CANGAROO

Masaki Mori*

for the CANGAROO team

**ICRR, The University of Tokyo*

Astrophysics of Ultra-High Energy Cosmic Rays, Photons, and Neutrinos (Miniprogram), May 19, 2005, KITP, UCSB

“CANGAROO”

=

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

Woomera, South Australia

CANGAROO team

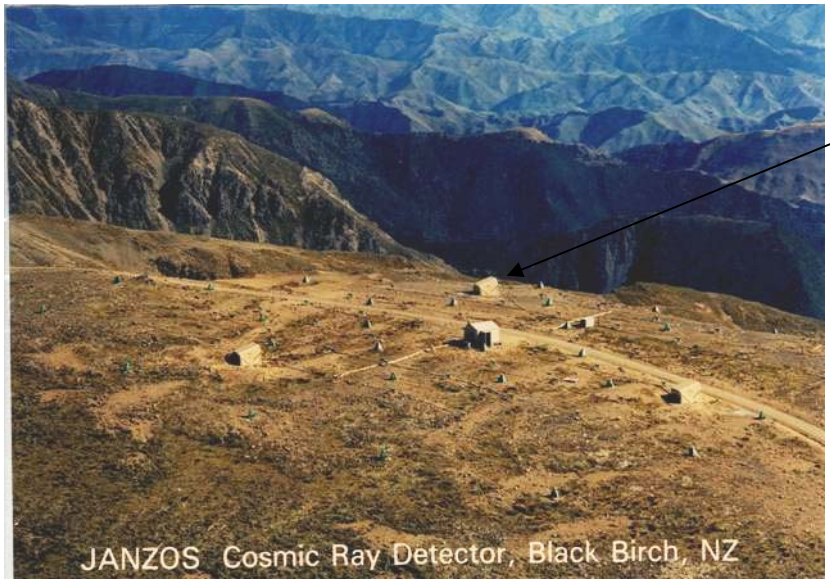
- University of Adelaide 
- Australian National University 
- Ibaraki University 
- Ibaraki Prefectural University 
- Konan University 
- Kyoto University 
- STE Lab, Nagoya University 
- National Astronomical Observatory of Japan 
- Kitasato University 
- Shinshu University 
- Institute of Space and Astronautical Science 
- Tokai University 
- ICRR, University of Tokyo 
- Yamagata University 
- Yamanashi Gakuin University 

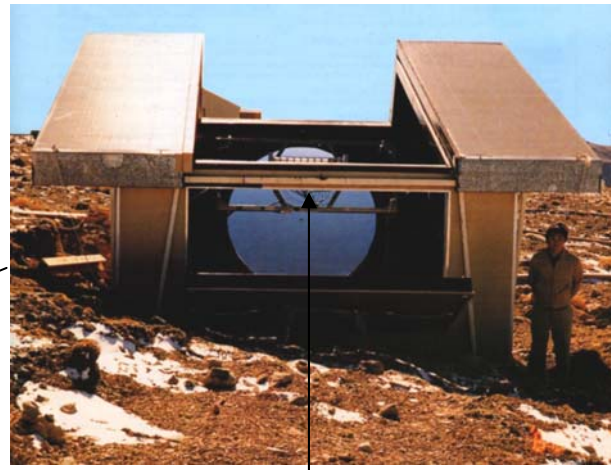
Brief history of CANGAROO

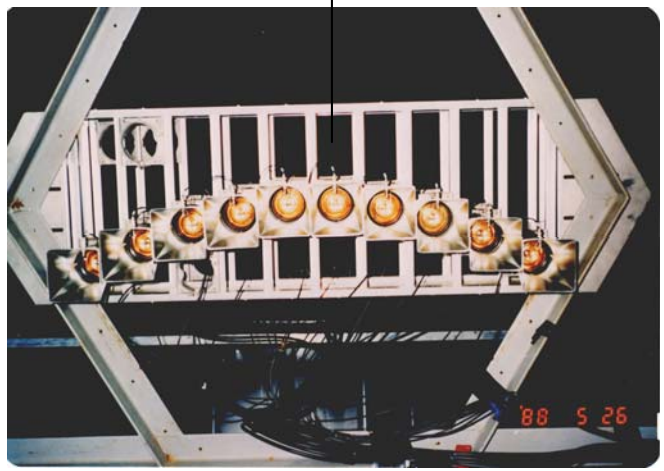
- 1987: SN1987A
- 1990: 3.8m telescope
- 1990: ICRR-Adelaide Physics agreement
- 1992: Start obs. of 3.8m tel.
- 1994: PSR 1706-44
- 1998: SNR1006
- 1999: 7m telescope
- 2000: Upgrade to 10m
- 2001: U.Tokyo-U.Adelaide agreement
- 2002: Second and third 10m tel.
- 2004: Four telescope system

JANZOS project in New Zealand

Japan Australia New Zealand
Observation of Supernova 1987A







Shower particle detector array

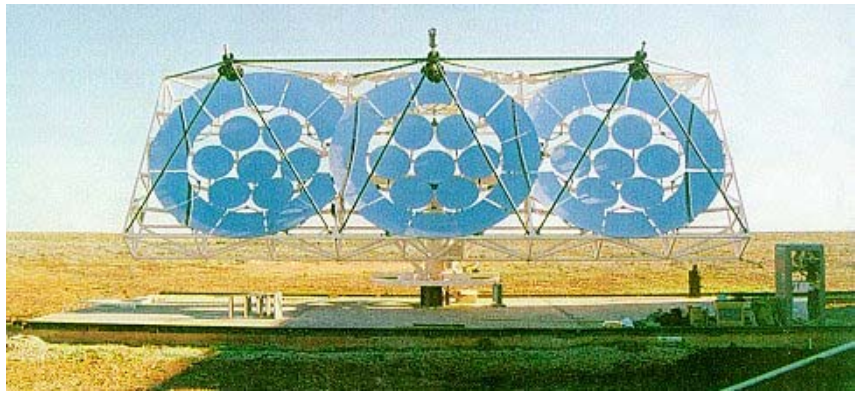
+

Three Fixed Cherenkov telescopes

Why Woomera?

- NZ: too wet, not many clear nights
- Woomera:
  - Former rocket range and prohibited area...infra-structure and support
  - Adeldaide group was operating BIGRAT

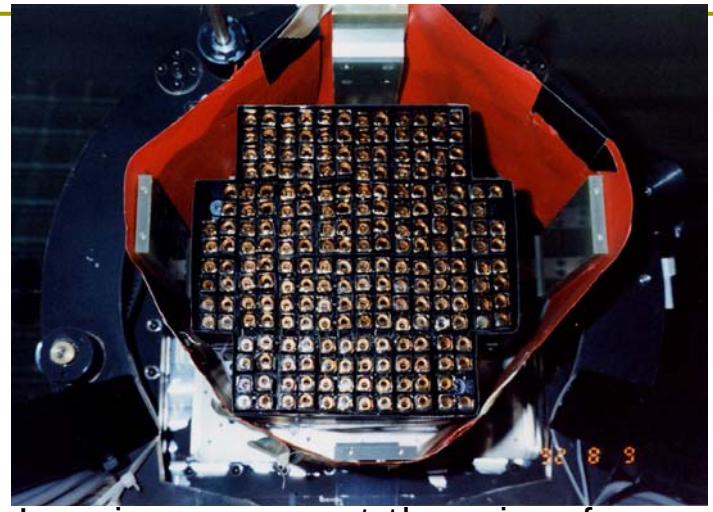
ELDO rocket Launch site in ’60s



BIGRAT

(BIcentinnial Gamma RAy Telescope)

3.8m telescope: ex. Lunar ranging



Imaging camera at the prime focus

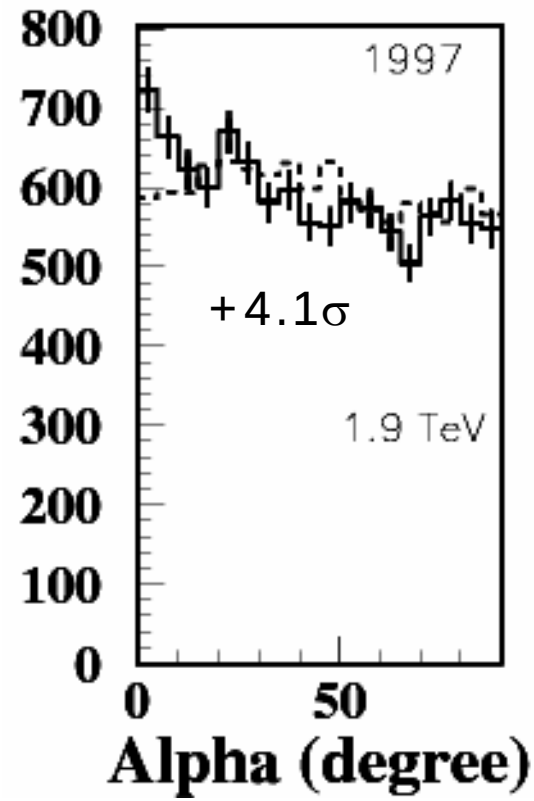
Tadashi Kifune & John Patterson

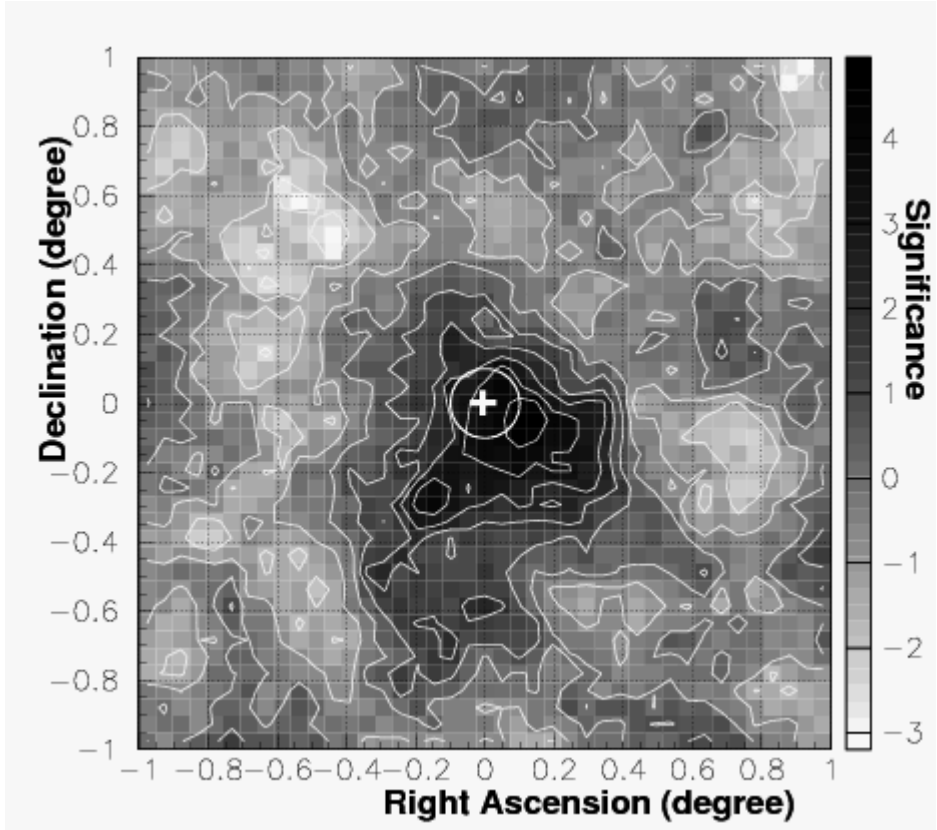
CANGAROO-I results: summary

	Signal	Publish	H.E.S.S.
SNR/Pulsar Crab	○	ApJL'94	○
SNR SN1006	○	ApJL'98	↓
SNR RX J1713.7-3946	○	A&AL'00	○
SNR W28	↓	A&A'00	
Pulsar PSR 1706-44	○	ApJL'95	↓
Pulsar Vela	○	ApJL'97	↓
Pulsar PSR 1509-58	Δ	ApJ'00	○
Pulsar PSR 1055-52	↓	(Ph.D.'97)	
AGNs: PKS0521-365, EXO0423.4-0840, PKS2005-489, PKS2316-423	↓	A&A'98	
Blazars: PKS0548-322, PKS2005-489 and PKS2155-304	↓	A&A'99	
Radio galaxy Cen A	↓	(Proc.'99)	

Signal: ○ detected, ↓ upper limit, Δ marginal

PSR 1509-58/MSH15-52

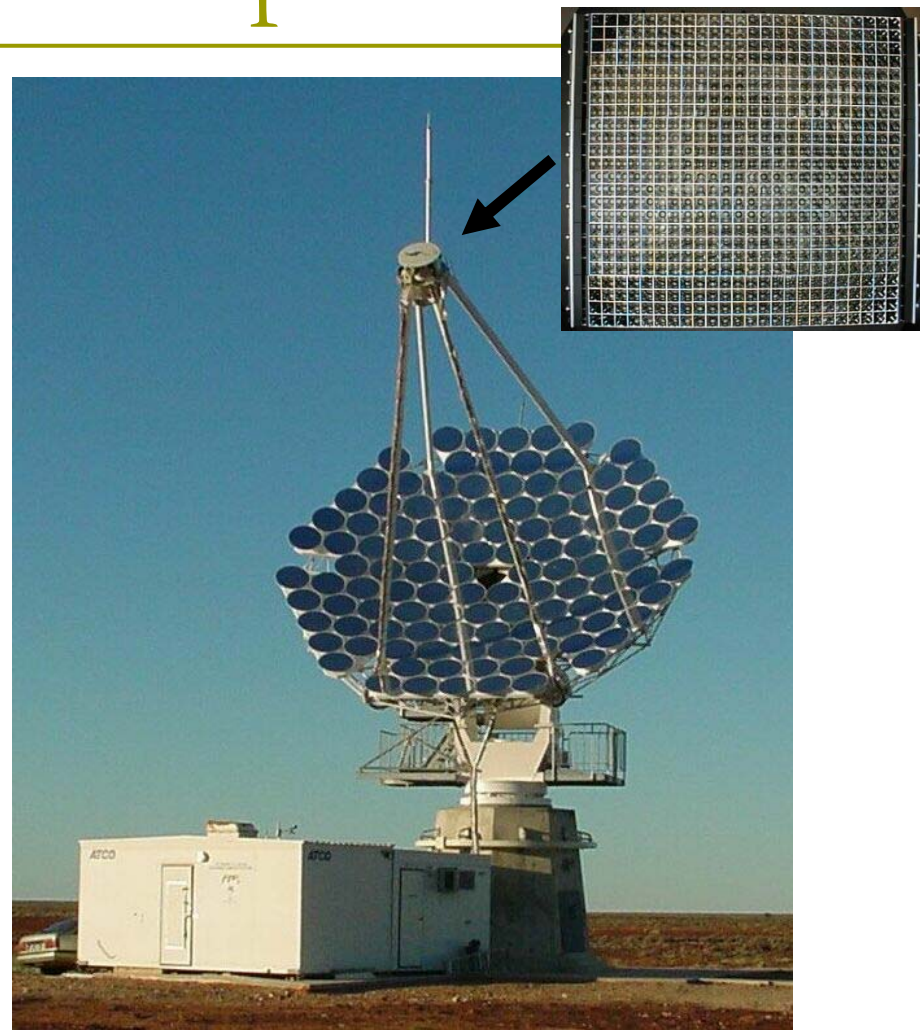




Sako et al., ApJ, 537(2000) 422

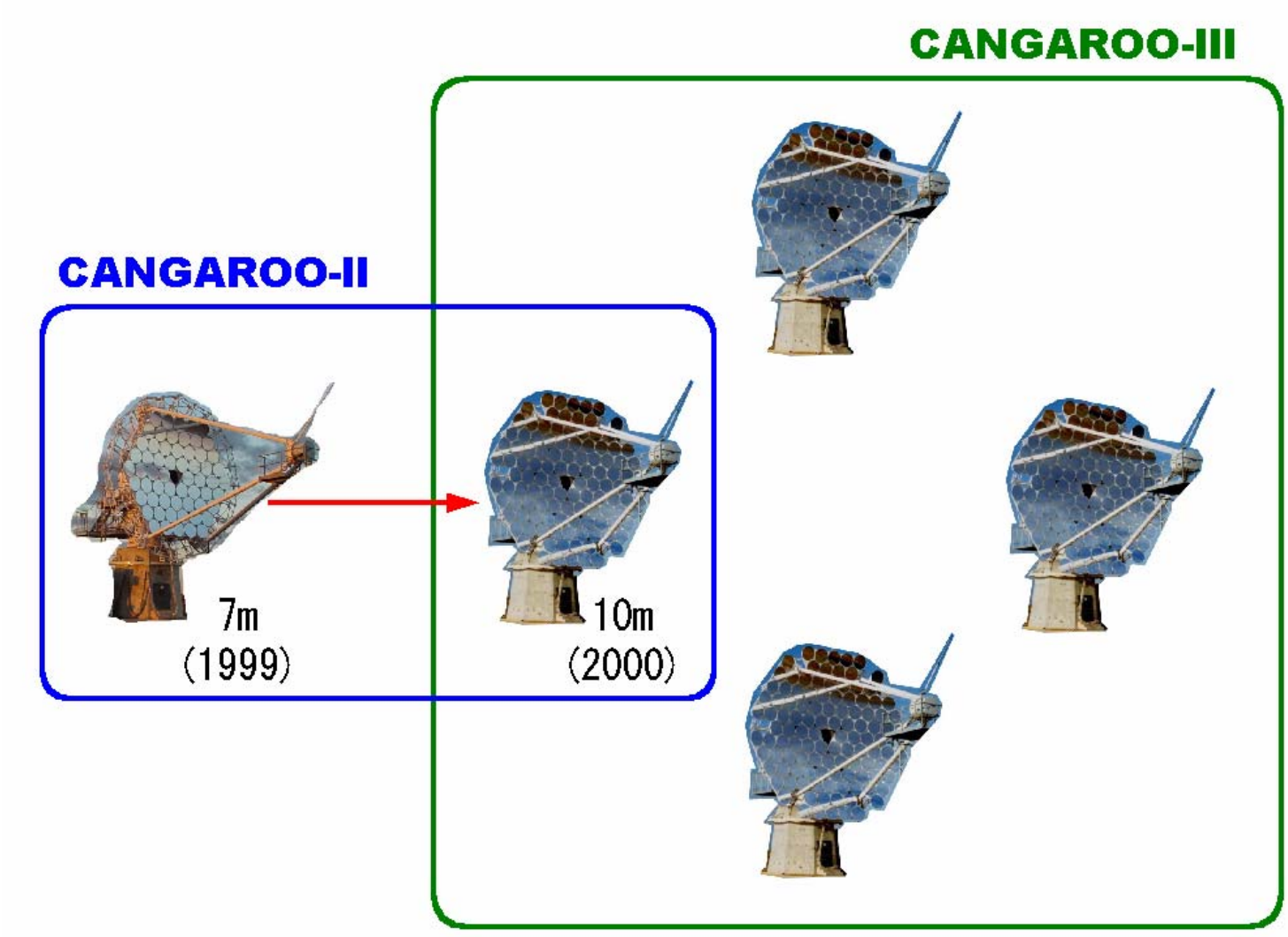
CANGAROO-II telescope

- Upgraded in 2000 from 7m telescope completed in 1999
- 114 x 80cm CFRP mirror segments
  (first plastic-base mirror in the world!)
- Focal length 8m
- Alt-azimuth mount
- 552ch imaging camera
- Charge and timing electronics



(March 2000)

CANGAROO-II & -III

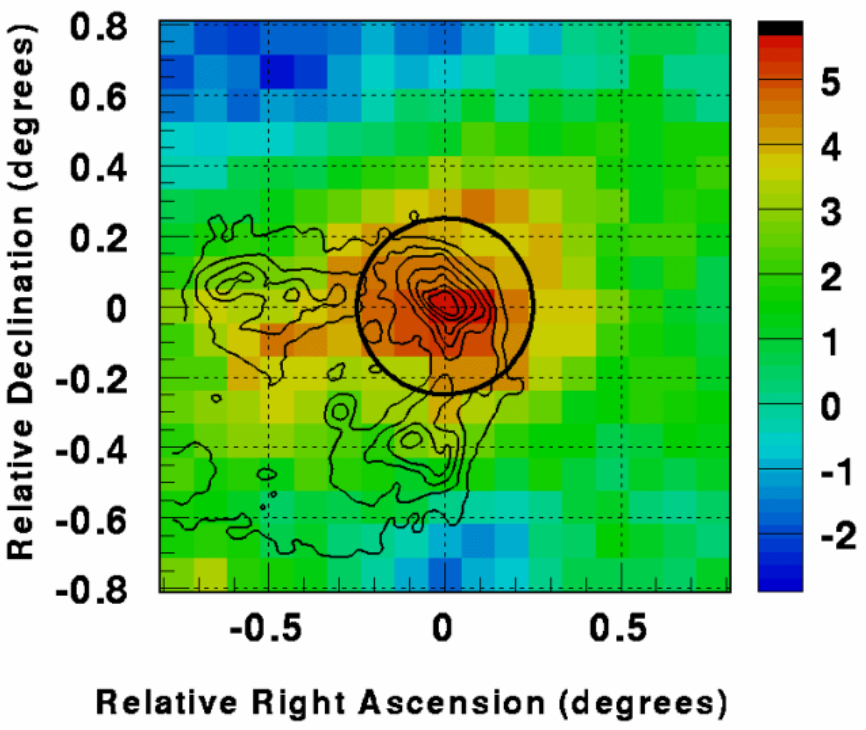


CANGAROO-II results: summary

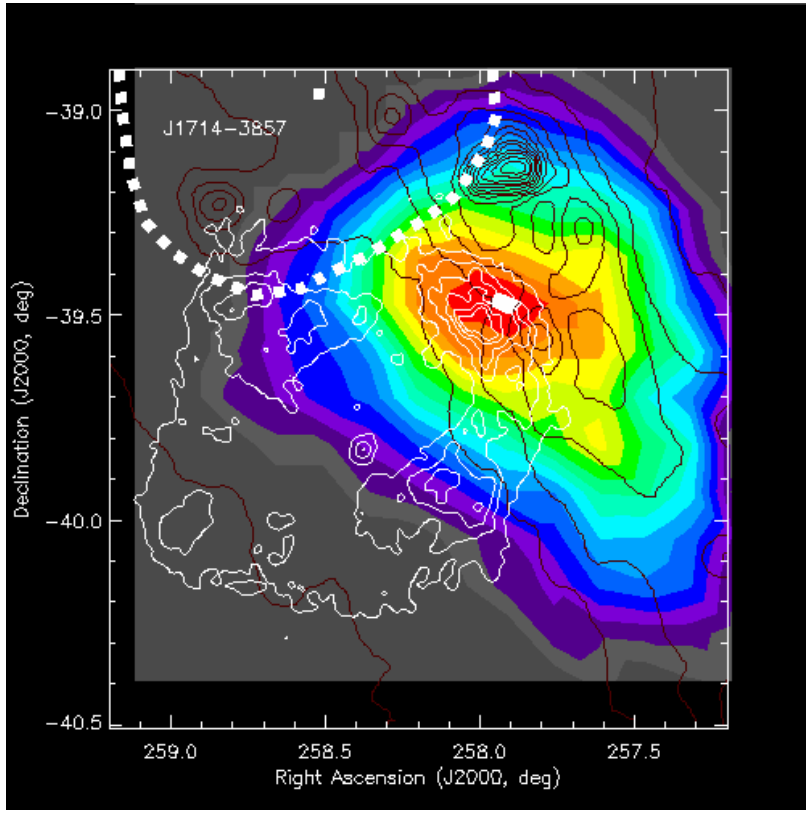
	Signal	Publish	H.E.S.S.
SNR RX J1713.7-3946	○	Nature'02	○
Blazar Mrk421	○	ApJL'02	○
Starburst galaxy NGC253	○	AAL'03	↓
SNR SN1987A	↓	ApJL'03	
Galactic Center	○	ApJL'04	○
Pulsar binary PSR 1259-63/SS2883	↓	ApJ'04	○
SNR RX J0852.0-4622 (Vela Jr.)	○	ApJL'05	○

Signal: ○ detected, ↓ upper limit, △ marginal

SNR RX J1713.7-3946



CANGAROO-I (Muraishi et al., 2000)

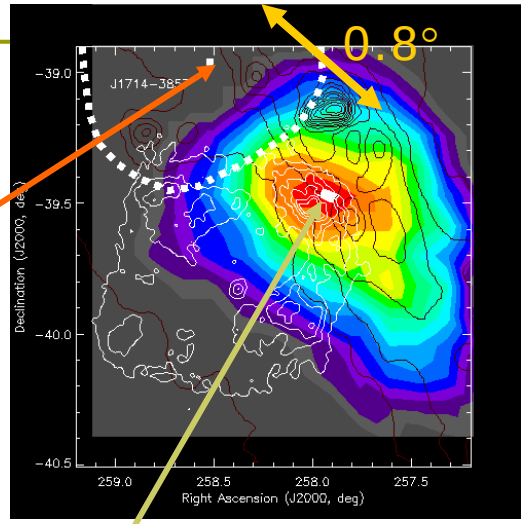


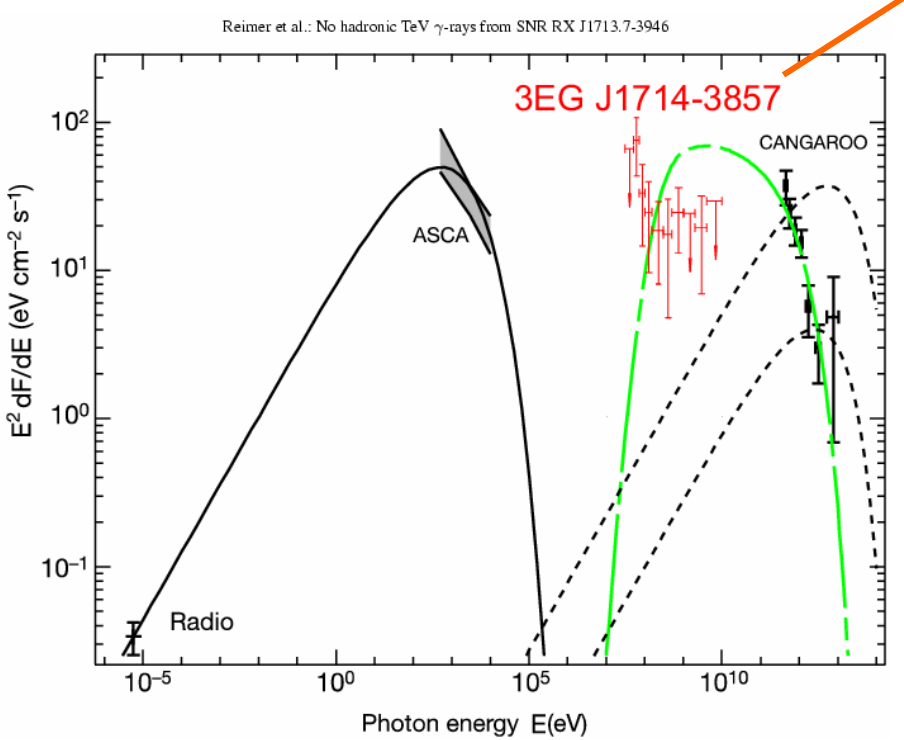
CANGAROO-II (Enomoto et al., 2002)

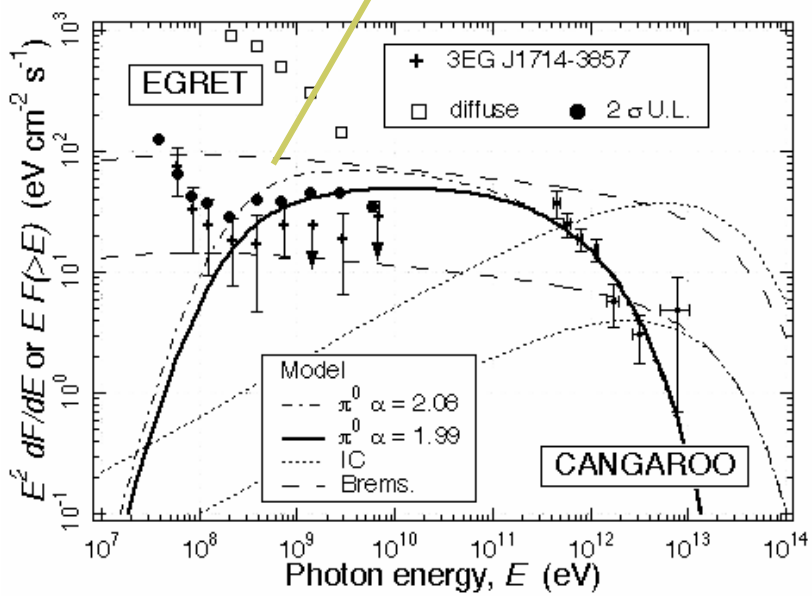
Spectrum of RX J1713.7-3946

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

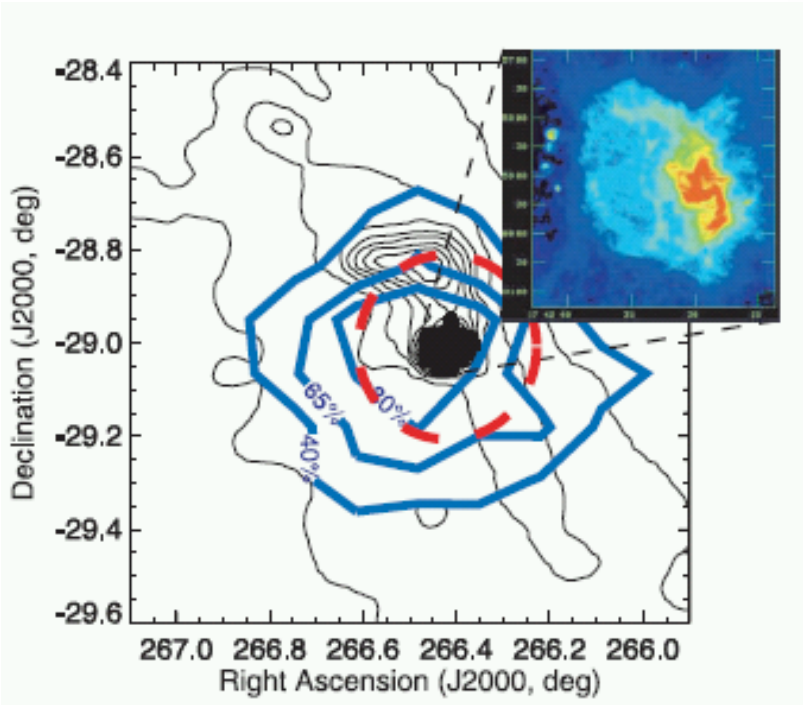
Butt et al., Nature 418 (2002) 489



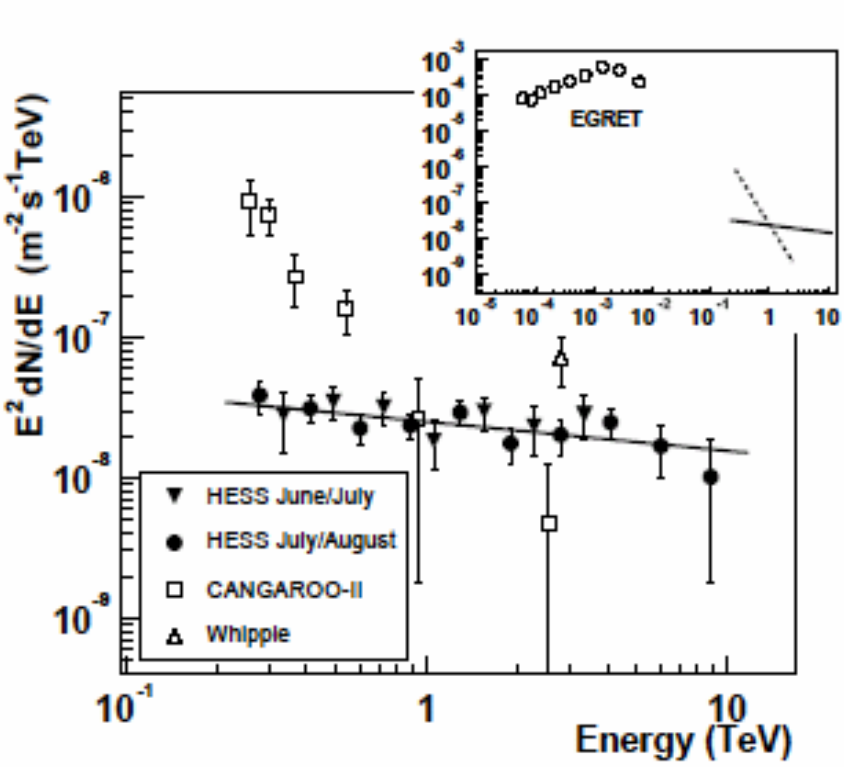




Galactic Center/Sgr A*



CANGAROO-II (Tsuchiya et al., 2004)



Aharonian et al., AA 425 (2004) L13

Dark matter signal from Sgr A*?

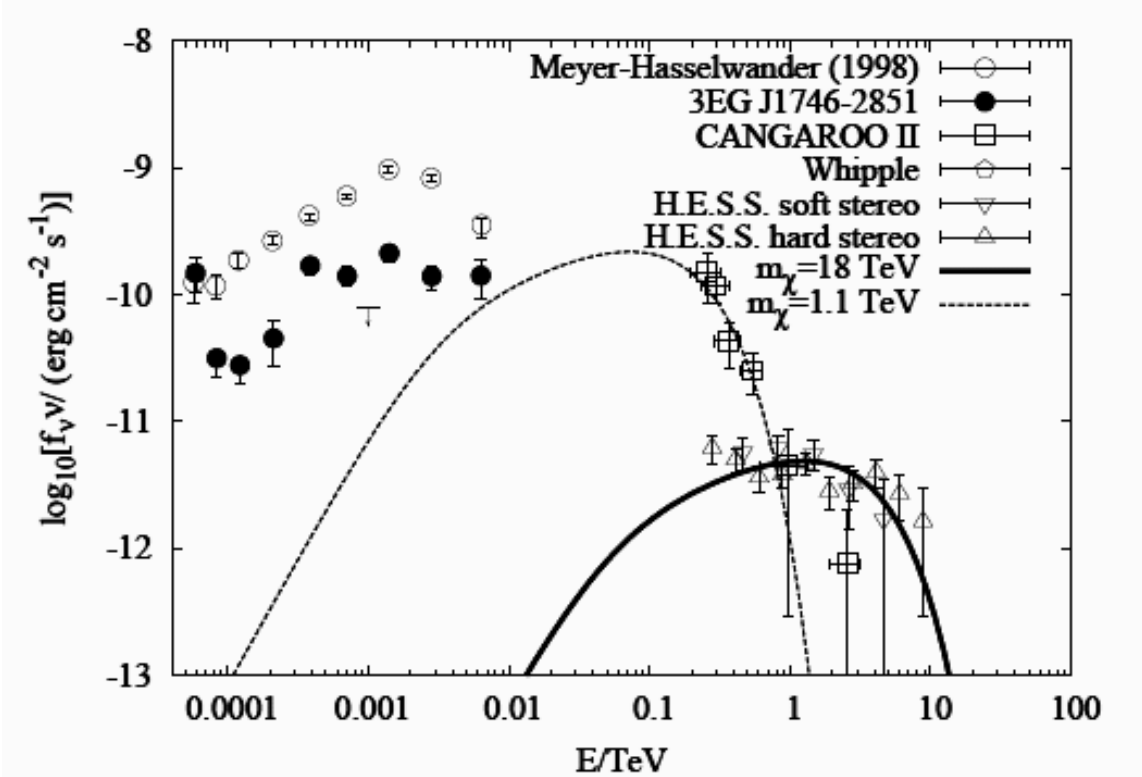
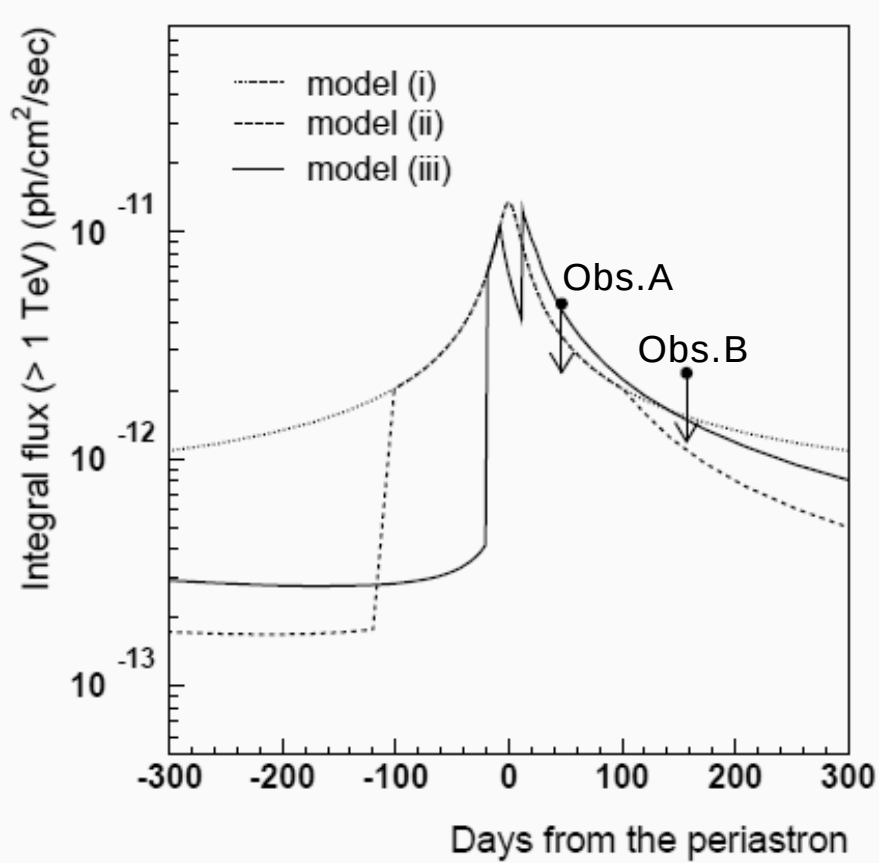


Fig. 2. A summary of data and best-fit models for WIMP annihilation from the Galactic center: H.E.S.S. (open triangles), CANGAROO (open boxes), EGRET (solid and open circles), 10m Whipple telescope of the VERITAS collaboration (solid diamond).

Horns, Phys.Lett. B607 (2005) 225

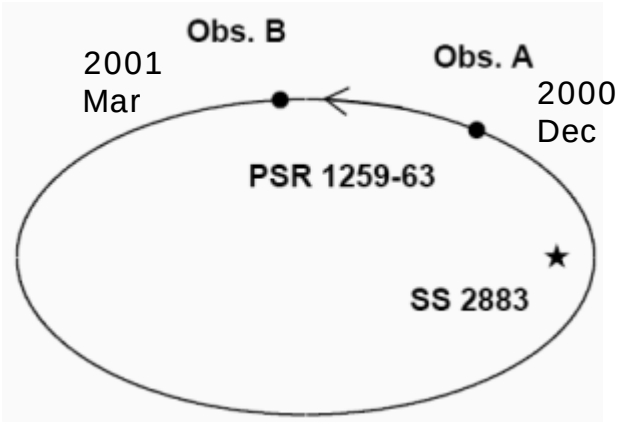
PSR 1259-63/SS2883



(i) aligned disc to the orbital plane and interaction throughout the orbit

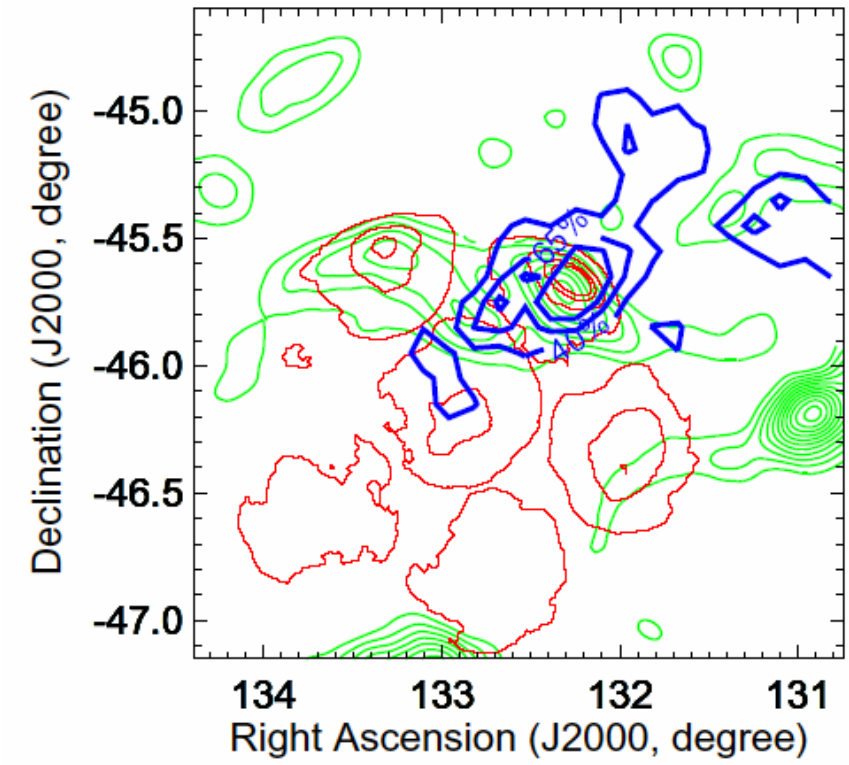
(ii) mis-aligned disc and interaction in the ~200-day period around periastron (τ), during which the radio emission is depolarized

(iii) mis-aligned disc and interaction in two short periods, [(τ -18 d) ~(τ ~ -8d)] and [(τ +12 d) ~ (τ

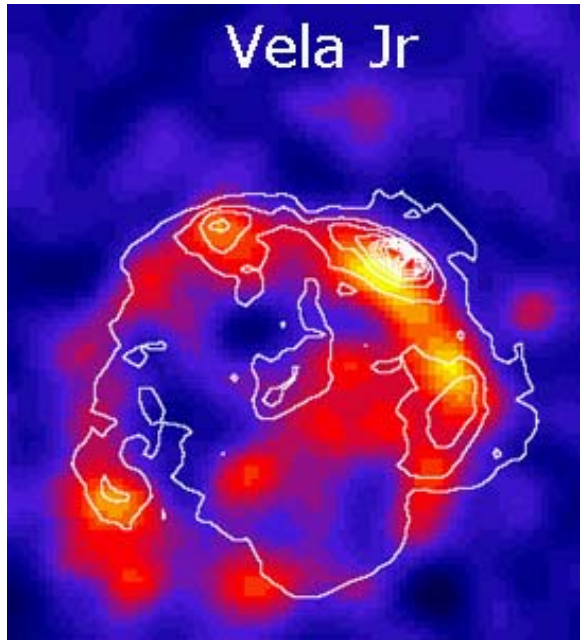


CANGAROO-II: Kawachi et al., ApJ, 607(2004) 949

SNR RX J0852.0-4622

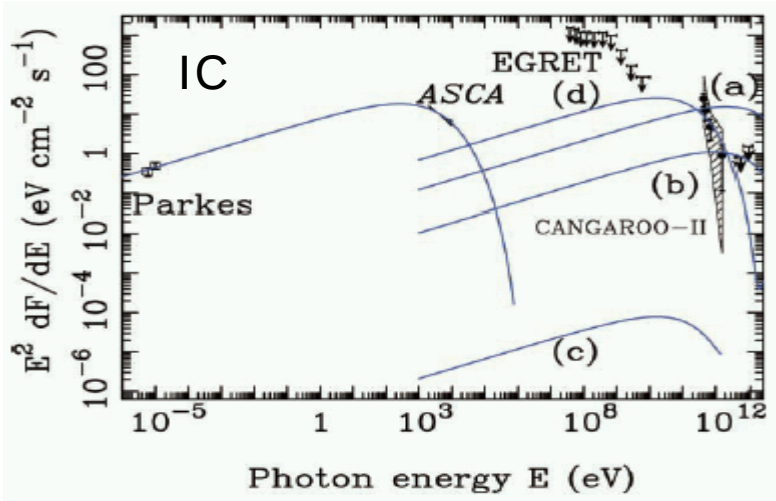


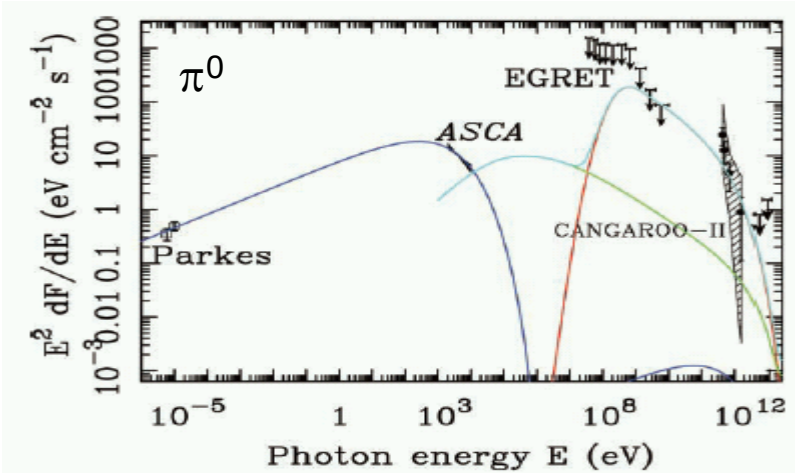
CANGAROO-II: Katagiri et al., ApJ, 619, (2005) L163



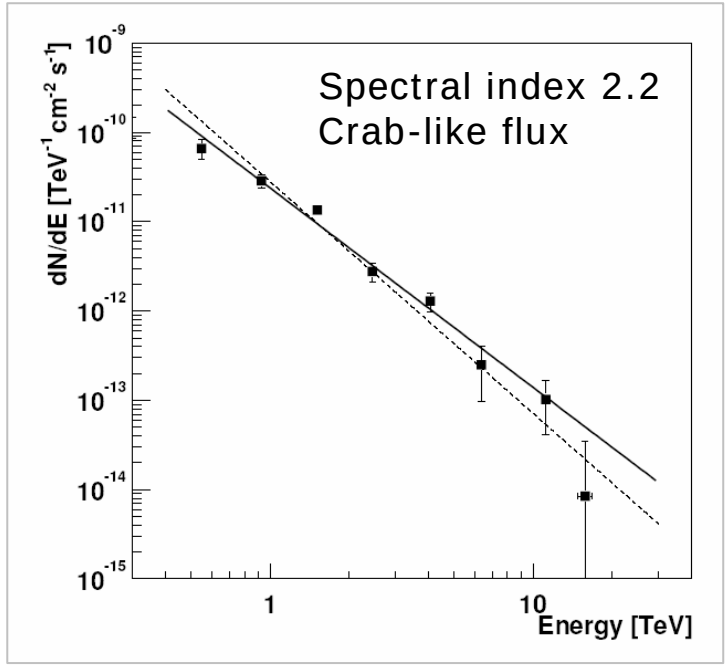
H.E.S.S. (Hofmann, Cherenkov2005)

RX J0852.0-04622 spectrum



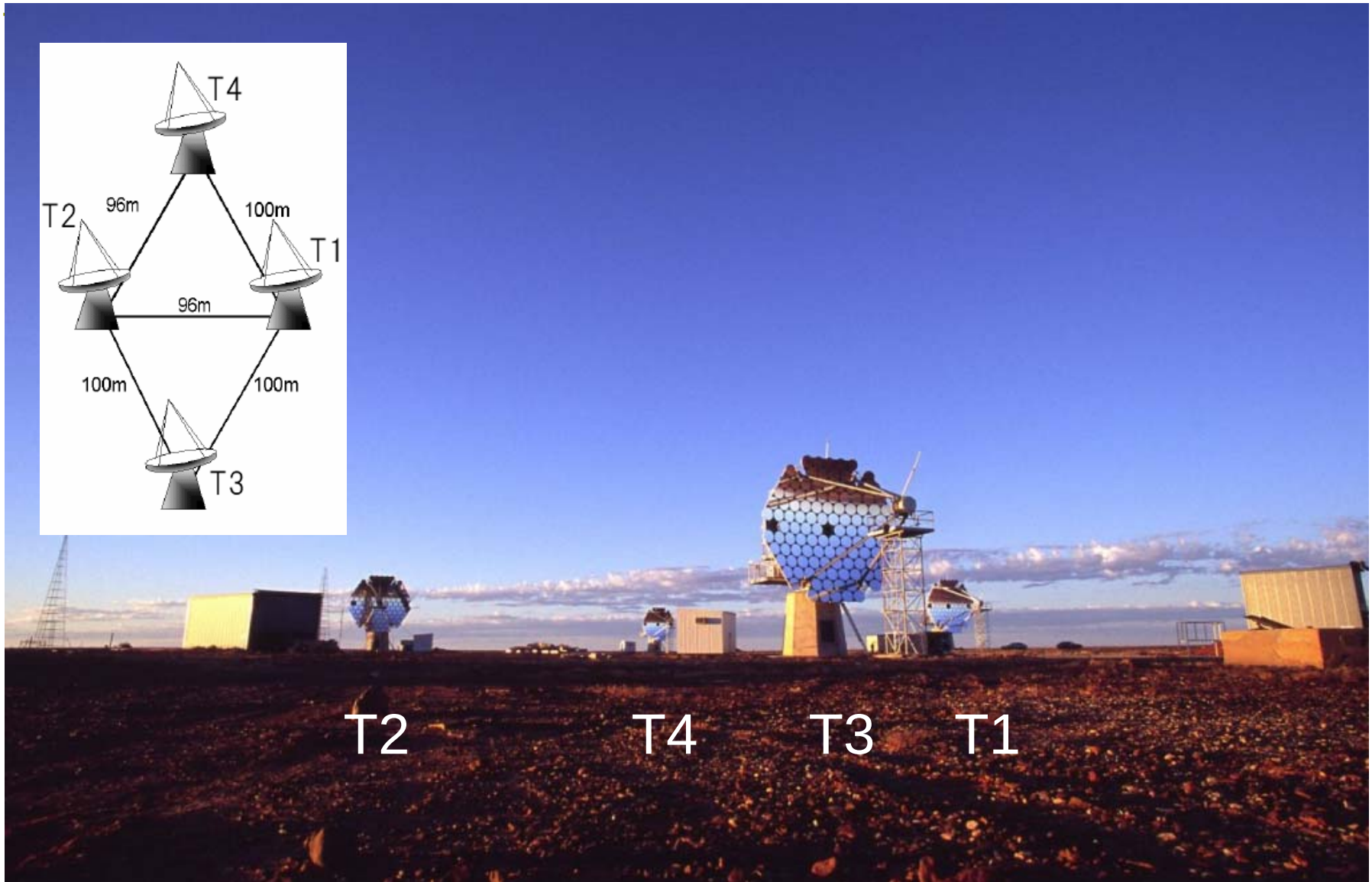


CANGAROO-II: Katagiri et al., ApJ, 619, (2005) L163



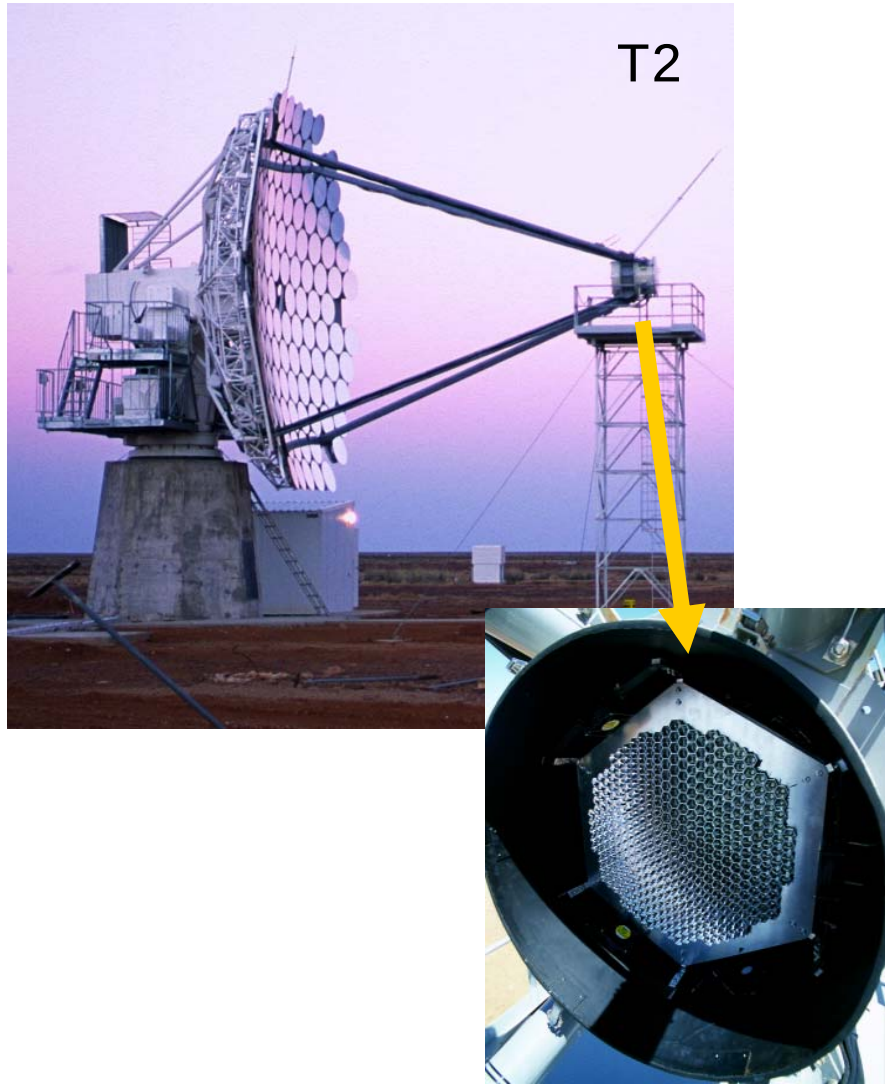
H.E.S.S. (Hofmann, Cherenkov2005)

Woomera: 2004 March

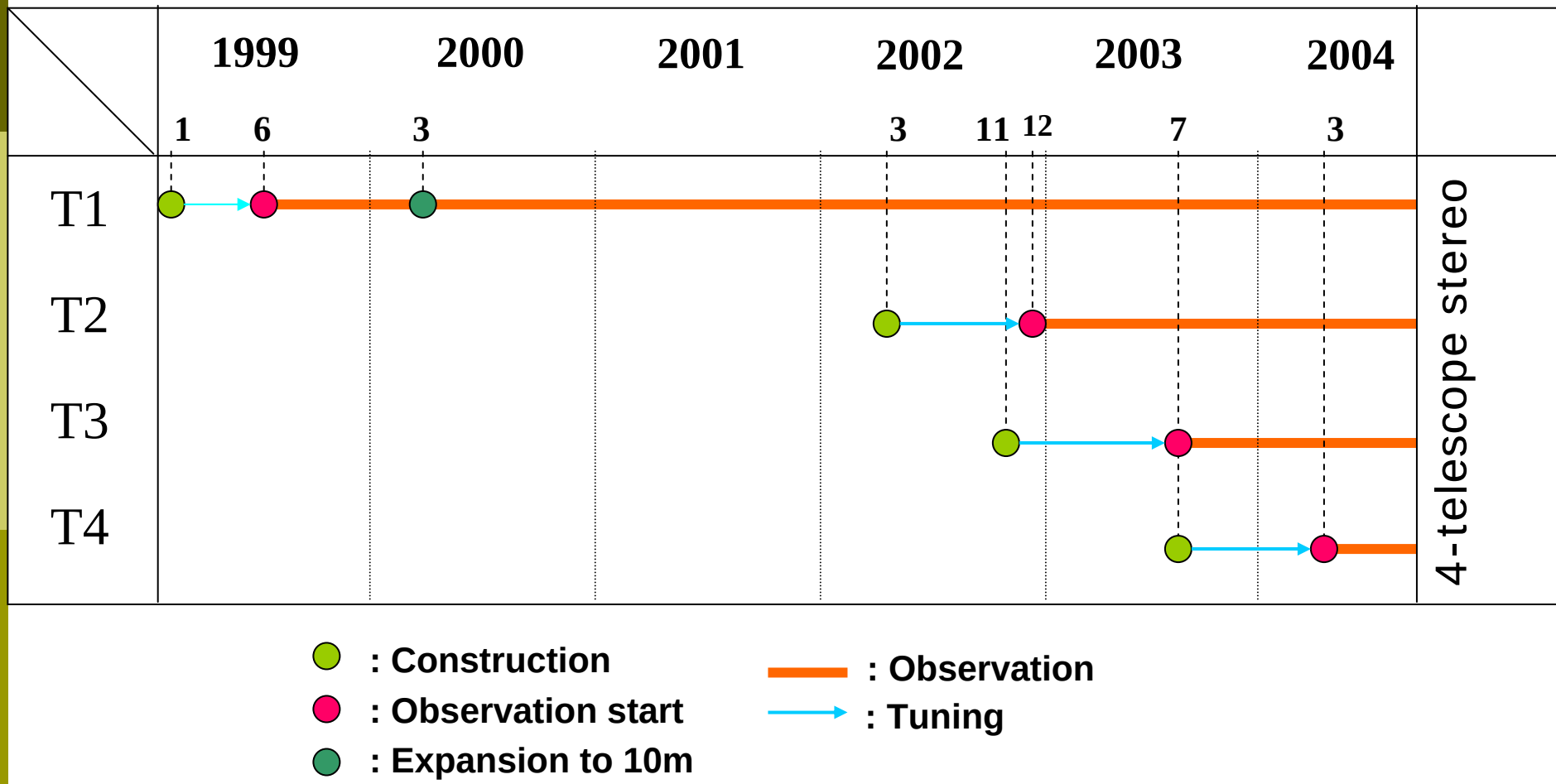


Basic specifications of telescopes

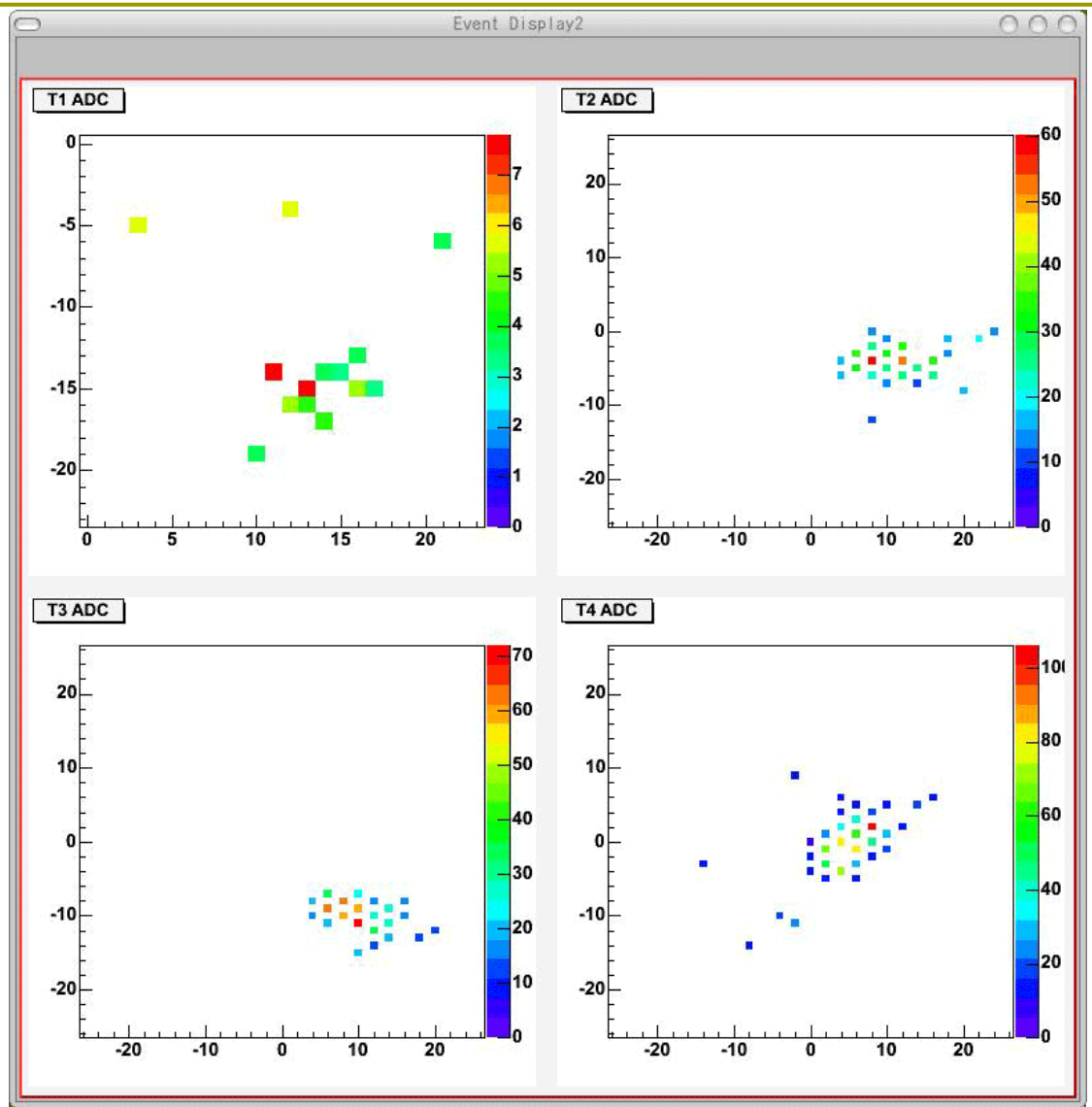
- Location:
  - 31°06'S, 136°47'E
  - 160m a.s.l.
- Telescope:
  - 114× 80cmϕ FRP mirrors (57m^2, Al surface)
  - 8m focal length
  - Alt-azimuth mount
- Camera:
  - T1: 552ch (2.7° FOV)
  - T2,T3,T4: 427ch (4° FOV)
- Electronics:
  - TDC+ADC



Construction of CANGAROO-III



Sample of 4-fold stereo events



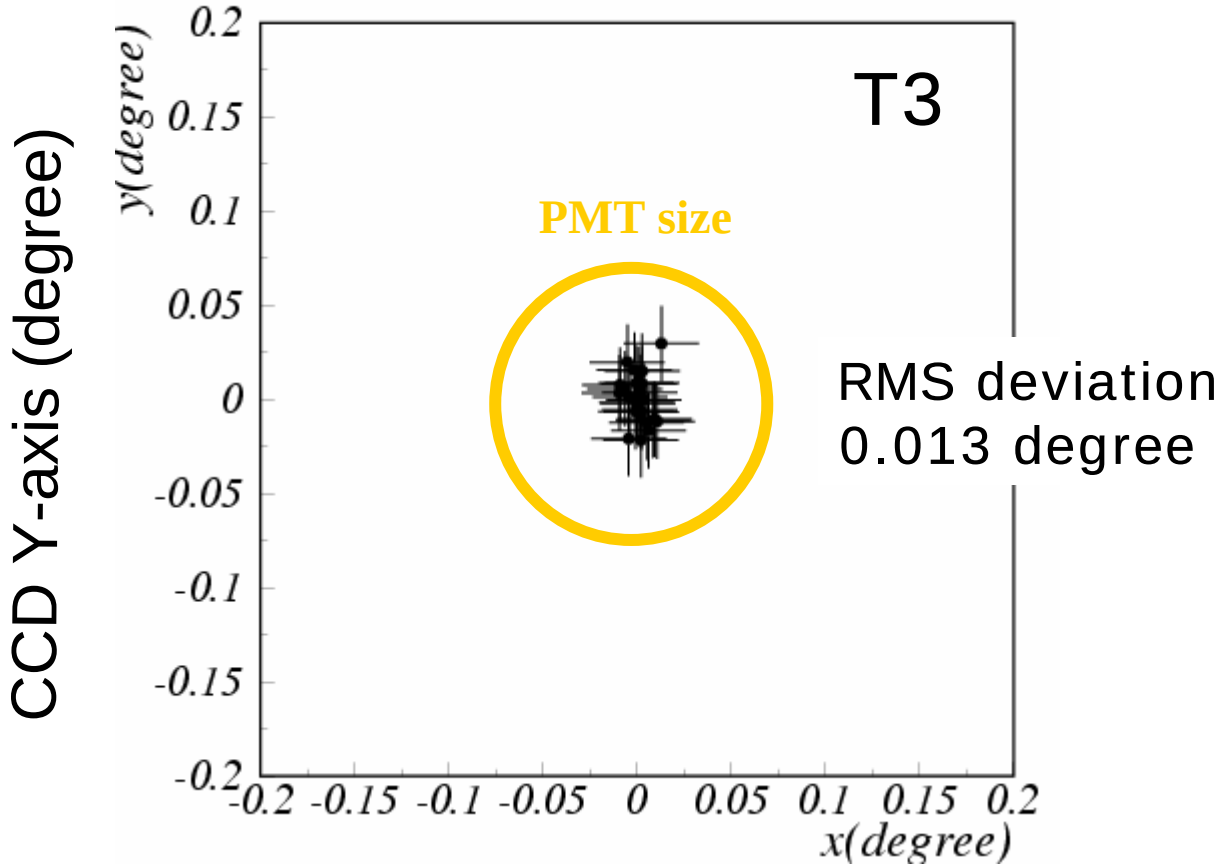
Data:
2004
March

Stereo analysis: still underway & in progress

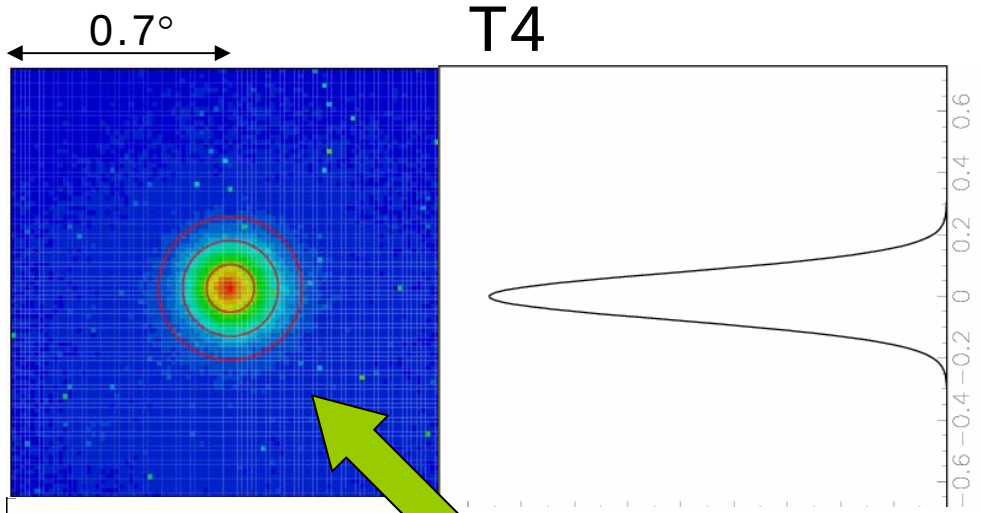
- Inconsistency with H.E.S.S results on some sources
  ⇒ New observations with CANGAROO III
  Efforts for advanced analysis procedures
- Measure more optical parameters
  - CCD measurements of spotsizes and stars
- Use muons for calibration
  - Tune Monte Carlo simulation
- Use the Crab as the standard candle
  - Flux obtained with Monte Carlo simulation is compared with those reported by other groups
- Independent teams within the collaboration are working:
  - Hereafter, referred to as Teams A, B, C ...
  - Results, especially detections, are double-checked

Star tracking

Star position error observed by a CCD camera



Spot size



Point Spread Function (FWHM)

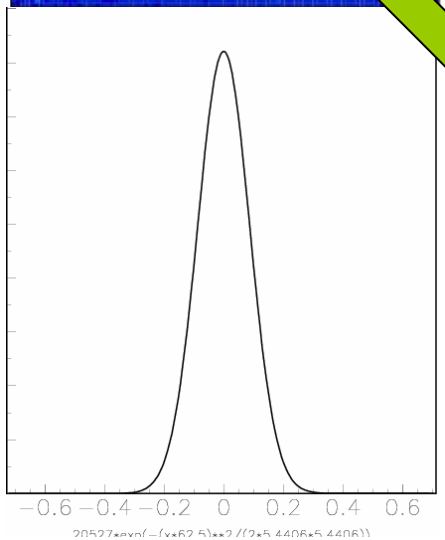
T1: 0.20°

T2: 0.21°

T3: 0.14°

T4: 0.16°

(measured at construction time)



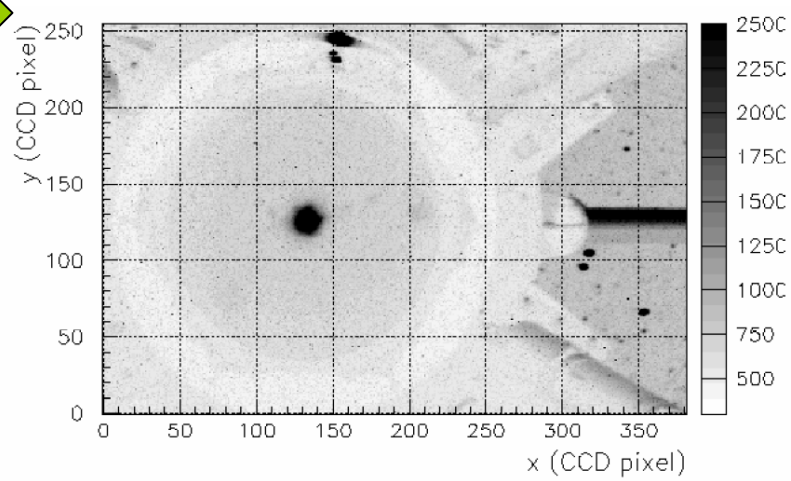
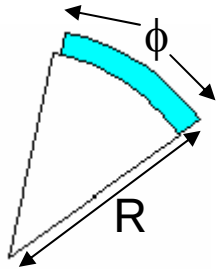


Image of a star on camera observed by a CCD camera

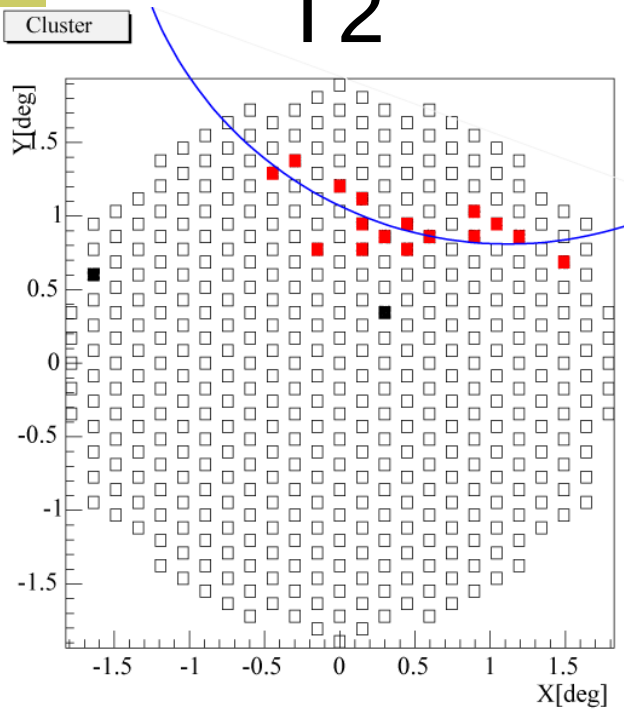
Muon events (1)

- Selected by
  1) clustering
  2) R×ϕ (arc length) >2deg•rad
  3) Small χ^2 (good fit)

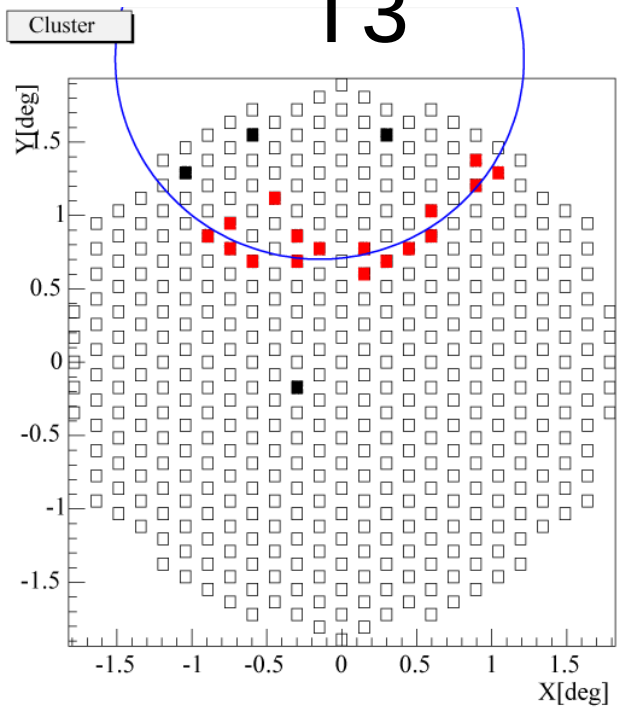


Data: 2004 March

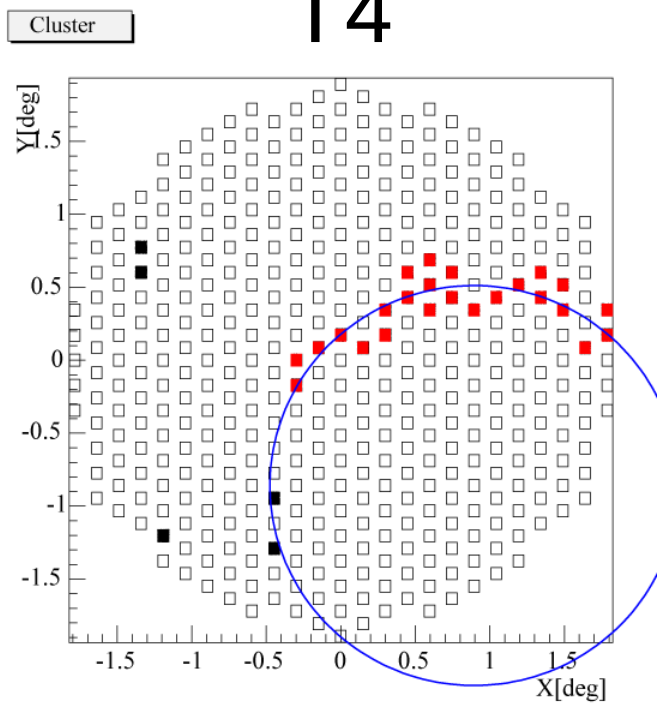
T2



T3



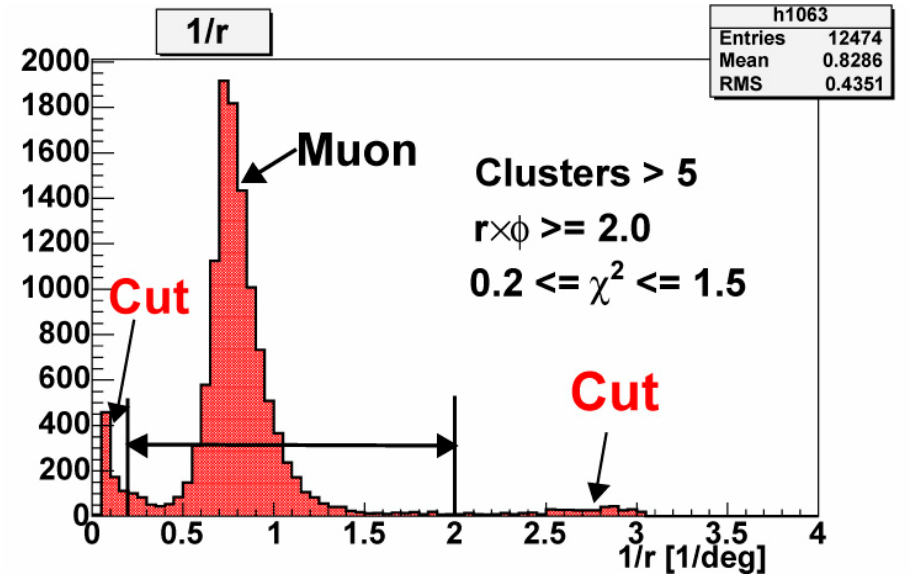
T4

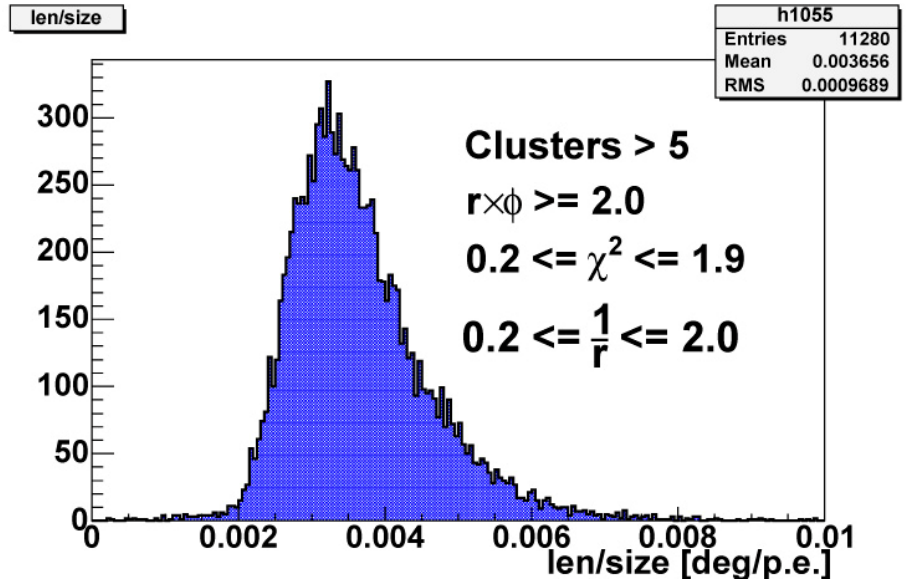


Muon events (2)

- T4 $r[m] \approx 8 \tan\theta_C$

  on the focal plane





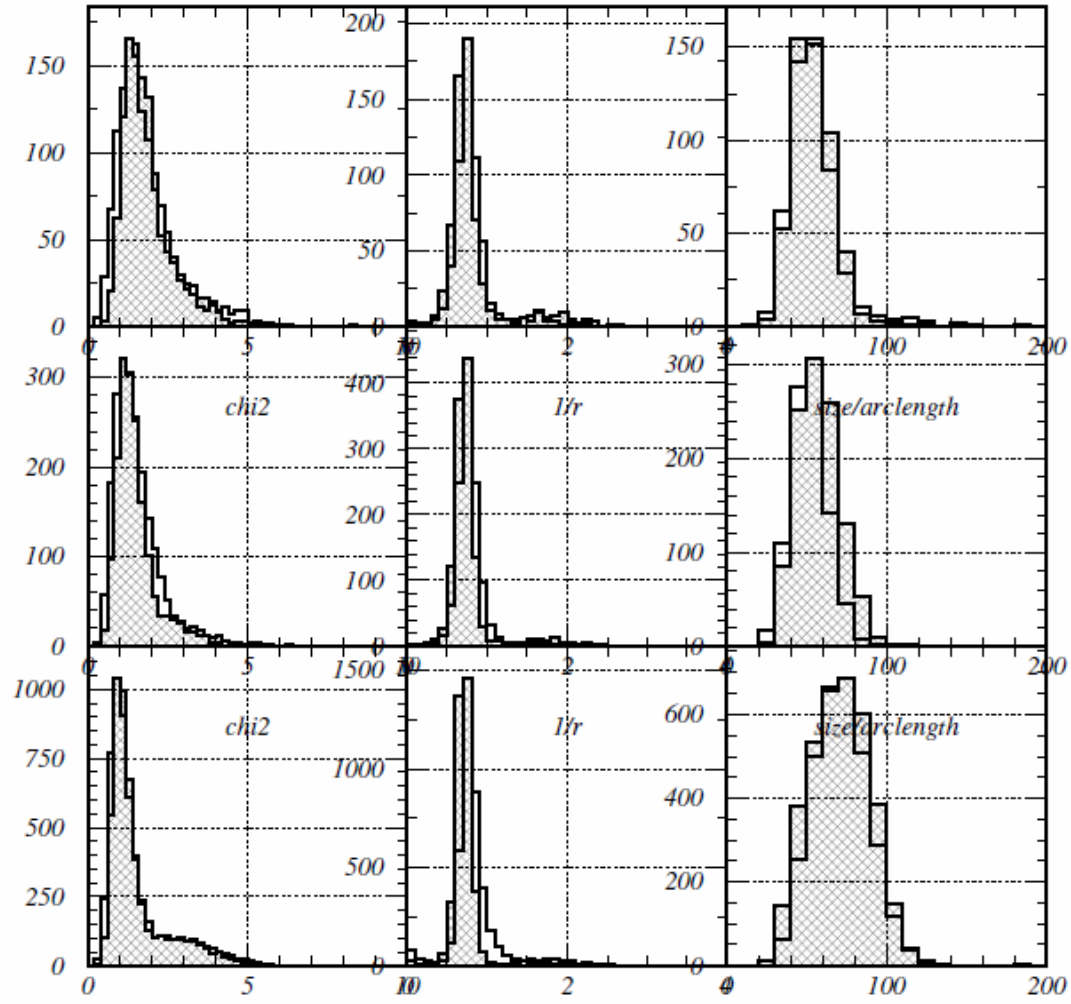
Curvature Distribution

Length/size Distribution

1-7GeV : 1/r >= 1.0 [1/deg]
> 7GeV : 1/r < 1.0 [1/deg]

Monte Carlo simulation

Muon parameters compared with Monte Carlo



Histogram: data

Hatched: M.C.

χ^2: for ring fitting

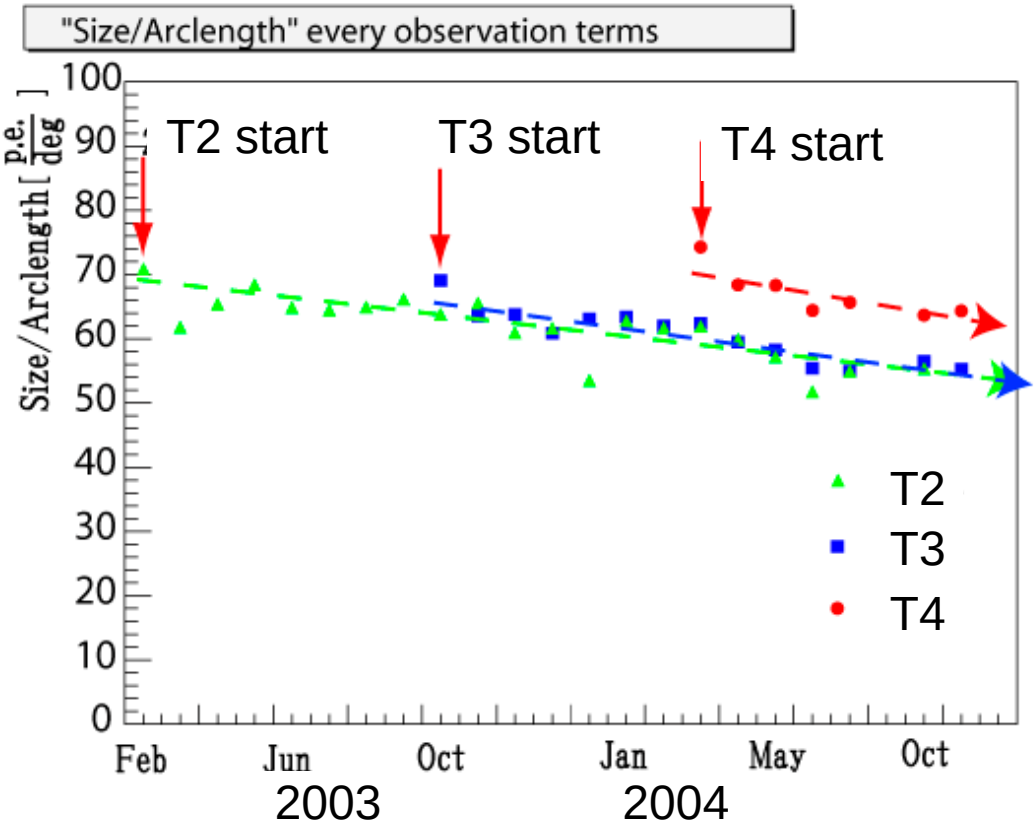
(sensitive to spot size)

r: curvature radius

(~0.8 for $v/c=1$)

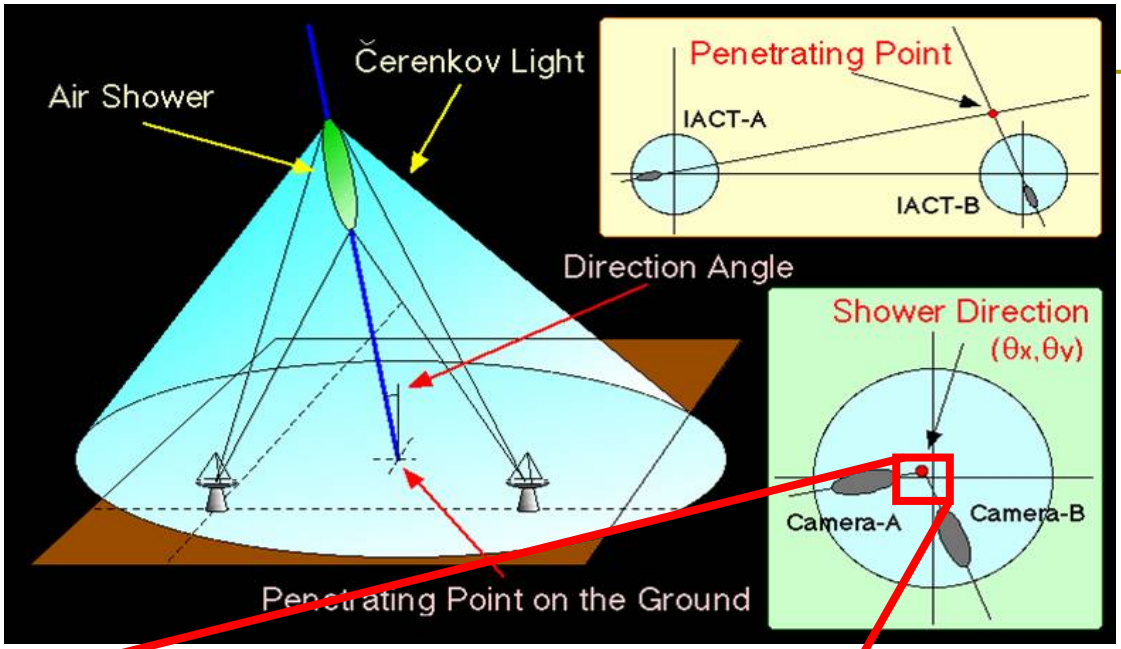
Size/arclength ∝ total light collection efficiency

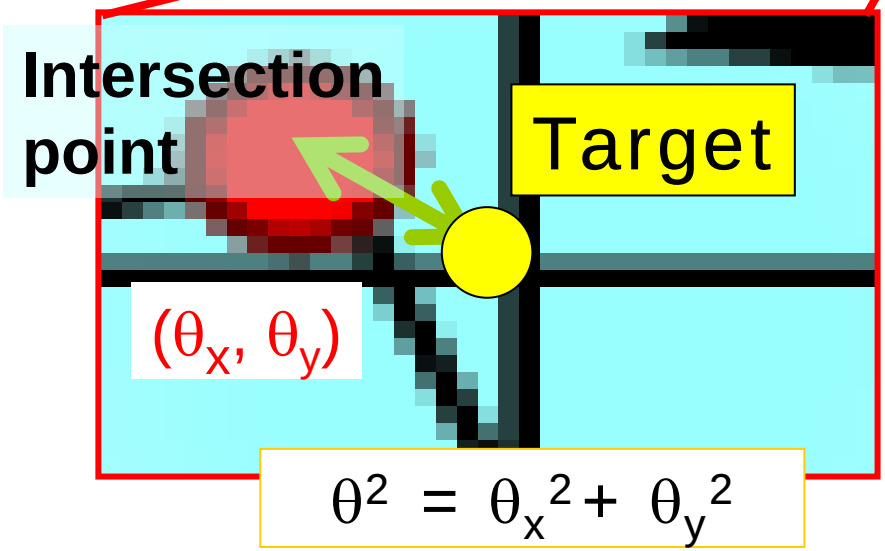
Time variation of Size/Arclength



- Monitor of total light conversion efficiency
- Gradually, *Size/Arclength* is decreasing (~5% / year)
- Mirror degradation due to dust etc.

Stereo observation





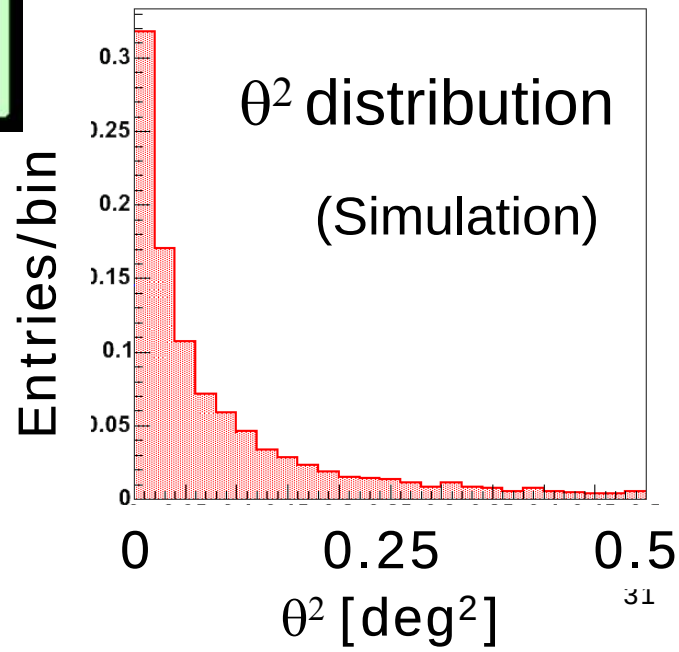
Angular resolution

0.25deg → 0.1 deg

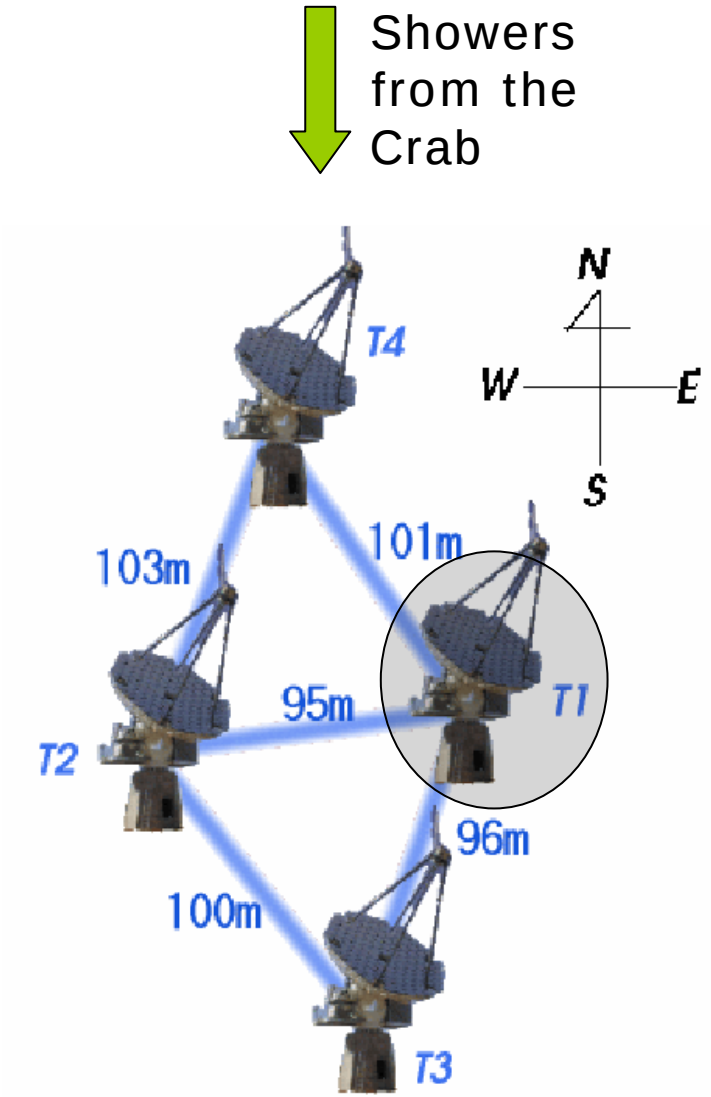
Energy resolution

30% → 15%

Better S/N (no local muons)

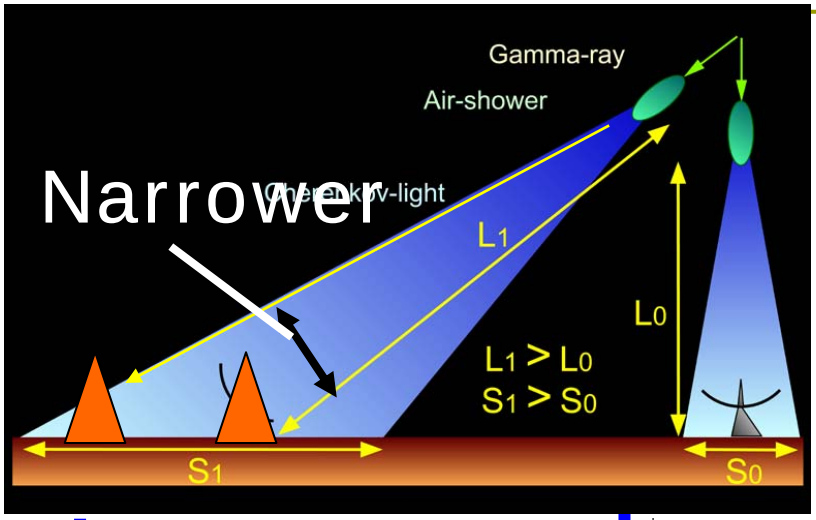


Unfortunate situation for the Crab



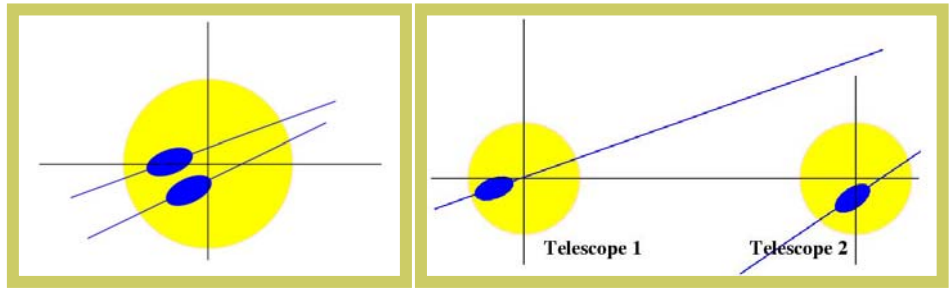
- The oldest T1 has higher energy threshold and bad efficiency for stereo observation
- Only T2/T3/T4 are used for stereo analysis
- Stereo baseline becomes short for the Crab observation at large zenith angles

Large zenith angle observation of the Crab

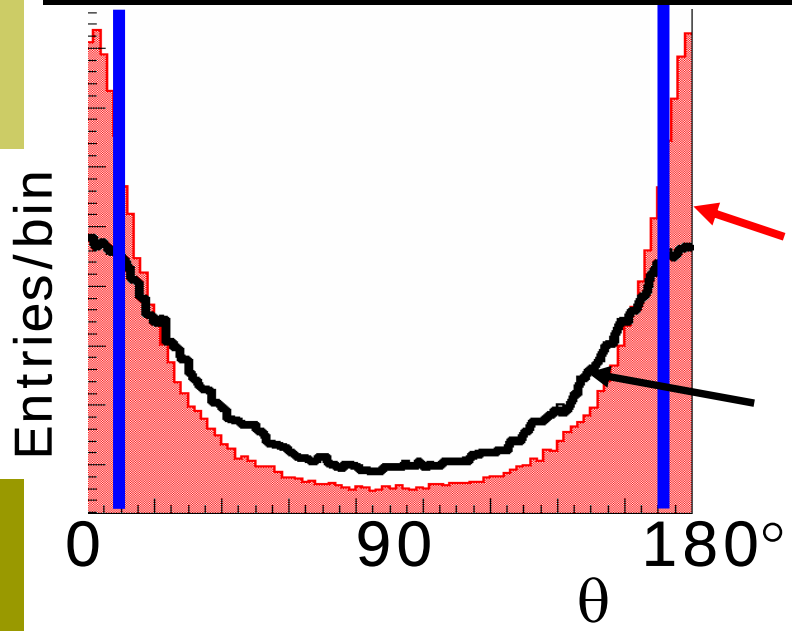


Higher energy threshold ~1TeV

Bad intersection accuracy

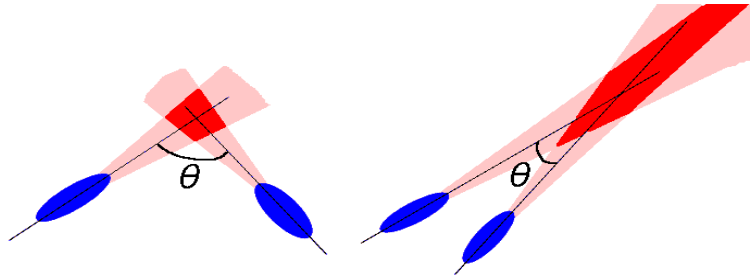


Far core→small angle→bad accuracy



h~30°

h~60°



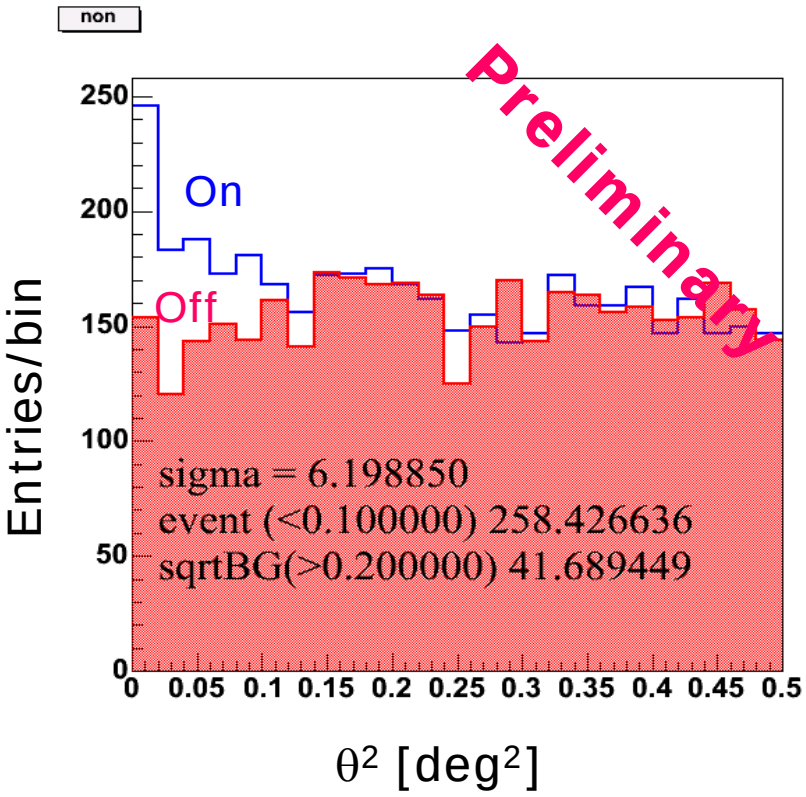
Accept 15°<θ<165° only

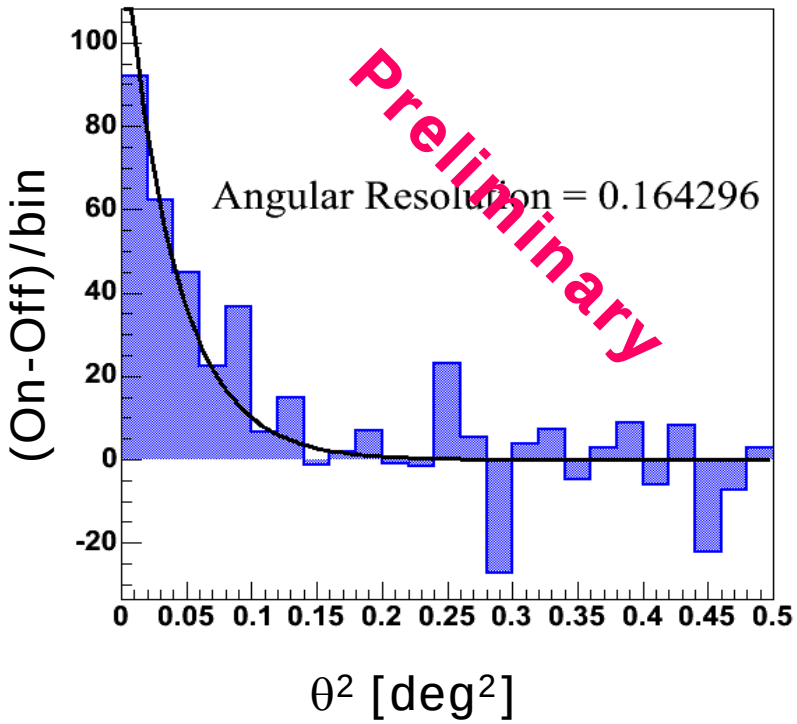
Crab signal (1)

Team “A”

(simple square cuts)

Nov 2003





Sigma : 6.19

Excess : 258±42 event

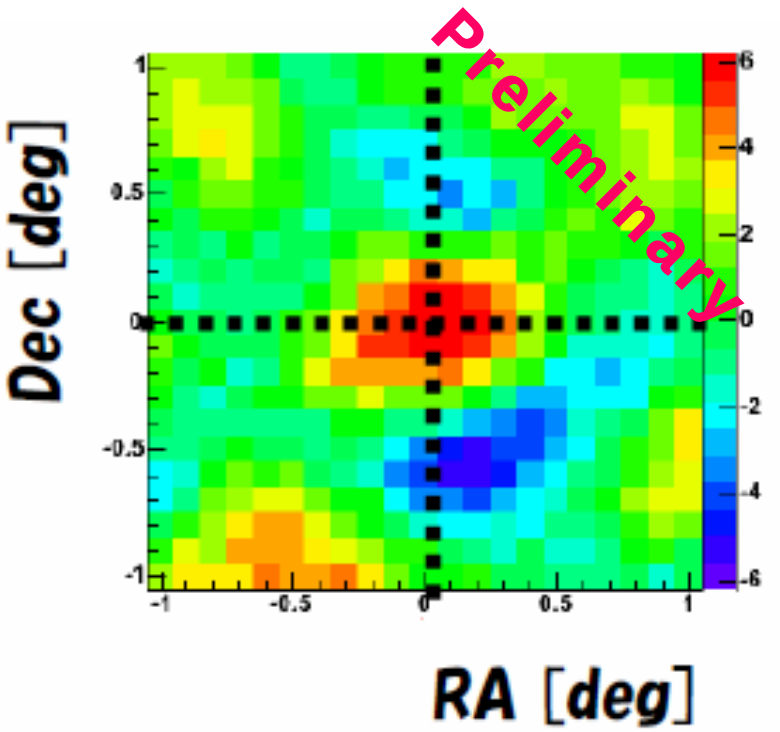
Angular Resolution : 0.16° (HWHM)

- T2 & T3
- ON 7.5hr
- OFF 7.0hr

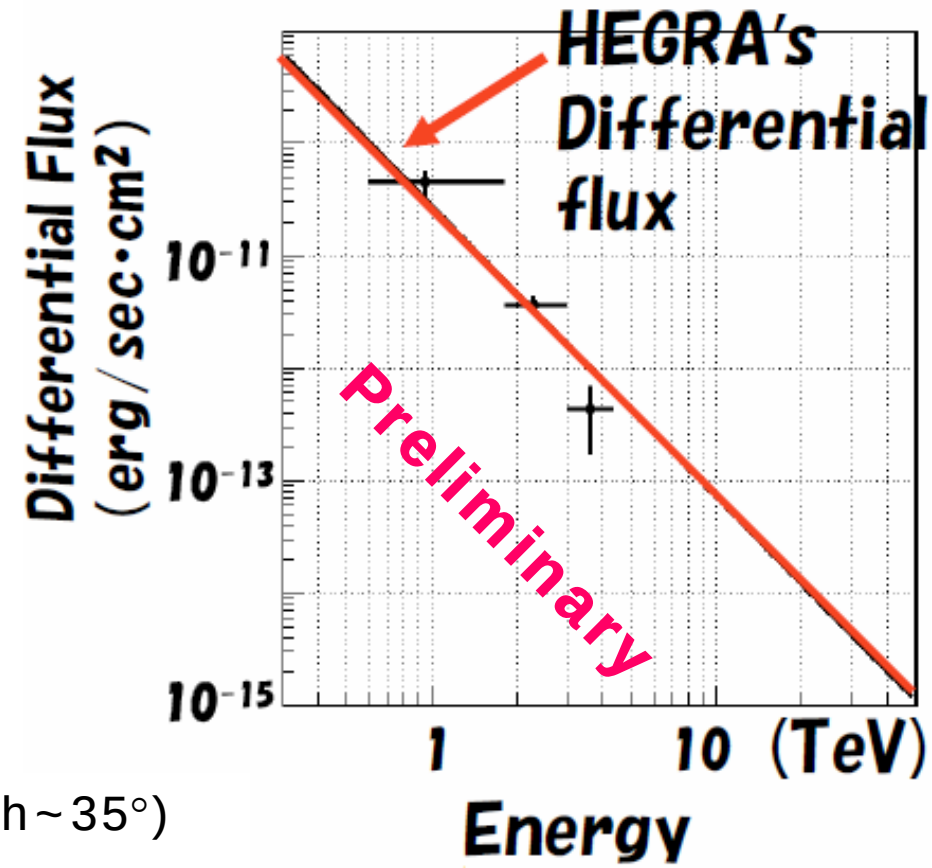
Crab signal (2)

Team “A”

- Significance map



- Differential flux



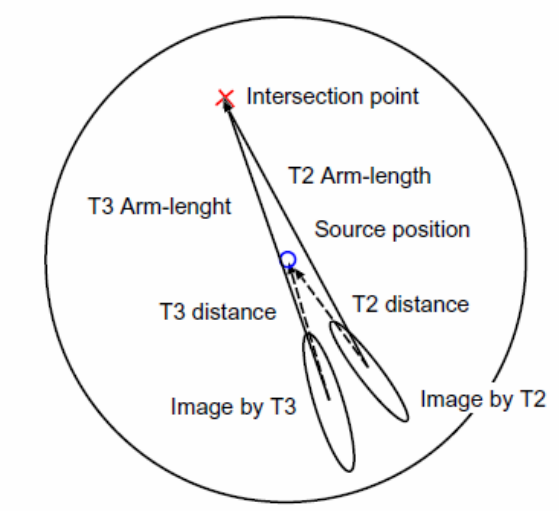
Angular resolution for the Crab (h~35°)

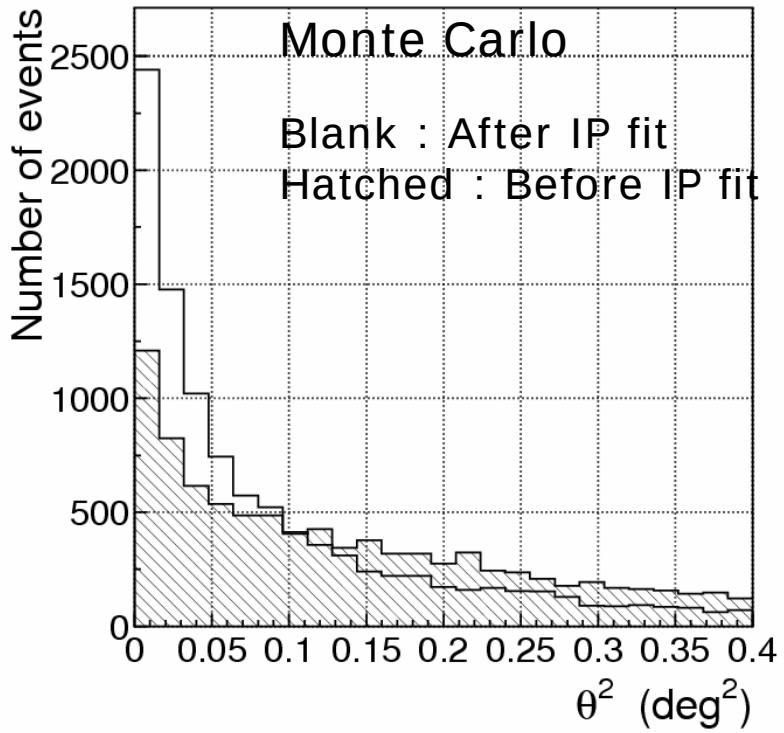
~0.17° (RA) / 0.14 ° (Decl)

IP constraint fit

$$\chi^2 \equiv \sum_{\text{Telescopes}} \left[\left(\frac{\text{Width}(x,y)}{\sigma_w} \right)^2 + \left(\frac{\text{Armlength}(x,y) - \langle \text{Armlength} \rangle}{\sigma_{ARM}} \right)^2 \right]$$

Search intersection point (IP) by minimizing χ^2 so that width along shower axis to be minimum and armlength to be near the expected value (<Armlength>=0.75, Mesh size 0.025°)





γ/h separation by Fisher discriminant

- Linear combination of image parameters (x_i)

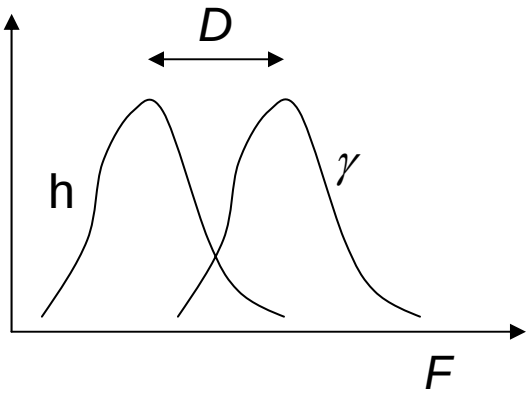
$$F \equiv \sum_i \alpha_i x_i$$

- Difference between signal (γ) and background (h)

$$D \equiv \langle F_\gamma \rangle - \langle F_h \rangle$$

- Determine α_i which maximize separation (solvable using correlation matrix)

$$S \equiv \langle D \rangle^2 / \langle (D - \langle D \rangle)^2 \rangle$$



- With calculated α_i for a known source, the (appropriately normalized) combination *F* could be the "Fisher discriminant" for other sources.

- We use *widths* and *lengths* of multiple telescopes for image parameters.

R.A. Fisher, Annals of Eugenics, 7 (1936) 179

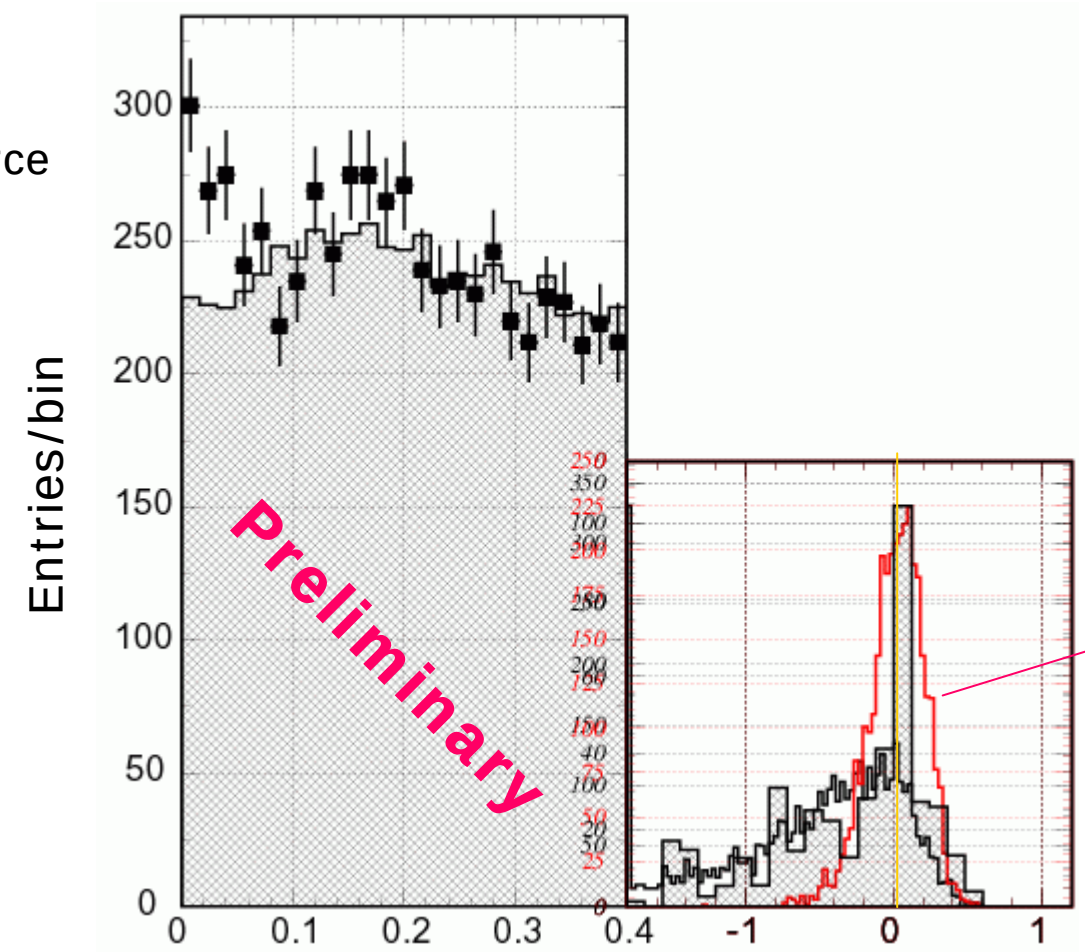
Crab signal (3)

Team “B”

(with IP fit & Fisher D.)

Points: On-source

Hatched: Off-source



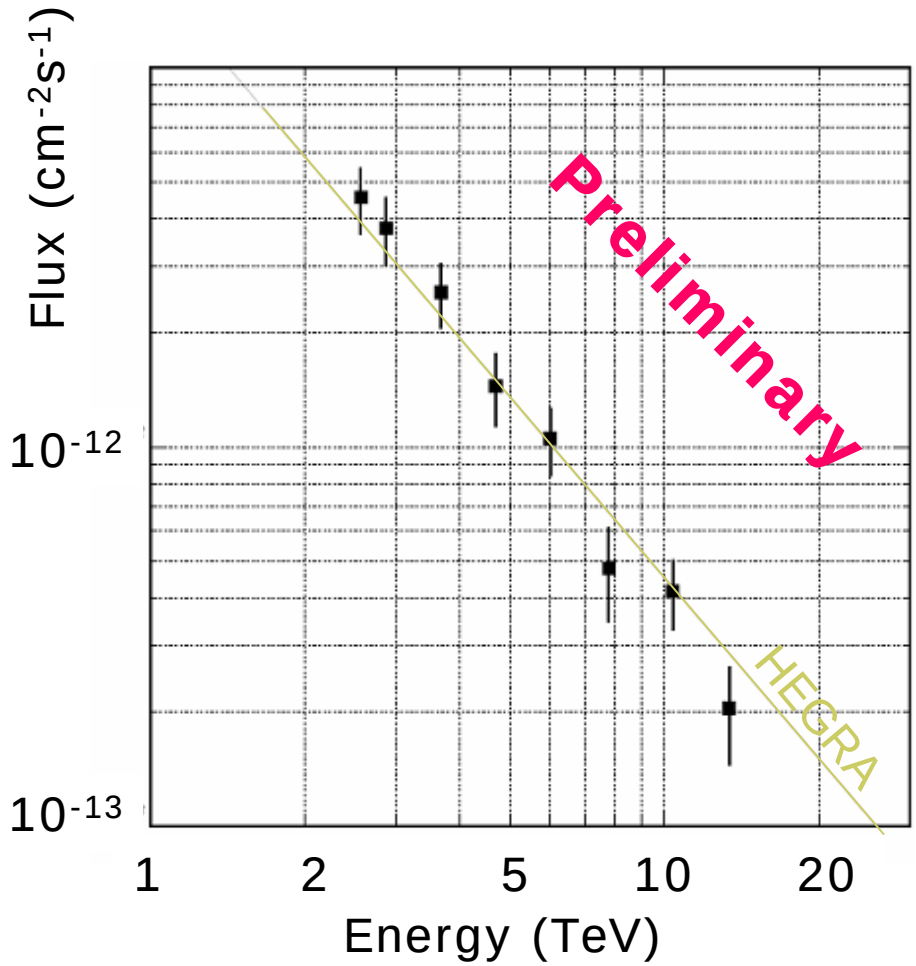
•T2 & T3

•890 min (Dec.2003)

Crab spectrum

Team “B”

(with IP fit & Fisher D.)



- T2 & T3
- 890 min (Dec.2003)

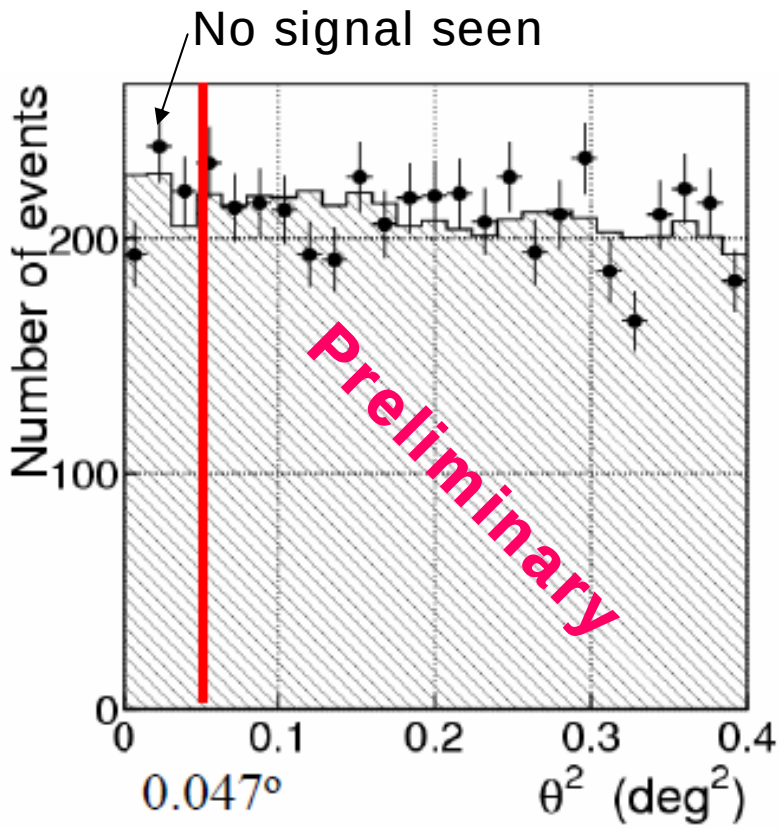
Cen A: the nearest AGN

S. Kabuki

Near infrared image
2MASS
1.2-2.17μm

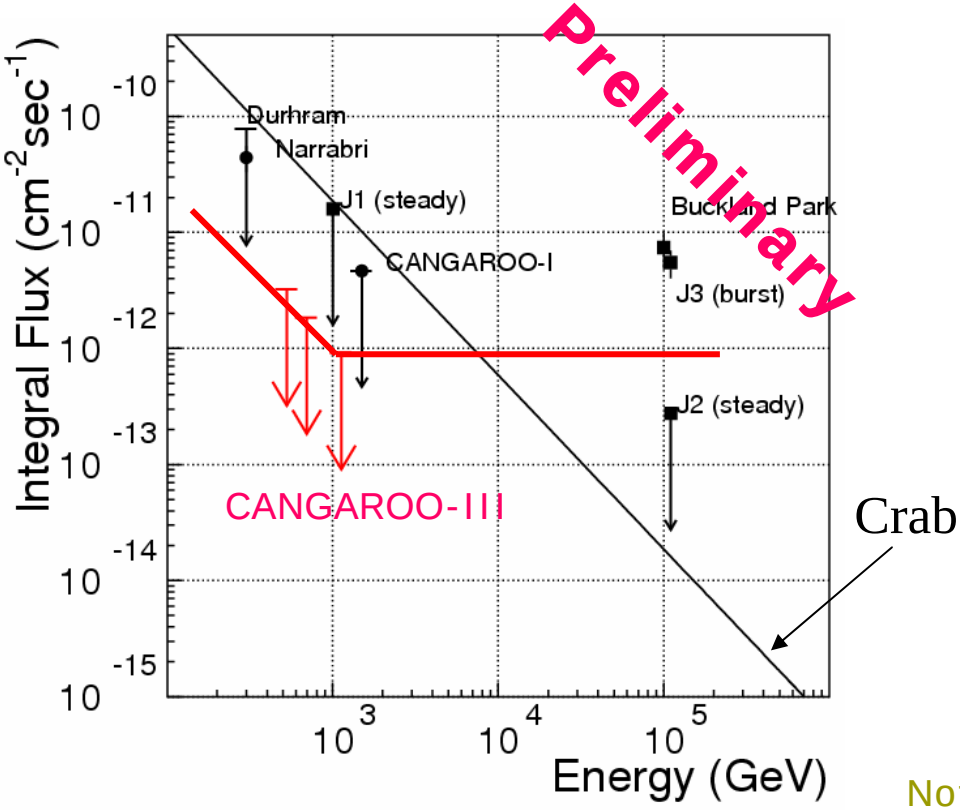
- Elliptical
- Radio galaxy
- Fanaroff-Riley type I
- "Misaligned" BL Lac (~ 60°)
- Distance 3.5 Mpc (z=0.00183)

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	



Cen A: flux limit

S. Kabuki



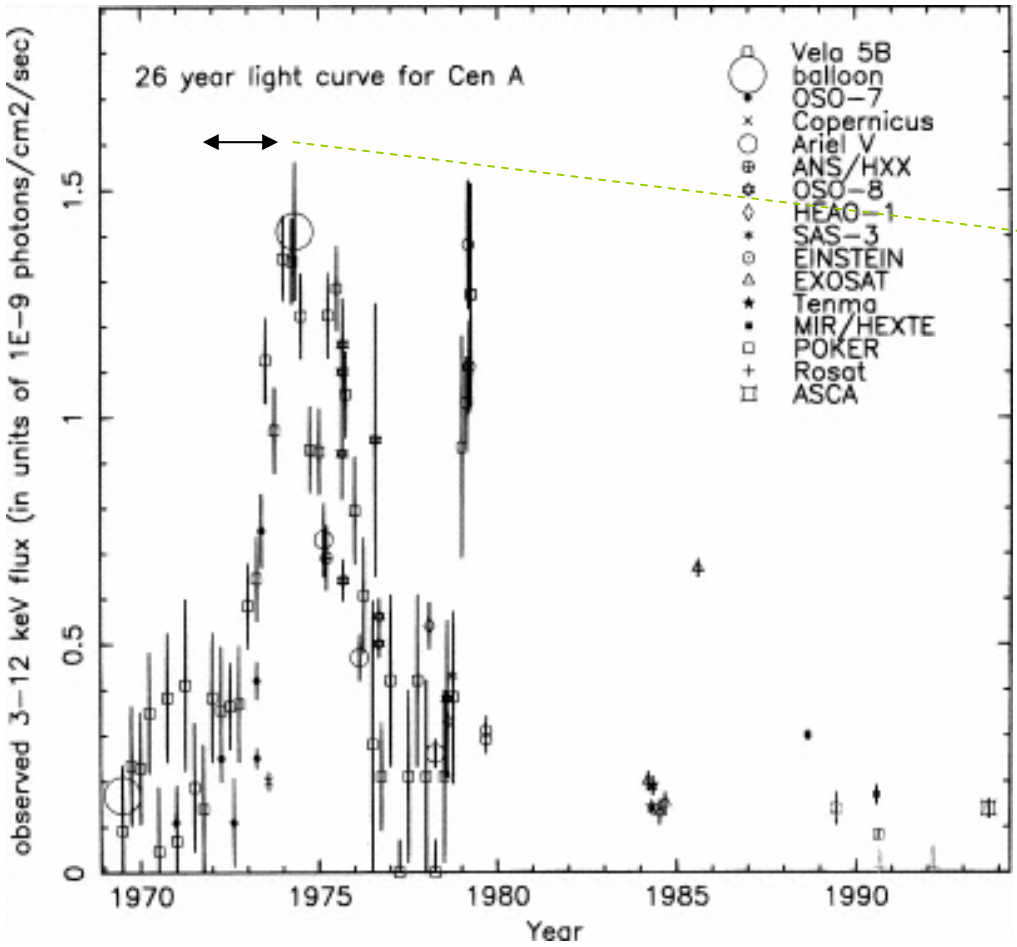
Upper limit:

~7% Crab

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

Note that this is a highly variable source, and the TeV claim in 70's was based on observations during its flaring activity.

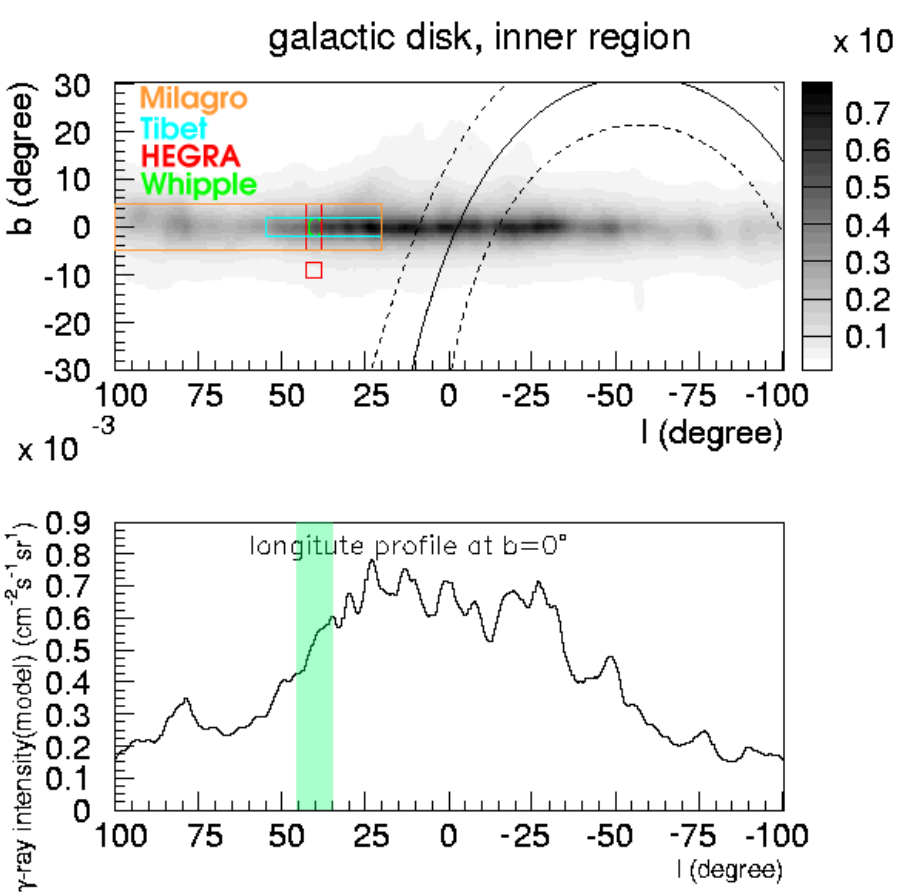
Cen A activity in the past

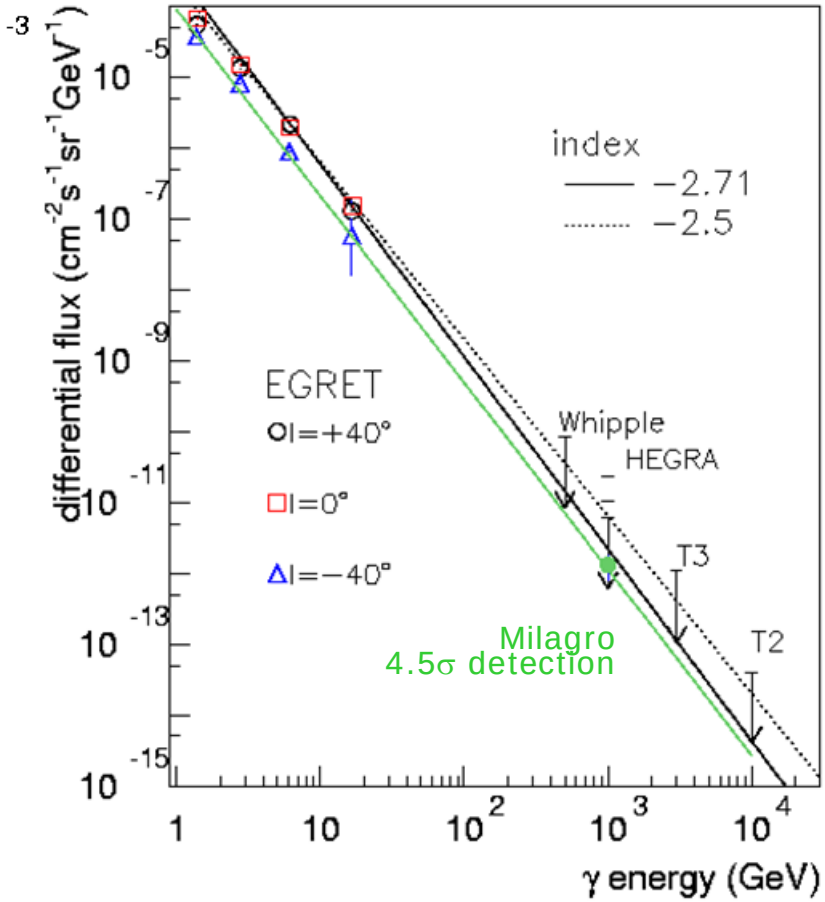


Grindlay et al.ApJ 197 (1975) L9

Turner et al., ApJ 475 (1997) 118

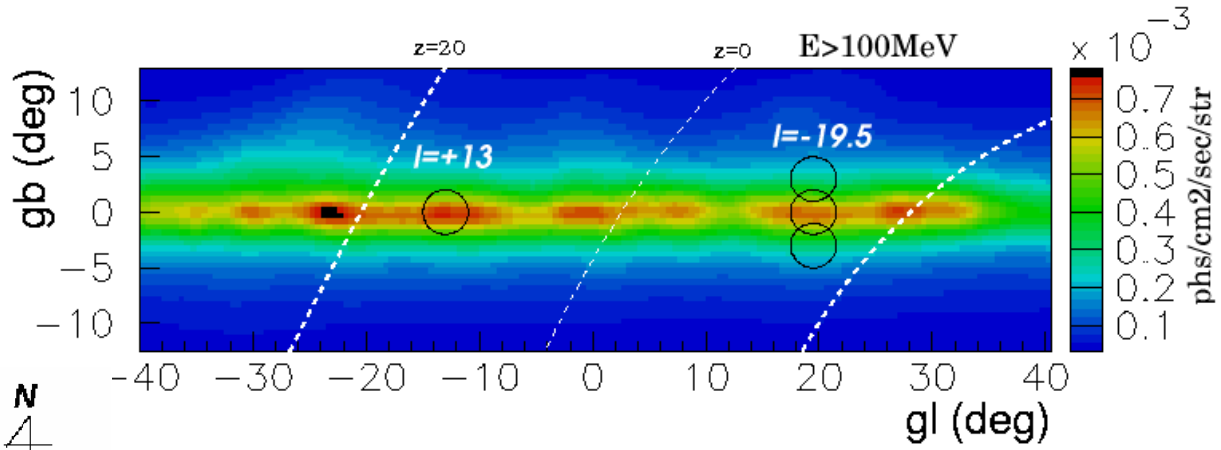
Galactic diffuse emission

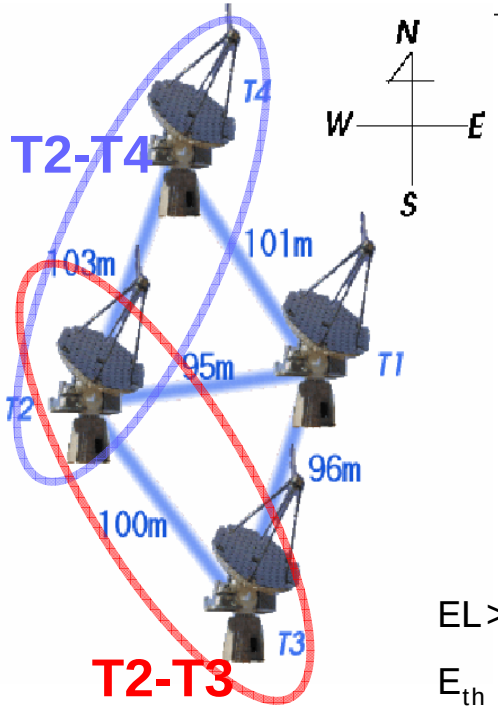




Observation of the Galactic disk

M. Ohishi





EL>45deg

E_{th} ~600 GeV

l=-19.5 2004Jun

(Obs.time in minutes)

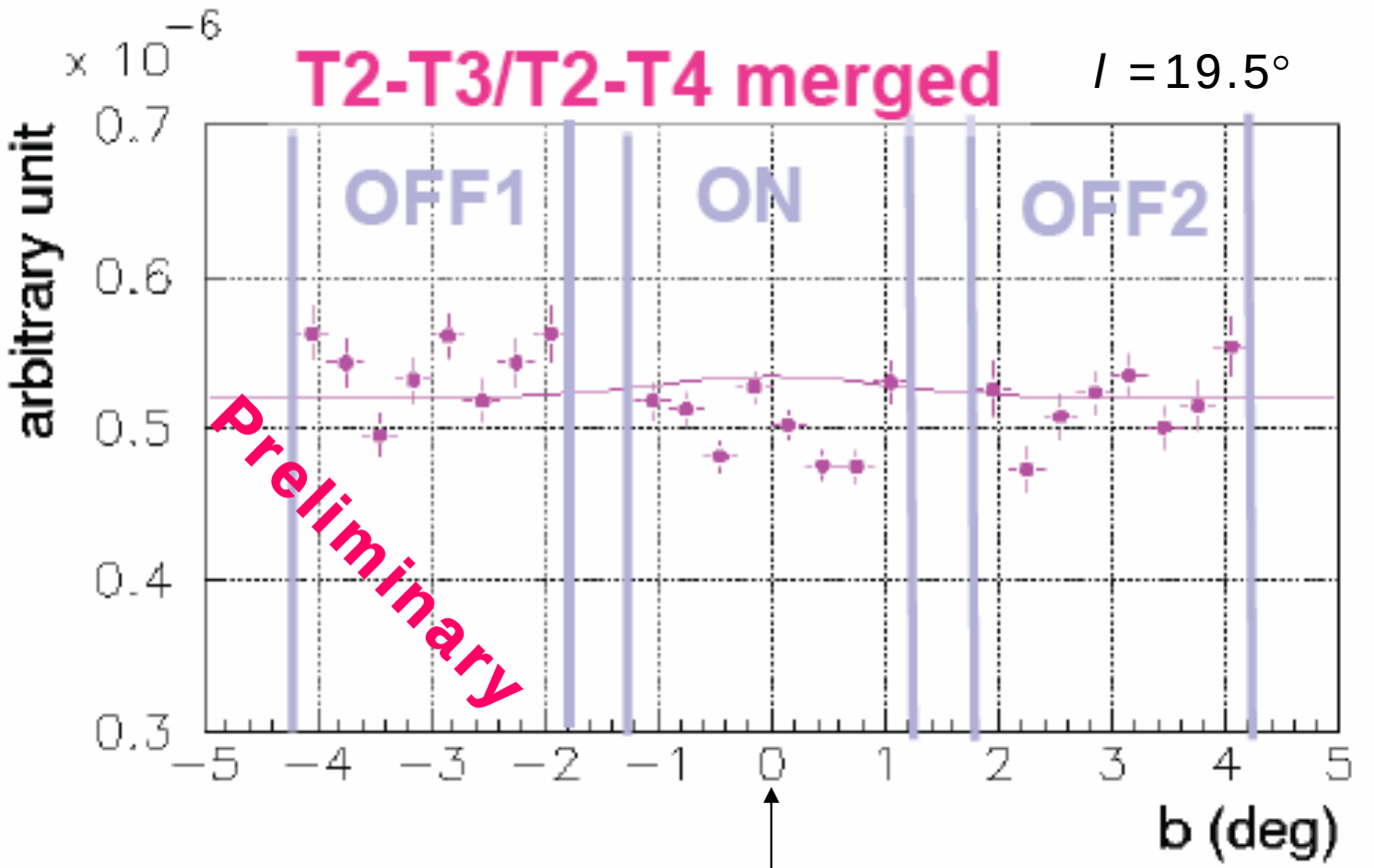
Obs.term	tel.pair	***b=0°***	***b=-3°***	***b=+3°***
2004Jun	T2-T3	635.3	322.3	292.9
2004Jun	T2-T4	380.0	201.9	192.5

l=+13 2004Jun/Aug

Obs.term	tel.pair	**ON**	**OFF**
2004Jun	T2-T3	289.6	340.0
2004Jun	T2-T4	199.5	270.0
2004Aug	T2-T3	224.9	183.6
2004Aug	T2-T4	280.0	85.7

Galactic disk scan result

M. Ohishi

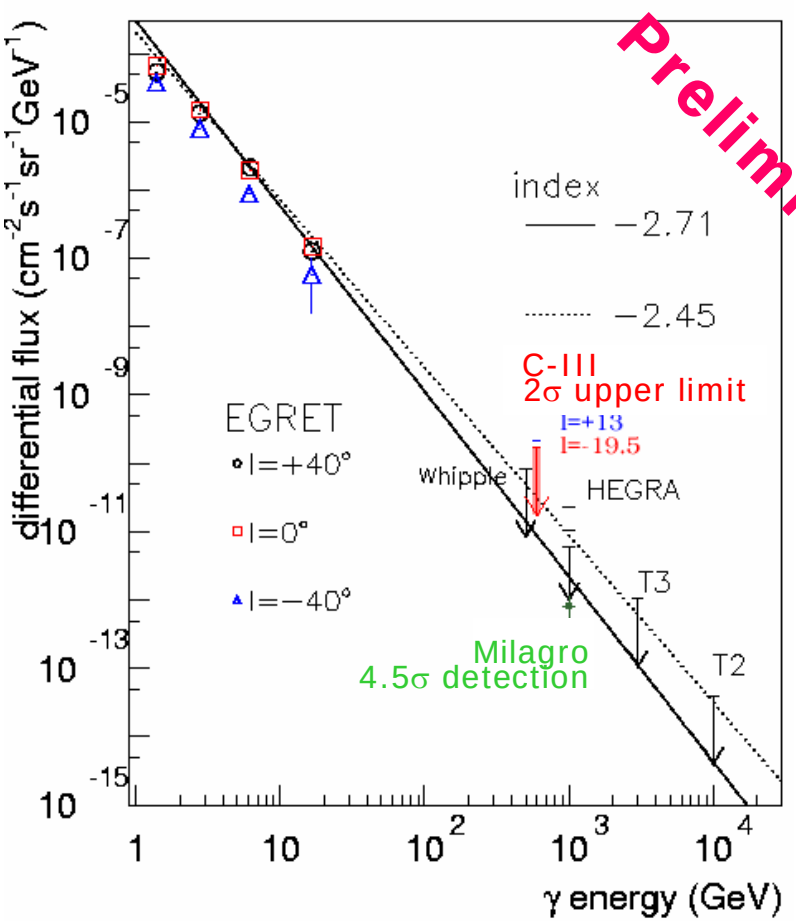


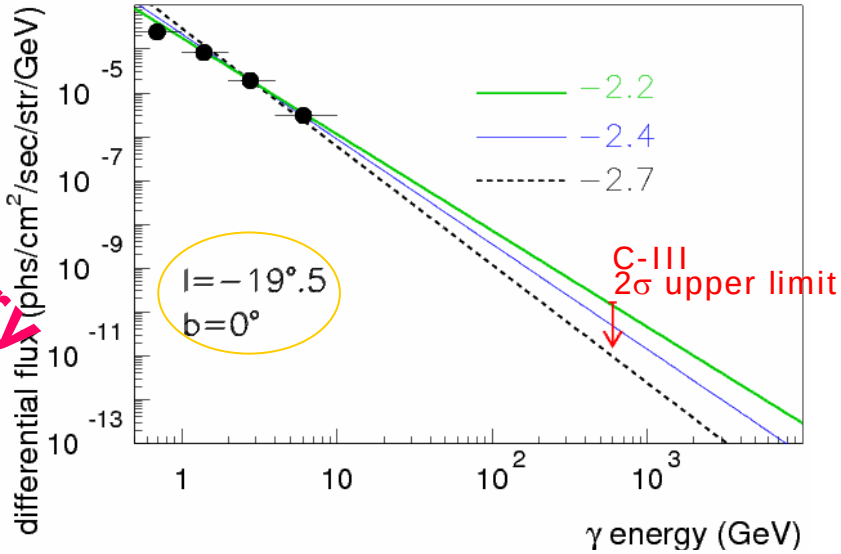
No excess at the disk!

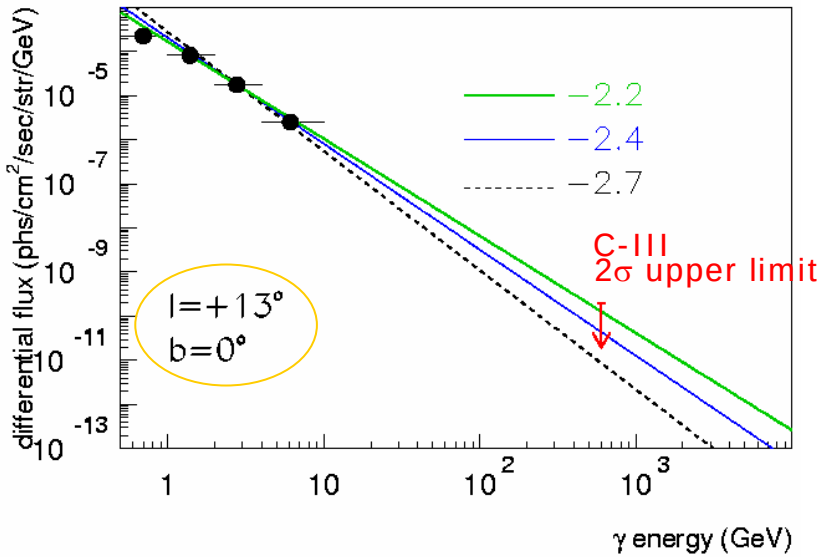
(expected σ~1deg)

M. Ohishi, preliminary

Galactic diffuse emission: upper limit







CANGAROO-III: syst.error included

Other TeV obs: Cygnus regions

Galactic diffuse emission: "GeV bump"

- Hard cosmic-ray spectrum?
  - Mori, ApJ 478 (1997) 225
- Inverse Compton?
  - Pohl & Esposito, ApJ 507 (1998) 327
- $pp \rightarrow \pi^0 X$ cross section?
  - Diffractive interaction & scaling violation
  - Kamae, Abe & Koi, ApJ 620 (2005) 244
- Dark gas contribution
  - 3EG catalogue may be changed (but not spectra)
  - Grenier et al., Science 307 (2005) 1292

Diffractive interaction included

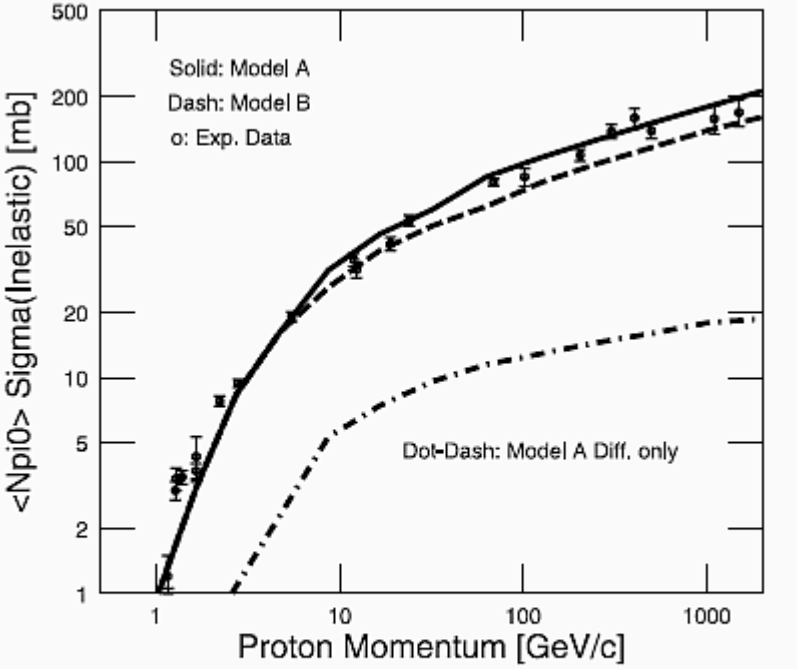


FIG. 5.—Averaged neutral pion multiplicity for the p-p and $\bar{p}$-p inelastic interaction. Curves are for model A All (*solid*), model B (*dashed*), and model A diffractive (*dot-dashed*). Data are from Table 1 of Dermer (1986).

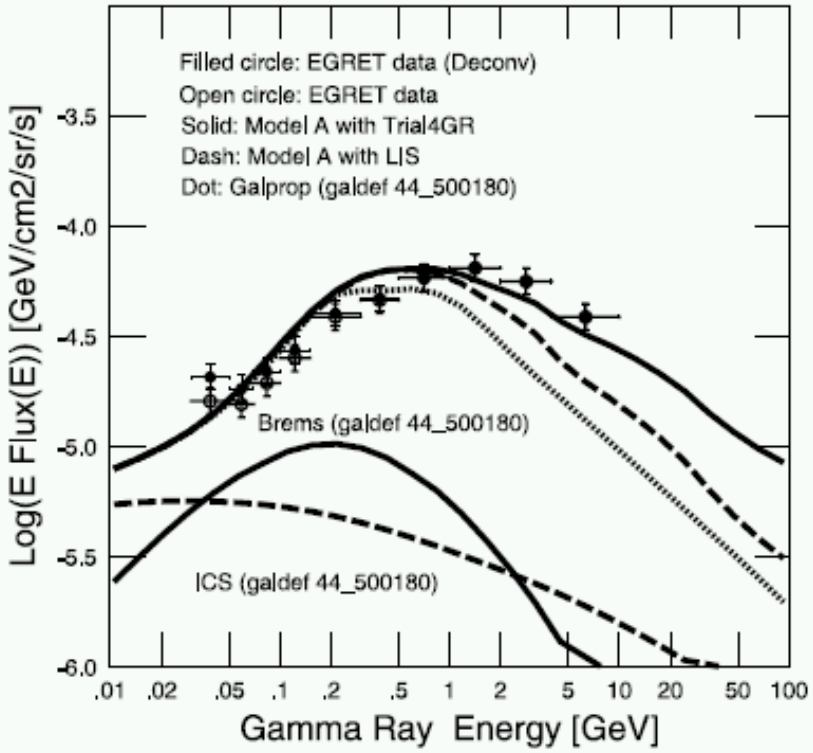
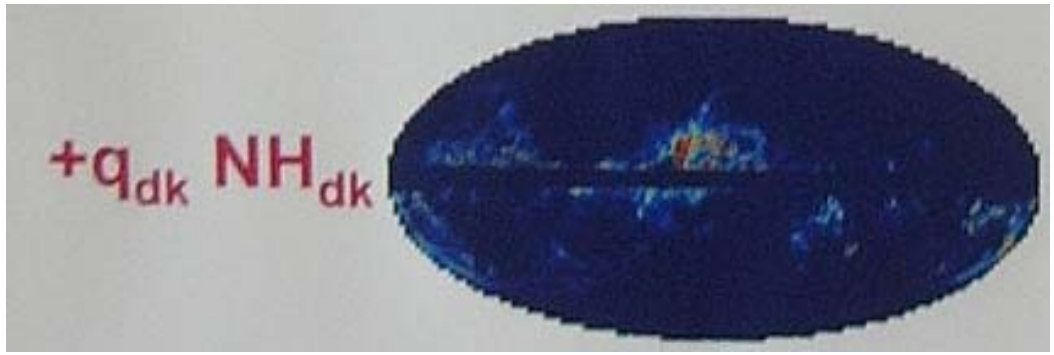


FIG. 8.—Model gamma-ray spectra including the contributions from bremsstrahlung and inverse Compton and the EGRET data; Data labels are same as in Fig. 7. Model curves are for the bremsstrahlung (Brems) and inverse Compton scattering (ICS) contribution, of GALPROP with parameters galdef 44_500180 in Strong et al. (2004). Other curves are for model A (Trial4GR)+Brems+ICS (*solid*); model A (LIS)+Brems+ICS (*dashed*); π^0+Brems+ICS by GALPROP with galdef 44_500180 (Strong et al. 2004; *dotted*).

Kamae, Abe & Koi, ApJ 620 (2005) 244

Dark gas contribution

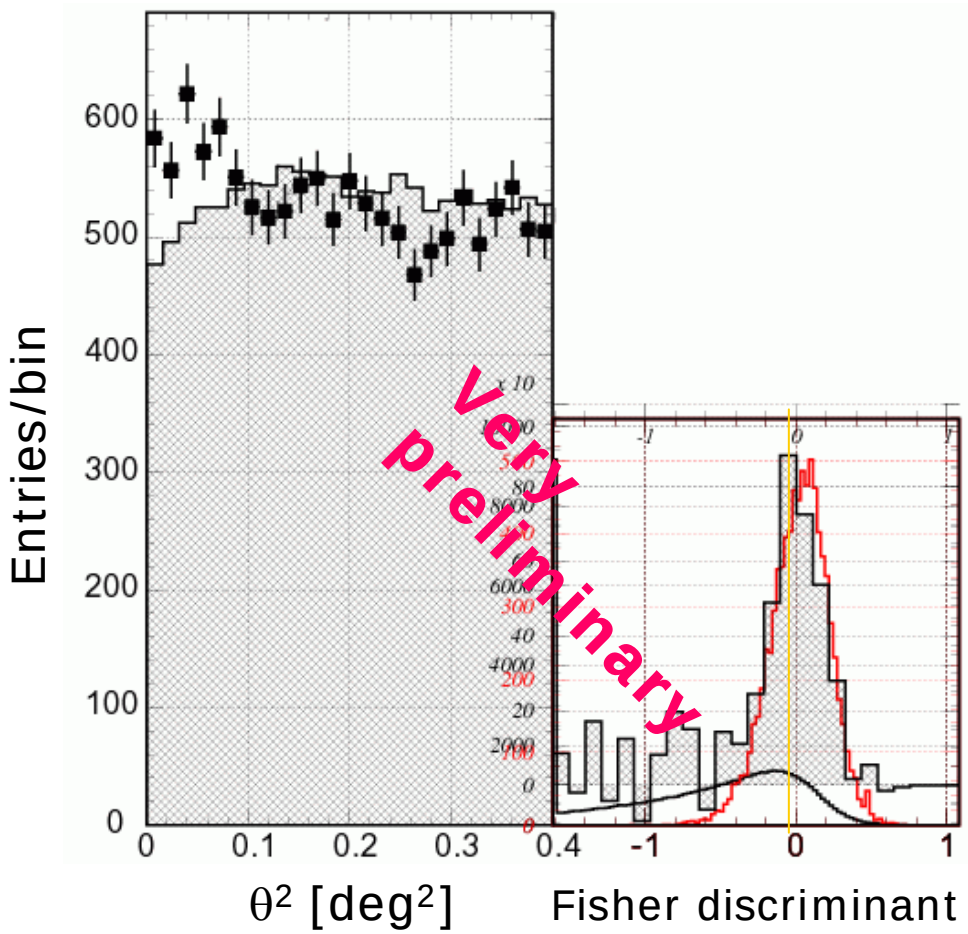


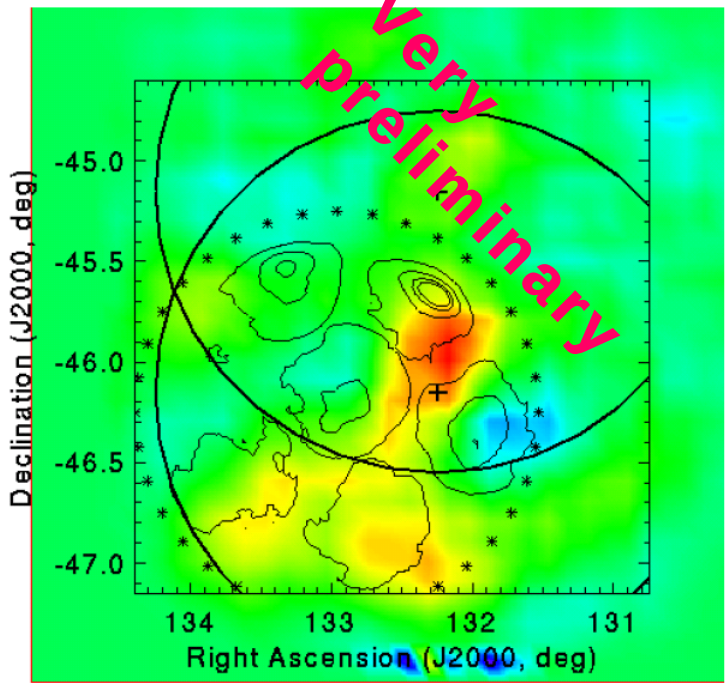
(old) EGRET catalogue (new)

Grenier, Cherenkov2005 poster

SNR RX J0852.0-4622

Team “B”





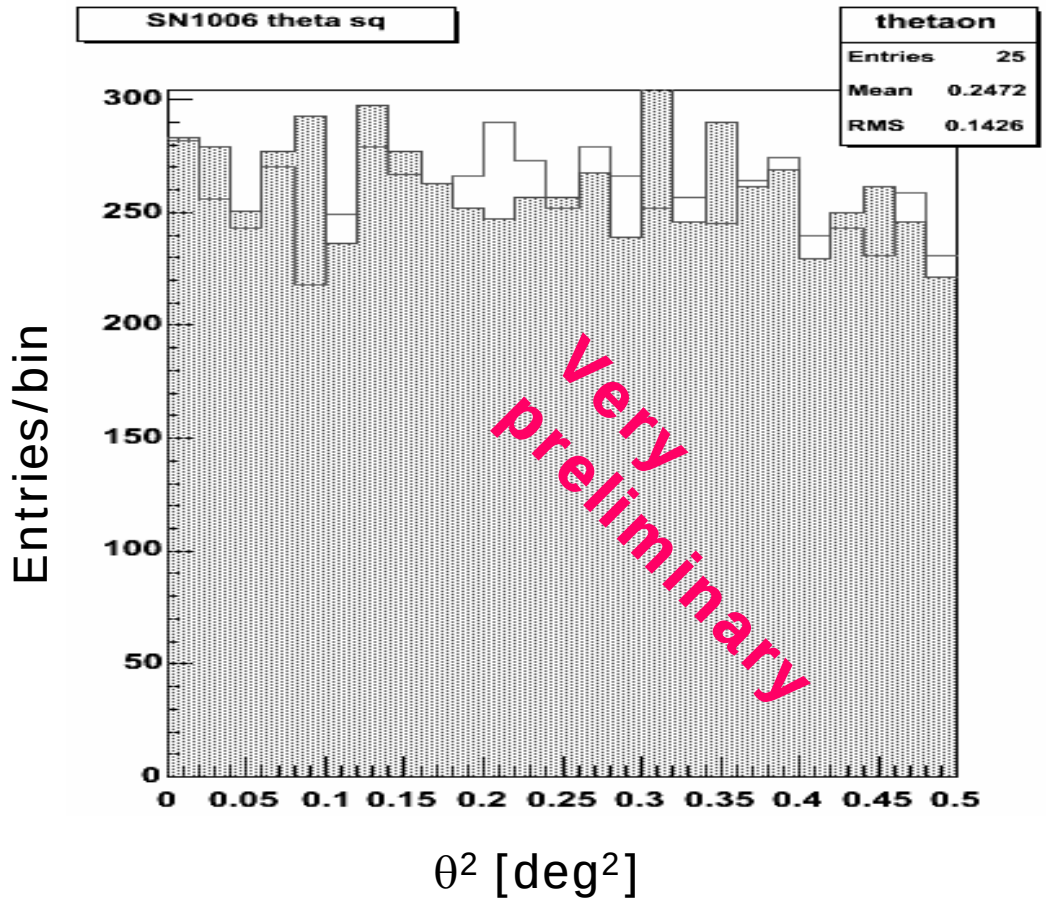
- T2 & T3
- 1204min (Jan.15-Feb.24, 2004)

Fisher D. set at the Crab level

For single telescope observations, see Katagiri et al., ApJ 619 (2005) L163

SN1006

Team “A”



Square cuts at the Crab level

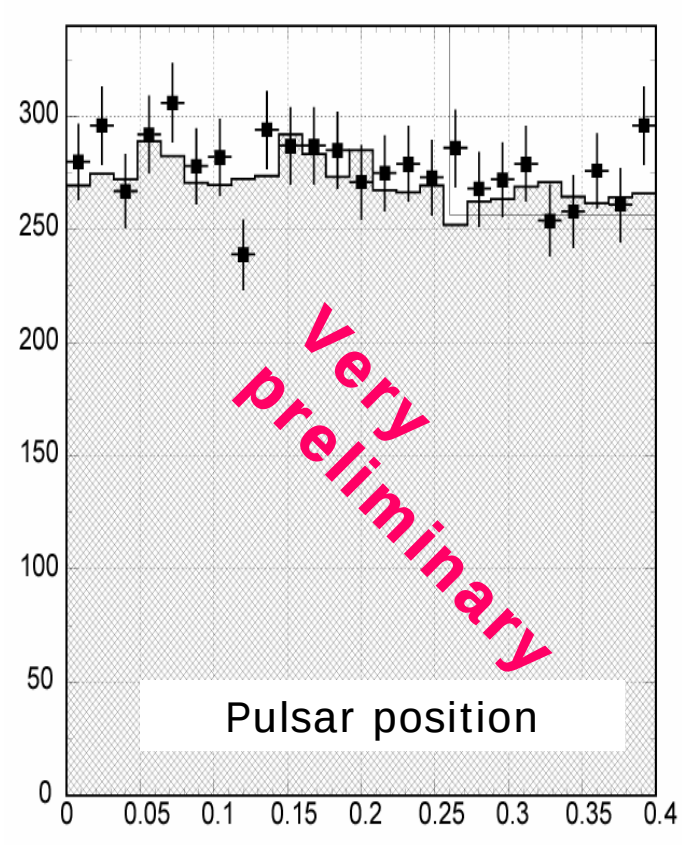
Blank: CANGAROO-I hot spot

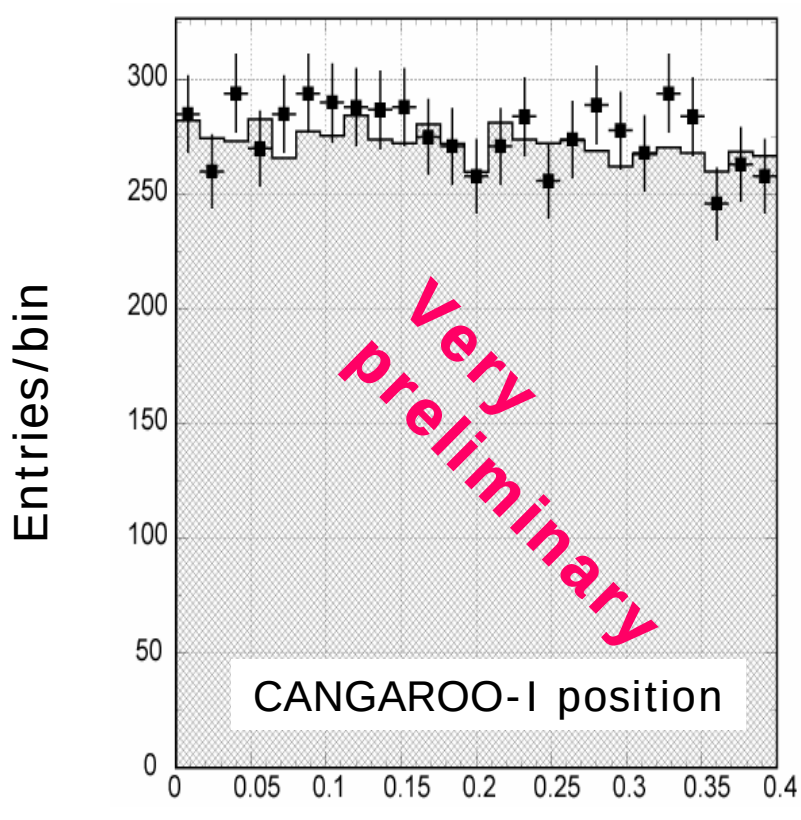
Hatched: Off-source

- T2 & T3
- ON 1954min
- OFF 1606min (May 14-26, 2005)

Vela pulsar

Team “B”



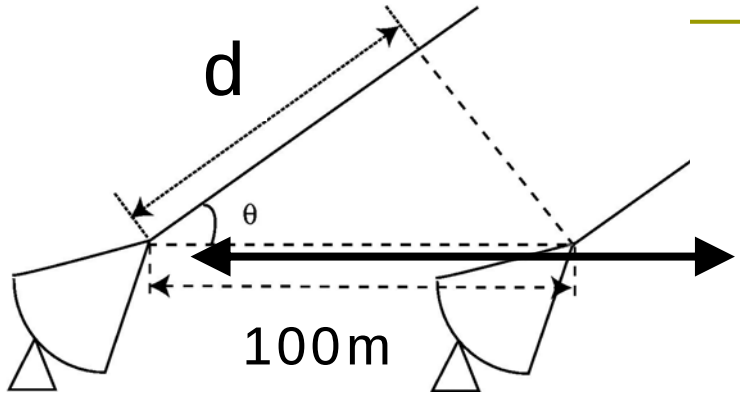


Fisher D. set at the Crab level

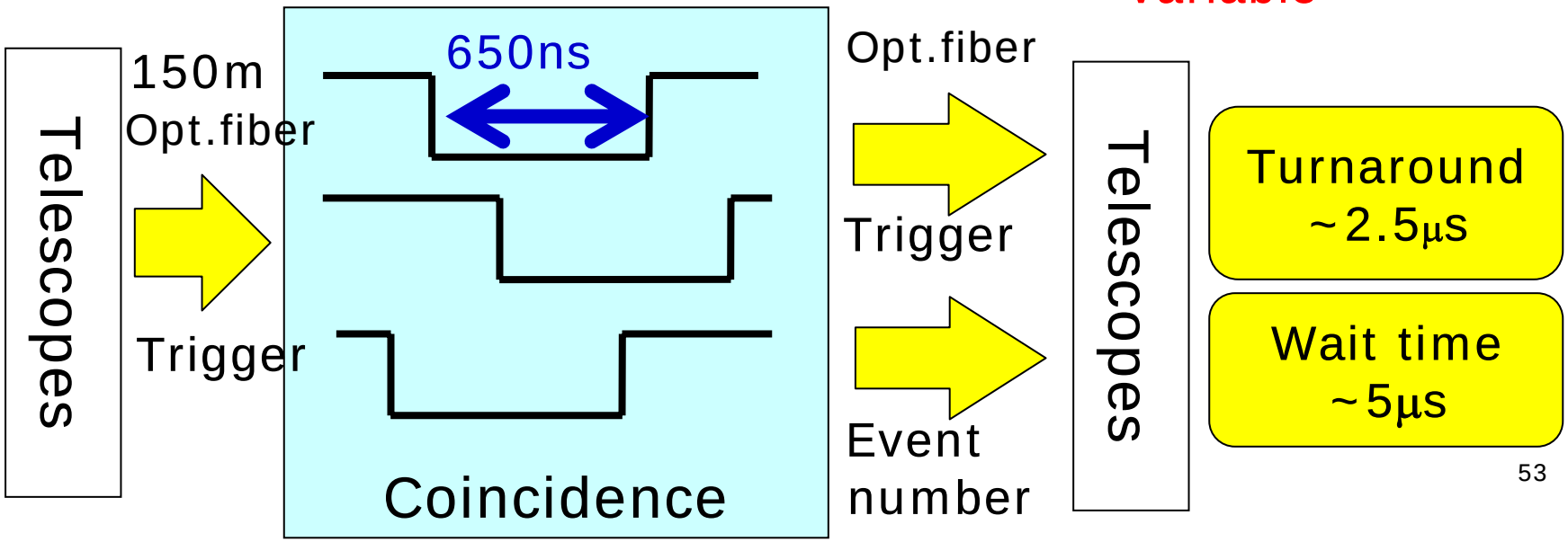
- T2 & T3
- 1311min (Jan.17-Feb.25, 2004)

Global trigger system

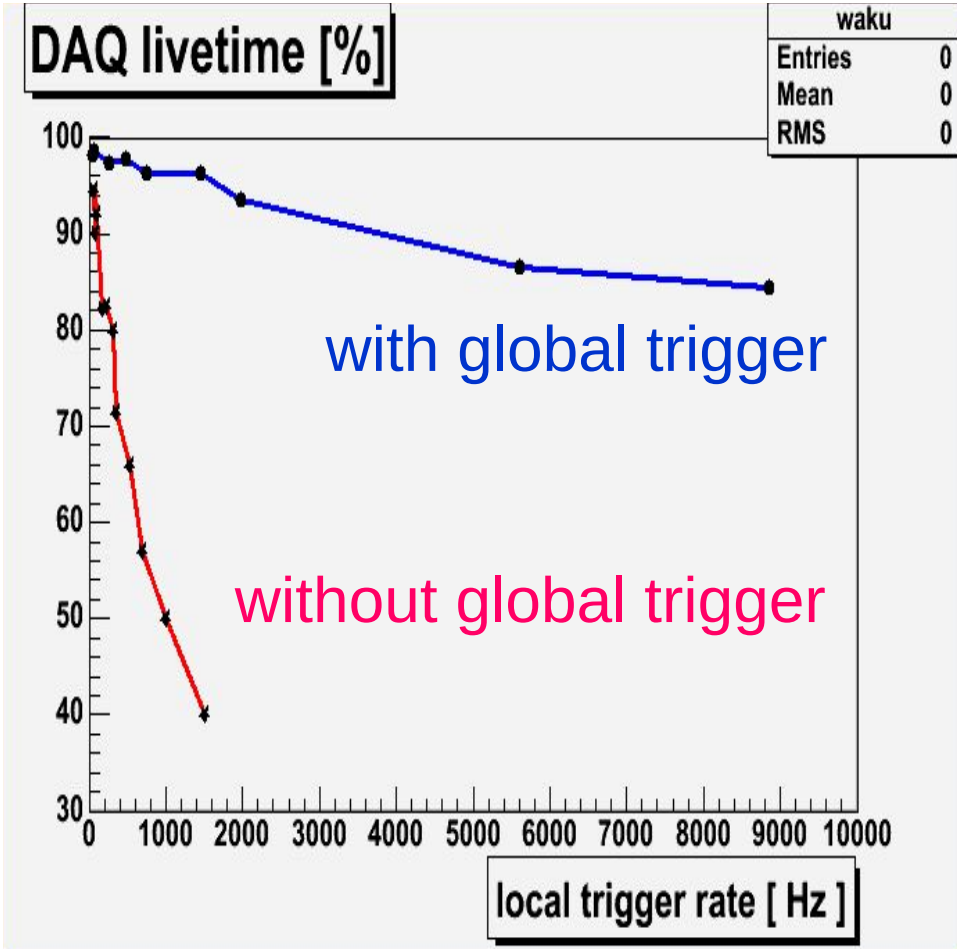
- Before: “software trigger”
  - Each telescopes triggered independently
- Now: “hardware stereo”
  - Requires at least 2 telescopes
- If no coincidence ⇒ Reset
  - Dead time ×1/100

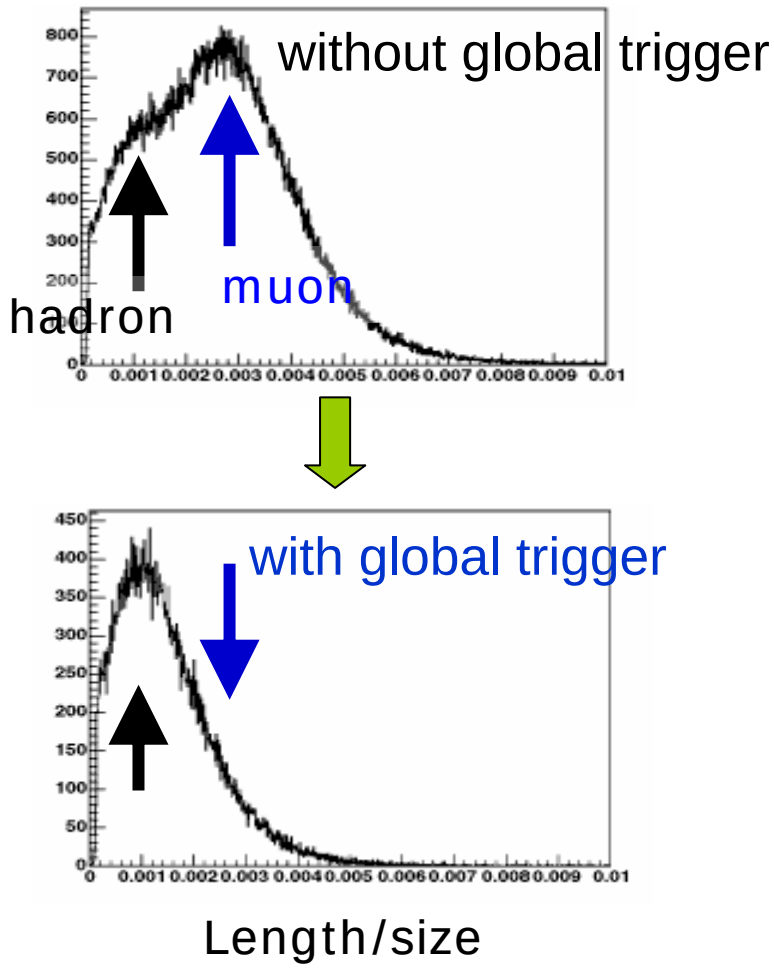


$\Delta t = d/c$ < 500ns
variable



Effect of global triggers





Muon events are removed!

Summary

- We have been carrying out 4-telescope stereo observations of sub-TeV gamma-rays since 2004 March. Now we have incorporated a global trigger system to reduce muons.
- Stereo analyses are being developed using muons for calibration, and the energy spectrum of the Crab is consistent with other results.
- Preliminary results on Cen A and the Galactic disk show no gamma-ray signal. SNR RX J0852.0-4622 appears as extended source, and the morphological study is progressing.
- Observations of SN1006 and Vela pulsar were made by using CANGAROO III telescopes. Very preliminary analyses appear to show no significant signals, which may suggest upper limits lower than the CANGAROO-I fluxes obtained several years ago.