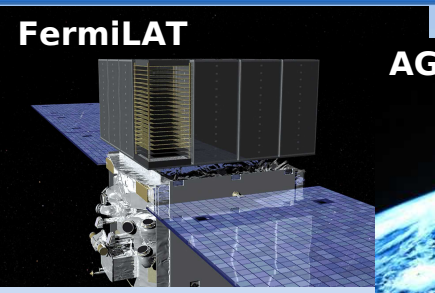
# Le Ciel au TeV:
## Le catalogue Tcherenkov, résumé des résultats les plus intéressants

Many thanks to ICRC rapporteurs
J Hinton (2007), D Torres (2009),
and many others
(W. Hofmann, H. Sol, A. Djannati-Ataï ...)

**M. Punch**

**APC – CNRS/IN2P3**

# The Gamma-ray World











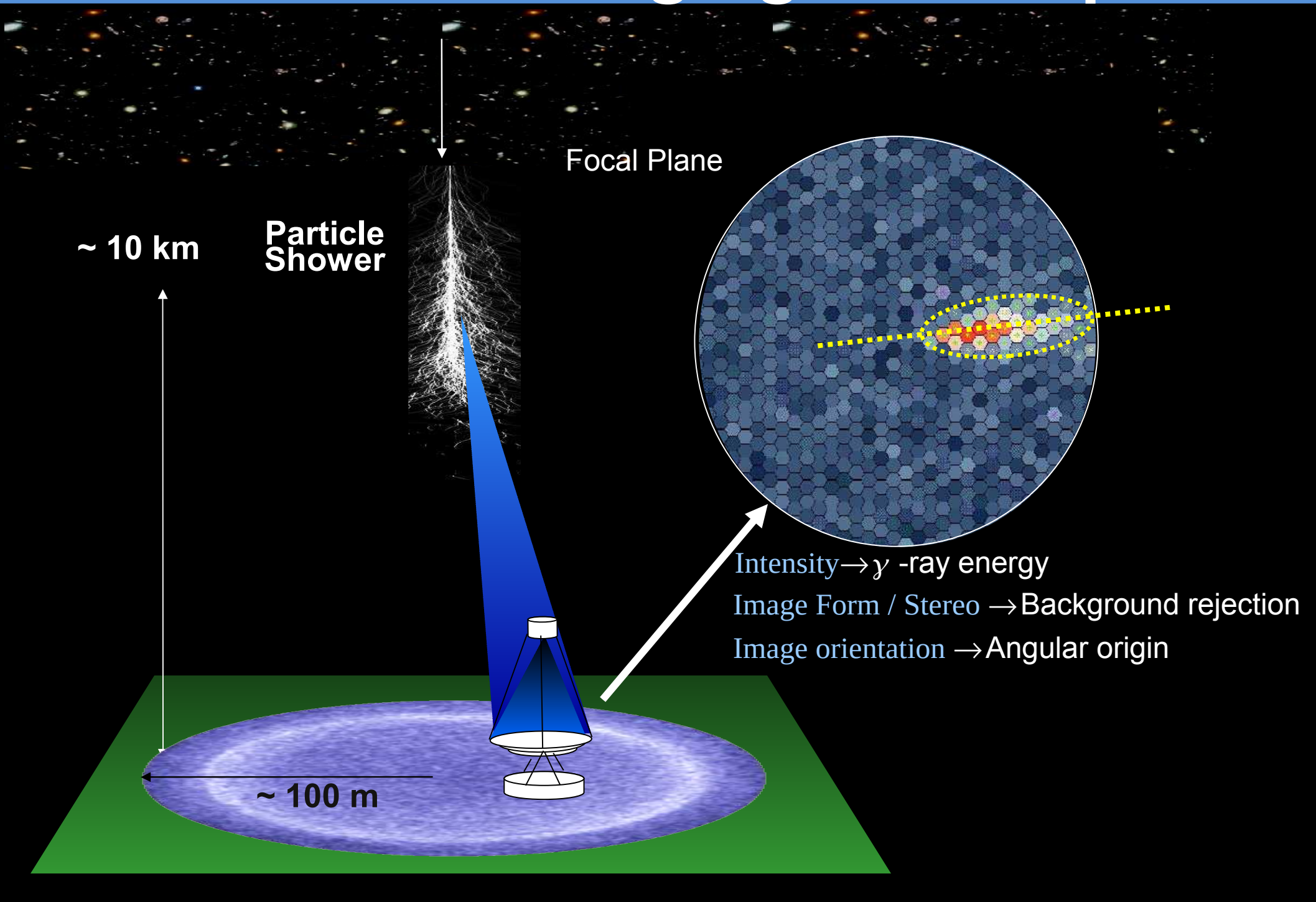


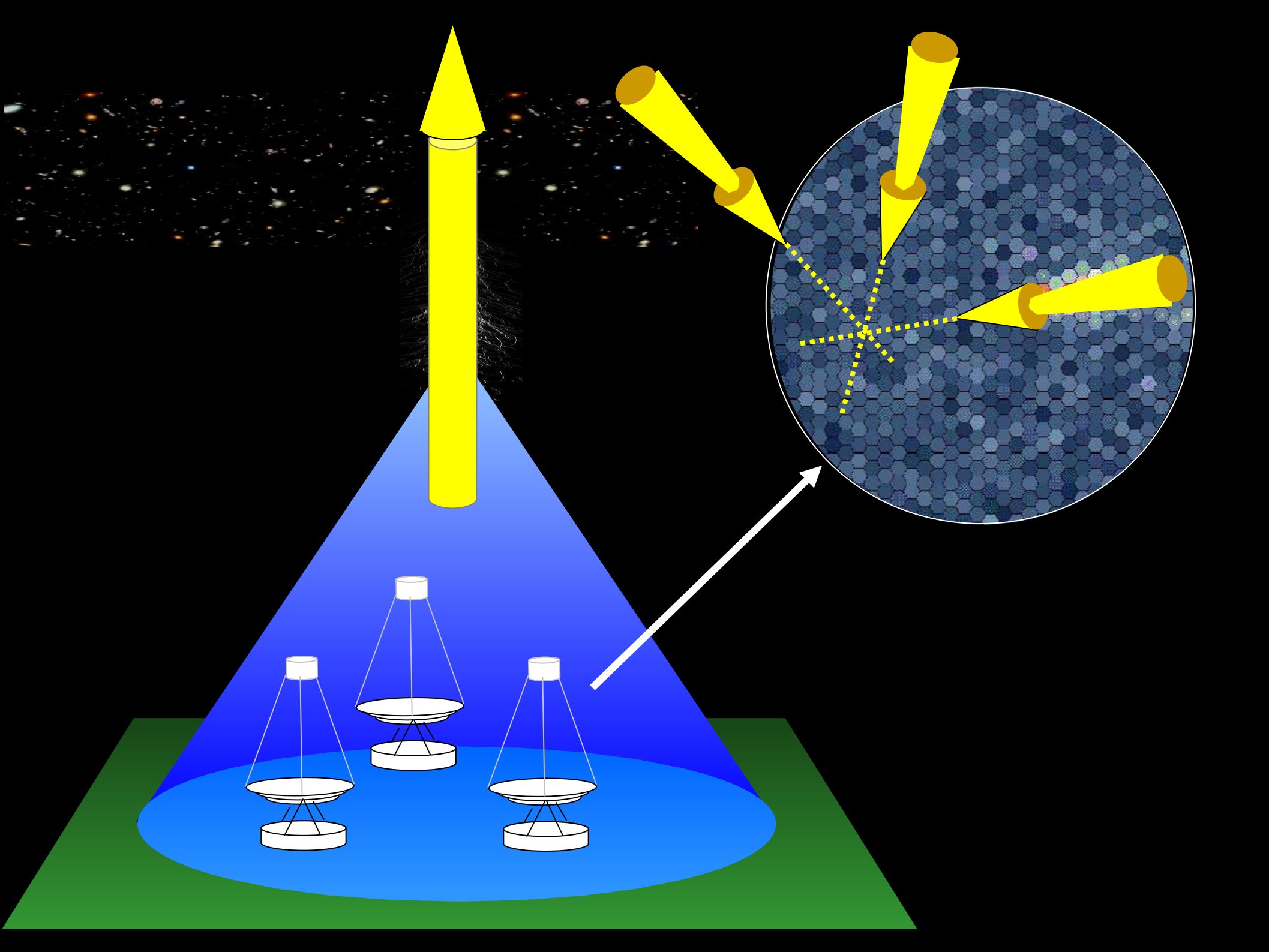


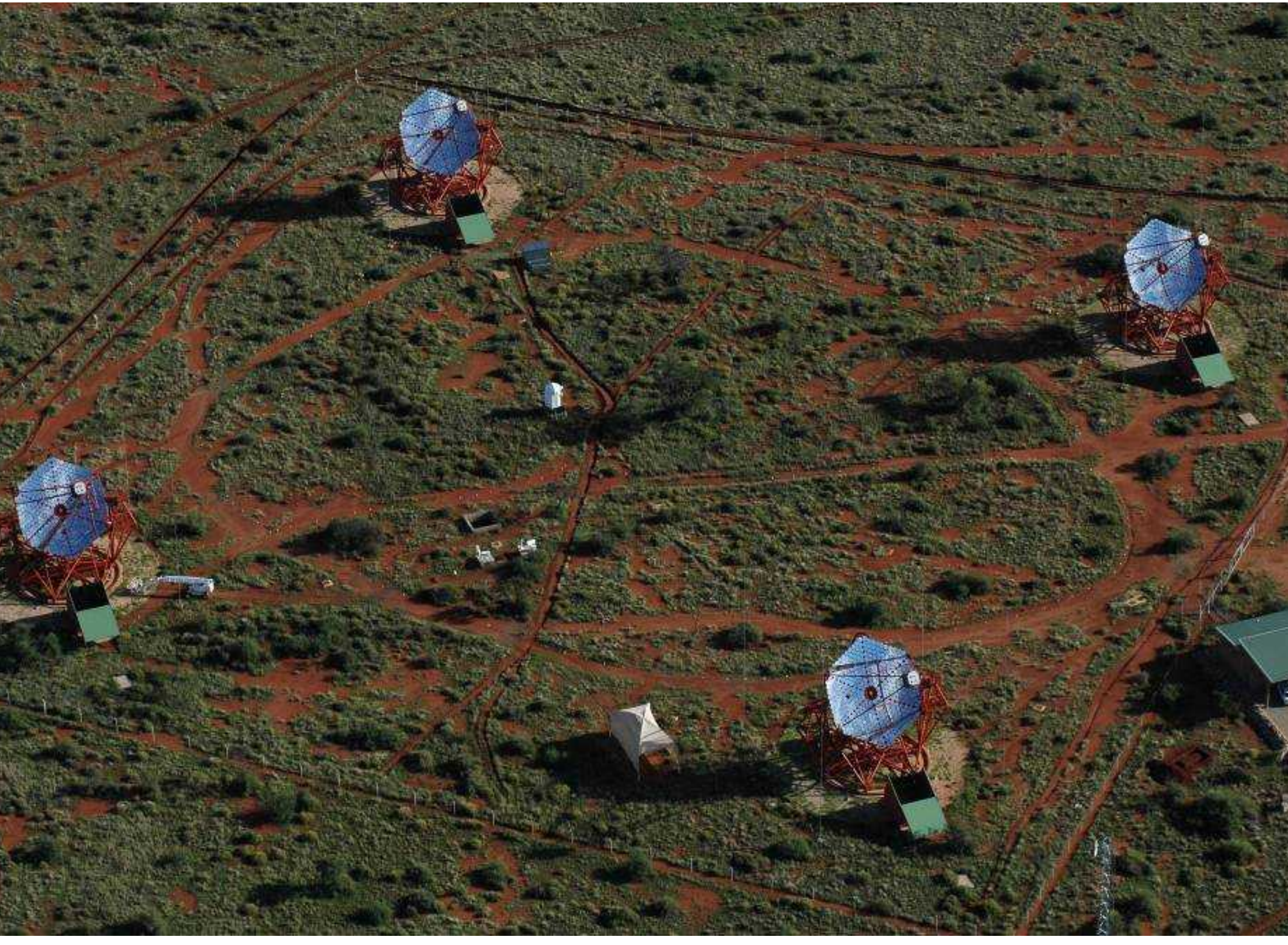




# Cherenkov Imaging Technique

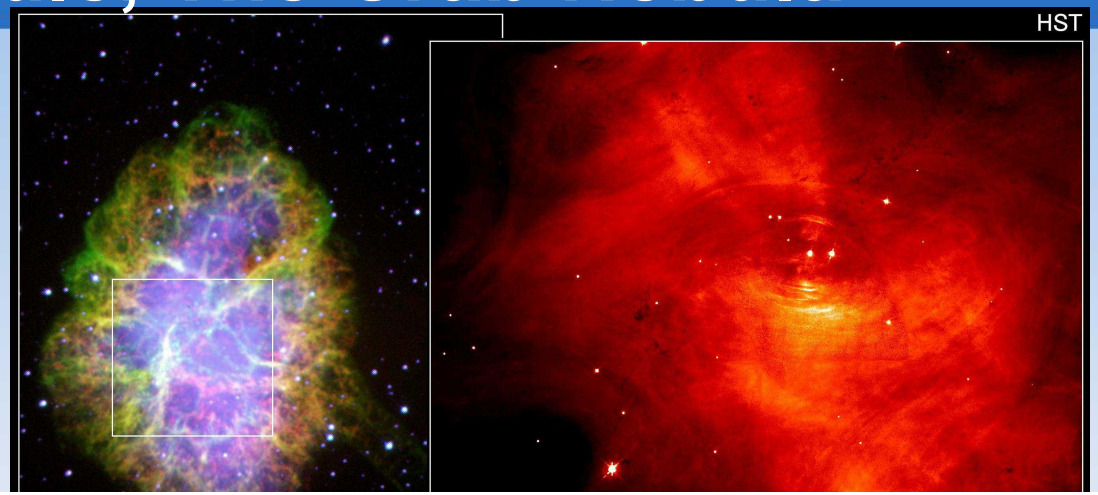


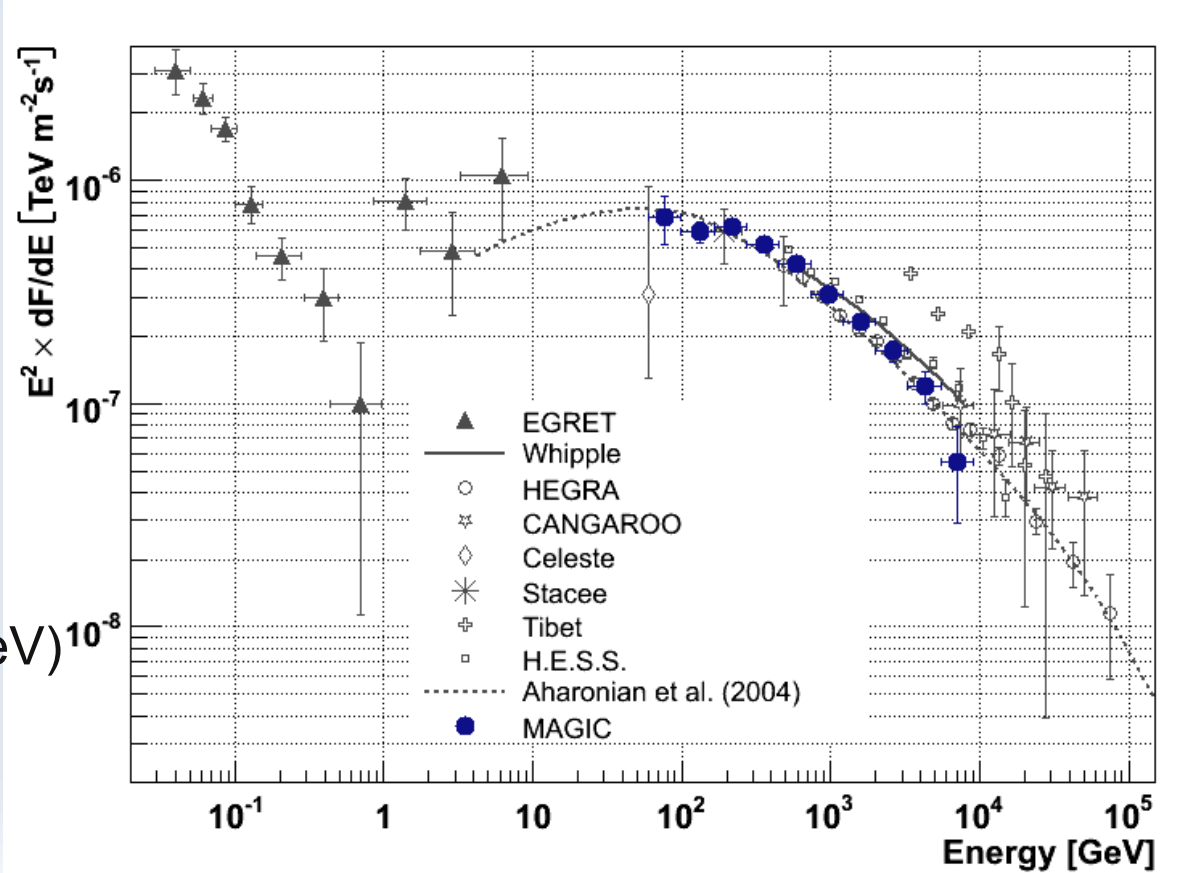




# Current sensitive ACT Detectors:
## with Standard Candle, The Crab Nebula

- H.E.S.S.
  - @ Large Zenith angle
    27 σ/√ h (6 γ/min)
  - now up to 80 TeV
- MAGIC
  - 19 σ/√ h
  - Curvature seen
  - Peak: 77±47 GeV
- VERITAS
  - 31 σ/√ h with 3 tels
- MILAGRO (now shutdown)
  - ~8 σ in 1 year
  - First spectrum from ASM
- ARGO YBJ
  - 5 σ in 190;420 days (>2;0.5 TeV)



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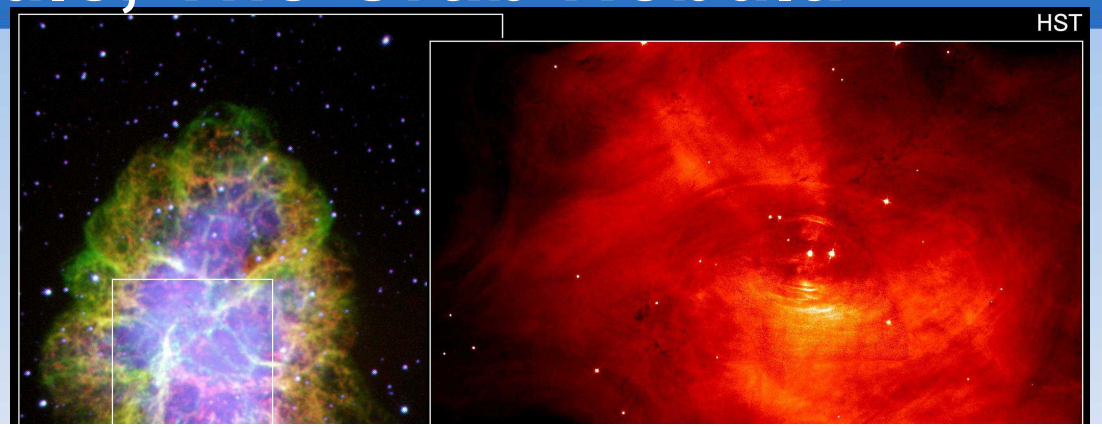
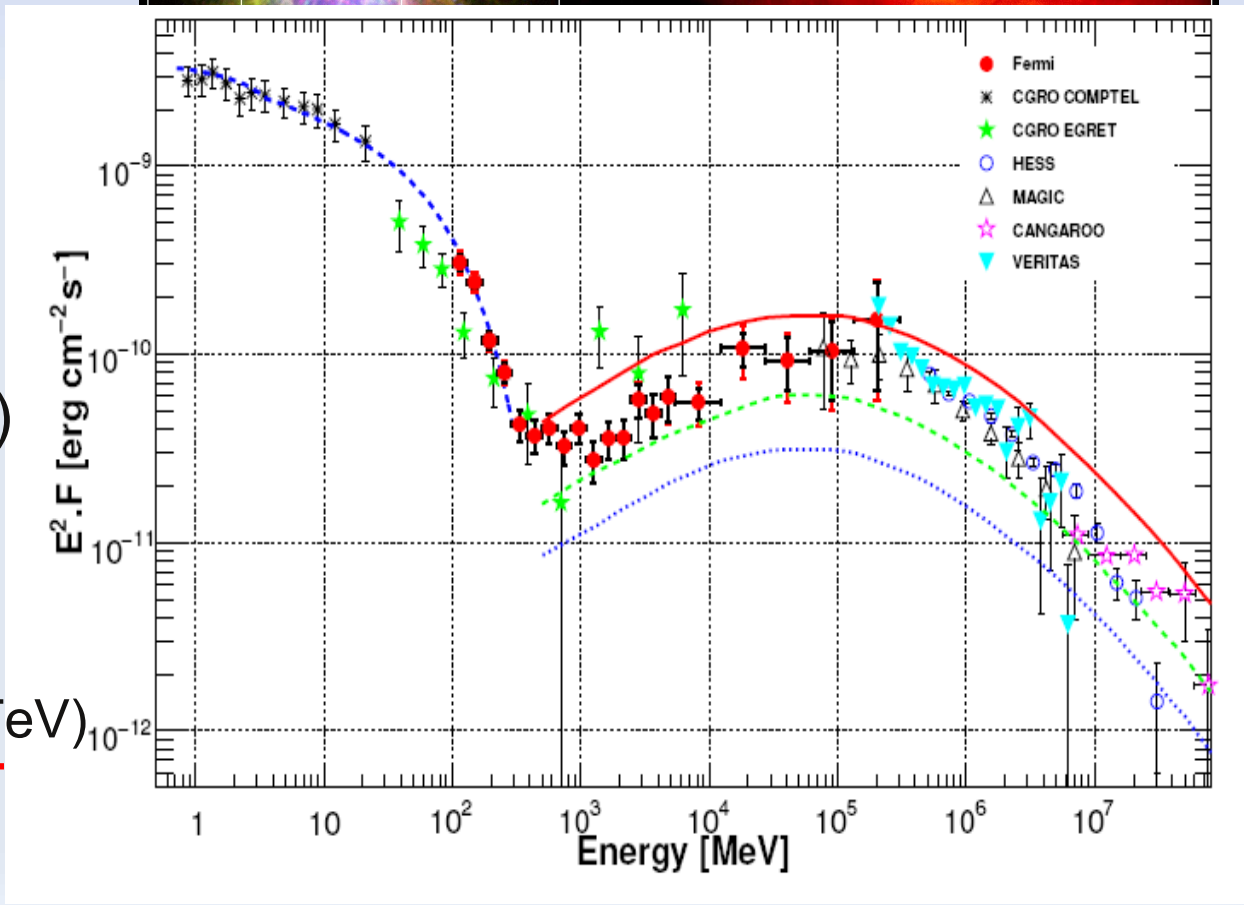
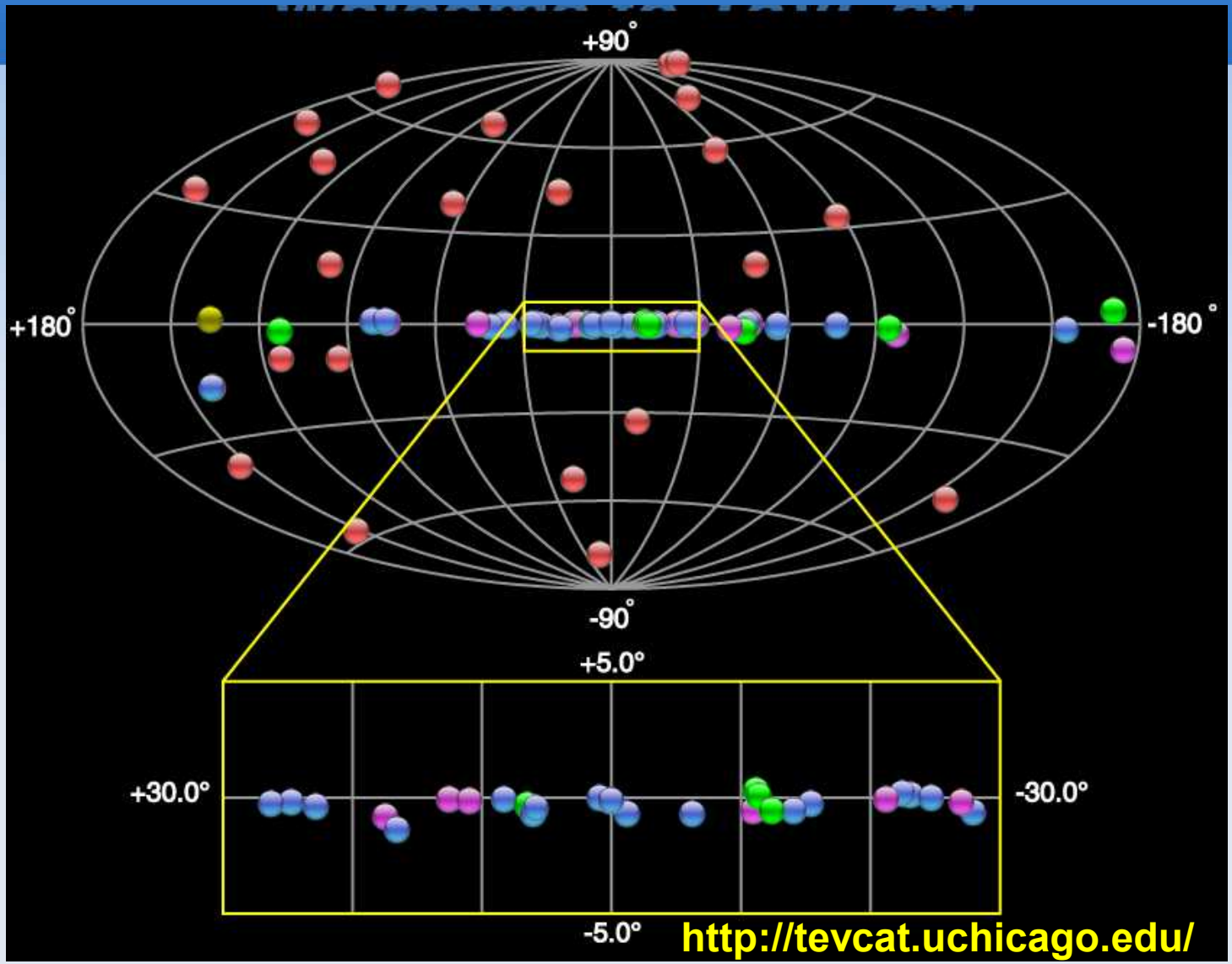
- Updated with Fermi-LAT



# The VHE Gamma-Ray Sky



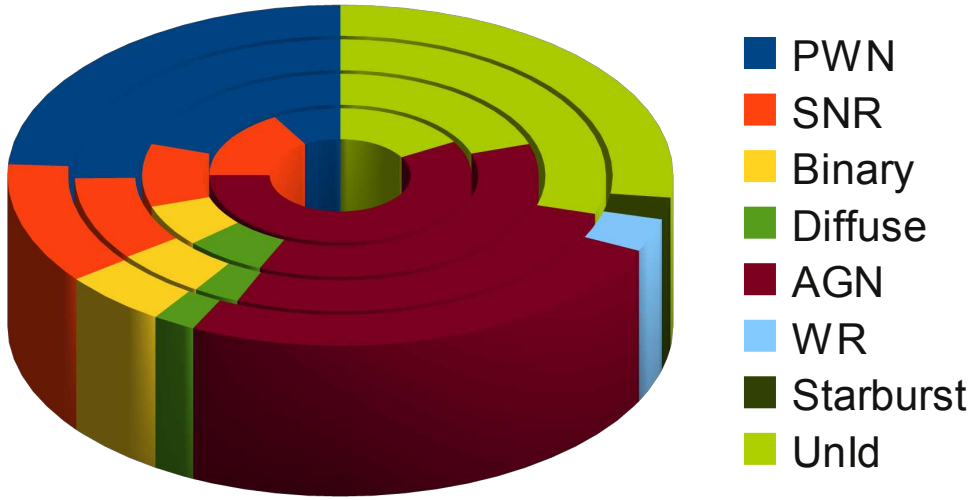

- From 1 source in 1988, 2 in 1992, 10 in ~2000

  **Today > 60 published sources**

  **SNRs, AGNs, Binaries, PWNs, WR, Starburst, UFOs...**

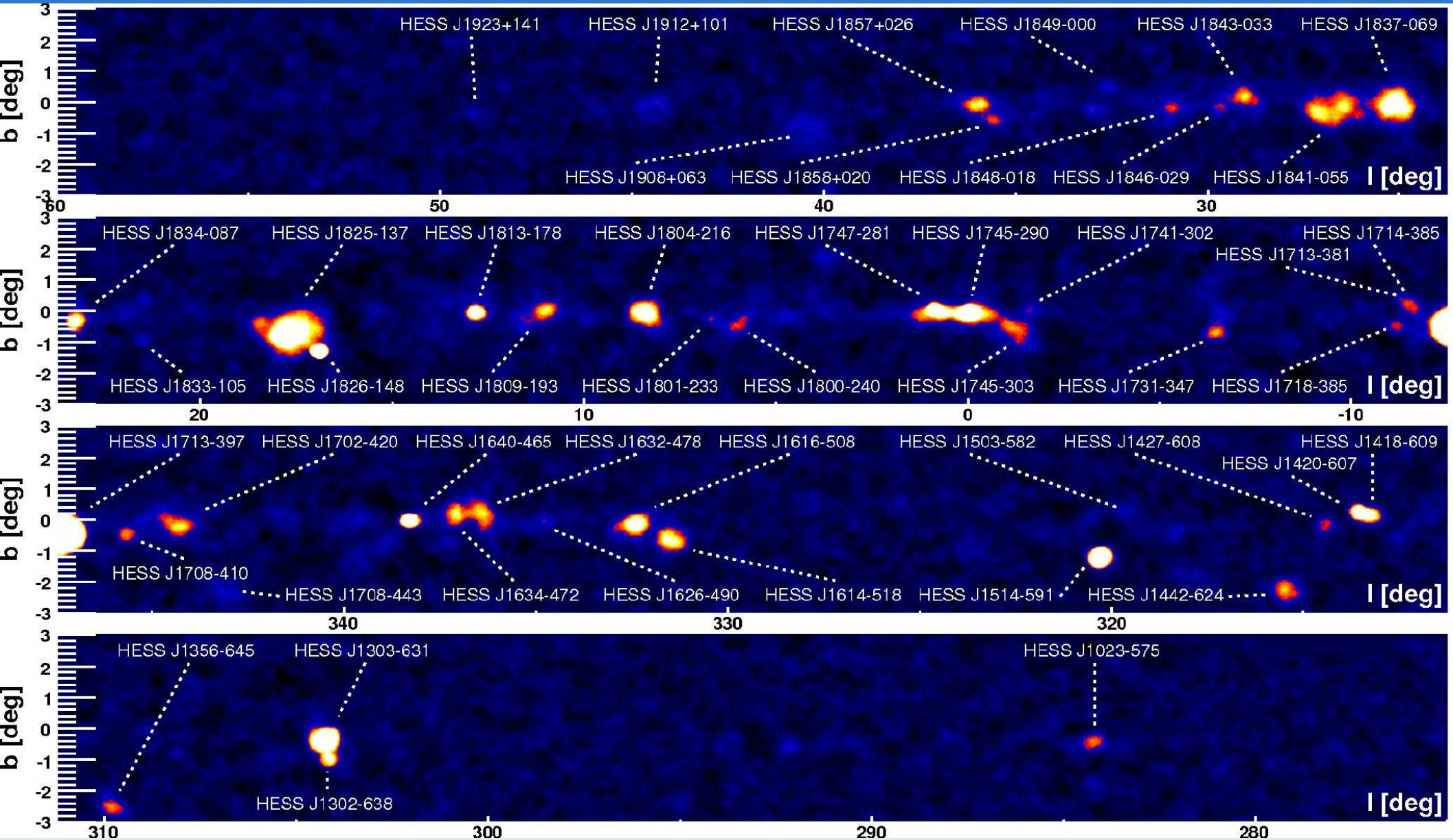
# Current VHE Source Numbers

| *Class* | *2003* | *2005* | *2007* | *2009* | |
|---|---|---|---|---|---|
| PWN (Pulsar Wind Nebula) | 1 | 6 | 18 | 23 | ← |
| SNR (Supernova Remnant) | 2 | 3 | 7 | 11 | |
| Binary | | 2 | 4 | 5 | |
| Diffuse | | 2 | 2 | 2 | |
| AGN (Active Galactic Nucleus) | 7 | 11 | 19 | 24 | ← |
| WR (Wolf-Rayet) | | | | 3 | |
| Starburst Galaxy | | | | 2 | |
| UnId (unidentified) | 2 | 6 | 21 | 26 | ← |
| Total | 12 | 30 | 71 | 96 | |




2009: Including 7
Milagro “source candidates”

# H.E.S.S. Galactic plane survey




First publication from -30° < l < 30° gave Sources > 4 sigma: 16 new (18 total), ApJ 636 (2006) 777
After extension -85° < l < 60°, currently **52 sources.**

R. Chaves
ICRC 2009

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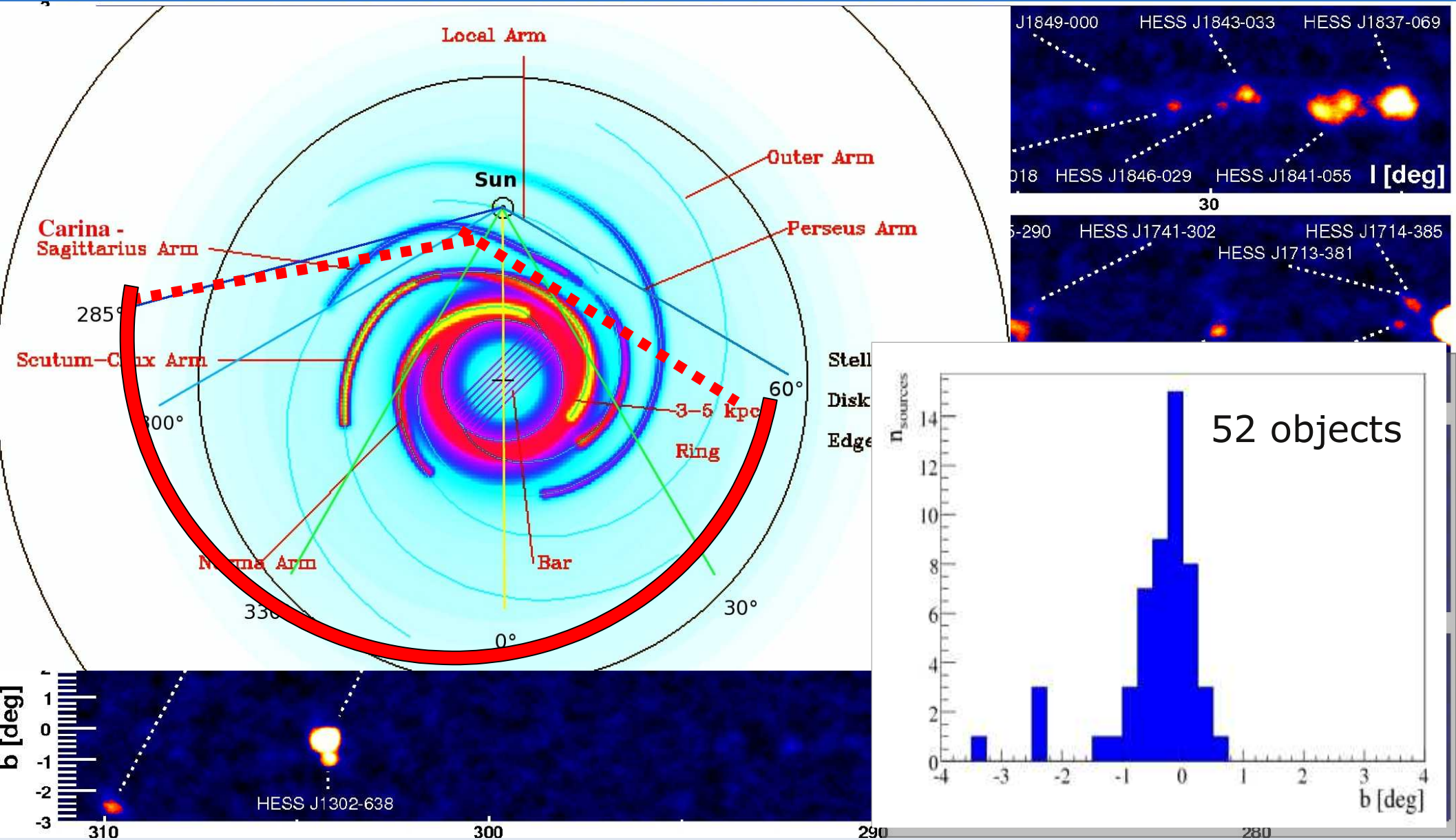


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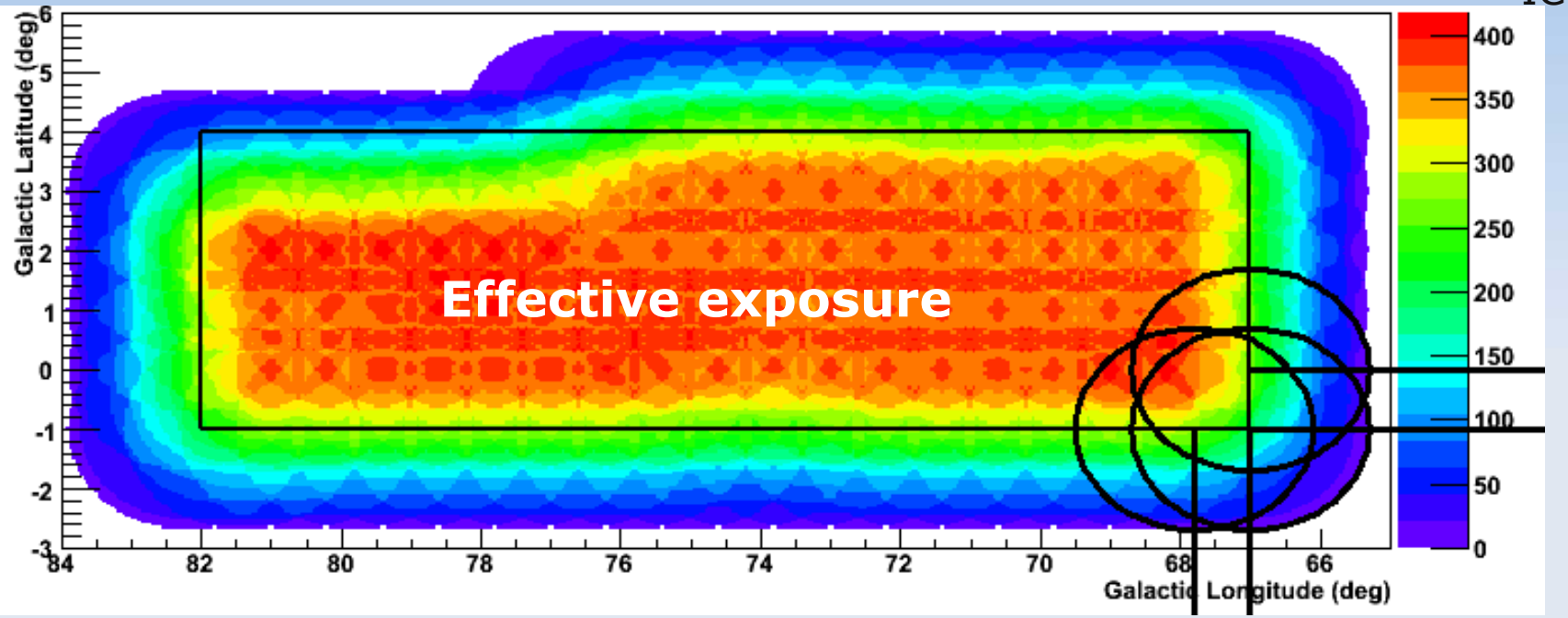
# VERITAS survey of Cygnus region

A. Weinstein
ICRC 2009




1.0°

140h of observations (112 in survey, rest in follow-up)

Source search with r=0.11°, 0.24° regions

No hotspots above 5σ post-trials in base survey

Limits 3% Crab flux for point sources at points below 3σ

8.5% Crab flux for extended 0.2° sources

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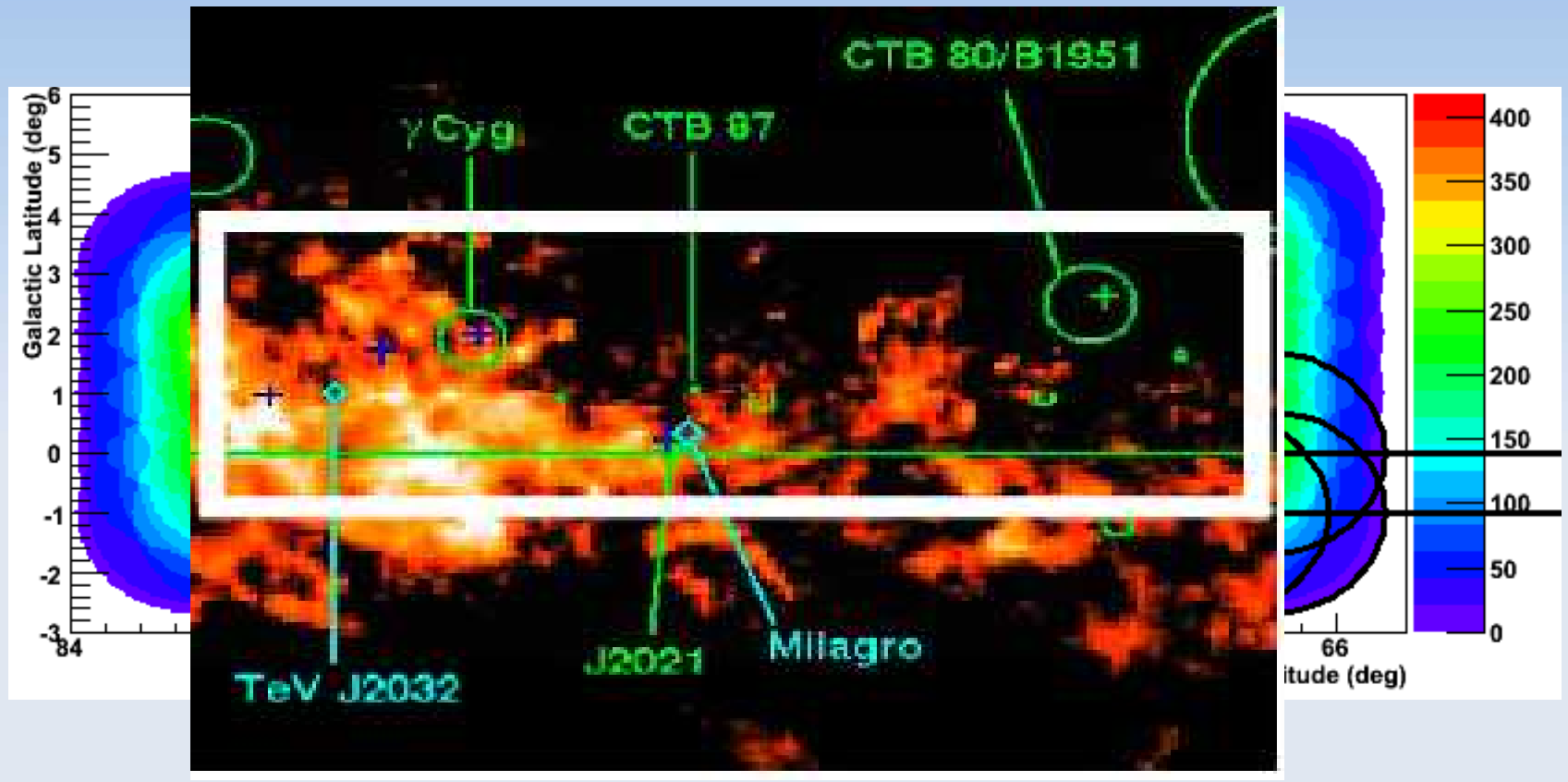


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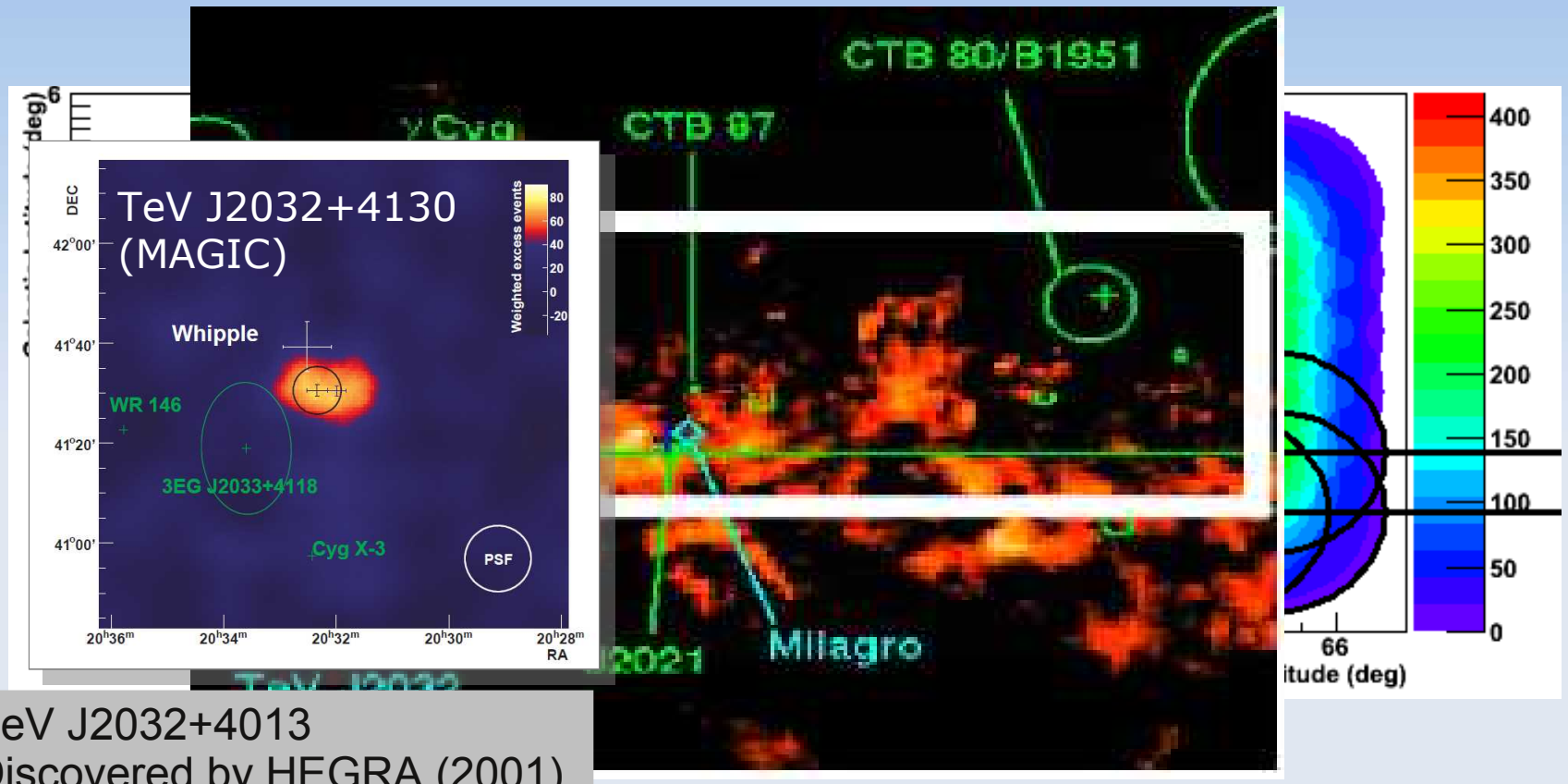


TeV J2032+4013
Discovered by HEGRA (2001)
Confirmed by H.E.S.S./MAGIC

140h of observations (112 in survey, rest in follow-up)

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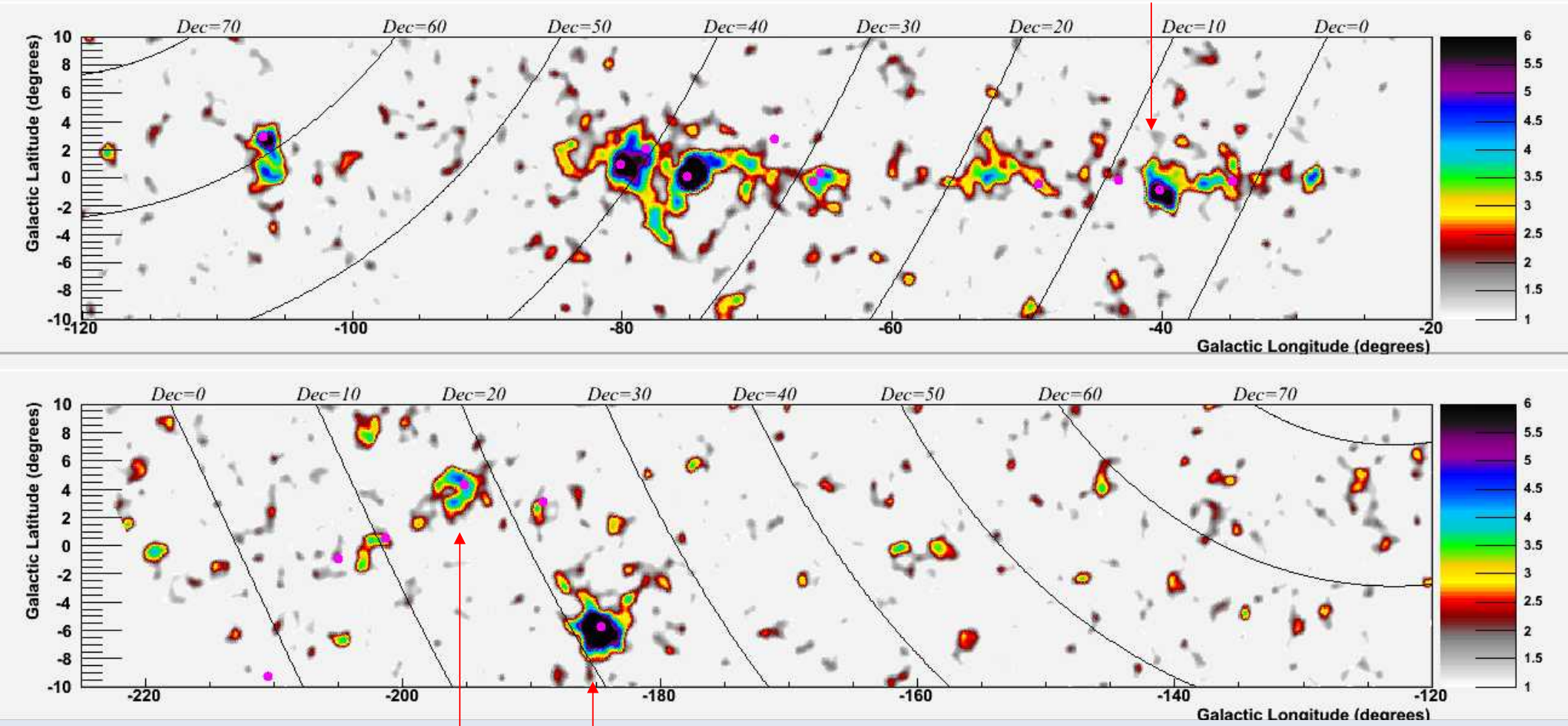
# MILAGRO survey, Northern sky

Cygnus region

J1908+06

B. Dingus







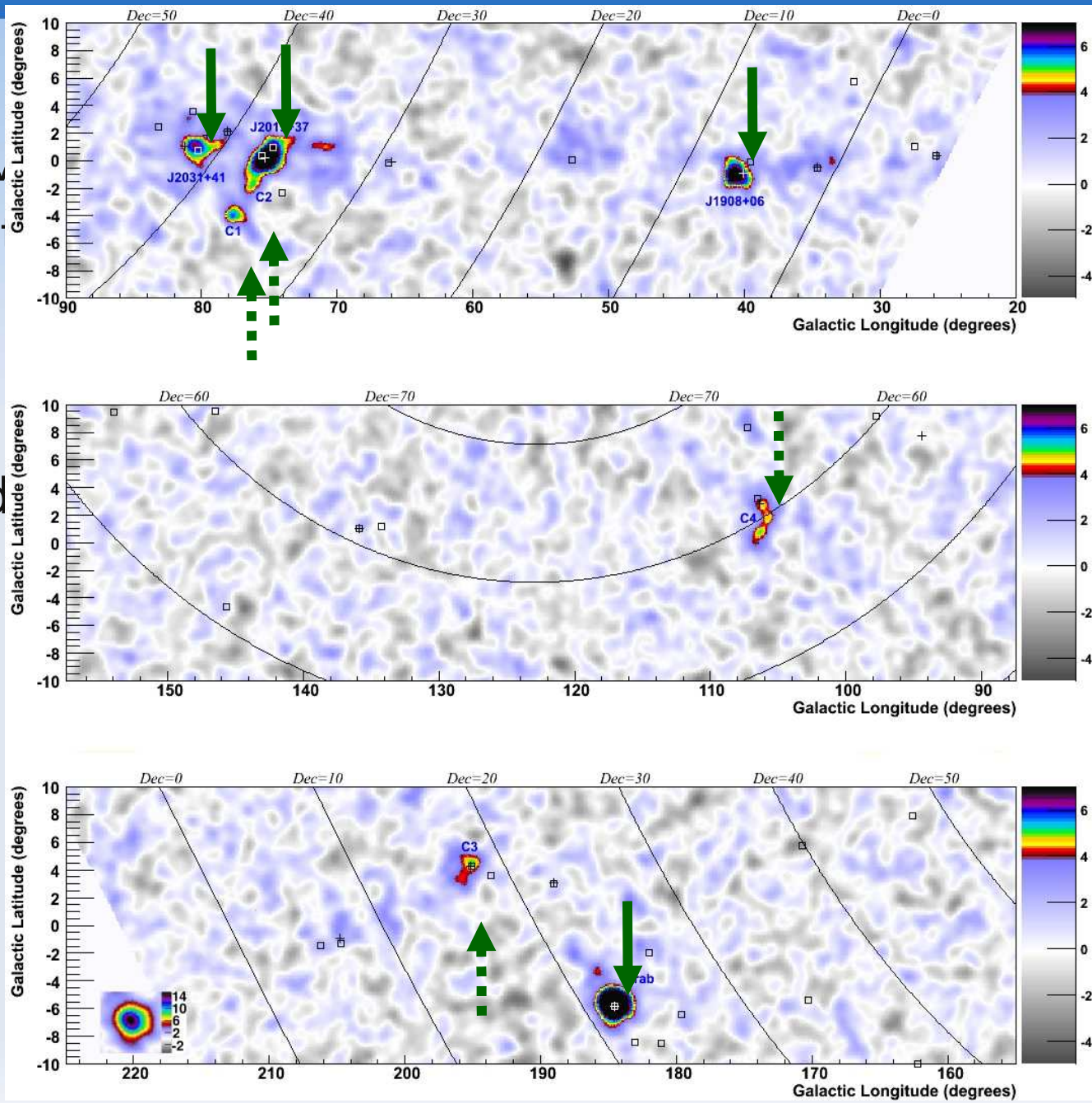
Geminga

Crab

Energy range ~5 … 100 TeV

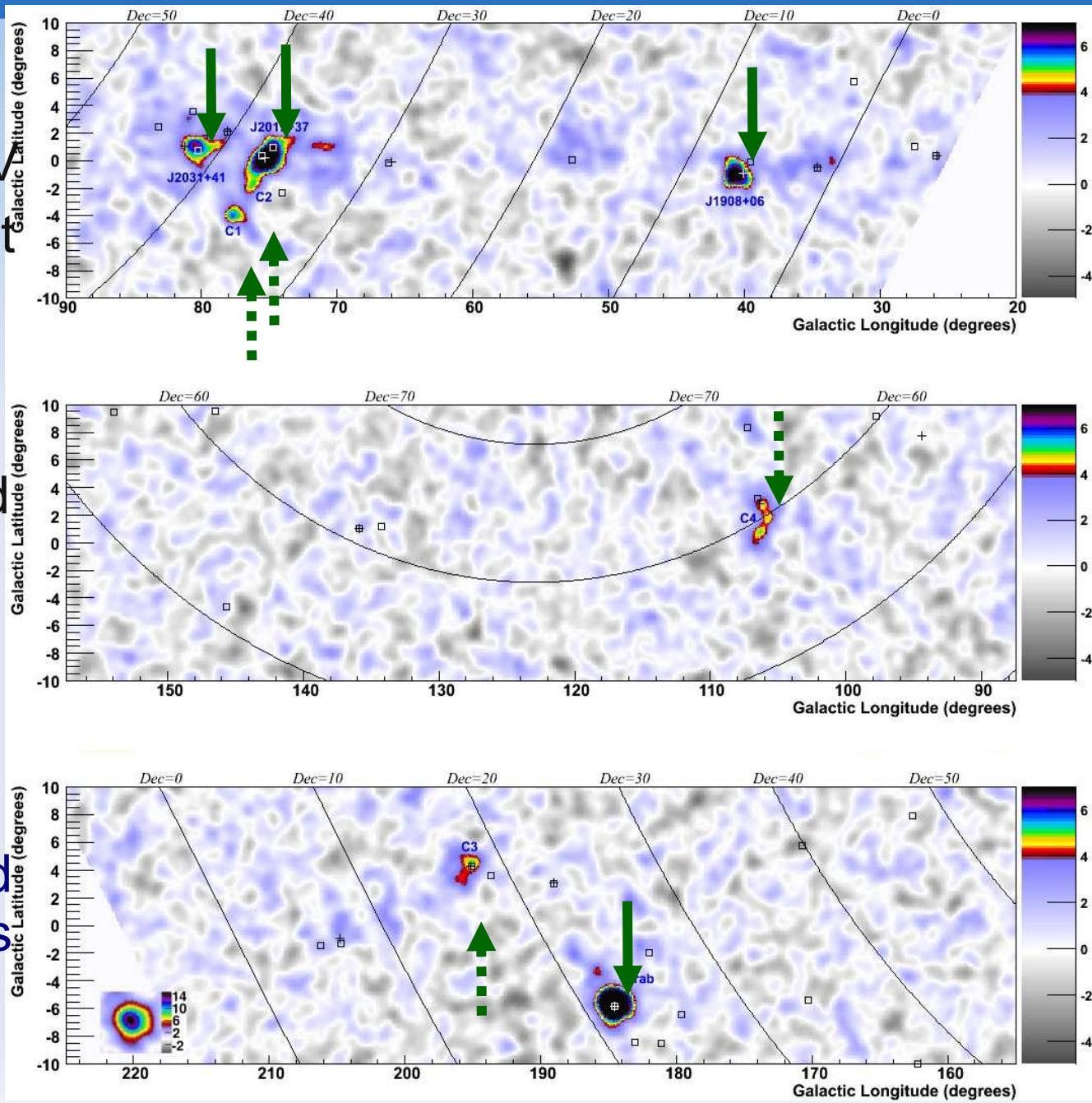
# Milagro Sources and Candidates

- 7 year map
- γ /hadron cut raises median energy to 20 TeV
- 3 new sources significant post trials
- 4 ‘hotspots’
- Interesting regime of hard spectrum/ extended sources



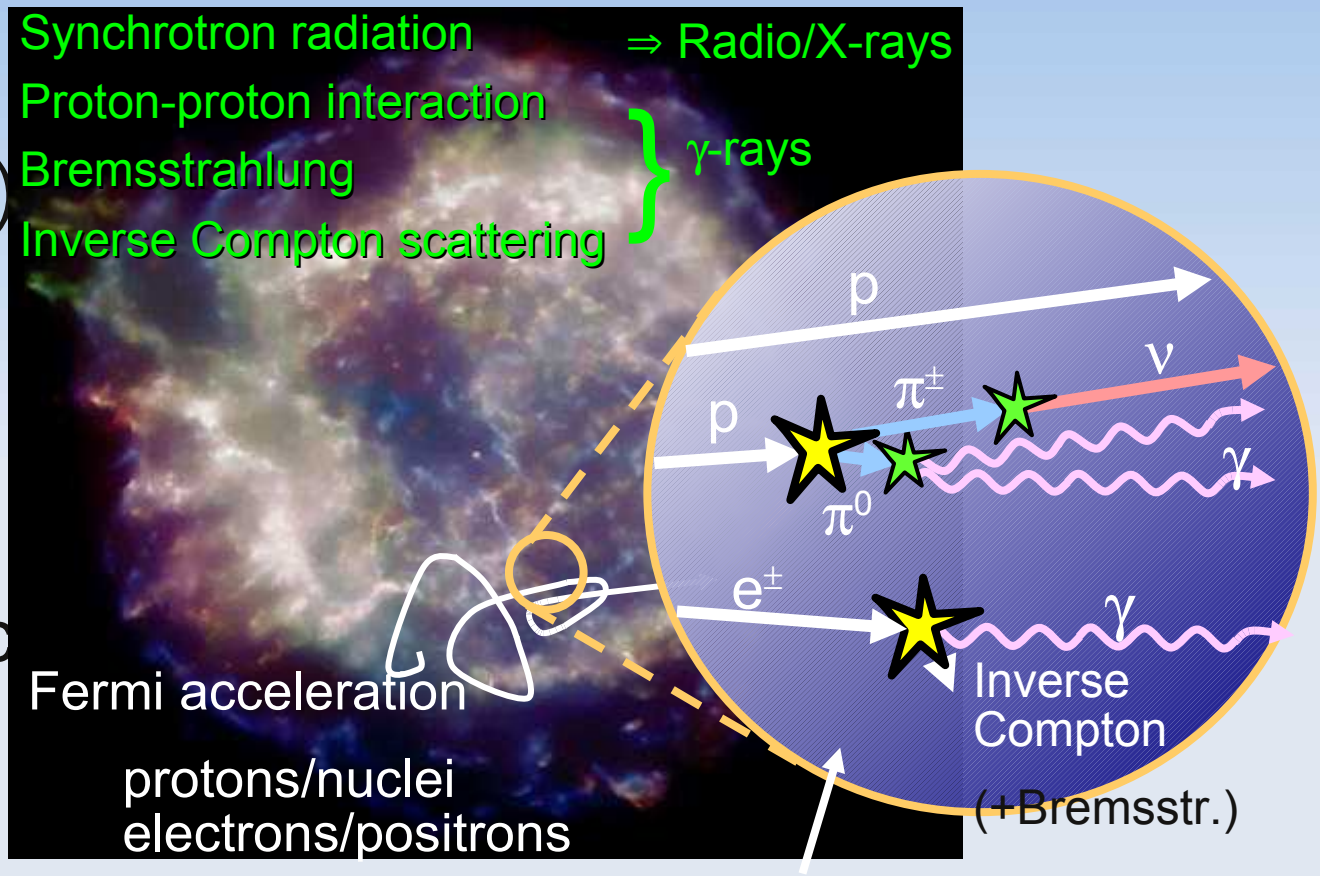
# Milagro Sources and Candidates

- 7 year map
- $\gamma$ /hadron cut raises median energy to 20 TeV
- 3 new sources significant post trials
- 4 'hotspots'
- Interesting regime of hard spectrum/ extended sources
- NEW analysis:
- Comparison with Fermi BSL (bright source list), 205 srcs
- In BSL, 14 are correlated with MILAGRO excesses (>5$\sigma$ that this correlation is not by chance)



# Supernova Remnants

- Long held to be the likely acceleration sites of the (hadronic) galactic cosmic rays
  - Diffusive shock acceleration
  - Require ~10% efficiency of kinetic energy to CR acceleration
- Several young objects well studied in X-ray synchrotron radiation
  - Thin filaments suggest rapid cooling of electrons: $B_{shock} >> B_{ISM}$

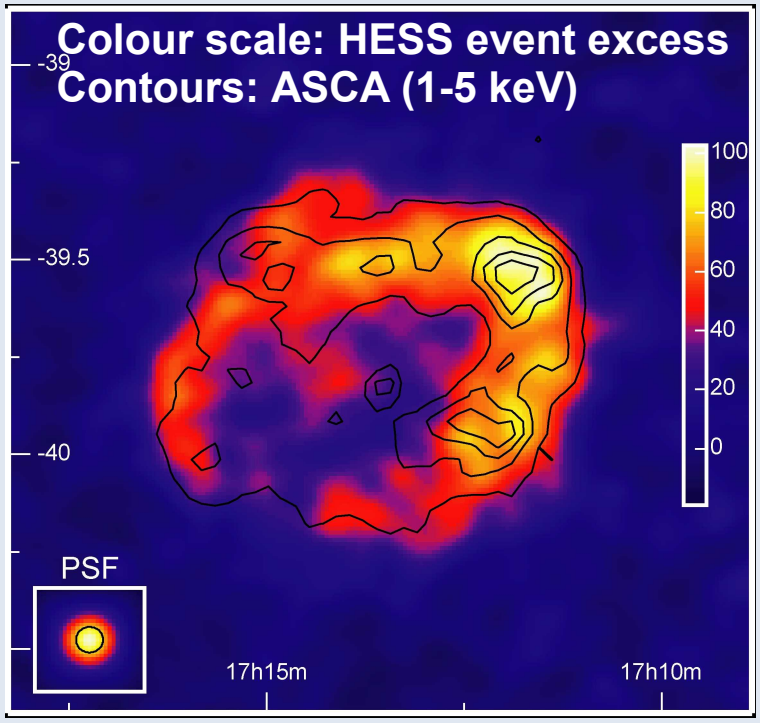


# Gamma-Ray Morphology of SNRs

## RX J1713.7-3946

**First-ever resolved γ-ray source**

**Strong correlation with X-rays: ~80%**



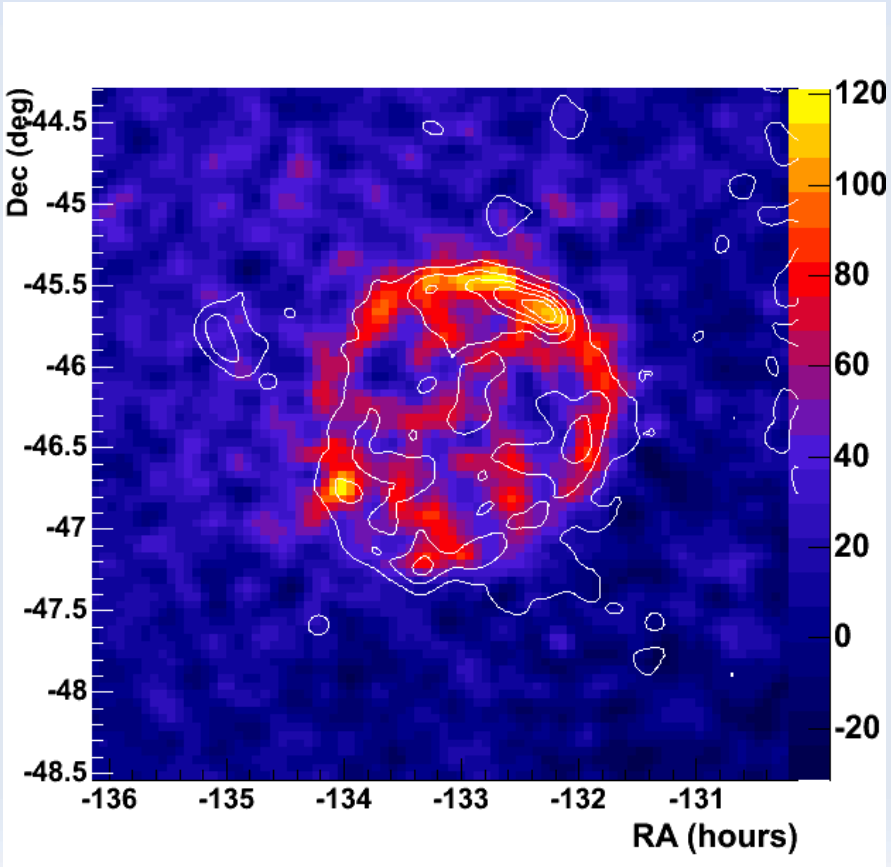

Angular resolution < 0.1°

## RX J0852.0-4622 (Vela jr)

**Thin shell resolved with HESS**

**Correlation with X-rays: ~65%**

**+ Correlation with Radio**



# Gamma-Ray Morphology of SNRs

Latest addition:

SN 1006

expands in uniform environment

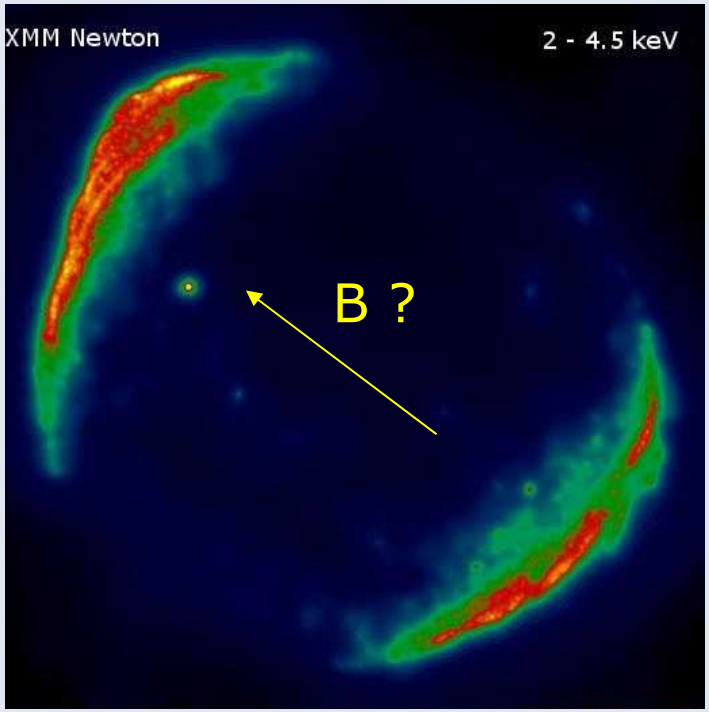
above the Galactic plane

1% Crab flux

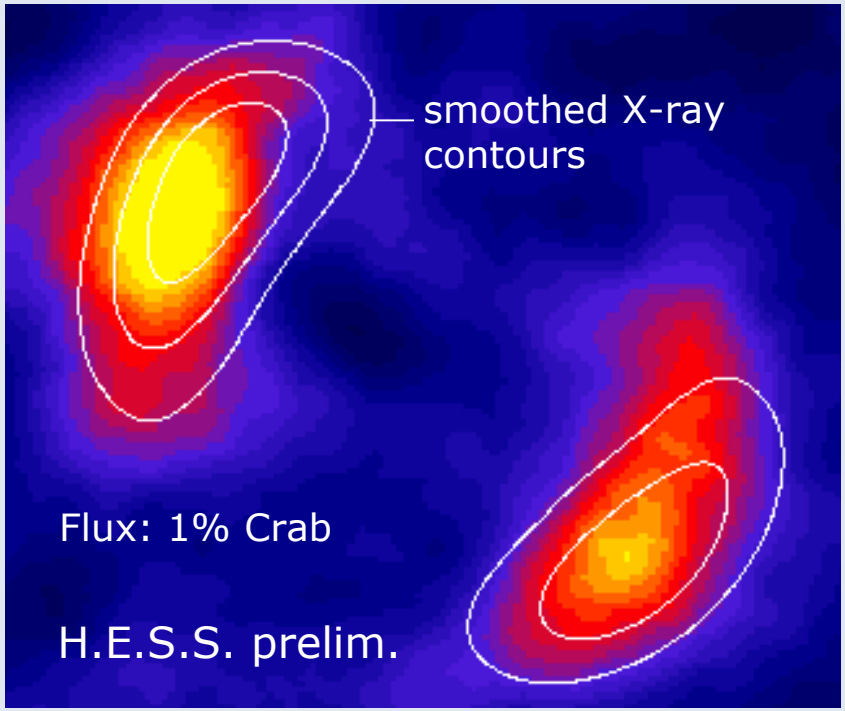
Good correlation between VHE γ-rays and X-rays

Similar spectra (index -2.4) for both regions of shell seen

2 – 4.5 keV X-rays




VHE γ -rays



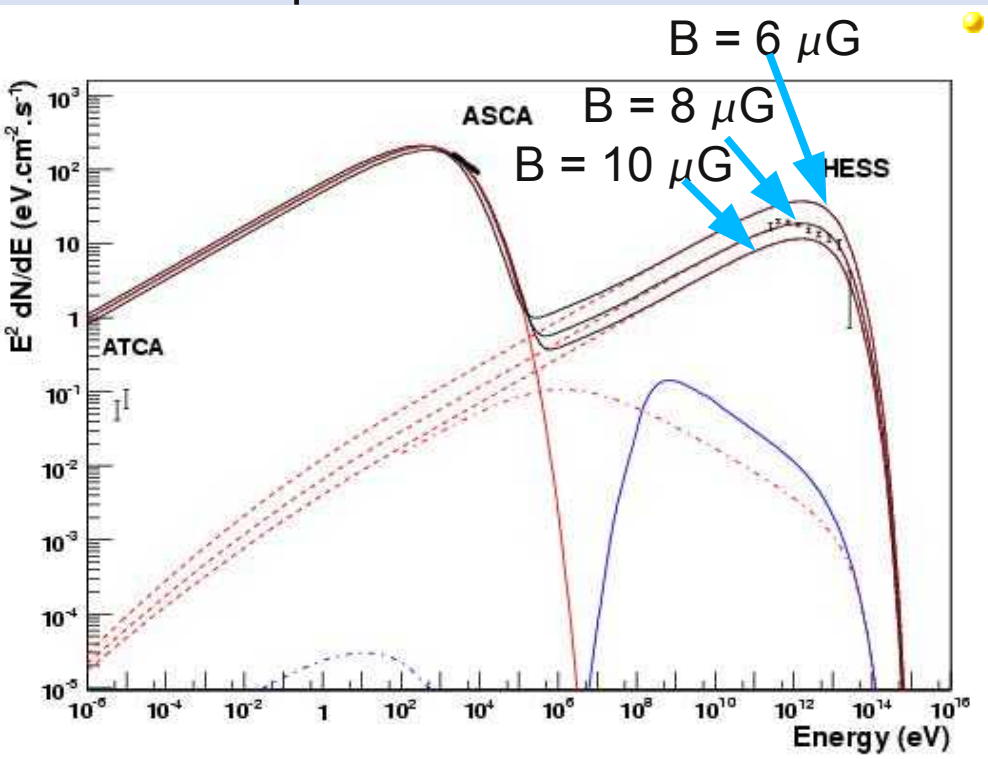
# Comparison of Emission models

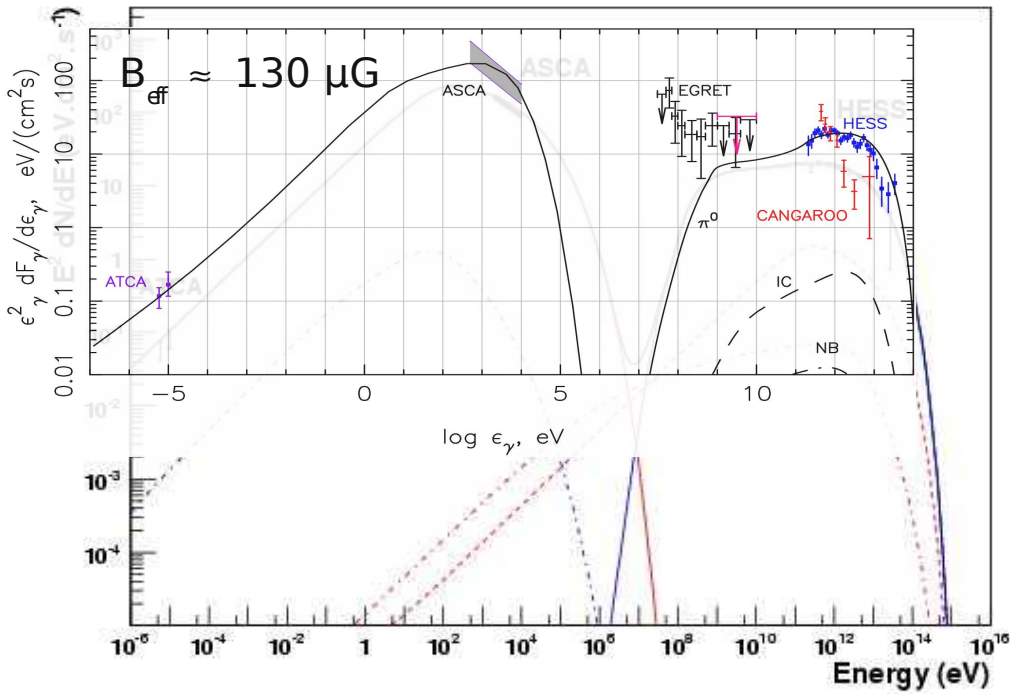
For RX J1713, γ-rays detected beyond 20 TeV ⇒ particles up to >100 TeV

But is the emission Hadronic or Leptonic ??? (link to the origin of Galactic CR?)

- **Electrons**: Power law, index 2.4
  + exp. cut-off at 80 TeV
- Injected energy: $10^{50}$ erg
- Electron/proton ration: ~ $3 \times 10^{-2}$

- **Proton** distribution: power law + exp cut-off
  $E_{cut}$ = 120 TeV  index = 1.98
- Injected energy = $10^{50}$ ergs
- Electron/proton ratio = $5 \times 10^{-4}$
- Magnetic field = 35 μG & Density = 1.5 $cm^{-3}$

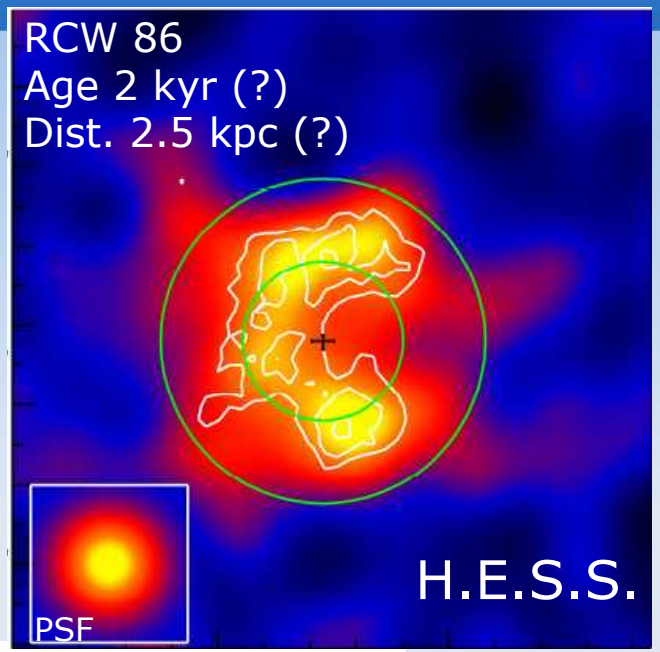


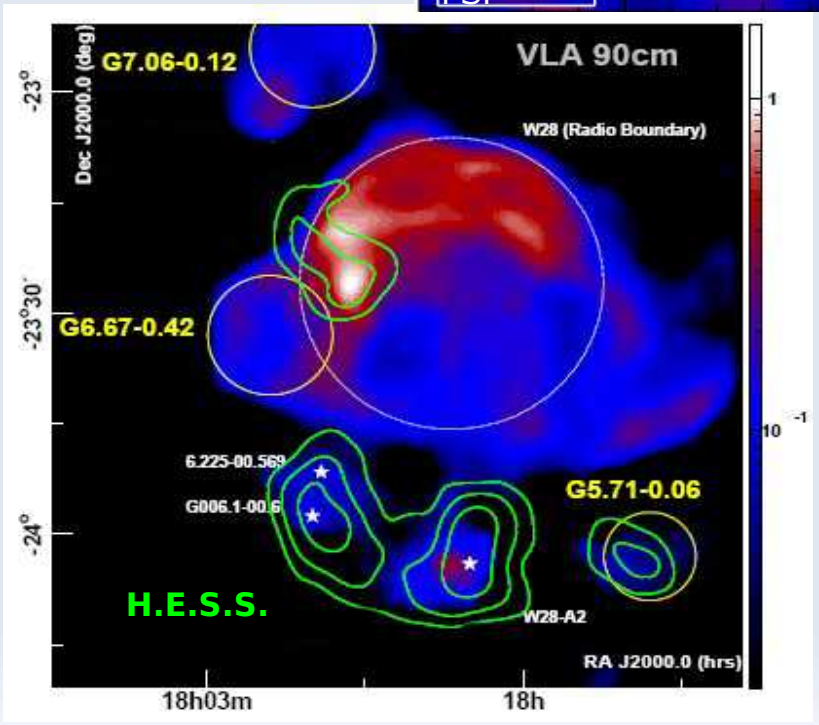

- *Leptonic scenario implies a low magnetic field*
- *Hadronic scenario requires relatively dense medium*

# Other Supernova Remnants

- RCW 86, young (~1-2 ky ?) shell-type SNR
  - H.E.S.S. 9.4 σ in 30 hours, $E^{-25 \pm 01}$ spectrum
  - Probably the third TeV SNR shell

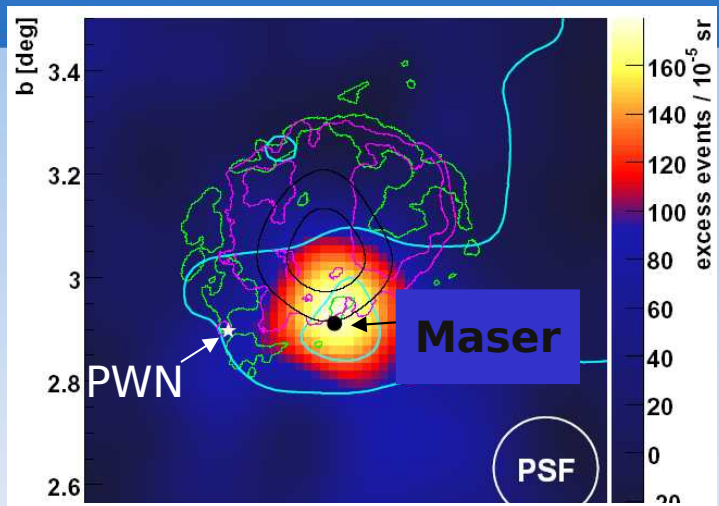


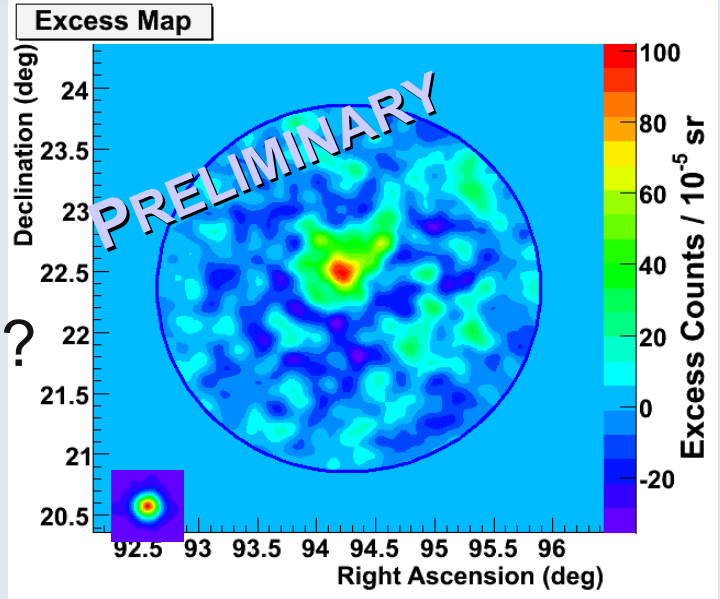

- W28, old (>$10^4$ year) SNR
  - H.E.S.S. TeV emission coincident with molecular clouds
  - First evidence for p-p in SNR/Cloud interactions



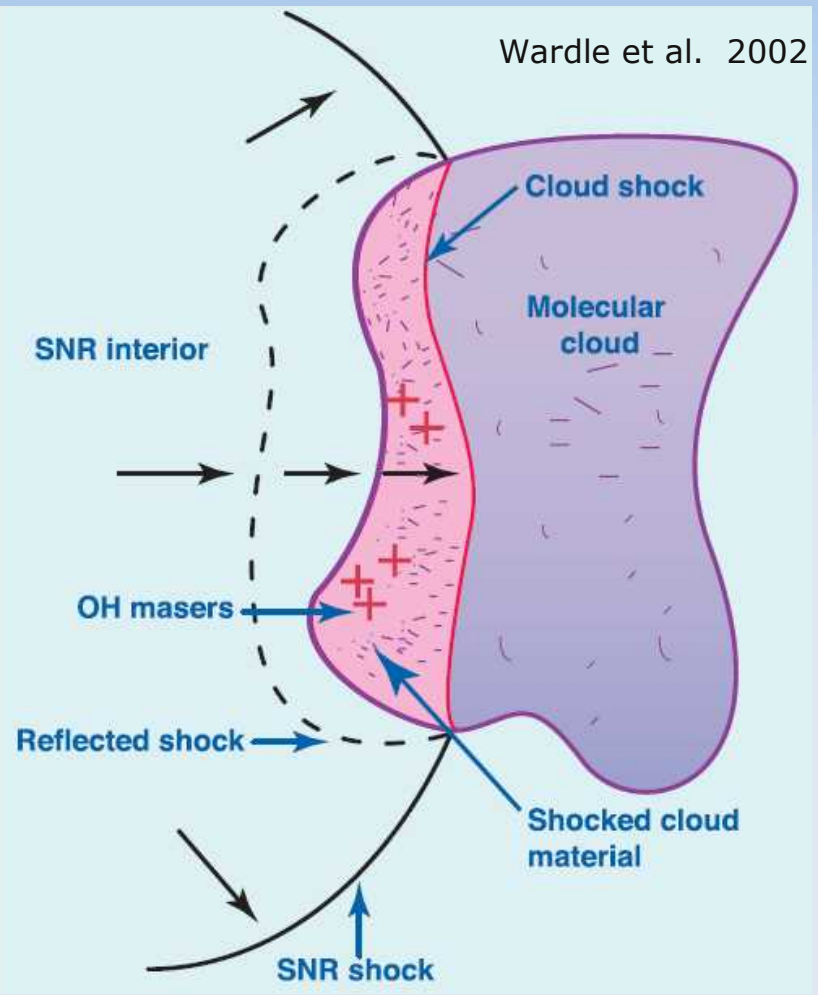
# Other Supernova Remnants (2)

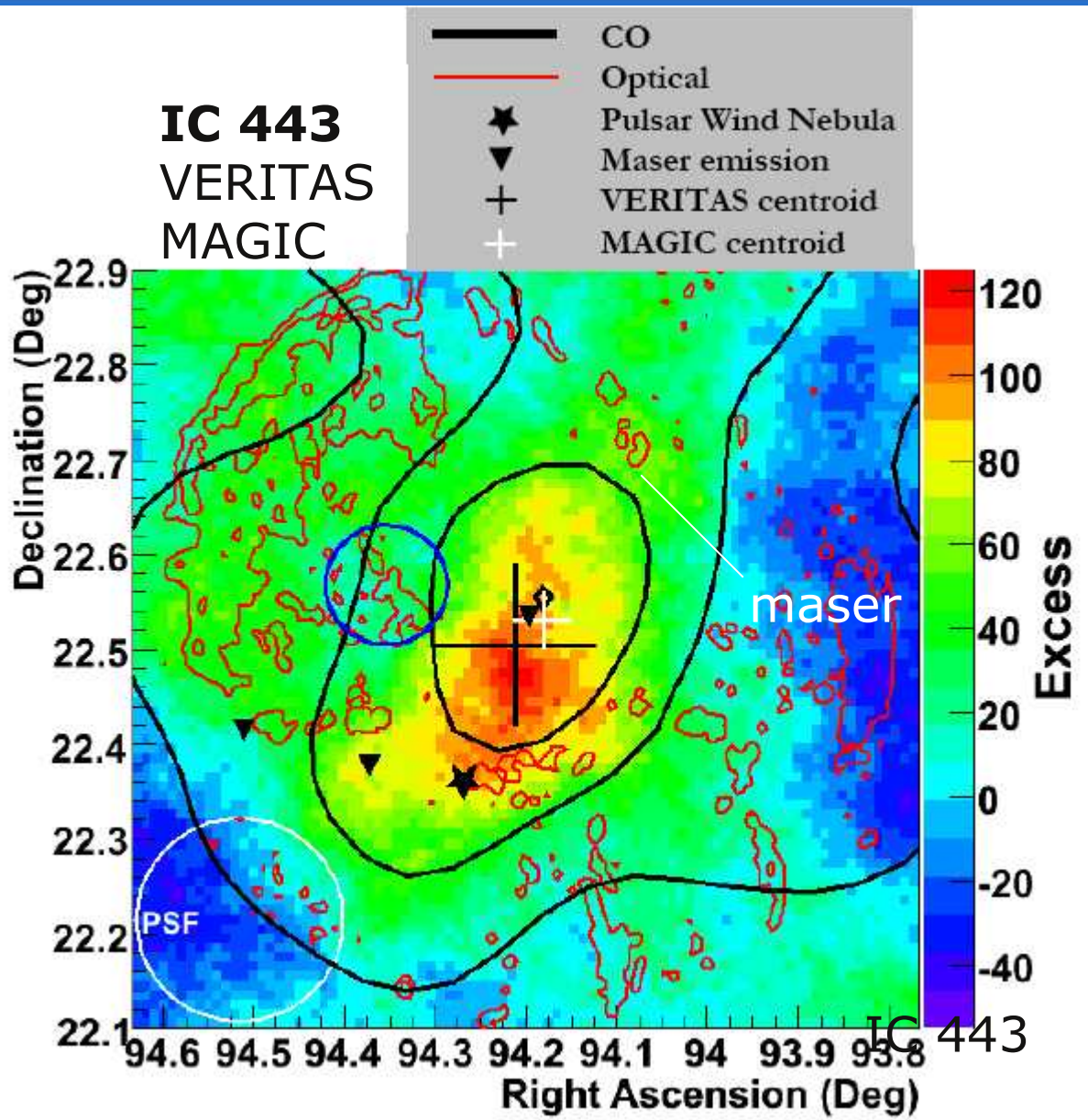
- IC433, 30kyr old, SNR
  - Maser showing shocked gas + PWN at edge of remnant
  - MAGIC 5.7σ in 29 h
    Steep spectrum $E^{-3.1 \pm 0.3}$
  - VERITAS 7.1σ in 16 h
    Consistent position
  - Position compatible with Maser
    - Interaction of SNR-accelerated hadrons?
- Cas A, young, bright radio/X-ray shell
  - MAGIC confirmation, 5.2 σ in 47 h
  - Consistent with HEGRA measurement, $\Gamma = 2.4 \pm 0.2$



# Supernovae interacting with clouds: e or p ?



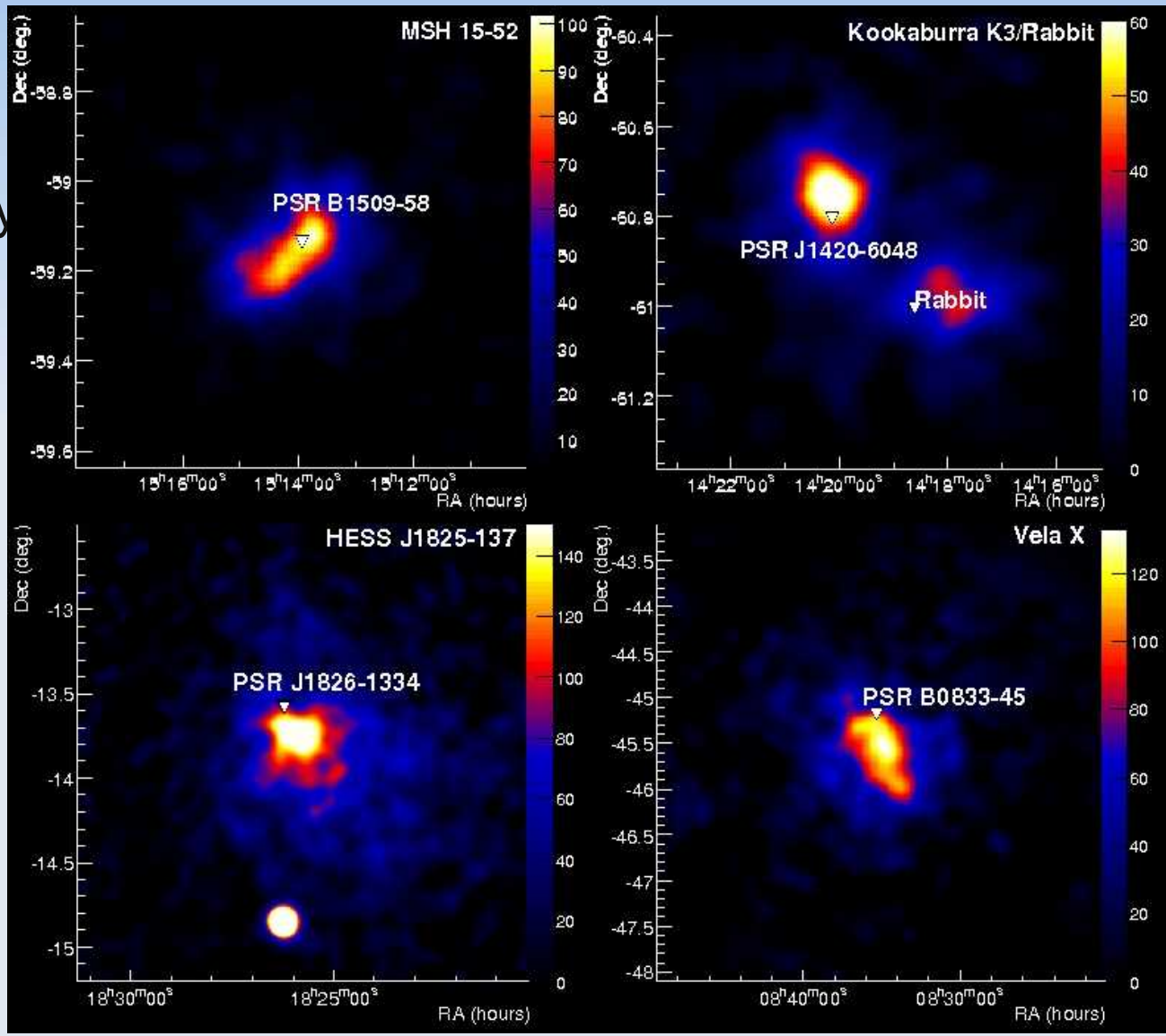




Another clue for the origin of Galactic CR ?

**MAGIC** 2007, arXiv:0705.3119
**VERITAS** 2007, 2008: arXiv:0810.0799

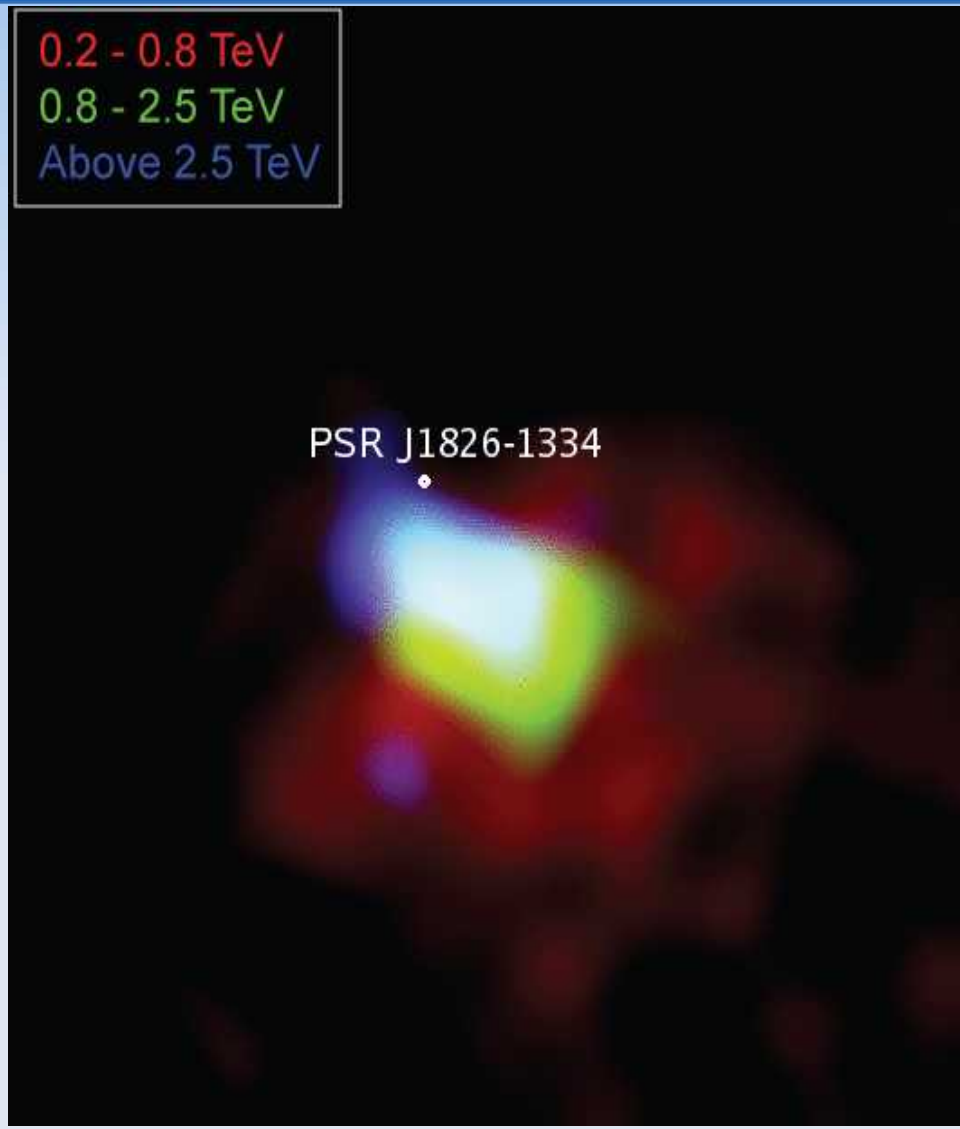
# Pulsar Wind Nebulae

- Major galactic TeV source population
  - Associated with relatively young (<$10^5$ year old) and energetic pulsars
  - Extended sources, 10s of pc
  - Often displaced from pulsar (expansion into inhomogenous medium)
- Generally believed that we see inverse Compton emission of 1-100 TeV electrons



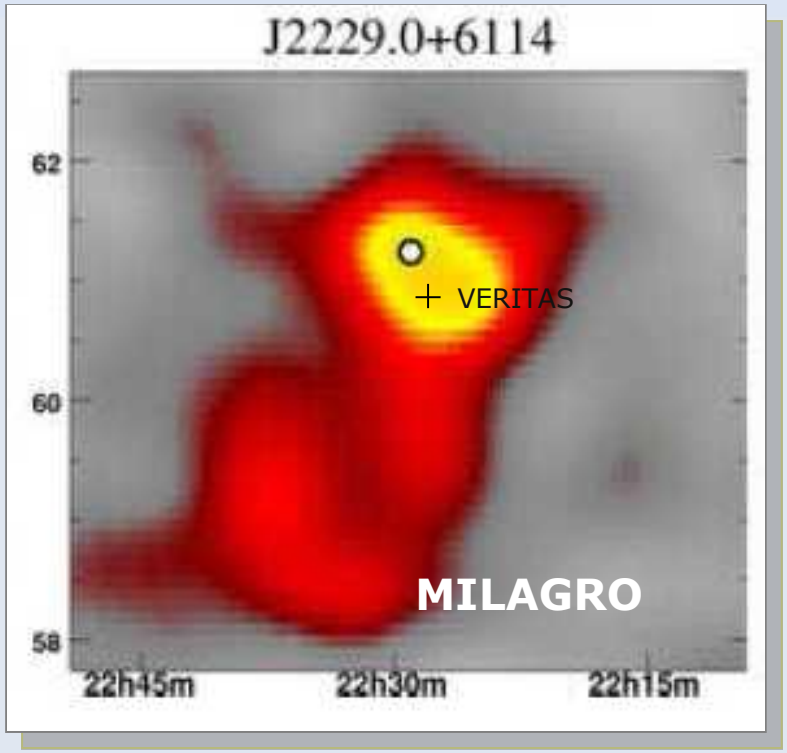
# PWN Energy Dependant Morphology

- HESS J1825-137 associated with energetic pulsar
- Spectral steepening seen away from the pulsar
- Very likely this is evidence for cooling of electrons in the Nebula
  - Seen in several *X-ray* PWN
- A first in gamma-ray astronomy!

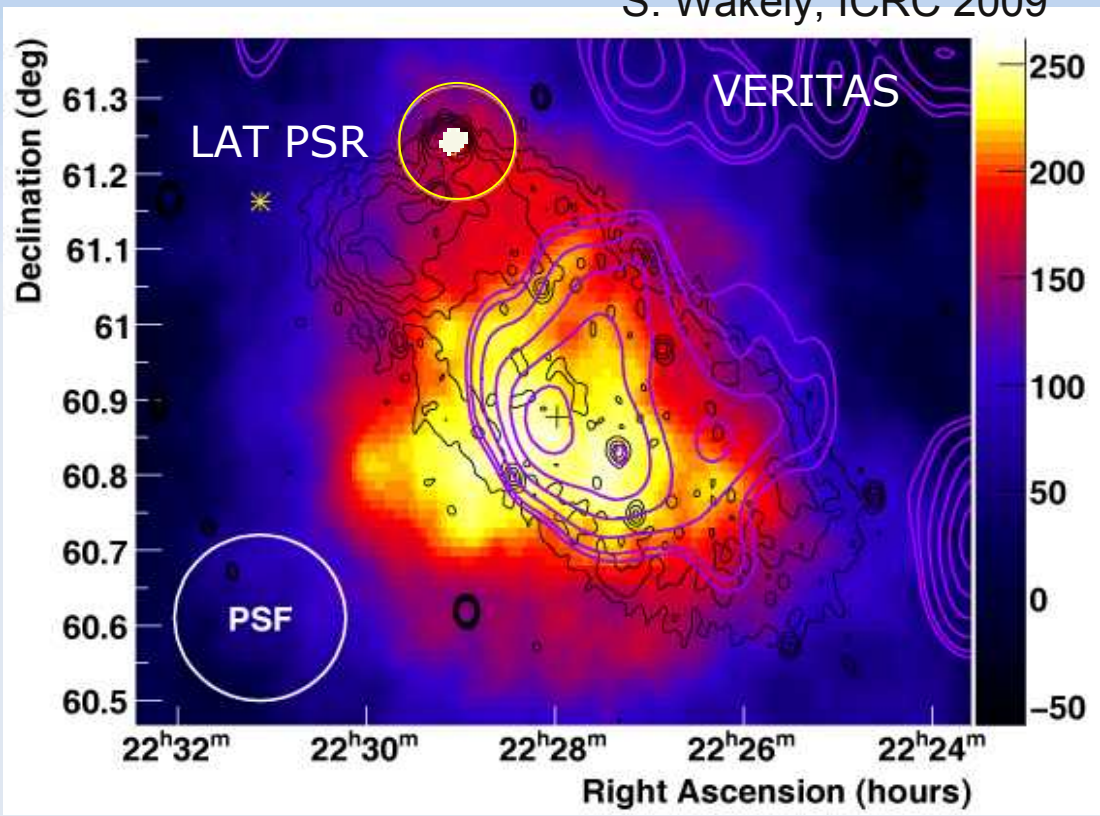


# Many other VHE Pulsar Wind Nebulae

Many other candidates,
e.g. PSR J1846-0258 in Kes 75, G21.5-0.9, HESS J1357-645, J1718-385, J1809-193, J1912+102, PSR B1706-44, Boomerang…




S. Wakely, ICRC 2009



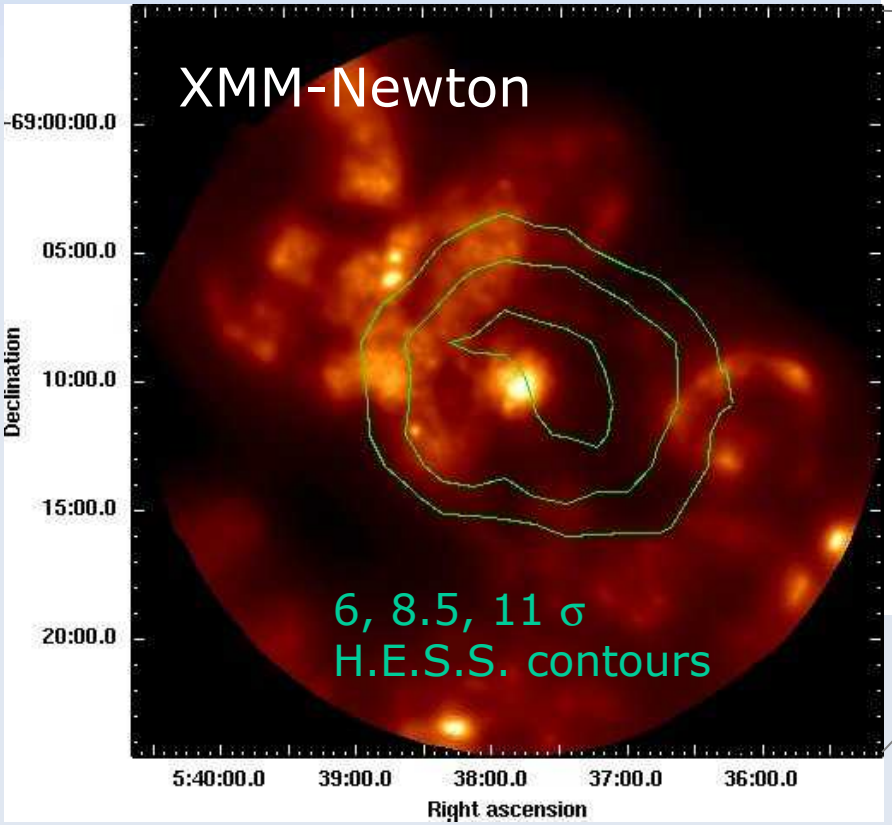

Boomerang / PSR J2229+6114
Black contours: radio, purple: CO
Also: MGRO source

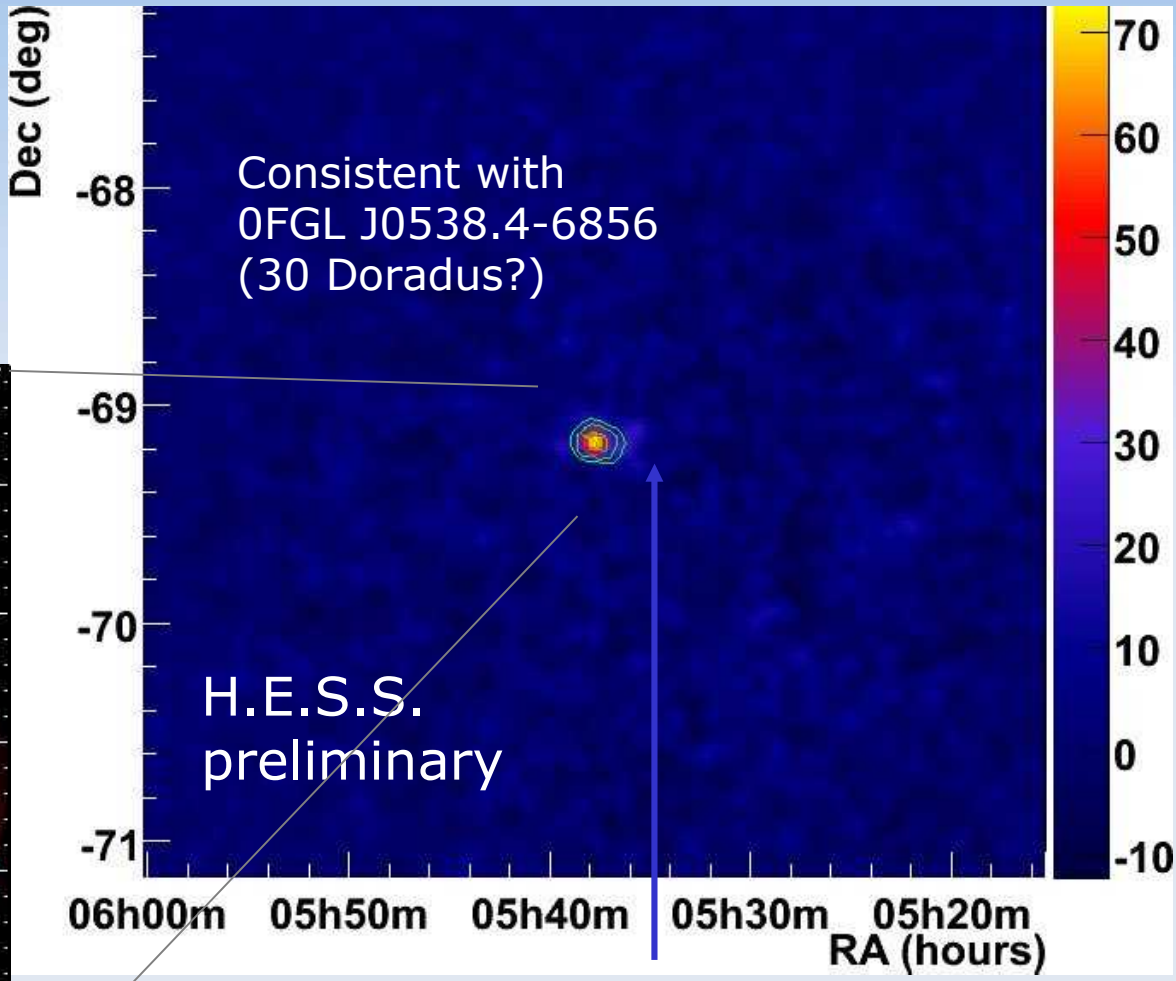
S. Wakely
ICRC 2009

# Most distant: N 157B / PSR J0537-6910 in LMC

Detected as point like source

About 1% of spin-down luminosity of 5 x $10^{38}$ ergs/s visible in 1-10 TeV $\gamma$ -rays



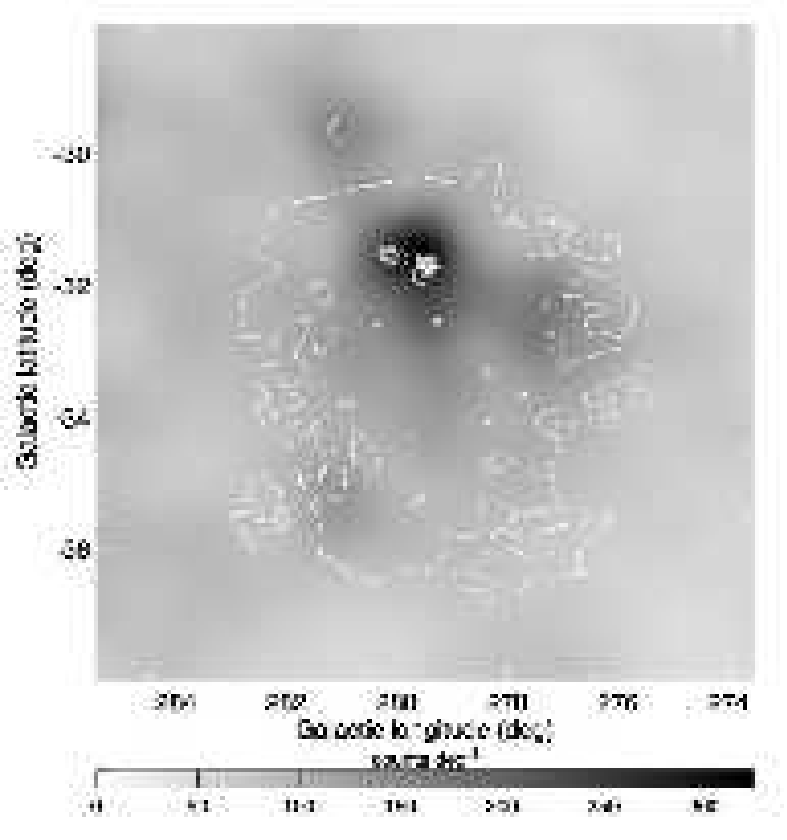

SN 1987a in FoV;
Upper limits close to predicted flux, no detection of 30 Doradus

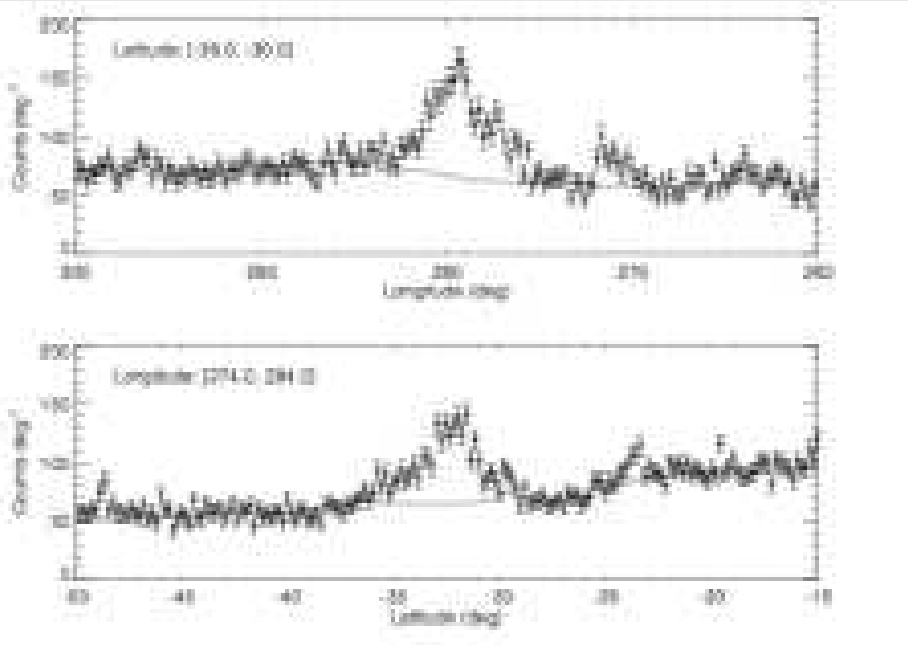
Nu. Komin
ICRC 2009

# LMC seen in HE (EGRET/FermiLAT)

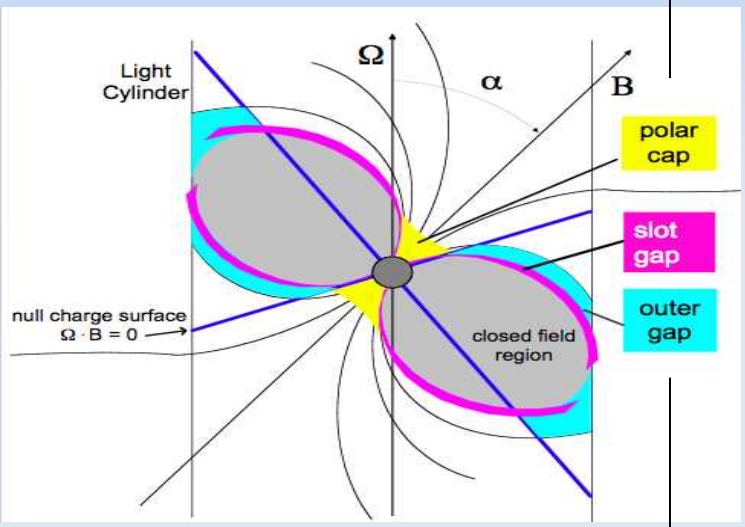
-HE: resolved for the first time!

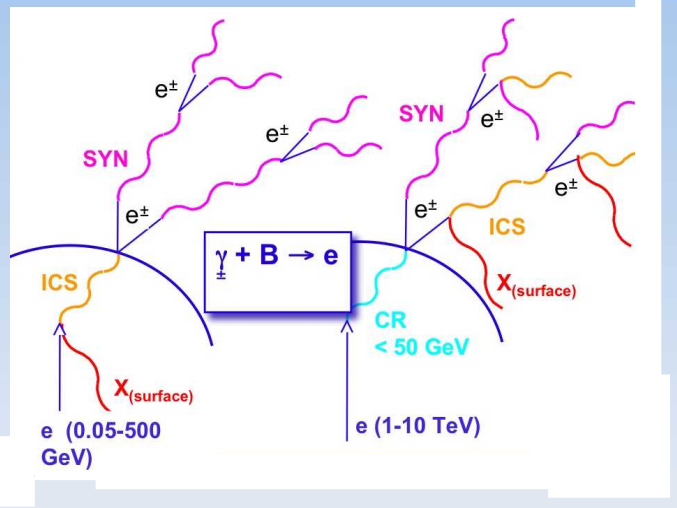
Significant part of the radiation (but not all) coming from 30 Doradus (containing SN1987A).

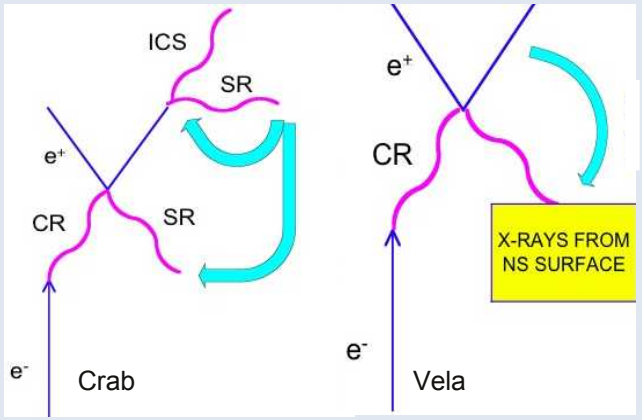


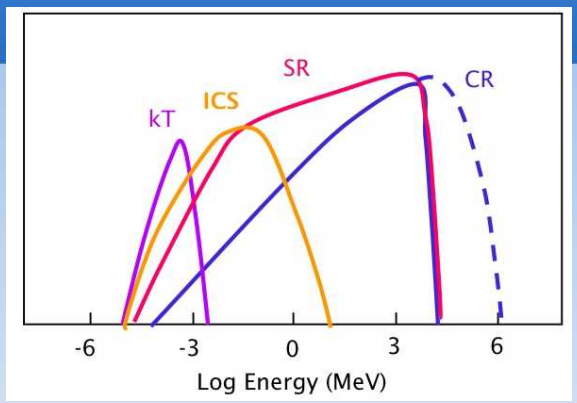


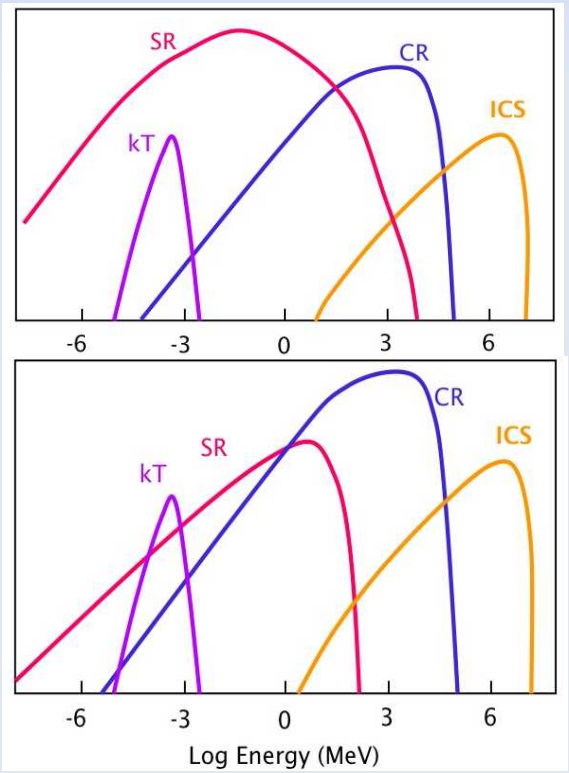
# Pulsar emission, the framework




Polar Cap: Daugherty & Harding 82, Zhang & Hardng 00, Sturner & Dermer 94, etc
Ouer Gap: Cheng et al. 86, Cheng 94, Romani 96, Zhang & Cheng 97, 00, Hirotani 99, etc,

# 1st VHE detection of pulsar's pulsed emission

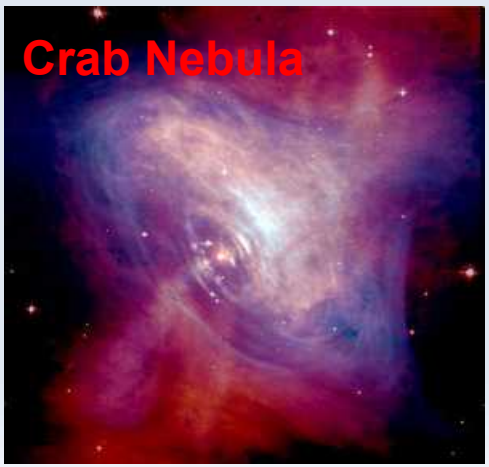
**MAGIC, Science 322, 2008**
**using special low-energy trigger**

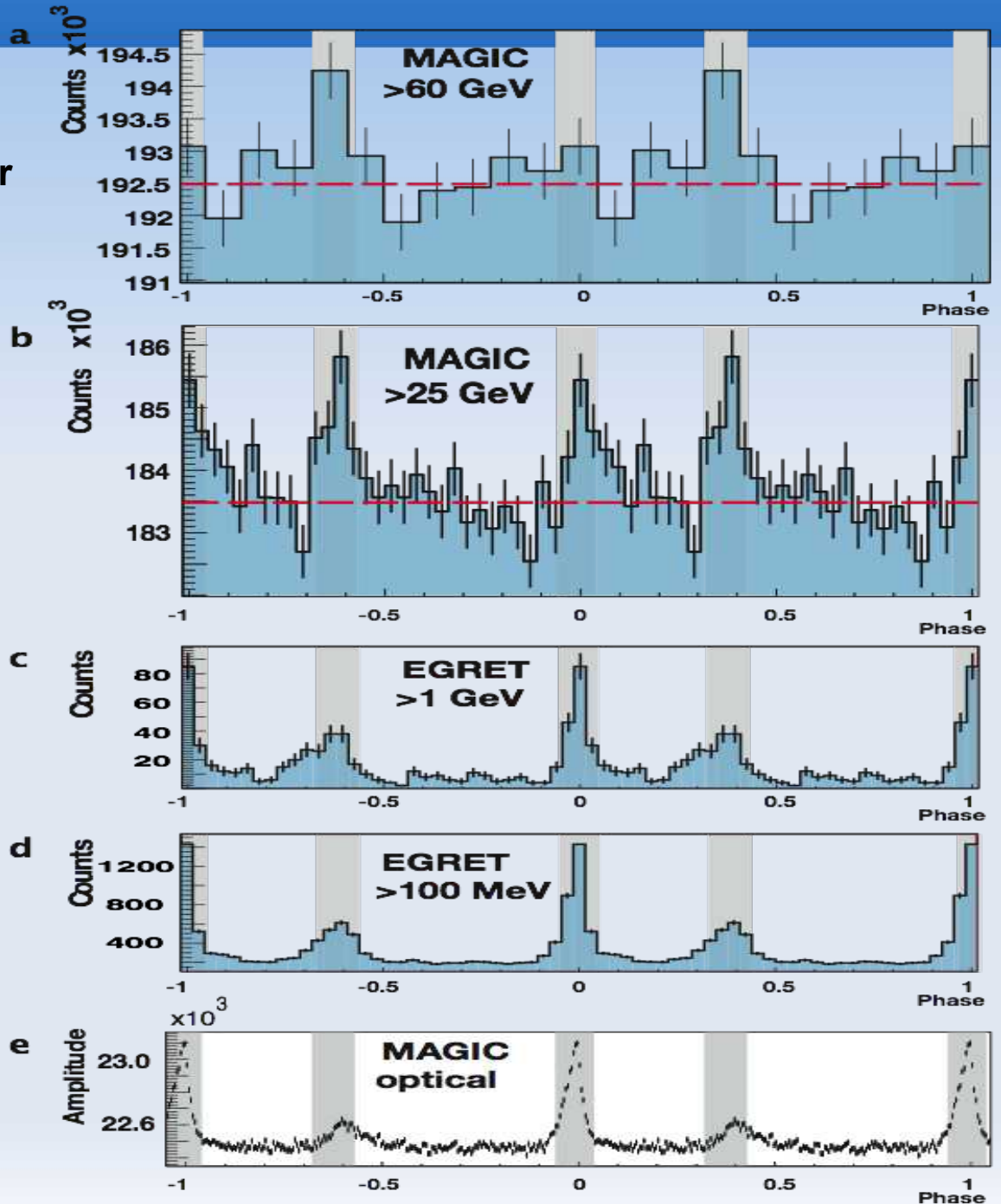
Spectral Fit:
Power-law with an exponential cutoff

F: 8.8±1.1+2.9-1.1
M: 17.7±2.8±5

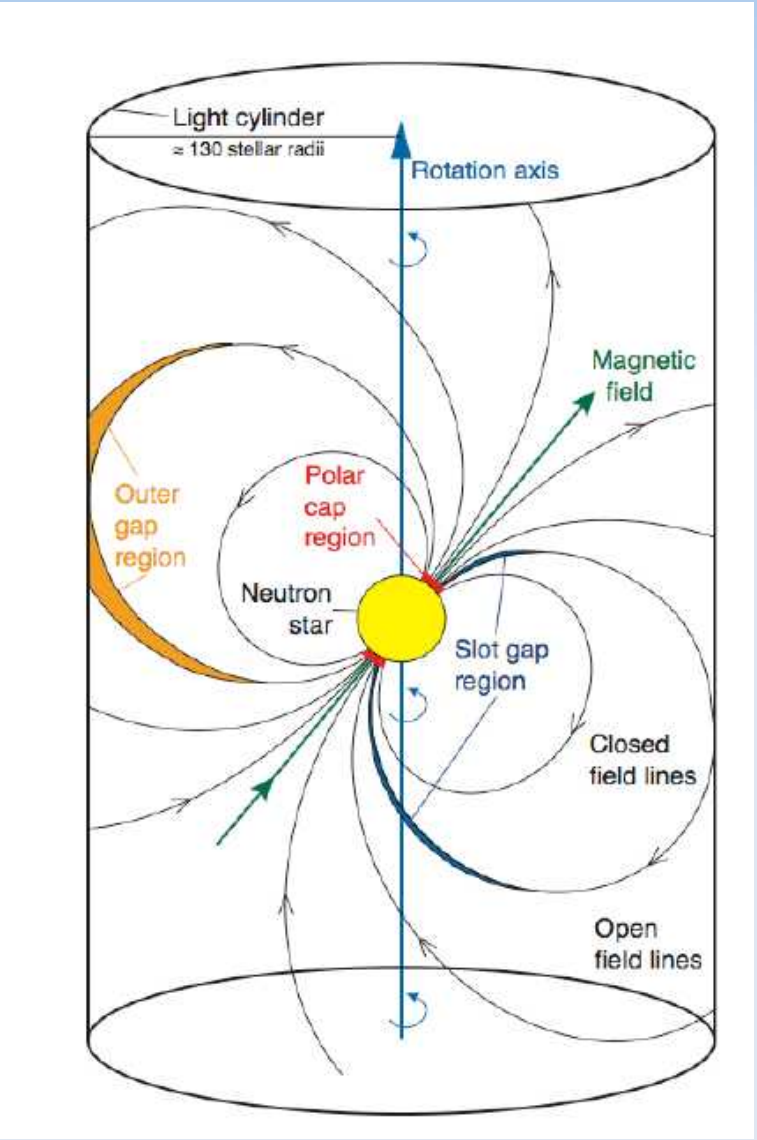
Power law with
Hyper-exponential cutoff rejected > 5σ

Cutoff energy limits the height of the emission (to avoid absorption) to be beyond 4 / 6 $R_*$

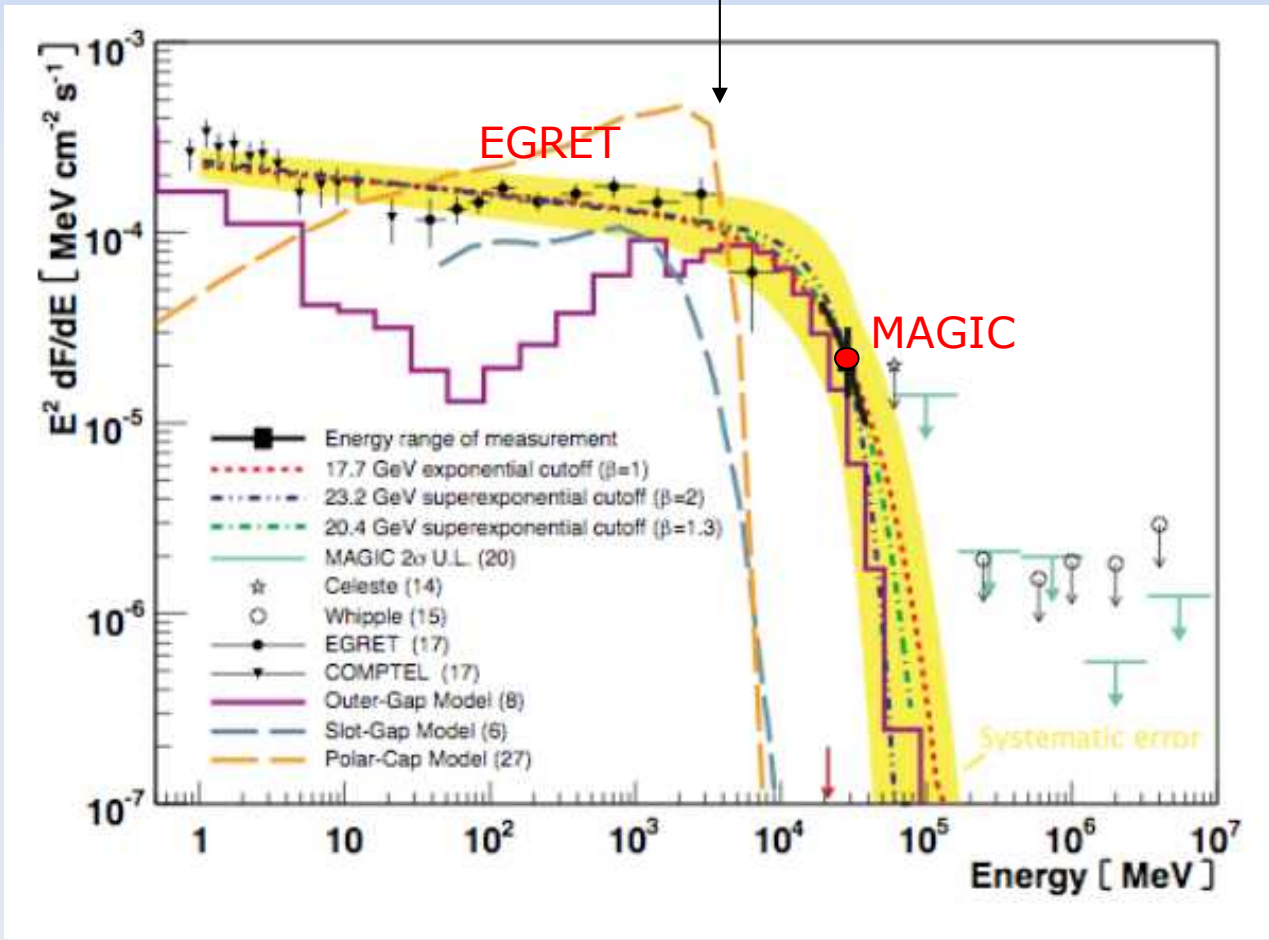


# … leading to preference for outer gap model



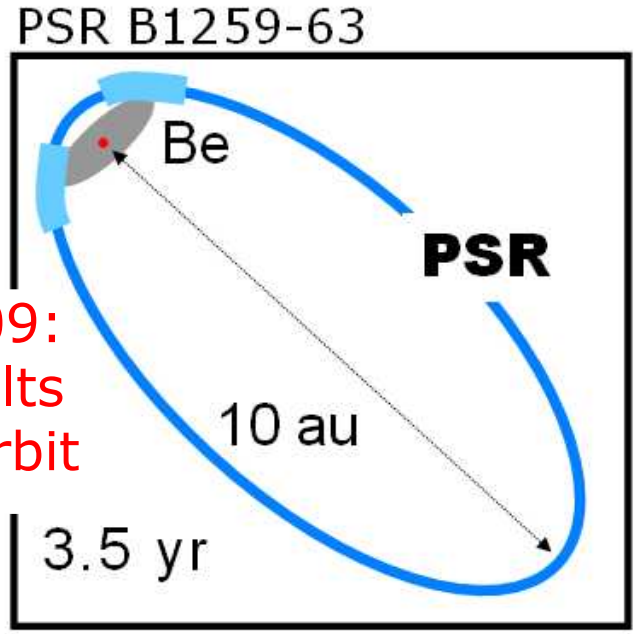

Emission from polar cap
and slot gap cut off around
10 GeV due to pair production

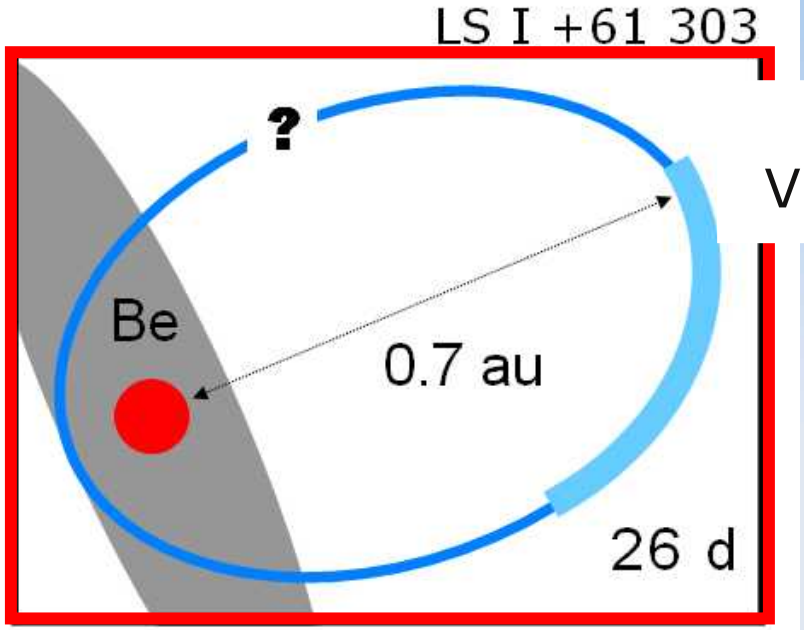


# Gamma-ray binaries

H.E.S.S.

ICRC 2009:
New results
on 2nd orbit

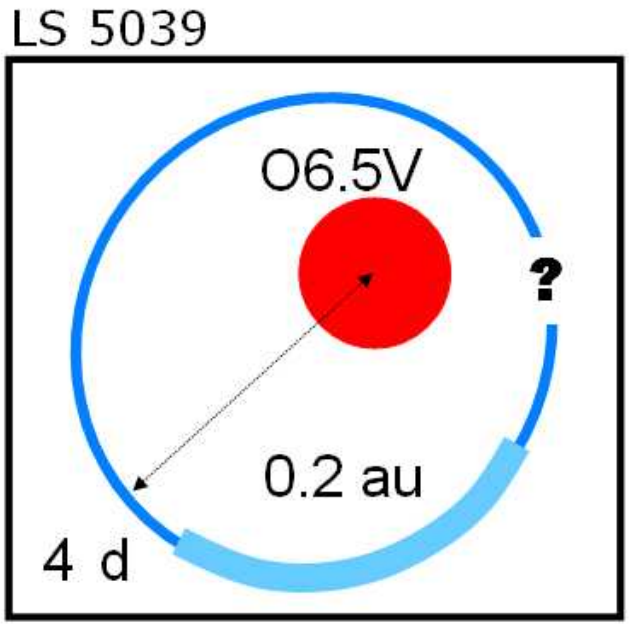


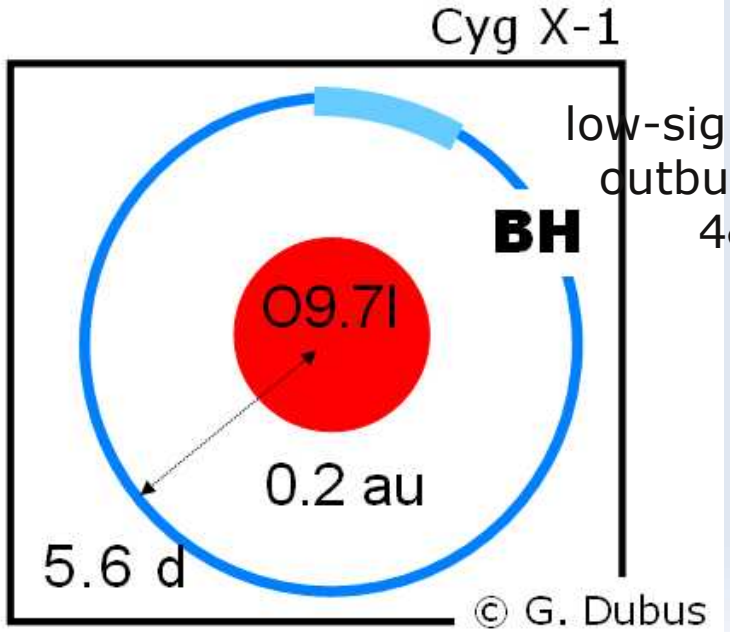

MAGIC
VERITAS

H.E.S.S.

Periodic
emission

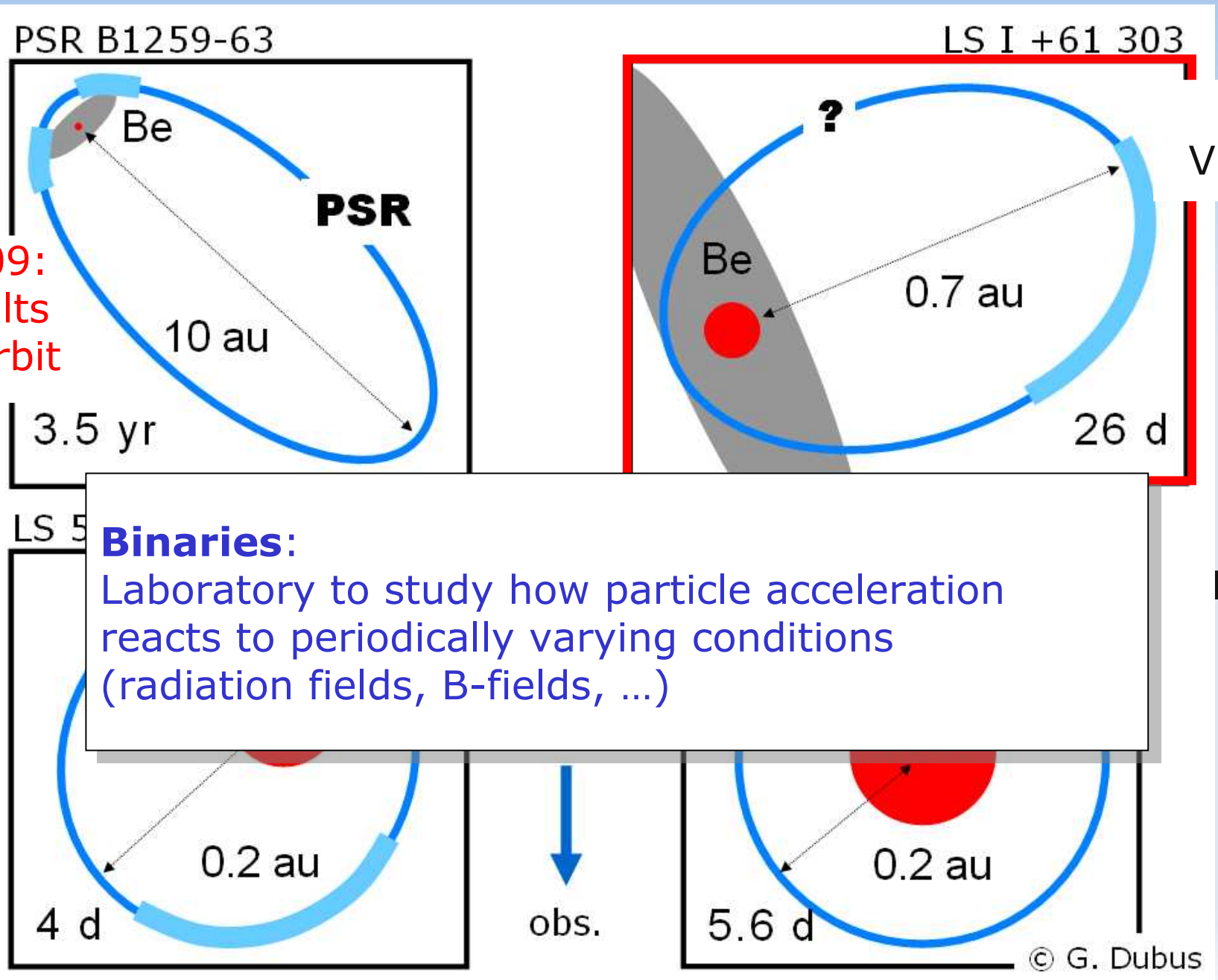



obs.




MAGIC
low-significance
outburst claim
4σ (2006)

# Gamma-ray binaries




H.E.S.S.

MAGIC
VERITAS

ICRC 2009:
New results
on 2nd orbit

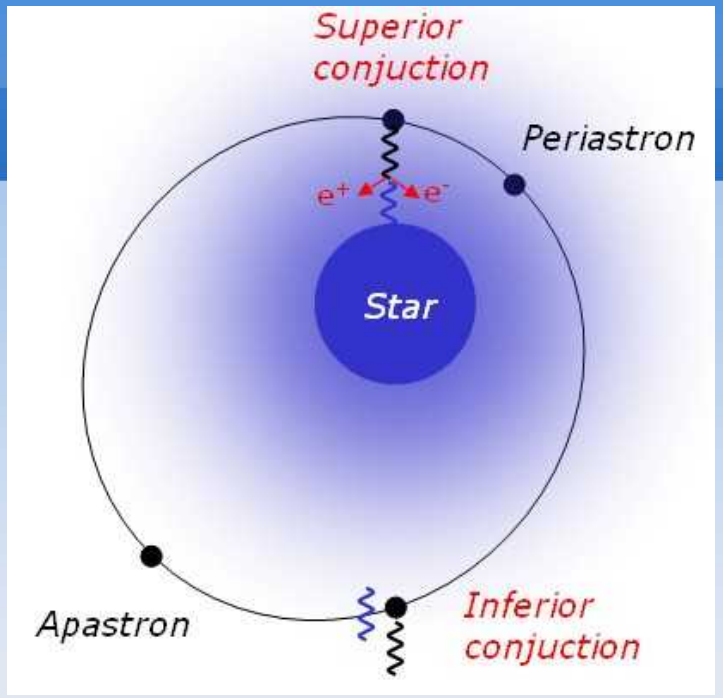
H.E.S.S.

MAGIC

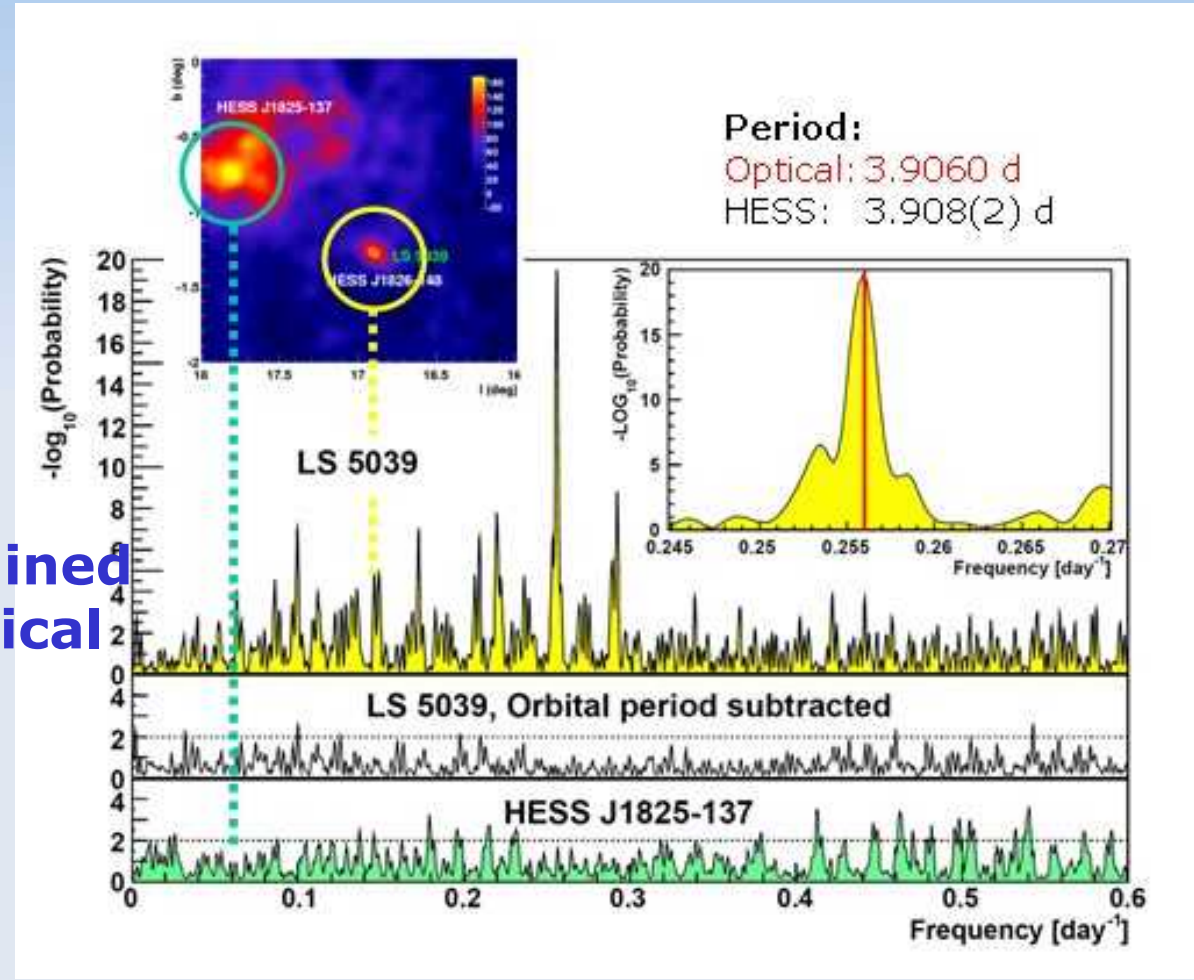
**Binaries**:
Laboratory to study how particle acceleration reacts to periodically varying conditions (radiation fields, B-fields, …)

Periodic
emission

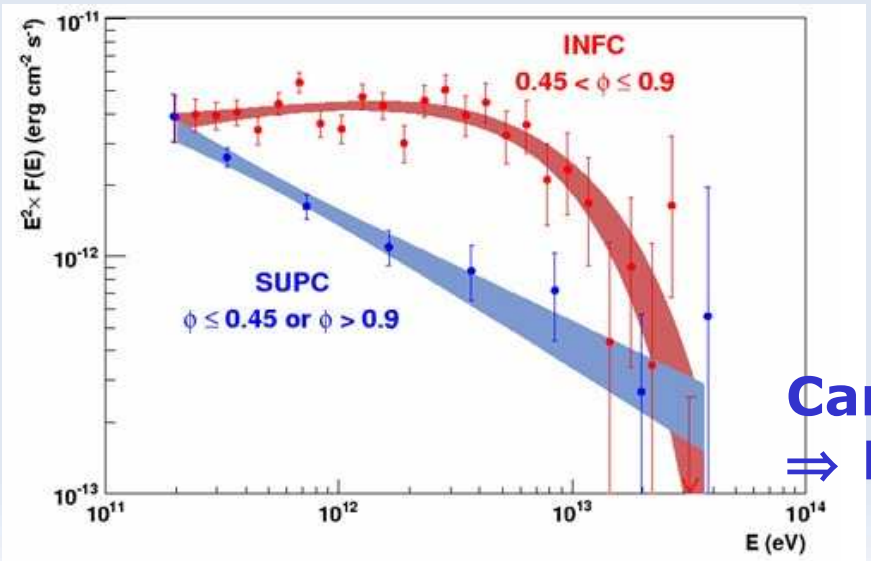
# LS 5039




H.E.S.S. collaboration, F. Aharonian et al., astro-ph/0607192 (2006).




**Clear orbital modulation, Frequency can be determined from VHE data == optical**

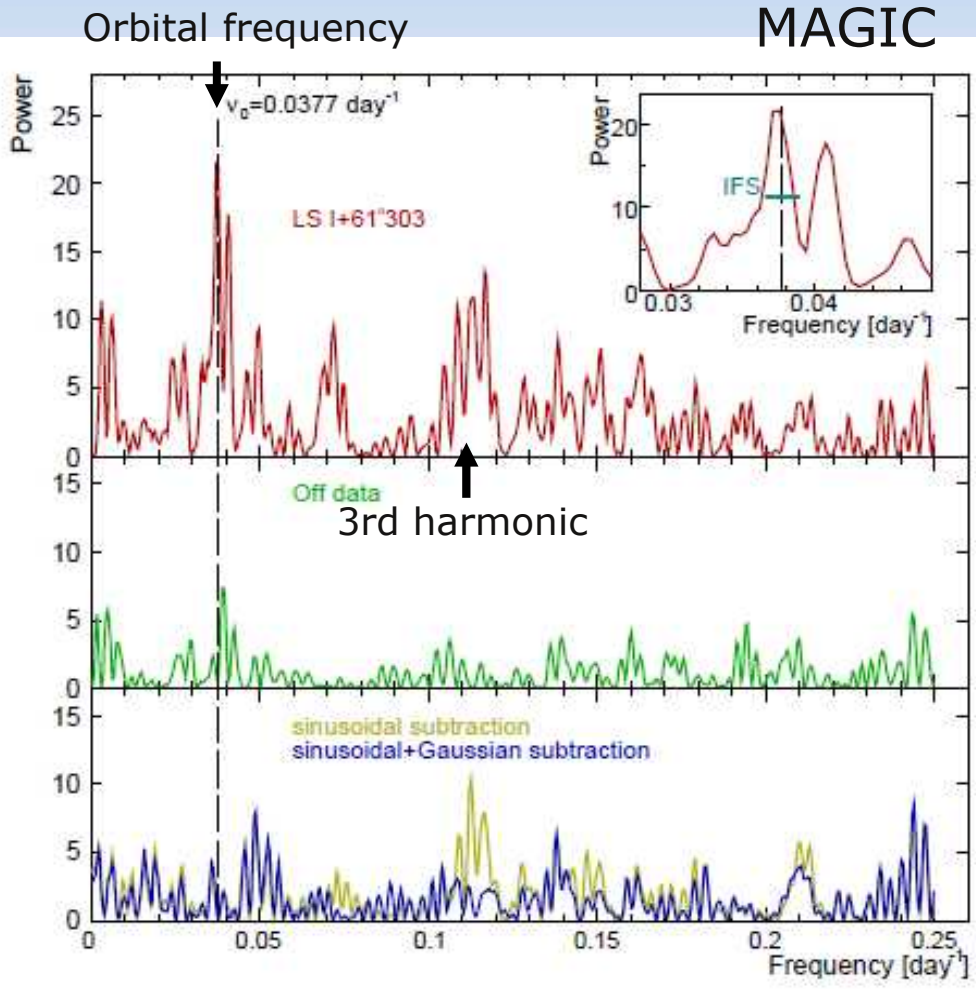


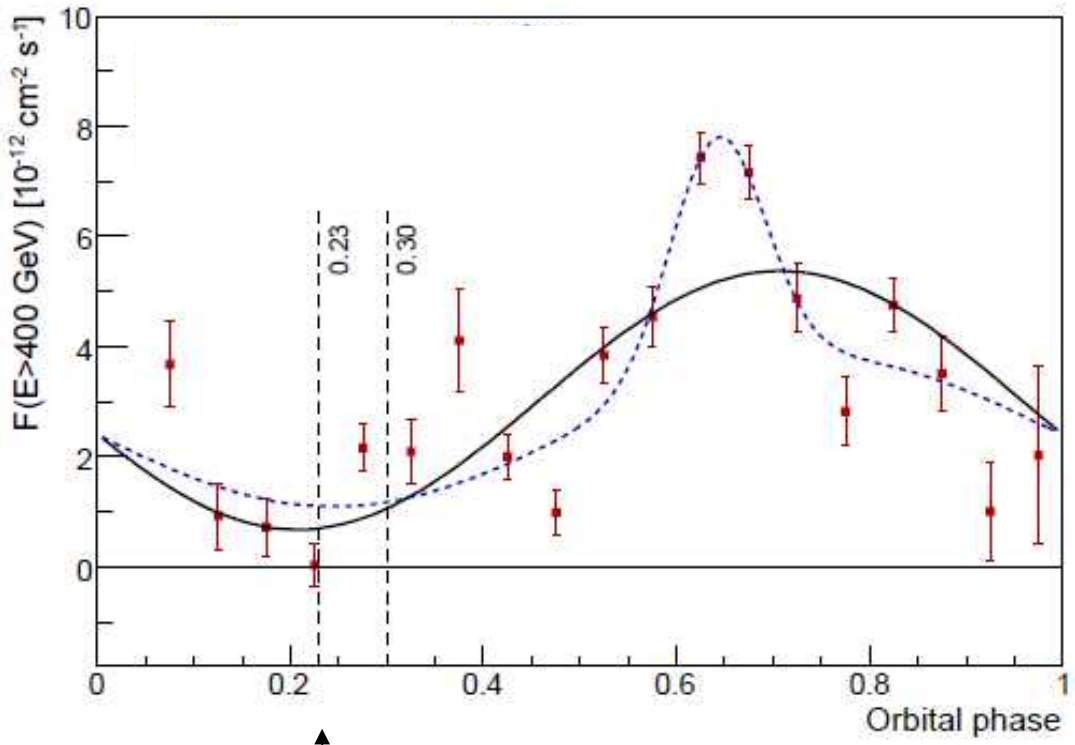

**Can measure spectrum along orbit**
**⇒ Laboratory for time-varying conditions**

# LS I +61 303

MAGIC arXiv:0809.4254, ICRC 2009,
also VERITAS arXiv:0904.4422

**Periodic variation**
**Of VHE flux along 4 orbits**




Periastron

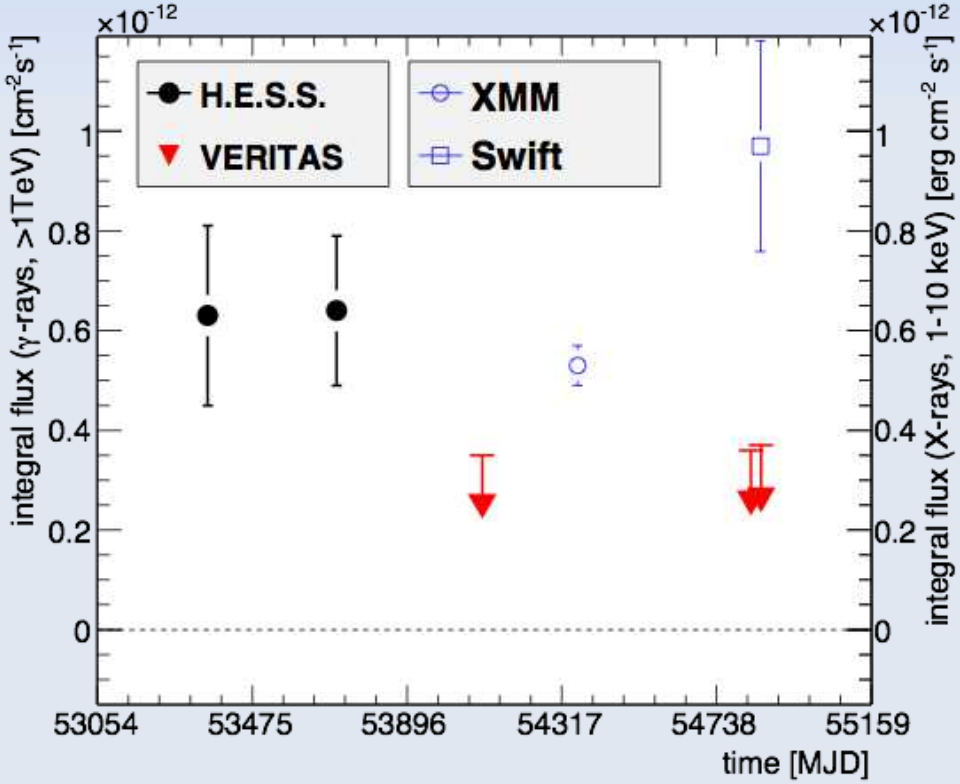
Fermi detections of LS5039 and LS I +61 303,
with anti-correlation between GeV-TeV!

# Variability of HESS J0632+057 - a new gamma-ray binary?

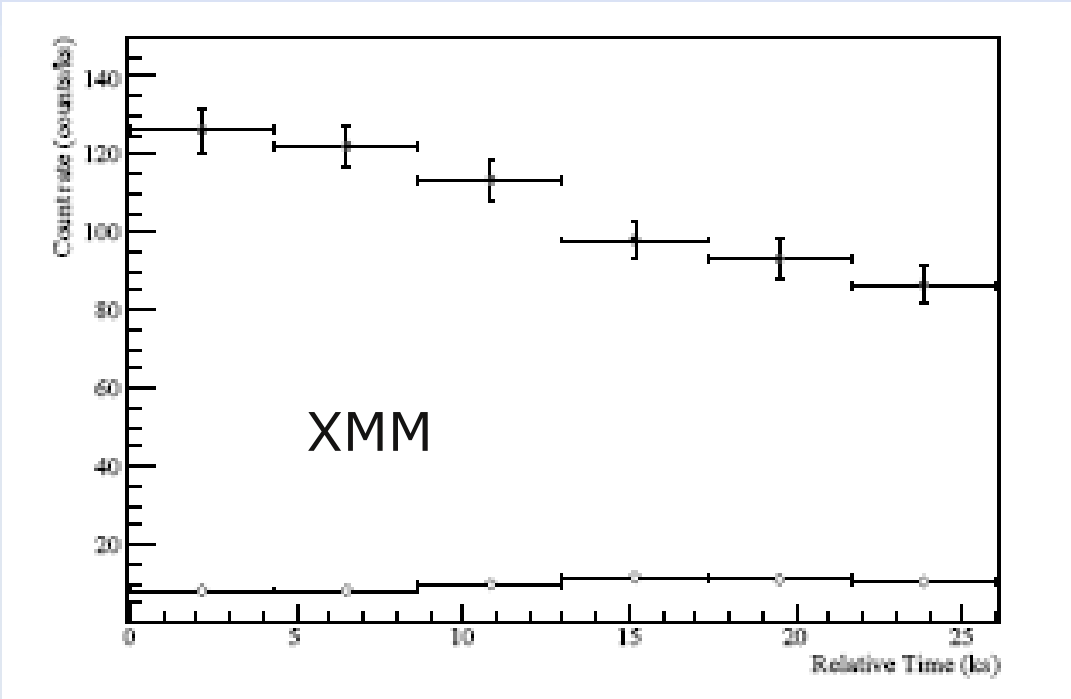
HESS J0632+057

One of the few point sources in the Galaxy survey

Consistent with MWC 148, Rosat source




Acciari et al.
arXiv:0905.3139

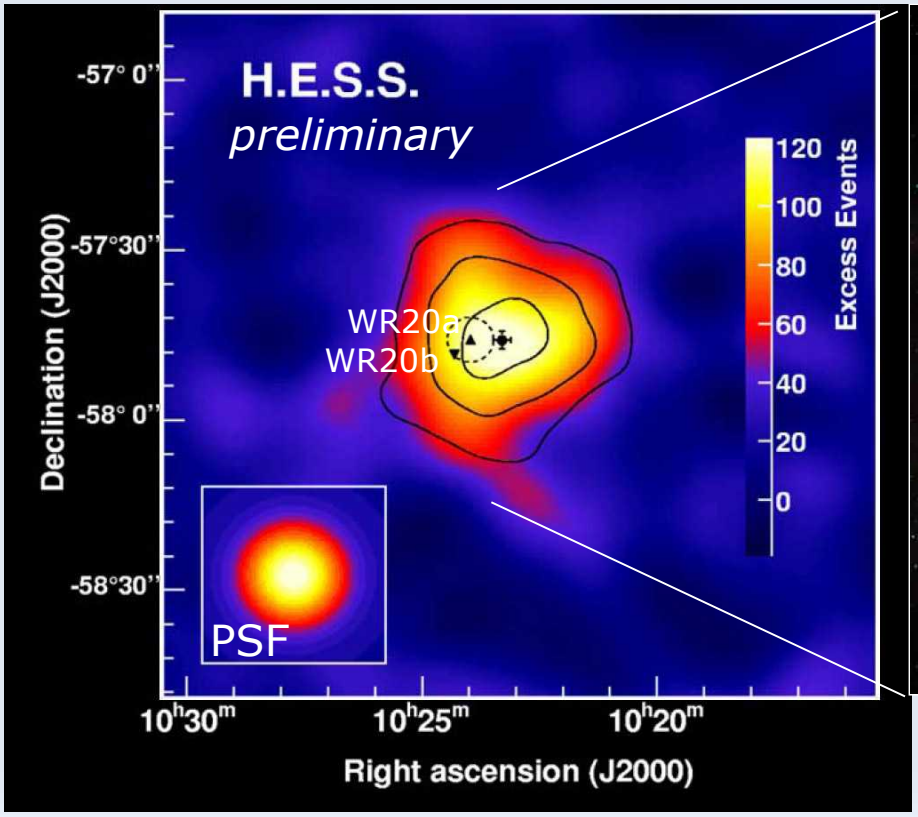


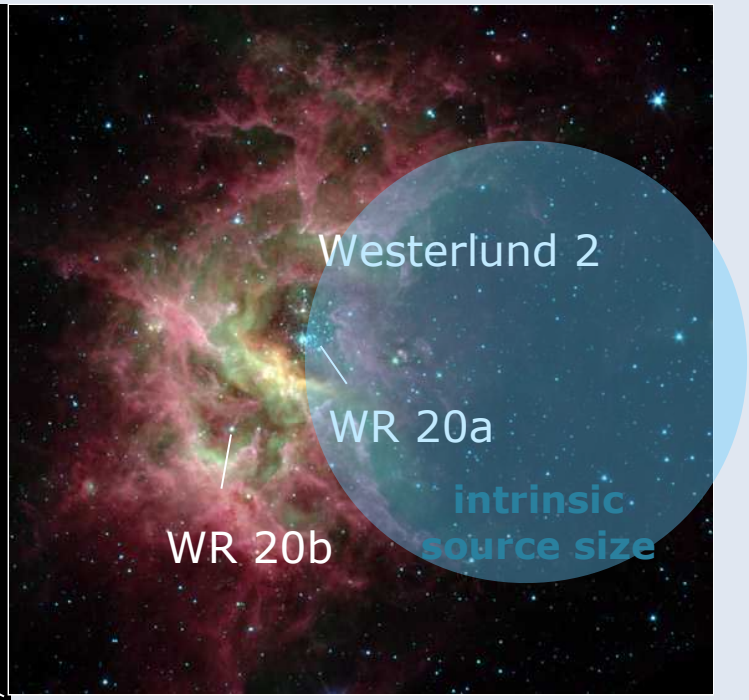

Hinton et al.
arXiv:0809.0584

# Stellar clusters: A new type of TeV source?

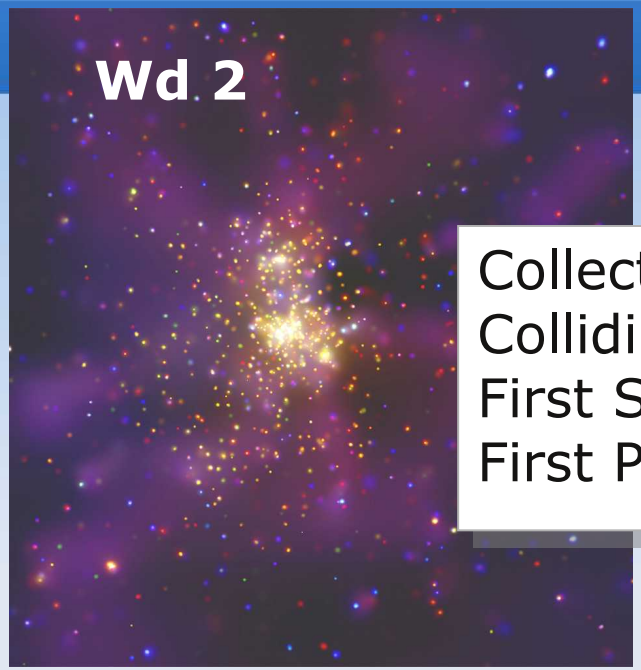
- Open Cluster Westerlund 2 : thousands of solar masses
  Wolf-Rayet & young stars
- Winds excavating bubbles in the ISM

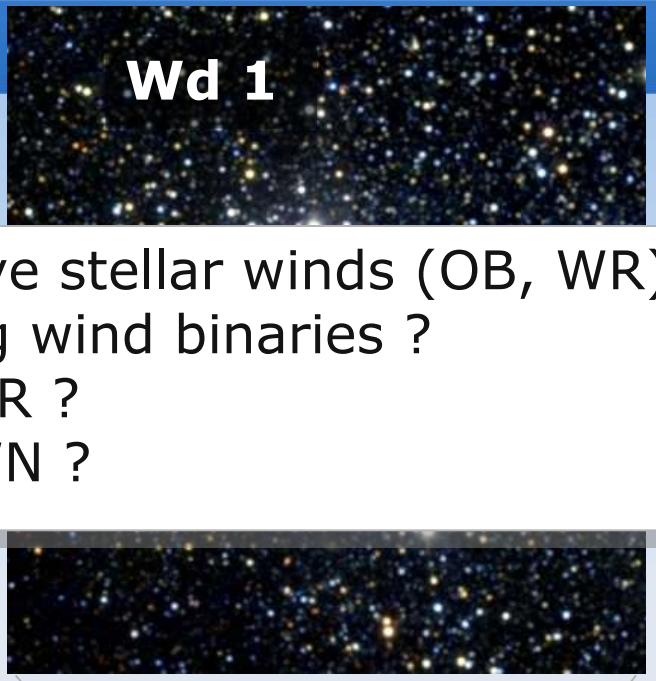
- HESS source coincides with the most prominent one in RCW 49
- Acceleration through collective wind effects or DSA at the boundary?
- Systematic search program undertaken with HESS

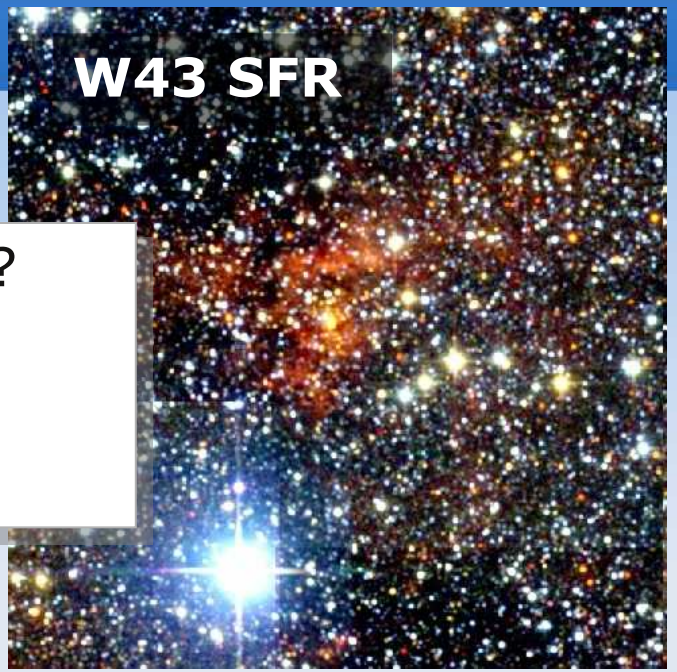


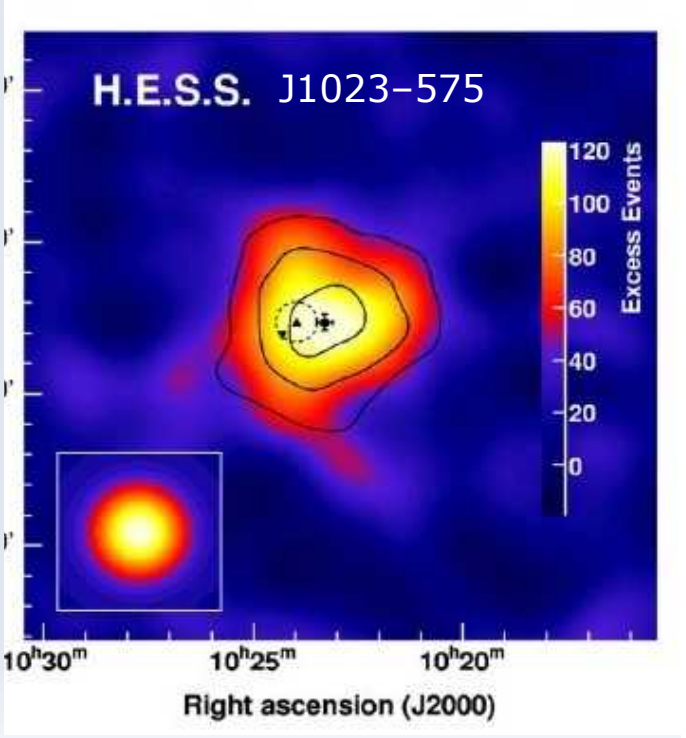
# Young stellar clusters / star forming regions

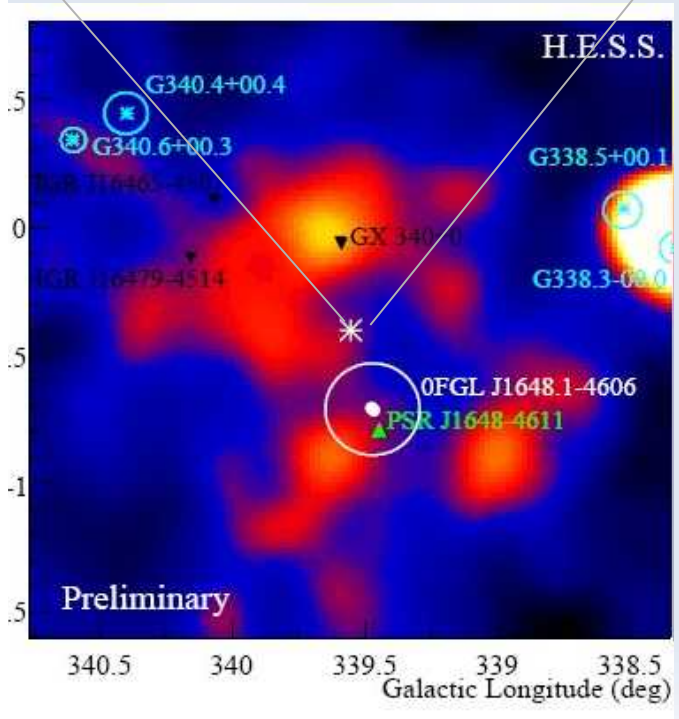


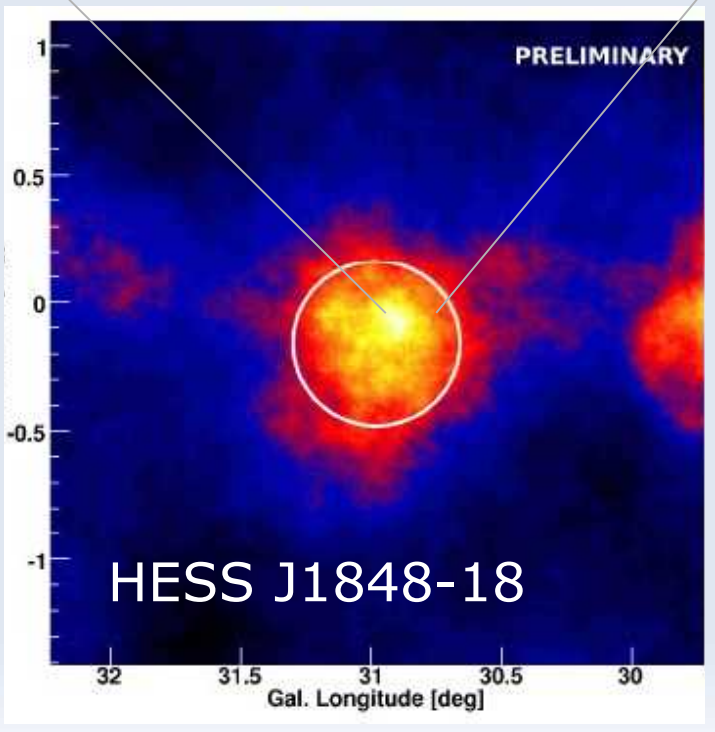




Collective stellar winds (OB, WR) ?
Colliding wind binaries ?
First SNR ?
First PWN ?

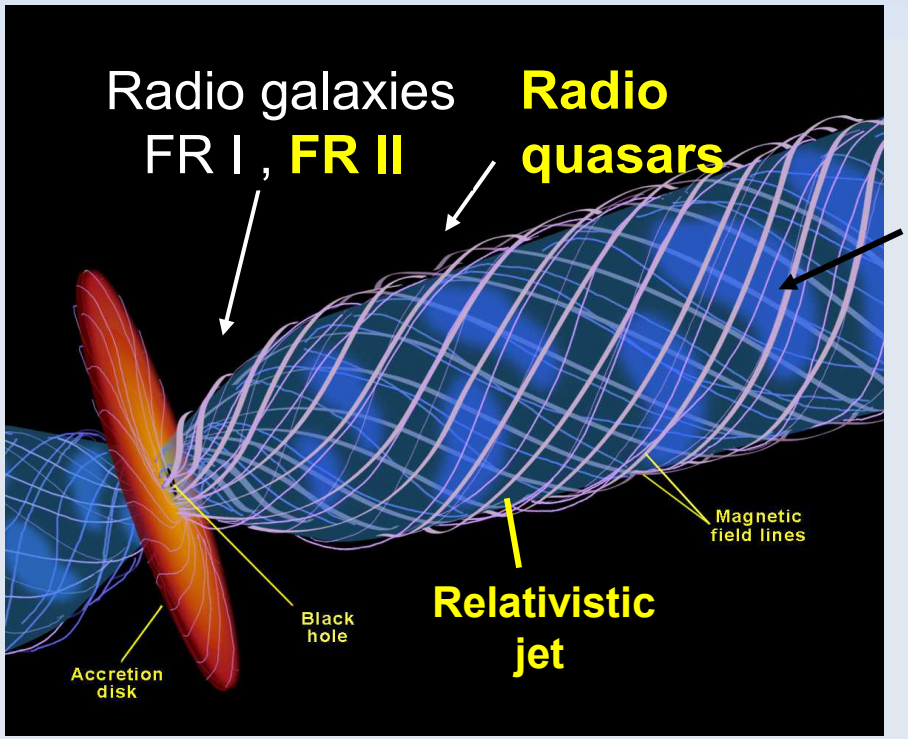


# Extragalactic sources

- Historically, the “second VHE source”
- Majority of extragalactic sources are distant AGNs (Active Galactic Nuclei), made visible by Doppler beaming/boosting from jet




**Strong relativistic boosting** (~ factor $\delta^4$) favours detection of blazars/BL Lac

- More recently at VHE, detections also of nearby “off-axis” AGNs
- This year, detection of new nearby extragalactic class: “Starburst galaxies”

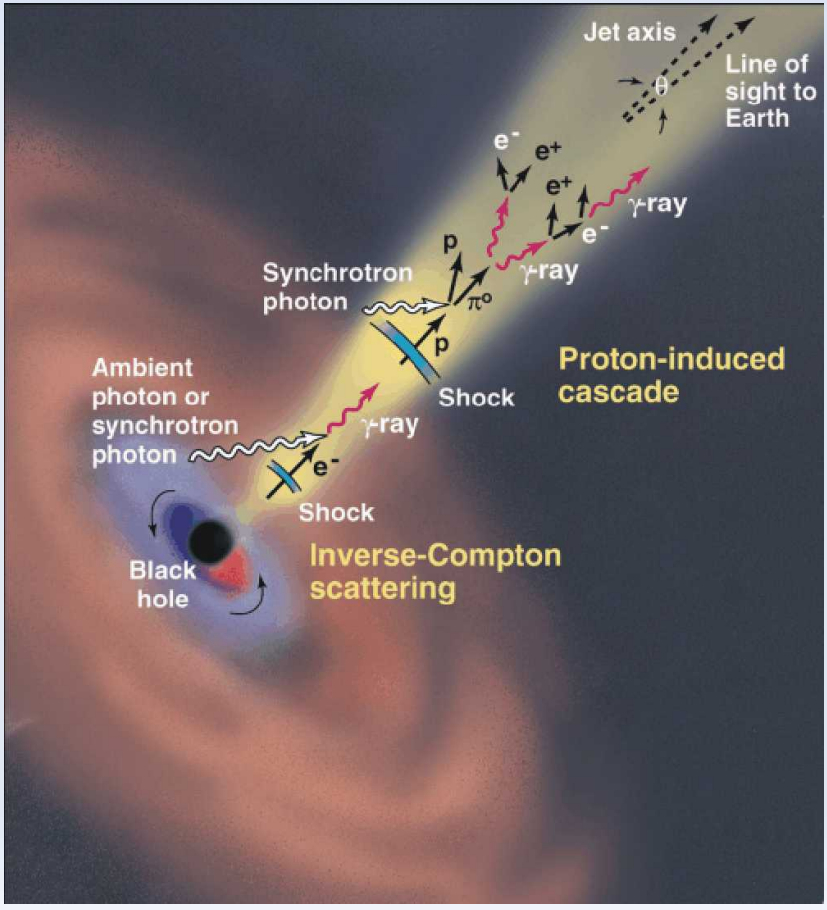
# Extragalactic sources

- Accumulating catalogue
- Nearby observations test source emission models (e.g. short time-scale variation of M 87 and PKS 2155-304 test emission region size and location)
- Observation of “Distant” (z~0.2-0.3...) sources at VHE probes

  Cosmic Infra-Red background produced by first stars and galaxies

**Key questions for Blazars**

- Emission mechanisms (especially for high energy component)
  - Leptonic (IC of synchrotron or external photons) vs hadronic ($\pi_0 \rightarrow \gamma\ \gamma$ , proton synchrotron)
- Emission location
  - Single zone for all wavebands (completely constraining for simplest leptonic models)
  - Opacity effects and energy-dependent photospheres
- Particle acceleration mechanisms
  - Shocks, Blandford-Znajek
- Jet composition
  - Poynting flux, leptonic, ions
- Jet confinement
  - External pressure, magnetic stresses
- Accretion disk—black hole—jet connection
- Blazars as probes of the extragalactic background light (EBL)
- Effect of blazar emission on host galaxies and galaxy clusters



# Extragalactic VHE sample (july 2009)

- 25 blazars :
  - 19 HBL *(High-frequency peaked BL Lac)*
  - 4 IBL and 1 LBL *(Intermediate and Low-frequency peaked BL Lac)*
  - 1 FSRQ *(Flat Spectrum Radio Quasar)*
- 2 (or 3) radio galaxies
- 2 Starbursts
- LMC

Number of TeV sources per type : highly peculiar !

AGN Redshifts : from 0.00183 to 0.536 (+ 3 uncertain)

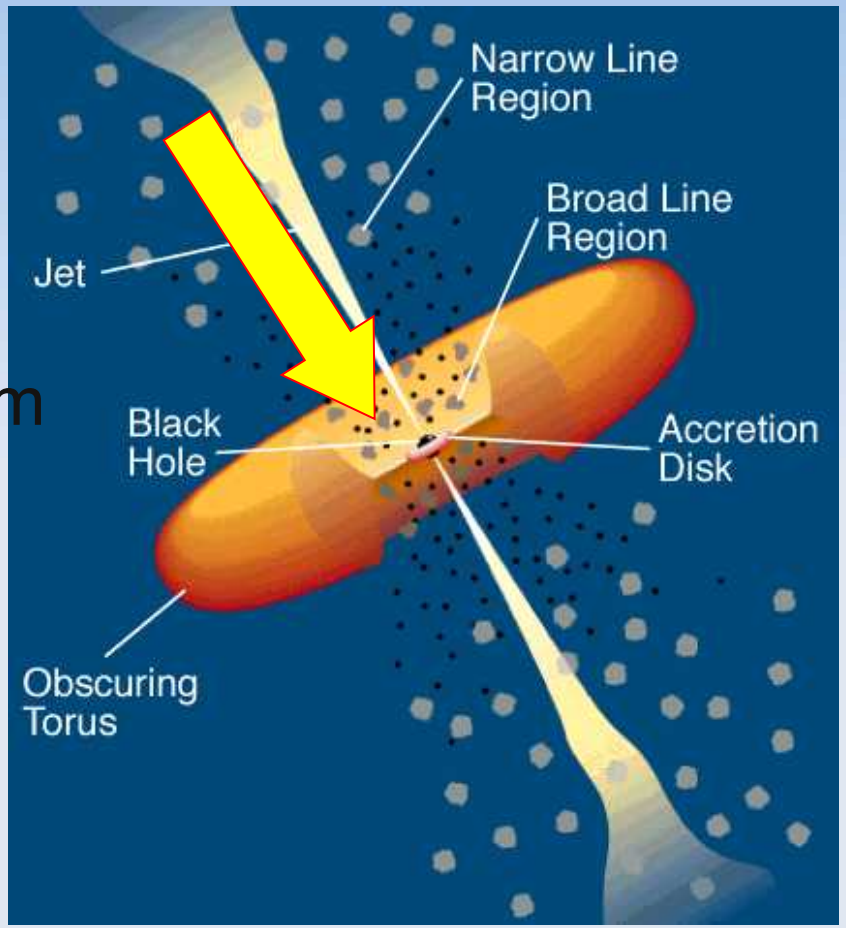
TeV variability : already seen in 18 sources (despite poor temporal coverage)

"Shortest observed time scales"

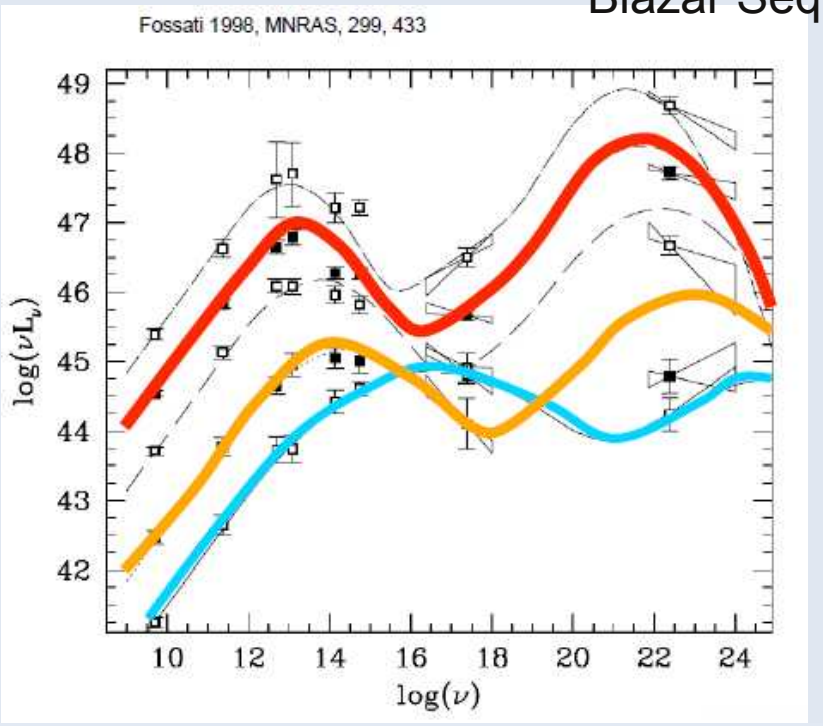
| | | |
|---|---|---|
| minutes : | 3 sources | (flares) |
| day : | 6 sources | |
| week : | 1 source | |
| month : | 3 sources | |
| year : | 5 sources | |

# BL Lacs

- Jets aligned very close to line of sight
  - Beaming allows us to see very distant objects with modest sensitivity
- Characteristic double peaked spectrum




"Blazar Sequence"

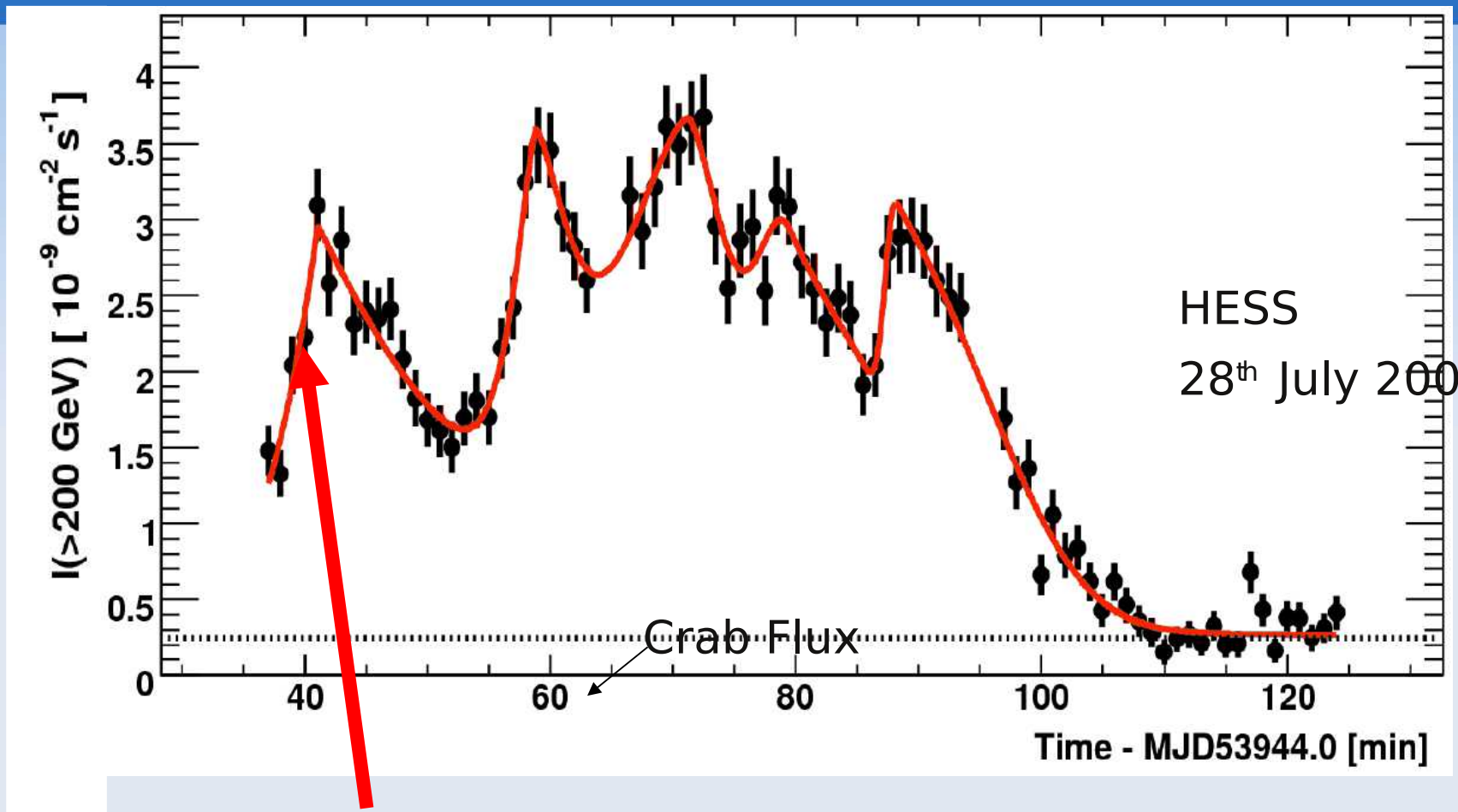



LBL:powerful, substantial external radiation fields

IBL: in between

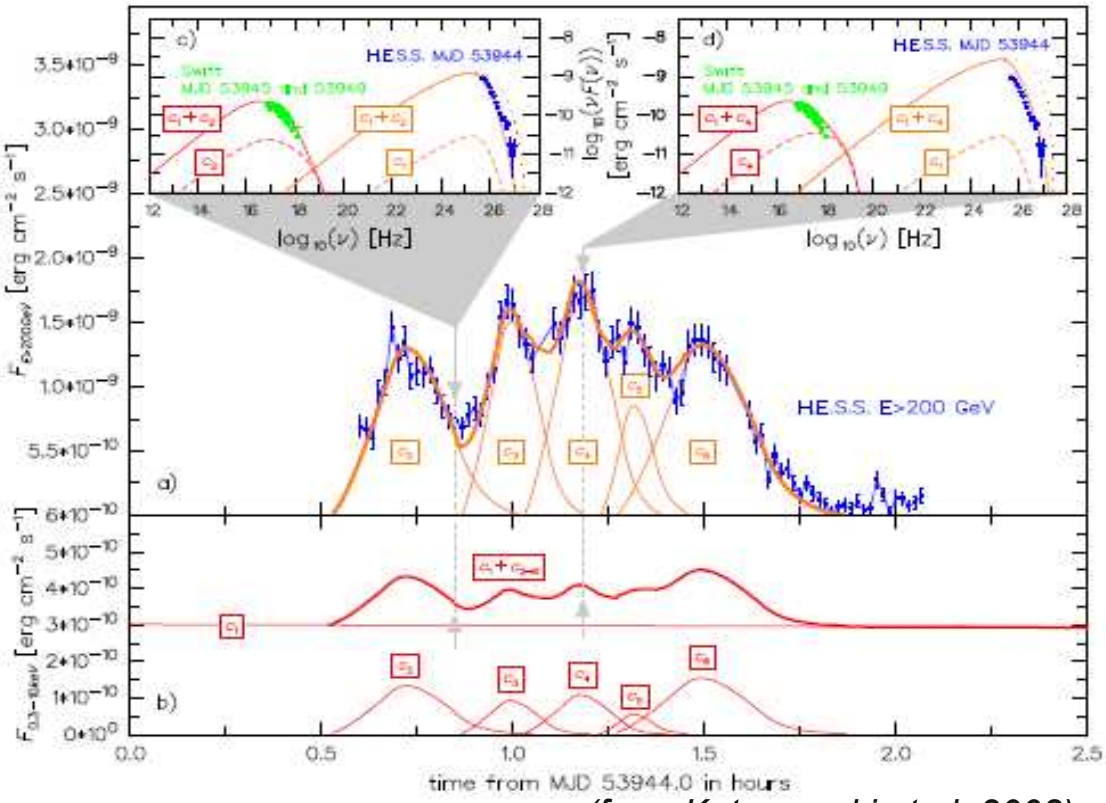
HBL:low power, weak external radiation fields

# VHE example: Flare From PKS 2155-304




- Best measured rise-time: 173 ± 28 s
- Two orders of magnitude brighter than typical state
- Time-scale probes size of emitting region if causality applies
- Such measurements also used to test Quantum Gravity (LIV)

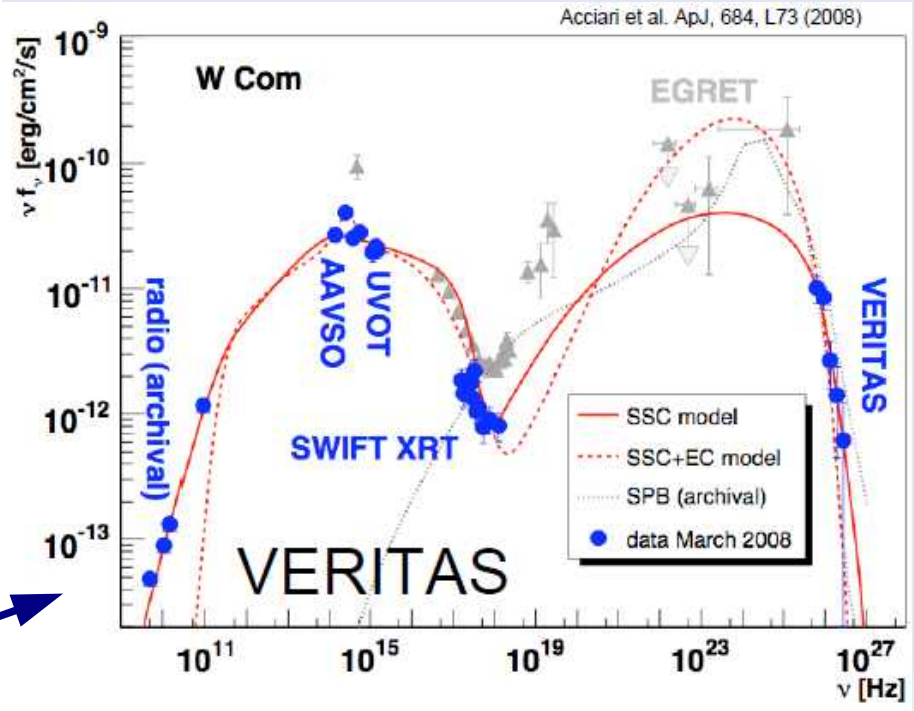
# VHE examples: PKS 2155-304 flare, W Com




*(from Katarzynski et al, 2008)*

Many efforts to fit, e.g.

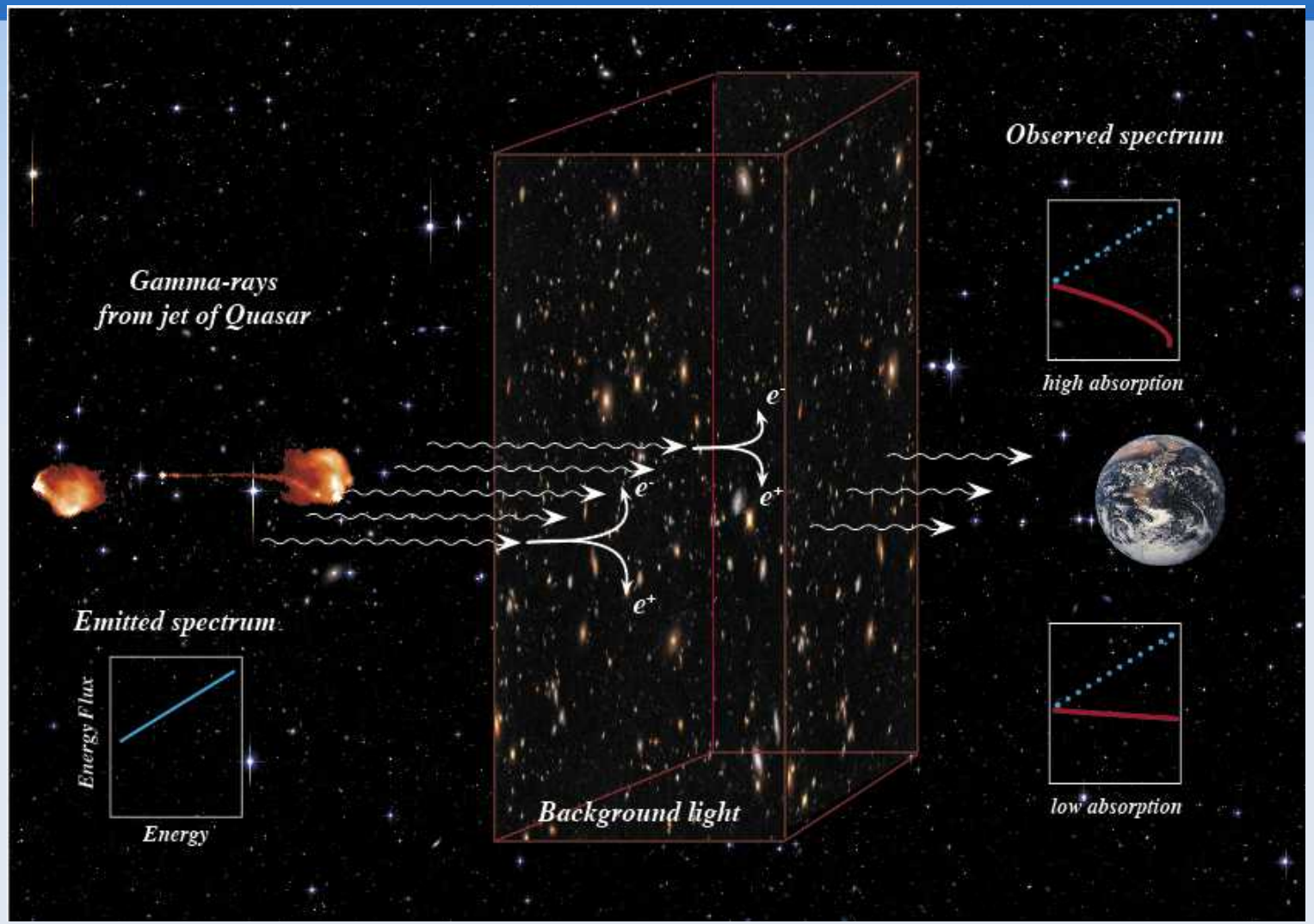
Example of modelling light curves and SED by time dependent SSC scenario, with 5 compact components in jet with slightly different parameters + a more extended slowly evolving component




Many other examples, on this and several other sources

- MWL campaigns (with X-rays, radio, FermiLAT)
- Long-term variability and spectral evolution studies
- Detailed MWL spectral studies

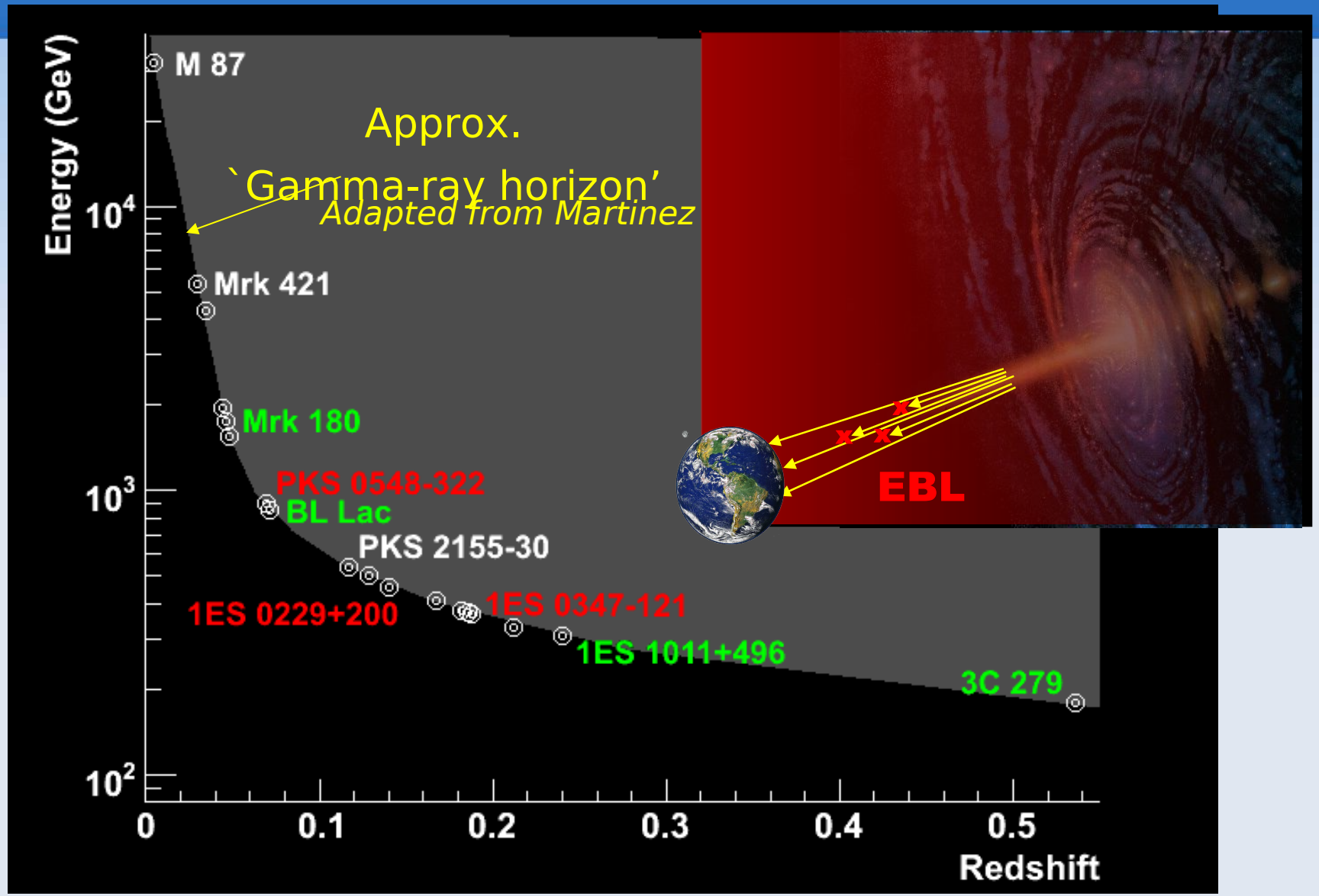
# Extragalactic Background Absorption




Effect of EBL absorption:

- modifies intrinsic spectral index
- introduces cut-offs or roll-overs,
- renders extremely distant sources undetectable at highest energies

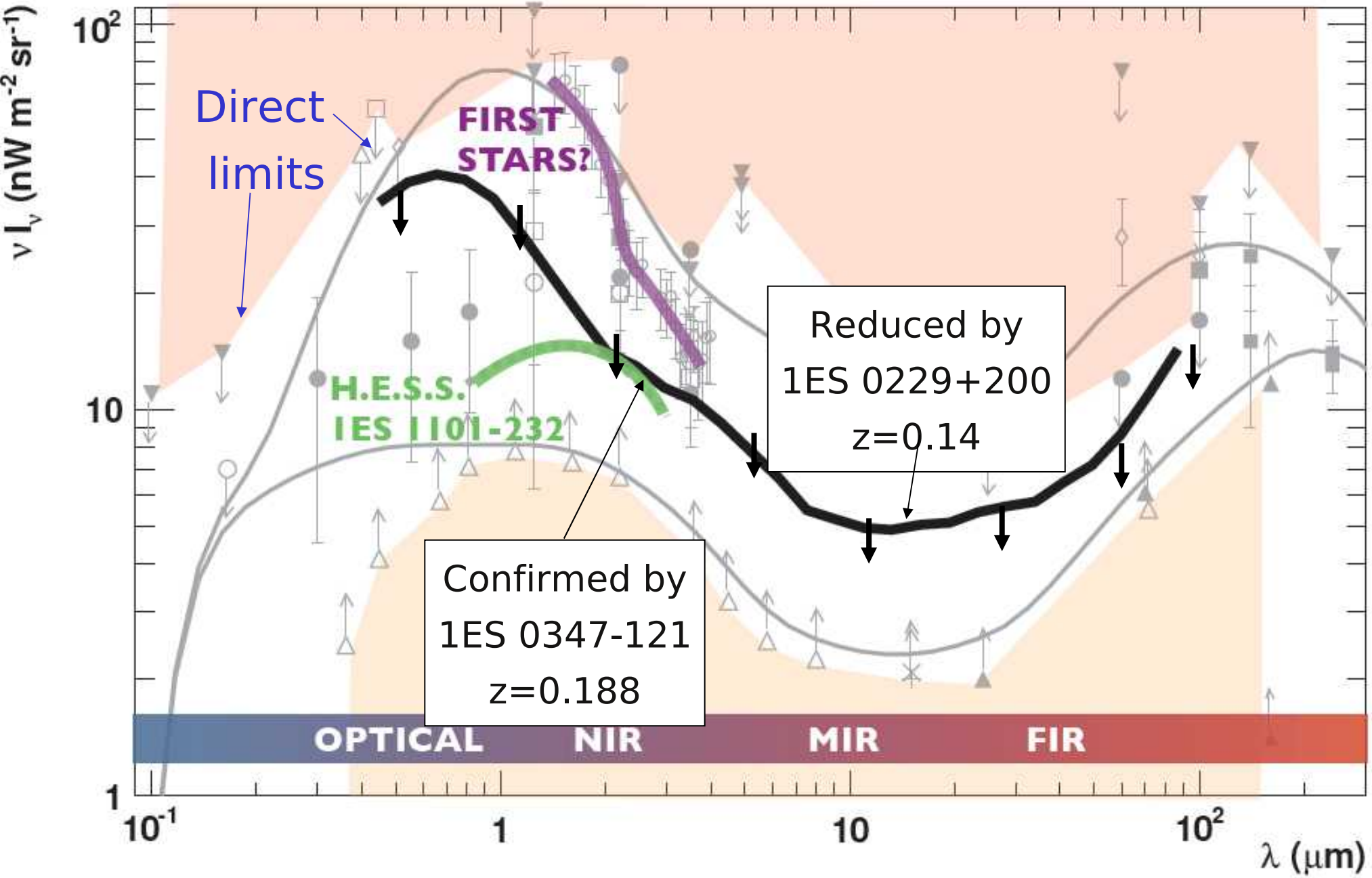
# Extragalactic Background Absorption




- VHE detectors... 100 GeV threshold implies can detect z < 1
  (but need very luminous sources for larger z !)

$\gamma_{VE}\gamma_{\square} \rightarrow e^+e^-$

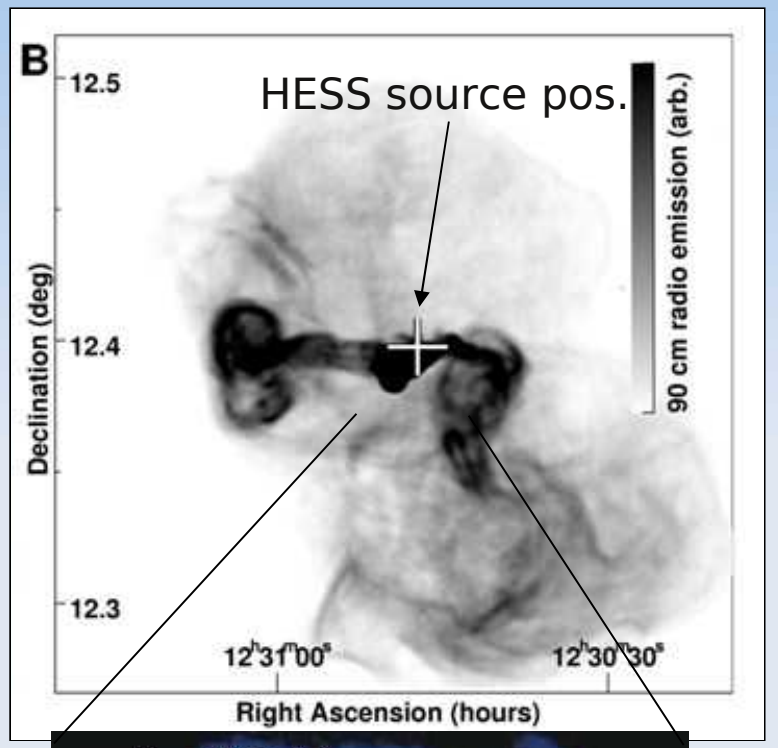
# EBL Limits from VHE Spectra

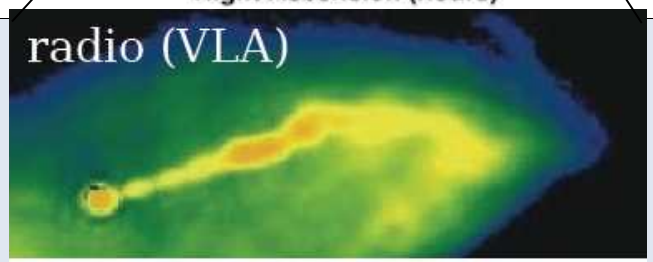


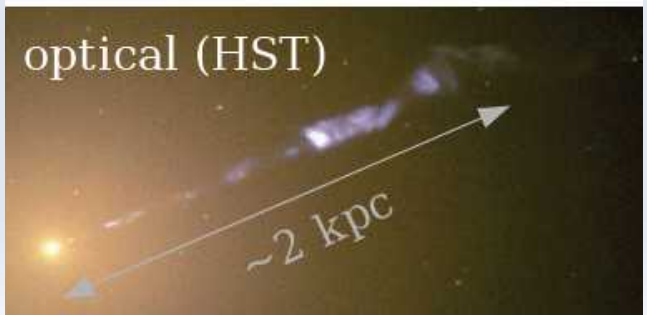
# Radiogalaxy example: M 87

- Famous nearby radio galaxy
  - 16 Mpc, Jet angle ~30°
- Discovered by HEGRA, confirmed by HESS, VERITAS
- HESS 2-day variability
  - Emission region

    $< 5\ \delta\ \ R_S$
- Emission site?
  - Knot HST1?
  - Very close to SMBH?
- Mechanism?
  - Hard spectrum $\Gamma = 2.2$ is a challenge for ‘standard’ models



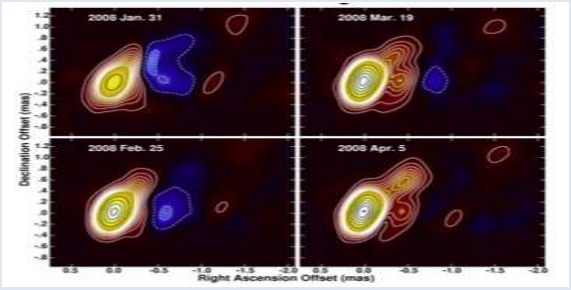
# M87 joint observing campaign 2008

Joint VHE campaign:

- MAGIC, HESS, VERITAS
- Jan. - May 2008
- 95 hrs. combined
- MAGIC ToO

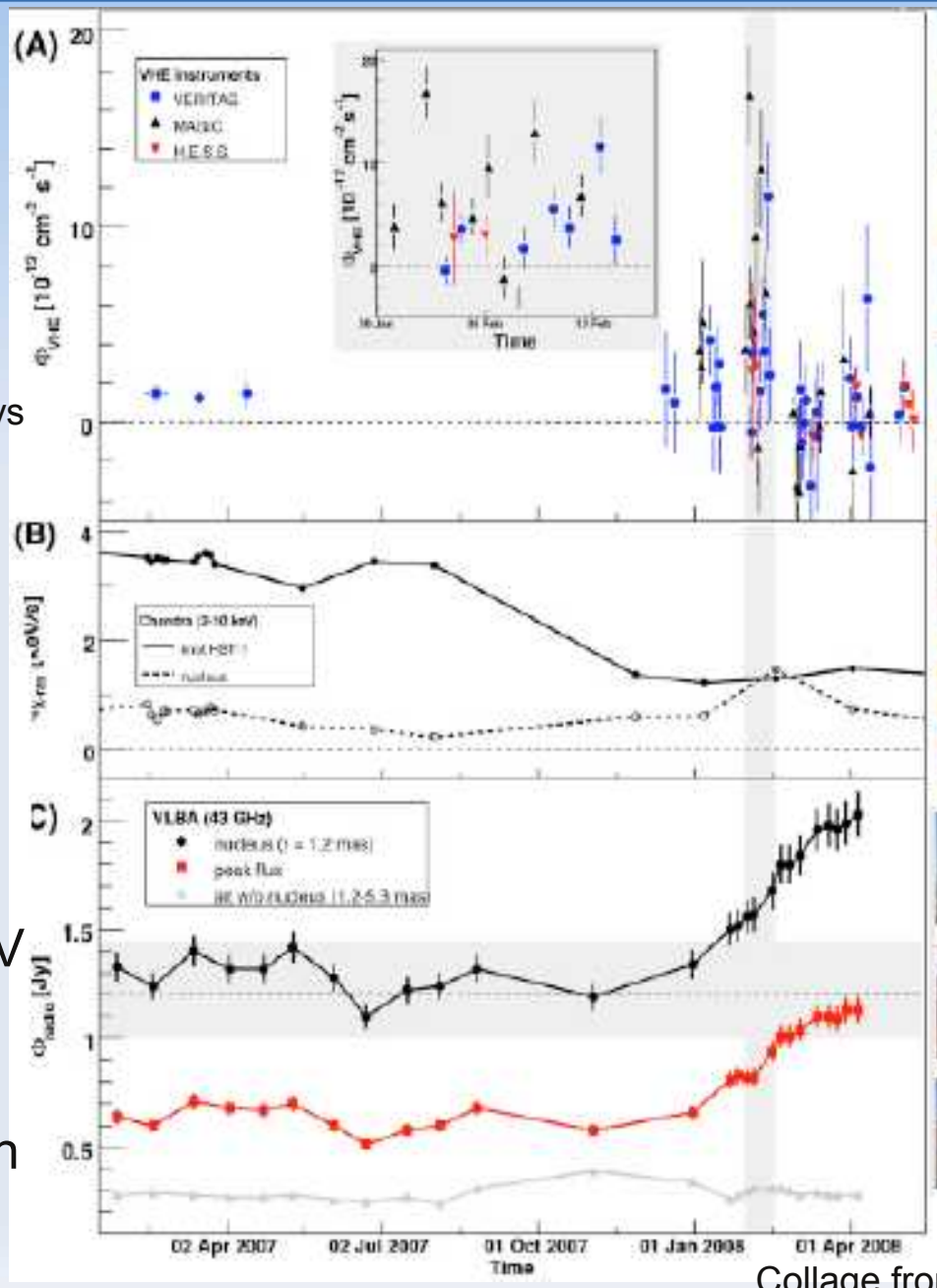
VLBA “movies”

- 14 shots in 2008, every 5 days
- ang. resolution 0.2 x 0.4 mas




X-ray light curve of HST-1 obtained by Chandra in 2008 does not follow TeV

Correlated core emission (radio, X and VHE)
→ favours scenarios with TeV emission from inner jet or central core.





Collage from F. Krennrich, TeVPA 2009

# New source category: Starburst galaxies

M82, the prototype starburst galaxy

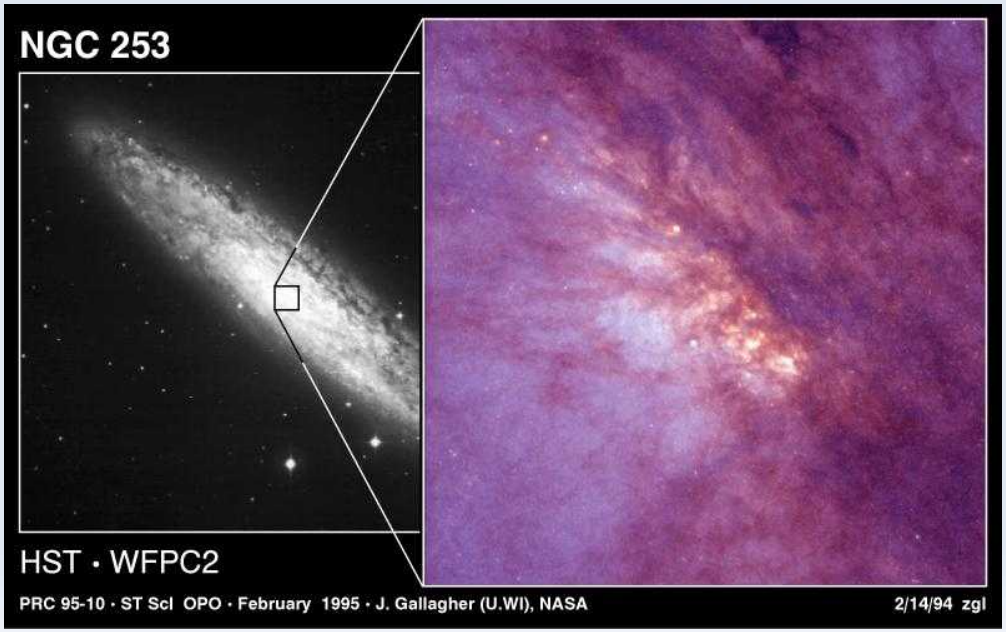
- Distance ~ 3.9 Mpc
- Diameter ~ 1'
- SMBH ~ 3 x 107 Msolar
- Interacts with group of galaxies (M81)
- HST: 200 massive star clusters
- High supernova rate ~ 0.1 - 0.3 per year
- High gas density 150 particles/cm3

⇒ excellent candidate for cosmic ray interactions & gamma ray emission.

- NGC 253: Closest spiral galaxy outside the local group
  - Distance 2.5 – 3.9 Mpc
  - Starburst nucleus
  - Supernova rate in central ~100 pc comparable to the rate in all Milky way
  - Central gas density almost three orders of magnitude larger than the average in Milky way
  - Luminous in infrared (dust reprocesses star light)
- Predicted gamma-ray emitter

Paglione et al. 1996; Aharonian et al. 2005, Domingo & Torres 2005, Rephaeli et al. 2009

probing paradigm that SNRs are origin of CR

# New source category: Starburst galaxies

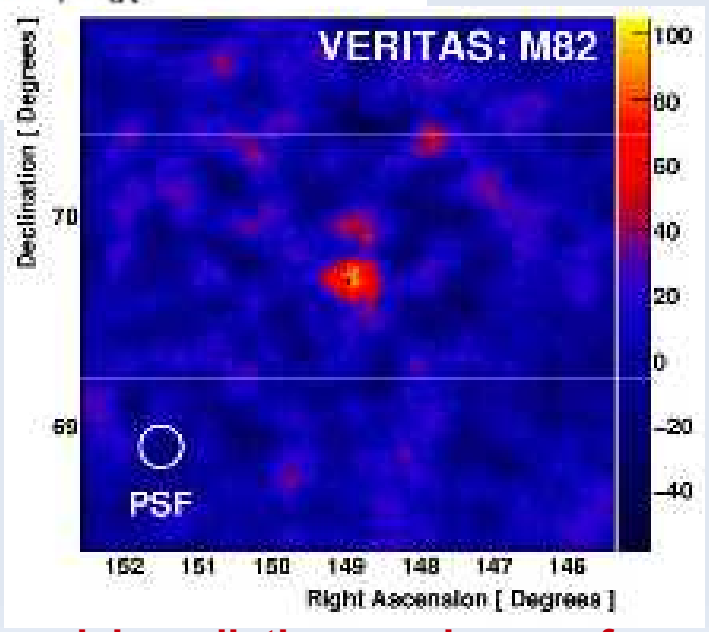
- M82, VERITAS measurements

- 2007-09: 137 h live time.
  Only dark time (no moonlight).
- 5.0 σ excess (pre-trials), 4.8 σ (post-trials).
- E > 700 GeV (LZA observations). Point-like.
- **Among weakest VHE sources ~0.9% Crab**

Fit Range: 875 GeV to ~5 TeV

- Fit to dN/dE ~ (E / TeV)$^{-\Gamma}$
- $\chi^2 = 0.1$, 1 NDF; $P(\chi^2) = 0.7$

$\Gamma = 2.5 \pm 0.6$



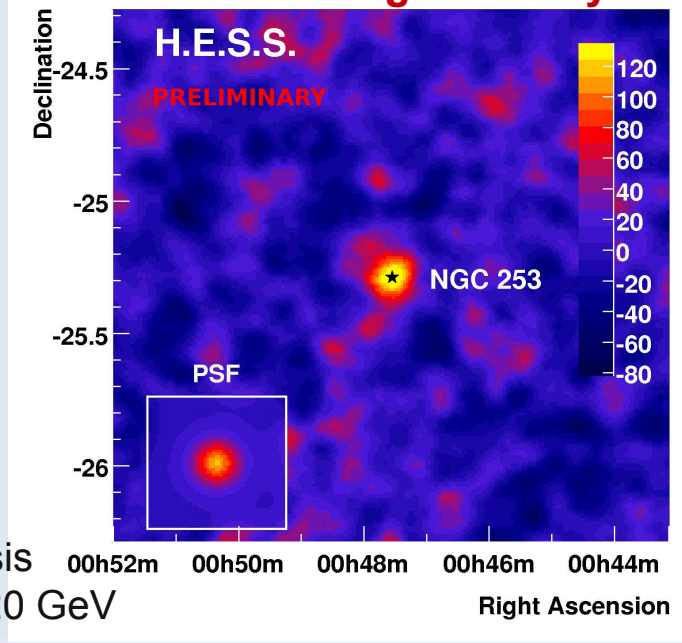

Benbow, ICRC2009

- NGC 253: H.E.S.S. measurement

- Deep observations with the full array, Campaign in 2005, 2007, 2008
- 119 hours of good livetime
- Careful data-quality selection
- Observations close to zenith to achieve low energy threshold
- Significance 5.2 σ, 247 excess events, pt-like

$F(>0.22\ \mathrm{TeV}) = (5.5 \pm 1.0_{stat} \pm 2.8_{sys}) \times 10^{-13}\ \mathrm{cm^{-2}s^{-1}}$ (0.3% Crab)

**Faintest source detected so far in VHE gamma rays**




Domainko, ICRC2009

Model analysis
Threshold 220 GeV

**Comparison with model predictions underway, for understanding of CR production and propagation,**

# Gamma-Ray Astronomy

## So many results, too many to tell

No mention of Diffuse emssion, GRBs, Dark Matter searches, etc...

- Gamma-ray astronomy gives us a glimpse into the most energetic regions of the Universe, leading to new insights

- VHE $\gamma$ -ray astronomy is currently a *very* active field
- Number of sources is rising rapidly with also precision measurements of the brighter sources

- HE field has got a new lease of life with FermiLAT & AGILE

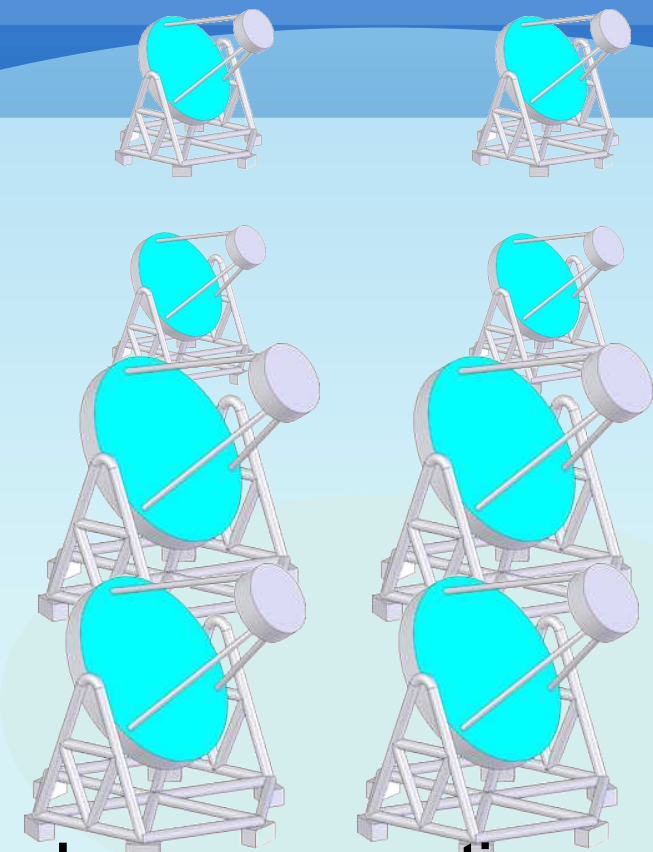
- Future is assured with MAGIC-II and HESS-II coming on-stream (2009/2010) and the preparation of the CTA and AGIS future large-array projects which will make surveys and deep studies more readily achievable

# The Future CTA Project: Ambitions and Goals

- Build on the extraordinary success of the current IACTs
  to create the future ground-based gamma-ray observatory
- Jump of factor 10 in sensitivity, down to mCrab: deeper VHE vision
- Very large spectral coverage: a few 10 GeV to above 100 TeV:
  New source classes, explore emission mechanisms
- Improved angular resolution down to arc-minute range: fine mapping
- Temporal resolution down to sub-minute time scale:
  a VHE timing explorer
- Flexibility of operations:
  deep field, monitoring, survey, alarms
- Full sky coverage using North & South installations

- Can achieve these goals with
  two extended, mixed arrays of Cherenkov telescopes

# CTA Concept: 50-100 mixed telescopes



Main array of 10m class telescopes over 1 km² area
100 GeV – 10 TeV
ex : ~ 28 telescopes

Low-energy section
ex : 4 x large telescopes

High-energy section with a halo of telescopes on 10 km² area
ex : ~ 20 telescopes

# CTA technical realisation

- The technology to build CTA is available, base-line solutions:
  "Prototypes" exist with HESS-I/II, MAGIC-I/II ...
- **Great challenges** concern cost and reliability/durability
  - ~100 telescopes in remote locations ± 10k€ each ⇒ ± 1M€
  - O(100 000) electronics channels ± 10€ each ⇒ ± 1M€
  - O(10 000m$^2$) mirror area ± 100€/m$^2$ ⇒ ± 1M€
- Require x10 increase in sensitivity with x10 cost factor
- Developments are under-way to address these issues
  (e.g., fuller integration of electronics functions on ASICs)
- Some parallel speculative research taking place,
  planned design should allow integration if mature or
  in later upgrade cycles (e.g., SiPMs)
- Major studies proceeding on array optimization, mirror sizes, pixelization, field of view, etc... for best performance vs. cost