

Recent results from CANGAROO-III

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for the CANGAROO team

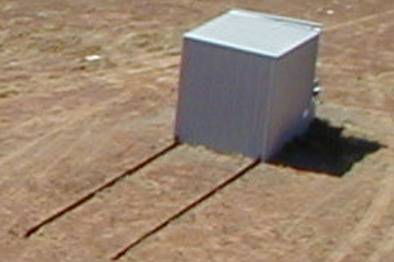
* *ICRR, The University of Tokyo*



“CANGAROO”

=

Collaboration of **Australia** and **Nippon** for a
GAMMA Ray Observatory in the **Outback**

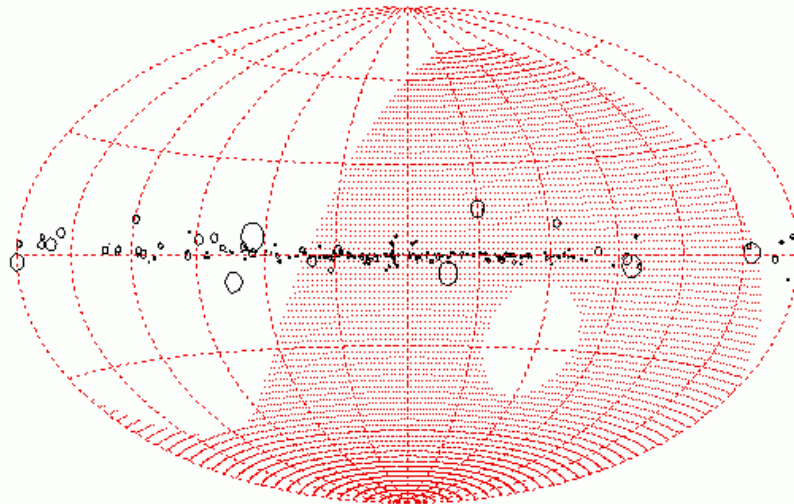


Woomera, South Australia

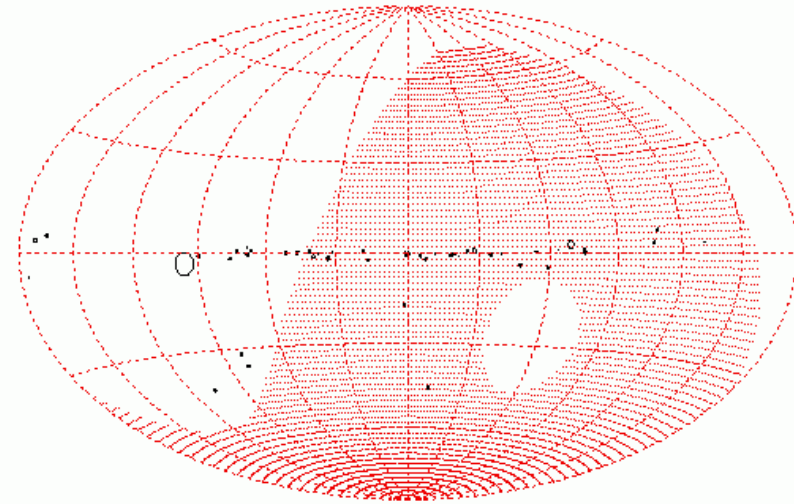


Southern sky objects

Supernova Remnants (Green 2004)



Pulsar Wind Nebulae (Roberts 2006)



(Hatched: observable from Woomera)

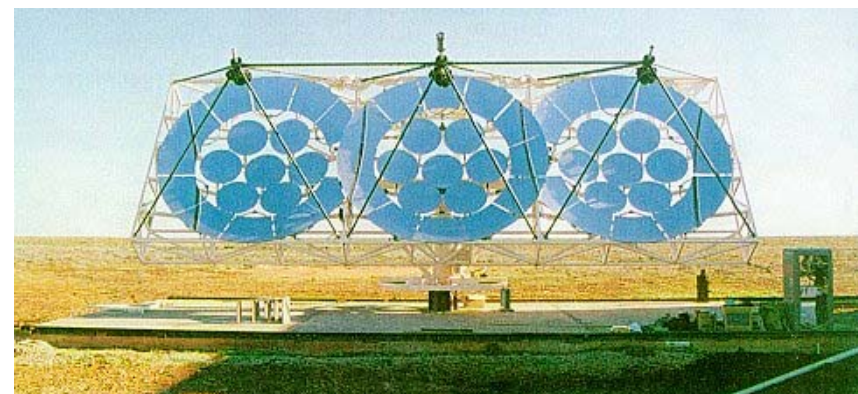
We placed first priorities on **Galactic objects**, i.e. supernova remnants and pulsar wind nebulae, since the beginning of the CANGAROO project, as the first imaging Cherenkov telescope observatory in the southern hemisphere.

Why Woomera?

- ❑ $136^{\circ}47'E$, $31^{\circ}06'S$,
160m a.s.l.
- ❑ Desert area...good
weather (72% clear
nights)
- ❑ Far from large
cities...dark sky
- ❑ Former rocket range
and prohibited
area...infra-structure,
support and safety
- ❑ Adelaide group was
operating
BIGRAT...experience


















ELDO rocket Launch site in '60s



BIGRAT

(Bicentennial Gamma RAY Telescope)

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 
- Australia Telescope National Facility 
- Tokai University 
- ICRR, University of Tokyo 
- Yamagata University 
- Yamanashi Gakuin University 
- Hiroshima University 

Brief history of CANGAROO

- ❑ 1987: SN1987A (JANZOS collaboration in New Zealand)
- ❑ 1990: 3.8m telescope
- ❑ 1990: ICRR-Adelaide Physics agreement
- ❑ 1992: Start obs. of 3.8m tel.
- ❑ 1999: 7m telescope
- ❑ 2000: Upgrade to 10m
- ❑ 2001: U.Tokyo-U.Adelaide agreement
- ❑ 2002: Second and third 10m tel.
- ❑ 2004: Four telescope system



CANGAROO-I (3.8m ϕ)



CANGAROO-II (10m ϕ)

CANGAROO-II results: summary

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

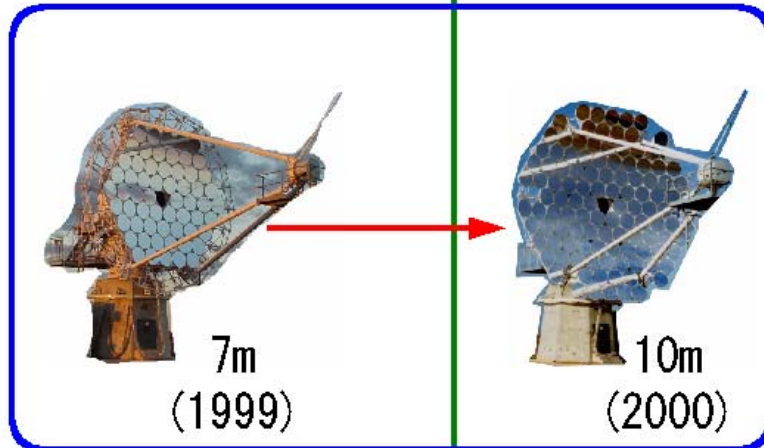
Signal: ○ detected, ↓ upper limit, v: variable

However, spectral indices differ significantly...

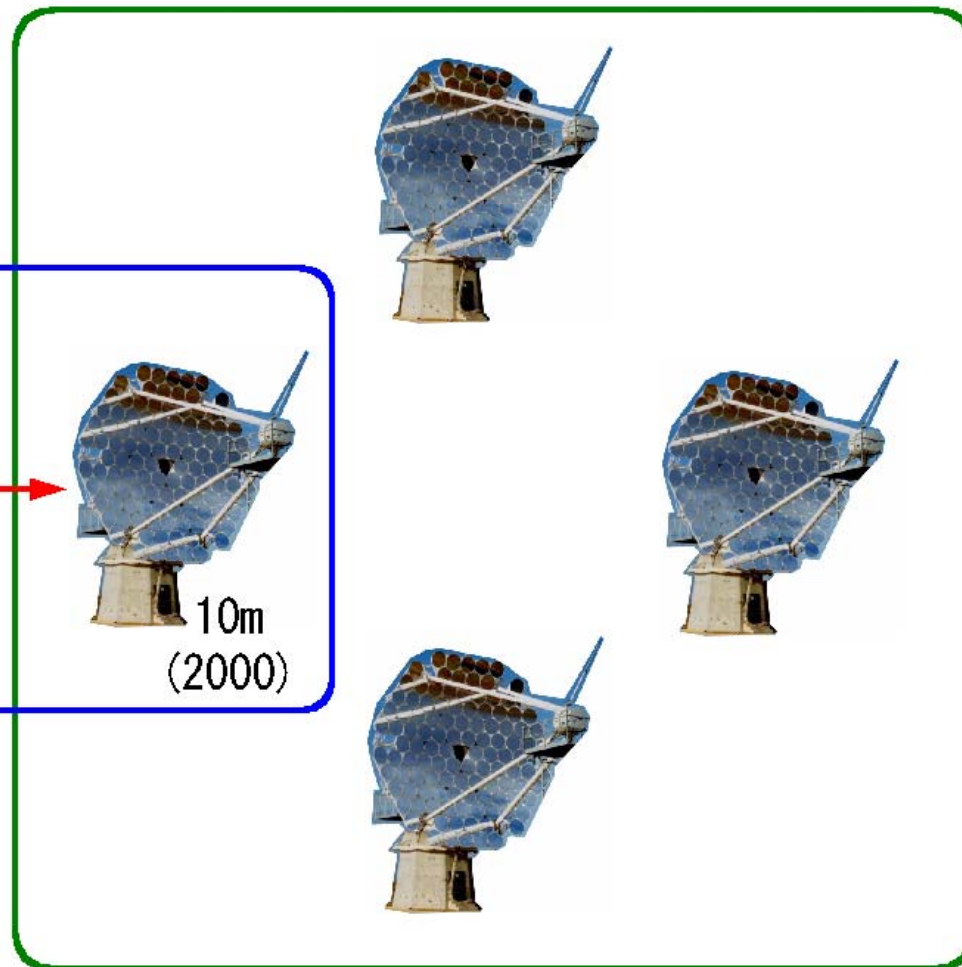
→ Re-observations with CANGAROO-III stereo system

CANGAROO-II & -III

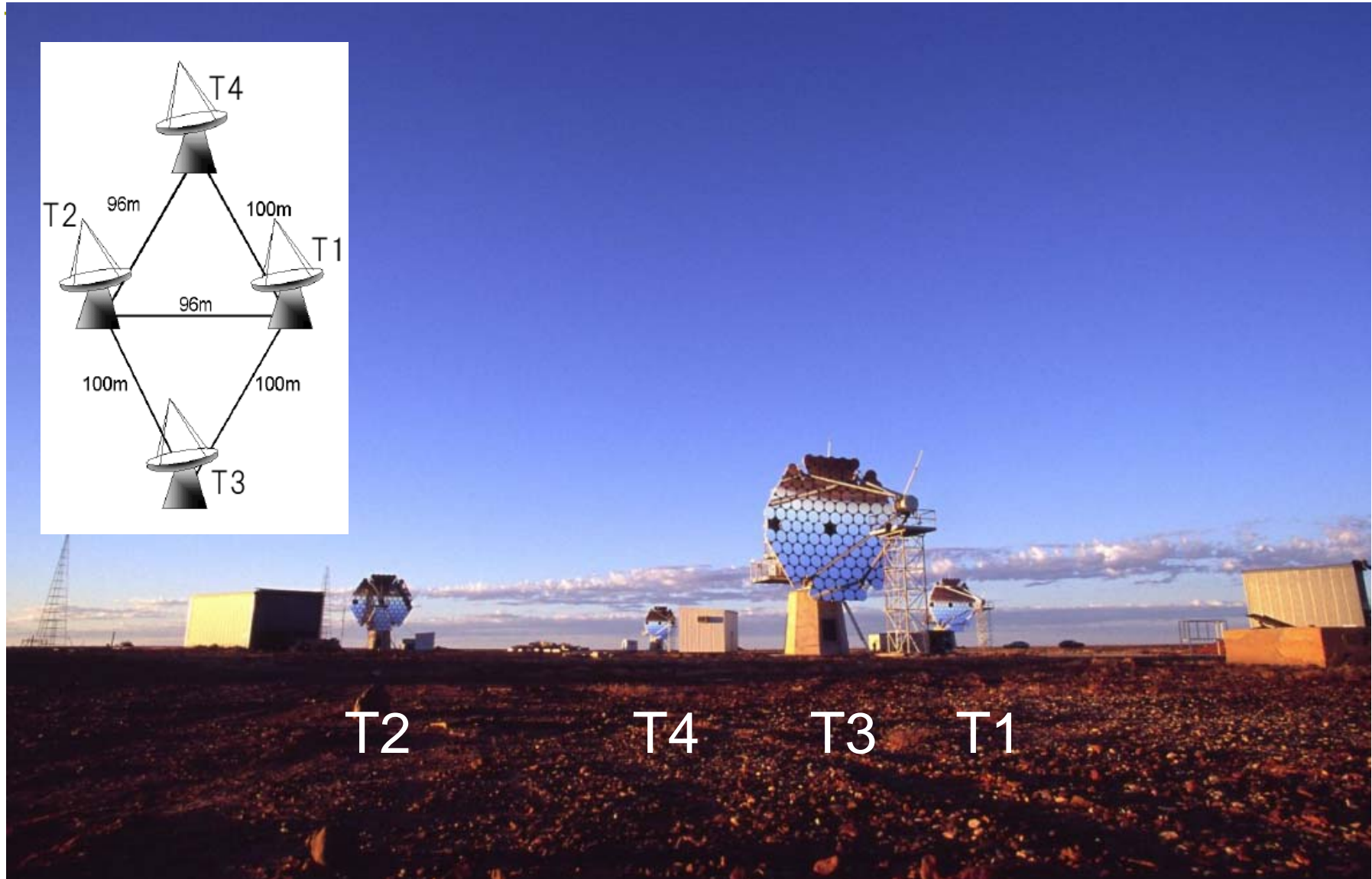
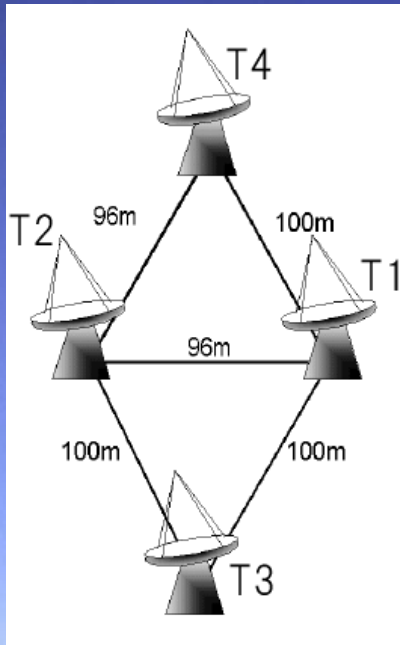
CANGAROO-II



CANGAROO-III

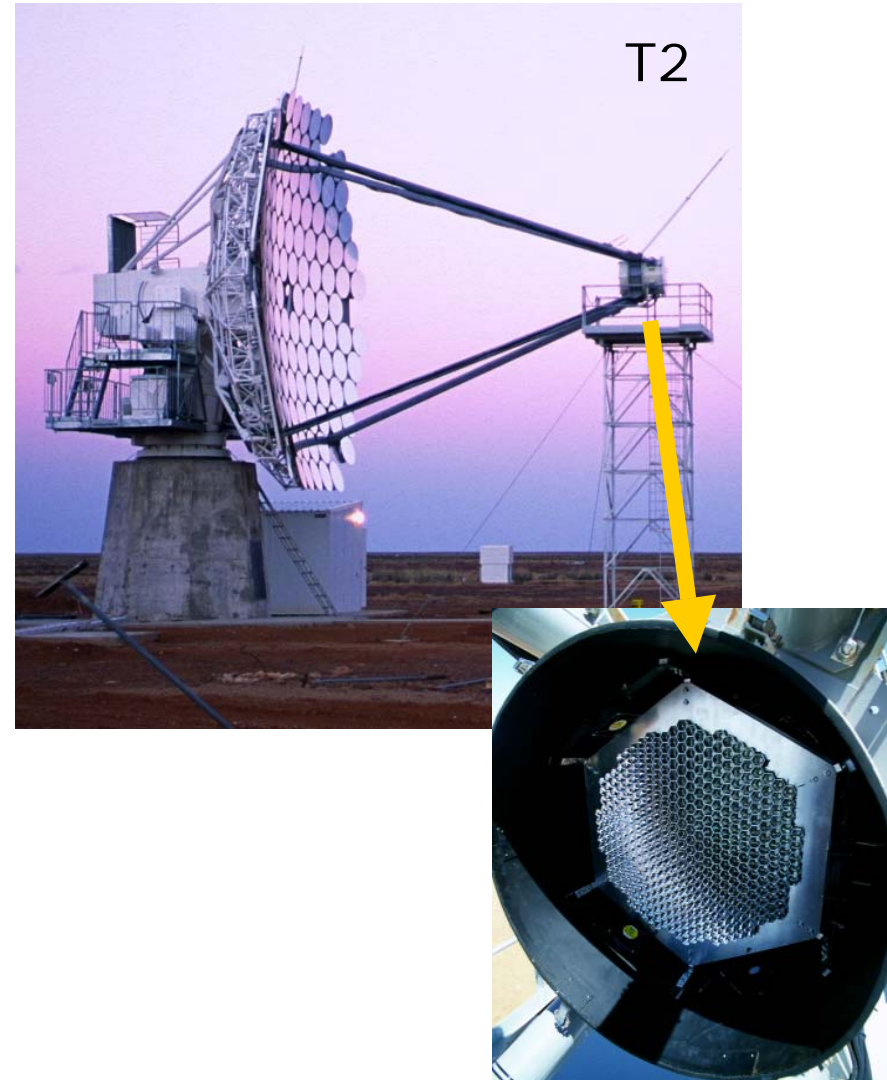


CANGAROO-III: 2004 March



Basic specifications of telescopes

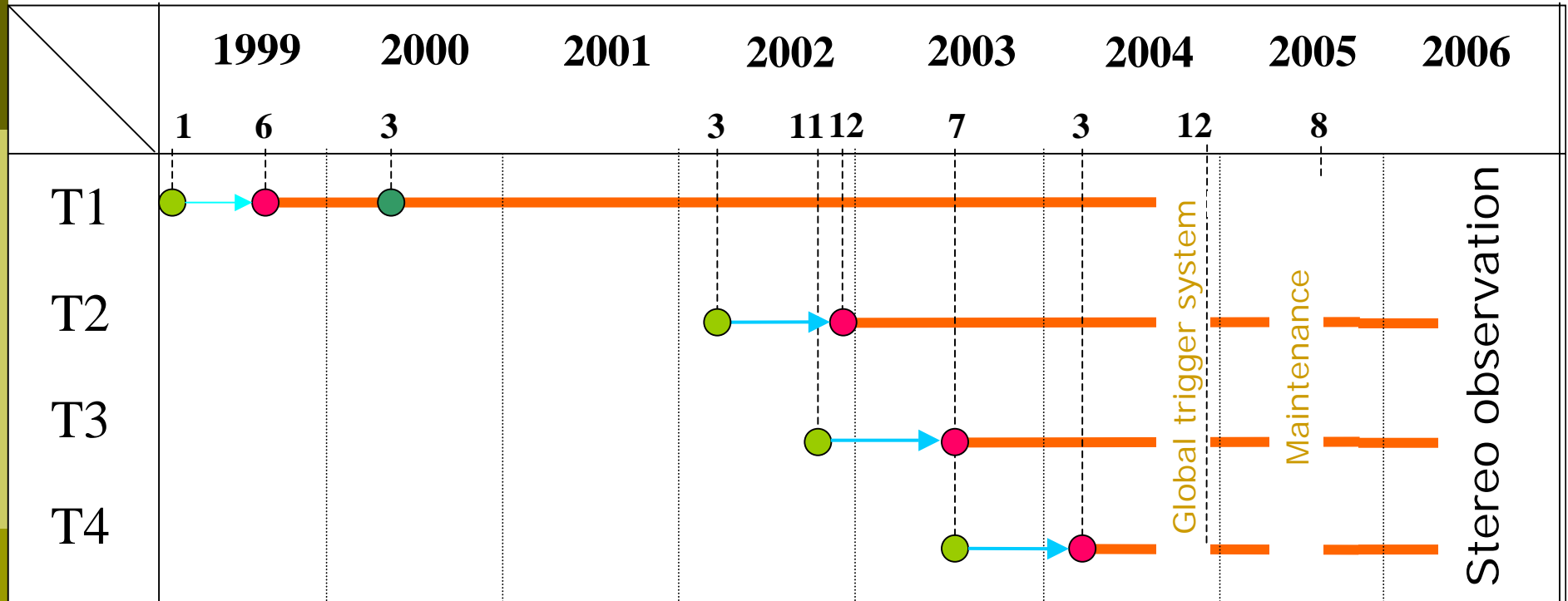
- Location:
 - $31^{\circ}06'S$, $136^{\circ}47'E$
 - 160m a.s.l.
- Telescope:
 - $114 \times 80\text{cm}\phi$ FRP mirrors (57m², Al surface)
 - 8m focal length
 - Alt-azimuth mount
- Camera:
 - T1: 552ch (2.7° FOV)
 - T2,T3,T4: 427ch (4° FOV)
- Electronics:
 - TDC+ADC



Monte Carlo simulation

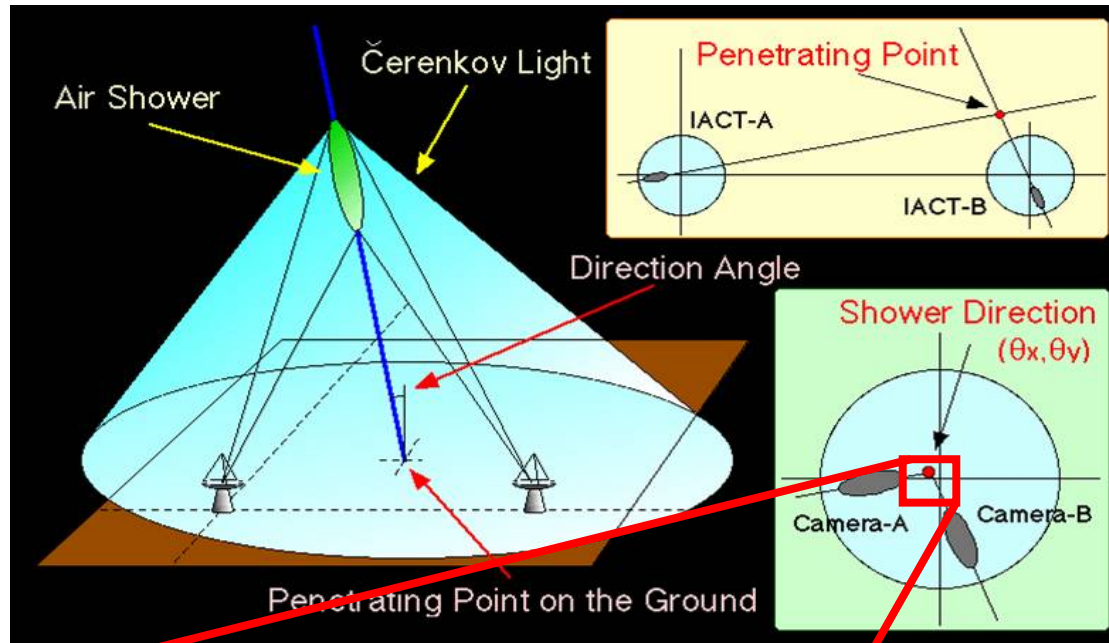
- GEANT 3.21 base
 - 80 layers for atmosphere (12.9g/cm² each)
 - (<10% change even if more layers were used)
 - Particle transport down to 20MeV
 - Proprietary code to generate Cherenkov photons
 - Only photons coming to telescopes are tracked
 - Geomagnetic field of 0.520G (vert.) / 0.253G (hor., 6.8°E of S)
 - Rayleigh scattering 2970g/cm²($\lambda/400\text{nm}$)⁴
 - (+Mie scattering ~10% effect)
 - Detector parameters: reflectivity, point spread function, light guide efficiency, PMT Q.E., etc.
 - Night sky background

History of CANGAROO-III



- : Construction
- : Observation start
- : Expansion to 10m
- : Observation
- : Tuning

Stereo observation



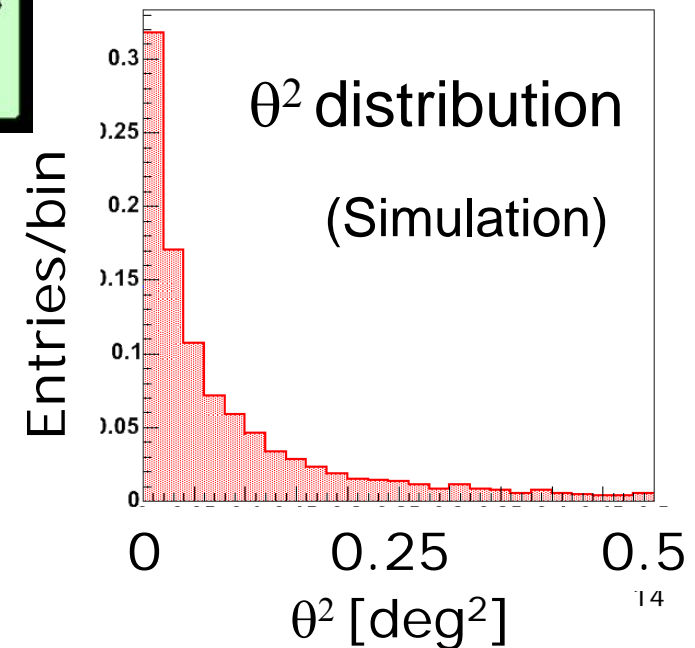
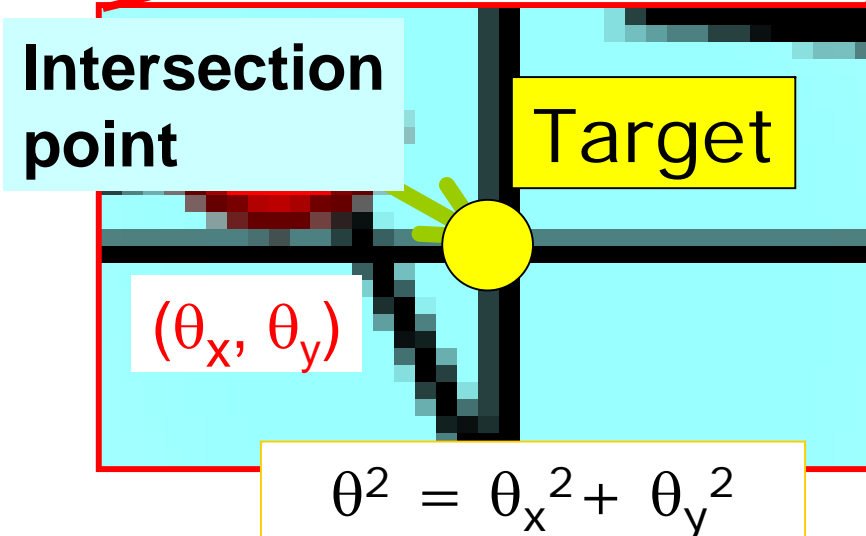
Angular resolution

0.25deg \rightarrow 0.1 deg

Energy resolution

30% \rightarrow 15%

Better S/N (no local muons)

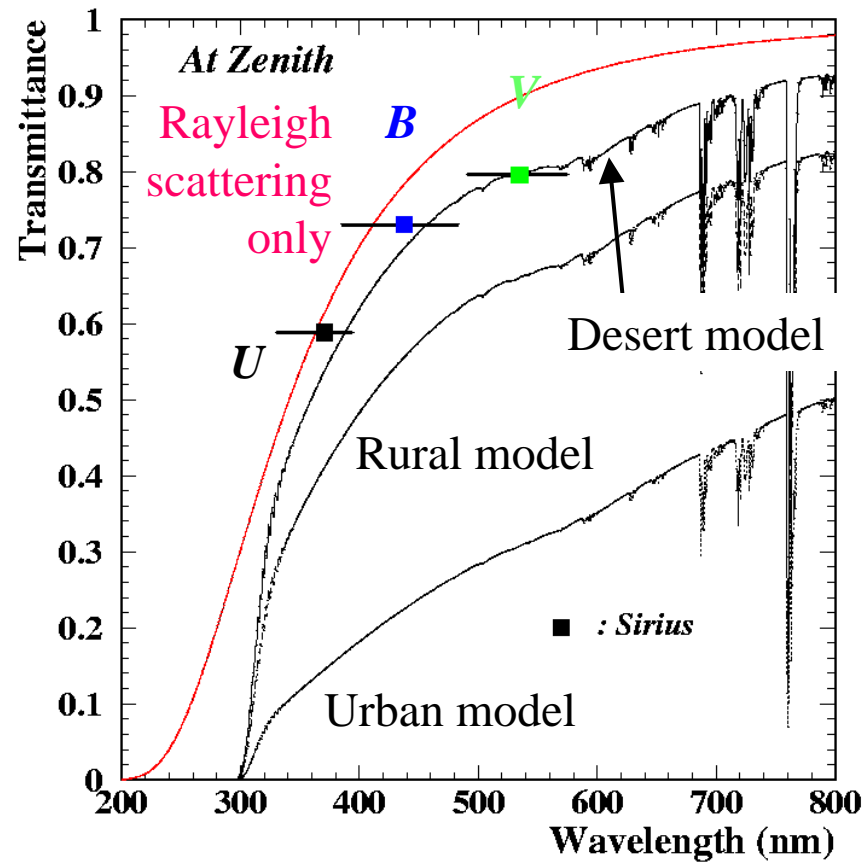


Analysis of stereo observation

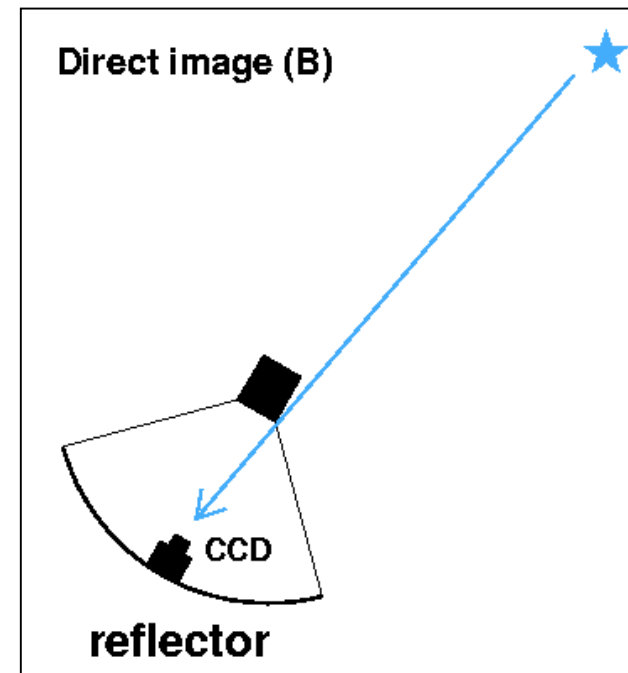
- ❑ Inconsistency with H.E.S.S results on some sources
 - ⇒ New observations with CANGAROO III
 - Efforts for advanced analysis procedures
- ❑ Measure more optical parameters
 - CCD measurements of spotsizes and stars
- ❑ Use muons for calibration
 - Tune Monte Carlo simulation
- ❑ Use the Crab as the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

Atmospheric transmission measurement

Atmospheric transmittance : Measurement data and Modtrans simulation

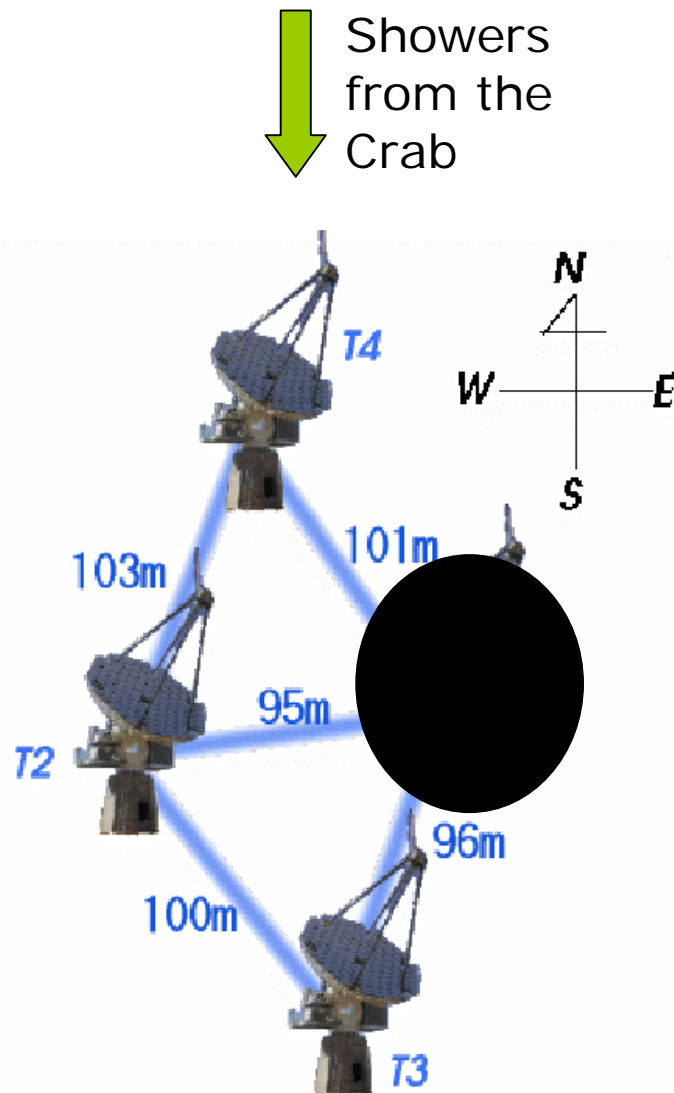


Take star images at various zenith angles with a cooled CCD camera



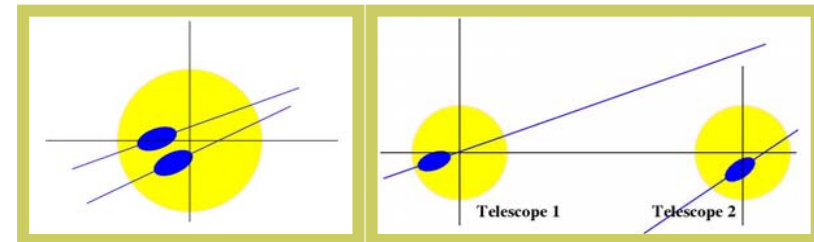
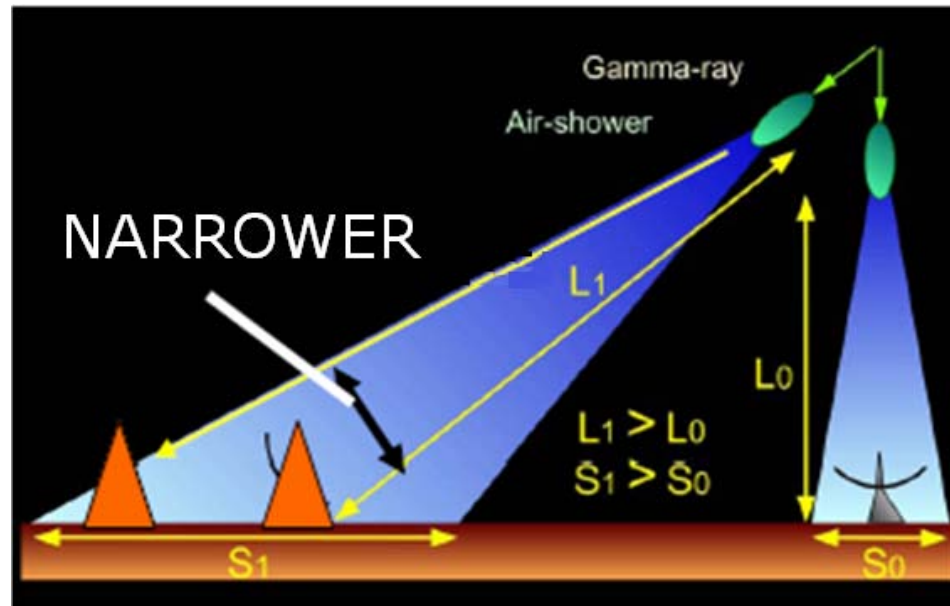
Data compatible with "Desert model" of MODTRAN4
Systematic errors under study

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

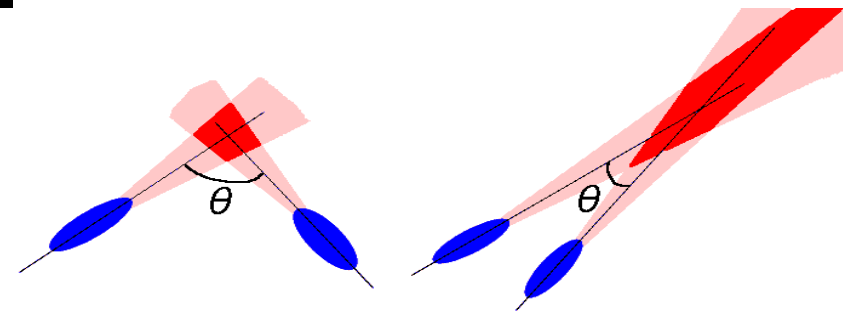
Large zenith angle observation of the Crab



Far core
→small angle
→bad accuracy

Higher energy threshold $\sim 1\text{TeV}$

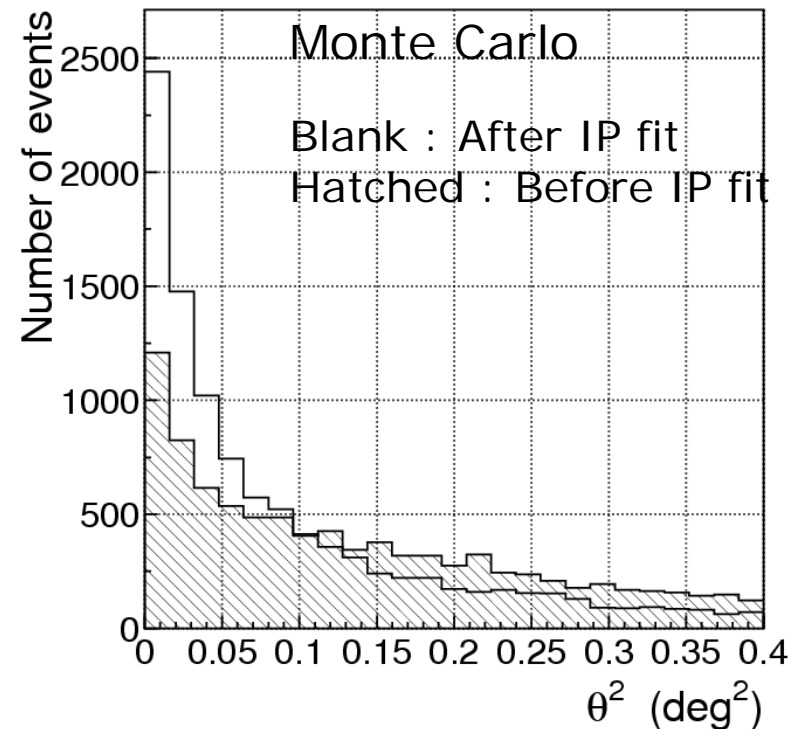
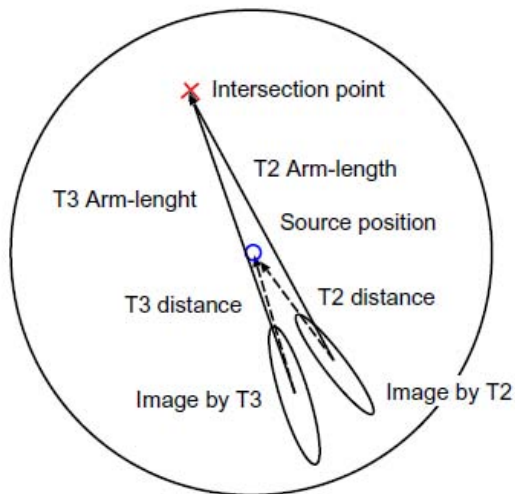
Bad intersection accuracy



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 ($\langle \text{Armlength} \rangle = 0.75$, 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)

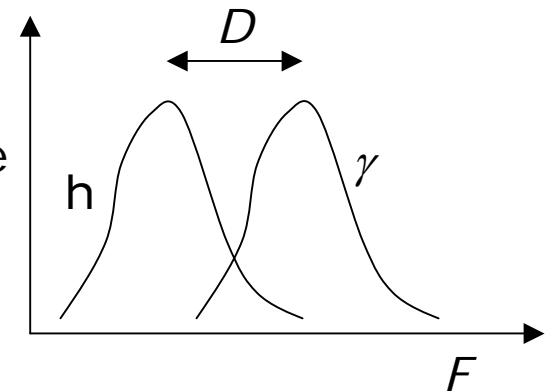
$$D \equiv \langle F_\gamma \rangle - \langle F_h \rangle$$

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

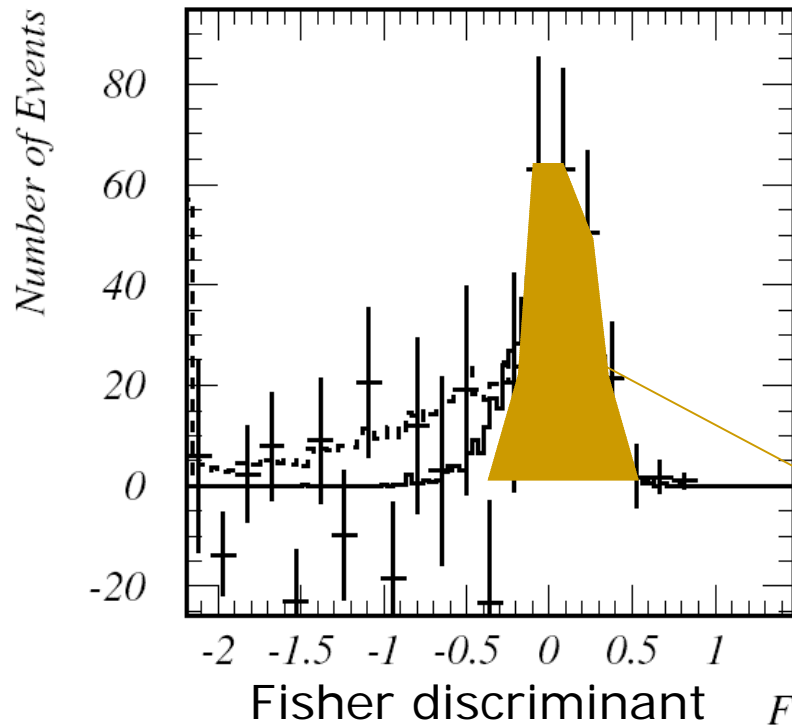
$$S \equiv \langle D \rangle^2 / \langle (D - \langle D \rangle)^2 \rangle$$

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

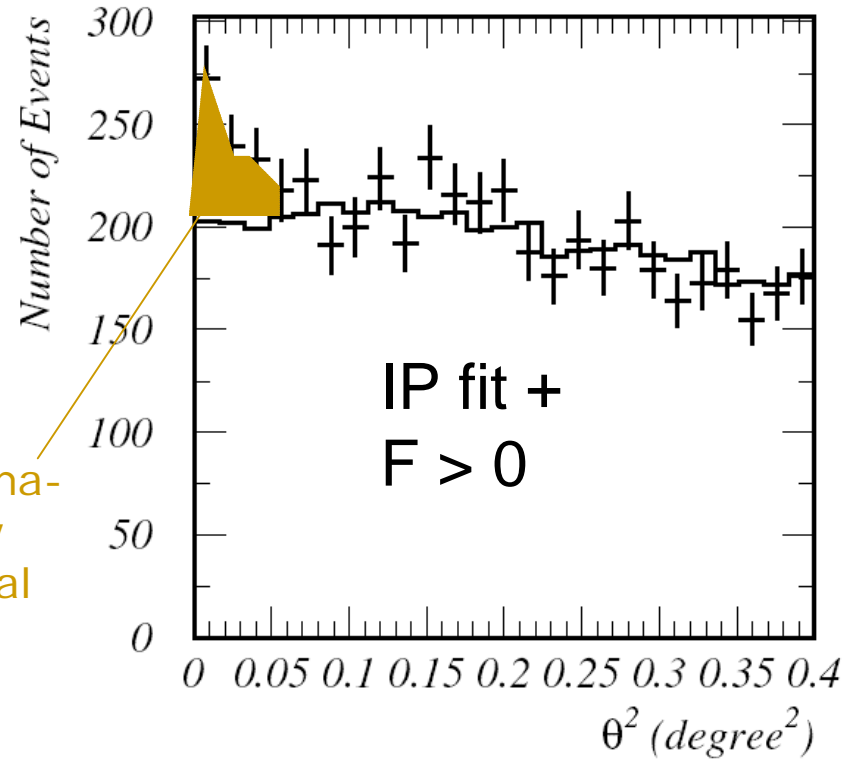
- We use *widths* and *lengths* of multiple telescopes for image parameters (x_i).



Crab signal



Gamma-ray signal



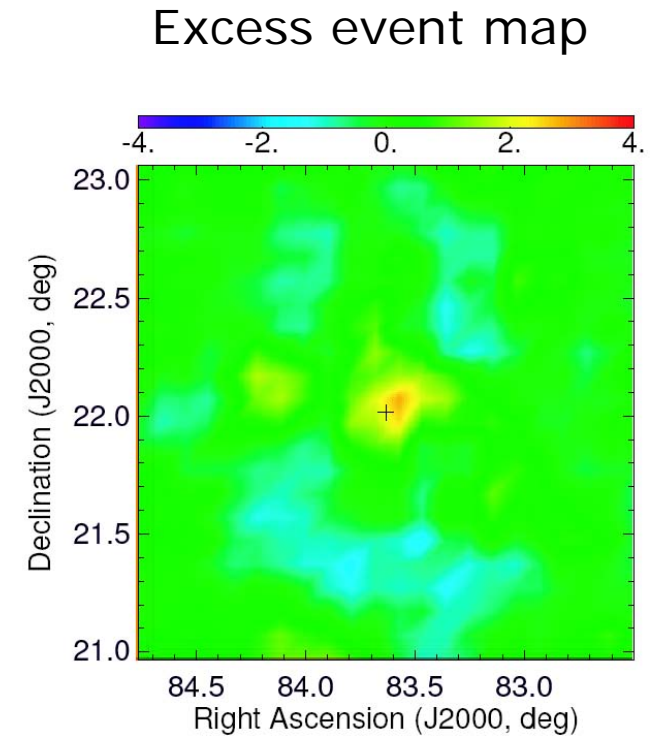
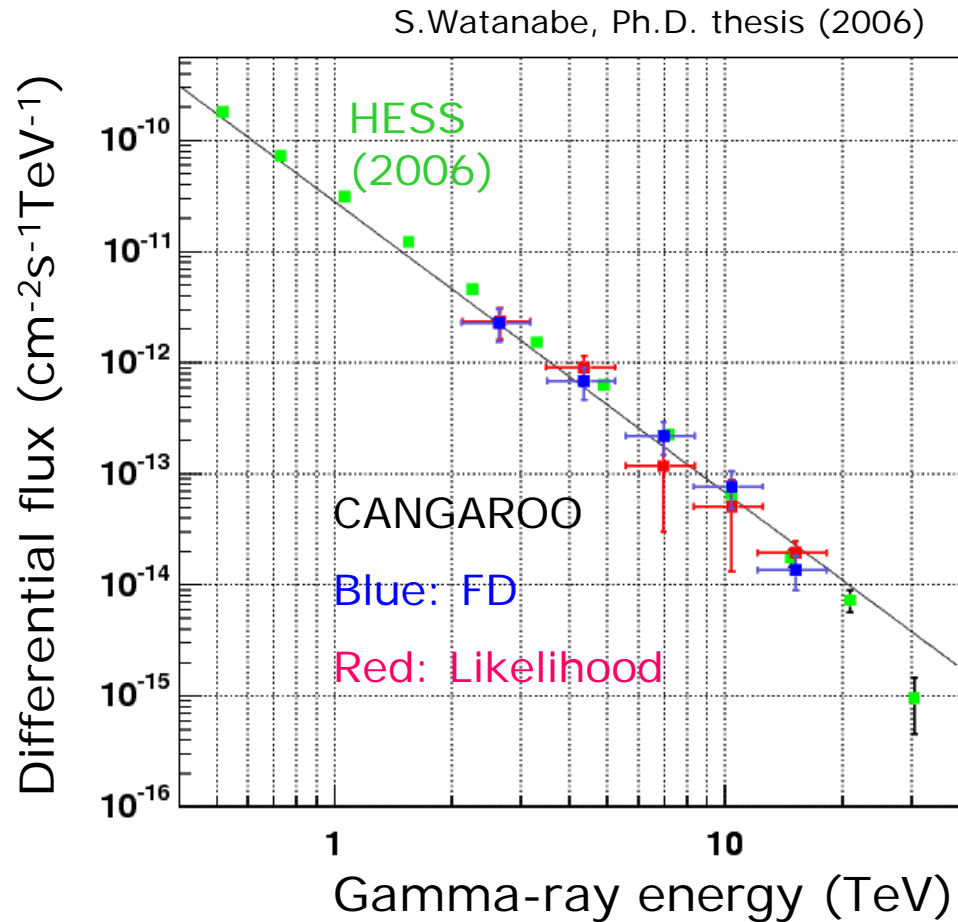
Plot : observation
Solid : MC gamma
Dashed : background

203 excess events
5.8 sigma

•T2 & T3

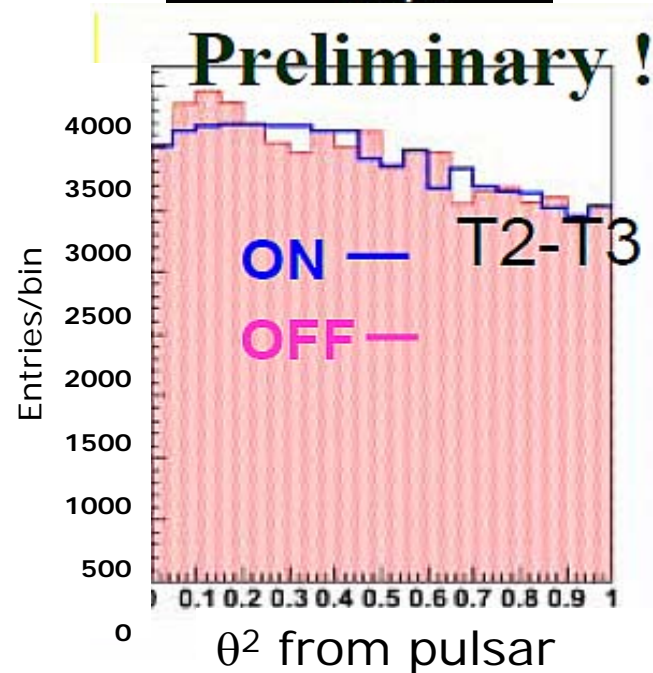
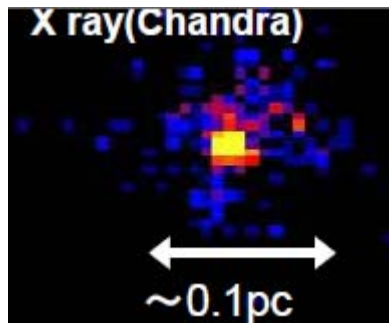
•890 min (Dec.2003)

Crab spectrum

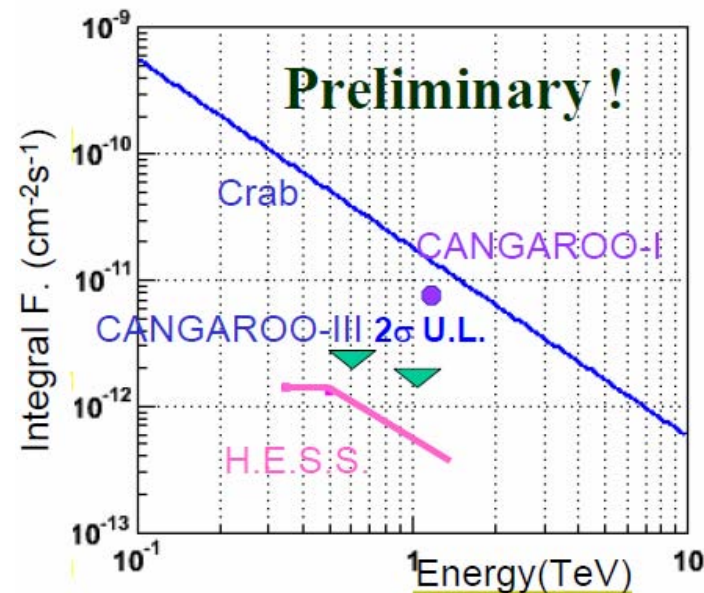


Angular resolution ~ 0.23 deg

PSR 1706-44

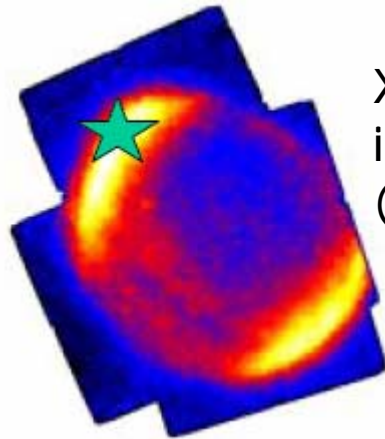


- Pulsar pointing (2004 May)
- Stereo (T2, T3 & T4 long ON/OFF)
- 1,625 min. ON, 1,738 min. OFF
- T2 & T3 results on square cut
- Independent analysis (Fisher disc.)



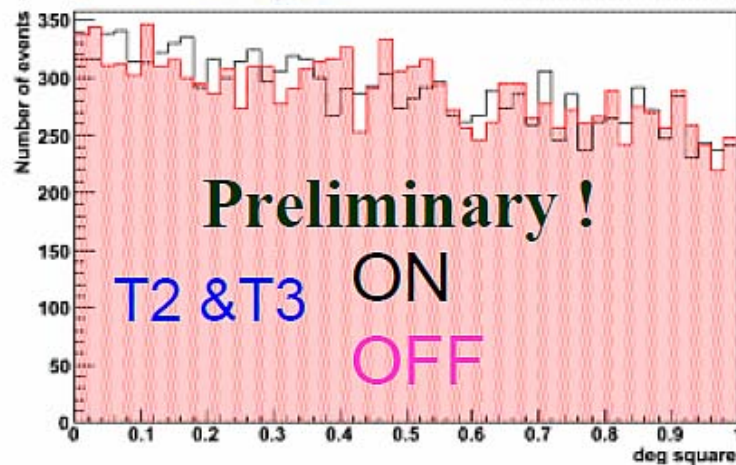
⇒ To be checked with our latest analysis methods

SN1006 (G327.6+14.6)

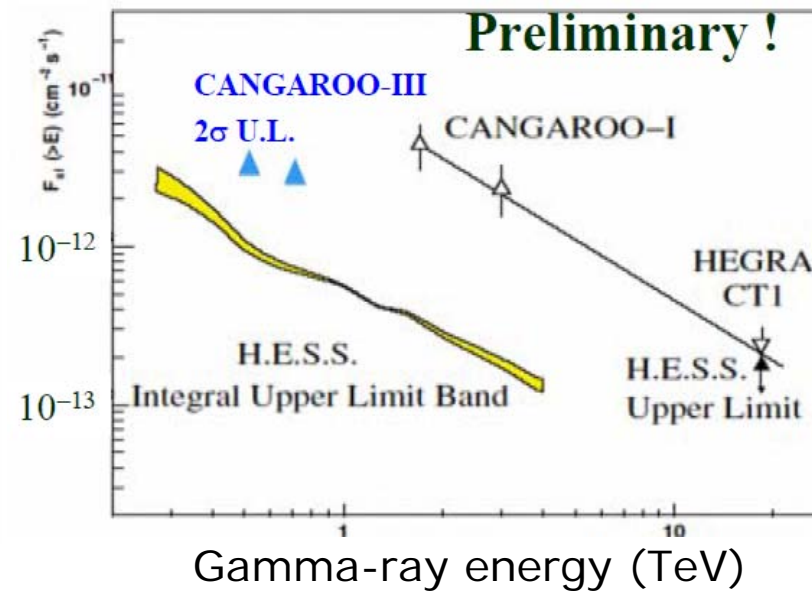


X-ray image (ASCA)

- NE-rim pointing (2004 May)
- Stereo (T2, T3 & T4 long ON/OFF)
- 1,625 min. ON, 1,738 min. OFF
- T2 & T3 results on likelihood
- Independent analysis (Fisher disc.)



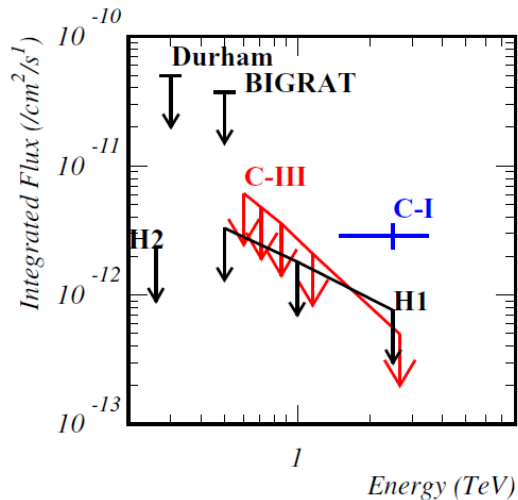
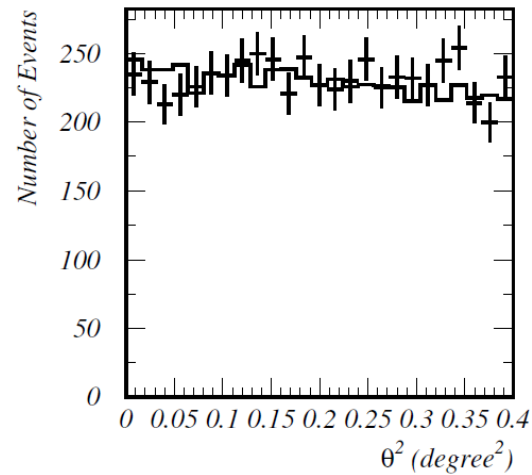
θ^2 from NE rim



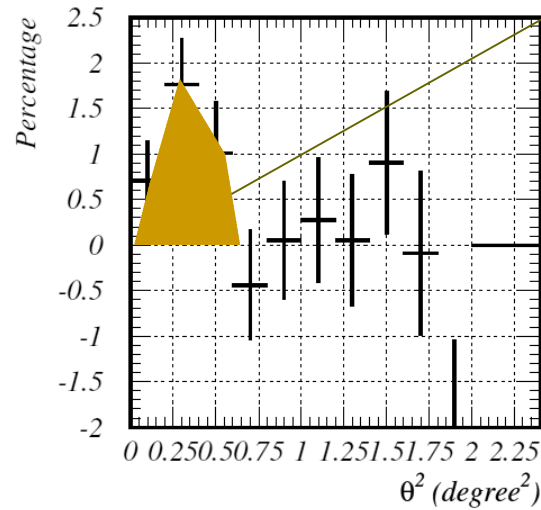
⇒ To be checked with our latest analysis methods

Vela pulsar/nebula

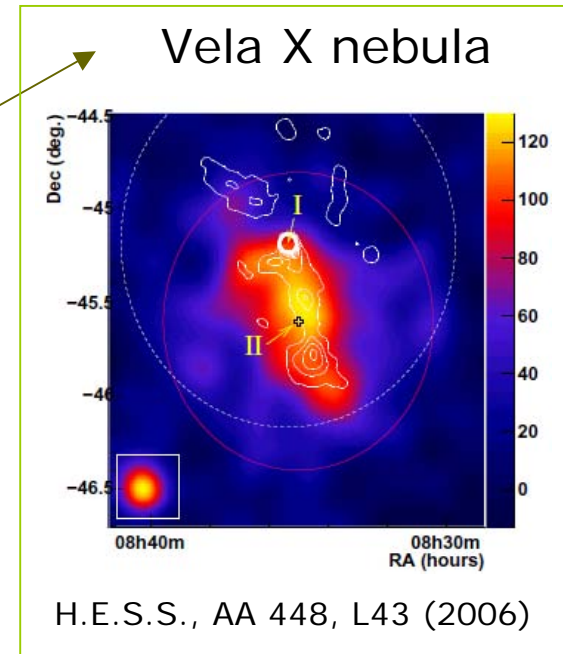
Pulsar position



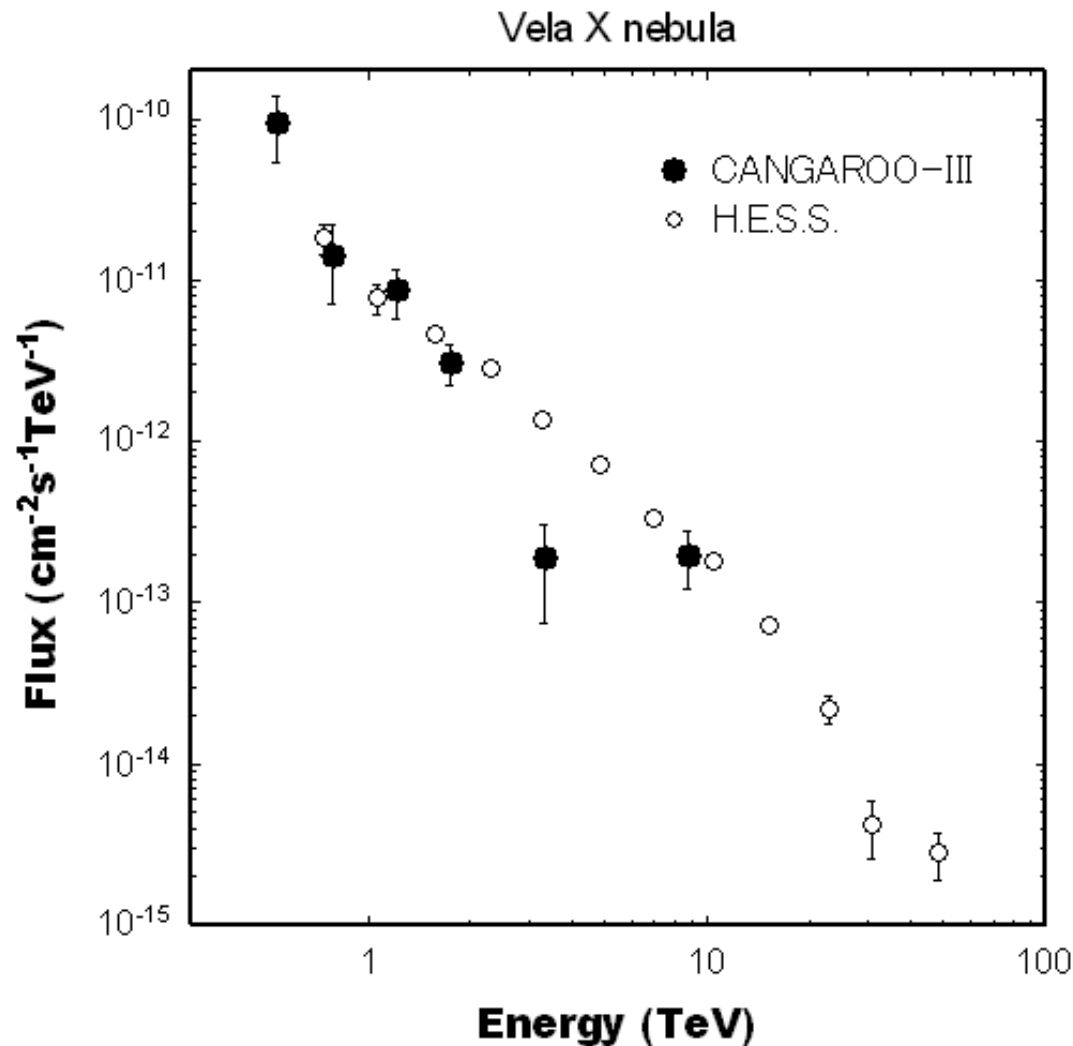
- Pulsar pointing (2004 Jan/Feb)
- Stereo (T2 & T3 wobble), 1,311 min.
- Fisher discriminant



θ^2 from Vela X center



Vela X nebula: spectrum



$\theta^2 < 0.6 \text{ deg}^2$

Excess 561 ± 114

H.E.S.S.:
Aharonian et al.,
AA 448, L43 (2006)
 $\propto E^{-1.45} \exp(-E/13.8 \text{ TeV})$

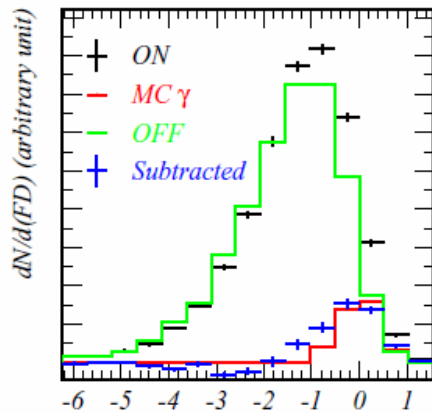
CANGAROO-II claims vs. H.E.S.S.

□ CANGAROO-II claims

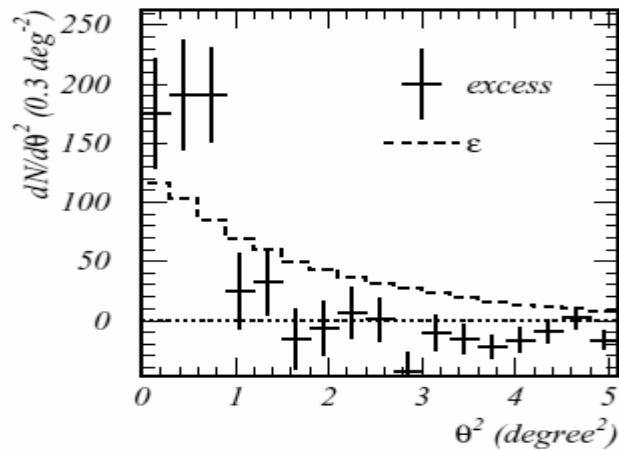
- SNR RX J1713.7-3946: 0.51Crab, $E^{-2.84 \pm 0.15 \pm 0.20}$ (11σ , >0.5 TeV)
[Enomoto et al., Nature 416, 823, 2002]
 - Cf. H.E.S.S. flux: 0.83Crab, $E^{-2.19 \pm 0.09 \pm 0.15}$
[Aharonian et al. Nature 432, 75, 2004]
- NGC253: 0.15Crab (11σ , >0.5 TeV)
[Ito et al., A&A 402, 443, 2003]
 - Cf. H.E.S.S. upper limit: 0.05Crab
[Aharonian et al. A&A 442, 177, 2005]
- Galactic center: $E^{-4.6(+1.2-5.0)}$
[Tsuchiya et al., ApJ 606, L115, 2004]
 - Cf. H.E.S.S. spectrum: $E^{-2.2 \pm 0.09 \pm 0.15}$
[Aharonian et al. A&A 425, L13, 2004]
- SNR RX J0852.0-4622 : $E^{-4.6(+1.7-4.4)}$
[Katagiri et al., ApJ, 619, L163, 2005]
 - Cf. H.E.S.S. spectrum: $E^{-2.1 \pm 0.1 \pm 0.2}$
[Aharonian et al. A&A 437, L7, 2005]

⇒ To be checked with CANGAROO-III stereo data

SNR RX J0852.0-4622



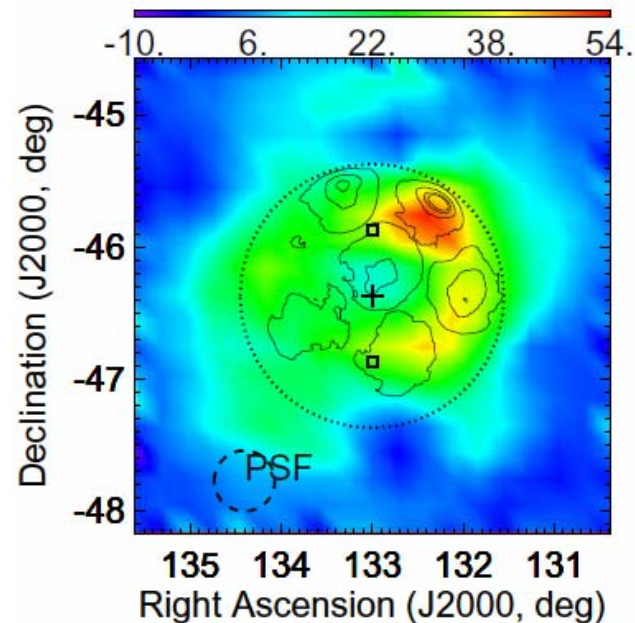
Fisher discriminant



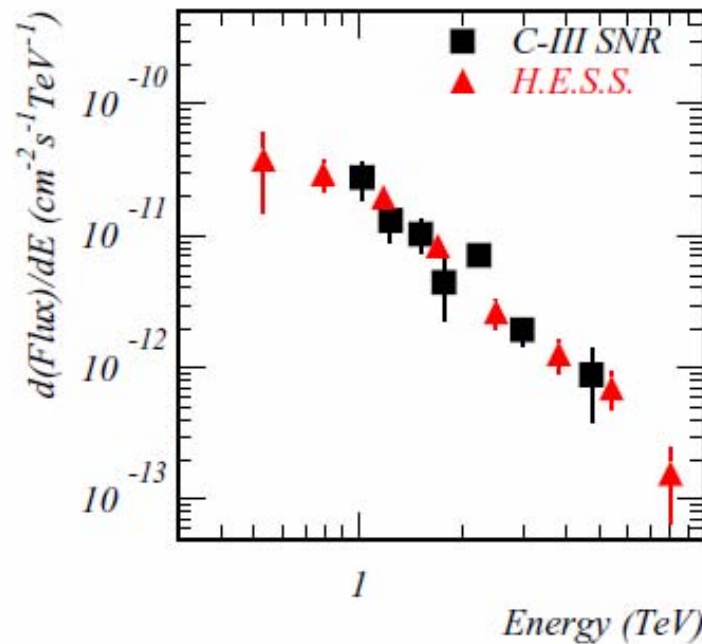
θ^2 from SNR center

- Distance ~ 1 kpc
(NANTEN: Moriguchi et al. ApJ 2005)
- Stereo (T2 & T3 & T4 wobble)
- 1,129 min. ON, 1,081 min OFF
(2005 Jan/Feb)
- Independent analysis (ICRR, Kyoto)

Excess event map

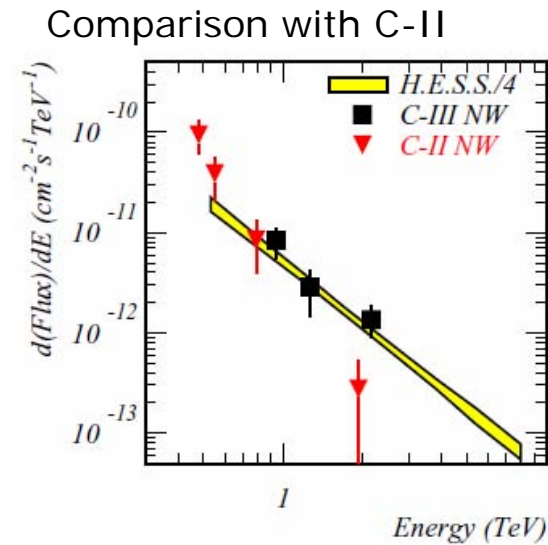


SNR RX J0852.0-4622: spectrum



$$\frac{dF}{dE} = [2.5 \pm 0.6(\text{stat.}) \pm 0.6(\text{sys.})] \times 10^{-11} \cdot \left(\frac{E}{1 \text{ TeV}}\right)^{2.2 \pm 0.3(\text{stat.}) \pm 0.3(\text{sys.})} \quad [\text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}]$$

FIG. 7.— Differential energy spectra; the red points by H.E.S.S. are for the whole remnant and the black points from these CANGAROO-III observations are also for the whole remnant. The error bars are statistical.



Starburst galaxy NGC253

- 3-fold, 2004 Oct, 1179min (ON), 753min (OFF)

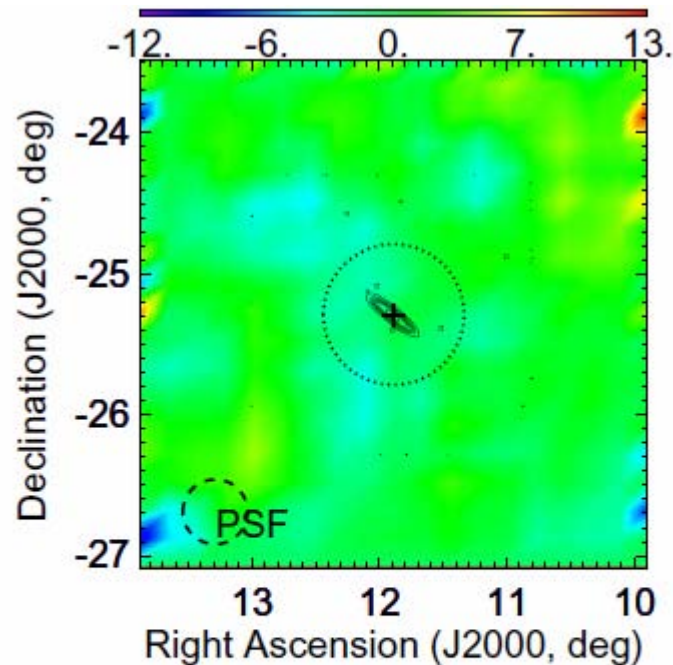


Fig. 3. Excess count map. The rainbow map is the excess count. The black contour is DSS2 (second version of Digital Sky Survey) data. The dotted circle is 0.5 degree radius. The point spread function is shown in left-below corner (the dashed line).

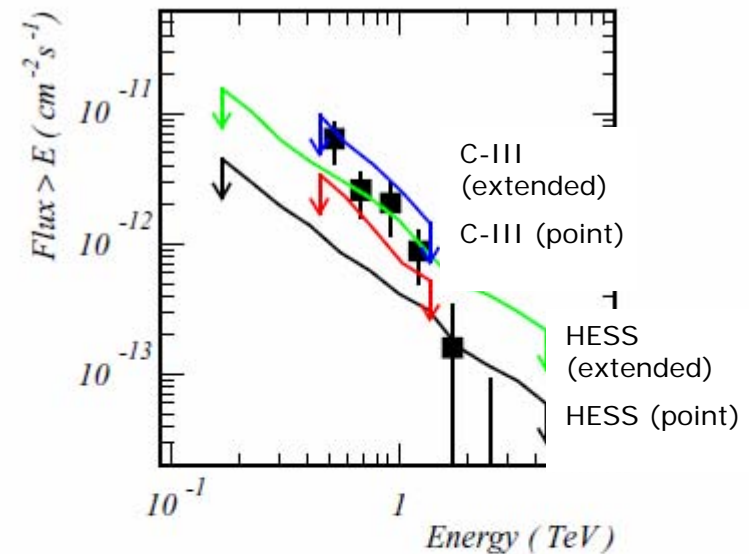
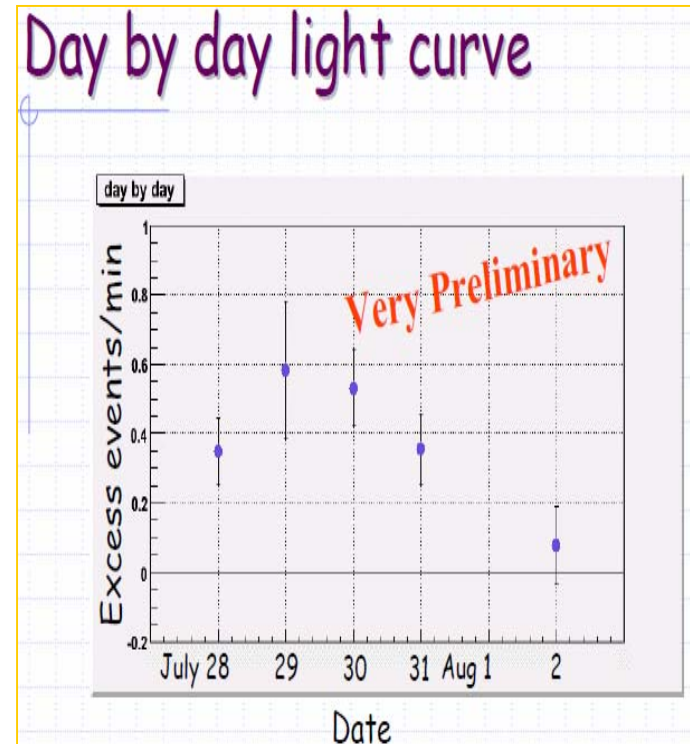
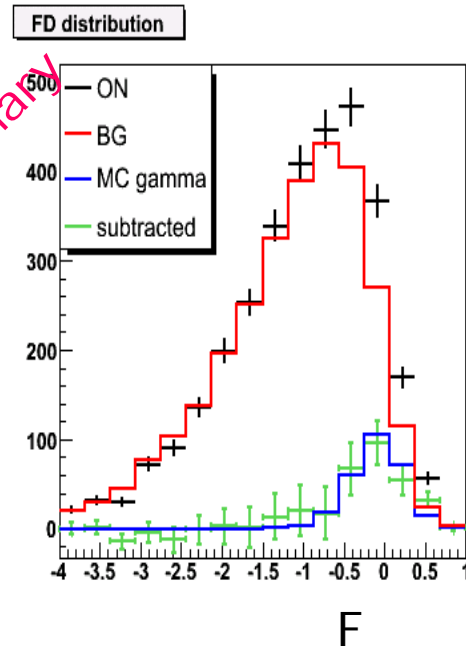
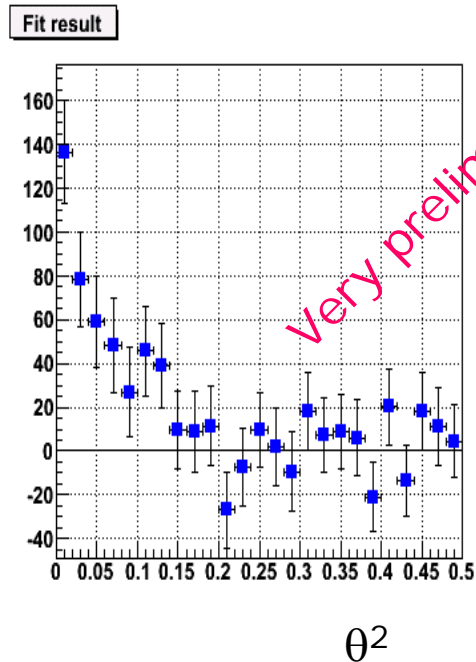


Fig. 4. Integral fluxes. The points with error bars are the CANGAROO-II's ones (see text for the detail). The black curve is 99% upper limit (UL) by H.E.S.S. for point source assumption. The green is that for 0.5 degree diffuse source. The red is 2σ UL for this observation for point source assumption and the blue for 0.5 degree diffuse.

Flare of Blazar PKS 2155-304

- Nearby high-frequency BL Lac ($z=0.117$)
- TeV flare report by H.E.S.S. in July-Aug 2006 (ATel#867)
- 1,053 min (wobble), 3-fold
- Analyzed by independent teams (ICRR, Tokai, Kyoto)



Summary table

Table 1: Summary of TeV source status claimed by CANGAROO compared with H.E.S.S. results.

Object	C-I	C-II	C-III	H.E.S.S.
Crab	Yes	Yes	Yes [2]	Yes
PSR 1706-44	Yes	†	U.L. [1]	U.L.
Vela pular	Yes (0.13° offset)	N/A	U.L. [2]	U.L.
Vela X	N/A	N/A	Yes [2]	Yes
SN1006	Yes	†	U.L. [1]	U.L.
RX J1713.7-3946	Yes	Yes	under analysis	Yes
PSR 1509-58	Yes	N/A	under analysis	Yes (MSH15-52)
Mrk 421	N/A	Yes	N/A	Yes
NGC 253	N/A	Yes	U.L.[4]	U.L.
Galactic center	N/A	Yes	under analysis	Yes
RX J0852.0-4622	N/A	Yes	Yes [3]	Yes

‘C-I’ means CANGAROO-I, etc. ‘Yes’: detection, ‘U.L.’: upper limit, ‘N/A’: not available. † means the result is not published yet.

[1] “Status of the CANGAROO-III Project”

T. Tanimori et al., 29th International Cosmic Ray Conference, Pune, India (August 3-10, 2005), published in Proceedings (Tata Institute of Fundamental Research, Mumbai, India, 2006) Vol.4, pp.215-218

[2] “A Search for sub-TeV Gamma-rays from the Vela Pulsar Region with CANGAROO-III”

Enomoto, R. et al., *Astrophys. J.*, 638, 397-408 (2006)

[3] “CANGAROO-III Observations of the supernova remnant RX J0852.0–4622”

Enomoto, R. et al., *Astrophys. J.*, in press (2006)

[4] “Erratum: Detection of diffuse TeV gamma-ray emission from the nearby starburst galaxy NGC 253”

Itoh, C. et al., *Astron. Astrophys.*, in press (2006)

Up and coming sources...

- MSH 15-52
 - Pulsar wind nebula (PSR 1509-58)
 - H.E.S.S. : 25% Crab, extended (~6'x2')
 - Observation: 40hr in 2005, 90hr in 2006
- HESS J1804-216
 - G8.7-0.1(SNR) / PSR J1803-2137
 - H.E.S.S. : 25% Crab, extended (~12')
 - Observation: 90hr in 2006
- HESS J1303-631
 - Unidentified
 - H.E.S.S. : 17% Crab, extended (~10')
 - Observation: 70hr in 2006
- And more...



Summary

- ❑ CANGAROO-III atmospheric Cherenkov telescope system are observing sub-TeV gamma-rays since 2004 March in stereoscopic mode.
- ❑ Observations of SN1006 and PSR1706-44 were made by using CANGAROO-III telescopes. Preliminary analyses appear to show no significant signals, yielding upper limits lower than the CANGAROO-I fluxes obtained several years ago.
- ❑ Observation of Vela pulsar showed no gamma-ray signal, but there is a hint of signal in the Vela X nebula.
- ❑ SNR RX J0852.0-4622 was detected as an extended source, and the morphology seems to follow the X-ray emission profile.
- ❑ Starburst galaxy NGC 253 was observed with CANGAROO-III but the signal reported by CANGAROO-II was not confirmed.
- ❑ A flaring activity of a blazar PKS 2155-304 was detected in July-August 2006 showing rapid time variation.
- ❑ Analysis of stereo observations are now established, and application to other sources are underway.