# TeV Gamma-Ray Astronomy: Some Recent Highlights (from HESS*) and Future Plans


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** for the HESS Collaboration*


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*Oct 2006*


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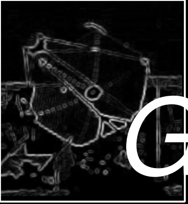


# *Gamma-Ray Astronomy*

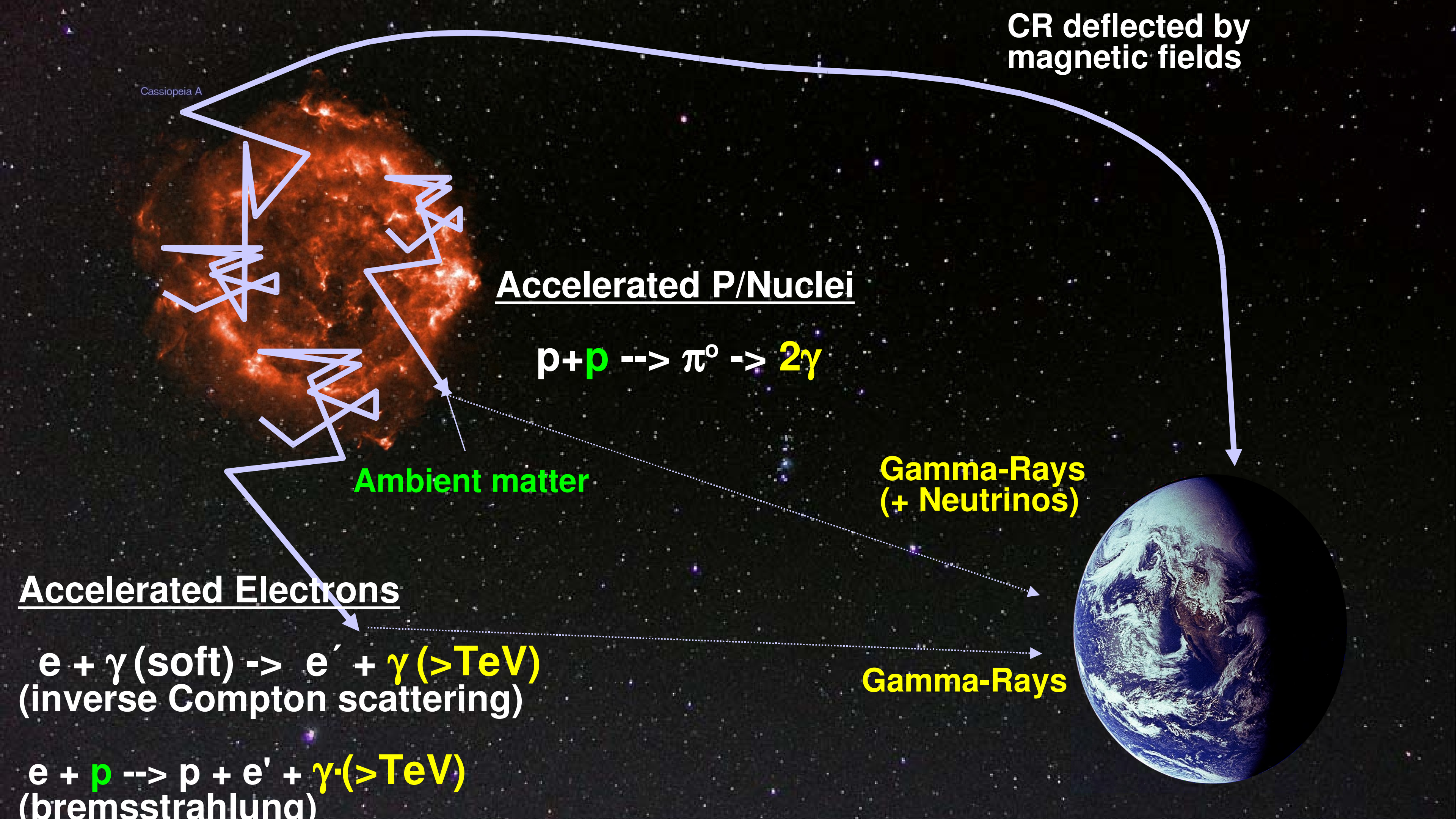
**A branch of high energy astrophysics studying the Universe at MeV, GeV, TeV (& above) photon energies.**

**It provides crucial window in the spectrum of cosmic EM radiation for exploration of nonthermal phenomena in the Universe in their most extreme and violent forms**

**It is the last window in the spectrum of cosmic EM radiation to be opened....**

**It is now (partly) opened!**

# Gamma Rays: Most Accessible Tracer of Particle Acceleration in the Universe.




(NOTE: at energies E>$10^{18}$ CR astronomy possible...Pierre Auger detector)

# Major Objectives of TeV Gamma-ray Astronomy

**Oldest question in modern astrophysics!**

## Origin of Galactic Cosmic Rays (CRs)

***SNRs, Molecular clouds, Diffuse radiation of the Galactic Disk..***

***... since the discovery of CRs (Viktor Hess 1912) – still no clear origin. However we are gathering clues!***

## Galactic and Extragalactic Sources with relativistic flows

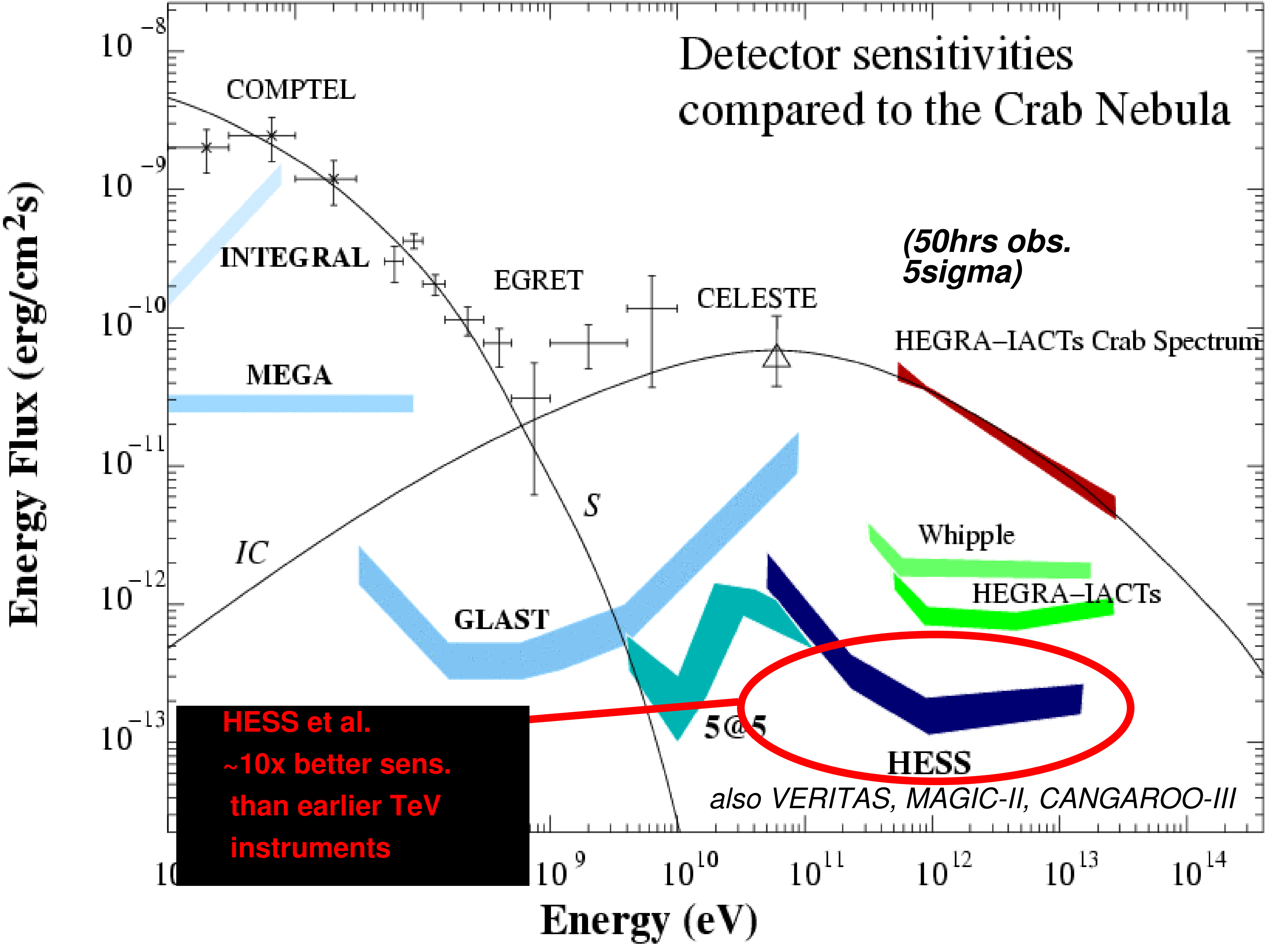
***Pulsars, Pulsar Winds, Microquasars, Small and Large Scale jets of AGN, GRBs***

## *OB Assoc & Stellar Wind Interactions*

***shock accel in wind/wind/ISM interactions, Superbubbles***

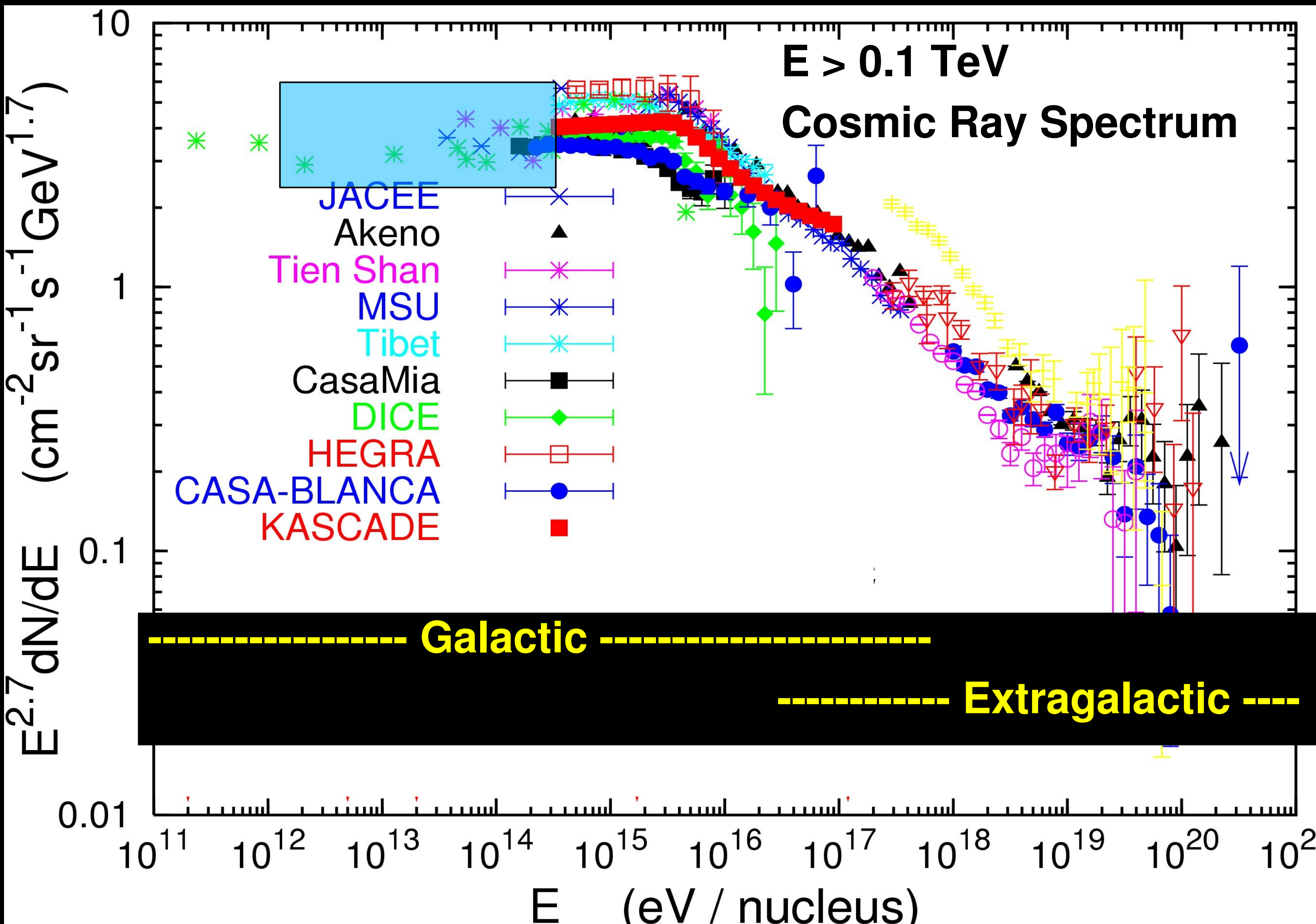
## Observational Gamma Ray Cosmology

***Large Scale Structures (Clusters of Galaxies),***
***Dark Matter Halos (indirect search)***
***Diffuse Extragalactic Background radiation (constraints)***
***Pair Halos***



Detector sensitivities
compared to the Crab Nebula
(50hrs obs.
5sigma)
COMPTEL
INTEGRAL
MEGA
EGRET
CELESTE
HEGRA–IACTs Crab Spectrum
GLAST
Whipple
HEGRA–IACTs
5@5
HESS
IC
S
also VERITAS, MAGIC-II, CANGAROO-III
HESS et al.
~10x better sens.
than earlier TeV
instruments
Energy Flux (erg/cm²s)
Energy (eV)

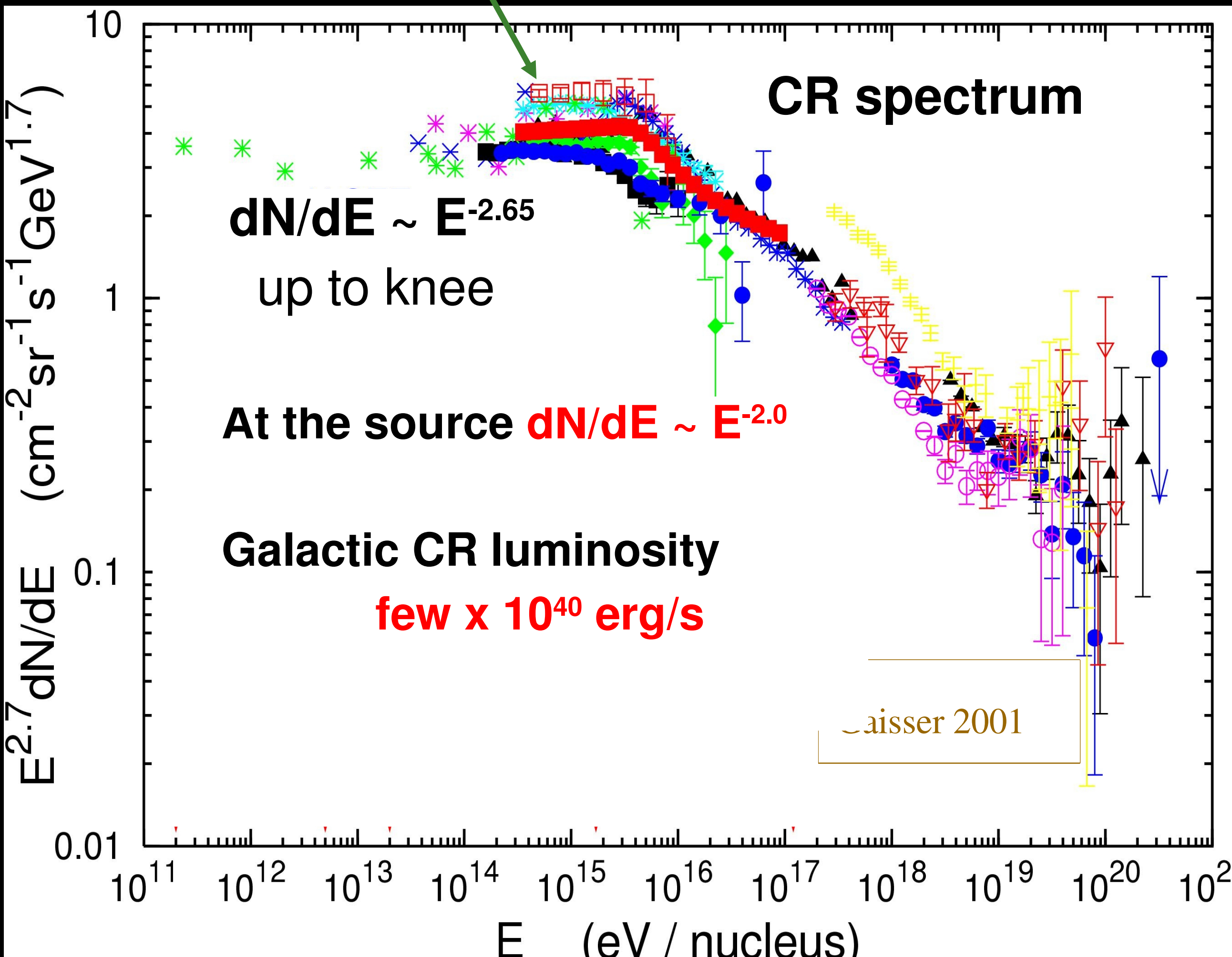
# 0.1 to ~10 TeV γ-Rays: Corresponds to ~1 – 100 TeV Particles



# Galactic **TeVatrons** and **PeVatrons**

**Particle accelerators responsible for Cosmic Rays (CR)**

**up to the *knee* ~$10^{15}$ eV (1 PeV)**




**Potential CR Accelerators**

**Shell Type Supernova Remnants?**

**Pulsar Wind Nebulae?**

**Pulsars?**

**WR, O & B stars?**

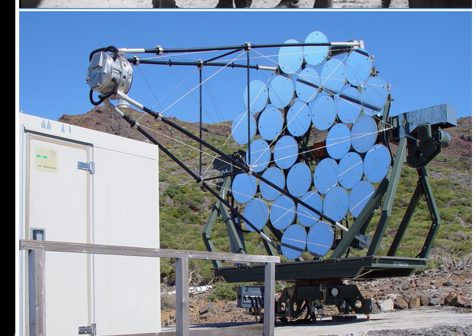
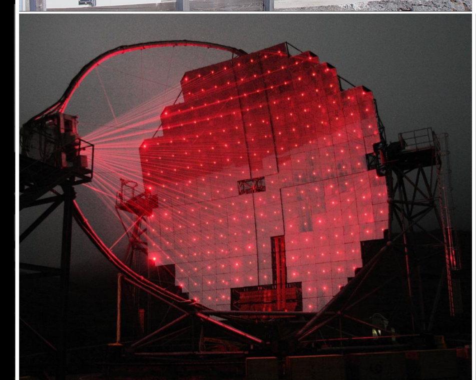
**Microquasars?**

**Galactic Centre?**

**Mechanism**

**Diffusive Shock Acceleration**

# History of Cherenkov Telescopes

**Whipple 1968 - 2004**

- 1989 Detection of Crab Nebula above 1 TeV
- 1992 First AGN, Mrk 421

**HEGRA 1992 - 2002**

- First Stereo system. Cas-A at 1 TeV
- First Unidentified TeV source

**CANGAROO 1992 -**

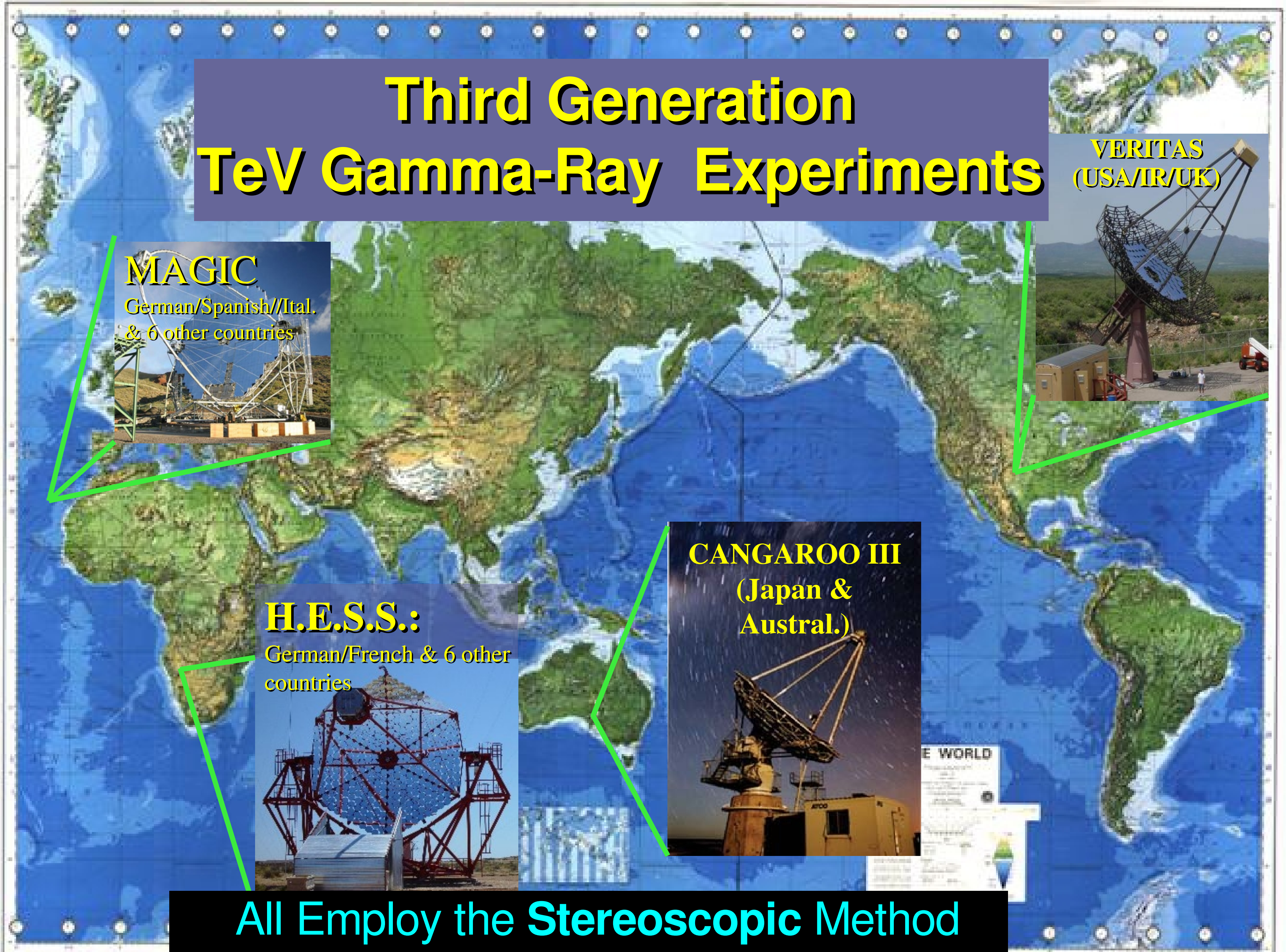
- Southern hemisphere. SNR RX J1713

**Also Durham Mrk 6, CAT… + non-imaging expts.**

**Since 2004: 3rd Generation instruments:**

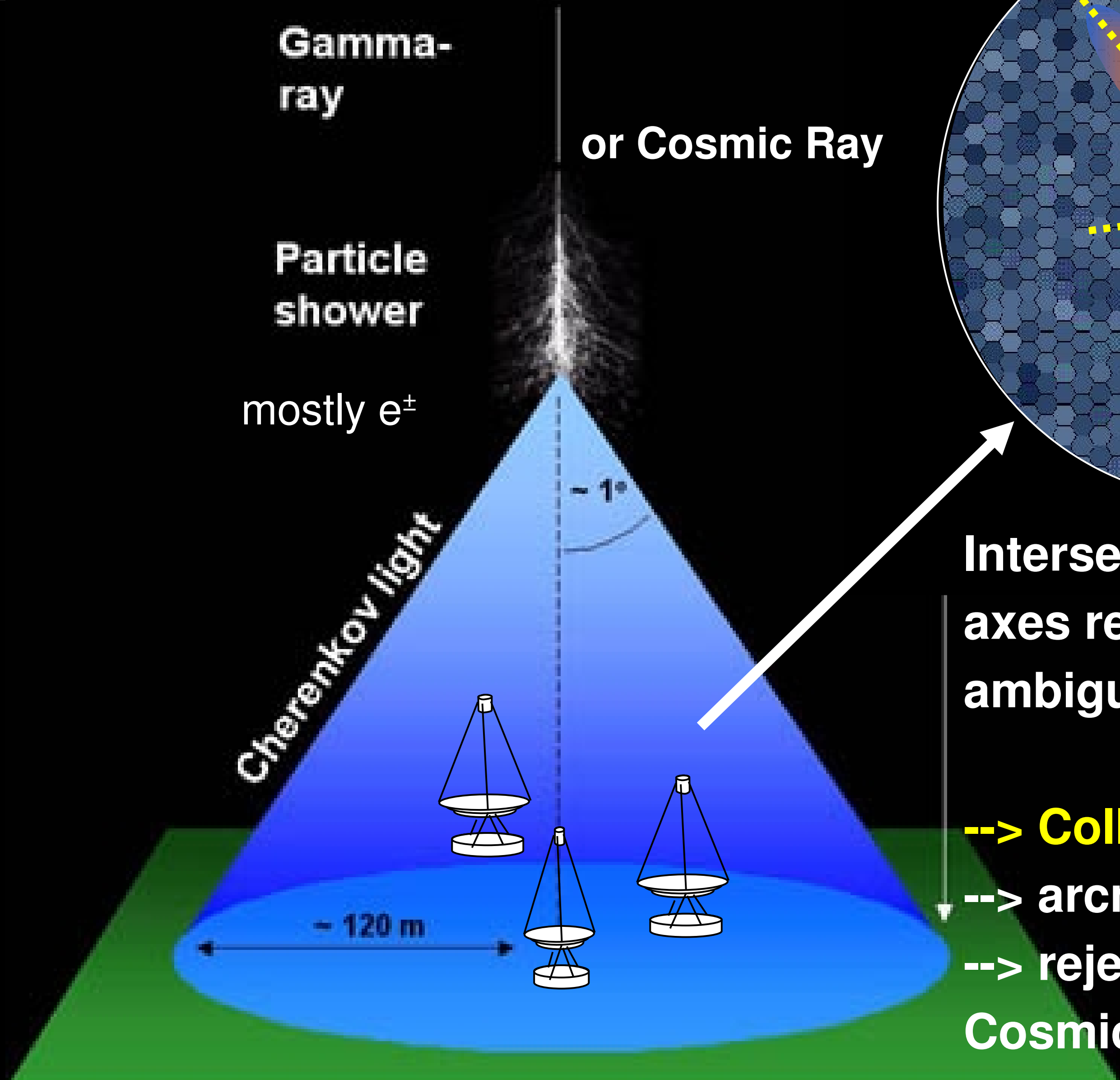
- HESS, MAGIC-II, VERITAS, CANGAROO-III
- Dramatic increase in TeV source catalogue
- Detailed spatial & spectral studies of sources

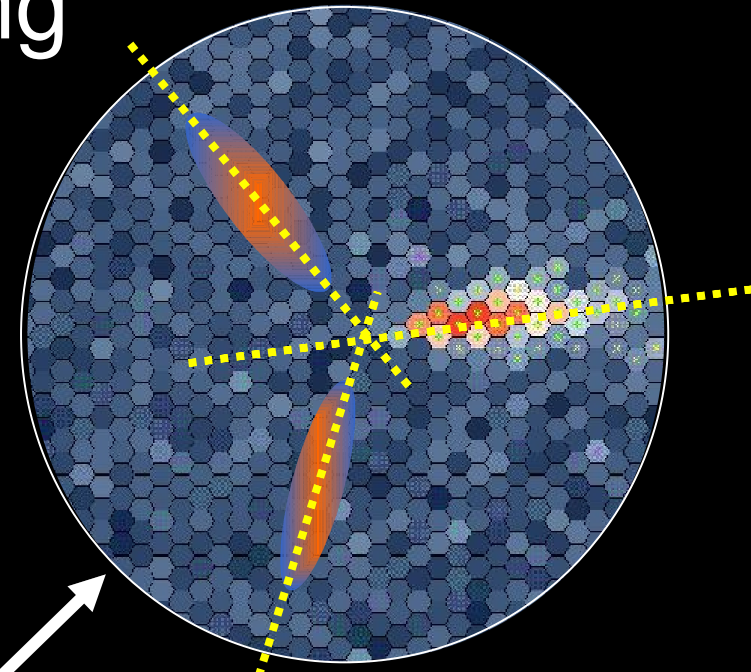
# Third Generation TeV Gamma-Ray Experiments




All Employ the **Stereoscopic** Method

# Stereoscopic Imaging



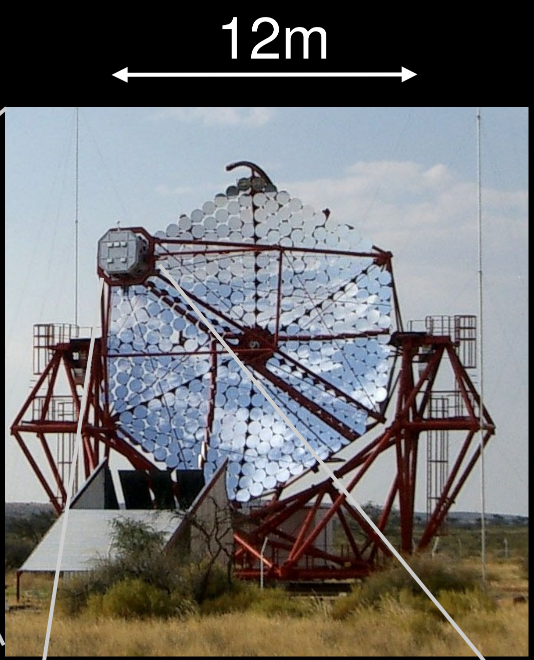
**Intersection of image axes removes direction ambiguity**

**--> Collection area >0.1 $km^2$**

**--> arcmin angular resolution**

**--> reject >99.9%of the CosmicRay background**

# The H.E.S.S. Telescopes



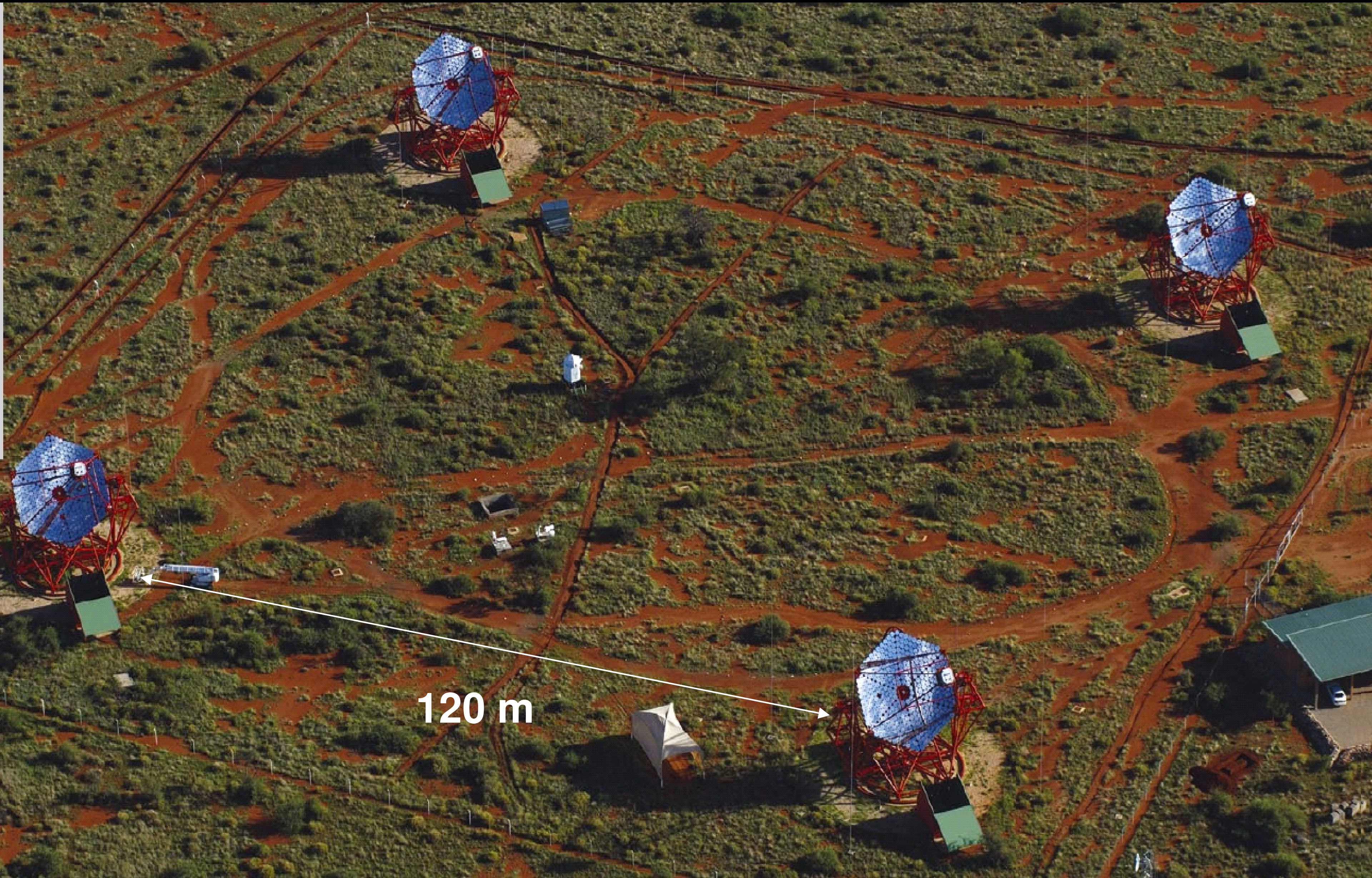

- **H**igh **E**nergy **S**tereoscopic **S**ystem
- 4 telescopes (in Namibia *23° S*)
  stereoscopic observation mode
- Each telescope: ~107m² mirror surface, 380 facets
- Photomultiplier camera (ns response)
  960 PMTs, ***~5° field of view (FoV)***
- Sensitive energy range:
  0.1 TeV up to several 10 TeV
- ***Angular resolution: ~0.1° per event***

→ ***arc-second src location***

***COST ~7-8 M Euro, several 100 kEuro/year***

***see http://www/mpi-hd.mpg.de/hfm/HESS.html***

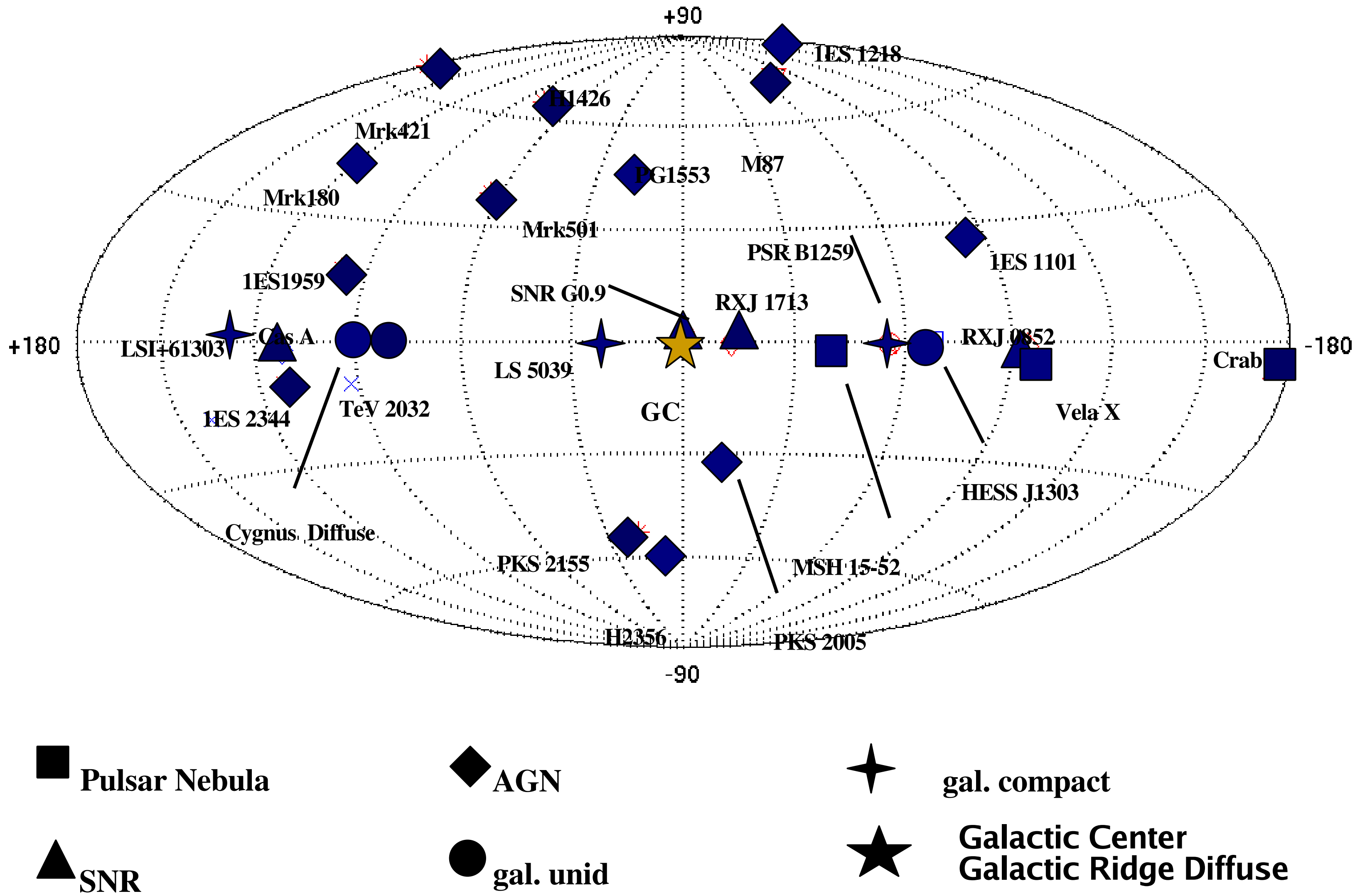
# HESS – From above



# The TeV Gamma Ray Sky – today

**Galactic, Extragalactic, GC, plus several unidentified**

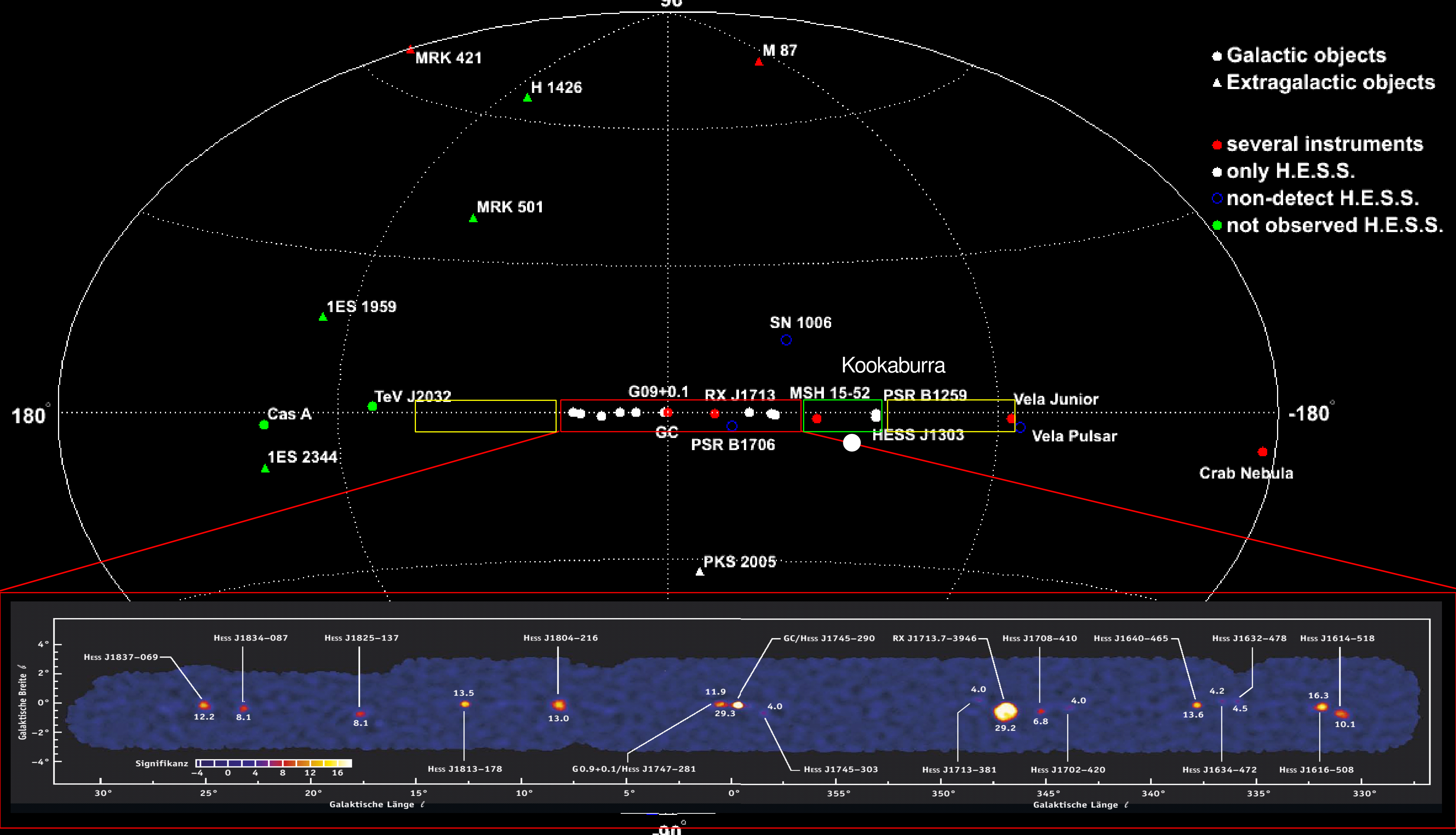
- many new source discoveries in recent years
- now at least 6-7 source types!



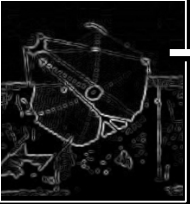
# H.E.S.S. surveys of the central Galactic Plane

## 14 new sources (2004) 2 new sources (2005)

## 2 new sources (2006)




## New scan regions 2006 (55° < l < 260°)



# TeV Gamma-ray Source Populations (Today)

**from all TeV experiments**

## Galactic Objects

- *Shell Type SNRs*
- Giant Molecular Clouds (star formation regions)
- *Pulsar Wind Nebulae (PWN)* Plerions
- several unidentified TeV sources …

## Compact Galactic Sources

- PRB 1259-63 (Binary pulsar*)*
- *LS5039* & LSI +61°303 (*Microquasars)*

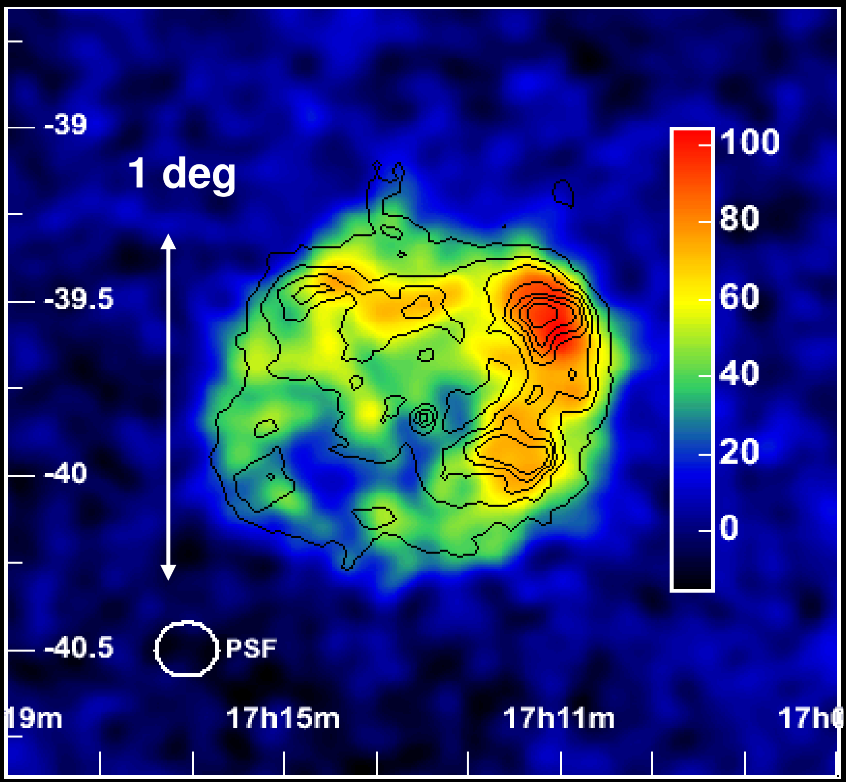
## Galactic Center

## Extragalactic objects

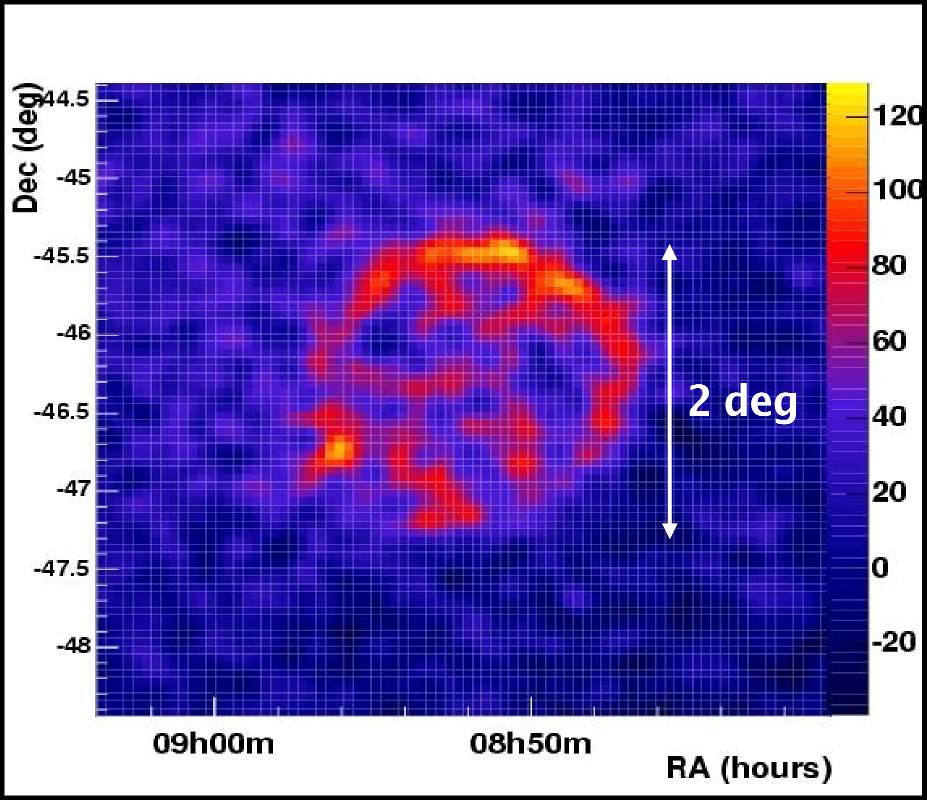
- M87 - a radiogalaxy
- TeV Blazars – with redshift from 0.03 to 0.18

# Shell-Type Supernova Remnants (SNRs)

**RX J1713.7-3946**



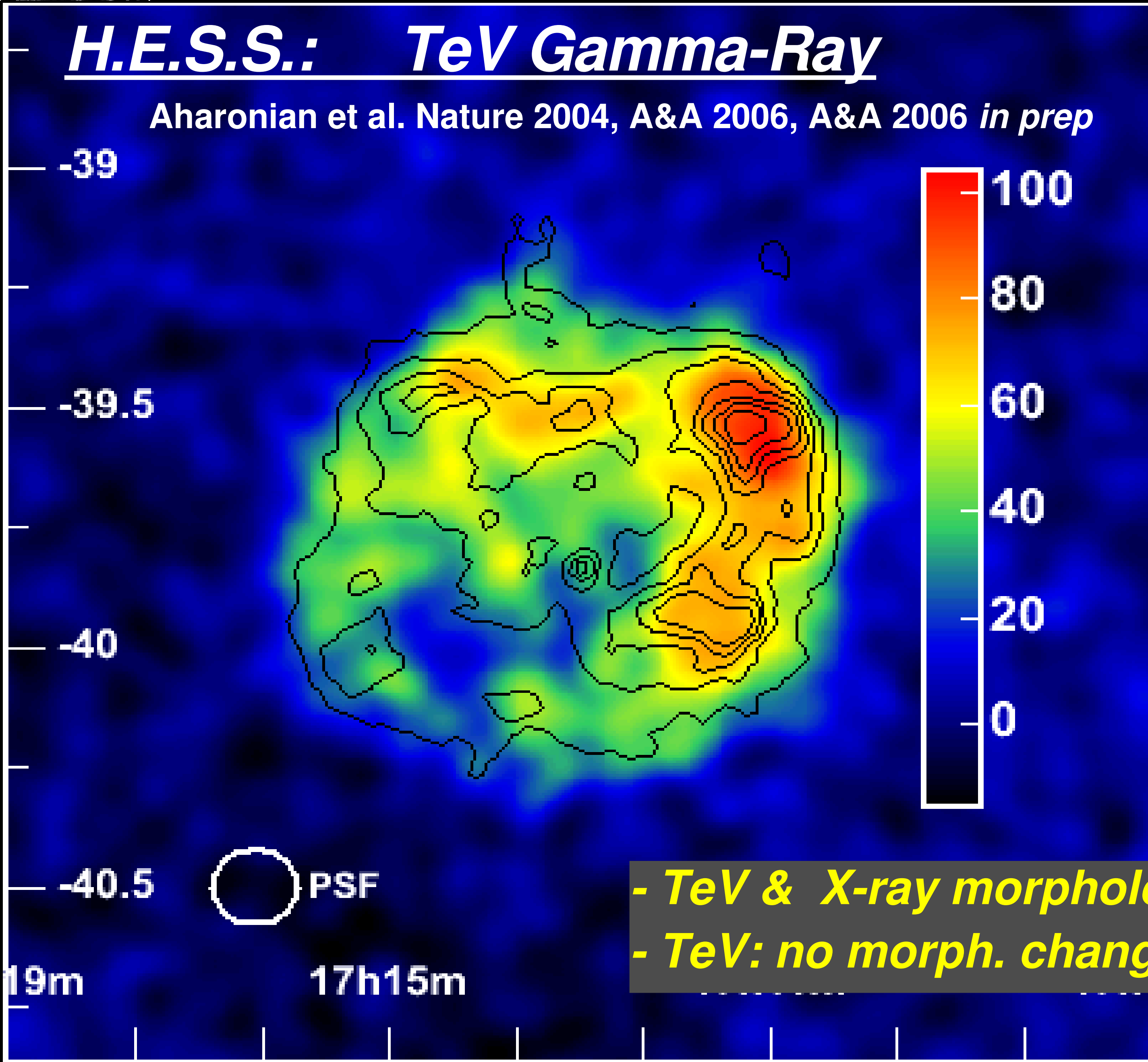

**RX J0852.0-4622 'Vela Junior'**

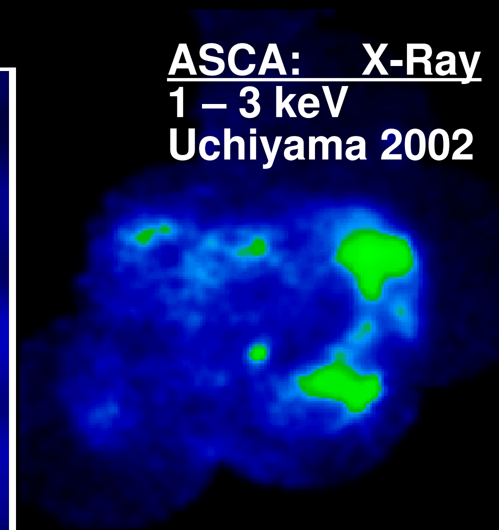



**The first images in gamma-ray astronomy.**

***Now we're doing real Astronomy!***

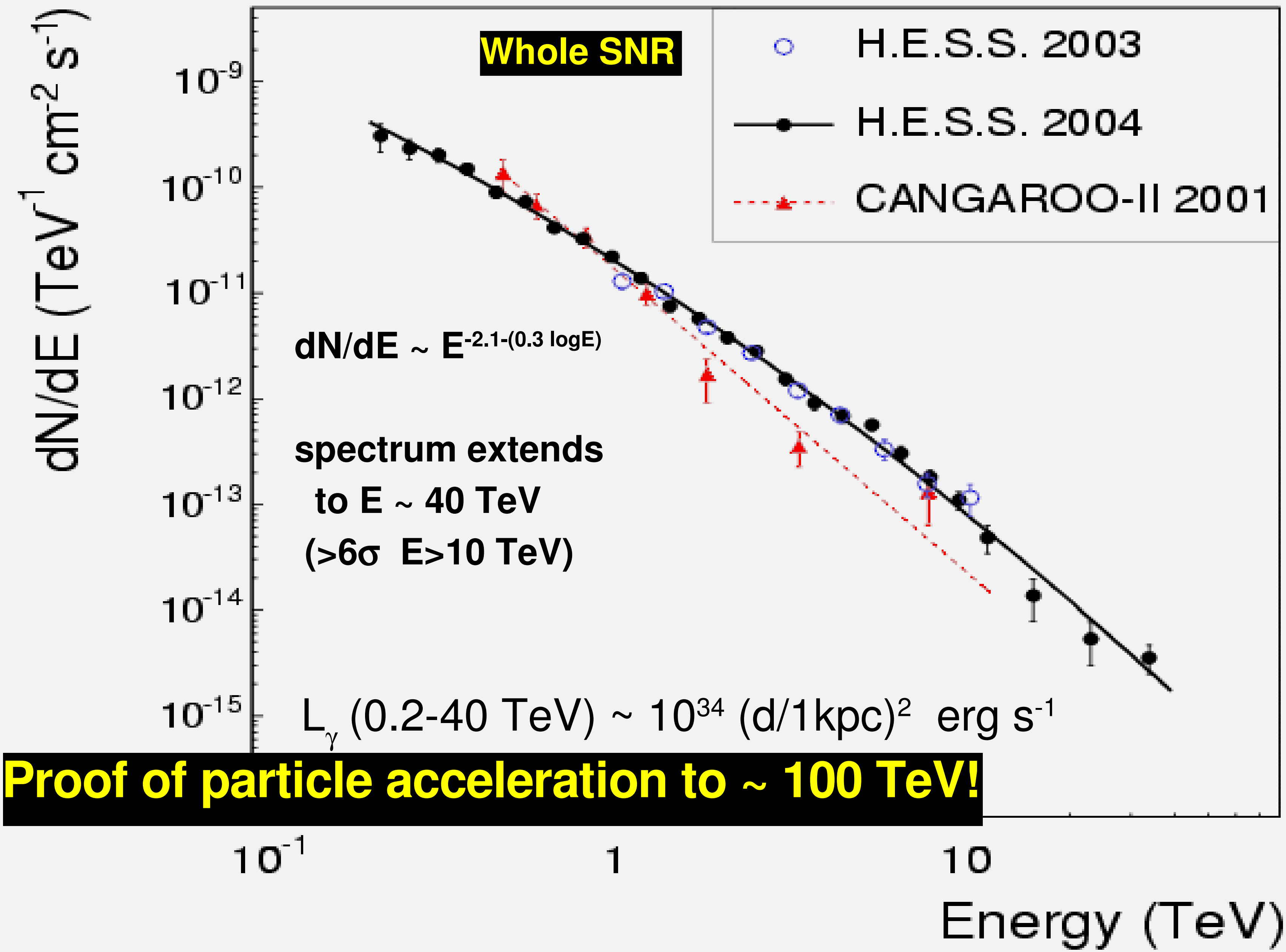
# RX J1713.7-3946



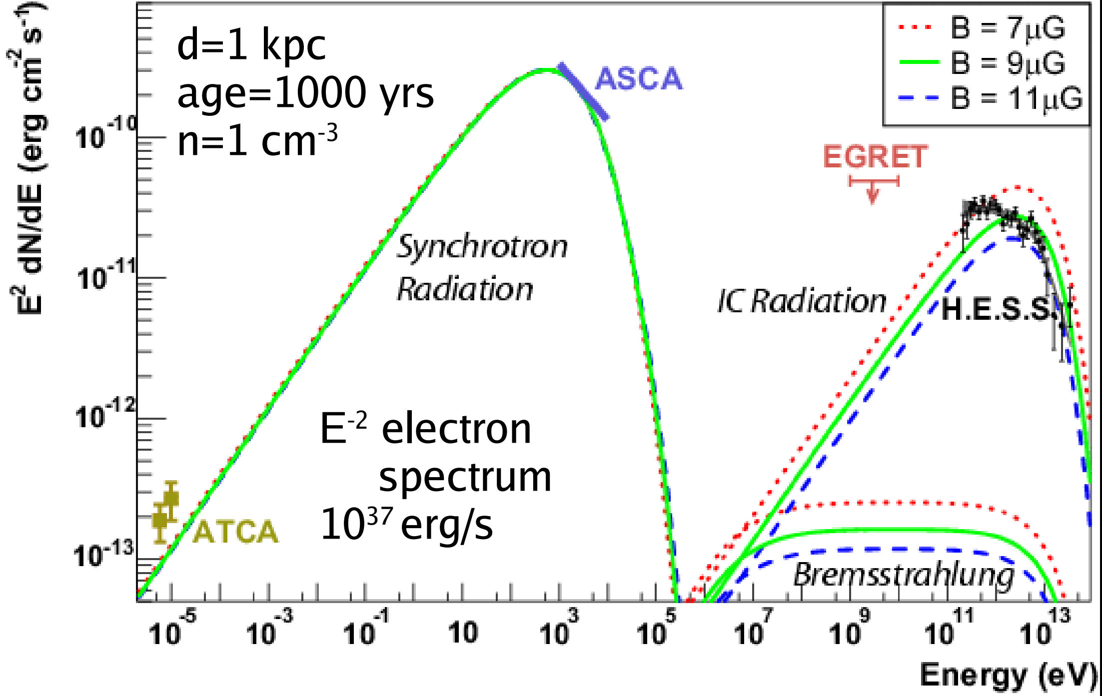




- *TeV & X-ray morphology v. similar*
- *TeV: no morph. change with energy*

# Energy Spectrum 0.2 – 40 TeV




**Proof of particle acceleration to ~ 100 TeV!**




**Synchrotron & IC Scenario (One zone)**

electrons dN/dE ~ $E^{-2}\exp(-E/E_c)$

IC – CMB + IR photons

Source age ~ 1000 yrs

n ~ 1 $cm^{-3}$ (NANTEN --> ~2 $cm^{-3}$)

- uncomfortably low B field
- difficult to match IC turnover with simplistic model.

But see Porter et al 2006

**Hadronic Scenario**

protons dN/dE ~ $E^{-2}\exp(-E/E_c)$

extrapolate to EGRET upper limit

-- > no violation

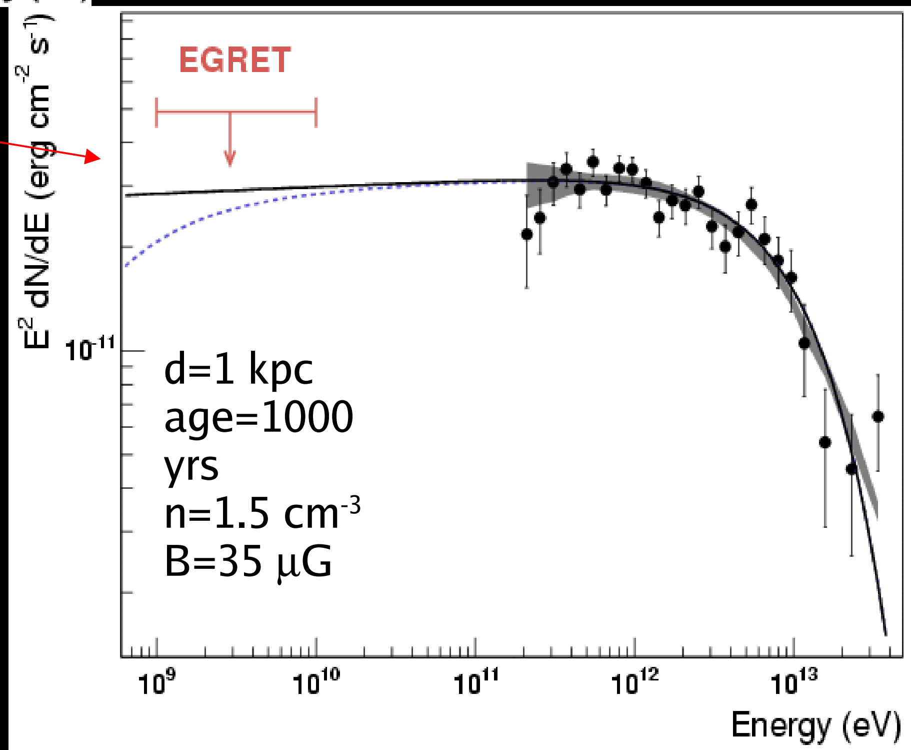
especially when $\pi^o$ decay kinematics included

Required proton energetics $W_p$

$W_p$ (2-400 TeV) ~ $6\times10^{49}$ erg $(D/1\mathrm{kpc})^2$ $(n)^{-1}$

$W_p$ (0.001-400 TeV) ~ $10^{50}$ erg

Hadronic scenario generally favoured



# RX J0852.0-4622 'Vela Junior'

**TeV discovery CANGAROO**
**Katagiri etal 2005**

**2004 & 2005 HESS Obs**
**Aharonian etal 2005, 2006 (in prep)**

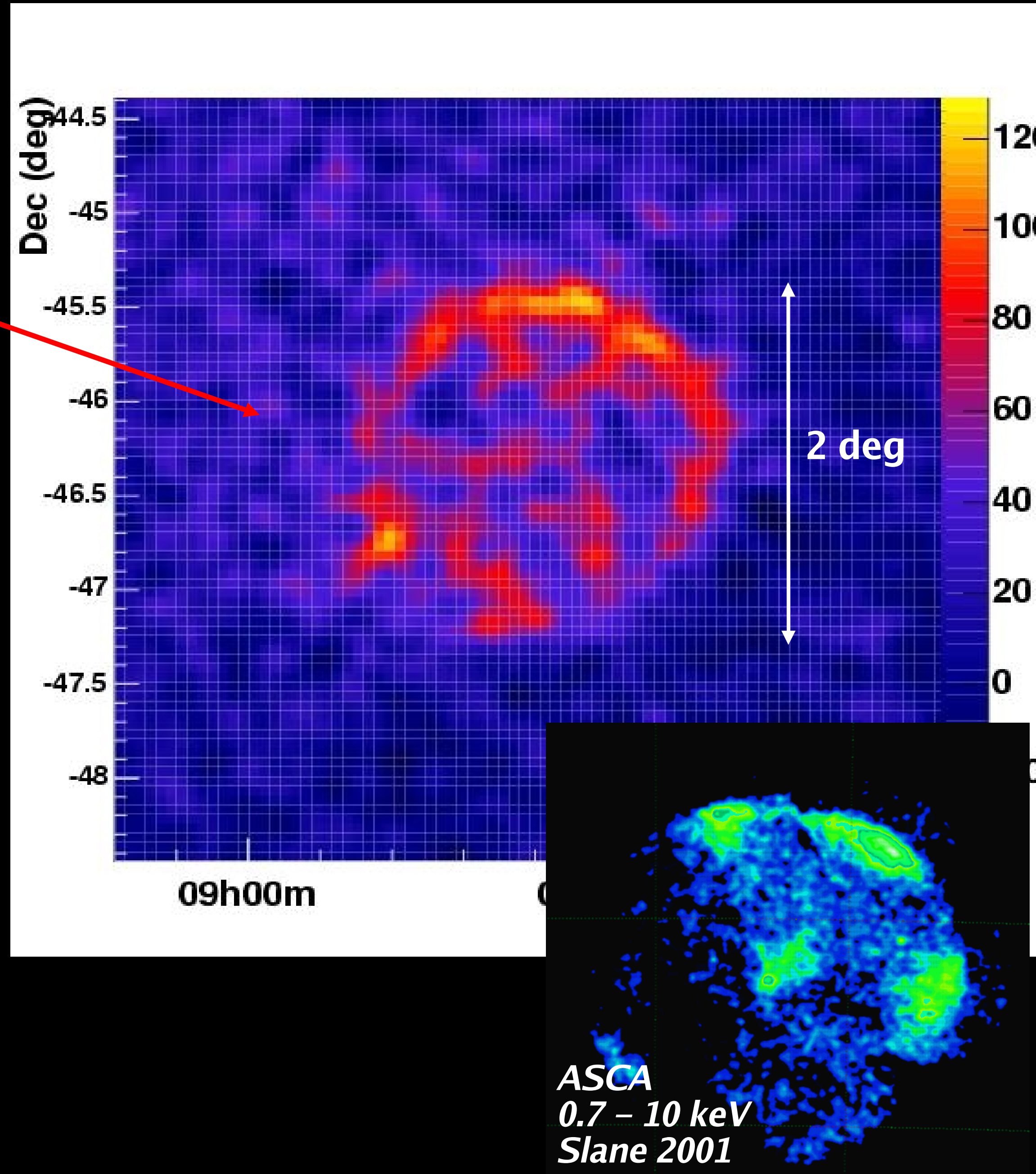
- **20 hr**
- **~ 1 Crab flux in total**
- **5200 events (19 $\sigma$ )**

**$L_\gamma$ (1-10 TeV)**

**~ $10^{32}$ $(d/200pc)^2$ erg $s^{-1}$**

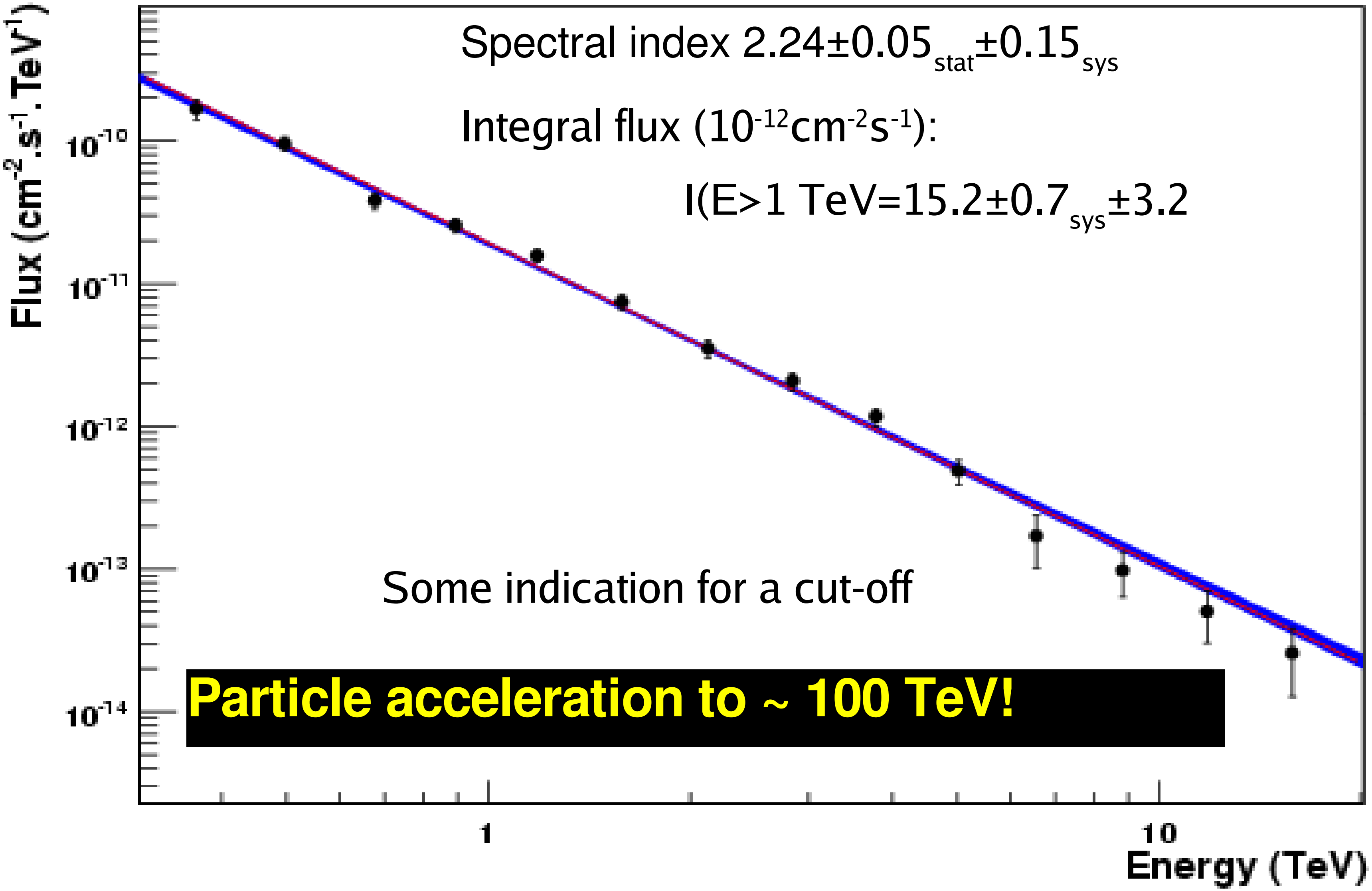
**Power Law spectrum**

**$\Gamma = 2.23$**



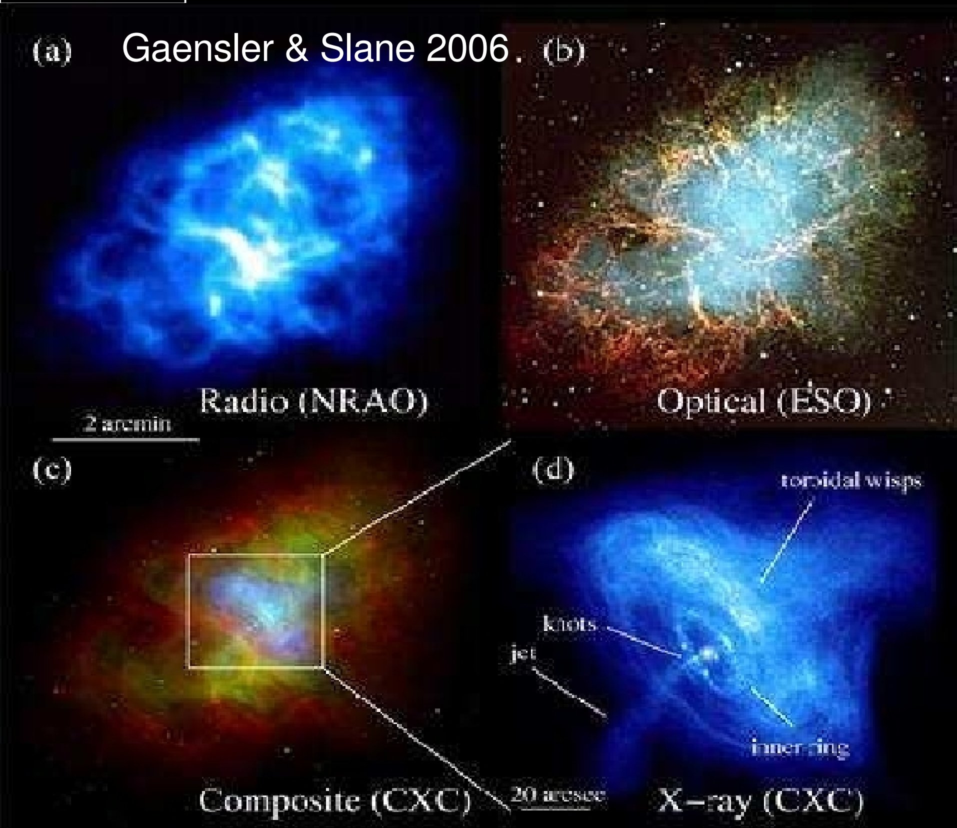
# Energy spectrum: 0.3-20 TeV

Power law:



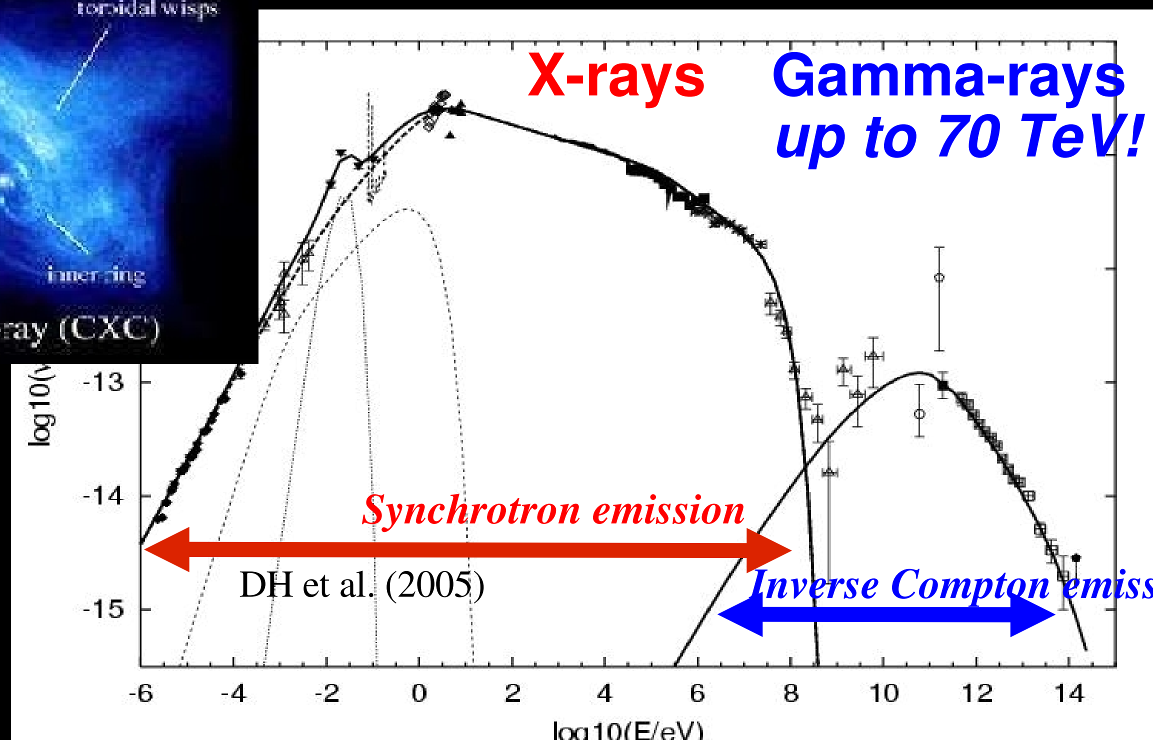
# Pulsar wind nebulae

## "Classical" Object: The Crab nebula (SN1054)




**Young, powerful pulsar.**
**Particle acceleration at pulsar wind *termination shock.***

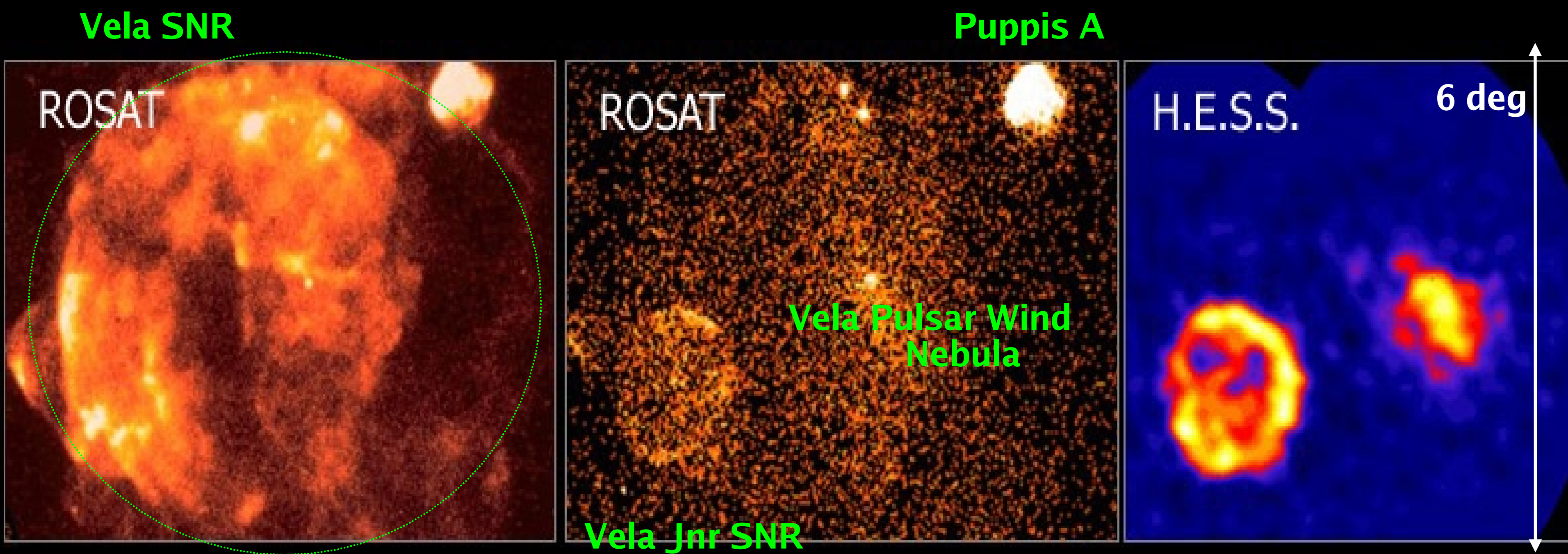
**Efficiency ~ 0.01% ($L\gamma$ / $E_{dot}$)**




**X-ray & Gamma-ray observations suggest electron acceleration**

**Key signature: sync+IC Double Peak**

# The Vela SNR Region




0.1< E < 2.4 keV E >1.3 keV TeV Energies

Aschenbach (1998)

**<u>Vela SNR</u> ~ 290 pc distance**

**age 10 kyrs**

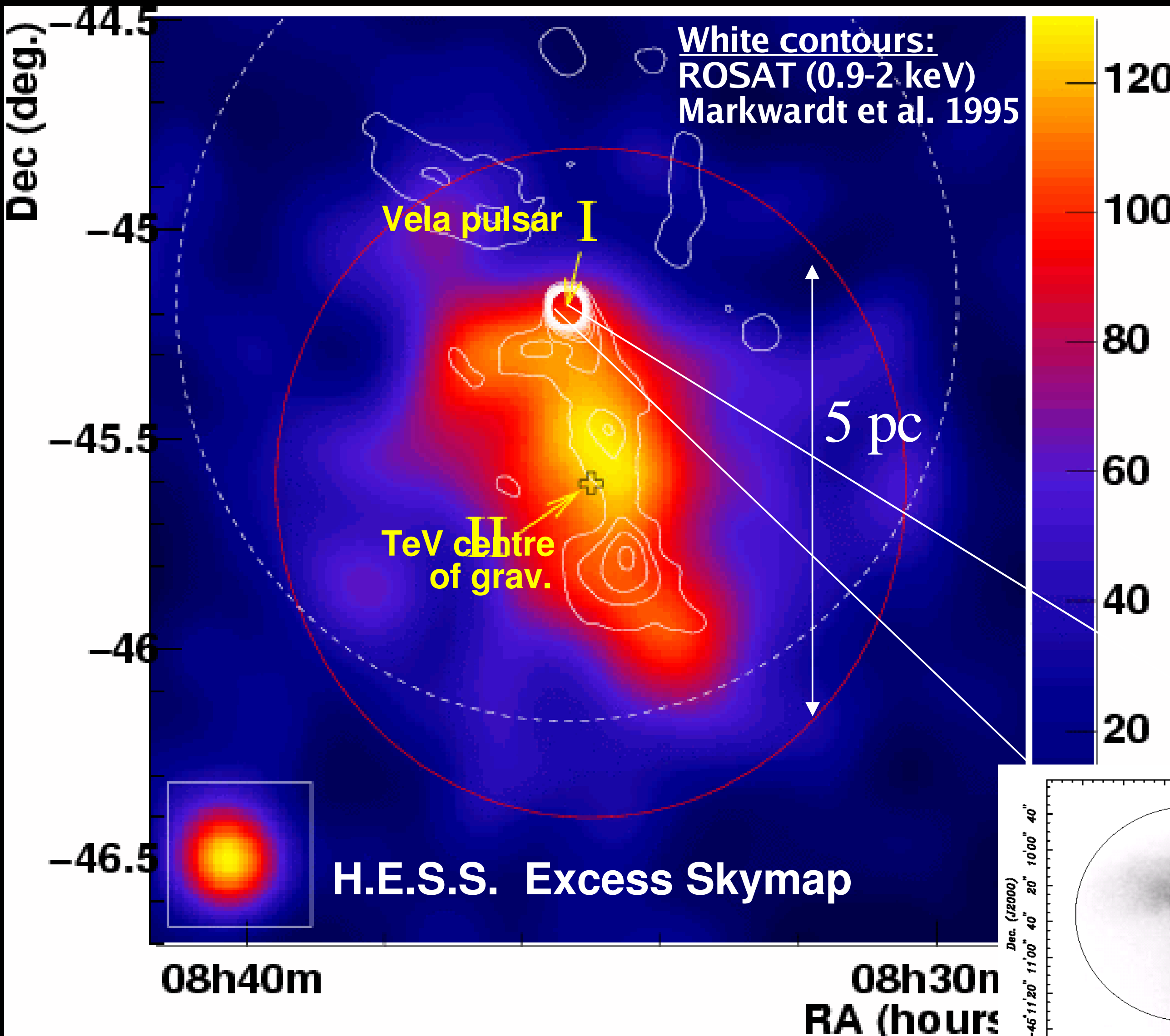
**<u>Vela Pulsar PSR B0833-45 (89 ms)</u>**

**E spin-down ~ $10^{37}$ erg $s^{-1}$**

**Central PWN in radio & X-rays**

# Vela–PWN (G263.9-3.3) Aharonian et al 2006

**Asymmetric pulsar wind nebula**

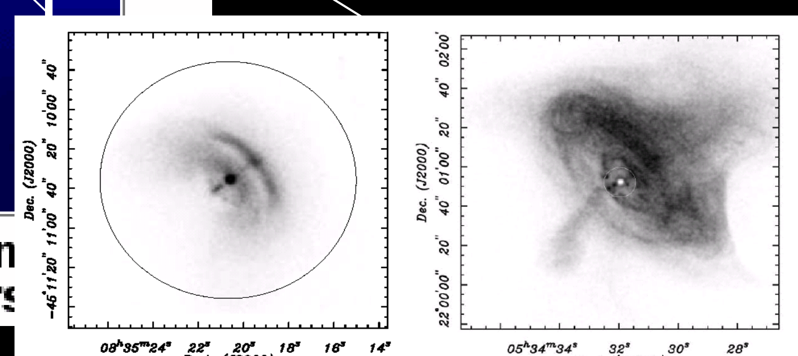



2004/2005 17 hrs obs

Extended TeV emission

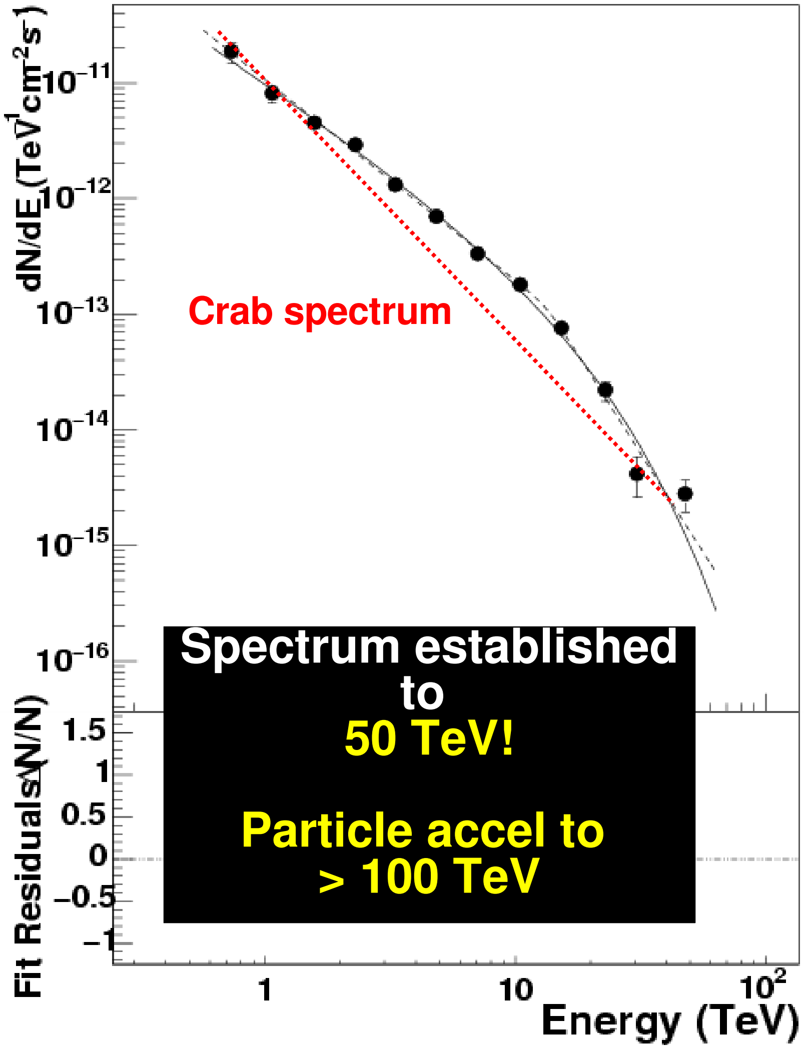
~ similar to X-ray morphology

Eff ~ 0.01%



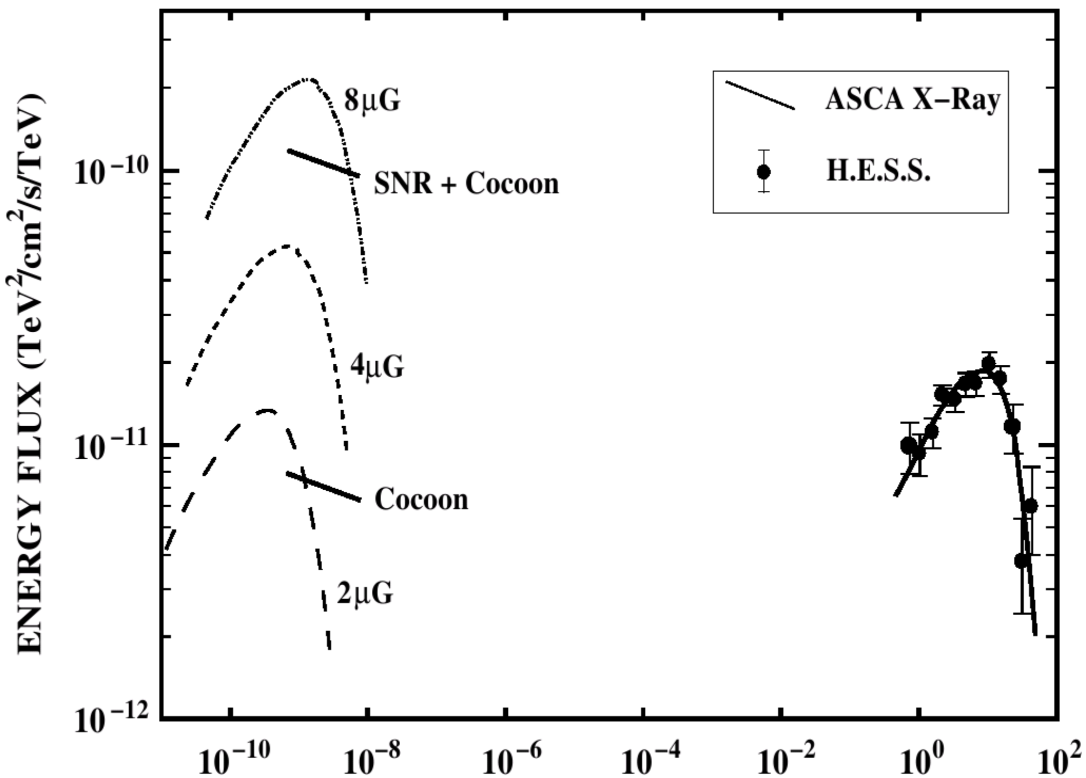
# TeV Energy spectrum: Vela Plerion

$dN/dE \sim E^{-1.45} \exp(-E/13.8)$




Spectrum established to **50 TeV!**

**Particle accel to > 100 TeV**




VERY hard power law + exp cutoff

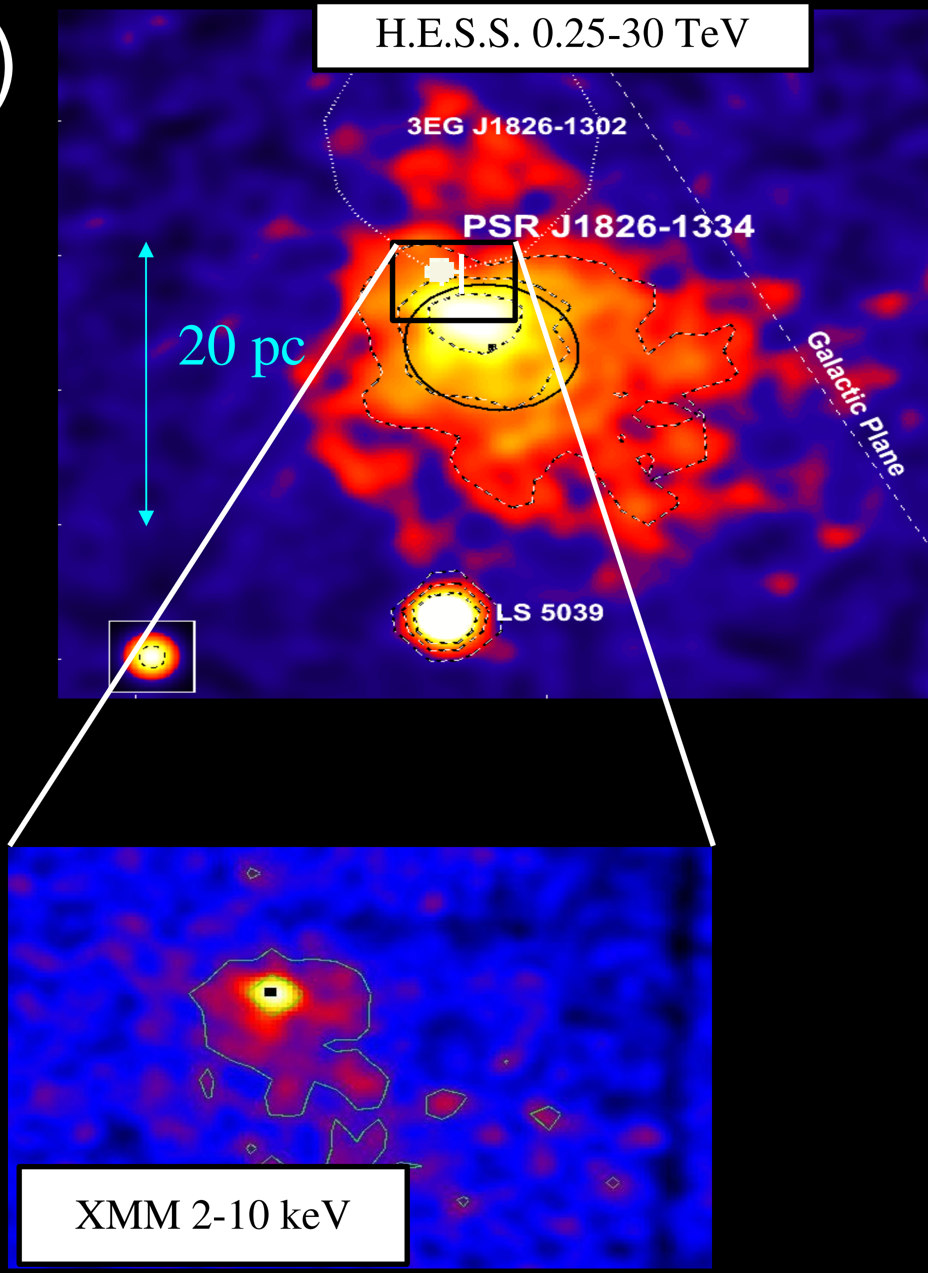
**First observation of a νFν (energy-flux) peak in a gamma-ray source**

One zone IC model --> B-field few μG
(uncertainties in size of sync. X-ray nebula)

Hadronic origin considered
(Horns et al 2006) B ~ 10μG

# The offset PWN: G18.0-0.7 (HESS J1825-137)

A&A 442, 25 (2005)
astro-ph/0607548, accepted for publication in A&A



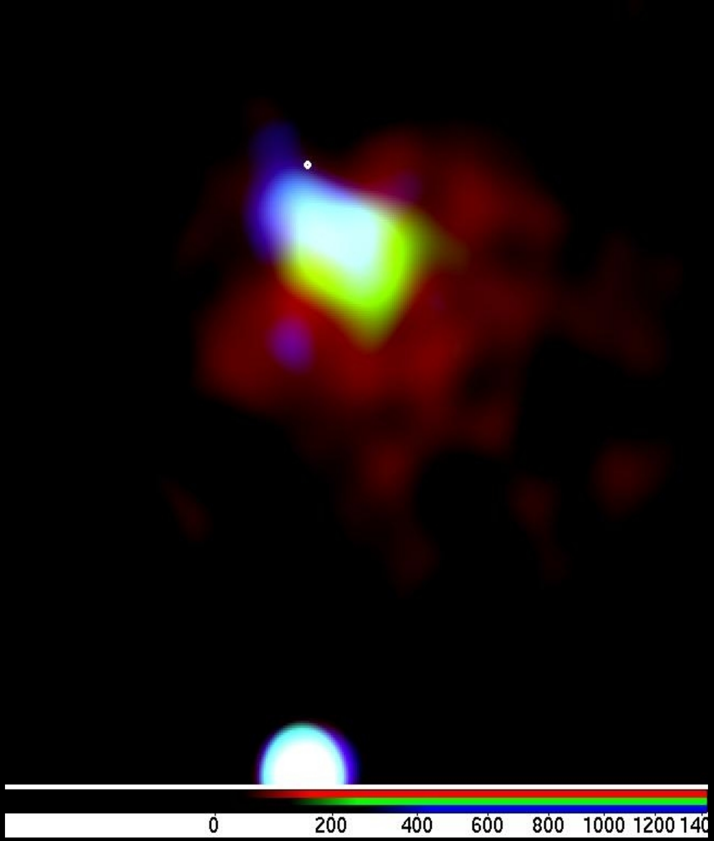

- **Middle aged (21 kyrs) pulsar at 4kpc PSR J1826-1334 powers asymmetric X-ray Synchrotron nebula (arc min size)**
- **TeV Gamma-ray emission from larger (1°) size and displaced region with asymmetric morphology**

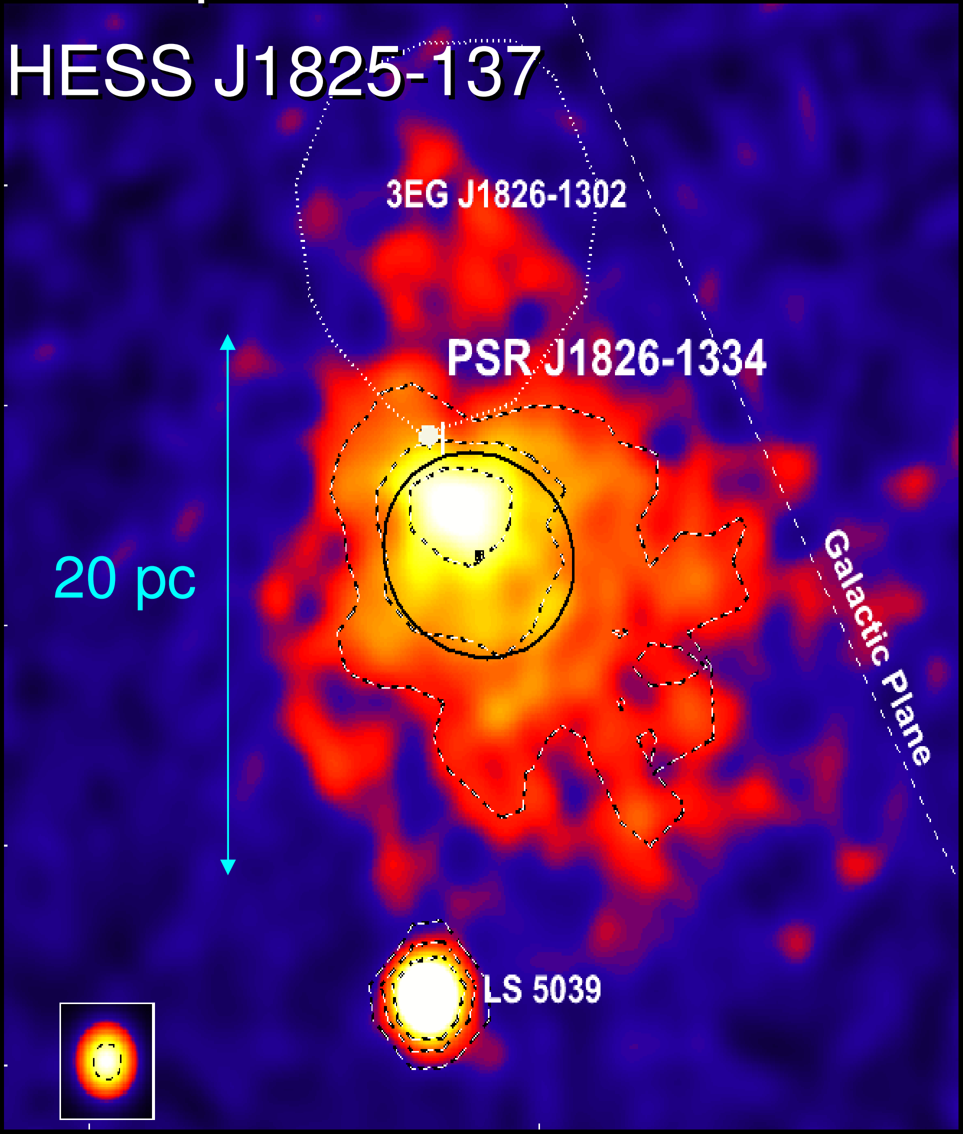
**Quite high $L\gamma > 10^{35}$ erg/s**

**Eff ~ 2%**

# Spatial variation of the TeV spectrum

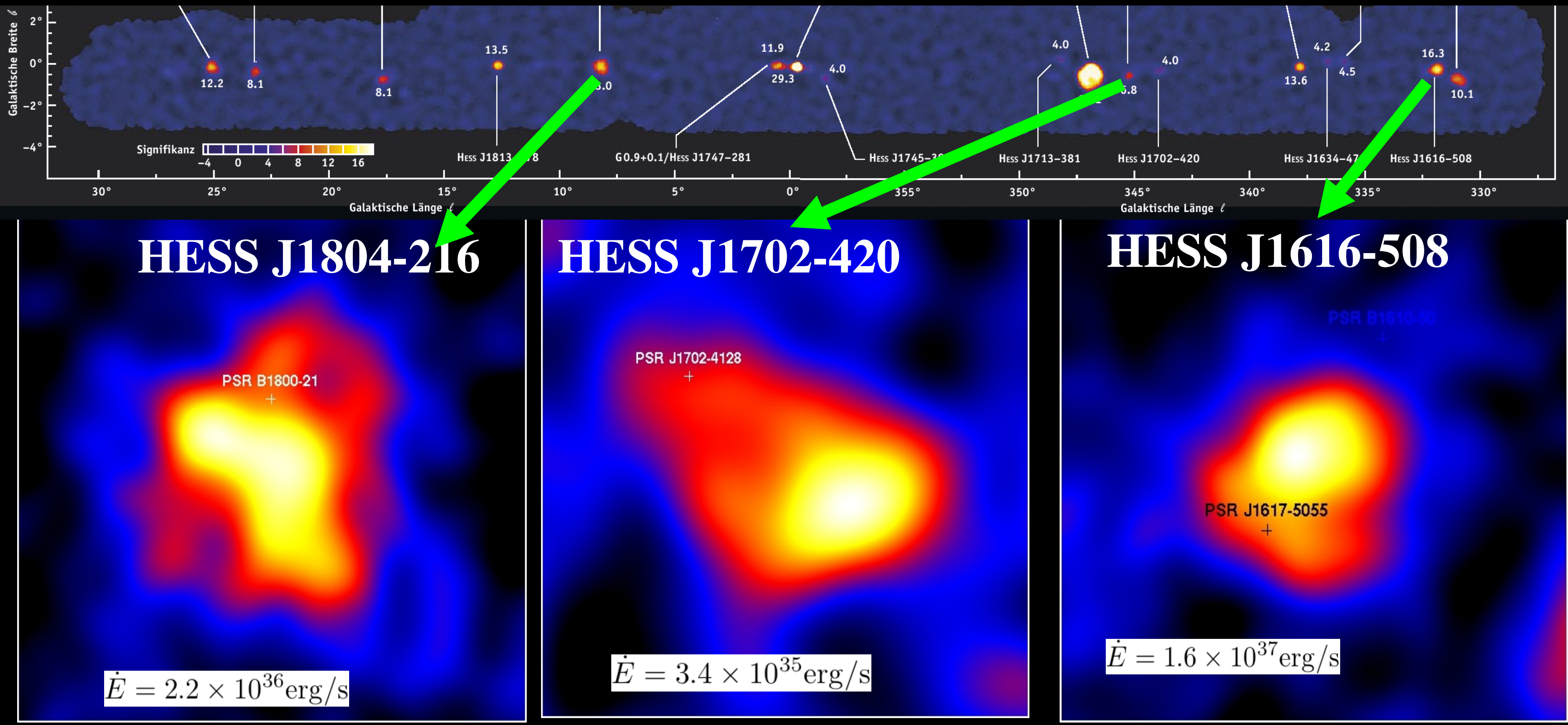
red – below 0.8 TeV
green – 0.8-2.5 TeV
blue – above 2.5 TeV




**Softening of γ-ray spectrum with distance from the pulsar:**
**--> evidence in favor of inverse-Compton (electrons) origin of γ-rays!**

# More TeV Pulsar Wind Nebulae..

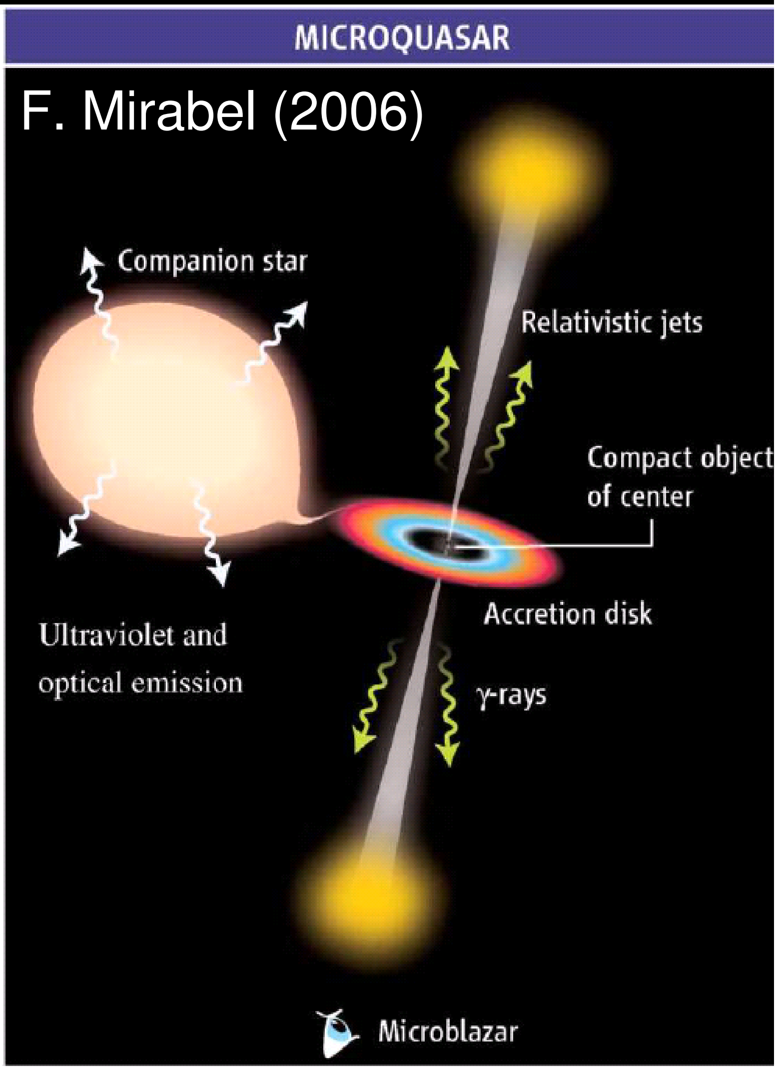


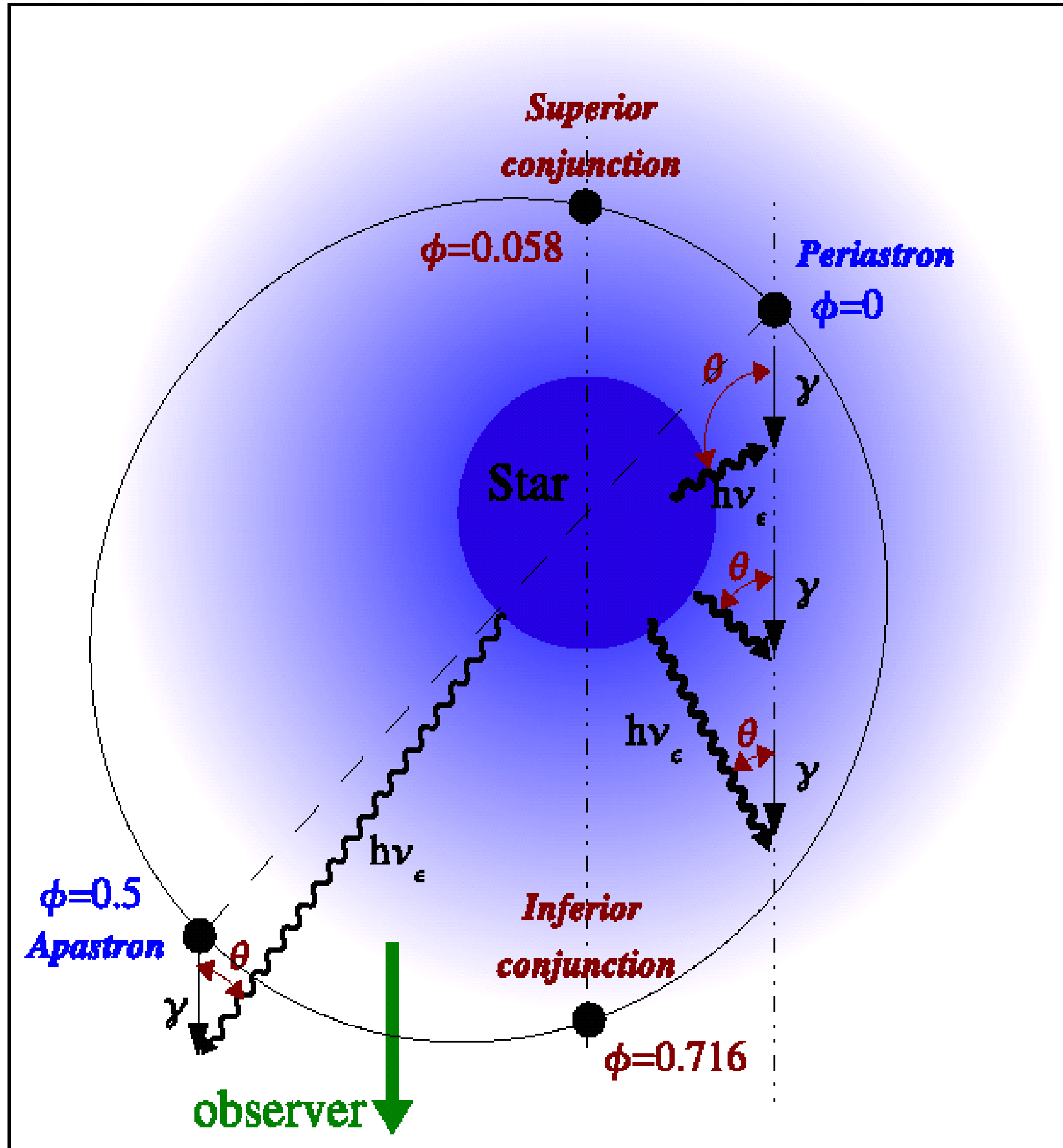

**PSR B1800-21**
*D* = 3.9 kpc
**Required efficiency 2.4%**

**PSR J1702-4128**
D = 4.8 kpc
**Required efficiency 11%**

**PSR J1617-5055**
*D* = 6.8 kpc
**Required efficiency 1.3%**

# Gamma-rays from binary systems: LS 5039



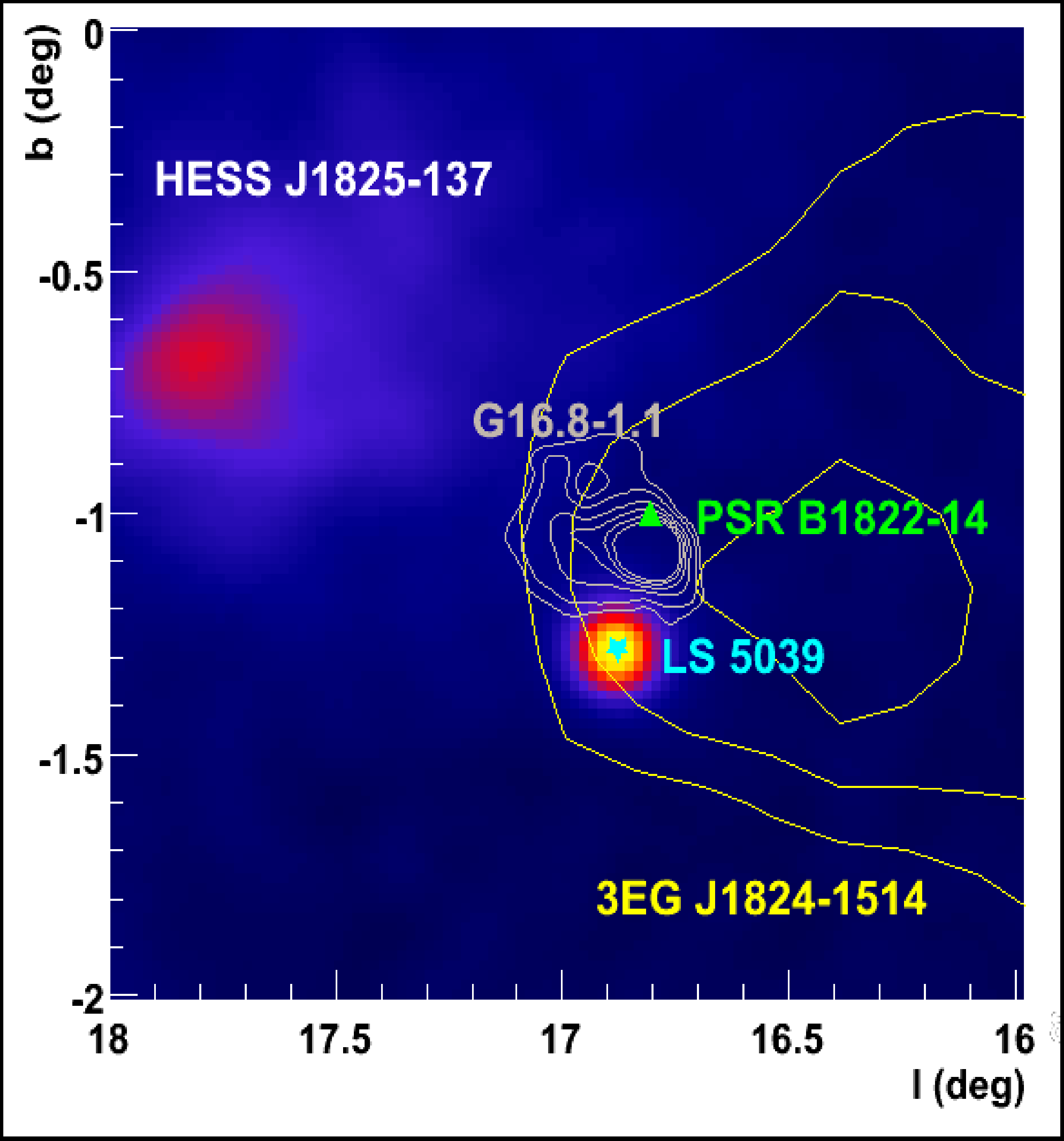
# LS5039

**HESS 2004 to 2006**

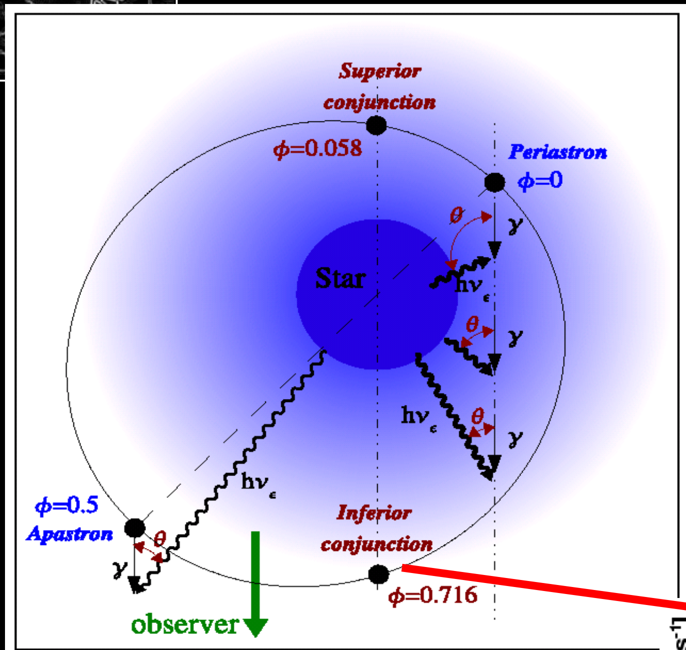
~60 hrs observation

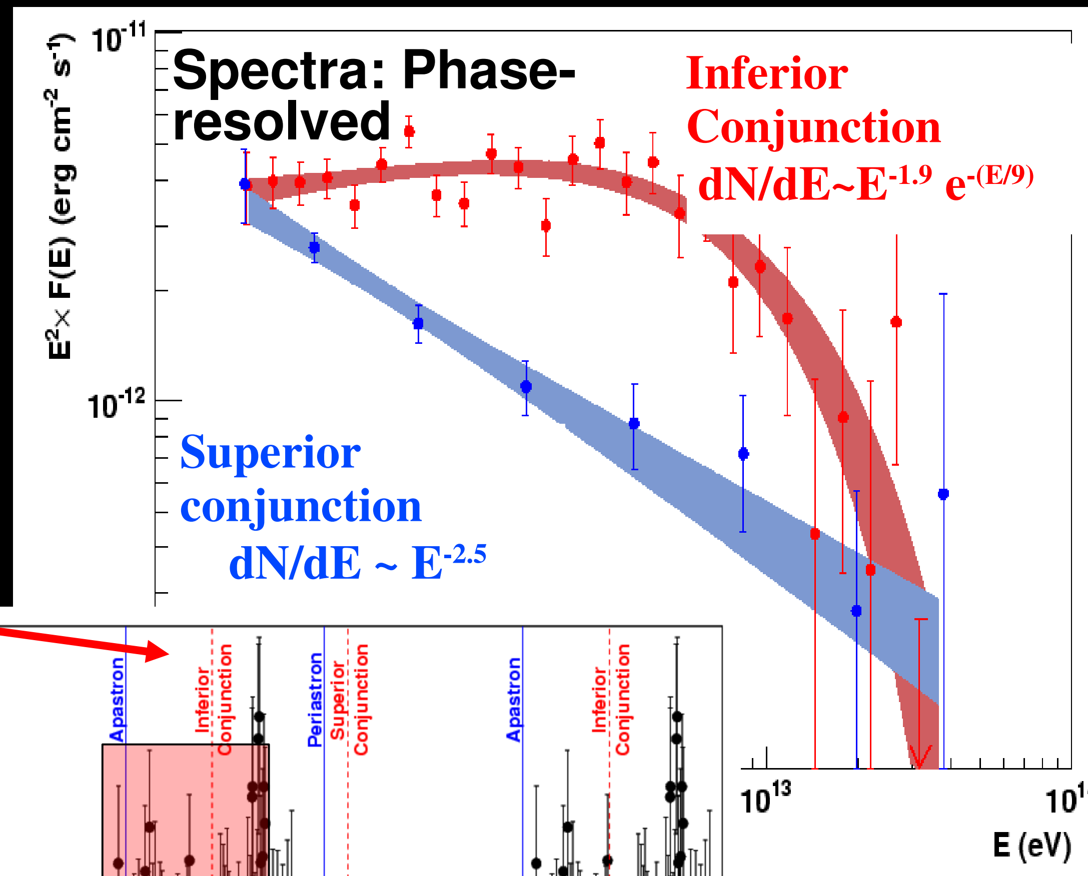
> 40σ detection

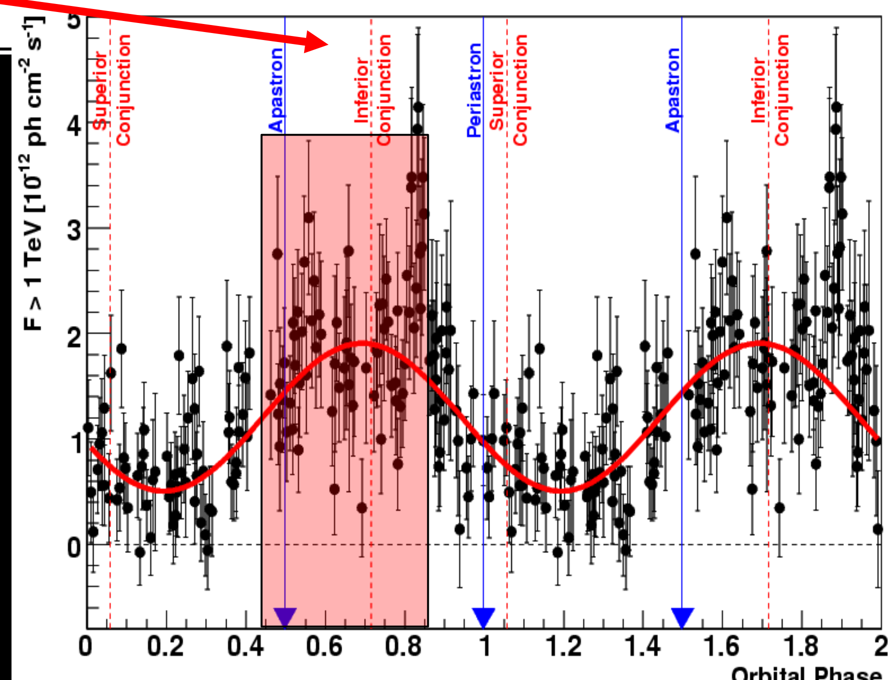
> 2000 gammas



# Orbital Phase-Resolved Analysis



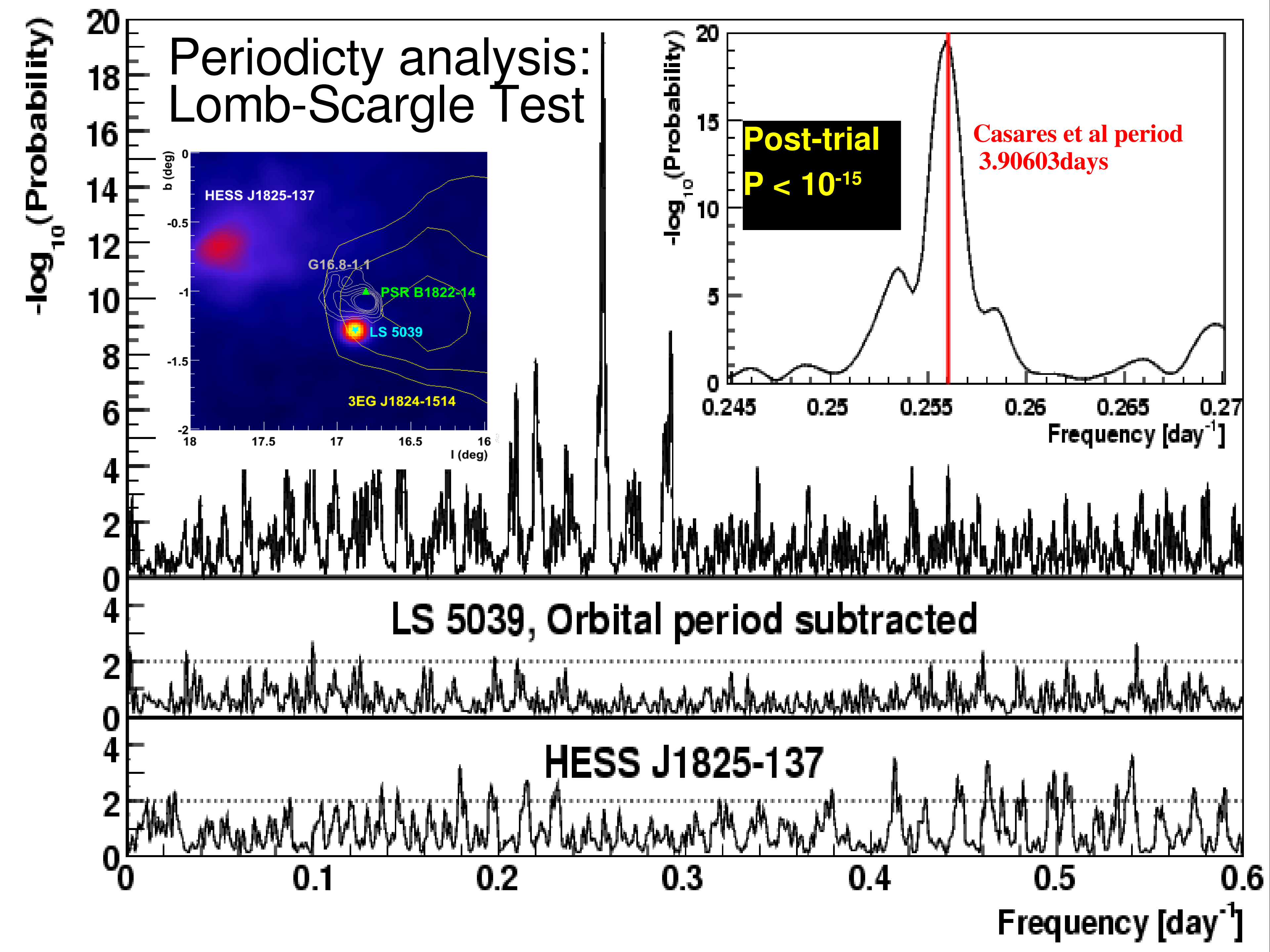




**Maximum coinciding with ~inferior conjunction**

Minimum around superior conjunction (non-zero!)

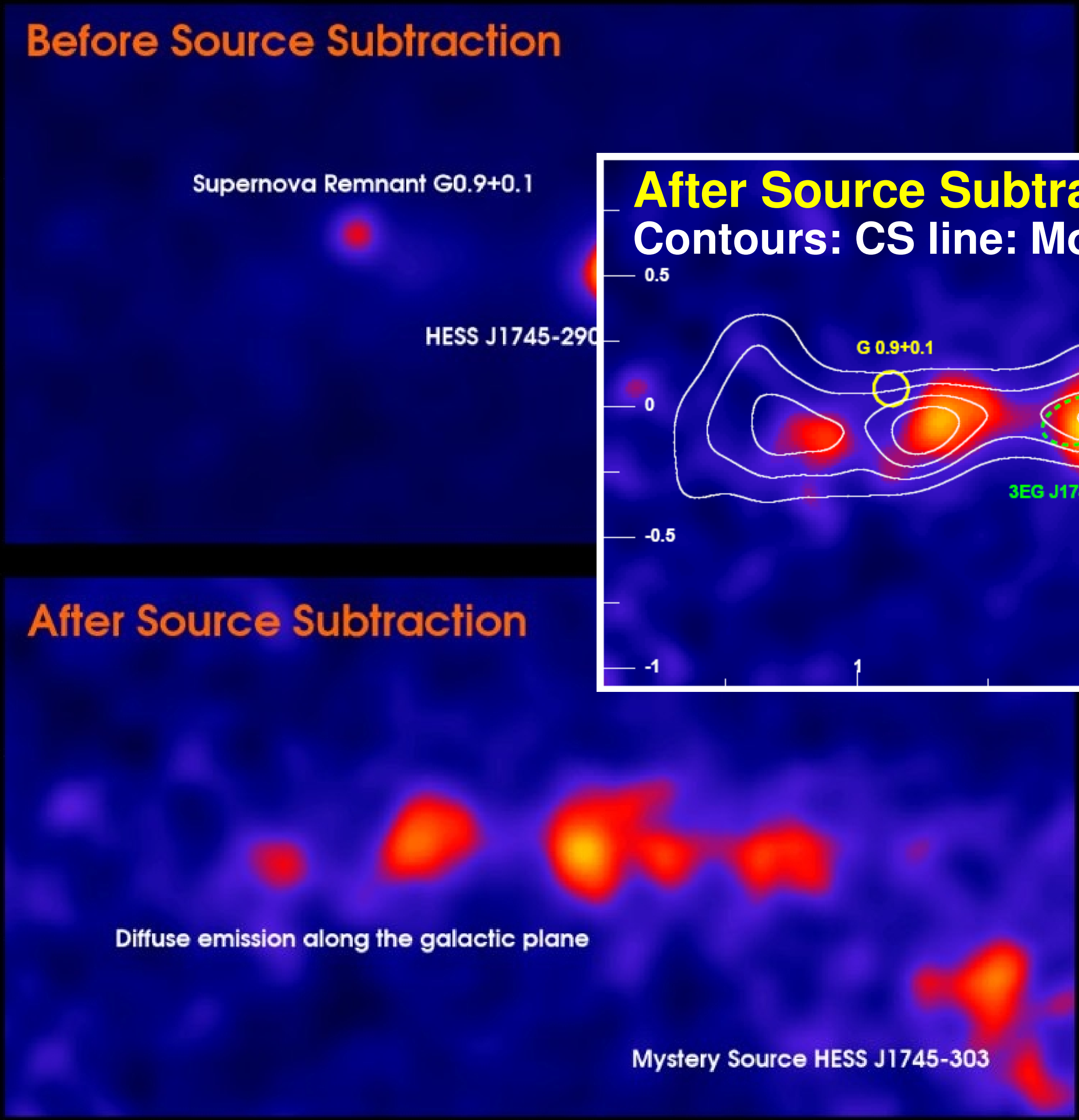
Sufficient statistics for phase-resolved spectroscopy

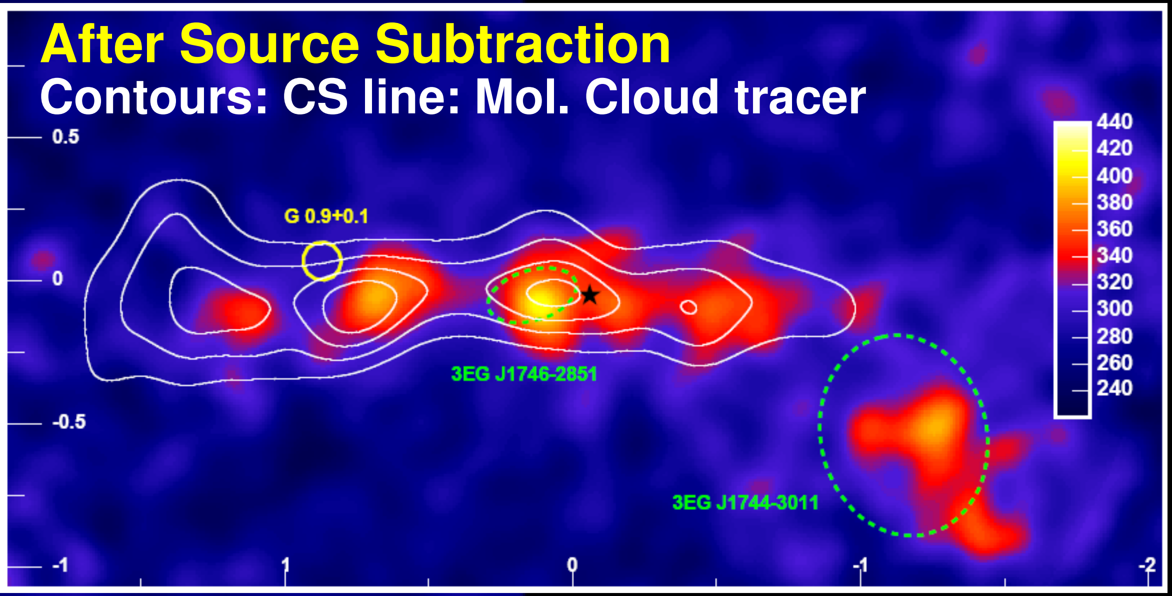


Periodicty analysis:
Lomb-Scargle Test
-log10(Probability)
HESS J1825-137
G16.8-1.1
PSR B1822-14
LS 5039
3EG J1824-1514
b (deg)
l (deg)
Post-trial
P < 10-15
Casares et al period
3.90603days
Frequency [day-1]
LS 5039, Orbital period subtracted
HESS J1825-137
Frequency [day-1]

# Galactic Centre Region: Diffuse Emission

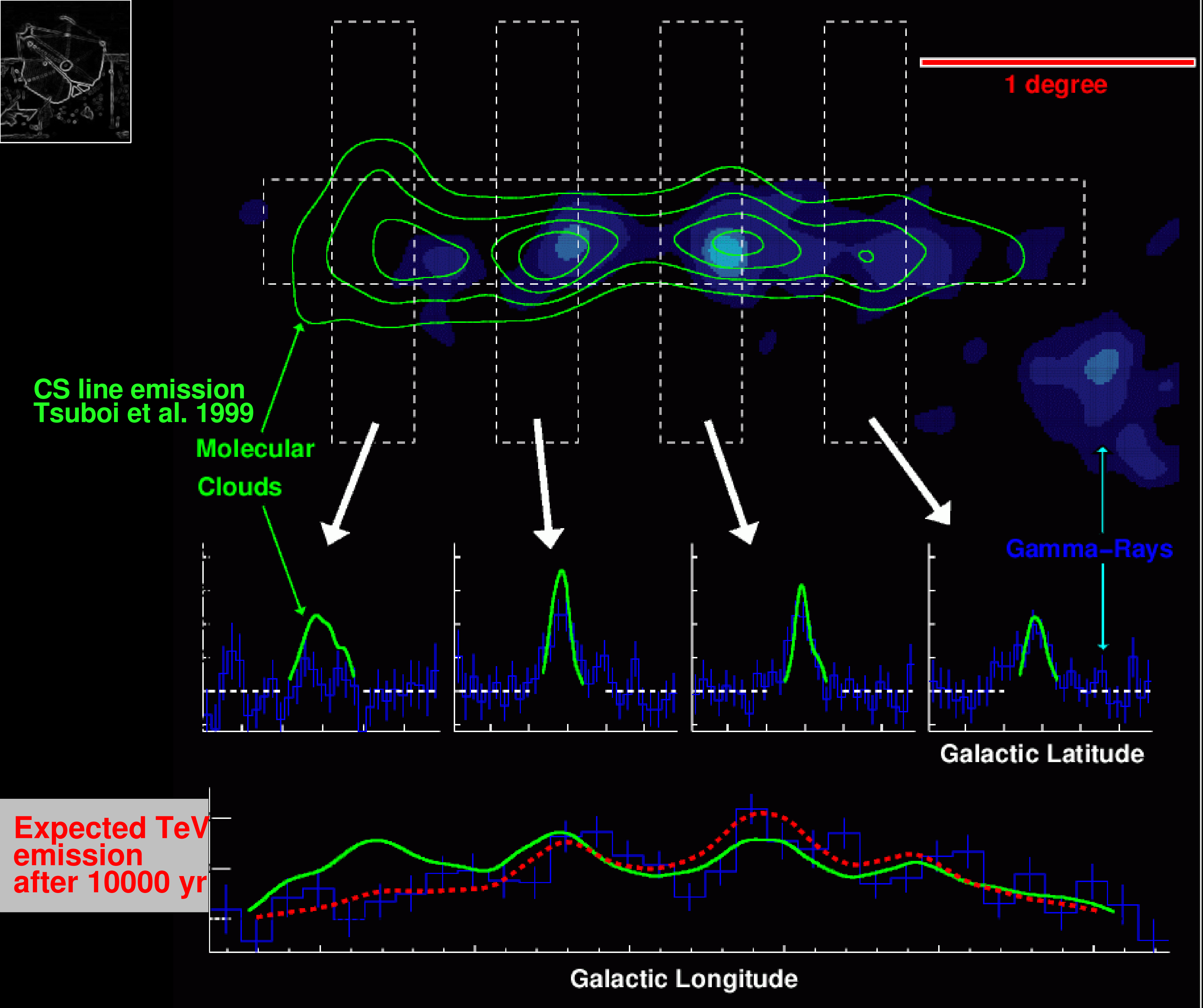
Aharonian et al (2005) Nature 439, 695



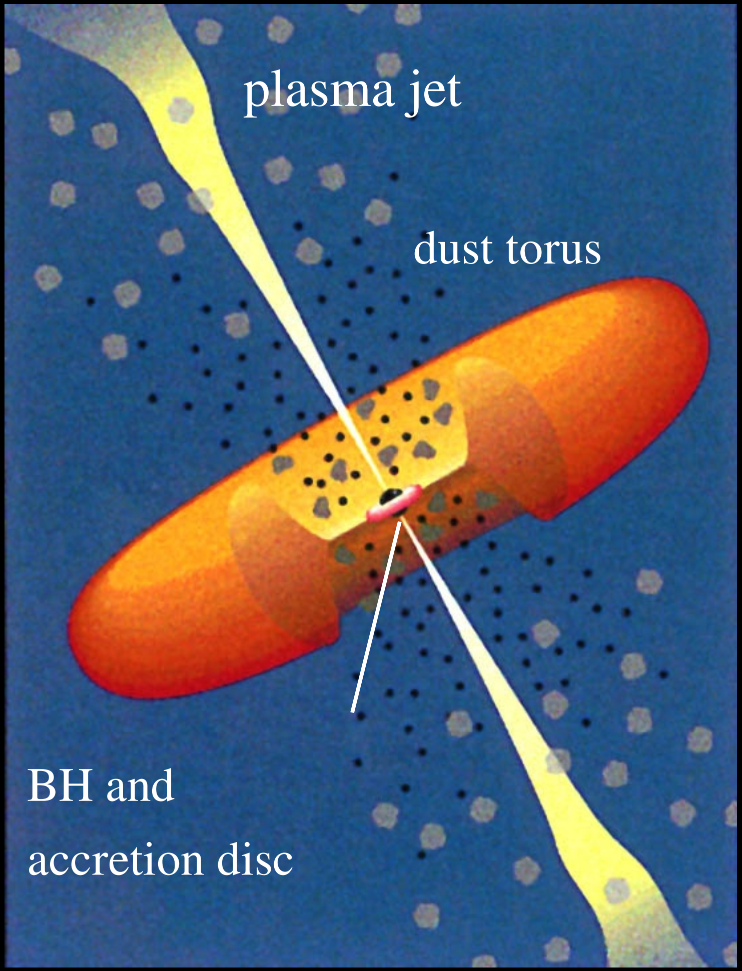

**First Time:**
**TeV & Molecular Cloud correlation!**

**--> v. good case for hadronic origin**


1 degree
CS line emission
Tsuboi et al. 1999
Molecular
Clouds
Gamma-Rays
Galactic Latitude
Expected TeV
emission
after 10000 yr
Galactic Longitude

# Active galactic nuclei (AGN) and blazars

- **AGN:** Luminous central region of a galaxy (found in ~1% of all galaxies)
- **AGN model:**
  - Central supermassive black hole
  - Matter accretion (thermal emission from radio to X-rays)
  - Relativistic plasma jet
- Observed AGN features depend on viewing angle (unification)
- **Blazar:** viewing angle ~ jet axis
  - Relativistic beaming
    **Doppler-boosting** $E_{obs} \sim \delta\ E_{src}$
  - **Pointlike TeV emission ( *pair halos)**
  - **Extreme variability**



# Extragalactic TeV γ-ray sources

| Name | redshift | reference |
|---|---|---|
| ● M 87 | 0.004 | Aharonian et al, A&A, 403, L1 (2003) |
| Markarian 421 | 0.030 | Punch et al., Nature, 358, 477 (1992) |
| Markarian 501 | 0.034 | Quinn et al., ApJ, 456, L83 (1996) |
| 1ES 2344+514 | 0.044 | Catanese et al., ApJ, 501, 616 (1998) |
| Markarian 180 | 0.045 | Albert et al., ApJL, submitted (2006) |
| 1ES 1959+650 | 0.047 | Nishiyama et al., 29th ICRC, 3, 370 (1999) |
| PKS 2005-489 | 0.071 | Aharonian et al, A&A, 436, L17 (2005) |
| ● PKS 2155-304 | 0.116 | Chadwick et al., ApJ, 513, 161 (1999) |
| H 1426+428 | 0.129 | Aharonian et al., ApJ, 571, 753 (2002) |
| ● H 2356-309 | 0.165 | Aharonian et al, Nature, 440, 1018 (2006) ← |
| 1ES 1218+304 | 0.182 | Albert et al., ApJ, 642, L119 (2006) ← |
| ● 1ES 1101-232 | 0.186 | Aharonian et al, Nature, 440, 1018 (2006) ← |
| PG 1553+113 | >0.25? | Aharonian et al, A&A, 448, L19 (2006) |

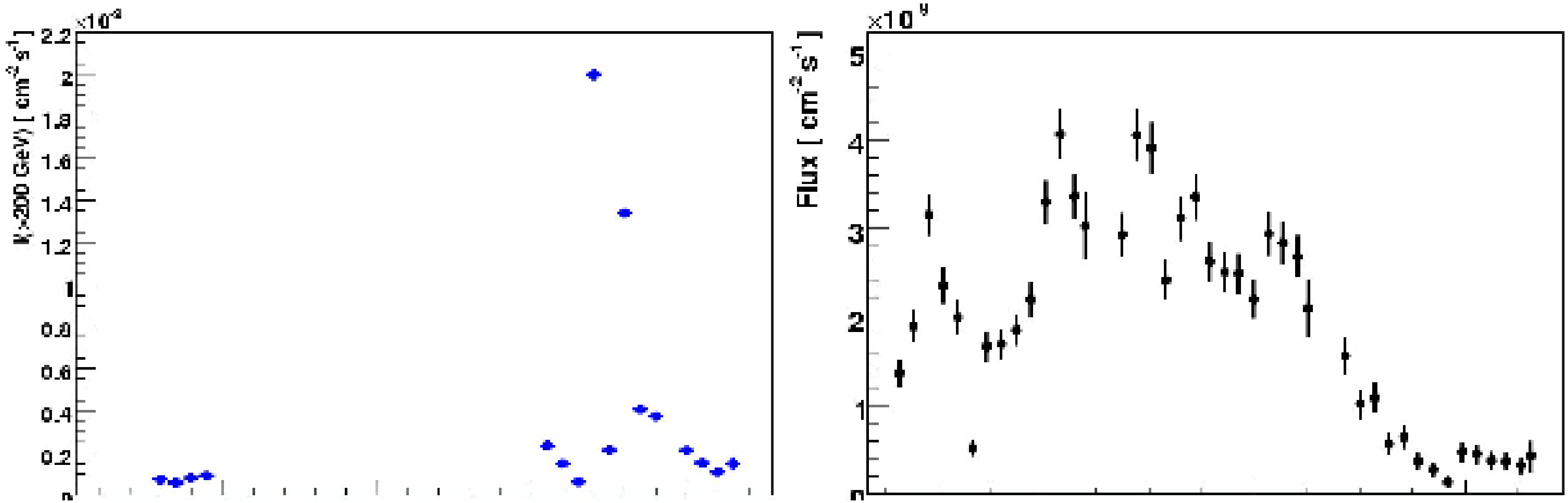
discovered by H.E.S.S. ●

seen by H.E.S.S.

**Provides constraints on the extragalactic background light (EBL)**

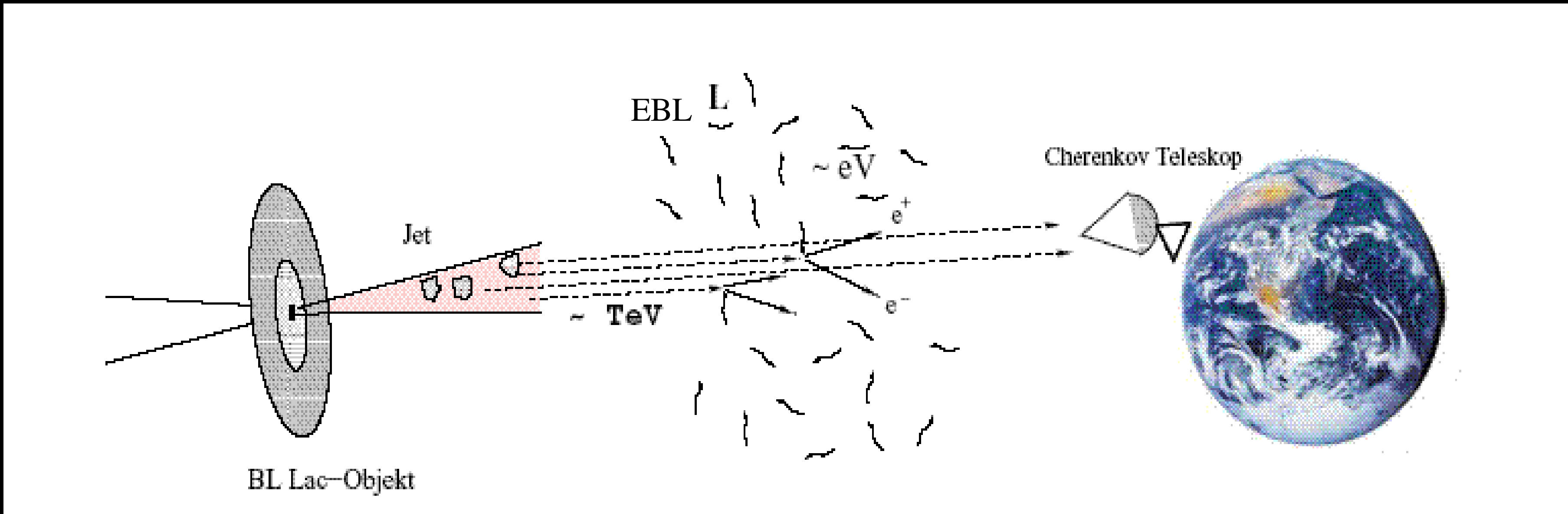
**Except for M87, all extragalactic TeV γ-ray sources are blazars**

# PKS 2155-304: 2006 outburst, VERY PRELIMINARY




- Huge flux level triggered ATel, MWL observations
- $2'$-minute lightcurve binning shows doubling timescales at $\approx 5'$
- Complex lightcurve with possibly substructures (to be confirmed with final analysis)
- Simultaneous RXTE, Swift, Chandra, optical observations

# Absorption of Gamma-Rays from Distant Extragalactic Sources




**Gamma Rays are absorbed via pair production on soft photon fields**

**Pair Creation: $\gamma + \gamma_{soft}$ --> $e^+ + e^-$**

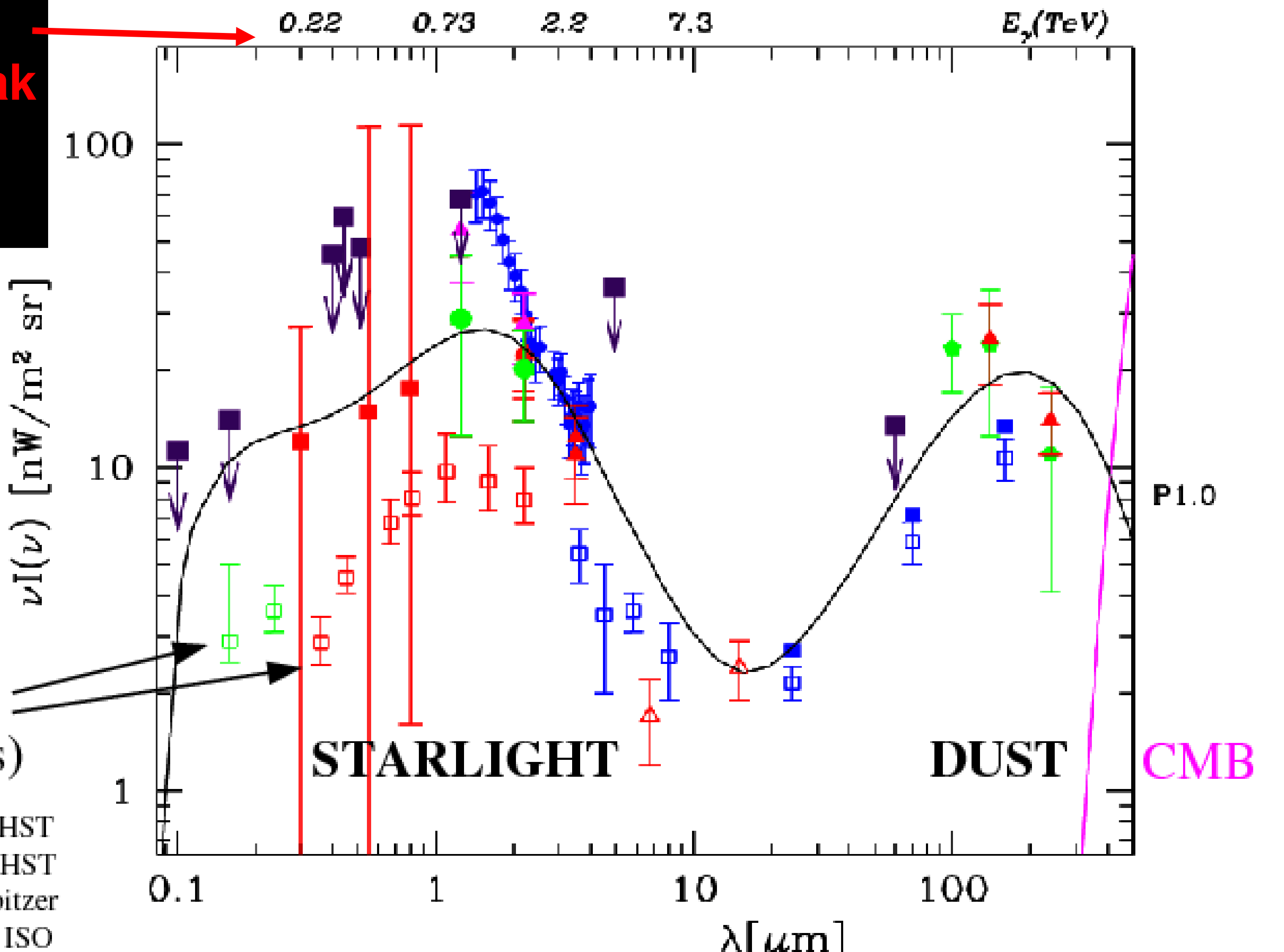
**0.1 to 10 TeV Gammas interact with**

**0.1 to 10 μm**
**Extragal. Back. Light (EBL)**

from L. Costamante

# Extragalactic Background Light: the SED

**Gamma Ray Energy for peak pair prod. X-section**

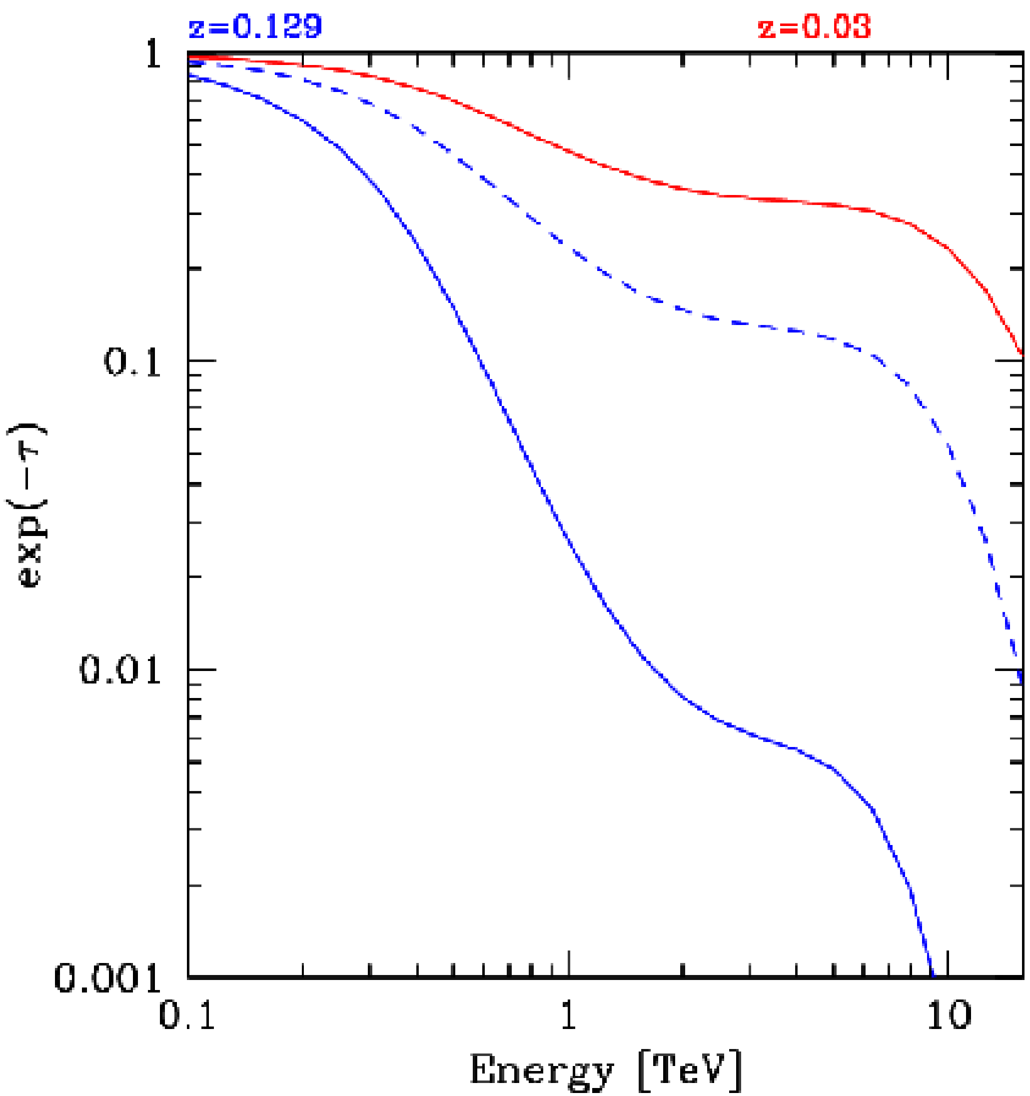



Lower limits (source counts)

| | |
|---|---|
| Gardner et al. 2001 | HST |
| Madau & Pozzetti 2000 | HST |
| Fazio et al. 2004 | Spitzer |
| Elbaz et al. 2002 | ISO |
| Dole et al. 2006 | Spitzer |

**EBL is poorly constrained!**

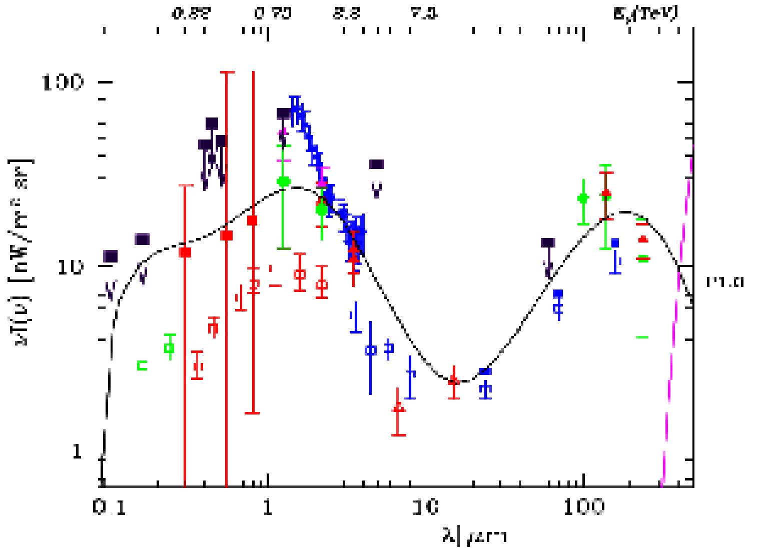
# How absorption deforms original TeV spectra




- 0.2-2 TeV: steepening
- 2-5 TeV : flattening

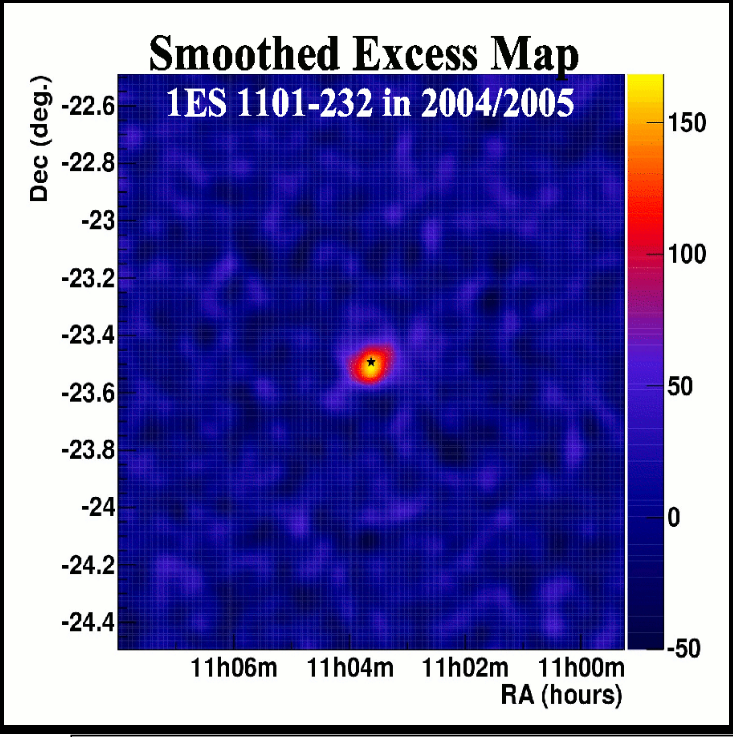
(partial recover of original spectrum: $n(\epsilon) \sim \epsilon^{-1}$ --> $\tau(E) \sim E^0$ ~constant )

- >6 TeV: cut-off




from L. Costamante

# 1ES 1101-232 (z=0.186) & H2356-309 (z=0.165): Two New Distant Blazars



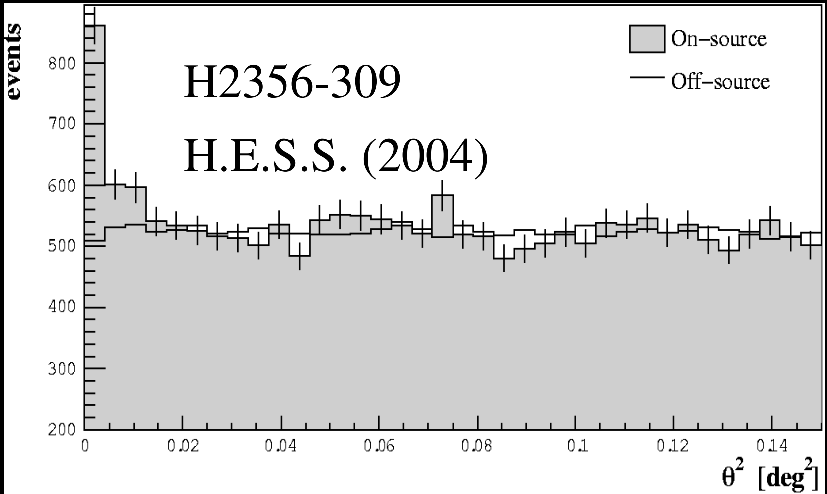

**Discovered by H.E.S.S. in 2004**

**~40h of observations, (>10σ)**

**<u>Enery spectra both are steep power laws</u>**

**1ES1101: $\Gamma = 2.88 \pm 0.17$**

**H2356-309: $\Gamma = 3.06 \pm 0.2$**




**Expect γ absorption from EBL**

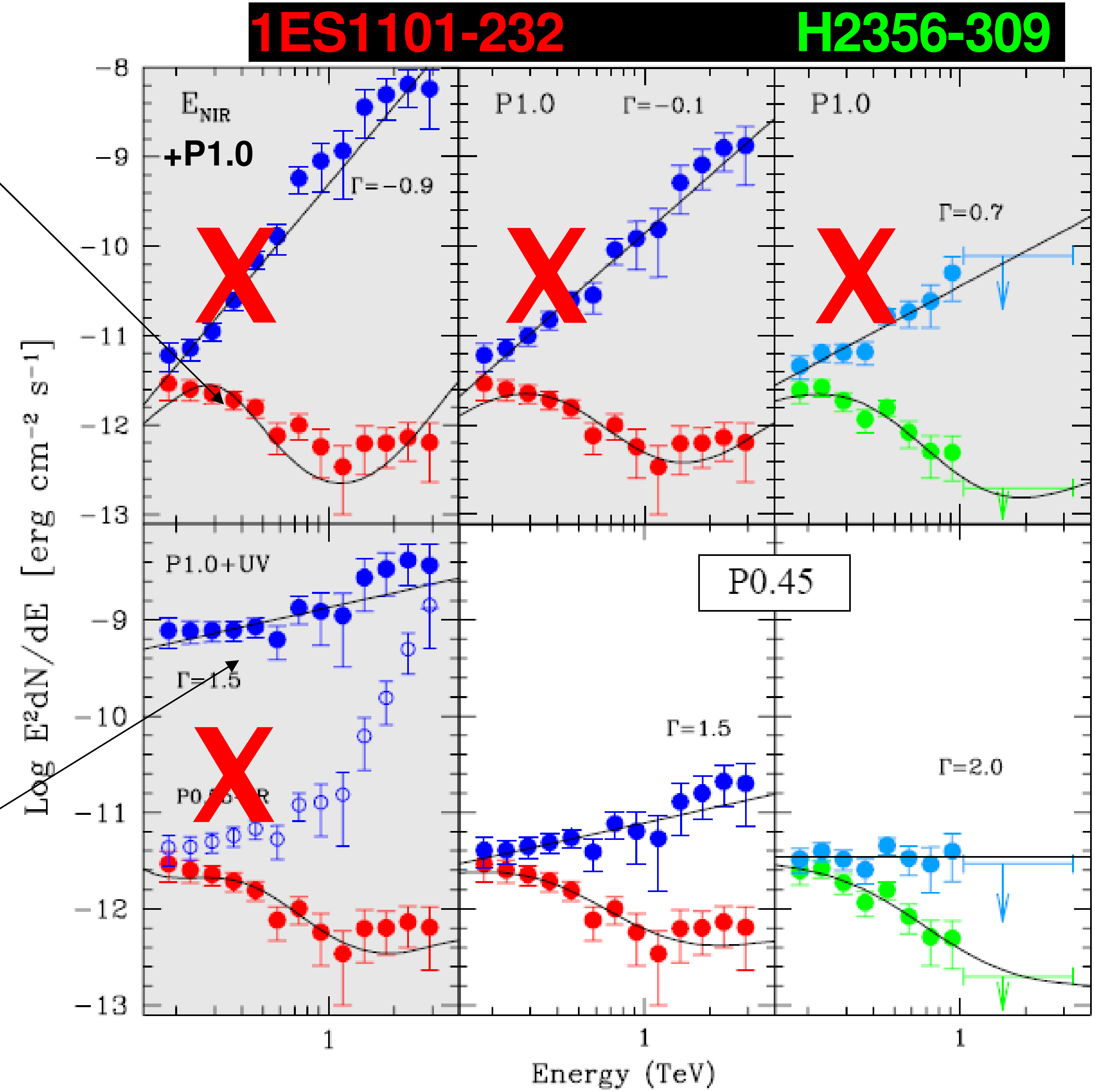
**→ strong implications on EBL**

Observed spectra (lower curves)

Look at various combinations of EBL scaling and other components on intrinsic spectra.

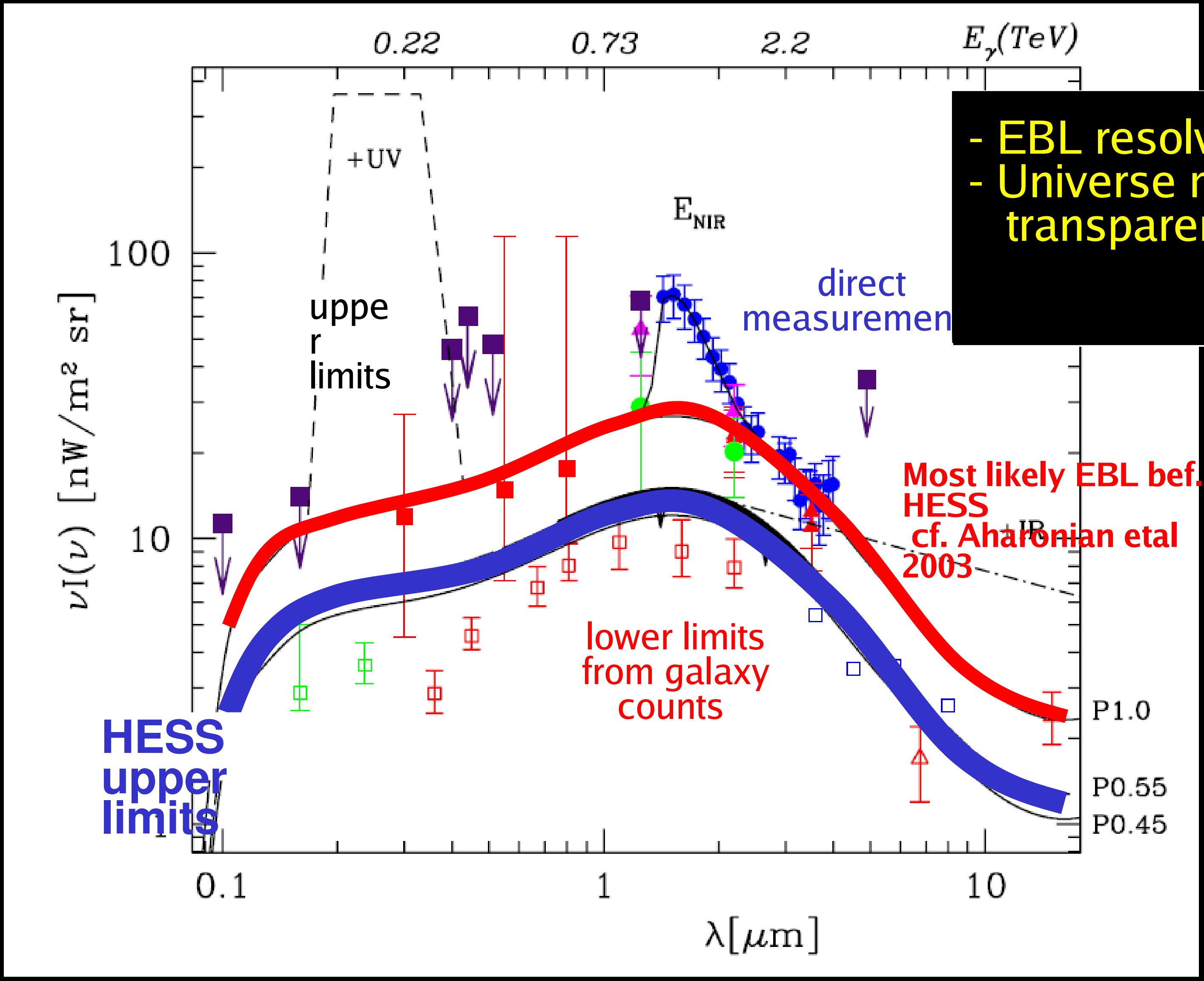
Intrinsic spectra (upper curves)

Constraints from condition instrinsic Γ > 1.5



# Spectra & ExtragalacticBackgroundLight

**See Aharonian et al. (2005) Nature 440, 1018**

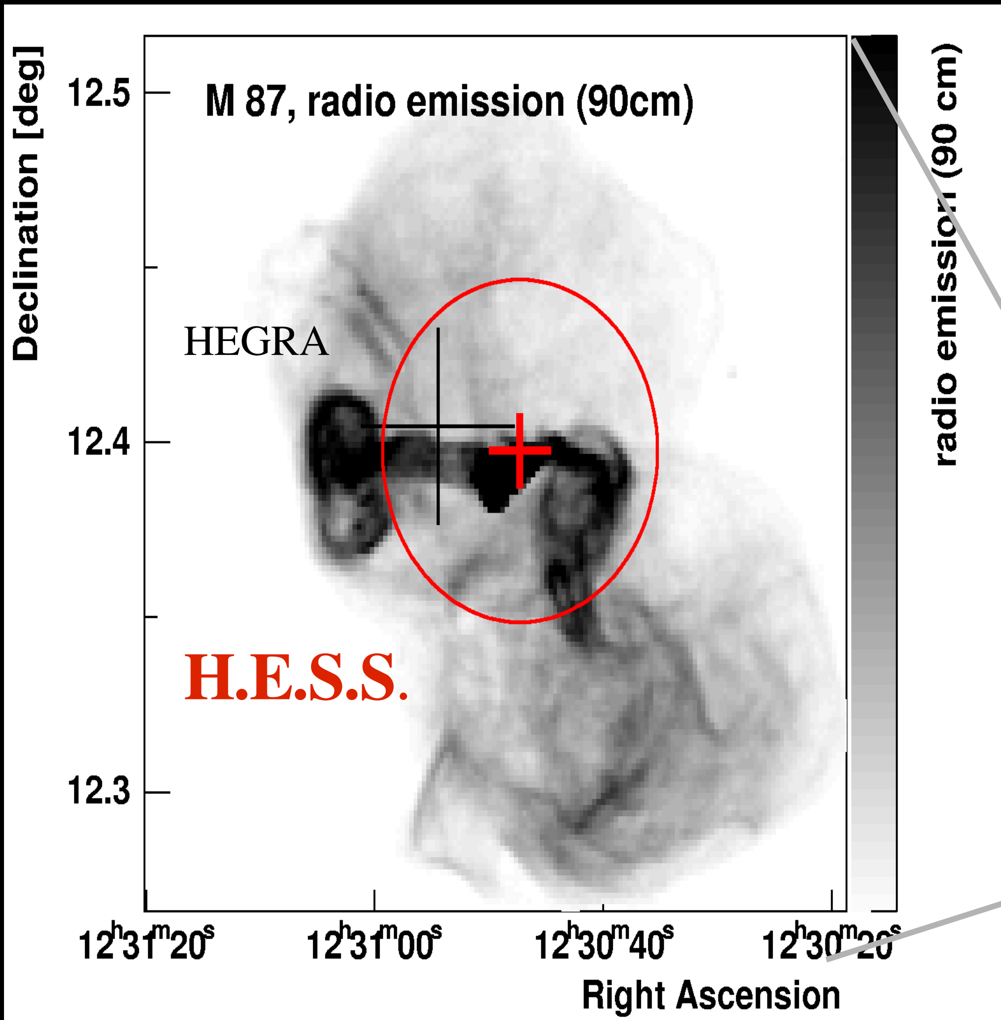


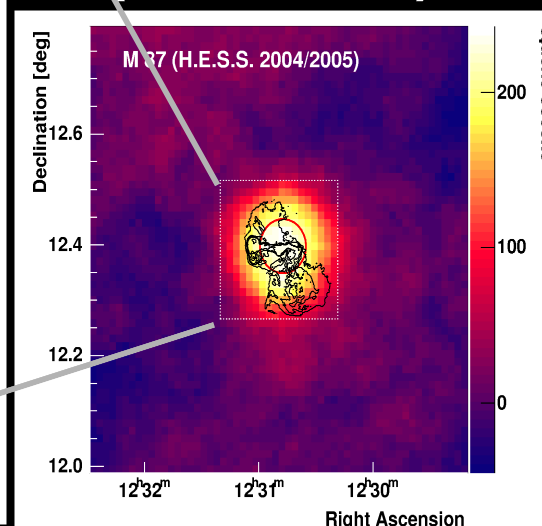

- EBL resolved
- Universe more transparent

# M87: TeV γ-ray source – HEGRA & H.E.S.S.

Dist: ~16 Mpc (z=0.00436)

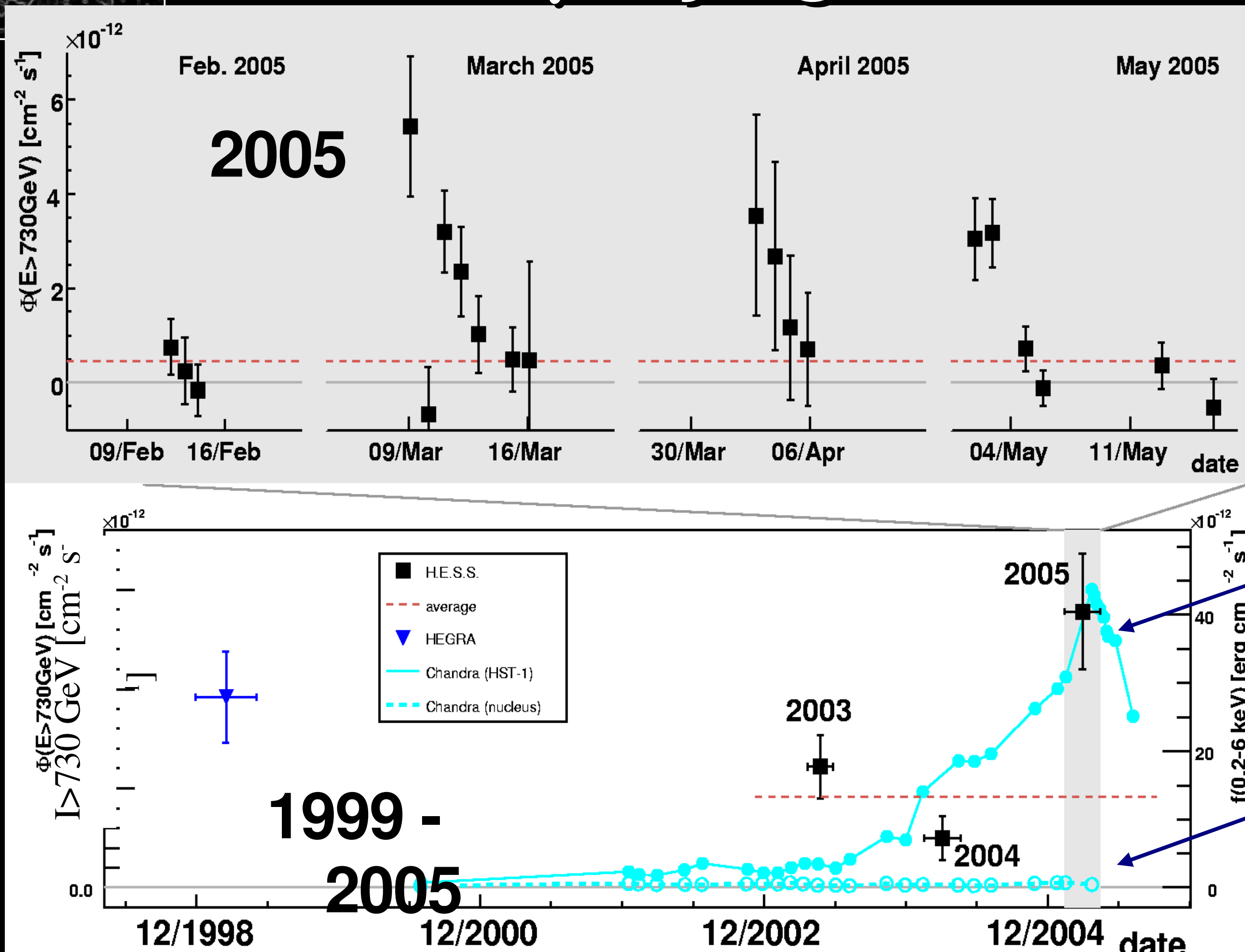
- H.E.S.S: 2003 to 2005
  - 2003 (19 h) 2005 (52h)
- Point-source, position compatible with M87 nucleus
- Upper limit for extension (99.9% c.l.):3 arcmin [14 kpc]

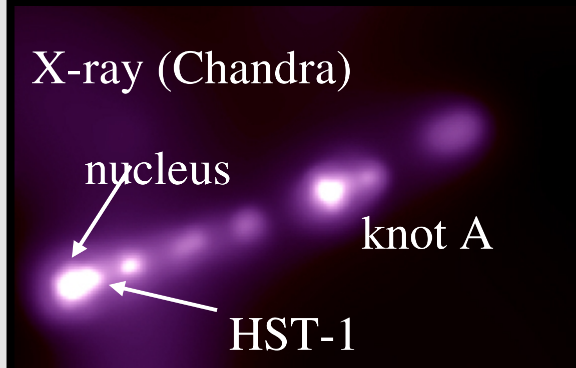



**First extragalactic non-blazar TeV γ-ray source**

# M87: TeV γ-ray light curve and variability




## X-ray emission:

- **knot HST-1**

  [Harris et al. (2005), ApJ, 640, 211]

- **nucleus**

  Courtesy to D.Harris (priv. communication)

**Variability: Constrain size of emission region: $R \sim 5 \times 10^{15}\ \delta$ cm**

**No X-ray/TeV correlation: Require further MWL observations**

# Conclusions & Lessons from HESS et al.

**- Hard spectra (harder than $E^{-2.4}$) for the majority of Galactic TeV sources.**
**- No clear sign of cutoffs above 10 TeV so far in many sources**
**- Require > 50 hrs observation to reach >50 TeV gamma energies**

**- Present instruments reach gamma-ray energies few x 10 TeV**
**ie few x 100 TeV Cosmic Rays**

**- Still want to search for Particle PeVatrons (the knee and beyond)**
**- PeV CR Acceleration much less well understood cf. Multi-TeV energies but present results are providing clues.**

**Along with current future efforts to lower the energy threshold and improve the sensitivity of instruments (eg. HESS-II, MAGIC-II, CTA....)**

***There is great potential for Gamma Ray telescopes optimised for the E> 10 TeV regime.***

# Acceleration of Cosmic Rays above the knee ($10^{15}$ ~ $10^{18}$ eV)

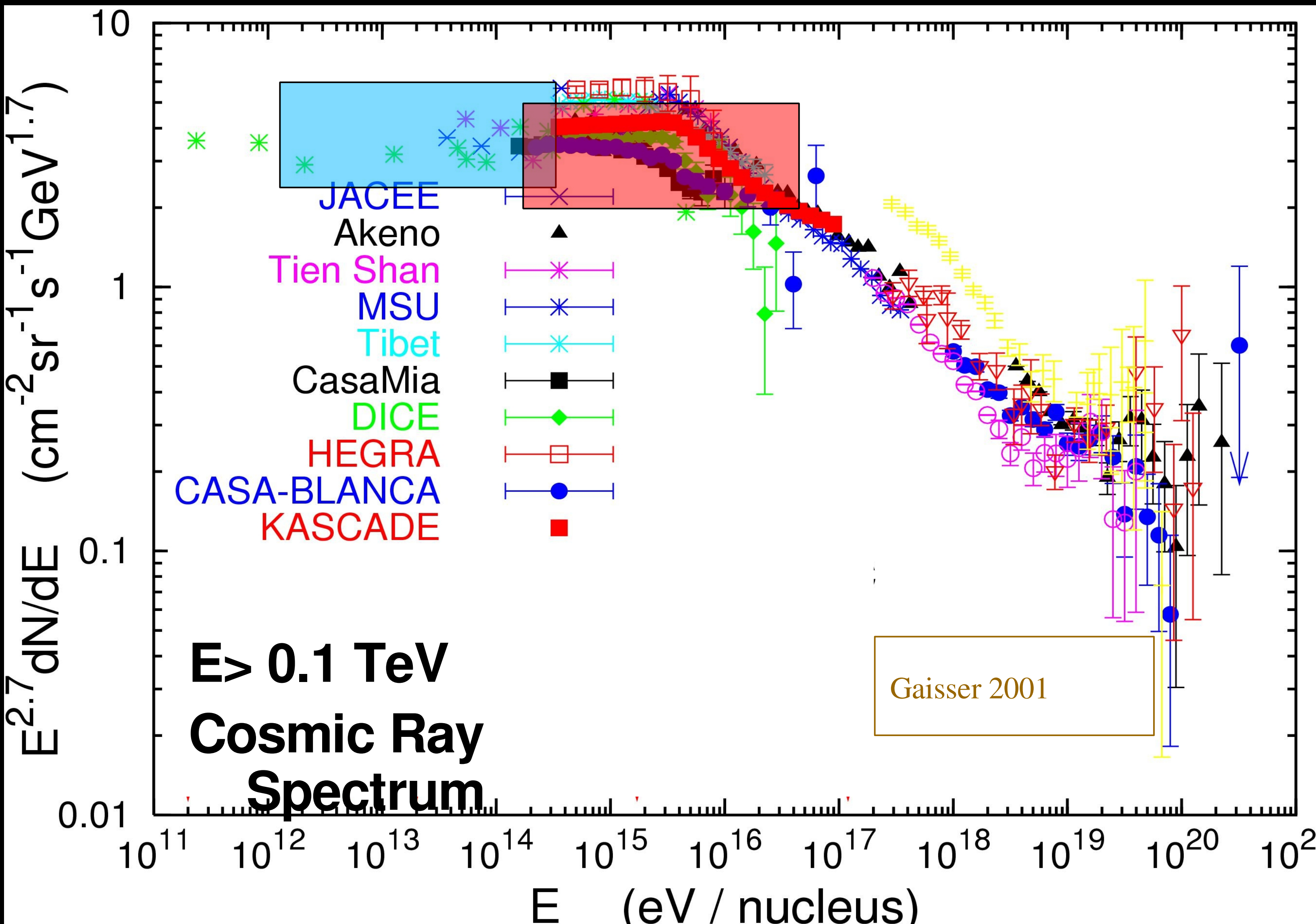
**A Major Mystery in High Energy Astrophysics...**

- Diffusive Shock Acceleration Theory  Emax ~ few x $10^{15}$ eV
 (Drury 1983, Lagage & Cesarsky 1983, Hillas 2006 for review)

Some ideas.....  eg.

- Magnetic field modification (Bell & Lucek 2001)
- Re-acceleration of Galactic Cosmic Rays (Jokipii & Morphill 1985, Voelk & Zirakashvili 2001)
- Acceleration by Galactic GRBs (Wick, Dermer, Atoyan 2004)
- Large-scale galactic shocks from Superbubbles via multi SNR, multi stellar winds from OB assoc. (Drury 2001, Bykov 2001, Parizot 2004)

# 10 - 100 TeV γ-Rays: Corresponds to ~100 TeV to multi-PeV Particles



# The *TenTen* Project: (Adelaide group + others)
# E > 10 TeV  Gamma Ray Astronomy

## Requirements (compared to HESS) Based on simulation studies

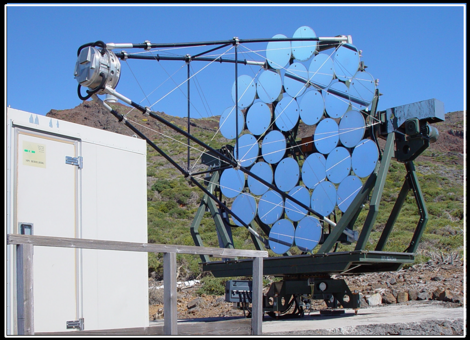
Plyasheshnikov et al.  (2000)

**Each telescope:**

**- Smaller mirror area/size  (~10 m²)     HESS ~100 m²**

**- Larger camera field of view (6°-10°)  HESS 5°**

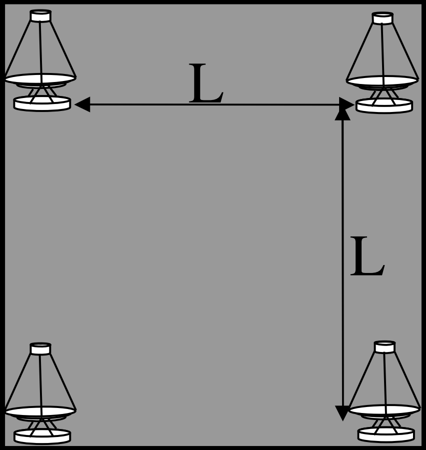
**- Larger telescope spacing (L >200 m)   HESS 120 m**



**Desired Effective collecting area:**

**10 km² at 10 TeV      --->      *'TenTen'*   project**

Telescope Cell




**- Multi-telescope array (stereoscopy also)**
**combining several telescope *Cells***
***Total 25 to 50 telesopes***

**Sites:  Sea-level altitude maybe favourable**
**--> Australian sites. Under investigation.**

# The *TenTen* Project:

**<u>Guaranteed Success:</u>**

**- Technical**

**No challenging innovation required. Can employ the same stereoscopic technique developed by HEGRA and HESS.**

**- Astrophysics**

**TenTen will study the growing number of existing TeV gamma ray sources but at higher energies. Greater chance of separating electronic & hadronic components (electron cooling).**

**- Workshop to discuss science goals & identify interested groups**

**Dec 6 - 8 Adelaide**

**<u>Rough Cost:</u> Shared with International Partners**

**~\$0.5M to \$1M per telescope --> under \$50M total array**

THE UNIVERSITY OF ADELAIDE AUSTRALIA

**Home**

Overview & Aims

Programme

Workshop Venue

Arrival, Accommodation & Travel Info

Registration & Abstract Submission
Deadline: 10 Nov. 2006

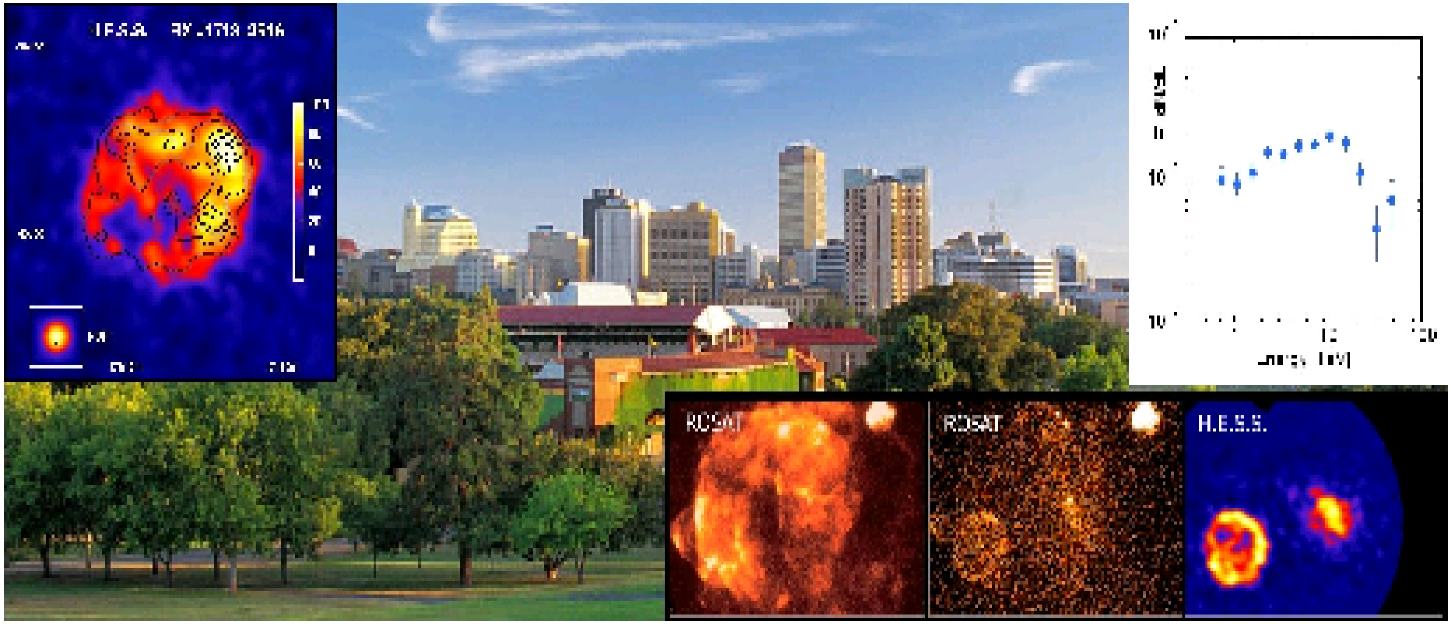
Local Organisation/Contact

Hosted by the
High Energy Astrophysics Group,
University of Adelaide,
Adelaide 5005

Local Contact:
Gavin Rowell
Tel: +61883036335
Fax: +61883034380

# *Locating PeV Cosmic-Ray Accelerators:* Future Detectors in Multi-TeV Gamma-Ray Astronomy

**Adelaide 6 - 8 December 2006**






## Workshop Agenda

- Motivations for E>10 TeV Gamma-Ray and PeV Cosmic-Ray Astrophysics
- Status Reports in TeV Gamma-Ray, Cosmic-Ray, Neutrino and X-Ray Astronomies
- Current Activities in E>10 TeV Gamma-Ray Astronomy
- New Array of E>10 TeV Cherenkov Imaging Telescopes

http://www.physics.adelaide.edu.au/astrophysics/pev_workshop/index.html

# Summary

- A growing TeV Gamma Ray catalogue due to HESS et al.
  - now *TeV astronomy* *(mainstream discipline)*
  - can study Astrophysical sources in detail

- Detailed TeV gamma-ray studies of Shell-SNR and a growing number of pulsar-wind-nebulae (PWN)

  (emission up to 50 TeV in some cases)

  --> particle acceleration above 100 TeV!!

- Shell SNRs: Hadronic &/or leptonic accelerators

  few x $10^{49}$ erg necessary in protons

- Pulsar Wind Nebulae: Spectral evolution in HESSJ1825-137

  Asymmetric morphology is often seen.

- Compact Binaries: TeV Orbital modulation

- Extragalatic jet sources: Sites of multi TeV particle production: fast variable down to minute timescales

.........

- Clear need for E>10 TeV Gamma Ray instruments *TenTen*

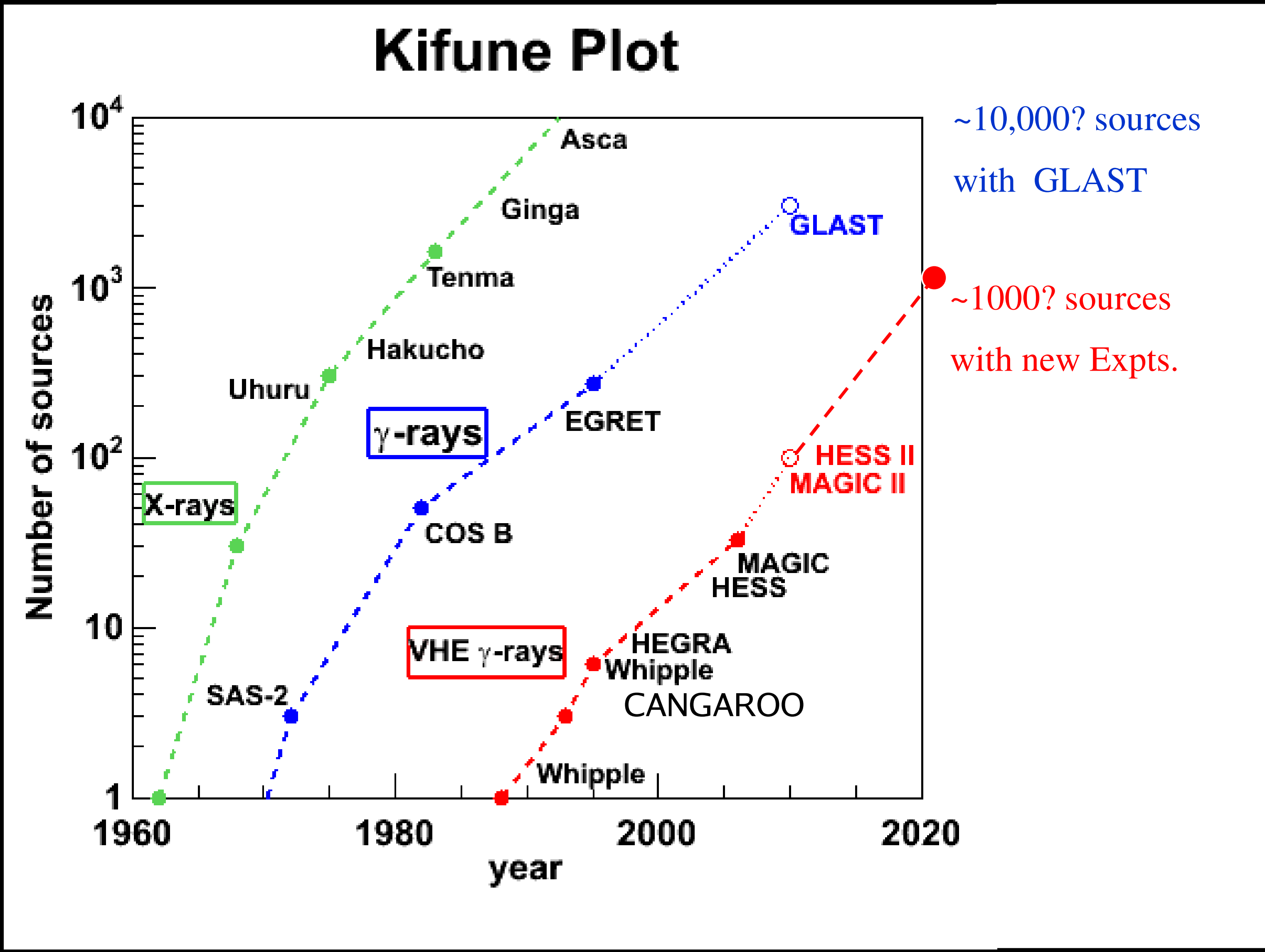
  gauranteed technical & scientific success

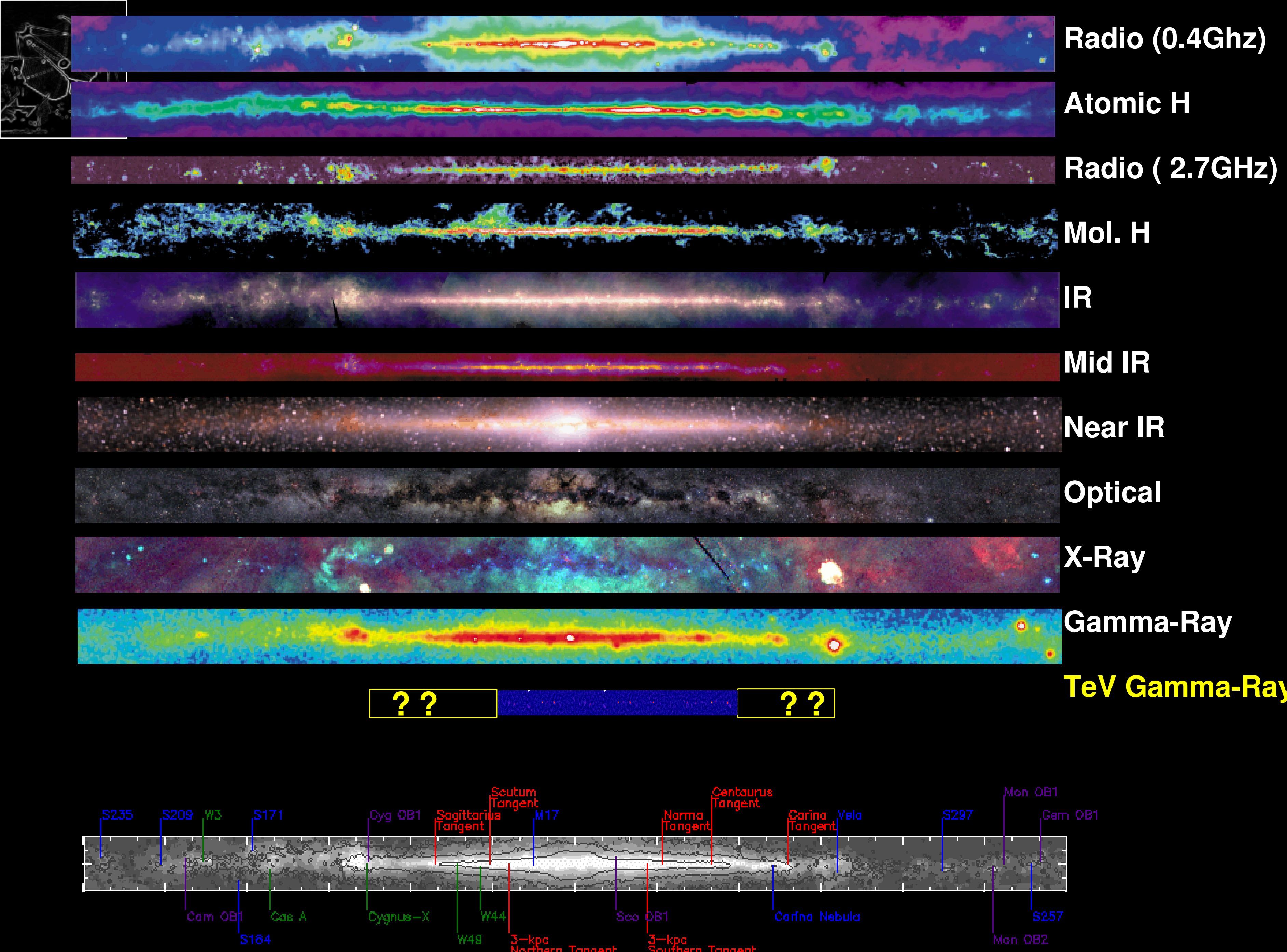
  *(complimentary to GLAST & $km^3$ neutrino experiments)*

*--> bright prospects for the future of the field*

# The 'Kifune' Plot

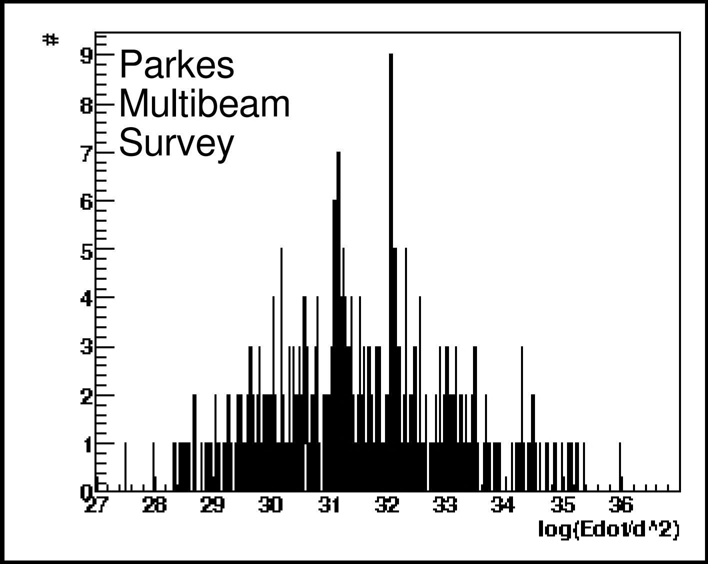
(Tadashi Kifune – founder of CANGAROO)





Radio (0.4Ghz)
Atomic H
Radio ( 2.7GHz)
Mol. H
IR
Mid IR
Near IR
Optical
X-Ray
Gamma-Ray
TeV Gamma-Ray
? ?
? ?
S235
S209
W3
S171
Cyg OB1
Sagittarius Tangent
Scutum Tangent
M17
Norma Tangent
Centaurus Tangent
Carina Tangent
Vela
S297
Mon OB1
Cam OB1
Cam OB1
S184
Cas A
Cygnus-X
W49
W44
3-kpc Northern Tangent
Sco OB1
3-kpc Southern Tangent
Carina Nebula
S257
Mon OB2

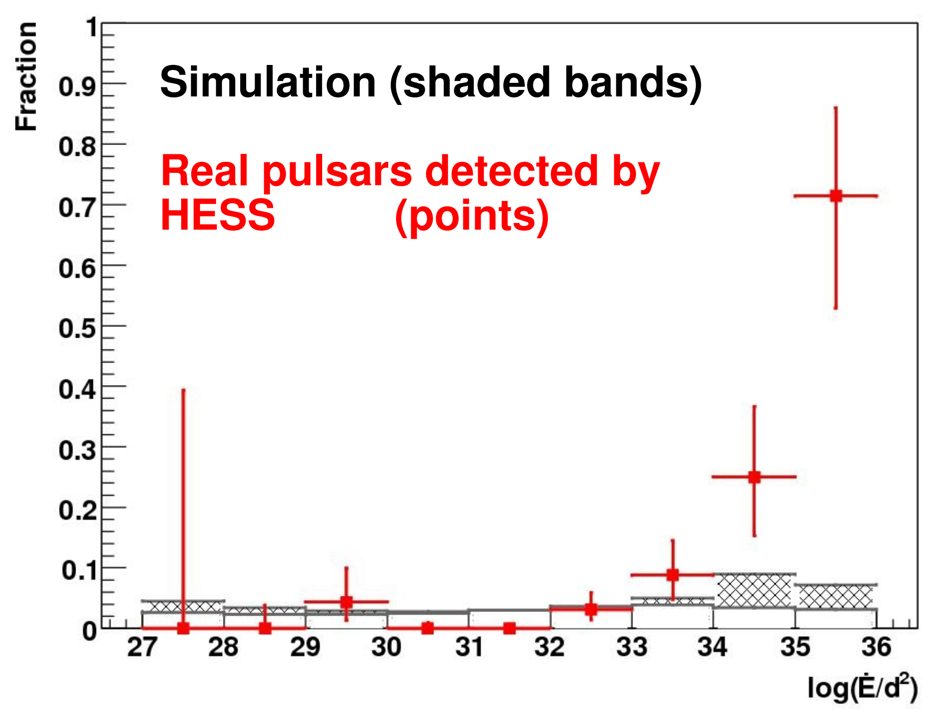
# Pulsar Ensemble Studies




**Carrigan et al 2006**
**Aharonian et al 2006 in prep**

**Sample from pulsar distribution (Parkes Multibeam Survey Camillo etal 2002)**
**Galactic long, lat, & Edot/d²**
**--> Simulate chance probability of random occurance**

**High Edot/d² pulsars/PWN are a distinct population of TeV gamma ray sources**



# *the last EM window....*

LE or MeV : 0.1 -100 MeV (0.1 -10 + 10 -100*)

HE or GeV : 0.1 -100 GeV (0.1 -10 + 10 -100*)

VHE or TeV : 0.1 -100 TeV (0.1 -10 + 10 -100*)

UHE or PeV : 0.1 -100 PeV

EHE or EeV : 0.1 -100 EeV

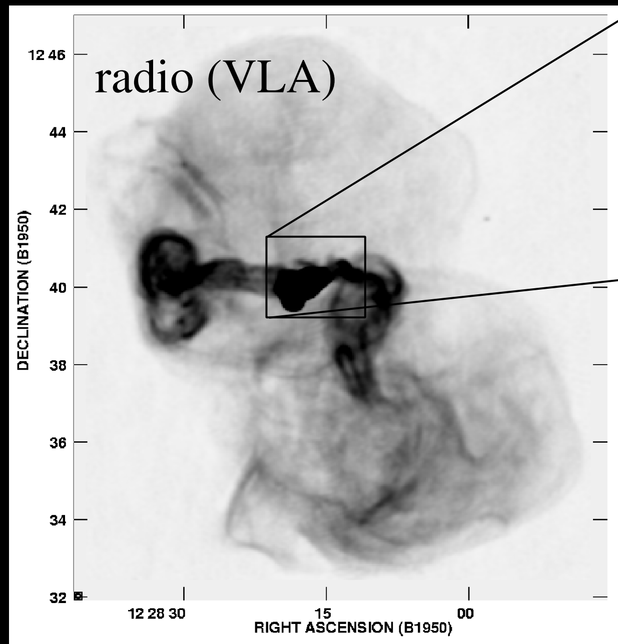
*the window is opened in MeV, GeV, and TeV bands*:

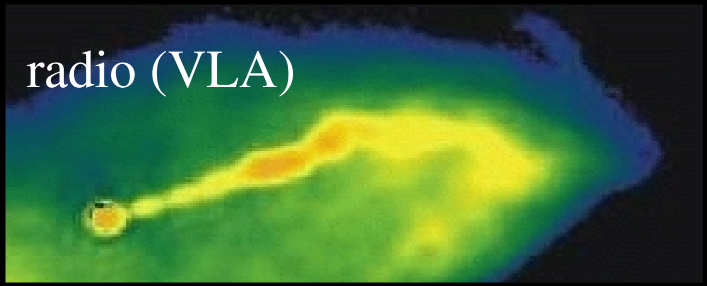
LE,HE domain of space-based astronomy

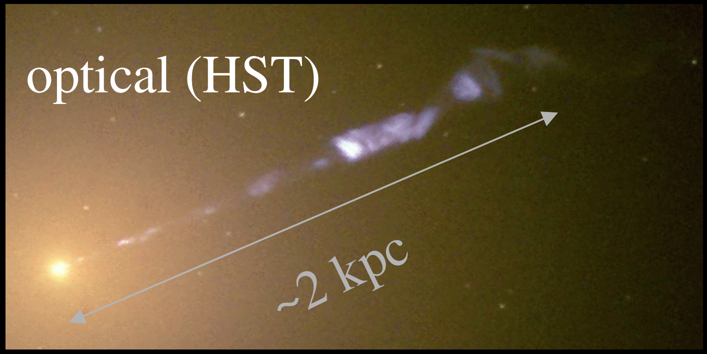
VHE + domain of ground-based astronomy

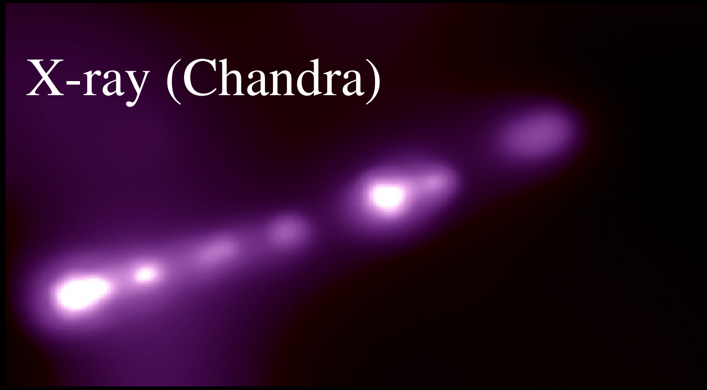
# The giant elliptical radiogalaxy M87

- V. prominent in Virgo gal. cluster.
- Dist: ~16 Mpc (z=0.00436)
- Central BH: $M_{BH} \sim 3 \cdot 10^9\ M_O$
- Jet angle: ~30 ° ⇒ not a blazar!



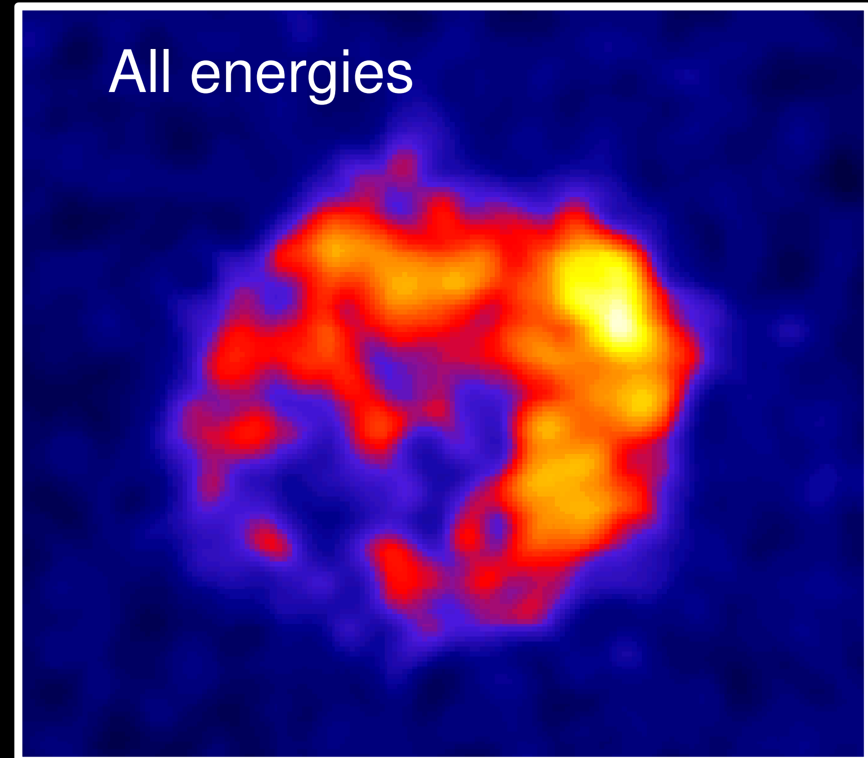



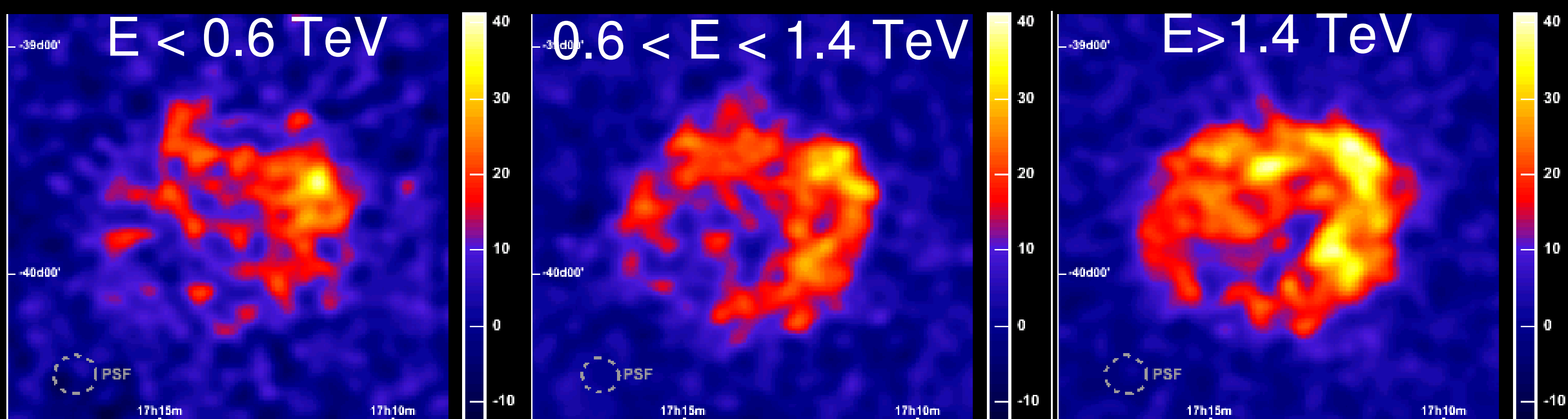

- TeV γ-ray emission and charged $10^{20}$ eV particles (UHECR)?
- First detection (>4σ) at TeV γ-ray energies by HEGRA in 1998/99

[Aharonian et al. (2003), A&A, 403, L1]

# Energy dependence of the Morphology




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



# *Crab Nebula – The First TeV $\gamma$ Source & the Standard Candle*

**Broad-band SED covering 20 decades up to ~70 TeV!**