Recent results from CANGAROO

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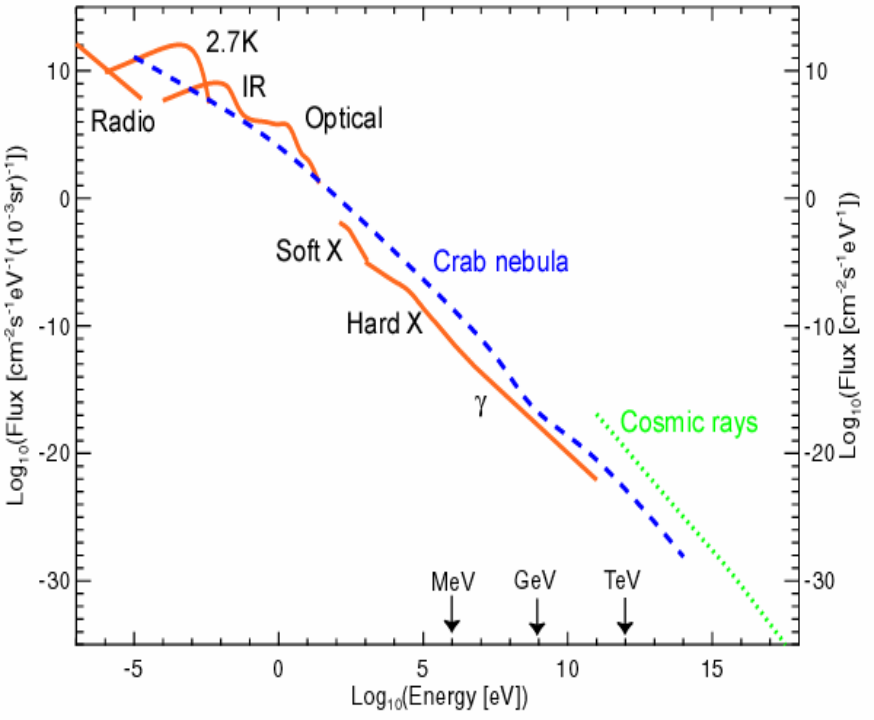
for the CANGAROO team

**ICRR, The University of Tokyo*

4th Workshop on Science with the New Generation of High Energy Gamma-ray Experiments, Elba Island, Italy, June 20-22, 2006

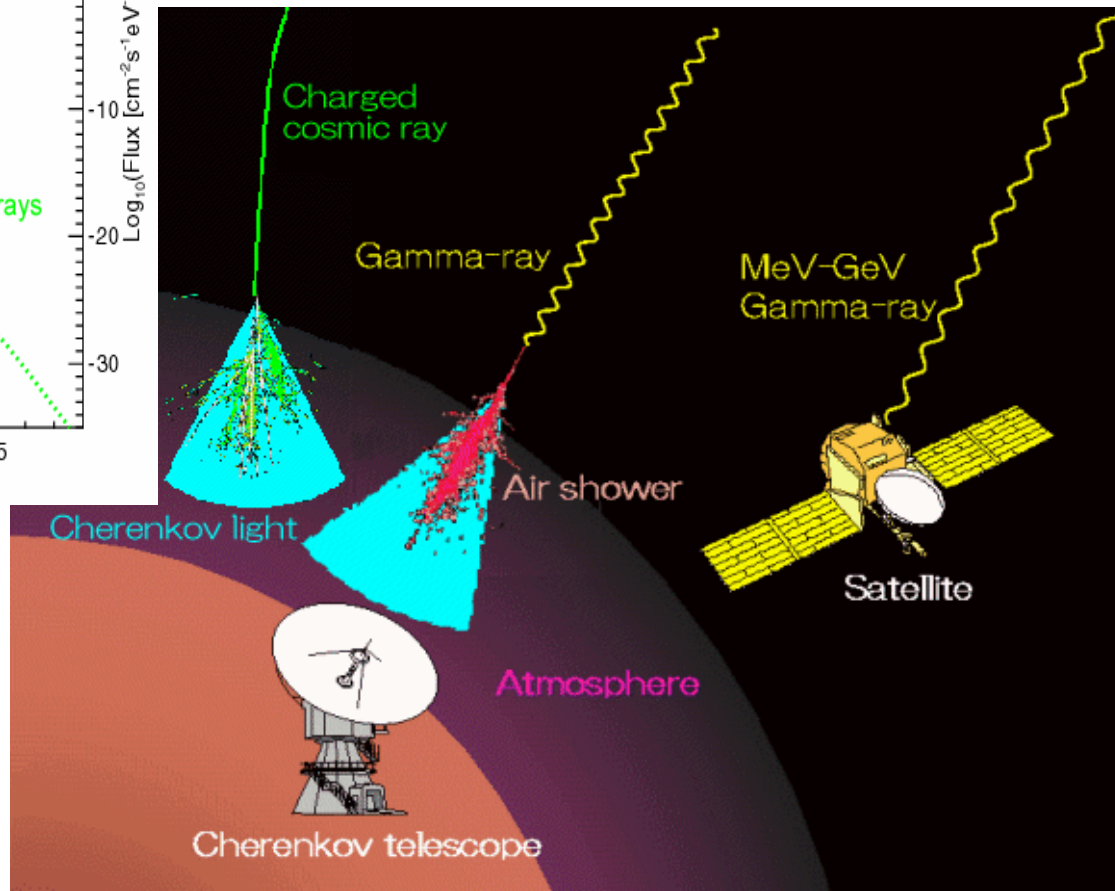
We have to rely on ground-based observation at TeV energies



Diffuse photon spectrum

$A \sim 10^4 m^2$ $\sim 1\ m^2$

$\Omega \sim 10^{-2} sr$ $\sim \pi\ sr$



“CANGAROO”

=

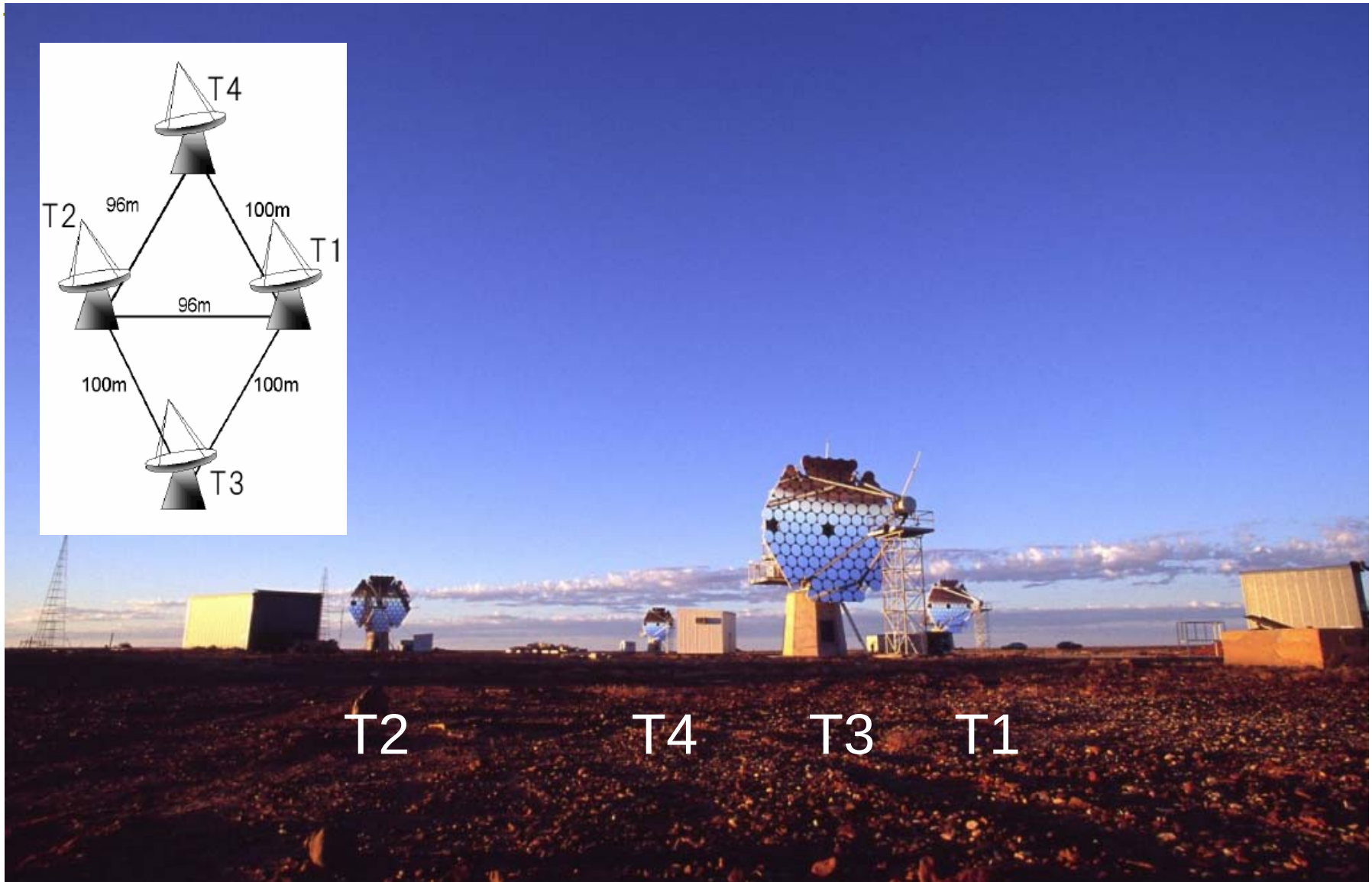
Collaboration of **A**ustralia and **N**ippon for a
GAmma **R**ay **O**bservatory in the **O**utback

Woomera, South Australia

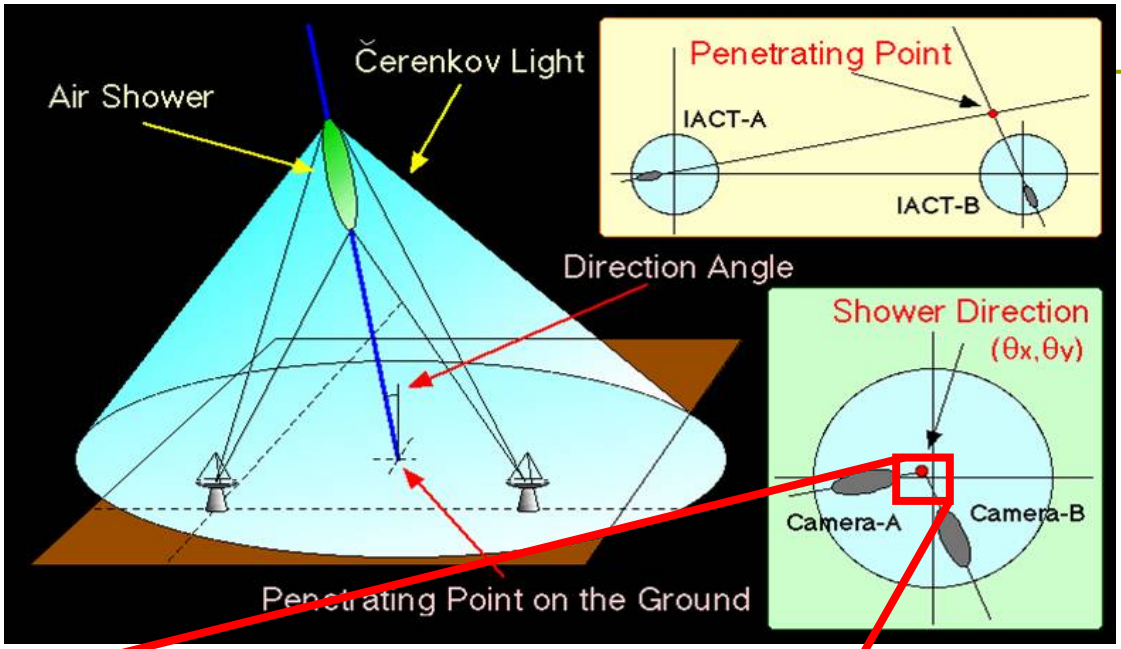
CANGAROO team

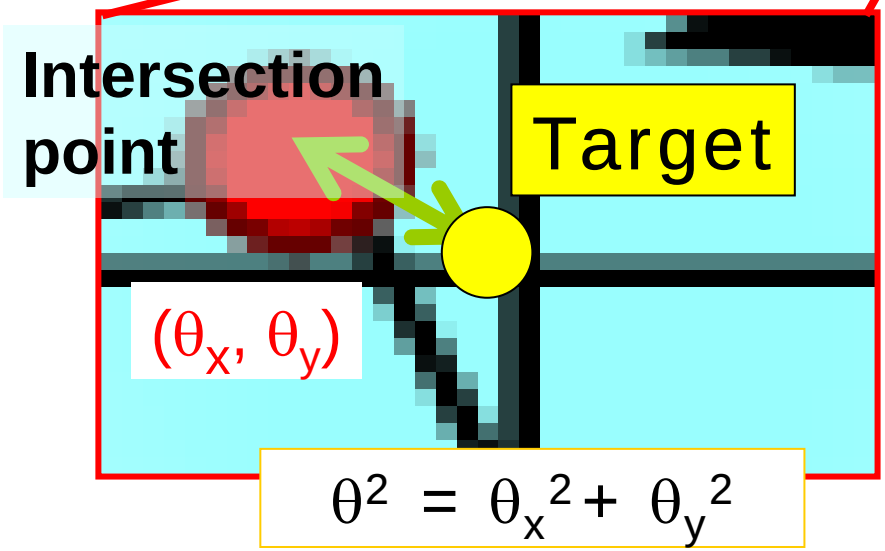
- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectural University
- Konan University
- Kyoto University
- STE Lab, Nagoya University
- National Astronomical Observatory of Japan
- Kitasato University
- Shinshu University
- Australia Telescope National Facility
- Tokai University
- ICRR, University of Tokyo
- Yamagata University
- Yamanashi Gakuin University
- Hiroshima University

CANGAROO-III: 2004 March



Stereo observation





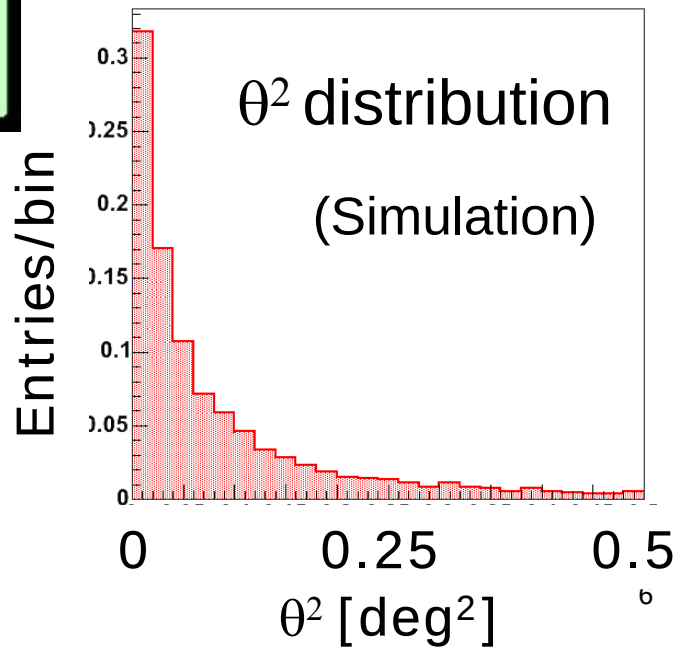
Angular resolution

0.25deg → 0.1 deg

Energy resolution

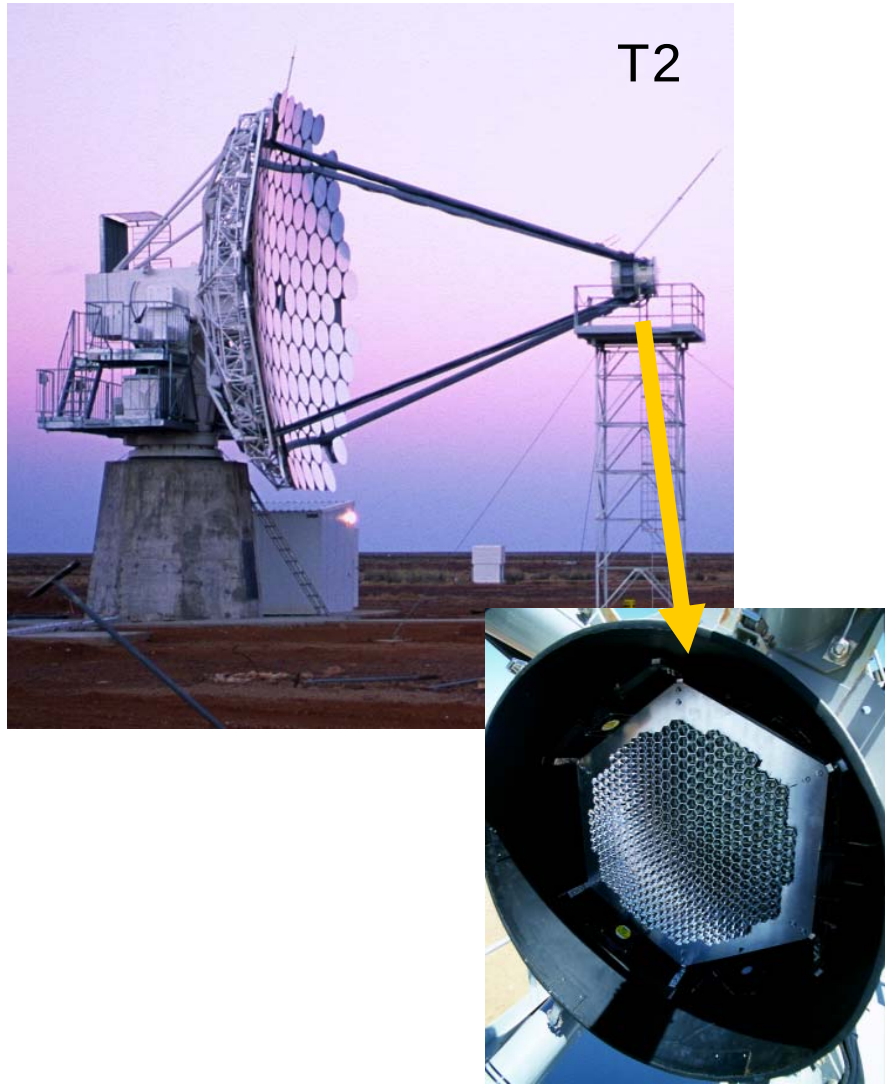
30% → 15%

Better S/N (no local muons)



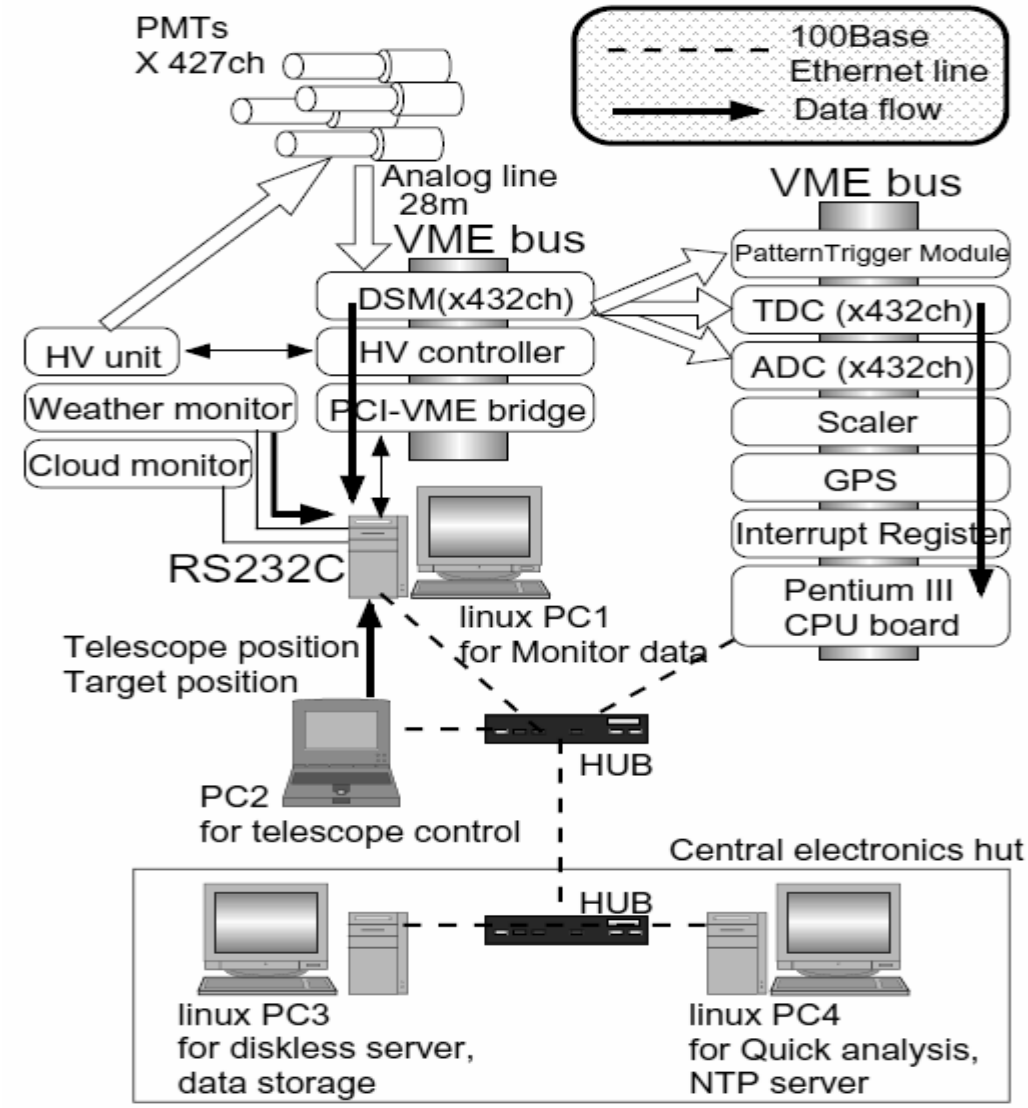
Basic specifications of telescopes

- 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

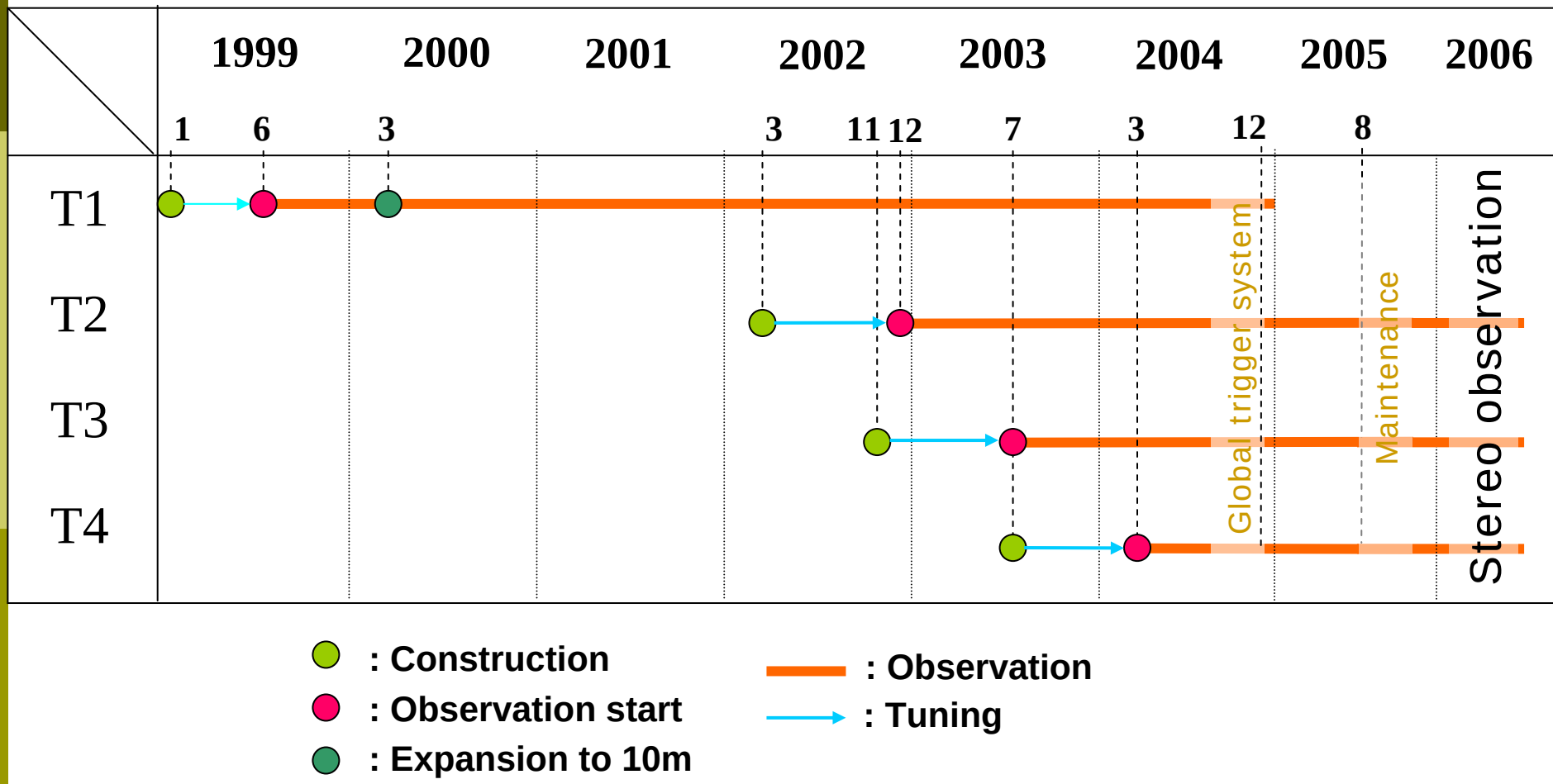


Kubo et al., Proc. ICRC 2003

CANGAROO-III electronics



History of CANGAROO-III

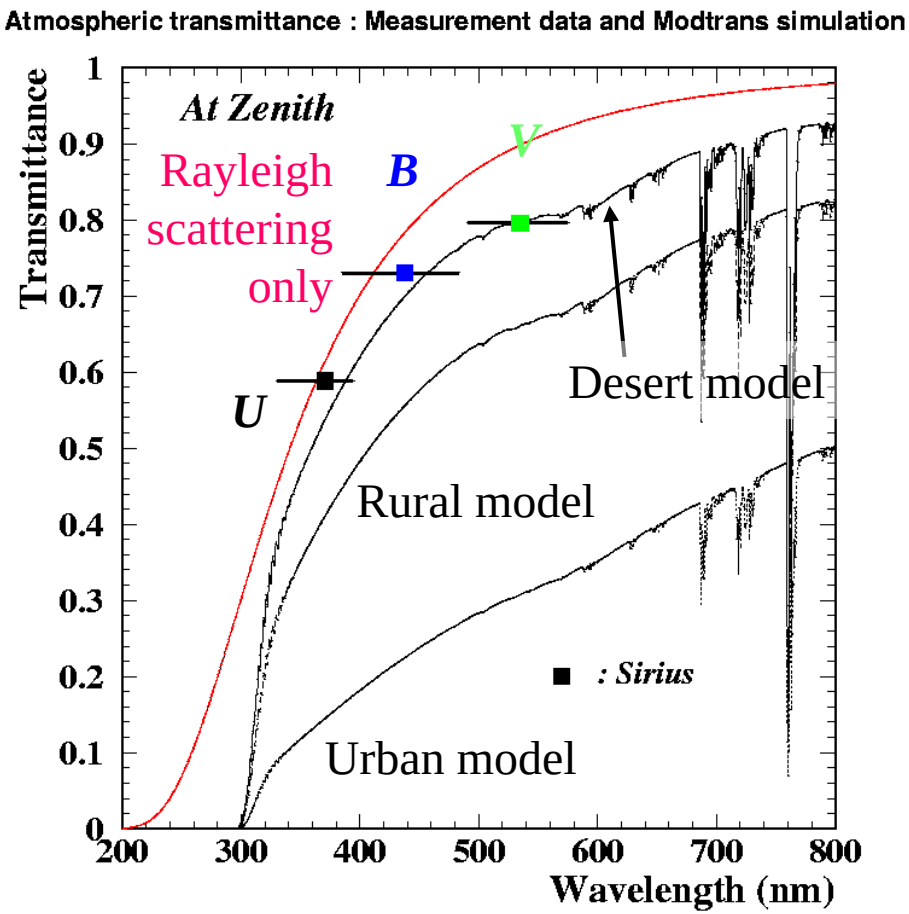


Monte Carlo simulation

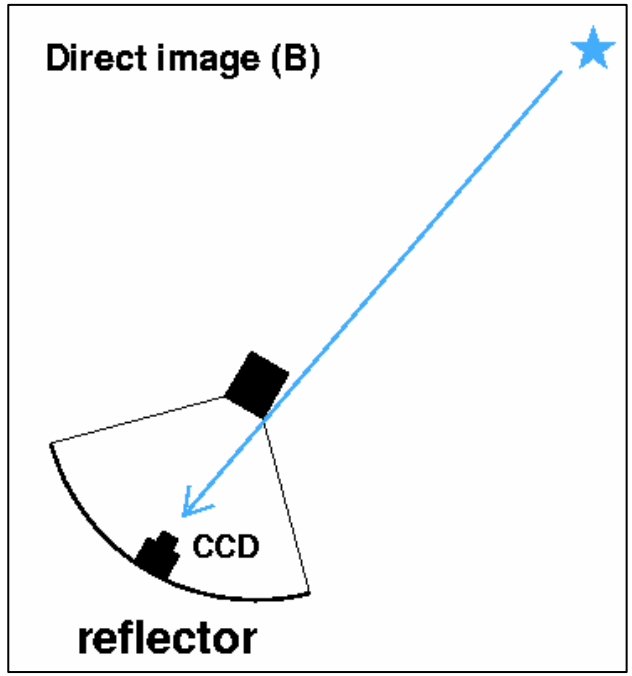
- GEANT 3.21 base
  - 80 layers for atmosphere (12.9g/cm^2 each)
    - (<10% change even if more layers were used)
  - Particle transport down to 20MeV
  - Proprietary code to generate Cherenkov photons
    - Only photons coming to telescopes are tracked
  - Geomagnetic field of 0.520G (vert.) / 0.253G (hor., 6.8°E of S)
  - Rayleigh scattering 2970g/cm^2(λ/400nm)^4
    - (+Mie scattering ~10% effect)
  - Detector parameters: reflectivity, point spread function, light guide efficiency, PMT Q.E., etc.
  - Night sky background

Kiuchi et al., Energy Budget in the High Energy Universe, Feb. 2006

Atmospheric transmission measurement



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

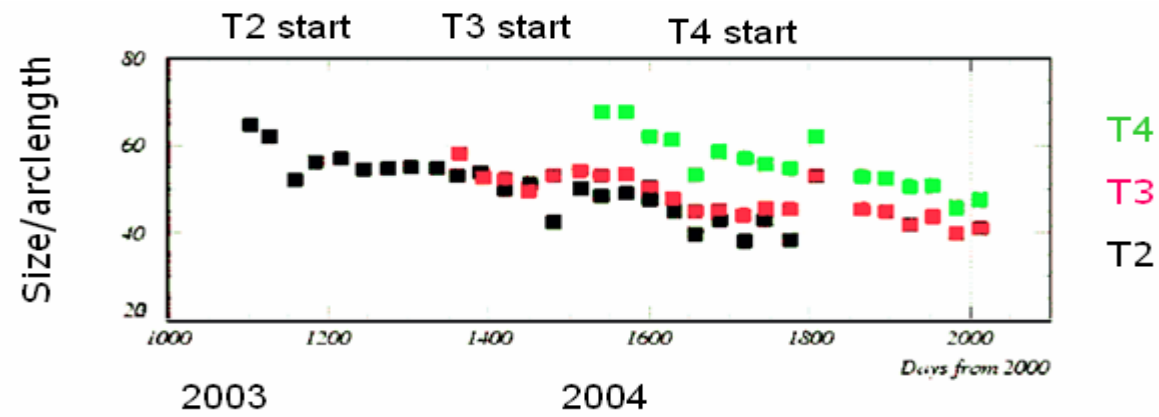


Data compatible with "Desert model" of MODTRAN4

Systematic errors under study

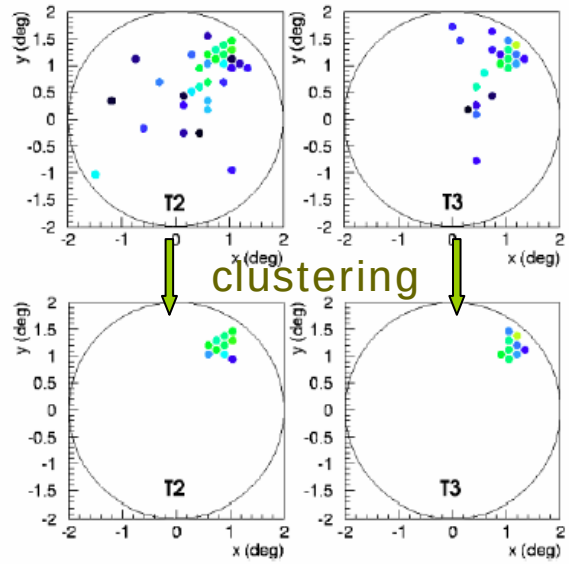
`Everyday' calibration

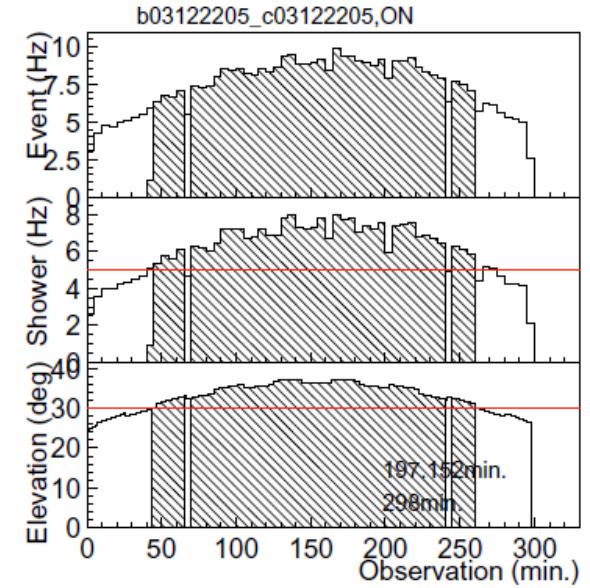
- Pedestal run
  - Camera closed / open (w/NSB)
- LED run
  - LED inside camera → gain
    $\mu_{p.e.} = (\mu_{ADC}/\sigma_{ADC})^2$
  - LED at reflector pole → time walk correction
- Muon rings
  - Size/arclength ∝ total light conversion efficiency



Data reduction

- Bad channel removal
  - Based on ADC & TDC distributions
- Basic cut
  - ADC >5p.e., TDC, Scaler, Cluster (5 adjacent PMTs)
- Good run selection
  - Cloud cut (event rate), elevation cut
- Selection using image parameters
  - Square cut (limiting ranges)
  - Likelihood (probability distribution)
  - Fisher discriminant (correlation incorporated)

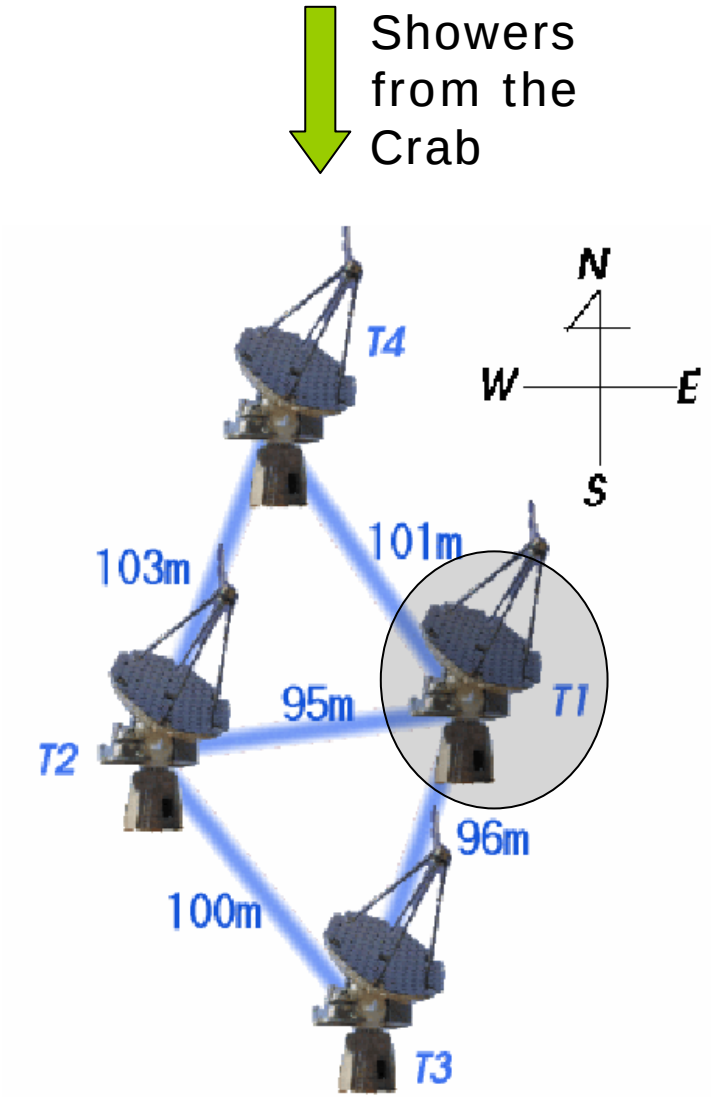




Stereo analysis: in progress

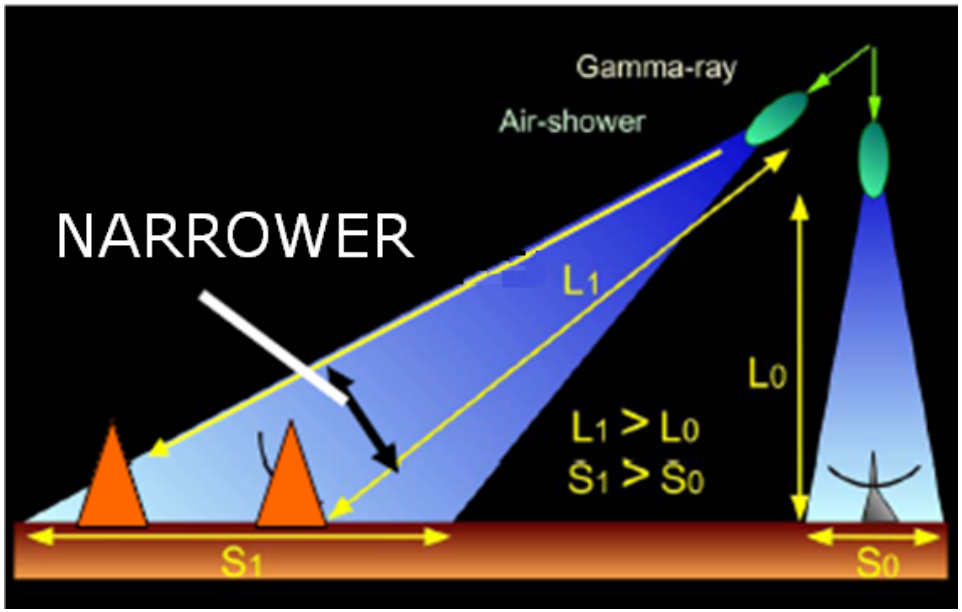
- Inconsistency with H.E.S.S results on some sources
  $\Rightarrow$ New observations with CANGAROO III
  Efforts for advanced analysis procedures
- Measure more optical parameters
  - CCD measurements of spotsizes and stars
- Use muons for calibration
  - Tune Monte Carlo simulation
- Use the Crab as 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

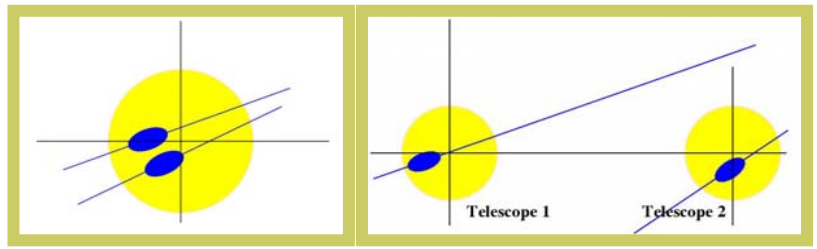
Unfortunate situation for the Crab



- 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

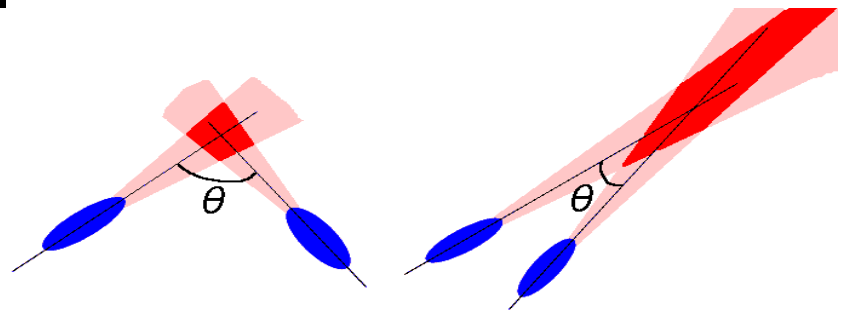




Far core
→small angle
→bad accuracy

Higher energy threshold ~1TeV

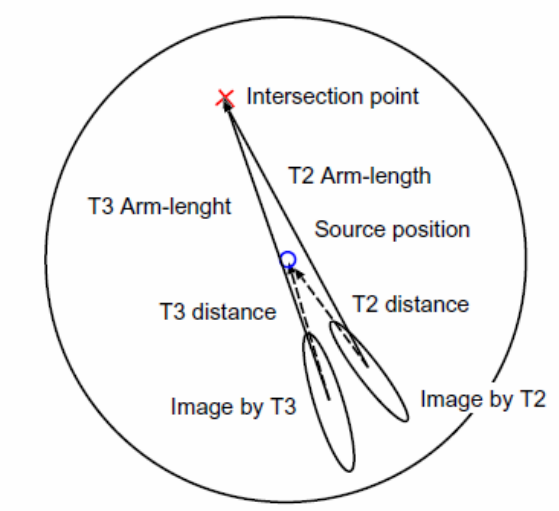
Bad intersection accuracy

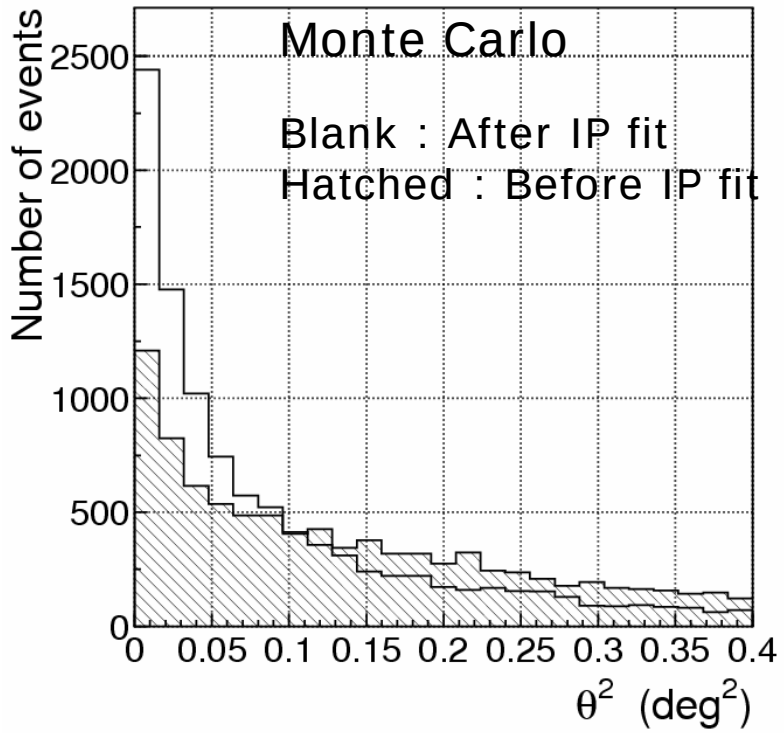


IP constraint fit

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

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 (<Armlength>=0.75, Mesh size 0.025°)





γ/h separation by Fisher discriminant

- Linear combination of image parameters (x_i)

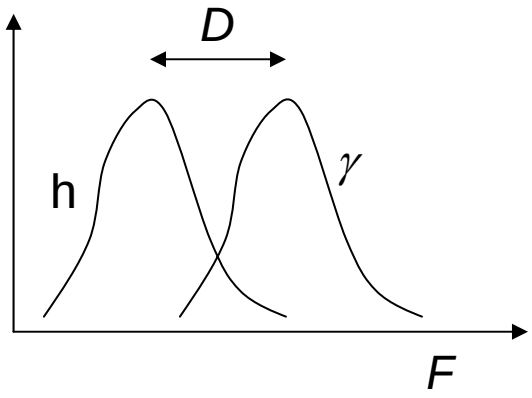
$$F \equiv \sum_i \alpha_i x_i$$

- 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)

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



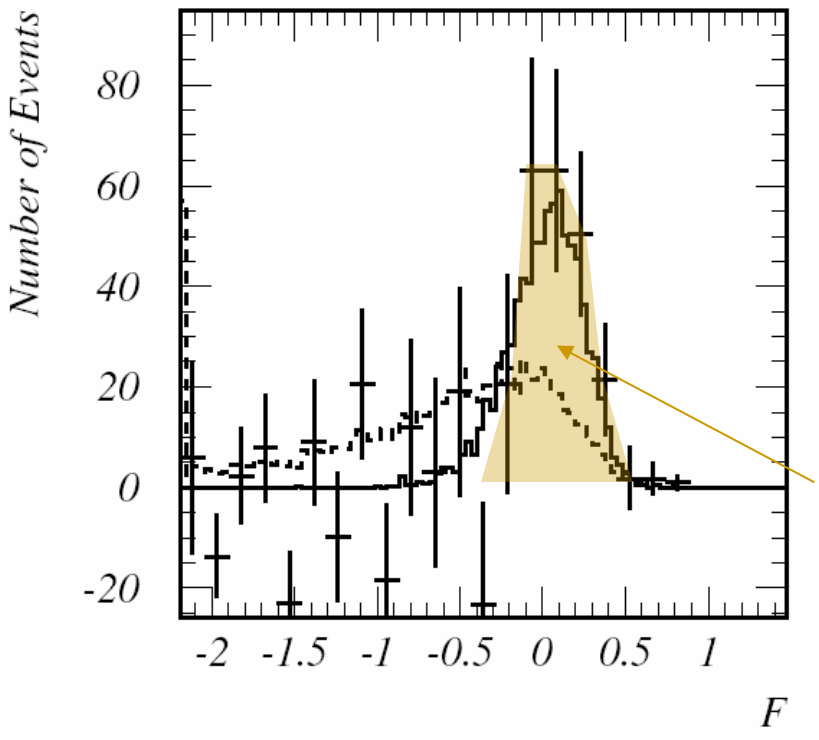
- With calculated α_i for a known source, the (appropriately normalized) combination *F* could be the "Fisher discriminant" for other sources.

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

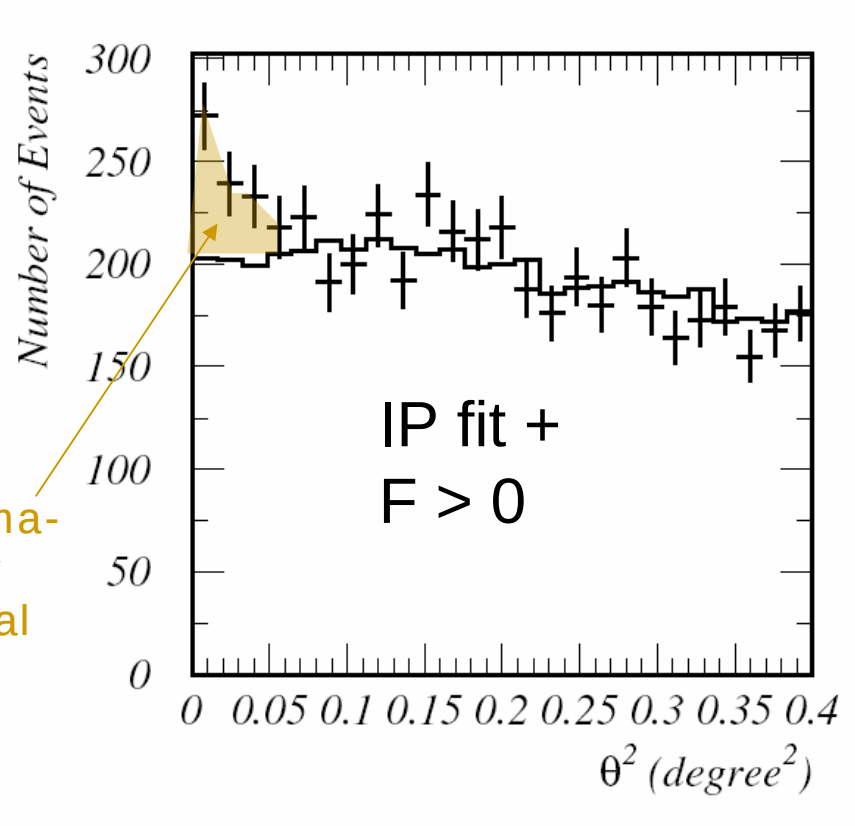
R.A. Fisher, Annals of Eugenics, 7 (1936) 179

R.Enomoto et al., ApJ 638, 397 (2006)

Crab signal (1)



Gamma-ray signal



Plot : observation
Solid : MC gamma
Dashed : background

203 excess events
5.8 sigma

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

R.Enomoto et al., ApJ 638, 397 (2006)

Crab signal (2)

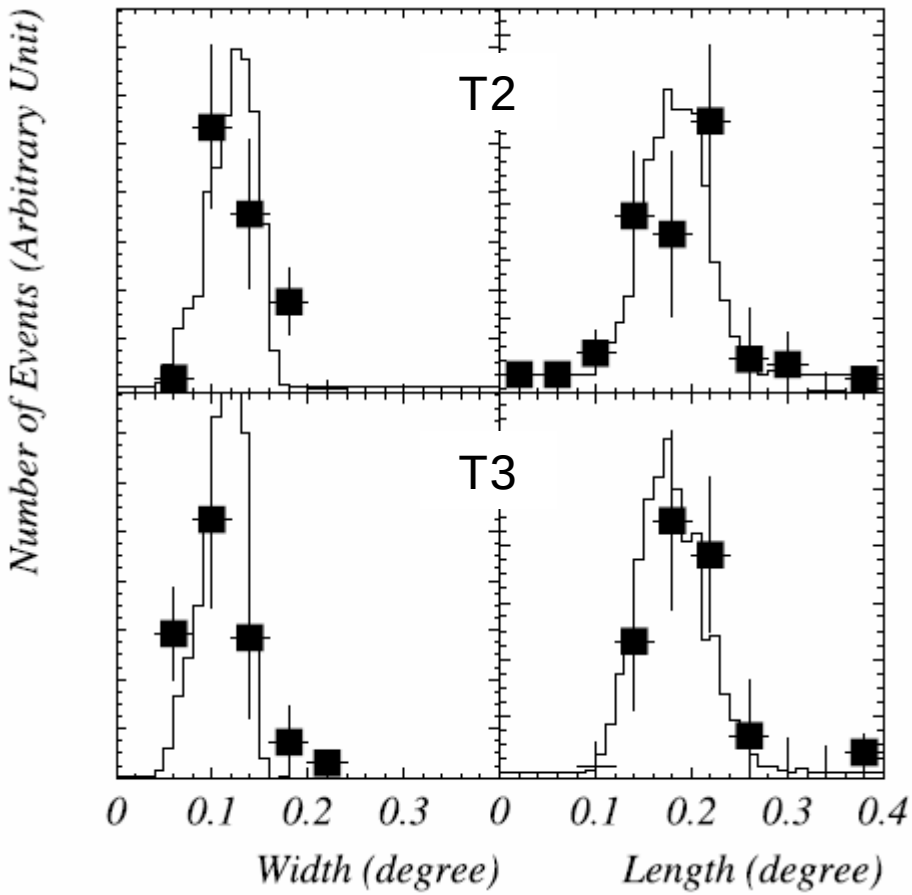


FIG. 9.—Hillas moment distributions. *Upper left*, T2 widths; *upper right*, T2 lengths; *lower left*, T3 widths; *lower right*, T3 lengths. The points with error bars were obtained after the subtraction of background events. The solid histograms are the Monte Carlo predictions where the total number of entries was normalized to that of the observations.

R.Enomoto et al., ApJ 638, 397 (2006)

Crab spectrum

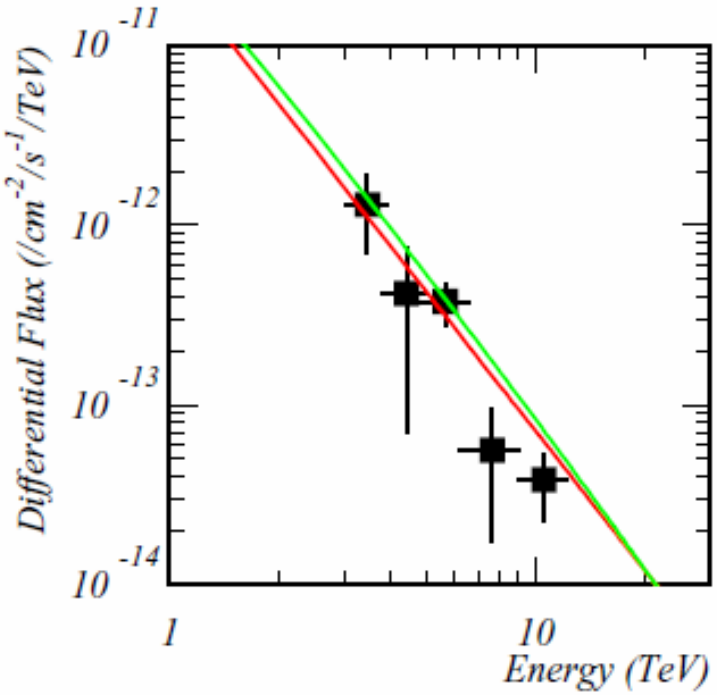
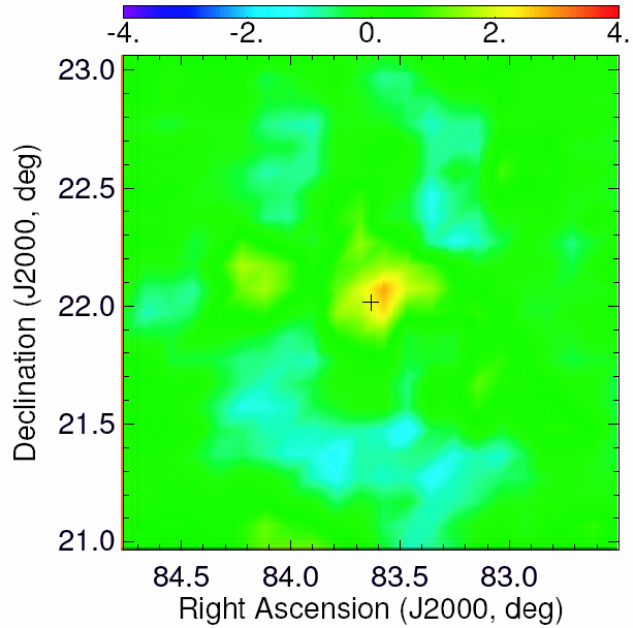


FIG. 17.— Differential gamma-ray flux from the Crab Nebula as a function of energy. The red line is the HEGRA result (Aharonian et al. 2000) and the green is the Whipple result (Hillas et al. 1998).

Excess event map



Angular resolution ~ 0.23 deg

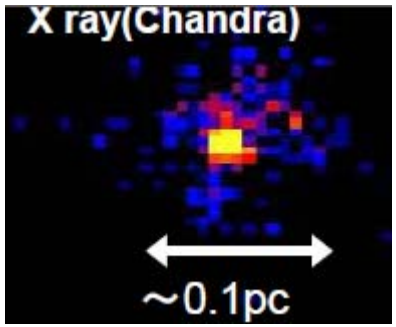
CANGAROO-I claims vs. H.E.S.S.

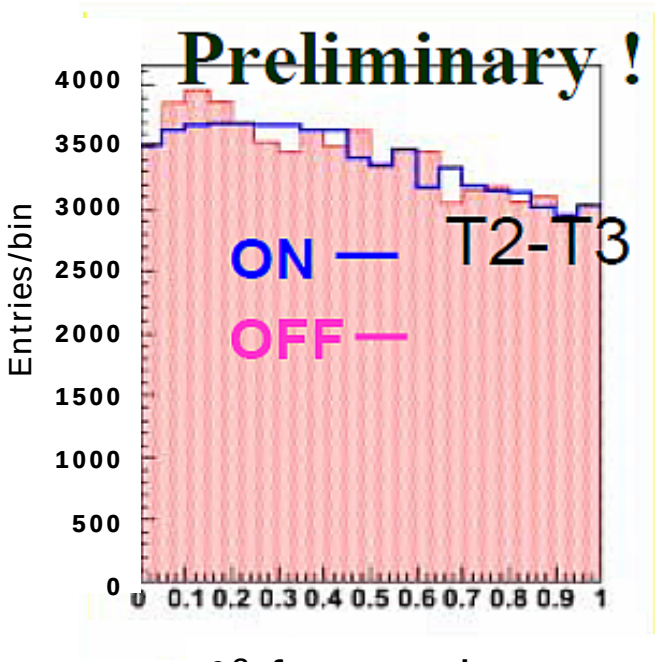
- CANGAROO-I claims
  - Pulsar PSR1706-44 : 0.57Crab (~8σ, >1 TeV)
    [Kifune et al. ApJ 431, L195, 1995]
    - Cf. H.E.S.S. upper limit: 0.024Crab (>0.5TeV)
      [Aharonian et al. A&A 432, L9, 2005]
  - SNR SN1006 : 0.81Crab (5.3σ, >3 TeV) [1996]
    0.62Crab (7.7σ, >1.7TeV) [1997]
    [Tanimori et al. ApJ 497, L25, 1998]
    - Cf. H.E.S.S. upper limit: 0.046Crab (>1.7TeV)
      [Aharonian et al. A&A 437, 135, 2005]
  - Vela pulsar : 0.73Crab (5.8σ, >2.5TeV) at 0.13°SE
    [Yoshikoshi et al. ApJ 487, L65, 1997]
    - Cf. H.E.S.S. Vela X (extended): 0.75Crab (>1TeV)
      [Aharonian et al., astro-ph/0601575]

* Fluxes are given in unit of the Crab integral flux at 1TeV

T.Tanimori et al., ICRC2005

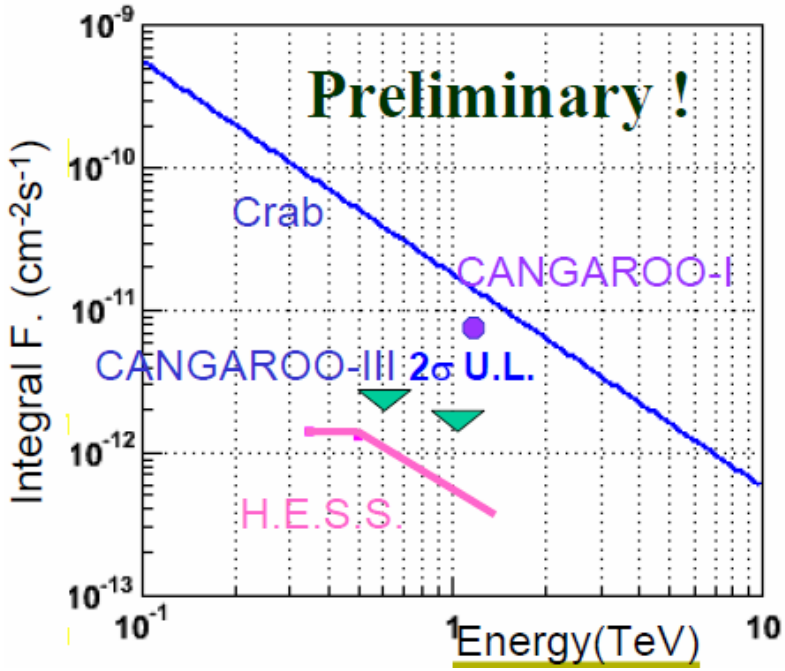
PSR 1706-44





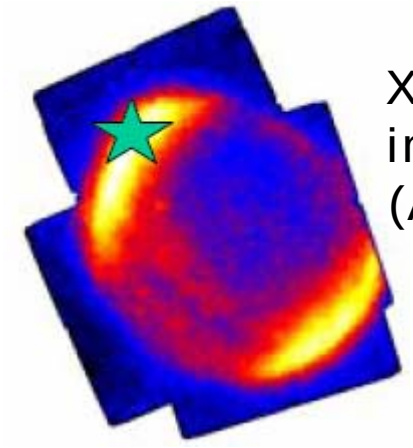
θ^2 from pulsar

- 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.)



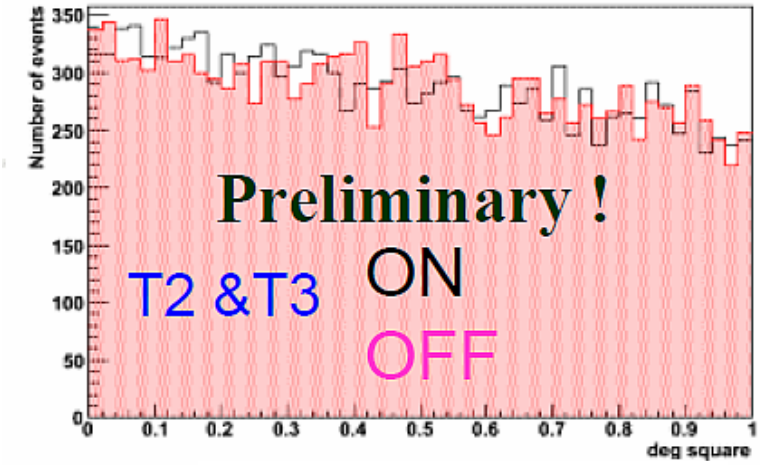
T.Tanimori et al., ICRC2005

SN1006 (G327.6+14.6)

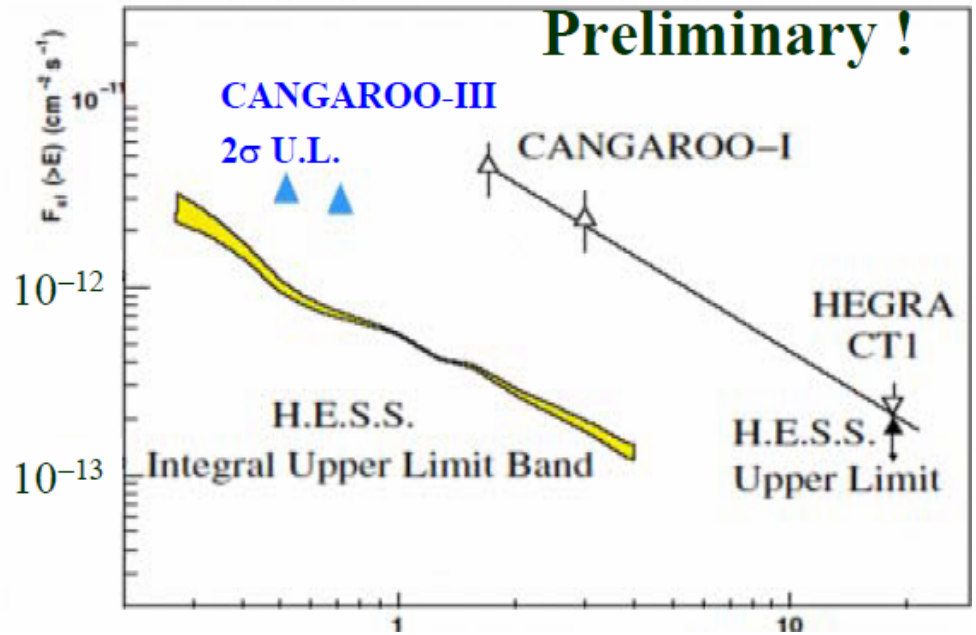


X-ray image (ASCA)

- 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.)



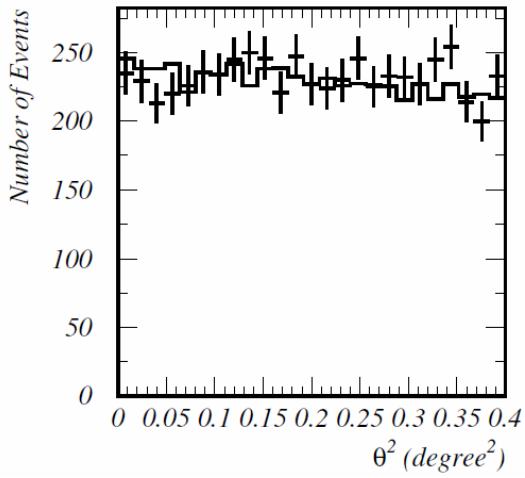
θ^2 from NE rim

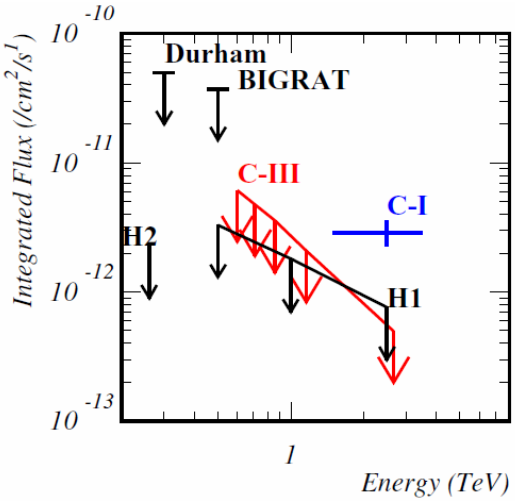


R.Enomoto et al., ApJ 638, 397 (2006)

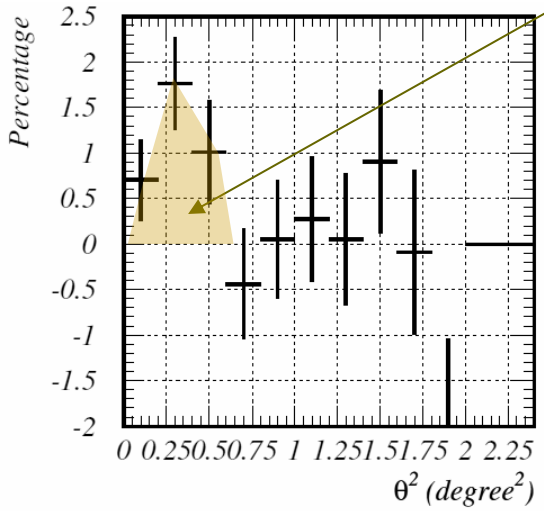
Vela pulsar/nebula

Pulsar position



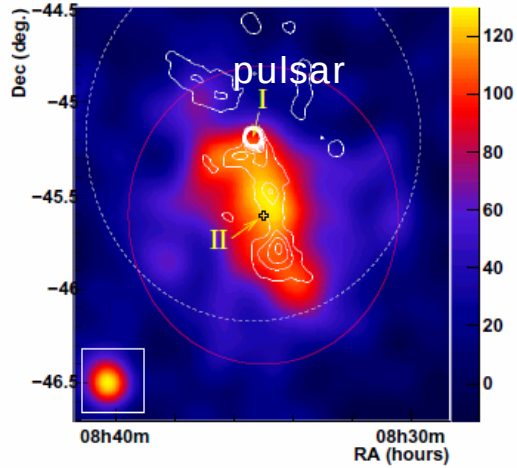


- Pulsar pointing (2004 Jan/Feb)
- Stereo (T2 & T3 wobble), 1,311 min.
- Fisher discriminant



θ² from Vela X center

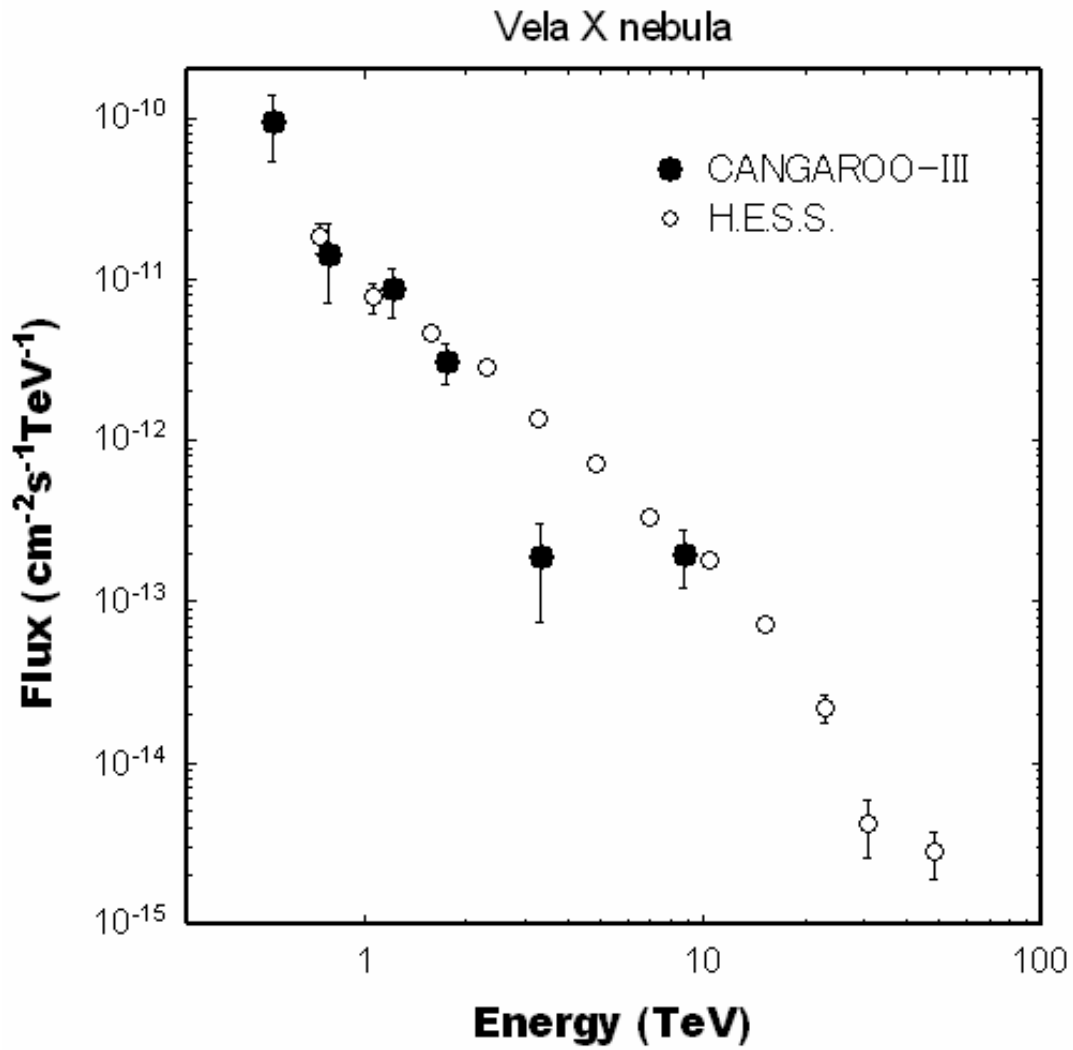
Vela X nebula



H.E.S.S.: Aharonian et al., A&A 448, L43 (2006)

R.Enomoto et al., ApJ 638, 397 (2006)

Vela X nebula: spectrum



$\theta^2 < 0.6$ deg^2

Excess 561±114

H.E.S.S.:
Aharonian et al.,
astro-ph/0601575
$\propto E^{-1.45}\exp(-E/13.8\text{TeV})$

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

- CANGAROO-II claims
  - SNR RX J1713.7-3946: 0.51Crab, $E^{-2.84\pm0.15\ \pm0.20}$ (11σ, >0.5 TeV)
    [Enomoto et al., Nature 416, 823, 2002]
    - Cf. H.E.S.S. flux: 0.83Crab, $E^{-2.19\ \pm0.09\pm0.15}$
      [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: $E^{-2.2\ \pm0.09\pm0.15}$
      [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: $E^{-2.1\ \pm0.1\pm0.2}$
      [Aharonian et al. A&A 437, L7, 2005]

⇒ To be checked with CANGAROO-III stereo data (analysis in progress)

B. Aschenbach, Nature, 396, 141 (1998)

SNR RX J0852.0-4622 (G266.2-1.2, Vela Jr.)

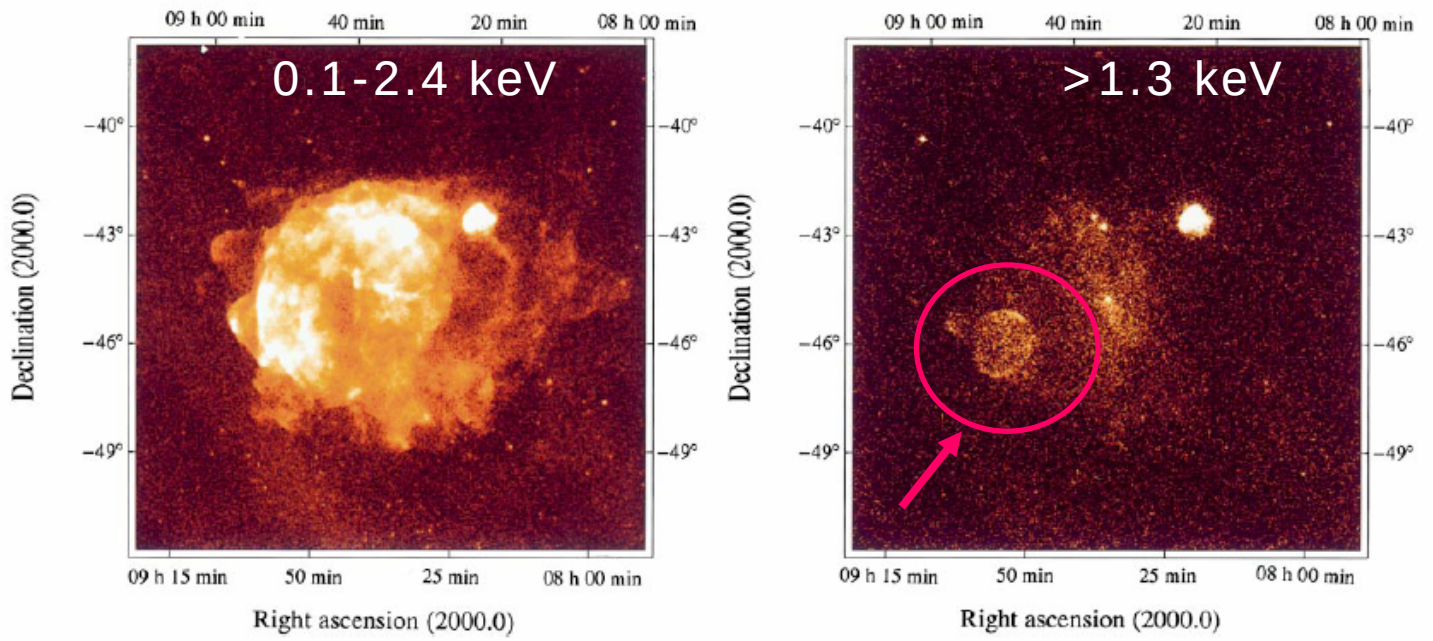
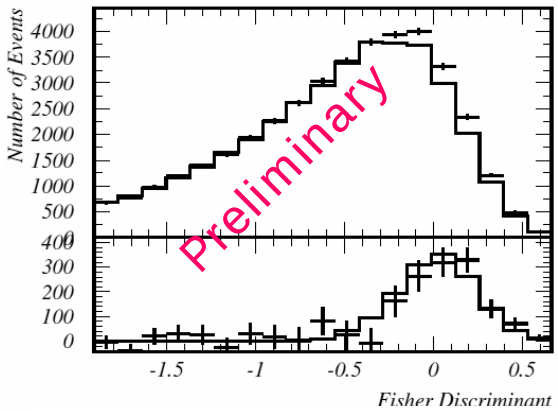


Figure 1 Rosat all-sky survey images of the Vela SNR and its surroundings. Angular resolution is 1 arcmin half-power radius; mean exposure is 993 s. The left-hand image was taken for photon energies $0.1 < E < 2.4$ keV; surface brightness increases from dark yellow to white by a factor of 500. The right-hand image is for photon energies >1.3 keV. Most of the Vela SNR X-ray emission which dominates at low energies had disappeared. At the centre, the synchrotron nebula around the Vela pulsar remains visible as well as the SSW beam-like structure, and at the very northwest (upper right) the bright Puppis-A SNR can be seen. The new shell-type SNR RX J0852.0 – 4622 shows up in the lower left. East of RX J0852.0 – 4622 hard X-ray photons from the D/D′ Vela SNR shrapnels are seen which, however, are associated with a much lower-temperature spectrum than RX J0852.0 – 4622 (ref. 14). For X-ray spectral analysis, RX J0852.0 – 4622 was divided into two regions, one containing the bright northern limb section (l) and the other one (r) excluding the northern and southern limbs. Spectral fits were performed with either power-law models, optically thin thermal emission equilibrium models (Raymond–Smith models) or combinations of both. Solutions with a reduced $\chi^2 < 1$ for region r are obtained only with a two-temperature model with $kT_{r,1} = 0.14^{+0.08}_{-0.03}$ keV, $kT_{r,2} = 2.5^{+4.5}_{-0.7}$ keV. The spectrum of the northern limb can be fitted by either a simple power law with index $\alpha = -2.6^{+0.3}_{-0.4}$ or a two-temperature model with $kT_{l,1} = 0.21^{+0.14}_{-0.09}$ keV, $kT_{l,2} = 4.7^{+4.5}_{-0.7}$ keV. The presence of low-temperature components may partially be due to a residual, uncorrected contribution from the much softer Vela SNR. The total, absorption-corrected flux of the high-temperature components is $F_x(0.1\text{–}2.4\,\text{keV}) = 3 \times 10^{-10}$ erg cm^{-2} s^{-1}.

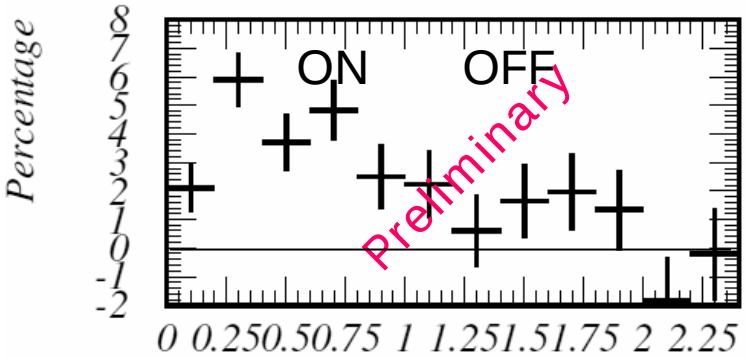
SNR RX J0852.0-4622

In preparation



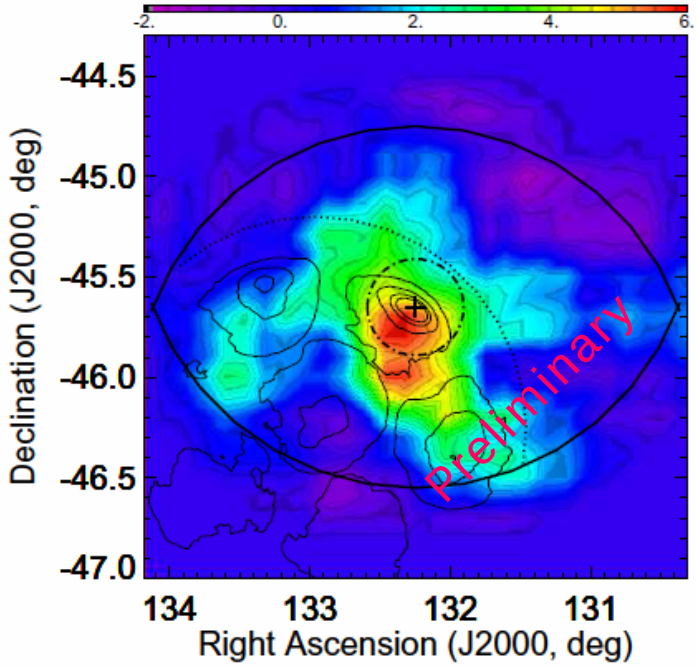
Fisher discriminant

- Stereo (T2 & T3 wobble)
- 1,204 min. (2004 Jan/Feb)
- Off region: Vela or out of SNR
- Distance ~1 kpc
  (NANTEN: Y.Fukui, private comm.)



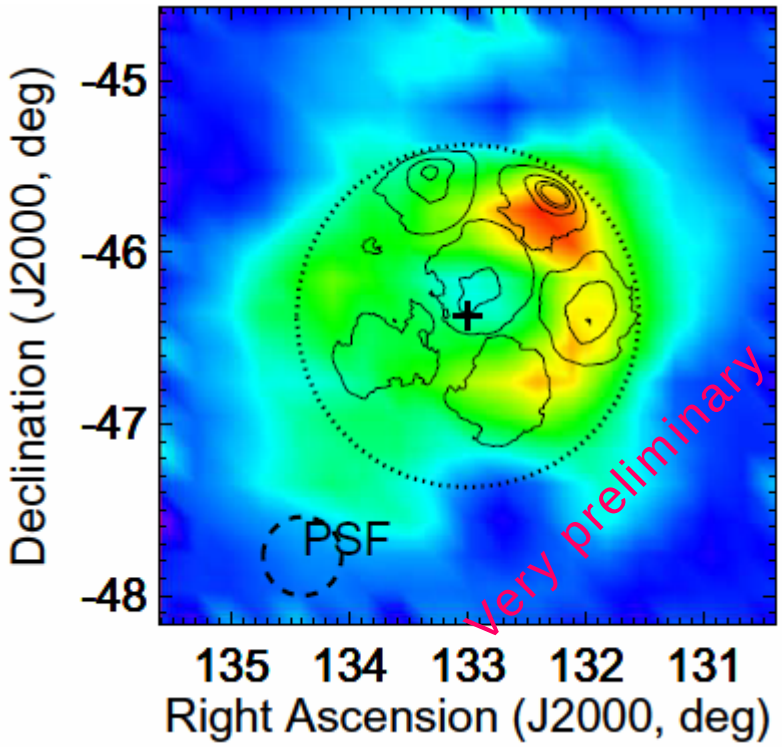
θ^2 from SNR center

Excess event map



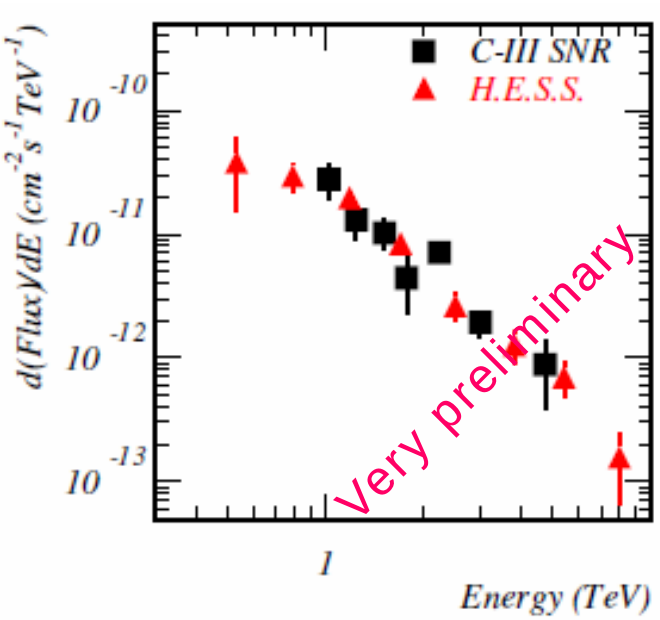
SNR RX J0852.0-4622

In preparation



2005 data

- Stereo (T2 & T3 & T4)
- 1,129 min. ON
  1,081 min OFF

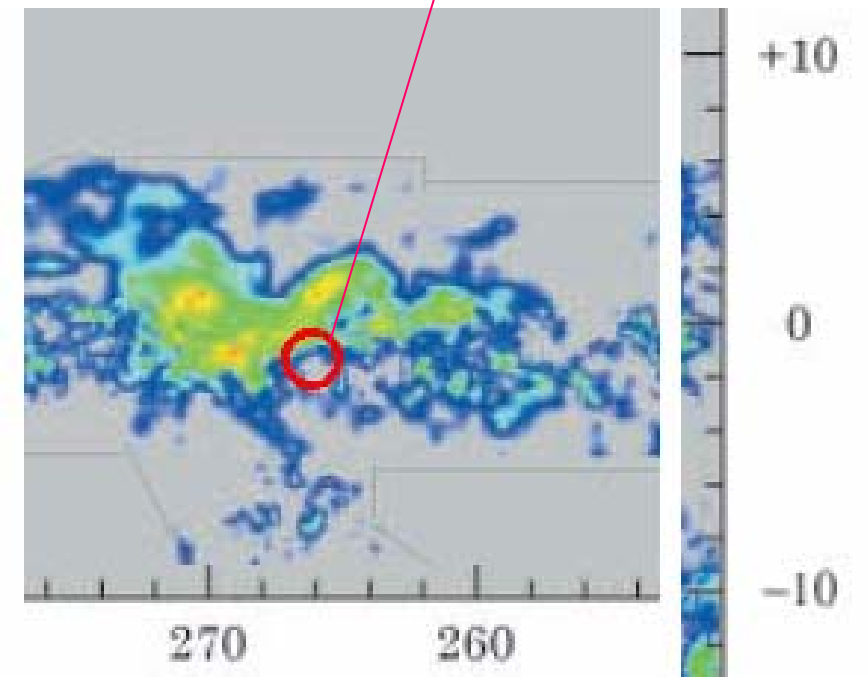


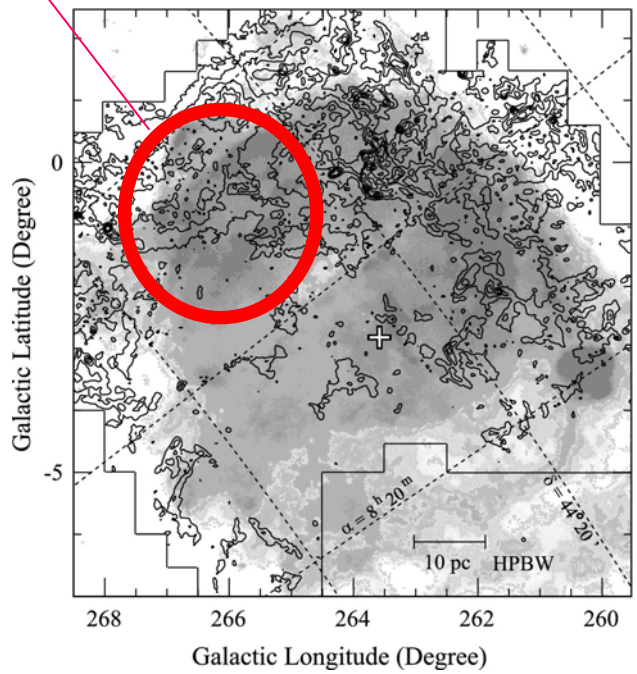
Correlation with CO

Dame et al., ApJ 547, 792 (2001)

Moriguchi et al., PASJ 53, 1025 (2001)

RX J0852.0-4622





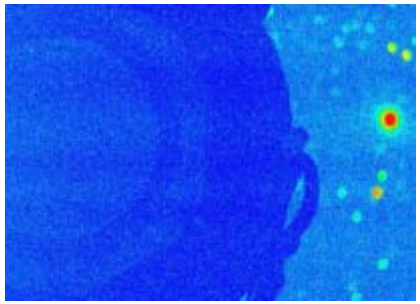
Galactic longitude (deg)

→ Need detailed study

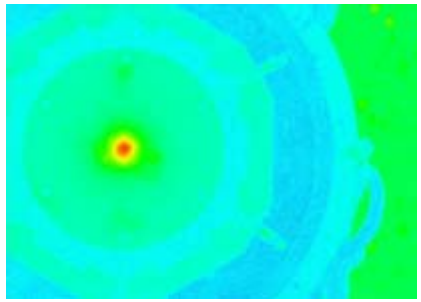
Maintenance works in 2005 Sep/Oct

- Intensive works...
  - Washing mirrors
  - Mirror realignment
  - Optical measurement
  - Electronics tuning
  - Muon data for calibration
  - Etc.

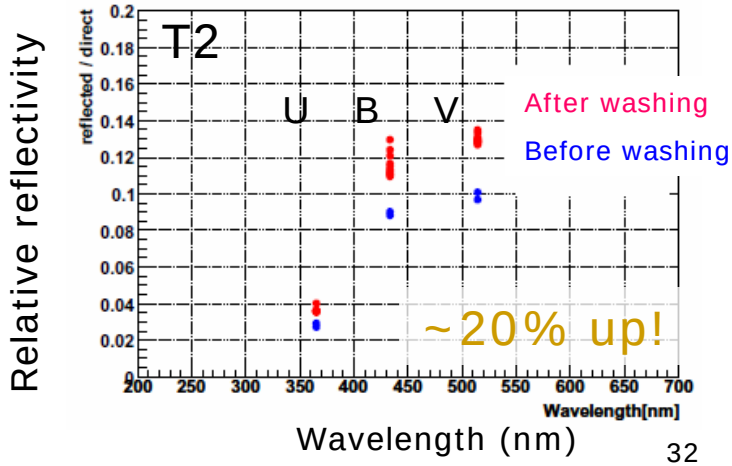
Reflectivity measurement using star images



Direct star images



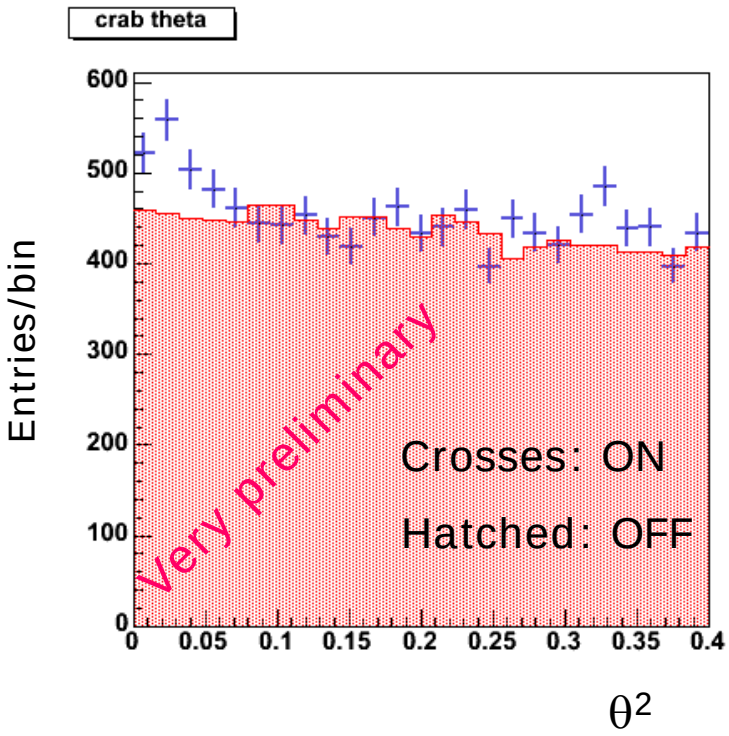
Reflected image of stars

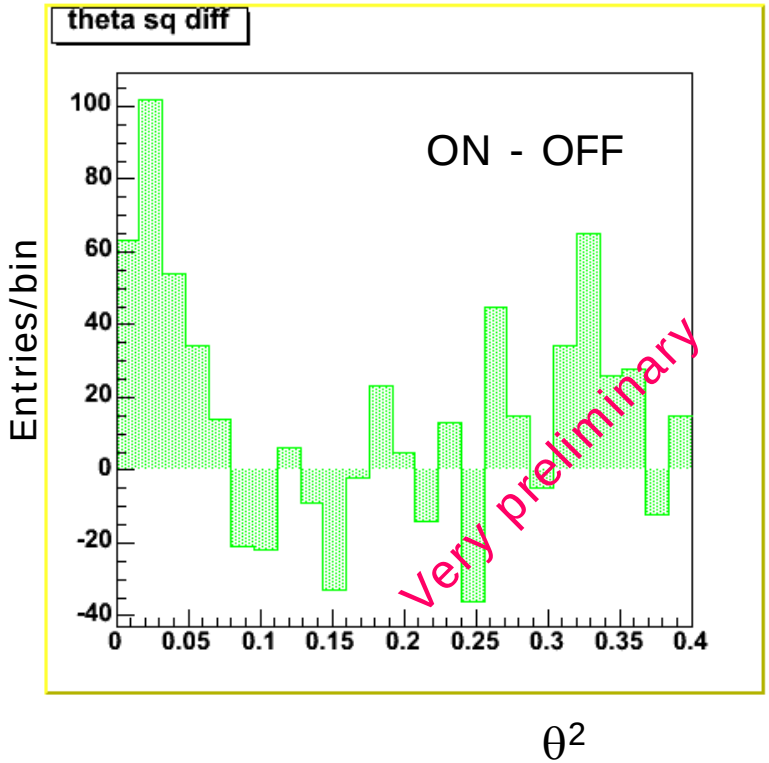


(See Kiuchi's poster!)

Crab observation after the maintenance

- Stereo (T2 & T3 & T4)
- Nov/Dec 2005, ~950 min. (wobble)
- Fisher discriminant





Sources under analysis…

- Galactic sources
  - SNR RX J1713.7-3946
  - SNR RCW86
  - Kepler SNR
  - Plerion MSH15-52
  - …
- Extragalactic sources
  - Blazar PKS 2155-304
  - Starburst galaxy NGC253
  - Radio galaxy Centaurus A
  - …

(Hatched: observable from Woomera)

Summary

- CANGAROO-III 4-telescope stereo atmospheric Cherenkov telescopes are observing sub-TeV gamma-rays since 2004 March.
- Stereo analyses are being developed using local muons for calibration, and the energy spectrum of the Crab is consistent with other results.
- 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 appears as extended source, and the morphological study is progressing.
- Detection of TeV gamma-rays from supernova remnants are confirmed, giving evidence for supernova origin of cosmic rays. We need more TeV SNRs to know their energetics.
- Analysis of stereo observations of other sources are underway.