TeVガンマ線観測の過去・現在・将来

東京大学宇宙線研究所
森　正樹

HEAPA 4th workshop, Oct. 1, 2003, Nagoya VBL lab.

概要

- 過去
  - チェレンコフ放射の実証
  - 天体ガンマ線検出への応用
- 現在
  - イメージング法
  - ステレオ観測
  - TeVガンマ線天体カタログ
- 未来
  - 第3世代プロジェクト
  - さらに…

CANGAROO-IIIチェレンコフ望遠鏡

大気チェレンコフ望遠鏡

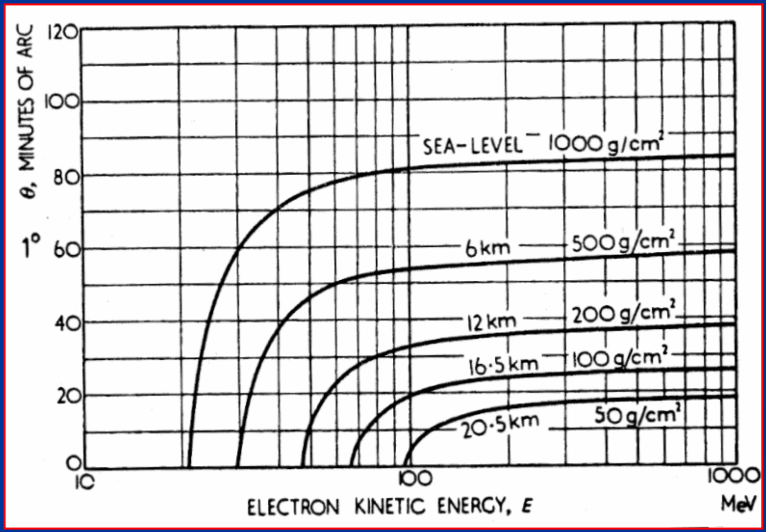
- チェレンコフ角

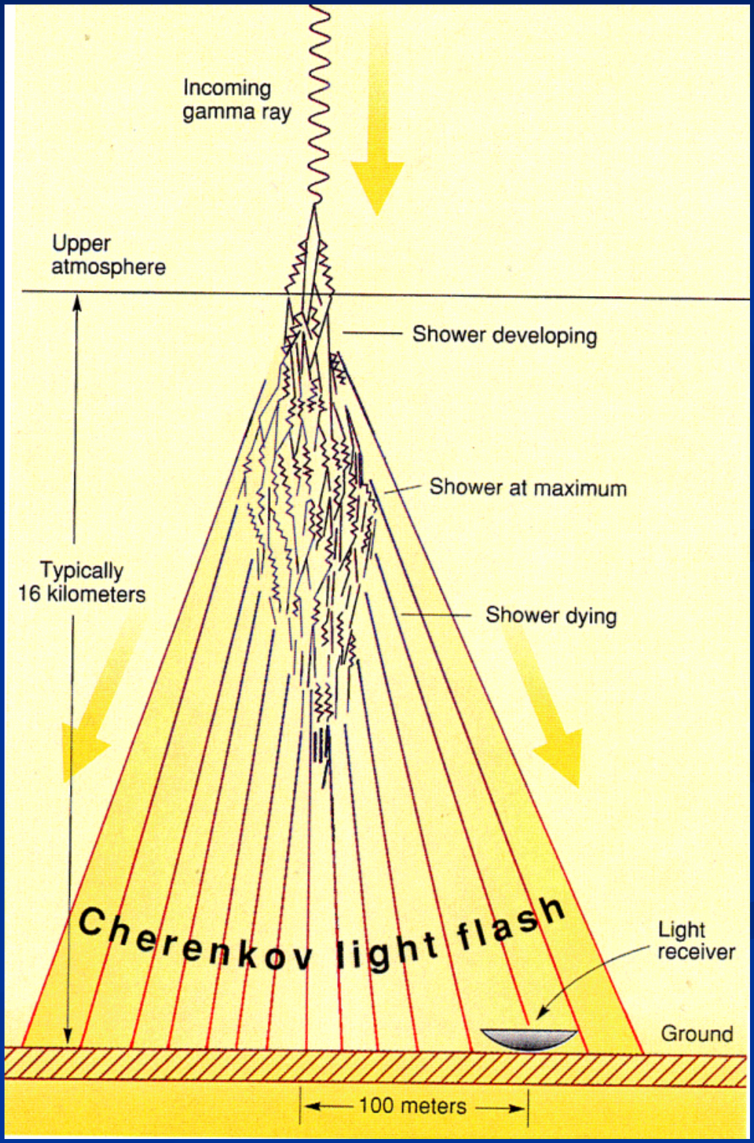
$\cos\theta = 1/n\beta$

$\beta = v/c$

$n = 1.0003$ (1atm)

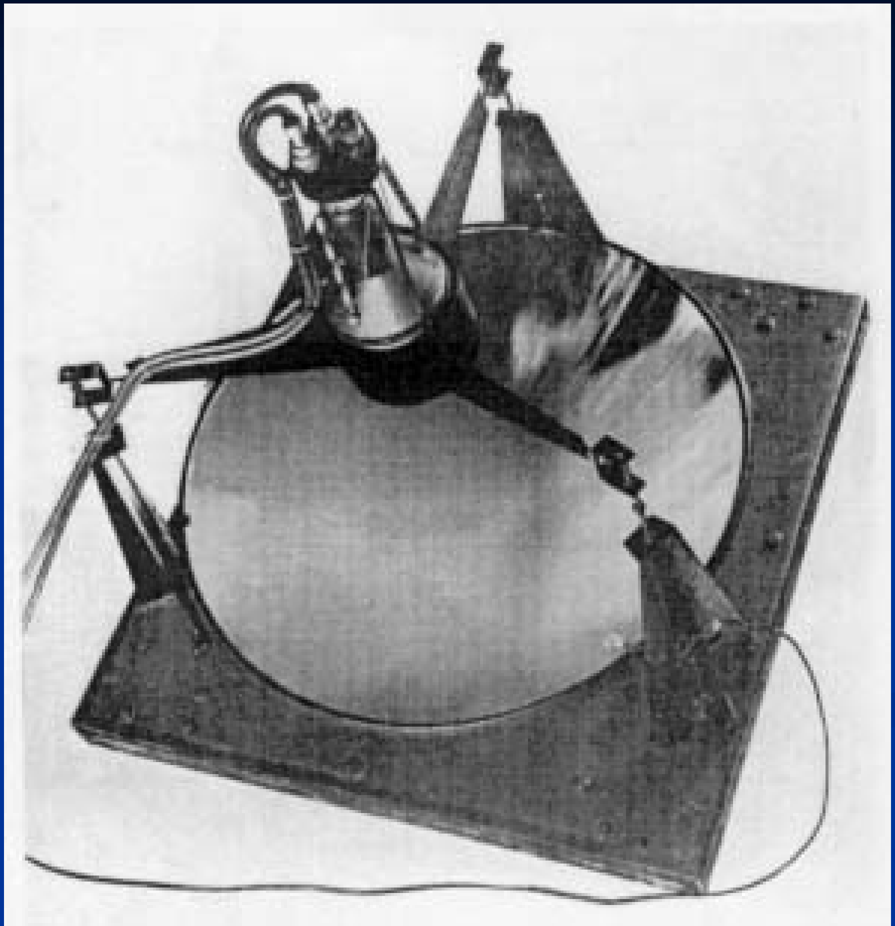
$\Rightarrow \theta=1.3^{o}$ (地上)





チェレンコフ放射の実証

- Blackett (1948) 夜光へのチェレンコフ光の寄与の指摘
- Jelly & Galbraith (1953) 空気シャワーからのチェレンコフ光の検出



ジェリーとガルブレイスによって1955年のチェレンコフ光検出実験に用いられた集光装置。口径61cm、F値0.5の放物鏡の焦点に5インチの光電子増倍管が置かれている。(J.V. Jelly, "Cherenkov Radiation and its Applications", Pergamon Press, London, 1958, p.216)

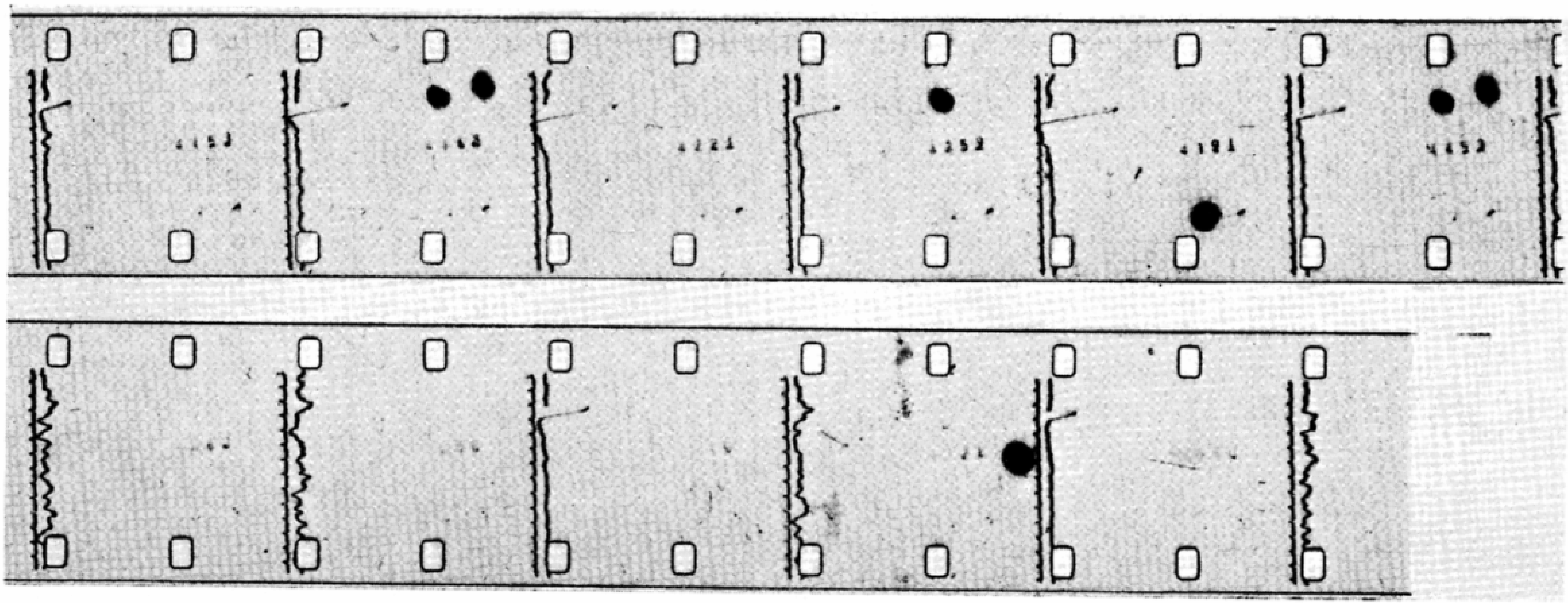


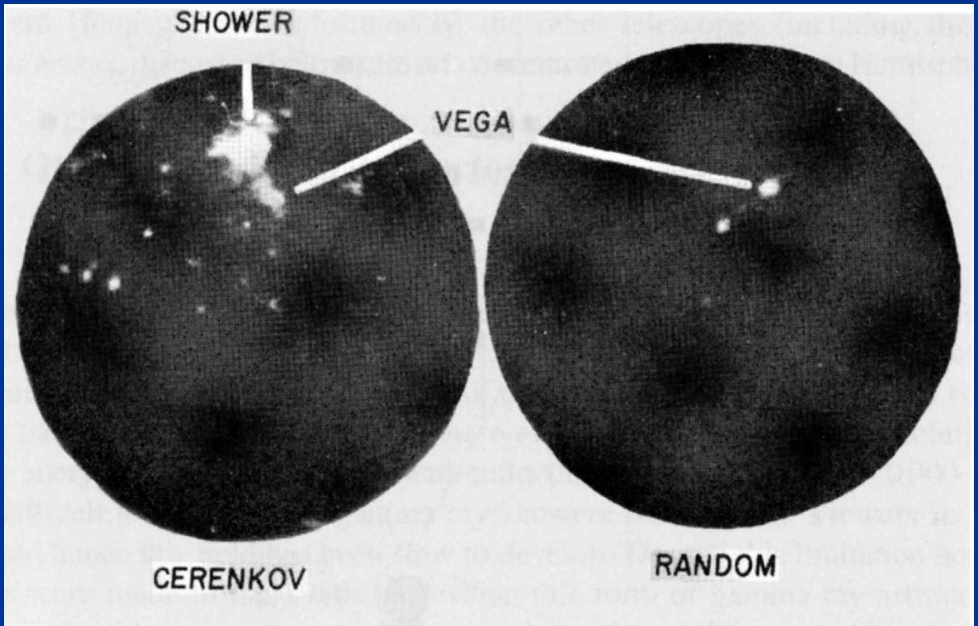
PLATE V (b).

(b) Typical recordings of light pulses from the night sky obtained with the light receiver shown in Plate V(a), pointing to the zenith on a clear night. The resolution of the night-sky "noise" is seen in relation to the 1 μ sec calibration pips, when operating with an amplifier whose cut-off frequency was ~ 5 Mc/s. The first, second, fourth and last traces in the lower group were caused by distant lightning. The black blobs indicate hodoscope data obtained with Geiger-counter trays operating in coincidence with the light receiver.

(J.V. Jelly, "Cherenkov Radiation and its Applications", Pergamon Press, London, 1958, p.217)

天体ガンマ線検出への応用

- Jelley (1954) 6インチ屈折望遠鏡によるかに星雲の観測
- Chudakov, Zatsepin et al. (1960-1964) 1.55mϕ反射鏡12台
- Fazio et al. (1968-) Mt. Hopkins, 10mϕ反射鏡



I.I.でとらえたチェレンコフ光のイメージ

(Jelley&Porter, Quart.J.R.A.S. 1963, 4,275)

最初のチェレンコフ望遠鏡

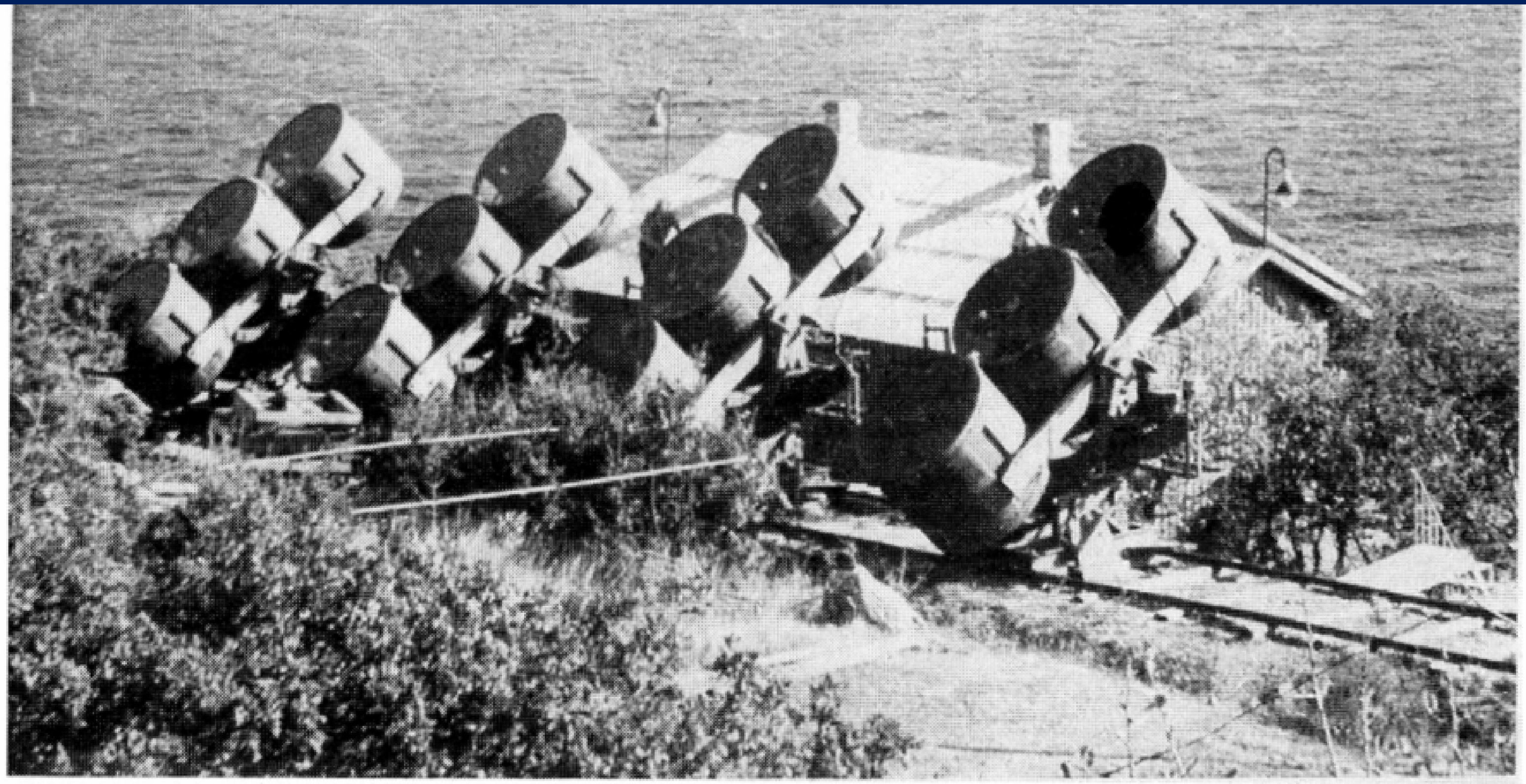


Figure 1.2. The Lebedev Institute experiment that operated in the Crimea, *c*. 1960–64. This was the first major VHE gamma-ray telescope. (Photo: N A Porter.)

チュダコフ・ザツェピンらがクリミアに設置した初めてのチェレンコフ光によるガンマ線望遠鏡。(A.E. Chudakov et al., Transl. Consultants Bureau, P.N. Lebedev Phys. Inst., 26, p.99)

Whipple 10m望遠鏡

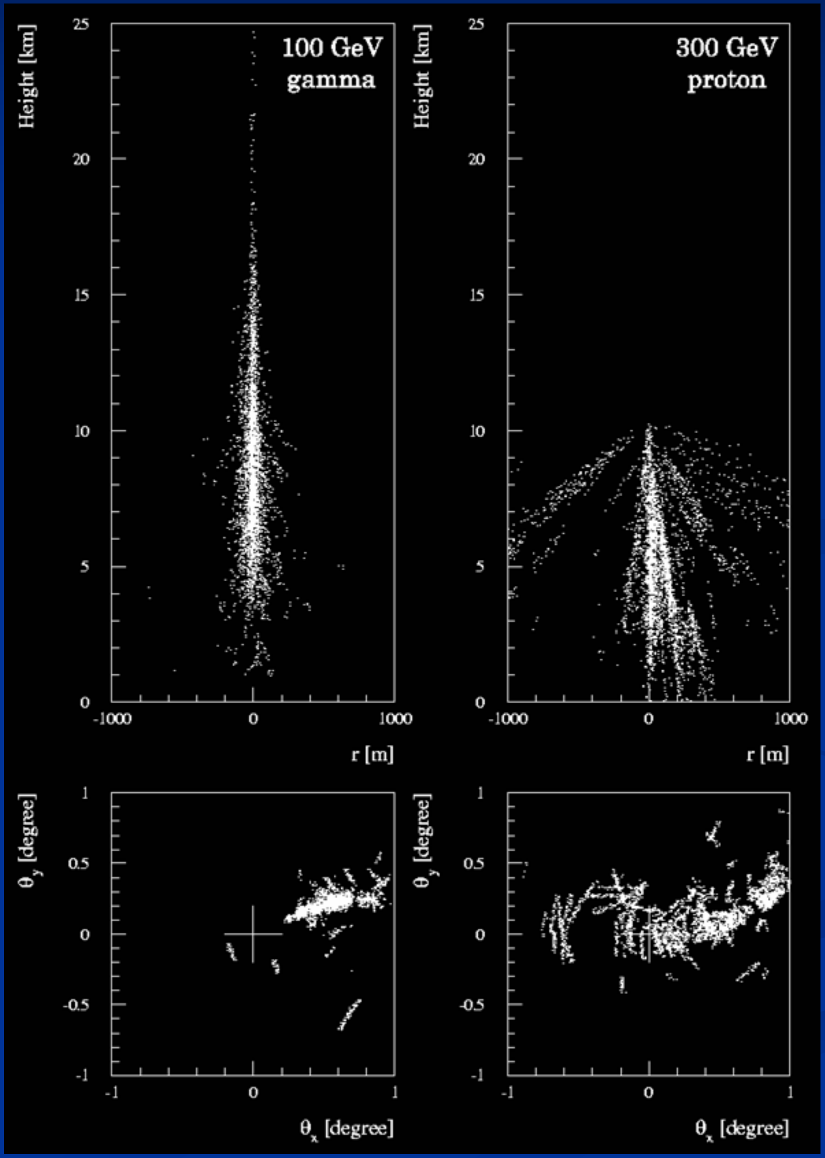
アリゾナ州ホプキンス山にあるホイップル天文台の10m口径チェレンコフ望遠鏡。

Fazio et al., Can.J.Phys. 46 (1968) S451

イメージング法

- Weekes & Turver (1977) [ESLab Symp]
  2次元観測の利点（主に角度分解能の向上）
- Weekes & Turver (1978) [Nuovo Cim.45B, 99]
  ガンマ線と陽子のイメージによる識別可能性
- Whipple 10m望遠鏡に最初のイメージングカメラ(37ch)の設置 (1982)
- Hillas (1985) [19th ICRC Vol.3, p.445]
  「イメージパラメータ」の定義
- Weekes et al. (1989) [ApJ 342, 349]
  かに星雲の検出

ガンマ線と陽子のシャワー



ガンマ線:

電磁シャワー

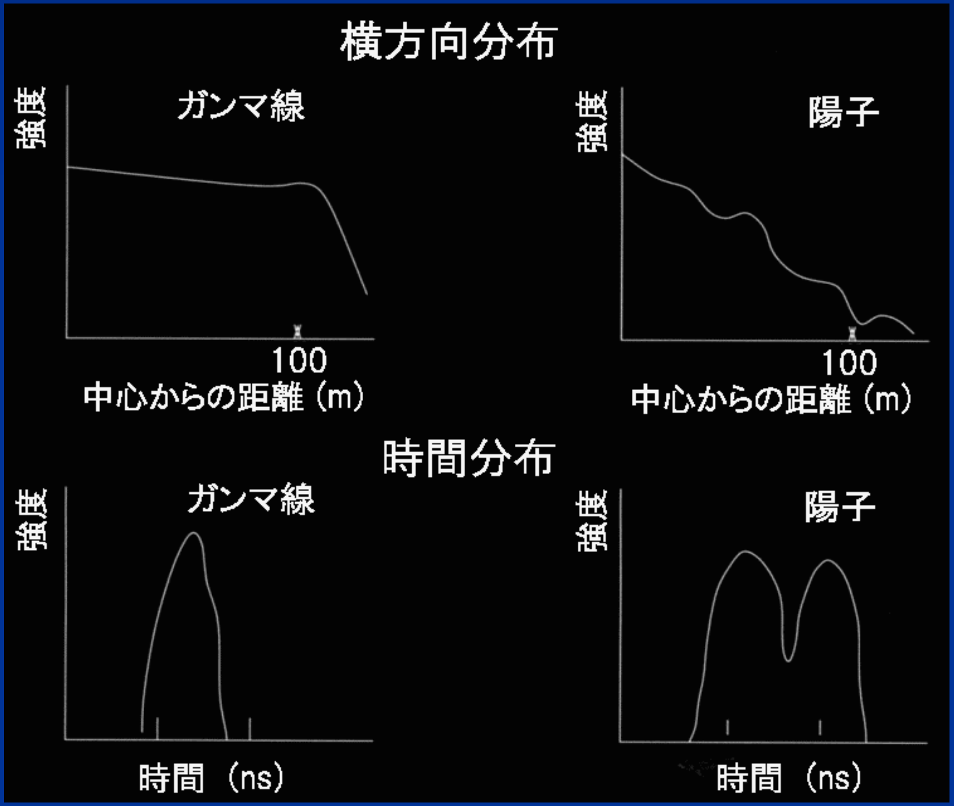
⇒ <u>シャープな</u>イメージ

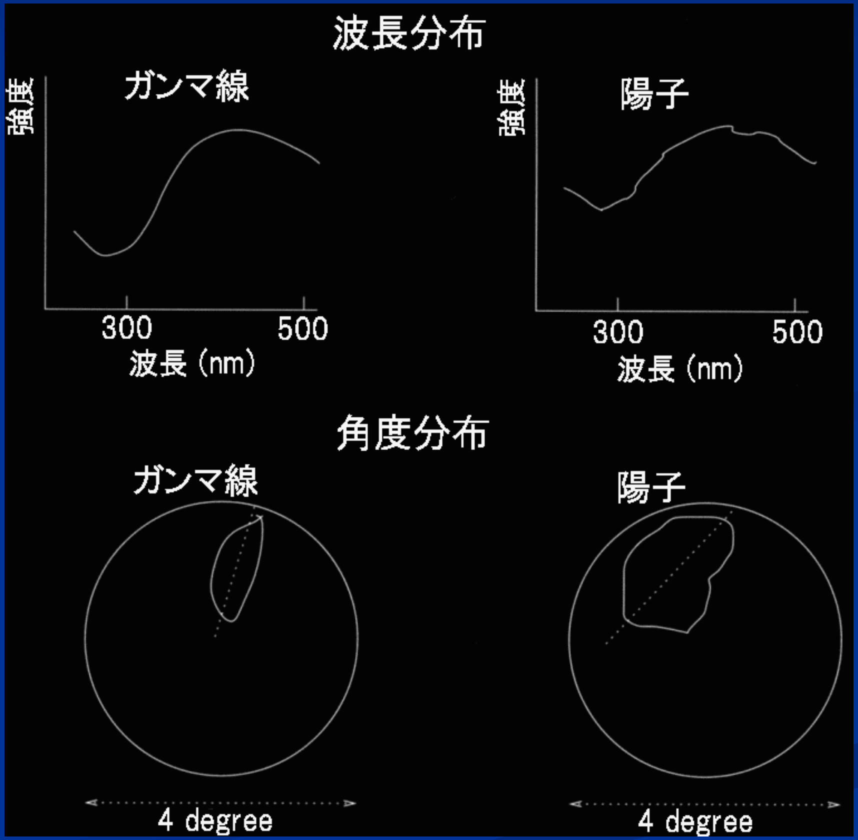
陽子:

核シャワー

⇒ <u>拡散した</u>イメージ

ガンマ線と陽子のチェレンコフ光

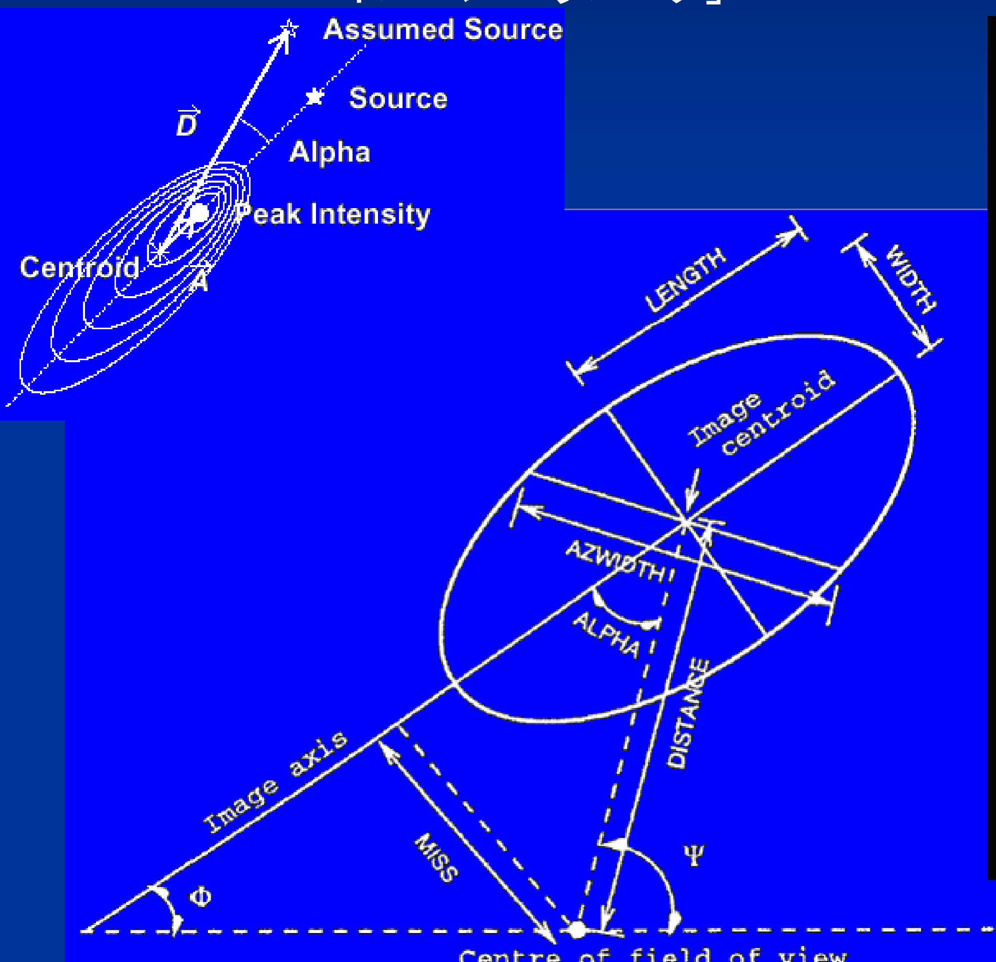




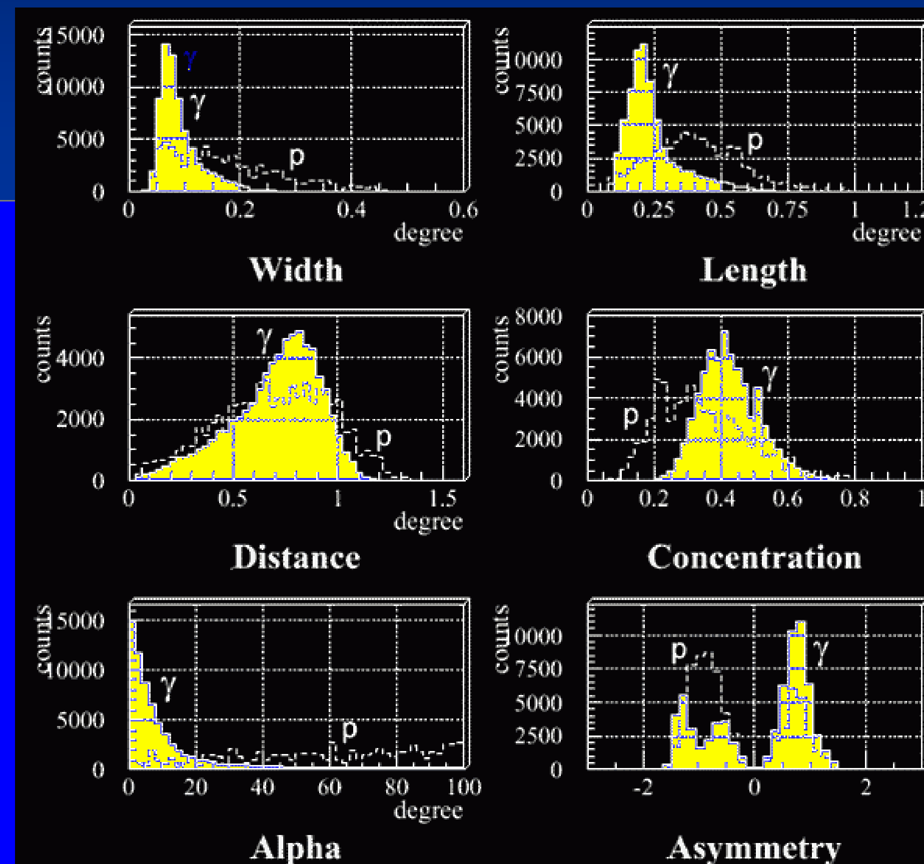
Weekes, "Very High Energy Gamma-ray Astronomy"

ガンマ線と陽子の識別

「イメージパラメータ」



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



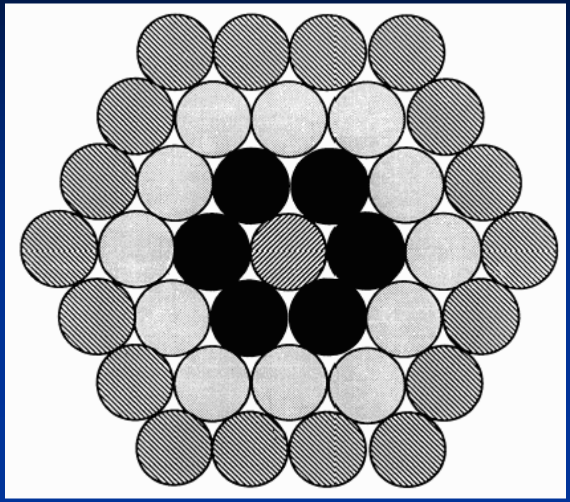
(Simulation)

Evolution of camera of the Whipple 10m telescope

1982-1987

37x2"

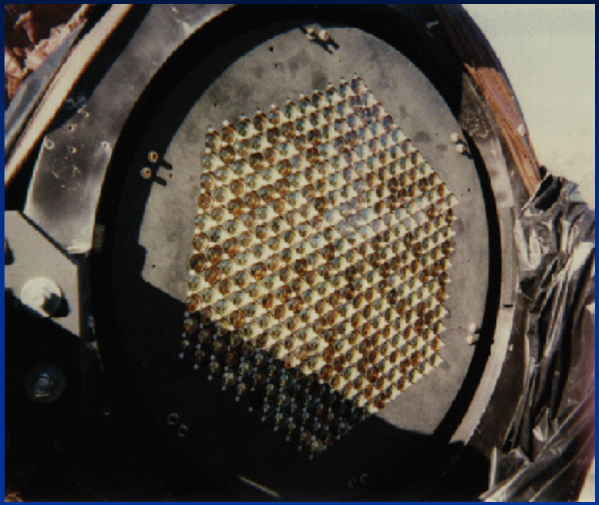
3.5deg



1996-1999

331x1"

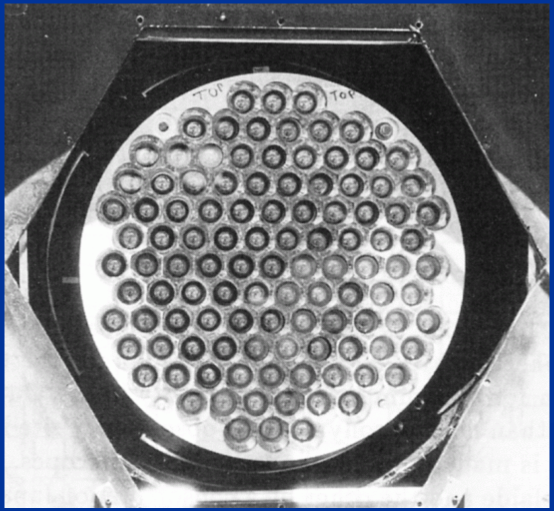
4.8deg



1988-1996

91x1", 18x2"

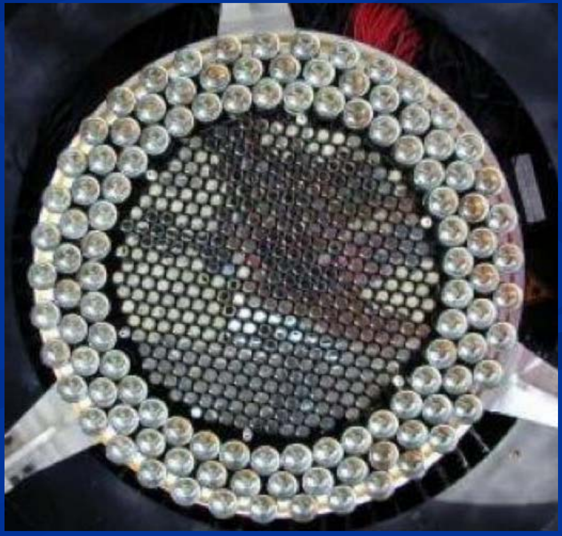
3.75deg



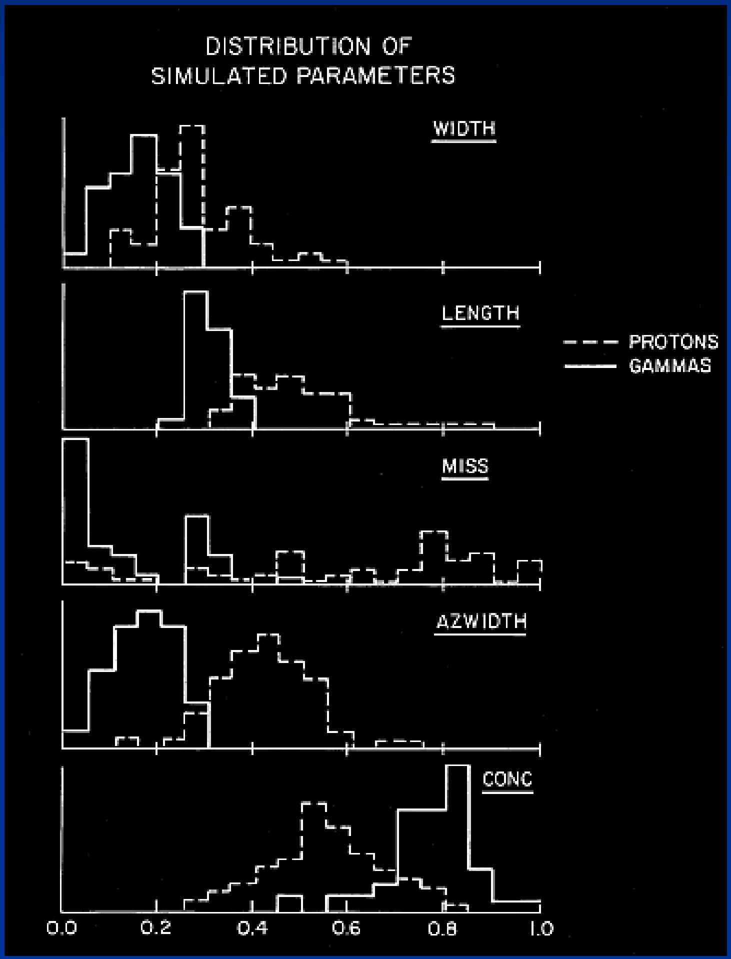
1982-1987

379x1/2", 111x1"

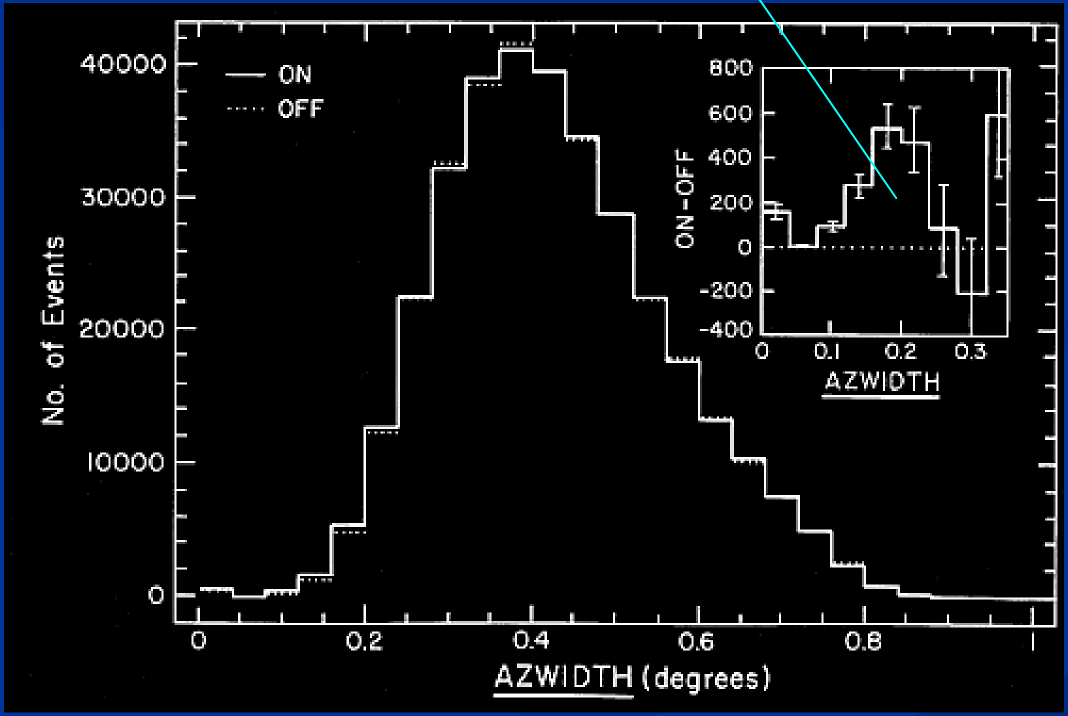
4.0deg



WhippleによるCrabの検出



ガンマ線信号

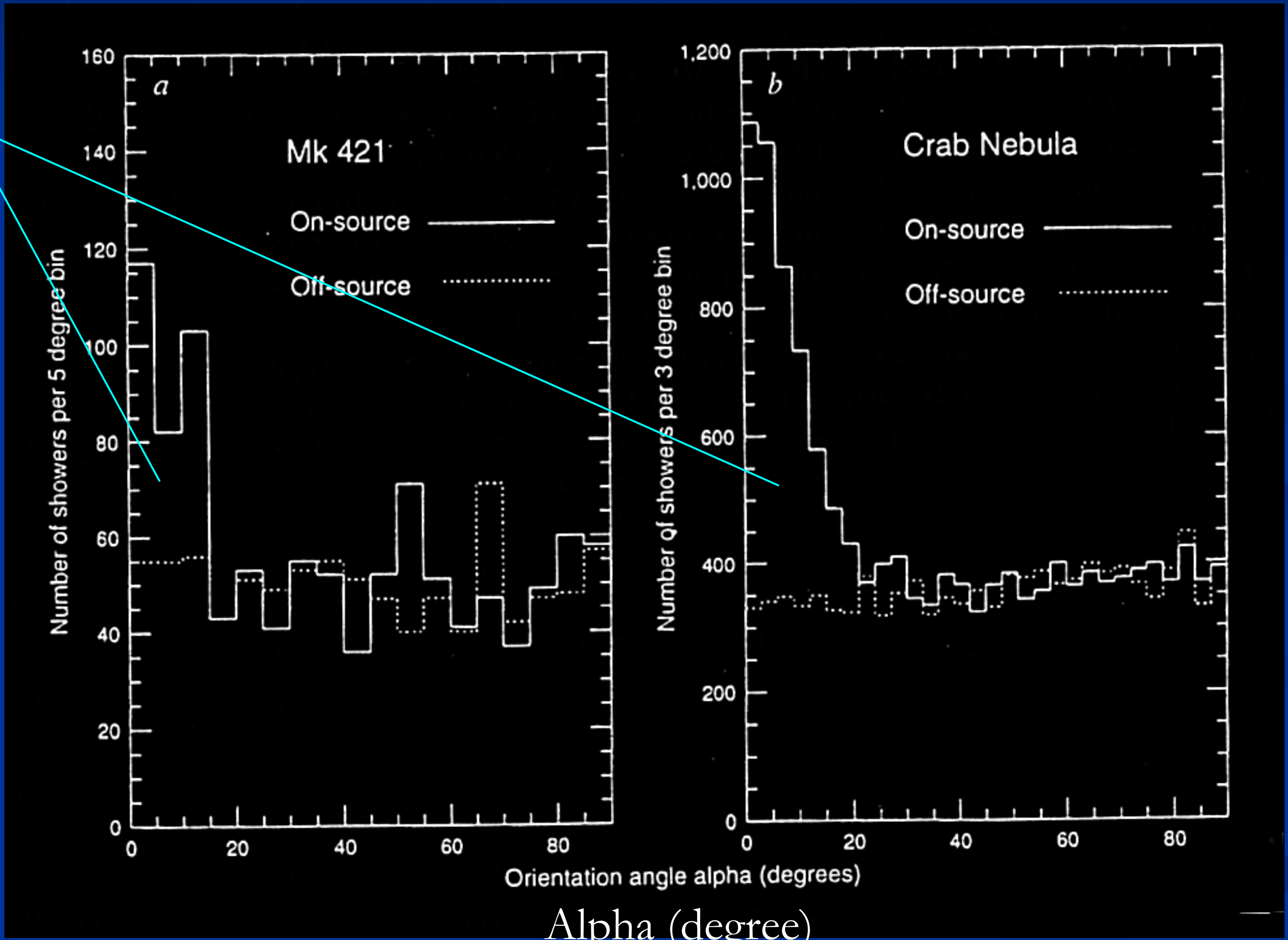


82hrs, 0.24γ/min

Weekes et al. ApJ 342 (1989) 349

WhippleによるMrk421の検出

ガンマ
線信号

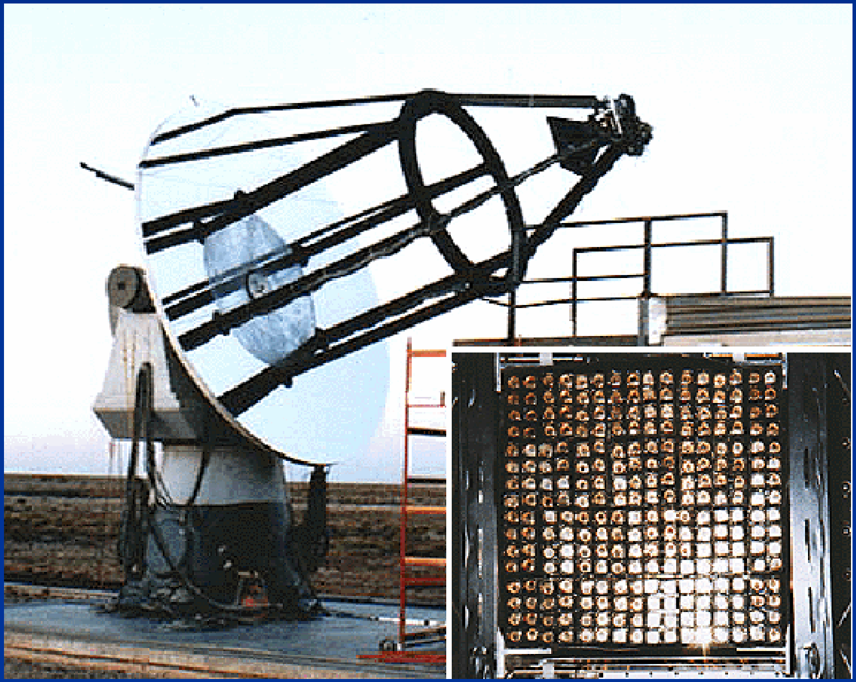


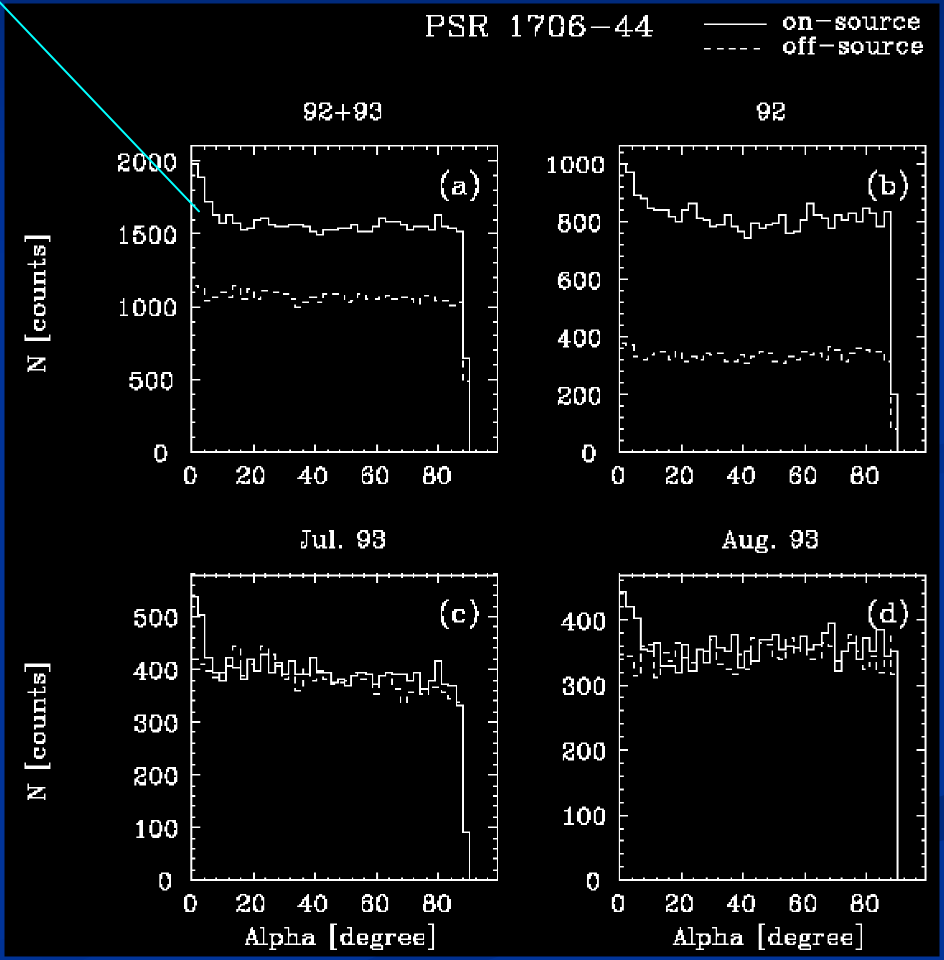
Alpha (degree)

Punch et al. Nature 358 (1992) 477

CANGAROOによるPSR1706-44の検出

ガンマ線信号





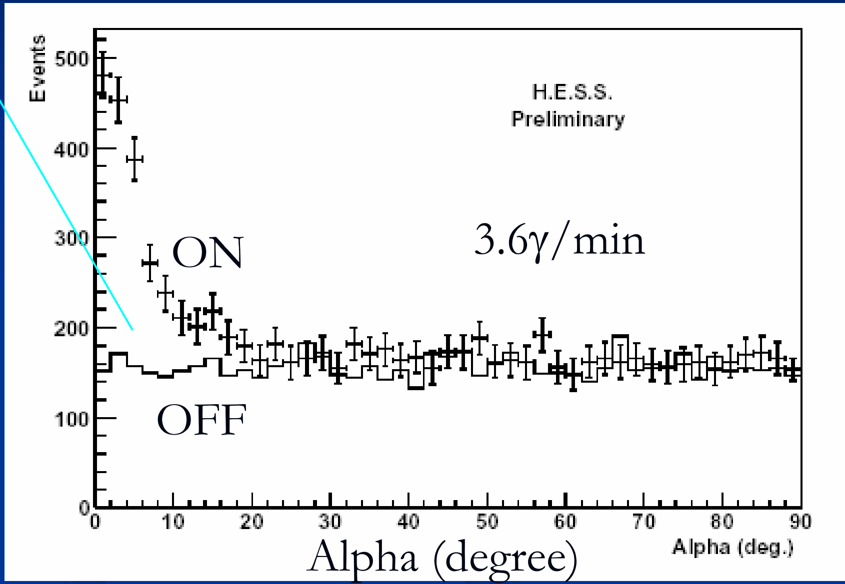
60hrs, 0.2γ/min

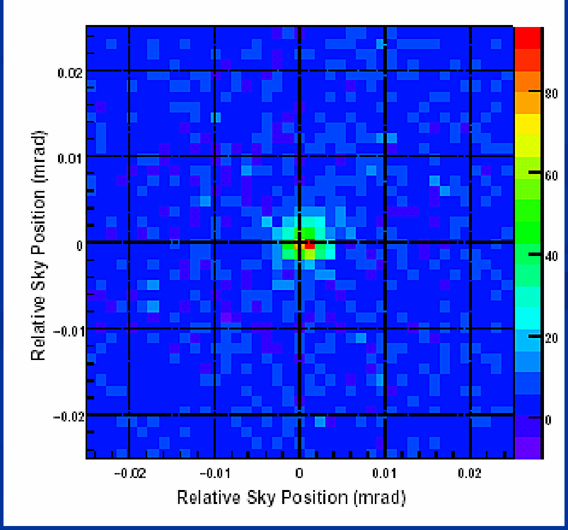
Alpha (degree)

Kifune et al. ApJ 438 (1995) L91

現在： H.E.S.S.によるCrabの観測

ガンマ線信号

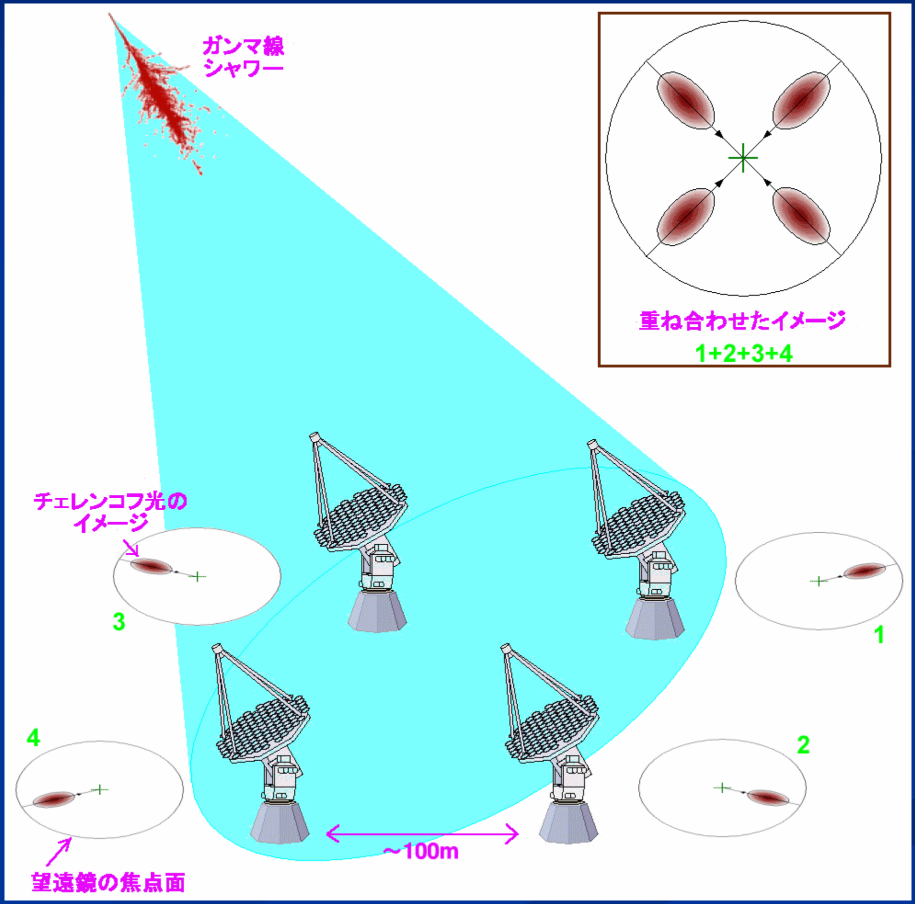




Masterson et al. 28th ICRC (2003)

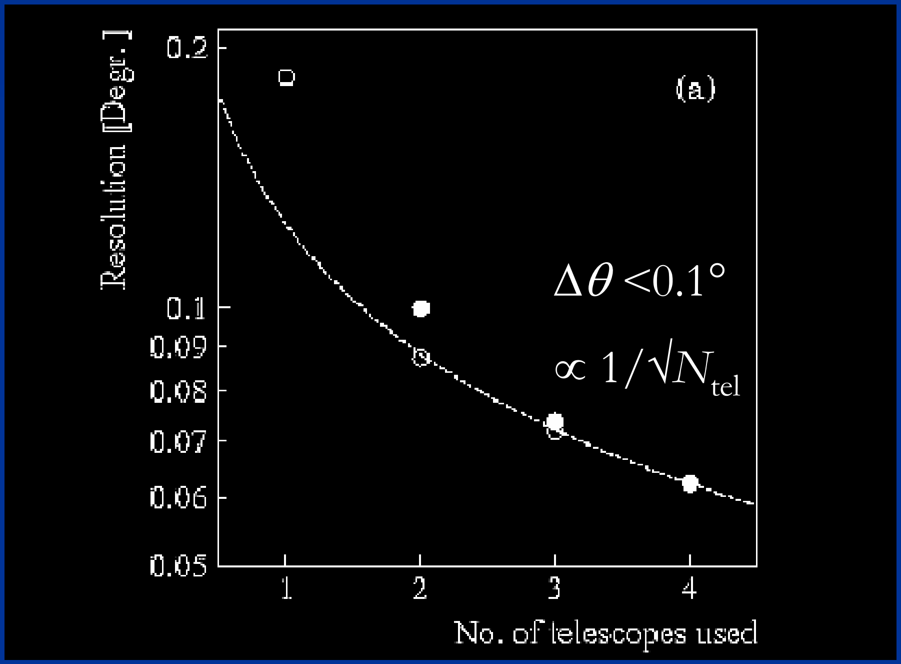
ステレオ観測

- チェレンコフ光の「円盤」: 直径~300m、厚さ~1m
- ステレオ観測 ⇒ シャワーまでの距離の情報
- 角度分解能の向上
- エネルギー分解能の向上



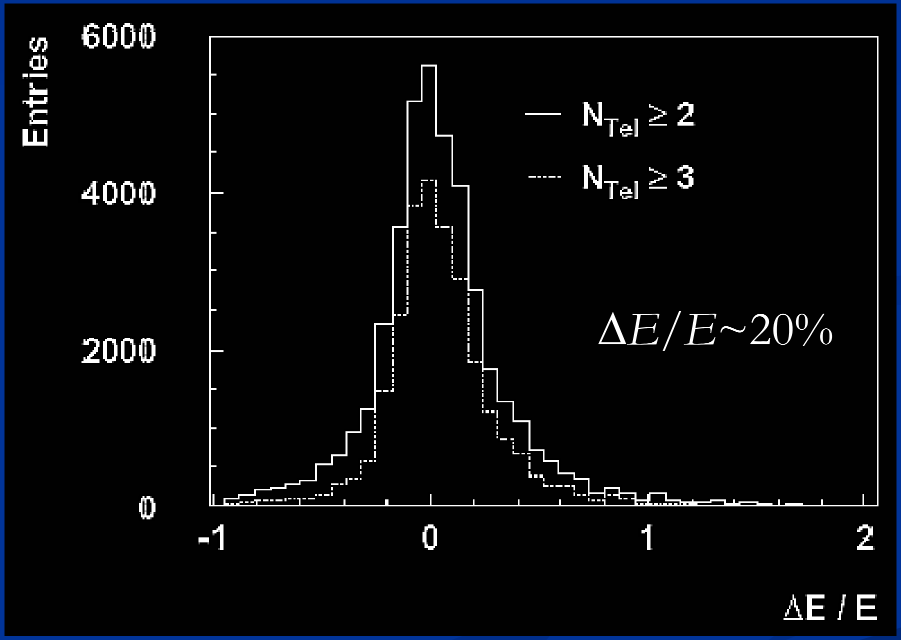
ステレオ観測のメリット

角度分解能



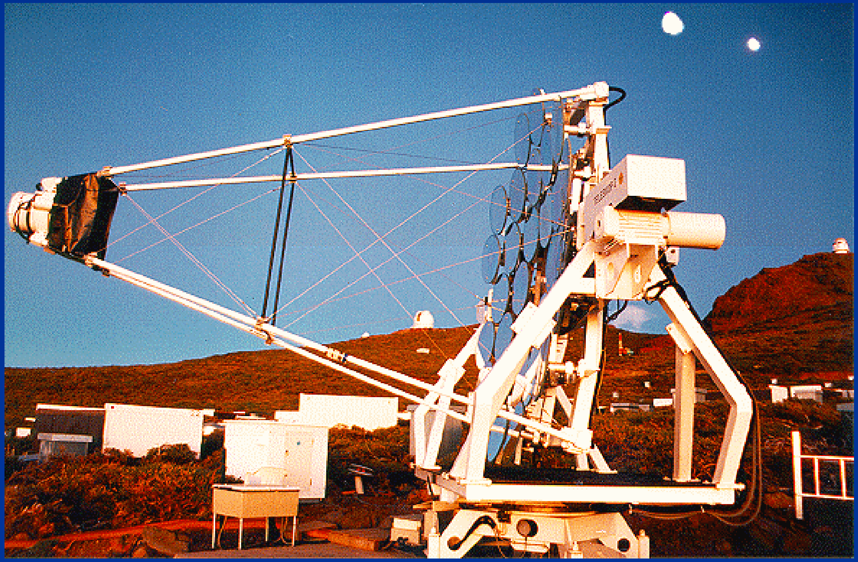
Hofmann et al. APh 12 (1999) 135

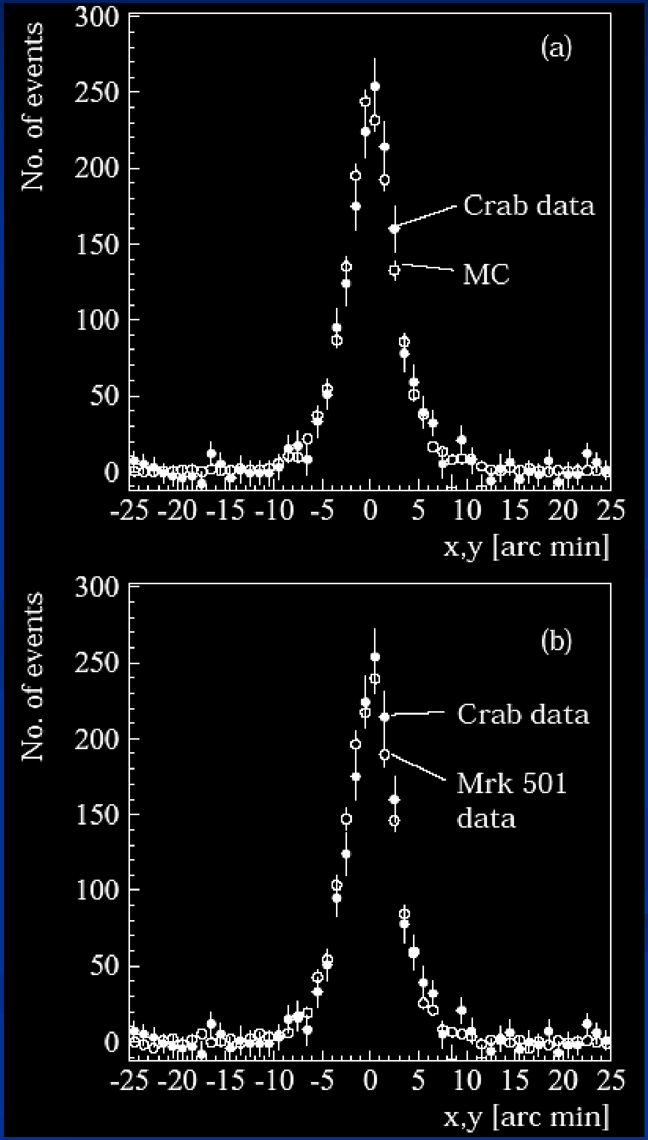
エネルギー分解能



Mrk501: Aharonian et al. A&A 342 (1999) 69

HEGRAによるCrabの観測

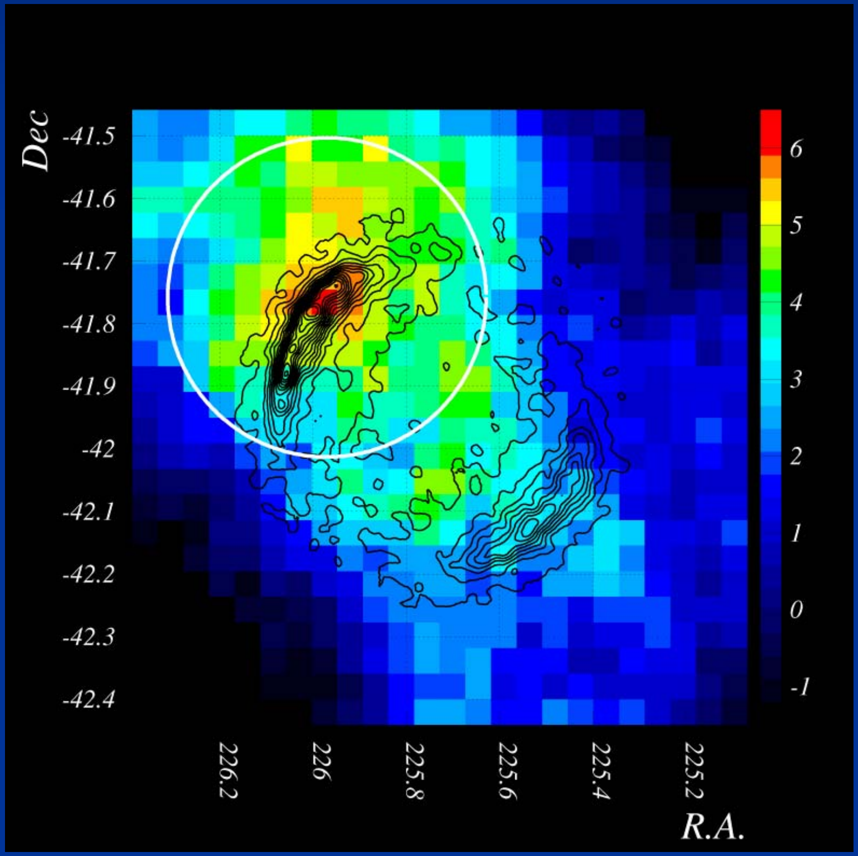


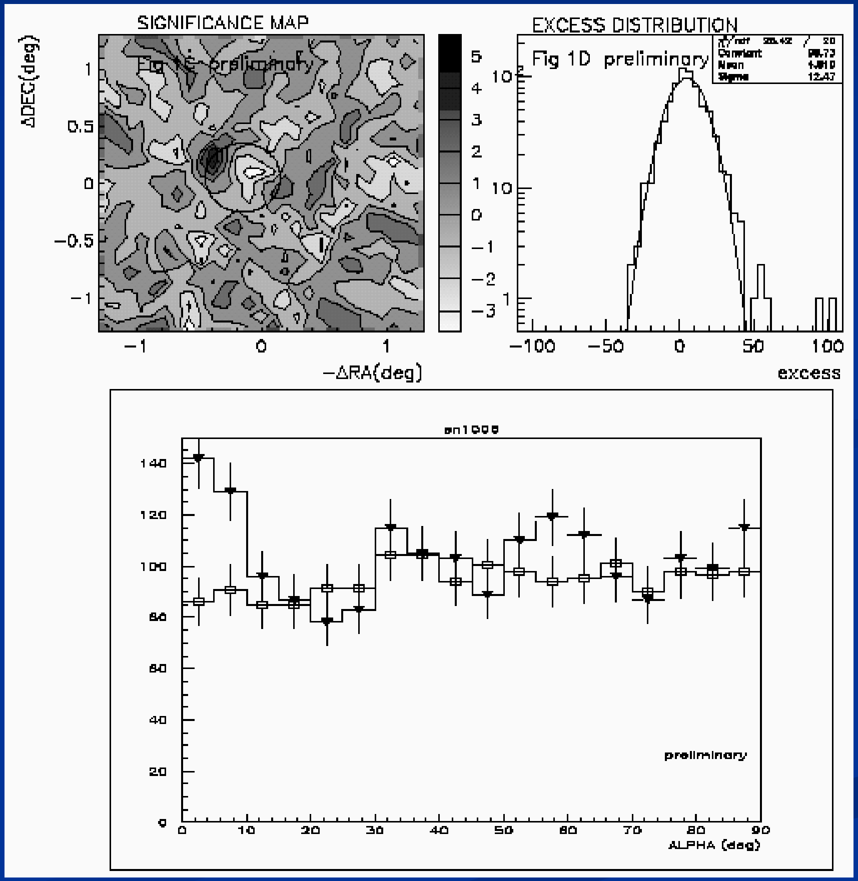


Emission region size <1.5'

Aharonian et al. AA 361 (2000) 1073

超新星残骸 SN1006 (1)





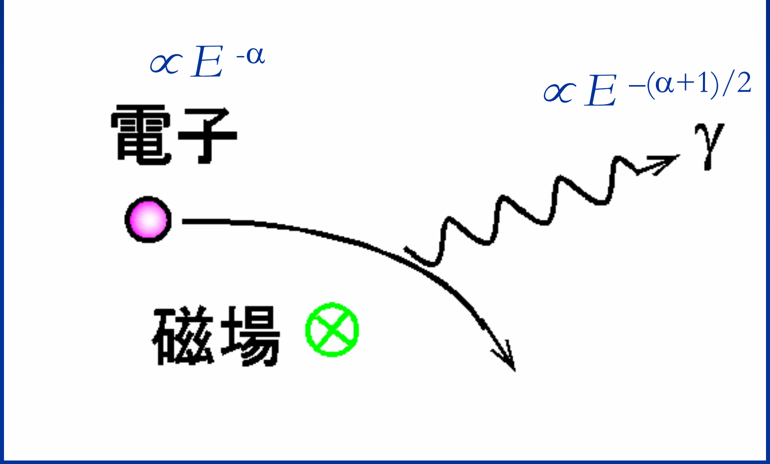
CANGAROO-II 10m (Hara Ph.D. 2002)

HEGRA CT1 (Vitale et al. 2003 ICRC)

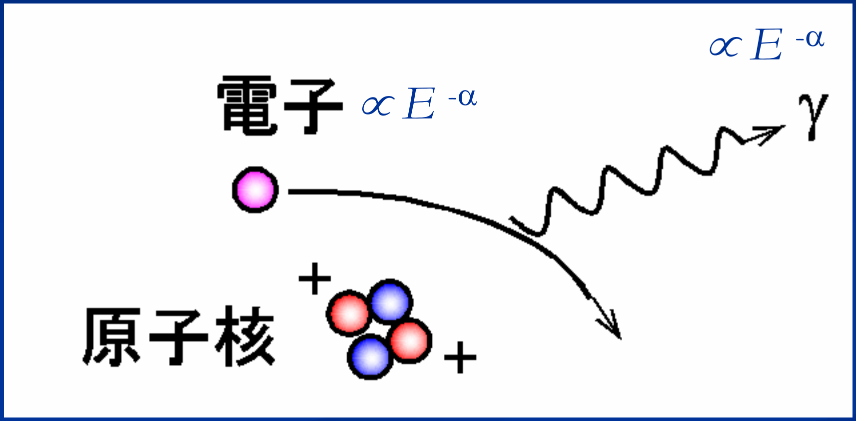
>18TeV, 219 hr

ガンマ線の放射機構

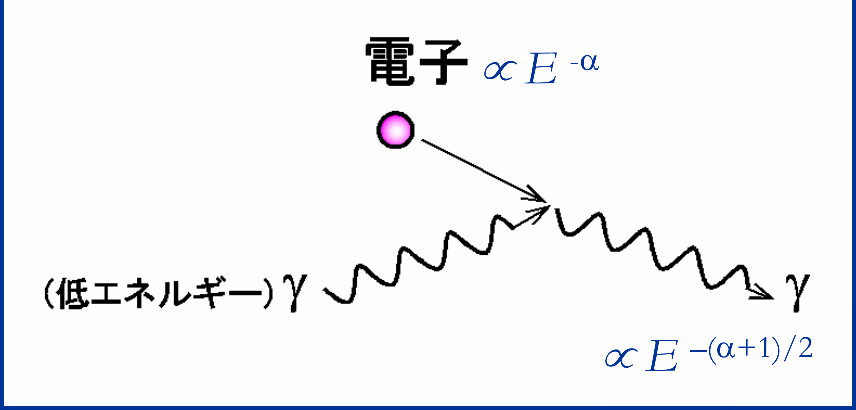
シンクロトロン放射



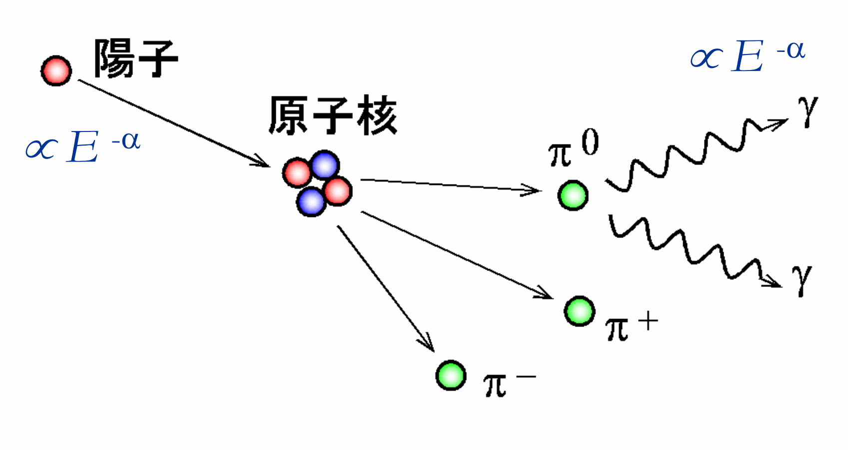
電子の制動放射



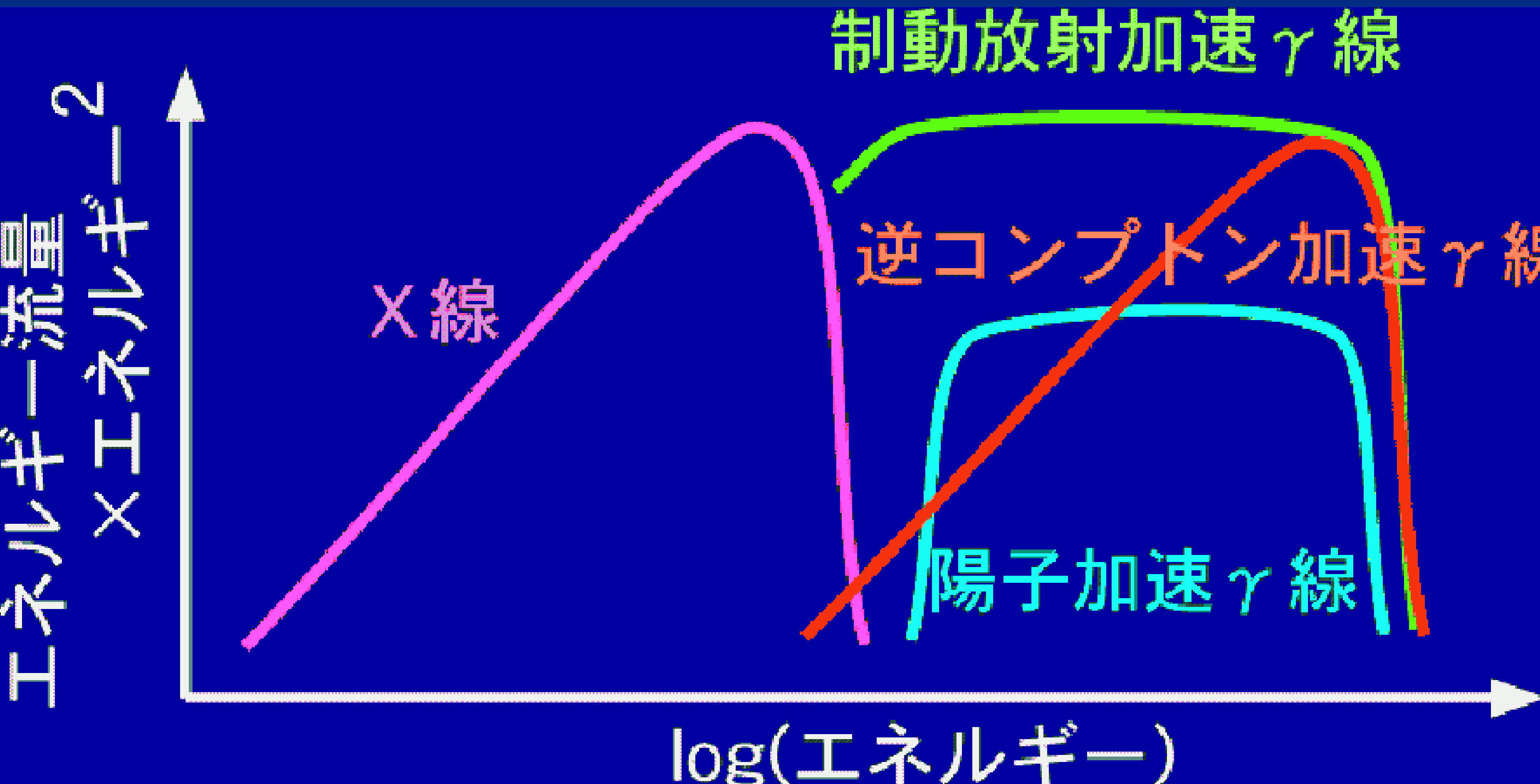
逆コンプトン放射



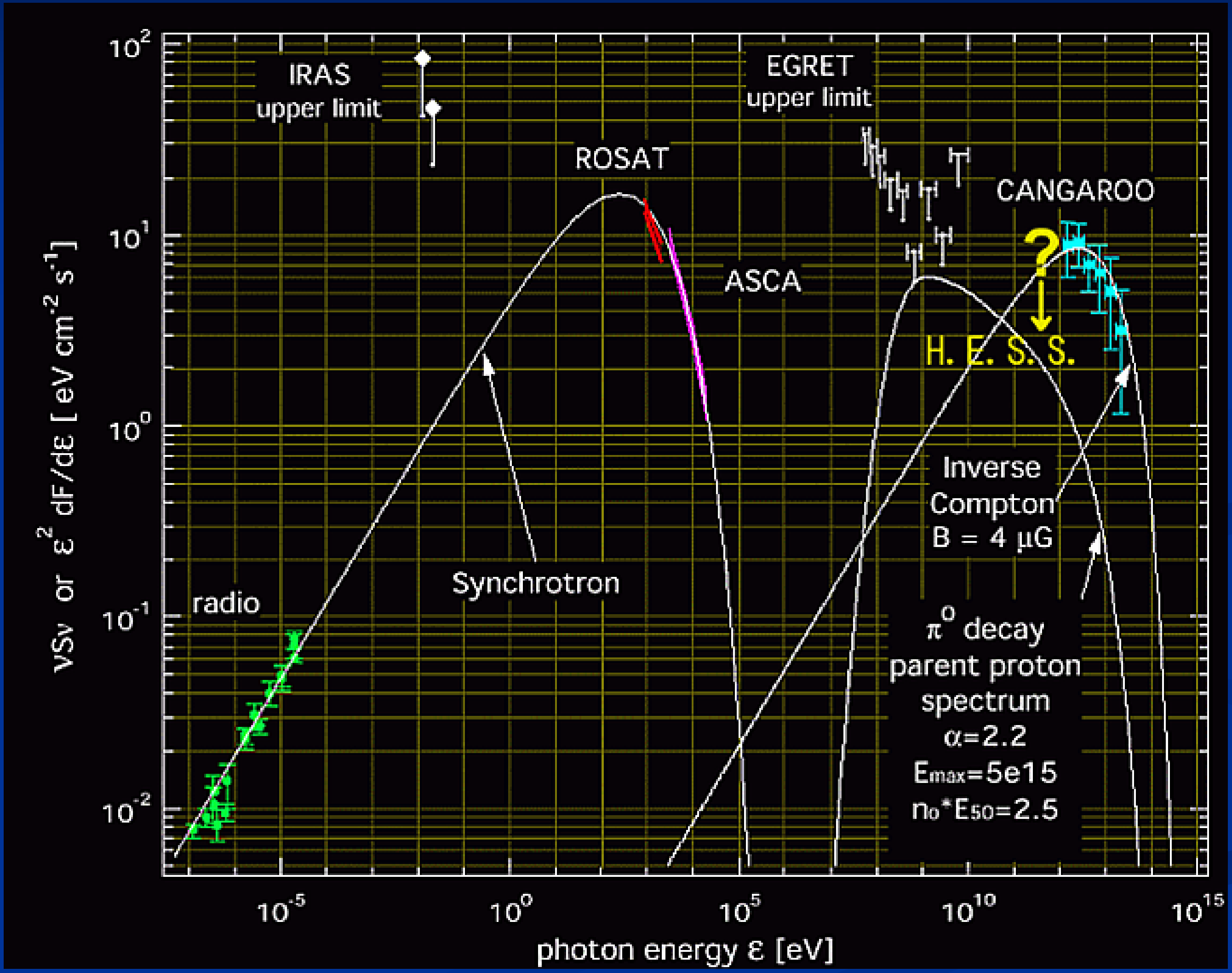
中性パイオンの崩壊



ガンマ線のスペクトル



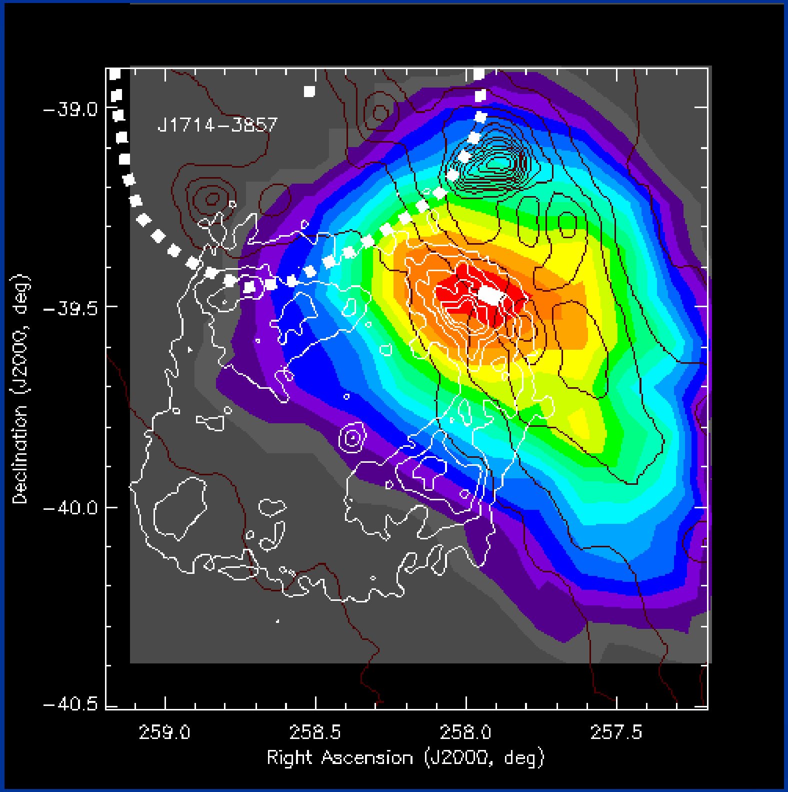
超新星残骸 SN1006 (2)



Naito et al. Astron.Nach.320 (1999) 205

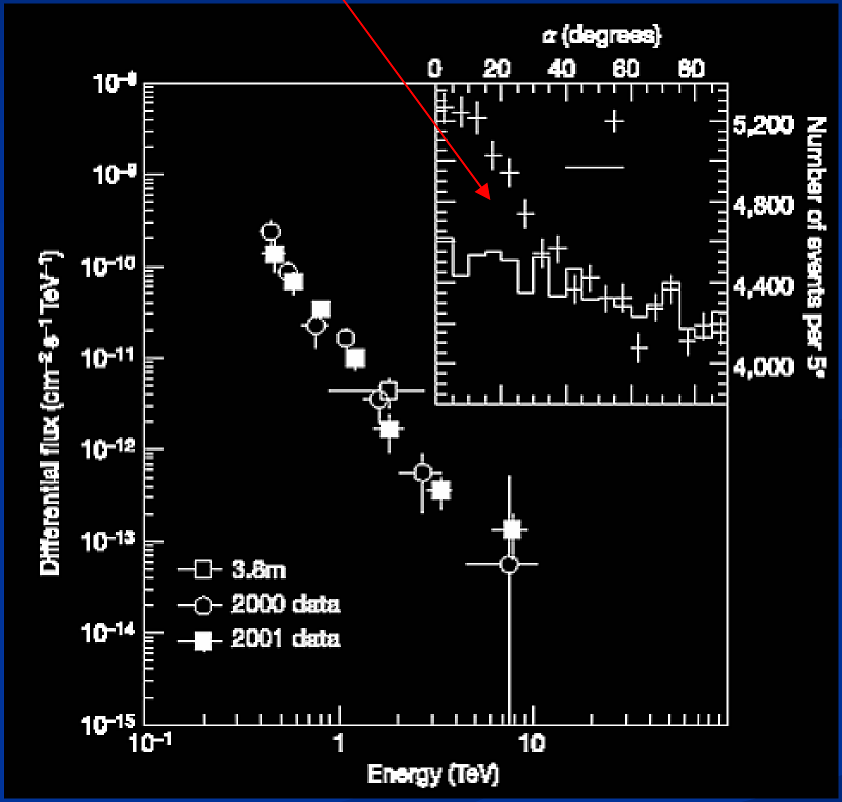
超新星残骸 RX J1713.7-3946 (1)

- X線で検出された超新星残骸
- 非熱的X線放射
- CANGAROO-I&IIによる検出



Significance map

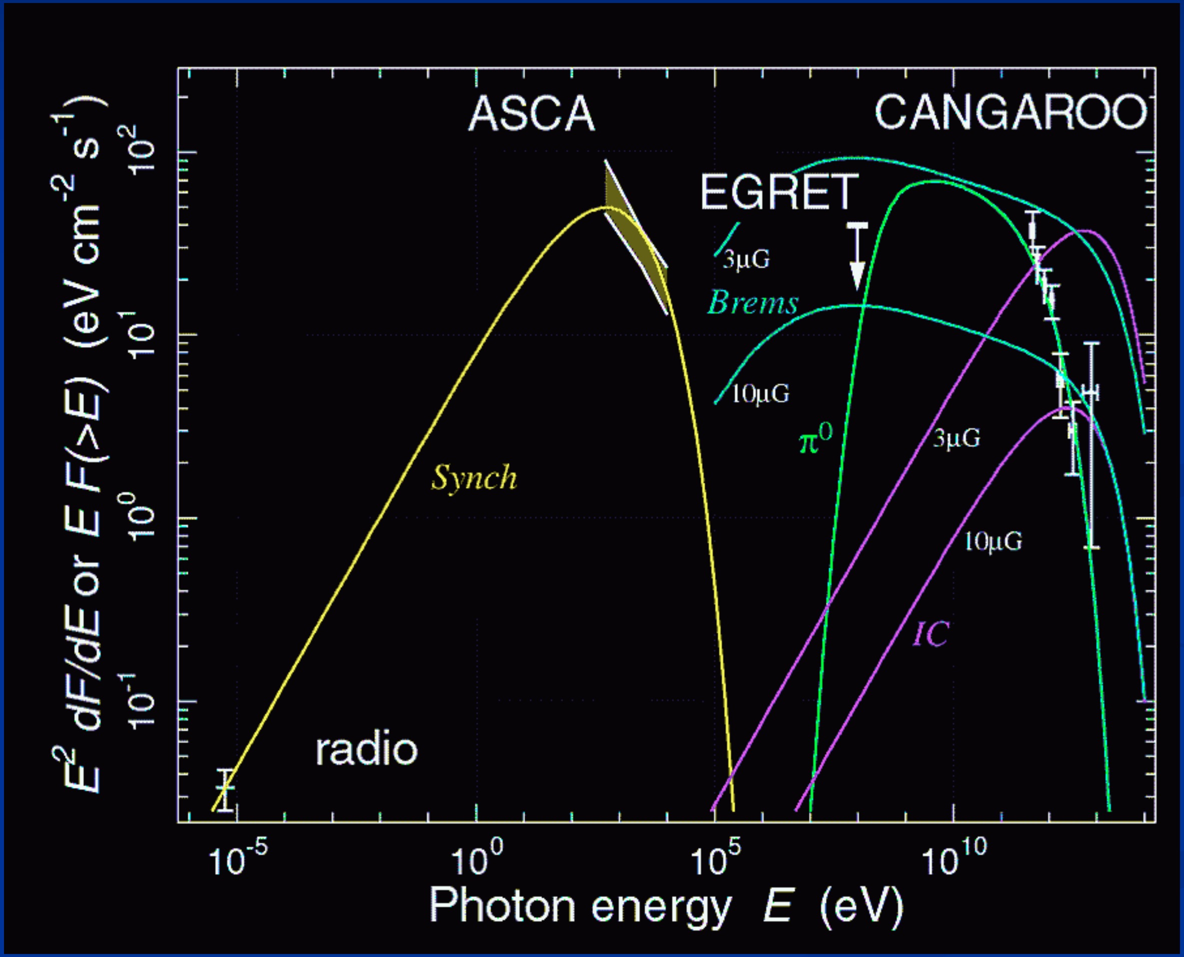
Gamma-ray signal = (ON) − (OFF)



Energy spectrum

Enomoto et al. Nature 416 (2002) 823

超新星残骸 RX J1713.7-3946 (2)



電子からの放射 (Brems, IC)としては説明困難

⇒ 陽子からの放射 (π^0)?

⇒ 宇宙線の起源?

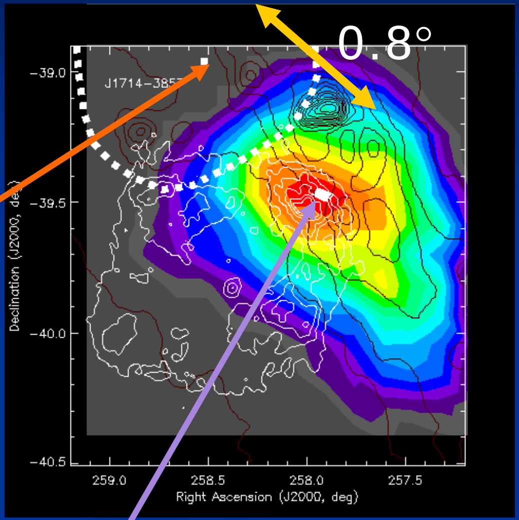
Enomoto et al. Nature 416 (2002) 823

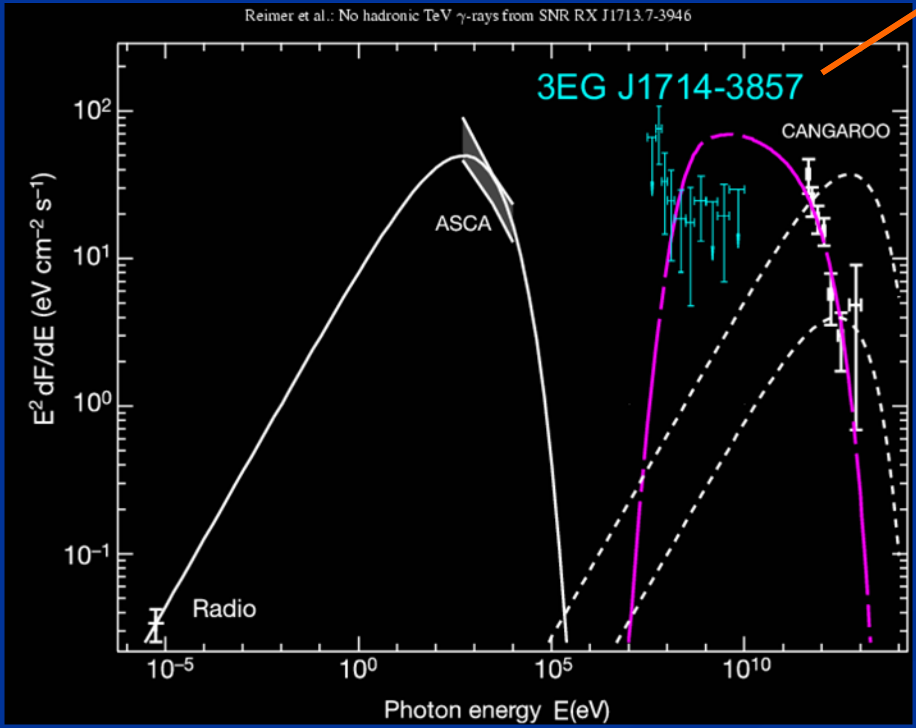
超新星残骸 RX J1713.7-3946 (3)

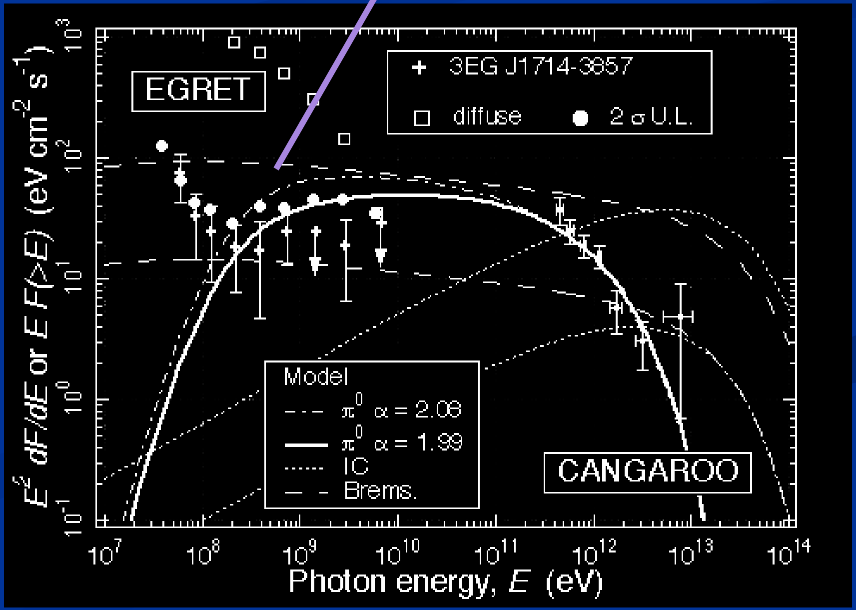
Counter arguments

* Reimer & Pohl, A&A 390 (2002) L43

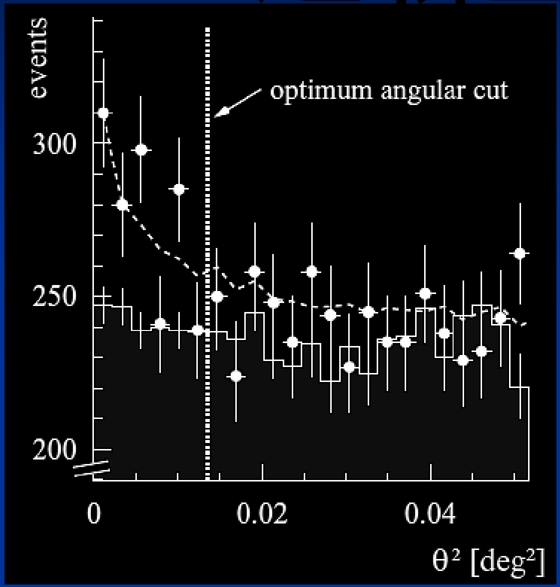
* Butt et al., Nature 418 (2002) 489





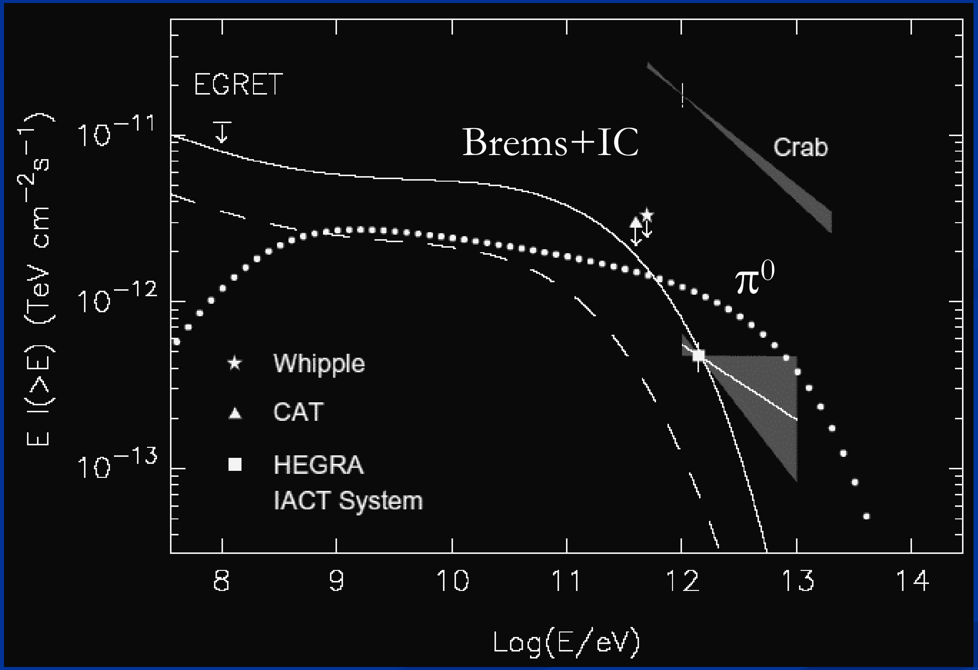


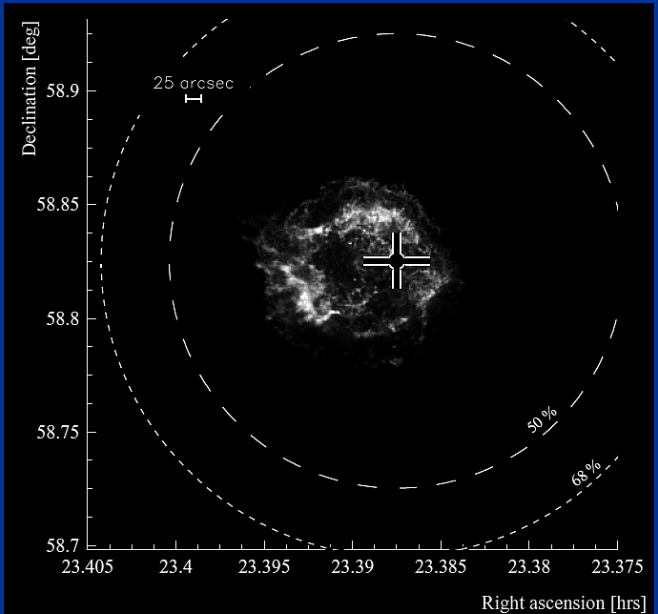
超新星残骸　Cas A



HEGRA-CT system ステレオ観測

232 hrs

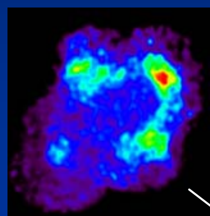




Aharonian et al. A&A 370 (2001) 112

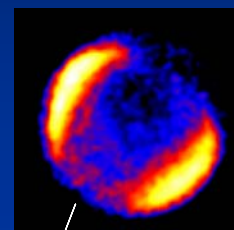
超新星残骸の系統的観測

RX J1713.7-3946（CANGAROO）



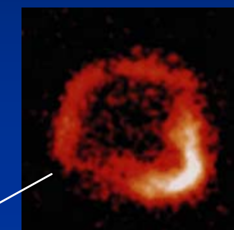
ASCA

SN1006（CANGAROO）

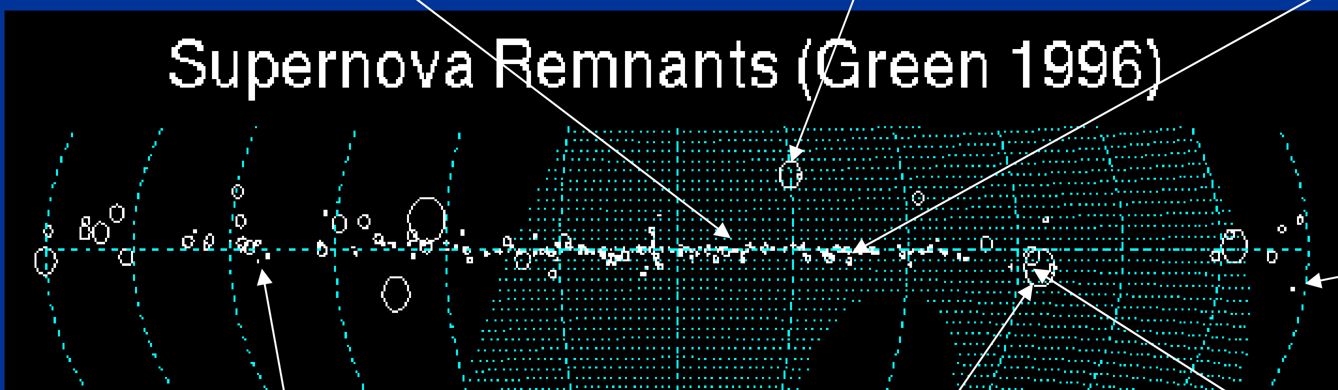


ASCA

RCW86（CANGAROO under analysis）



ROSAT

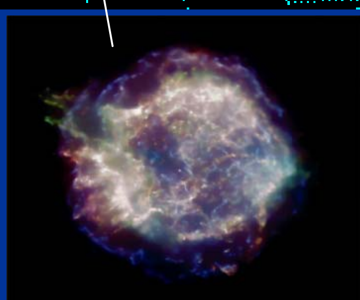


Crab nebula

（"Standard candle"）

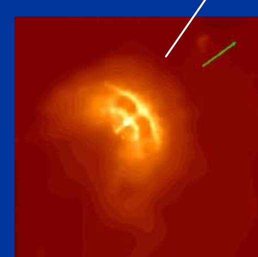
Chandra

・optical



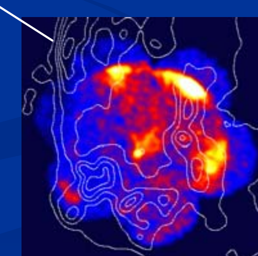
Chandra

Cas A（HEGRA）



Chandra

Vela（CANGAROO）



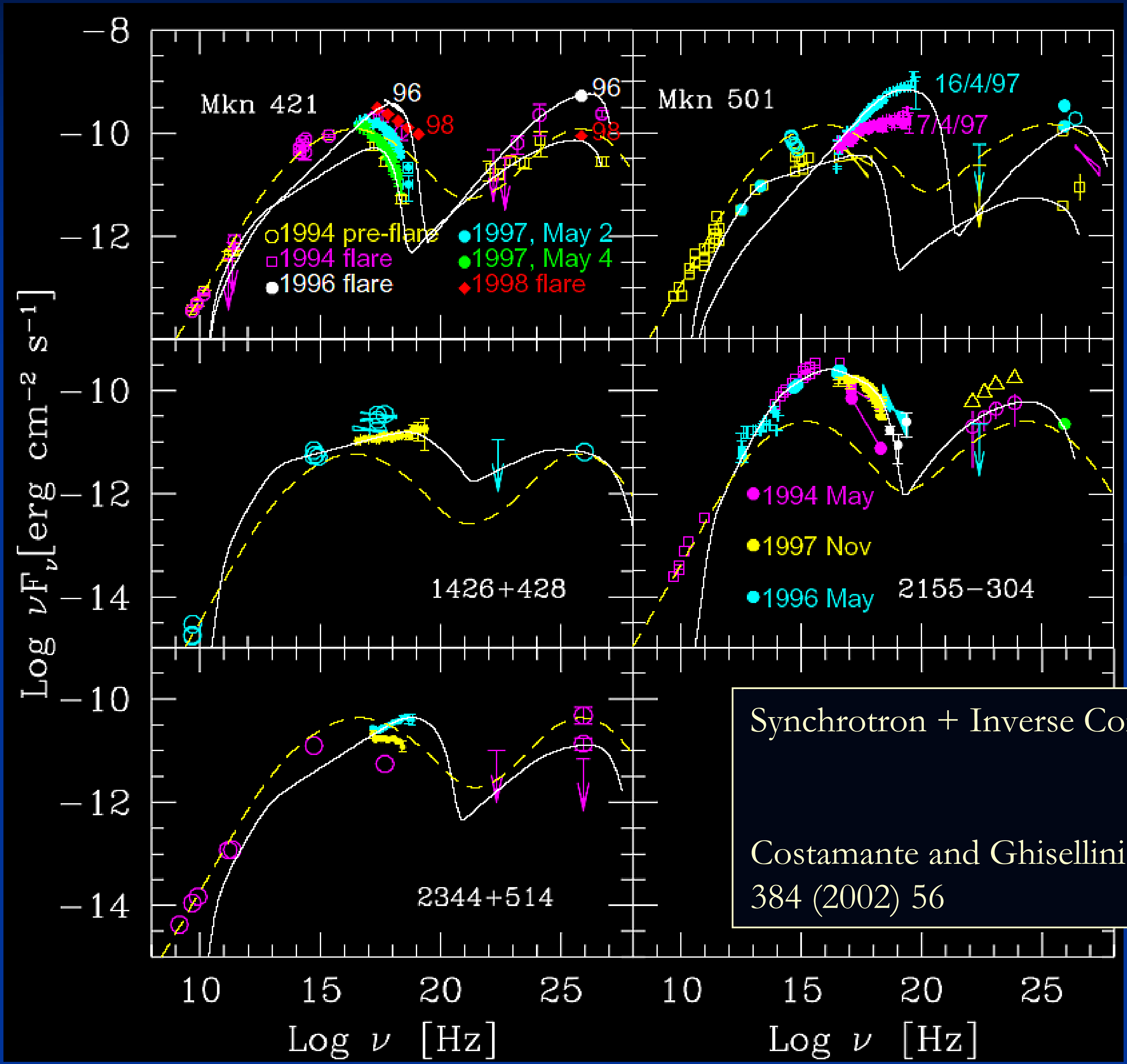
ROSAT

RX J0852-46（CANGAROO under analysis）

TeVブレーザー

Source	Type	Redshift	Group	EGRET source
Mrk421	XBL	0.031	*Many*	Yes
Mrk501	XBL	0.034	*Many*	No
1ES2344+514	XBL	0.044	Whipple, HEGRA	No
PKS 2155-304	XBL	0.116	Durham, HESS	Yes
1ES1959+650	XBL	0.048	7TA, HEGRA, Whipple	No
1H1426+428	XBL	0.129	*Many*	No
BL Lac	XBL	0.069	Crimea	Yes
3C66A	RBL	0.44	Crimea	Yes

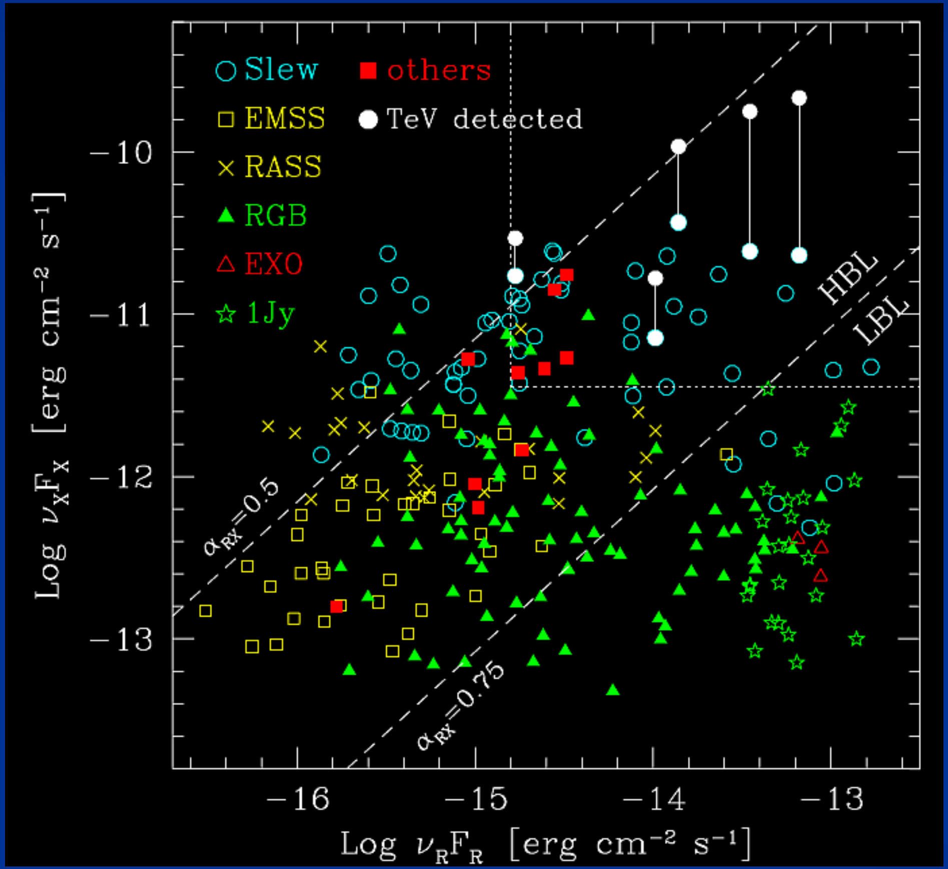
TeVブレーザーのSED



Synchrotron + Inverse Compton

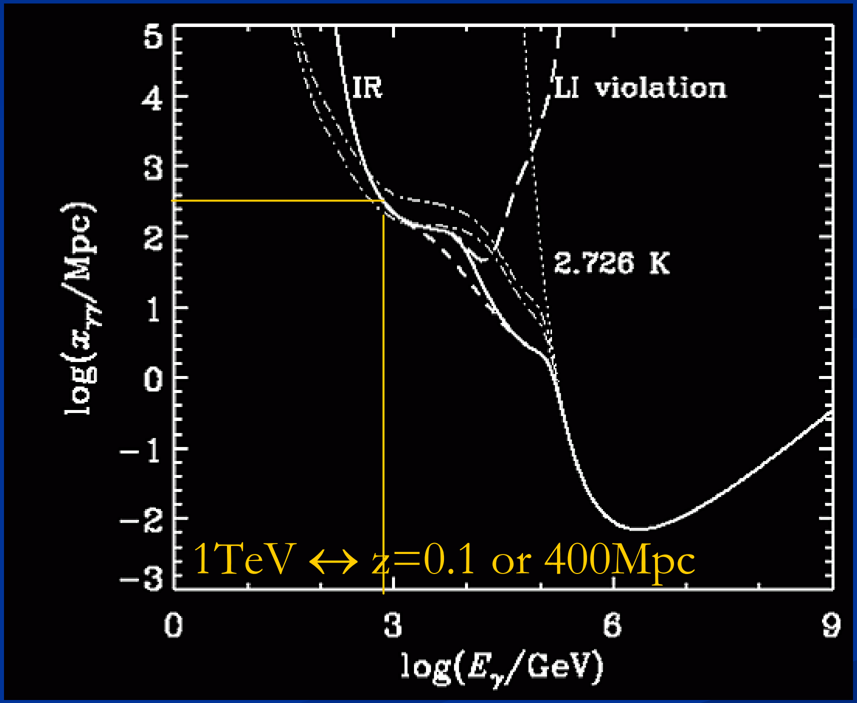
Costamante and Ghisellini A&A 384 (2002) 56

TeVブレーザーと赤外吸収



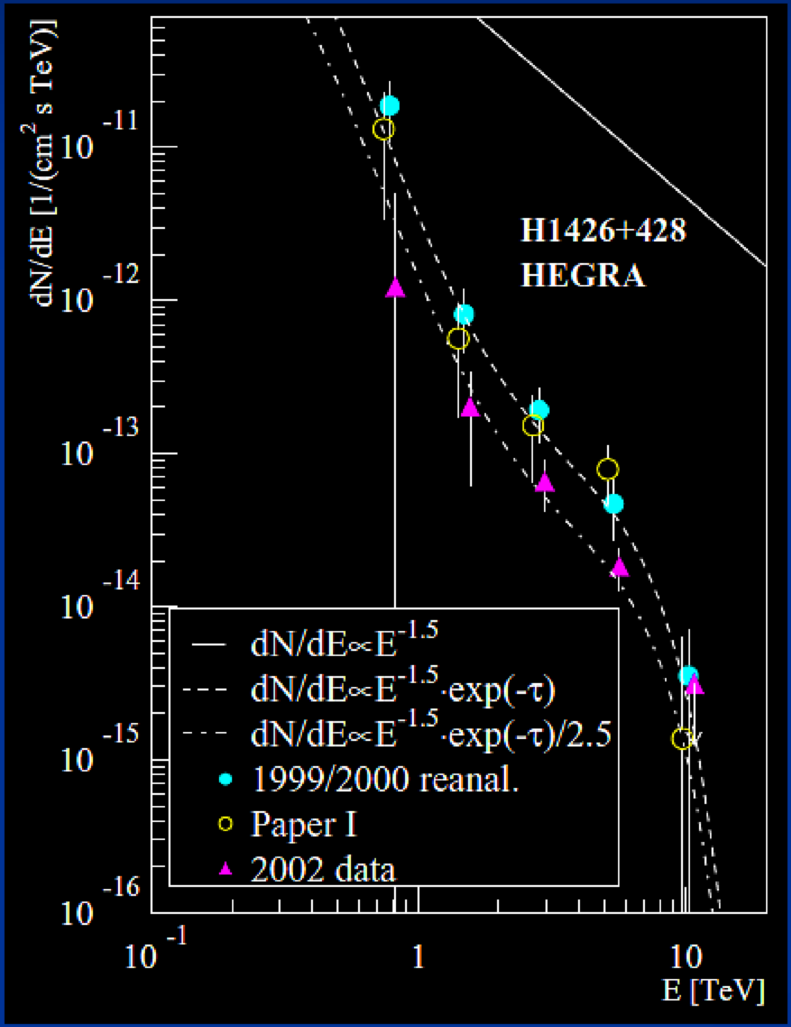
Costamante and Ghisellini A&A 384 (2002) 56

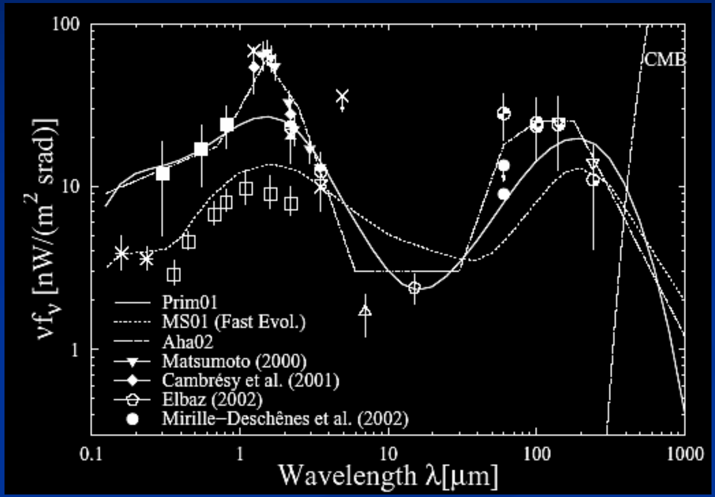
Mean free path for e^+e^- pair production

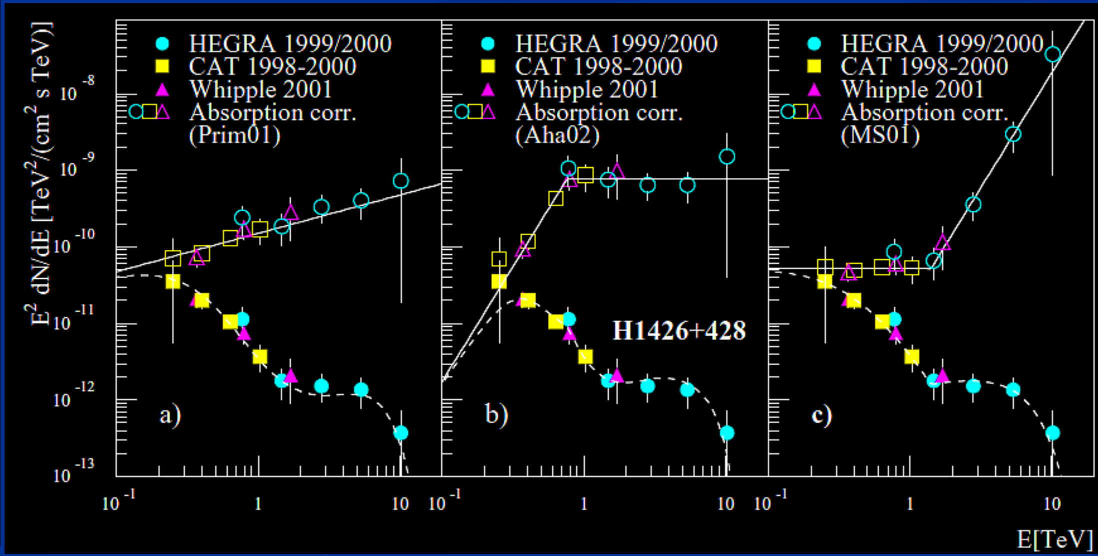


Protheroe & Meyer, Phys.Lett. B493 (2000) 1

1H1426+428 (z=0.129)







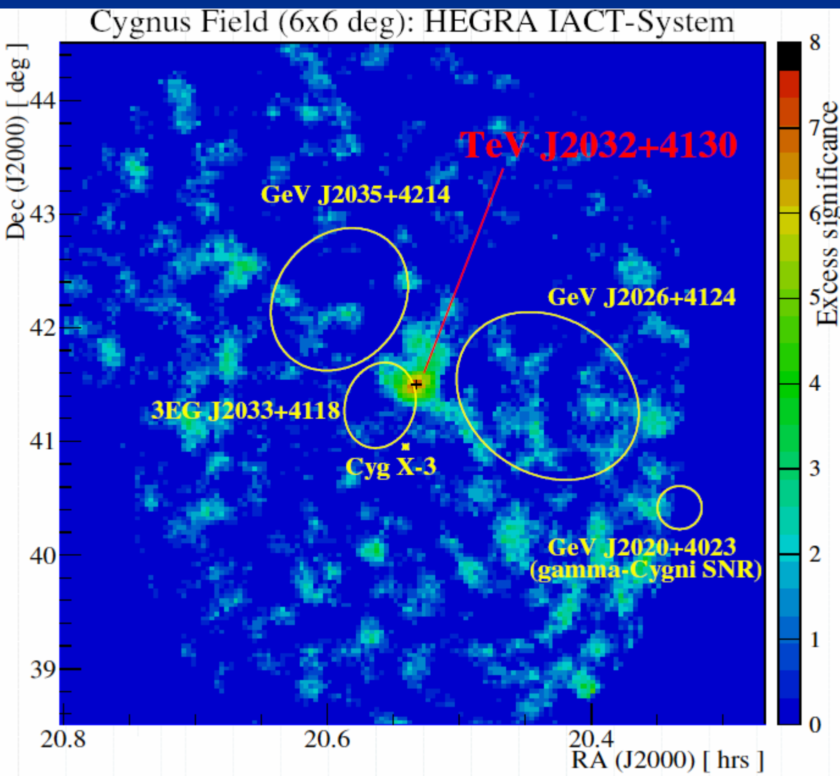
Aharonian et al. 2003 A&A 403, 523

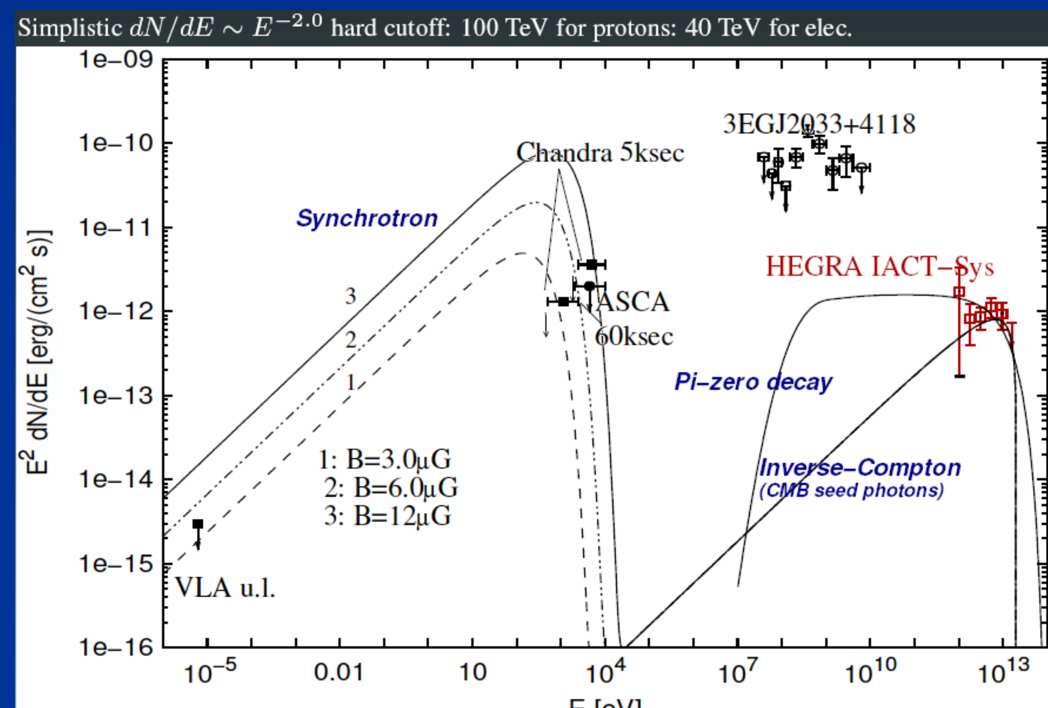
新たなタイプのガンマ線天体

- J2032+4130: Unidentified TeV source
  - Cyg OB2 association? Cyg X-3?
- NGC253: Spiral galaxy with starburst activity
  - Extended?
- M87: Radio galaxy
  - Proton-initiated cascade?
- Galactic plane
  - Milagro signal “weakend”…
- *What’s next?*

TeV J2032+4130

- HEGRA CT system





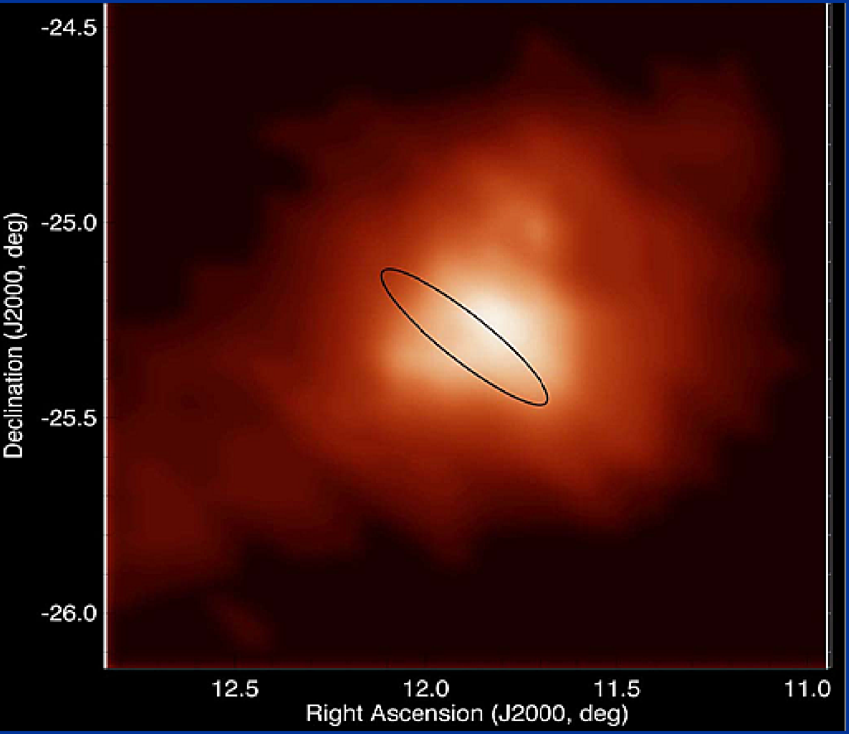
Rowell, ICRC2003

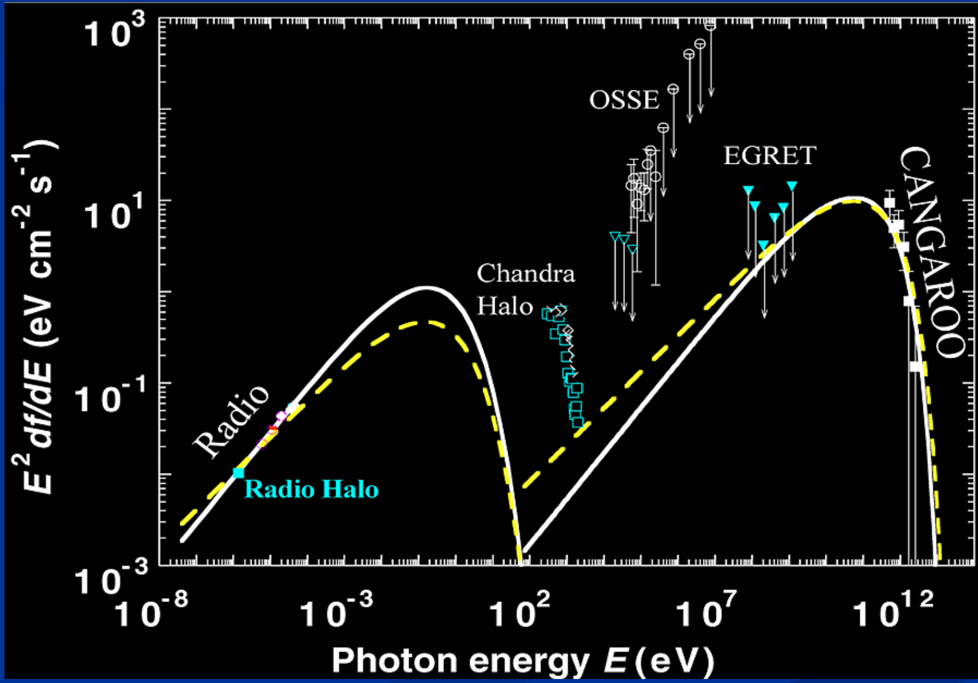
Aharonian et al. A&A 393, L37-40 (2002)

NGC 253

Optical image

- CANGAROO 10m



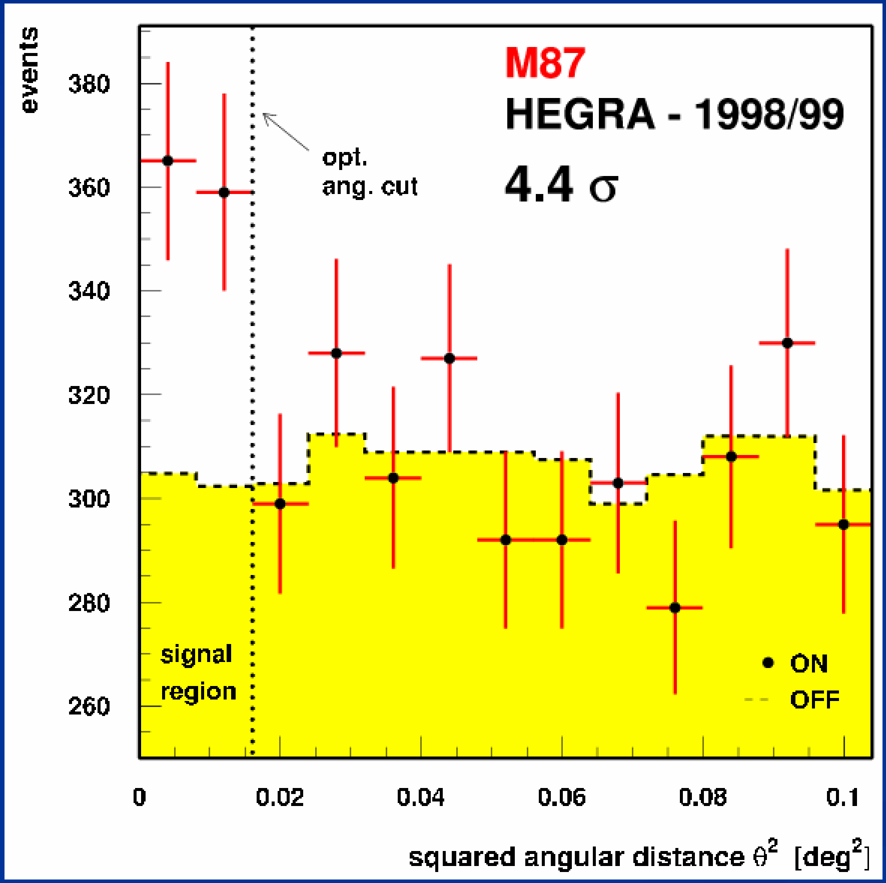


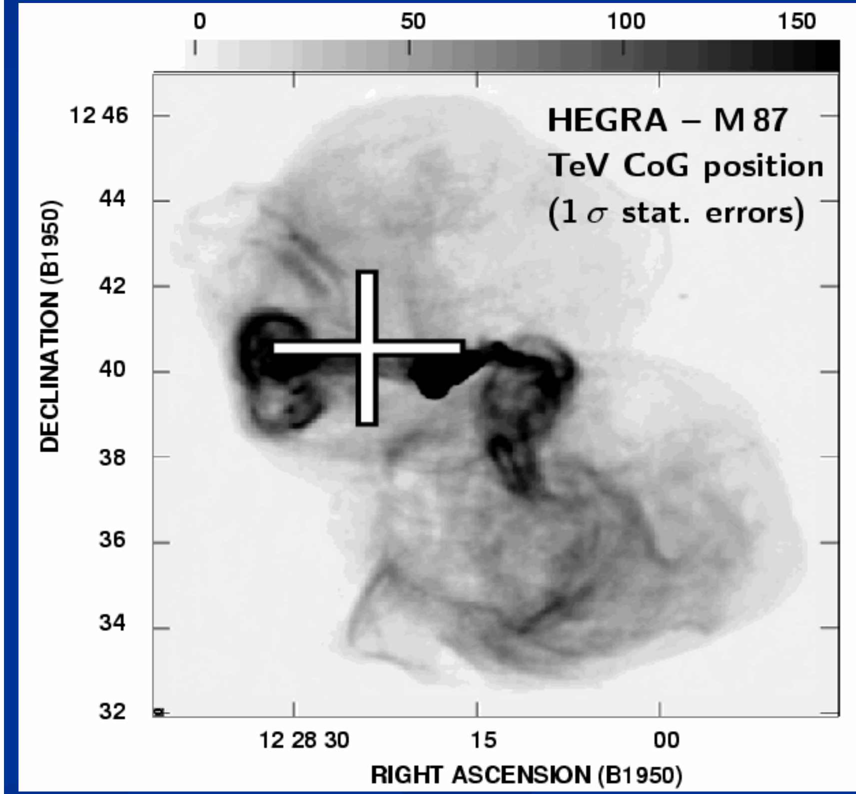
Itoh et al. A&A 396, L1 (2002);

A&A 402, 443 (2003)

M87

- HEGRA CT system 1998-1999 4.4σ

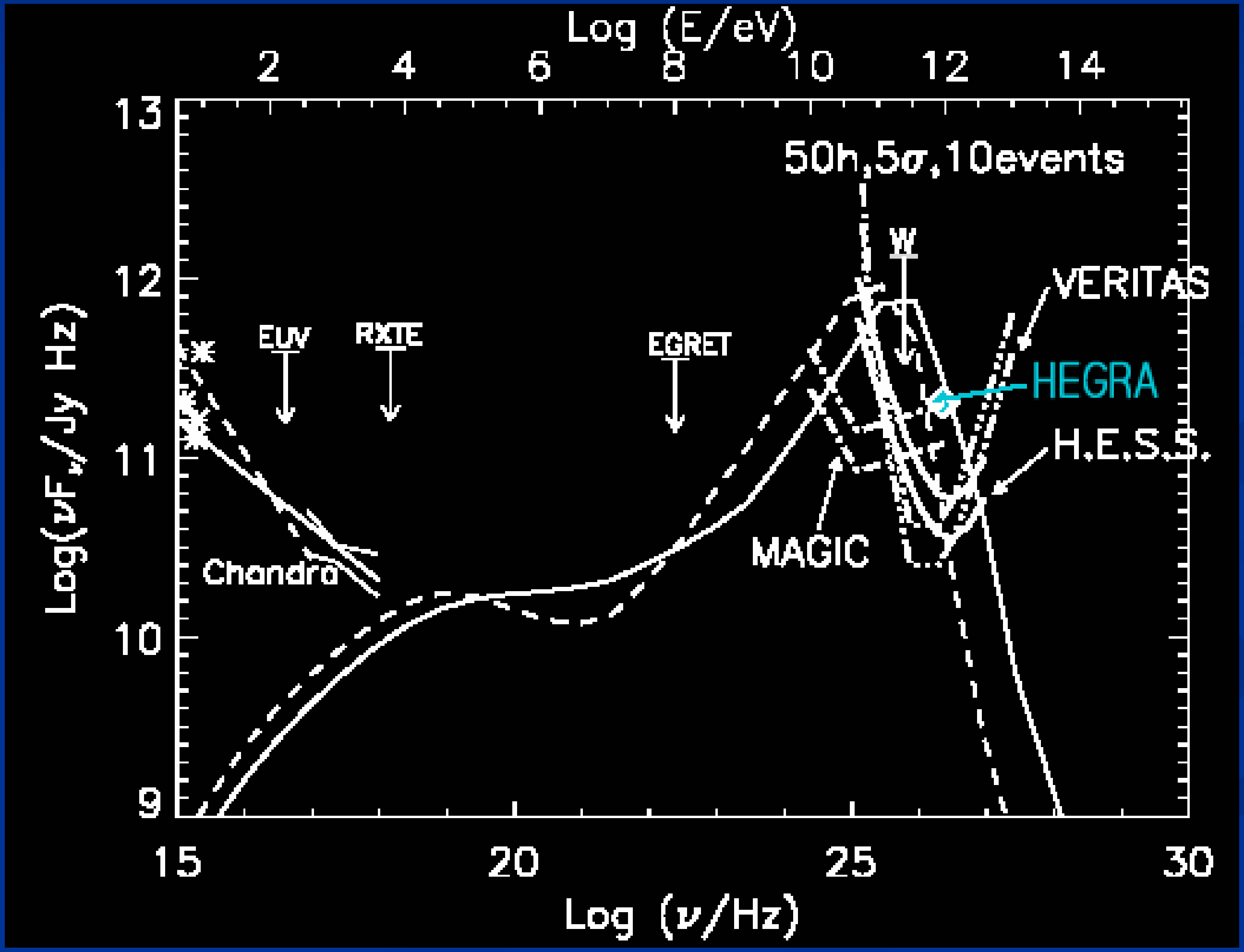




Goetting 2003 ICRC

M87 model

- Misaligned 'synchrotron proton blazar' model



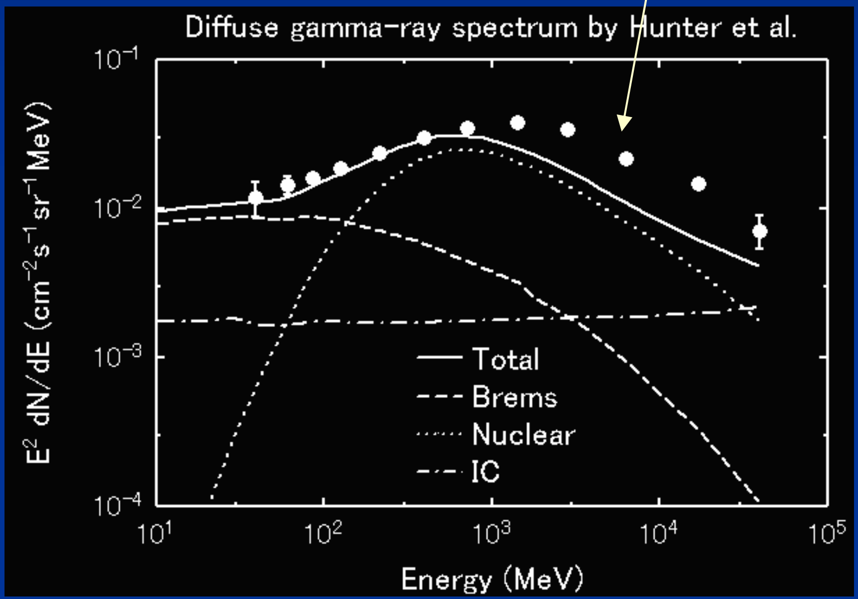
Reimer 2003 ICRC

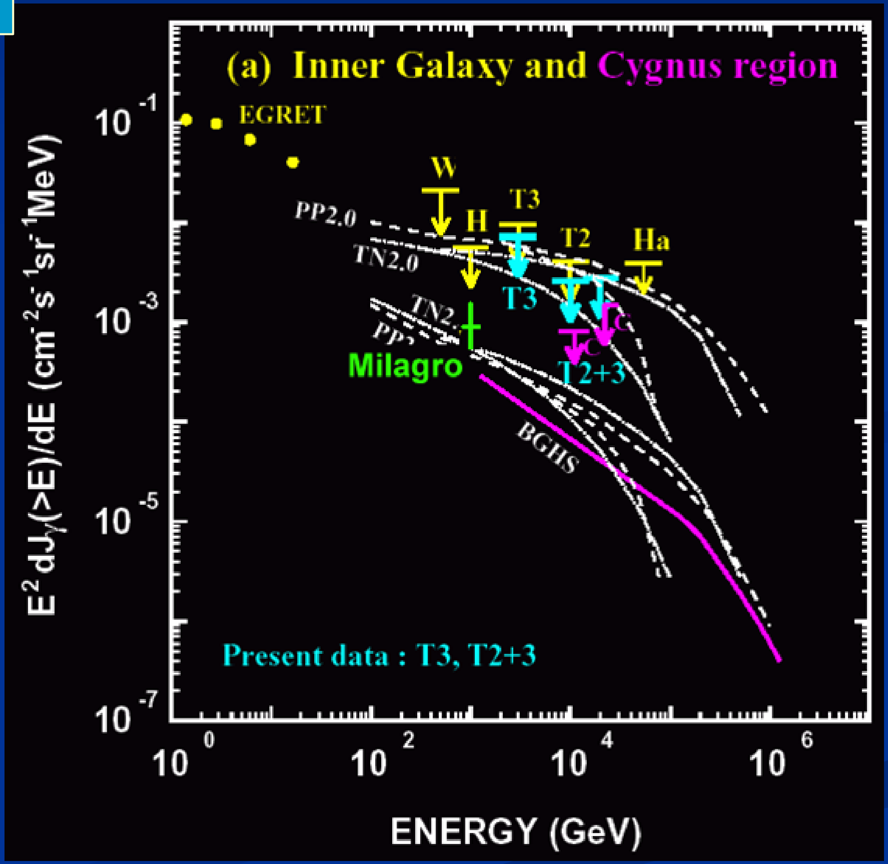
Galactic plane

EGRET “GeV bump”

(Hunter et al.1997)

60% Excess





Mori 2003 ICRC

Milagro [Fleysher et al. ICRC2003]

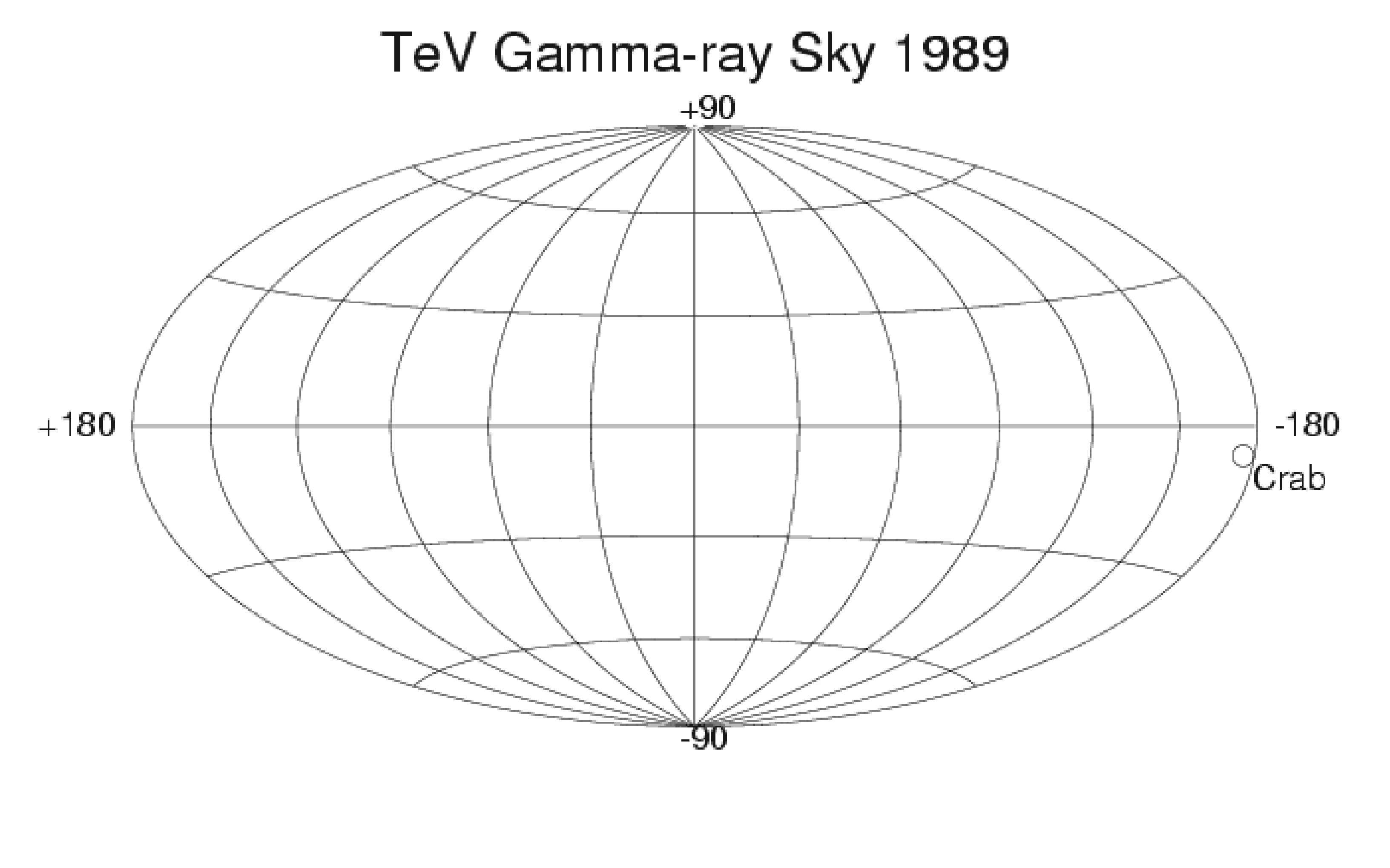
- Water Cherenkov air shower detector
- 2.8σ excess: 20°<l<100°, -7°<b<7°
- *F*γ/*F*CR=(5.3±1.9) × 10-5 @1TeV

TeVガンマ線天体カタログ

[T.Weekes *Highlight talk* “Before 28^{th} ICRC”]

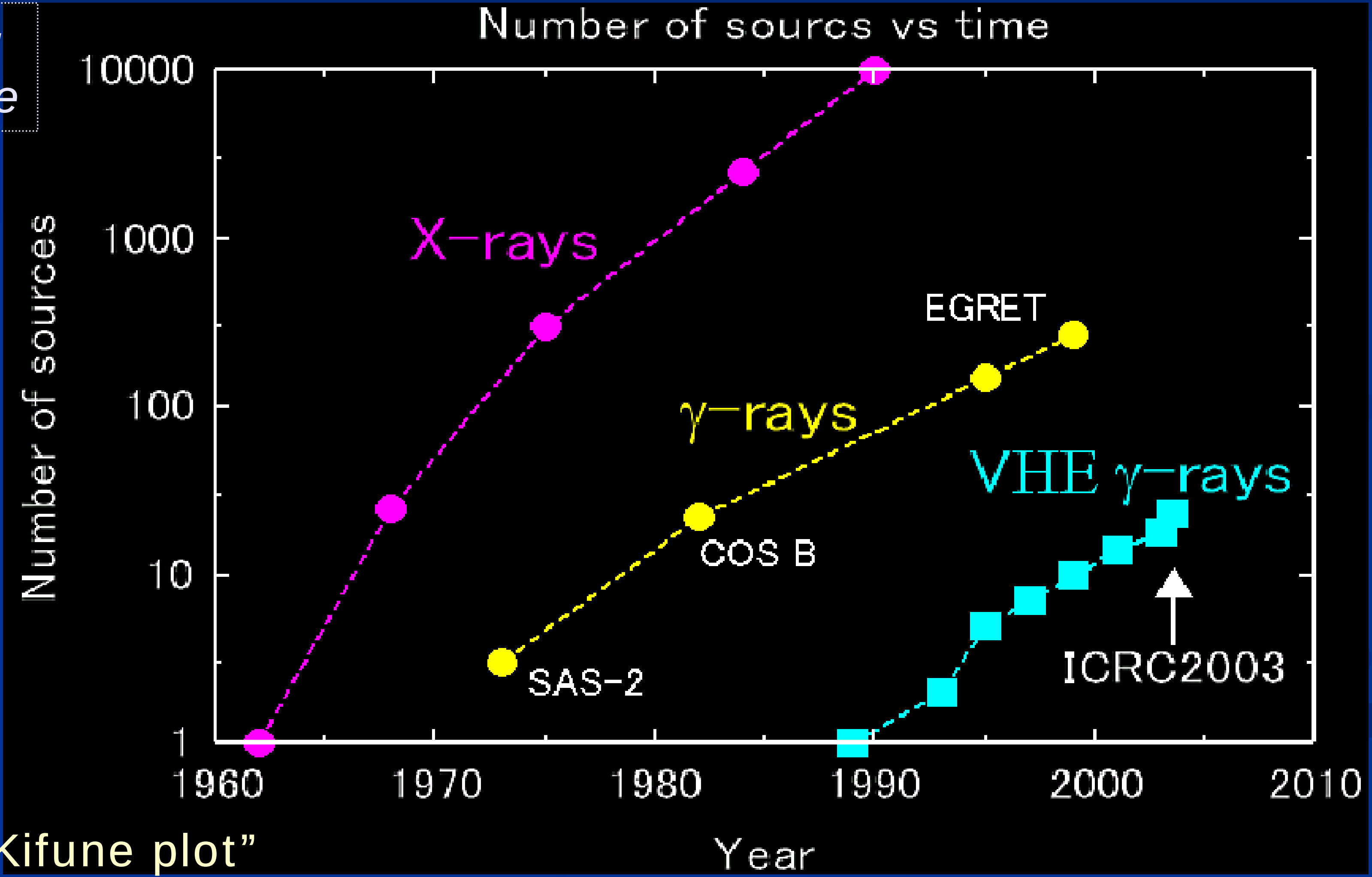
Catalog Name	Source	Type	Date/Group	EGRET	Grade
TeV 0047-2518	NGC 253	Starburst	2003/CANG.	no	B
TeV 0219+4248	3C66A	Blazar	1998/Crimea	yes	C-
TeV 0535+2200	Crab Nebula	SNR	1989/Whipple	yes	A
TeV 0834-4500	Vela	SNR	1997/CANG.	yes	C
TeV 1121-6037	Cen X-3	Binary	1999/Durham	yes	C
TeV 1104+3813	Mrk 421	Blazar	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ガンマ線の天空の「進化」



天体数の「進化」

Log
scale

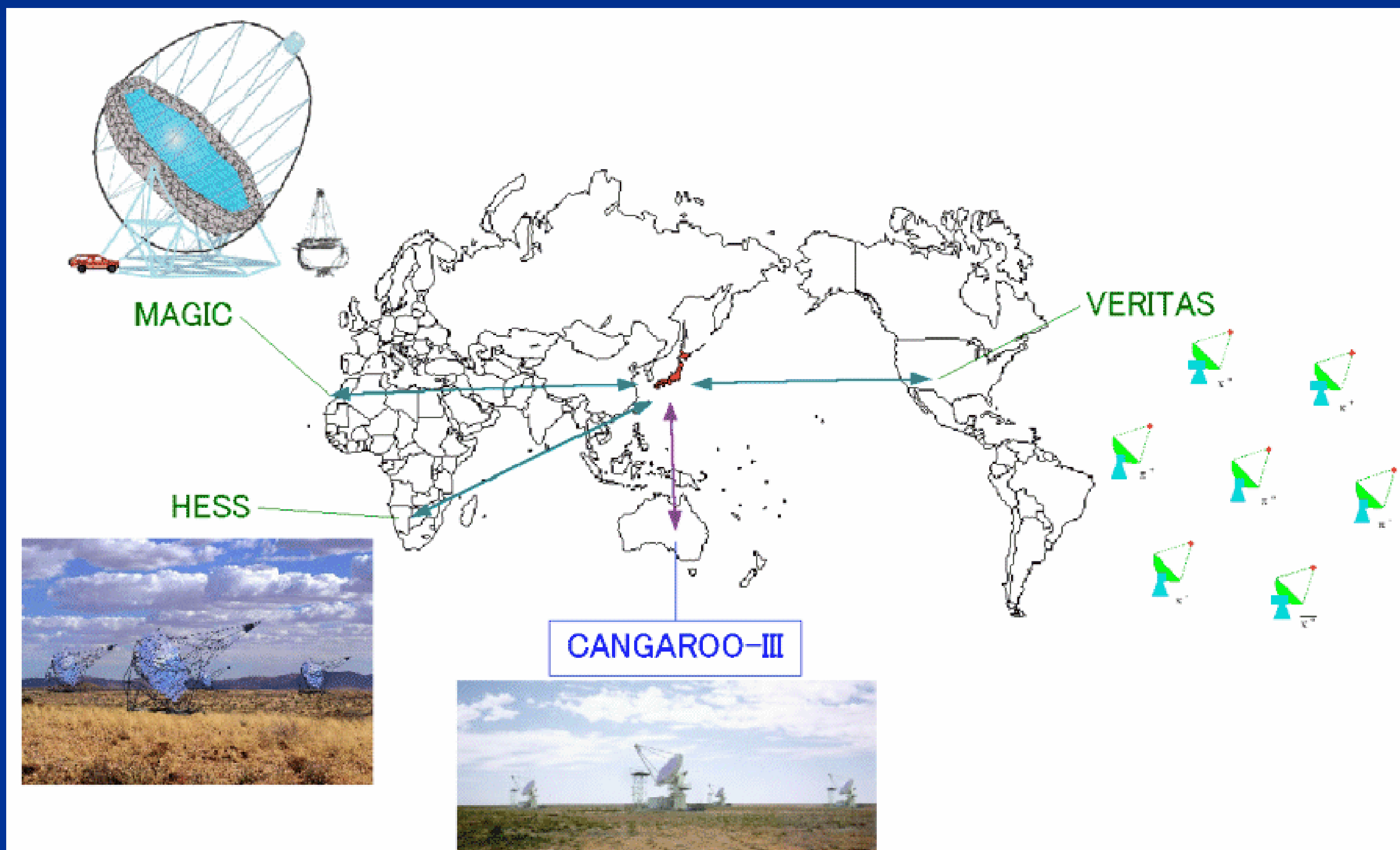


“Kifune plot”

©Rene Ong 2002

第3世代プロジェクト

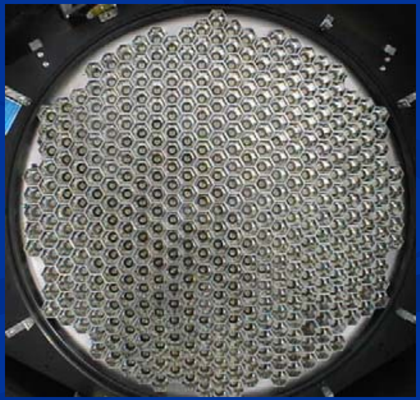
- CANGAROO-III
- H.E.S.S.
- MAGIC
- VERITAS



Woomera, South Australia

CANGAROO-III

- 4×10m ϕ、F/0.8
  (FRP製小型球面鏡114枚)
- Alt-Az マウント
- 427ch・4°カメラ(1号機:552ch・3°)
- VME-ADC/TDC electronics
- 2003Dec完成予定

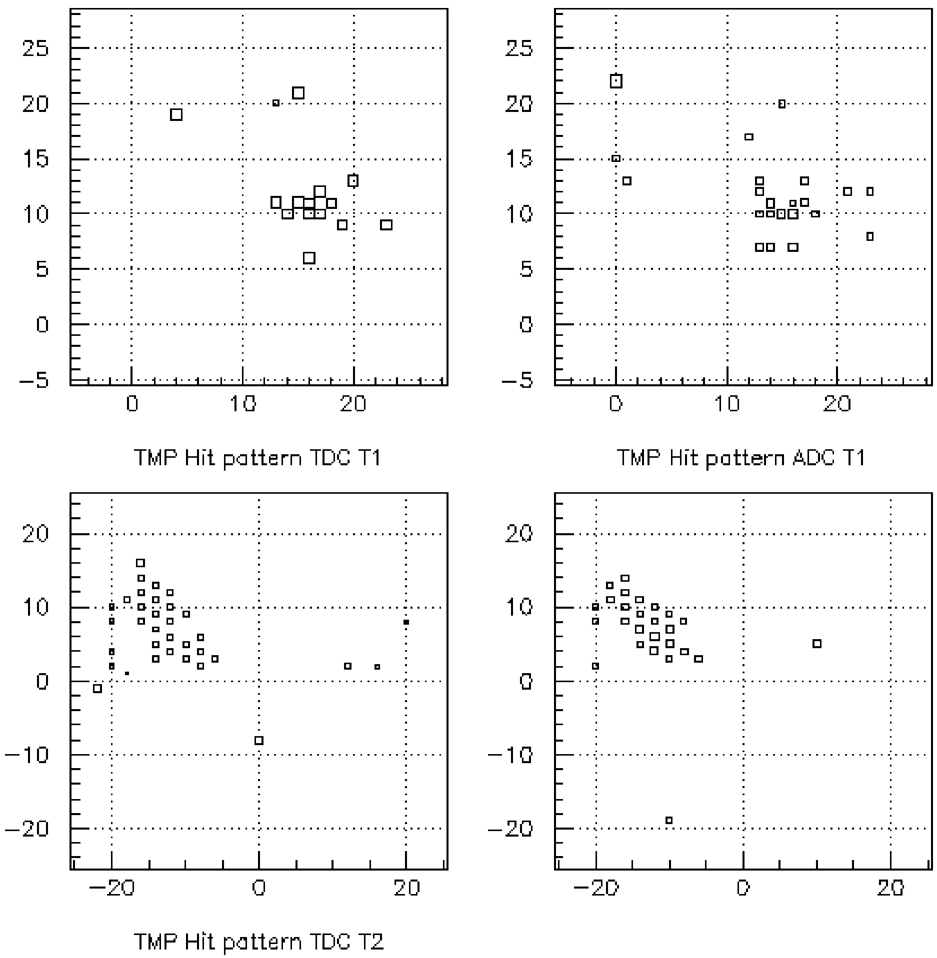


2,3,4号機の解像型カメラ

ステレオイベント例

T1 TDC

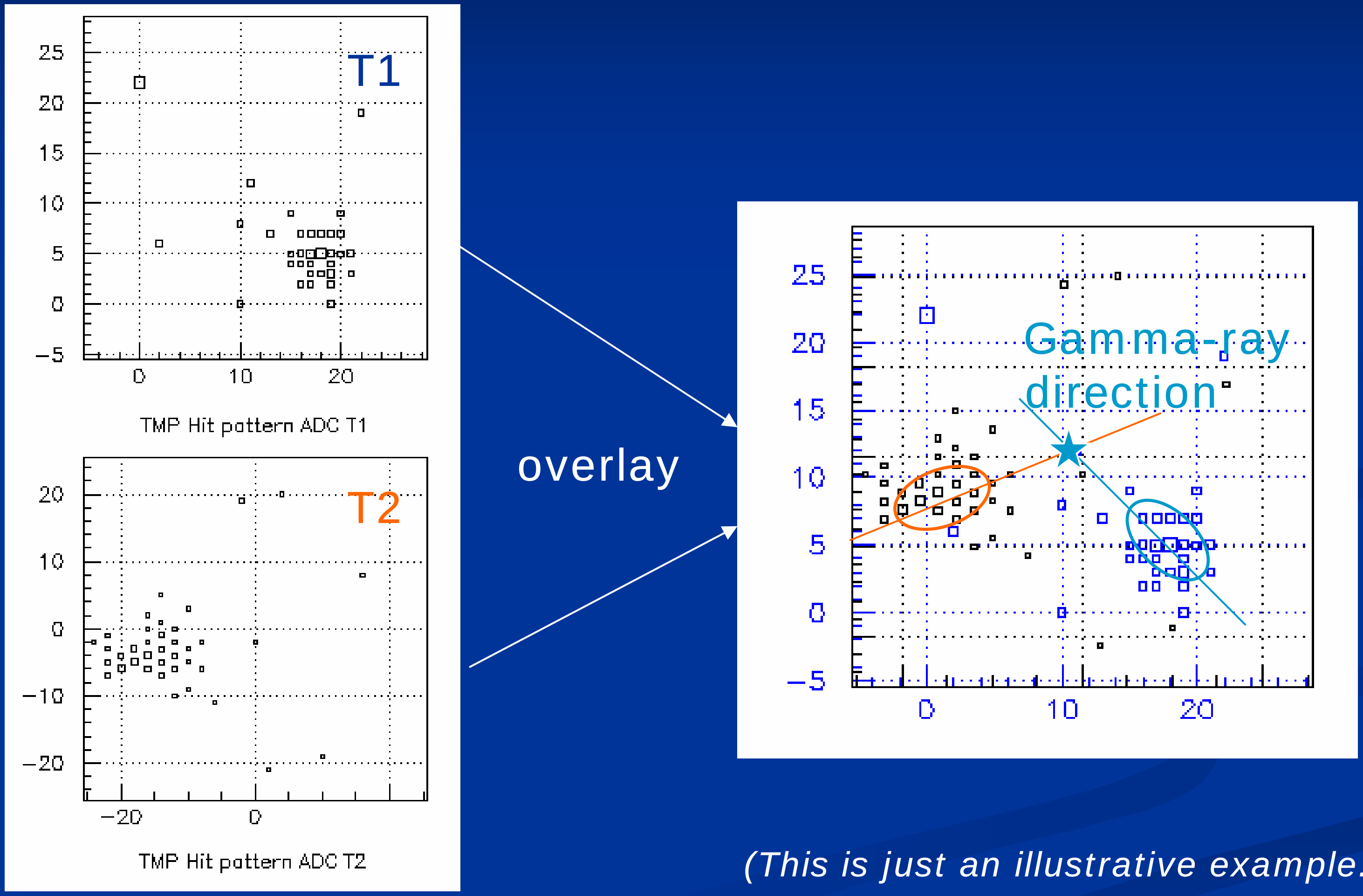
T2 TDC



T1 ADC

T2 ADC

ステレオイベントの再構成



(This is just an illustrative example.)

H.E.S.S.

Namibia, Africa

HESS : Stereo Imaging Cherenkov Telescope ~100 GeV-50 TeV

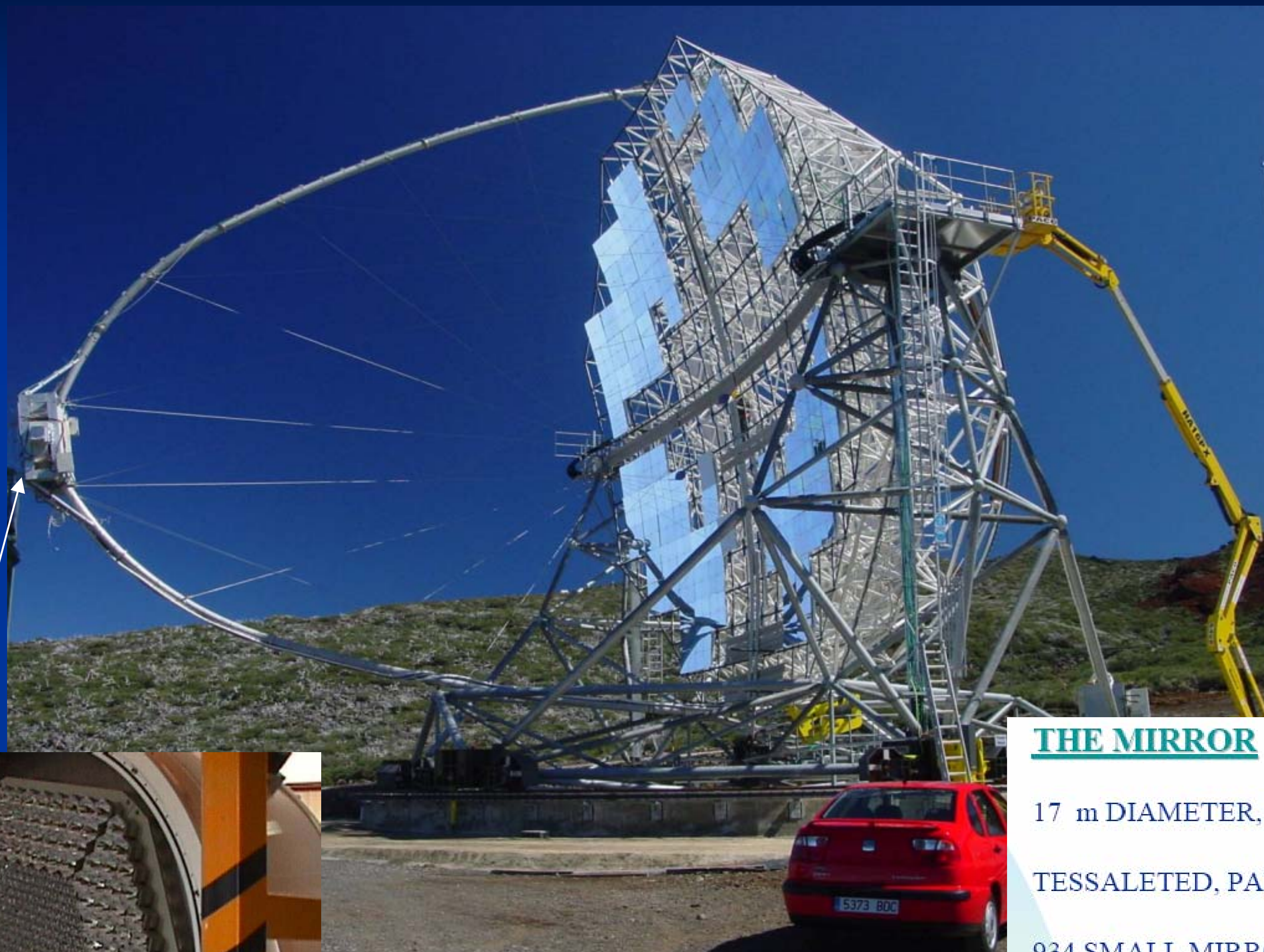
- First light: June 11 2002
- Mirror area ~107 m^2
- Diameter 13 m, focal length 15 m
- Camera: 960 pixels , 5° f.o.v

MPI Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Hamburg
Landessternwarte Heidelberg
Univ. Kiel
Ecole Polytechnique, Palaiseau
Collège de France, Paris
Univ. Paris VI-VII
CEA Saclay
CESR Toulouse
LAOG Grenoble
Paris Observatory
Durham Univ.
Dublin Inst. for Adv. Studies
Charles Univ., Prag
Yerewan Physics Inst.
Univ. Potchefstroom
Univ. of Namibia, Windhoek

- 2/4 HESS Telescopes are complete with cameras
- 12 $\sigma/\sqrt{h}$ for a Crab-like source in mono-mode at zenith

Canary Island

MAGIC



CAMERA IMPROVEMENTS

**(4° DIAMETER :394 PIXELS 0.1°, 180 PIXELS 0.2°
6 DYNODE , HEMISPHERICAL CATHODE PMTS,
GAIN≈ 2X10**4 + FAST PREAMP -> OPERATION DURING
MOONSHINE POSSIBLE)**

THE MIRROR

17 m DIAMETER, 234 m**2

TESSALETED, PARABOLIC PROFILE

934 SMALL MIRRORS 49.5x 49.5 cm,

All raw blanks made,

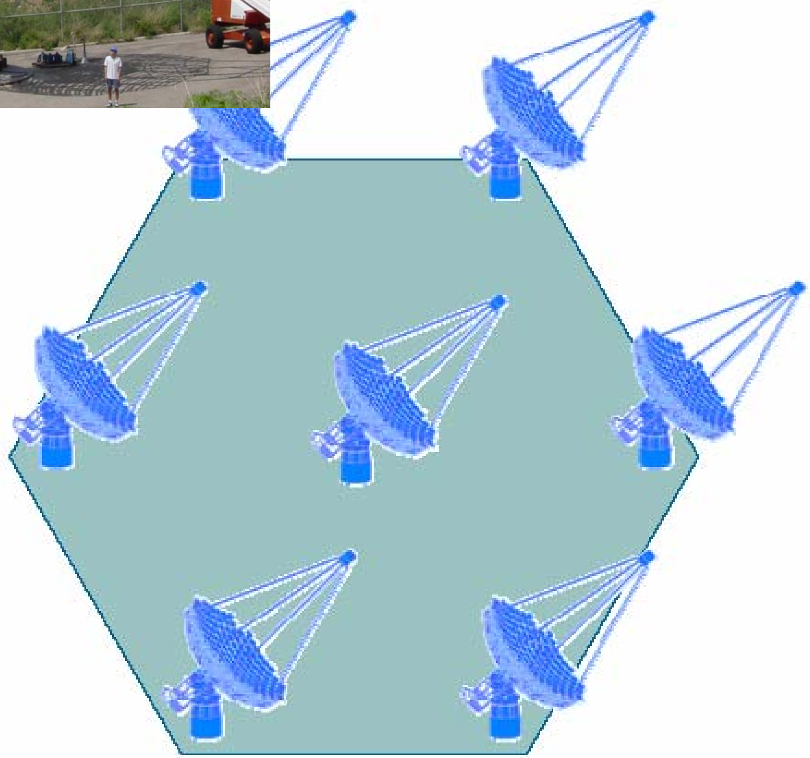
700 mirrors diamond turned

45 m** 2 installed -> 100 m**2 in October

Kitt Peak, Arizona

VERITAS

VERITAS specifications



Array:
Six telescopes spaced equidistantly on the circle of 80 m radius and one telescope in the center.

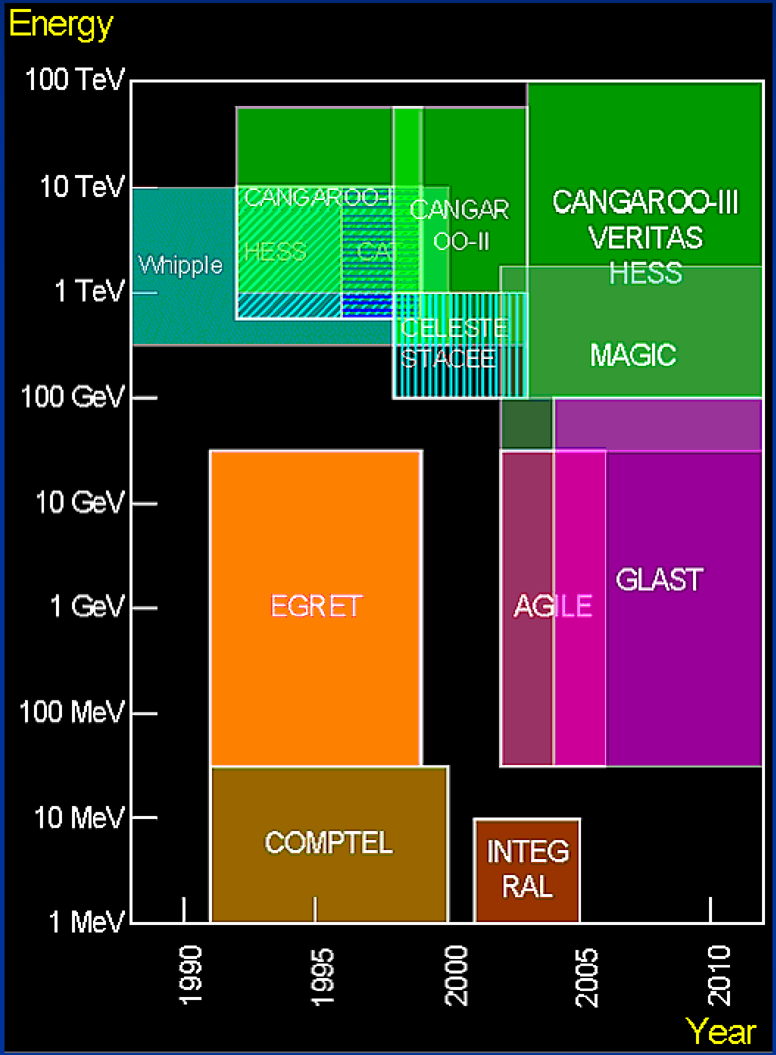
Reflector:
Diameter – 12m
F/number – 1.0
Number of facets – 350
Facet size – 61 cm

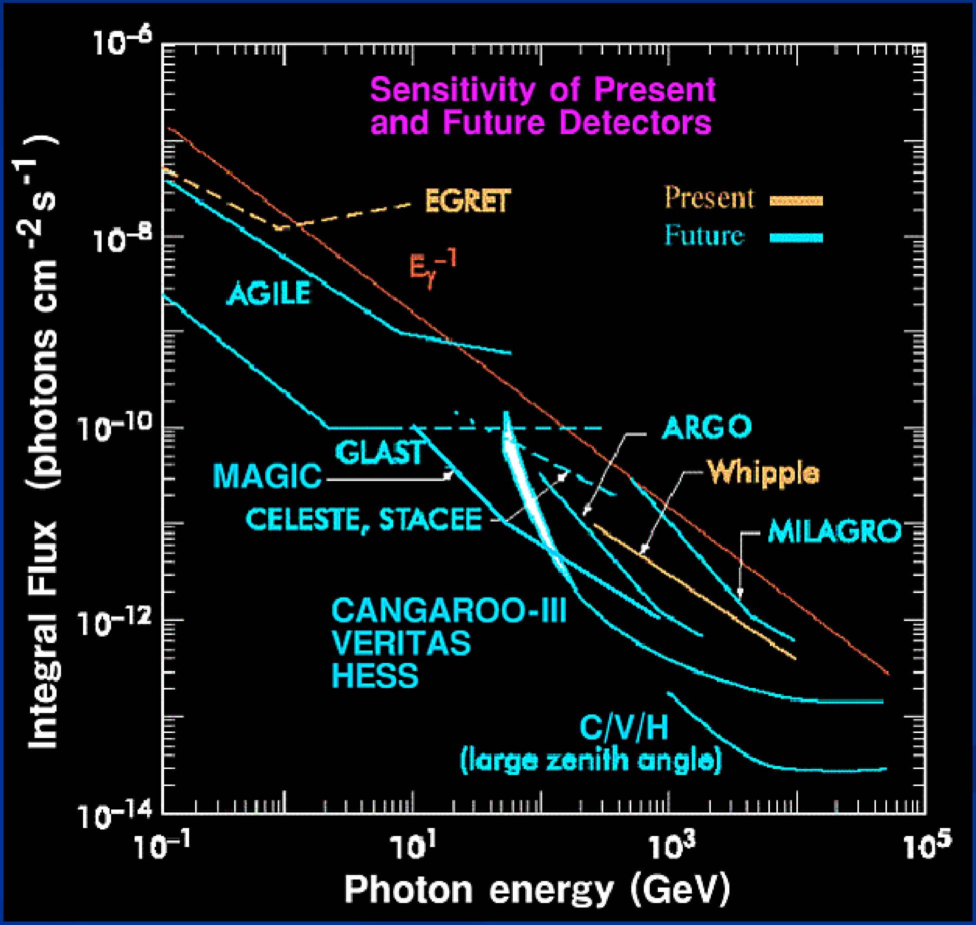
Telescope Camera:
Number of Pixels - 499
Pixel size - 0.15 deg
Field of View - 3.5 deg

Telescope Electronics:
Custom made Flash ADC –
500 MHz, 10Bit*, 64 msec depth
Three level trigger –
pixel, image pattern, array

V.Vasilliev

近未来の検出感度


Energy
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
Whipple
CANGAROO-I
HESS
CAT
CANGAROO-II
CANGAROO-III
VERITAS
HESS
CELESTE
STACEE
MAGIC
EGRET
AGILE
GLAST
COMPTEL
INTEGRAL
1990
1995
2000
2005
2010
Year


Sensitivity of Present and Future Detectors
Present
Future
EGRET
E_γ^{-1}
AGILE
GLAST
MAGIC
CELESTE, STACEE
ARGO
Whipple
MILAGRO
CANGAROO-III
VERITAS
HESS
C/V/H
(large zenith angle)
Integral Flux (photons cm^{-2} s^{-1})
Photon energy (GeV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-1}
10^{1}
10^{3}
10^{5}

さらに…

- **5@5**
  - Max Planck Inst. for Nuclear Physics
  - $50\mathrm{m}^2$ mirror area
  - 5 telescopes (4 in 100m grid and 1 at center) at 5000m a.s.l.
  - 3.2° camera, 721 pixels
  - 5 GeV threshold

Aharonian et al. 2001 APh 15, 335

- **ECO-1000**
  - Max Planck Inst. for Physics
  - 35mϕ, $1000\mathrm{m}^2$ mirror area
  - <5° camera, >2000 pixels
  - 5 GeV threshold

Merck et al. ICRC2003

SuperCANGAROO

- "Strawman" design parameters
  - <10 GeV energy threthold
    → *10 times more area × 2 times QE*
  - 30mϕ, f=30m (F/1.0), parabola
  - Field-of-view ~10° ← survey mode
  - Short barrel preferred to keep long focal length → new optical design necessary
  - 0.1° -class pixel camera with advanced photon sensors
  - Stereo observation is essential

Ex. Paul-Baker optics

All-sky TeV gamma-ray monitor

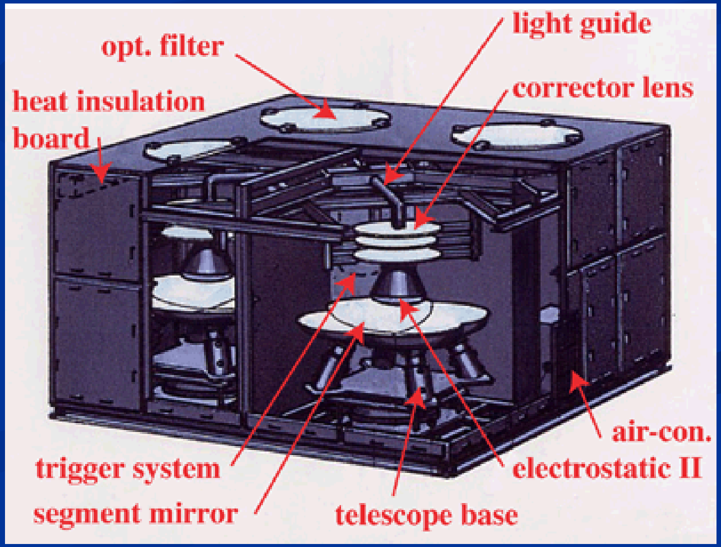
- 5 m ϕ, 1 sr telescope, 1 TeV threshold
  - CR rate (>1 TeV):
    $8 \cdot 10^{-6} cm^{-2} s^{-1} \times 3 \cdot 10^{8} cm^{2} = 3$ kHz
  - Muons (>1 GeV):
    $7 \cdot 10^{-3} cm^{-1} s^{-1} \times 2 \cdot 10^{5} cm^{2} = 1.4$ kHz
  - High threshold to reduce N.S.B.
  - 0.1^{o} resolution camera (many channels…)
  - Stereo if necessary
  - Good monitor for GRBs
- Not far away from the present technology!

Kifune and Takahashi, TMACD-IV, 1997

- **GAW** (Gamma Air Watch, Cusmano et al. ICRC 2001)

  3m ϕ, 5.2^{o} FOV

- **ASHRA** (Asaoka et al. ICRC 2003)



3年間の進歩

[Mori 2000 HEAPA WS]

Science to come

- Plerions (pulsar nebula)
  Inverse Compton? ← synchrotron origin?
- Pulsars
  Cutoff in pulse component? ← polar cap/outer gap
- SNRs
  π^0 contribution? ← cosmic ray origin
- AGNs
  Gamma-ray source: $e^{\pm}$ or p?
  Intergalactic IR ← cosmology
- EGRET unIDs, Neutralinos, GRBs, QG, Diffuse gamma,…, and more?

RX J1713-3946 (?)

1H1426+428 (z=0.129)

NGC253
M87
TeV unID

まとめ

- TeVガンマ線観測は、チェレンコフ光のイメージング法というブレークスルーと共に急速に進展している。
- ステレオ法により角度分解能･エネルギー精度も向上している。
- TeVガンマ線天体はパルサー星雲、ブレーザー、超新星に加えて拡大している。
- TeV超新星残骸は高エネルギー粒子加速の証明ではあるが、宇宙線の起源として陽子が加速されている証拠はまだ十分とはいえない。
- 大型計画が各地で進行中であり、衛星観測とのエネルギーギャップが縮まっていく。
- さらなる次期大型計画も構想されており、衛星観測とオーバーラップしていく。