Are supernova remnants PeV accelerators ?
The contribution of HESS observations

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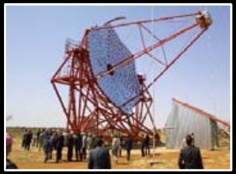
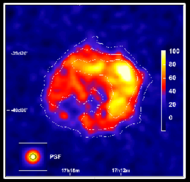
Outline

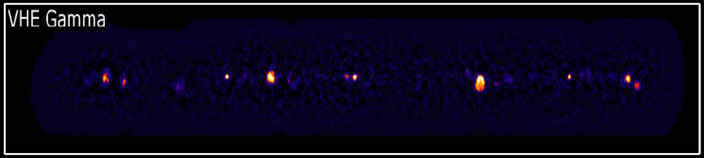
1. VHE Gamma-ray Astronomy & HESS



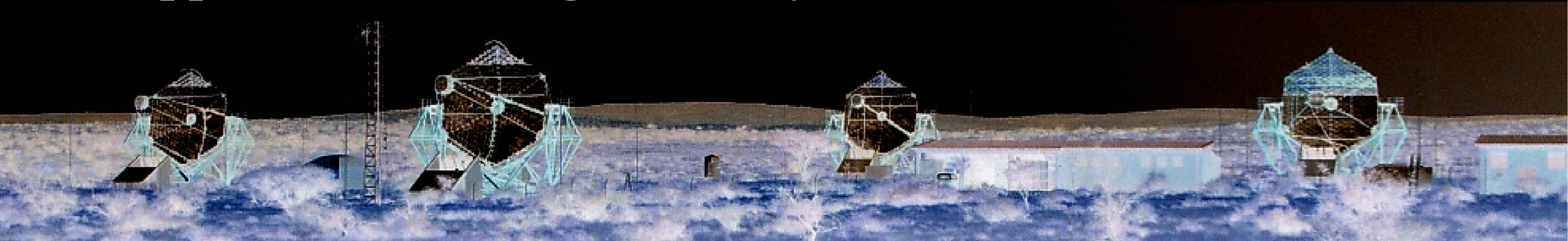
2. Clearly identified shell-type supernova remnants



3. HESS sources from the Galactic Plane survey compatible with shell-type SNRs



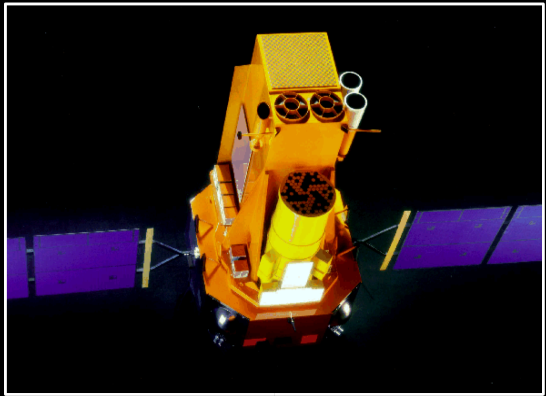
4. Upper limits on the gamma-ray flux from non-detected SNRs



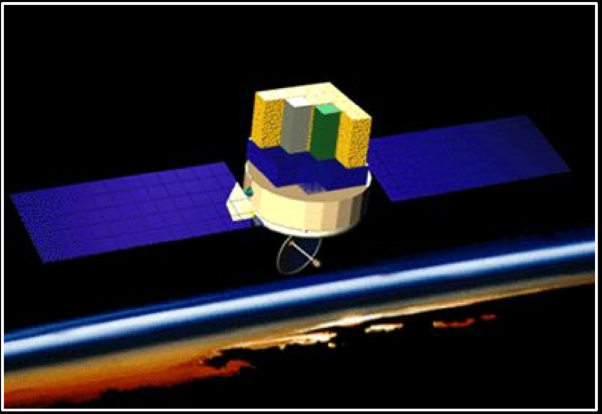

VHE Gamma-ray Astronomy
& H.E.S.S.

Gamma-ray Astronomy instruments

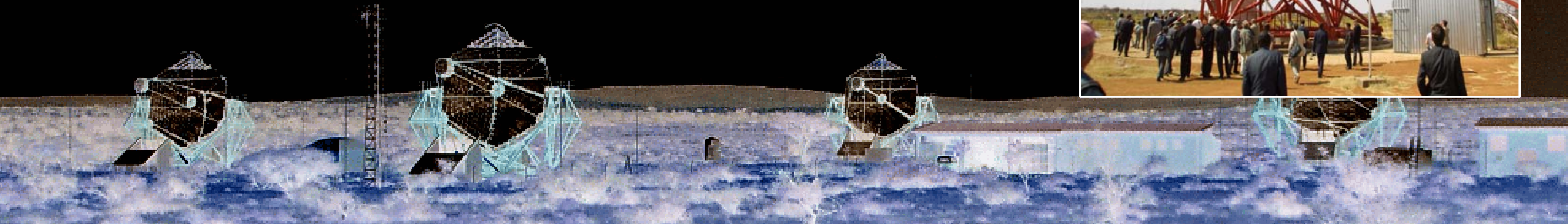
soft γ-rays: E < 10 MeV
INTEGRAL



HE γ-rays:
10 MeV < E < 100 GeV
EGRET, AGILE, GLAST

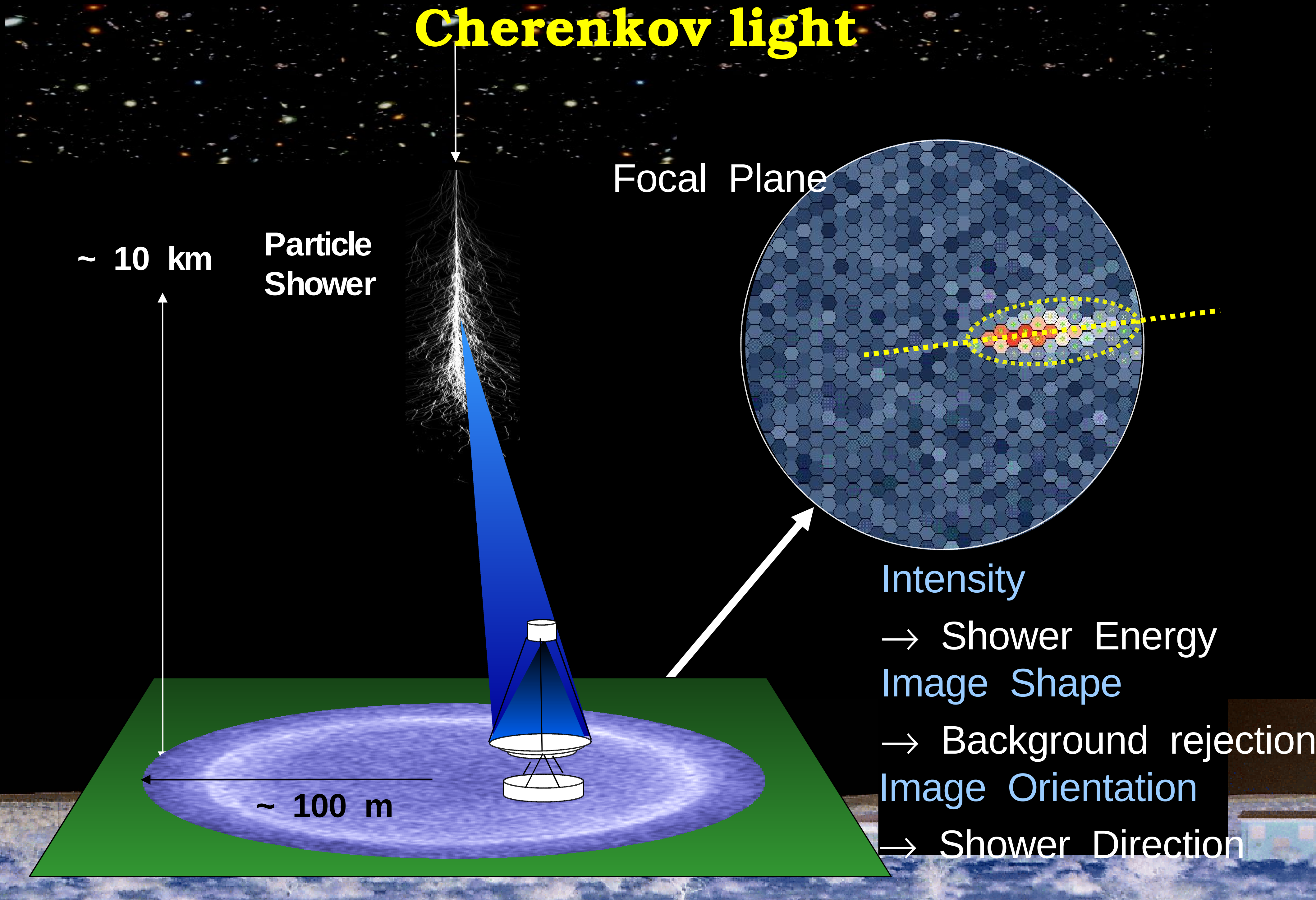


VHE γ-rays
E > 100 GeV
H.E.S.S., VERITAS...



Cherenkov telescopes worldwide

Detecting very high energy γ-rays with Cherenkov light

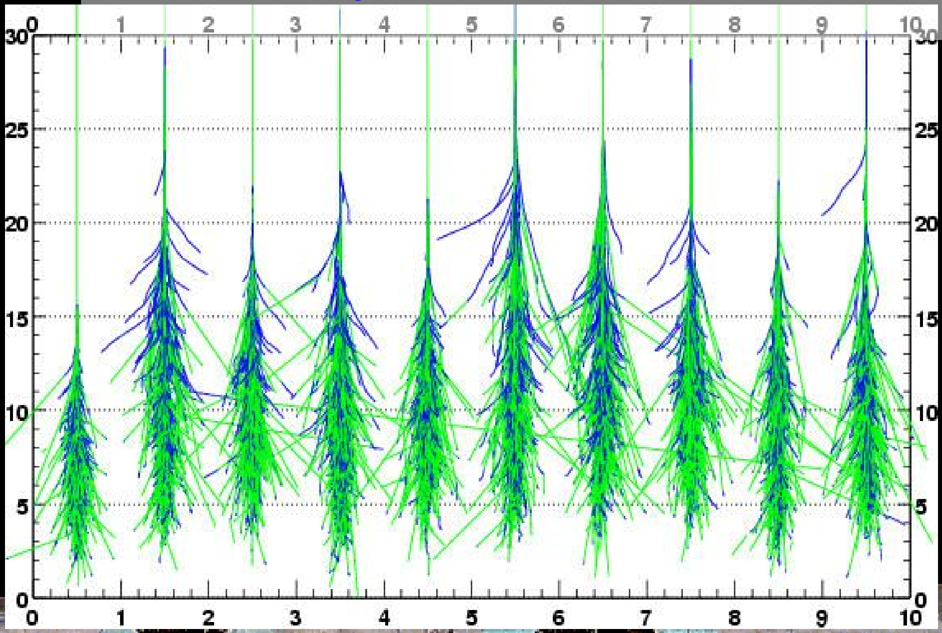


Hadronic background

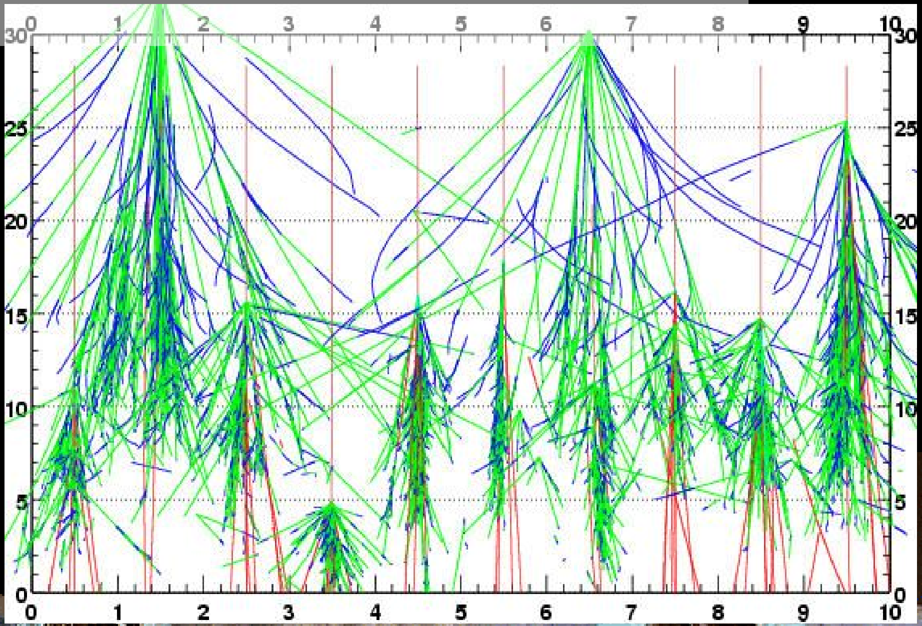
The development of hadronic showers is different from gamma-ray showers:

- Broader transverse moments
- No rotational symmetry

γ-rays

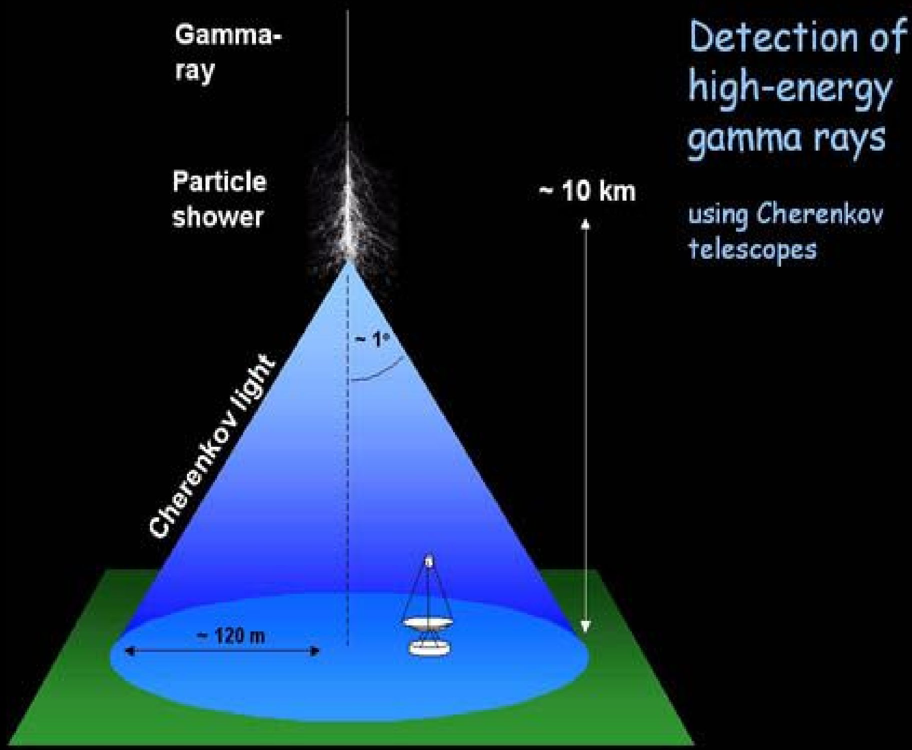


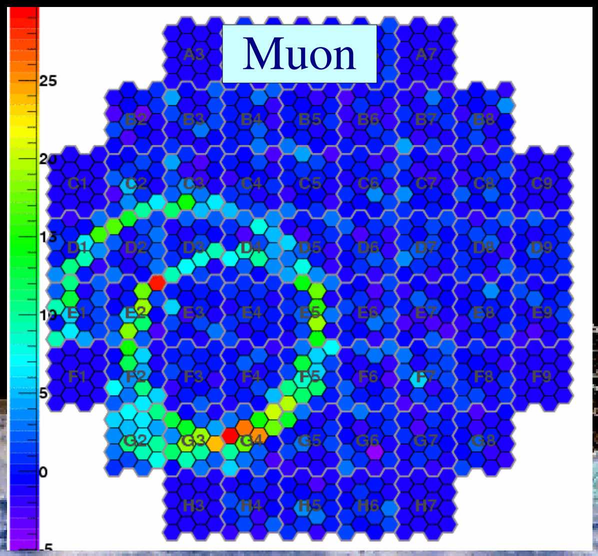
Hadrons

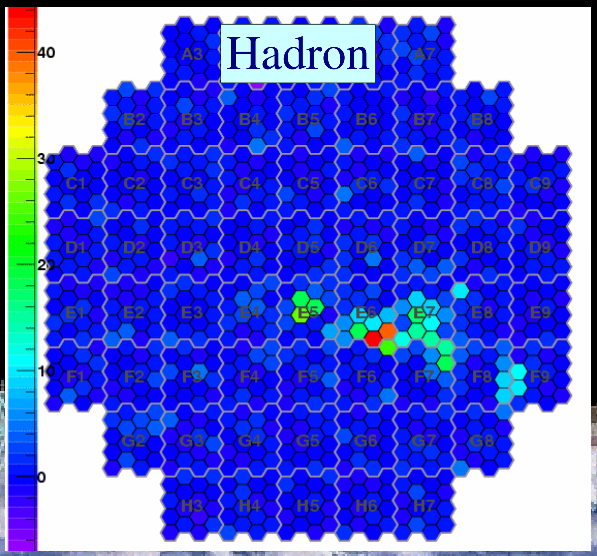


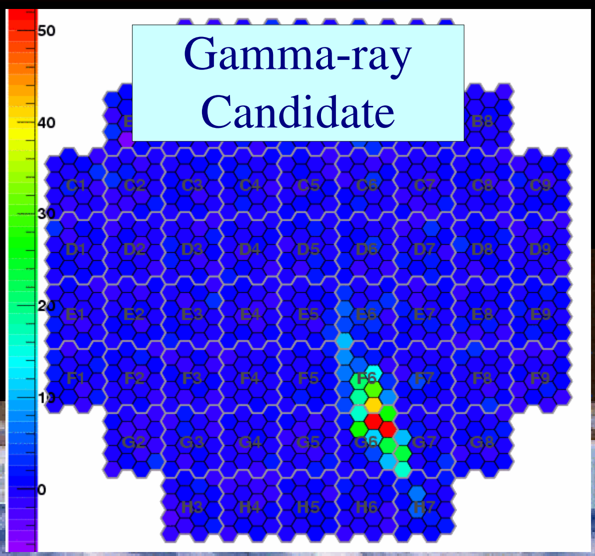
The atmospheric Cherenkov technique

- Electromagnetic showers develop in the atmosphere emitting Cherenkov radiation
- Image obtained in the cameras
- Morphological analysis of the image









Standard reconstruction

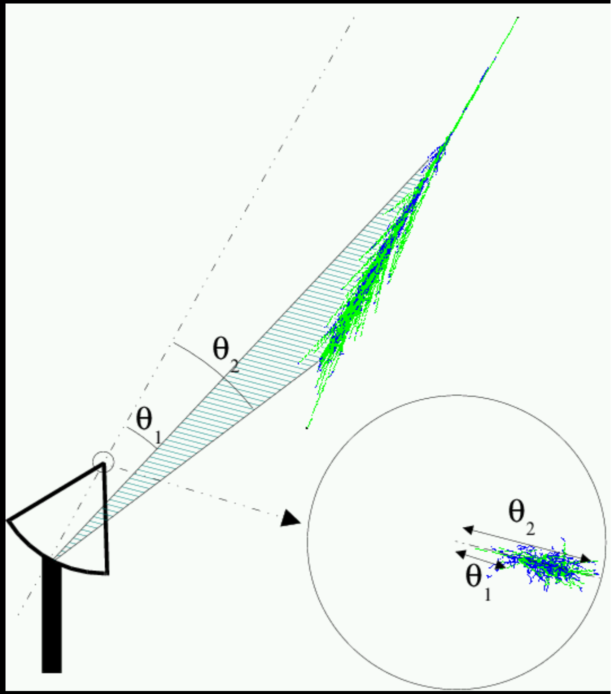
Hillas Parameters (1984):
γ images are elliptical
⇨ reduce image properties to a few numbers:

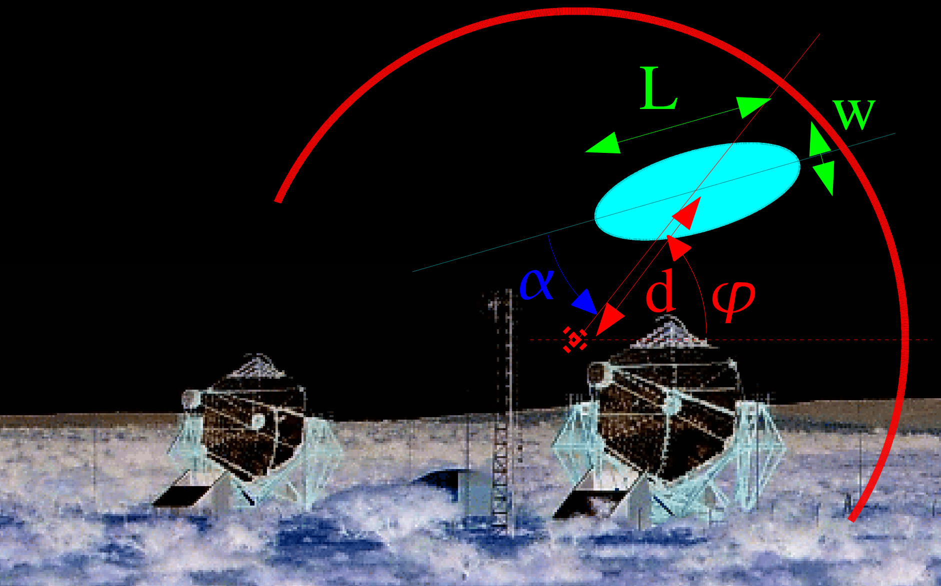
Length (L) & Width (w)

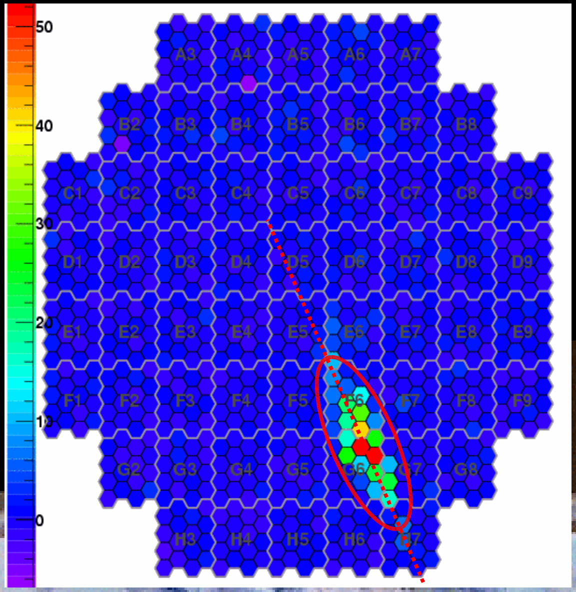
Amplitude (size)

Nominal Distance (d)

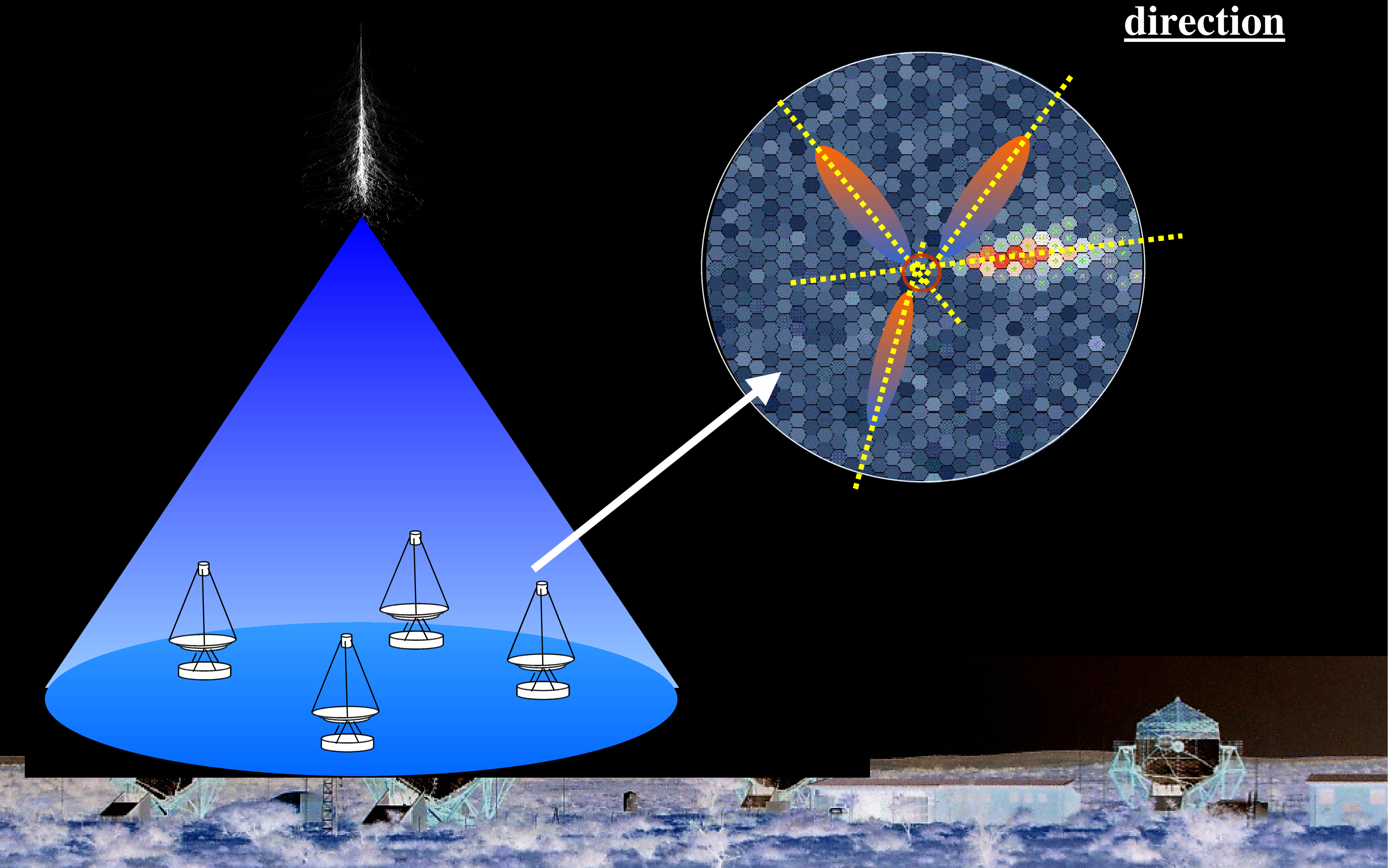
Azimuthal angle (ϕ) and orientation angle (α)



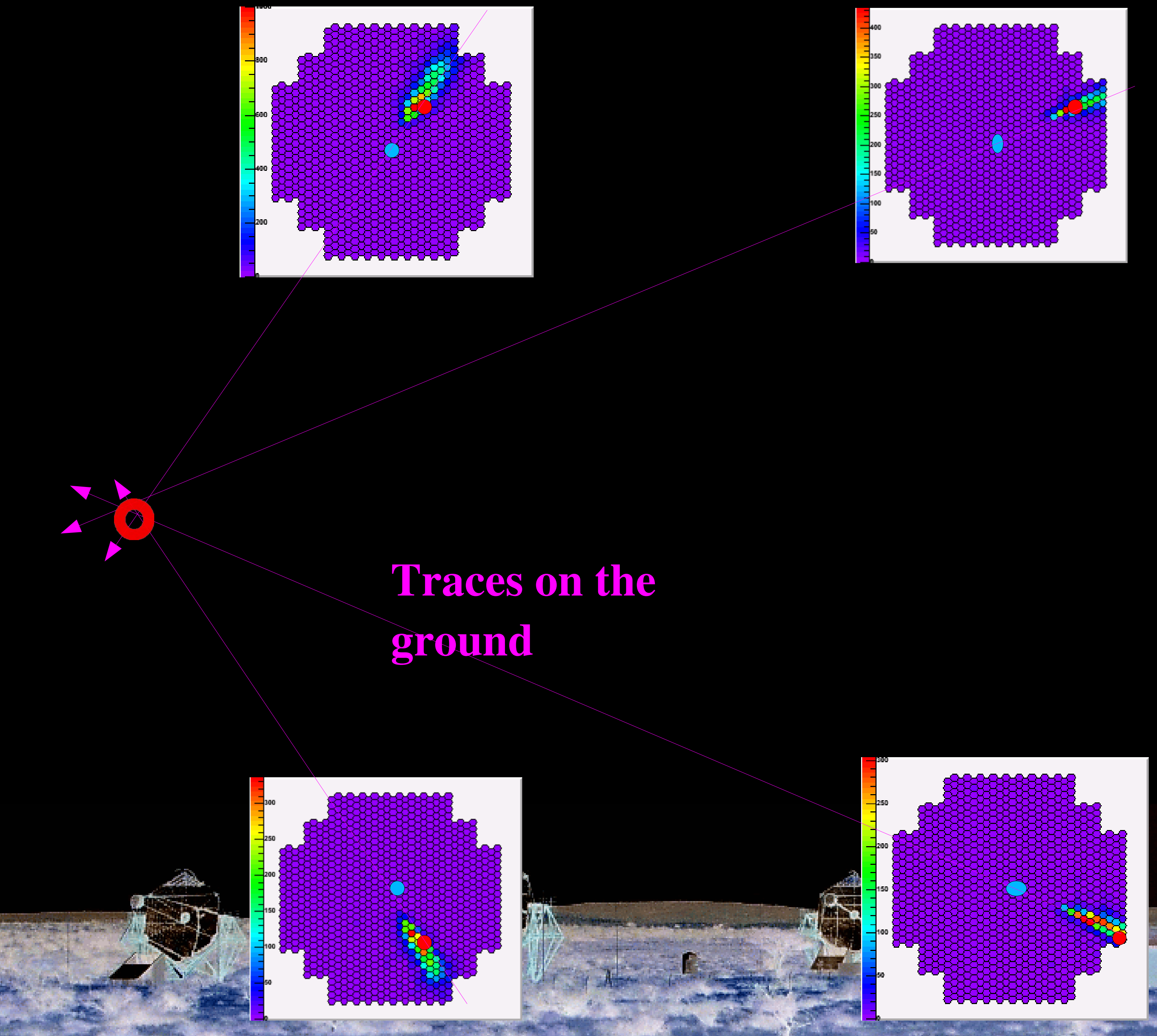




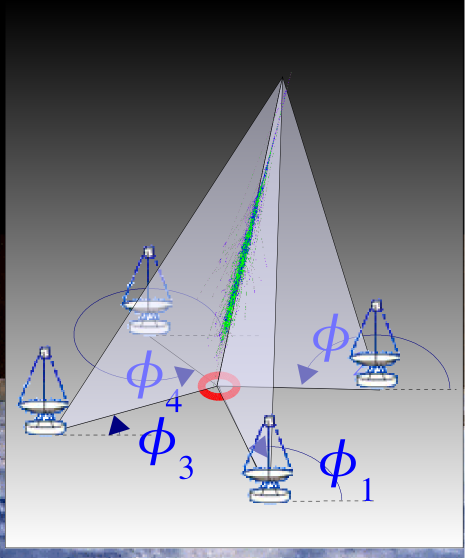
Stereoscopy:
tells where the shower came from



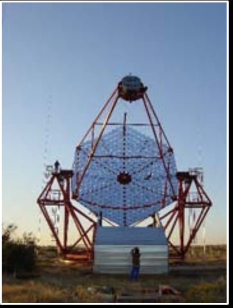
Stereoscopy : tells where the shower hit

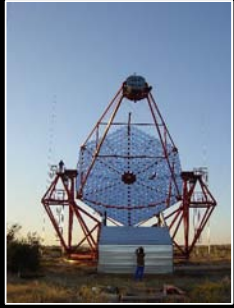


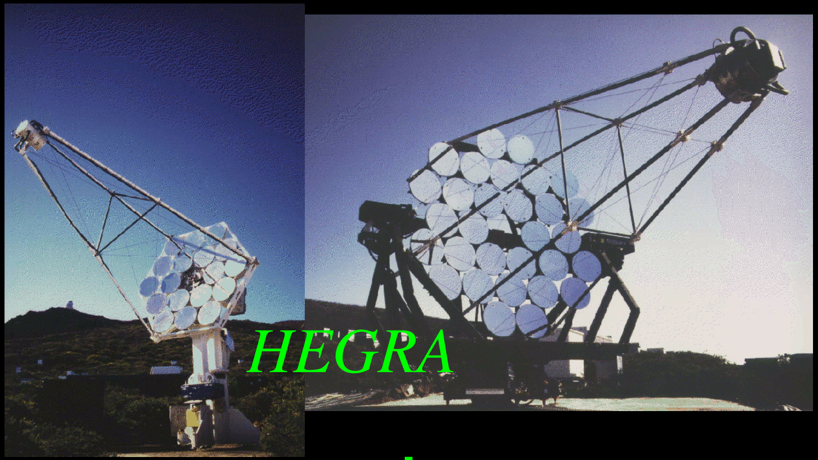
- Position of the target
- Centre of gravity of the image



H.E.S.S.

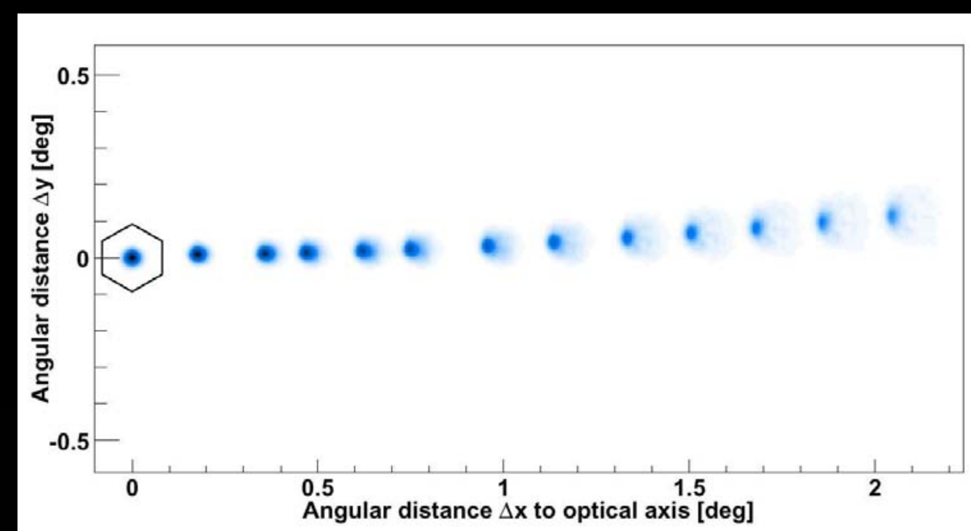


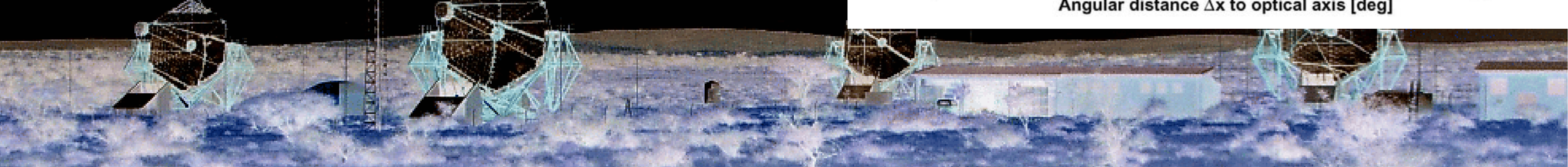




H.E.S.S. telescopes

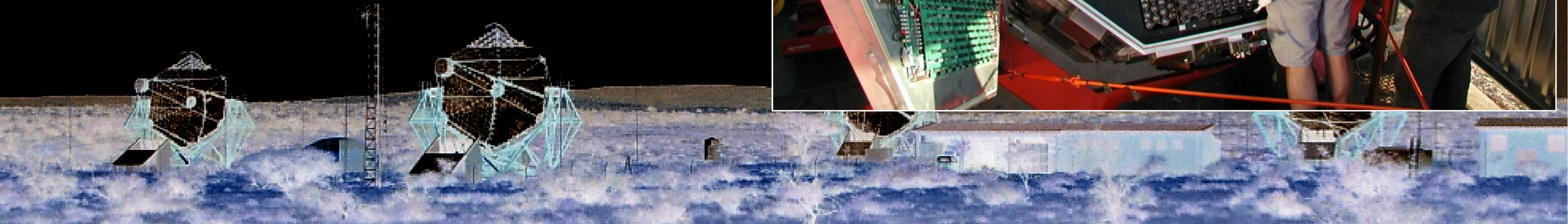
- Four-Telescope network
  - Located in Namibia, 23°S 15°E
    1800 m altitude
  - Telescope separation: 120 m
- Telescope Structures
  - Mirror dishes: $4 \times 107\ m^2$
  - Diameter: 12 m, Focal length: 15 m
- Mirrors
  - 380×60cm circular facets
  - PSF after alignement ($r_{80\%}$)
    1.3' / 0.38 mrad on axis





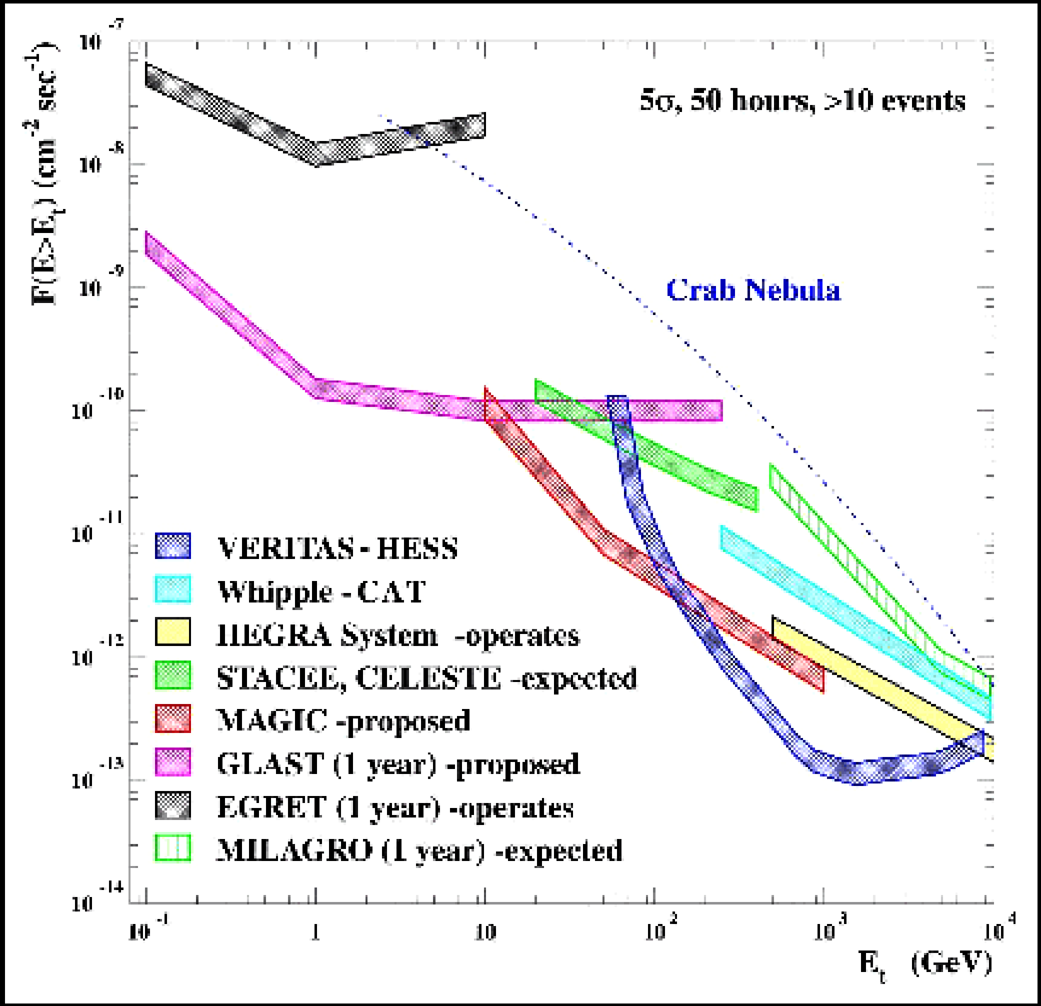
H.E.S.S. cameras

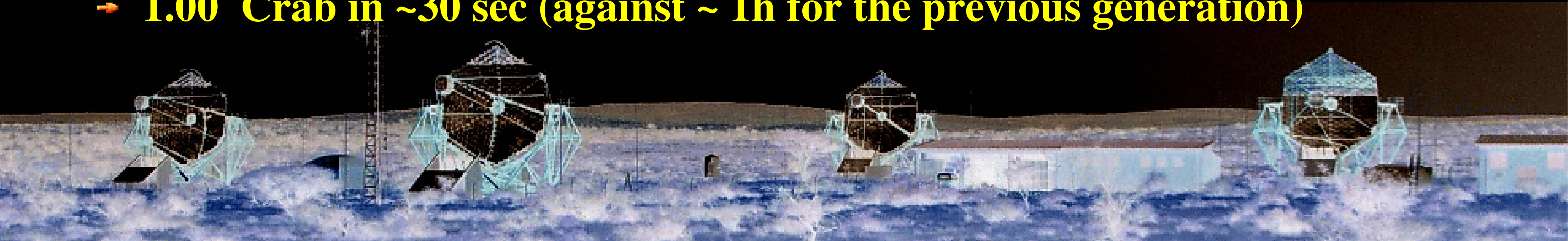
- 960 photomultiplier pixels
- Pixels of 0.16° / 2.8 mrad
- Wide field of view, 5°
- 16ns integration window, fast trigger coincidence
- All electronics integrated in-camera
- 3 cables (1 power , 2 optic fibres)
- Fits in 2 m cube
- Weight ~ 900 kg



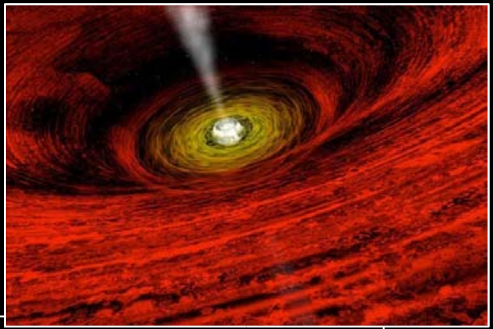
H.E.S.S. performances

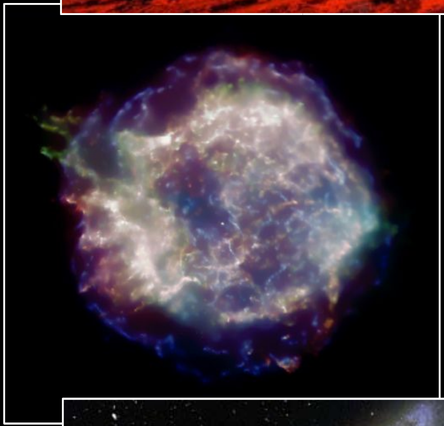
- Threshold ~ 100 GeV at zenith
- Angular resolution < 0.1°
- Energy resolution ≈ 15%
- Trigger rate ~ 300 Hz
  with ~ 10% dead time (stereo)
- ~ 25 γ/min for a source type *Crab Nebula* at zenith:
  - **0.01 Crab in ~25 hrs**
  - **1.00 Crab in ~30 sec (against ~ 1h for the previous generation)**

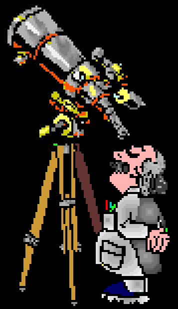


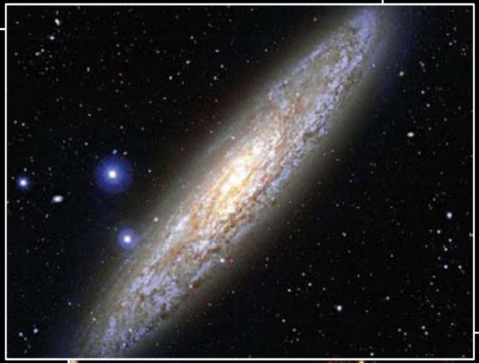


Astrophysics with H.E.S.S.









Extragalactic sources

- Active galactic nuclei
- Starburst galaxies
- Clusters of galaxy
- Gamma-ray bursts ??

Galactic sources

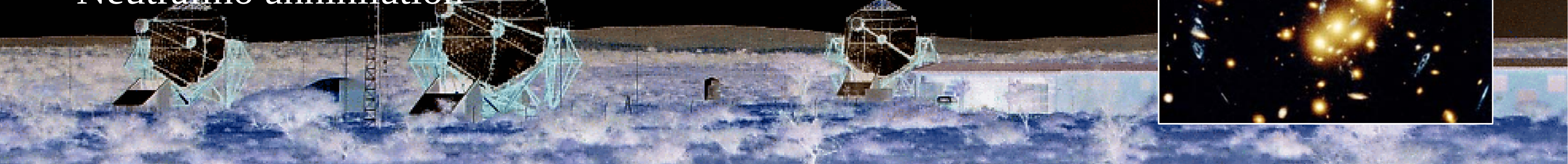
- Supernova remnants
- Plerions
- Binary systems
- Unidentified sources

Astroparticule physics

- Extragalactic infra-red background with the study of AGNS

$$\gamma_{TeV} + \gamma_{IR,vis} \rightarrow e^{+} e^{-}$$

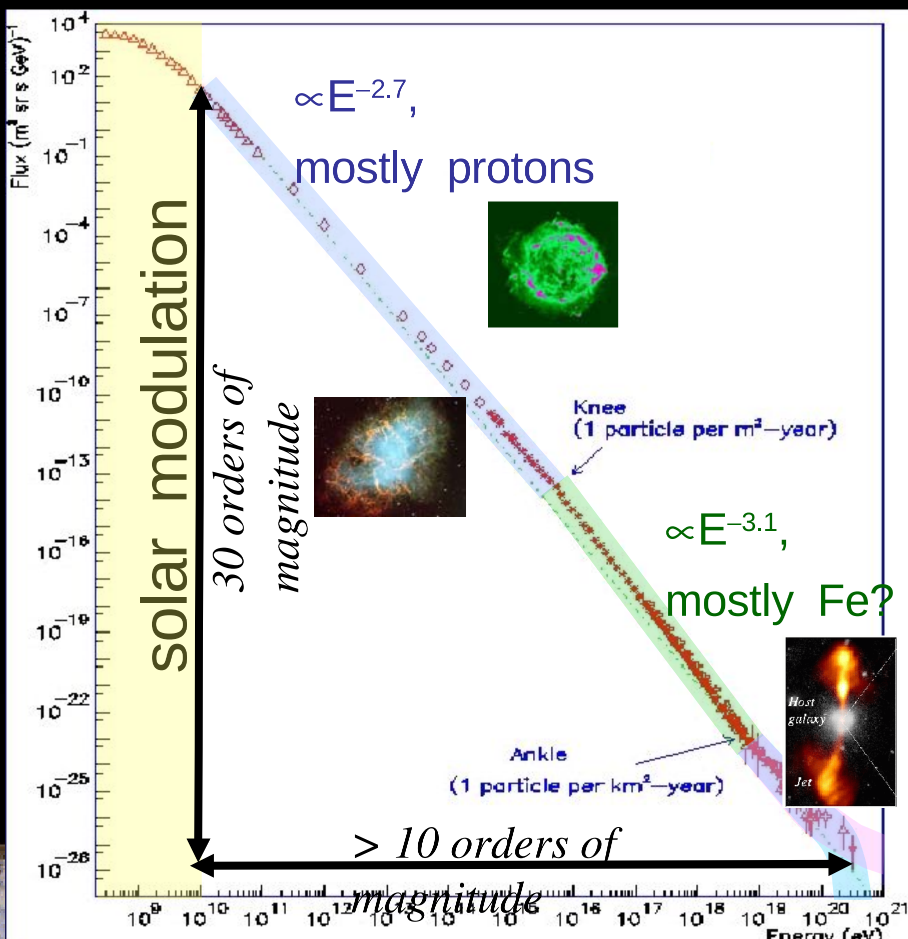
- Neutralino annihilation



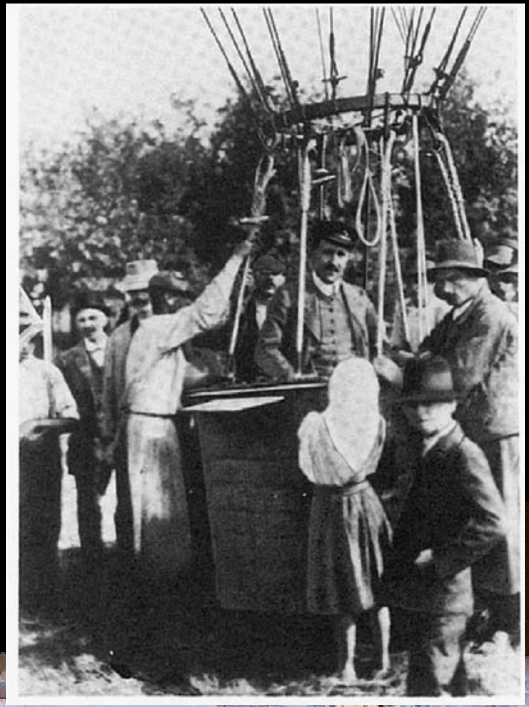
Supernova remnants

The cosmic ray mistery

- Discovered in 1912 (Victor HESS)
- 10 orders of magnitude in energy, 30 in flux
- Origin still unknown



Discovery
Balloon Flight
Victor Hess, 1912



Cosmic-ray sources ?

Cosmic rays are charged particles :

- Galactic origin (Energy < 10^{15} eV)
- PROPAGATION IN TURBULENT MAGNETIC FIELD

→ **LOOSE THE INFORMATION ON THE SOURCE**

GAMMA :

- Cosmic-ray sources are gamma-ray emitters
- Direct propagation of the gamma-rays

→ **KEEP THE INFORMATION ON ITS SOURCE**

One possible candidate :

- Supernova remnants

Mystery not solved since 1912 !

Supernova remnant

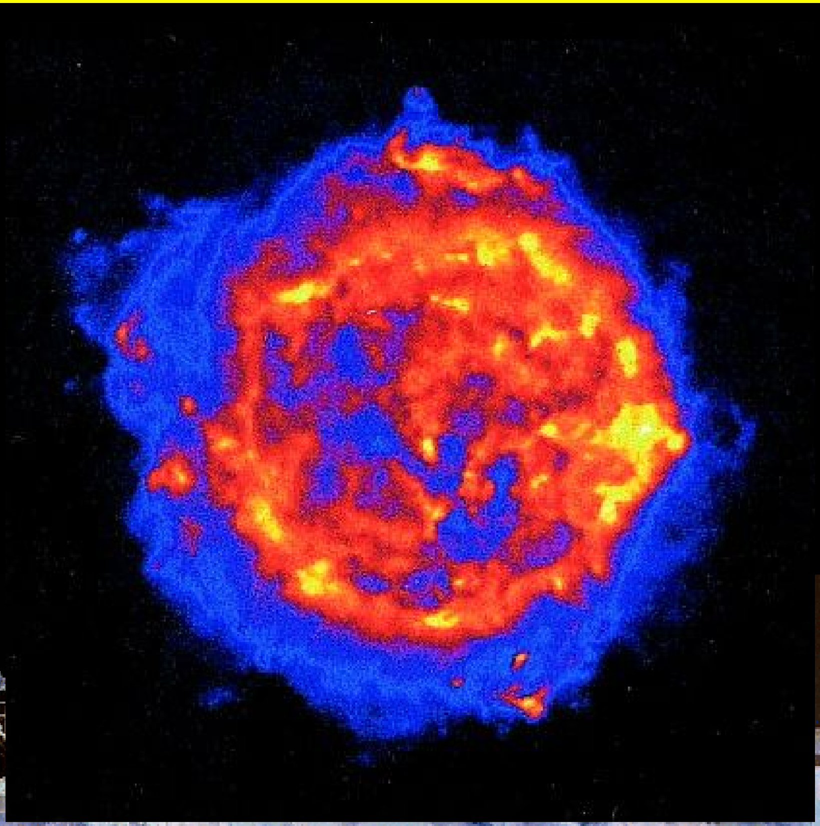
Supernova remnant :

Explosion of a star or a binary system

Blast wave → particles accelerated by Fermi process

Possible source for the acceleration of cosmic rays up to 10^{15} eV

Radio image of Cas A

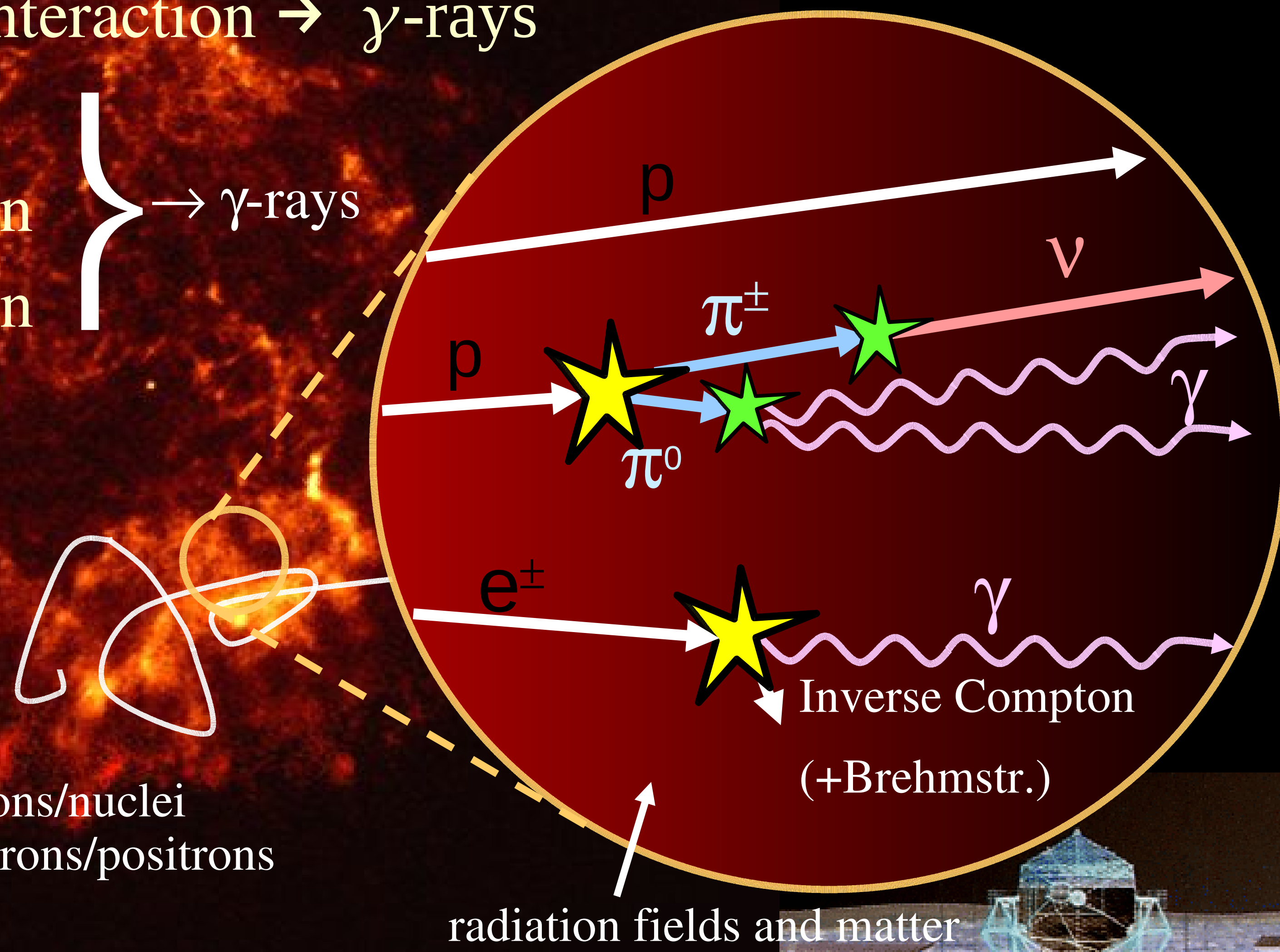


- High emission associated to the ejecta
- Plateau due to the blast wave

Non-thermal radiative processes

- Synchrotron emission → Radio to X-rays
- Proton-Proton interaction → γ-rays
- Bremsstrahlung
- Inverse Compton
- Pair Annihilation

(Bremsstrahlung, Inverse Compton, Pair Annihilation) → γ-rays

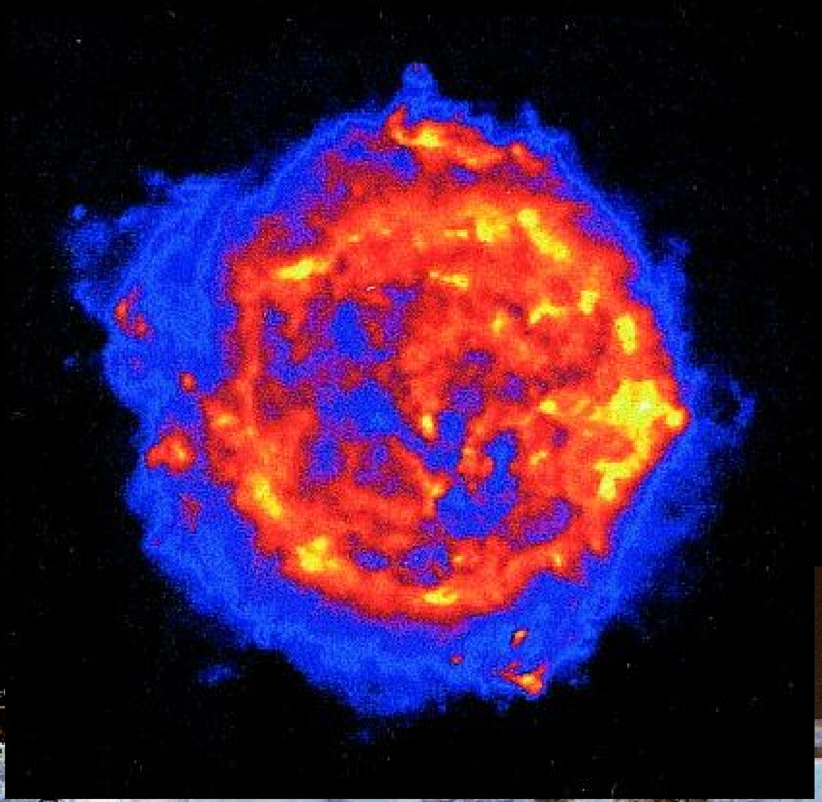


First observational evidences (I)

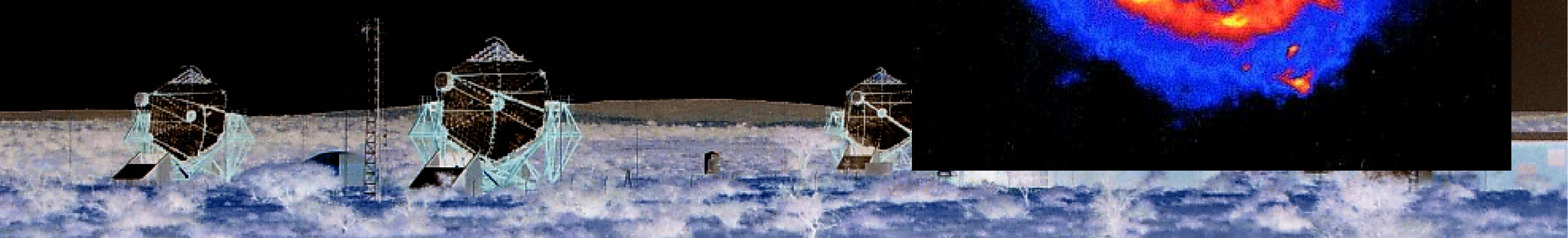
1. In the radio range :

Since 1950, discovery of radio emission from different supernova remnants (Cas A, Tycho) is a direct evidence of the acceleration of high-energy electrons up to the **GeV**.

Radio image of Cas A



$$\nu_{\mathrm{sync}} = 1.65 \times 10^7 \, B_{\mu G} \, E^2_{GeV}$$

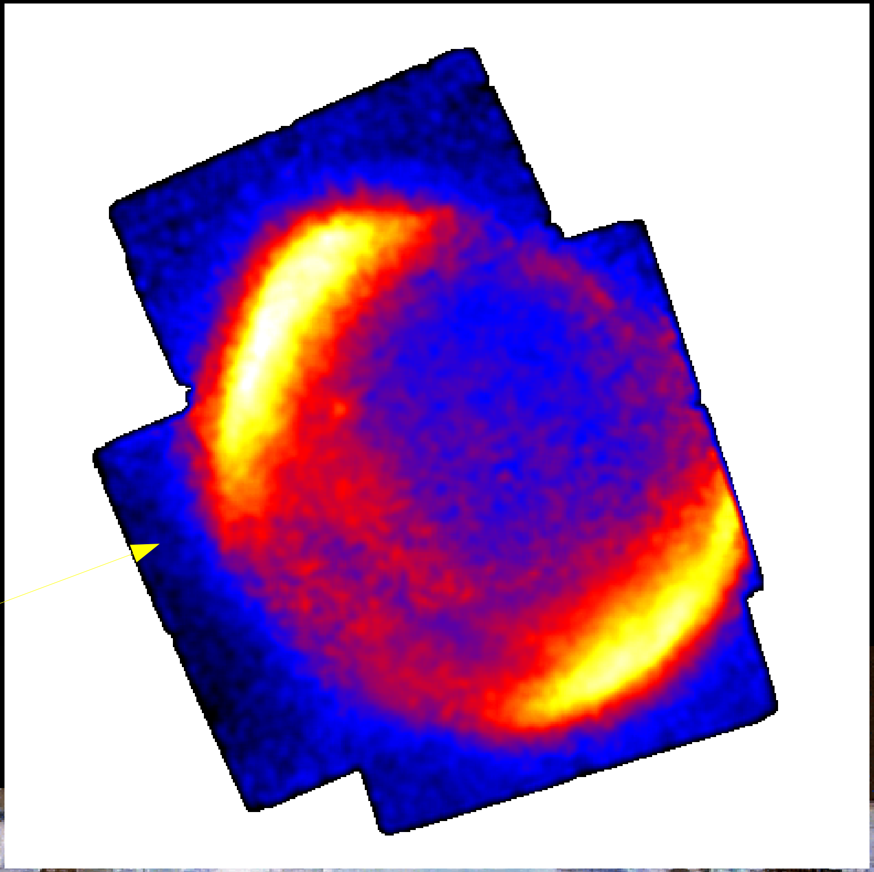


First observational evidences (II)

2. In the X-ray range :

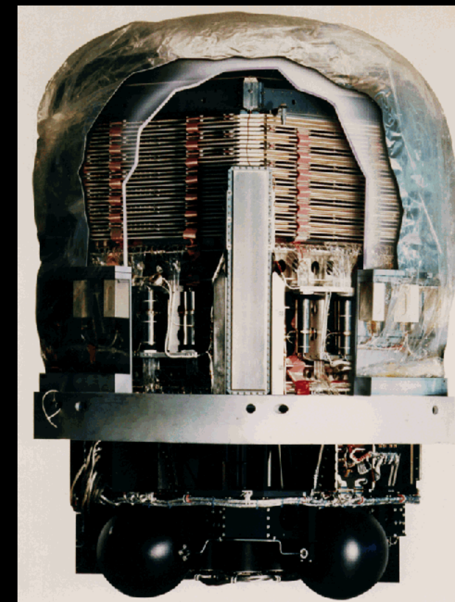
In 1995, ASCA shows that the emission of the 2 rims of SN1006 are dominated by the radiation of high energy electrons accelerated up to **<u>100 TeV</u>**. (Koyama et al., Nature, 1995)

ASCA GIS : 0.8-10 keV



SN1006 observed by ASCA

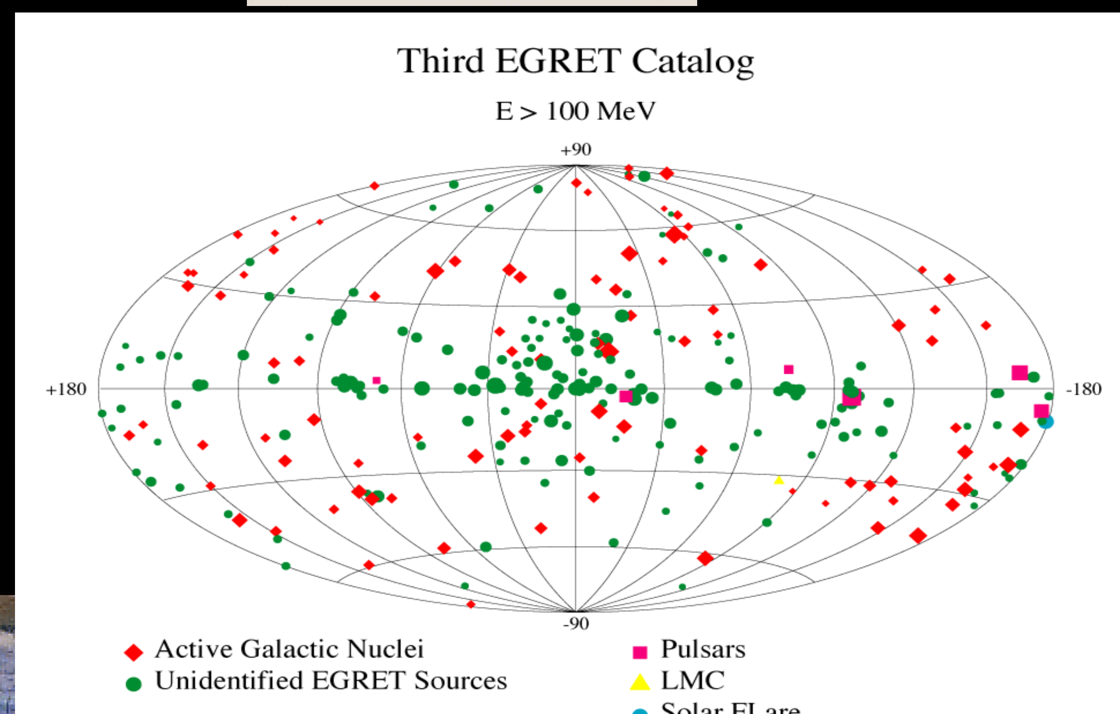
Evolution of the γ-ray domain



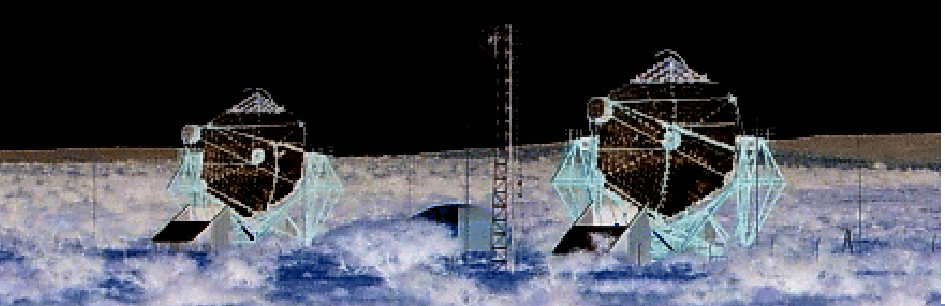
CGRO/EGRET :

- April 1991 – June 2000
- 30 MeV – 30 GeV

271 detected sources



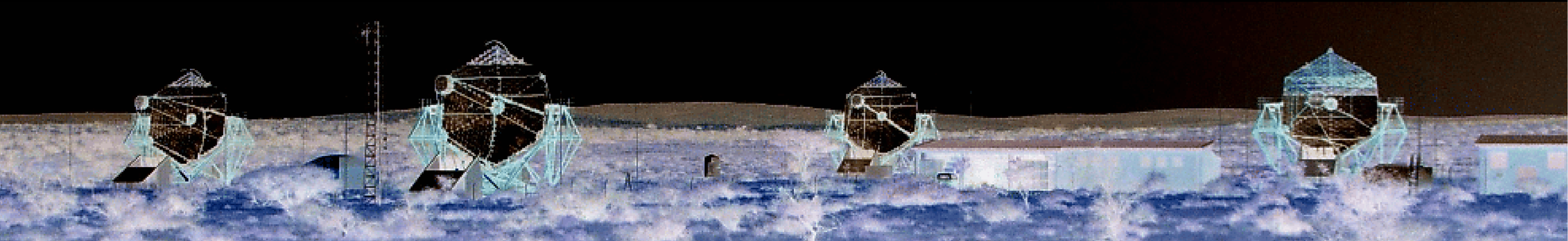
R.C. Hartman et al., ApJS, 1999



Supernova remnants: sources hardly detectable with EGRET

1. Effective area of gamma-ray satellites are at most equal to the detector area

2. Poor angular resolution of satellites like EGRET (6° à 100 MeV) => identification of a gamma-ray signal with a radio or an X-ray counterpart rather hard



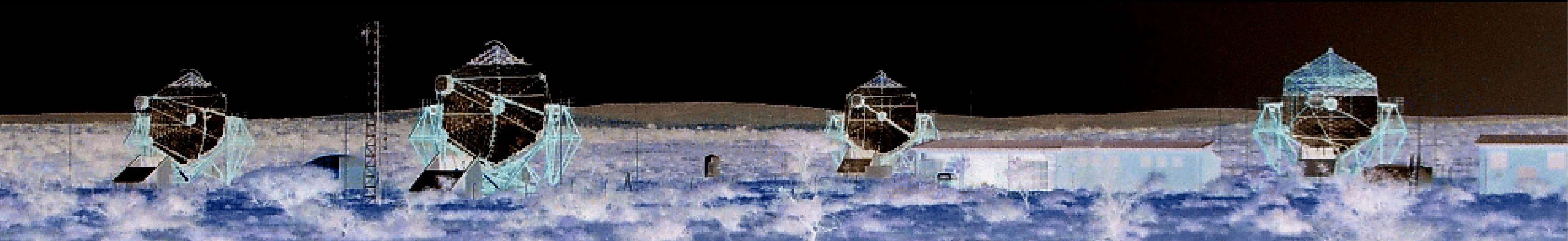
Atmospheric Cherenkov detectors advantages

=> Atmospheric Cherenkov telescopes are currently the only instruments to do such study (waiting for GLAST)

Effective area: several hectares (area of the Cherenkov light on the ground)

Angular resolution: < 0.1°

Unique difficulty : rejection of the hadronic background



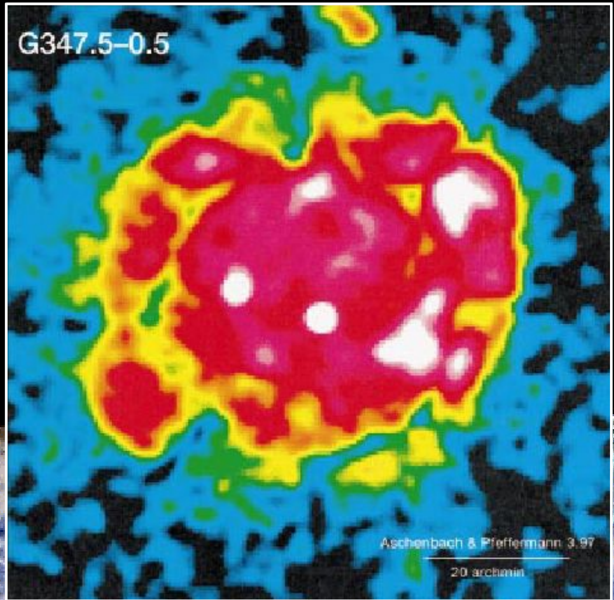
RX J1713.7-3946
Multi-Wavelength Observations

- Discovery: ROSAT All-Sky Survey (1996)
- X-ray emission mostly non-thermal
- Distance re-estimated at 1kpc

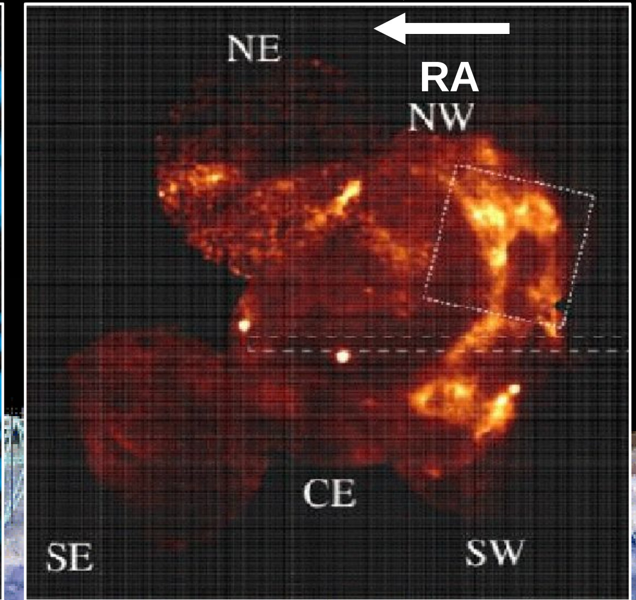
(Cassam-Chenai et al. and Fukui et al., 2004)

- CANGAROO observed TeV excess from western rim (Enomoto et al., 2000)
- Detection by H.E.S.S. in 2004 (Aharonian et al., 2004)

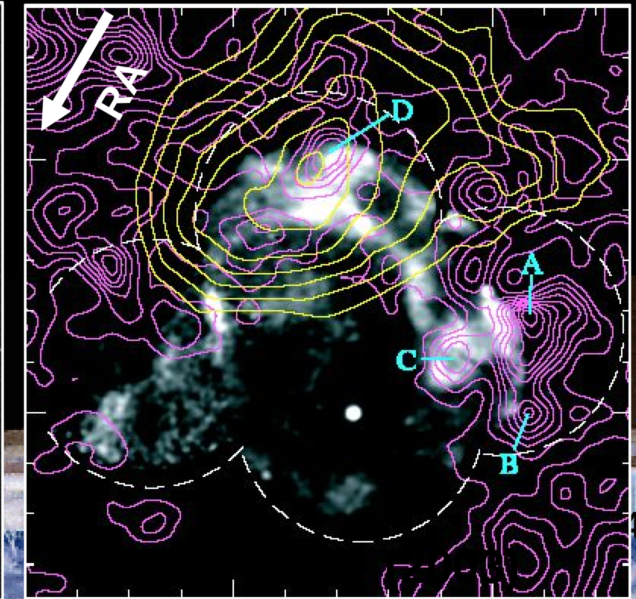
ROSAT (0.1-2 keV)



XMM-Newton (2-10 keV)



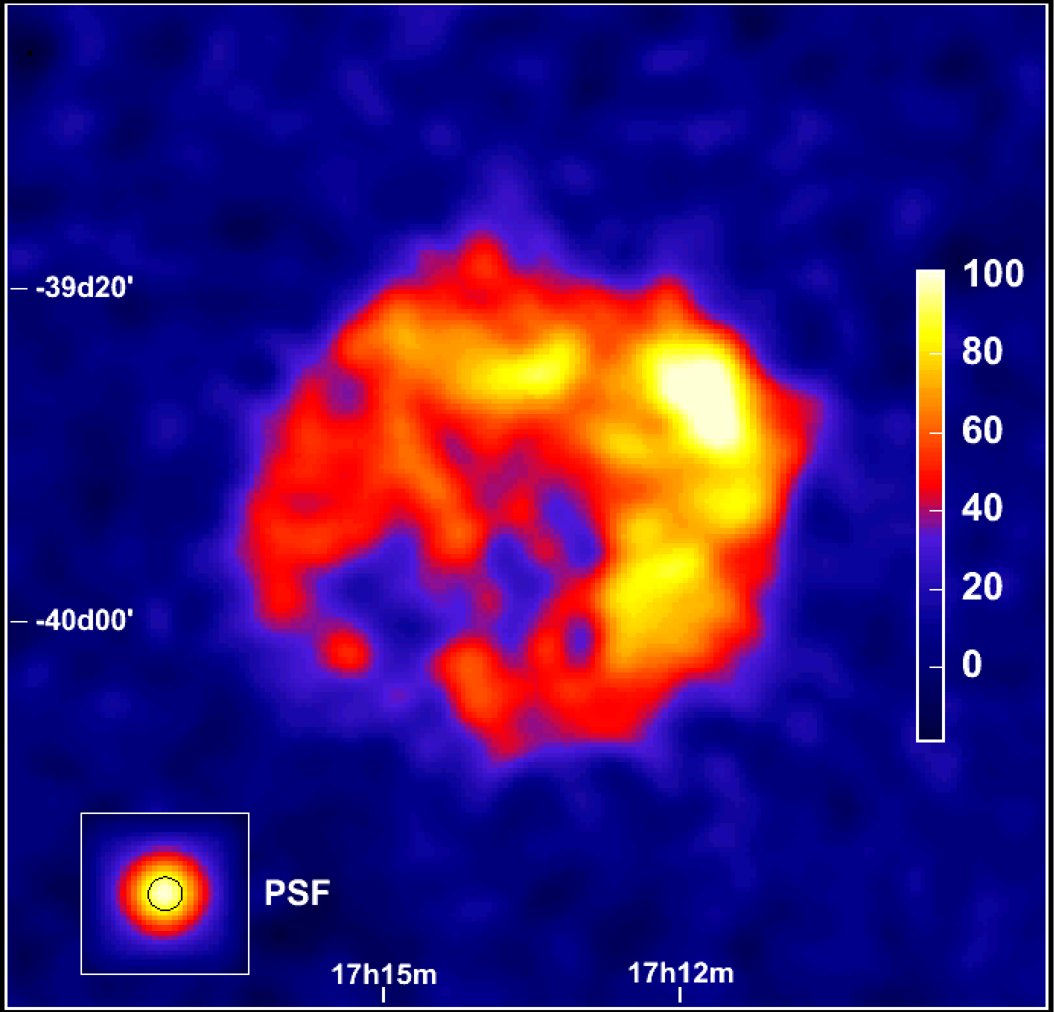
XMM + NANTEN

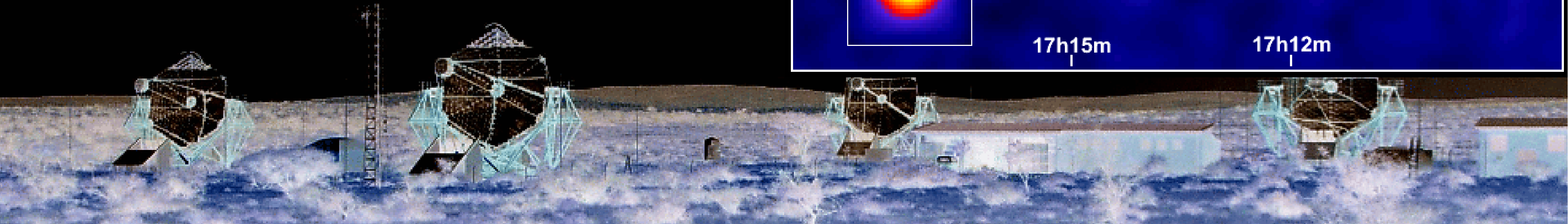


H.E.S.S. Observations in 2004

Angular resolution < 0.1° ➔ morphology resolved

- Observations with the full array of 4 telescopes
- 33 hours live-time ON source
- Zenith angles from 15 to 60 degrees
- Standard cuts are applied
- Shell of the remnant resolved





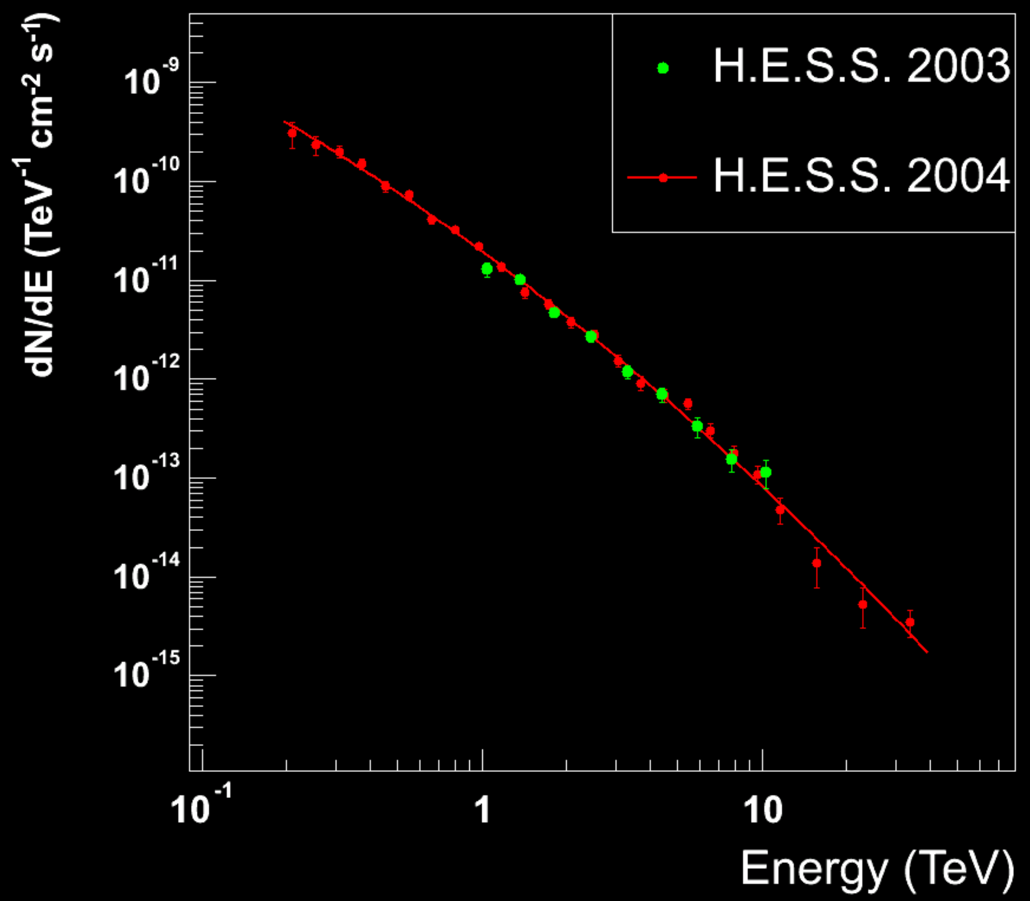
RX J1713.7-3946 Spectrum

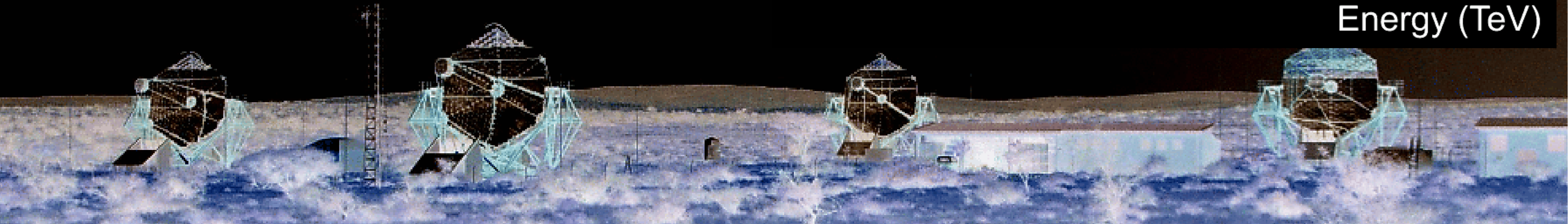
Extension of the spectrum up to 40 TeV
➔ Particles accelerated up to ~100 TeV

- Spectrum obtained with the 2004 dataset compatible with the one from 2003
- Photon index of the remnant :

  -2.26 ± 0.02 ± 0.15

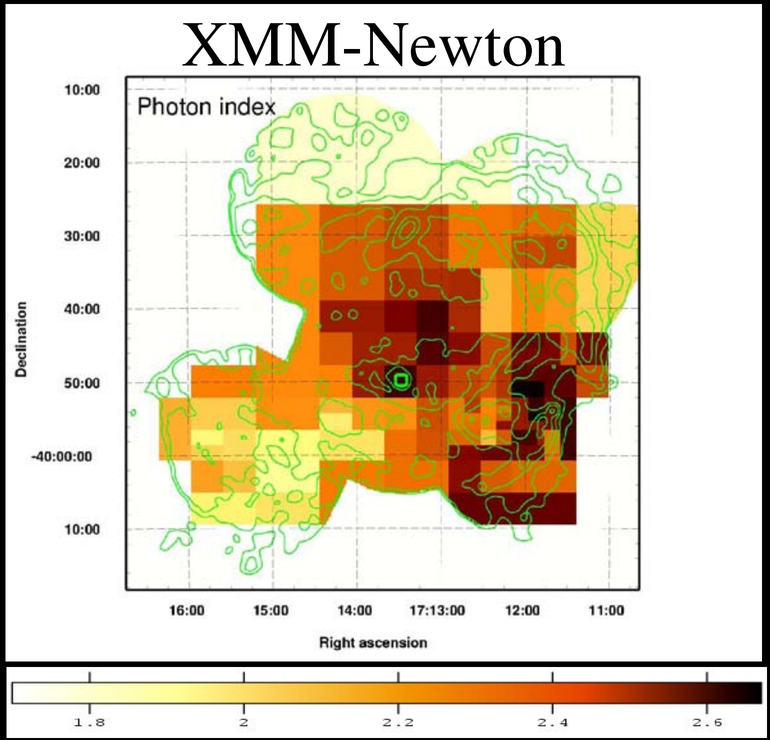
- Flux ~ 1 Crab
- Deviation from a pure power-law a high energy: E_{cut} = 17.9 ± 3.3 TeV

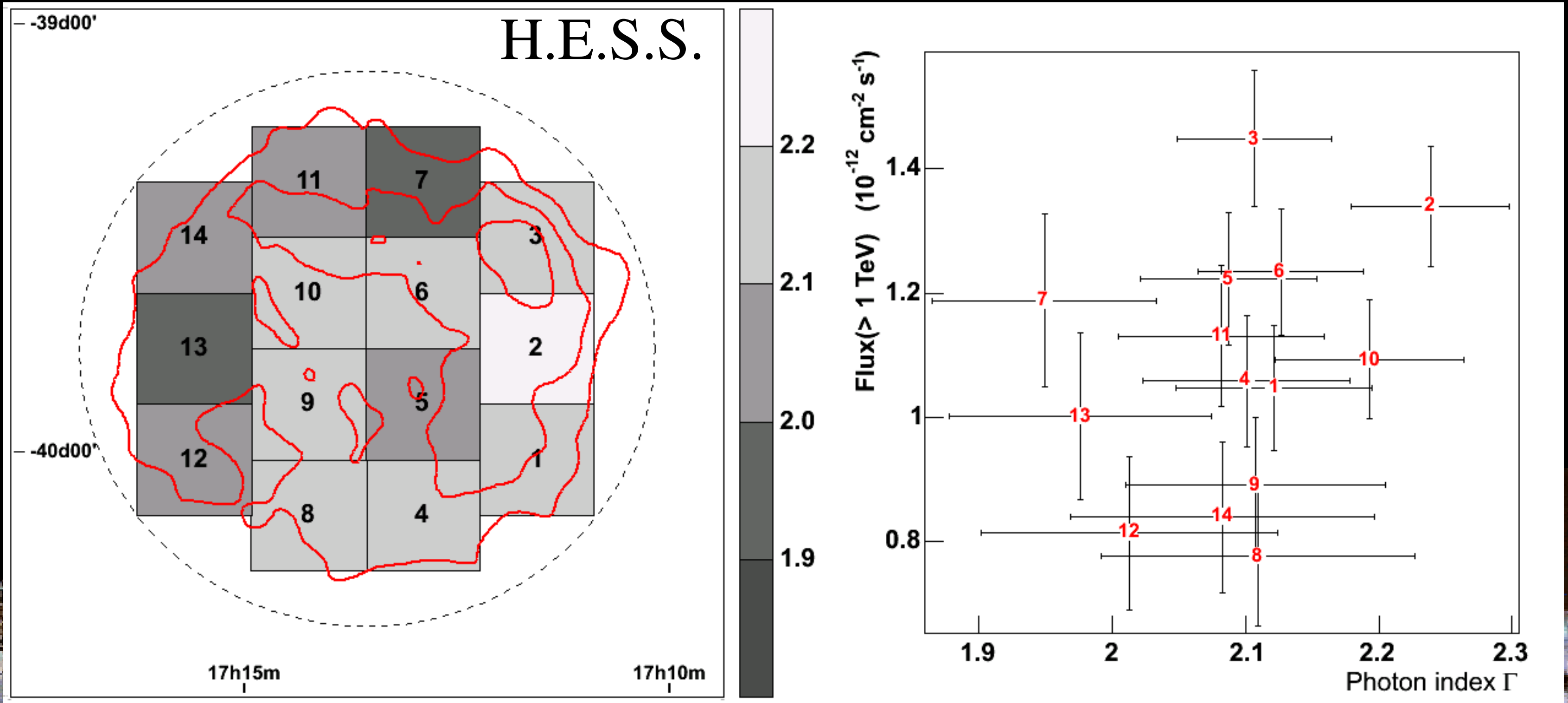




Spatially resolved spectra

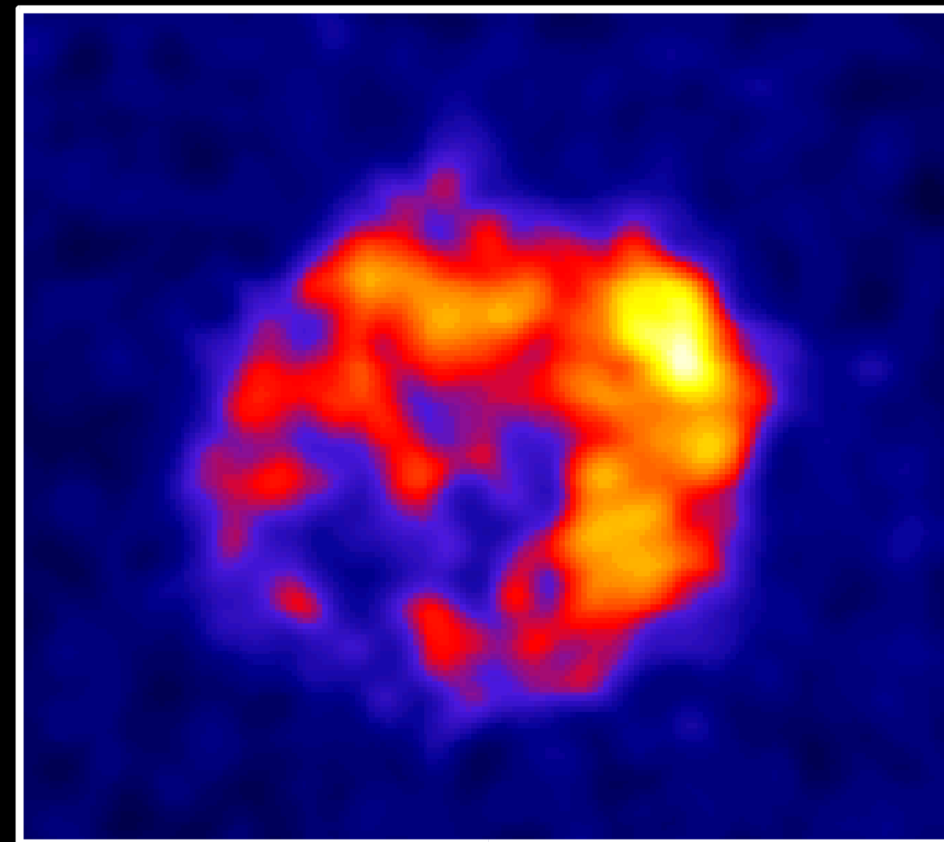
- No significant change of the spectral shape from one region to another in TeV
- Significant changes of the spectral index observed in X-rays

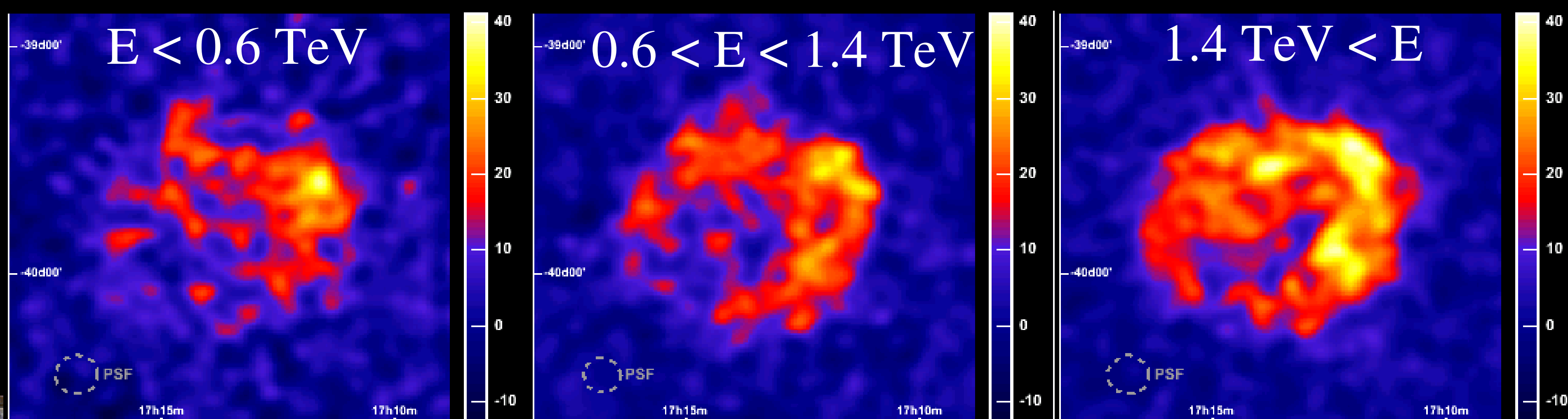




Energy dependence of the Morphology

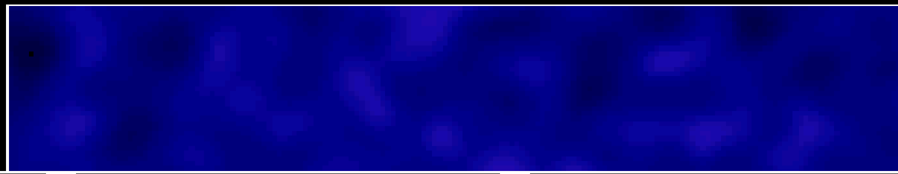
As opposed to X-rays, TeV morphology doesn't change significantly with energy

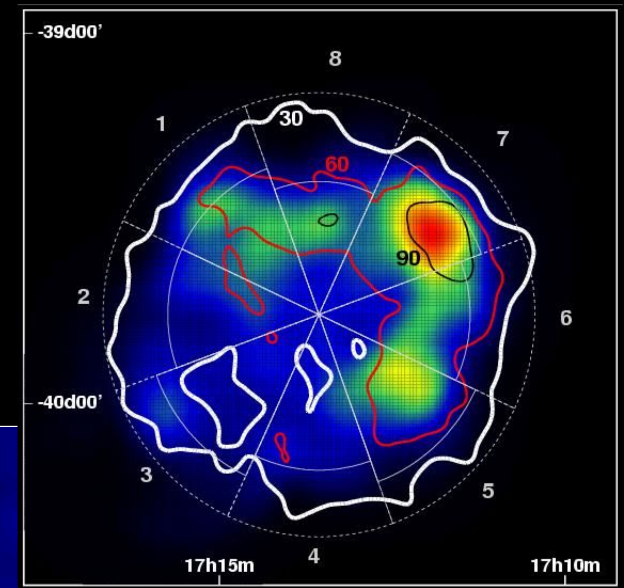


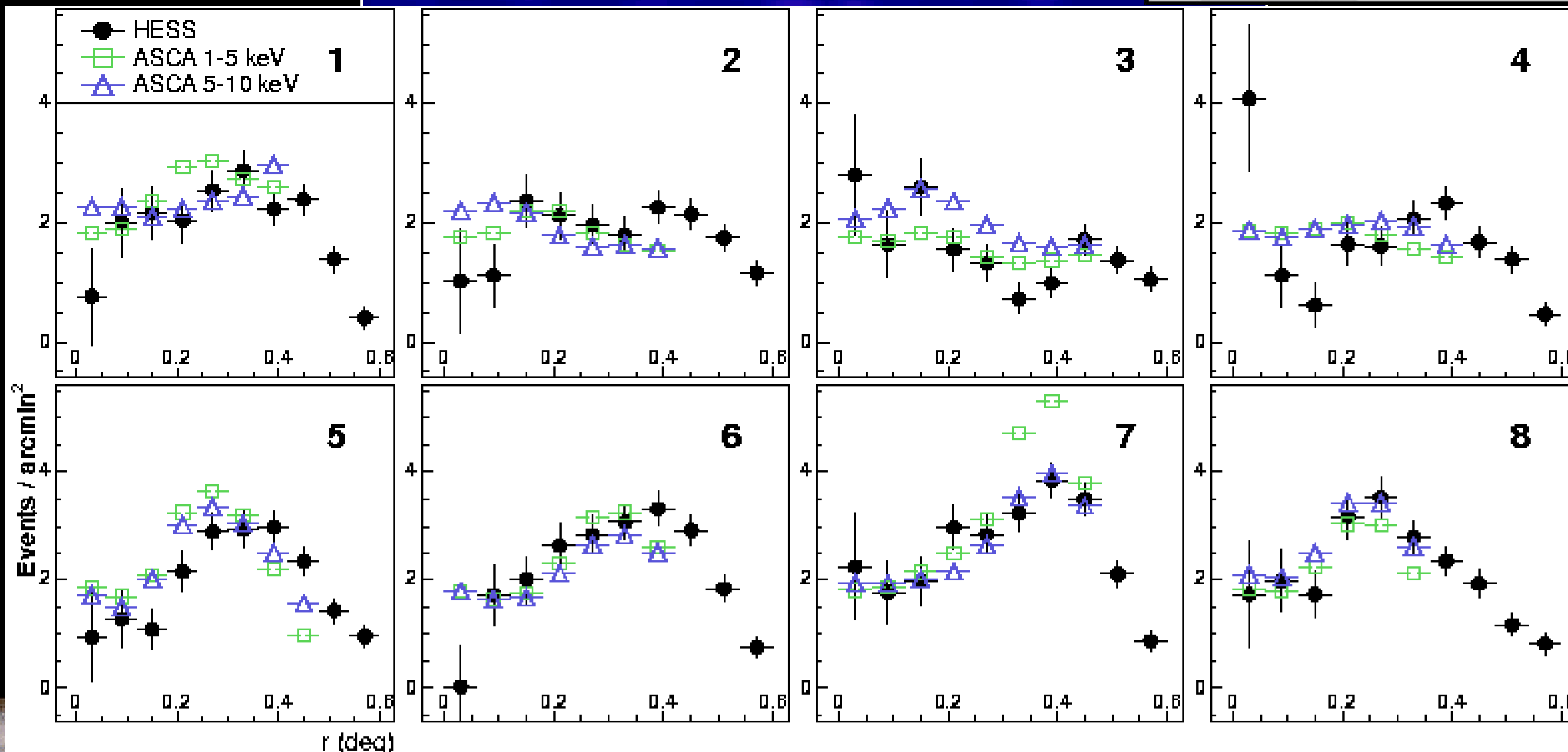


Correlation with X-rays

Correlation coefficient between ASCA & HESS ~ 80%





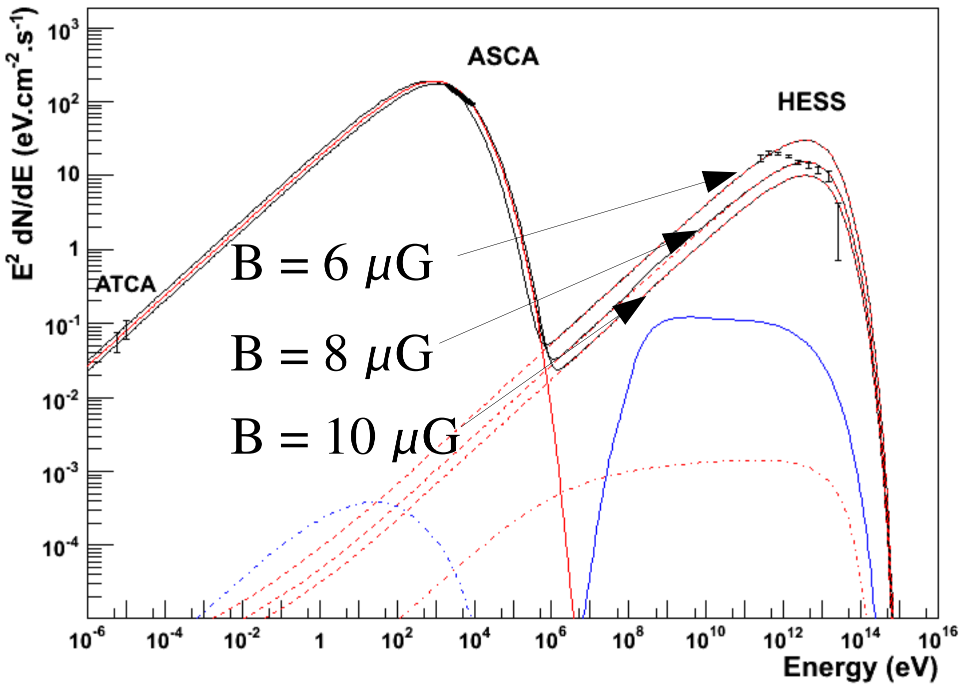


Primary population: electrons ?

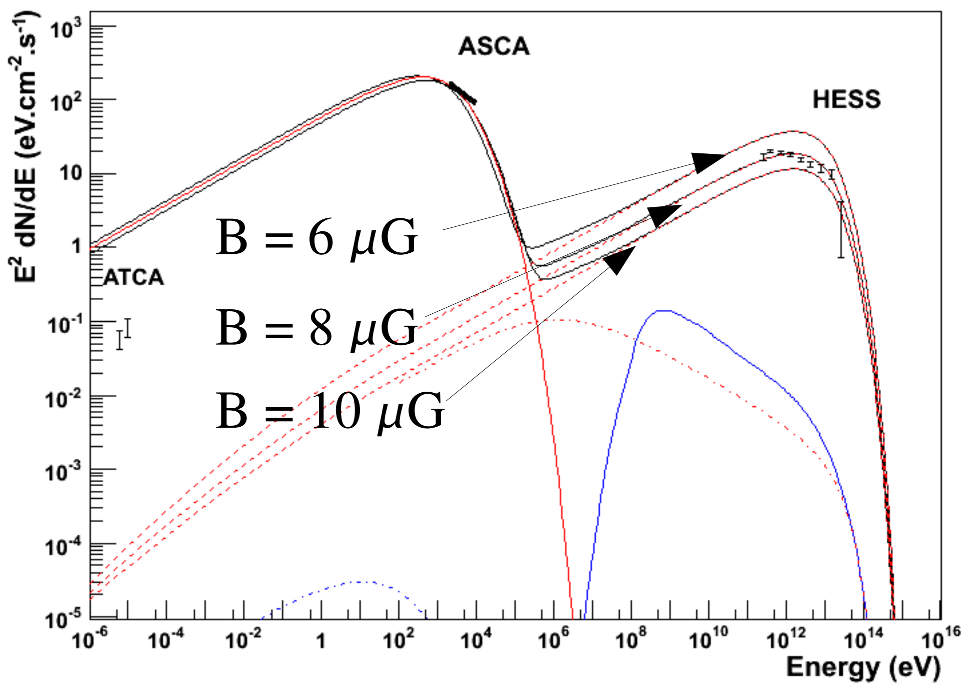
- Need about 8 μG B field to match flux ratios
- Simplest electronic models don't work well

- Simple one-zone model
- Electrons & protons injected with the same spectral shape
- Energy losses + escape of particles out of the shell taken into account

Power-law index = 2.2 at injection level

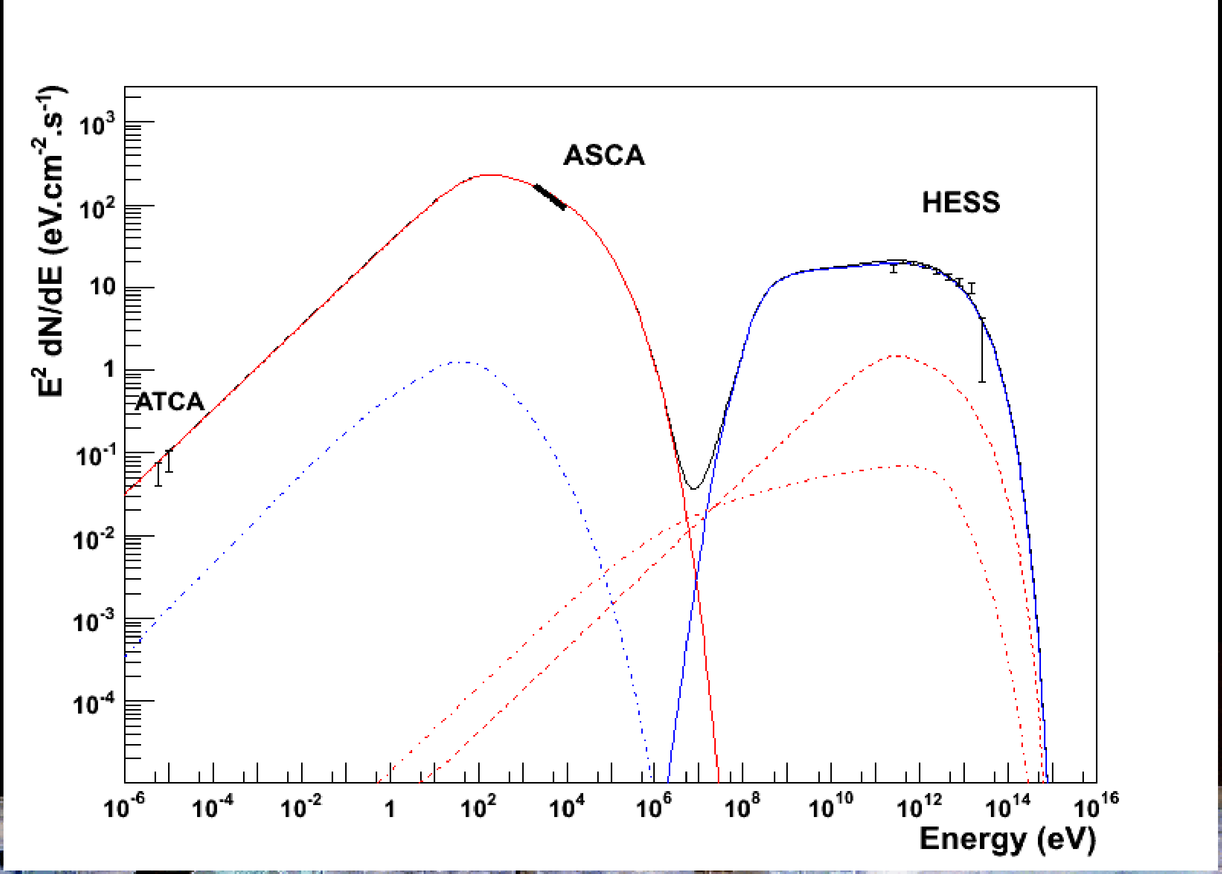


Power-law index = 2.4 at injection level



Primary population: protons ?

- Spectral shape at the injection level: power-law + exponential cut-off
  E_{cut} = 120 TeV and index = 2.0
- Energy injected = 10^{50} ergs
- Electron/proton ratio = 5×10^{-4}
- Magnetic field = 35 μG & Density = 1.5 cm^{-3}

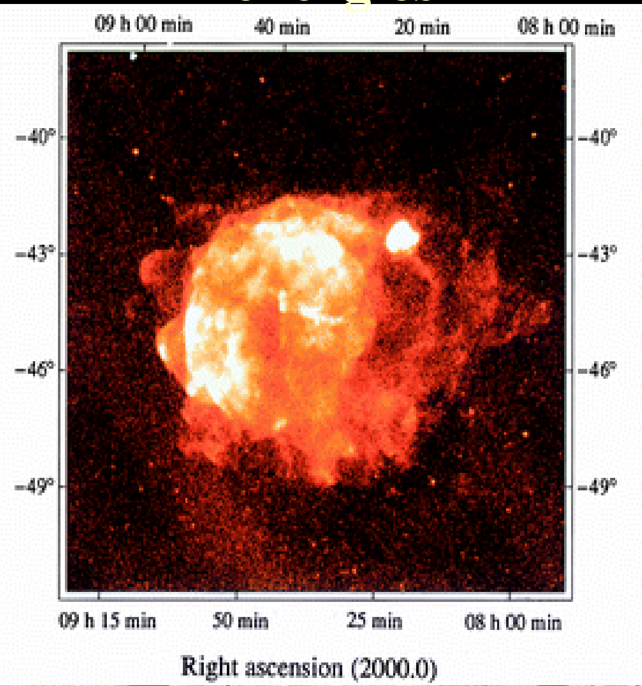


RX J0852.0-4622
Multi-Wavelength Observations

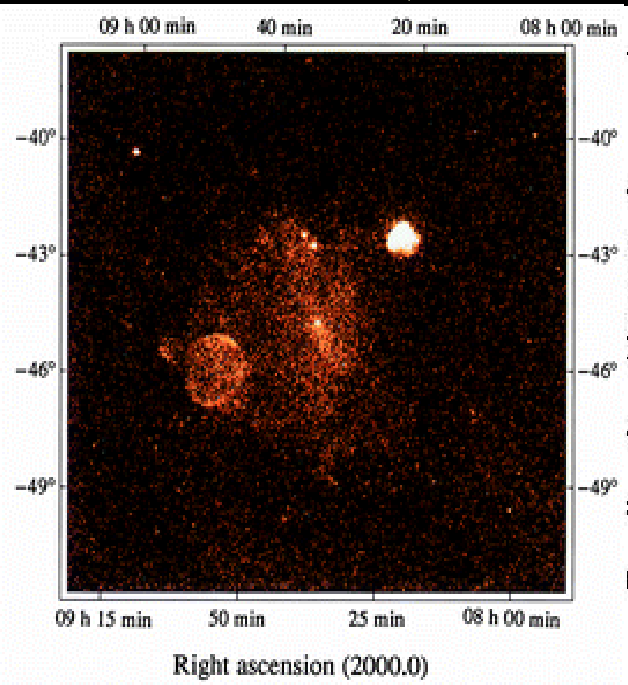
- Discovery: ROSAT All-Sky Survey (1998)
- X-ray emission mostly non-thermal
- Distance is controversial 200 pc - 1kpc
- Detected with H.E.S.S. in 2004

ROSAT all Sky Survey

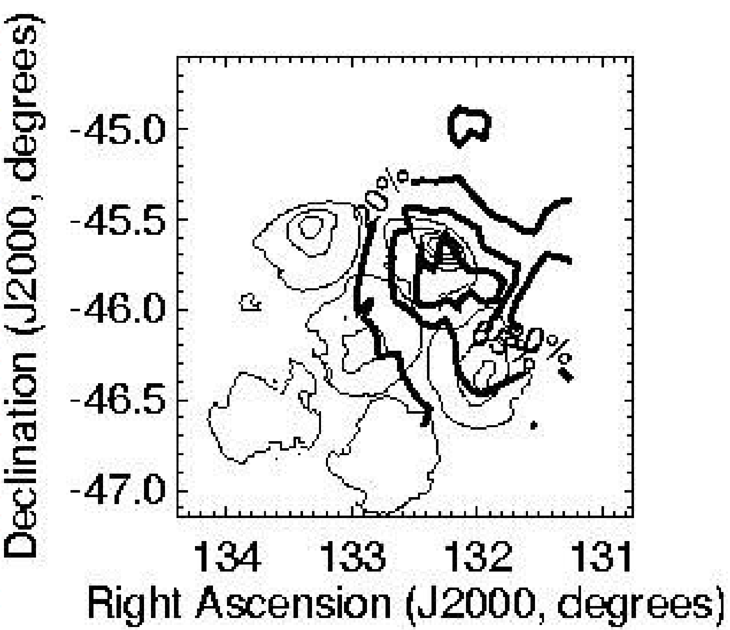
All energies



E > 1.3 keV



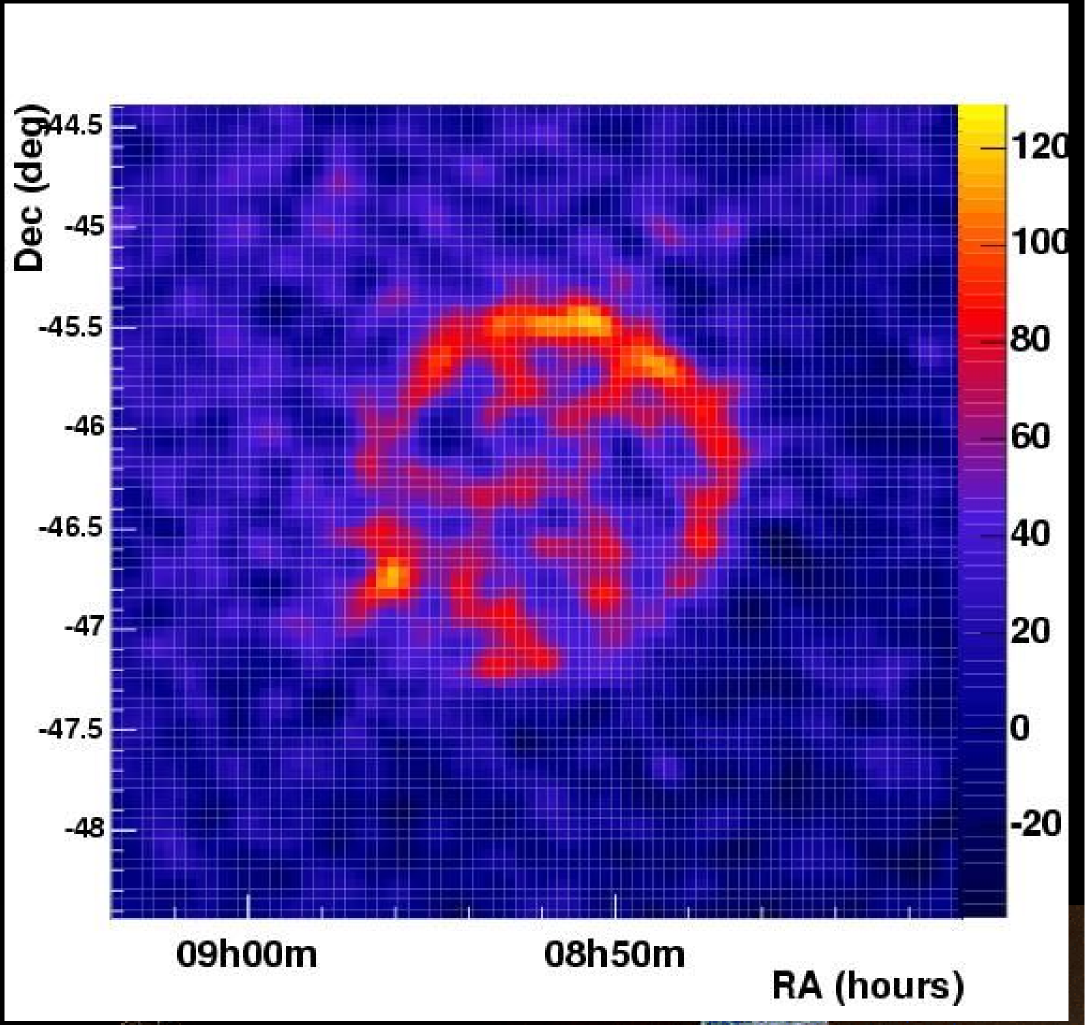
ASCA + CANGAROO contours

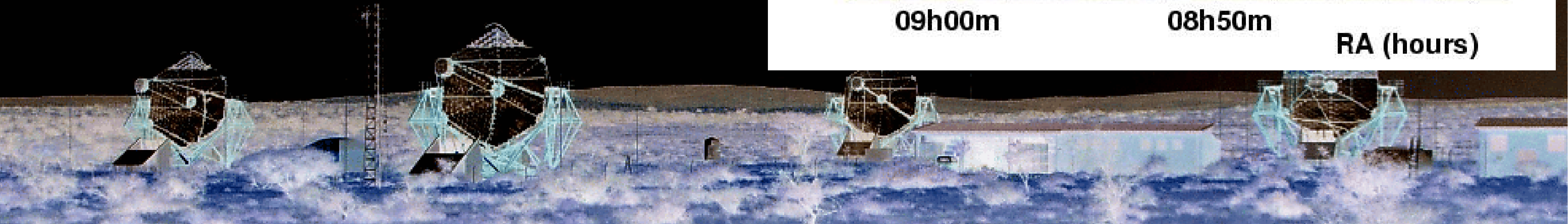


H.E.S.S. Observations in 2004-2005

Angular resolution < 0.1° ➔ morphology resolved

- Observations from December 2004 to May 2005
- 20 hours live-time ON source
- Zenith angles between 20° and 50°
- Energy threshold : 250 GeV
- Results confirmed by an independent analysis

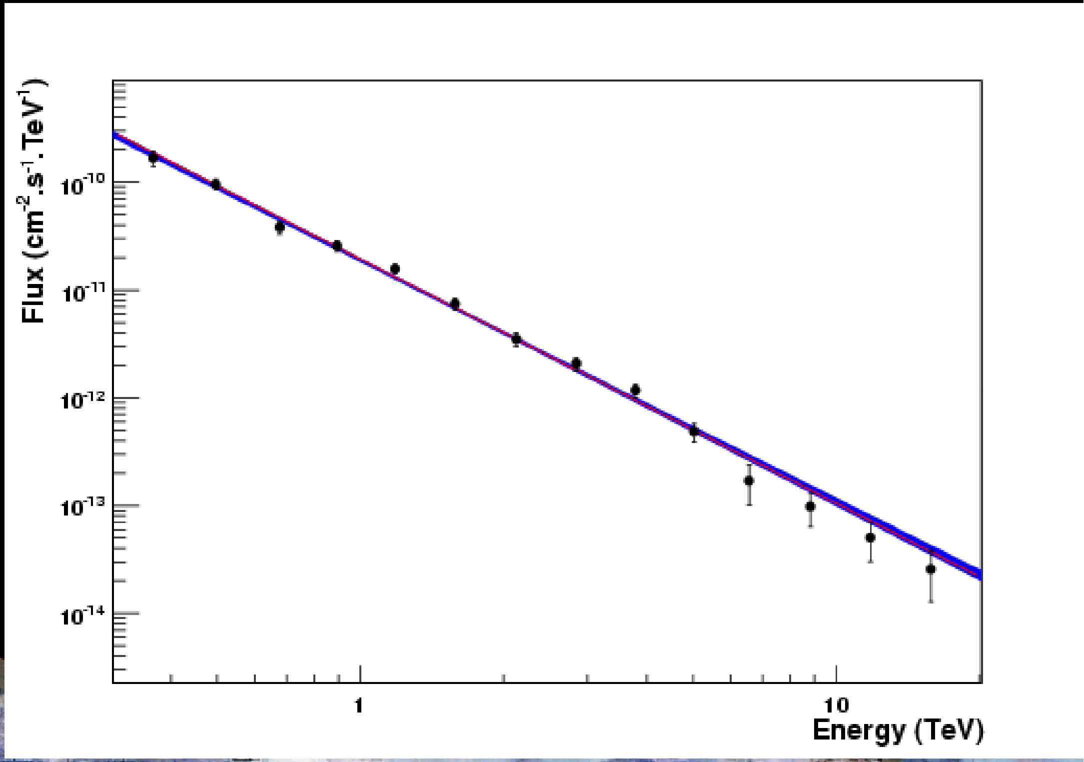




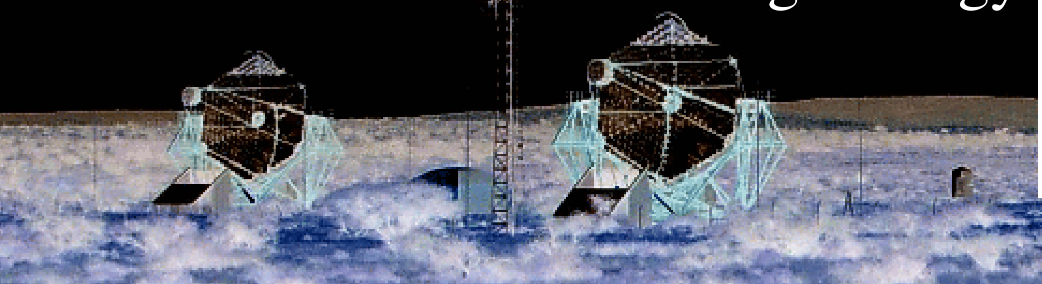
RX J0852.0-4622 Spectrum

Extension of the spectrum up to 20 TeV
➔ Particles accelerated up to ~100 TeV

- Spectrum ranges from: 300 GeV up to 20 TeV
- Spectral index: $2.24 \pm 0.05_{stat} \pm 0.15_{syst}$
- $I(> 1\text{TeV}) = (15.2 \pm 0.7_{stat} \pm 3.20_{syst}) \times 10^{-12}\ cm^{-2}s^{-1}$

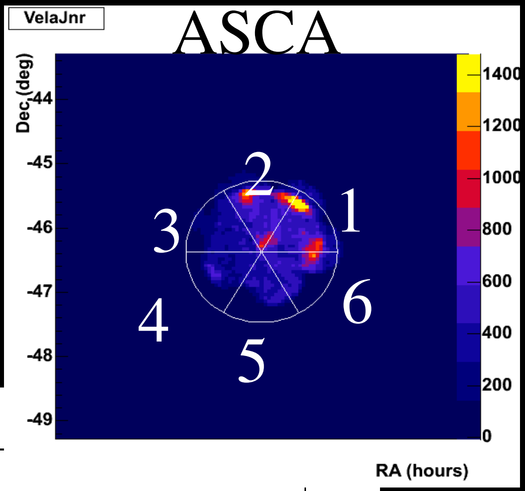


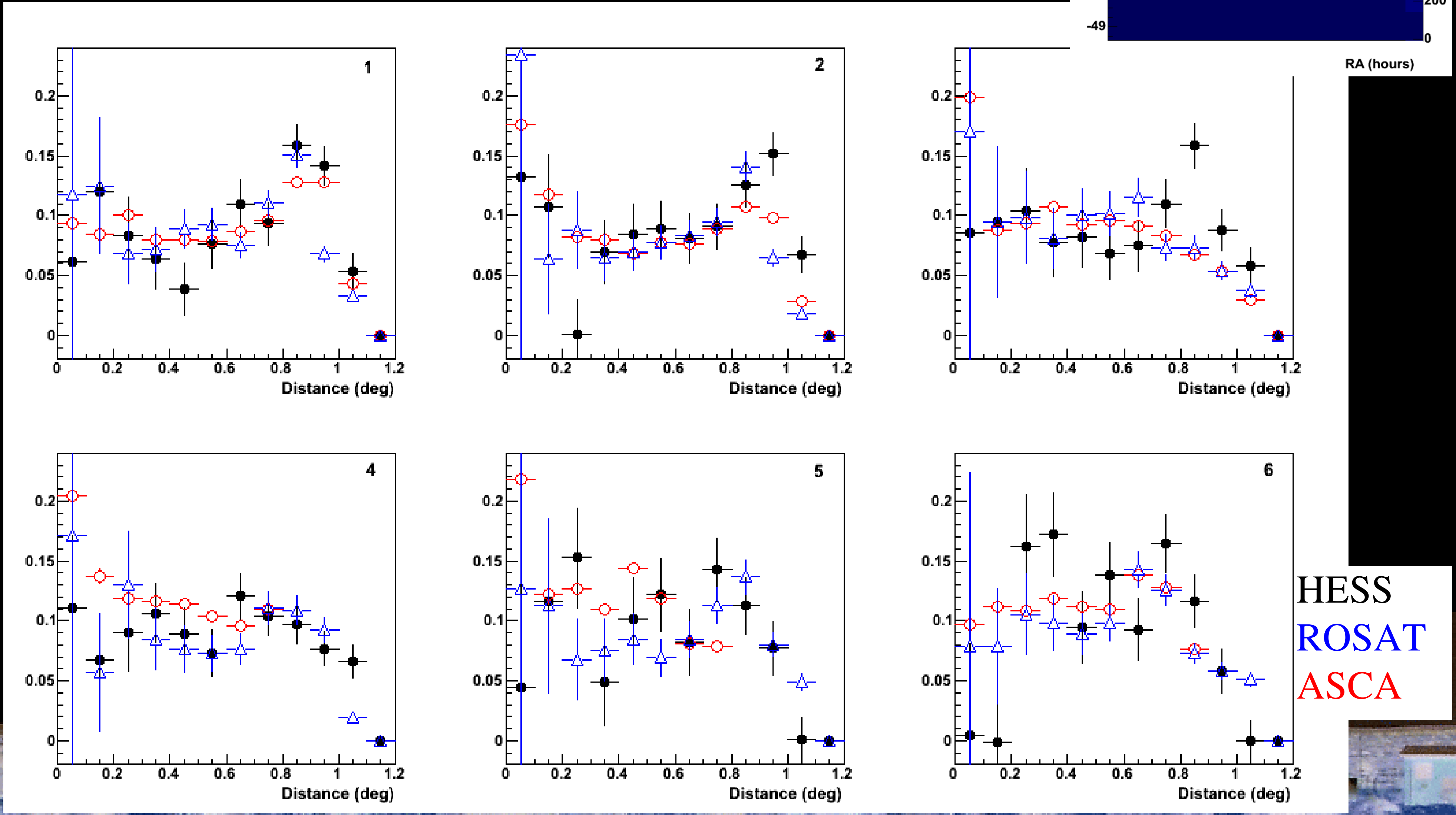
- Flux and spectral index compatible with the results published in A&A
- Indication of deviation at high energy



Correlation with X-rays

Correlation coefficient between X-rays and HESS ~ 70%



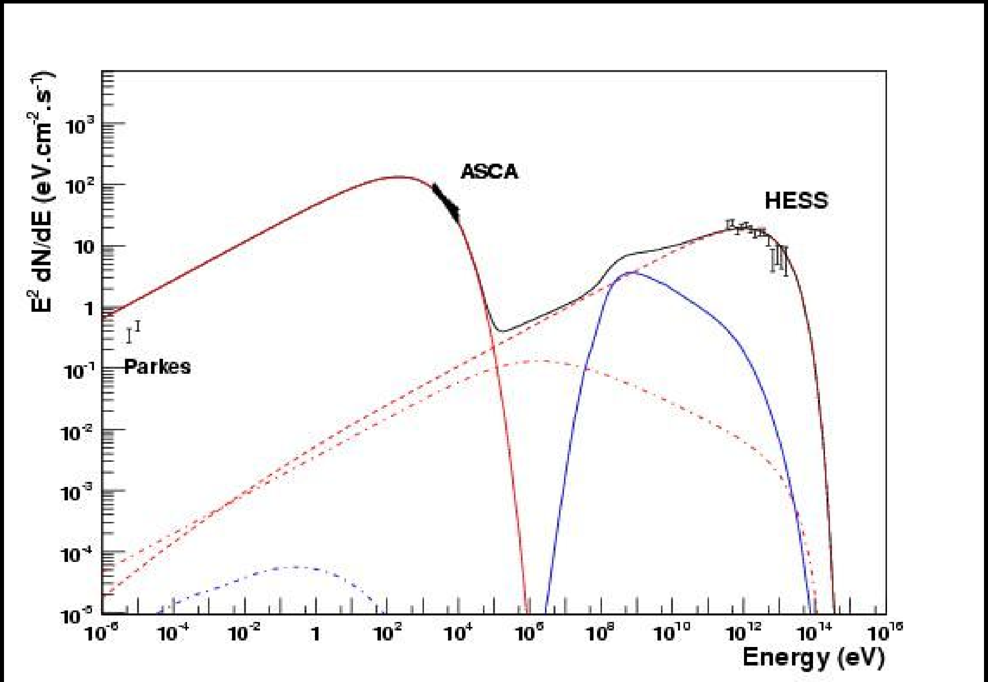


Primary population: electrons ?

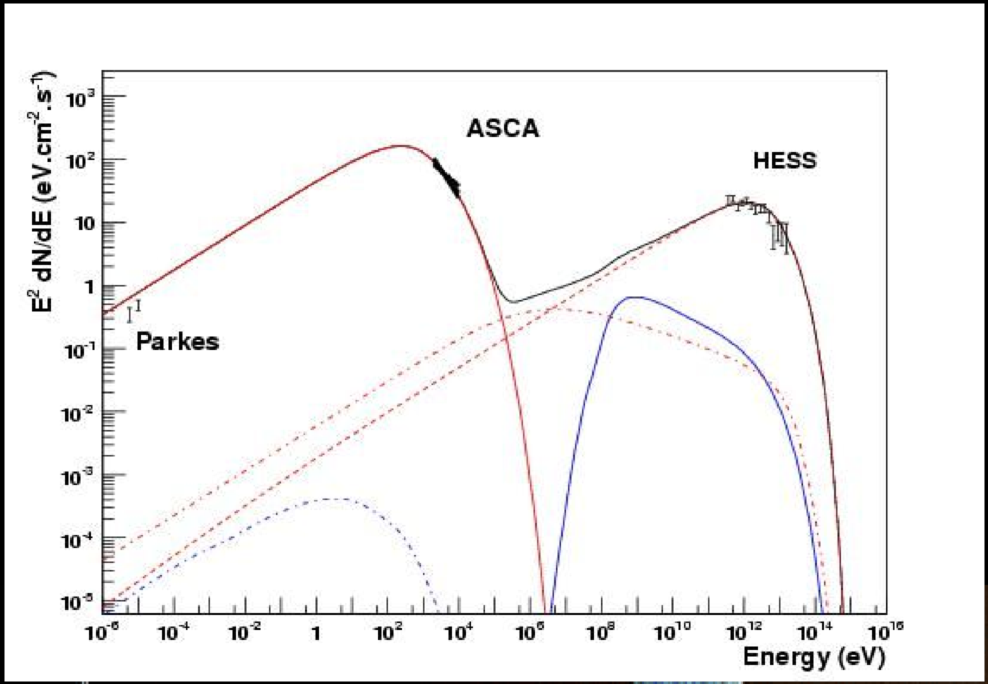
Leptonic process => Magnetic field ~ 7 μG

Nearby case (D ~ 200 pc)

=> Difficulty to confine electrons in the very thin shell resolved by HESS



Distant case (D ~ 1 kpc)

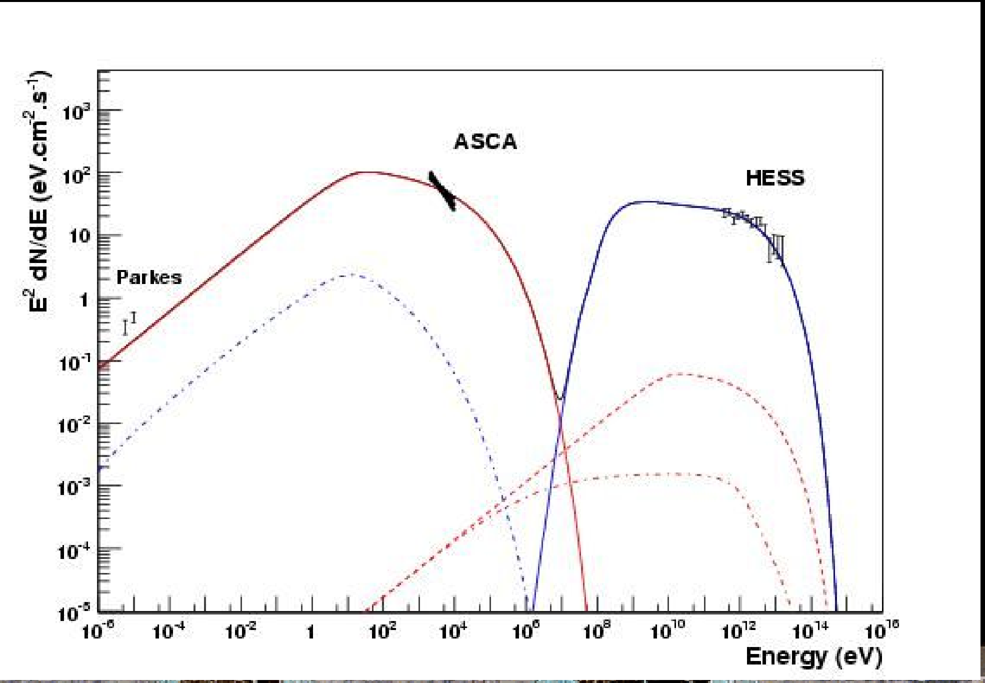


Primary population: protons ?

Hadronic process => Magnetic field > 40 μG to fit the X-ray data and suppress the IC-scattering component

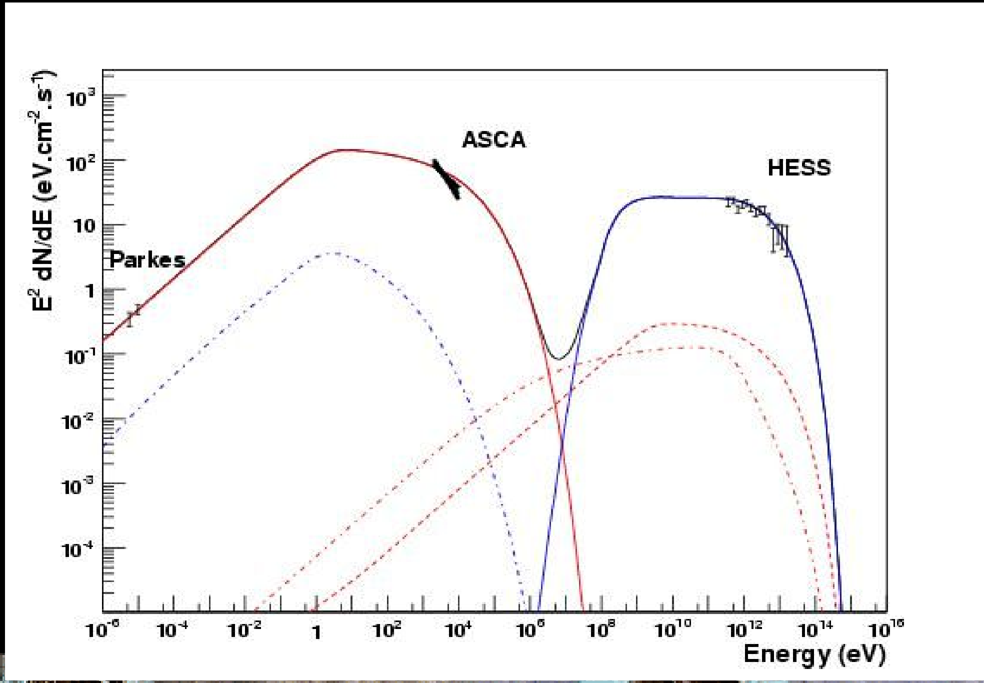
Nearby case (D ~ 200 pc)

=> Electron/proton ratio ~ 4×10^{-6}

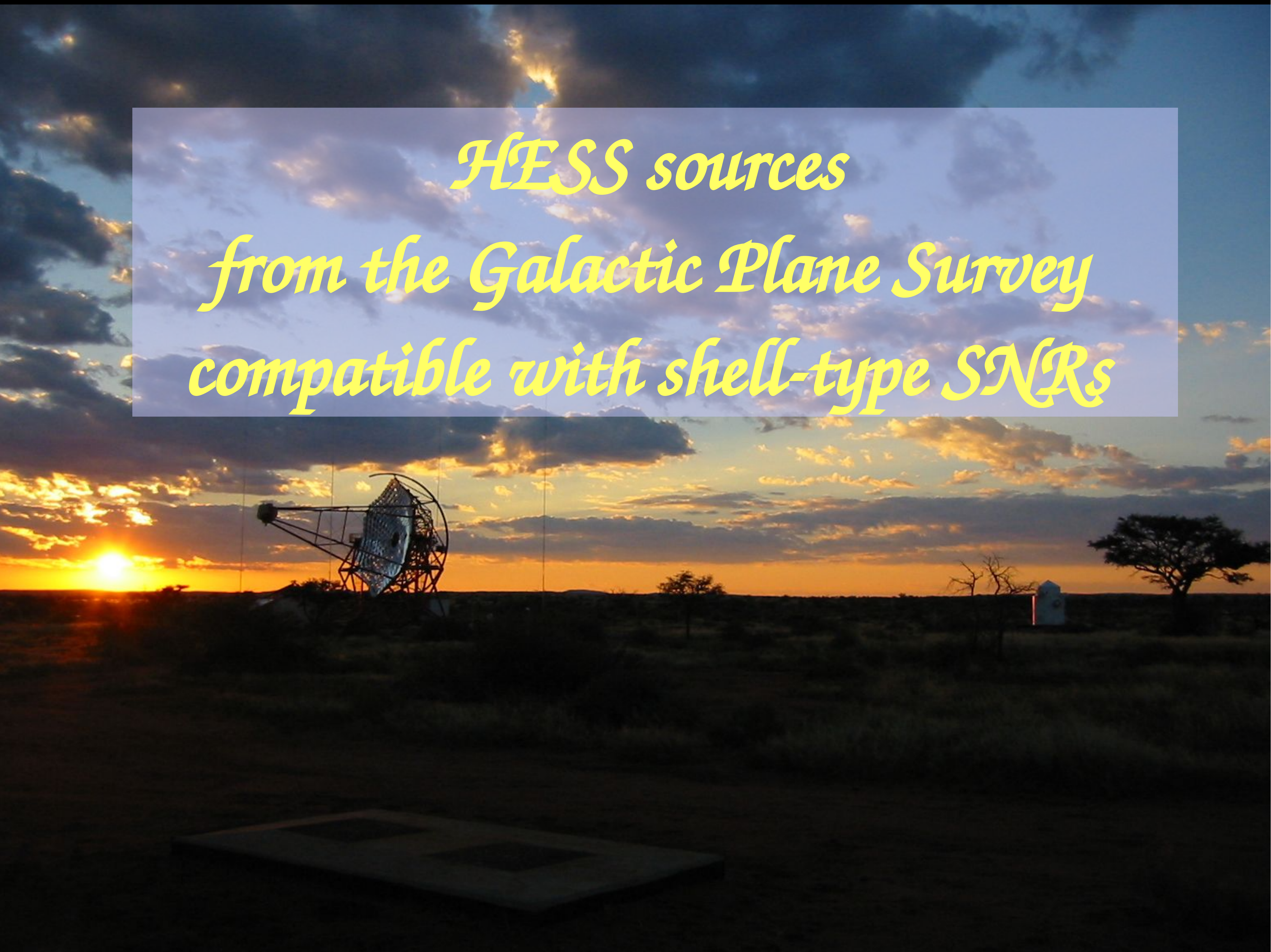


Distant case (D ~ 1 kpc)

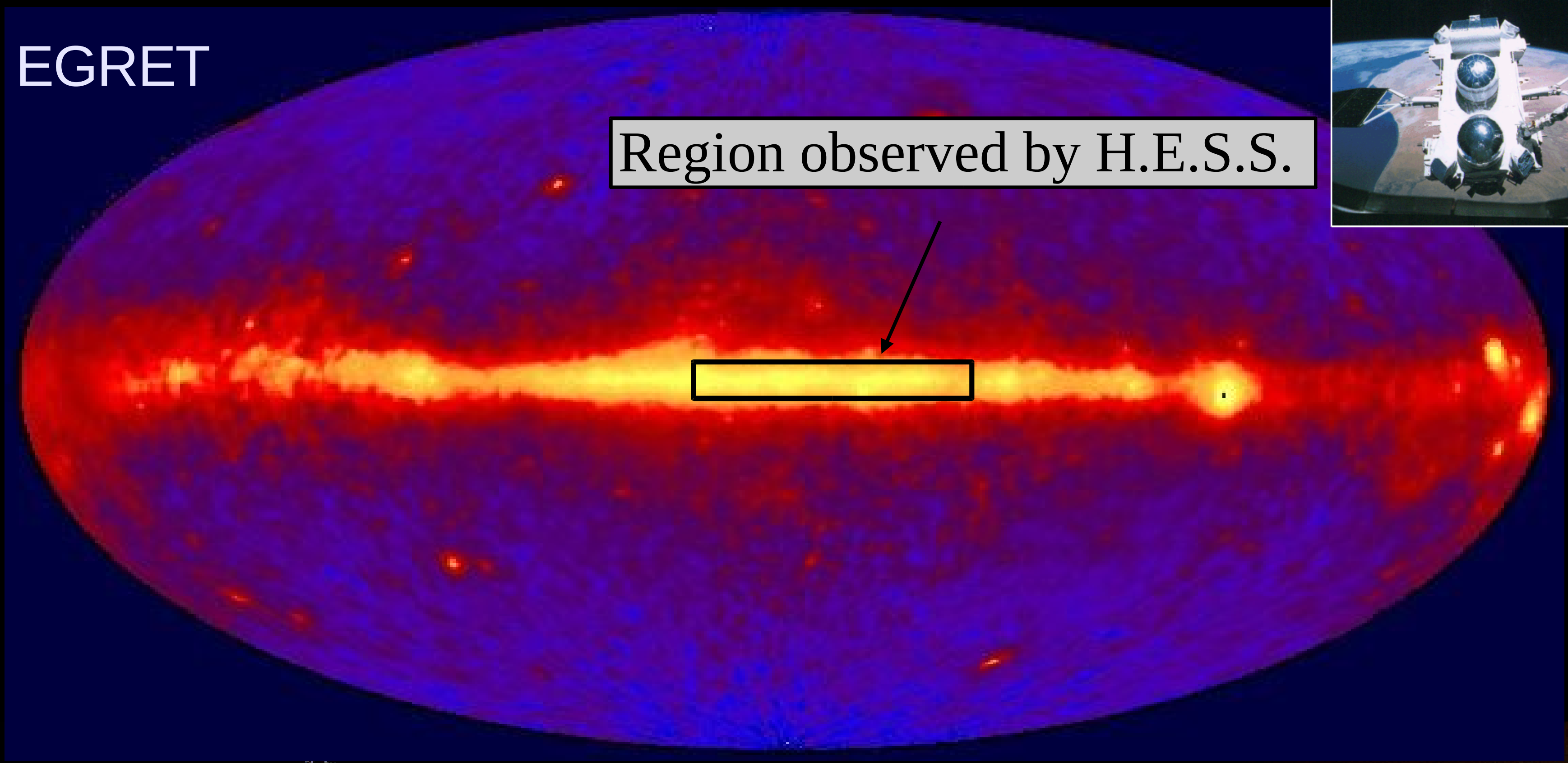
Density ~ 2.2 cm^{-3} => Bubble mechanism needed to explain the absence of thermal X-rays

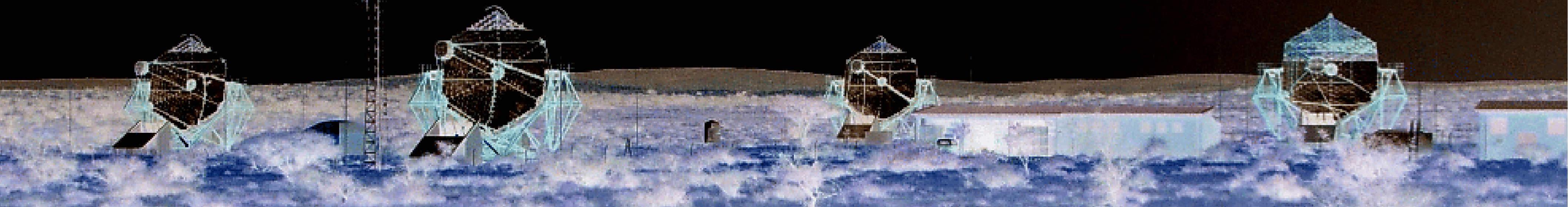


HESS sources from the Galactic Plane Survey compatible with shell-type SNRs

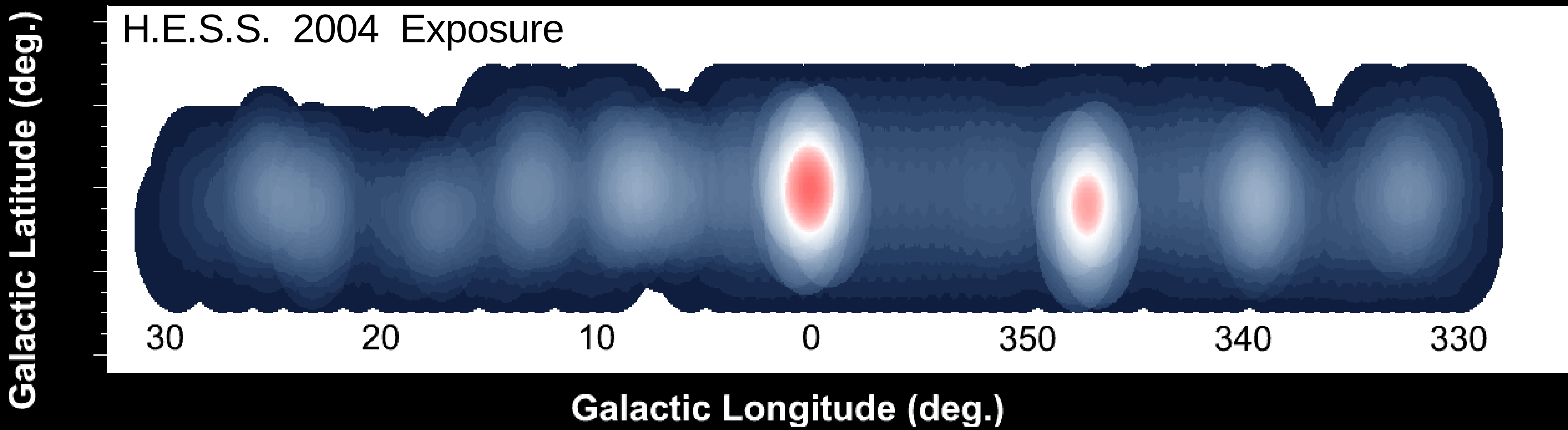


The gamma-ray sky observed by EGRET (~ 100 MeV)





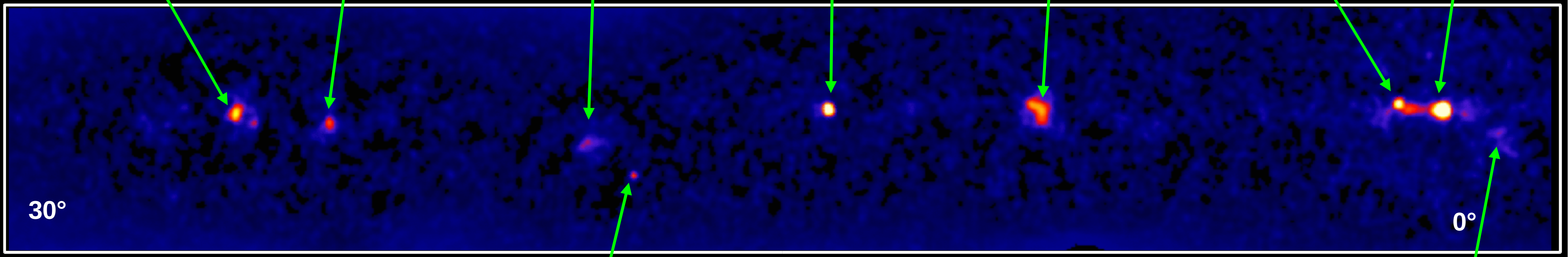
The HESS survey (I)

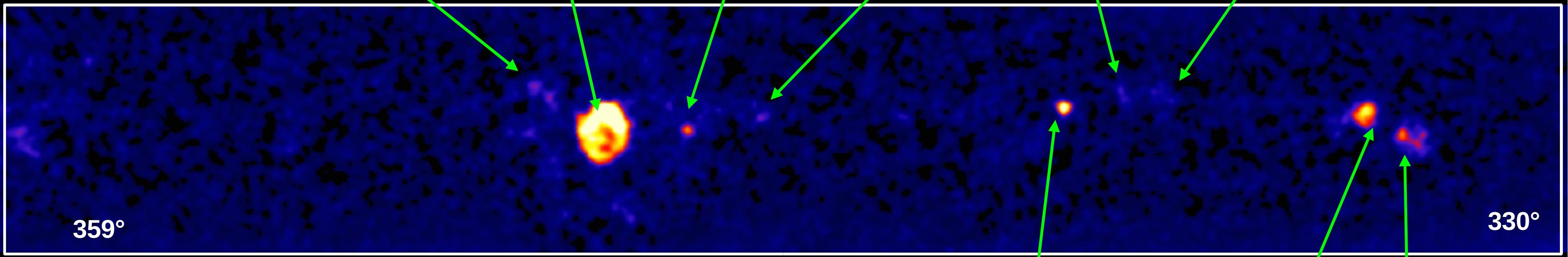


- -30 to 30 degrees in longitude, approx. ± 3° in latitude
- 112 hours scanning plus:
- ~50 hour exposures of RX J1713 and the Galactic Centre
- Re-observations of new sources

- Green's Catalogue SNRs
  - 91 SNRs in the survey region

The results of the scan

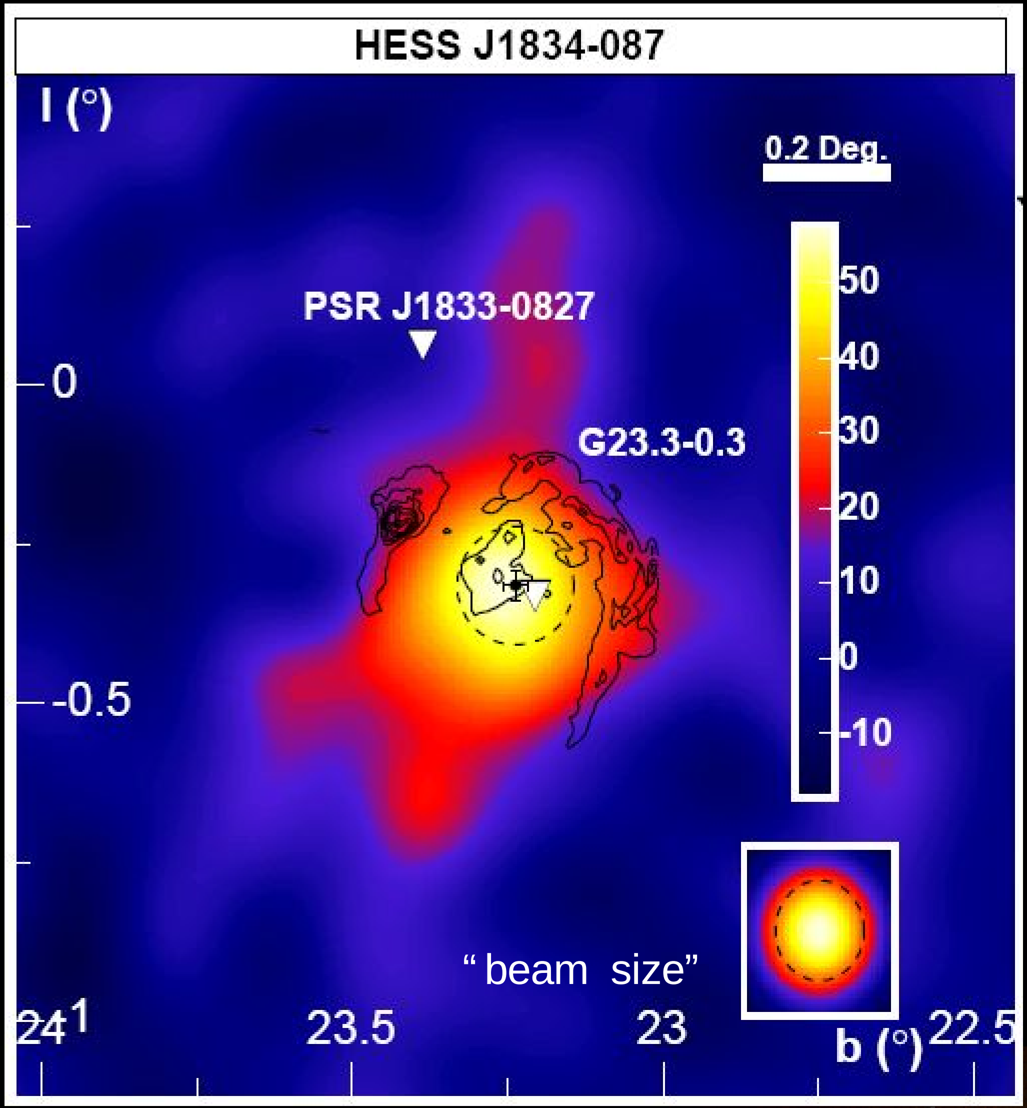


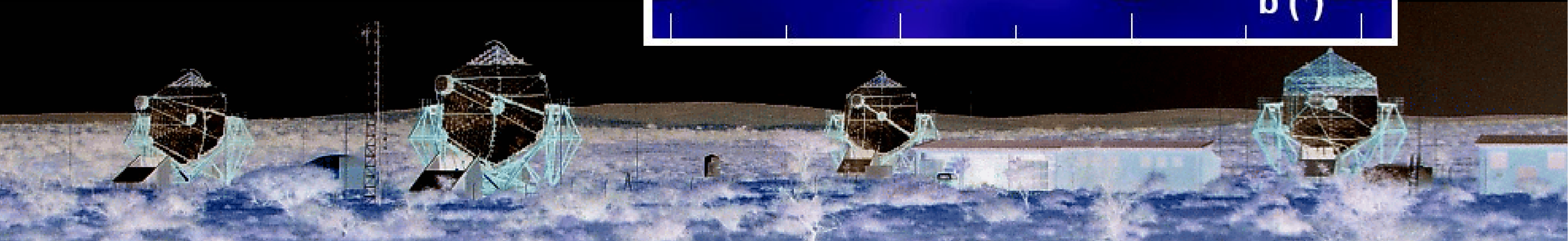


14 new sources detected with a significance > 4 σ

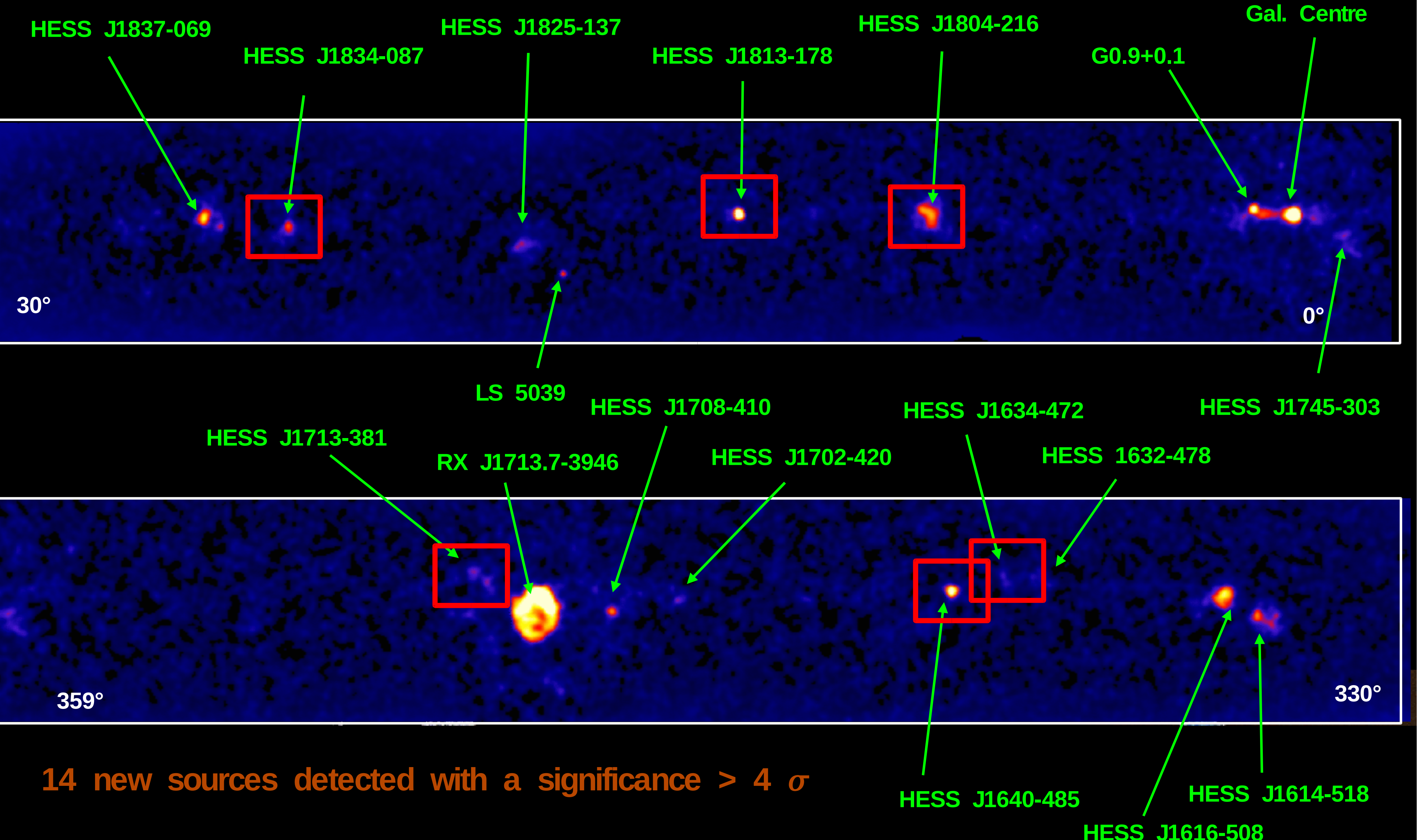
What are these new sources ?

- 3 could be pulsar wind nebulae, typically displaced from the pulsar
- 1 microquasar (LS5039)
- Some coincide with EGRET, ASCA, … unidentified source
- 6 sources could be associated with SNR, e.g. HESS J1834-087



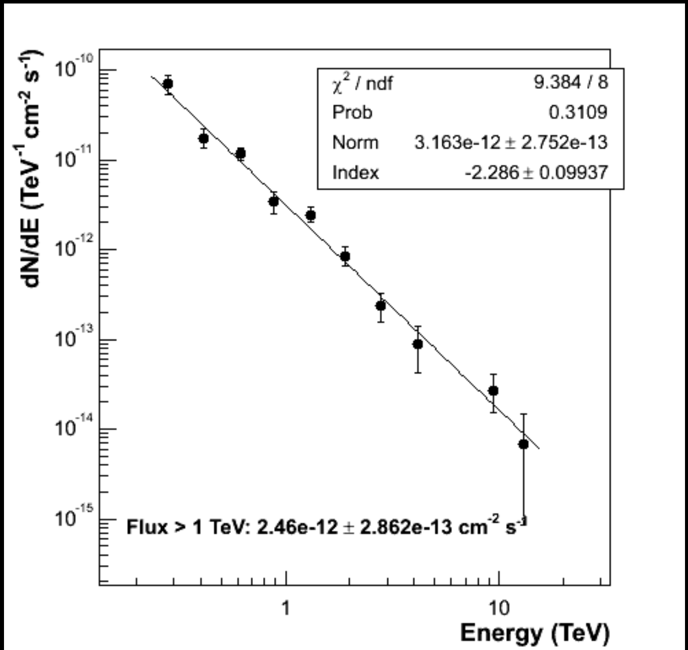


Possible SNRs detected during the Galactic Plane Survey



14 new sources detected with a significance > 4 σ

Example of perfect positional match: HESS J1640-465



Possible SNR or PWN but insufficient MWL data

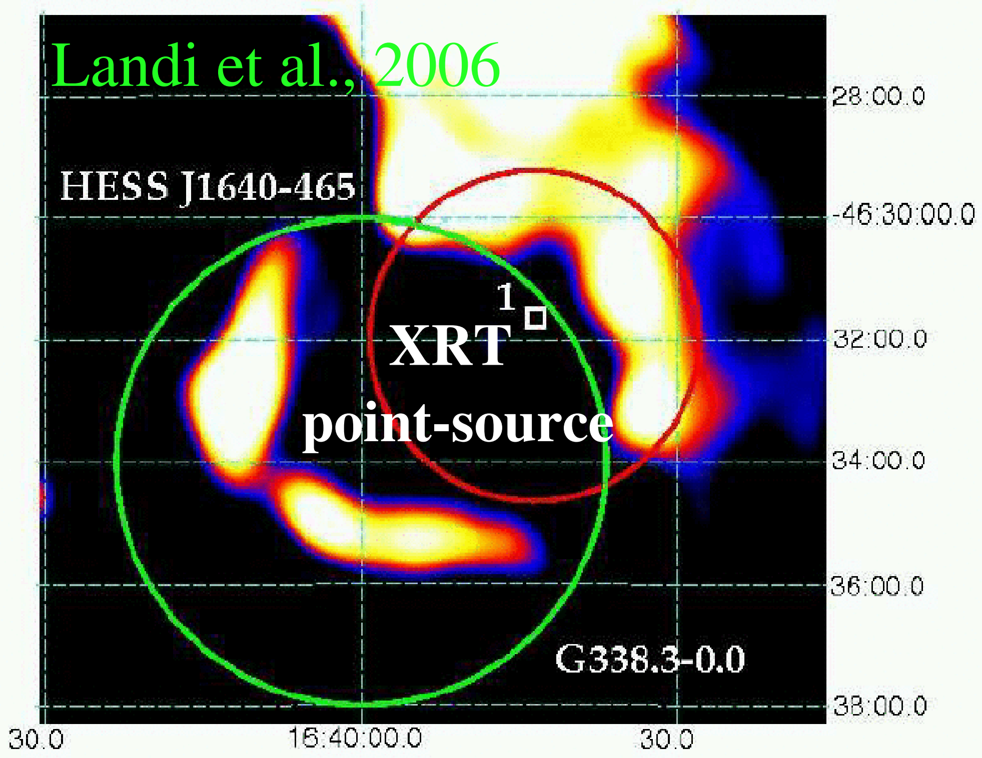
Marginally extended with respect to the HESS PSF

Photon index: 2.42 ± 0.14

Flux ~ 9% Crab nebula above 200 GeV

Excellent spatial correlation with G338.3-0 (broken shell SNR lying on the edge of a bright HII region)

Position compatible with the unidentified EGRET source 3EG J1639-4702



Example of positional offset: HESS J1804-216

SNR or PWN candidate ?

Largest source detected during the Survey

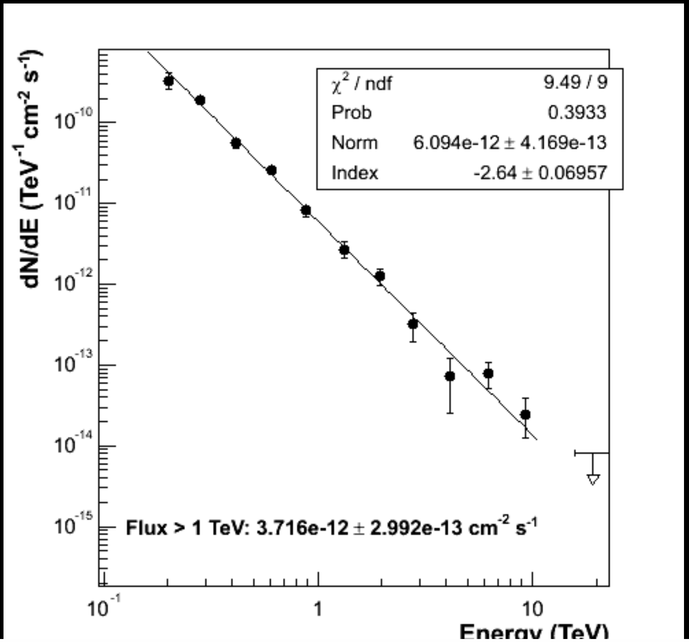
Brightest source:
Flux(>200 GeV) ~25% Crab Nebula

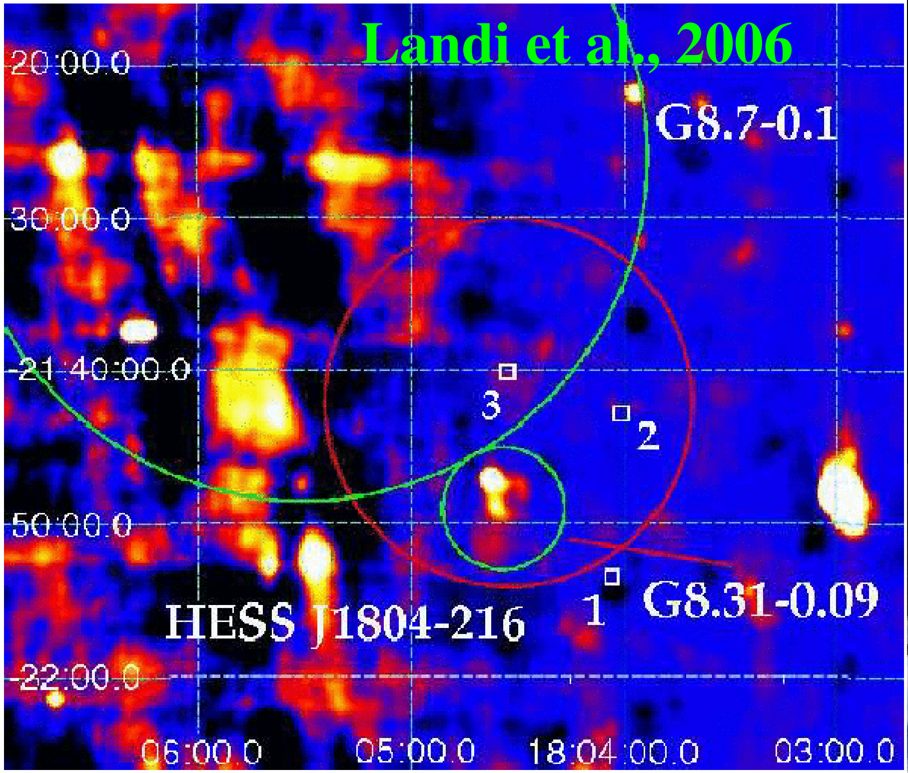
One of the Softest source:
Index: 2.72 ± 0.06

Possible association with the SW part of the shell of SNR G8.7-0.1

Possible association with the Vela-like pulsar PSR J1803-2137

+ new SNR G8.31-0.9 (Brogan et al. 2006)
+ 2 XRT point-sources (Landi et al., 2006)



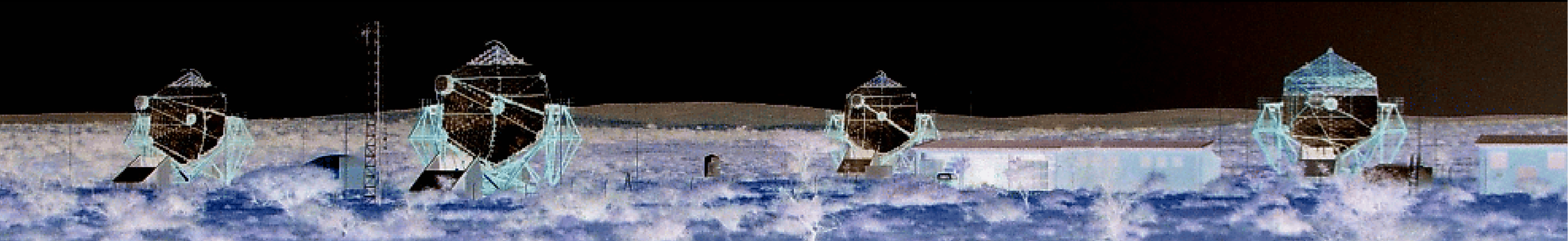


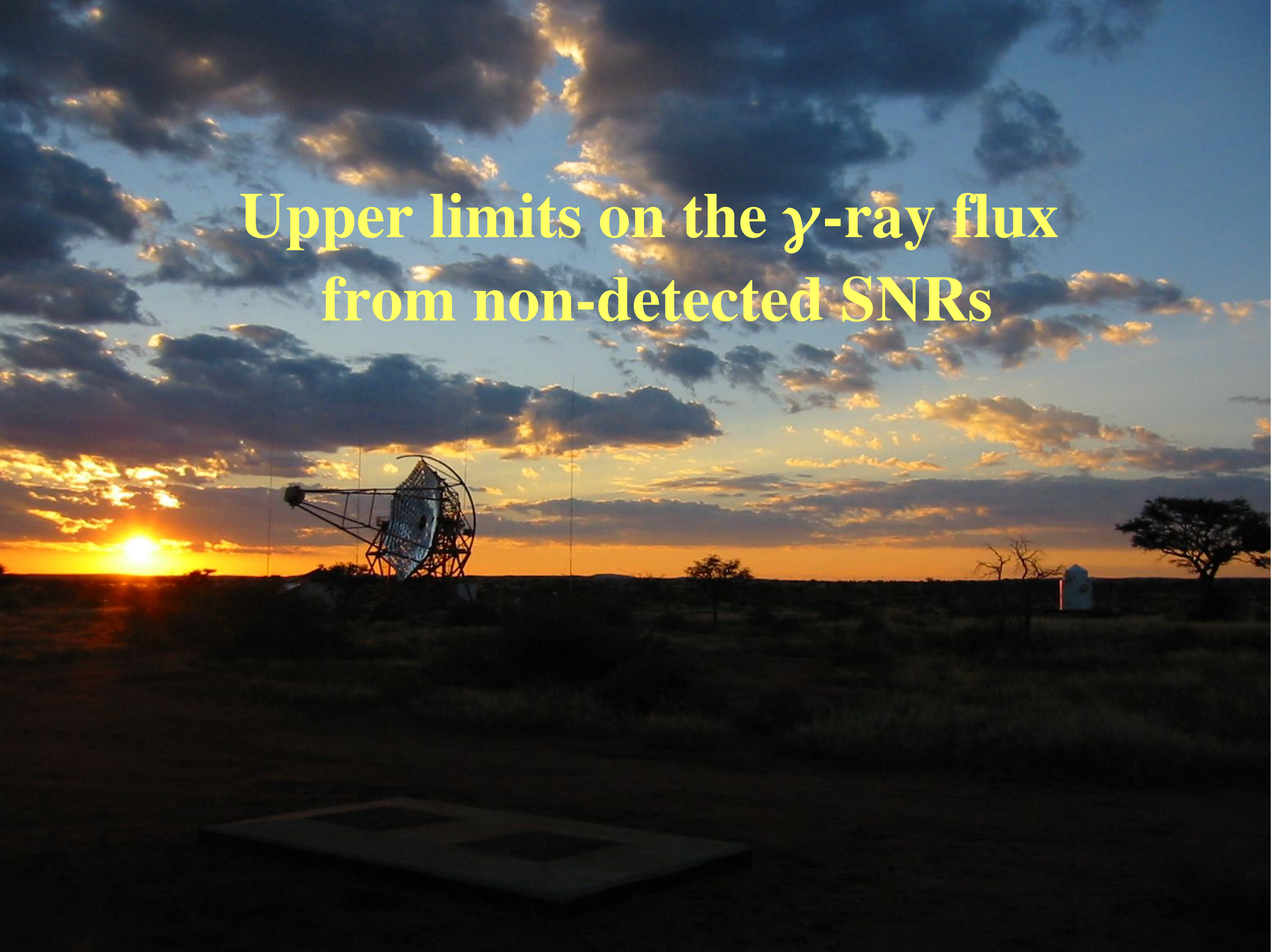
HESS sources / SNRs candidates ?

Sources	Live time (hrs)	Flux (E > 200 GeV)	Photon index	Comments
J1640-465	14,8	20,9±2,2	2,42±0,15	Excellent spatial correlation with SNR G338.3-0.0
J1713-381	37,3	4,2±1,5	2,27±0,48	Clear positional match with CTB 37B
J1834-087	7,3	18,7±2,0	2,45±0,16	Excellent positional match with SNR G23.3-0.3
J1813-178	9,7	14,2±1,1	2,09±0,08	Spatial coincidence with G12.82-0.02
J1634-472	6,6	13,4±2,6	2,38±0,27	Large offset with SNR G337.2+0.1
J1804-216	15,7	53,2±2,0	2,72±0,06	Offset with SNR G8.7-0.1 or PSR J1803-2137

SNR / PWN?

Offsets




Upper limits on the γ-ray flux
from non-detected SNRs

SN 1987A

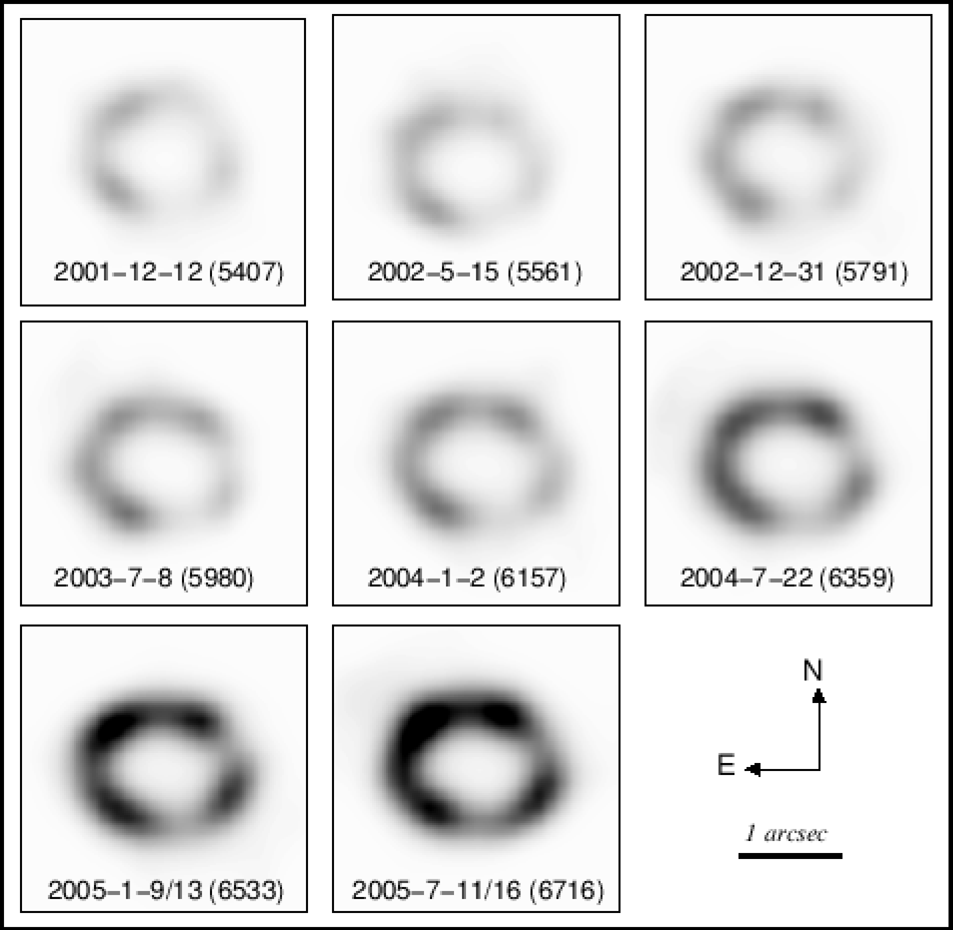
Core collapse supernova 23 Feb 1987

Progenitor ~ 50 kpc distant in LMC

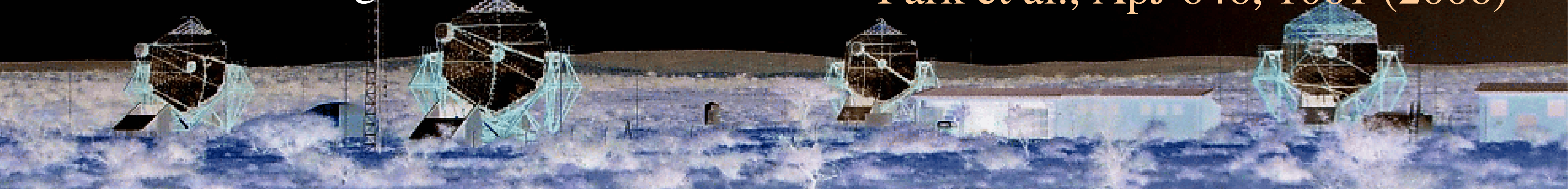
Since early 2004: strong brightening of the remnant
=> **blast wave shock front hits the inner ring**

=> CR acceleration ?
=> TeV production ?

Not detected by CANGAROO in 2003
Annual monitoring with HESS



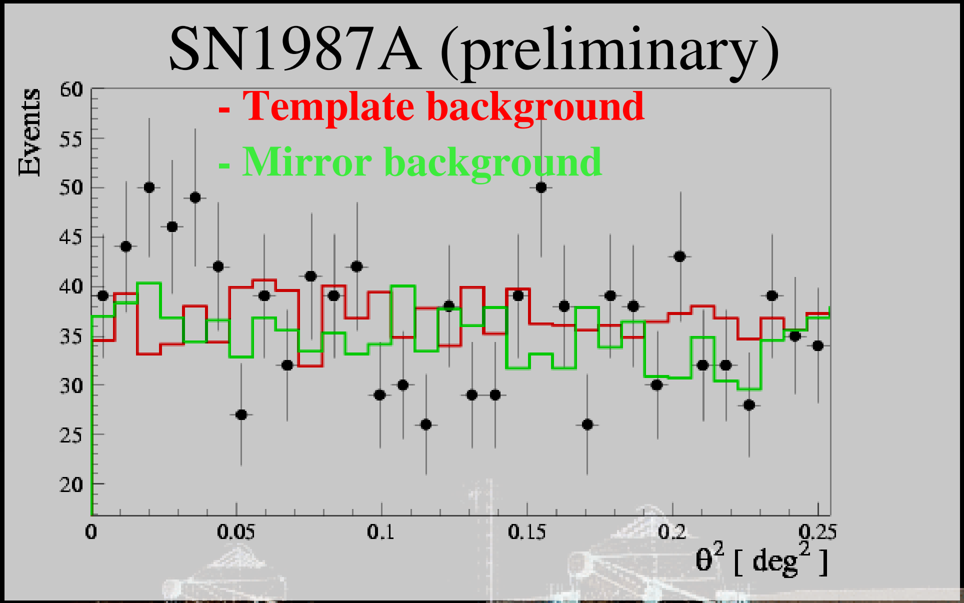
Chandra ACIS (0.3 – 8.0 keV)
Park et al., ApJ 646, 1001 (2006)



HESS limits on the γ-ray signal

2003/2004: 4.2 hr 2 tels
2004/2005: 1.8 hr 4 tels
Total: 6.0 hr at $\theta_{zen} = 51.5°$
$E_{th} \sim 0.55$ TeV

Mirror background: 0.8 σ
Template Background: 0.3 σ

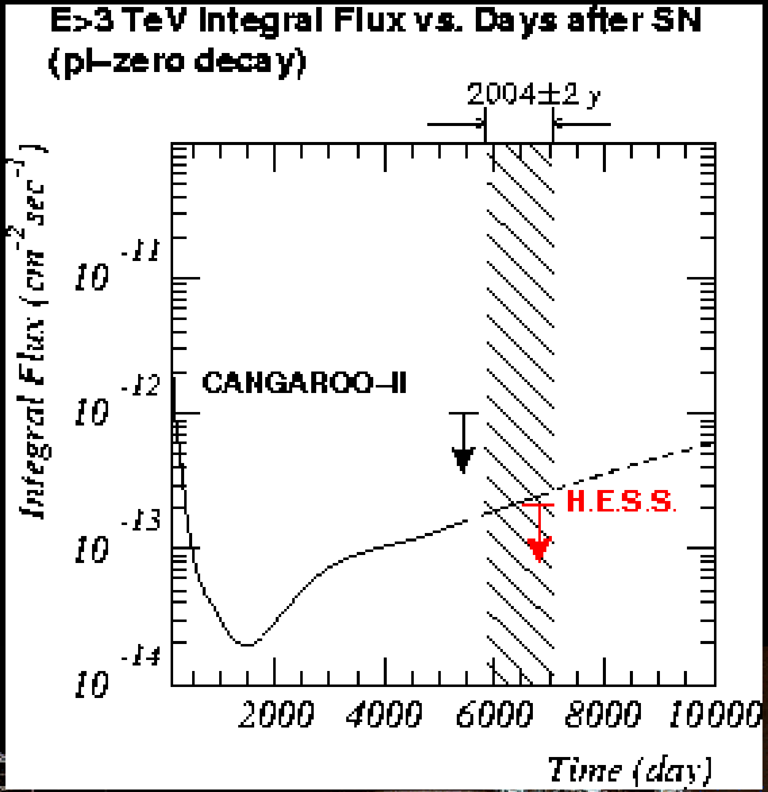


Assuming E^{-2} spectrum

$F(E > 3\ \mathrm{TeV}) < 2.2\times10^{-13}$ ph cm^{-2} s^{-1}

at 99% c.l.

G. Rowell et al., ICRC 2005



Berezhko & Ksenofontov 2000 Astron. Lett 26,639
Enomoto et al. 2003 ApJ 591 L25

Supernova 1006

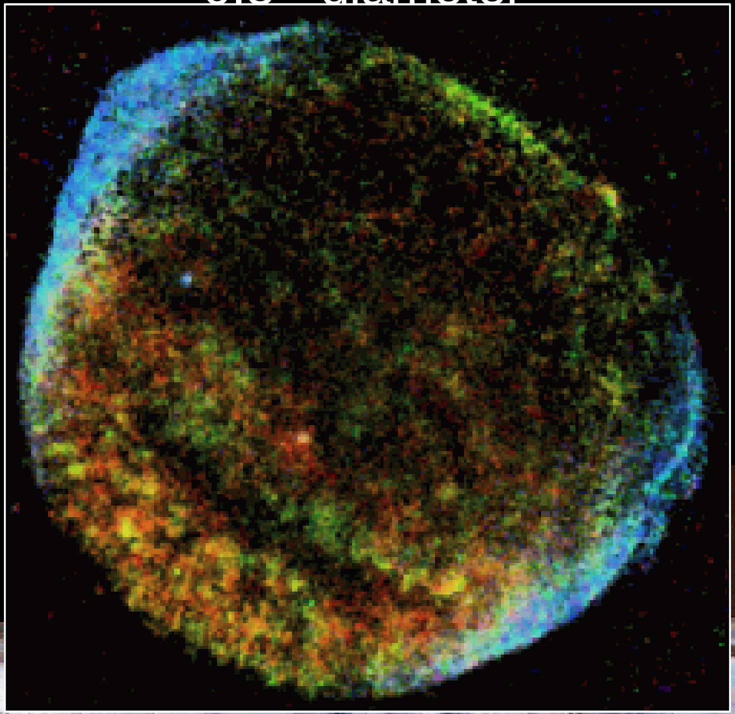
First non-thermal hard X-ray SNR (1995)

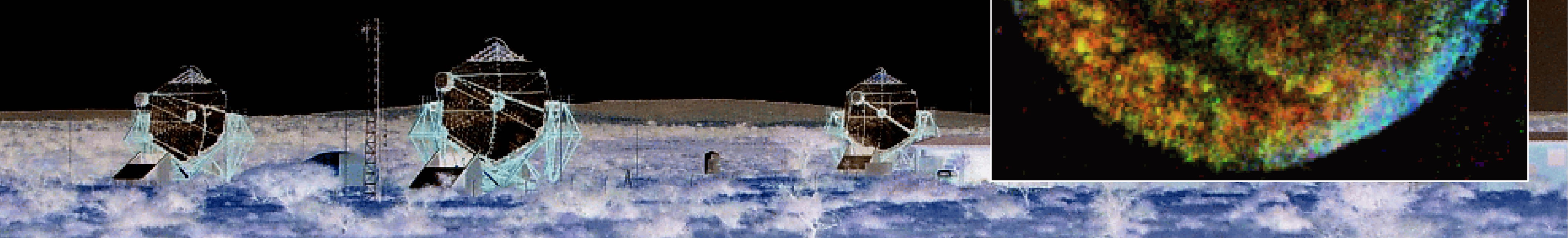
Shell-type supernova

distance = 1.8 - 2.2 kpc

Winkler et al. (2003)

N_H = 0.05 - 0.3 cm^{-3}





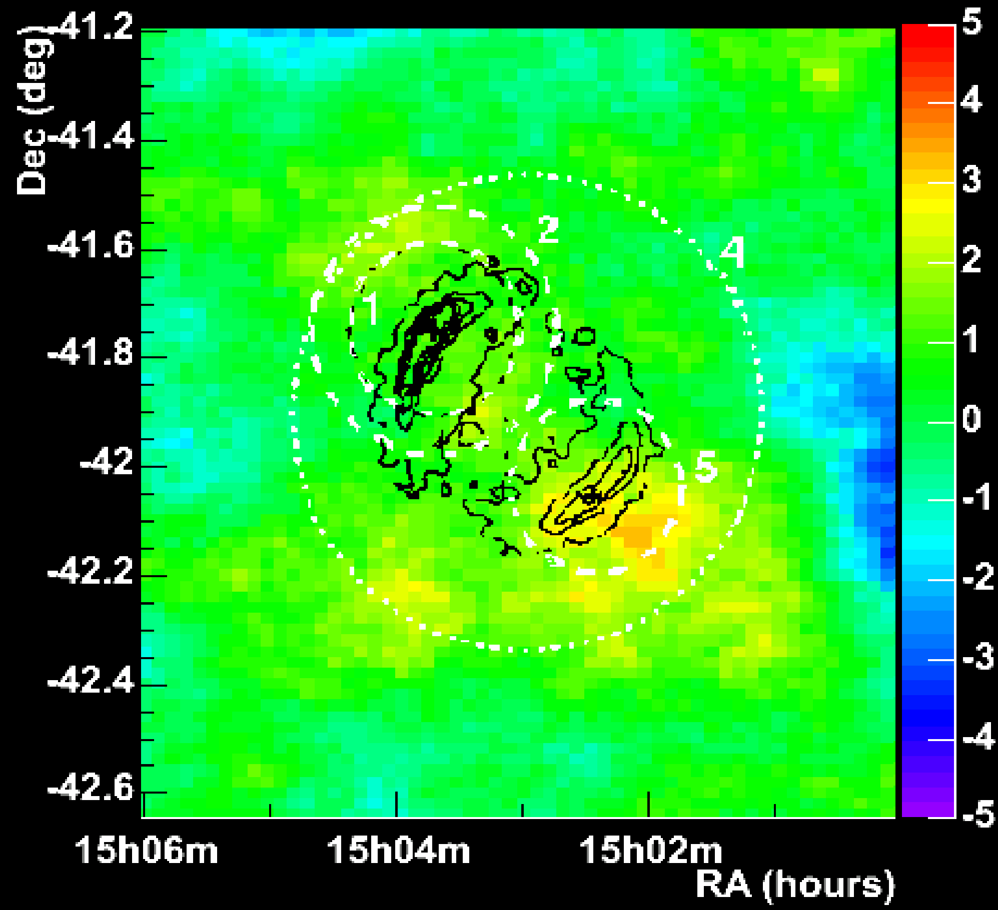
No signal seen by H.E.S.S.

18.2 hours live time with 2 telescopes (2003)

+

6.3 hours with all 4 telescopes (2004)

Mean zenith angle ~ 24 degrees



Significance skymap + ASCA X-ray contours (black)

see Aharonian et al. (HESS Collaboration) A&A 437, 135 (2005)

Upper limits & leptonic scenario

Integral limit band at the CANGAROO position (assuming a spectral index from 2 to 3)

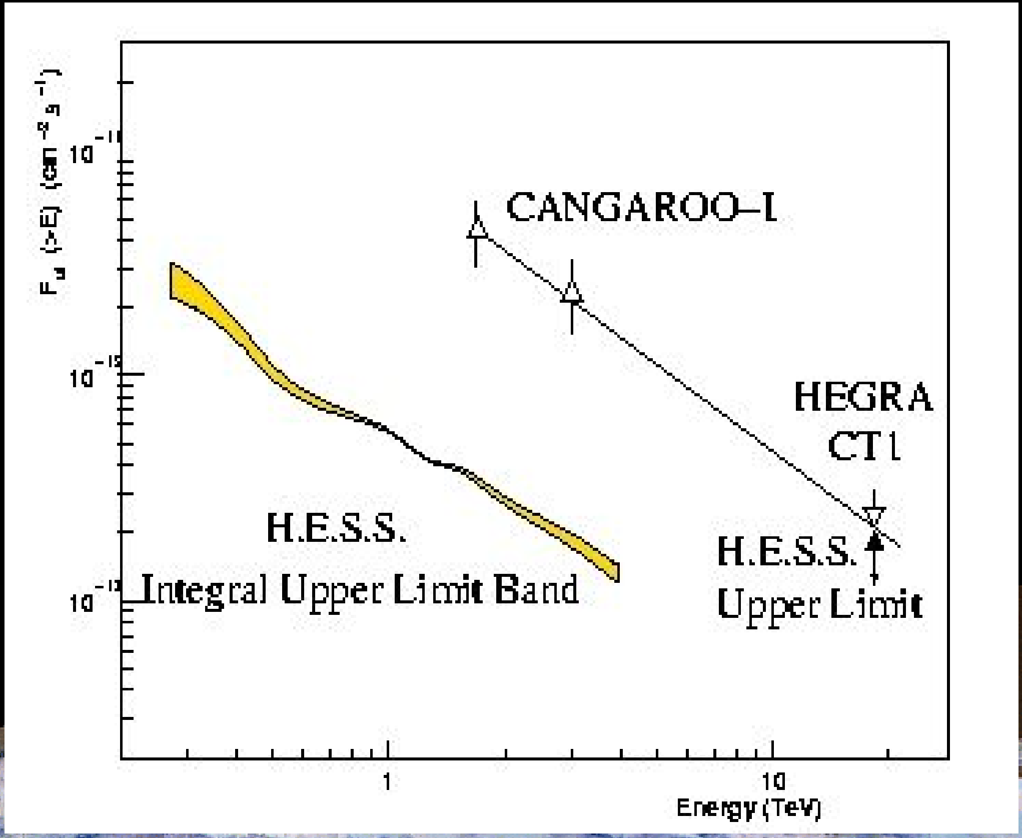
$$f_\gamma(E_\gamma)/f_x(E_x) \sim 0.1(B/10\mu G)^{-2}\xi \text{ (Aharonian et al. 1997)}$$

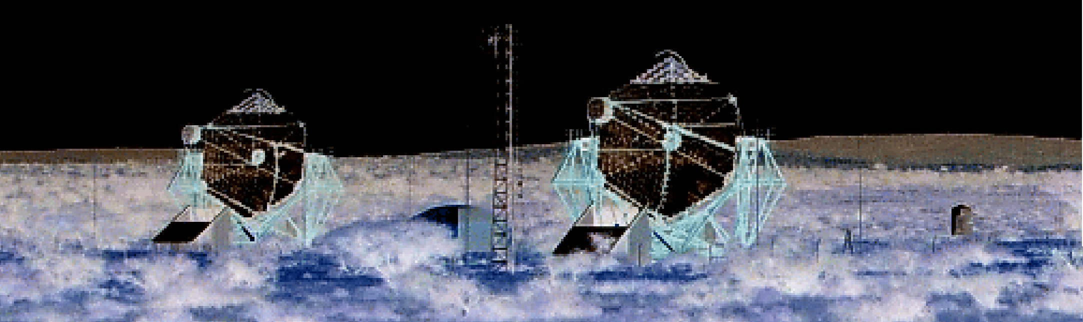
$$f_x = 1.42 \times 10^{-10} \text{ erg cm}^{-2}\text{s}^{-1}$$ Allen et al., 2001

$$f_\gamma = 2.29 \times 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1}$$ (Assuming -2 spectral index)

↓

B > 25 μG

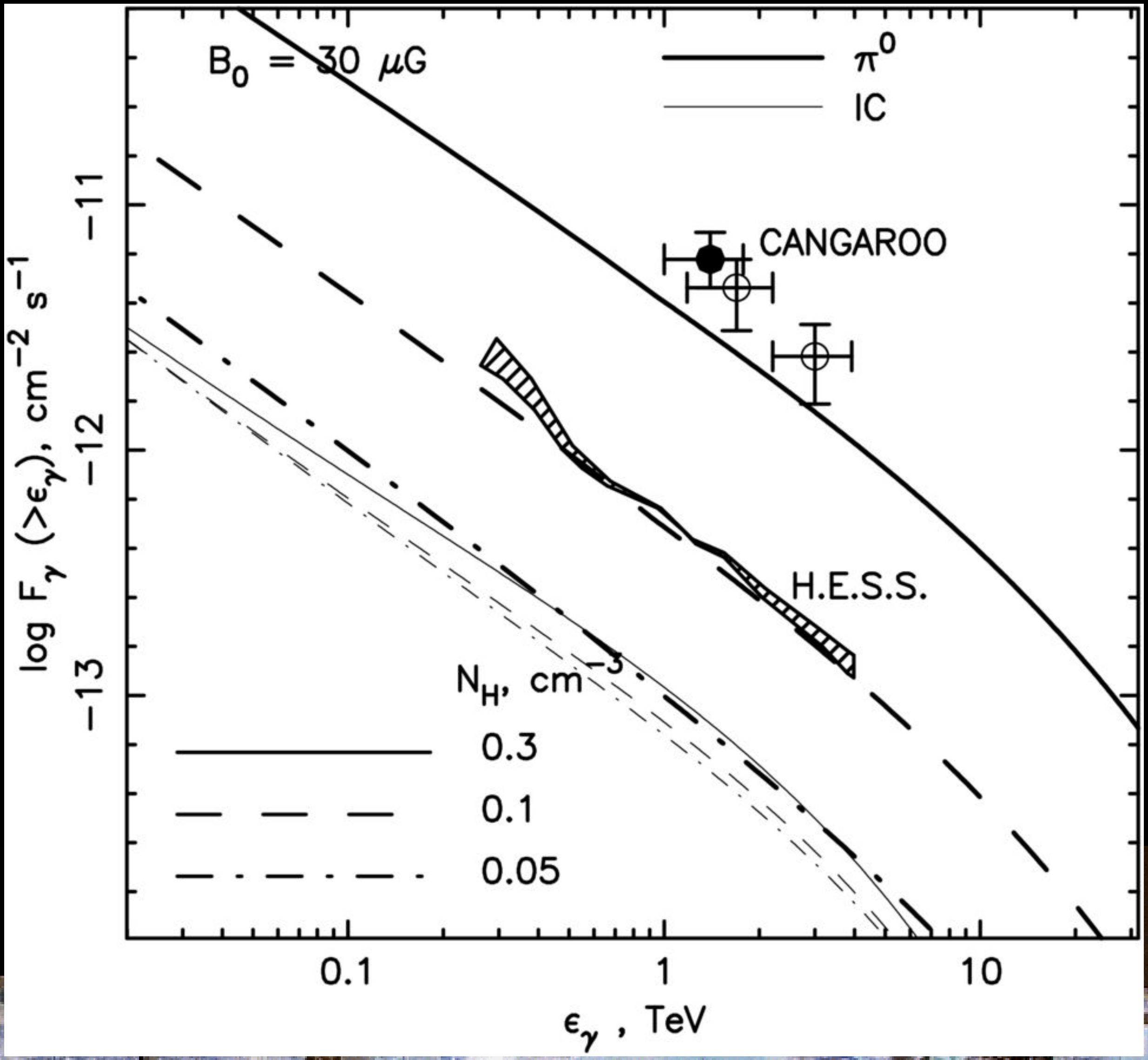




Upper limits & hadronic scenario

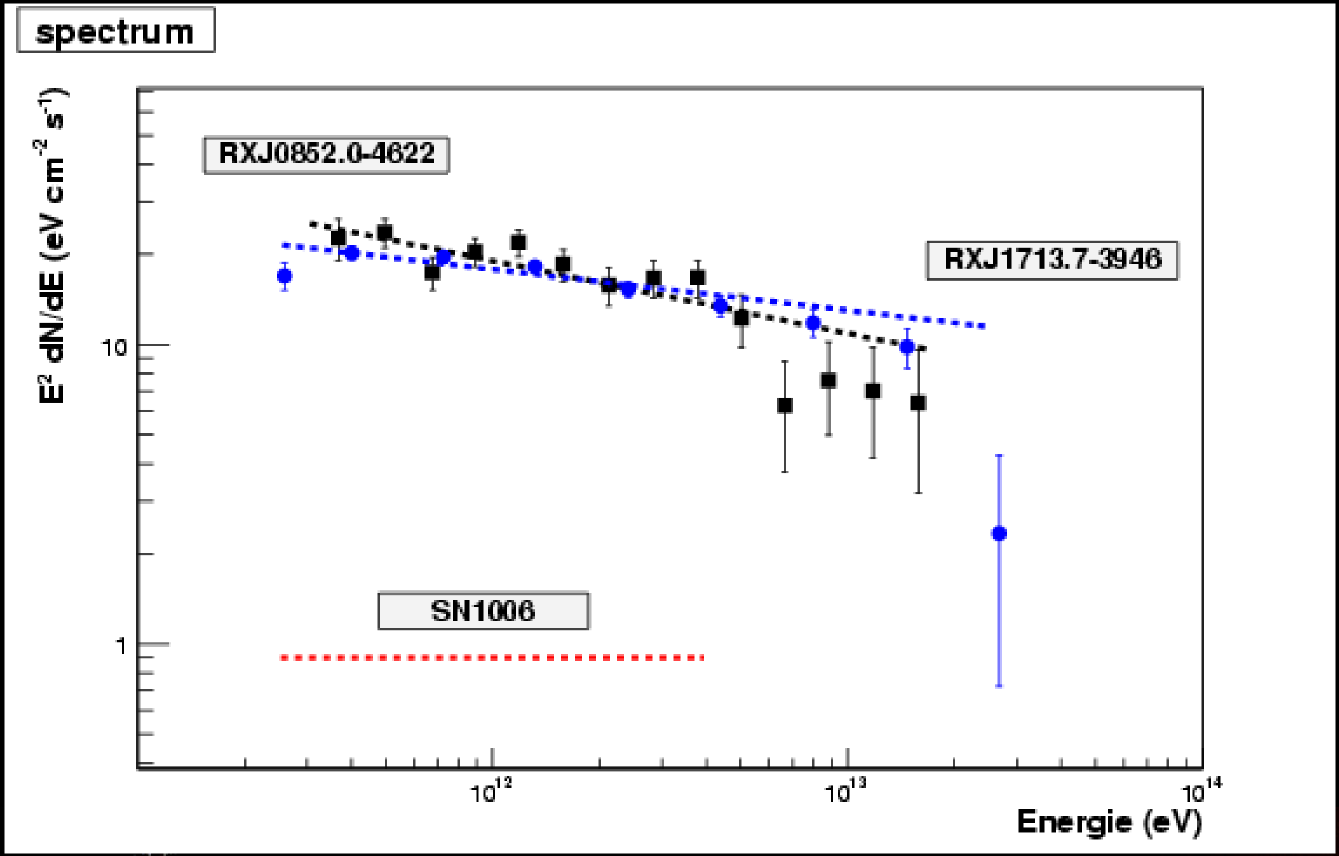
Ksenofontov et al. A&A 443 (2005) 973

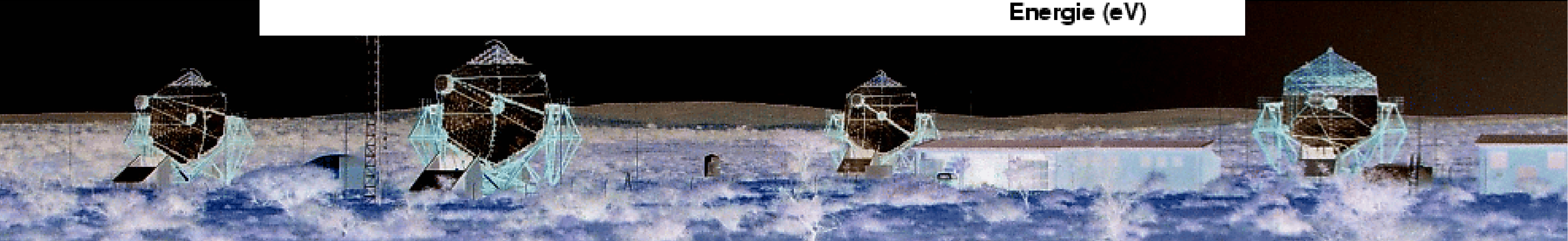
H.E.S.S. upper limit still about three times larger than the total γ-ray flux (Hadronic + Inverse Compton) expected for N_H = 0.05 cm^{-3} (which is at the lower end of the expected range of ambient densities)



Consistent with upper limit *!*

Comparison of the 3 different shell-type SNRs with mostly non-thermal X-rays





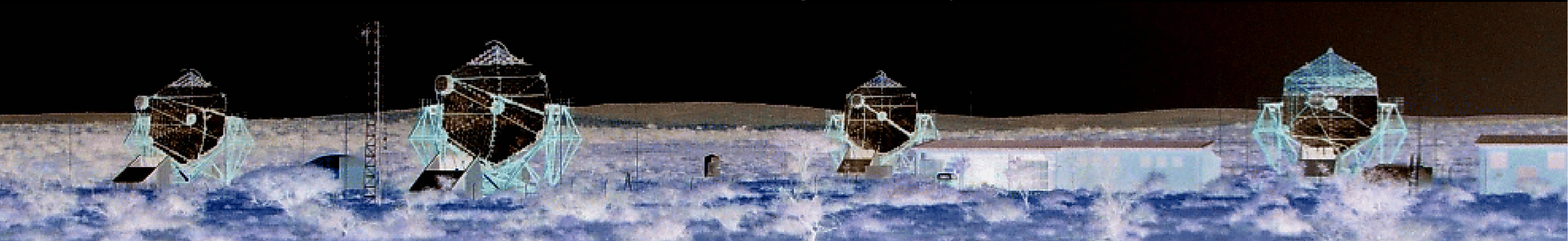
Comparison of 3 shell-type supernova remnants

	SN 1006	RX J1713.7-3946	RX J0852.0-4622
Morphology	Bilateral with 2 bright rims	Several bright rims	Several bright rims
X-ray emission	Mostly nonthermal	Mostly nonthermal	Mostly nonthermal
Radio flux density at 1 Ghz (Jy)	~ 19 (Green et al., 2001)	~ 4 ? (Ellison et al., 2001)	~ 50 ? (Duncan et al., 2000)
Location	High Galactic latitude	In the Galactic plane	In the Galactic Plane
Ambient medium density (cm-3)	0.05 – 0.3 (Dwarkadas et al., 1998; Allen et al., 2001)	< 0.02 (Cassam-Chenai et al., 2004)	< 0.03 (for d = 1 kpc) (Aschenbach et al., 1999)
Molecular clouds ?	No	Yes	Yes
Distance (kpc)	1.8 – 2.2 (Ghavamian et al., 2002)	1 (Cassam-Chenai et al., 2004; Fukui et al., 2004)	0.2 – 2 (Aschenbach et al., 1999 ; Slane et al., 2001)
Radius (pc)	~ 10	~10	~20 (for d = 1 kpc)
Age (yrs)	1000	~1600 ? (Wang et al., 1997 ; Cassam-Cheani et al., 2004)	~3400 ? (for d = 1 kpc)

And what about the magnetic field ???

Conclusions (I)

- 2 shell-type supernova remnants established as γ-ray emitter and resolved for the first time in TeV
- X-ray morphology very similar to the γ-ray morphology observed with HESS
- First time ever spatially resolved spectral study of a gamma-ray source (RX J1713.7-3946)
- Flux ~ 1 Crab & Photon index ~ 2.2
- Question of electron or hadron accelerator remains difficult to answer (=> solution should be given by HESS II & GLAST)

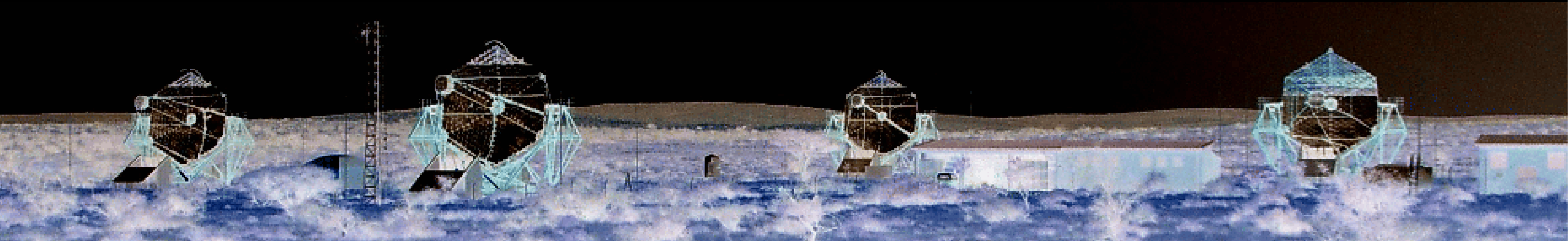


Conclusions (II)

- New shell-type SNR candidates detected during the Galactic Plane Survey

- Need more MWL data to firmly identify the HESS sources

- More sources are currently observed with HESS: building a catalogue useful for GLAST, AGILE...

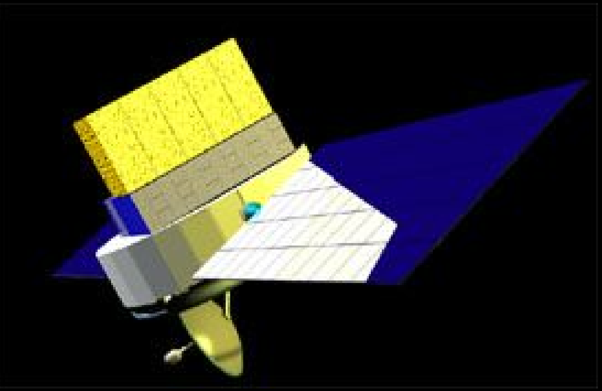


Future ?

Potential discrimination between leptonic and hadronic scenarios with HESS II & GLAST

H.E.S.S.

H.E.S.S. II



GLAST