Recent results from CANGAROO

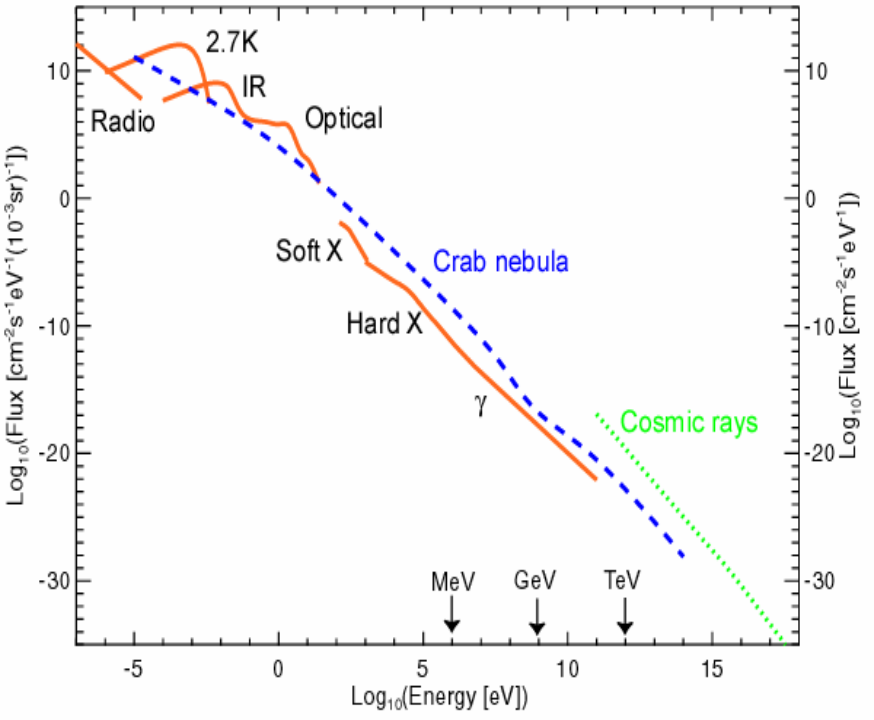
Masaki Mori*

for the CANGAROO team

**ICRR, The University of Tokyo*

International Workshop on Energy Budget in the High Energy Universe, February 22-24, 2006, Kashiwa, Japan

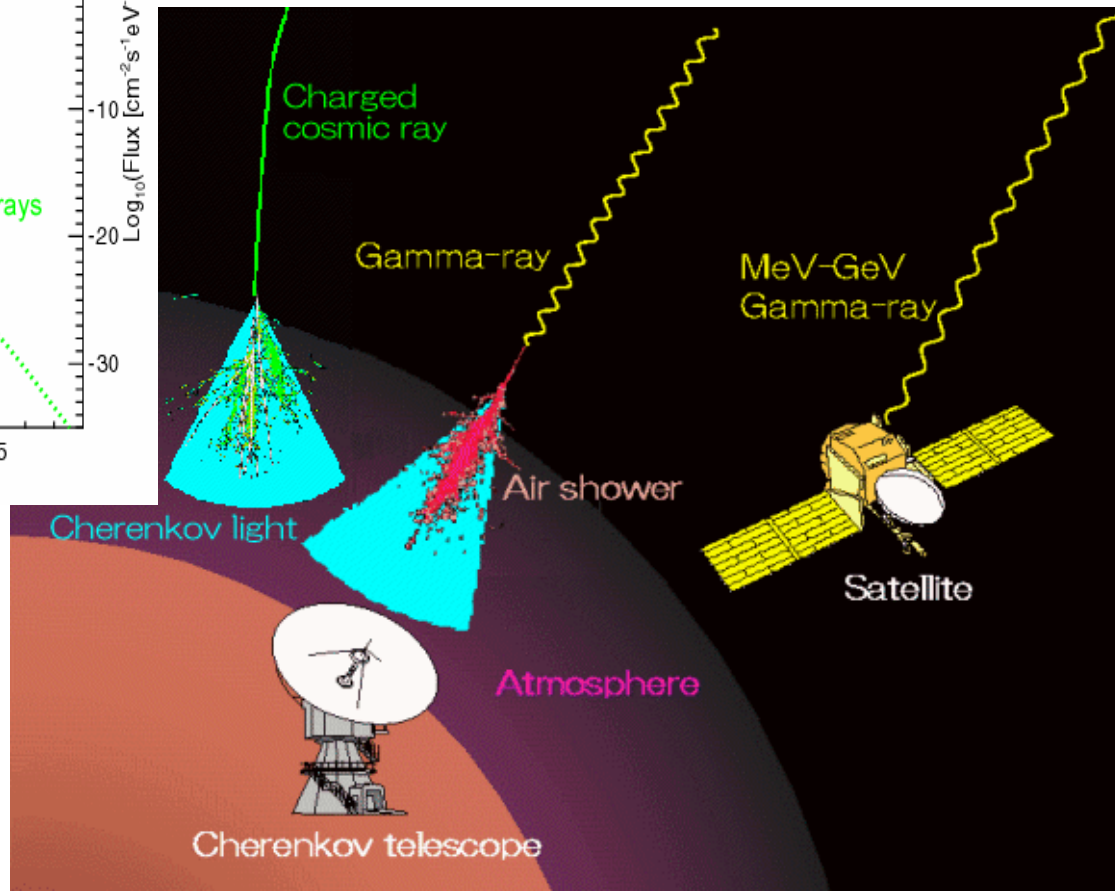
We have to rely on ground-based observation at TeV energies



Diffuse photon spectrum

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

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



Not much to say since you have heard Trevor's talk today...

“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 
- National Inst. Of Radiological Sciences 

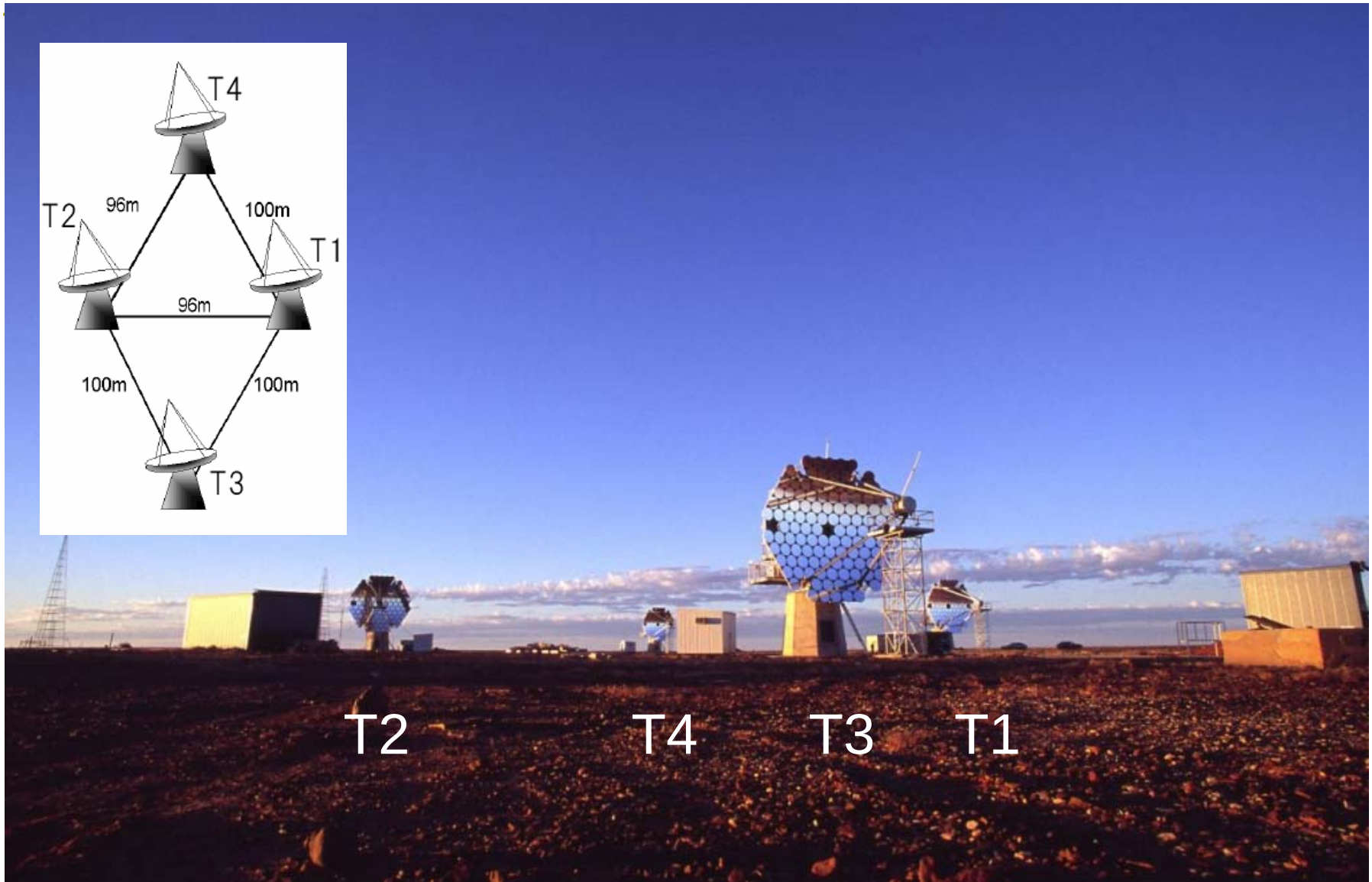
Brief history of CANGAROO

- 1987: SN1987A
- 1990: 3.8m telescope
- 1990: ICRR-Adelaide Physics agreement
- 1992: Start obs. of 3.8m tel.
- 1994: PSR 1706-44
- 1998: SNR SN1006
- 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 (3.8mϕ)

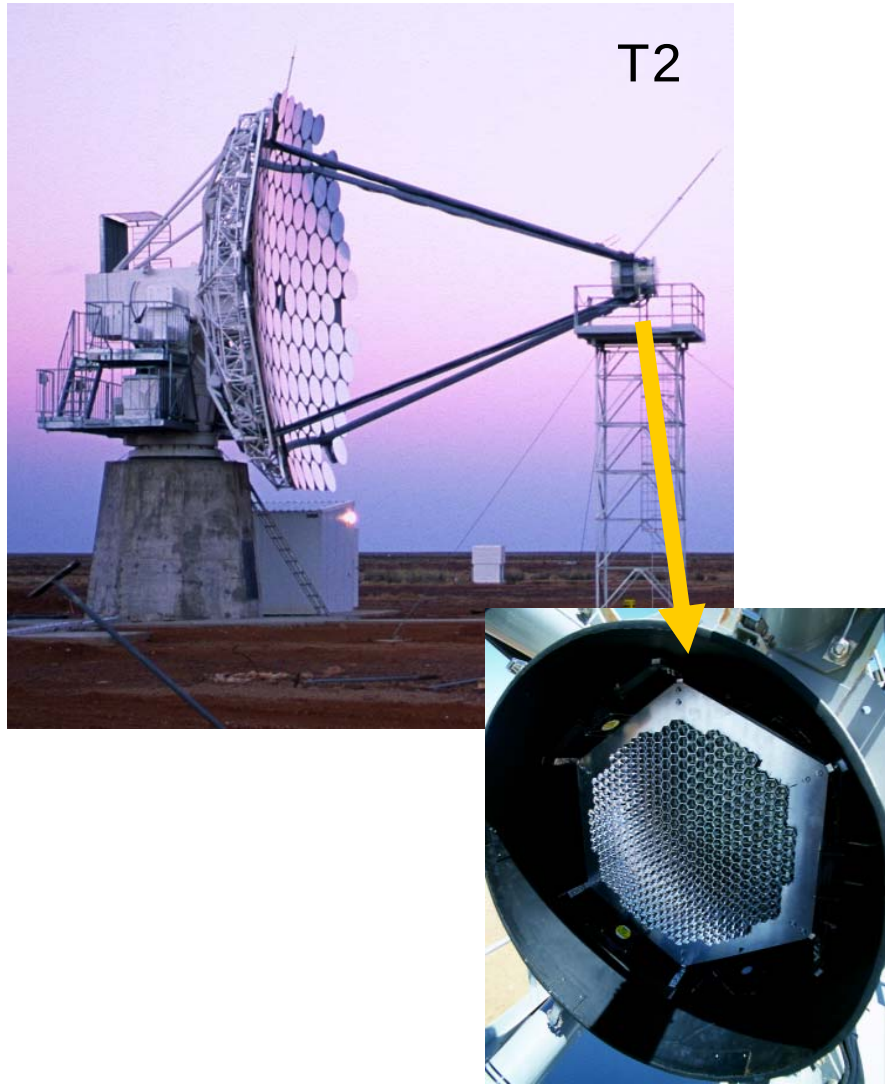
CANGAROO-II (10mϕ)

CANGAROO-III: 2004 March

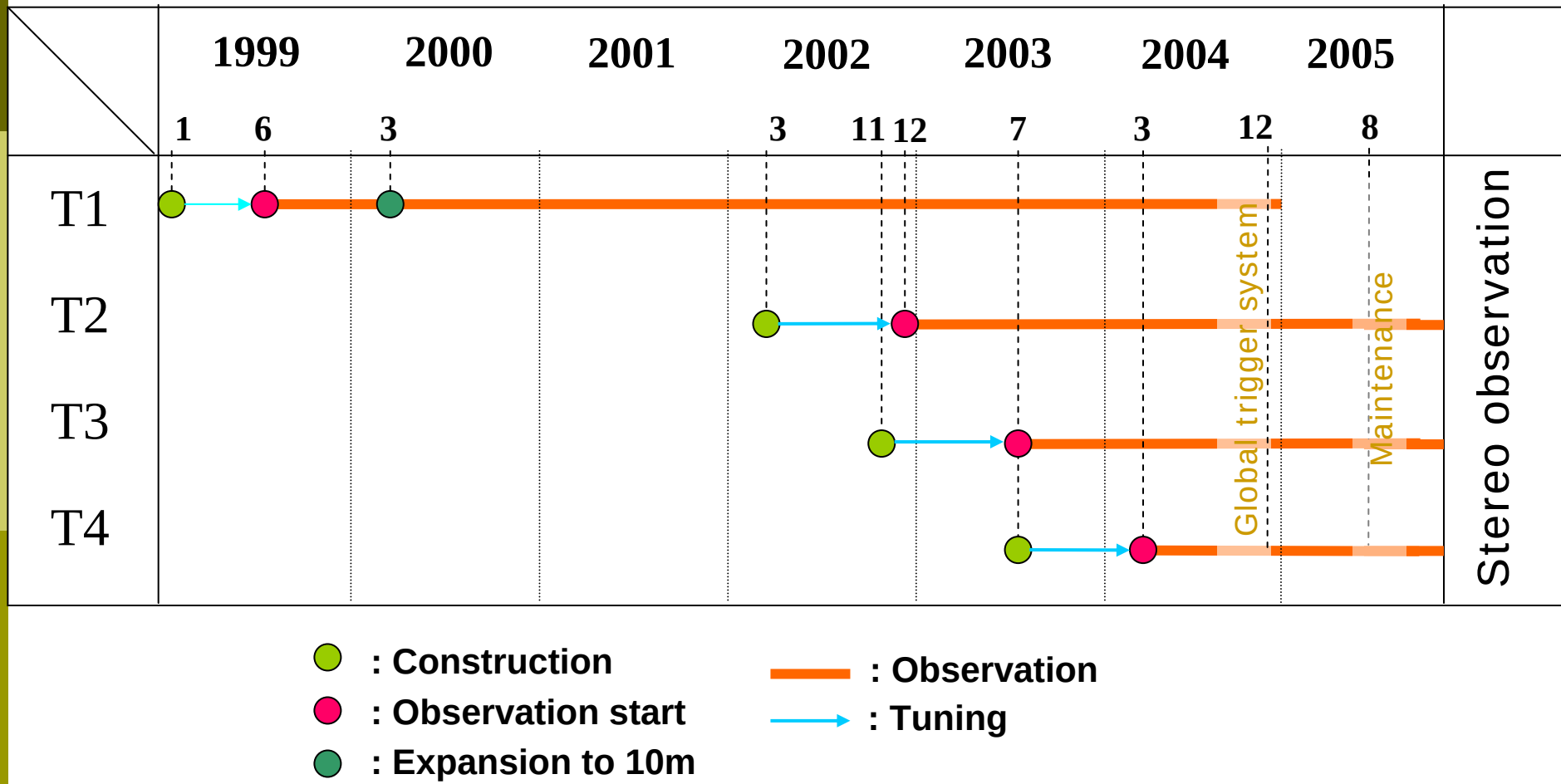


Basic specifications of telescopes

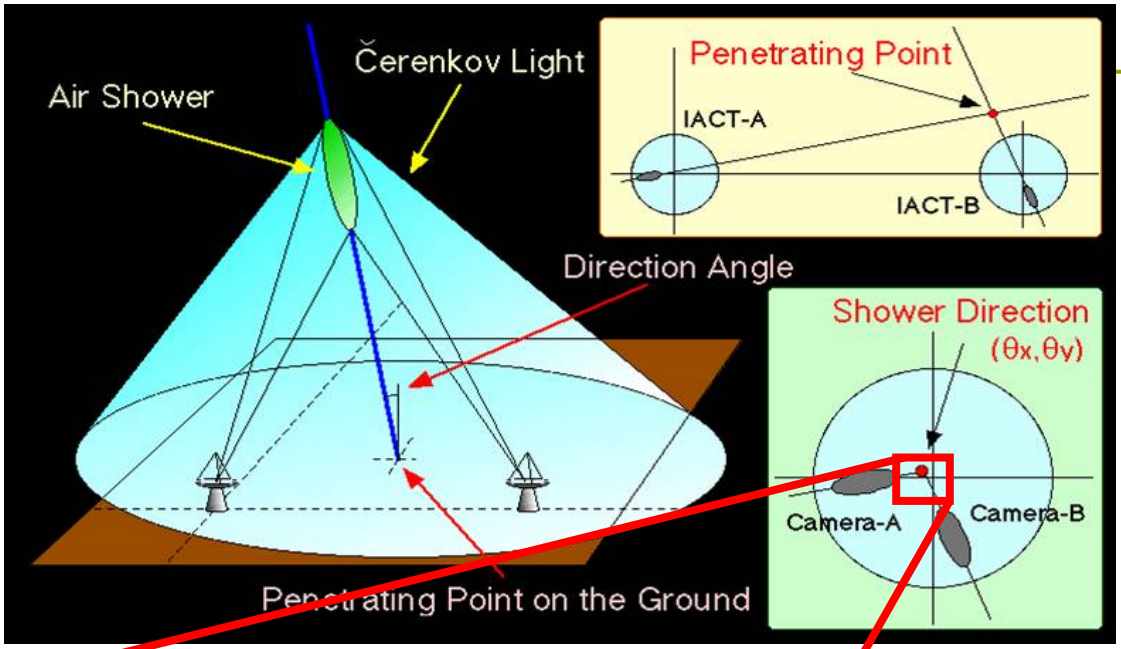
- Location:
  - 31°06'S, 136°47'E
  - 160m a.s.l.
- Telescope:
  - 114× 80cmϕ FRP mirrors (57m^2, Al surface)
  - 8m focal length
  - Alt-azimuth mount
- Camera:
  - T1: 552ch (2.7° FOV)
  - T2,T3,T4: 427ch (4° FOV)
- Electronics:
  - TDC+ADC

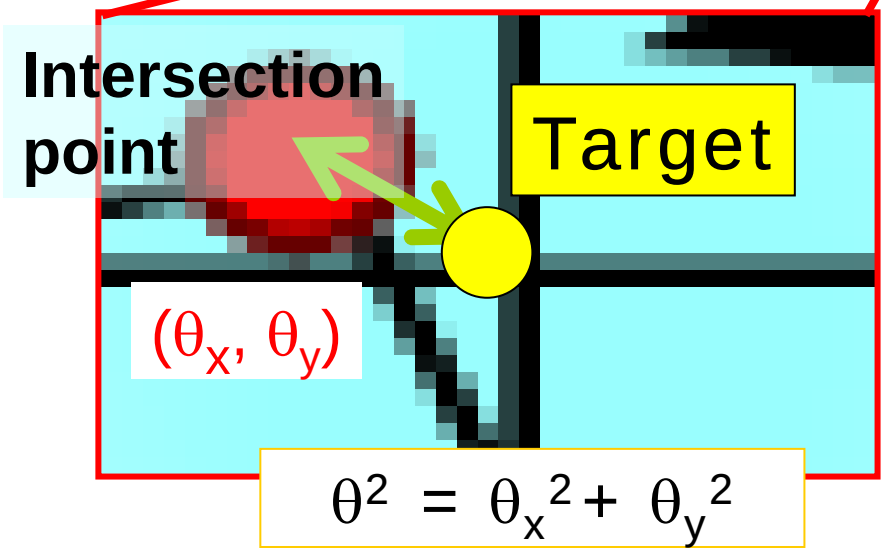


History of CANGAROO-III



Stereo observation





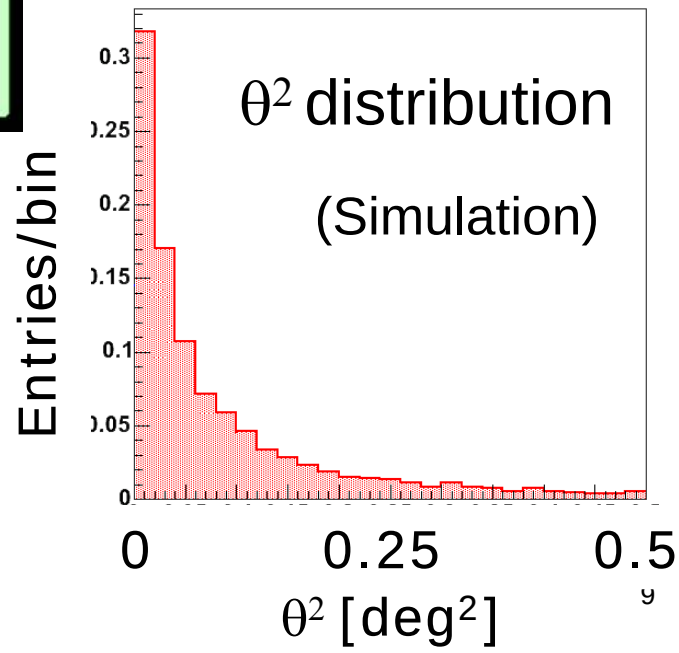
Angular resolution

0.25deg → 0.1 deg

Energy resolution

30% → 15%

Better S/N (no local muons)

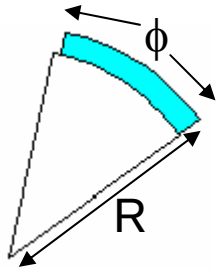


Stereo analysis: in progress

- 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

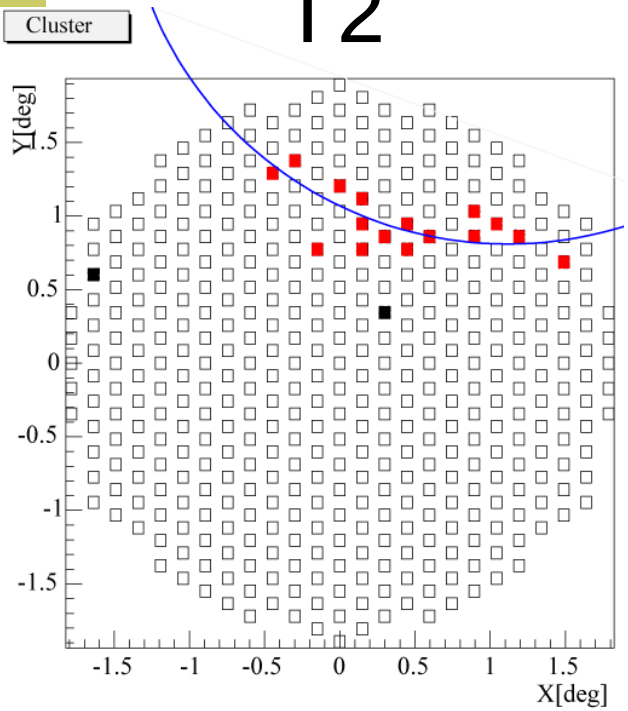
Muon events (1)

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

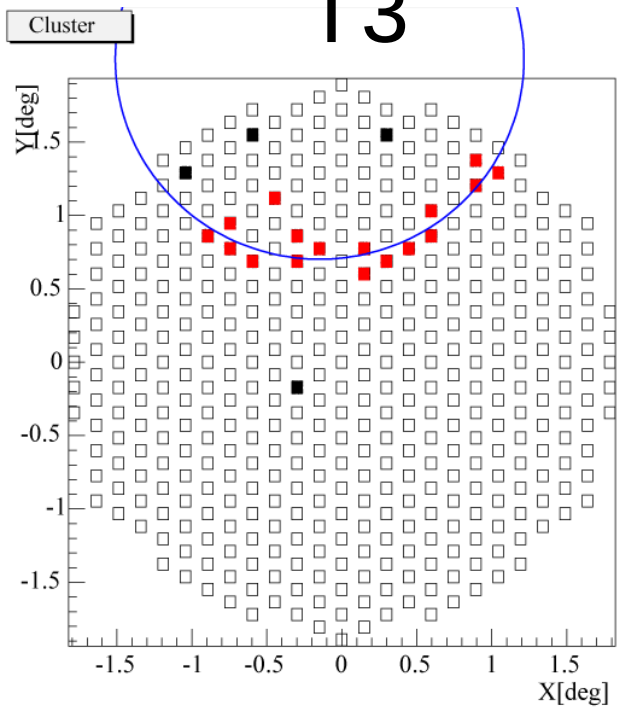


Data: 2004 March

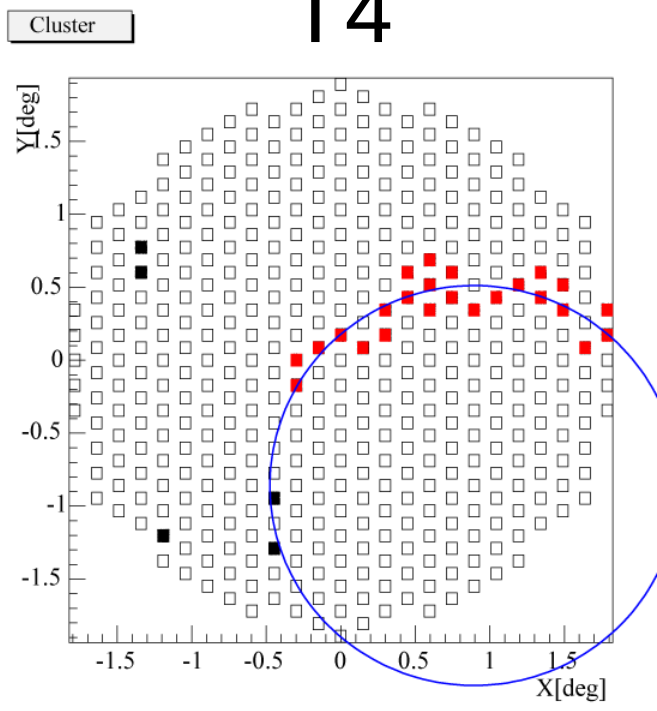
T2



T3



T4



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

Muon events (2)

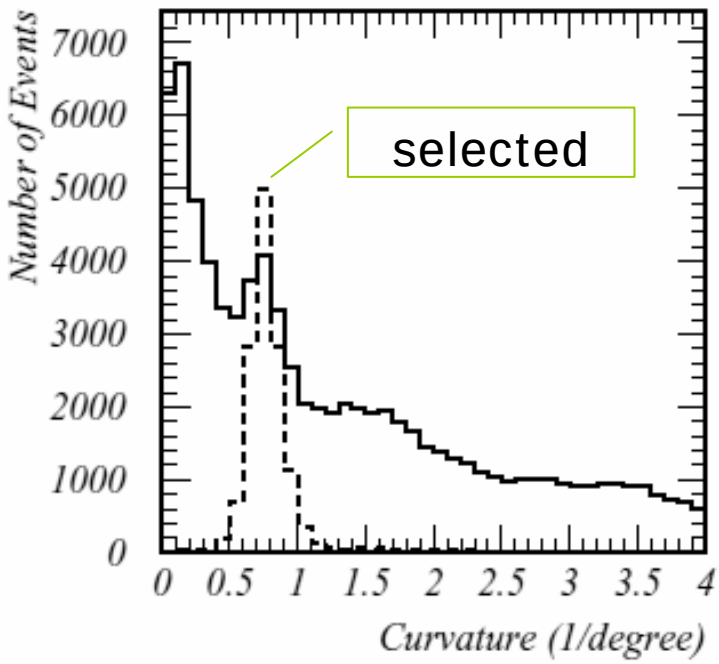


FIG. 2.— Curvature distribution for the circular fitting results of all events for T3. The solid histogram is for all events and the dashed one for the selected events (with the vertical scale multiplied by 5).

Local muons:

Cherenkov angle ~1.3°

or

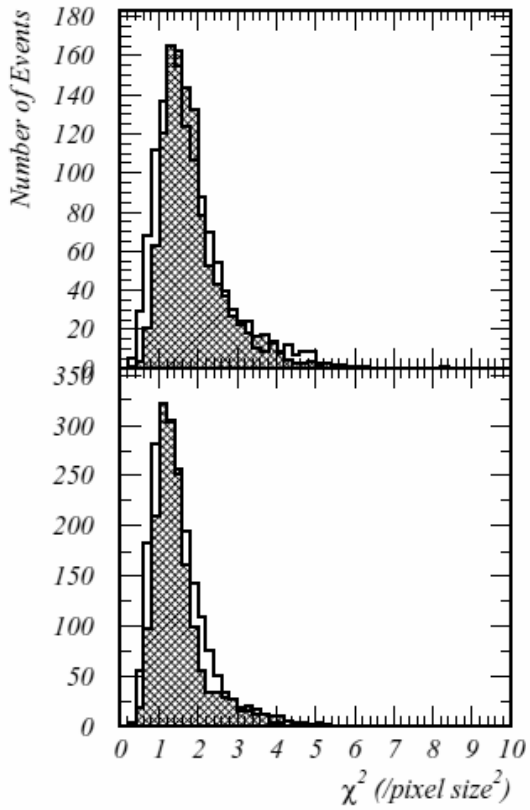
Curvature ~1/1.3°

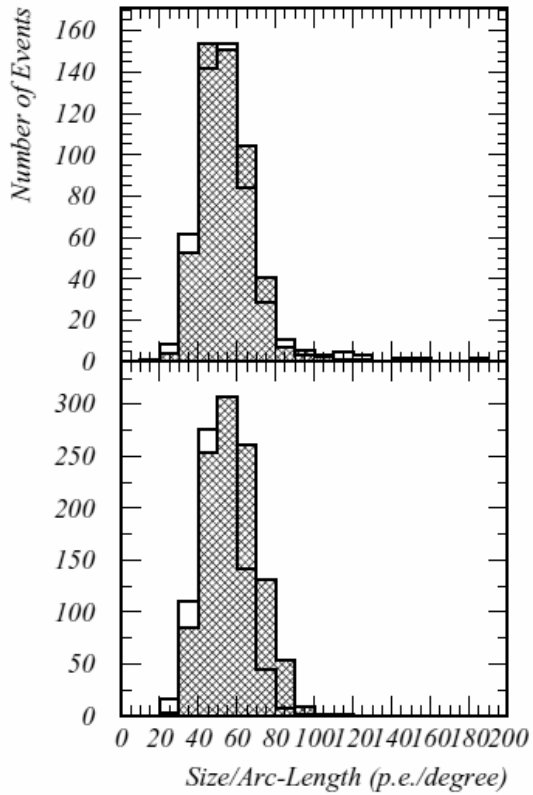
R.Enomoto et al., ApJ 638, 397 (2006)

Muon parameters compared with Monte Carlo

T2

T3





χ^2

size/arclength

Histogram: data

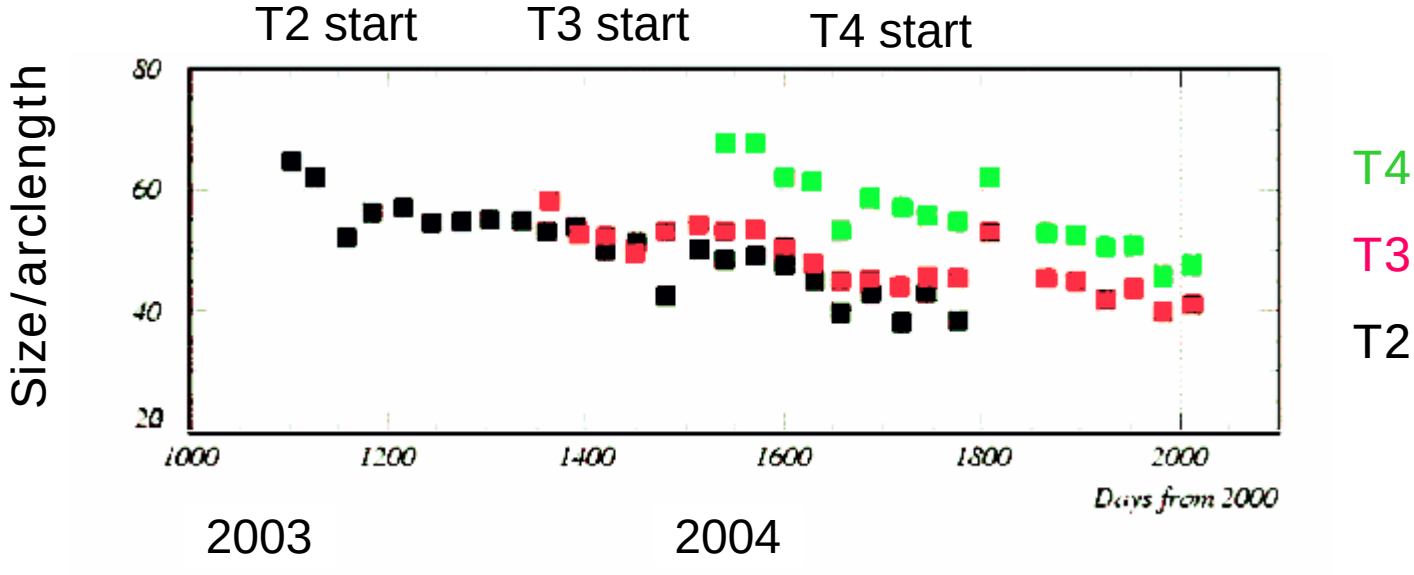
Hatched: M.C.

χ^2: for ring fitting

(sensitive to spot size)

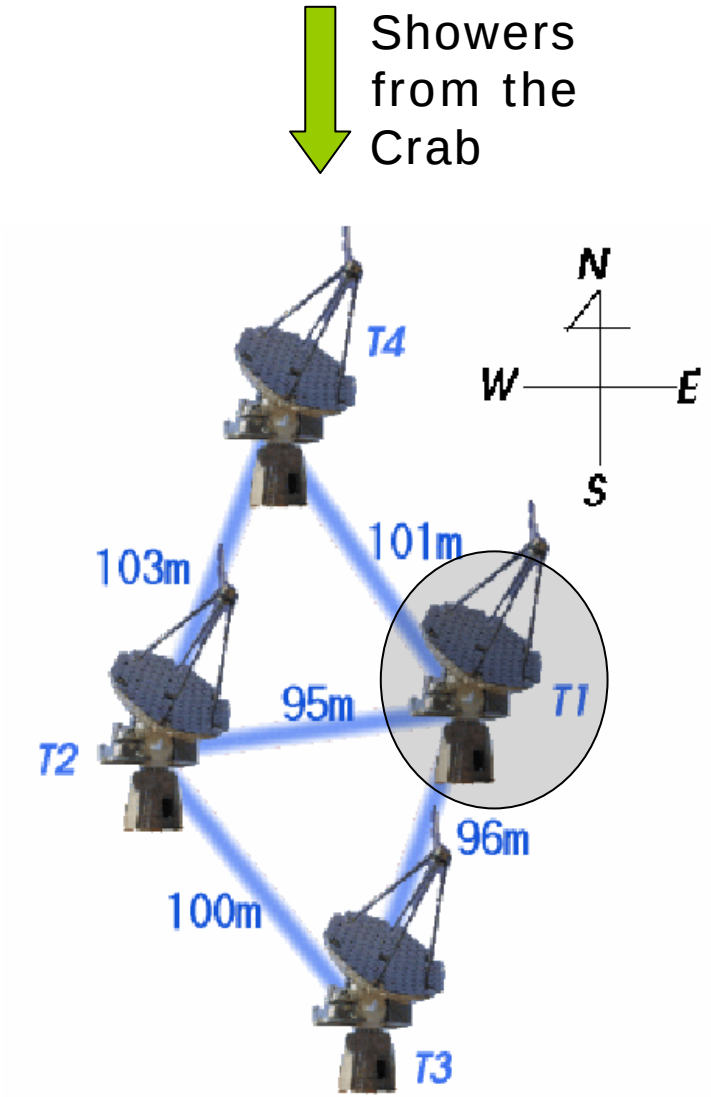
Size/arclength $\propto$ total light collection efficiency

Time variation of Size/Arclength



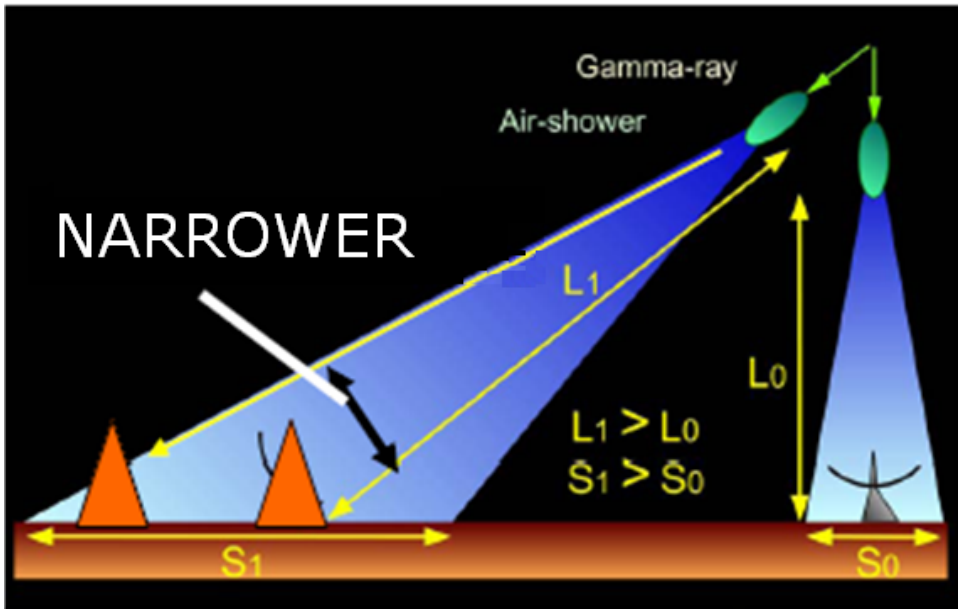
- Monitor of total light conversion efficiency
- Gradually, *Size/Arclength* is decreasing (~5% / year)
- Mirror degradation due to dust etc.

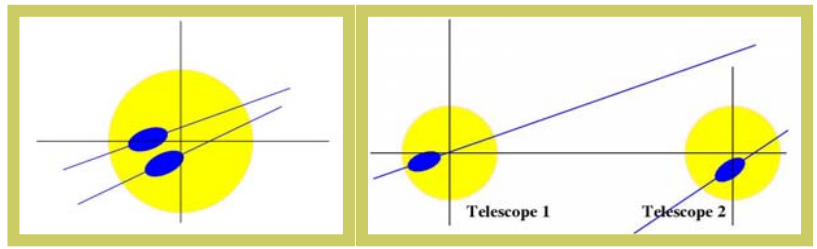
Unfortunate situation for the Crab



- 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

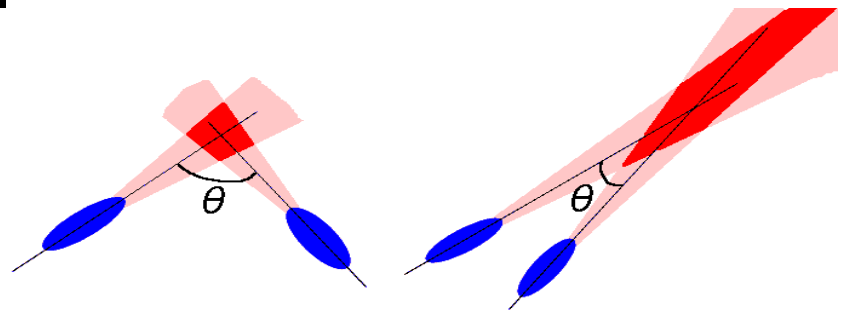




Far core
→small angle
→bad accuracy

Higher energy threshold ~1TeV

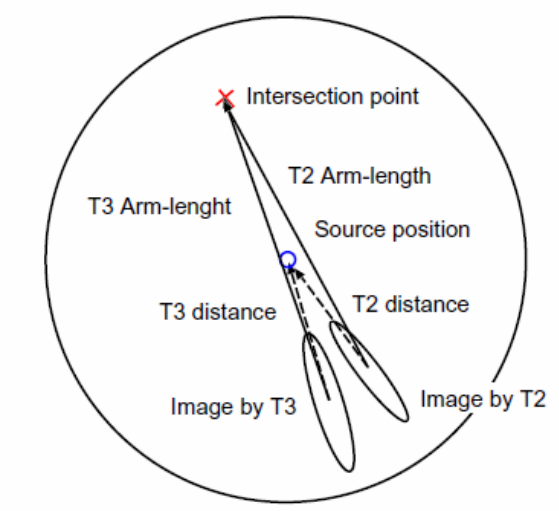
Bad intersection accuracy

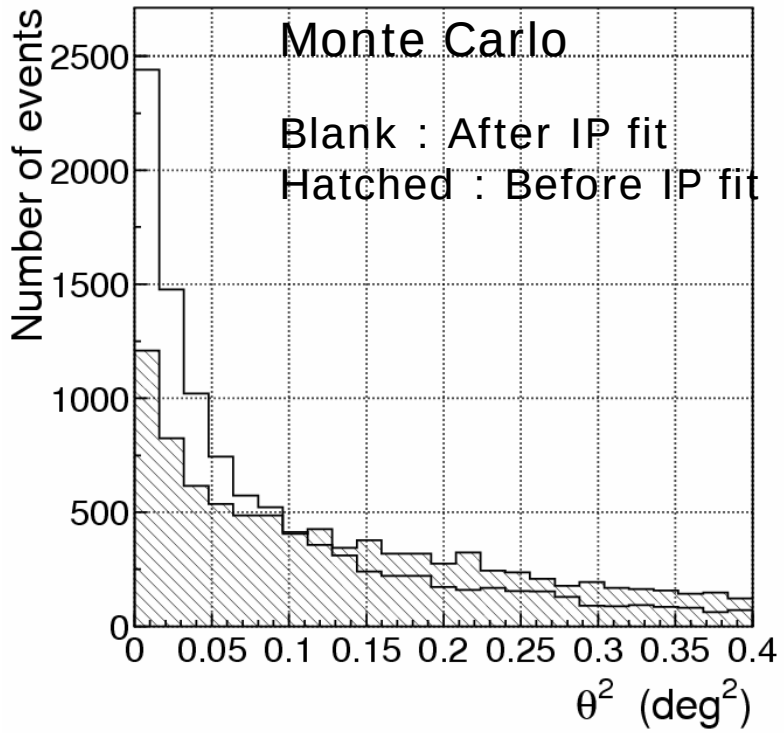


IP constraint fit

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

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)

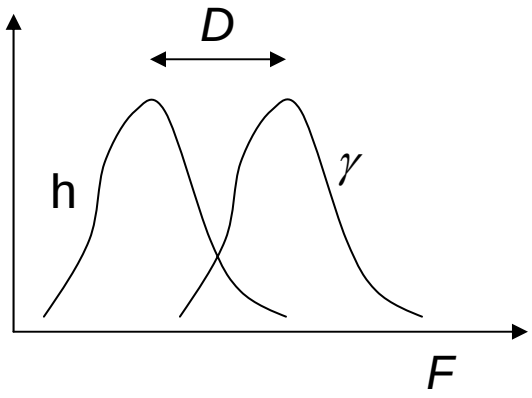
$$F \equiv \sum_i \alpha_i x_i$$

- 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)

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



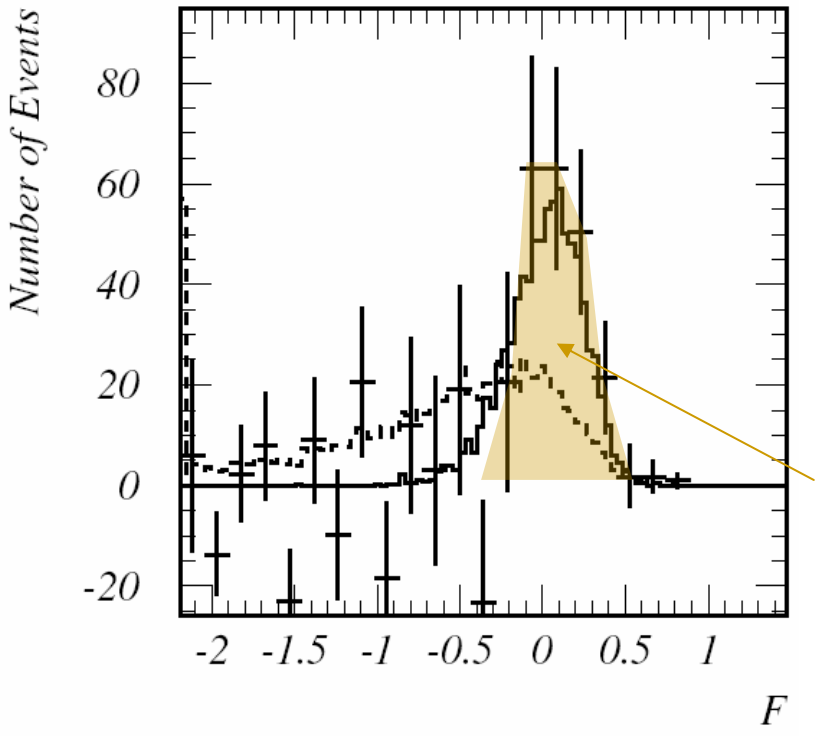
- With calculated α_i for a known source, the (appropriately normalized) combination *F* could be the "Fisher discriminant" for other sources.

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

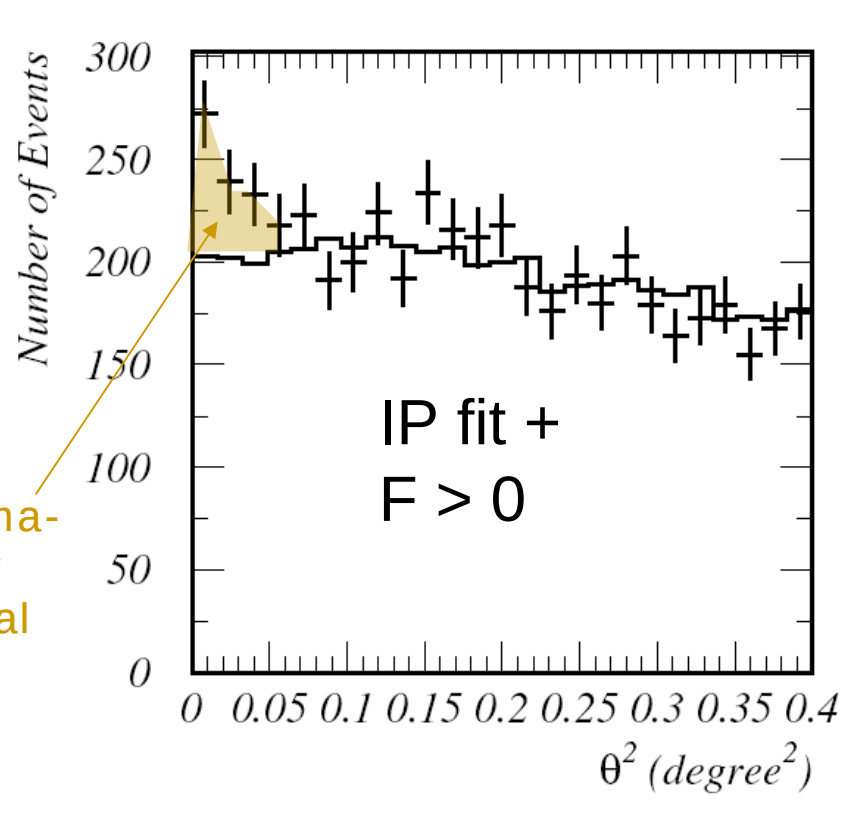
R.A. Fisher, Annals of Eugenics, 7 (1936) 179

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

Crab signal



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 spectrum

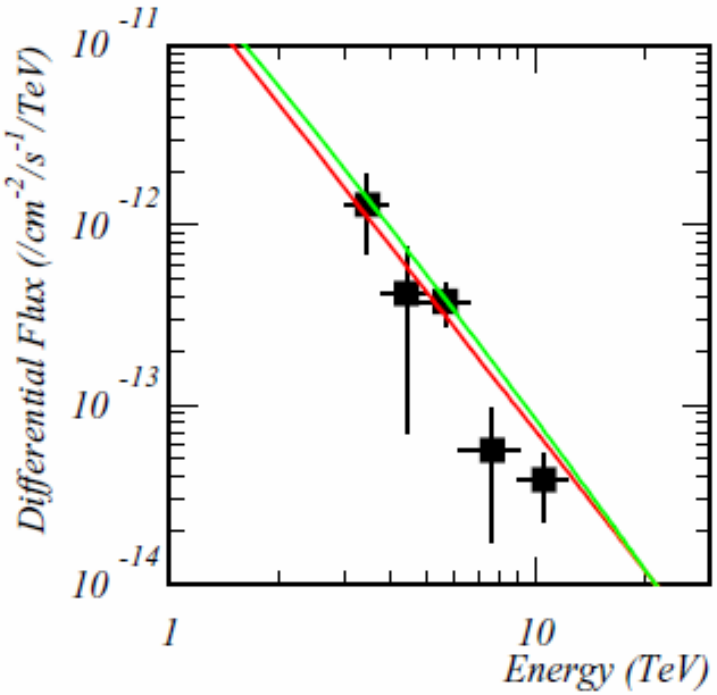
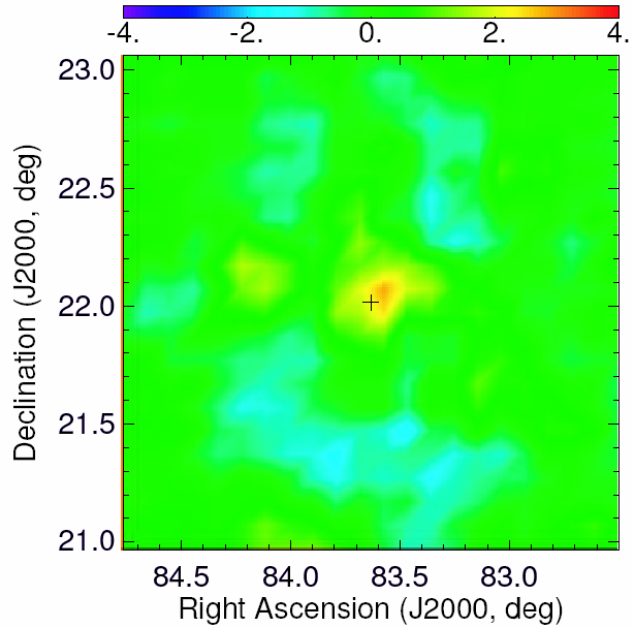


FIG. 17.— Differential gamma-ray flux from the Crab Nebula as a function of energy. The red line is the HEGRA result (Aharonian et al. 2000) and the green is the Whipple result (Hillas et al. 1998).

Excess event map



Angular resolution ~ 0.23 deg

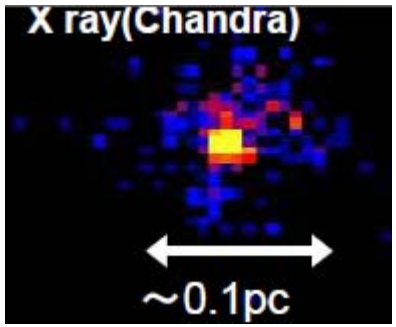
CANGAROO-I claims vs. H.E.S.S.

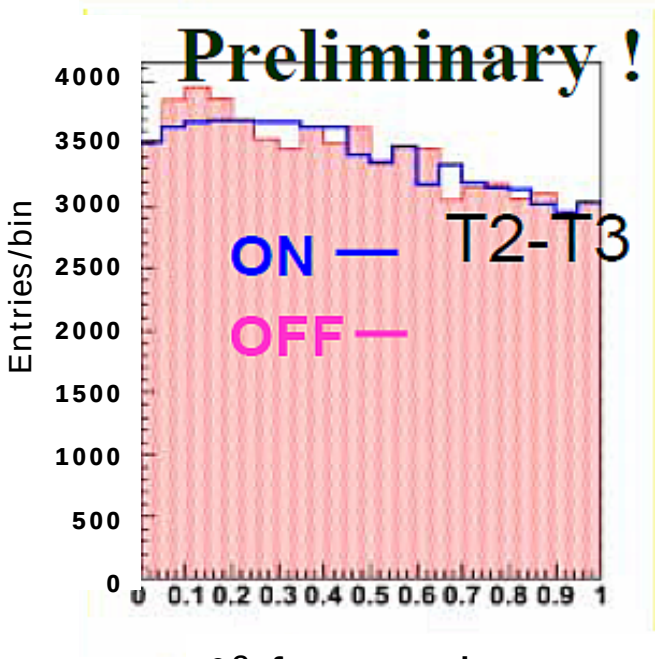
- CANGAROO-I claims
  - Pulsar PSR1706-44 : 0.57Crab (~8σ, >1 TeV)
    [Kifune et al. ApJ 431, L195, 1995]
    - Cf. H.E.S.S. upper limit: 0.024Crab (>0.5TeV)
      [Aharonian et al. A&A 432, L9, 2005]
  - SNR SN1006 : 0.81Crab (5.3σ, >3 TeV) [1996]
    0.62Crab (7.7σ, >1.7TeV) [1997]
    [Tanimori et 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

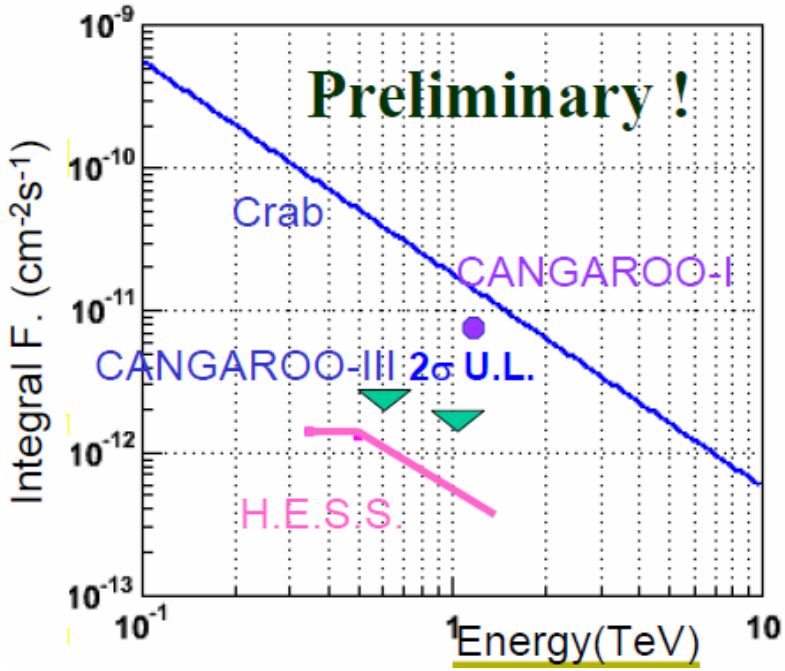
PSR 1706-44





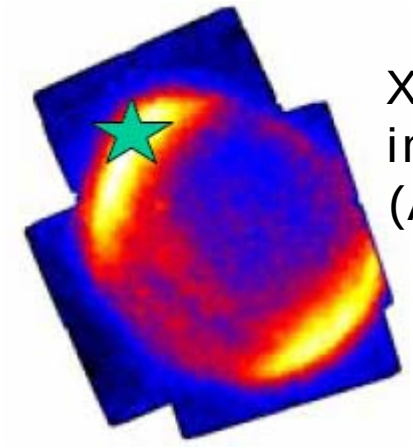
θ^2 from pulsar

- 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.)



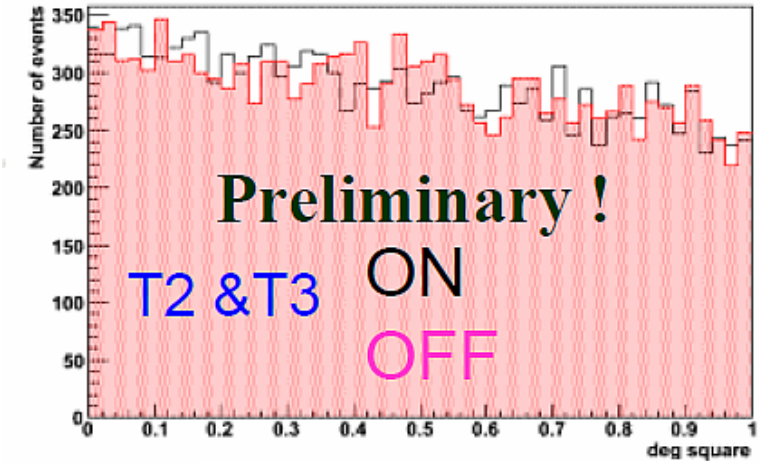
T.Tanimori et al., ICRC2005

SN1006 (G327.6+14.6)

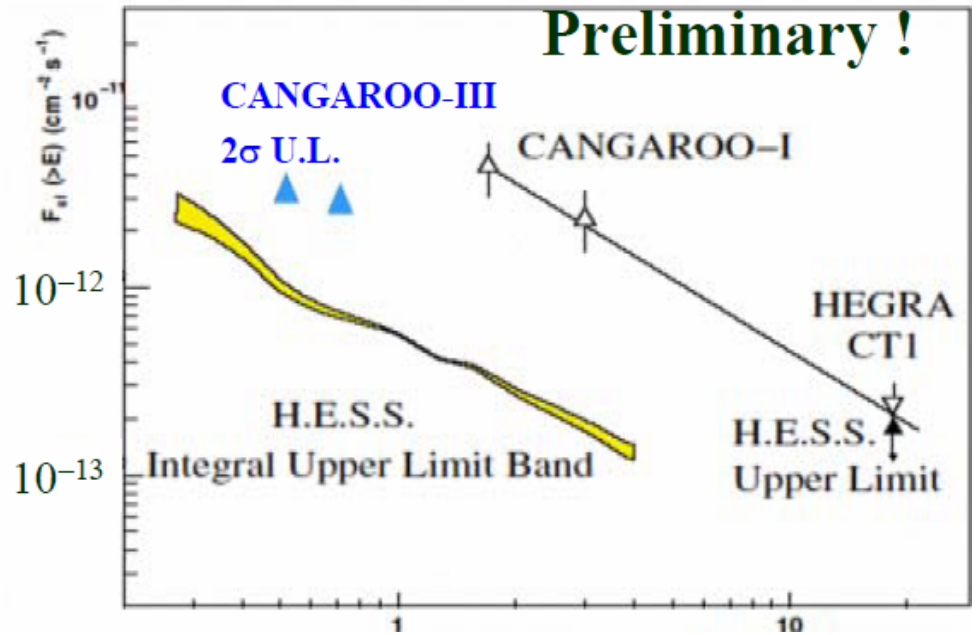


X-ray image (ASCA)

- 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.)



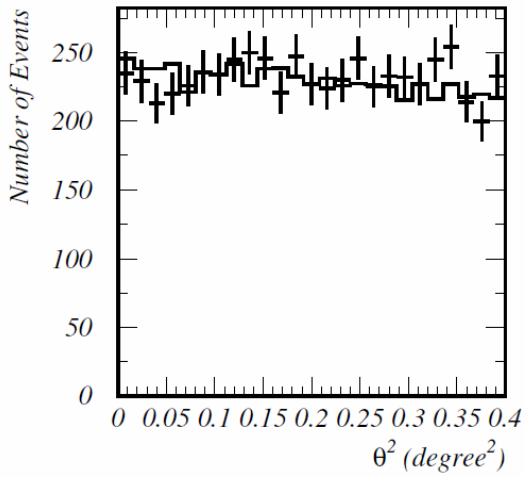
θ^2 from NE rim

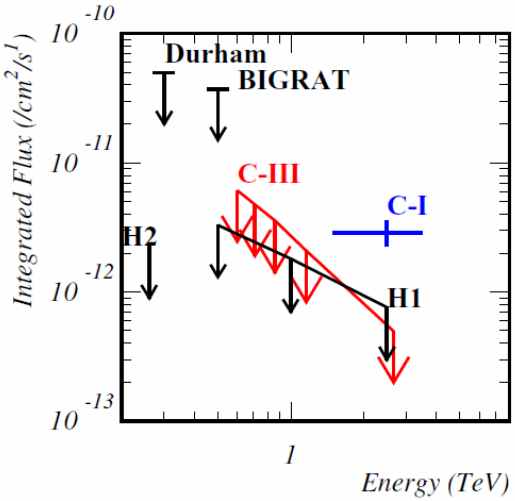


R.Enomoto et al., ApJ 638, 397 (2006)

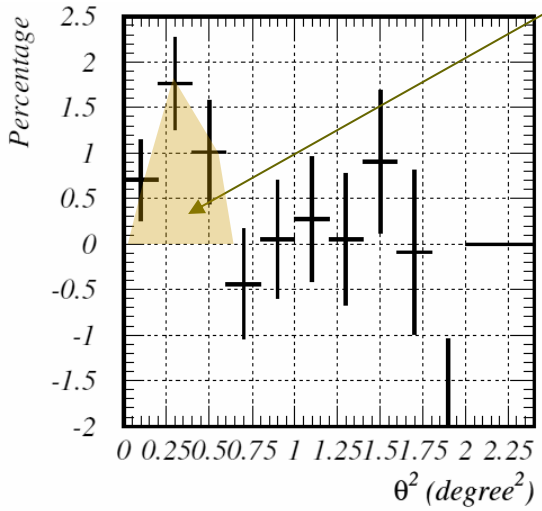
Vela pulsar/nebula

Pulsar position



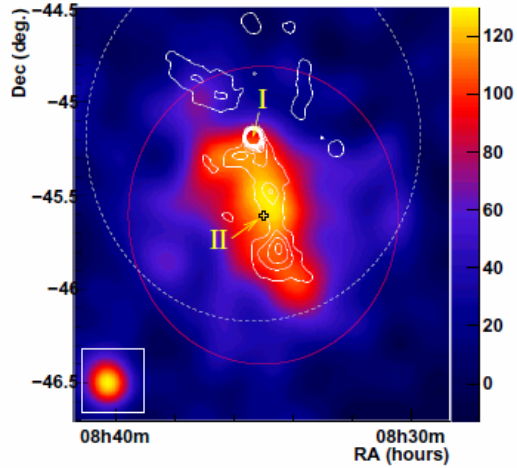


- Pulsar pointing (2004 Jan/Feb)
- Stereo (T2 & T3 wobble), 1,311 min.
- Fisher discriminant



θ² from Vela X center

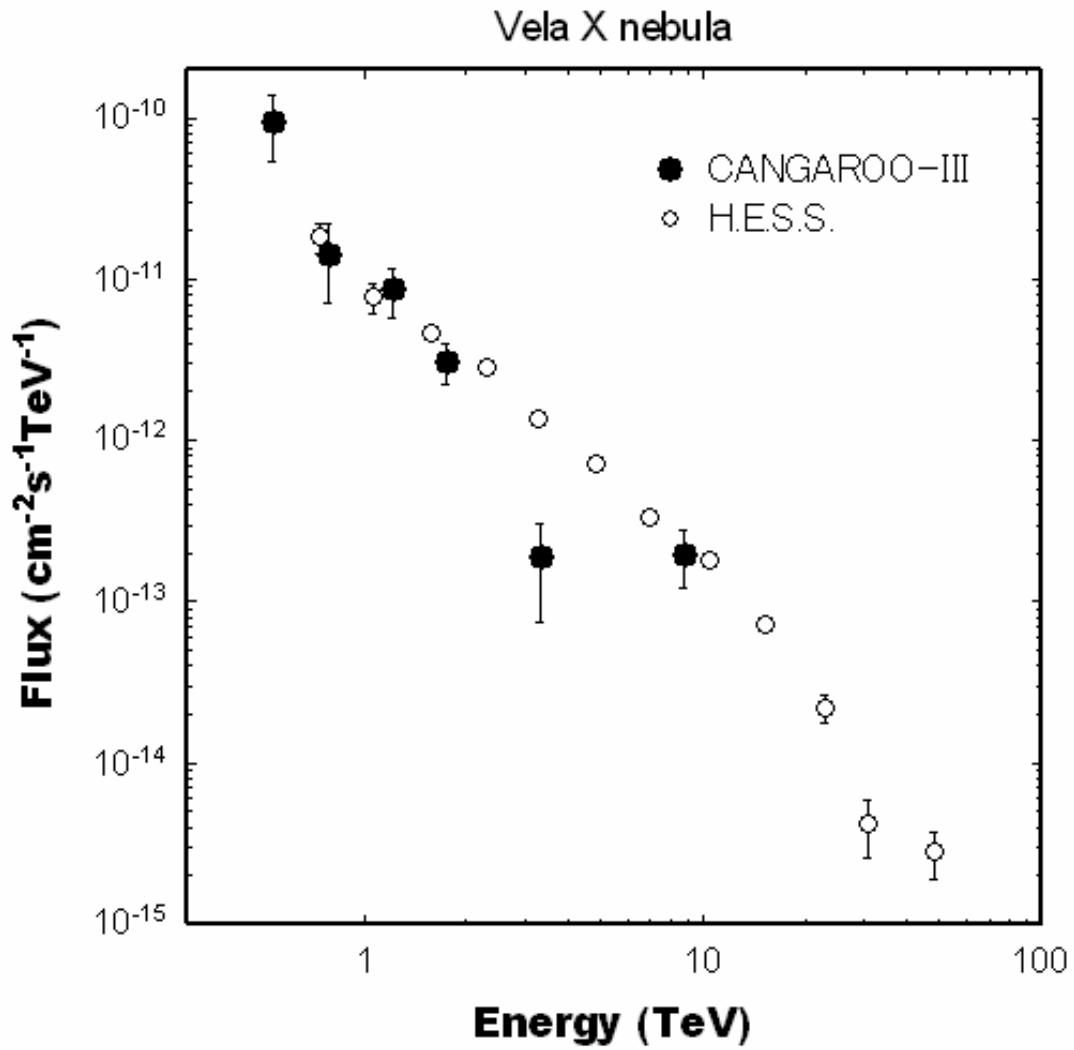
Vela X nebula



H.E.S.S., astro-ph/0601575

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
$\propto E^{-1.45}\exp(-E/13.8\text{TeV})$

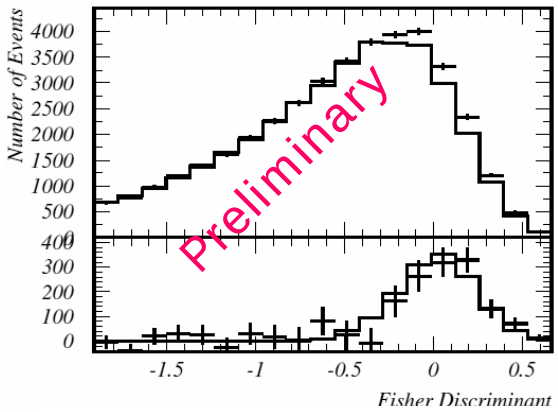
CANGAROO-II claims vs. H.E.S.S.

- 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)

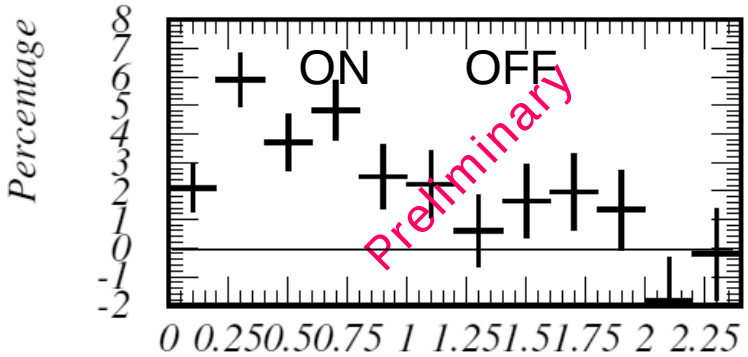
SNR RX J0852.0-4622

In preparation

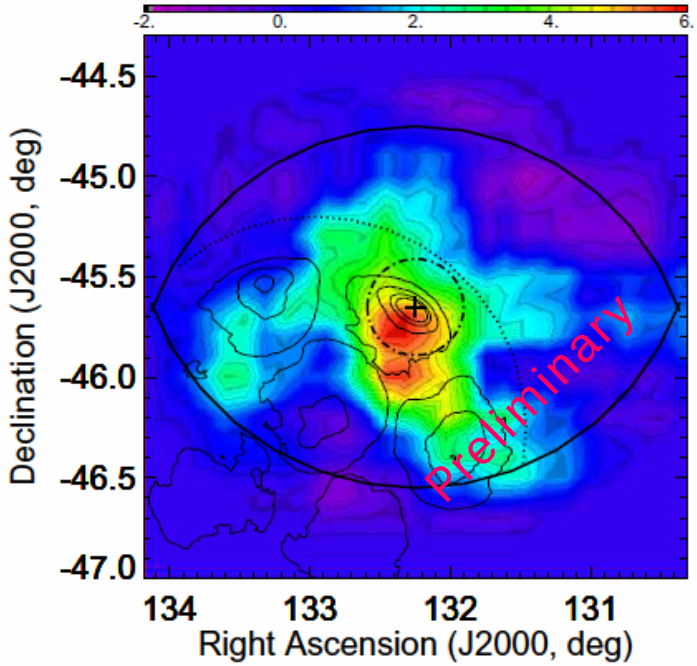


Fisher discriminant

- 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.)

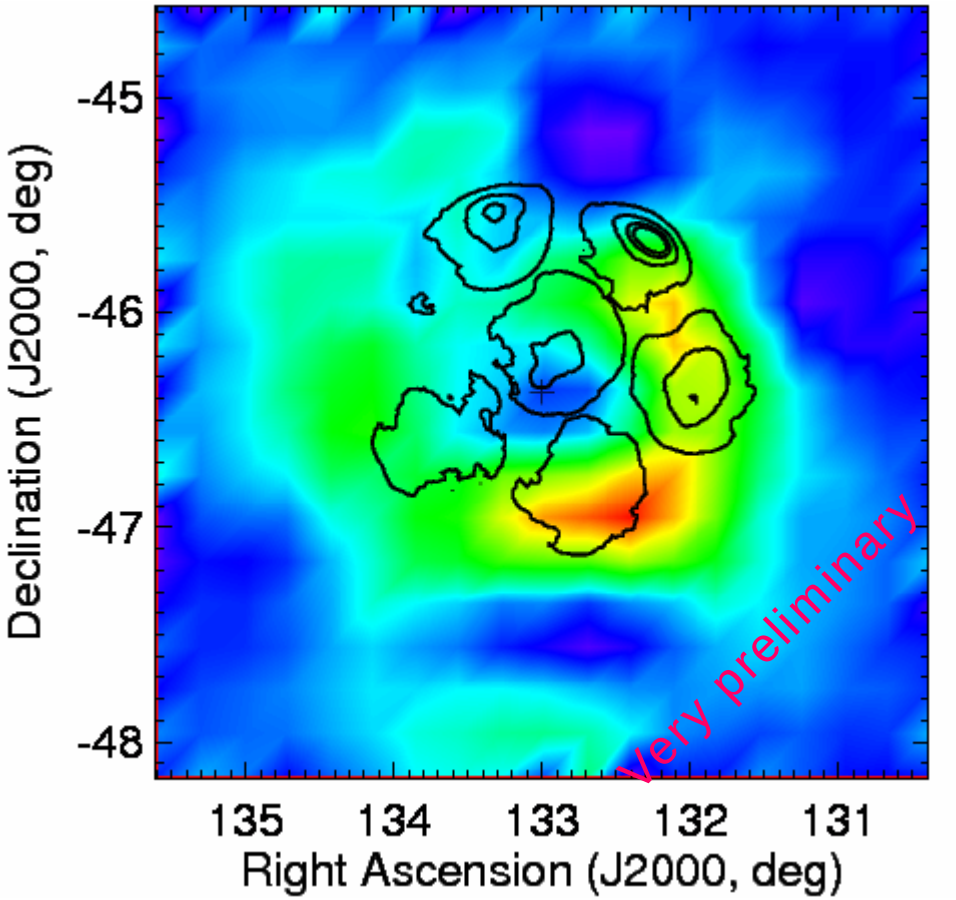


Excess event map



SNR RX J0852.0-4622

In preparation



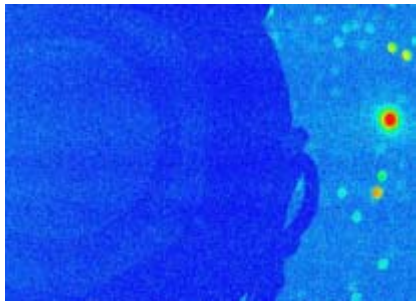
2005 data

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

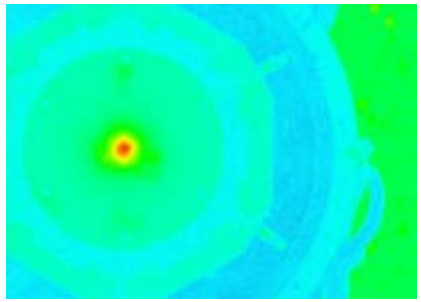
Maintenance works in 2005 Sep/Oct

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

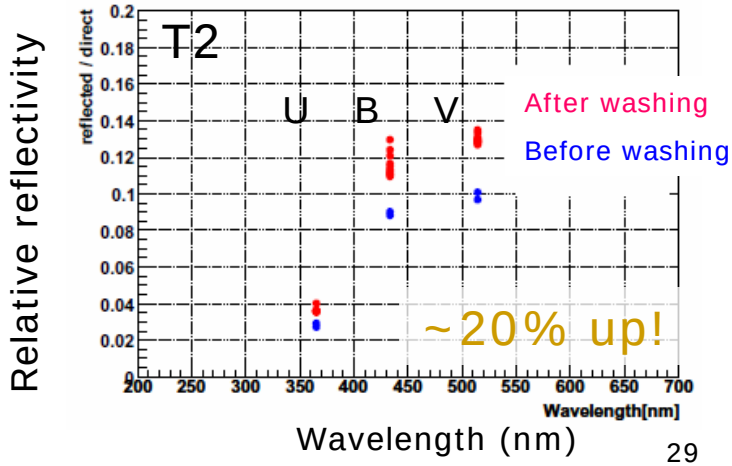
Reflectivity measurement using star images



Direct star images



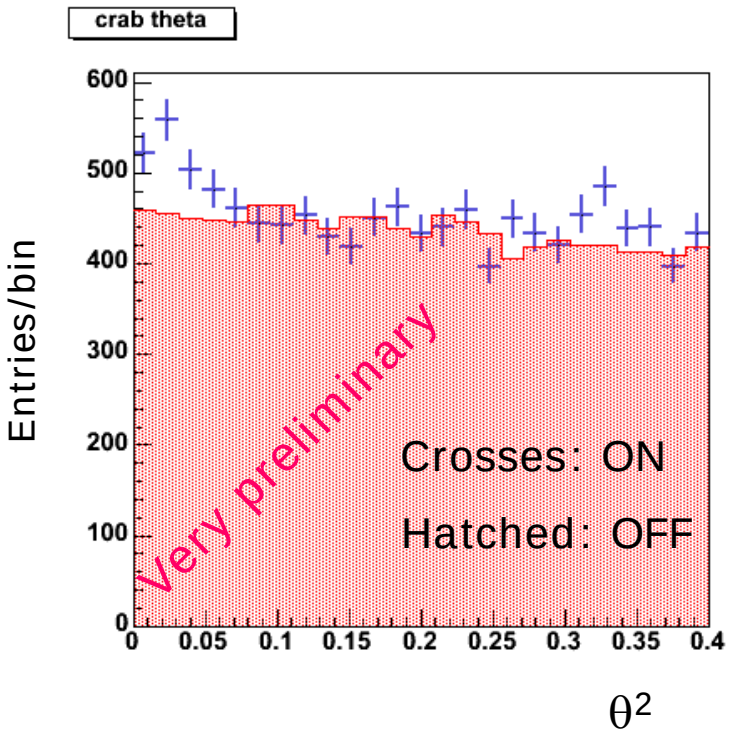
Reflected image of stars

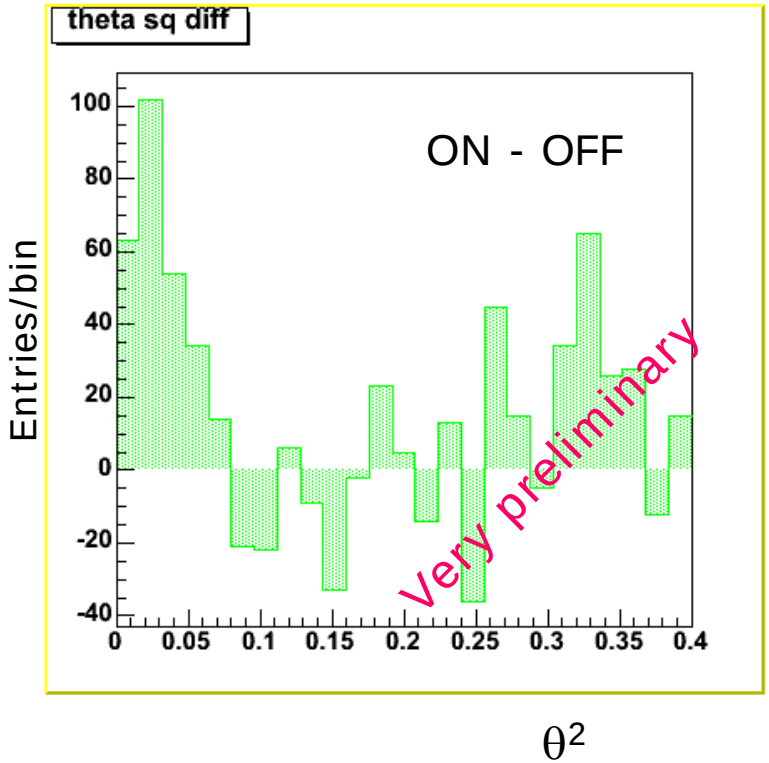


(See Kiuchi's poster!)

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)

CR energetics & SNR: How many TeV SNRs?

- Number of active SNRs in Galaxy
  - SN rate ~ 1/30yr, accelerating particles during ~ 10^4yr
    $\Rightarrow$ ~300 active SNRs
    $\Rightarrow$ ~3 SNRs within 1kpc (assuming Case & Battacharya distribution [A&AS 120, 437,1996])
- We have two SNRs (RXJ1713, RXJ0852) emitting ~1*Crab* TeV gamma-rays, both at ~1 kpc
  - L_γ ~ 6×10^{35}erg/s (>GeV, assuming $E^{-2.6}dE$)
  - 300 SNRs $\Rightarrow$ W_γ(Galaxy) ~ 2×10^{38}erg/s
- Cosmic ray power in Galaxy
  - 1 eV/cm^3, V~$10^{66\text{-}67}$cm^3, τ~$10^{14\text{-}15}$s $\Rightarrow$ W_{CR} ~10^{40}erg/s
- $\therefore$ $W_\gamma \sim 0.02 W_{CR}$: low efficiency!? Or more SNRs?

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.