furthermore, when Cen A is HBL, we can give the following limits,

  $$L_c/L_s < 1/400 < 1,$$

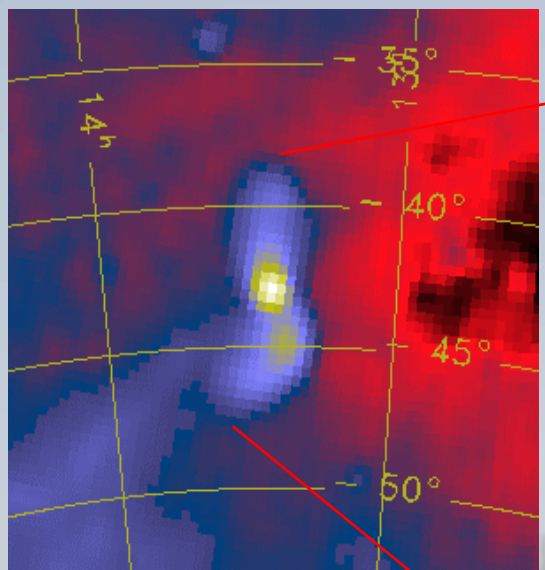
  $U_B > 400$ U sync= 2400eV/cc, and

  $B > 210\,\mu G(R/12kpc)^{-1.}$

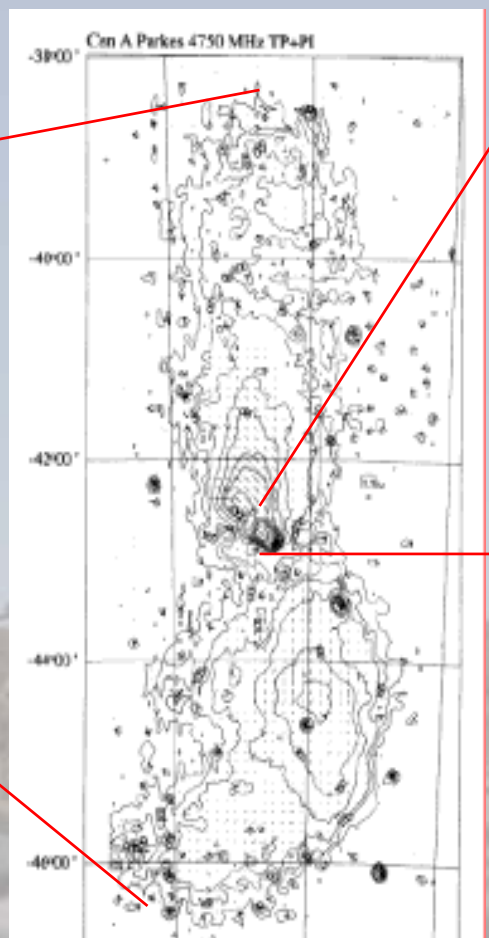
  In this observation period, the flare was not observed.
  The variation in a TeV region was also quiet.
- Although restriction of CDM was 100 times as large as the mass of the Galaxy, this is the first result of Cen A.

Appendix : Radio Structure

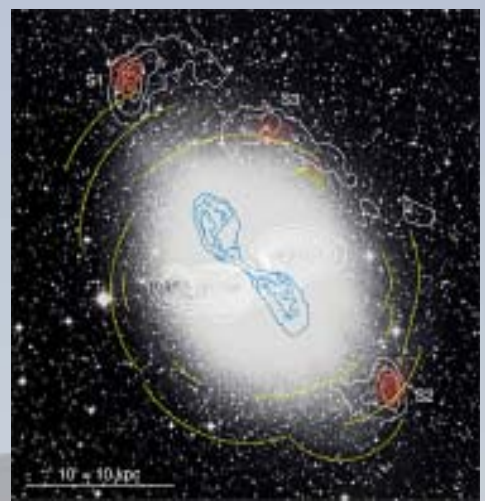
30 kpc ~ 0.3°



Outer lobes (408MHz)
(20°×20°, Haslman 1982)



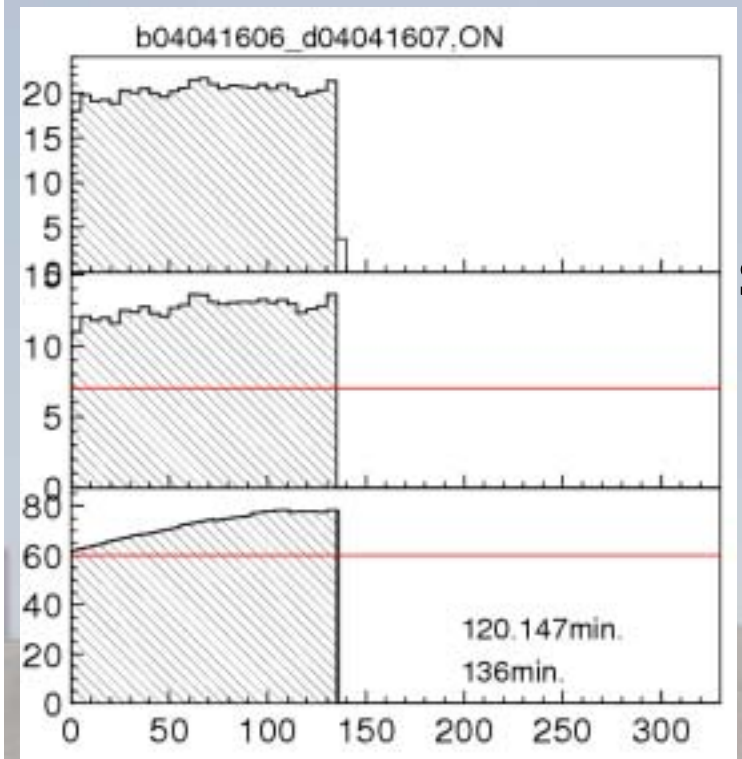
Outer lobes 6.9cm(4.75GHz)
(5°×9°, Junkes 1993)



Blue : Radio jet
Red : CO
White : Atomic hydrogen gas
Yellow : shell
(32' ×32', Charmandaris 2000)

Appendix : Data reduciton

Good conditon

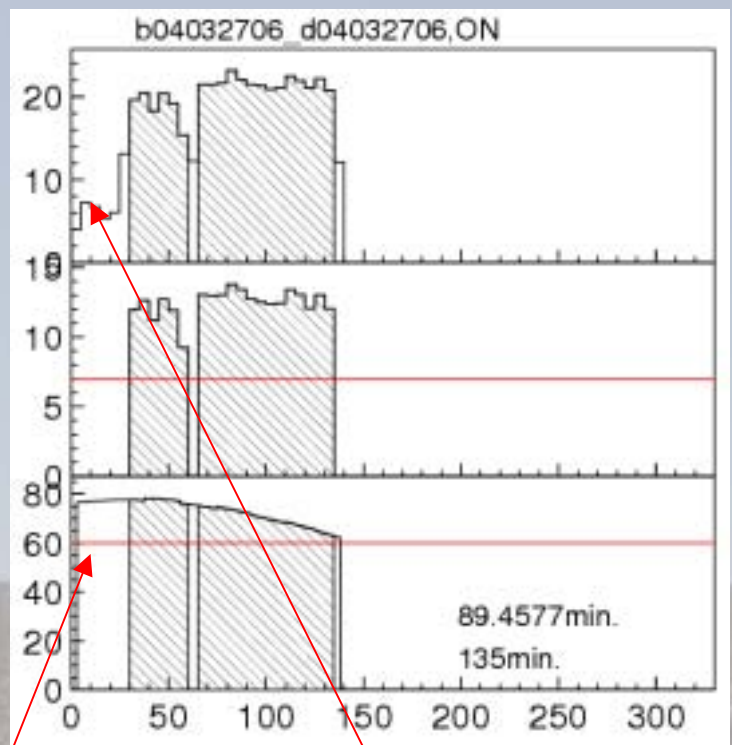


Event rate

Shower rate

Elevation

Bad condition

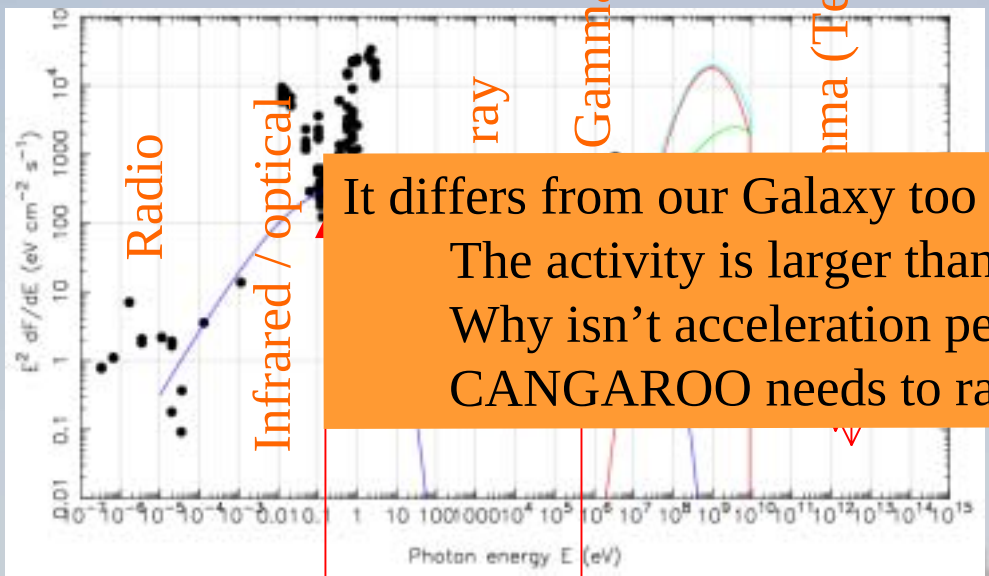


Elevation cut

Cloud cut

Appendix : Difficulties on LBL assumption

Assume SSC model



Typical AGN value

$$\nu_c / \nu_s \sim 10^8$$

$$L / L \sim 1$$

It differs from our Galaxy too much.

The activity is larger than our Galaxy.

Why isn't acceleration performed to the TeV region?

CANGAROO needs to raise sensitivity further

We can not explain LBL physics.

Synchrotron peak

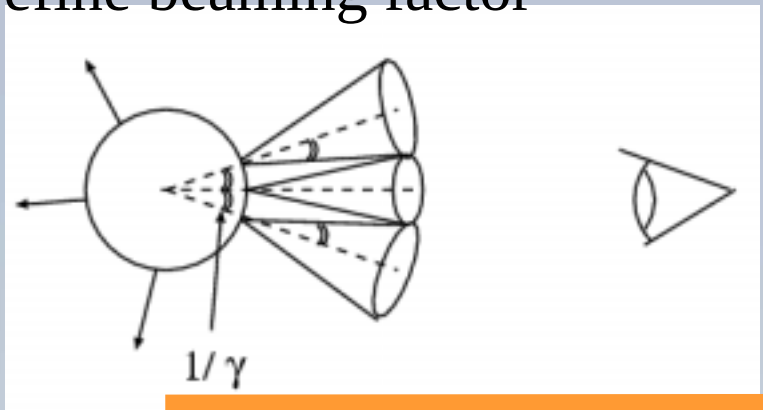
IC peak

HBL model ?

Appendix : Relativistic beaming effect

The gamma-ray is undetectable.→ The problem of angle of the jet?

Define beaming factor



$$\delta = \{\gamma\,(1-\beta\,\cos\theta)\}^{-1}$$

Blazer q ~ 1/ γ

δ ～ γ ～10

In this result, gamma-rays were not detected
in the TeV region.
Cen A may not belong to the unification model of AGN.

The

If 60 degree of Mrk501 lean like Cen A,

a typical value, γ ～5, and p～ 3 are used,

the flux changes

1.3×10^{-4}.

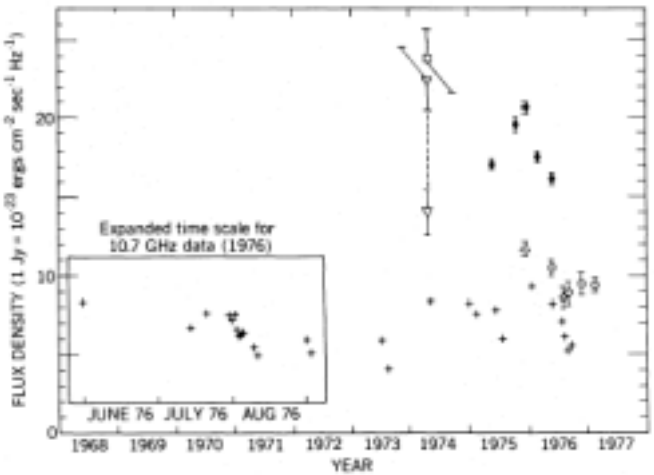
If Mrk501 assumes that it is in the same distance as Cen A

$(\mathrm{Mrk501/CenA})^2=(0.034/0.0008)^2=1.8\times10^4$

Even if 60 degrees leans like CenA, the signal should be detected.

Appendix : Time variation of Cen A

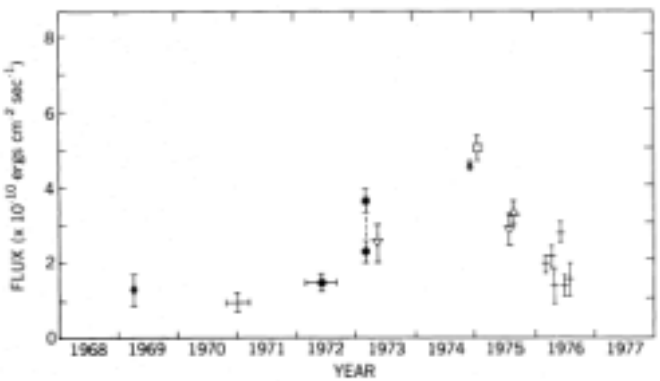
Radio
10.7~ 90 GHz



Graf and Price (10.7 GHz) = +; Dent and Hobbs (31.4 GHz) = ϕ, (85.2 GHz) = ϕ; Kellermann (31.5 GHz) = ϕ, (89 GHz) = ϕ; Conklin and Ulich (90 GHz) = ϕ.

FIG. 1.—Radio emission from the nucleus of Cen A. Data taken from Price and Stull 1973, Stull and Price 1975, Dent and Hobbs 1973, Kellermann 1974, and current observations.

X ray
2~6 KeV

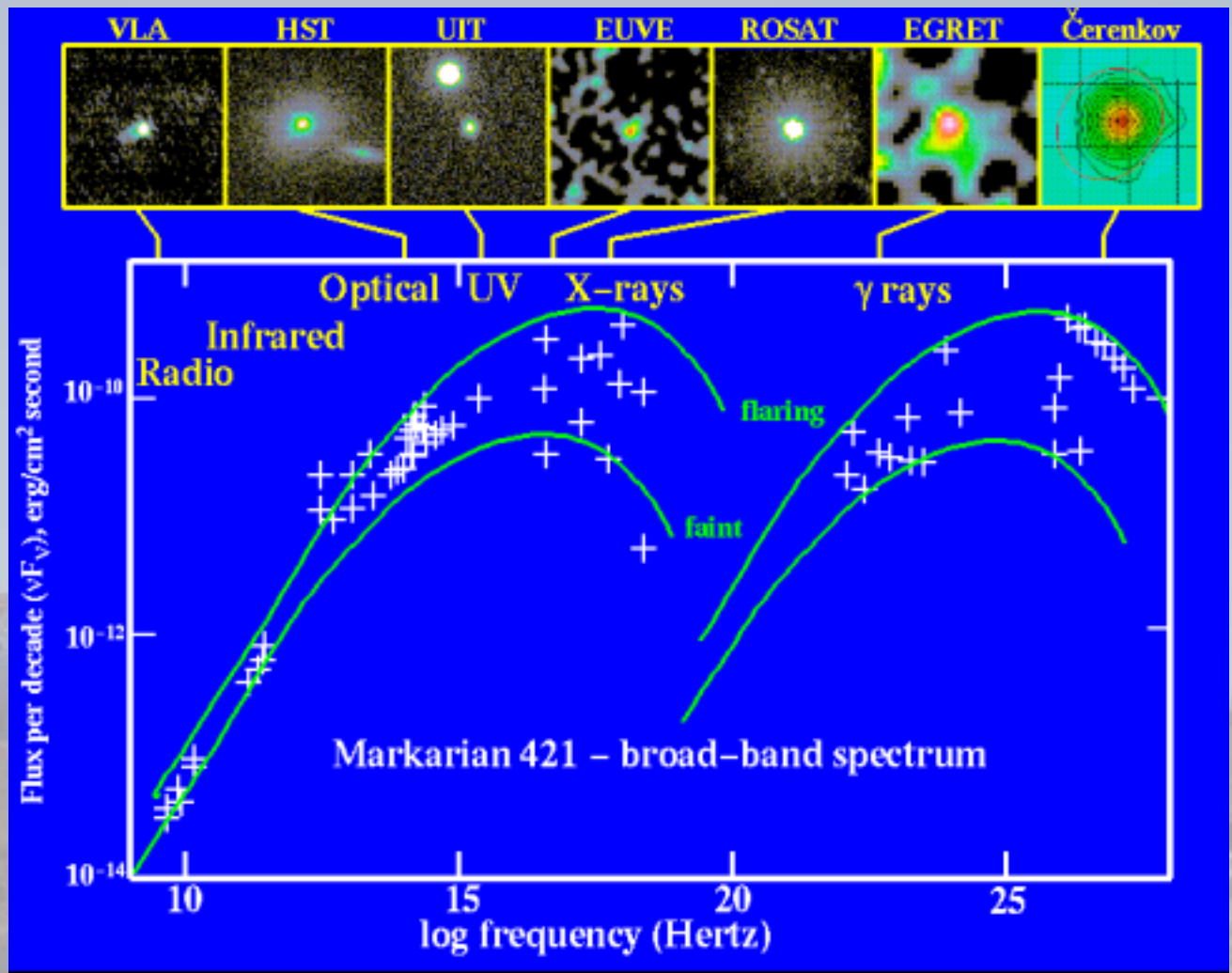


Lampton et al. (Rocket) = ϕ; Tucker et al. (Uhuru) = ϕ; Winkler and White (OSO-7/MIT) = ϕ; Davison et al., Stark et al. = ϕ; Stark et al. (Ariel V) = ϕ; Grindlay et al. (ANS) = ϕ; Stark et al. (Copernicus) = ϕ; Serlemitsos et al. (OSO-8) = ϕ; Sanford (Copernicus) = ϕ.

FIG. 2.—History of Cen A 2–6 keV X-ray flux. Data taken from Lampton *et al.* 1972, Tucker *et al.* 1973, Winkler and White 1975, Davison *et al.* 1975, Stark *et al.* 1976, Grindlay *et al.* 1975*b*, Serlemitsos *et al.* 1975, Sanford 1976.

Beall 1978

Appendix : Time variation of Mrk 421



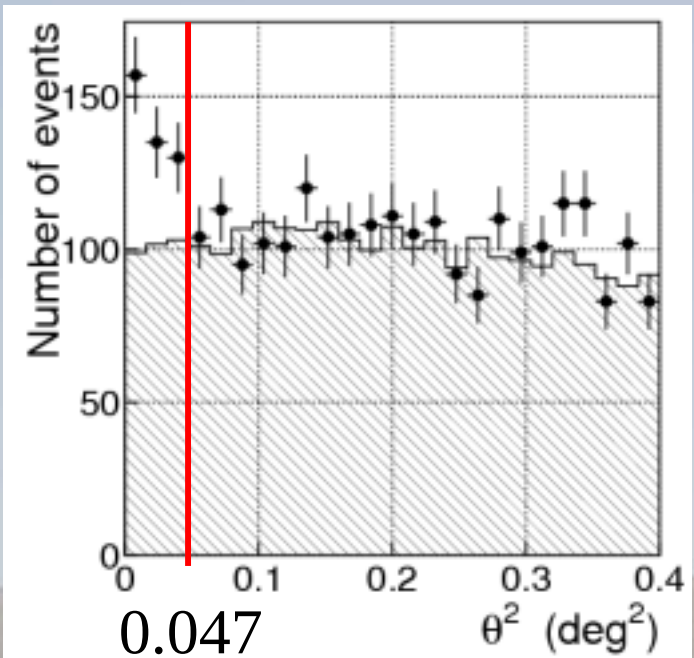
Appendix : Crab Analysis

- Crab

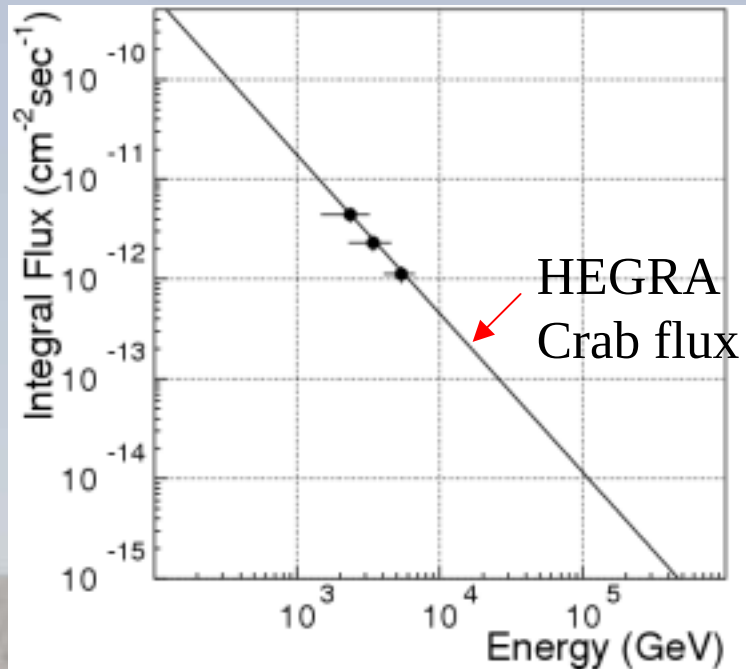
Observation date	Observation time (T2-T3)	Average zenith angle
15 – 28 Dec, 2003	1215 min	62 degree

Appendix : Likelihood : Result

θ^2 distribution
L : 0.9 <



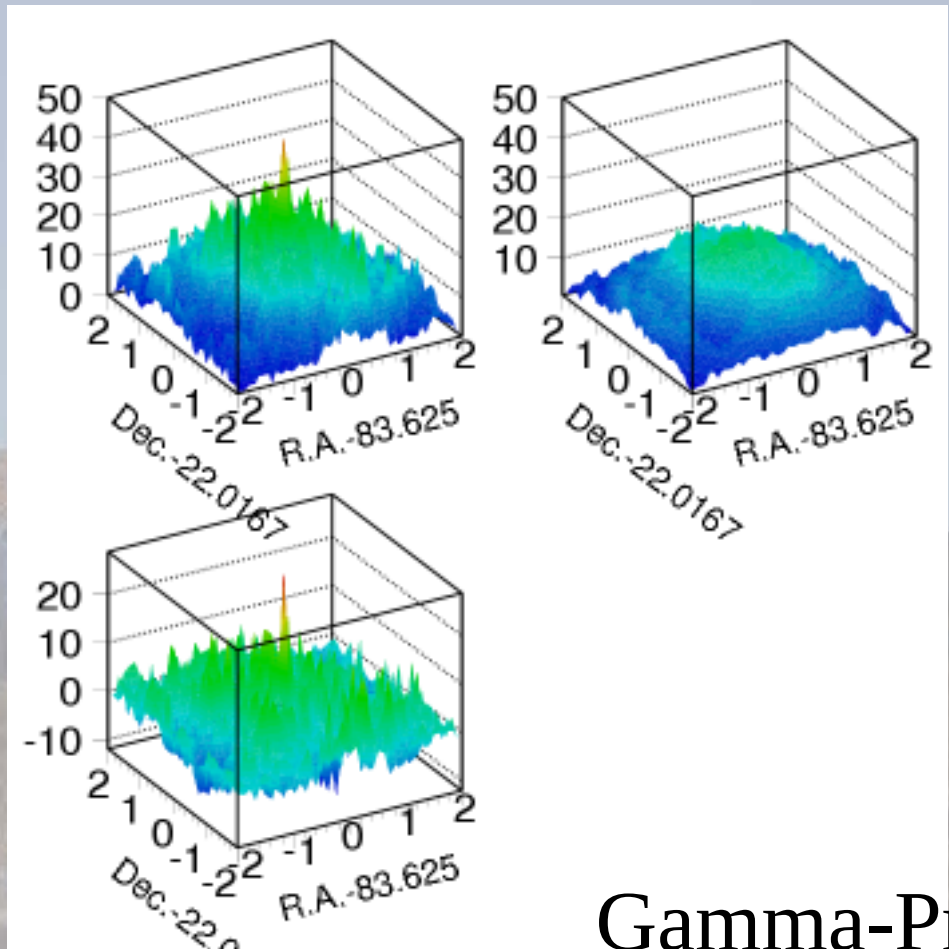
Integral Flux
L : 0.9 <



Excess : 123±21 event (@2350GeV)
Significance : 6.0 σ
1 Crab : 125 event/840.3 min.

Appendix : Crab arrival point map

Gamma
L>0.9



Proton
L<0.2

Gamma-Proton