The Galaxy Viewed in a New Light – High Energy Gamma Astronomy with H.E.S.S.

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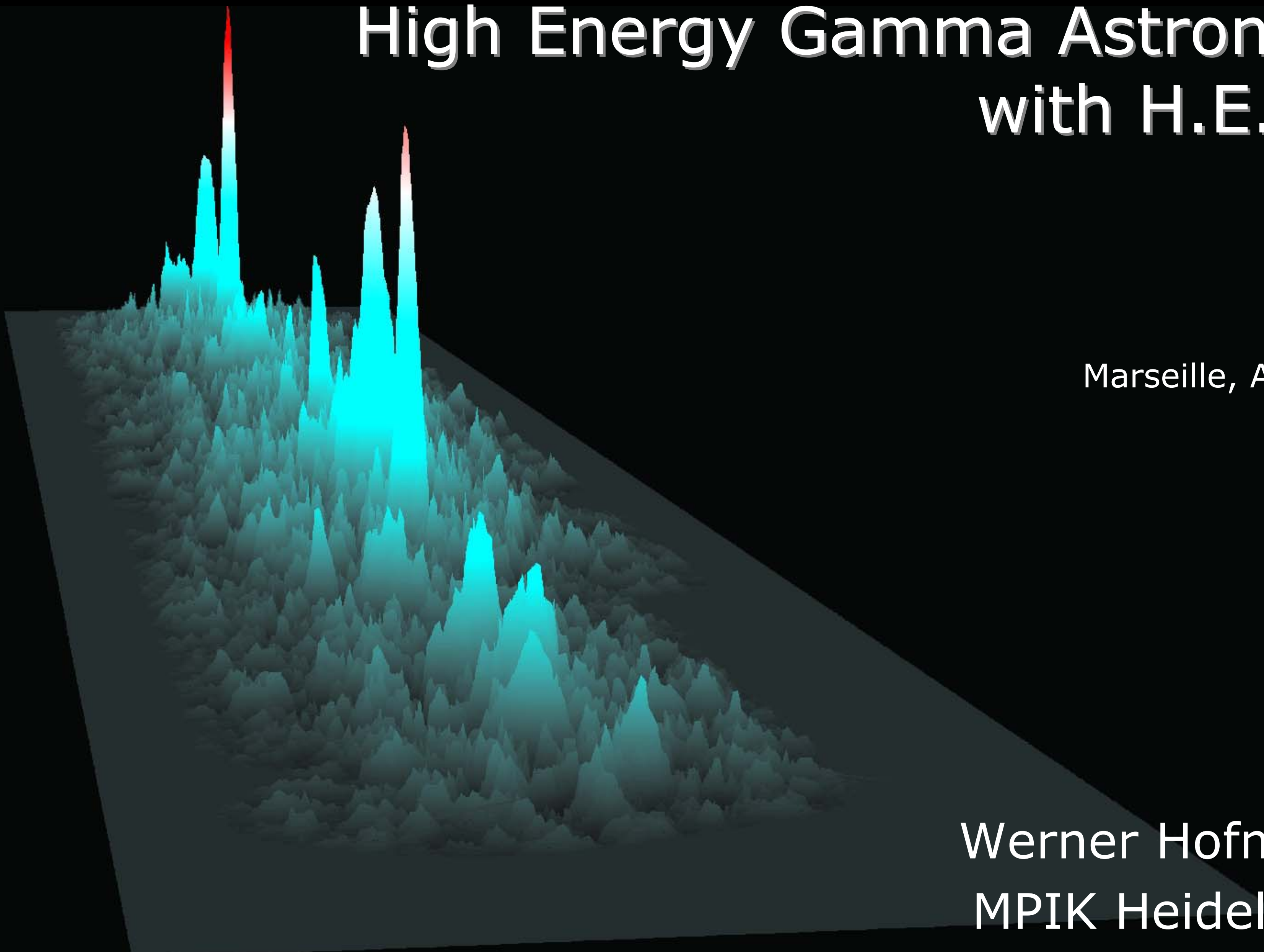
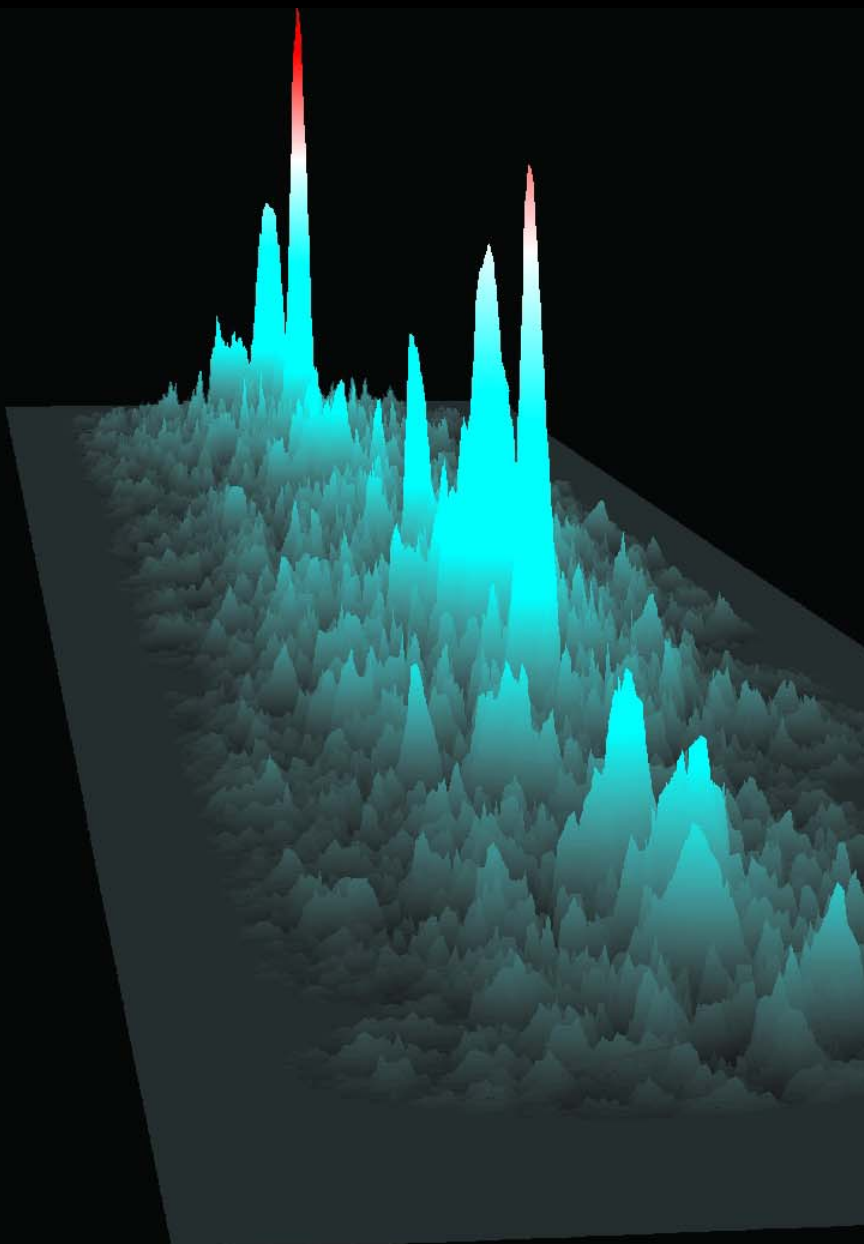


Marseille, April 4

Werner Hofmann
MPIK Heidelberg



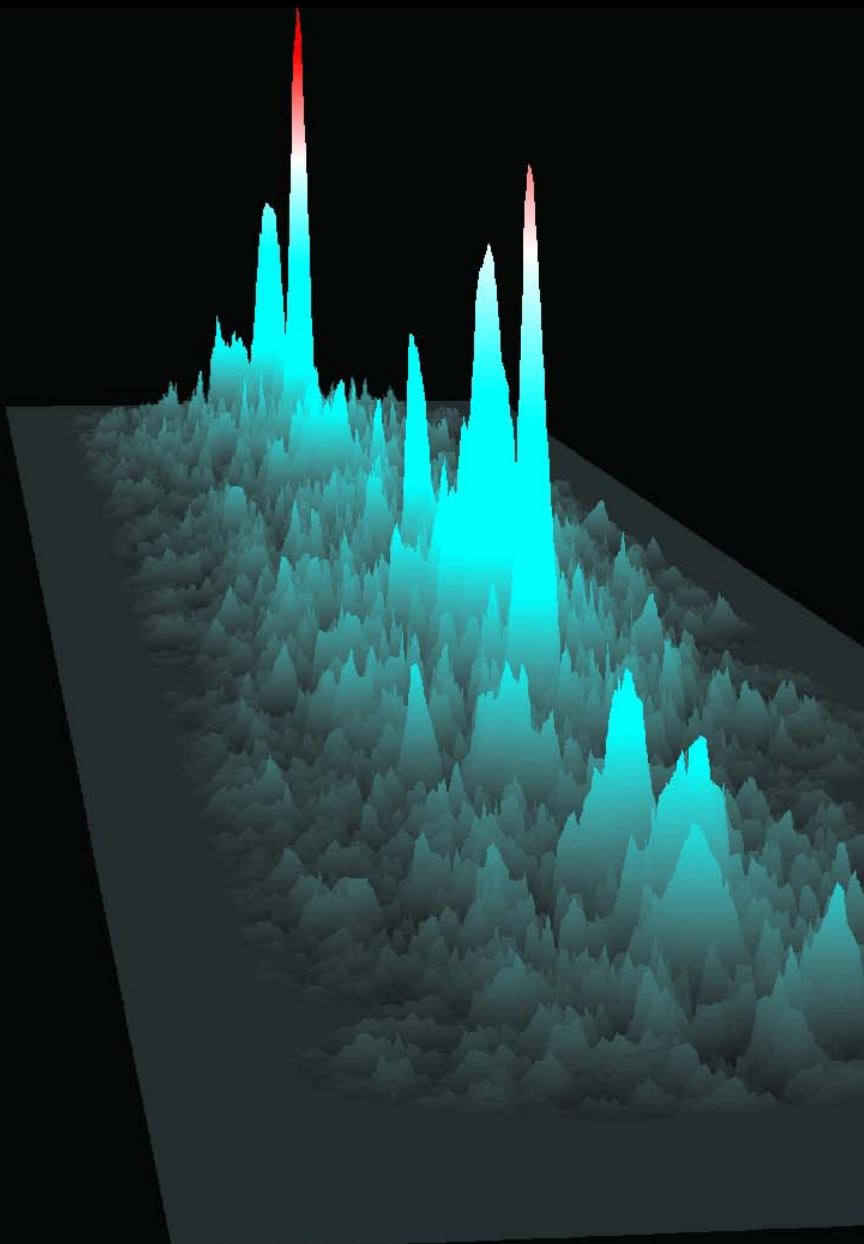
Very high energy gamma astronomy

The H.E.S.S. telescopes and how they work

Supernovae as cosmic particle accelerators

Pulsar winds
& mystery sources

Gamma rays from the Galactic Center



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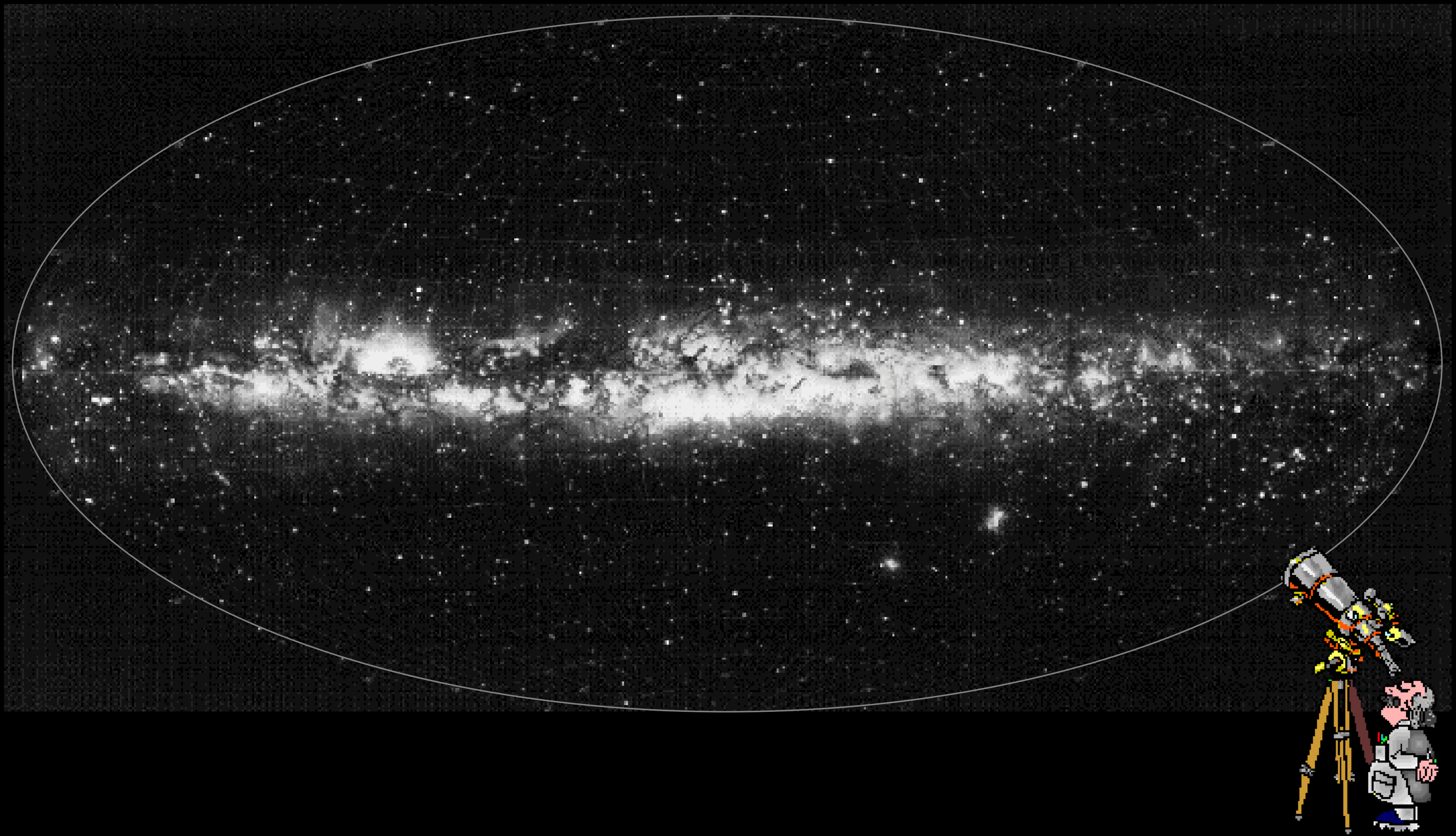
Radio Infrared **Visible Light** X-rays Gamma rays

(eV)



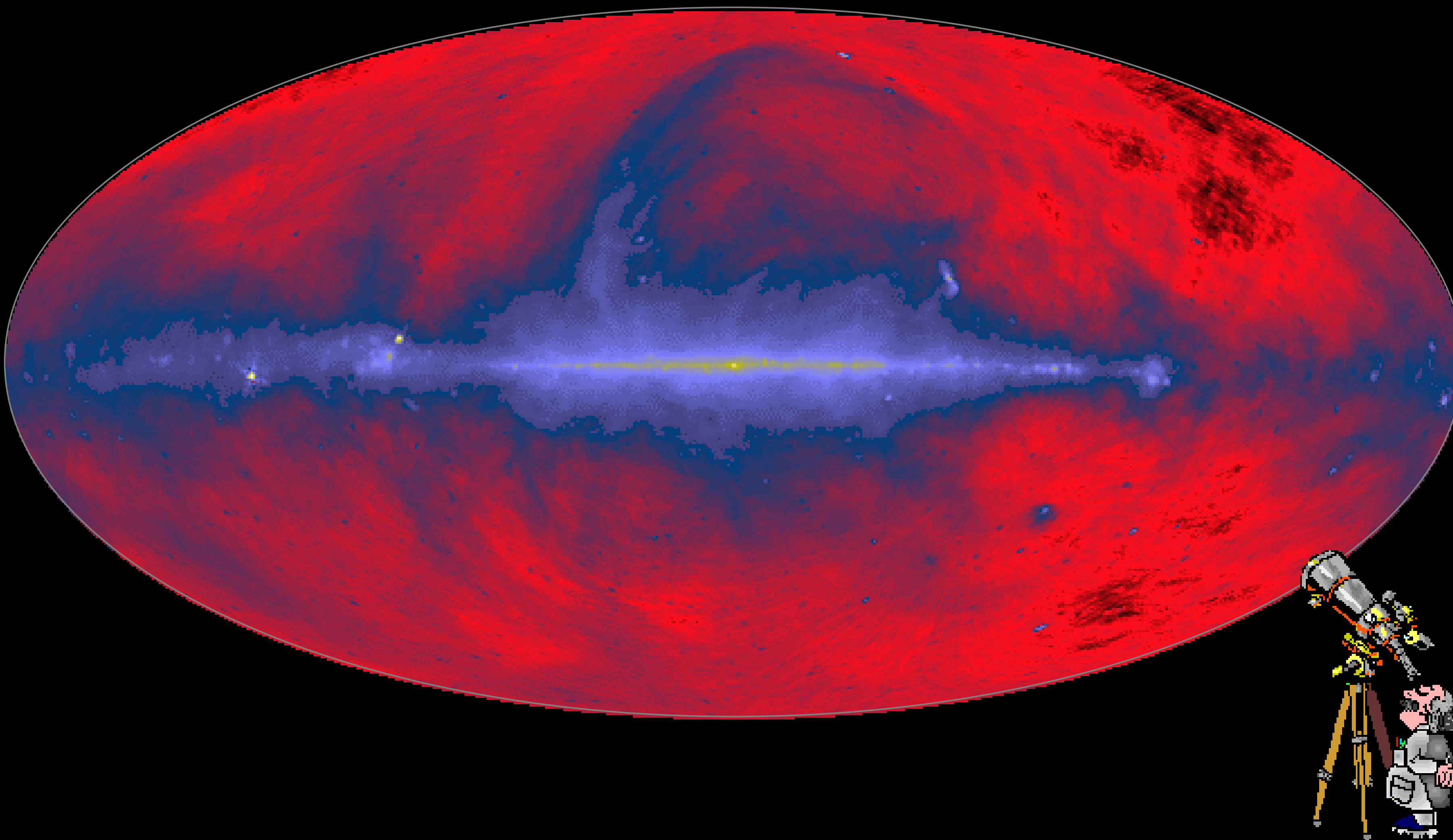
Radio
(10^{-6} eV)

Infrared

Visible Light

X-rays

Gamma rays



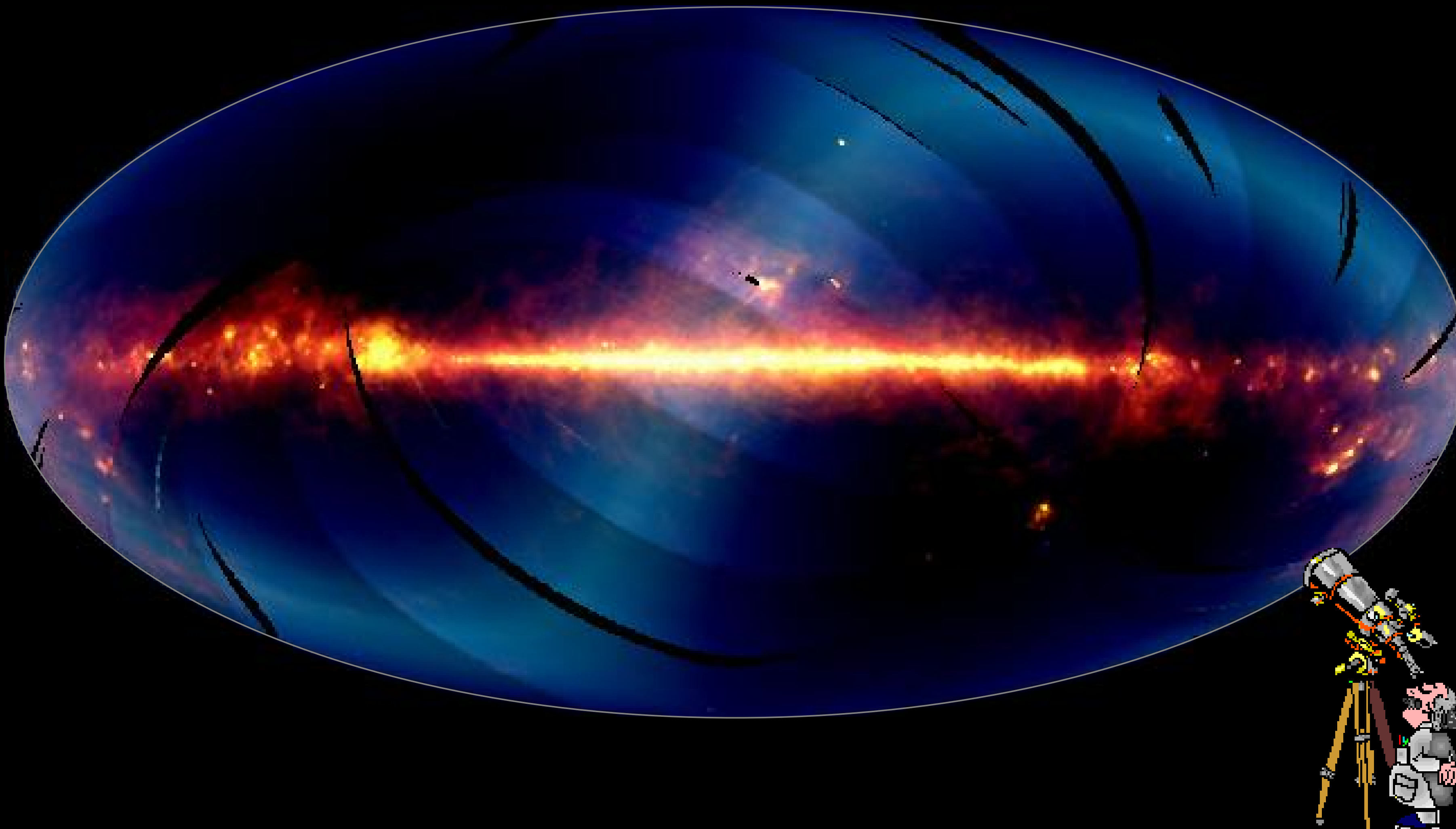
Radio

Infrared
(10^{-2} eV)

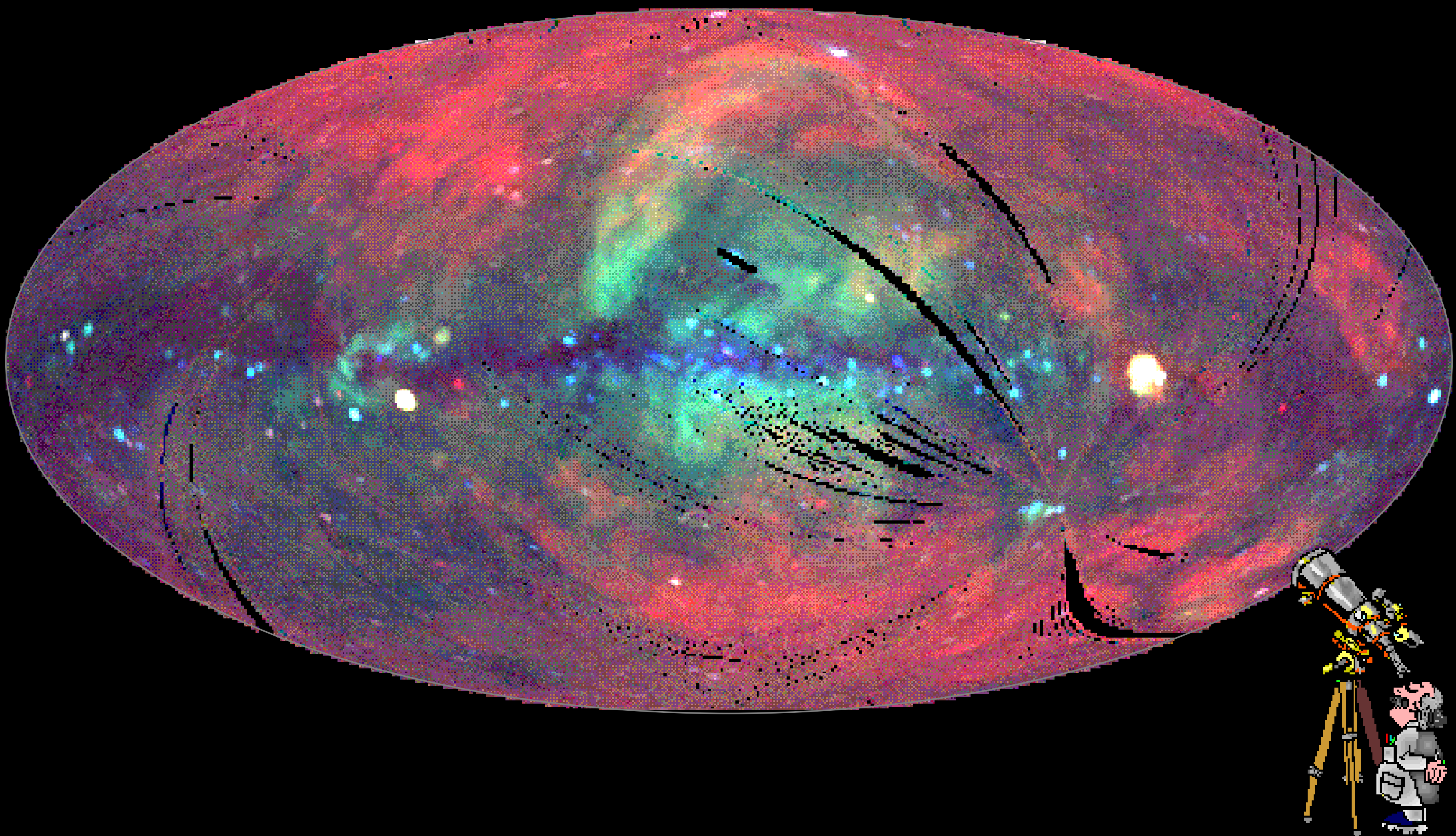
Visible Light

X-rays

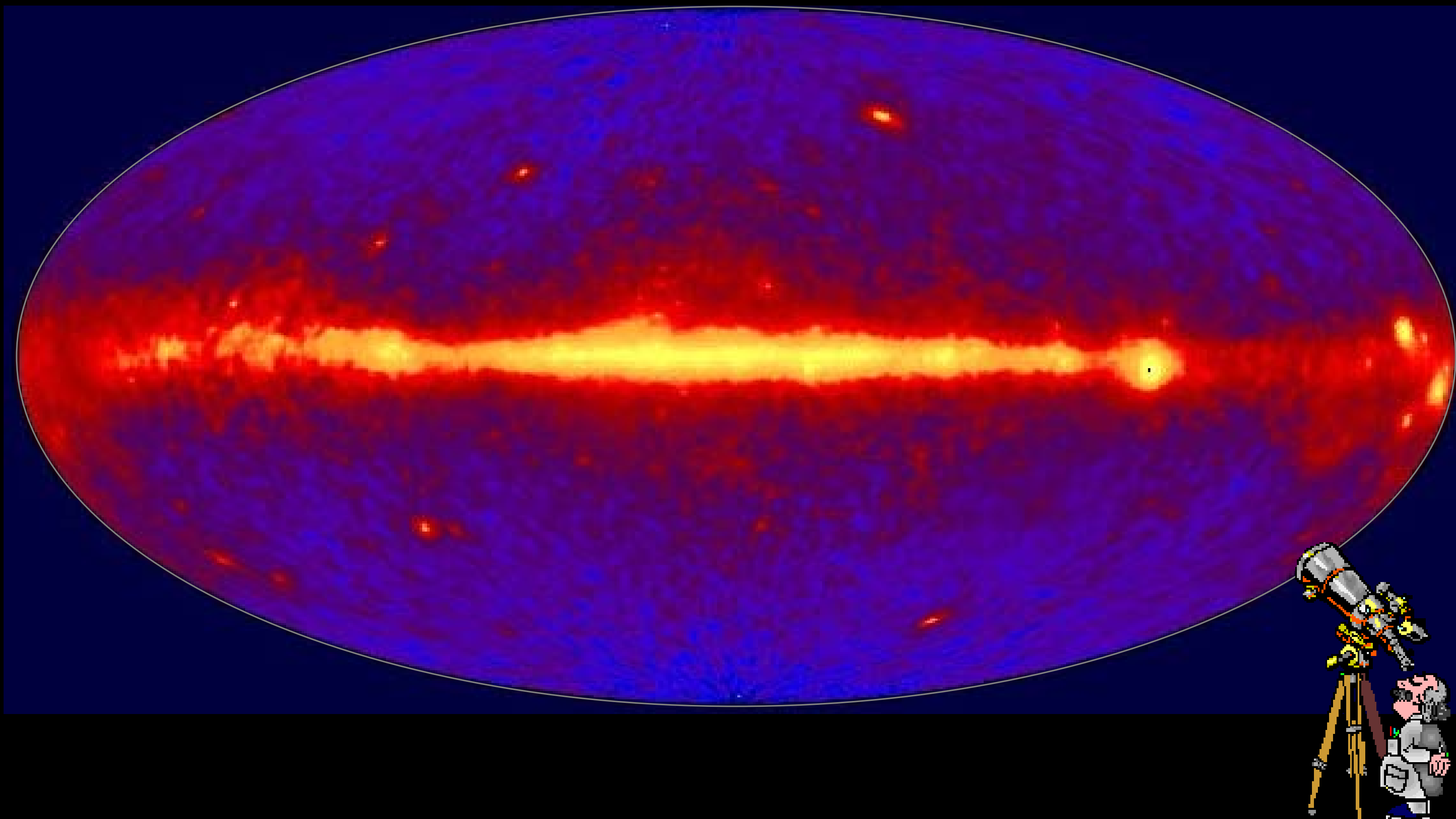
Gamma rays



Radio | Infrared | Visible Light | X-rays (10^3 eV) | Gamma rays



Radio Infrared Visible Light X-rays **Gamma rays (10^9 eV)**



Gamma
(TeV = 10^{12} eV)

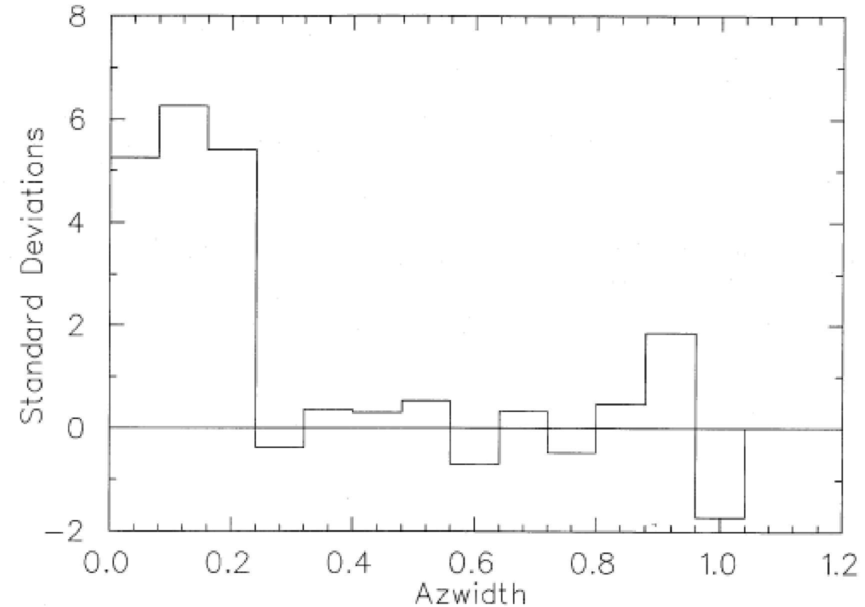


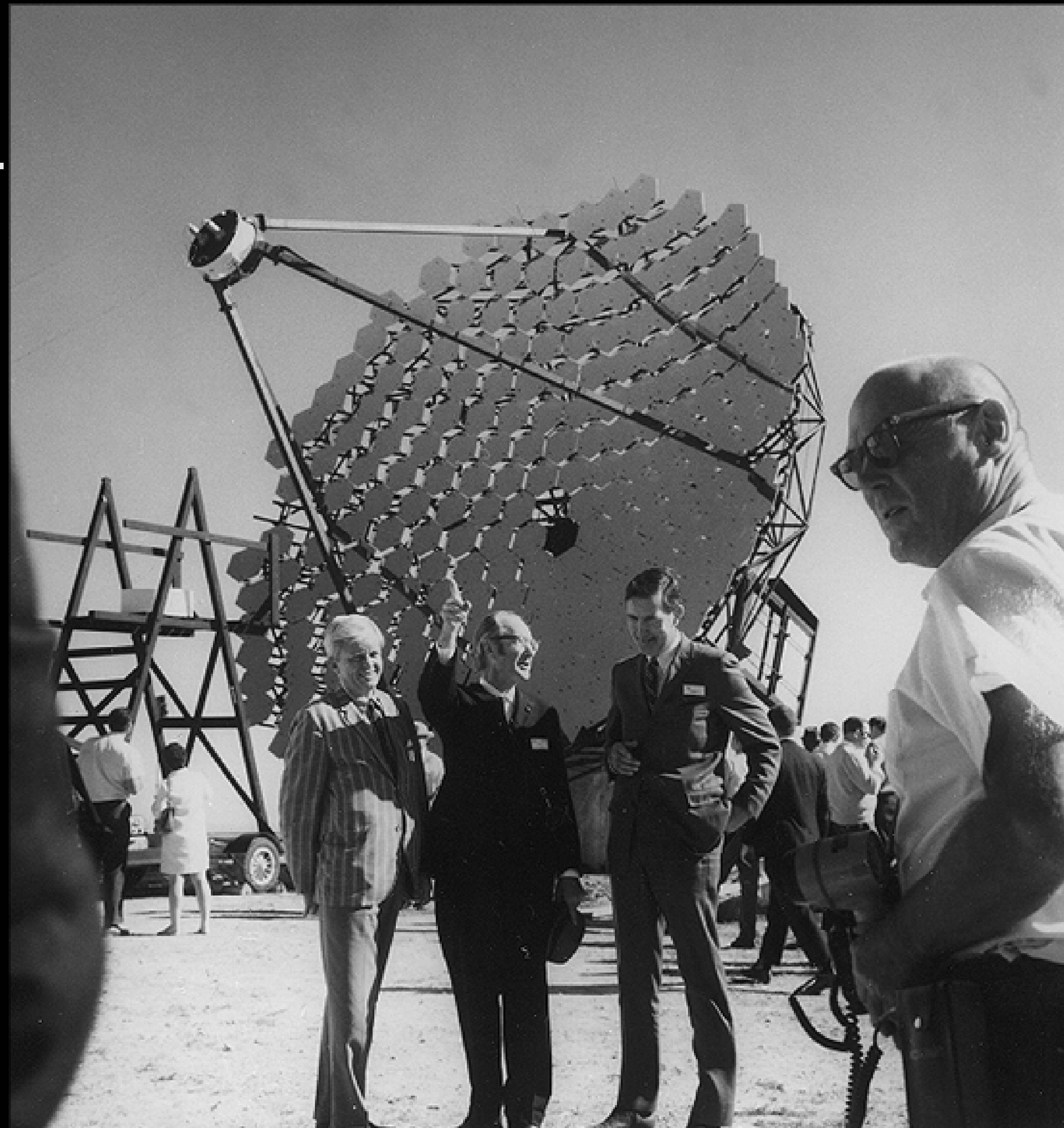
FIG. 7.—Distribution of *azwidth* (ON − OFF) in terms of standard deviations as a function of *azwidth*

TeV Gamma rays
from the Crab Nebula
Whipple Cherenkov Telescope
1989

Whipple 1968

Detection of
the Crab Nebula
1989:

50 h observation
time for 5σ signal

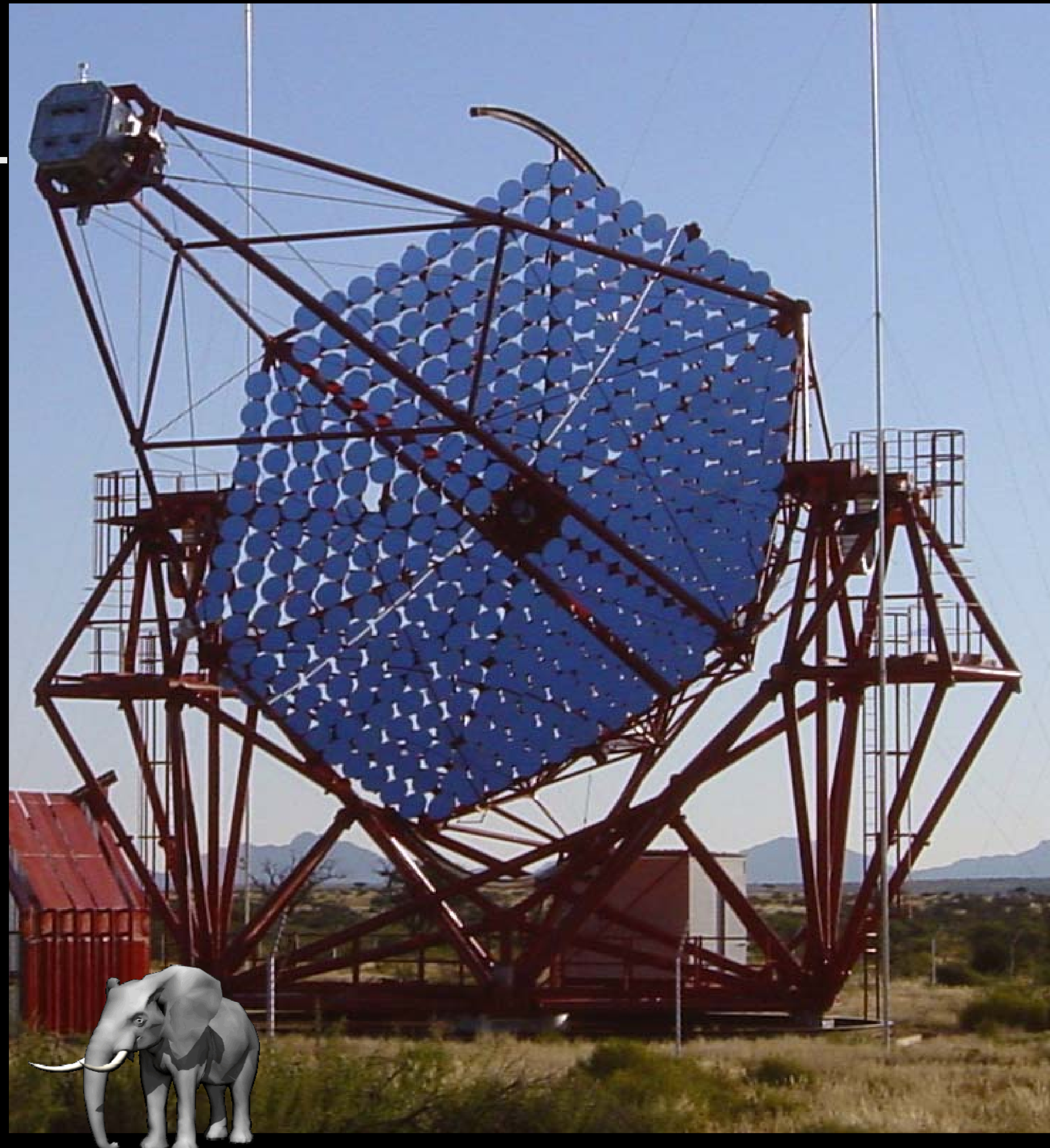


H.E.S.S. 2003

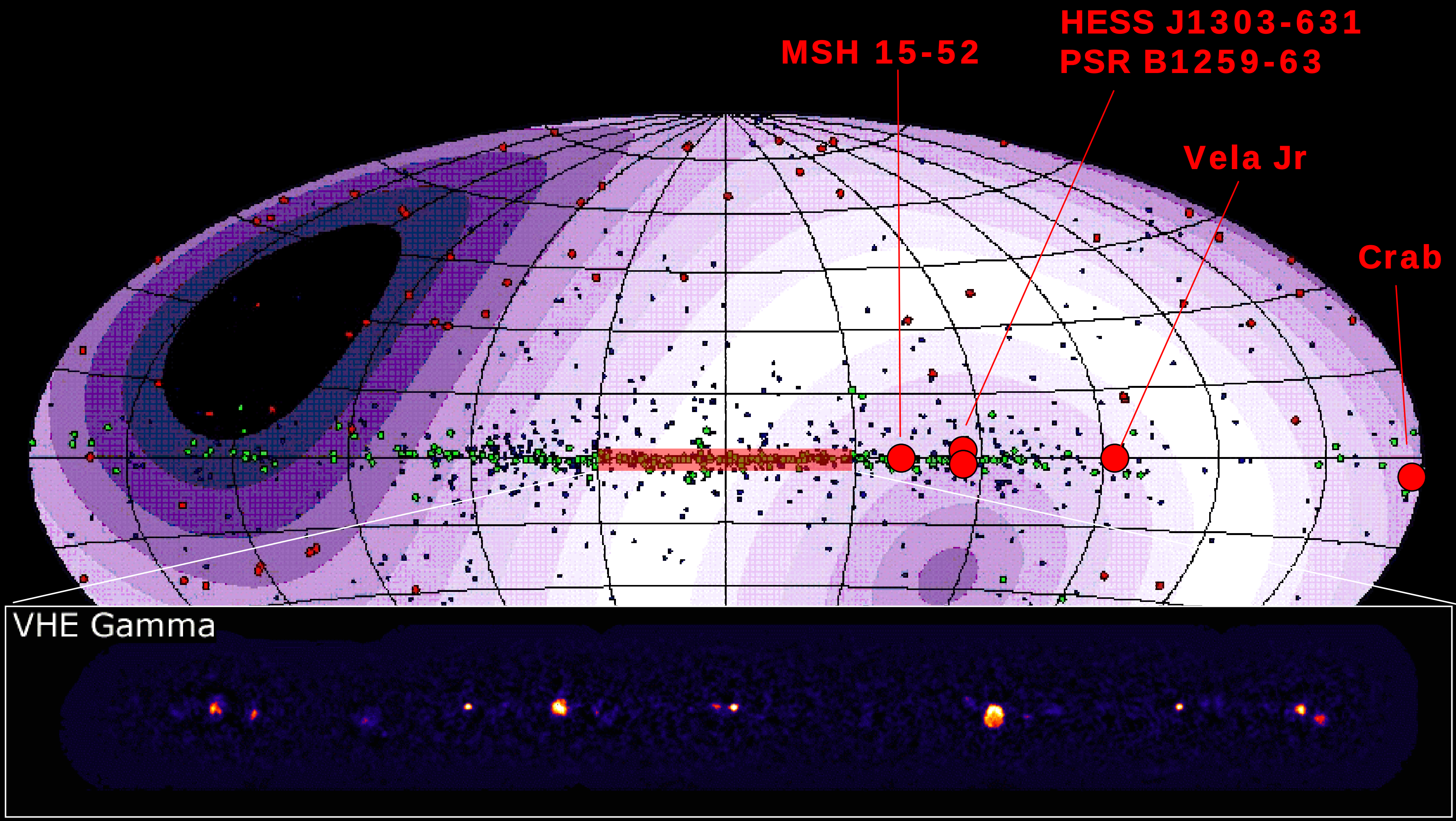
Detects Crab-like source in

30 seconds

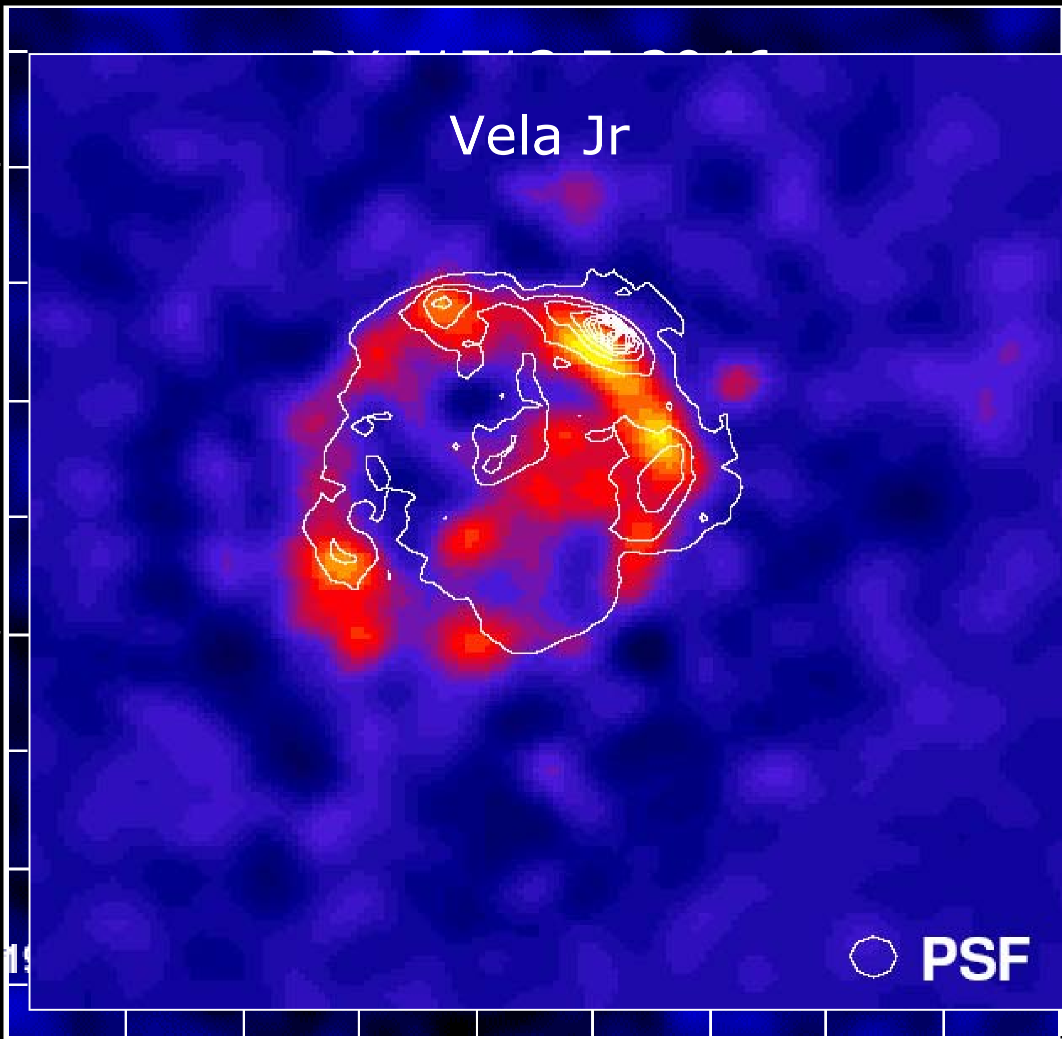
< 1% Crab in 50 h

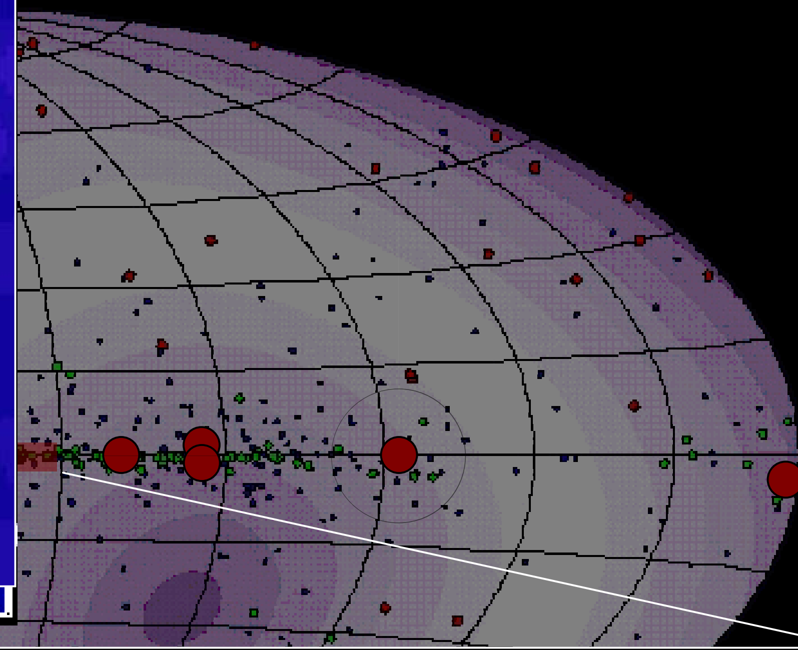


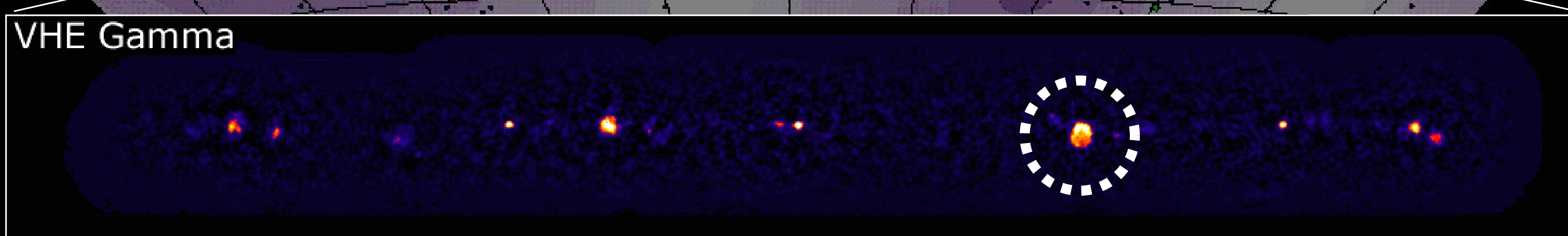
H.E.S.S. Galactic TeV Sources



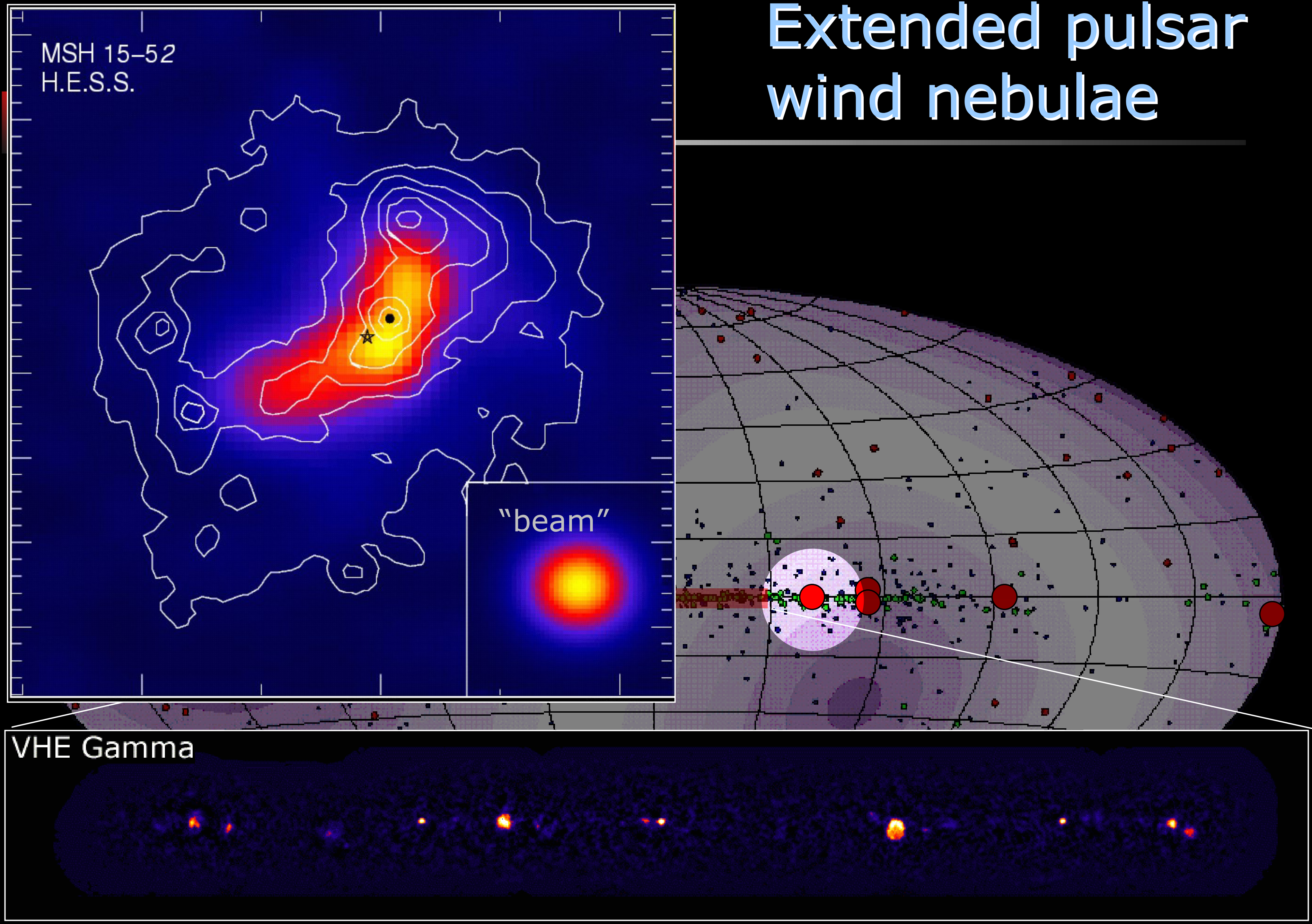
Supernova Remnants



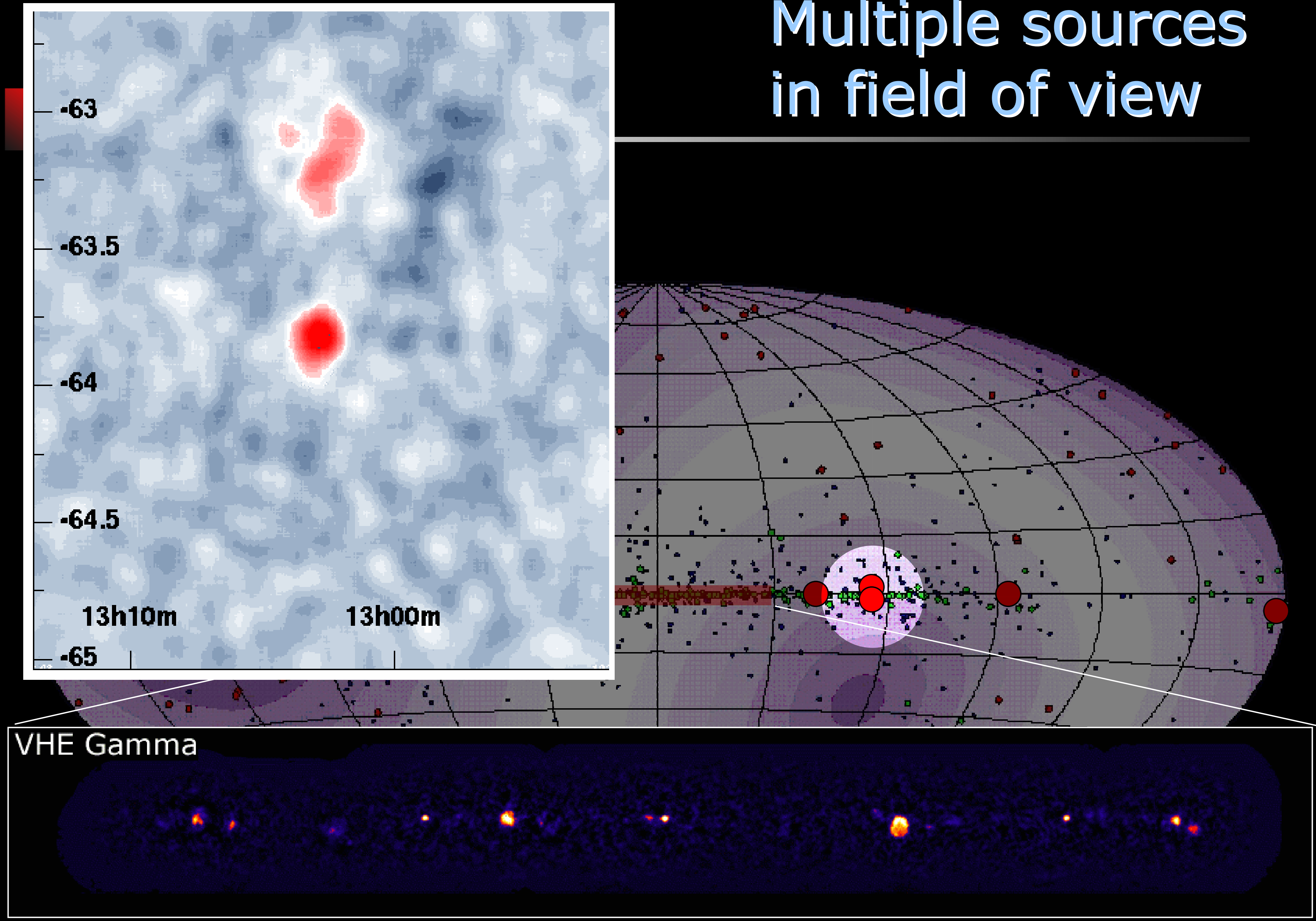




Extended pulsar wind nebulae



Multiple sources in field of view

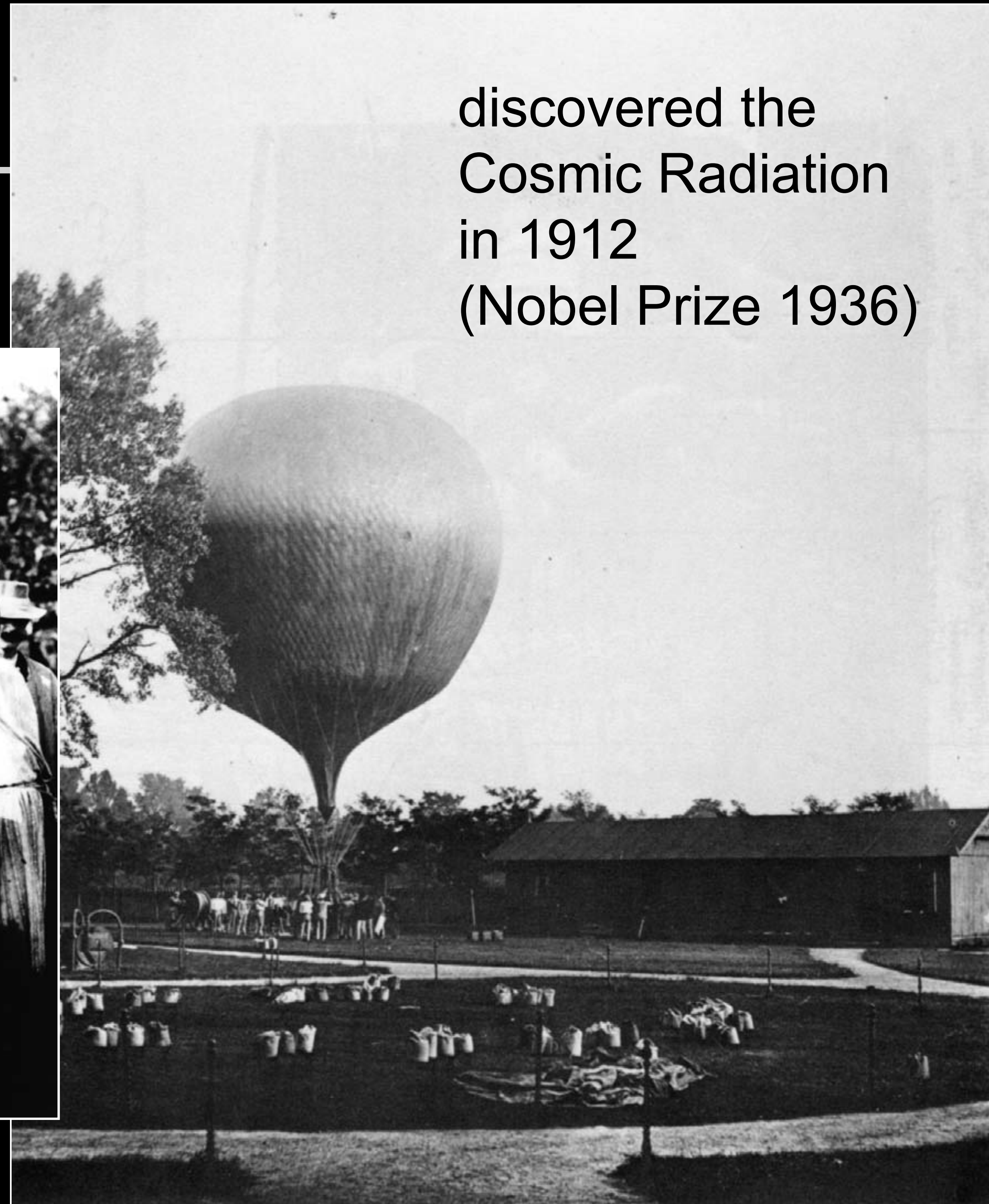


Exploring the nonthermal universe

Cosmic particle accelerators

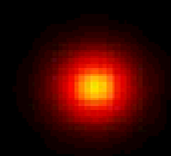
Victor Hess

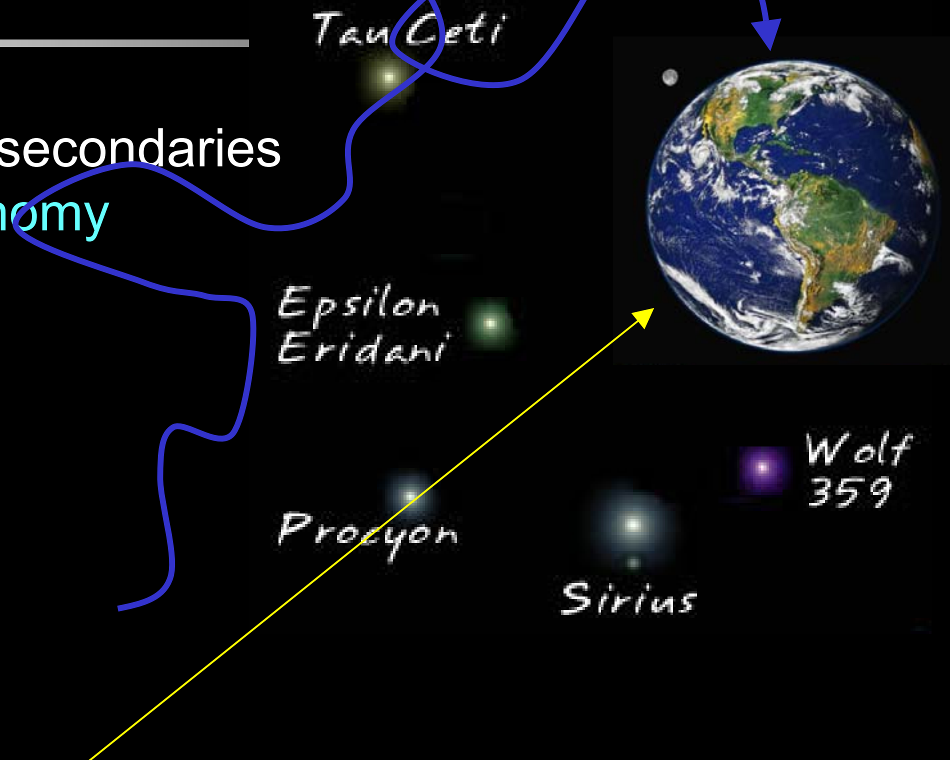
discovered the
Cosmic Radiation
in 1912
(Nobel Prize 1936)



Particle acceleration in supernova shock fronts ?

- ➔ Image accelerators with neutral secondaries
- ➔ Gamma-ray and Neutrino Astronomy





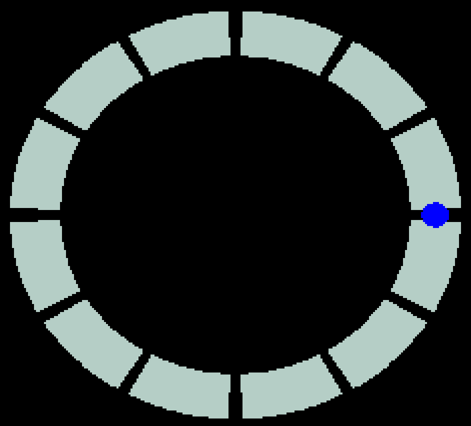
$$p + \text{nucleus} \rightarrow \pi + X$$

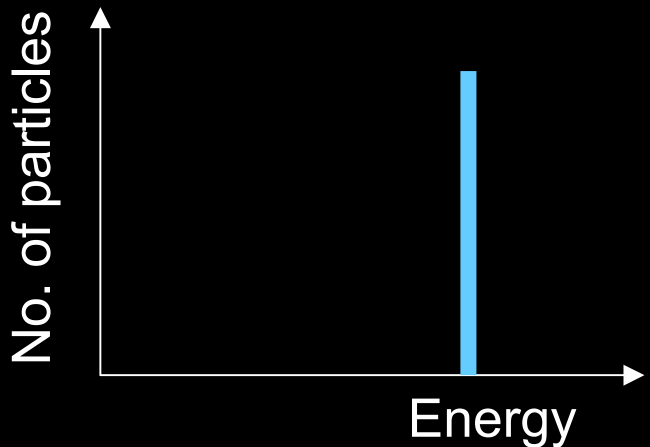
$$\pi^{o} \rightarrow \gamma\gamma$$

$$\pi^{\pm} \rightarrow \mu^{\pm}\, \nu$$

How could cosmic accelerators work?

Man-made accelerators

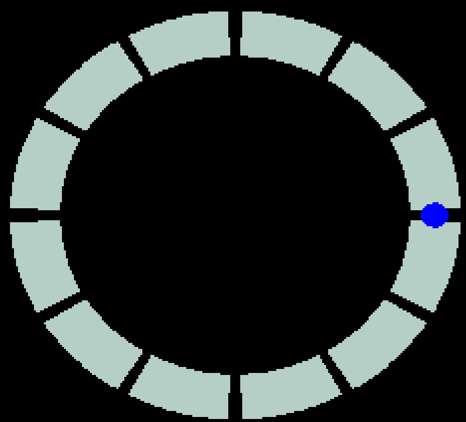


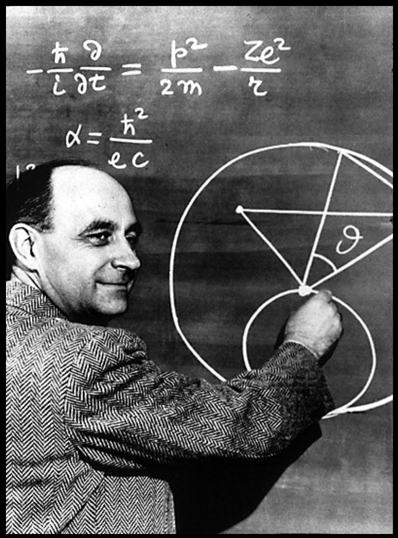


How could cosmic accelerators work?

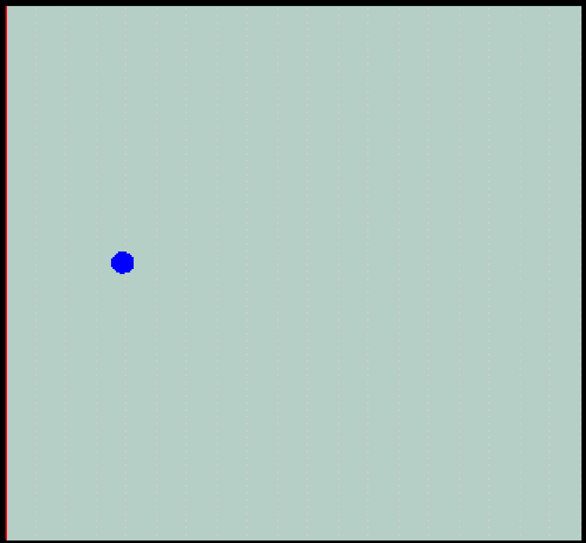
Man-made accelerators

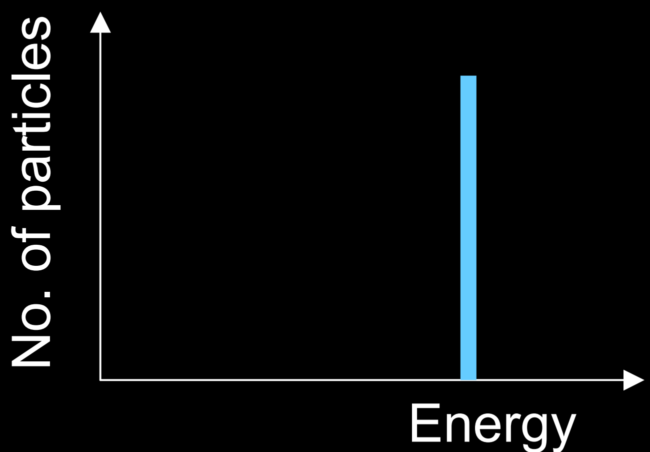
Nature's accelerators

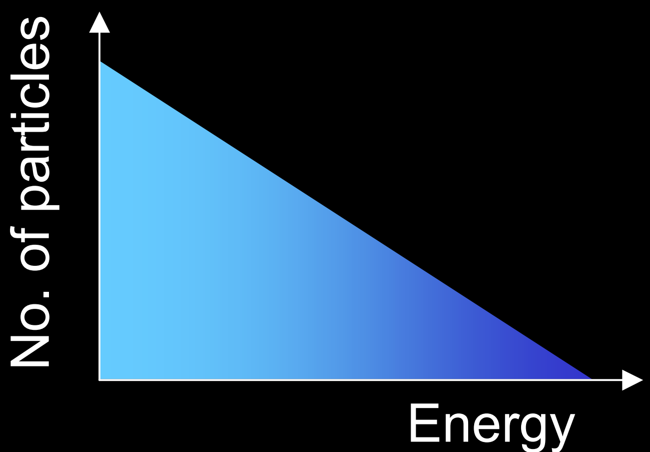




Enrico Fermi







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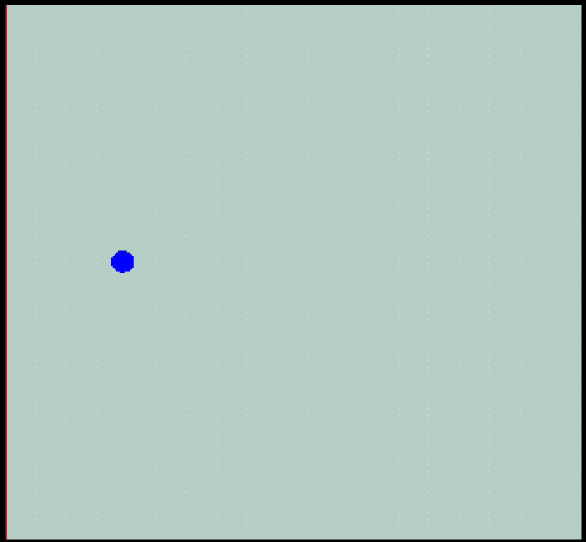
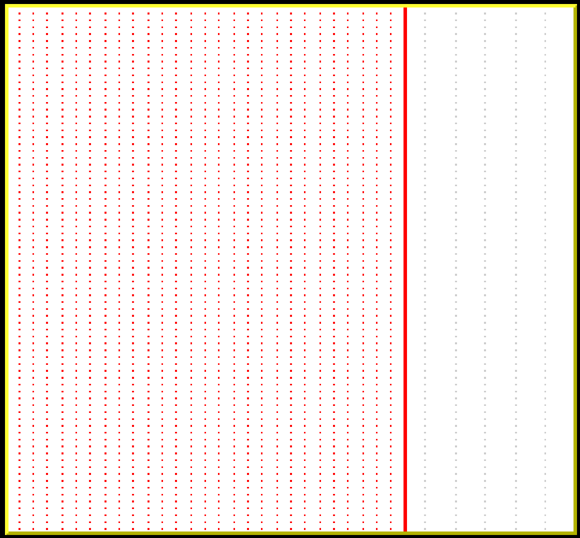
Nature's accelerators





Energy gain / cycle $\Delta E/E \sim \beta_{shock}$

... many 100 cycles to reach TeV energies …

... takes several 100 years

Generates power law spectrum $dN/dE \sim E^{-(2+\varepsilon)}$

… at some point, particle falls behind shock …

Peak energy $\sim 10^{15}$ eV

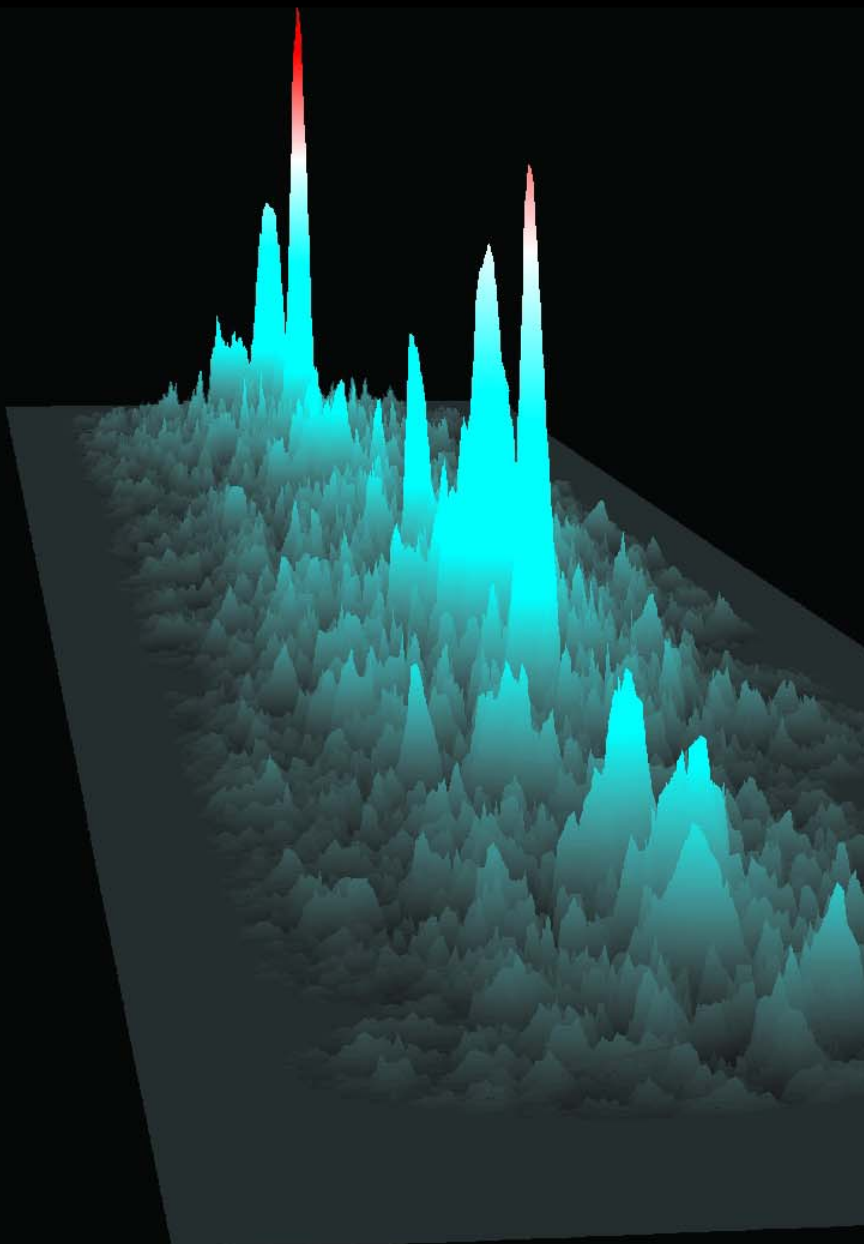
… depending on size of shock front …

Nonlinear process with efficiency ~50%!

… accelerated particles generate plasma waves …

≥10% required to generate cosmic rays from supernovae

In rest frame of shock front



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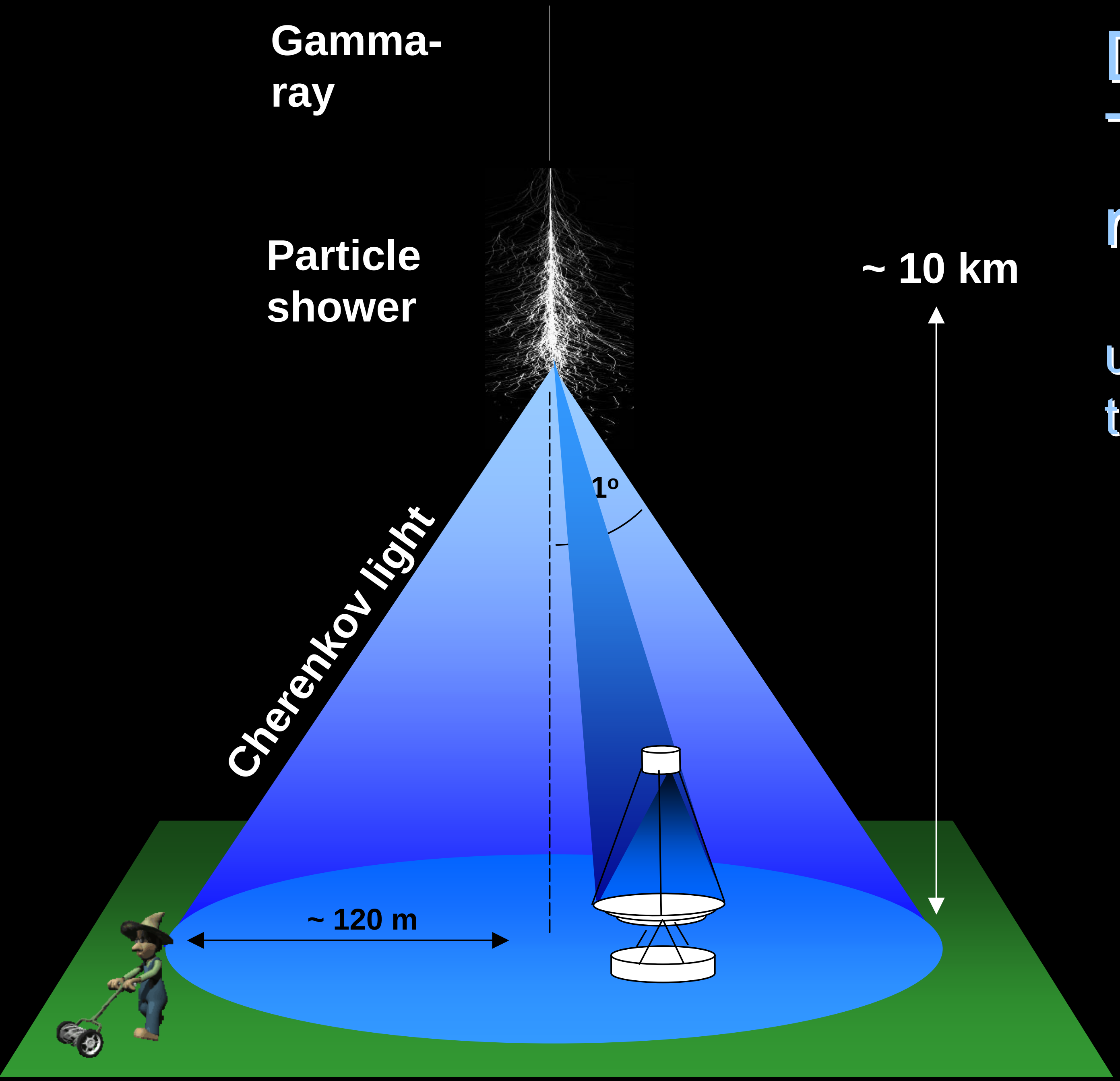
Pulsar winds
& mystery sources

Gamma rays from the Galactic Center

Detection of TeV gamma rays

using Cherenkov telescopes



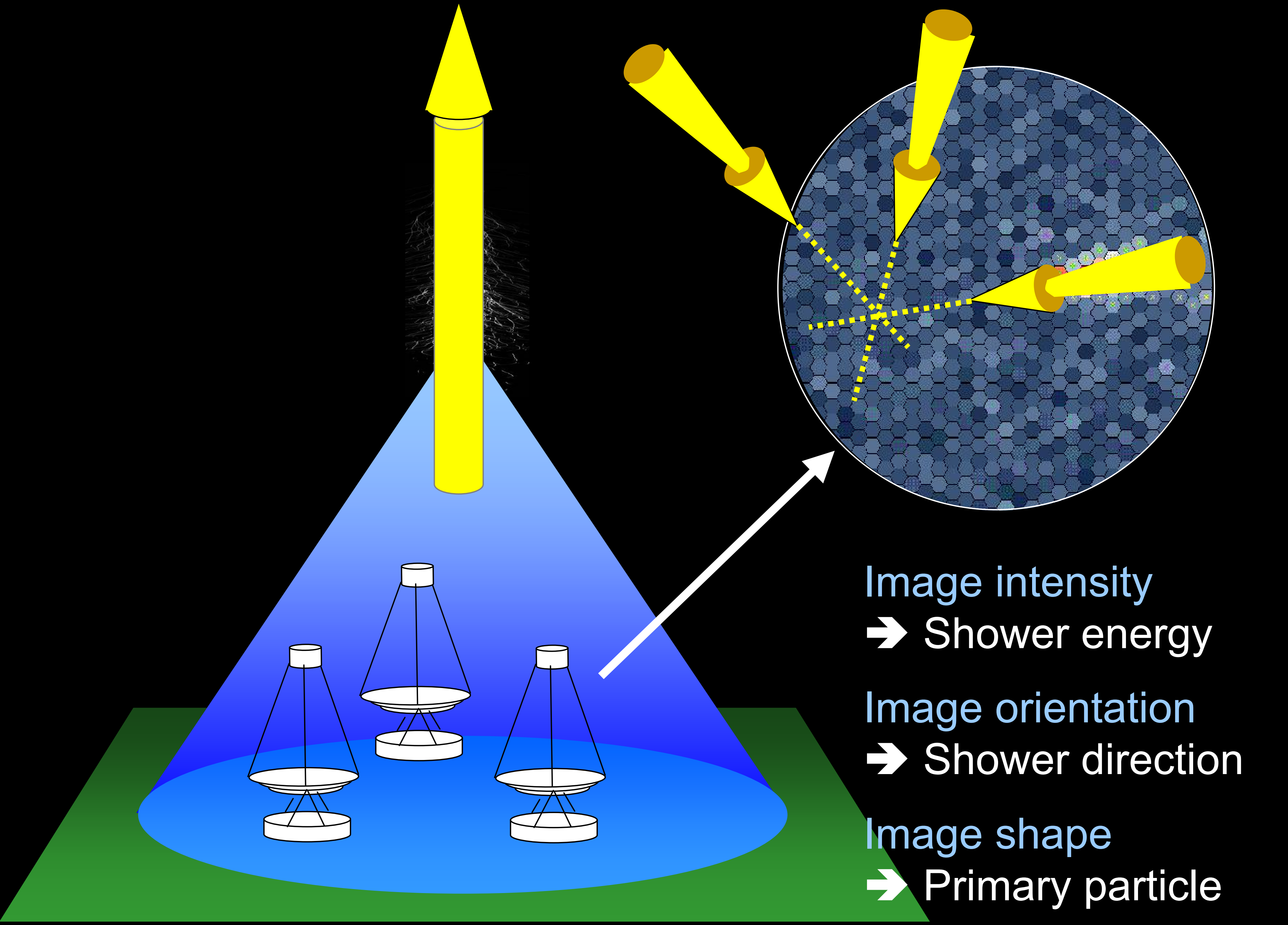
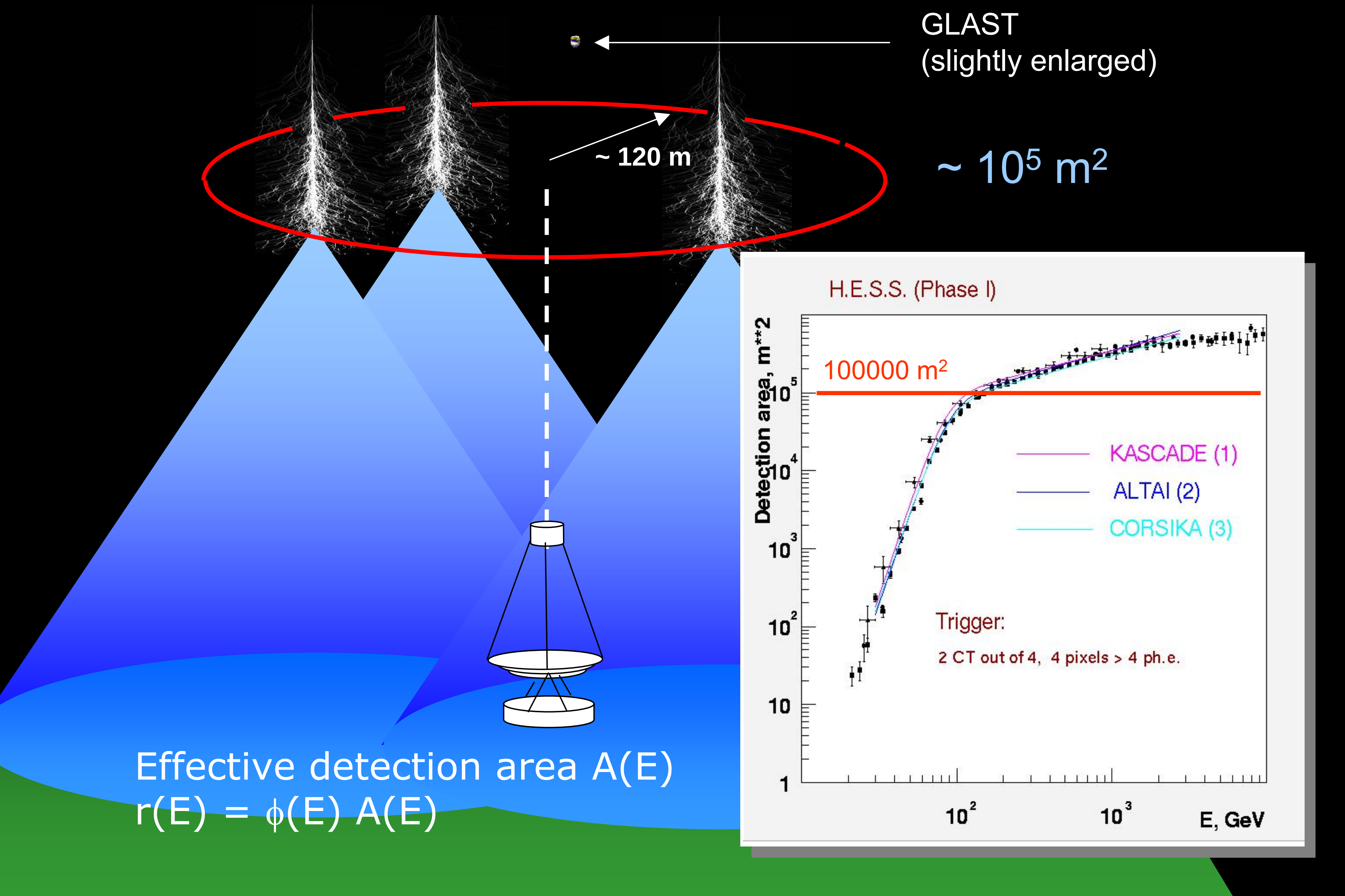


Image intensity
➔ Shower energy
Image orientation
➔ Shower direction
Image shape
➔ Primary particle

Detection area of Cherenkov telescopes



Effective detection area A(E)

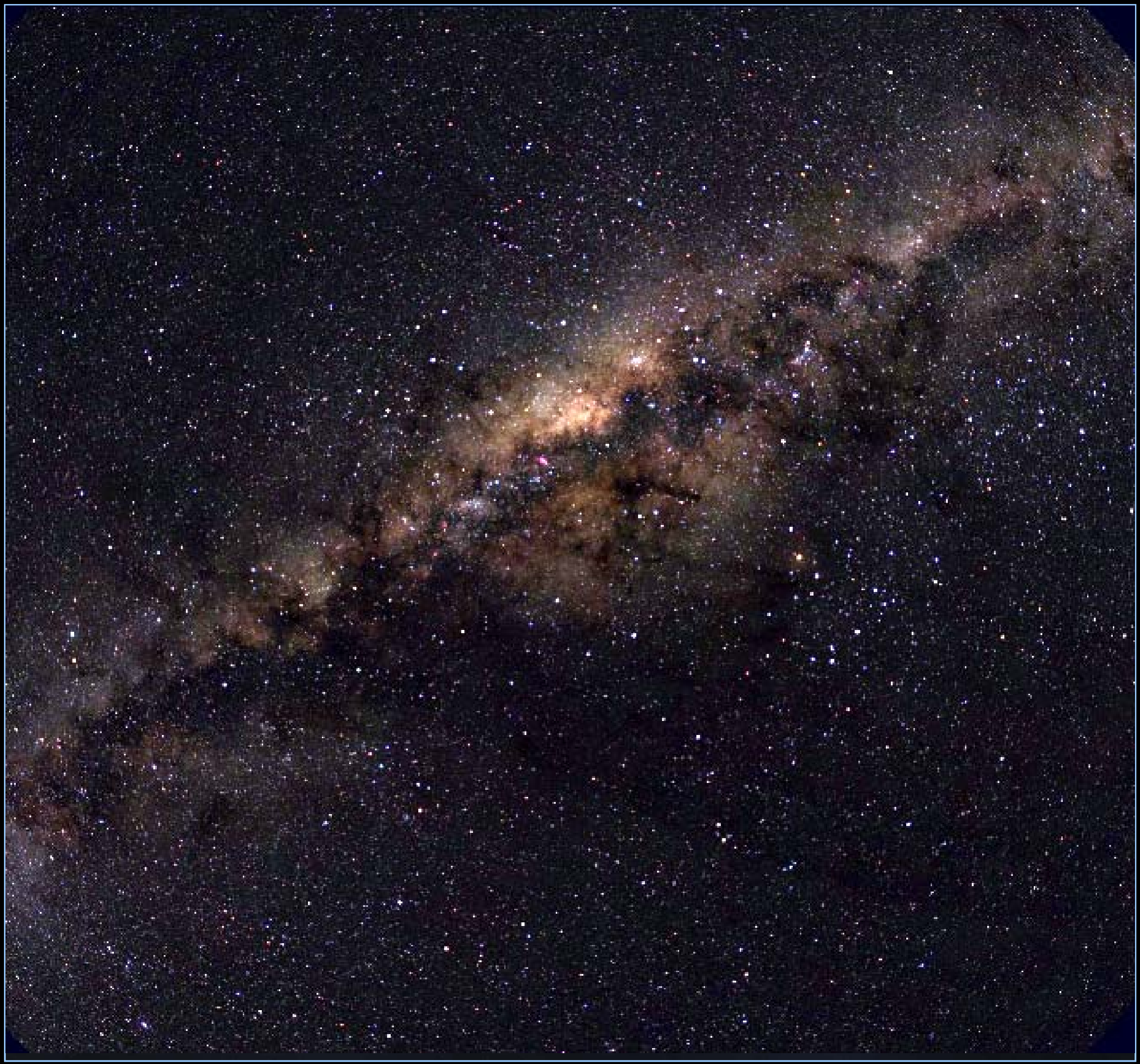
$r(E) = \phi(E)\, A(E)$

MPI Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Hamburg
Landessternwarte Heidelberg
Univ. Kiel
Ecole Polytechnique, Palaiseau
College de France, Paris
Univ. Paris VI-VII
CEA Saclay
CESR Toulouse
GAM Montpellier
LAOG Grenoble
Paris Observatory
Durham Univ.
Dublin Inst. for Adv. Studies
Charles Univ., Prag
Yerewan Physics Inst.
Univ. Potchefstroom
Univ. of Namibia, Windhoek


September 28, 2004:
Inauguration of the H.E.S.S. telescopes

Location: Khomas Highland, Namibia

Why Namibia ?



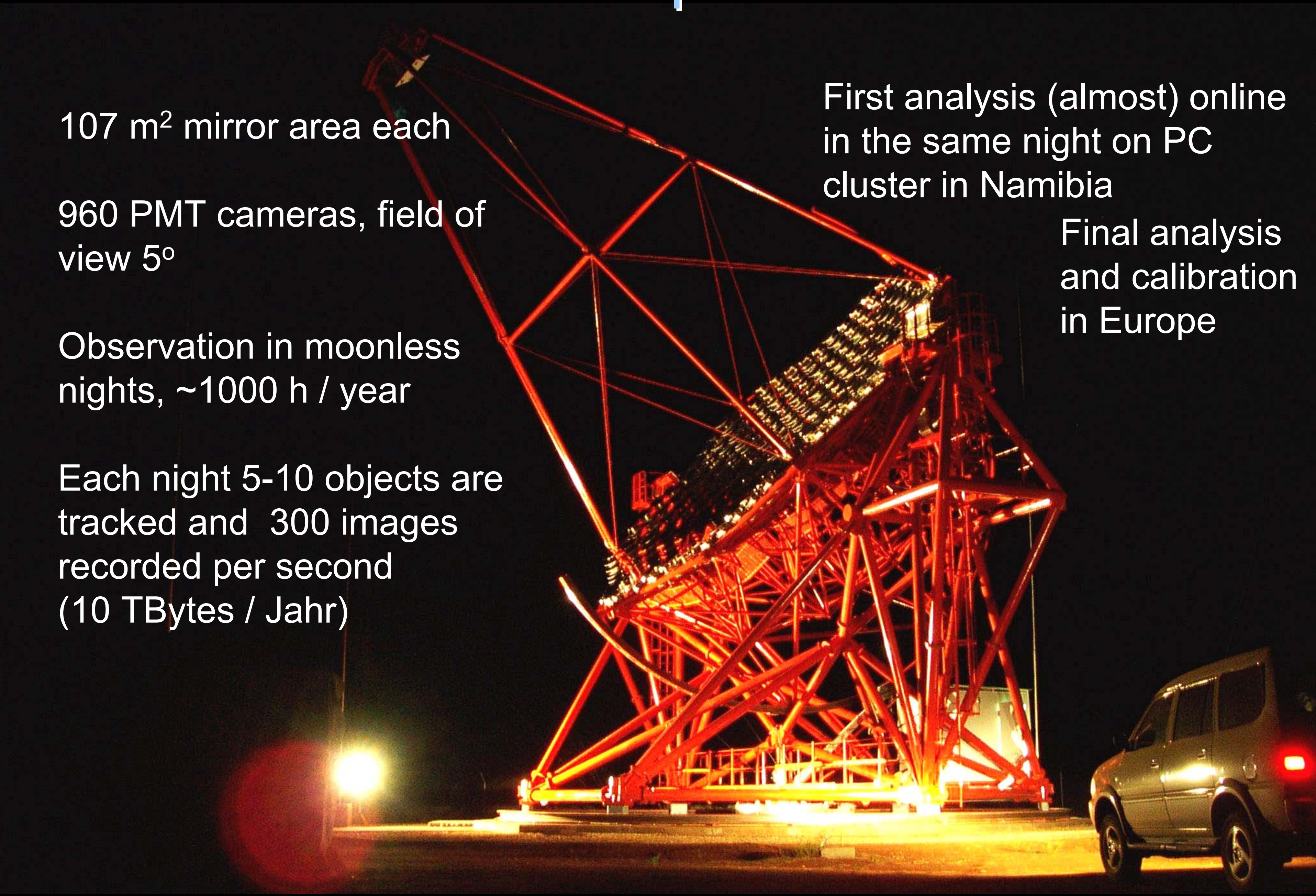
- Optimum viewing conditions for central region of Galaxy
- Dark, clear skies
- Mild climate
- (Relatively) easy access
- Local partners (UNAM)

new challenges …

… the only real danger …

December shift crew

The H.E.S.S. telescopes



107 m^2 mirror area each

960 PMT cameras, field of view 5^o

Observation in moonless nights, ~1000 h / year

Each night 5-10 objects are tracked and 300 images recorded per second (10 TBytes / Jahr)

First analysis (almost) online in the same night on PC cluster in Namibia

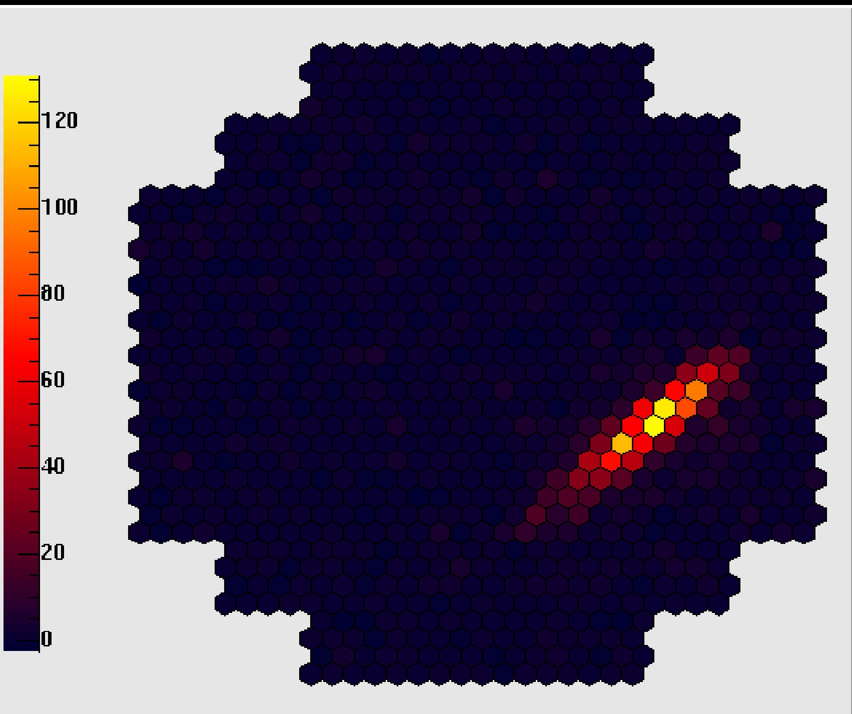
Final analysis and calibration in Europe

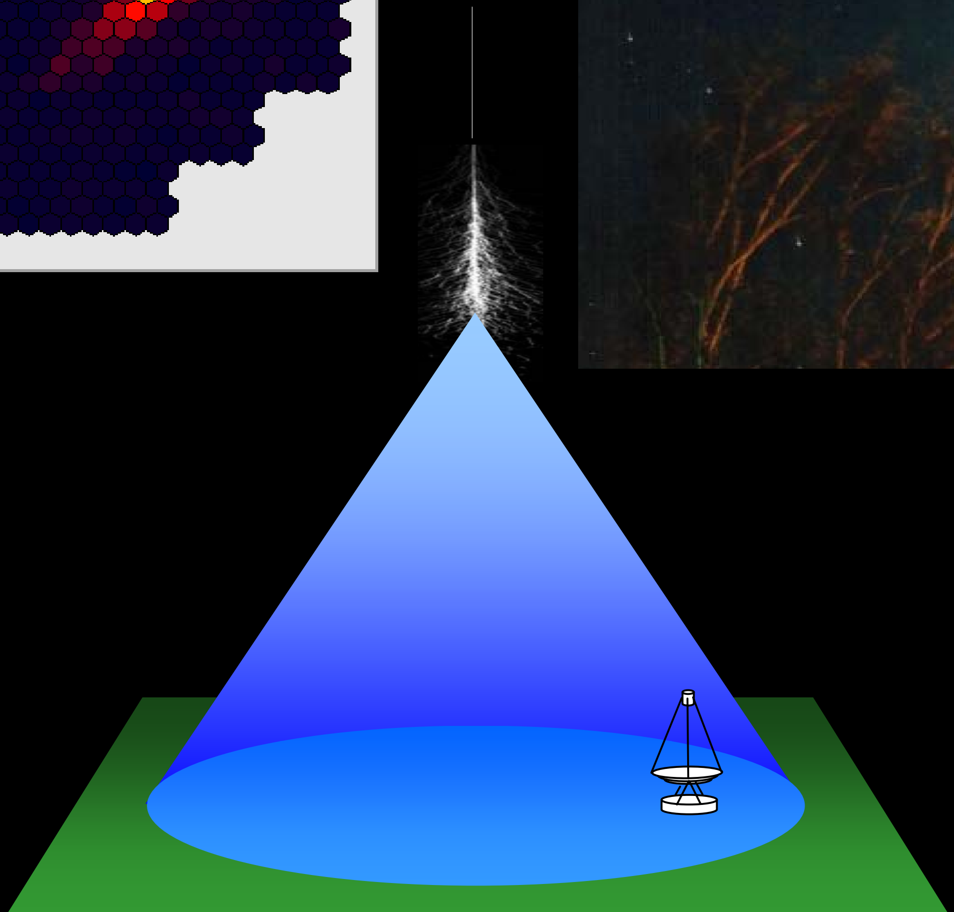
Camera:

960 pixels, 0.16^o

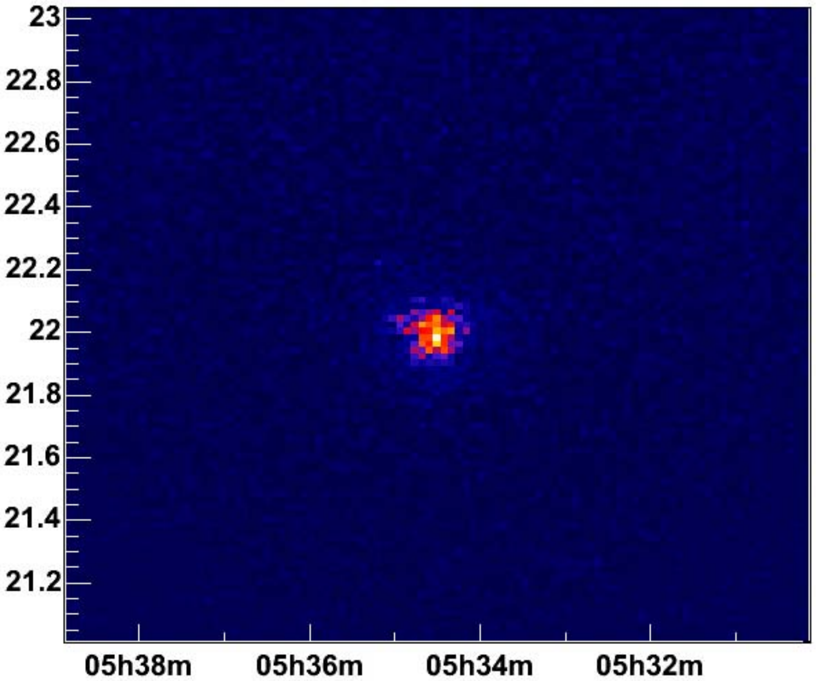
5^o field of view (1.4 m)

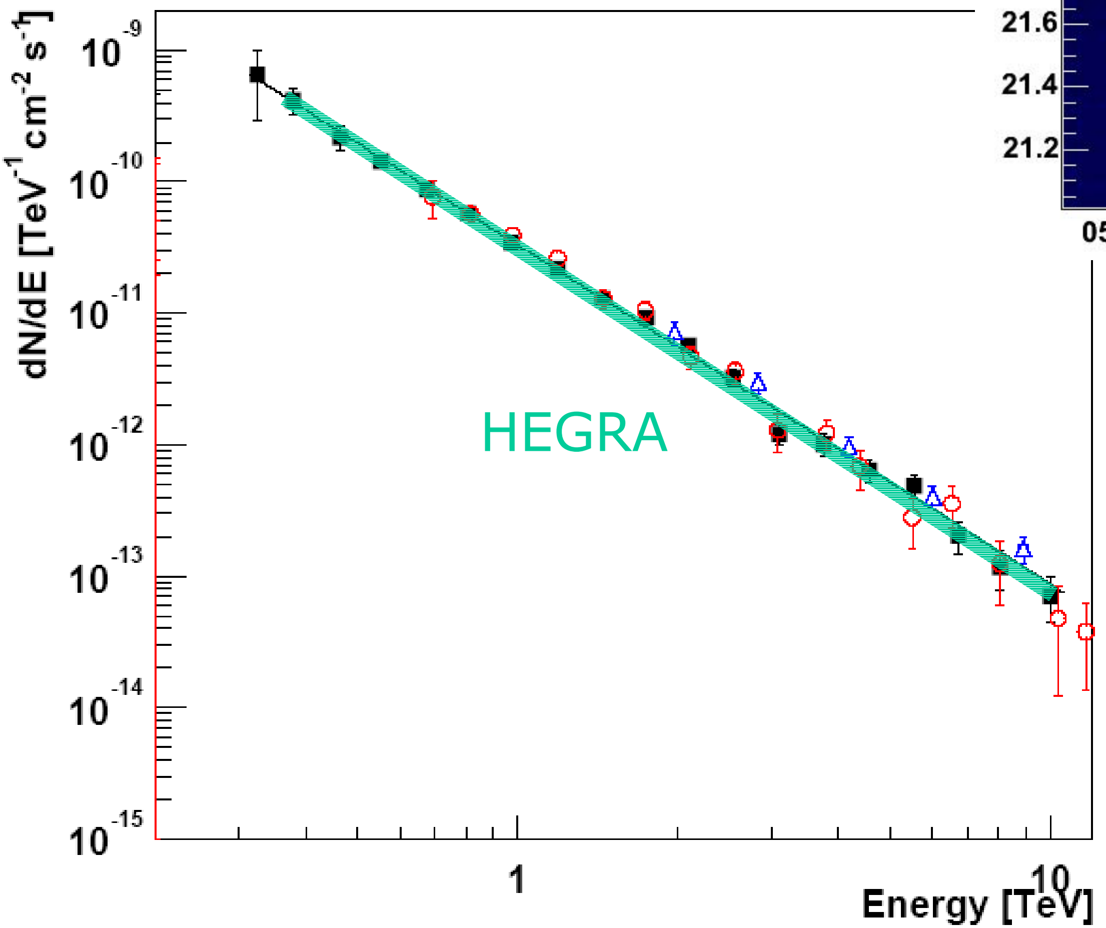
Readout electronics in camera body


120
100
80
60
40
20
0

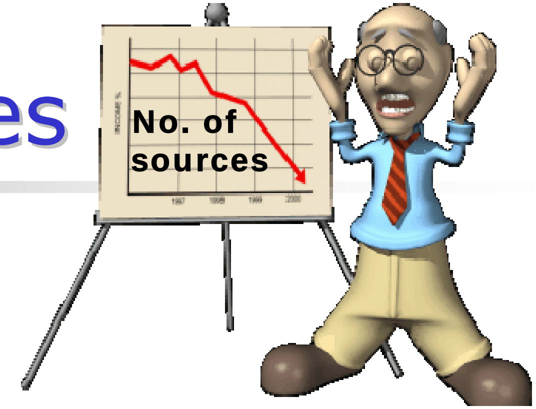


Reference: the Crab Nebula



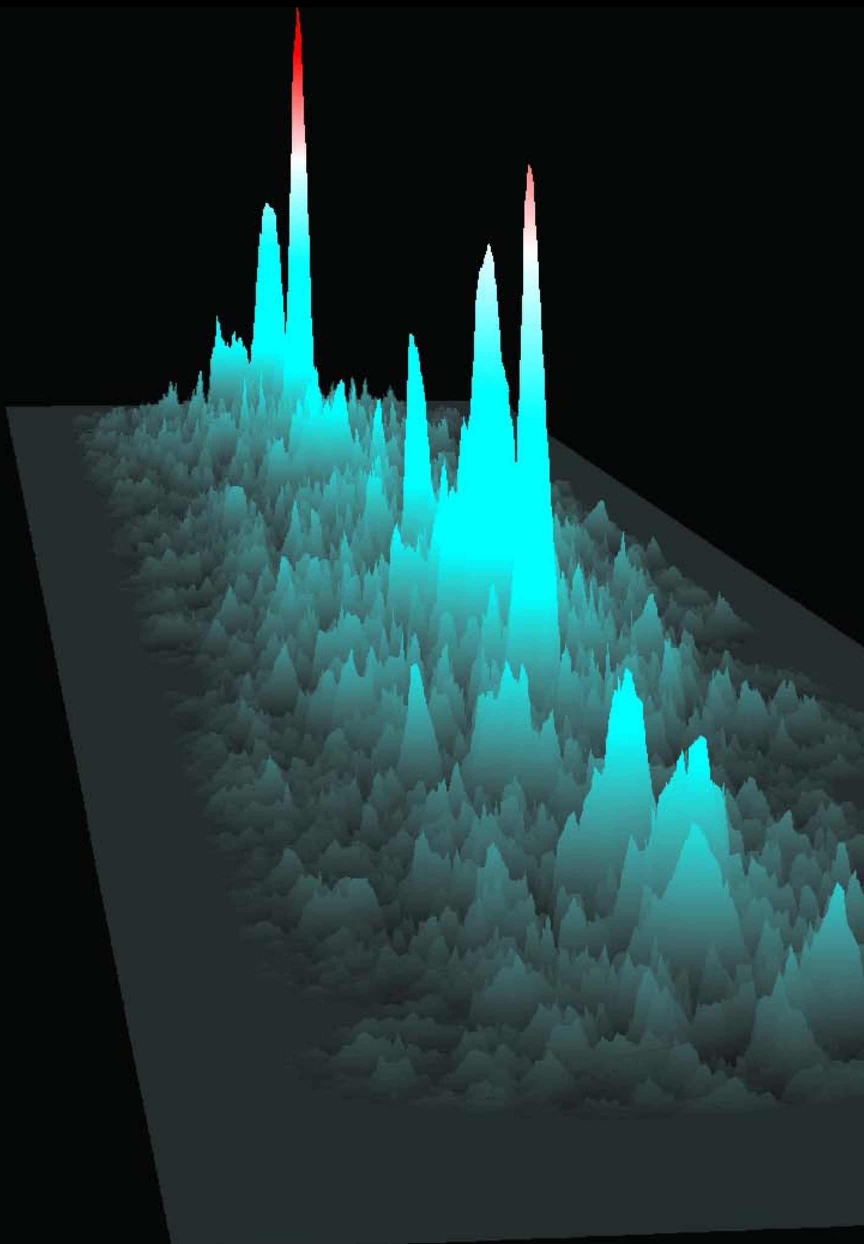


H.E.S.S. and the “known” sources



Southern hemisphere TeV sources

Object
PSR 1706-44
Vela
SN 1006
NGC 253
Gal. center
RX J1713
PKS 2155



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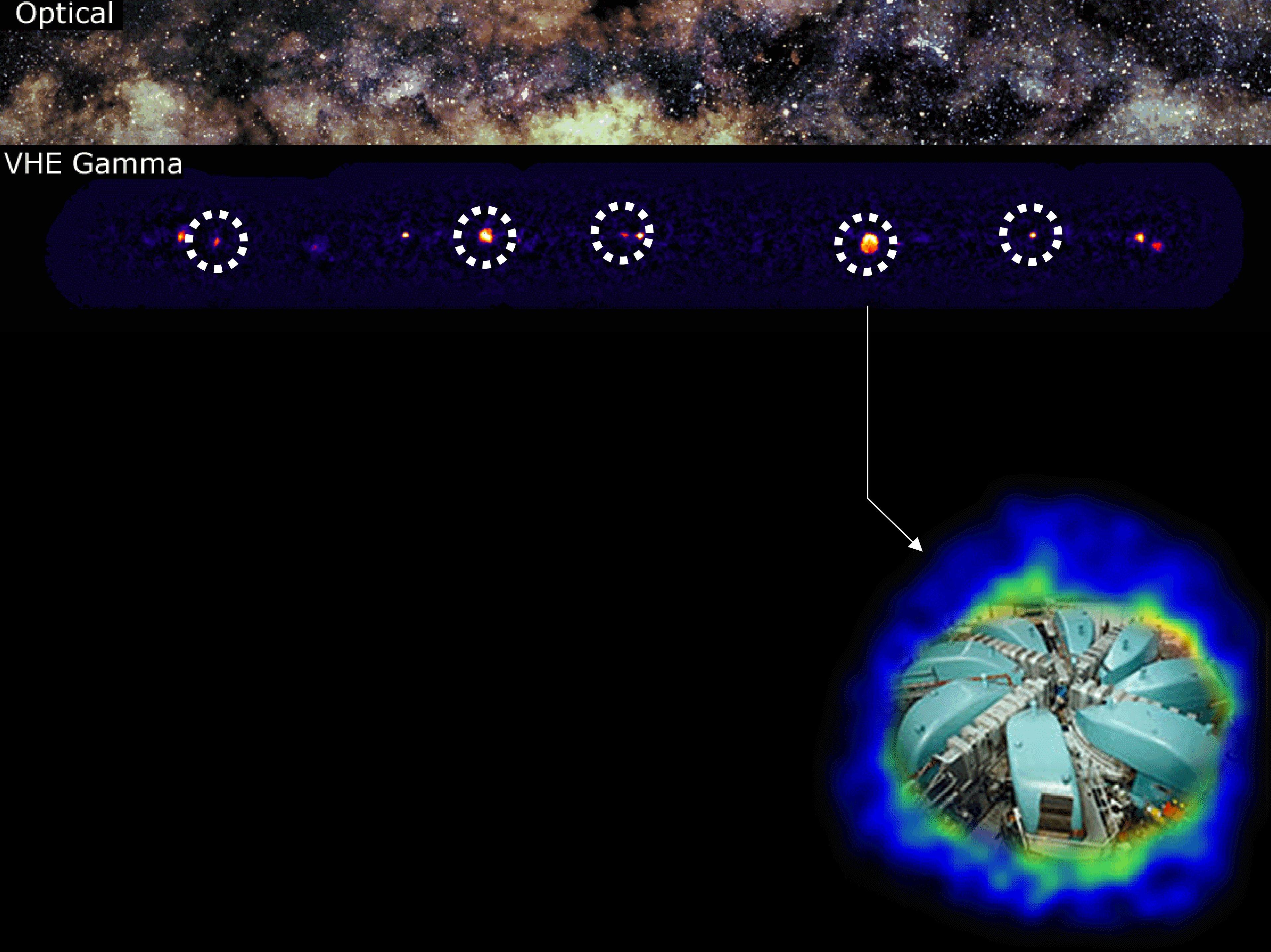
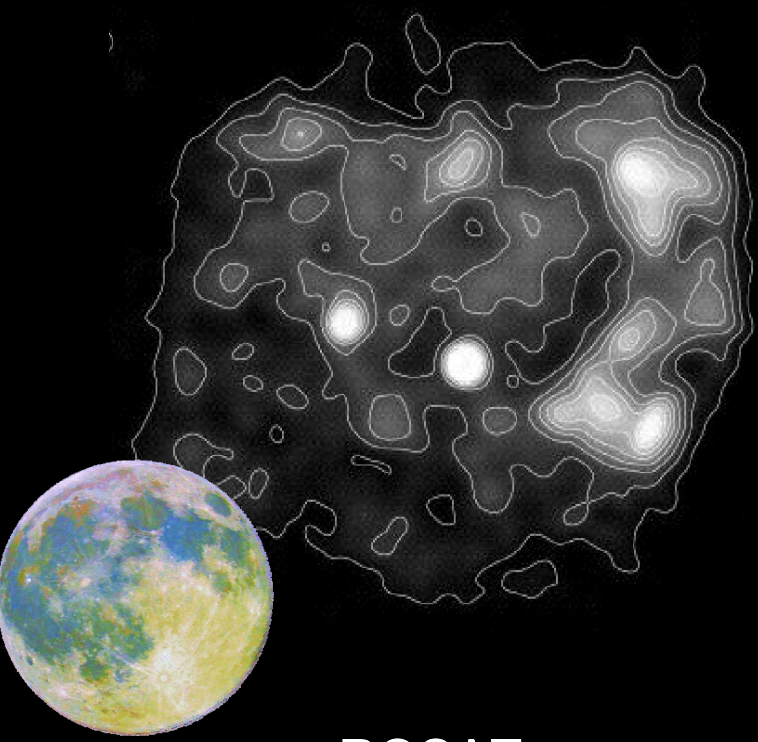
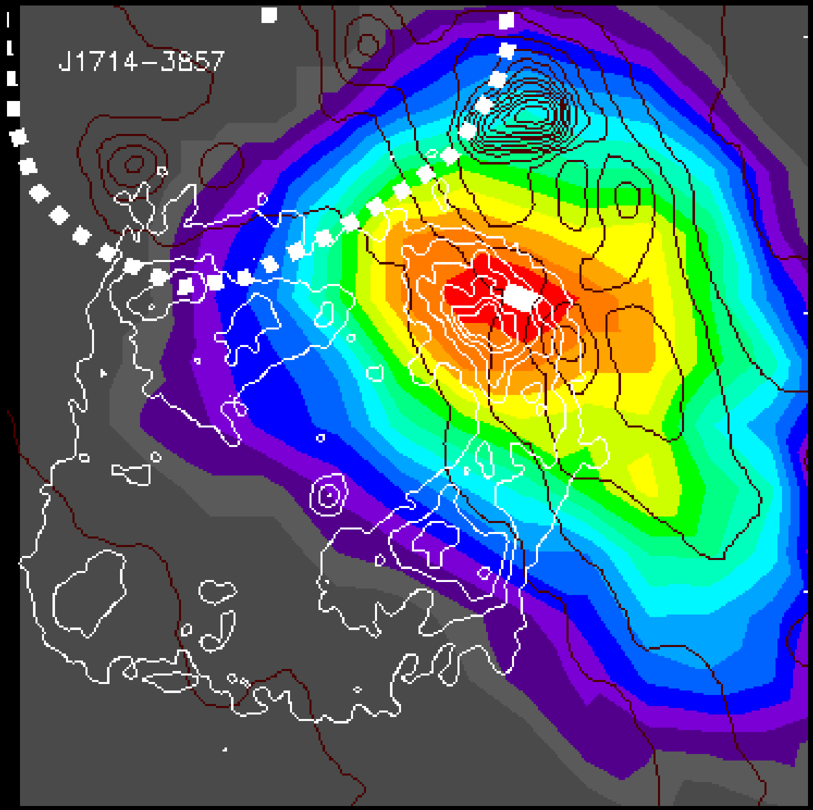

Optical
VHE Gamma

The supernova remnant G347.3-0.5 (RX J1713.7-3946):

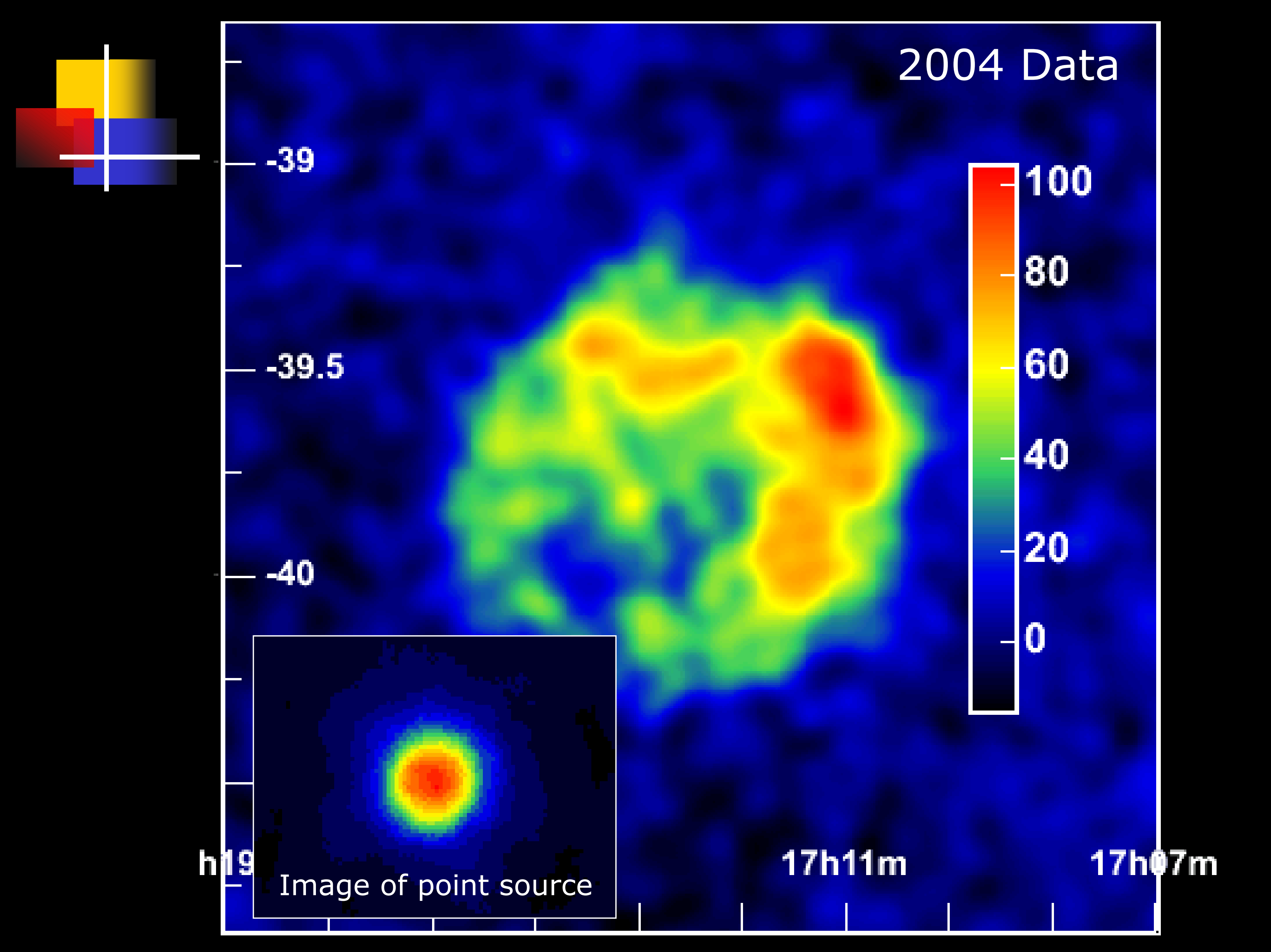


ROSAT
(keV)

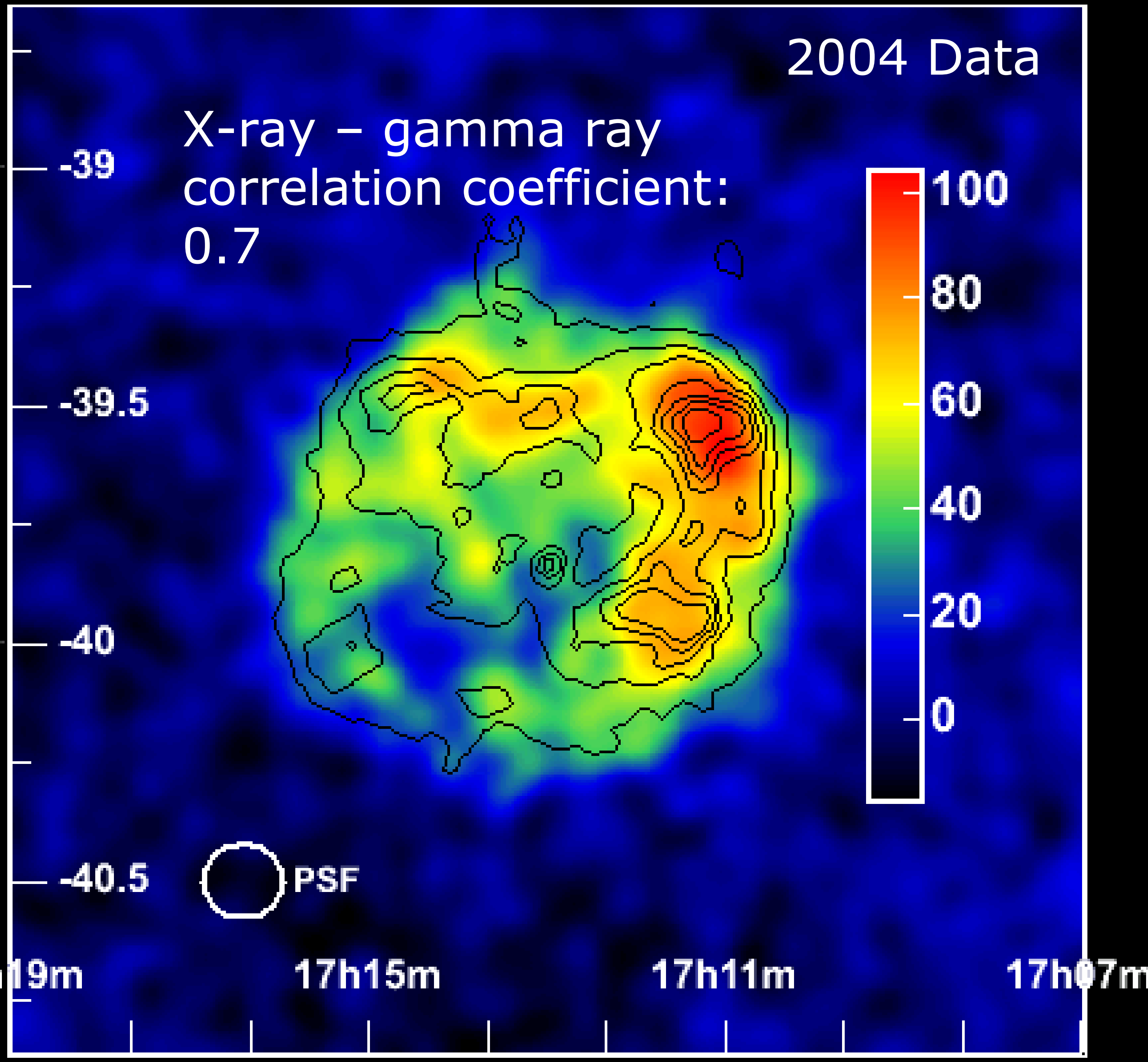


CANGAROO
(TeV)

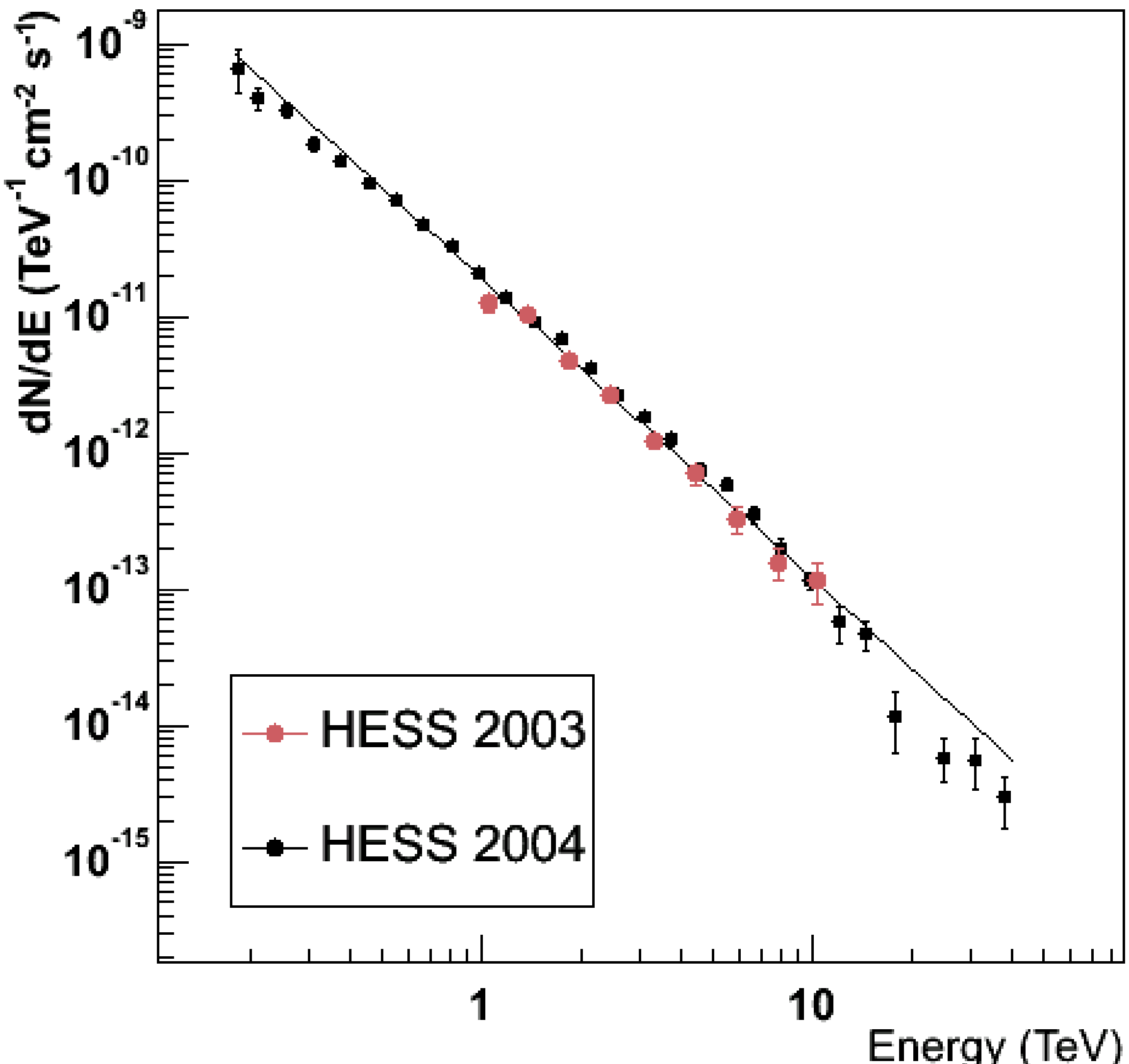
H.E.S.S.
First-ever astronomical TeV image



2004 Data
-39
-39.5
-40
100
80
60
40
20
0
h19
17h11m
17h07m
Image of point source

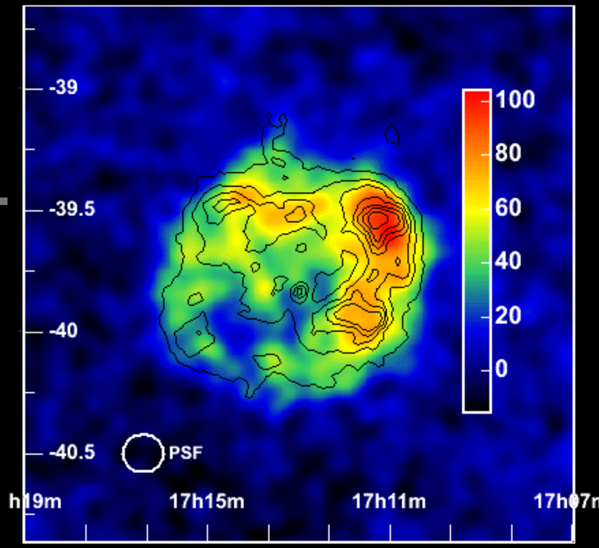

2004 Data
X-ray – gamma ray correlation coefficient: 0.7
-39
-39.5
-40
-40.5
100
80
60
40
20
0
PSF
h19m
17h15m
17h11m
17h07m

Energy spectrum



Spectral index: 2.2

Implications

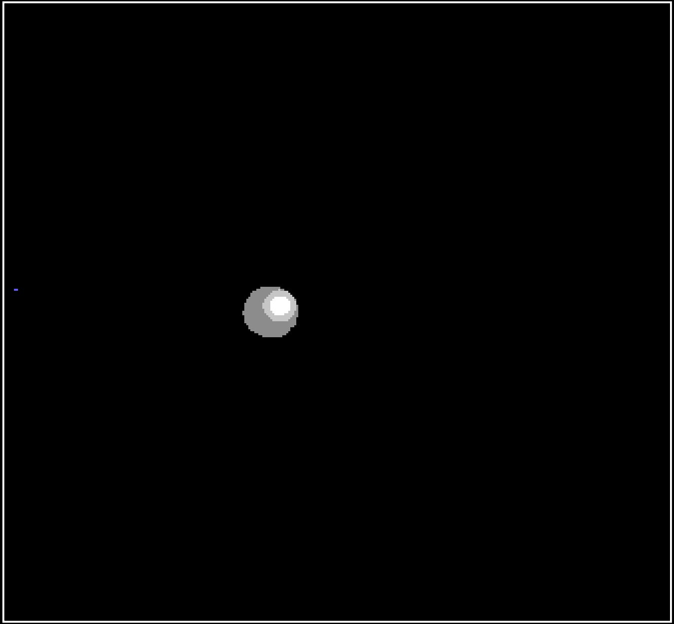


Unambiguous proof that
supernova shock waves are cosmic accelerators;
they accelerate particles to O(100 TeV)

But are they the sources of (nucleonic) cosmic rays ?

Is the kinetic energy released in the explosion converted to cosmic-ray energy with O(10%) efficiency ?

From cosmic rays to gamma rays



X-rays

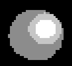
Gamma rays

Proton accelerator

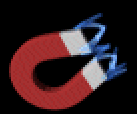
$E_\gamma \approx O(0.1)\ E_p$

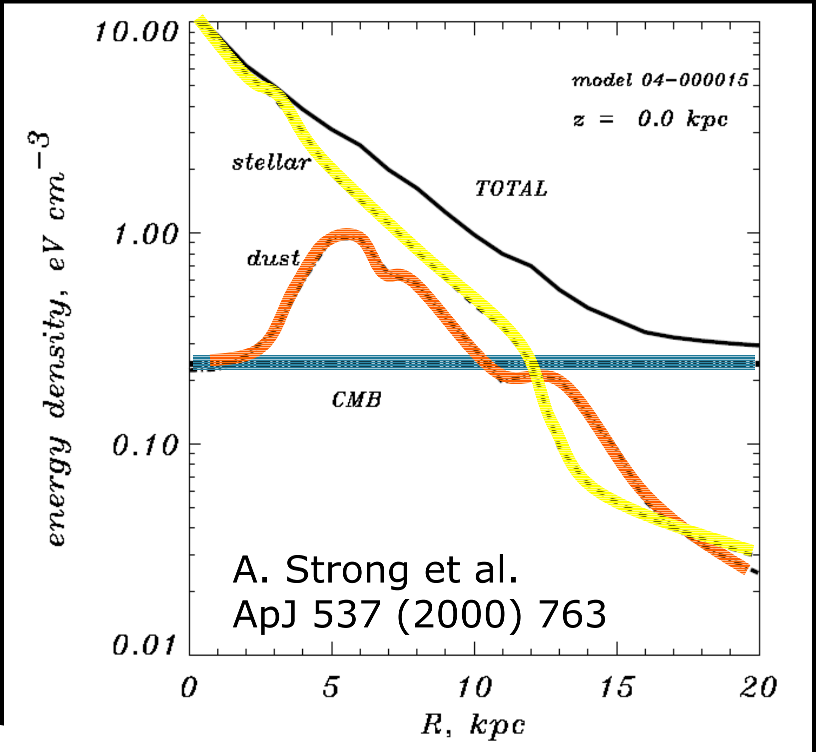
Gamma rays trace proton population x gas density

usually poorly known
<10^{-2} to >$10/cm^3$



Electron Accelerator



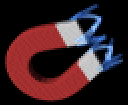


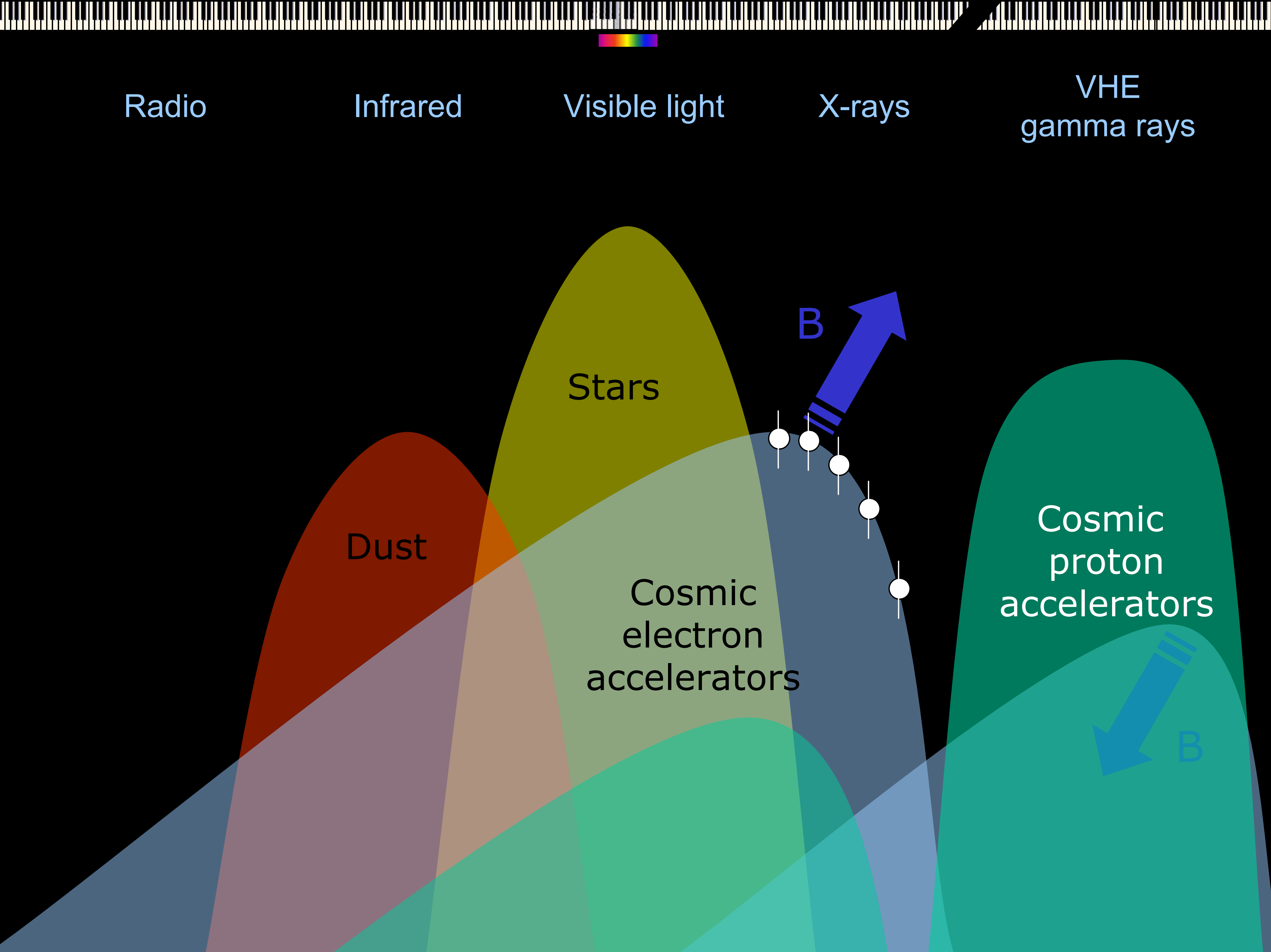
$dE/dt_{IC} = k\gamma^2 U_{rad}$

IC radation traces electron population $\otimes$ target photon density

usually poorly known

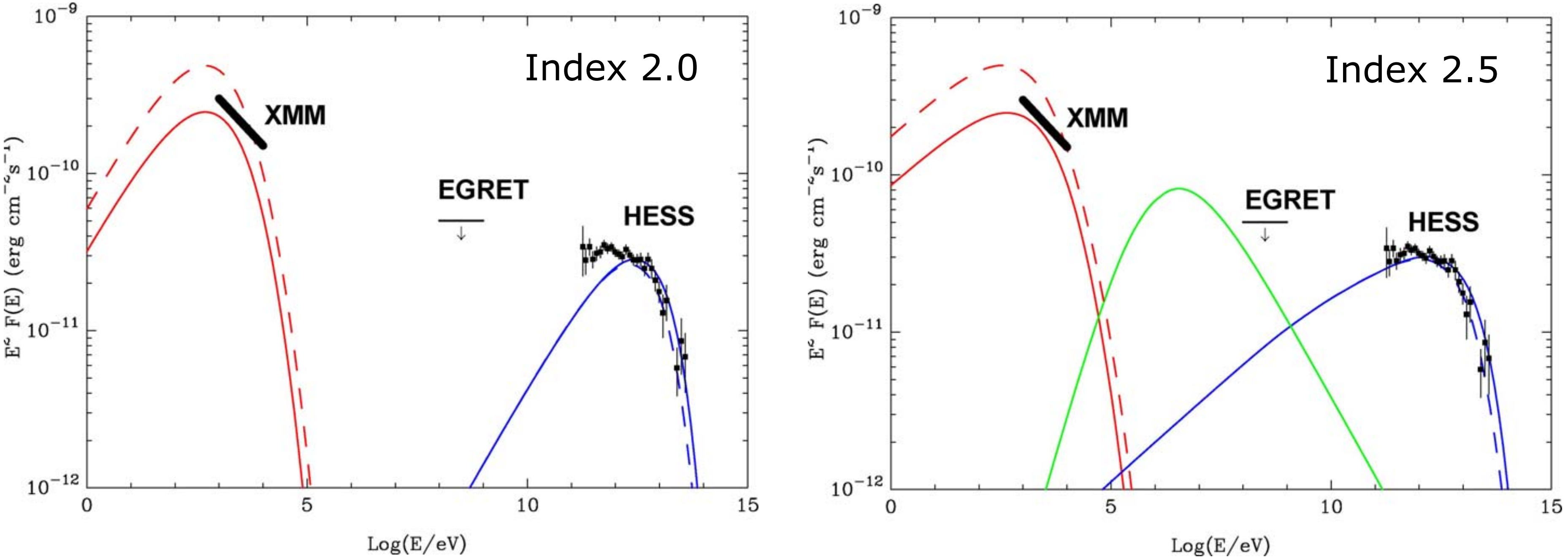
Electron Accelerator




Radio
Infrared
Visible light
X-rays
VHE gamma rays
Stars
B
Dust
Cosmic electron accelerators
Cosmic proton accelerators
B

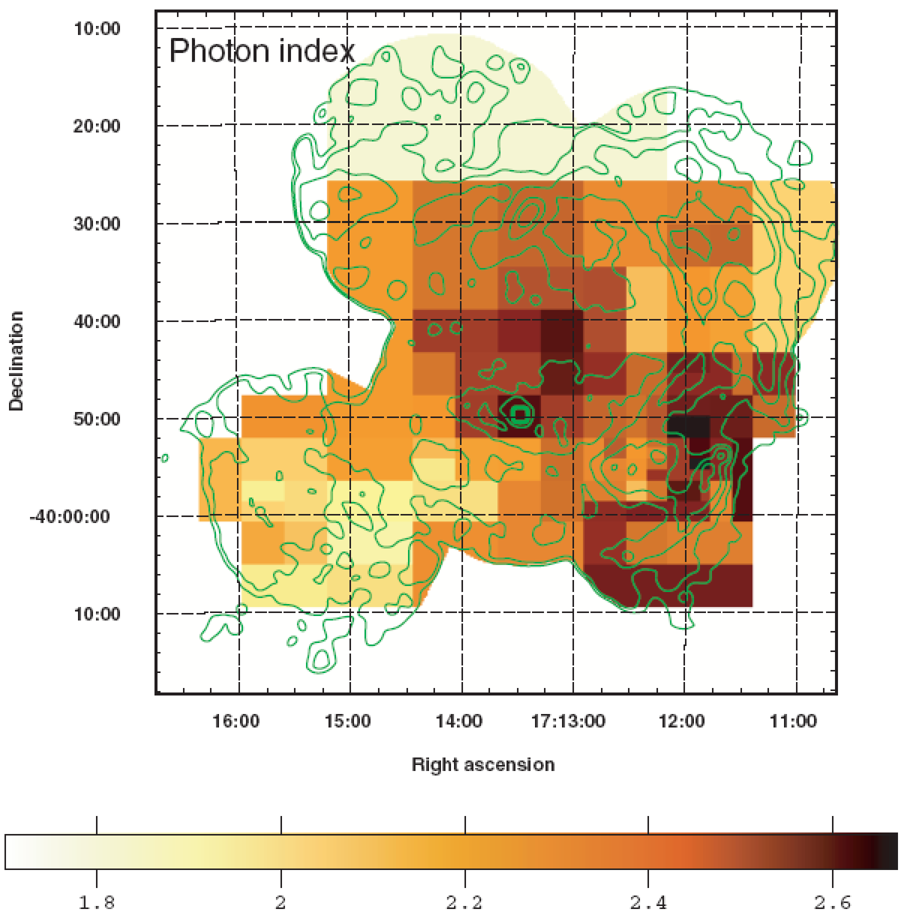
Electron accelerator

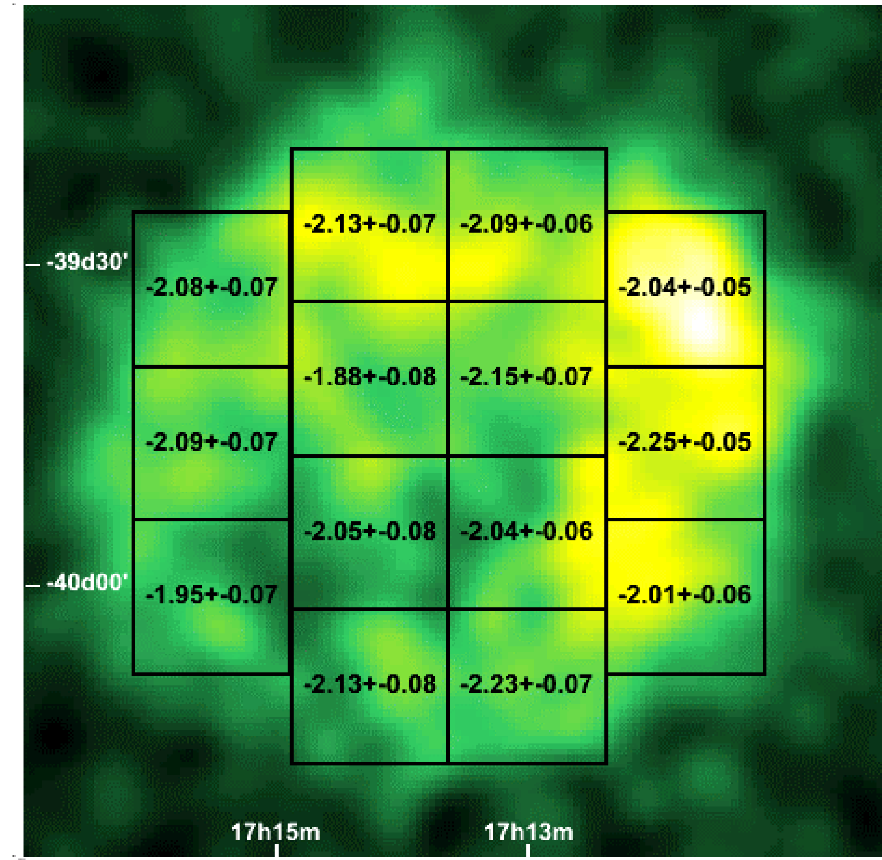
F.A. Aharonian



- Continuous electron injection over 1000 years
- Injection spectrum: power law with cutoff
- Magnetic field 8 μG (——) or 12 μG (----)

Spatially resolved spectra





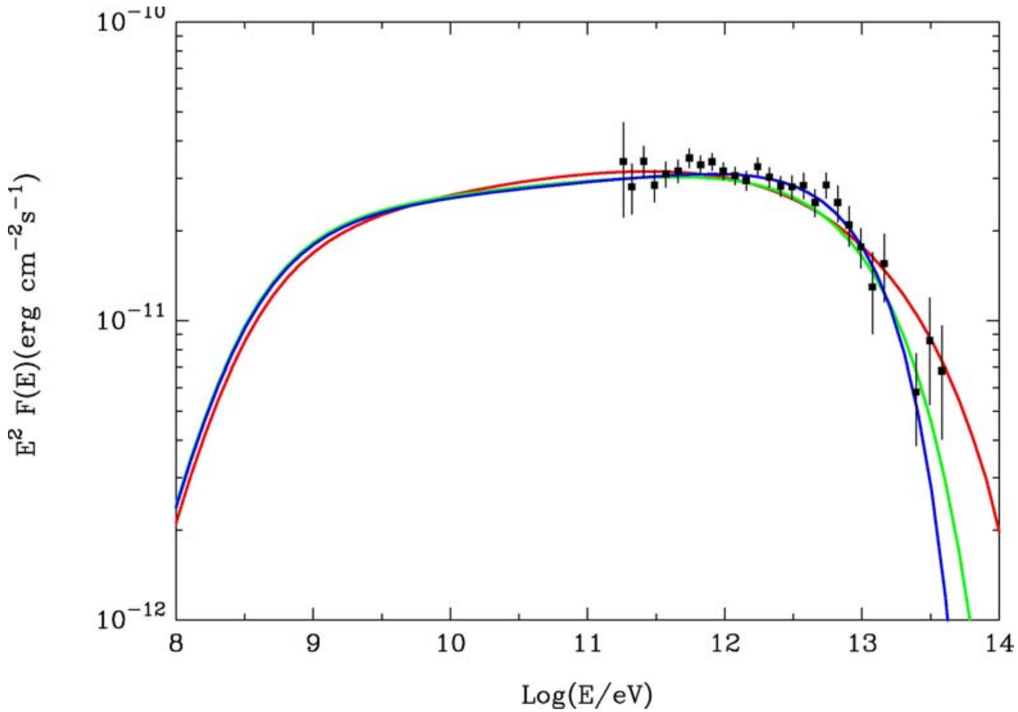
X-ray photon index

G. Cassam-Chenaï A&A 427, 199 (2004)

TeV photon index

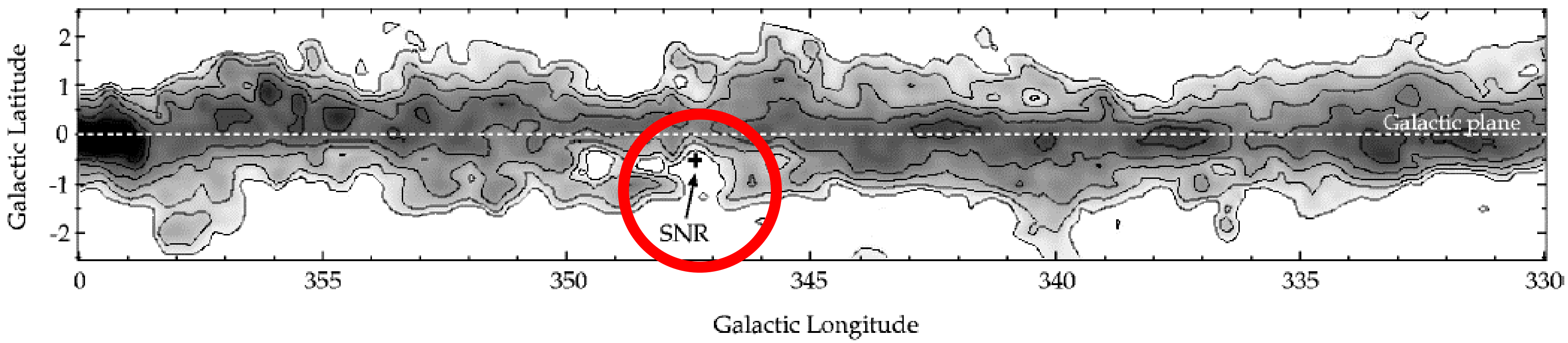
Proton accelerator

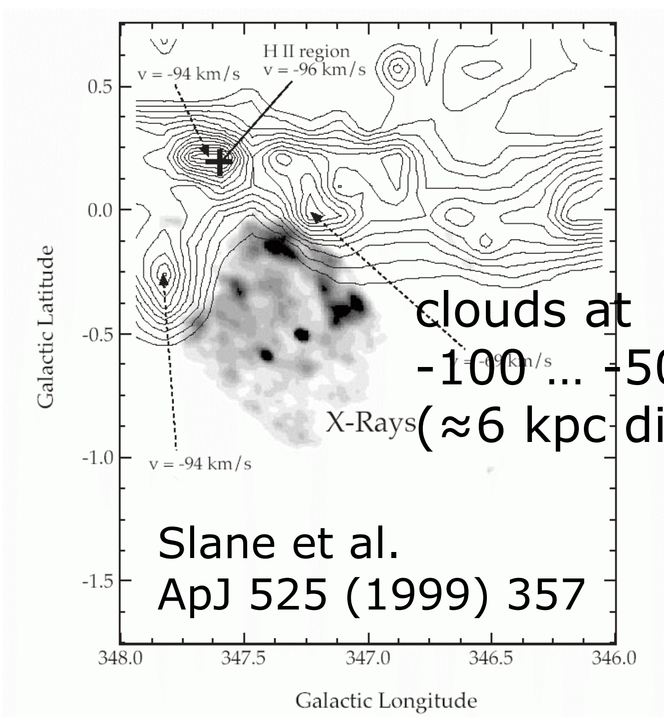
F.A. Aharonian



- Continuous proton injection over 1000 years
- Injection spectrum: power law, index ~2
- Different cutoff shapes

Distance and environment ??



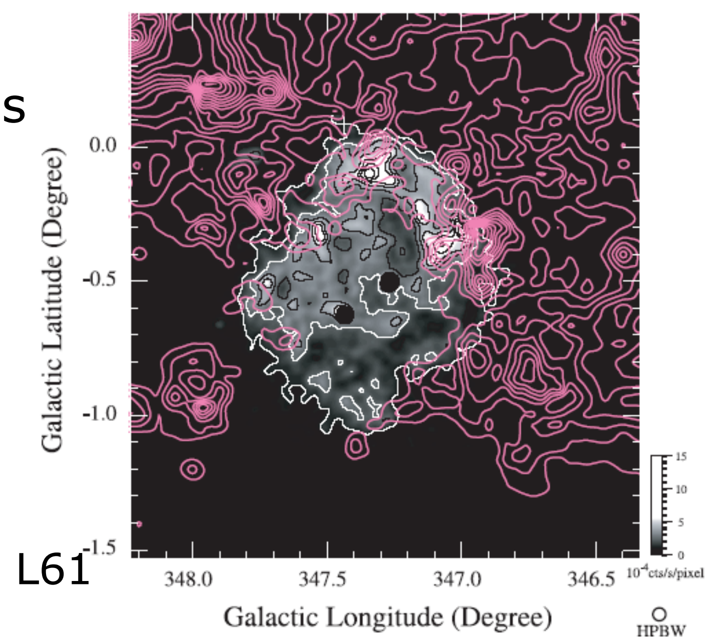


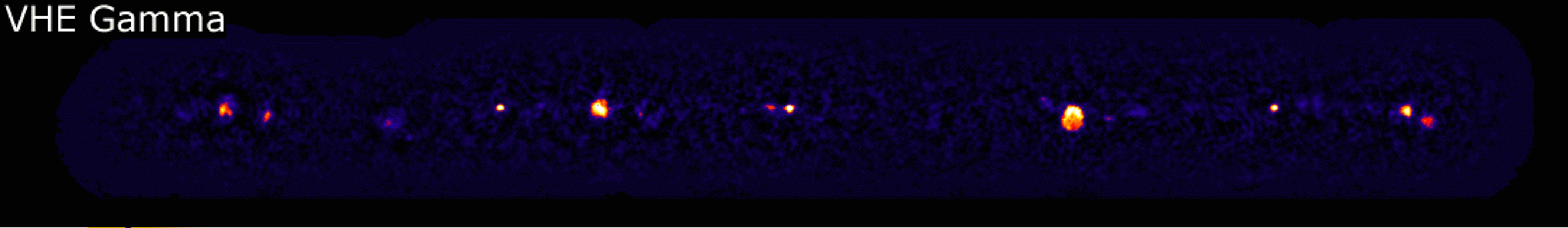
clouds at
-100 … -50 km/s
(≈6 kpc distance)

Slane et al.
ApJ 525 (1999) 357

clouds at
-11 … -3 km/s
(≈1 kpc)

Fukui et al.
PASJ 55 (2003) L61

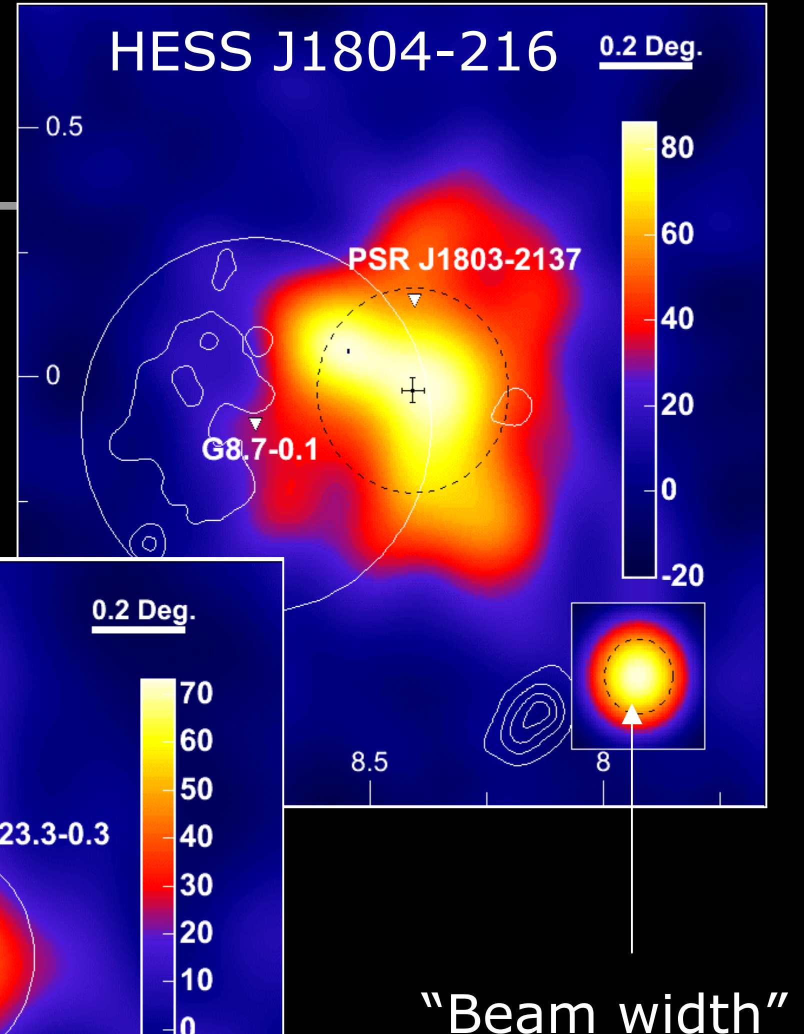


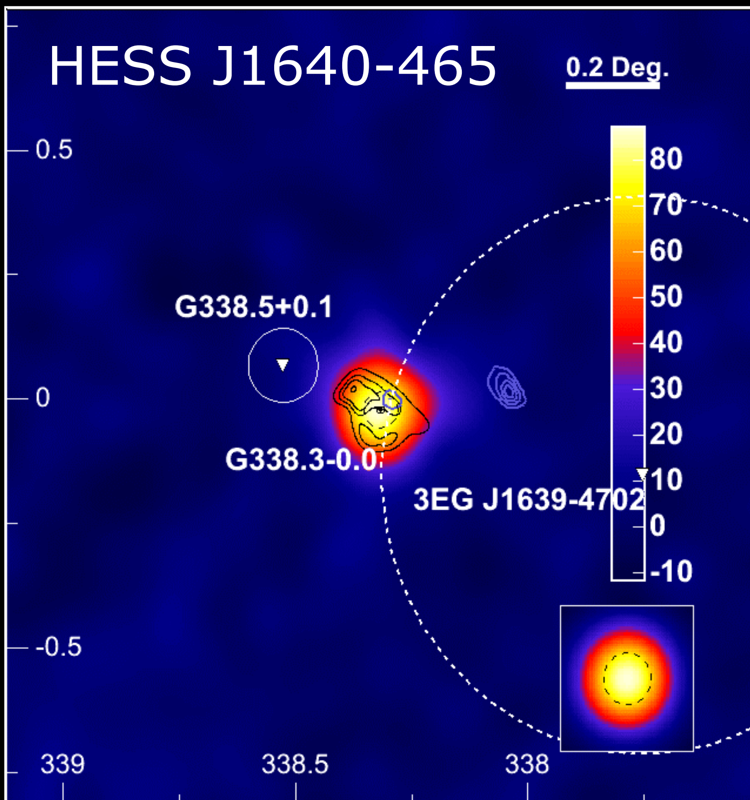


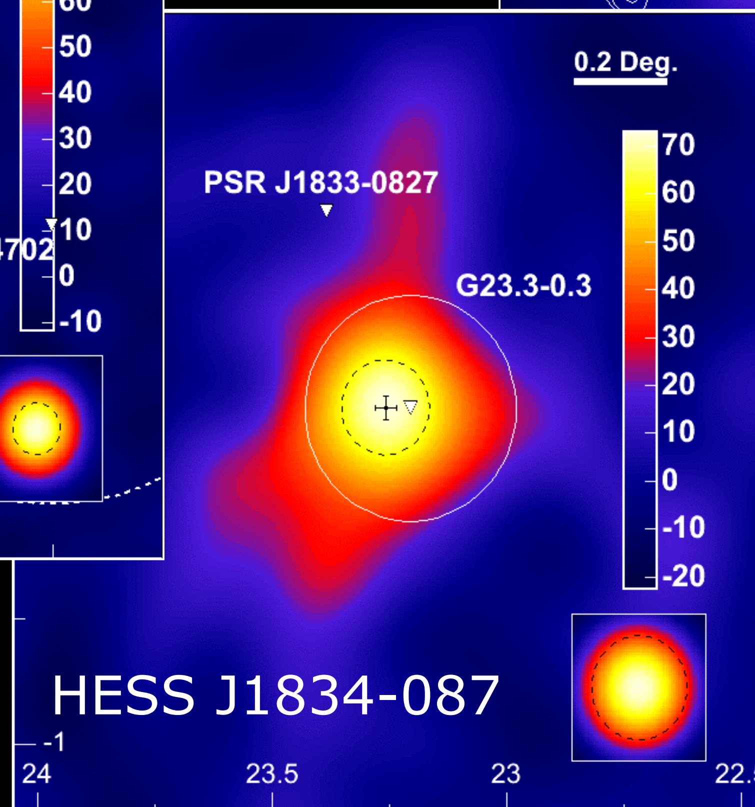
published results only

Source identifier	Flux (c.u.)	Size (arcmin.)	Counterpart / other names
HESS J1614-518	~4%	**~12**	-
HESS J1616-508	~7%	**~11**	PSR J1617-5055 **?**
HESS J1640-465	~8%	**~2**	G338.3-0.0 **?**
HESS J1713-397	~66%	**~15**	RXJ 1713.7-3946, G347.3-0.5
HESS J1745-290	~5%	< 3	Sgr A* / Sgr A East **?**
HESS J1747-281	~2%	<1.3	G0.9+0.1
HESS J1804-216	~6%	**~13**	G8.7-0.1 / W30 **?**
HESS J1813-178	~5%	**~3**	-
HESS J1825-137	~4%	**~20**	PSR J1826-1334/ 3EG J1826-1302 **?**
HESS J1834-087	~5%	**~12**	G23.3-0.3 / W41 **?**
HESS J1837-069	~4%	**~4**	G25.5+0.0 **?**
HESS J2158-302	up to 50%	<1.5	PKS 2155-304

SNR associations of survey sources





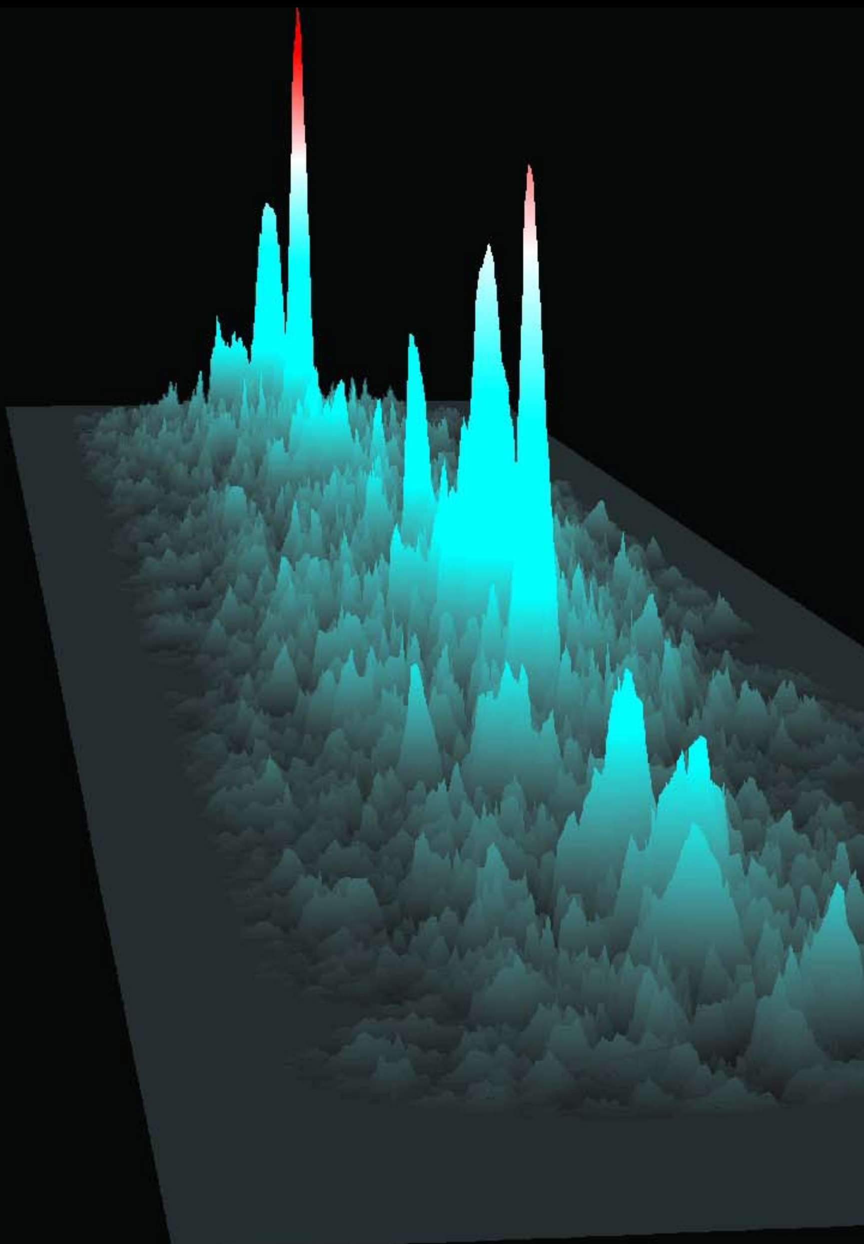


How to search for sources of cosmic rays ?

A proton accelerator will not exhibit strong radio or X-ray signals

but …

Virtually all candidates for TeV observations are selected based on radio or X-ray data!



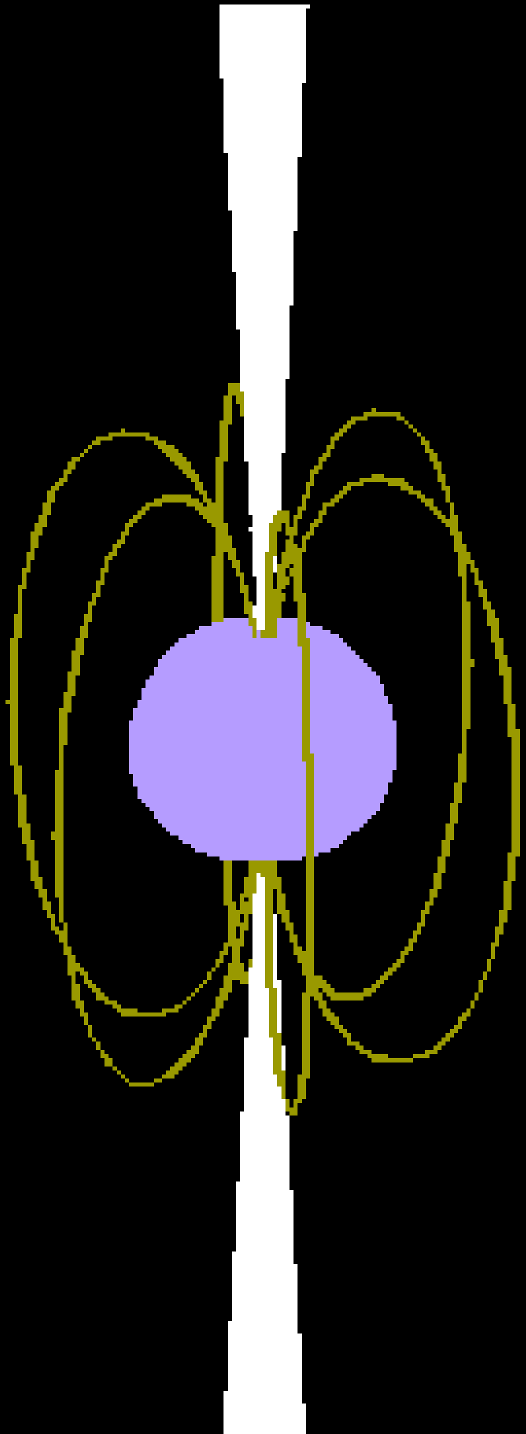
Very high energy gamma astronomy

The H.E.S.S. telescopes and how they work

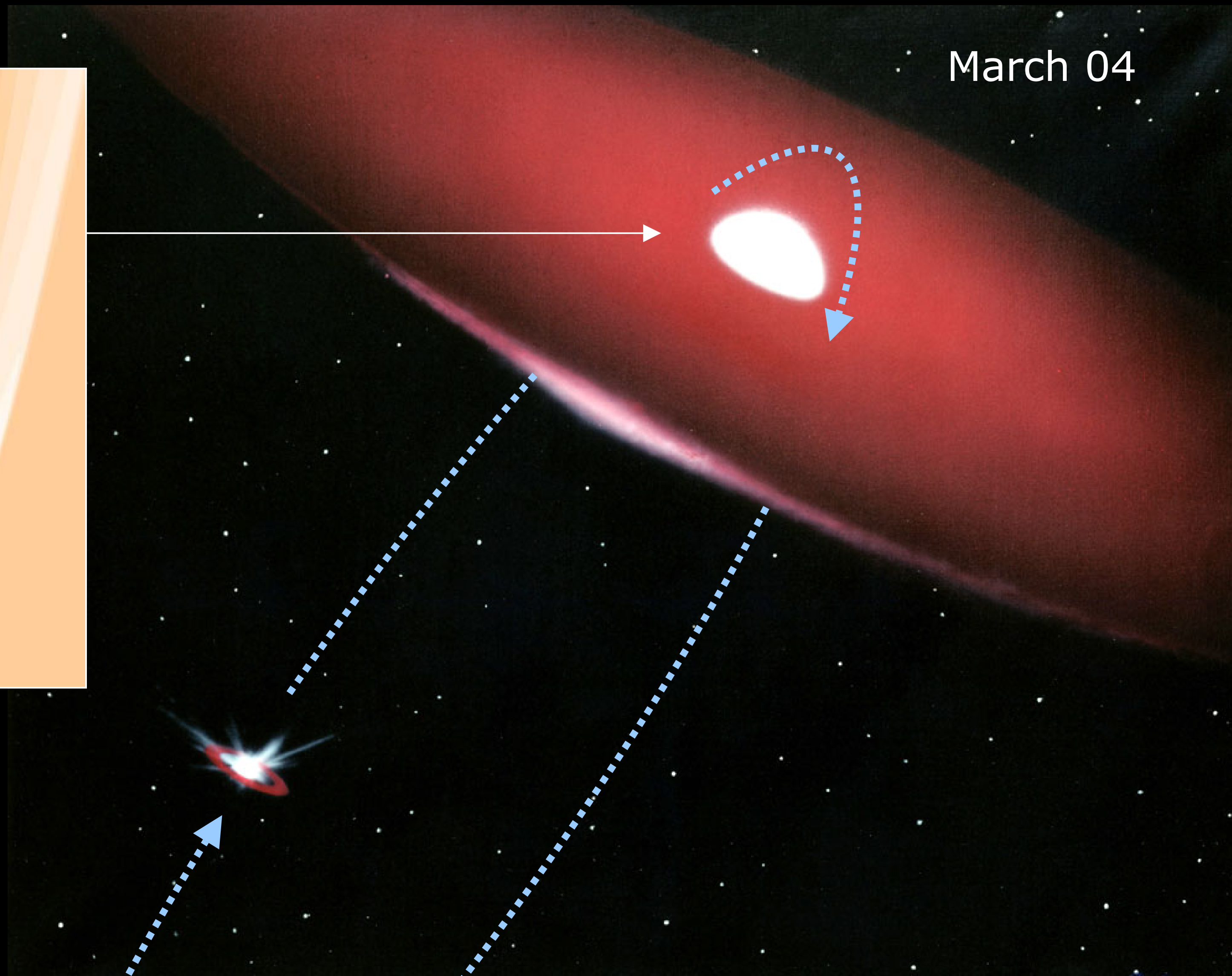
Supernovae as cosmic particle accelerators

Pulsar winds & mystery sources

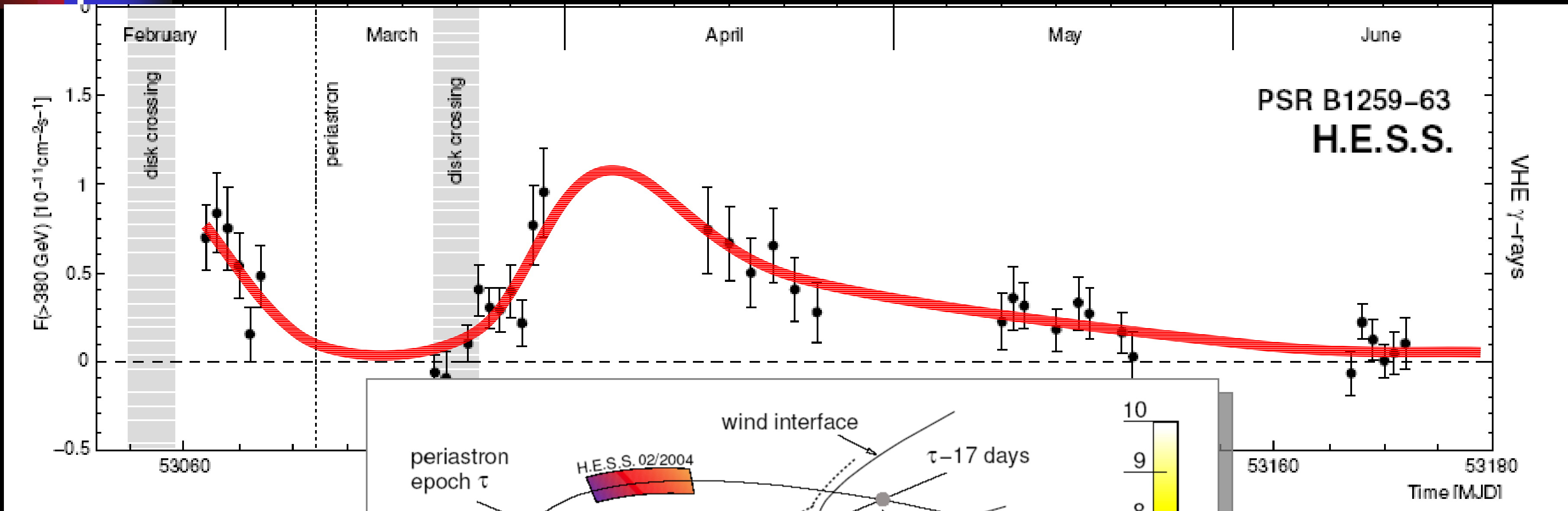
Gamma rays from the Galactic Center

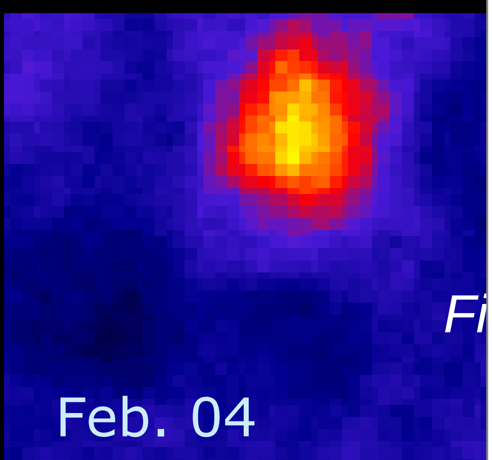


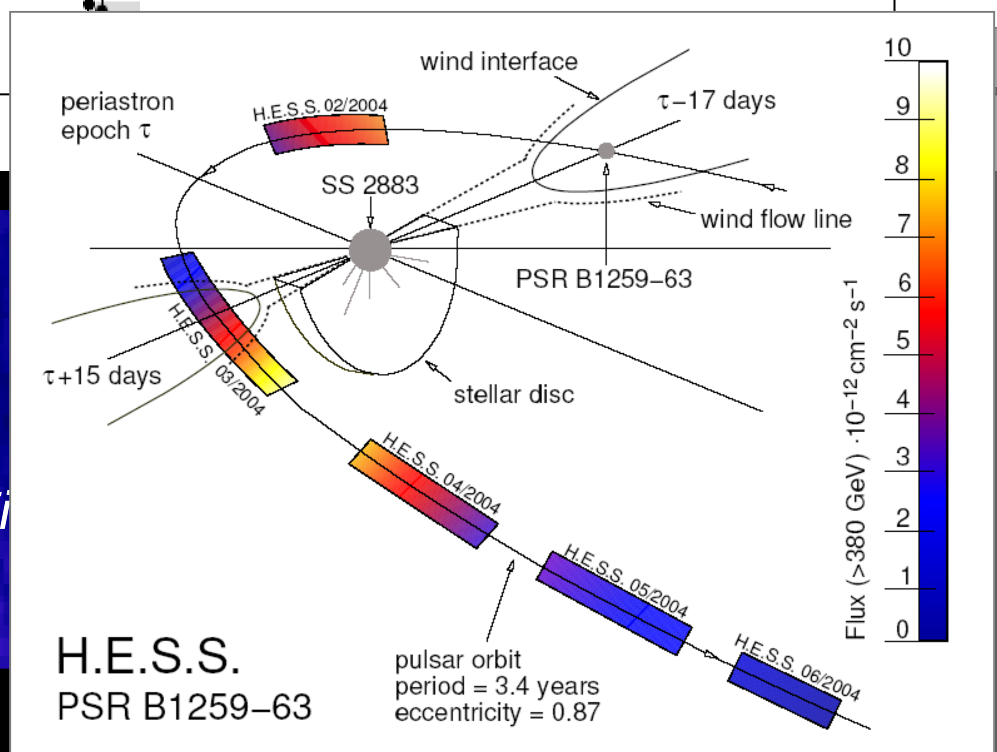
Pulsar B1259-63



The B1259-63 field of view



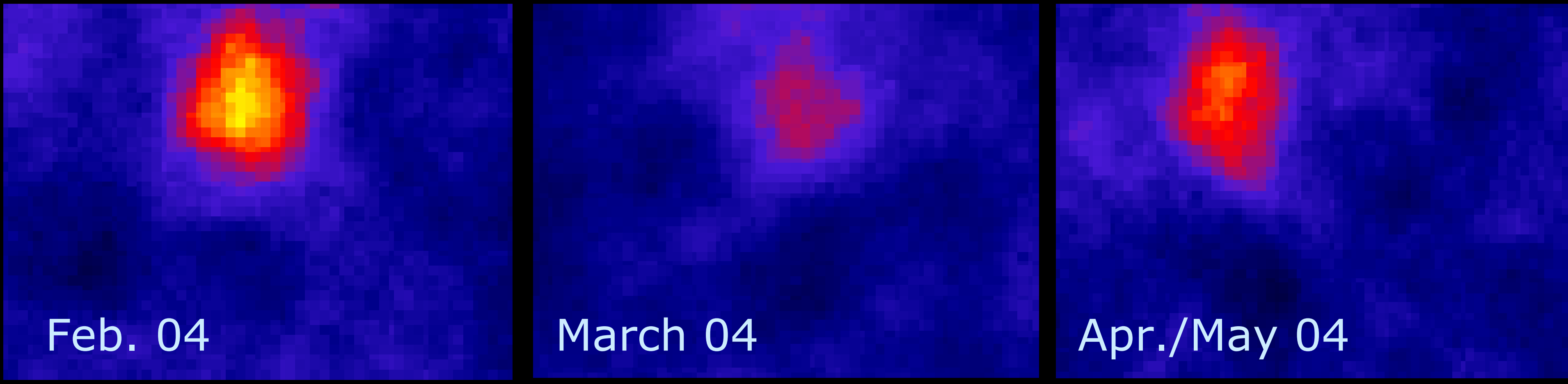




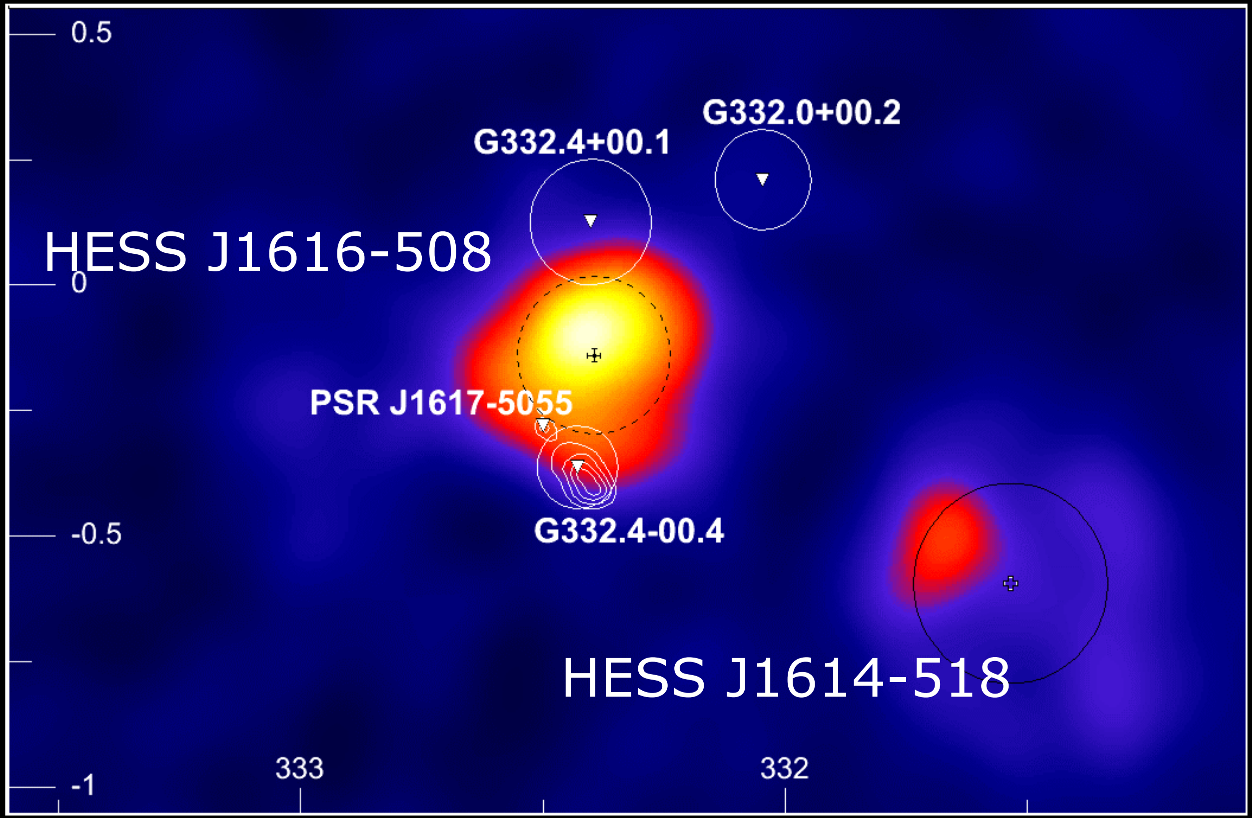
The B1259-63 field of view

Source HESS J1303-631

- is extended
- has no radio or X-ray counterpart
- has a hard spectrum, index ~ 2



More unidentified sources, e.g. HESS J1614-518



A huge pulsar wind: MSH 15-52

Chandra
X-ray image

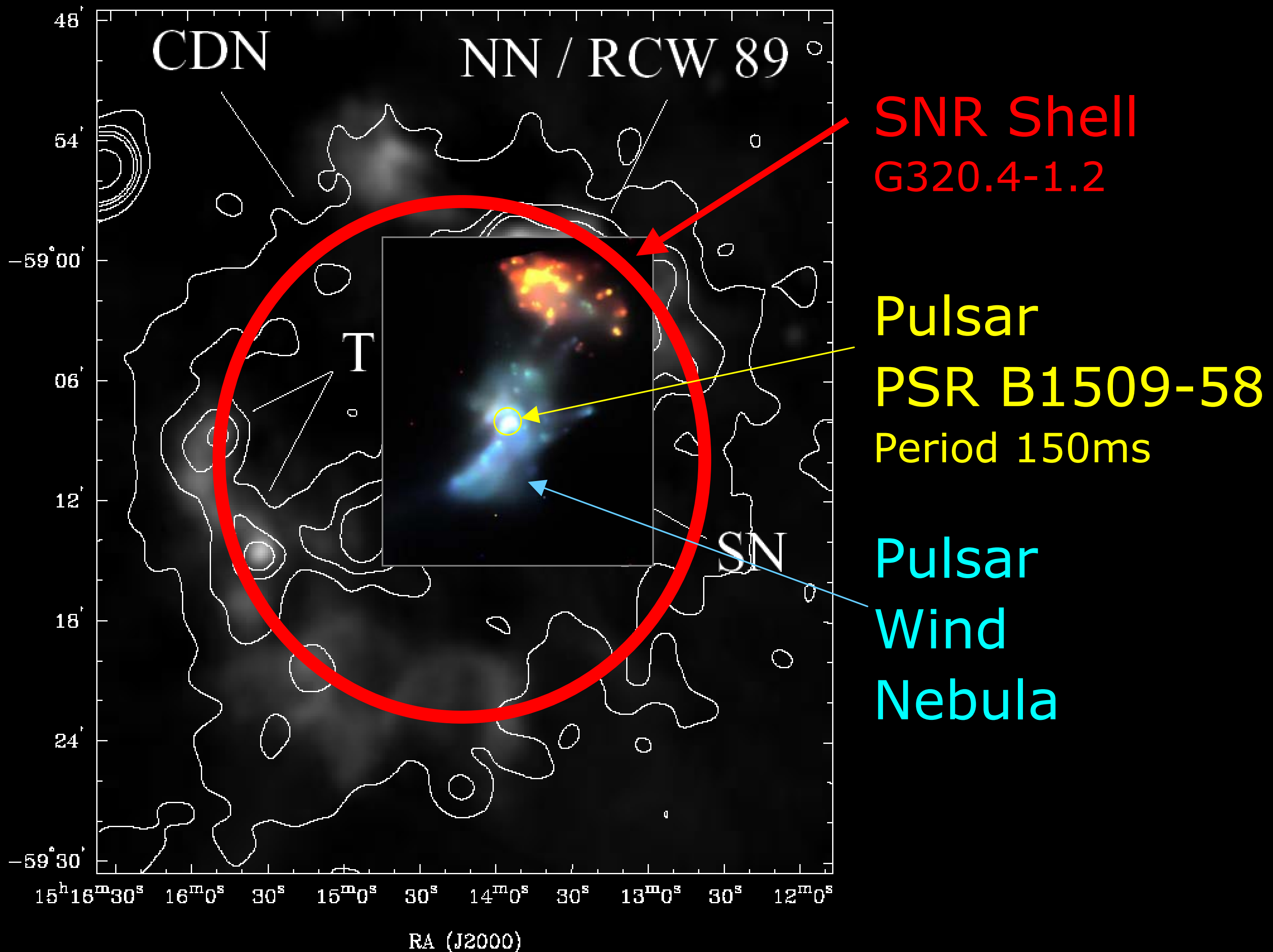
The MSH 15-52 Complex

Contours:
ROSAT x-ray

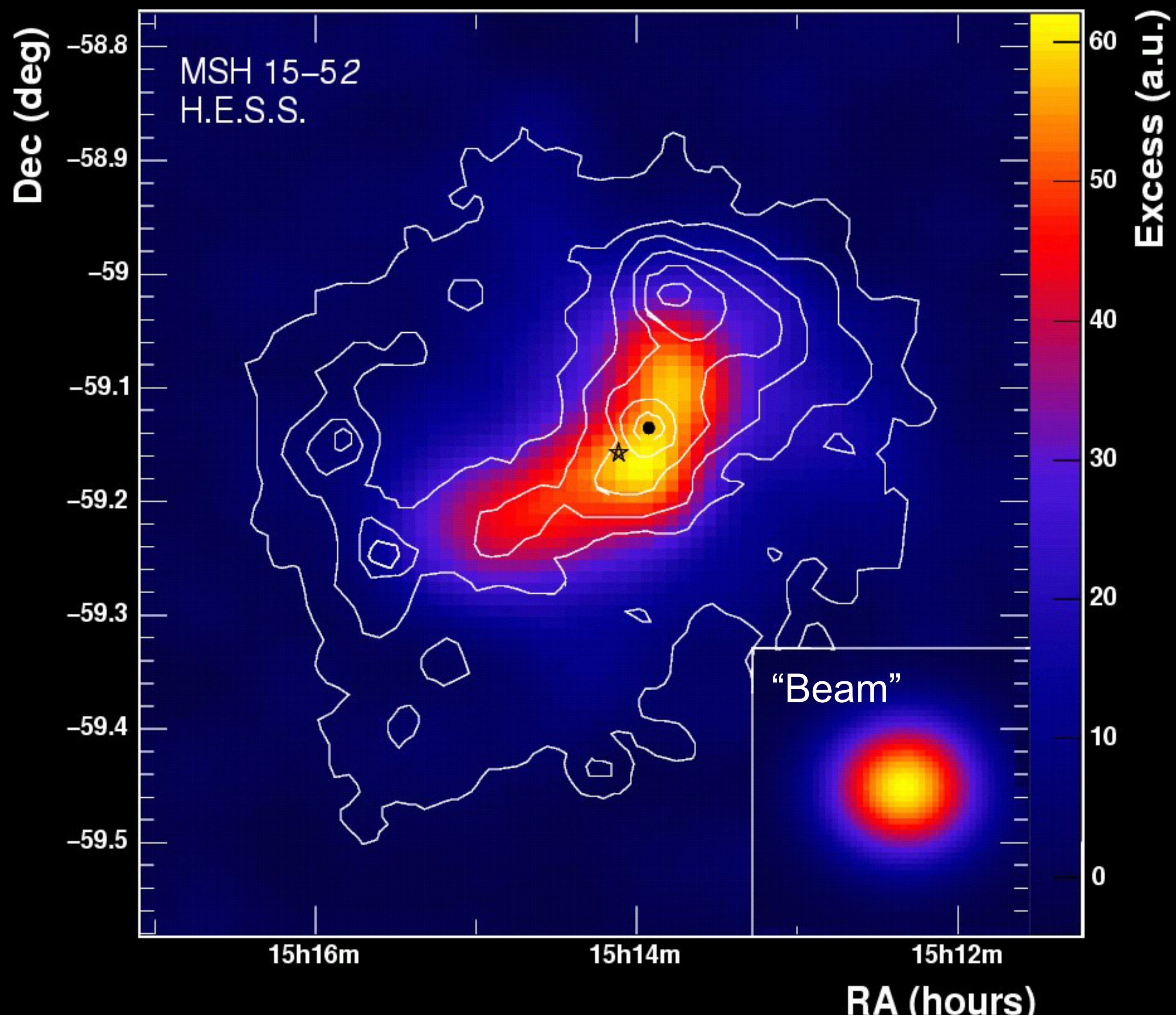
Greyscale:
Radio

Age:
1.7- 20 kyr

Distance:
5.2 ± 1.4 kpc



MSH 15-52 with H.E.S.S.



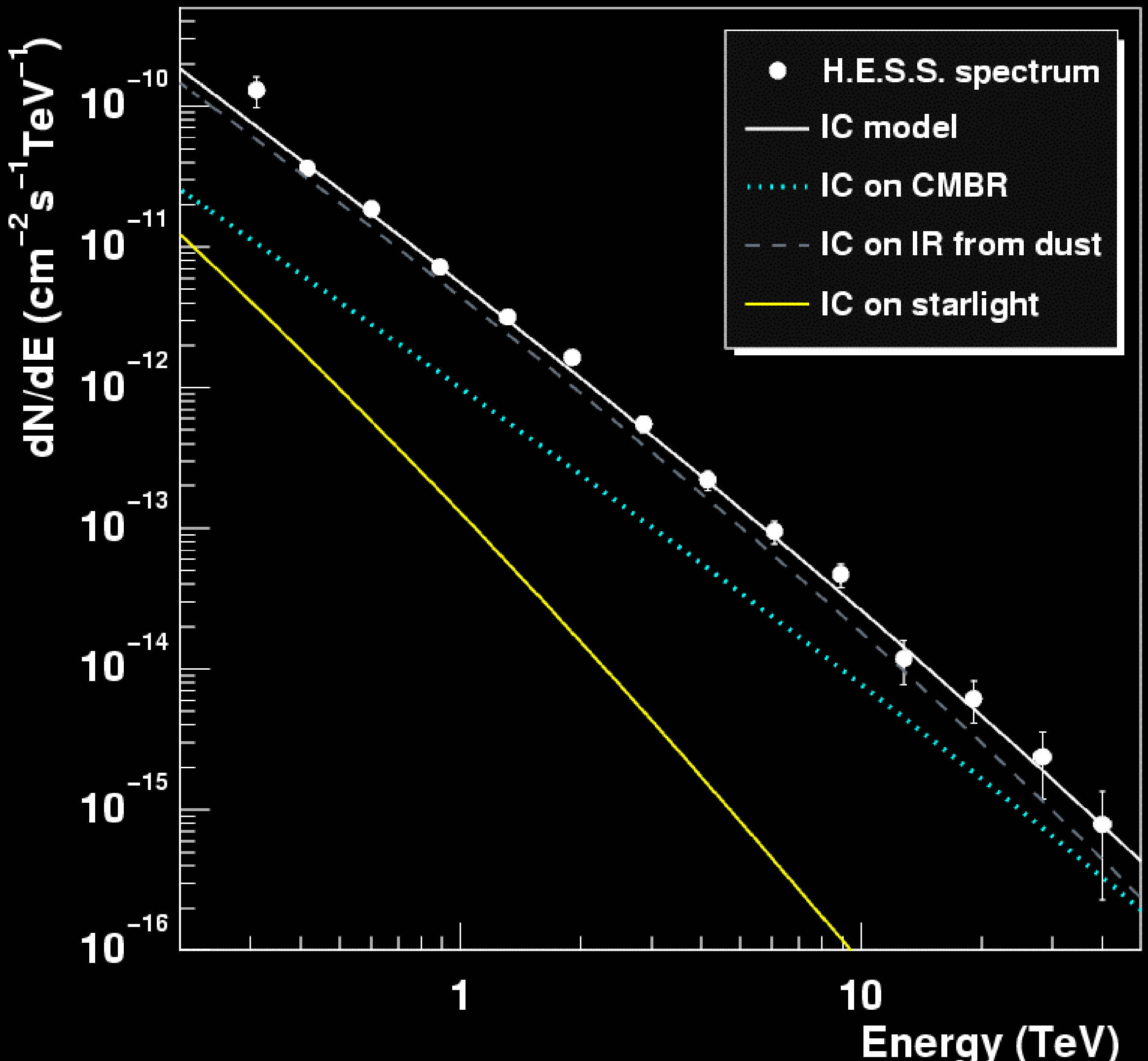
H.E.S.S. Energy Spectrum

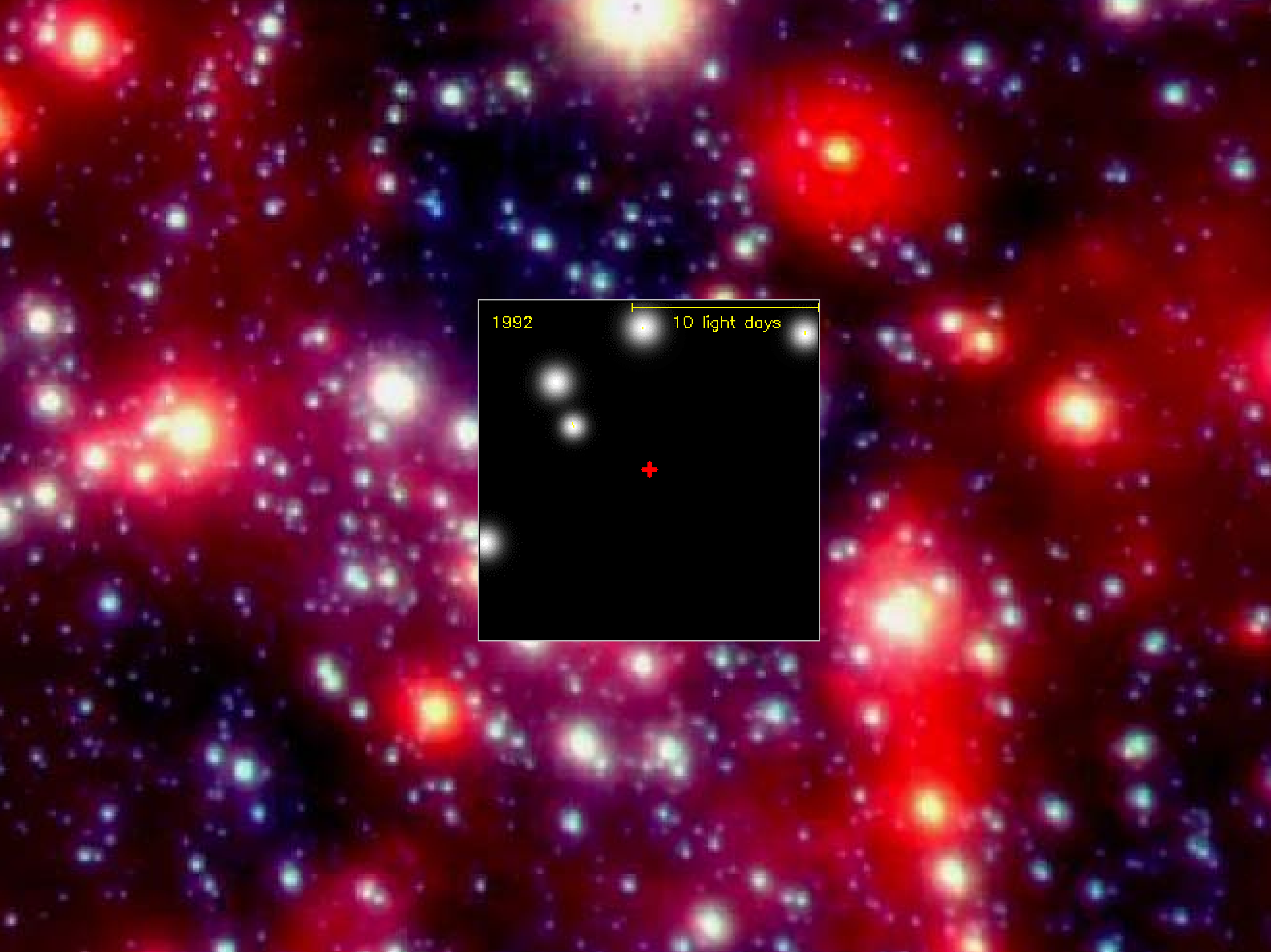
covers 2 orders of magnitude in energy

power law
N(E) ~ $E^{-2.3}$

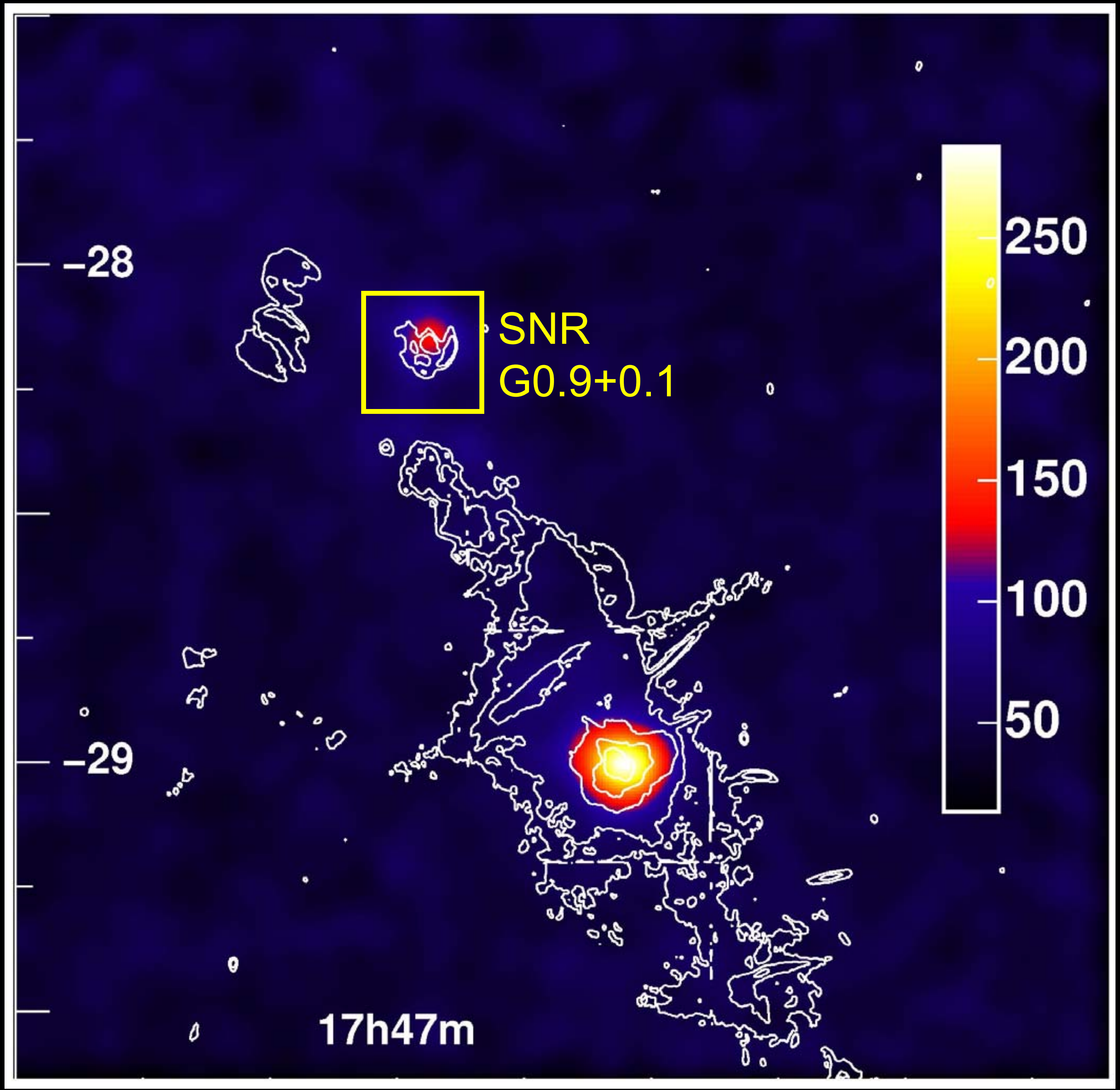
IC from electron population in 15 μG field?

but: would expect to see cooling break in spectrum…

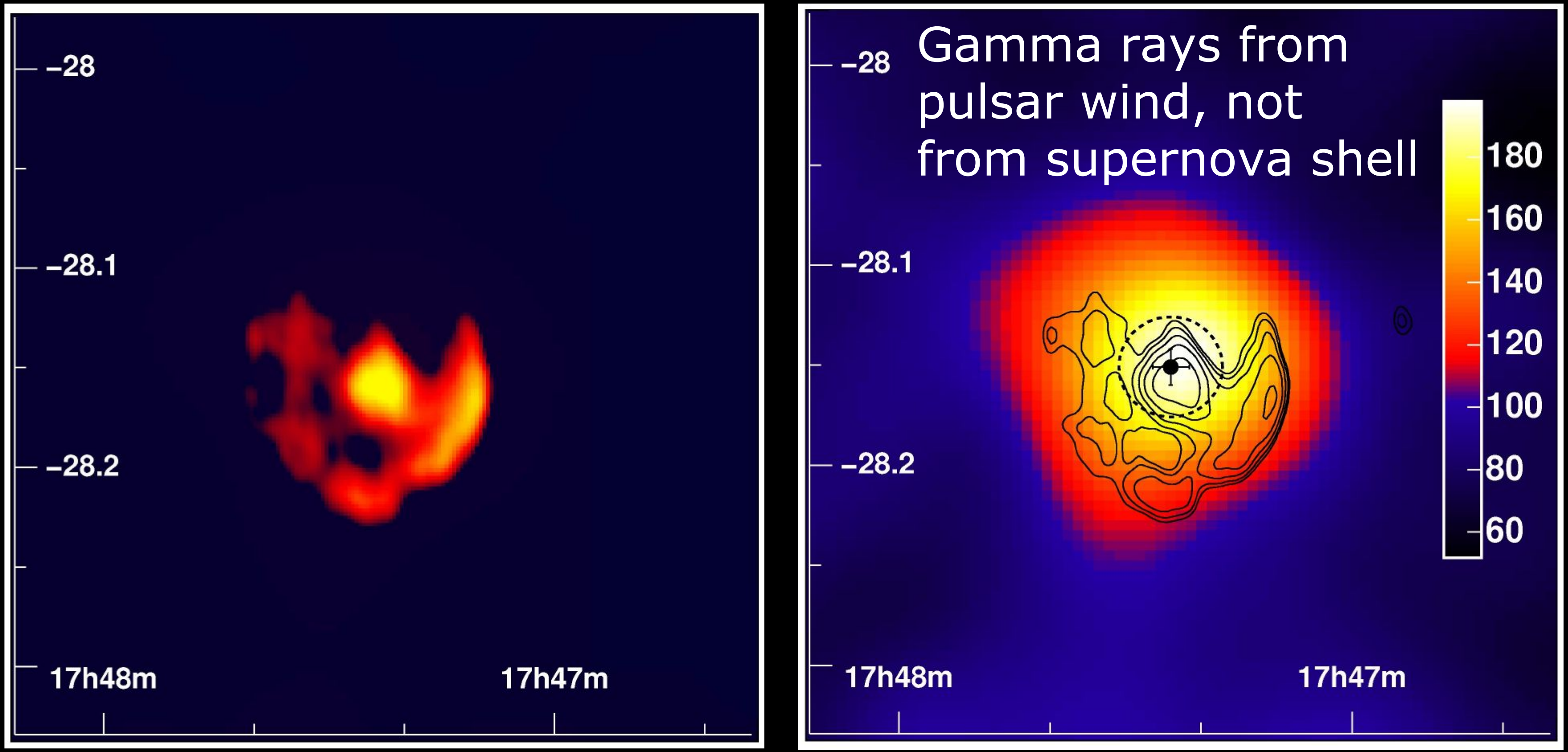



1992
10 light days

H.E.S.S.
2004 data



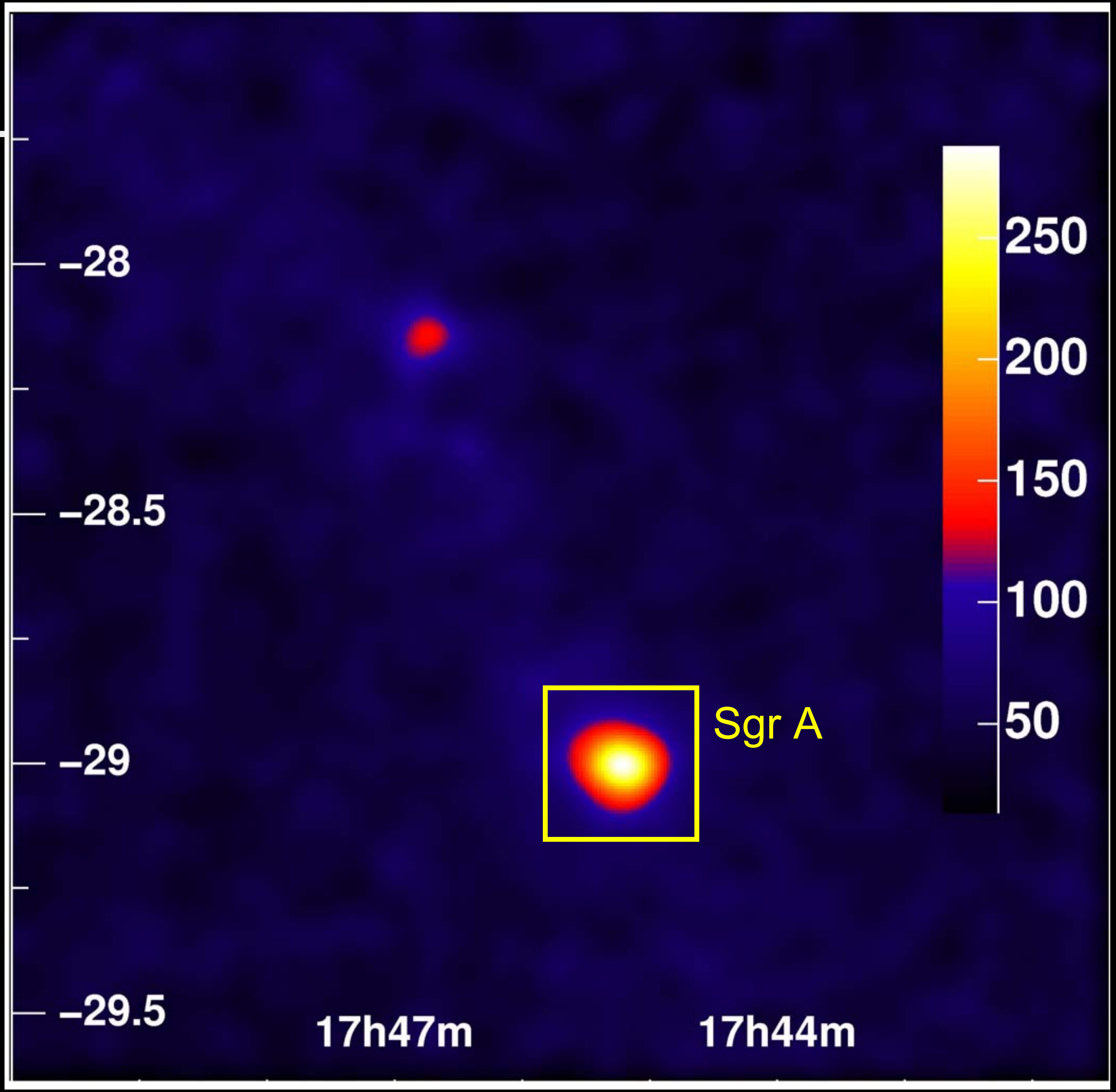
Supernova Remnant G0.9+0.1



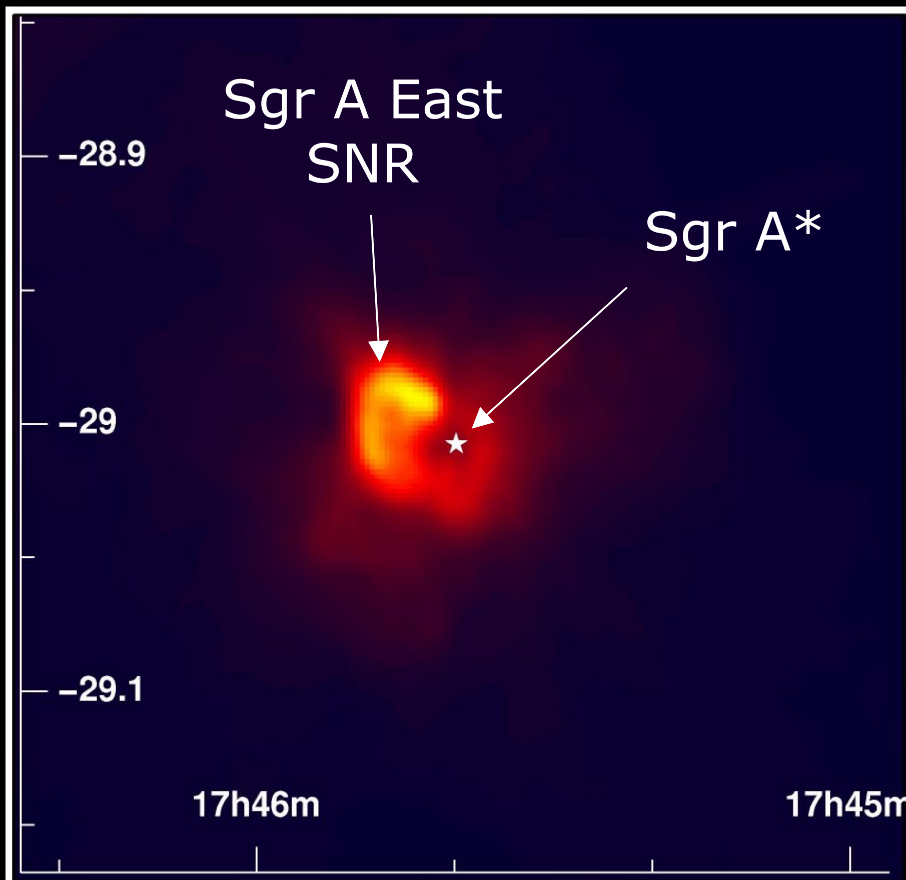
Radio

TeV H.E.S.S.

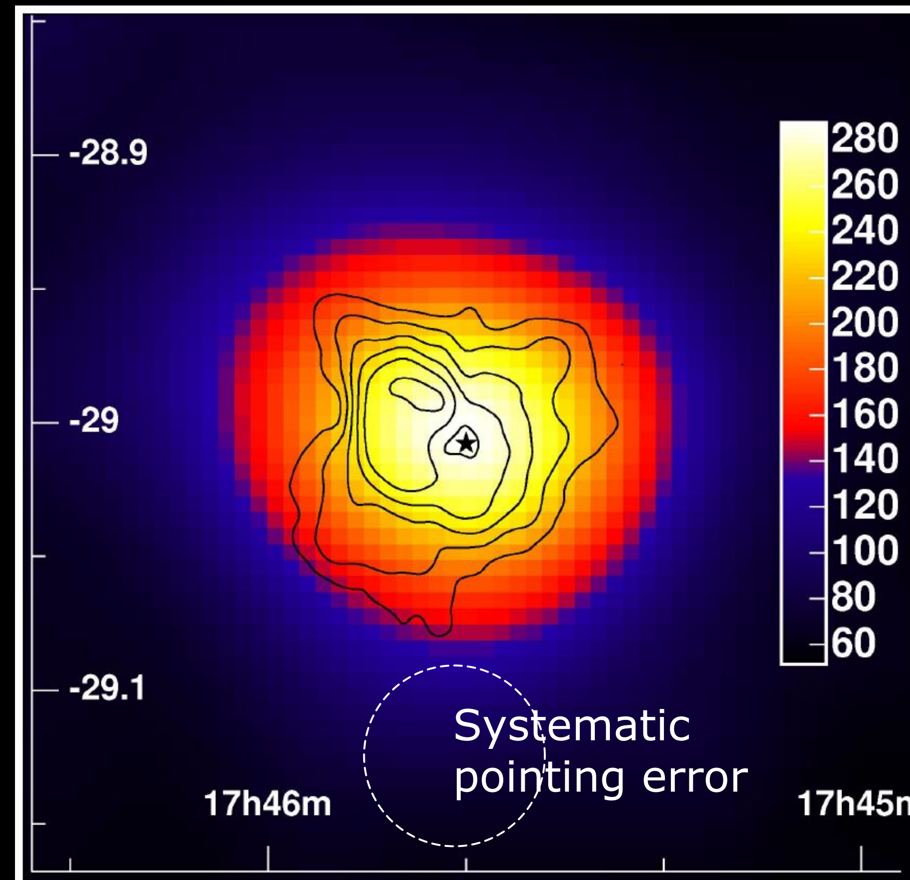
H.E.S.S.
2004 data



Sagittarius A



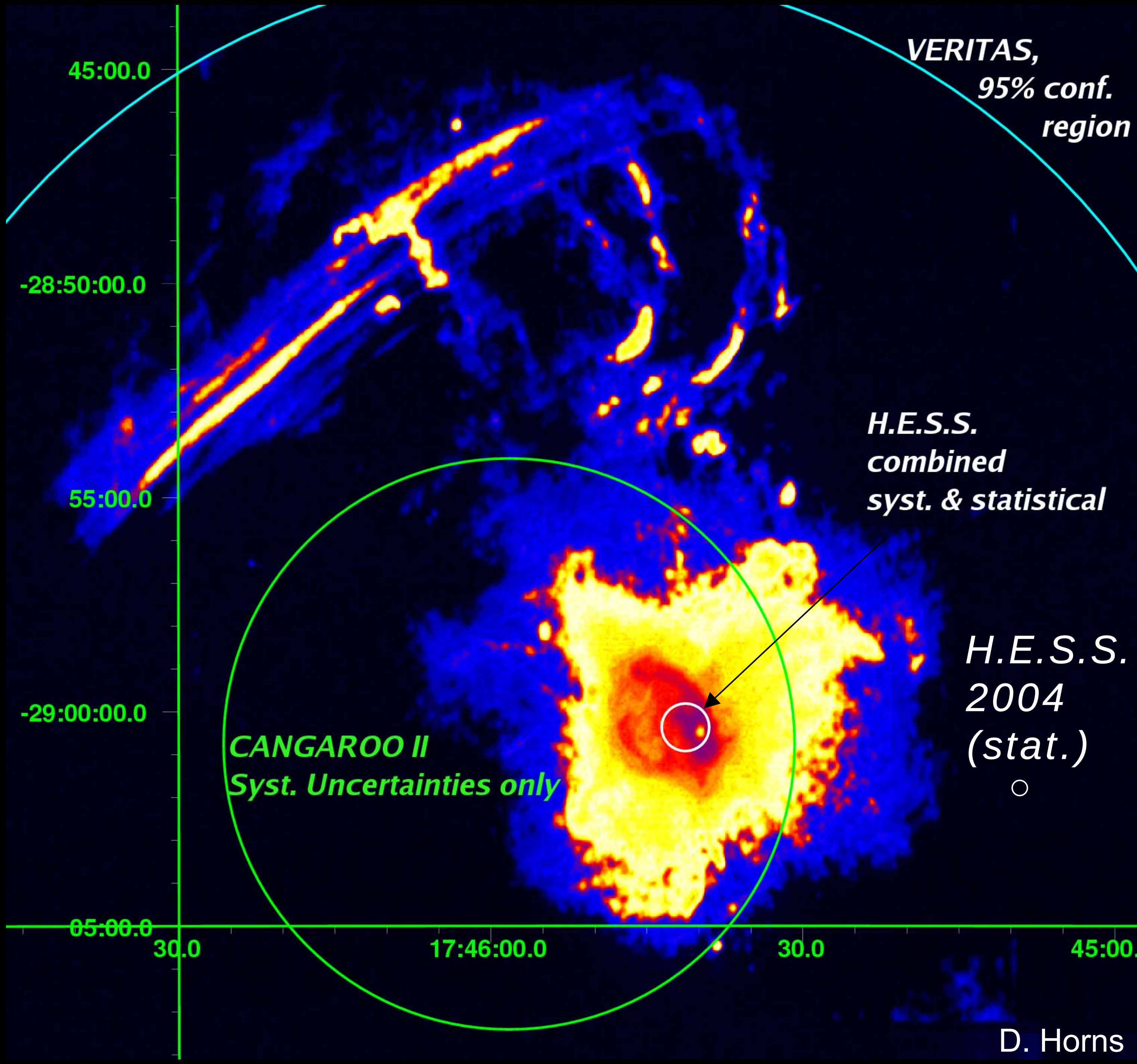
Radio



TeV H.E.S.S.

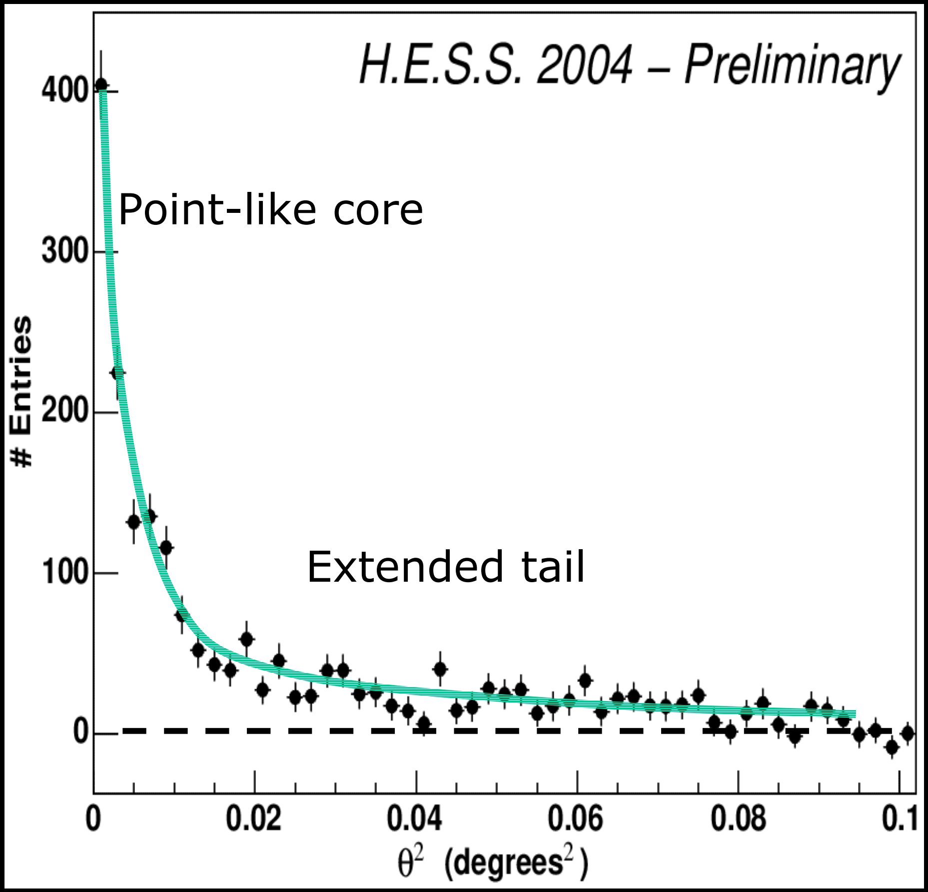
Source location

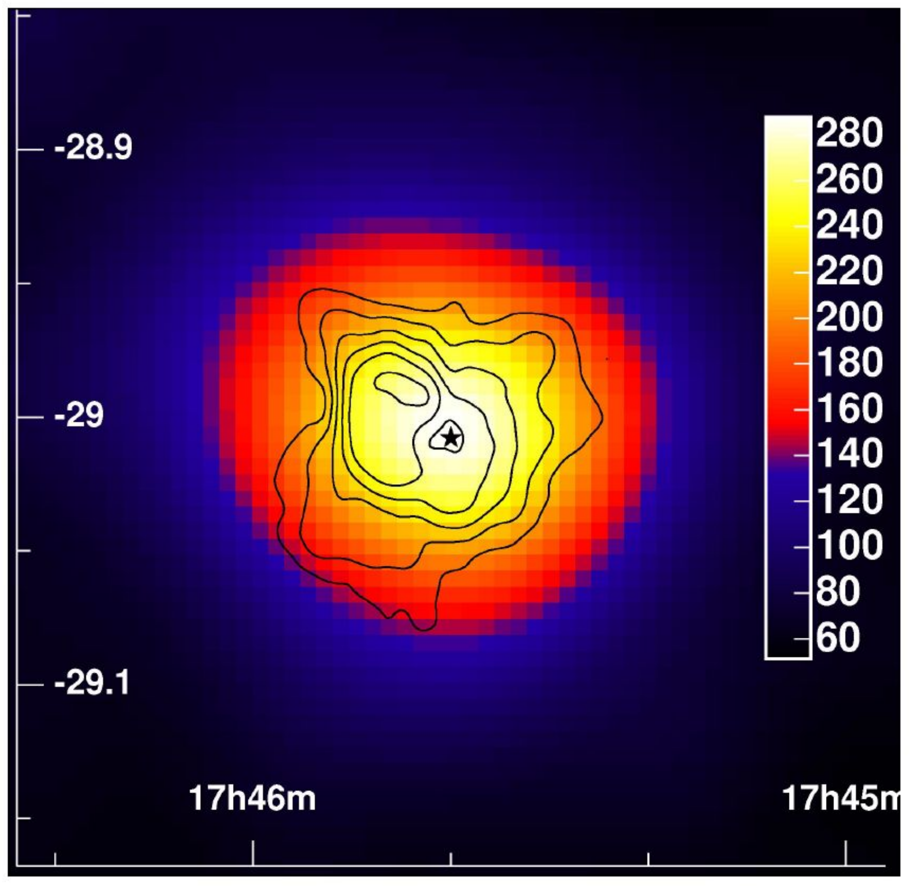
2003
Data



D. Horns

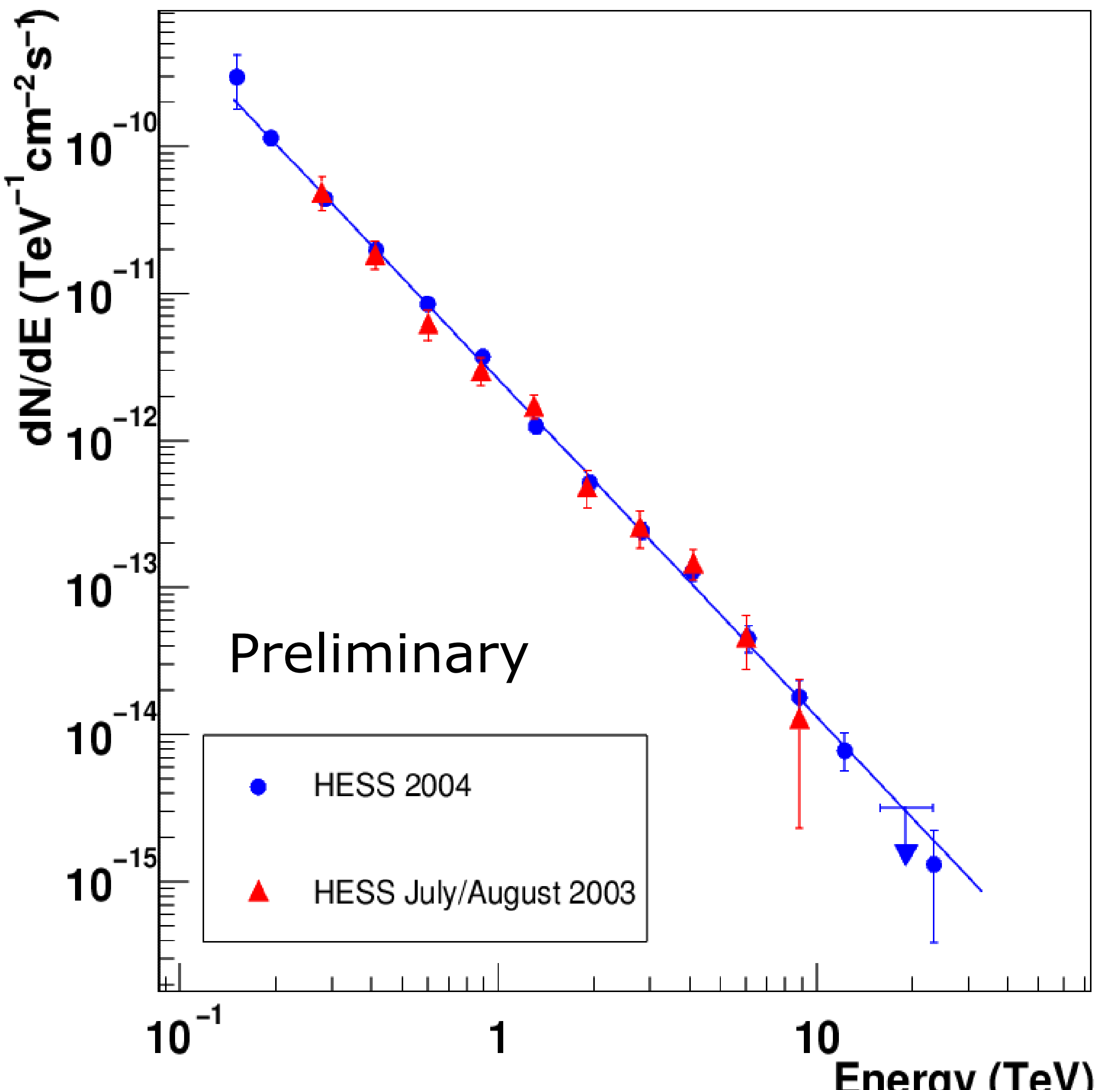
Sagittarius A



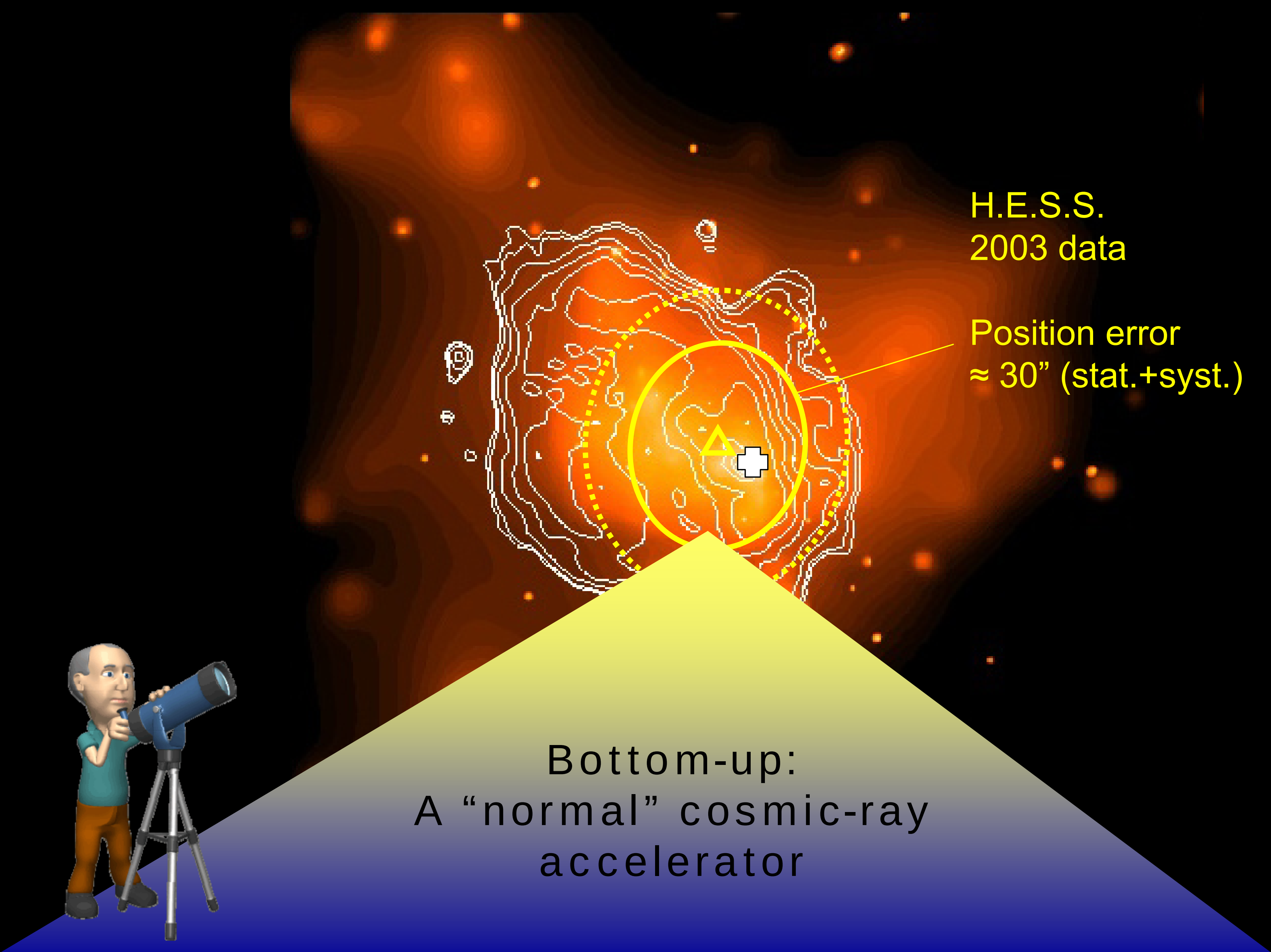


TeV H.E.S.S.

Gamma ray spectrum



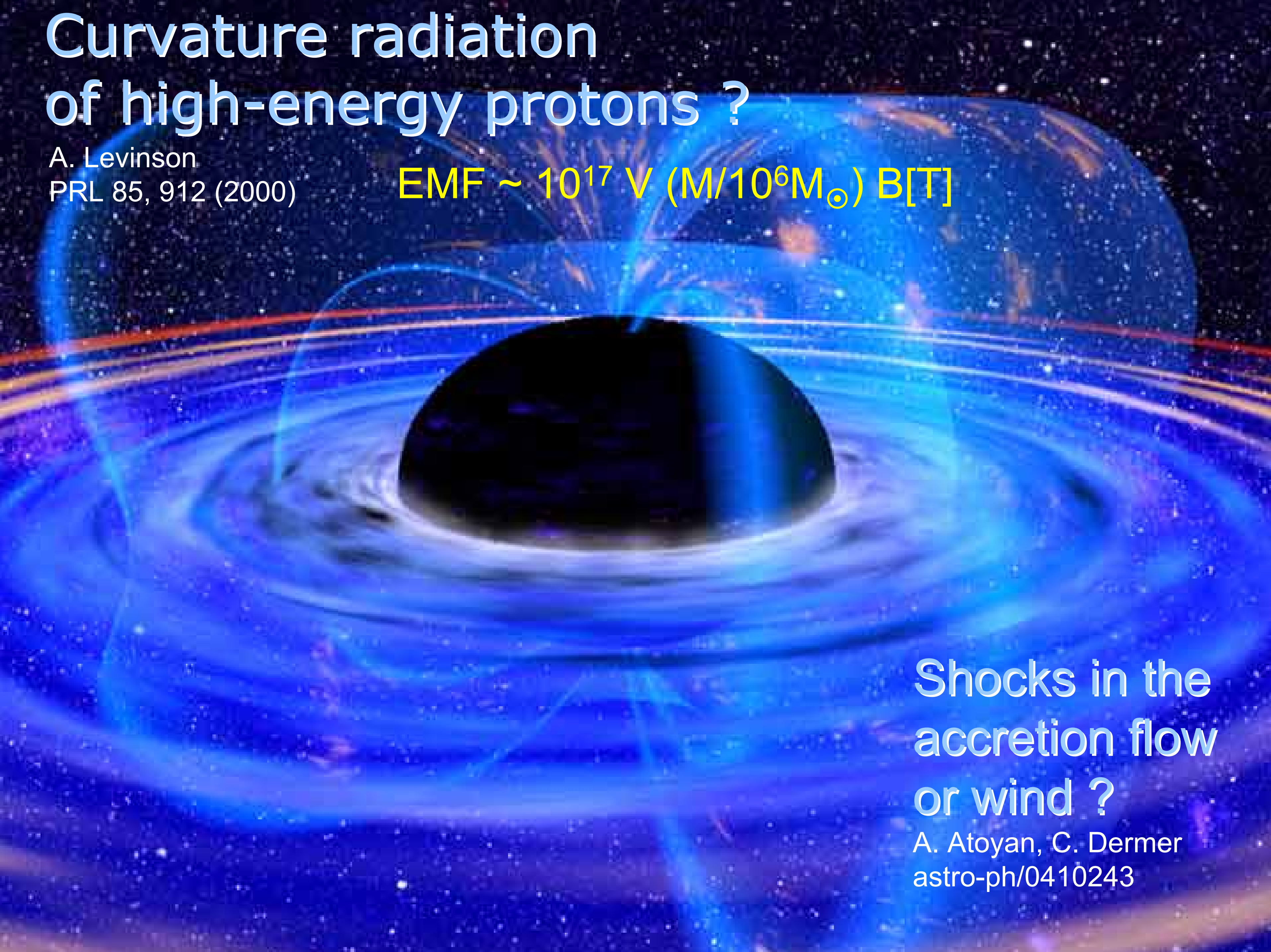
- Power law, index 2.3
- No significant variability
  - on year scale
  - on month scale
  - on day scale
  - on hour scale
  - on minute scale


H.E.S.S.
2003 data
Position error
≈ 30” (stat.+syst.)
Bottom-up:
A “normal” cosmic-ray
accelerator

Curvature radiation of high-energy protons ?

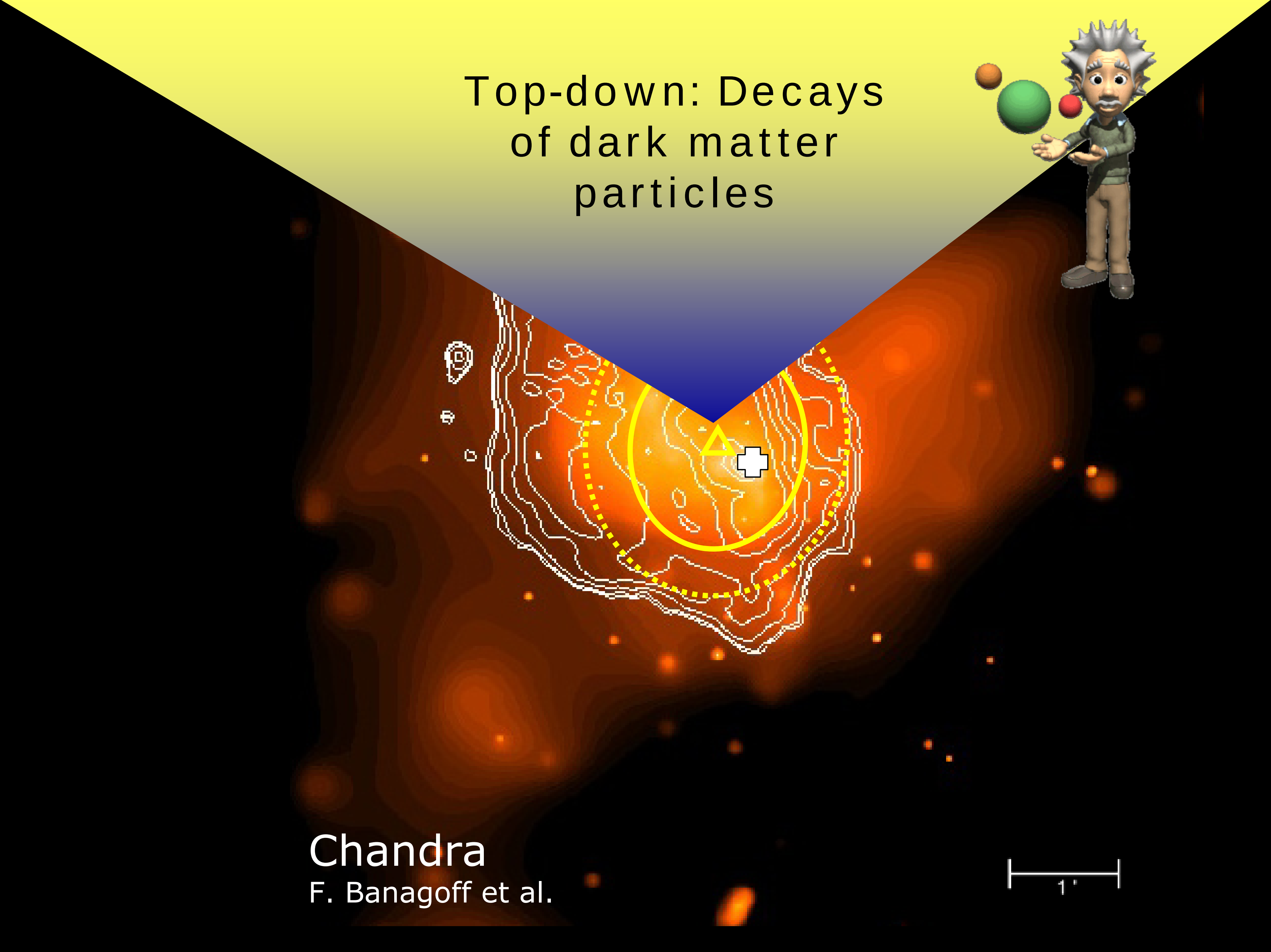
A. Levinson
PRL 85, 912 (2000)

EMF ~ 10^{17} V $(M/10^{6}M_{\odot})$ B[T]

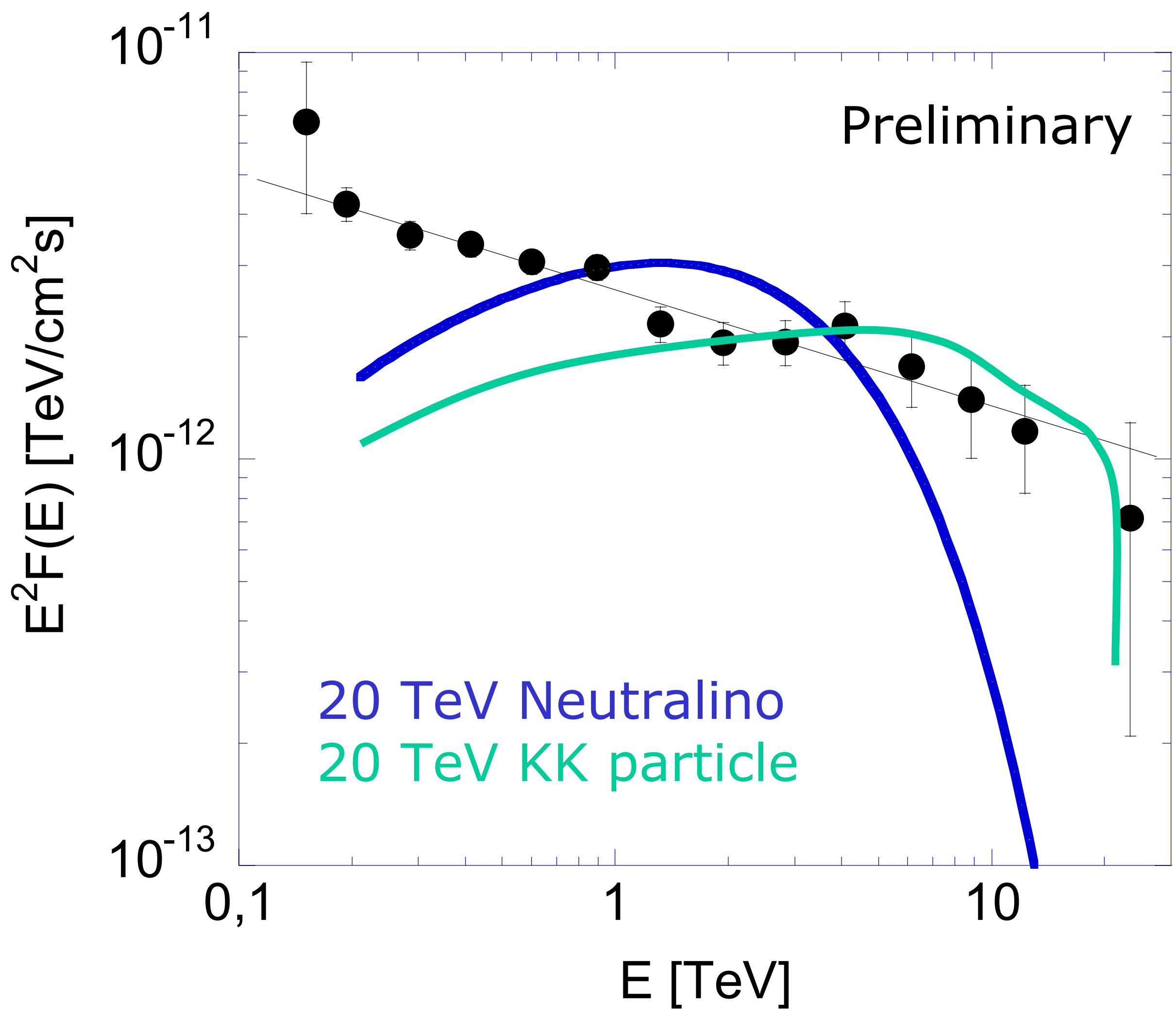


Shocks in the accretion flow or wind ?

A. Atoyan, C. Dermer
astro-ph/0410243


Top-down: Decays
of dark matter
particles
Chandra
F. Banagoff et al.
1'

Dark matter annihiation ?



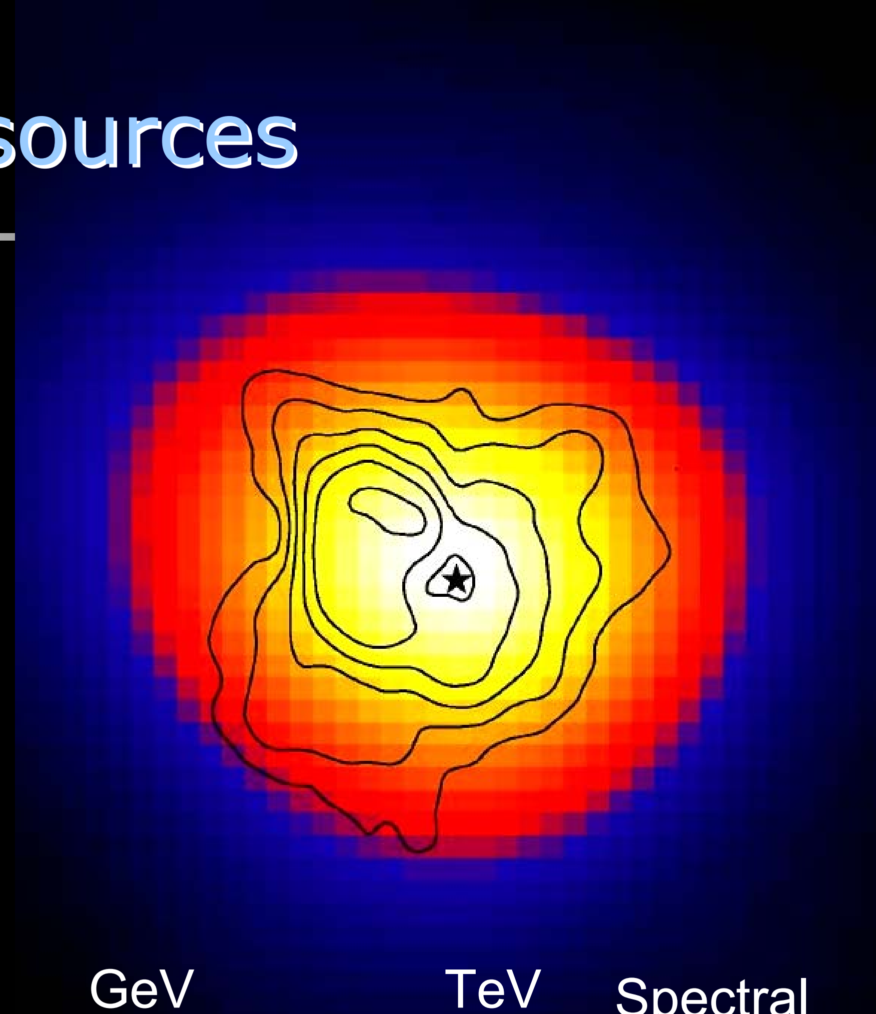
Identification of sources

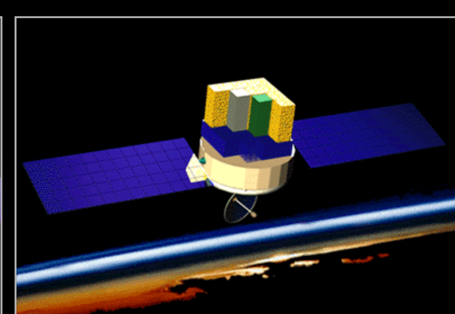
Source
- location,
- size,
- shape

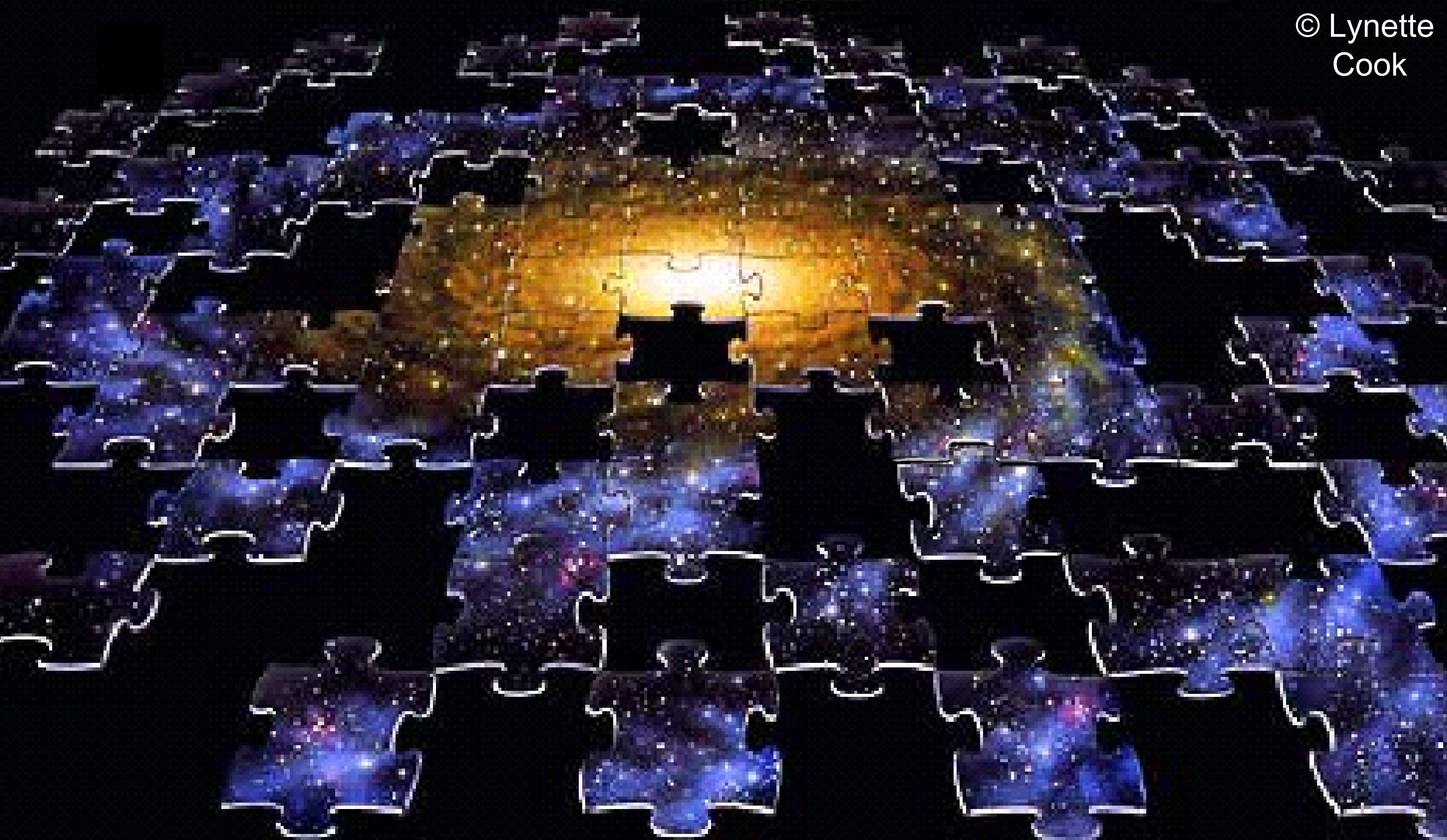
Variability of flux

keV MeV GeV TeV

Spectral information







H.E.S.S. Phase II