H.E.S.S.: Astrophysics above 10^{11} eV

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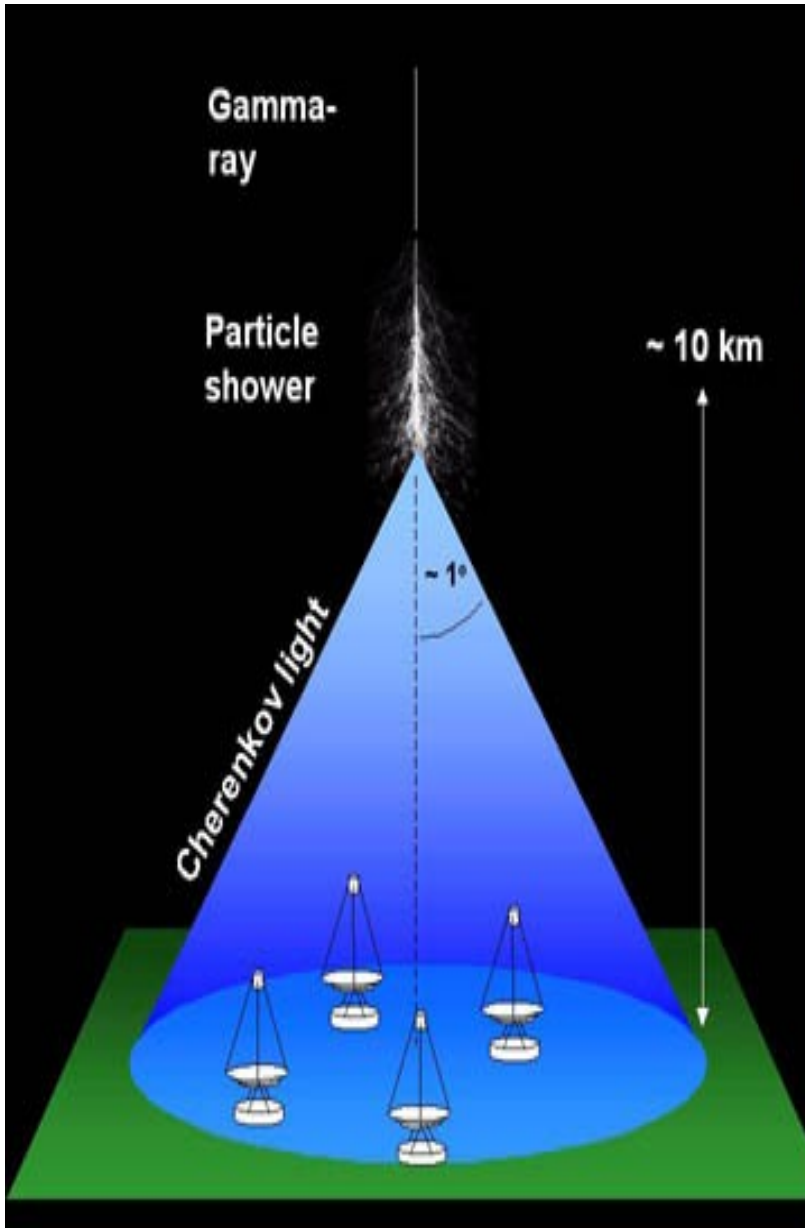
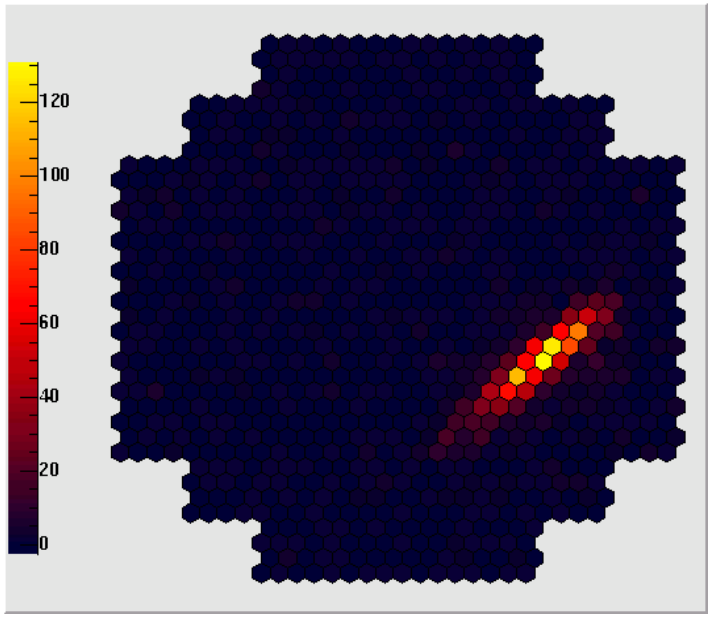
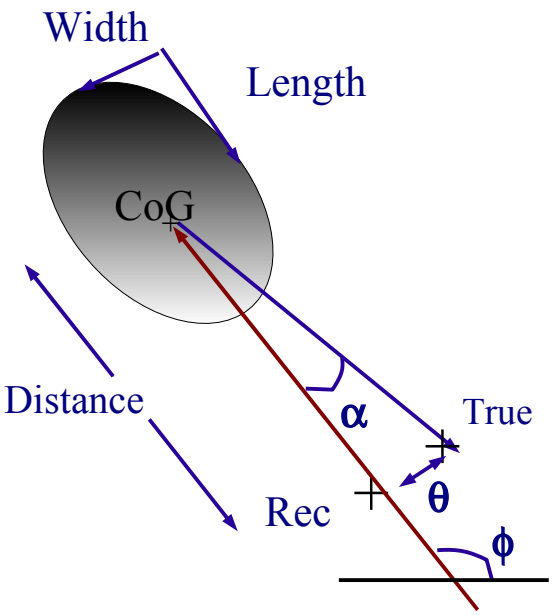
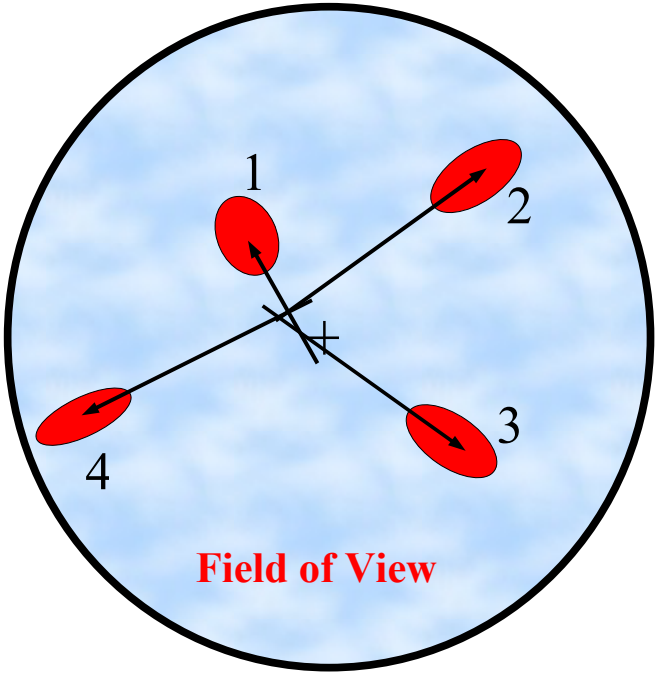
How does H.E.S.S. detect high-energy gamma rays?





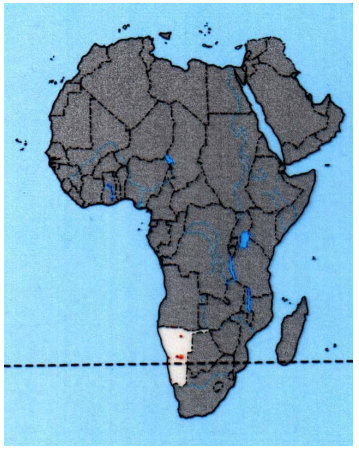




The H.E.S.S. Phase-I Telescopes

Location:

- Namibia (1800 m asl)



Telescope:

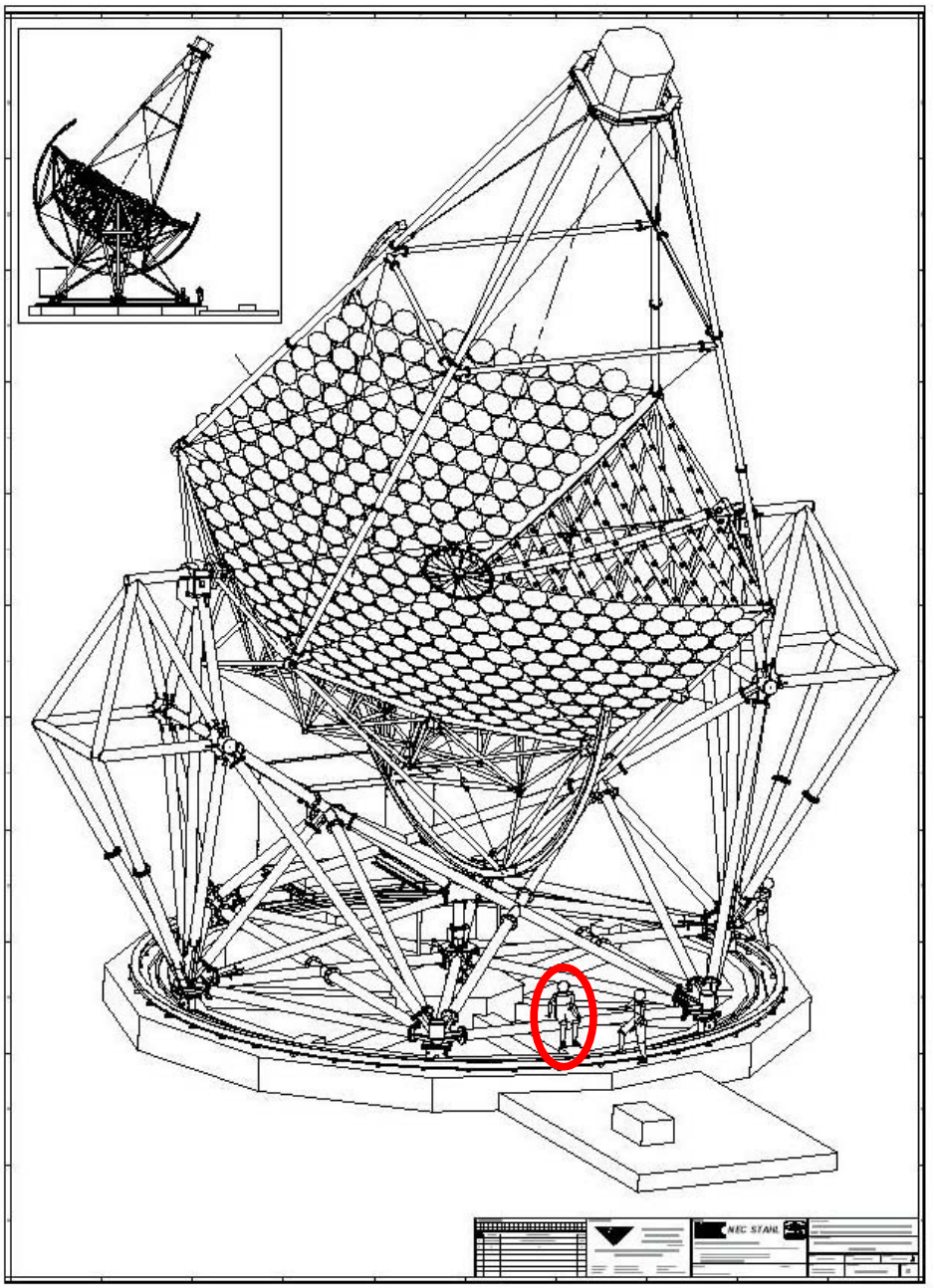
- Altitude-azimuth mount
- Davies-Cotton reflector
- Rigid steel structure
- Diameter: 12 m
- Focal length: 15 m (f/d ~1.2)
- **4 telescopes separated by 120 m**

Mirror:

- Mirror area ~107 m^2
- 380 individual mirrors (60 cm diameter)
- **Image of a star focused to 1/3 of camera pixel**

Central Trigger System:

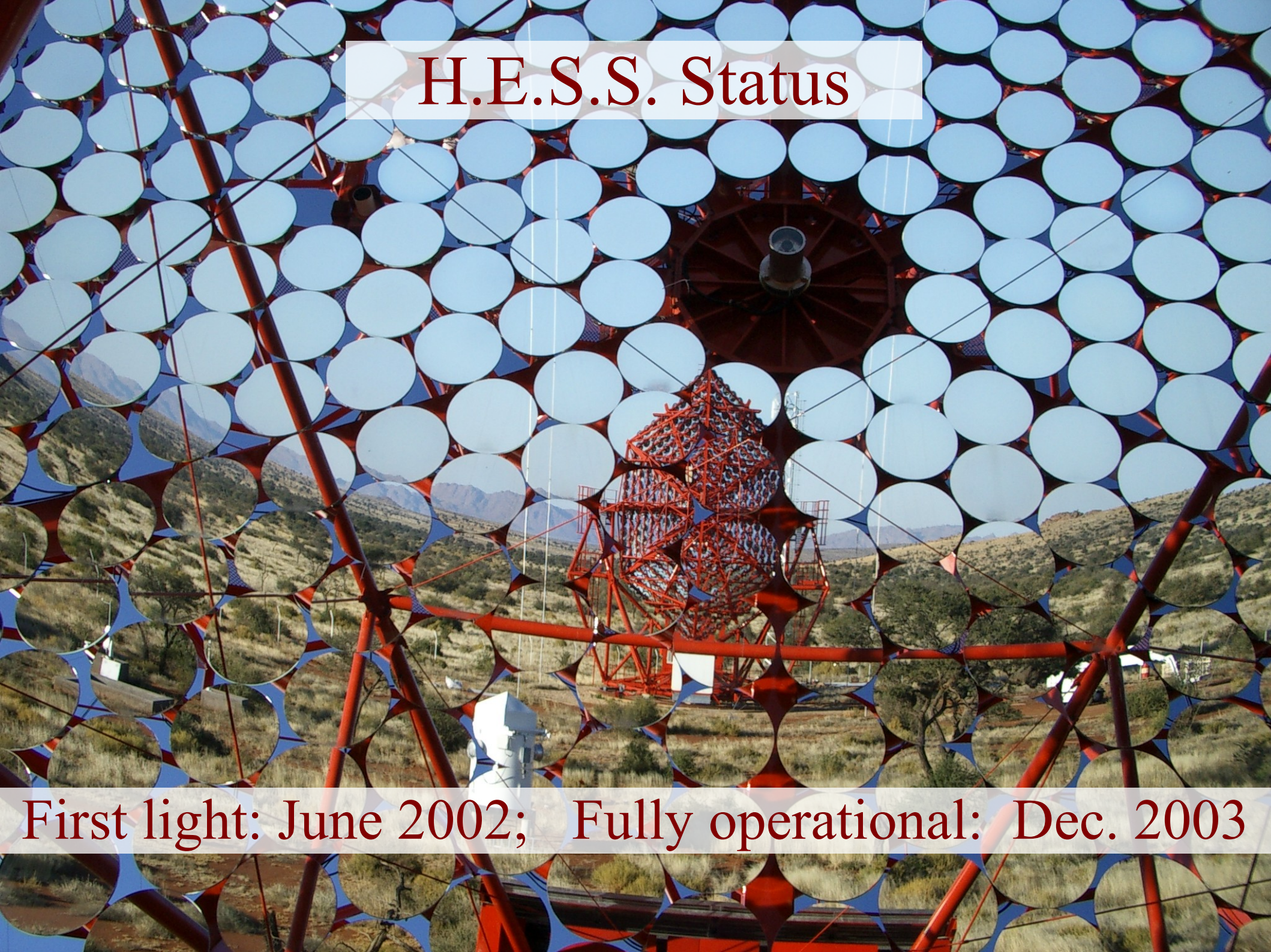
- **Require a 2-telescope conicidence**
  - Removes muons
  - Lower threshold
  - Enables stereoscopic techniques



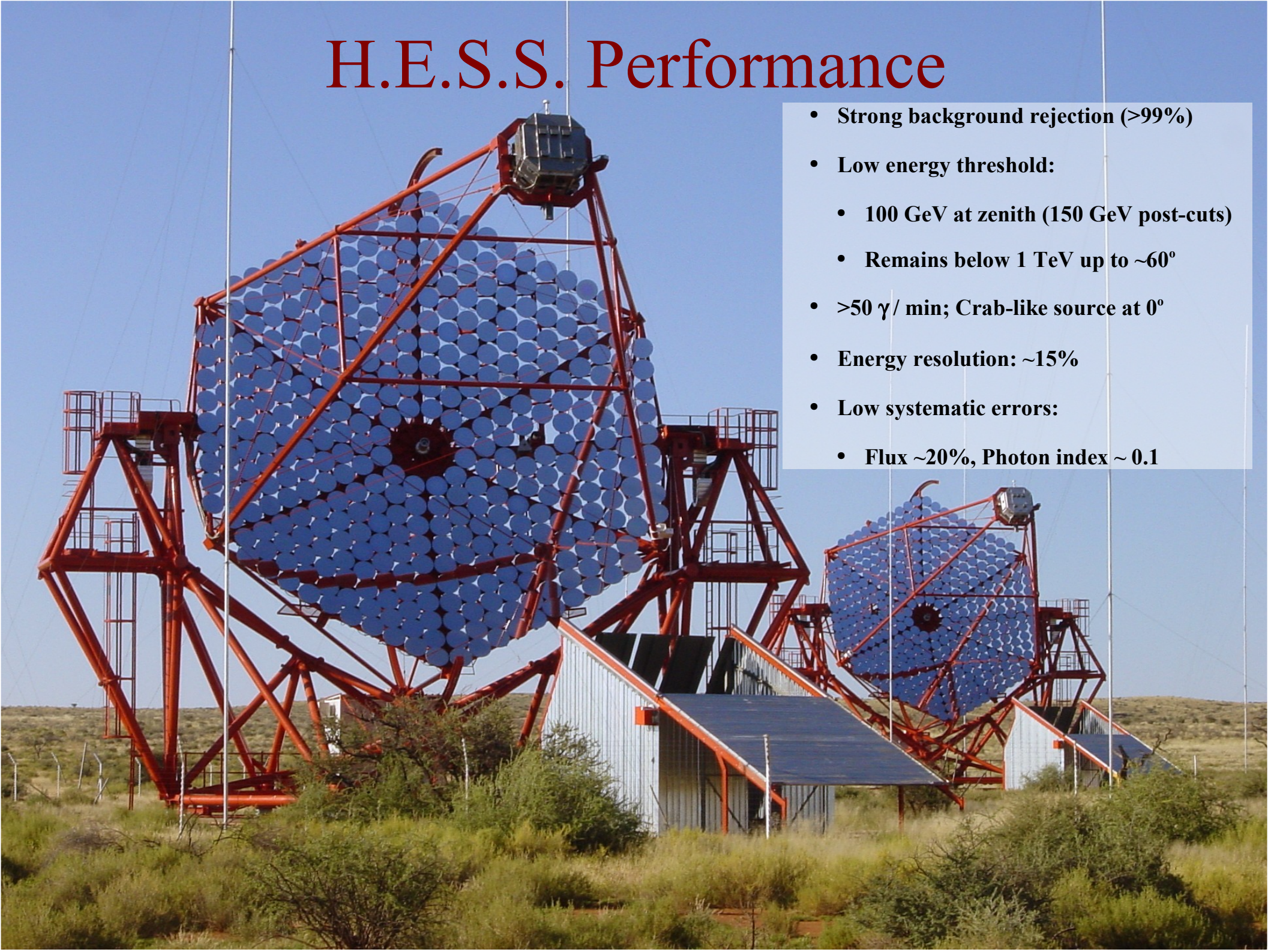
The H.E.S.S. Cameras

- 960 pixels of 0.16°
- 5° field of view (1.4 m)
- Readout integrated in camera body
- 16 ns integration, 1 GHz sampling

"Light in,
light out"

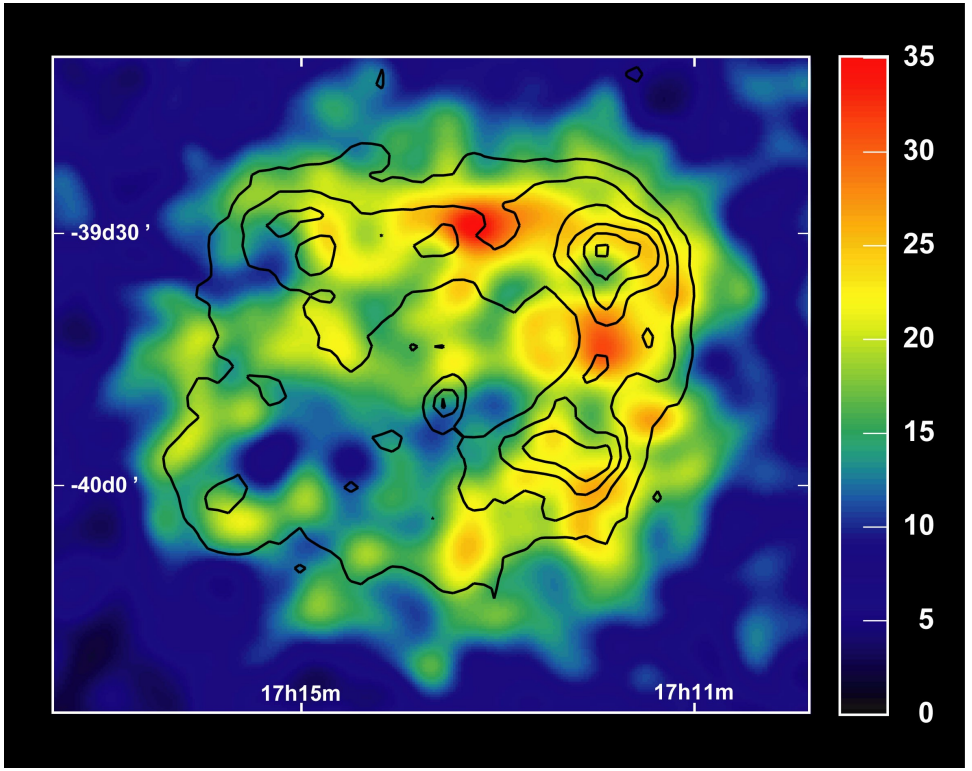

H.E.S.S. Status
First light: June 2002; Fully operational: Dec. 2003

H.E.S.S. Performance



- **Strong background rejection (>99%)**
- **Low energy threshold:**
  - **100 GeV at zenith (150 GeV post-cuts)**
  - **Remains below 1 TeV up to ~60°**
- **>50 γ / min; Crab-like source at 0°**
- **Energy resolution: ~15%**
- **Low systematic errors:**
  - **Flux ~20%, Photon index ~ 0.1**

H.E.S.S. Performance

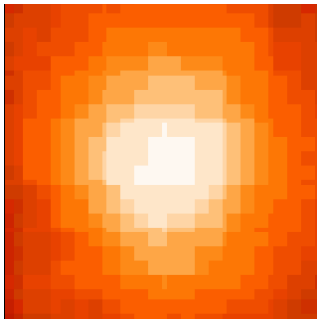


- **Small point spread function**
  - Width < 0.1°,
  - Comparable to ASCA
- **Large field of view (5°)**
- **Pointing error < 20"**
- **Great for surveys:**

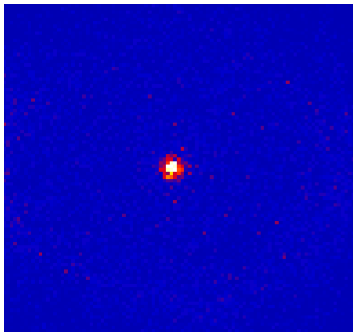
Aharonian et al., 2005, *Science*, **307**, 1938

Resolve γ-ray morphology of extended objects (e.g. SNR) like RXJ 1713.7-3946

Aharonian et al., 2004, *Nature*, **432**, 75



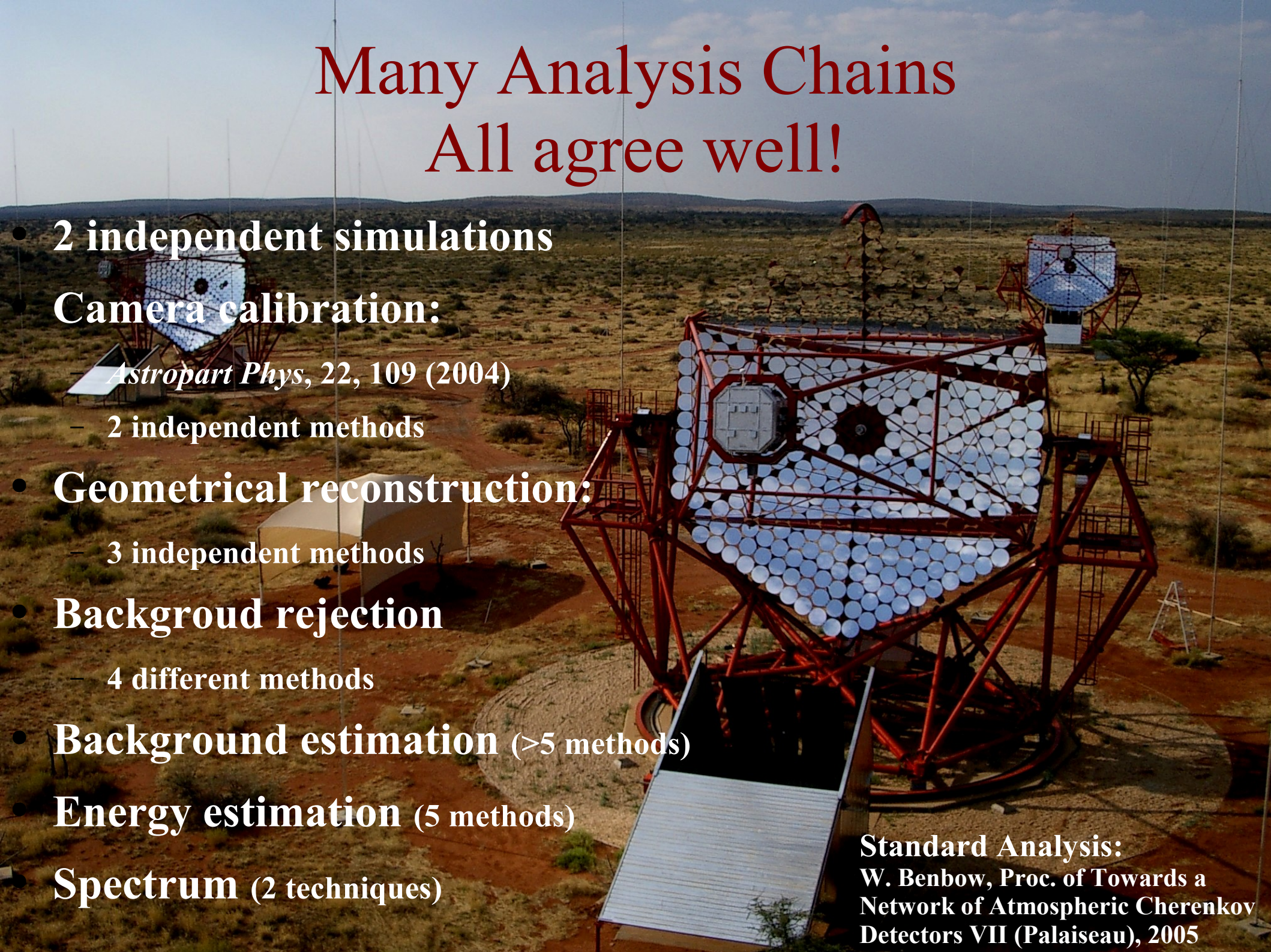
Crab with EGRET



Crab in TeV

Many Analysis Chains
All agree well!

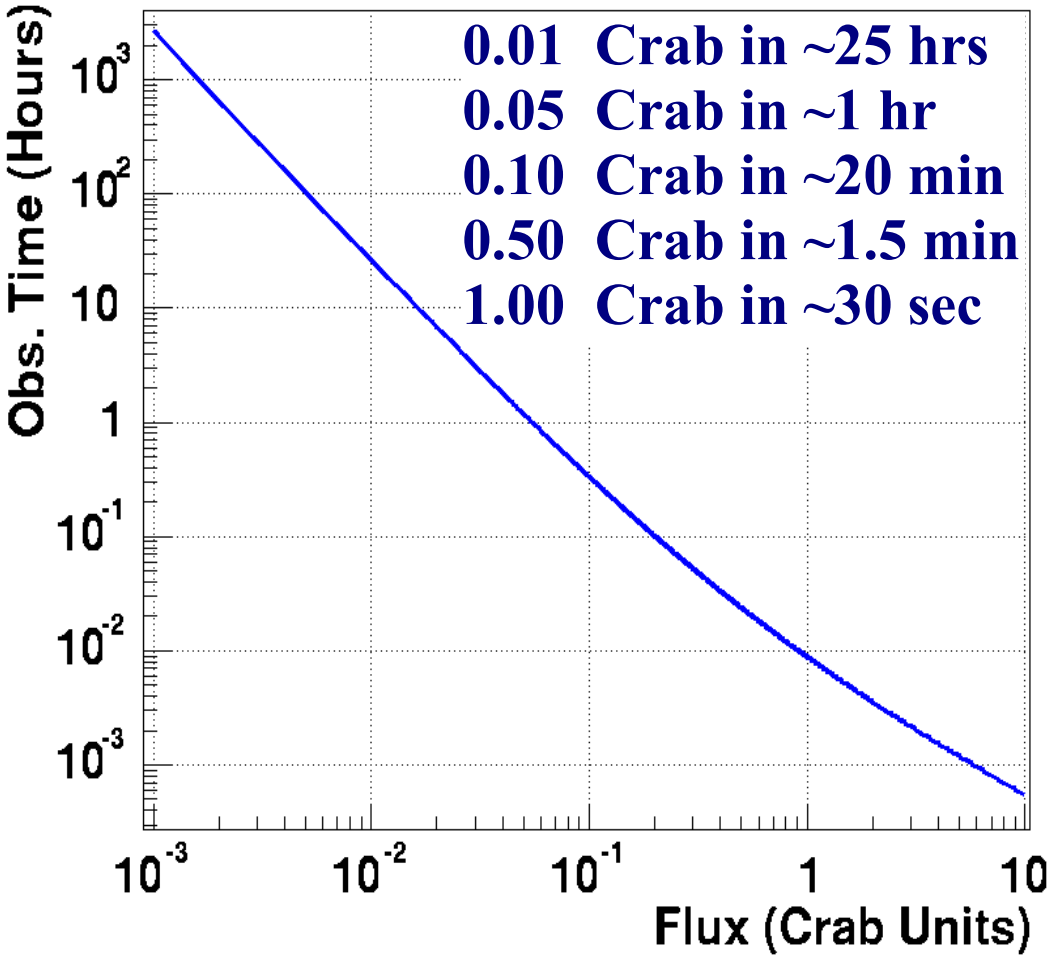
- **2 independent simulations**
- **Camera calibration:**
  - ***Astropart Phys*, 22, 109 (2004)**
  - **2 independent methods**
- **Geometrical reconstruction:**
  - **3 independent methods**
- **Backgroud rejection**
  - **4 different methods**
- **Background estimation (>5 methods)**
- **Energy estimation (5 methods)**
- **Spectrum (2 techniques)**



Standard Analysis:
W. Benbow, Proc. of Towards a Network of Atmospheric Cherenkov Detectors VII (Palaiseau), 2005

H.E.S.S. Sensitivity

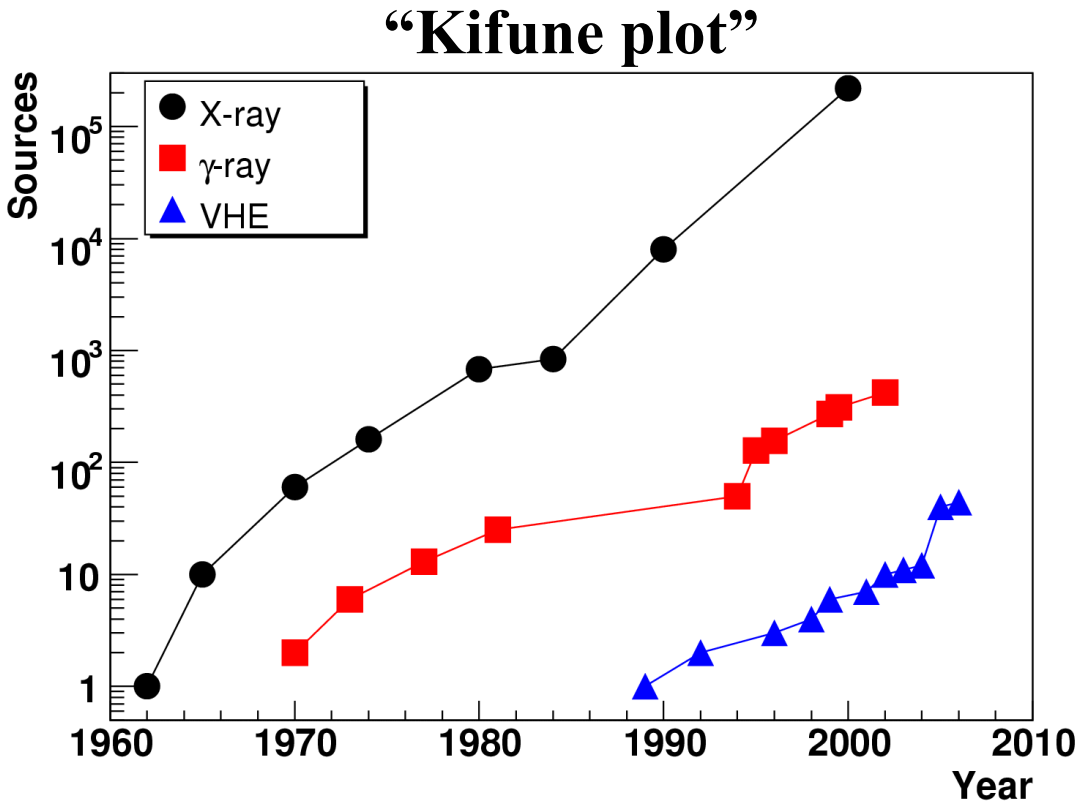
Time Required for a 5σ Detection at 20°



For comparison: HEGRA needed ~100 hrs to detect 5σ from a 5% Crab source

The Rapidly Increasing VHE Catalog

(& some shameless propaganda)



- 46 total VHE sources
  - 12 extragalactic (AGN)
- 37 are H.E.S.S. sources
  - 7 extragalactic (AGN)
- 30 are H.E.S.S. discoveries
  - 4 extragalactic (AGN)
- Many more to come....

30 scientific H.E.S.S. publications in refereed journals

3 Nature letters & 2 Science letters

www.mpi-hd.mpg.de/hfm/HESS/

H.E.S.S. Galactic Plane Scan

15 new VHE sources
+3 known

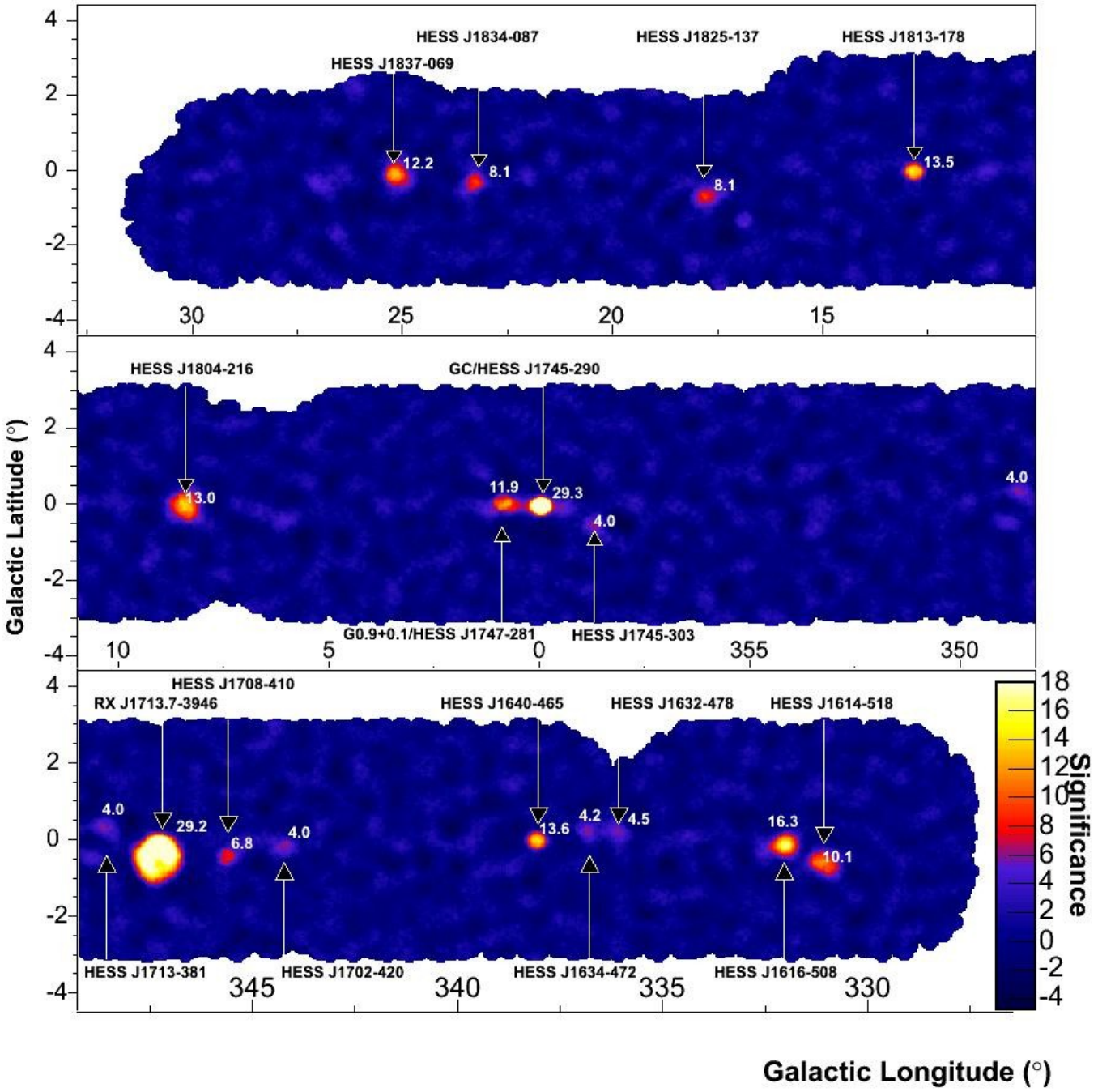
Science, 307, 1938 (2005)

- 8 sources (>6σ post-trials)

ApJ, 636, 777 (2006)

- 6 more sources (>4σ p.t.)
- For all 14 sources:
  - Spectra
  - Location
  - Size
  - Morphology
  - Counterpart searches

All sources seen in 2005 re-observations



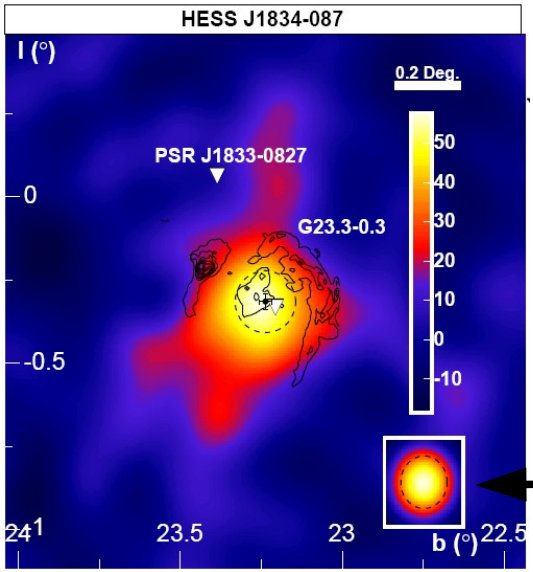
Scan extended in 2005/2006 ($-90^\circ < l < 60^\circ$)

New Source Characteristics

All within 1° of Galactic Plane

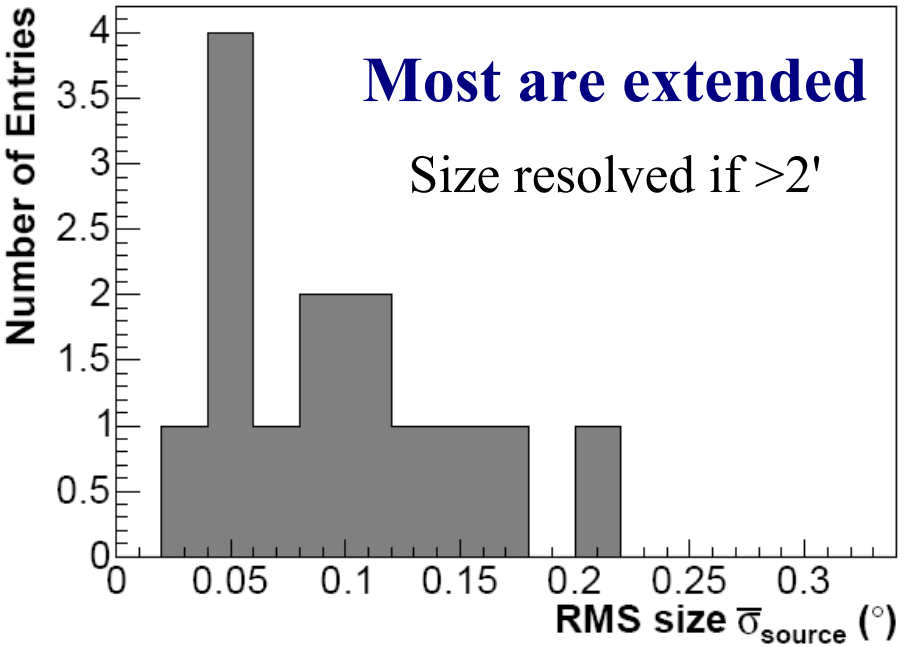
What are they?

- 5 sources could be associated with SNR, e.g. HESS J1834-087
- 3 could be pulsar wind nebulae, typically displaced from the pulsar
- Some coincide with EGRET, ASCA, ... unidentified sources
- 3 have no known counterpart



"Beam" size

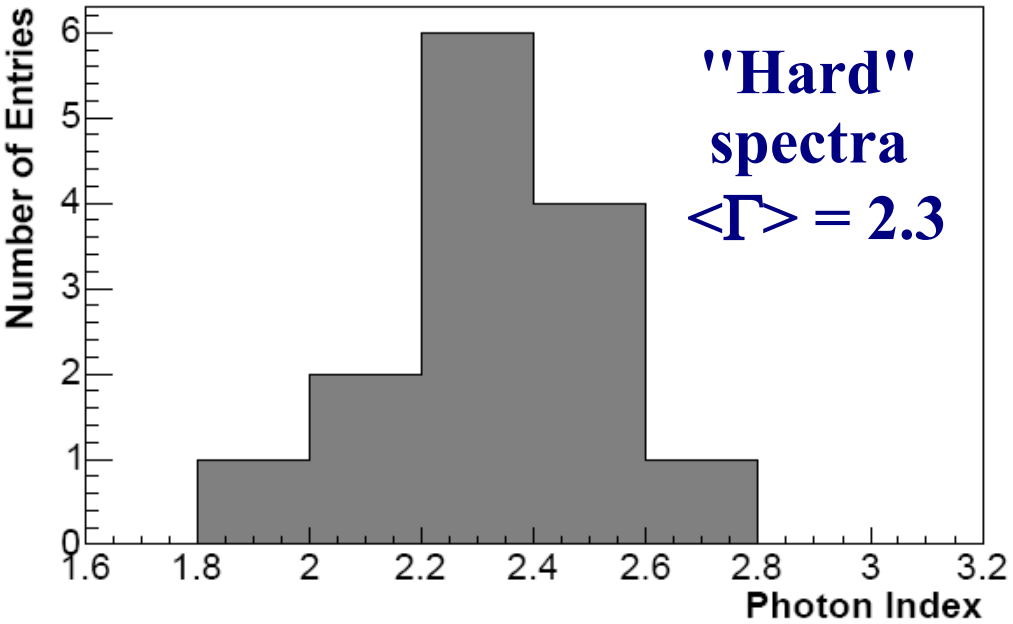
Source Size Distribution



Most are extended

Size resolved if >2'

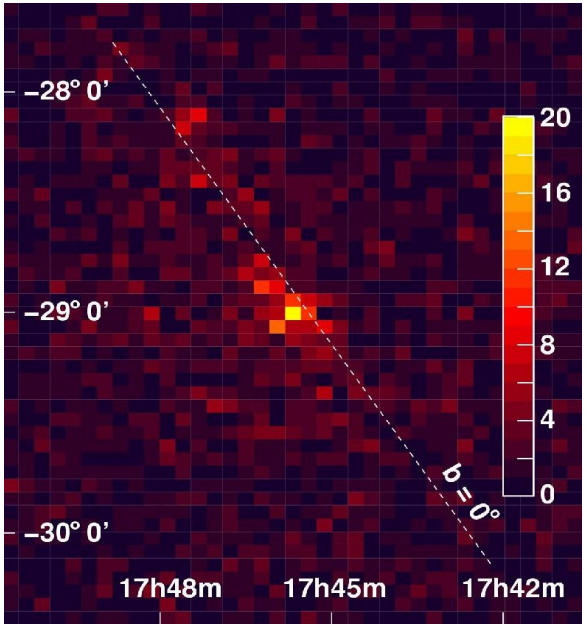
Fit Photon Index Distribution



"Hard" spectra

<Γ> = 2.3

The Galactic Center

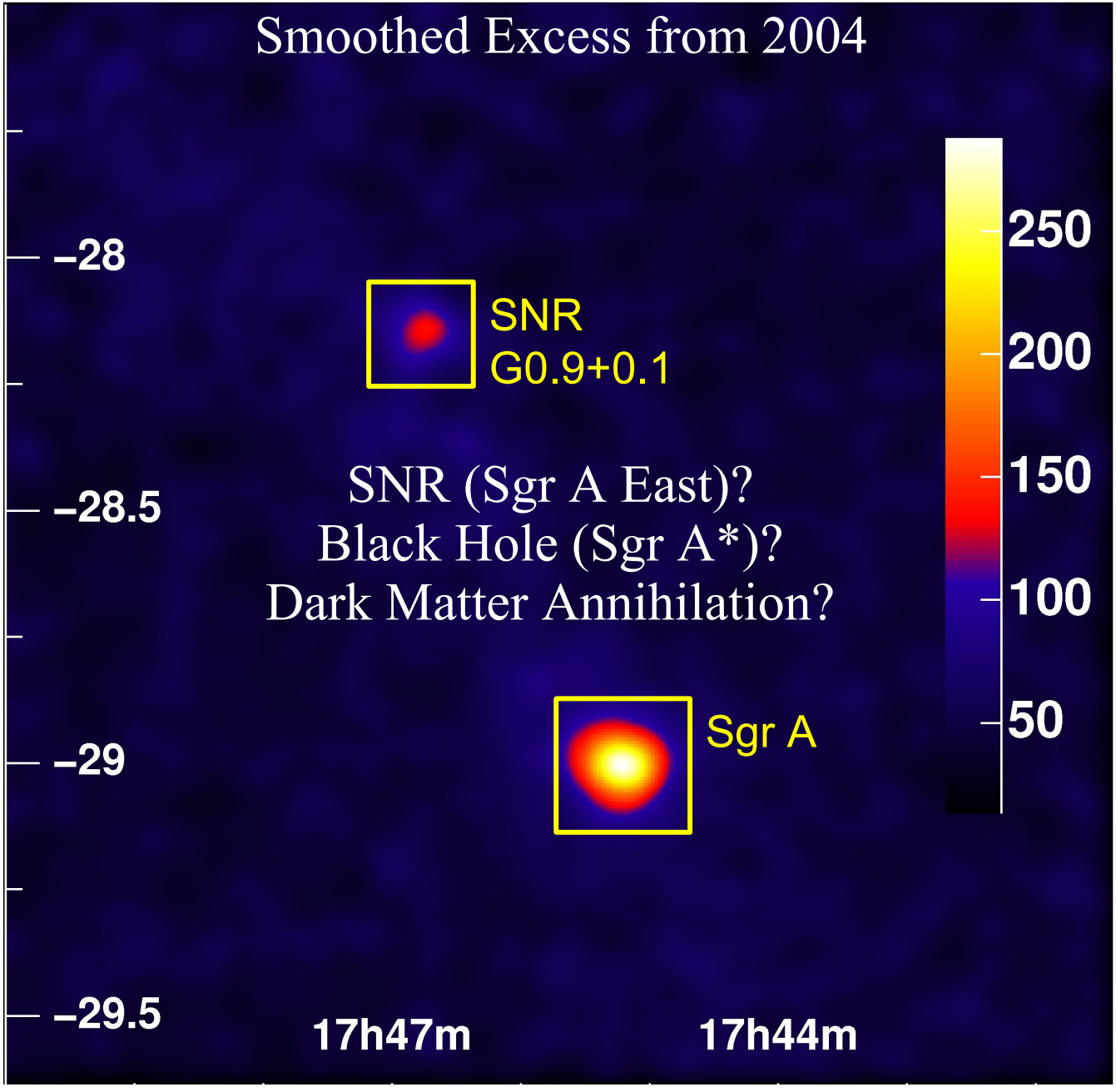


2003: 17 hrs of 2-tel data
A&A, 425, L13, 2004

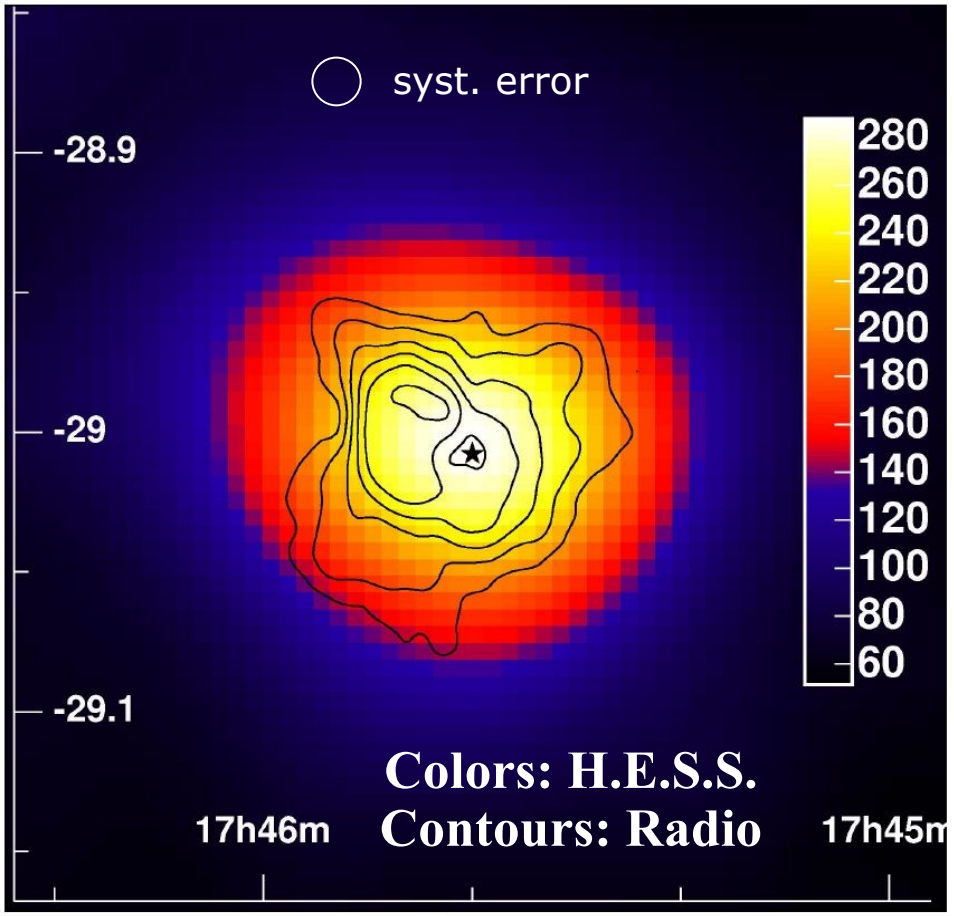
2004: 50 hrs of 4-tel data

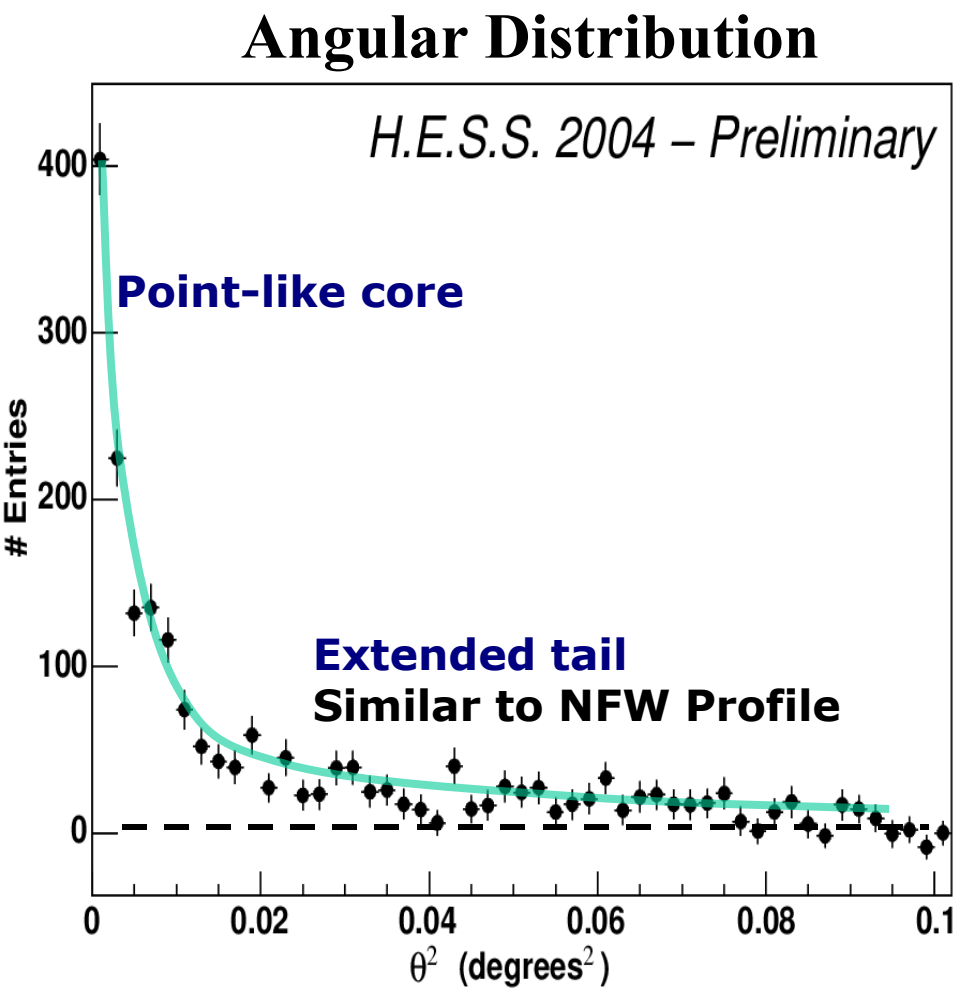
2005: ~65 hrs of data

2006: ~5 hrs so far



HESS J1745-290

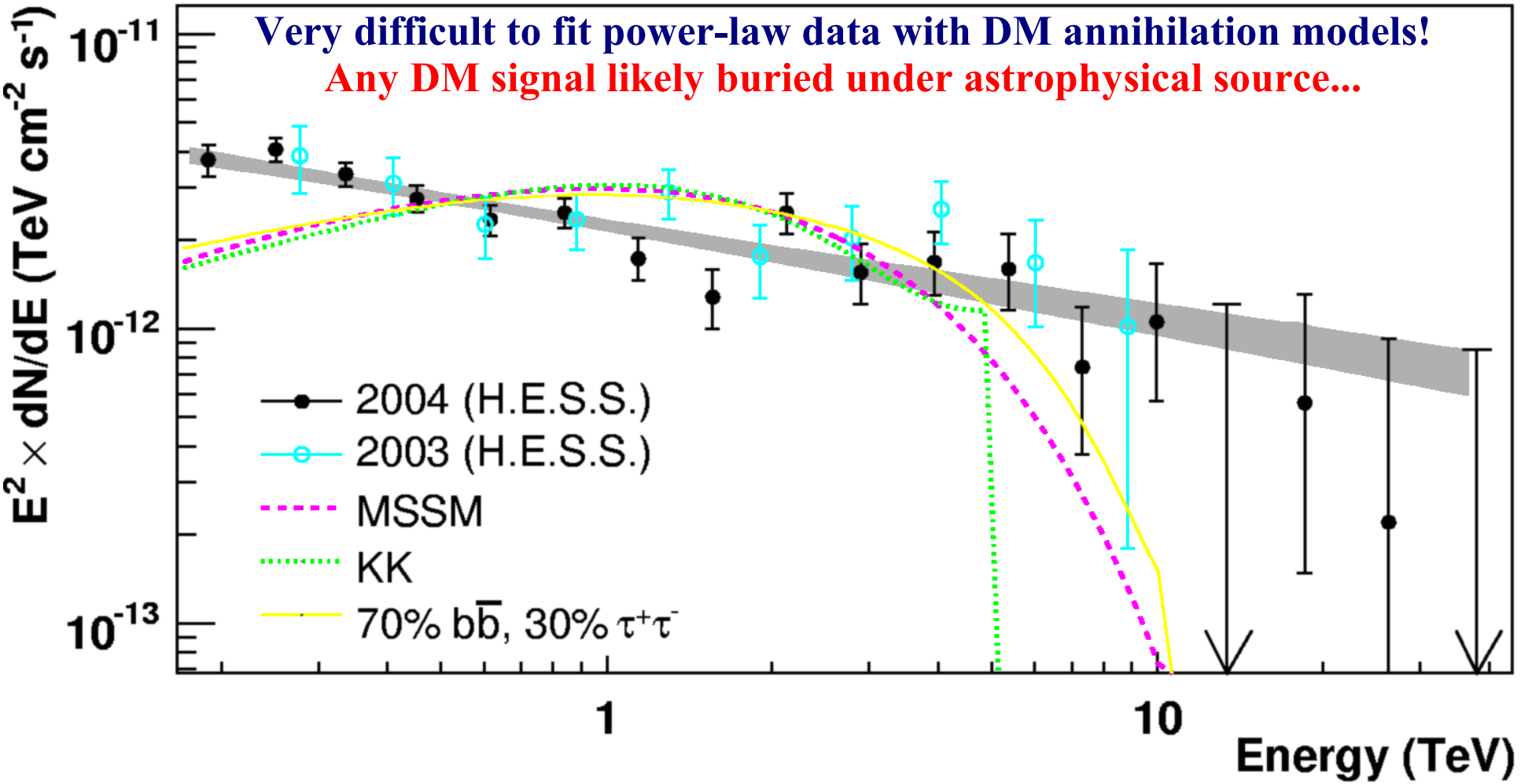




Difficult to discern whether excess is from SNR or Sgr A* based on location

The angular distribution looks like something one might see from DM

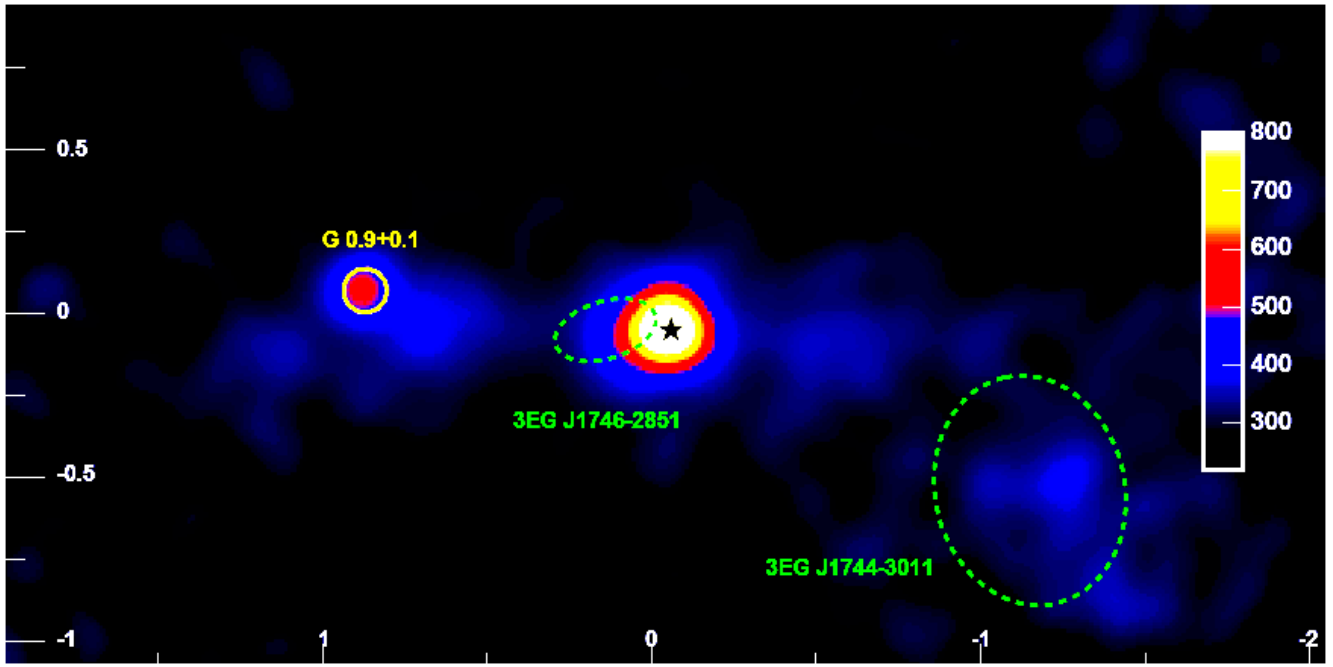
Is it Dark Matter or Astrophysics?



No flux/spectral variability seen on any time-scale (years to minutes)!

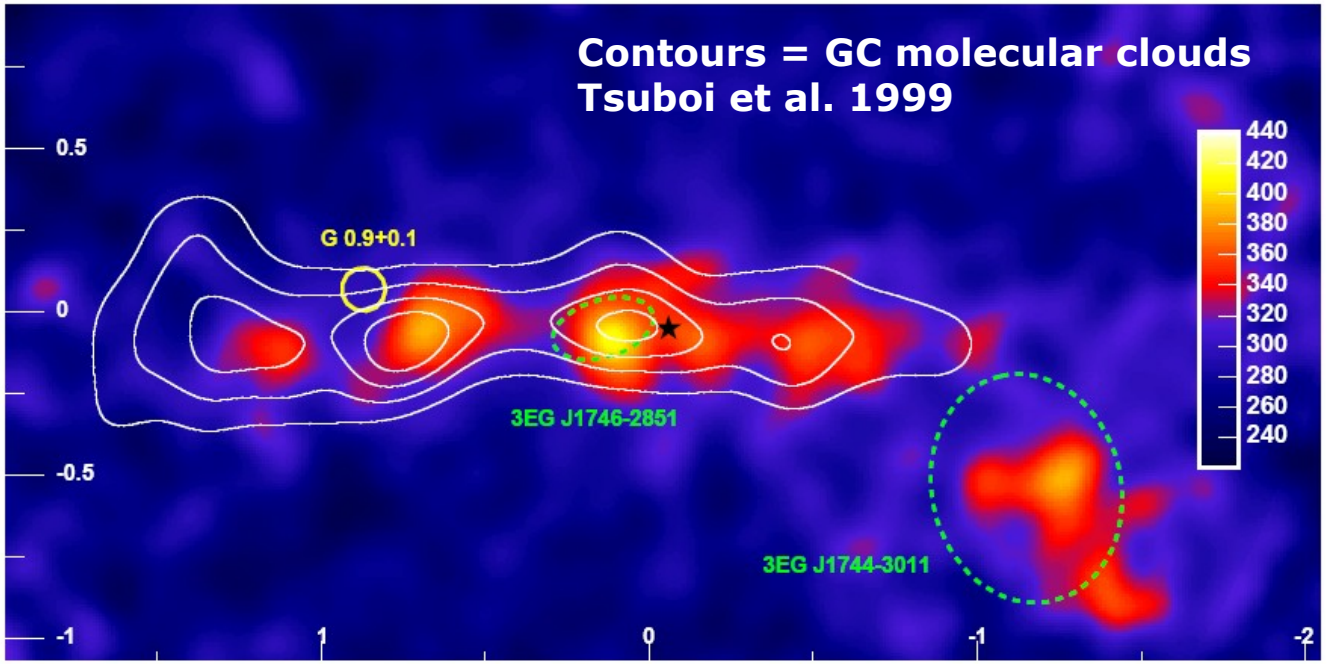
Sgr A* never flared in X-rays while we were looking!

Discovery of Diffuse VHE Emission



H.E.S.S. Excess Map in GC Region (zoom in z-scale)

Nature, 439, 695 (2006)



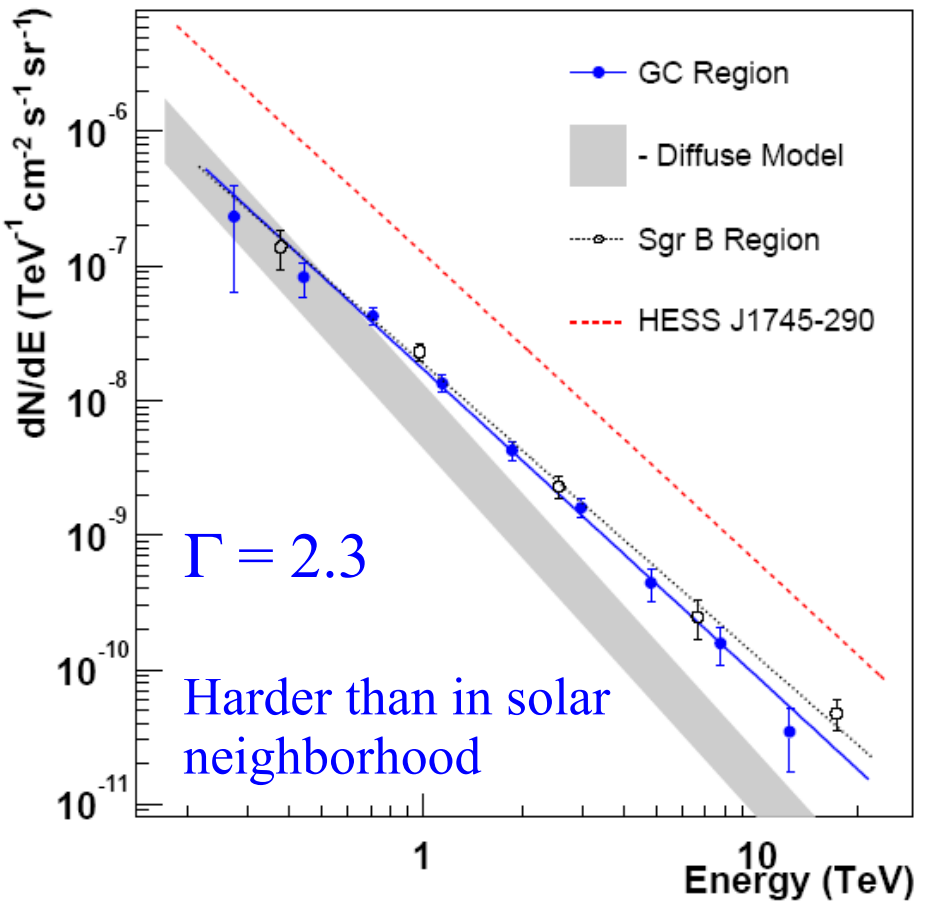
H.E.S.S. Excess Map in GC Region with HESS J1745 & G 0.9+0.1 Signals Subtracted

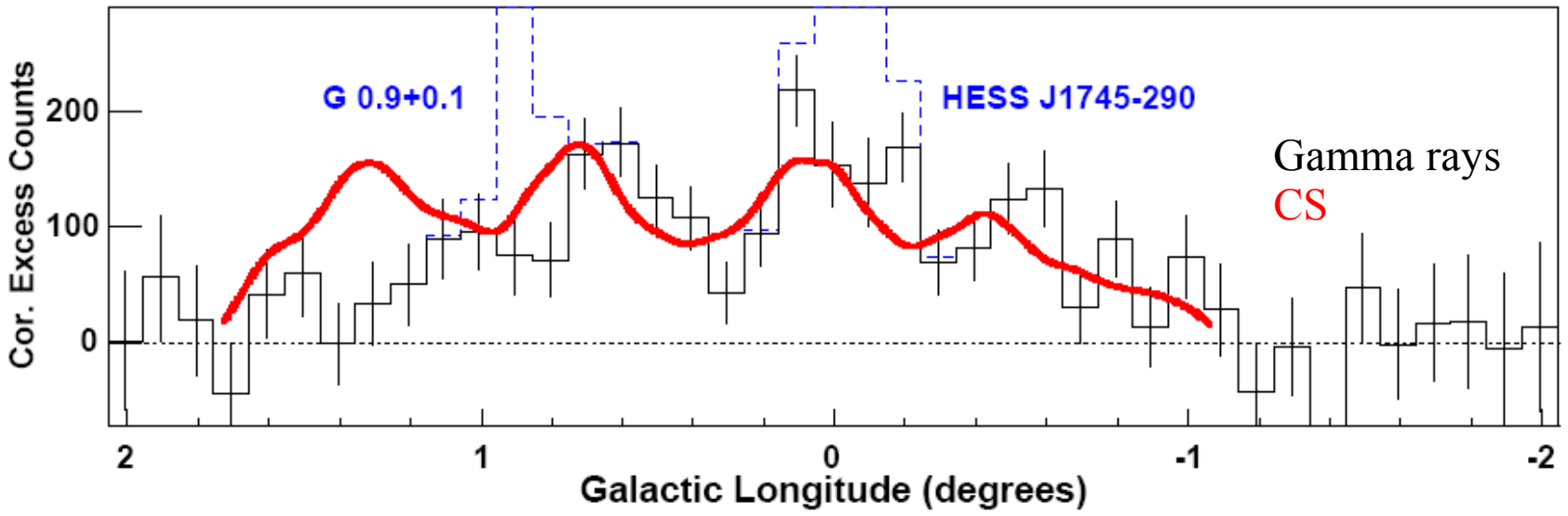
VHE Diffuse Emission

Good correlation of diffuse H.E.S.S. excess & molecular clouds

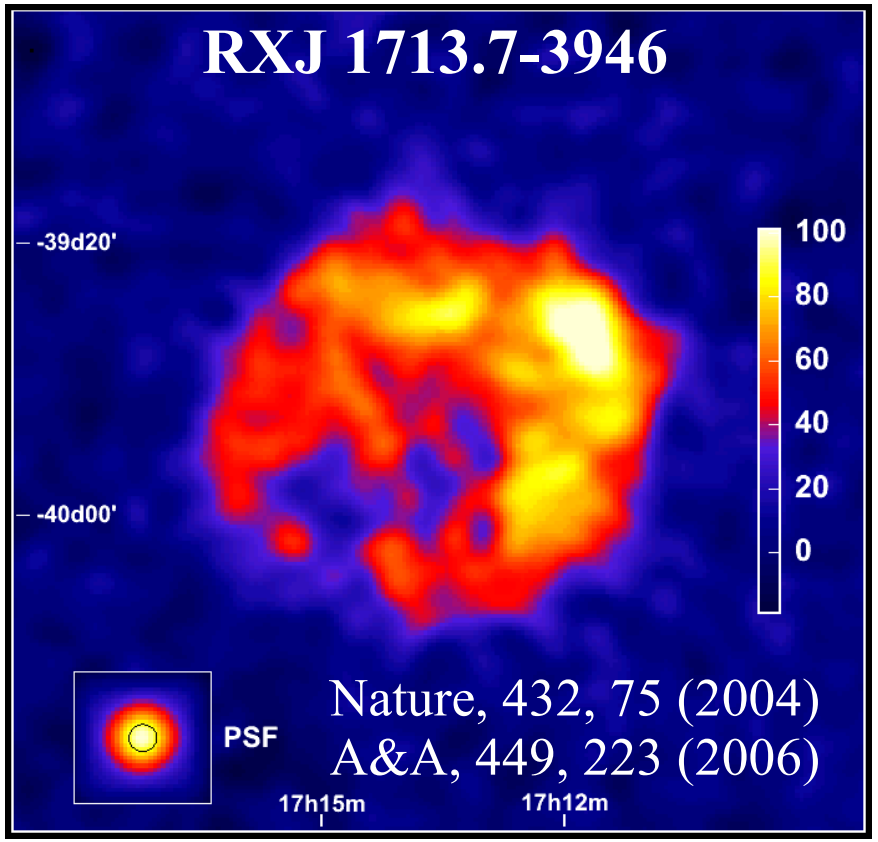
Correlation implies cosmic rays interacting with molecular clouds

The hard spectrum & morphology suggests recent (~10^4 year) CR acceleration close to the G.C.

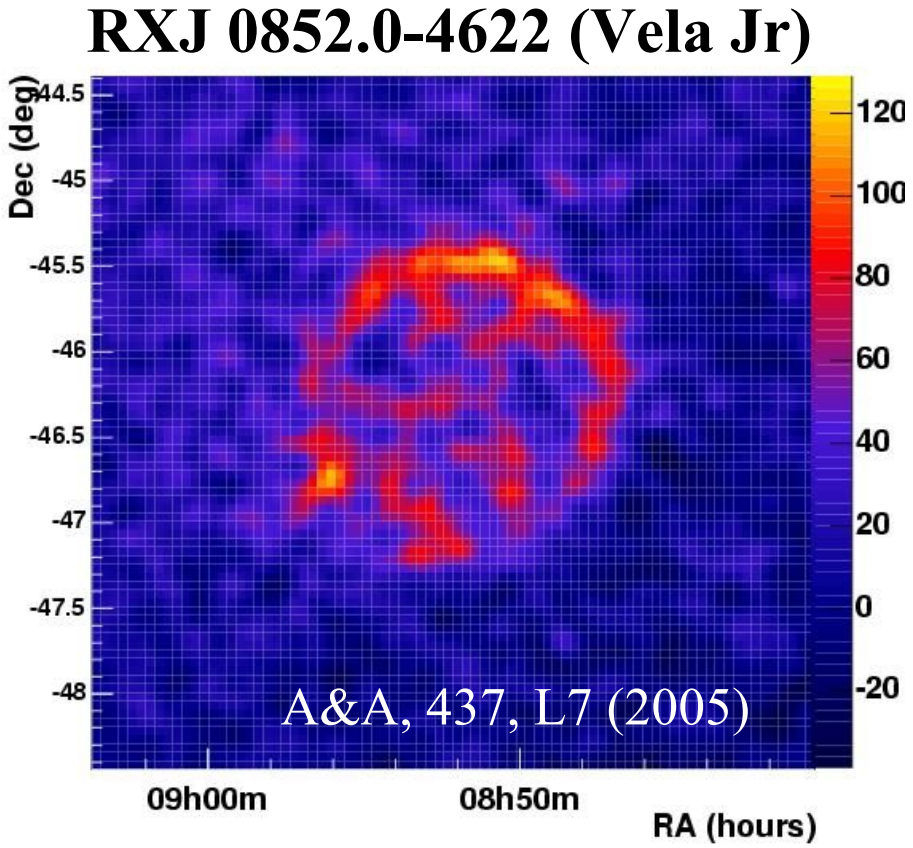




1st Resolved Supernova Remnants



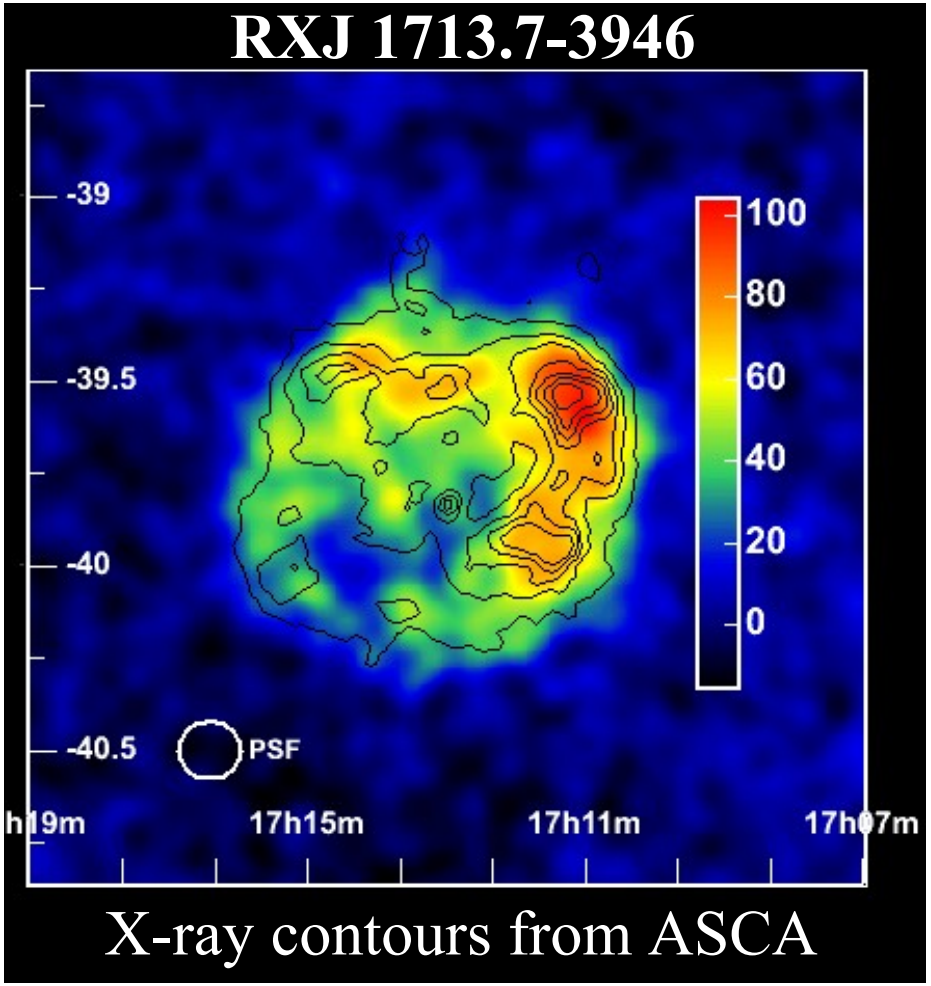
Age: ~1000 yrs
Distance: ~1 kpc
Radius: 0.5° (shell ~55%)

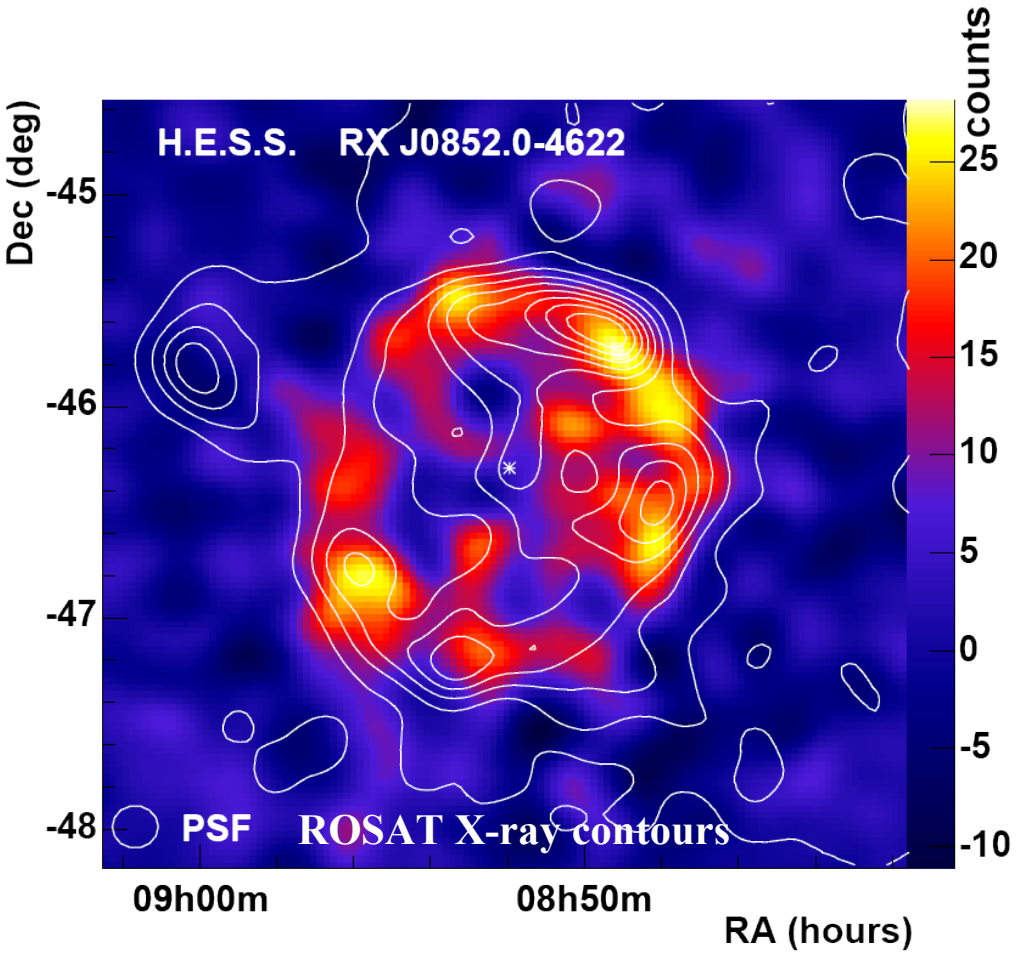


Age: ~700 yrs
Distance: 0.2 - 1 kpc
Radius: 1° (shell <22.5%)

At least 4 other SNR identified in H.E.S.S. Galactic Plane scan:
Too small to resolve shell-type features

Correlation of X-rays & VHE γ-rays

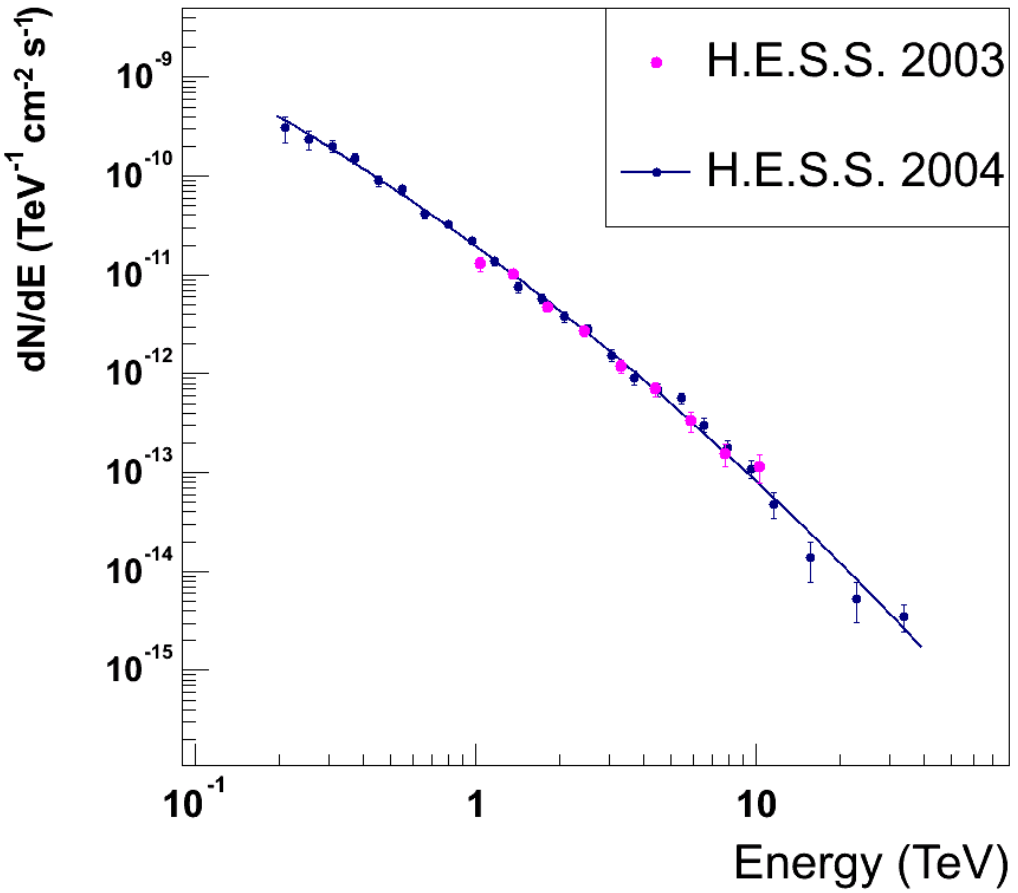




Correlation is very good for both SNR:
R ~ 0.7 for 1713 & R ~ 0.8 for "Vela Jr"

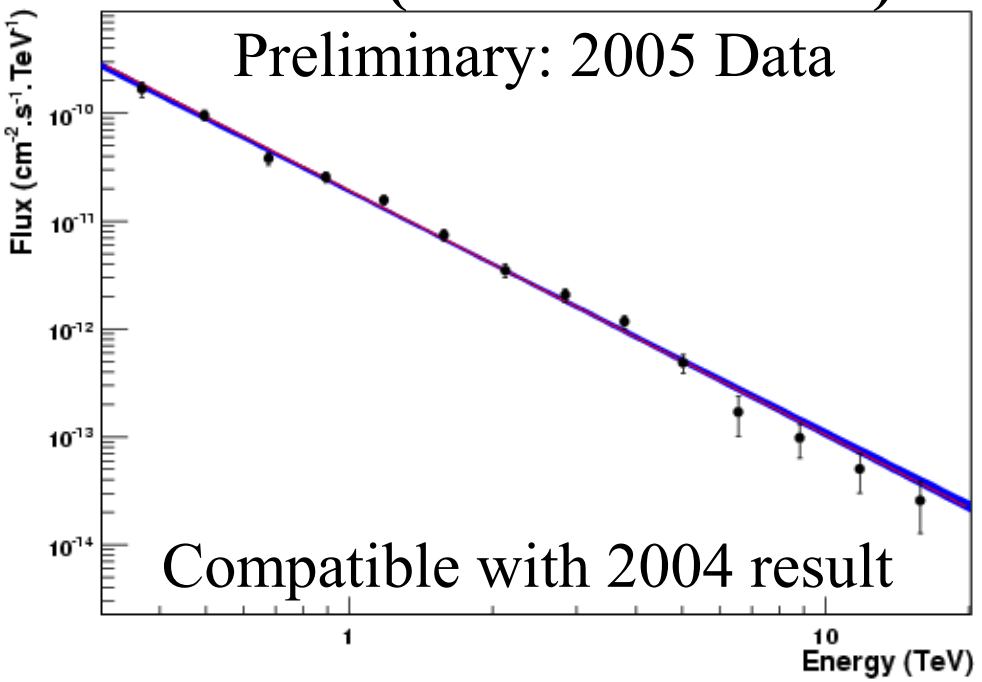
Similar Spectra for Both SNR

RXJ 1713.7-3842



Fit range: 190 GeV to 40 TeV
Photon index: $1.98 \pm 0.05 \pm 0.15$
Cutoff energy: 12 ± 2 TeV
Flux (>1 TeV): ~0.7 Crab

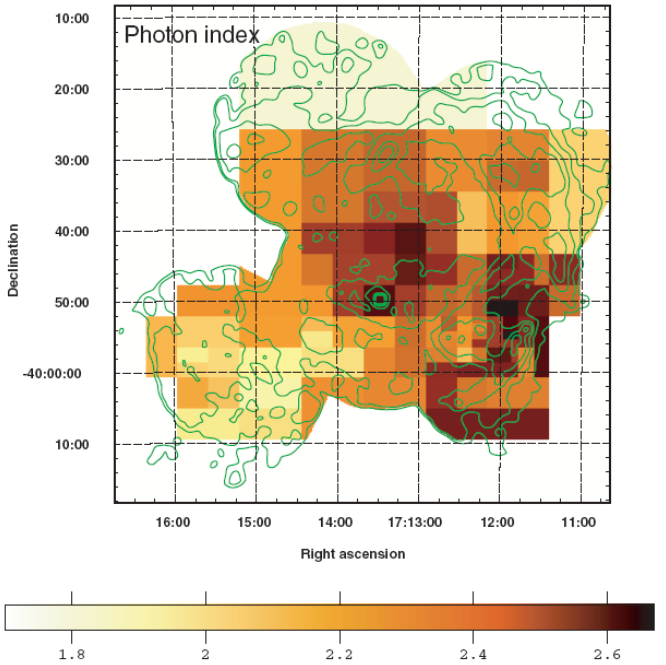
Vela Jr (RXJ 0852.0-4622)



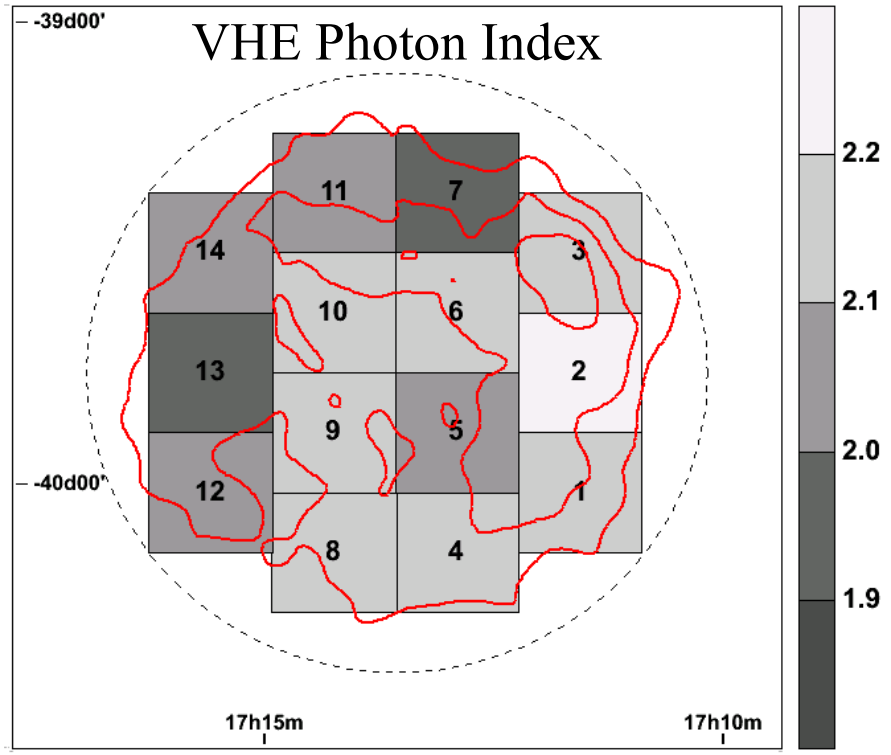
Fit range: 300 GeV to 20 TeV
Photon index: $2.24 \pm 0.05 \pm 0.15$
Indications for a cutoff
Flux (>1 TeV): ~0.7 Crab

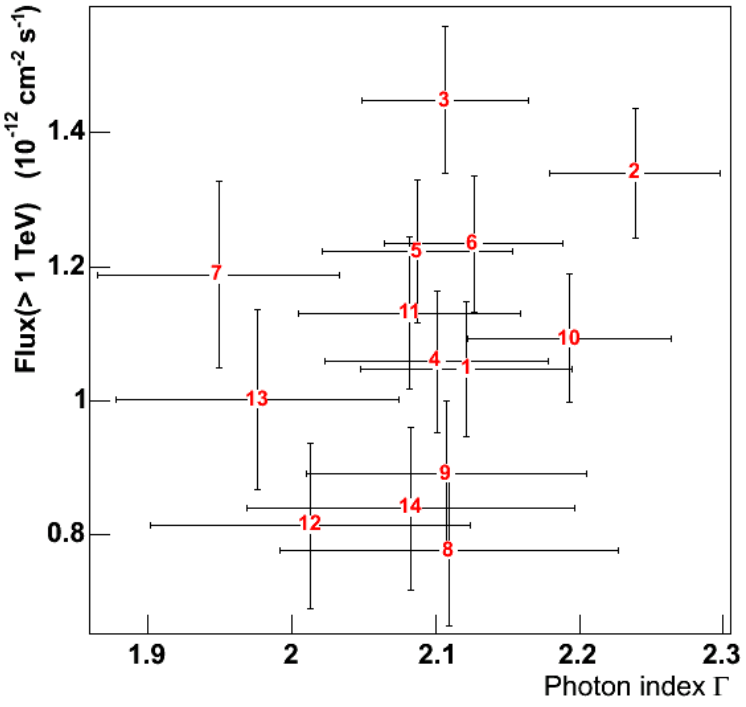
RXJ 1713: Spatially Resolved Spectra

- No significant change of the spectral shape from one region to another in TeV
- Significant changes of the spectral index observed in X-rays
- **VHE morphology does not change with energy, whereas X-ray morphology does**

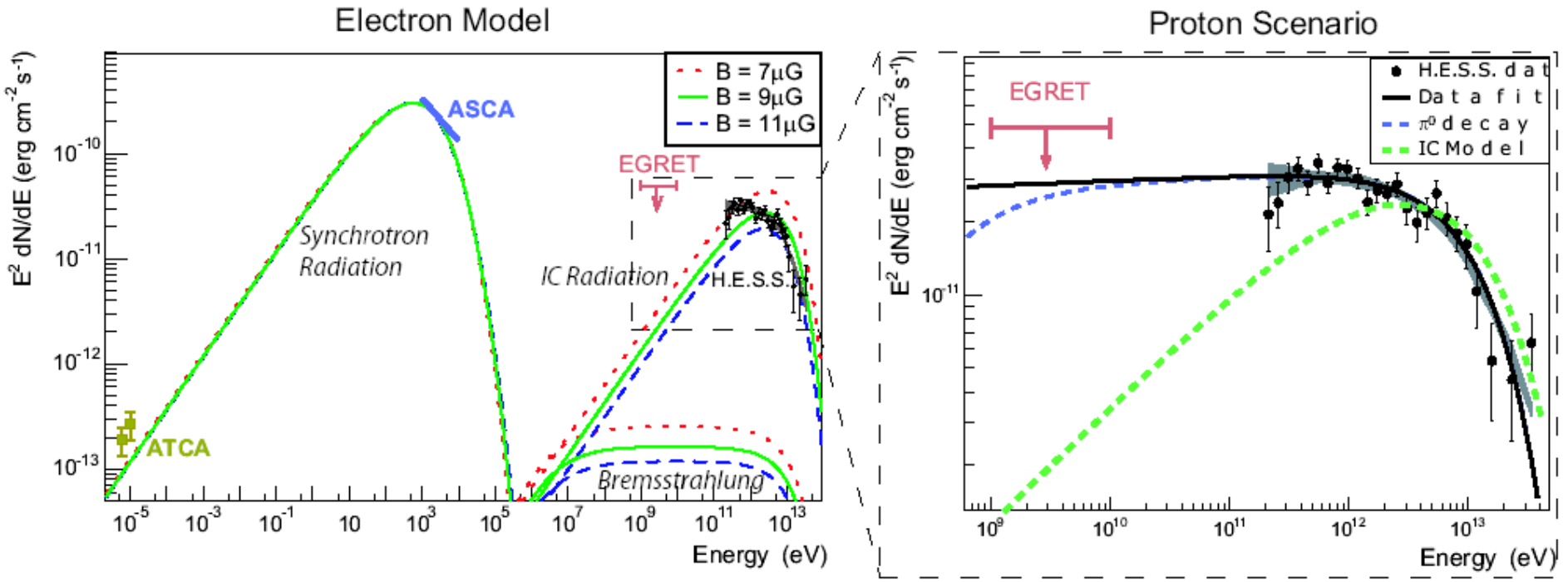


X-ray photon index (XMM)
A&A 427, 199 (2004)





Modelling of RXJ 1713



Leptonic model: difficult to fit SED using "simple" inverse-Compton models

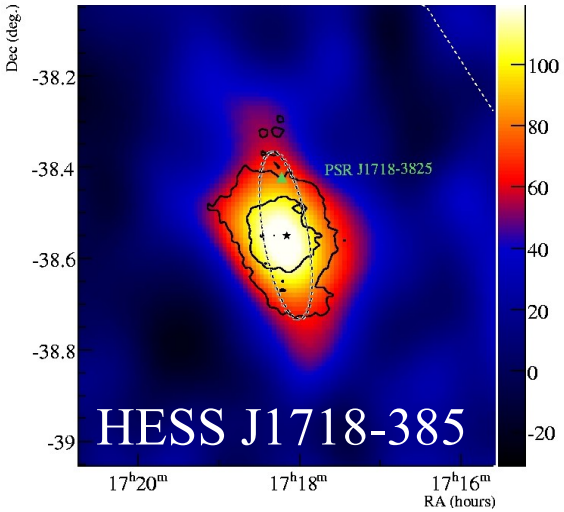
Hadronic model: Works much better, but need lower E observations (i.e. GLAST)

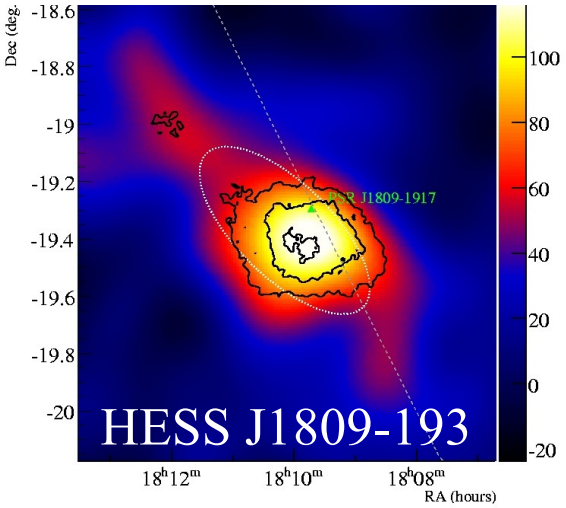
If could "prove" hadronic model => SNR are a source of cosmic rays

Similar modelling of Vela Jr complicated due to poorly measured distance

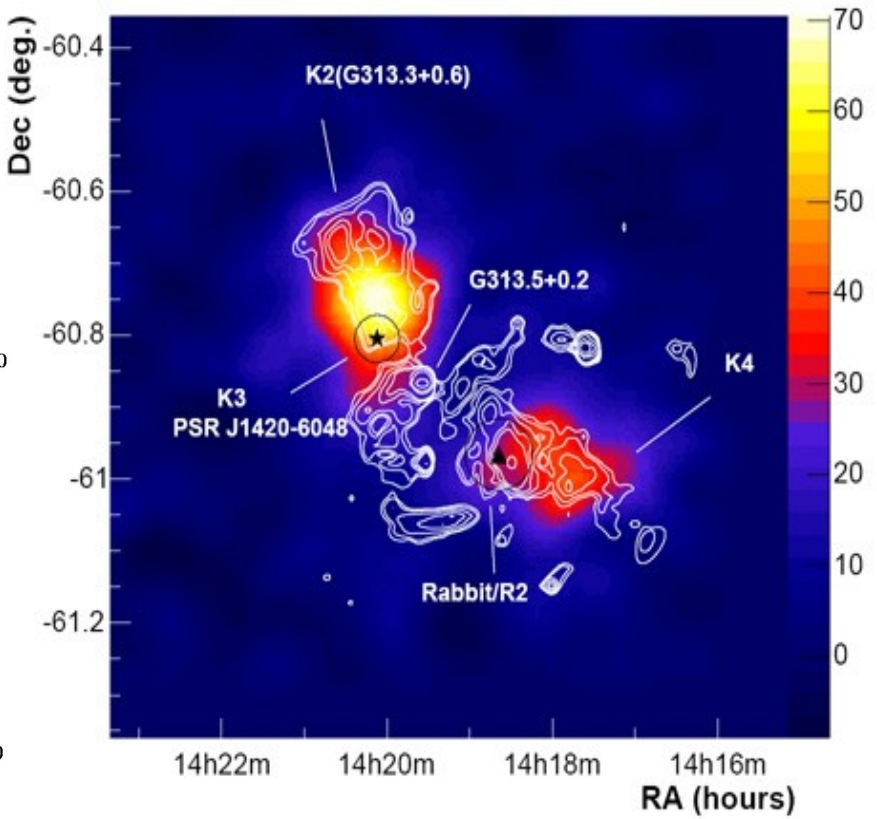
10 Pulsar Wind Nebulae

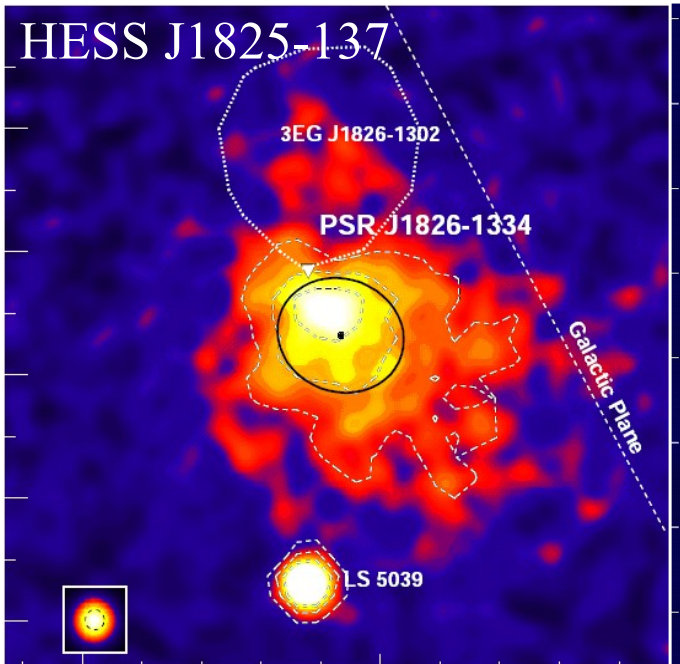
- **7 of 10 are extended & offset from pulsar**
  - Point-like not shown: Crab, G0.9+0.1, PSR B1259-63
- **All are X-ray/γ-ray sources: Good correlation**

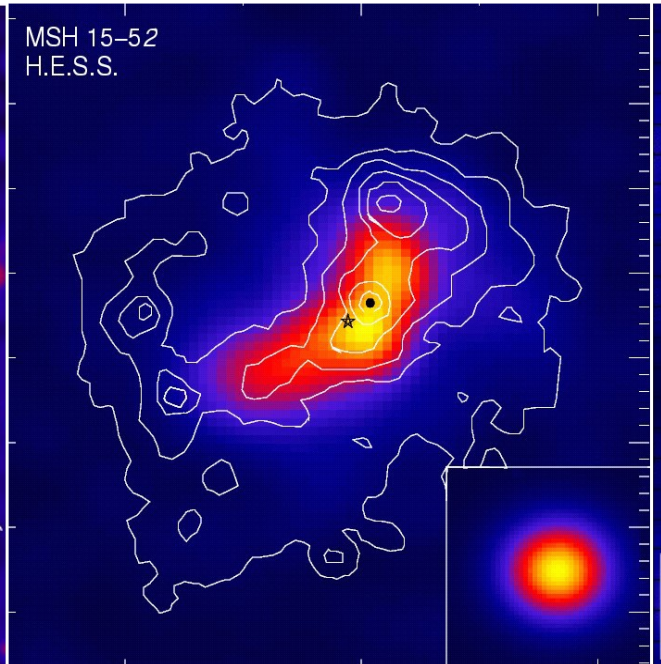


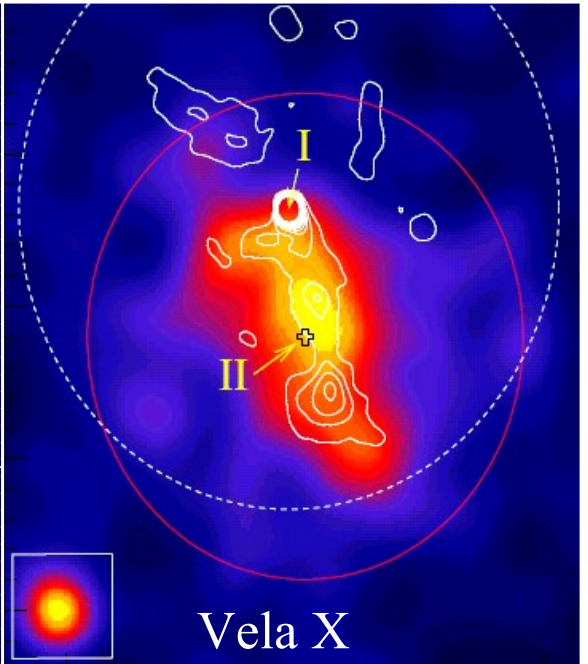


The Kookaburra

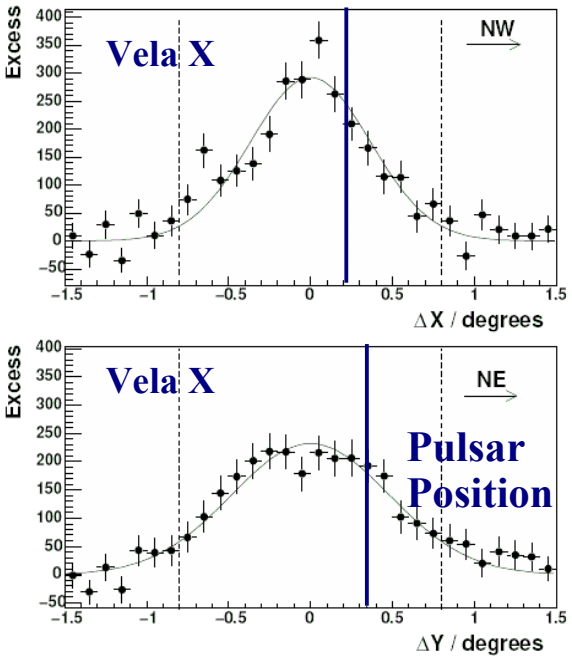


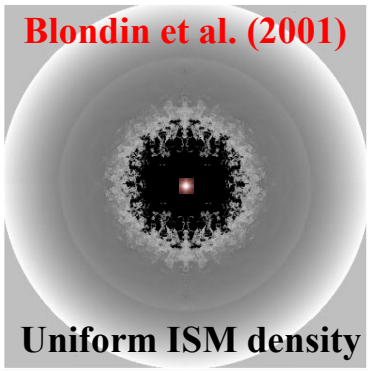


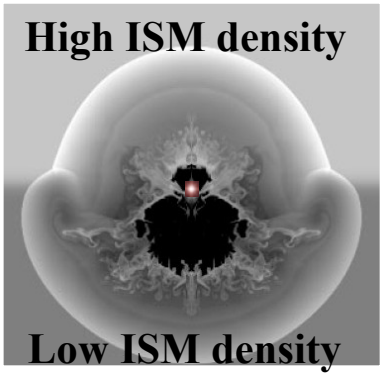


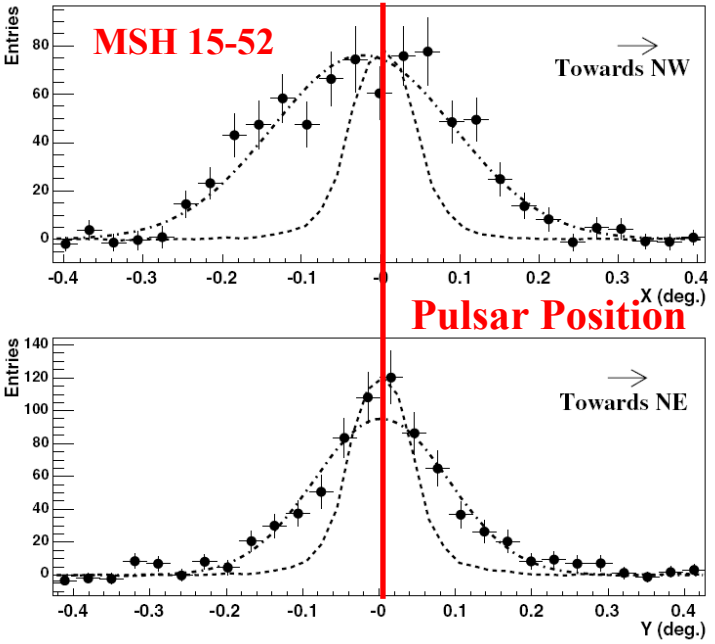


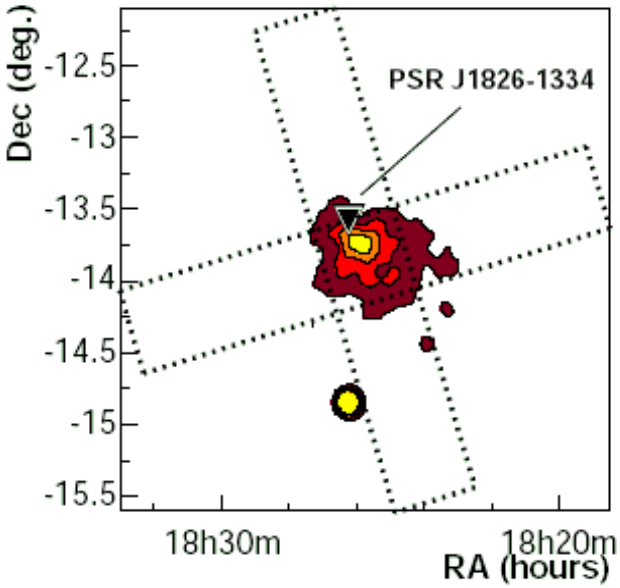
PWN Asymmetry

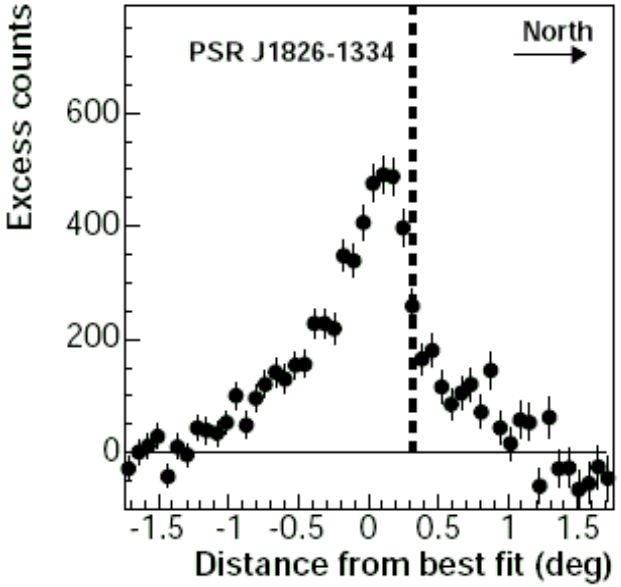


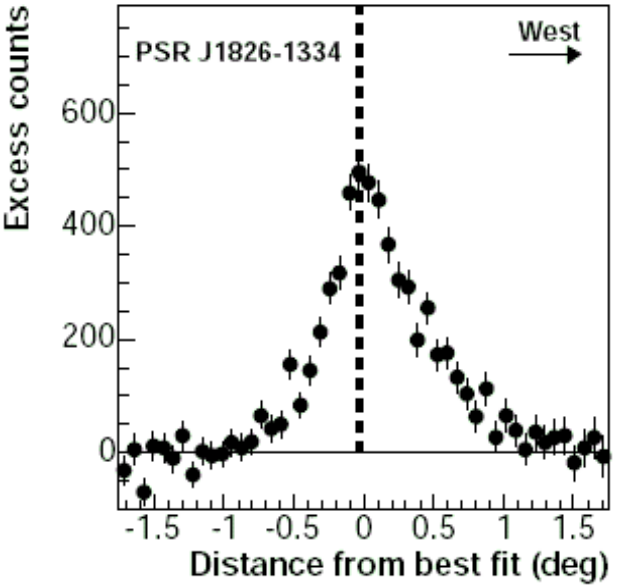












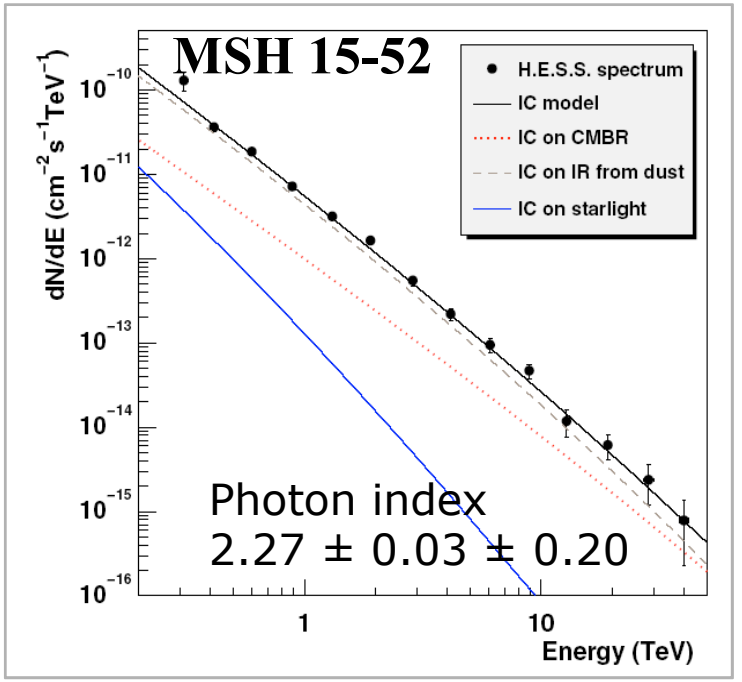
Spectra & Modeling of VHE PWN

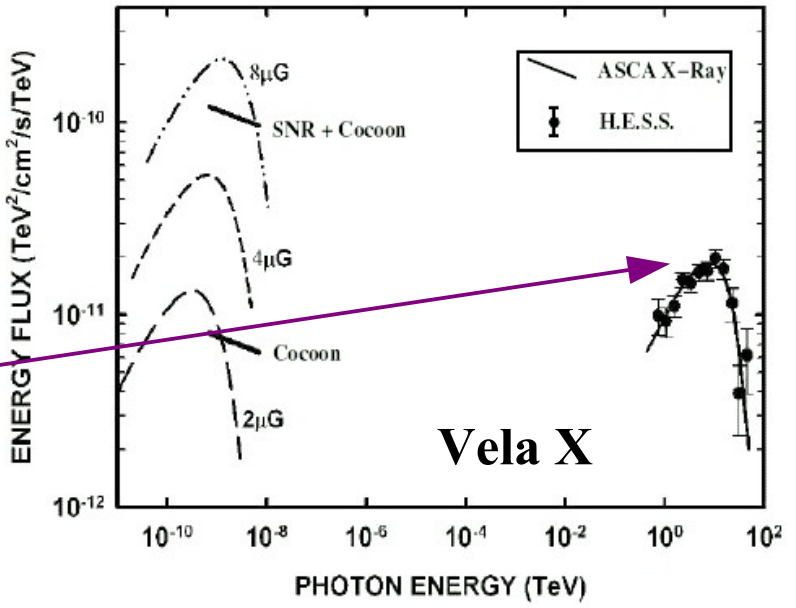
Spectra are "hard"

- Often extend to ~50 TeV
- Cover more than two orders of mag.

Model:

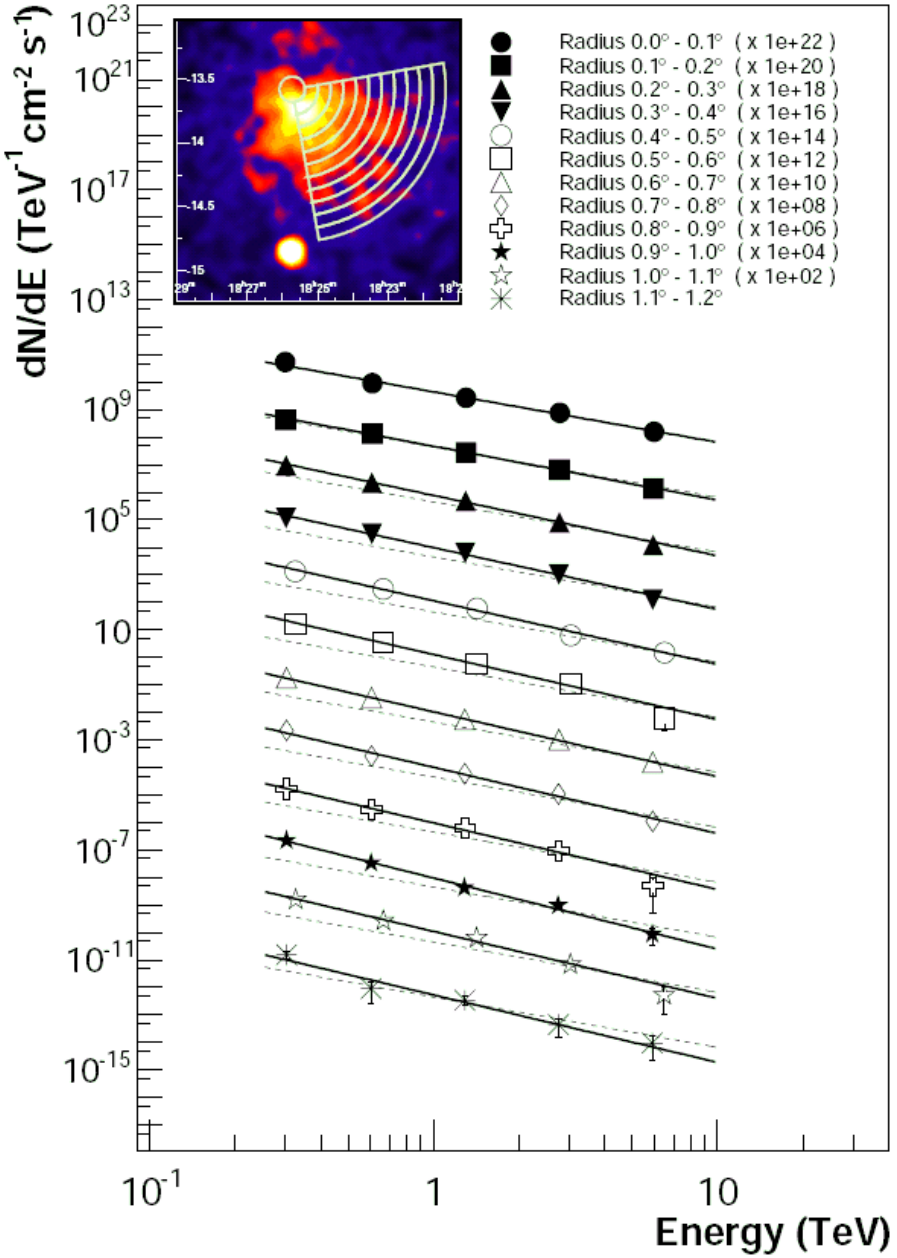
- Correlated X-ray & γ-ray observations suggest a population of synchrotron electrons in the nebulae
- Pulsar spin-down powers electrons
- Origin of γ-rays likely from inverse-Compton scattering of electrons on seed photons
- Generally hard spectra are consistent with IC interpretation

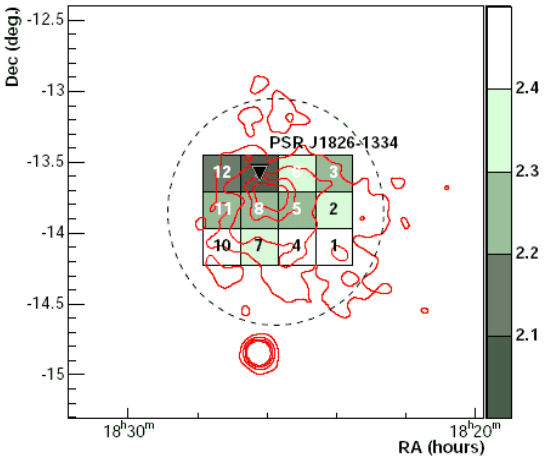


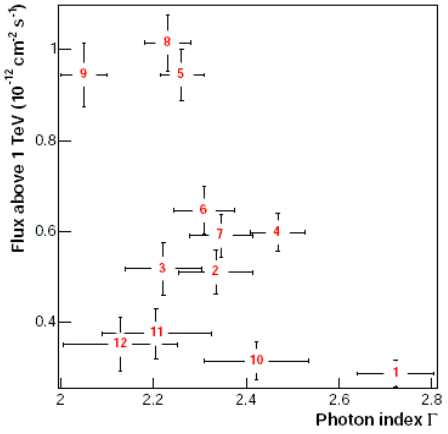


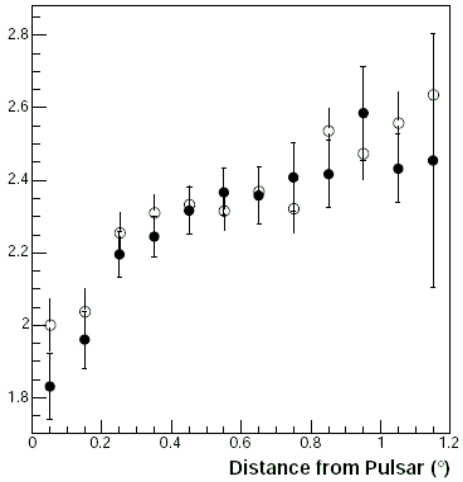
First detection of a spectral maximum in SED at VHE energies

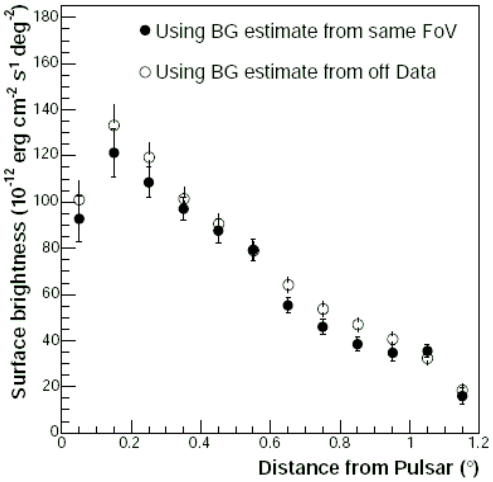
Energy Dependent Morphology in HESS J1825-137







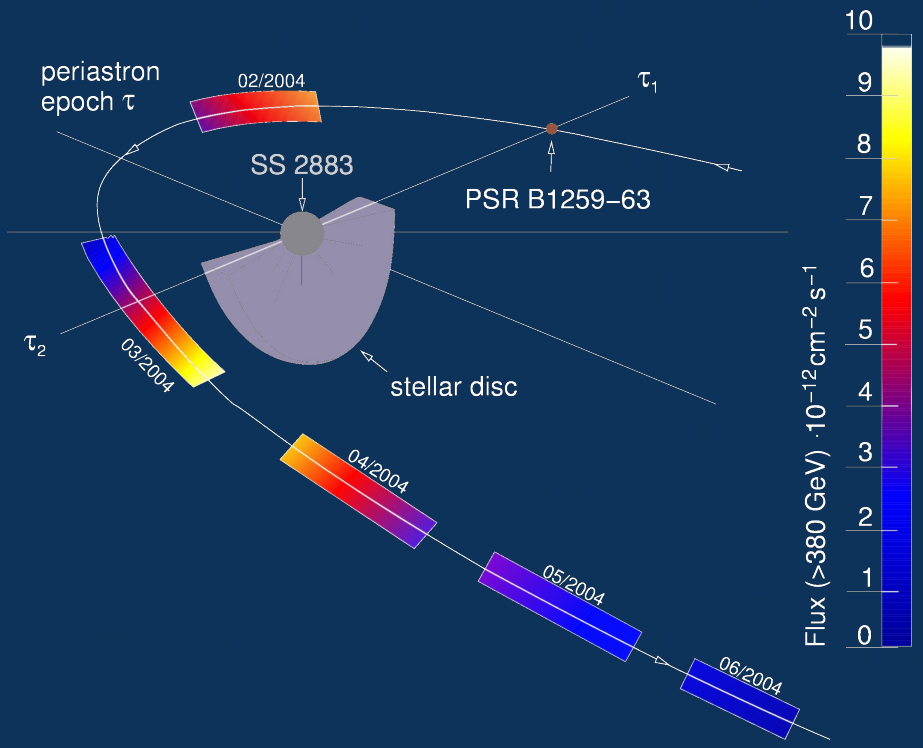


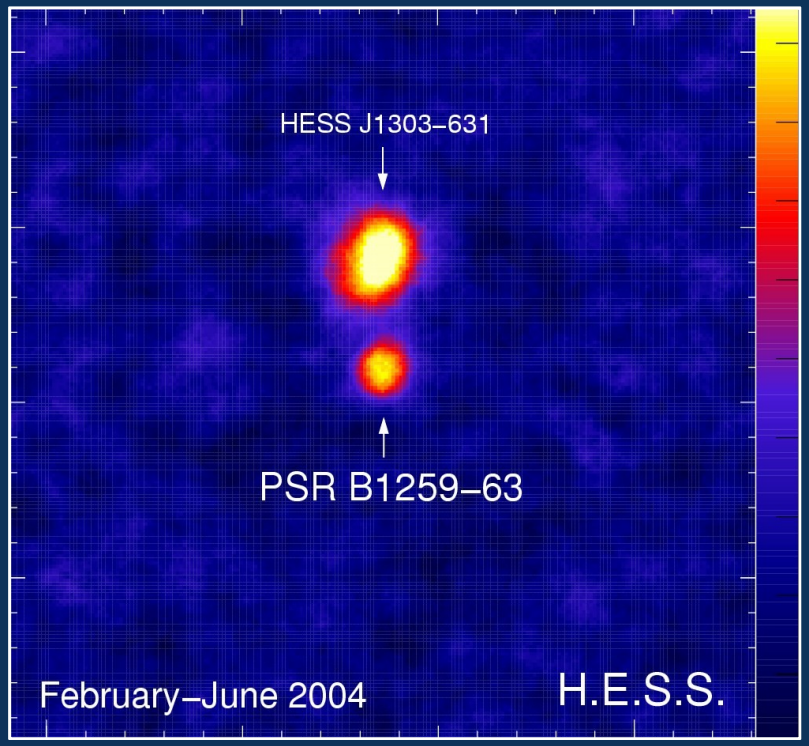


Spectrum softens with distance from pulsar

High energy e^- cool faster!

Observations of PSR B1259-63





PSR B1259 (A&A, 442, 1, 2005)

Point-like excess

~5% Crab flux, Γ=2.7+/-0.2, Γ is const.

Not seen in 2005 observations

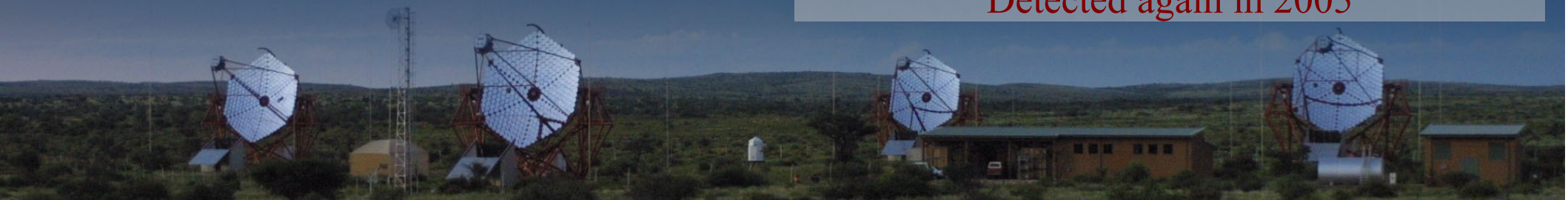
HESS J1303 (A&A, 439, 1013, 2005)

Extended (0.16^{o} +/- 0.02^{o}) excess

Const flux: ~17% Crab flux, Γ=2.4+/-0.2

No known counterpart at other λ

Detected again in 2005



LS 5039: An New Source Class

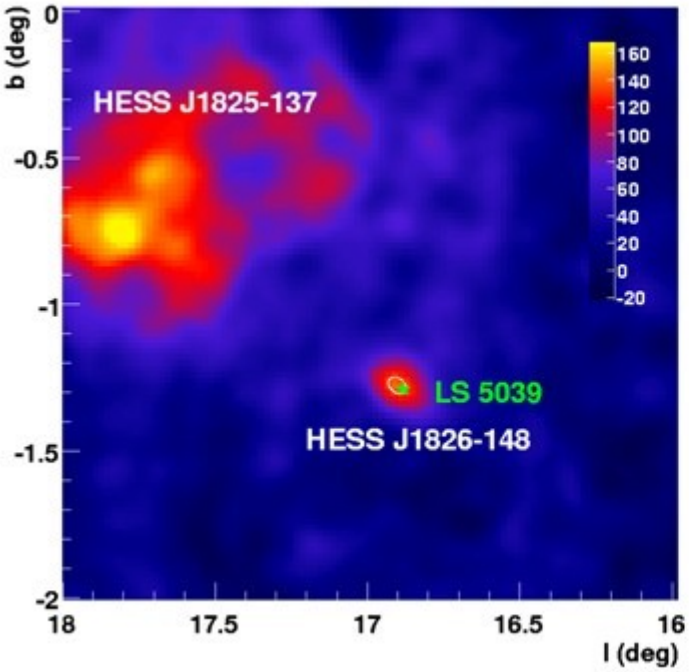


Image: ESA & Hubble European Space Agency Information Centre

Initially detected in 2004 Galactic Plane scan

A weak (7σ), point-like excess in limited exposure (~10 hrs)

Constant flux & Hard spectrum (Γ~2.1)

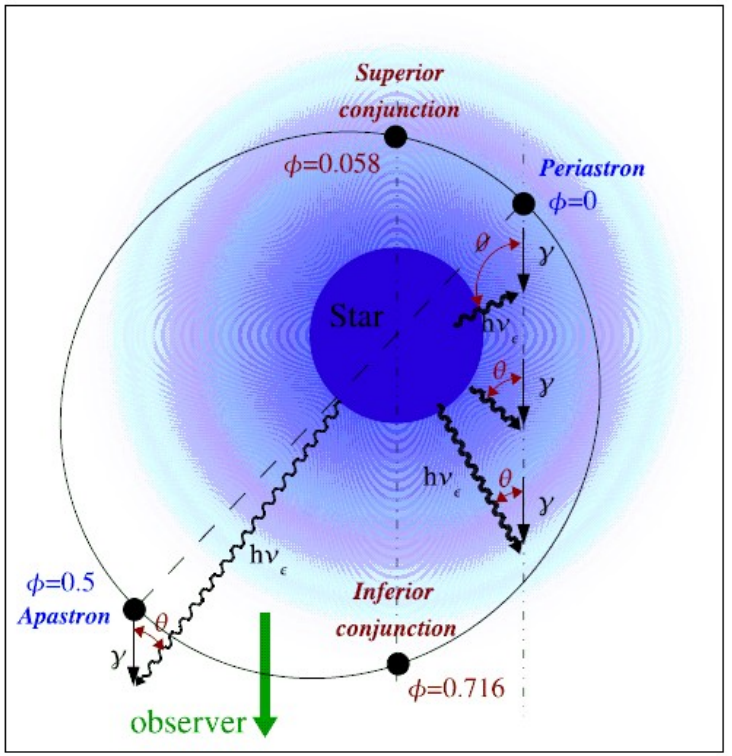
Science 309, 746, 2005

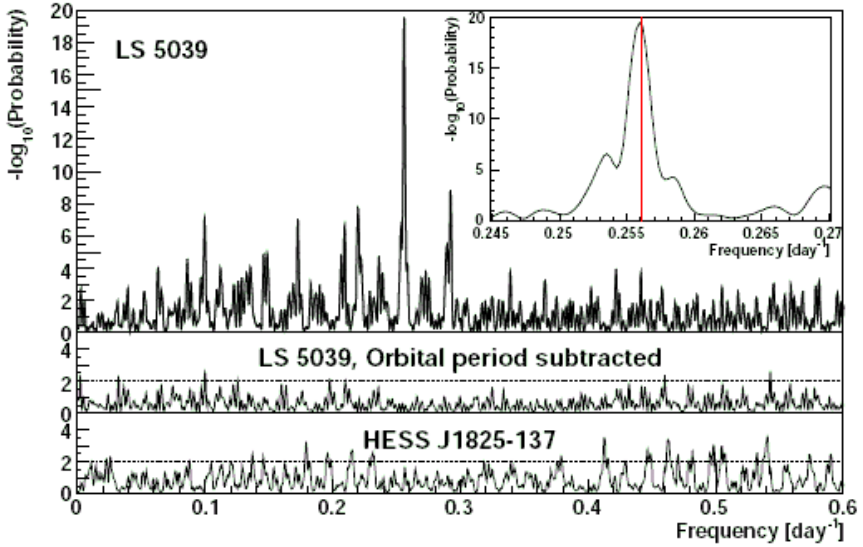
Now: A strong (~40σ), Point-like excess (<28'') in long exposure (~70 hrs)!

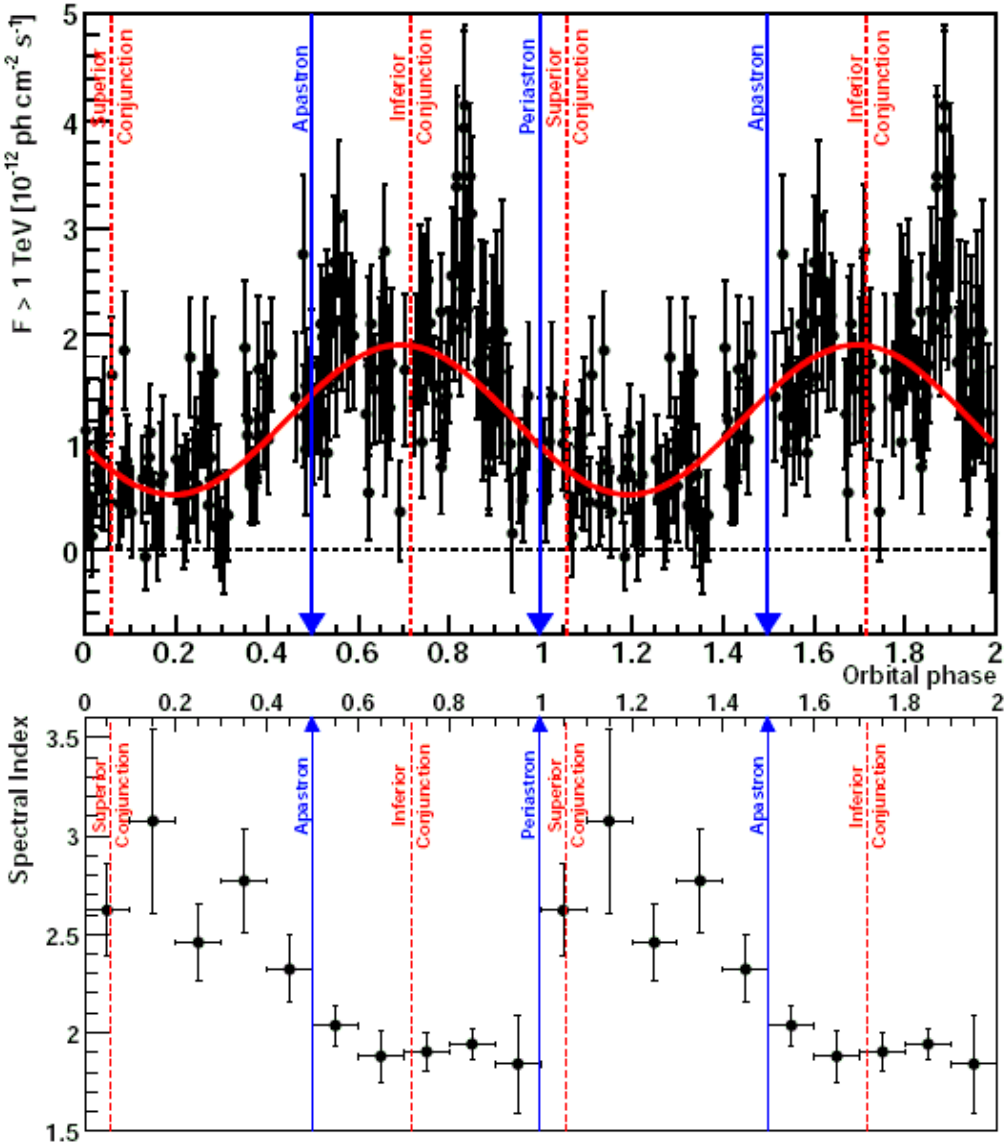
What about the flux & spectrum?

Submitted to A&A (astro-ph/0607192)

Periodic Variations in LS 5039

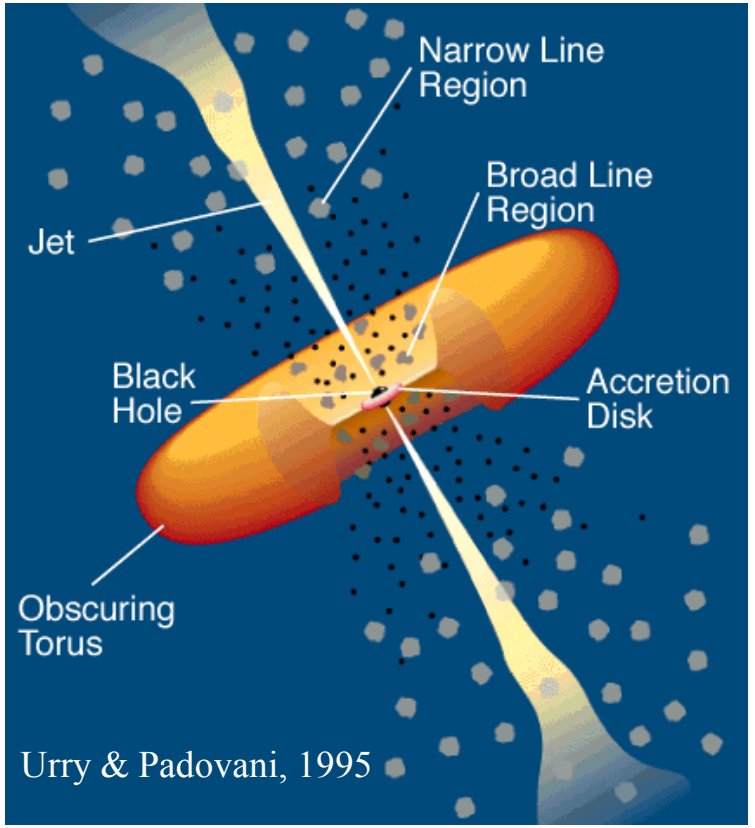


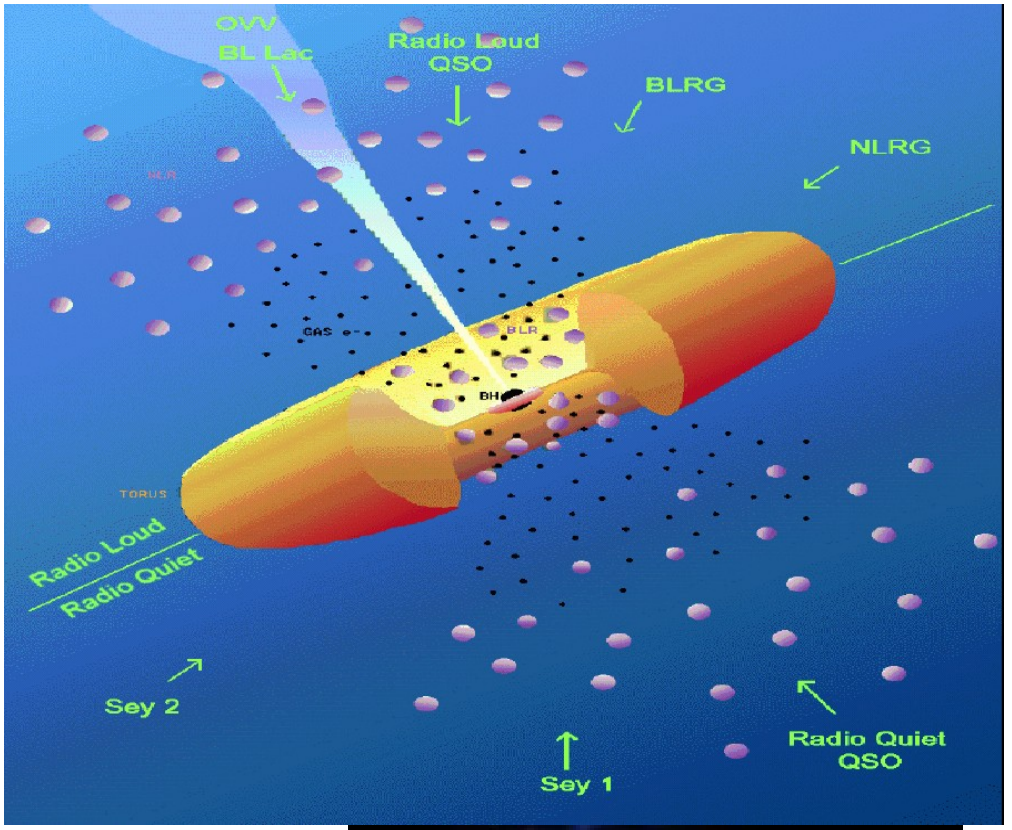


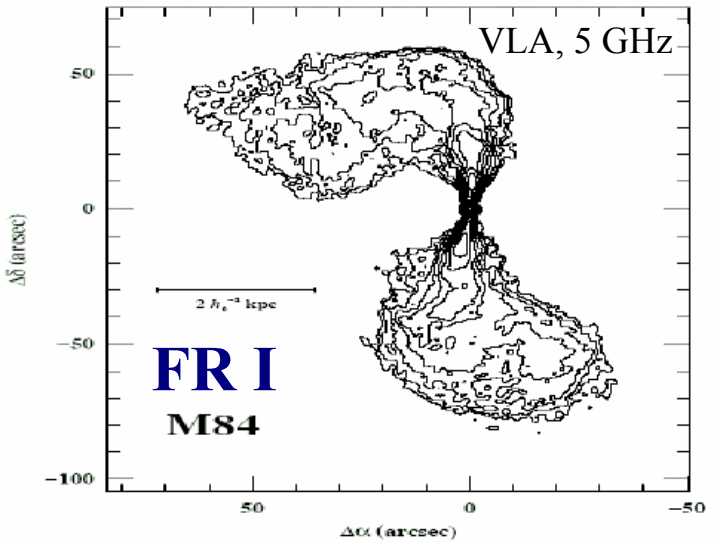


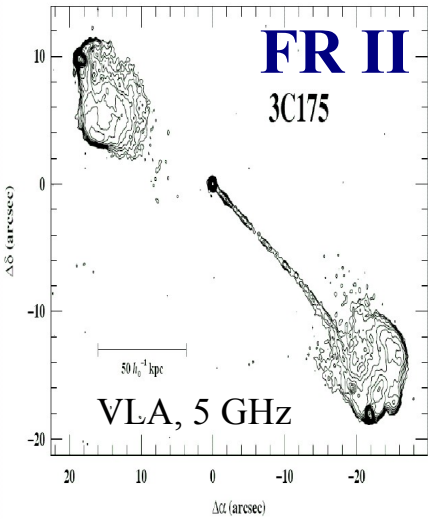
First indication of VHE absorption by an astrophysical source

Active Galactic Nuclei





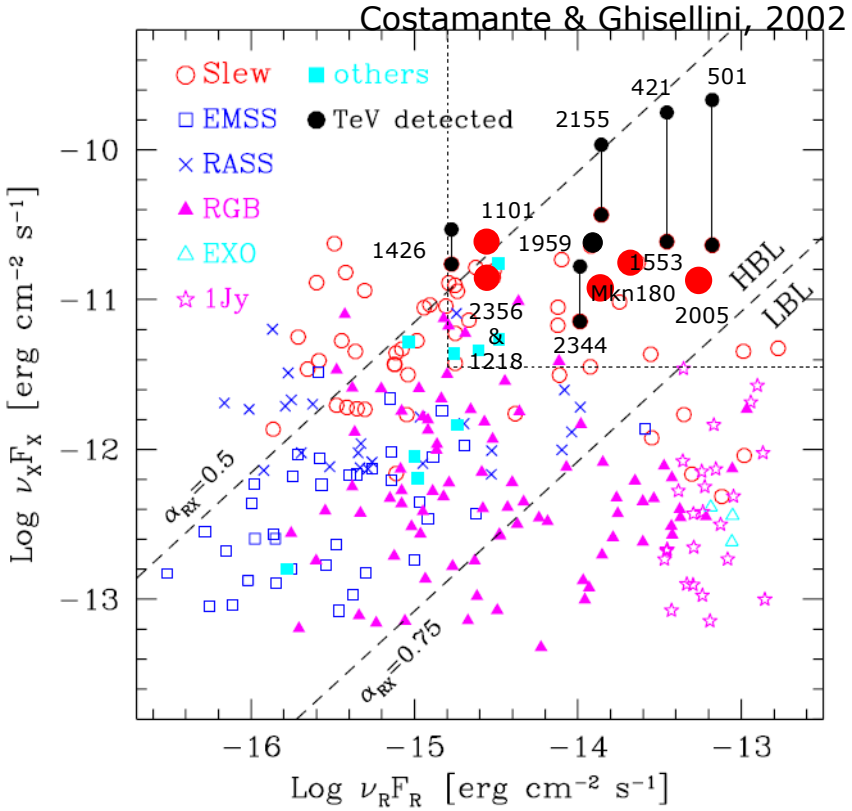




13 Known VHE AGN in 2006

Object	Redshift	Type	1st Detection	H.E.S.S. Reference
M 87	0.004	FR I	HEGRA	astro-ph/0504395
Mkn 421	0.030	HBL	Whipple*	A&A, 437, 95, 2005
Mkn 501	0.034	HBL	Whipple*	---
1ES 2344+514	0.044	HBL	Whipple*	---
Mkn 180	0.046	HBL	MAGIC	---
1ES 1959+650	0.047	HBL	7-Tel. Array*	---
PKS 2005-489	0.071	HBL	H.E.S.S.	A&A, 436, L17, 2005
PKS 2155-304	0.116	HBL	Mark VI	A&A, 430, 865, 2005
H 1426+428	0.129	HBL	Whipple*	---
H 2356-309	0.165	HBL	H.E.S.S.	Nature, 440, 1018, 2006
1ES 1218+304	0.182	HBL	MAGIC	---
1ES 1101-232	0.186	HBL	H.E.S.S.	Nature, 440, 1018, 2006
PG 1553+113	>0.25	HBL	H.E.S.S.	A&A, 448, L19, 2006

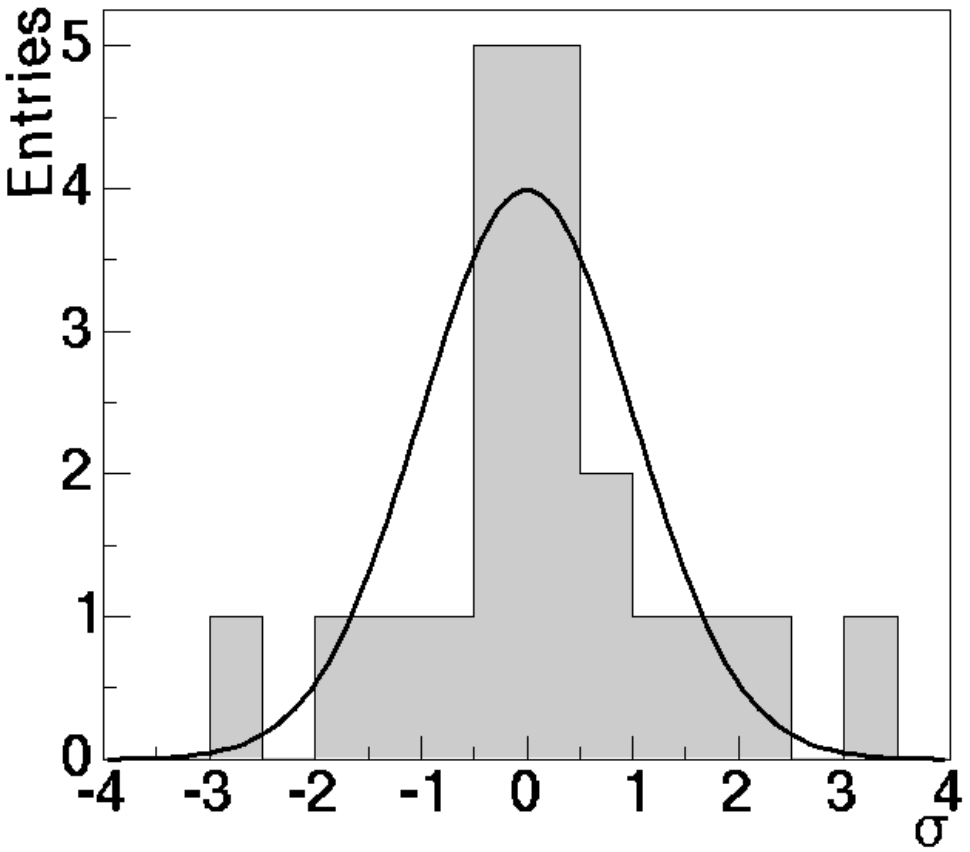
* = detected by many (>2) observatories



H.E.S.S has detected 7 AGN at VHE energies!

4 are "discoveries", 2 are 1st confirmations of "weak" detections

AGN Upper Limits



20 other AGN observed

- 13 BL Lacs (mostly HBL)
  - 7 from Costamante & Ghisellini 2002
- 4 Radio-loud objects
  - FR I: Pictor A, Cen A (prototype)
  - FR II: 3C 120
  - FSRQ: 3C 273
- 3 Seyferts
  - Type I: NGC 3783 (brightest), NGC 7469
  - Type II: NGC 1068 (prototype)

No significant signal

- Mkn 501 (3.1 σ, ~15% Crab flux)

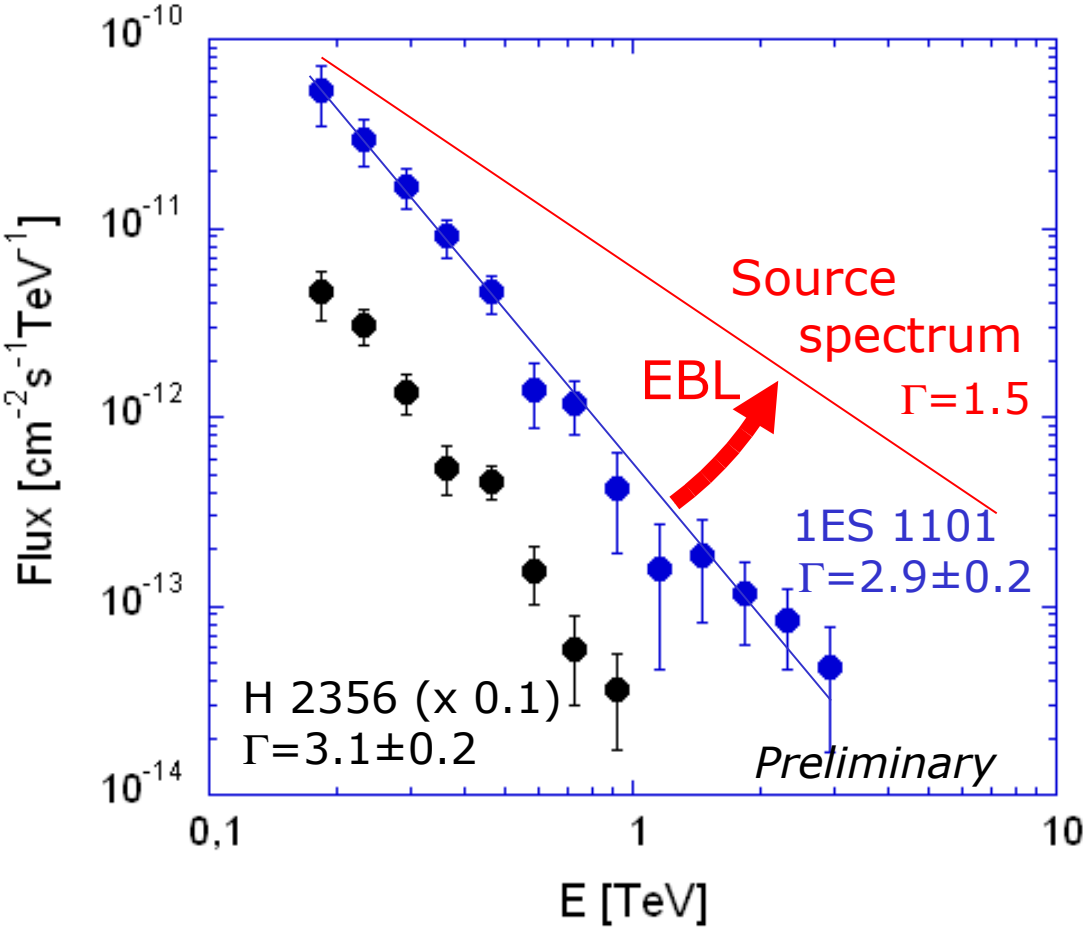
Exposure: 1 to 8 hrs each (avg 3.2 h)

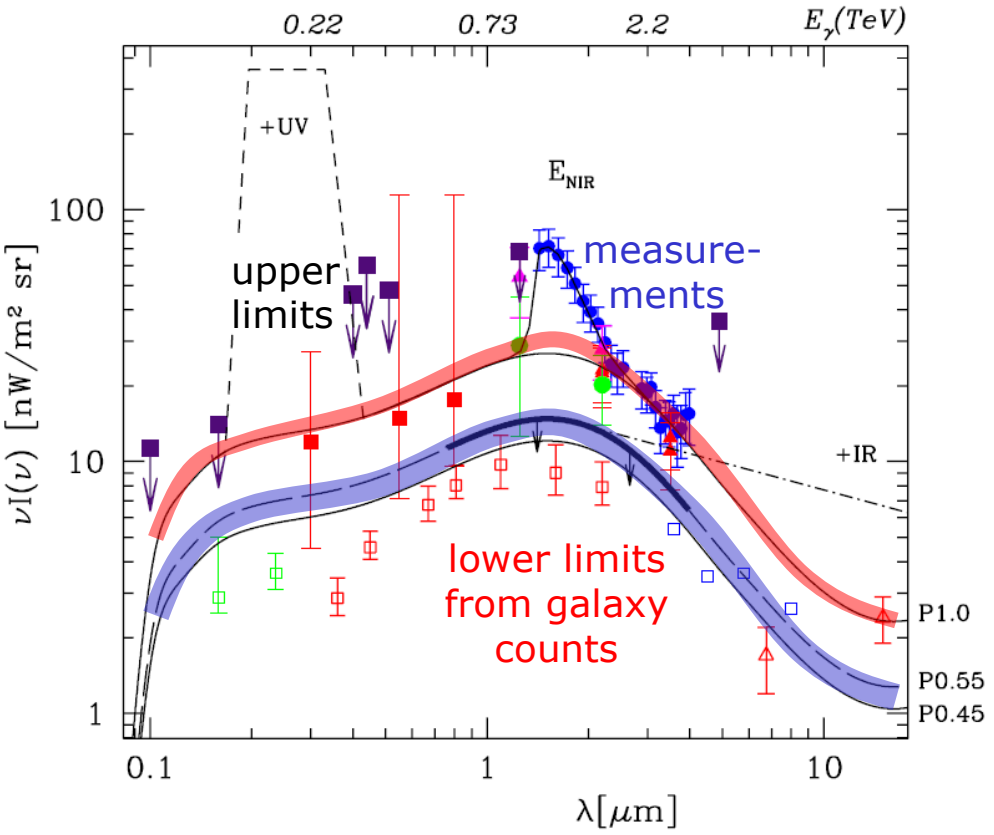
99.9% Upper limits: 0.4 to 5.1% Crab

A&A, **441**, 465 (2005)

Distant BL Lacs

- VHE γ-rays absorbed by EBL
- Absorption increases with E & z
- Large z => Softer observed spectra
- More EBL = More absorption





EBL less than previously thought!

- Density must be less than 0.45x shape
- Account for errors, etc => 0.55x
- Within a factor of 2 of lower limits

We can see much further in VHE!

Nature 440, 1018, 2006

BL Lac Highlights

Most spectra follow a pure power-law with no features

- $dN/dE \sim E^{-\Gamma}$

Soft spectra measured for all the H.E.S.S. BL Lacs:

- 1ES 1101-232: $\Gamma = 2.88 \pm 0.17$
- H 2356-309: $\Gamma = 3.06 \pm 0.21$
- PKS 2155-304: $\Gamma = 3.32 \pm 0.06$
- PKS 2005-489: $\Gamma = 4.0 \pm 0.4$
- PG 1553+113: $\Gamma = 4.0 \pm 0.6$
- Mkn 421: $\Gamma = 2.1 \pm 0.1 \pm 0.3$
  - $E_{cut} = 3.1\ (+0.5,-0.4) \pm 0.9$ TeV

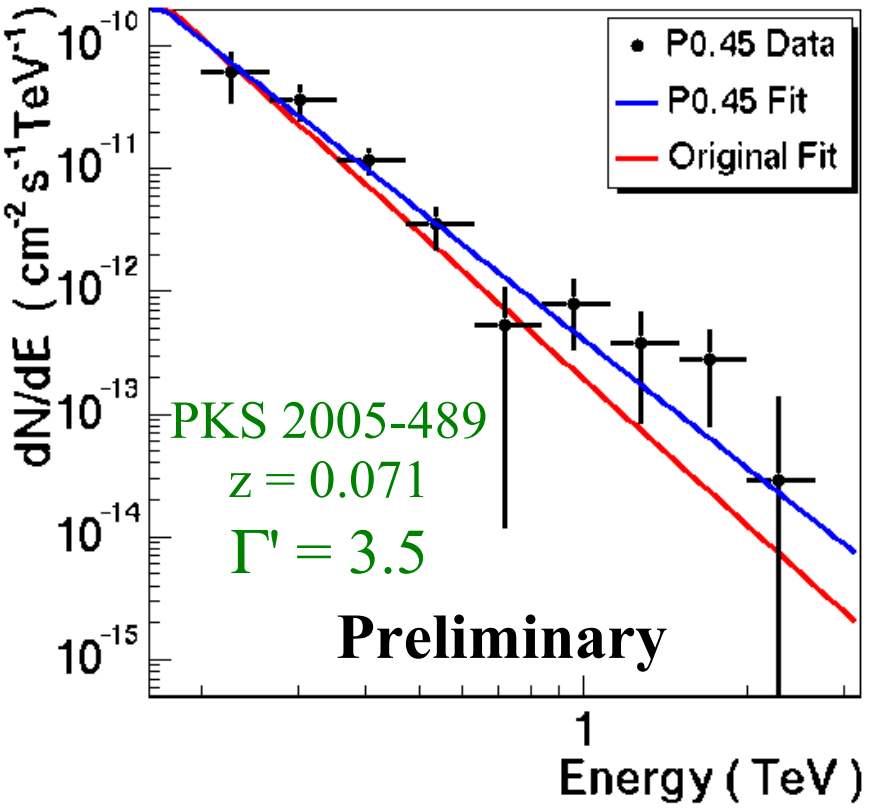
Some VHE flux variability observed:

- PKS 2155-304: years to sub-hour
- Mkn 421: sub-hour

Spectral hardening with increased flux observed from Mkn 421

•All detected in multiple years

Softness not only EBL effect!



Deabsorbed $\Gamma = 3.5$
uses upper limit on EBL
The effect could be even less!

AGN Multi-wavelength Campaigns

Blazars highly variable

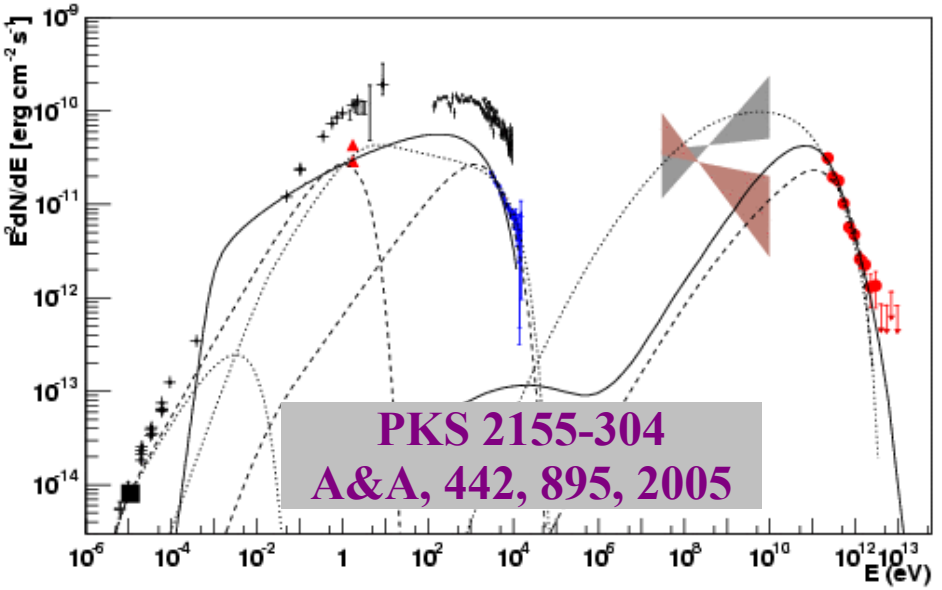
- Complications using VHE data to model archival measurements

Need: Simultaneous radio, optical, X-ray & VHE observations

- Model the SED
- Search for correlated variability & orphan flares

H.E.S.S. has 12 total (so far...)

- 3 for PKS 2155-304
  - 2 XTE, 1 XTE + Spitzer
- 3 for PKS 2005-489
  - 1 XTE, 2 XMM
- 3 for 1ES 1101-232
  - 1 XMM, 1 XTE, 1 Suzaku
- 2 for H 2356-309
  - 1 XTE, 1 XMM
- 1 for Mkn 421 (MAGIC & Suzaku)



Leptonic (dashed & dotted lines) & Hadronic (solid line) models

1 more scheduled for 2006:

- PG 1553+113 with Suzaku, MAGIC & H.E.S.S.

Several ToO proposals:

- Chandra, XTE, Suzaku

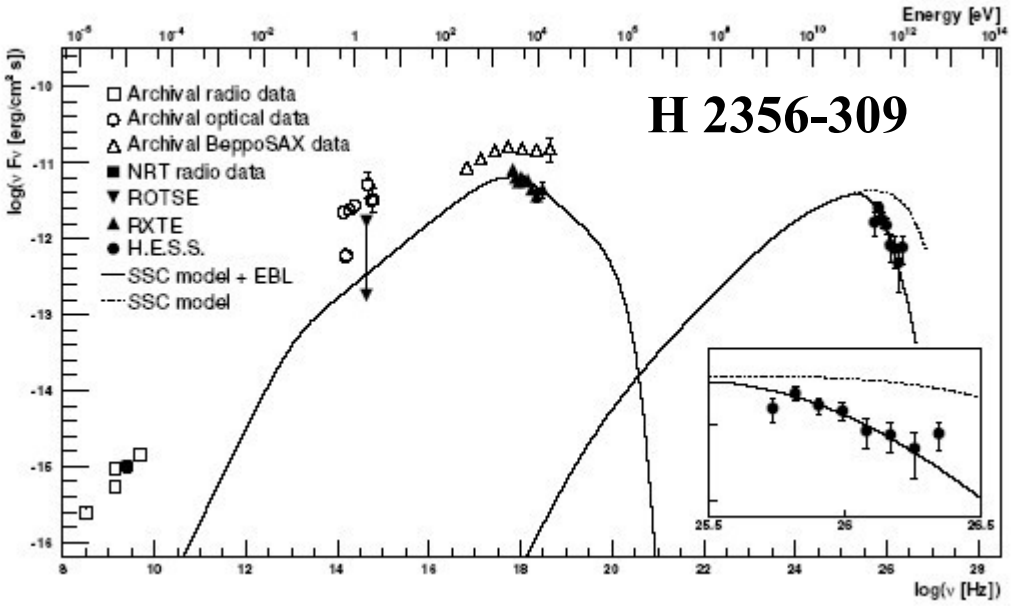
AGN Multiwavelength Campaigns

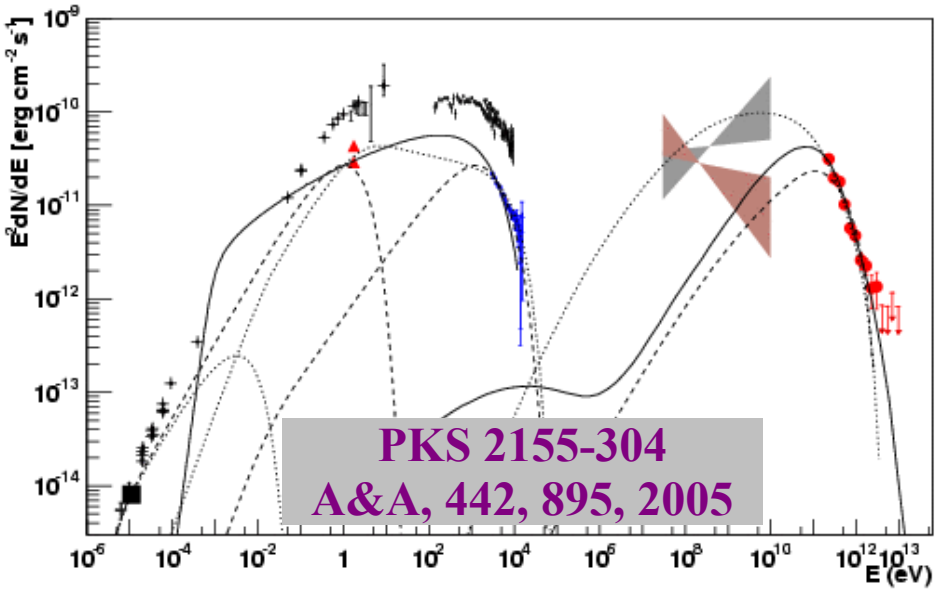
SED Modelling Trends:

- Both leptonic & hadronic scenarios provide acceptable fits
- Parameters reasonable

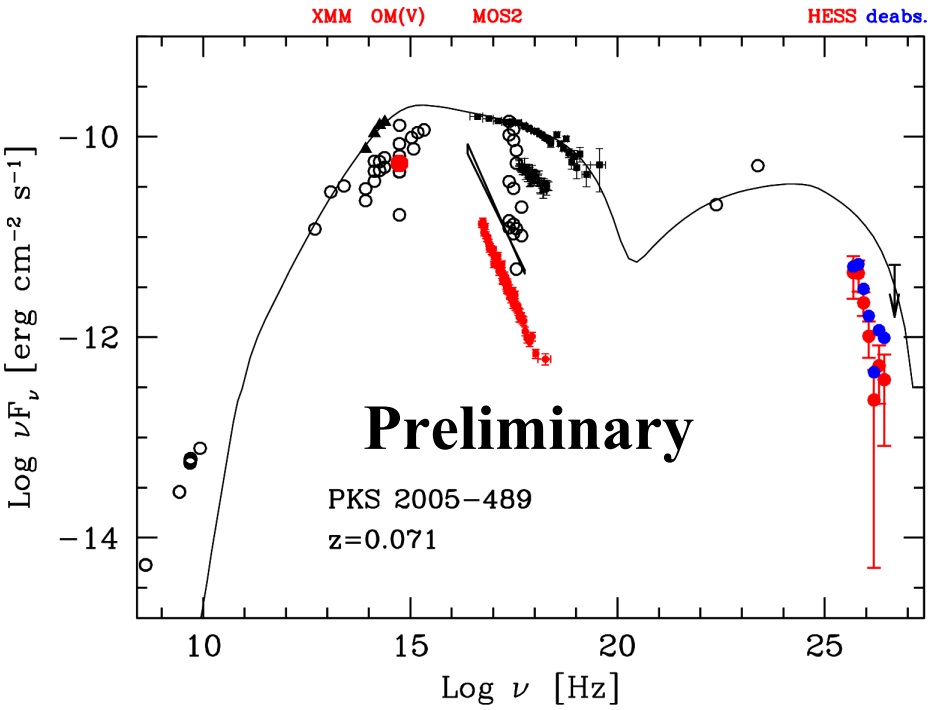
Interesting Trend:

- Historical Lows in X-ray & optical fluxes for all campaigns
- Often softest X-ray spectra ever



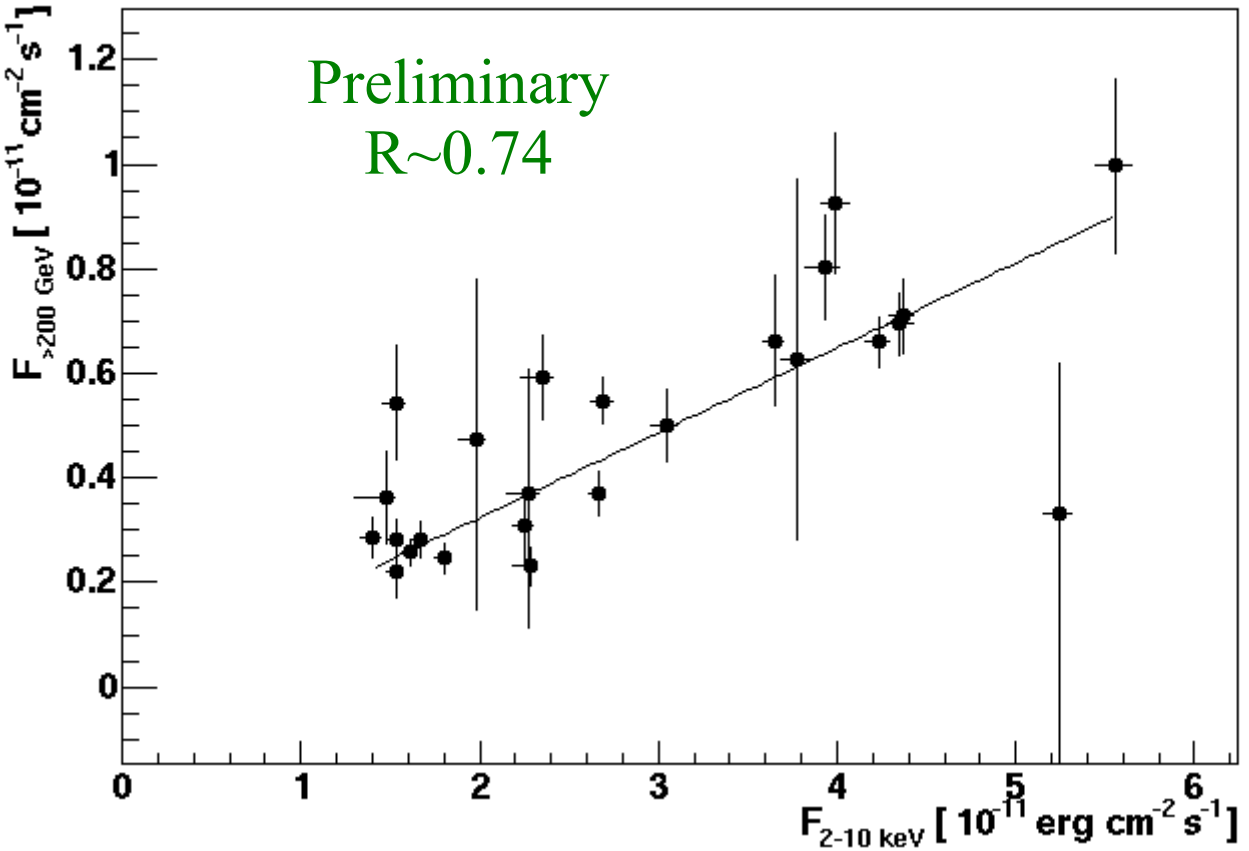


Leptonic (dashed & dotted lines) & Hadronic (solid line) models



MWL: Correlated X-ray/VHE Variability

Largest MWL campaign "ever" with VHE: PKS 2155-304 in 2004
H.E.S.S.: ~130 hours; RXTE, Spitzer, Radio, Optical



Clear indication for correlated X-ray/VHE flux variability
Only strictly simultaneous data shown!
Implies: Same particle population responsible for X-ray/VHE flux

M 87: non-blazar

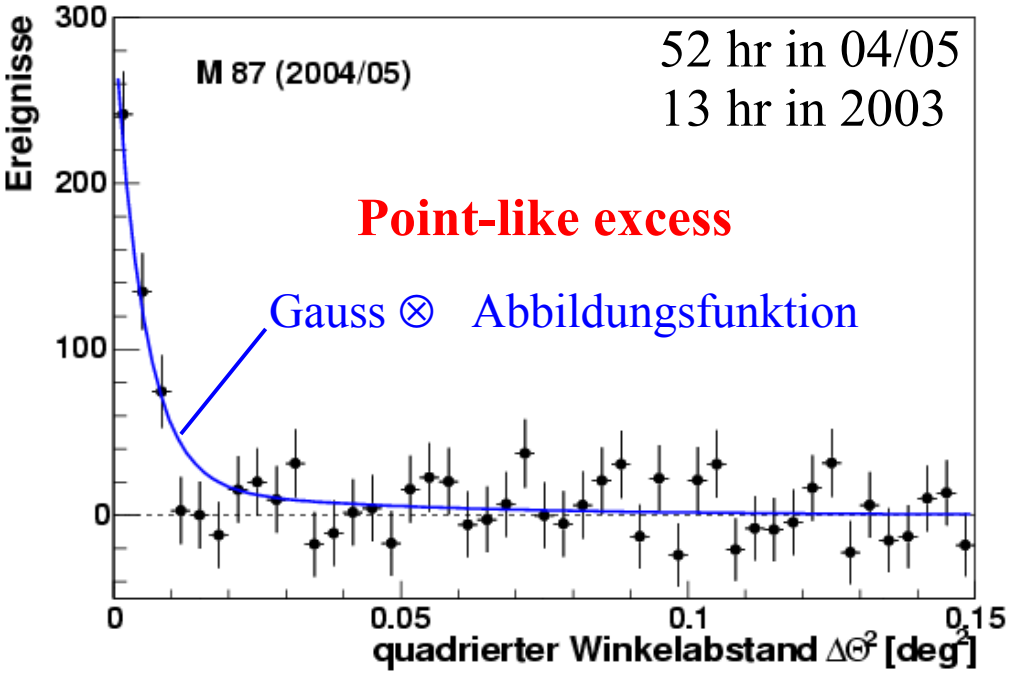
Fanaroff-Riley Type-I Galaxy:

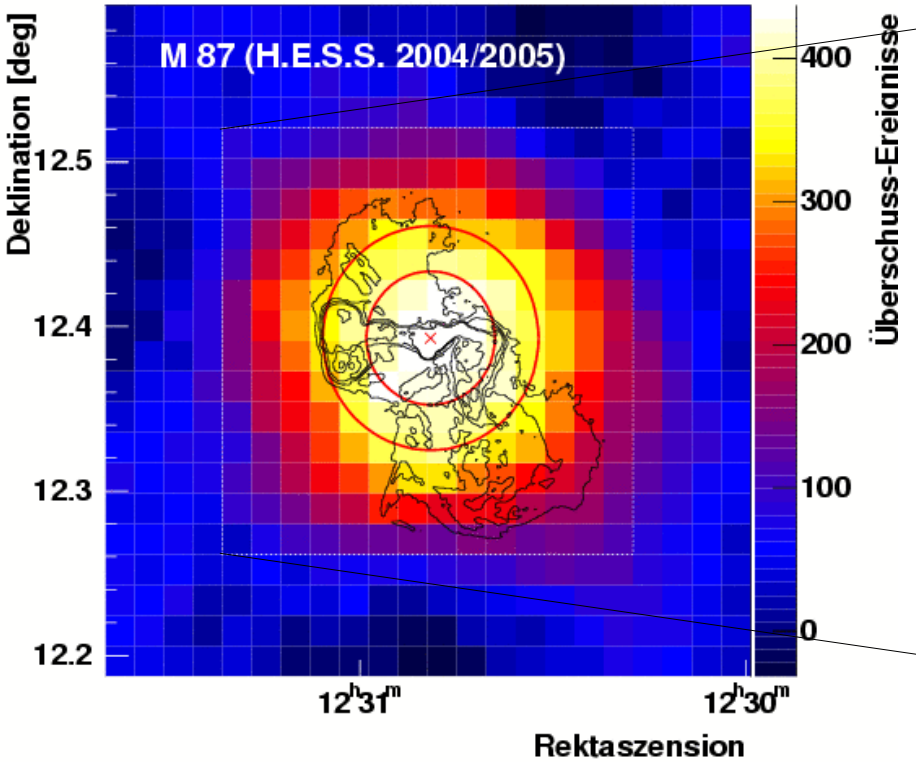
- A mis-aligned BL Lac?
- Jet angle: 20° to 40°
- Distance: ~16 Mpc

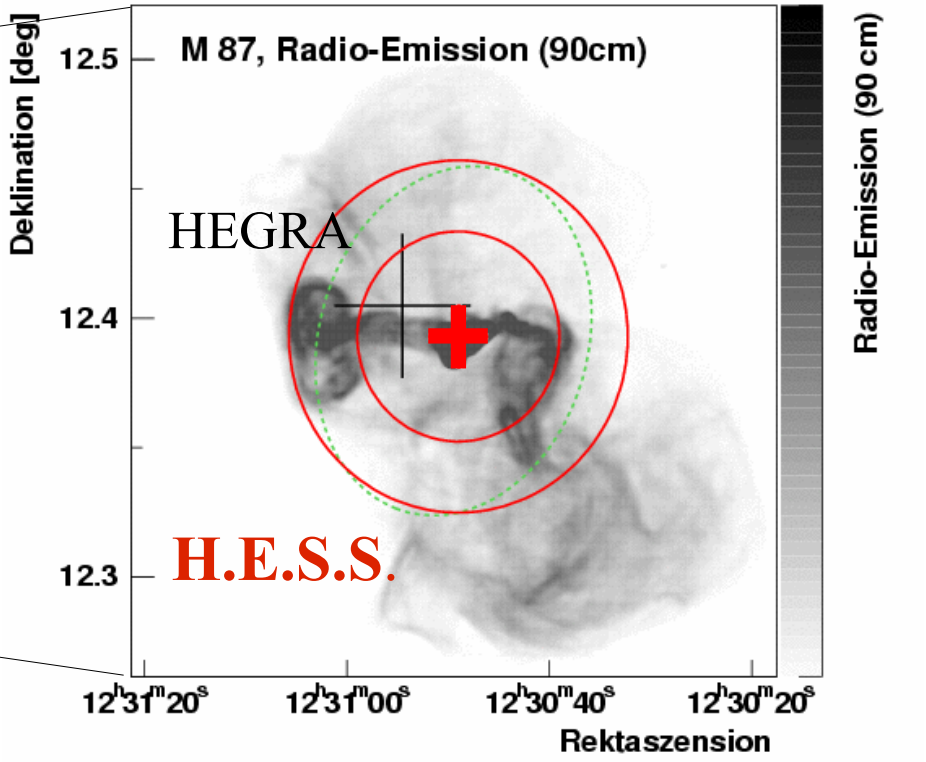
HEGRA: 4.7 σ in 77 hrs (1998-99)

Whipple: Upper limits in 2000-03

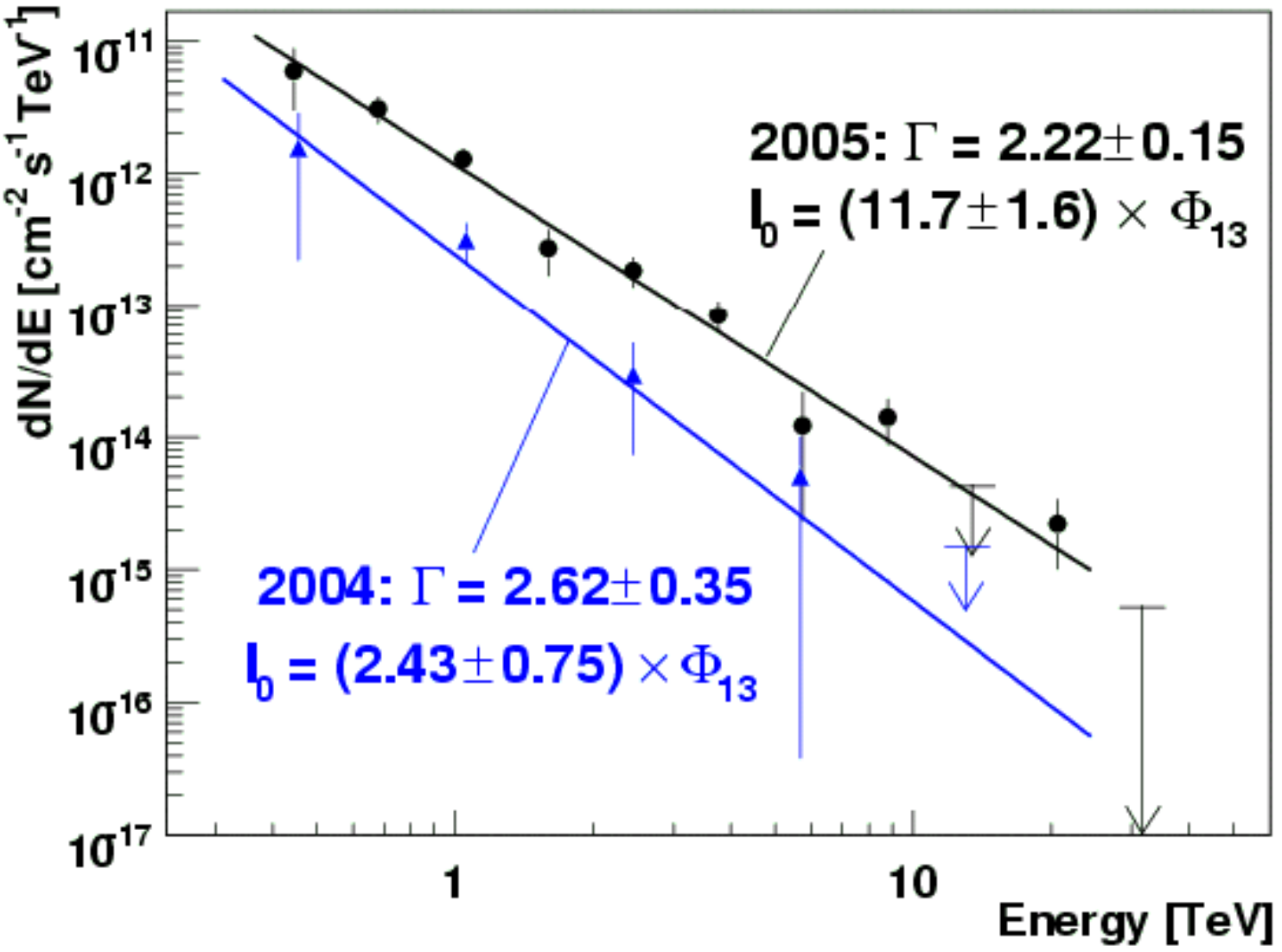
H.E.S.S.: ~11 σ (471 γ-rays)







M 87 Spectrum is Hard



Annual spectra:

- 2004 (5σ)
- 2005 (10σ)

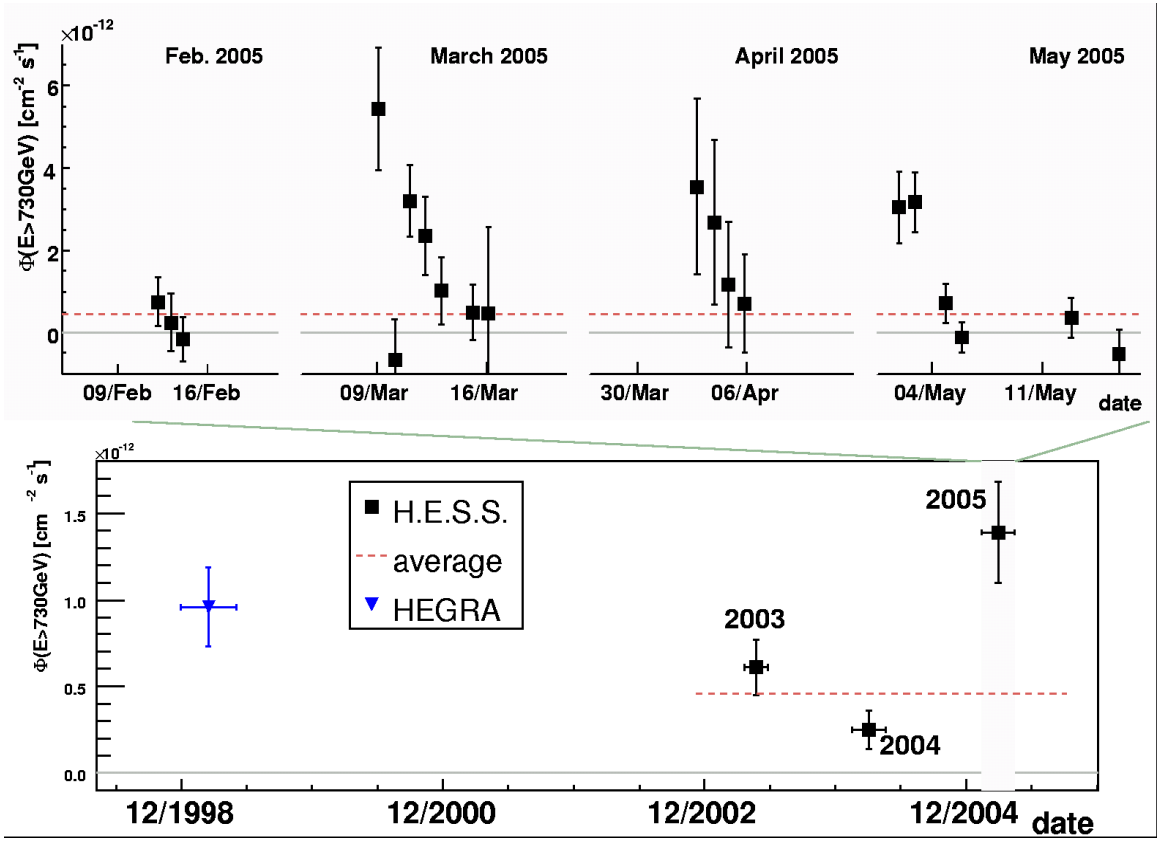
Both spectra follow a pure power-law:

- $dN/dE = I_o\ (E/TeV)^{-\Gamma}$
- $\Phi_{13} = 10^{-13}$ cm^{-2} s^{-1} TeV^{-1}

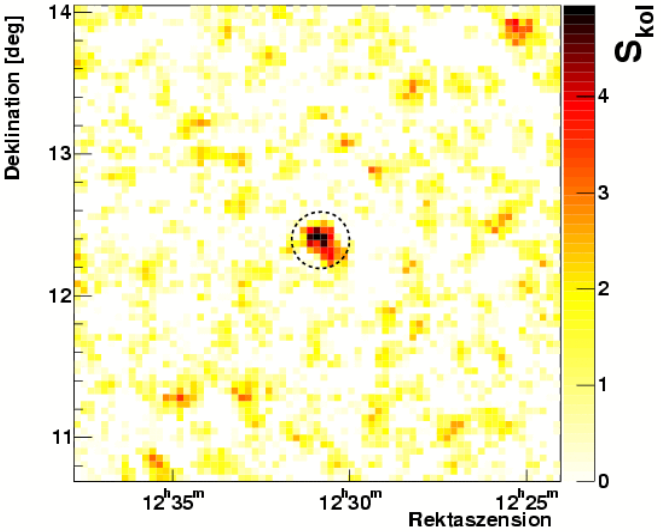
Photon index similar

Flux is less in 2004

> 730 GeV Flux Variability from M 87



Kolmogorov-Test



Apply Kolmogorov test to distribution of photon arrival times: 4σ variability

Fit a constant to annual HESS data: 3.2σ variability

Surprise: Fit of a constant to 2005 nightly flux shows >4σ variability

Fast variability, hard spectrum & point-like emission from core is very difficult to model: Excludes most!

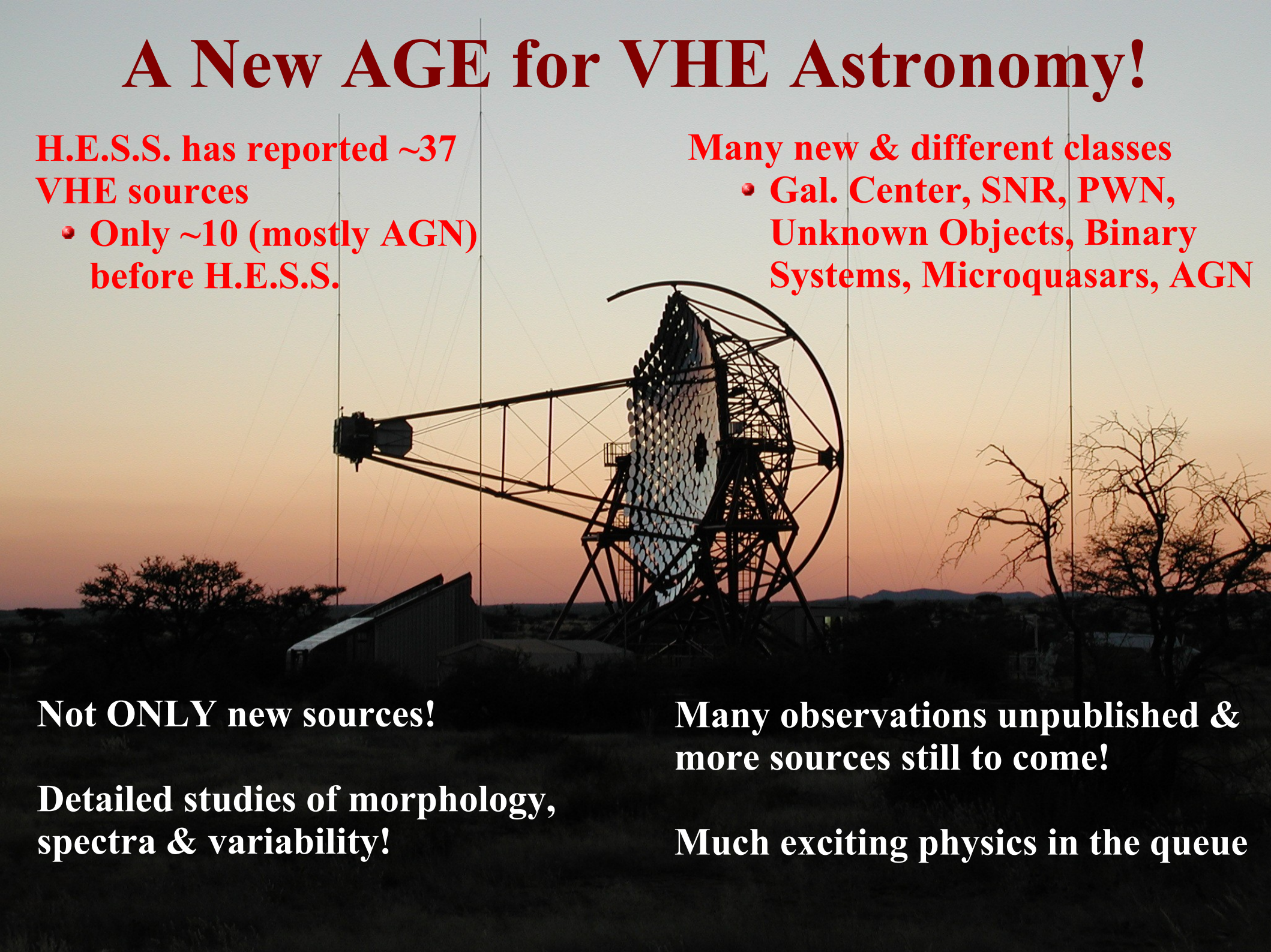
A New AGE for VHE Astronomy!

H.E.S.S. has reported ~37 VHE sources

- **Only ~10 (mostly AGN) before H.E.S.S.**

Many new & different classes

- **Gal. Center, SNR, PWN, Unknown Objects, Binary Systems, Microquasars, AGN**



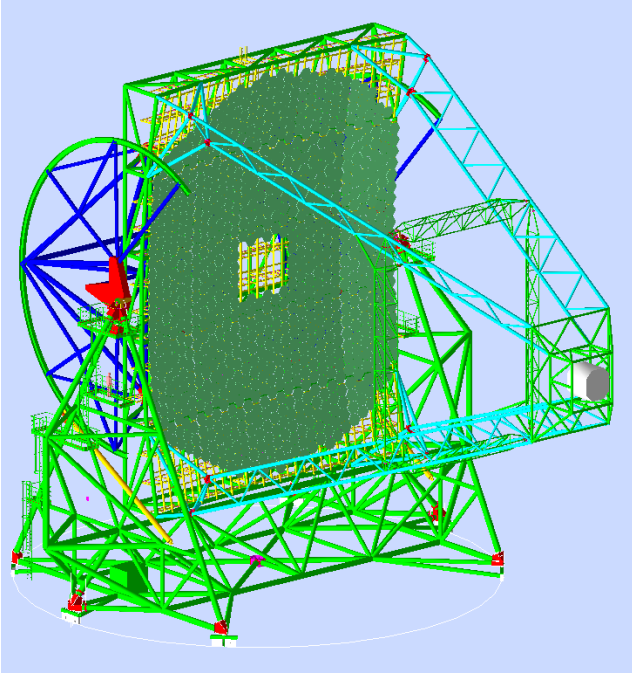
Not ONLY new sources!

Detailed studies of morphology, spectra & variability!

Many observations unpublished & more sources still to come!

Much exciting physics in the queue

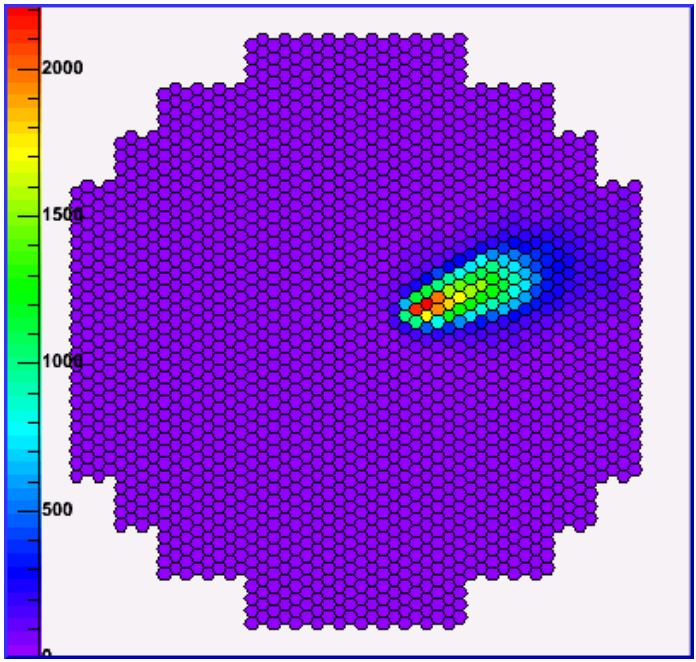
The Future: H.E.S.S. Phase-II



- Diameter = 30 m
- Focal Length = 36 m
- Rigid steel structure: ~560 Tons

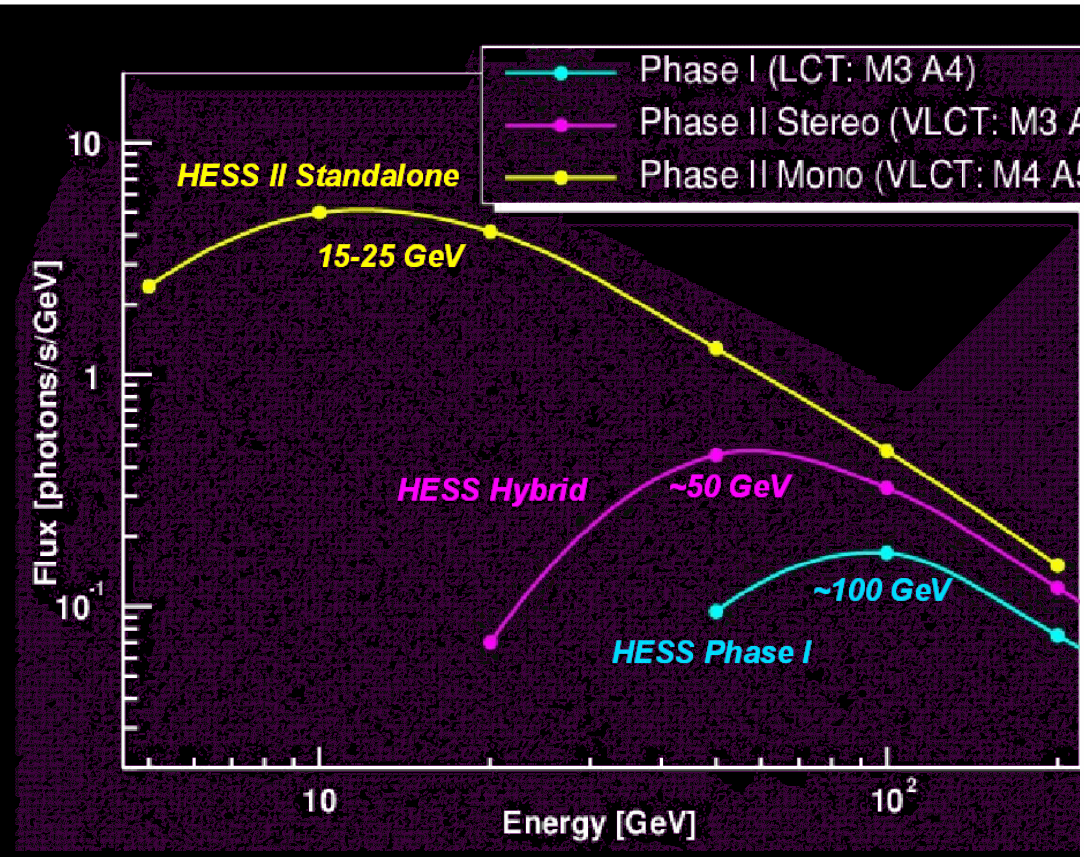
- 851 Mirrors
- Mirror Area = ~600 m^2

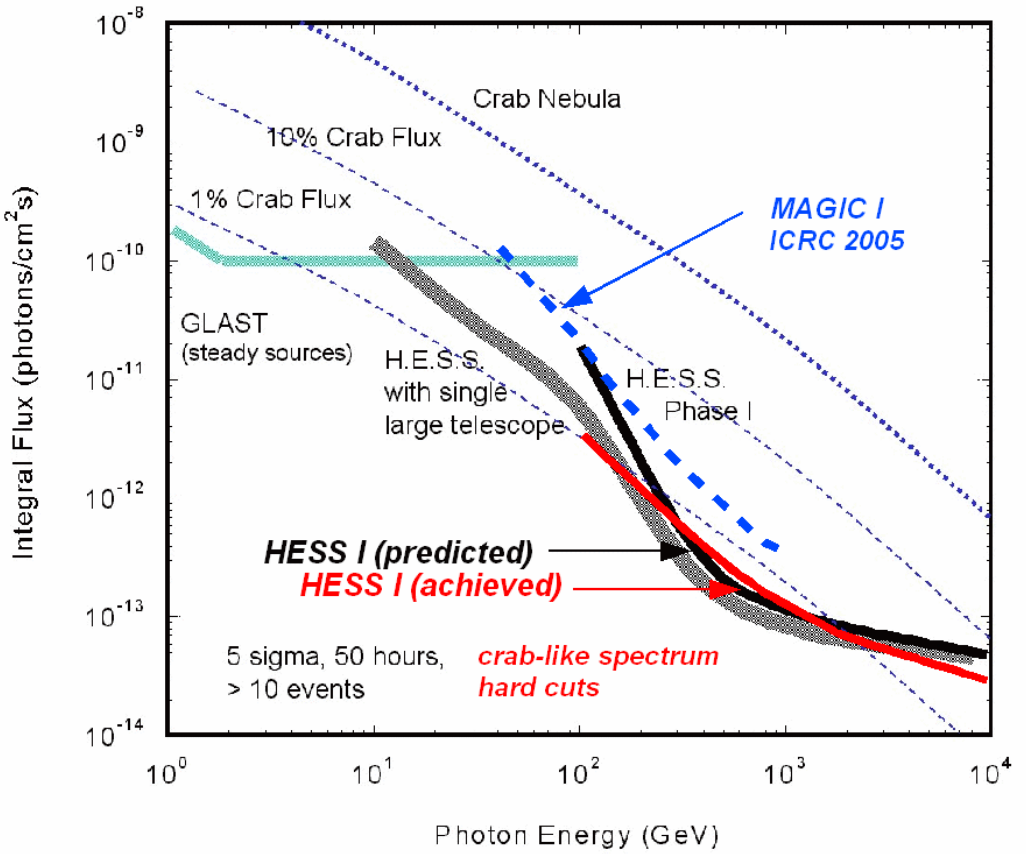
- 2048 Pixel Camera
- Pixel size: 0.07°
- 3.6° Field of View



Telescope: 2007; Camera & Mirrors: 2008; Data: 2009

Phase II: Threshold & Sensitivity





Let's see and learn

Guaranteed new window

Improved Sensitivity

Thank you for your time!