
CANGAROO-III解像型大気チェレンコフ望遠鏡による
活動電波銀河Centaurus Aからの
TeVガンマ線の観測
Feb 23, 2005 ICEPP Symposium
１、宇宙線を観測
２、検出原理
３、CANGAROO-III telescopes
４、Centaurus A観測、解析
５、まとめ
宇宙線研究所
CANGAROO グループ
株木 重人

宇宙線の起源

宇宙線

Power-law ↔ Non-thermal origin

Energy density 1eV/cm^3
Life 10^6~10^7 years

ガンマ線

高エネルギーまで加速された電子、陽子

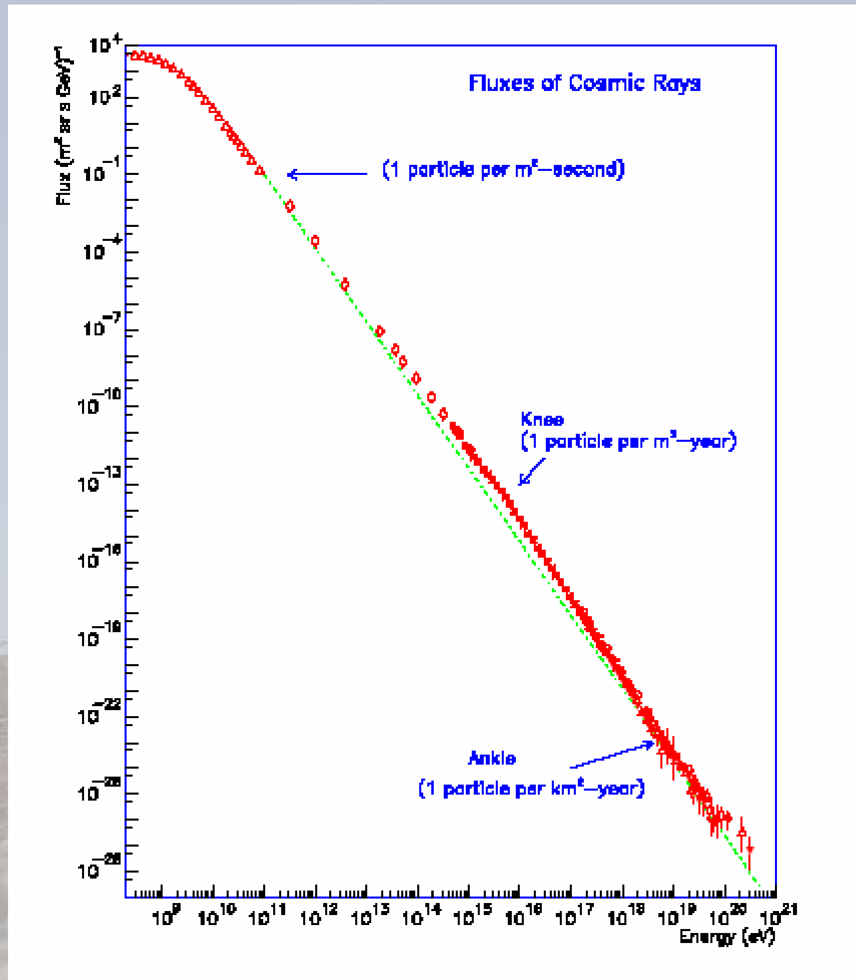
↓

ガンマ線の発生

↓

地球まで直進してくる。

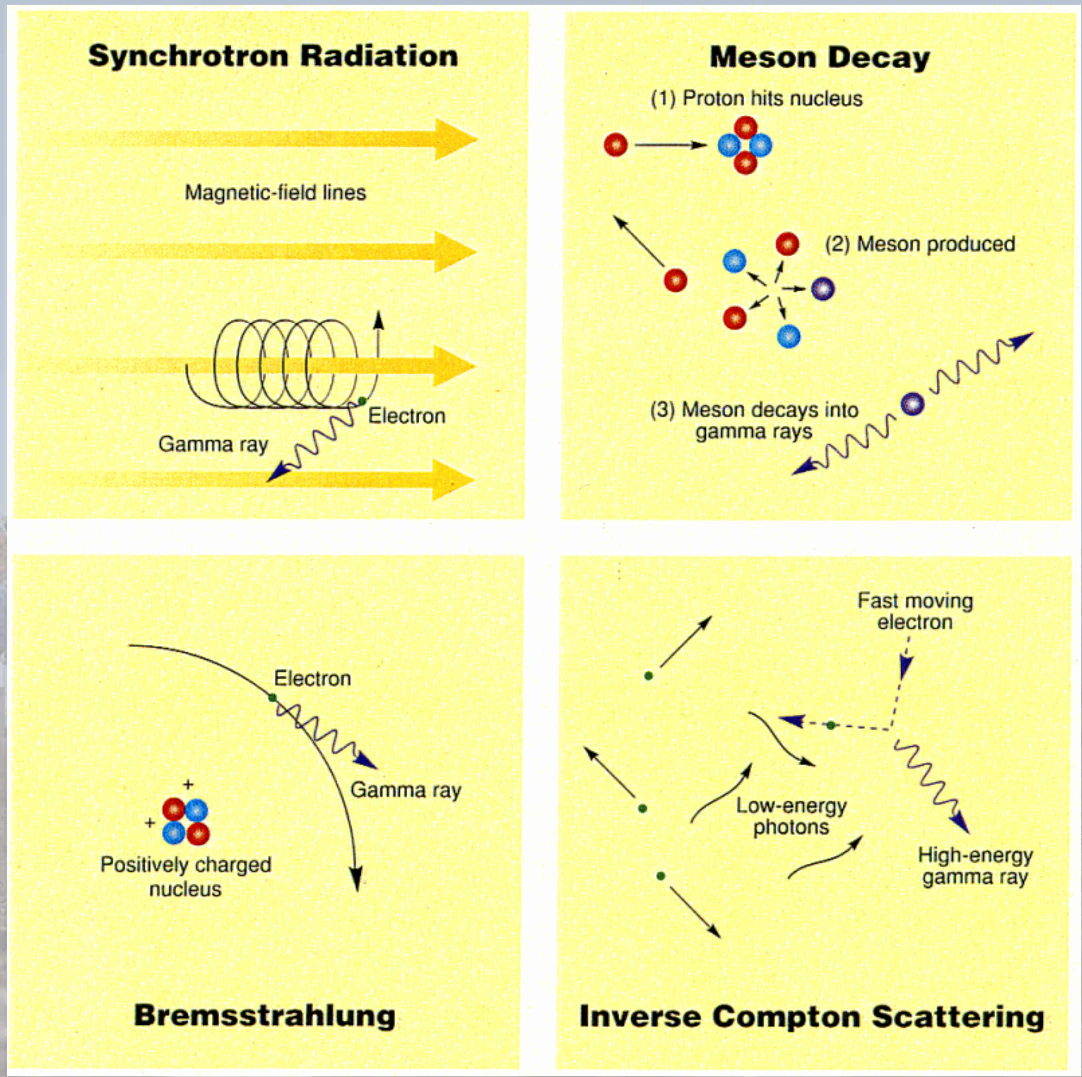
我々の銀河での宇宙線スペクトル



ガンマ線の放射機構　:　非熱的

High energy electron + magnetic field

High energy electron + atomic electric field



High energy proton + matter

High energy electron + photon field

Active Galactic Nuclei (AGN)

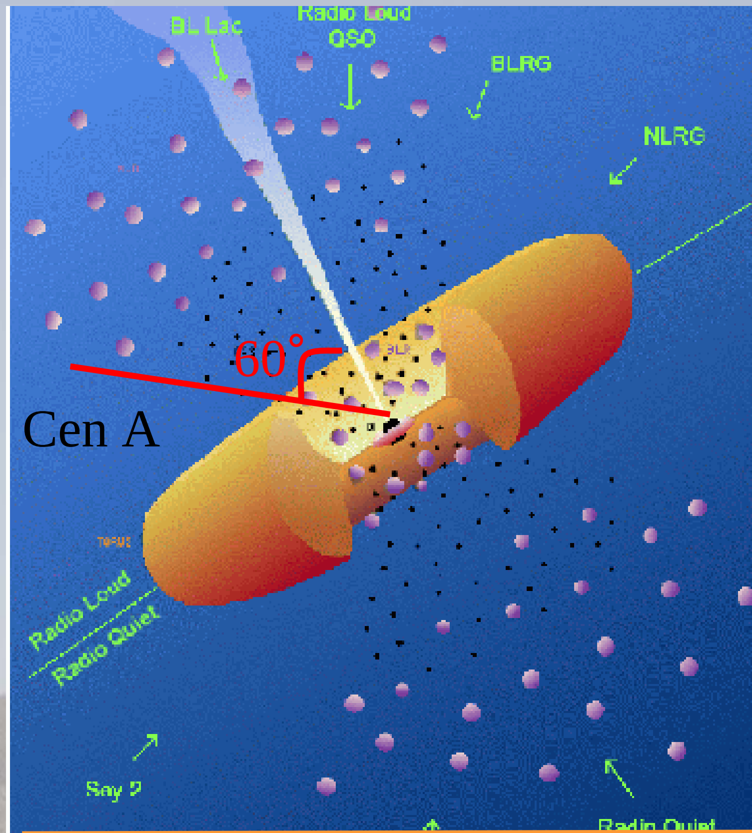
Galaxy 10% ⇒ AGN

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 nuclei.

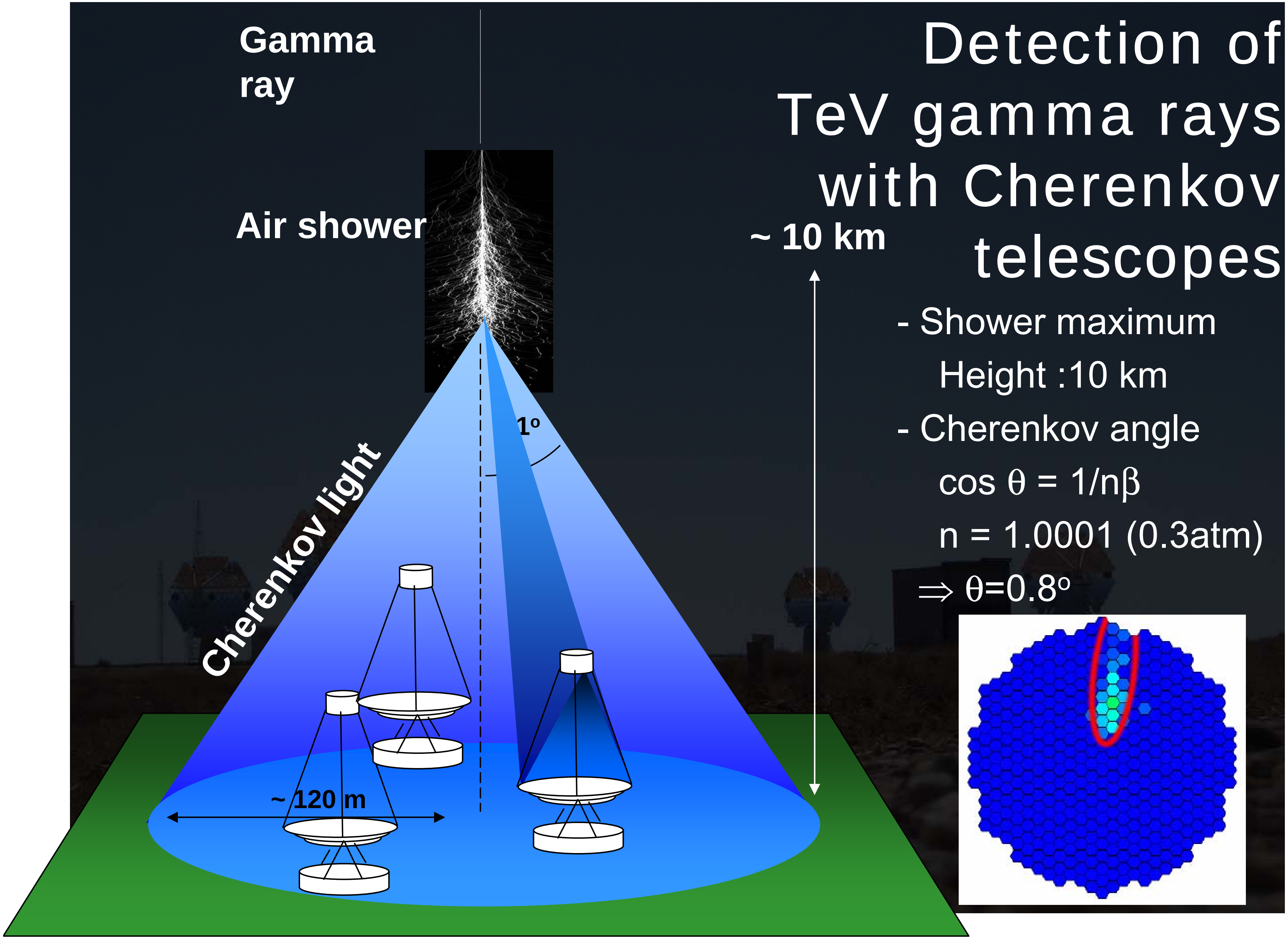
AGN 10% ⇒ Jet (Blazer)

Jet - Radio lobe
- Hot spot
- Knot

AGN 統一モデルによる分類

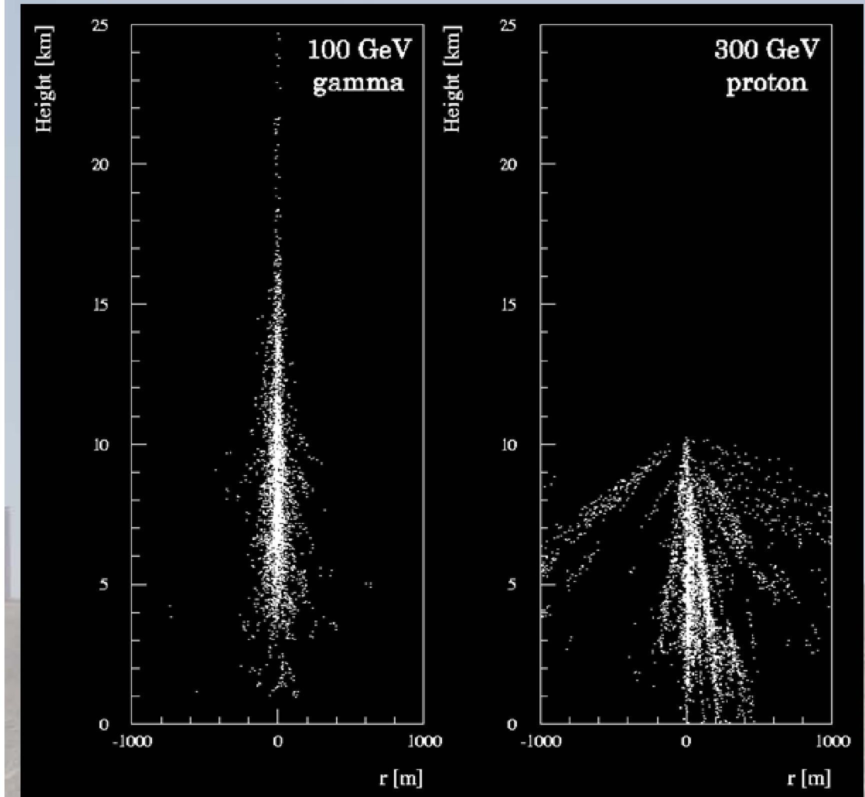


この統一モデルはX-ray 以下のエネルギーで良く合う。
ではTeV領域ではどうか？


Detection of TeV gamma rays with Cherenkov telescopes
Gamma ray
Air shower
Cherenkov light
1º
~ 10 km
~ 120 m
- Shower maximum Height :10 km
- Cherenkov angle
cos θ = 1/nβ
n = 1.0001 (0.3atm)
⇒ θ=0.8º

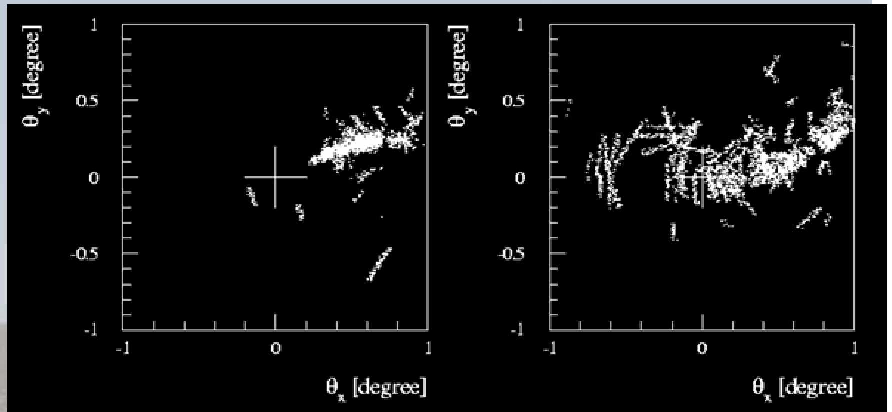
Cherenkov image

Gamma　Proton



カメラ面上でのシャワーイメージ
(MC Simulation)

Gamma　Proton

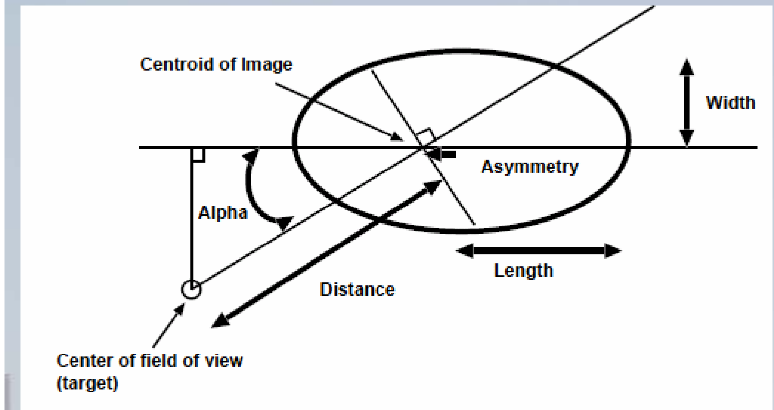


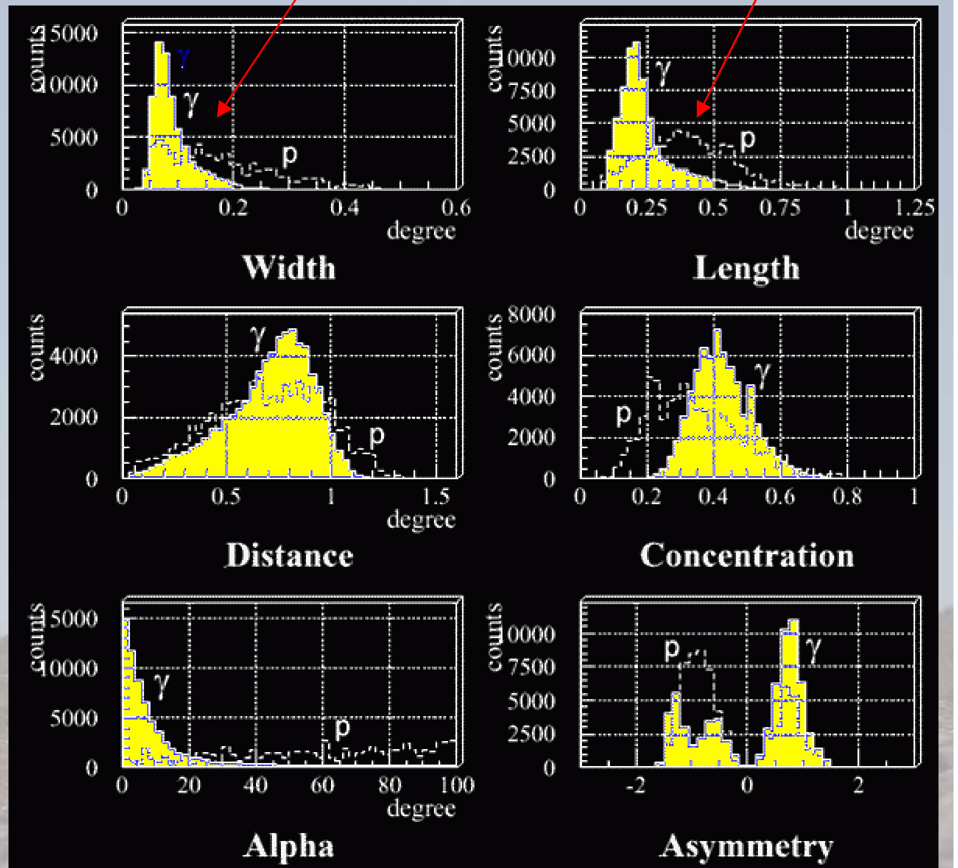
Sharp　Diffuse

Hillas parameters

Protonに比べgammaはイメージがシャープ

シャワーパラメータ





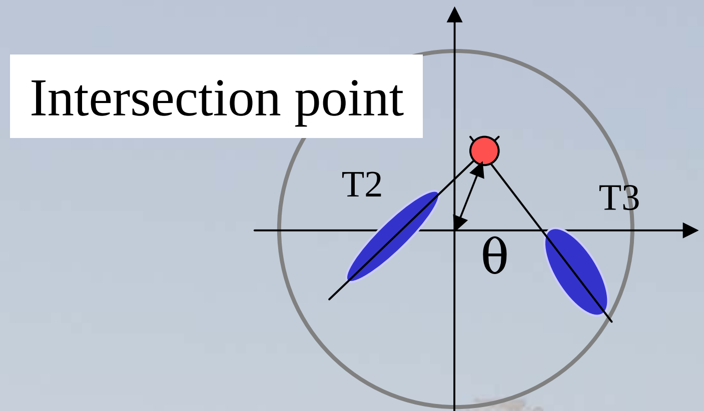
Stereo analysis

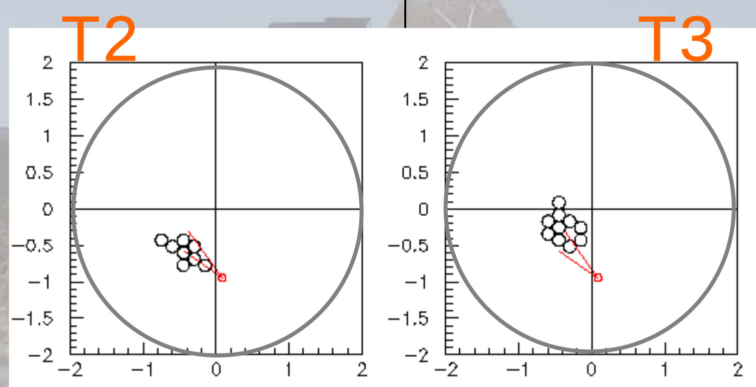
1. We can determine the direction of gamma-rays event by event.

2. We can explore the spatial structure of a gamma-ray objects as well as discriminate background cosmic-ray showers more efficiency.

3. The energy resolution of gamma rays has been improved the production height of Cherenkov light

- Shower reconstruction





“CANGAROO”

=

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

Observation of high-energy gamma-rays from celestial objects with imaging atmospheric Cherenkov telescopes in Woomera, Australia

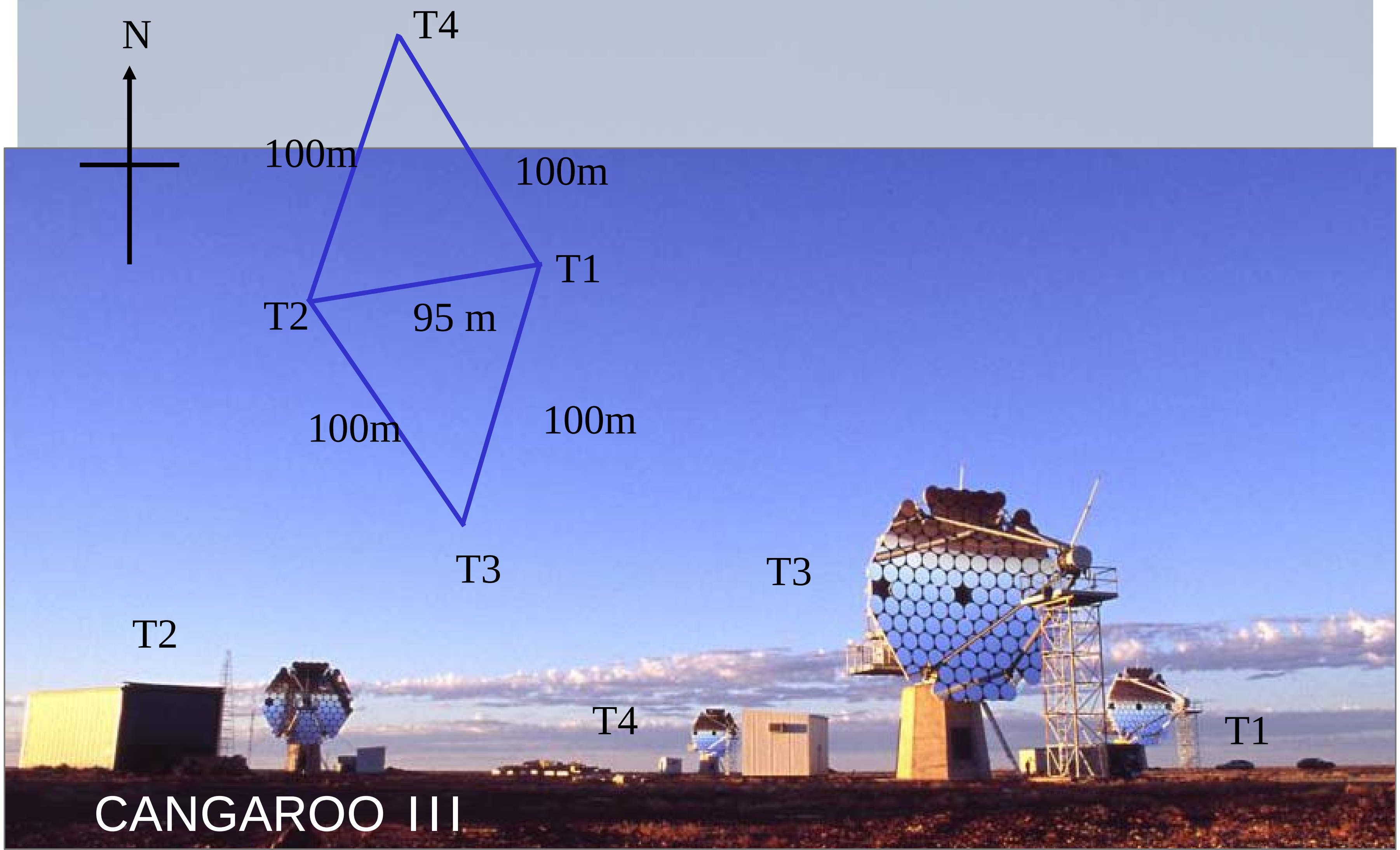
Woomera, South Australia

136^{o}.46’E, 31^{o}.06’, 220m a.s.l

CANGAROO team

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

CANGAROO-III Cherenkov telescopes



Reflector

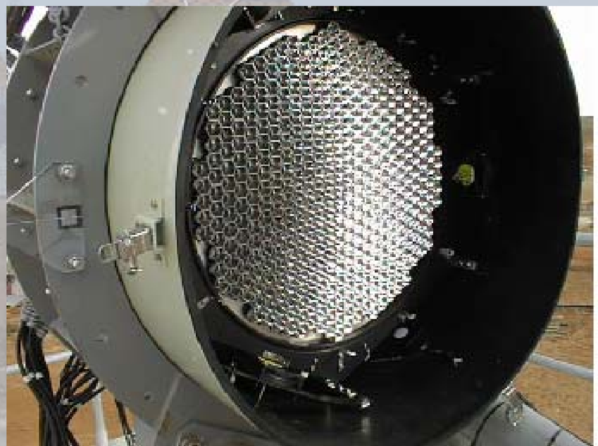
Frame	: parabolic
Diameter	: 10.4 m
Focal length	: 8 m
F	: 0.77
Total collecting area	: 57.3 m^2
Number of segments	: 114
Mirror diameter	: 80 cm
Mirror shape	: spherical
Mirror material	: GFRP

Camera

PMT (R3479, HPKK)

Light guide (LG)

Camera



Camera design

- Aluminum alloy
- Weight 110kg
- Diameter 800mm
- Length 1000mm
- 427 pixels
- Field of view 4°
  0.168°/pixel
- Hexagonal arrangement

-The characteristics of all PMT modules were calibrated individually.

-The linearity is up to 200 p.e.
-The deviation of uniformity is 11%.
-Light correction efficiency is 2 times up.

Active Galaxy Centaurus A

About Centaurus A

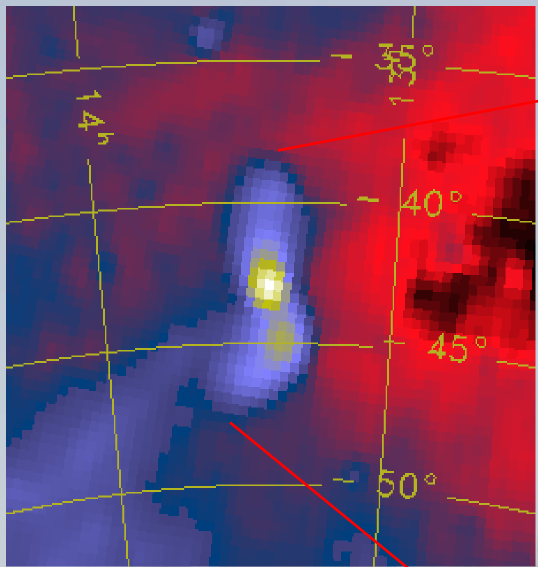
Radio galaxy
Elliptical
Fanaroff-Riley type I
Misaligned BL Lac (~ 60^o)
Distance 3.5 Mpc

Parameter	value
α(J2000)	$201^o.3650633$
δ(J2000)	$-43^o.0191125$
Galaxy Size	18×14 arcmin
Radio Souce size	8×4 degrees
Distance	3.5 Mpc
Apparent Magnitude	7.96 mag
Total galaxy mass	$(4\pm1) \times 10^{11}$ 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

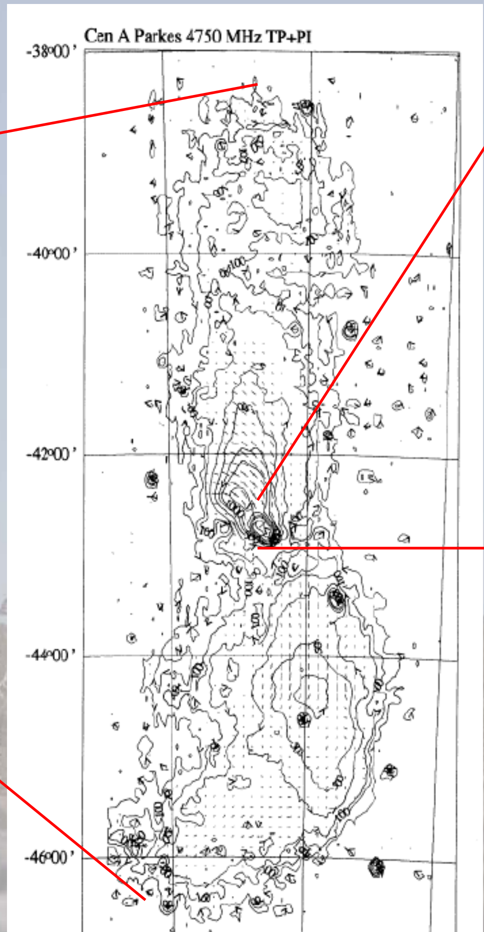
The Optical image of Centaurus A
(ESO/MPG 2.2-m telescope with WFI)

Radio Structure

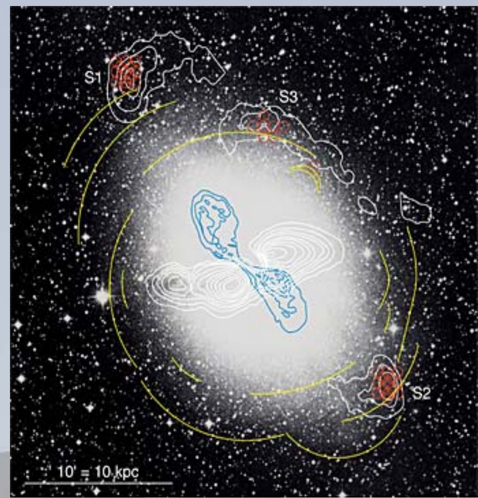
30 kpc ~ 0.3^o



Outer lobes (408MHz)
(20^o×20^o, Haslman 1982)



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



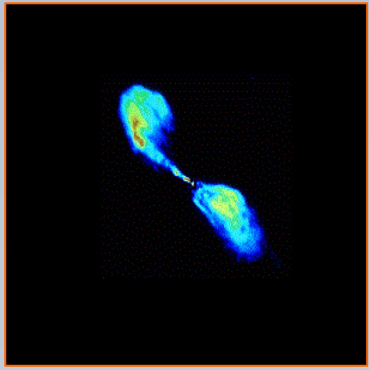
Blue : Radio jet
Red : CO
White : Atomic hydrogen gas
Yellow : shell
(32' ×32', Charmandaris 2000)

Multiwave images

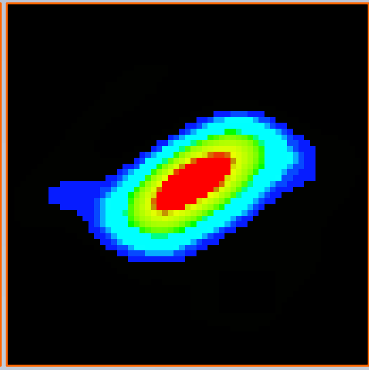
Image Size = 15 × 14 arcmin

（今回は中心部分の観測を行った。）

0.25°



Radio
VLA(6cm)
4.9GHz



Far infrared
IRAS
60-100μm

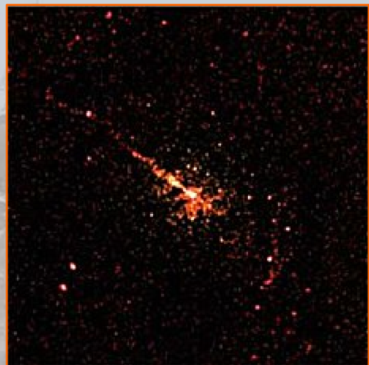
Mid infrared
Spitzer
3.6 to 8μm

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

Observation

今回の観測では2台の望遠鏡のステレオ観測を行った。
Three fold coincidence での観測は行っていない。
２台でのステレオイベントはOFFラインで解析する。

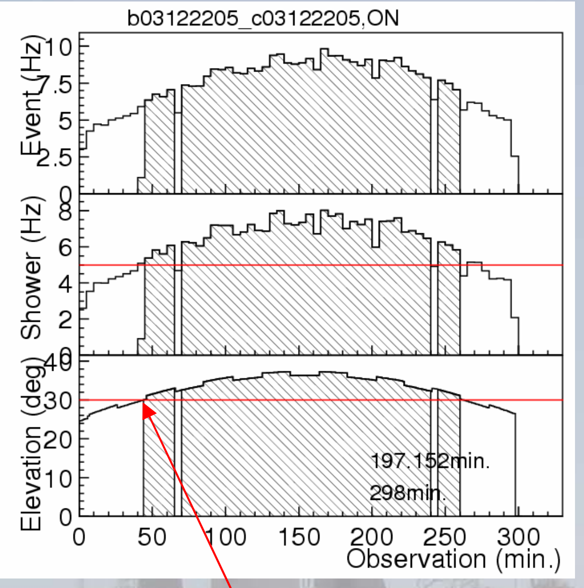
Centaurus A

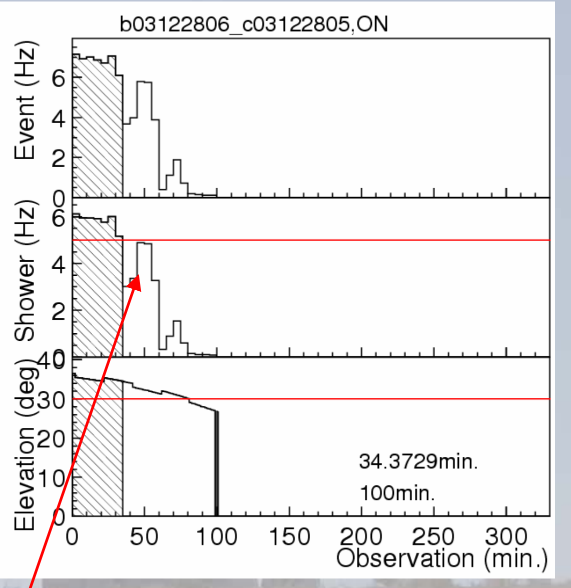
Observation date	Observation time (T2-T3)	Observation time (T2-T4)	Average zenith angle
15 – 28 Mar 2004	603 min	414 min	17 degree
15 – 28 Apr 2004	444 min	468 min	17 degree
Total	1047 min	882 min	

Data reduciton

Good conditon

Bad condition





Event rate

Shower rate

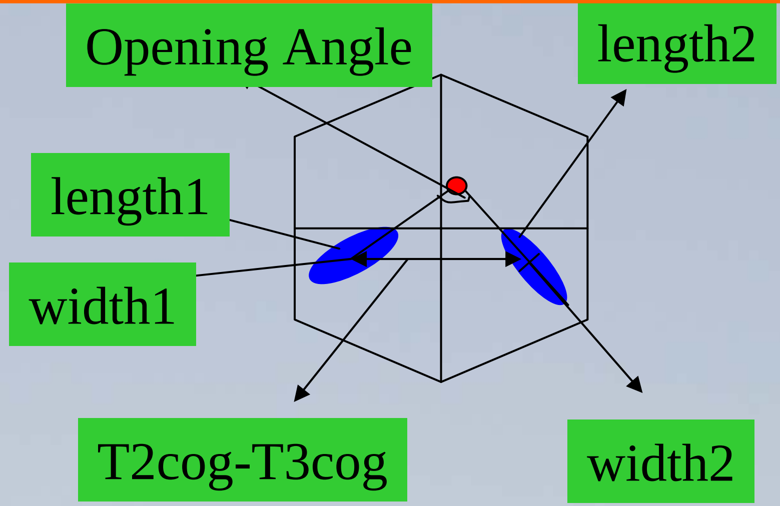
Elevation

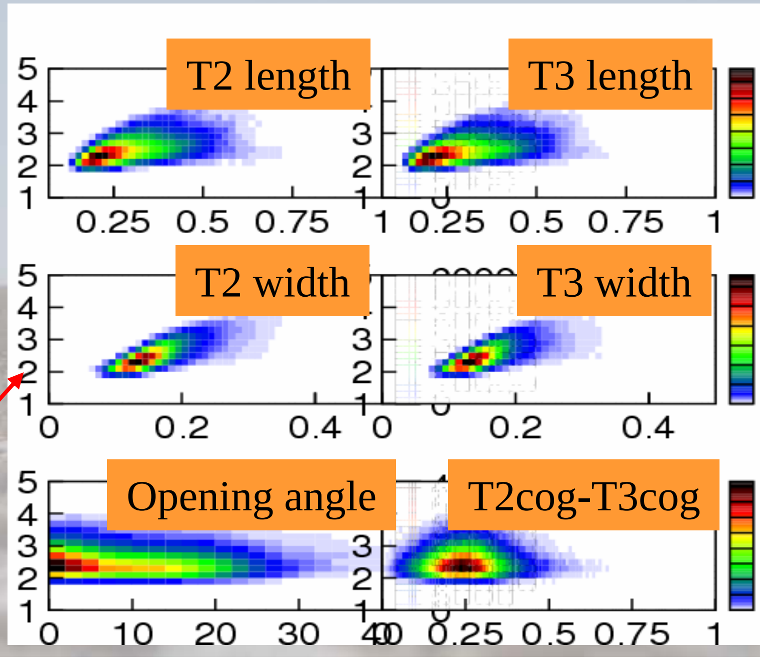
Elevation cut

Cloud cut

Analysis method : Likelihood cut

ADC 5 p.e. <
-25<TDC<25 nsec
Scaler Top 40
Clustering : T6a
Sum p.e. : 0 p.e <
Distance
 0 < distance < 1.9
Likelihood parameters
 length,Width,
 Opening Angle,T2cog-T3cog
L ratio cut 0.9 <





Probability density function

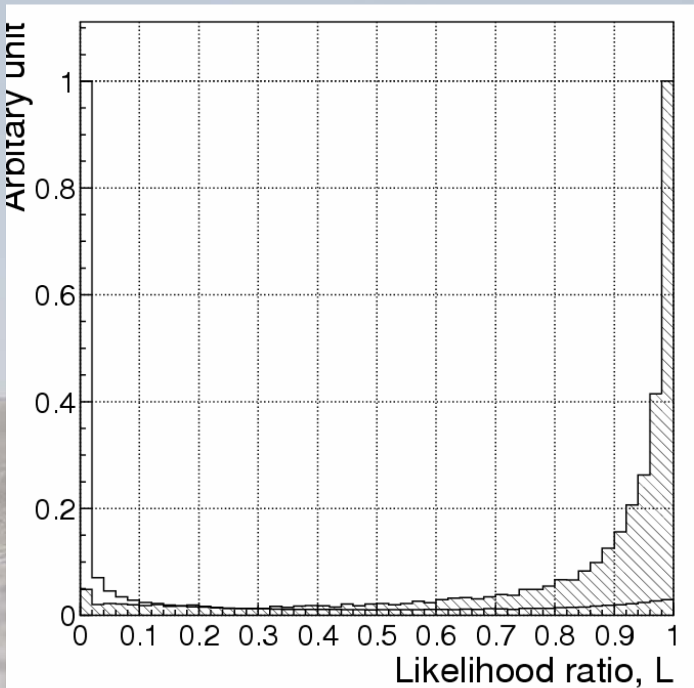
Likelihood analysis

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)) ･･･

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

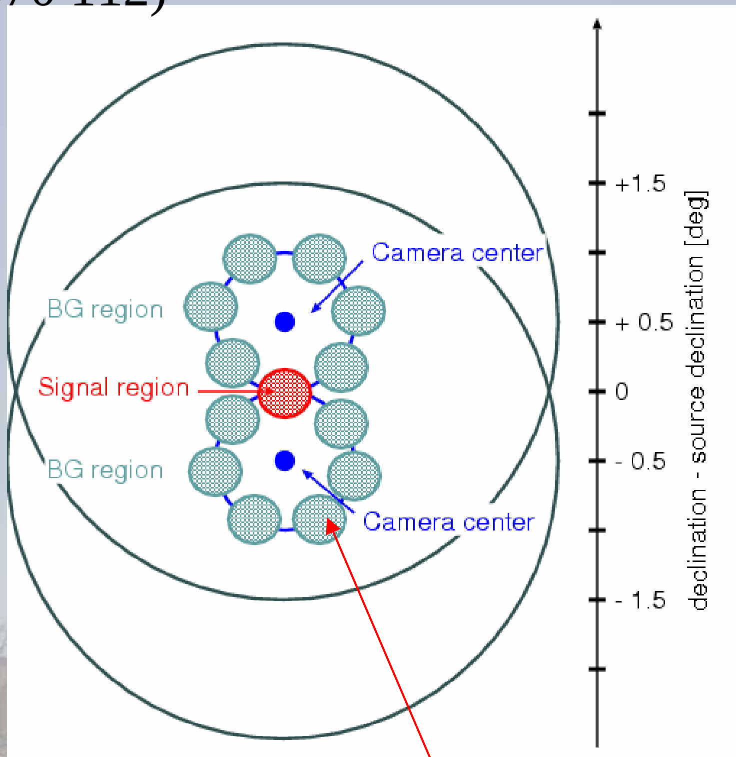
PDFのNormalizationが不適
↓
確率みたいな量



Hatched ：MC
Blank ：OFF

BG region selection

Wobble mode
(Aharonian, A&A 370 112)

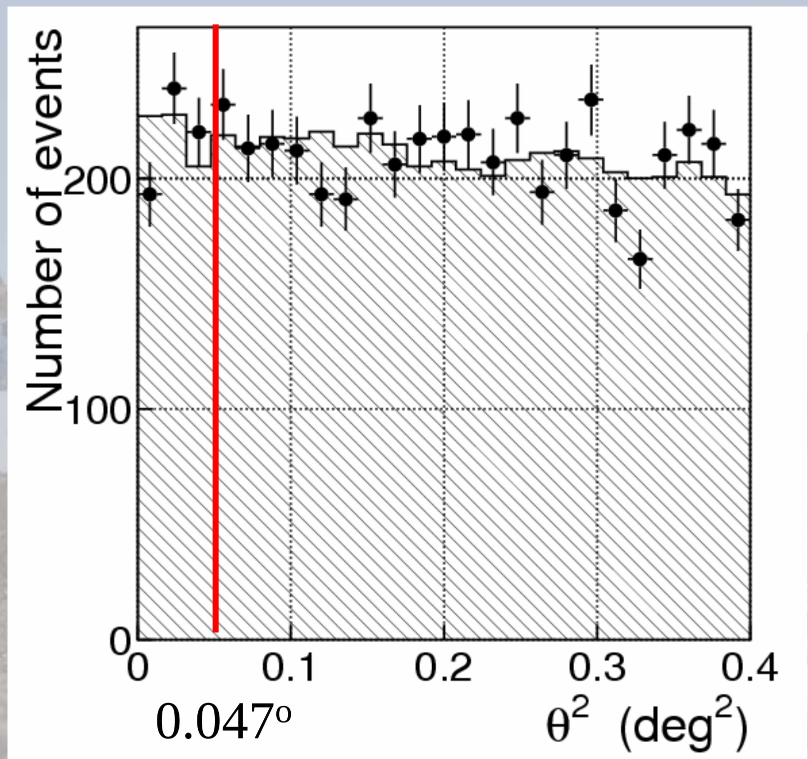


Number of BG region is 6.

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

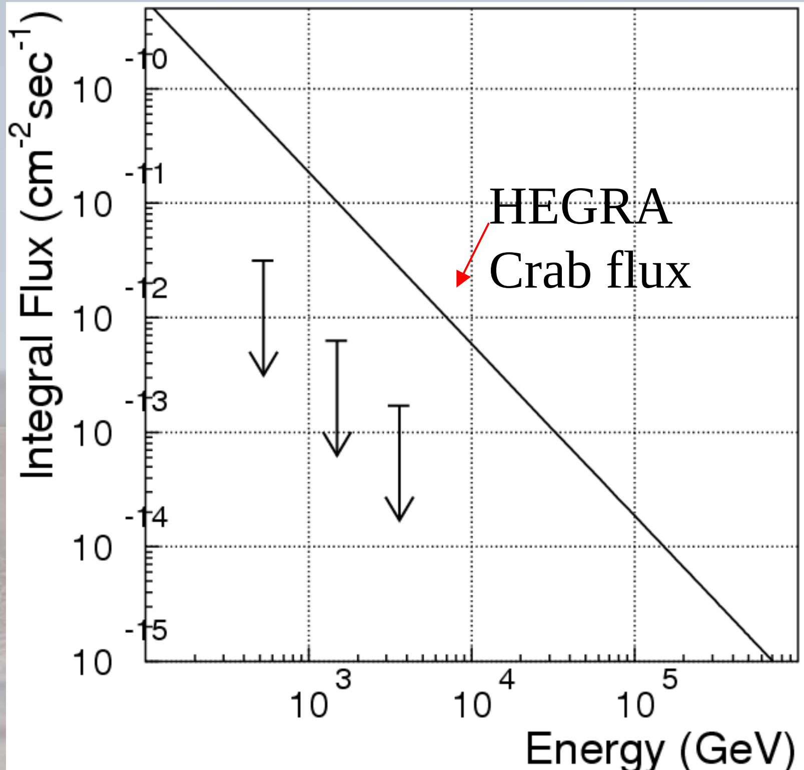
Centaurus A result

θ^2 distribution



Integral Flux : 2-σ upper limit

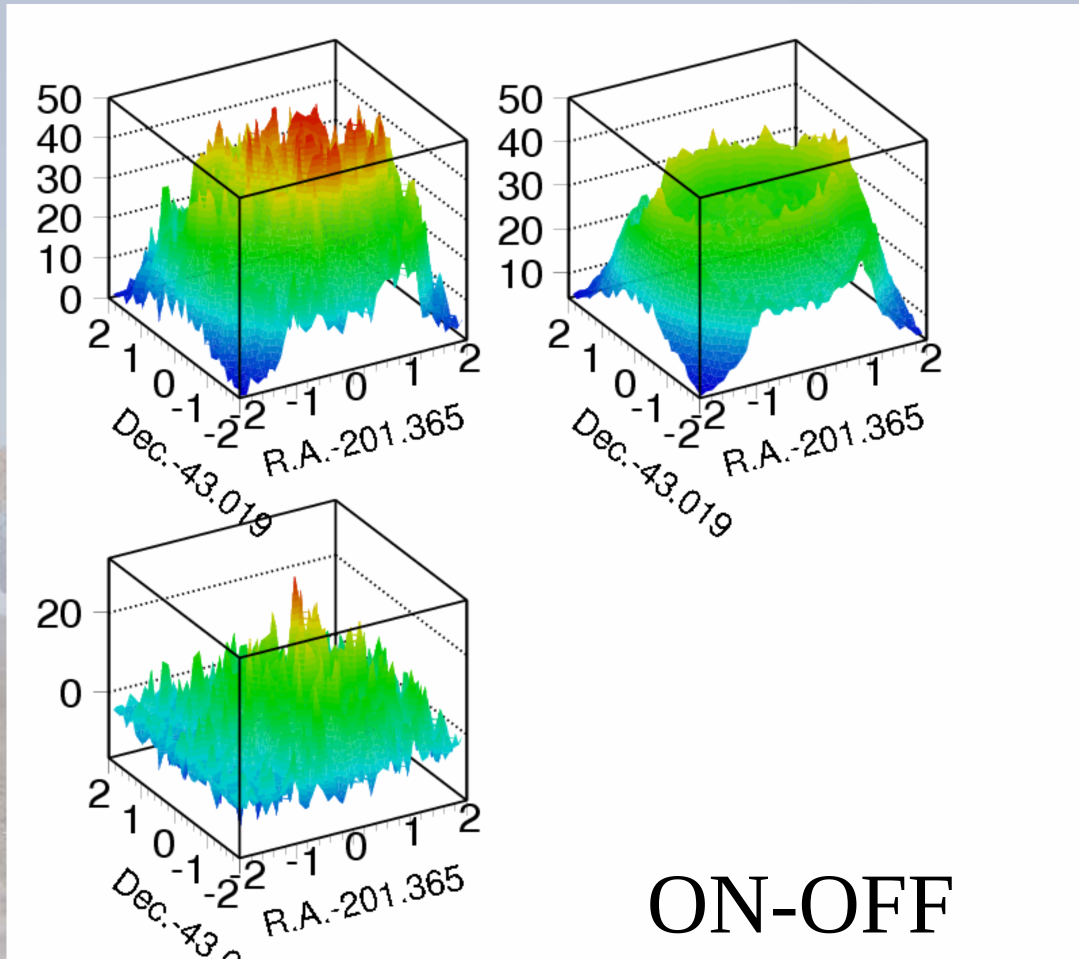
Energy bin (GeV)	530	1490	3600
2 σ upper limit flux ($\times 10^{-11} cm^{-2} sec^{-1}$)	0.31	0.063	0.017



6% Crab Flux

Centaurus A arrival point map

ON
L>0.9

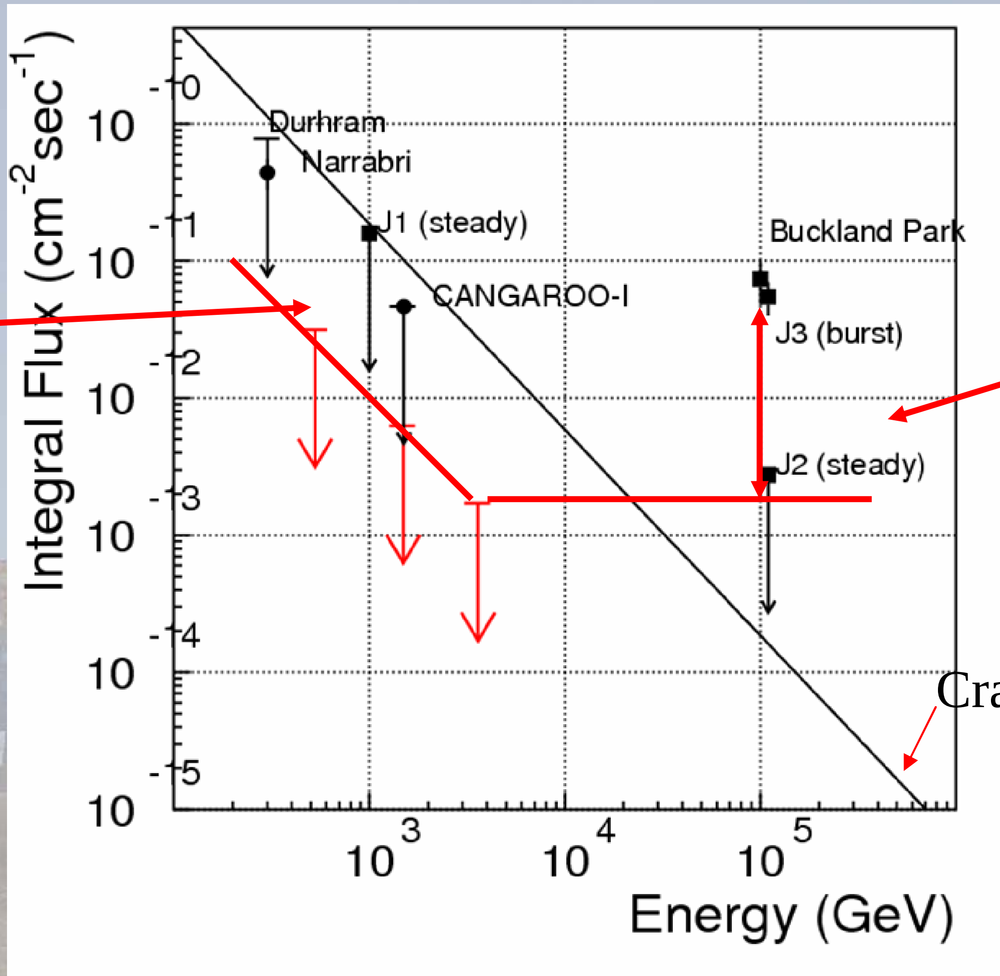


Proton
L<0.2

ON-OFF

Comparison with the past data

0.1 Flux



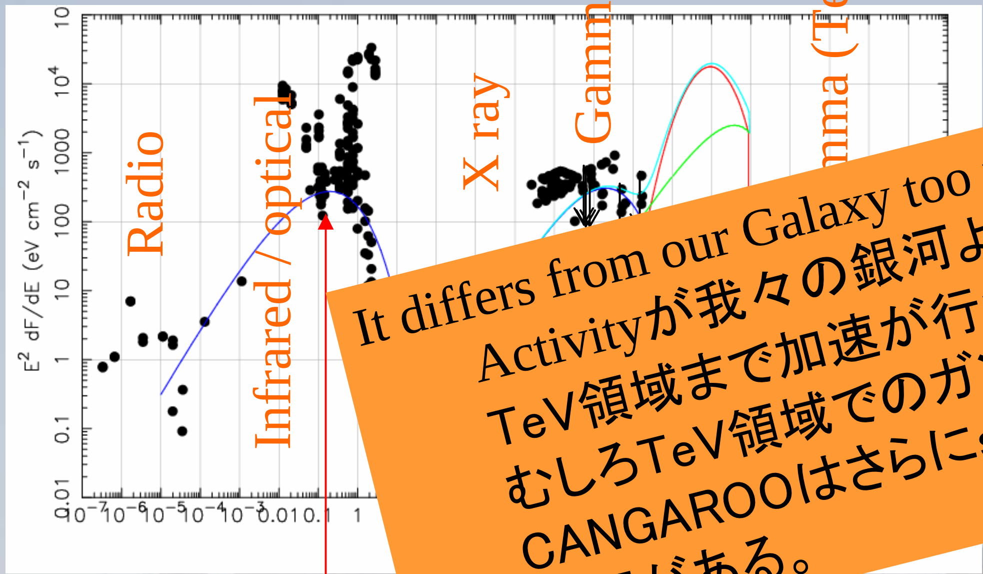
0.01 Flux ?

Crab flux

Our limit is 10 times lower flux than previous result.

Difficulties on LBL assumption

Assume SSC model



Synchrotron peak

IC peak

It differs from our Galaxy too much.
Activityが我々の銀河よりも大きいのに
TeV領域まで加速が行われていないのか？
むしろTeV領域でのガンマ線はあるべきで、
CANGAROOはさらにsensitivityを上げて行く
必要がある。

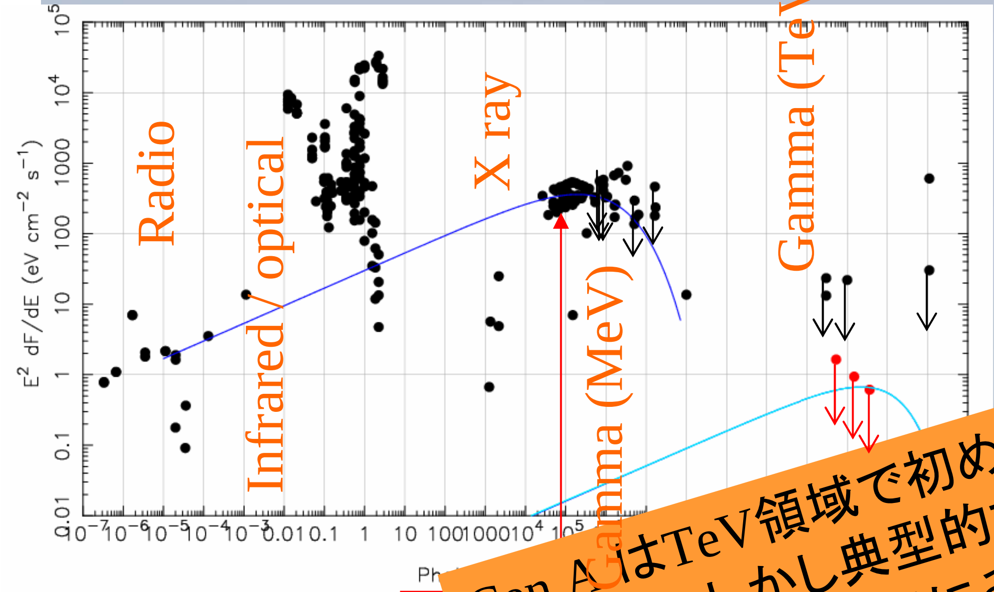
Typical AGN value

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

We can not explain LBL physics.

HBL model ?

Possibility on HBL assumption



Sy…
pe…

IC peak

Typical AGN model

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

$$L_c / L_s \sim 1$$

But Ce… A…

$$1/580 << 1$$

Cen A はTeV領域で初めて観測された
天体 → しかし典型的なAGNと大きく
異なるようにみえる。

$$R = 12kpc$$

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

$$U_B > 580U_{sync} = 3500eV/cc$$

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

$$B > 250\mu G \times (R/12kpc)^{-1}$$

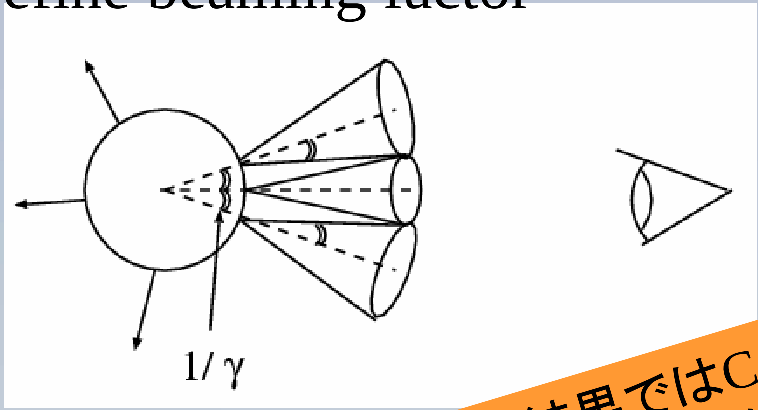
$$\frac{L_{ssc}}{L_{sync}} = \frac{U_{sync}}{U_B}$$

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

Relativistic beaming effect

Cen Aで信号が見えないのはジェットの角度の問題か？

Define beaming factor



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

しかし今回の結果ではCen A は
TeV領域では検出できなかった。
Cen AはAGNの統一モデルには属さないかもしれない。

Fluxは ... と書ける。

Mrk501 ... 様に60°傾いていたなら、

典型的な ... 、γ～5、p～3を用いると、

1.3×10^{-4}倍

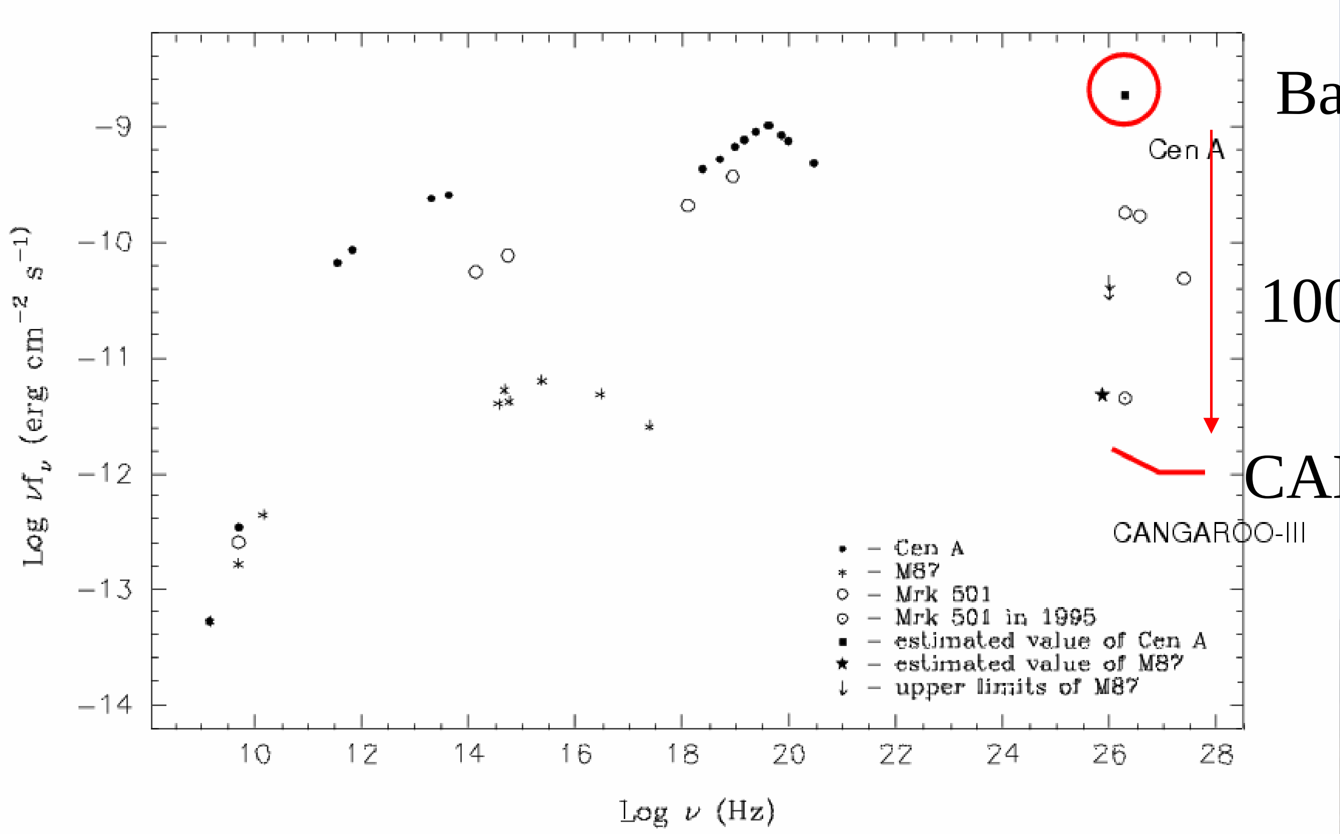
だけ変化する。

Mrk501がCen Aと同じ距離にあると仮定すると、

（Mrk501/CenA）^{2}=(0.034/0.0008)^2＝1.8×10^4

なのでCenAのように60°傾いていても信号が見えるはずである。

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

Conclusion

- 我々はCANGAROO-III望遠鏡を用いて活動電波銀河
  Centaurus Aをステレオ観測した。
- CANGAROO－IIIでは望遠鏡を3台増設し、ステレオ観測を
  可能にした。
  その結果エネルギー閾値が500GeVで角度分解能は0．2°となった。
- ２次元Likelihoodを用いて解析
  を行った結果、有意な信号は検出できなかった。
  1050分の観測で0.31×10^{-11}cm^{-2}sec^{-1}の２σの上限値を
  つけた。さらにHBLである場合、

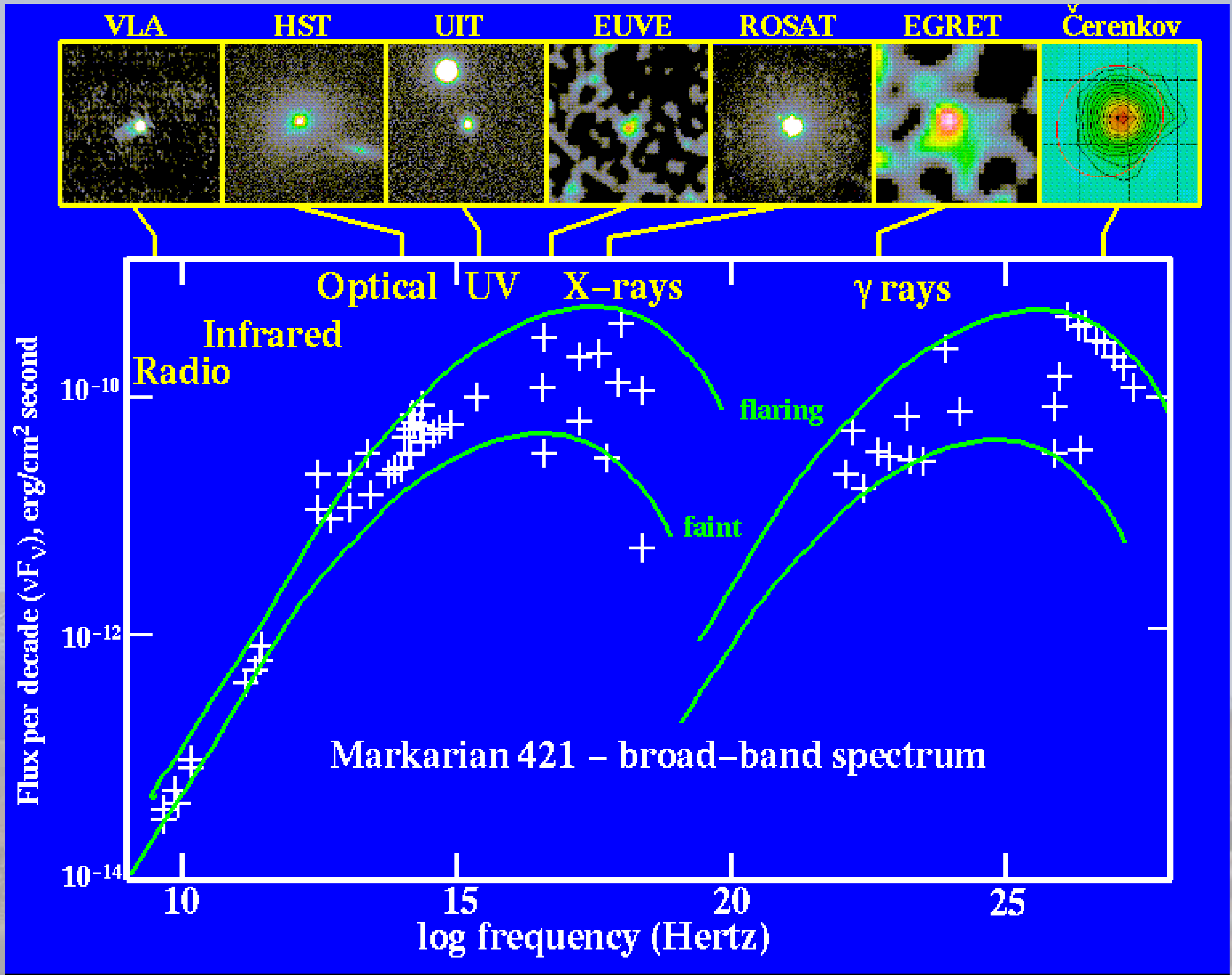
  $L_c/L_s < 1/580 < 1.$

  $U_B > 580$ U sync= 3500eV/cc

  $B=250\mu G(R/12kpc)^{-1}$

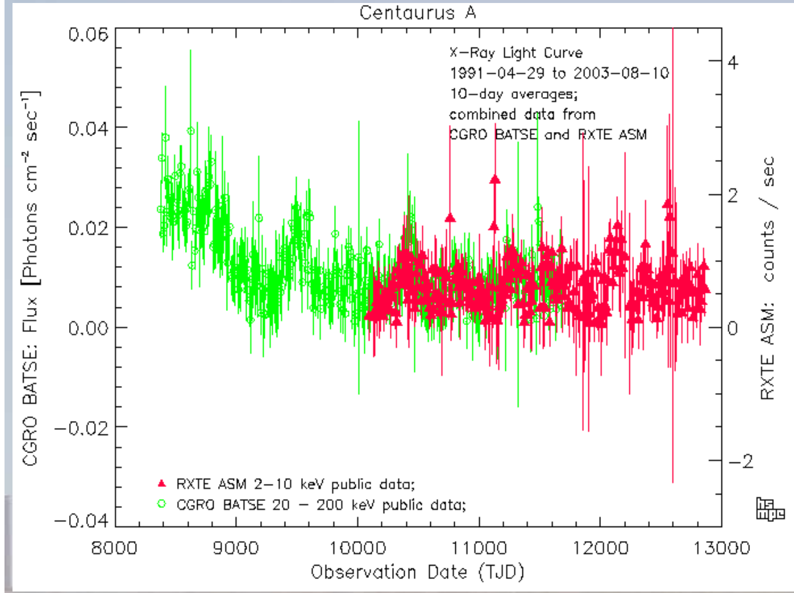
  の制限をつけることができた。
  この観測期間では大きなフレアは観測されず、TeV領域での
  変動もquietであった。

Mrk 421の時間変動



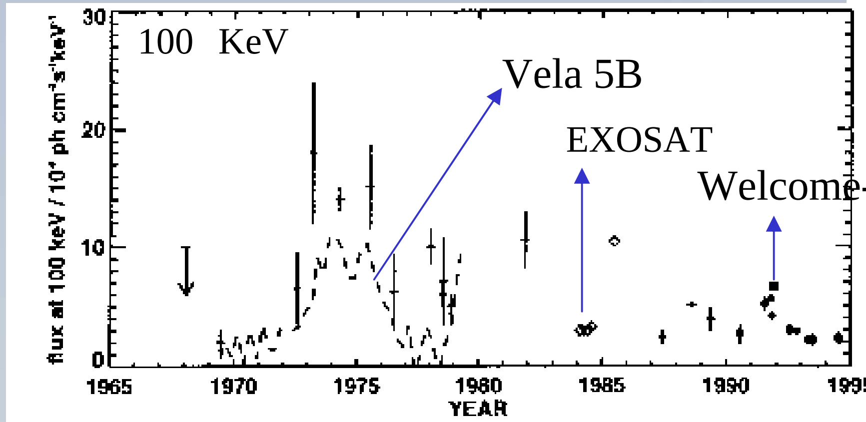
Cen Aの時間変動

Cen Aの時間変動



1991-04-29 ~ 2003-08-10のデータ
Green: BATSE
1991-04-29 ~2000-05-25(TJD11690)
Red : RXTE ASM (~2003~08-10)

Cen Aの長期的な時間変動



70年代に大きなburstが起きていたと考えられる。
1993からの4年間のlow stateの時期はRXTE ASMと結果が重なる。

Bond et al 1996

Cen Aの過去のFluxの変化

Radio
10.7~ 90 GHz

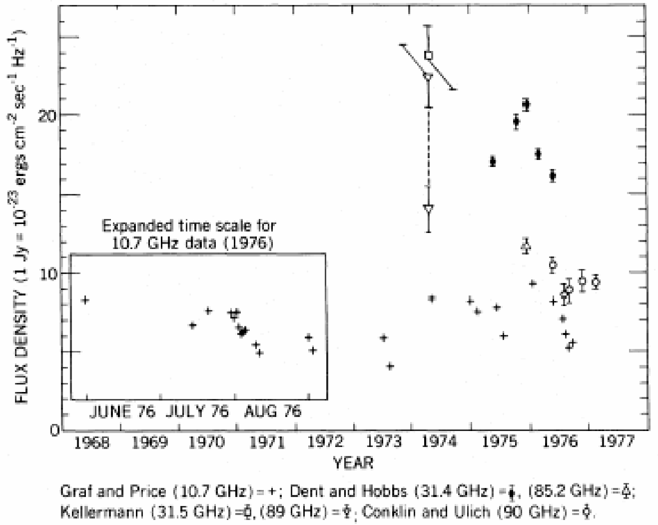


FIG. 1.—Radio emission from the nucleus of Cen A. Data taken from Price and Stull 1973, Stull and Price 1975, Dent and Hobbs 1973, Kellermann 1974, and current observations.

X ray
2~6 KeV

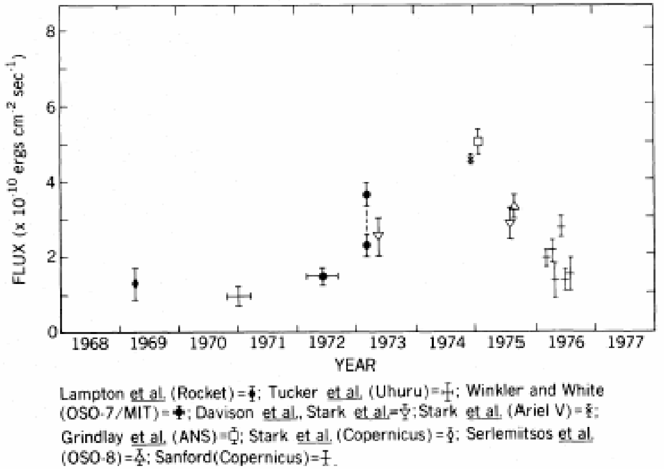


FIG. 2.—History of Cen A 2–6 keV X-ray flux. Data taken from Lampton *et al.* 1972, Tucker *et al.* 1973, Winkler and White 1975, Davison *et al.* 1975, Stark *et al.* 1976, Grindlay *et al.* 1975*b*, Serlemitsos *et al.* 1975, Sanford 1976.

Beall 1978

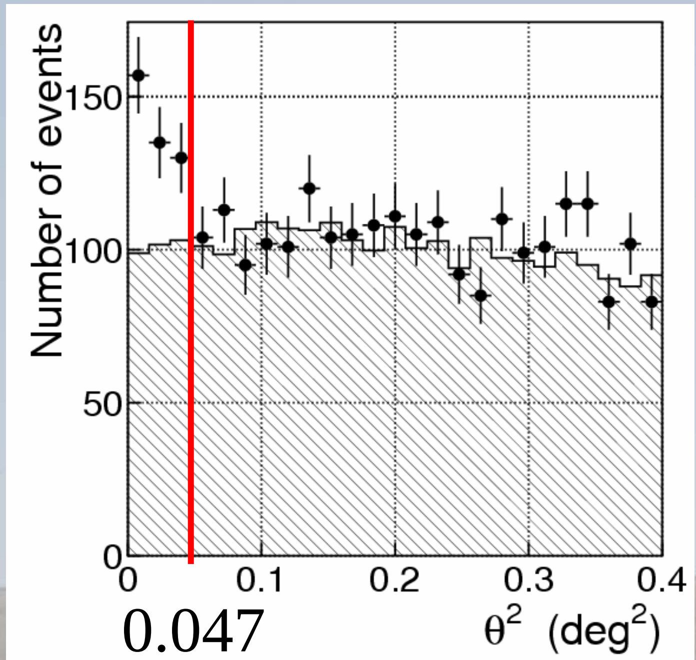
Crab Analysis

- Crab

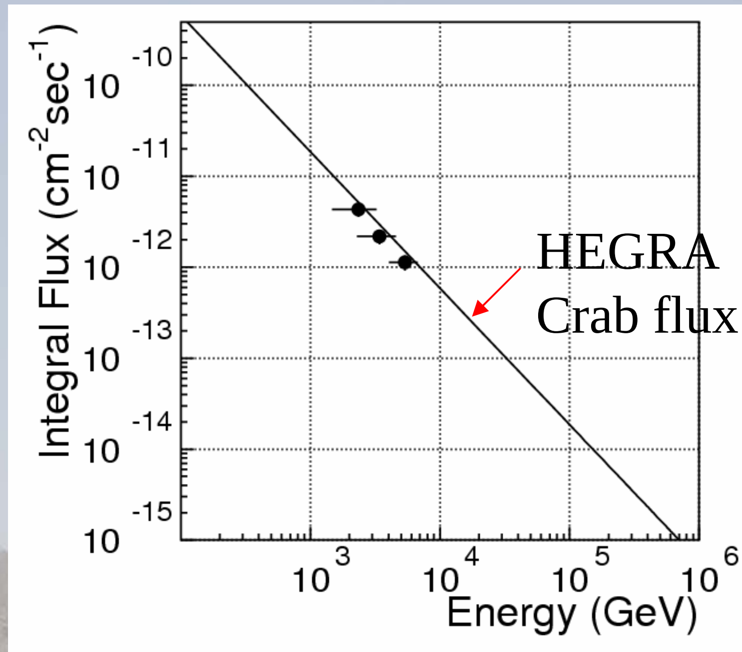
Observation date	Observation time (T2-T3)	Average zenith angle
15 – 28 Dec, 2003	1215 min	62 degree

Likelihood : Result

θ² distribution
L : 0.9 <



Integral Flux
L : 0.9 <



Excess : 123±21 event (@2350GeV)

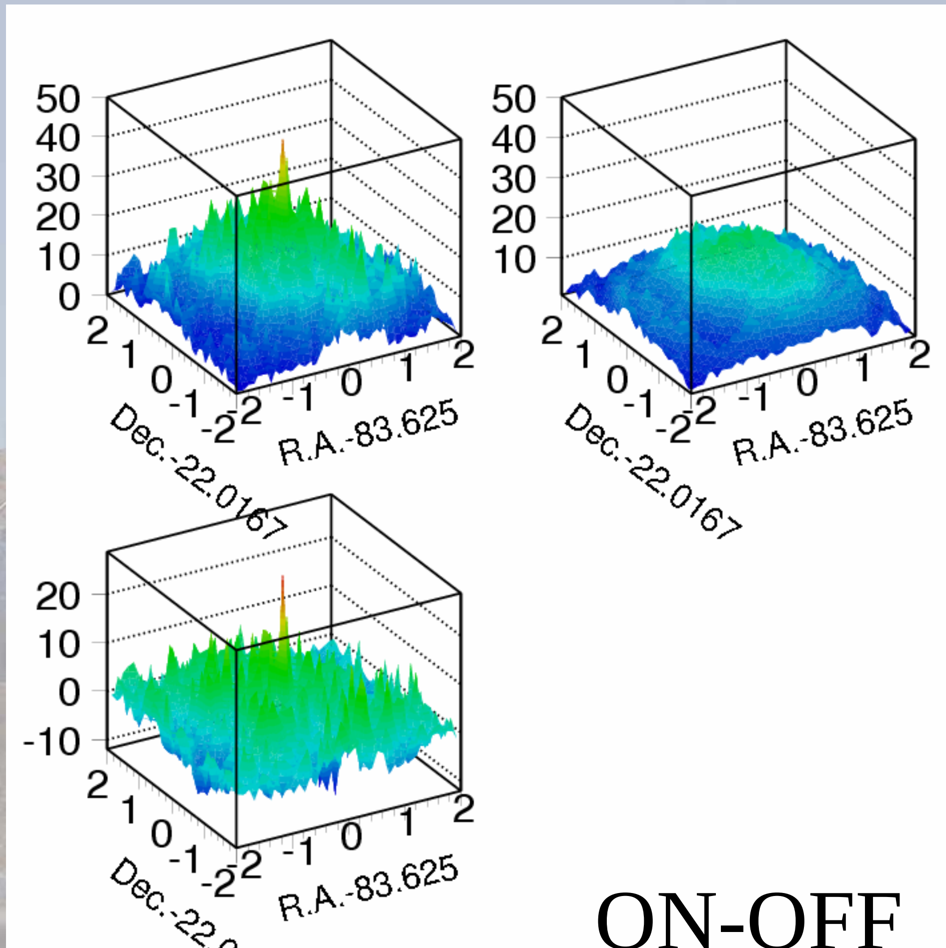
Significance : 6.0 σ

1 Crab : 125 event/840.3 min.

Crab arrival point map

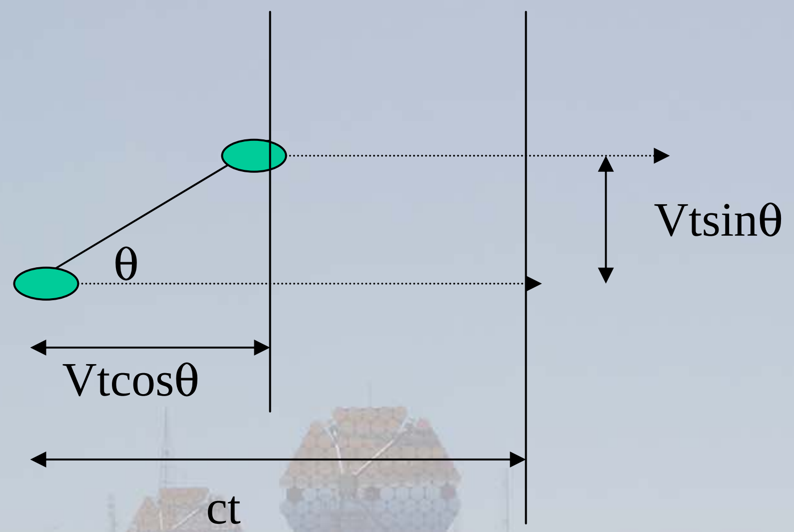
ON
L>0.9

OFF
L<0.2



ON-OFF

Super luminal motion



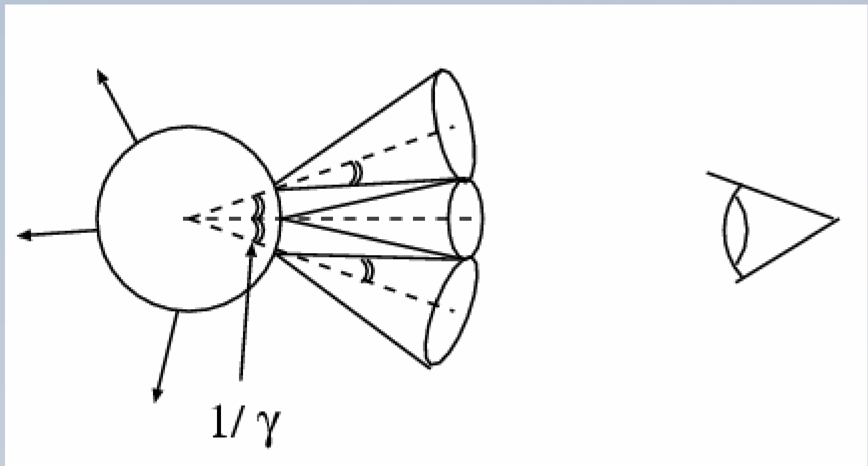
$$\Delta t = \frac{ct - Vt\cos\theta}{c}$$

$$\beta_{app} = \frac{\beta t\sin\theta}{\Delta t} = \frac{\beta\sin\theta}{1-\beta\cos\theta}$$

Maximum : $\cos\theta = \beta$

Relativistic beaming effect

Define beaming factor



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

Blazer $q \sim 1/\gamma$

$\delta \sim \gamma \sim 10$

(1) frequency $\Rightarrow$ $\nu_{obs} \sim \nu_{jet}\,\delta$

(2) time $\Rightarrow$ $t_{obs} \sim t_{jet} / \delta$,

(3) Solid angle $\Rightarrow$ $W_{obs} \sim W_{jet} / \delta^{2}$

(4) luminocity $\propto \nu\, t^{-1} \Omega^{-1}$ $\Rightarrow$ $L_{obs} \sim \delta^4 L_{jet} \sim 10^{4} L_{jet}$

電子の最大加速エネルギー

磁場が強いので（B～0.1G）、冷却と加速の釣り合いで決まる

- $$t_{cool}(\gamma) = \frac{3m_e c}{4\,(U_B + U_{sync} + U_{BLR})\,\sigma_T\,\gamma} \quad \propto \gamma^{-1}$$

- $t_{acc}(\gamma) \propto \gamma^n$ （$n > 0$ の定数）

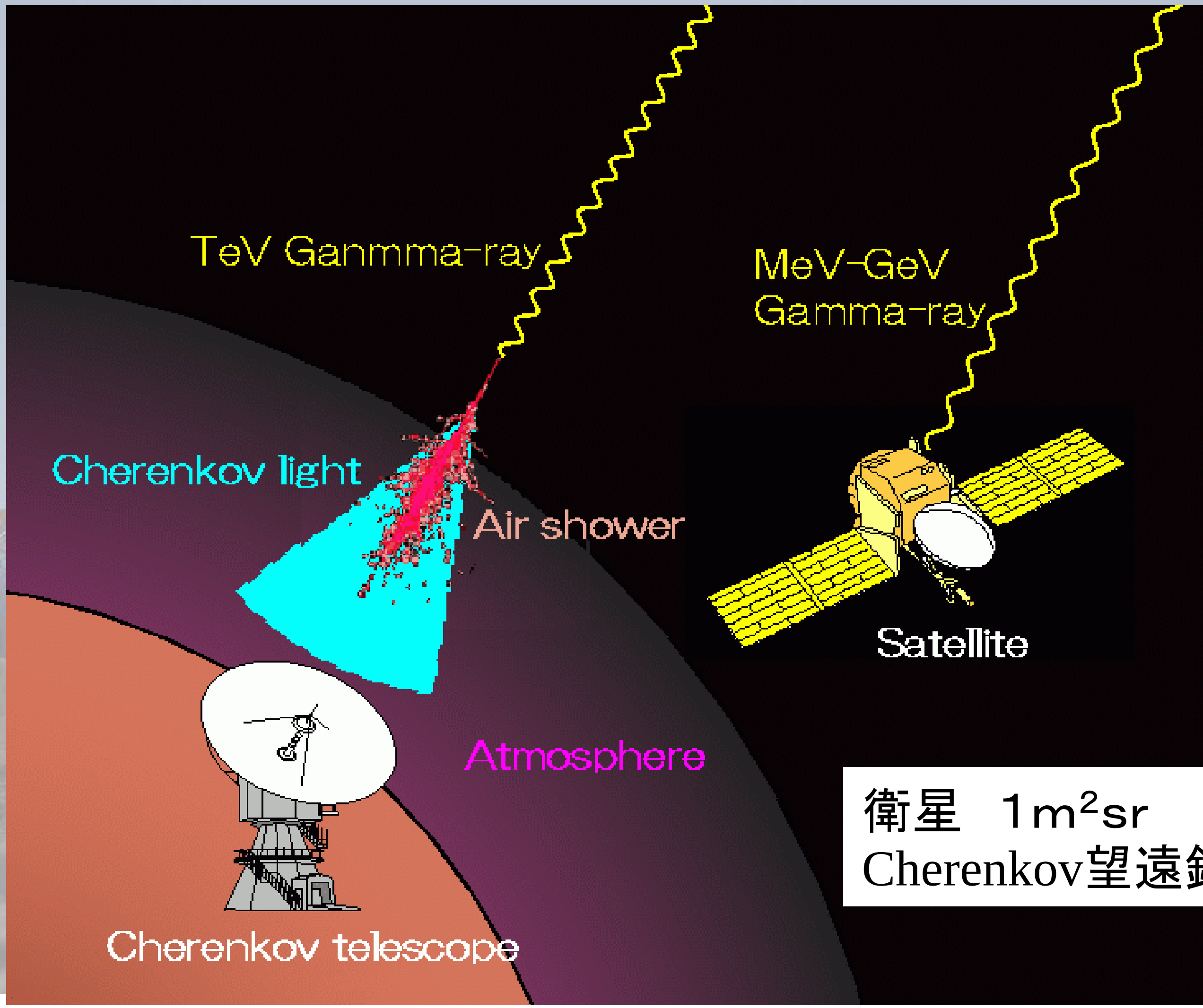
$$\gamma_{max} \propto (U_B + U_{sync} + U_{BLR})^{-1/(n+1)}$$

“暗い”ブレーザー： $\gamma_{max} = 10^{5-6}$

“明るい”ブレーザー： $\gamma_{max} = 10^{2-3}$

暗い天体のJetほど、加速されている。

ガンマ線の検出



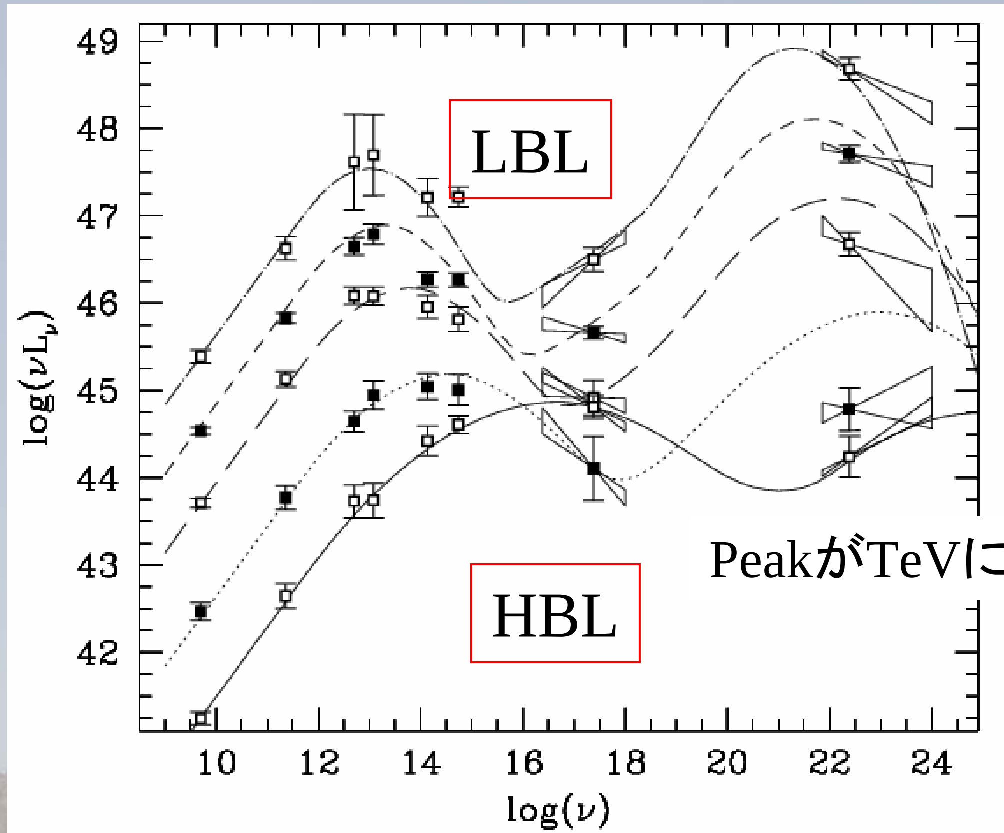
衛星　$1 m^2 sr$

Cherenkov望遠鏡　10^5 m^2

Synchrotron self-Compton model

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

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



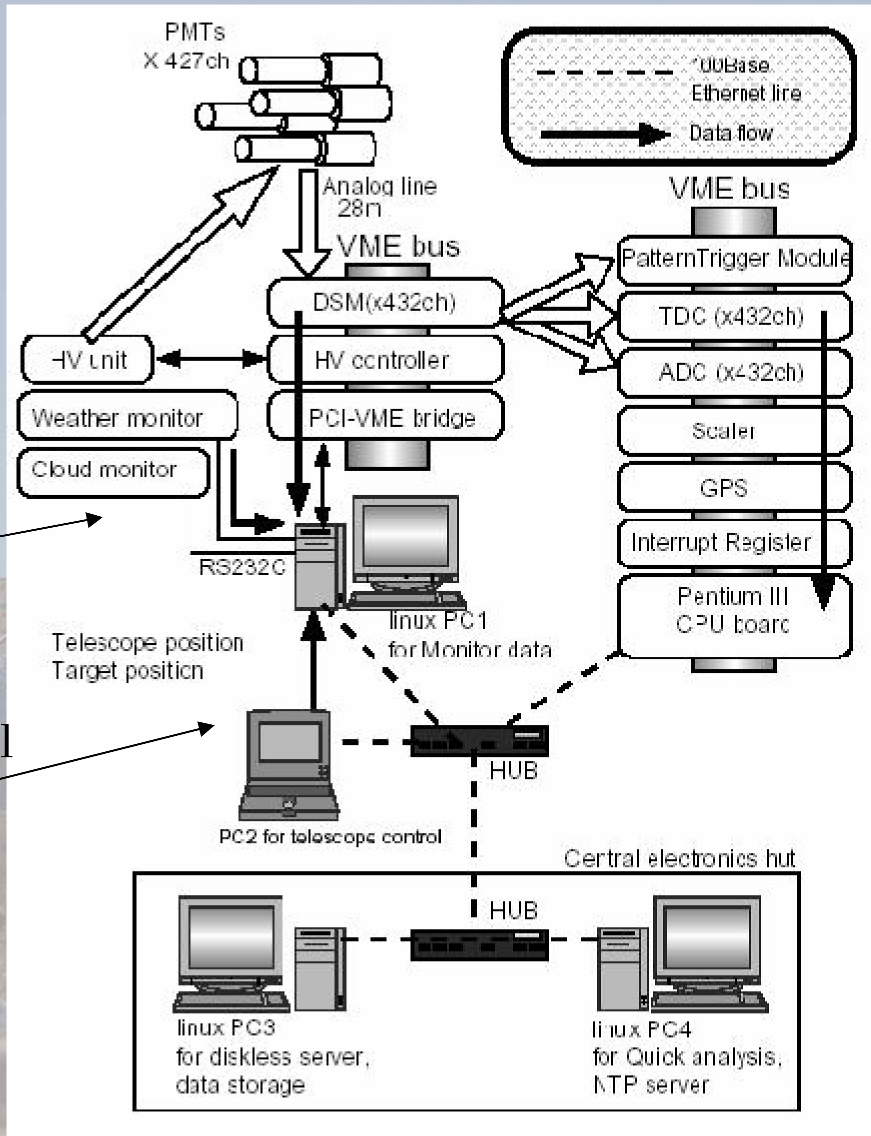
PeakがTeVにある

X ray

Electronics

Acquisition of weather monitor data

Telescope control and information



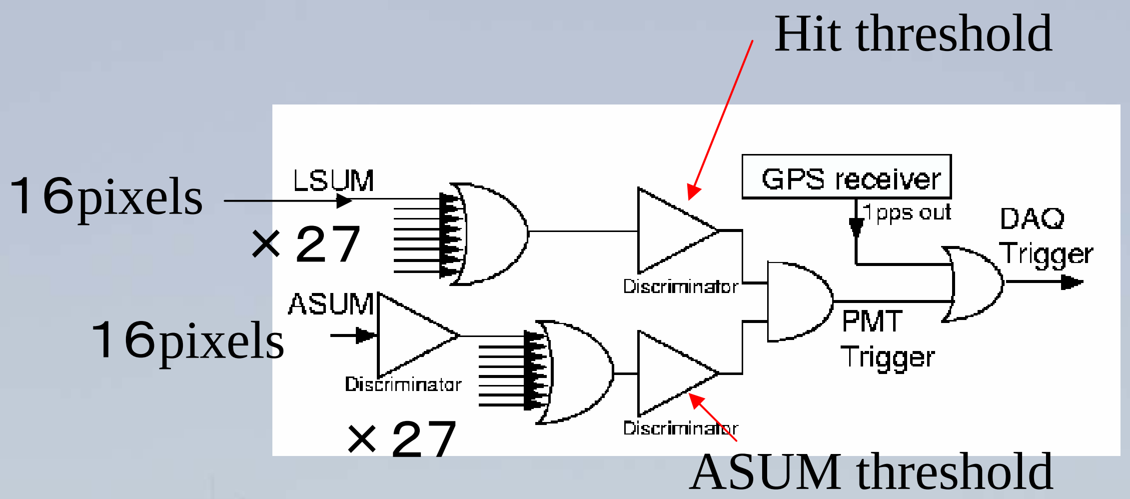
TDC
0.78ns resolution

ADC
gate 100 ns

Scaler
remove NSB

GPS
Acquisition of time information

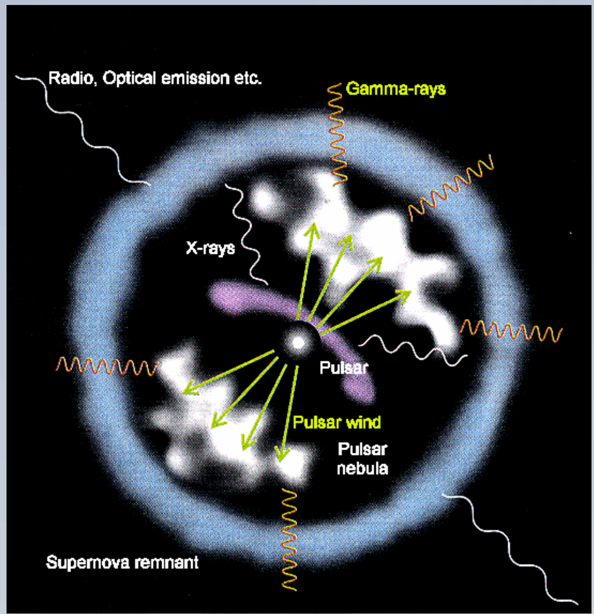
Trigger logic



LSUM　threshold を超えた logic 信号のsumが
Hit thresholdを超えた時、かつ、アナログ信号の
１６pixel分のsunがASUM　thresholdを超えた時に
DAQのトリガーがかかるようになっている。

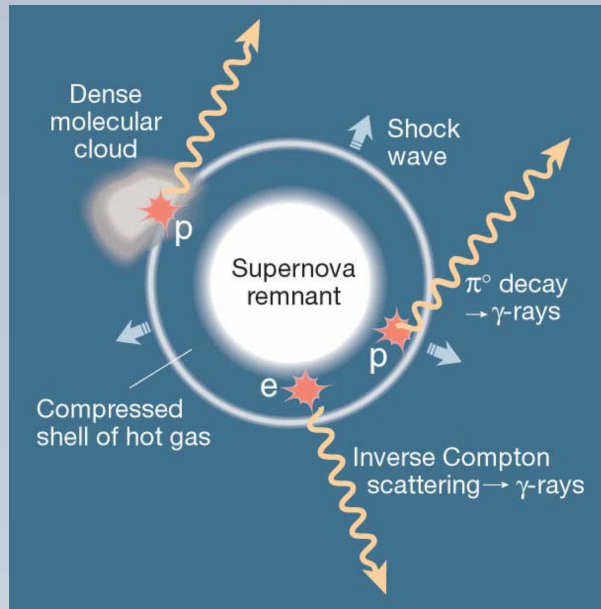
Gamma-ray sources

Pulsar



- Fast rotating magnetized pulsar
  = power generator
- Energy
  ⇒ Pulsar wind out of light cylinder
- Shock wave in ambient medium
  ⇒ particle acceleration
- Gamma-rays by IC

Supernova remnant



- Expanding blast wave from explosion
  ⇒ shock wave
- Particles accelerated in shock wave
- Interaction with ambient medium
  - e + B (syncrotron)
  - e + Photons (IC)
  - p + Gas (π^0)

  ⇒ Gamma-rays
- Cosmic ray origin?
  (energetics argument)