Very High-Energy Gamma Ray Astronomy

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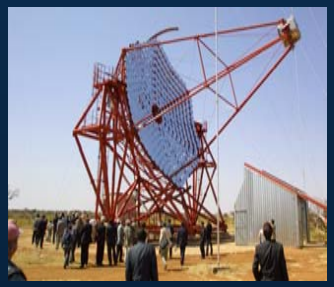
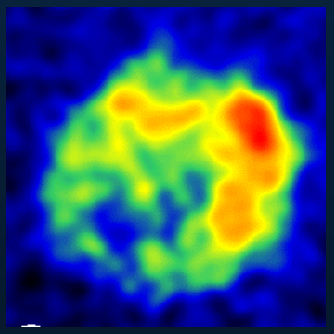
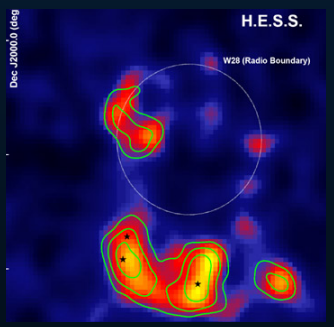


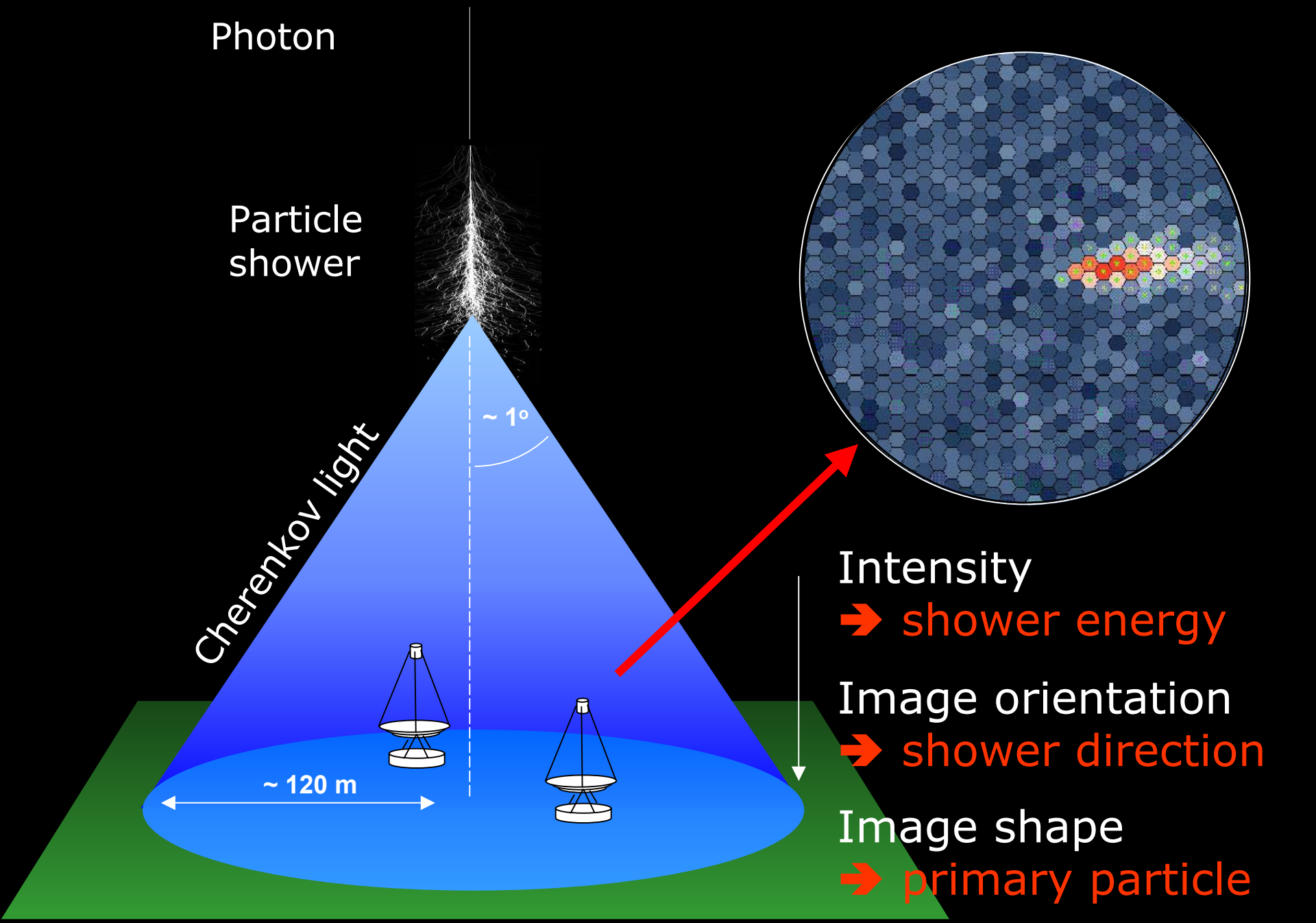




New = compared to M. Teshima‘s 2006 PIC talk

VHE gamma-ray astronomy in a nutshell

Experiments: Cherenkov Telescopes

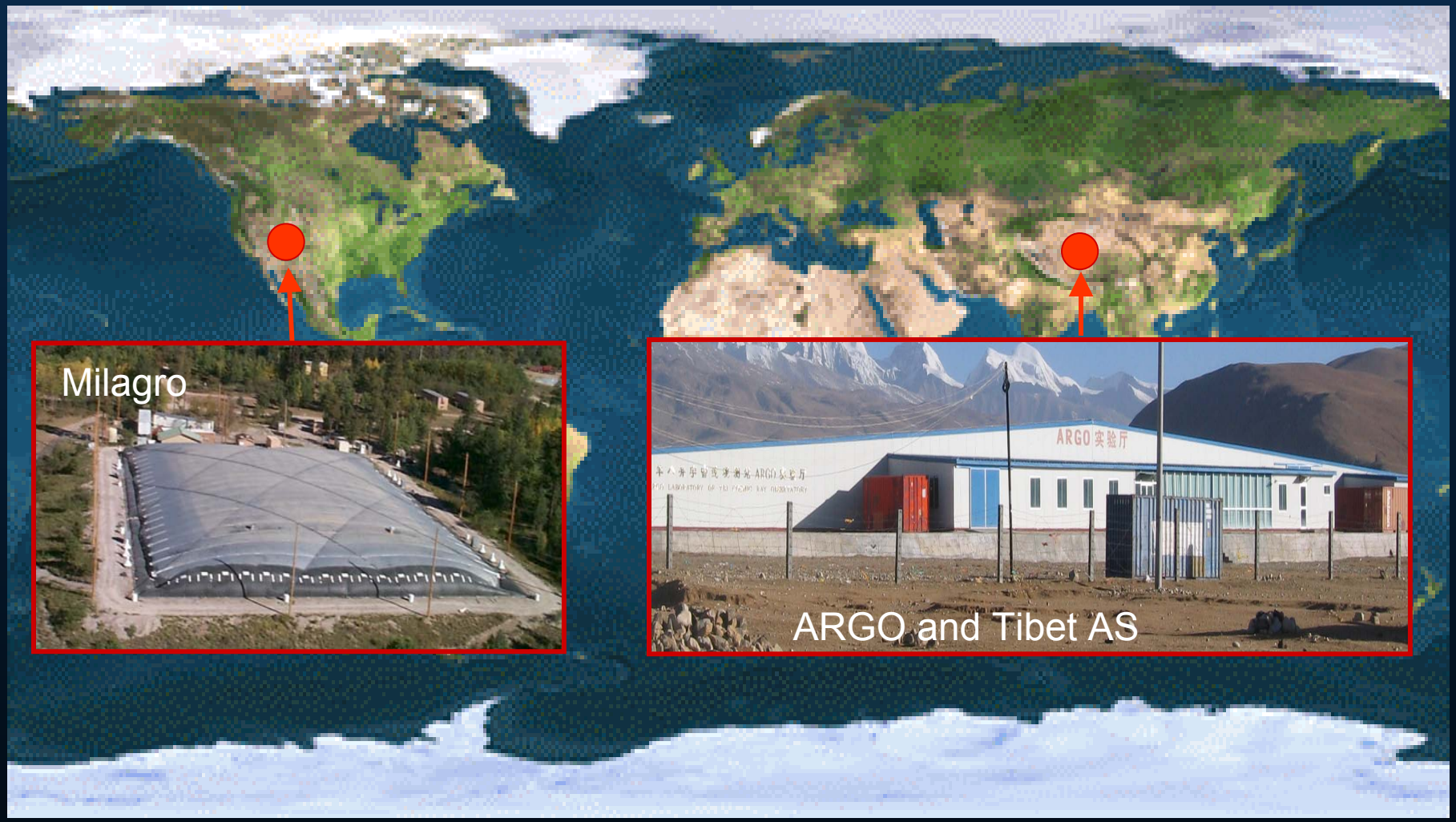

Photon
Particle shower
Cherenkov light
~ 1°
~ 120 m
Intensity
➔ shower energy
Image orientation
➔ shower direction
Image shape
➔ primary particle

Cherenkov Telescopes

	Started	# Tel	Mirror (m^2)	F.o.V (^{o})	Energy threshold (GeV)
MAGIC	08/2004	1	239	3.5	30-50
H.E.S.S.	12/2003	4	108	5	100
CANGAROO III	03/2004	4	57	4	~250
Veritas	04/2007	4	100	4.5	100

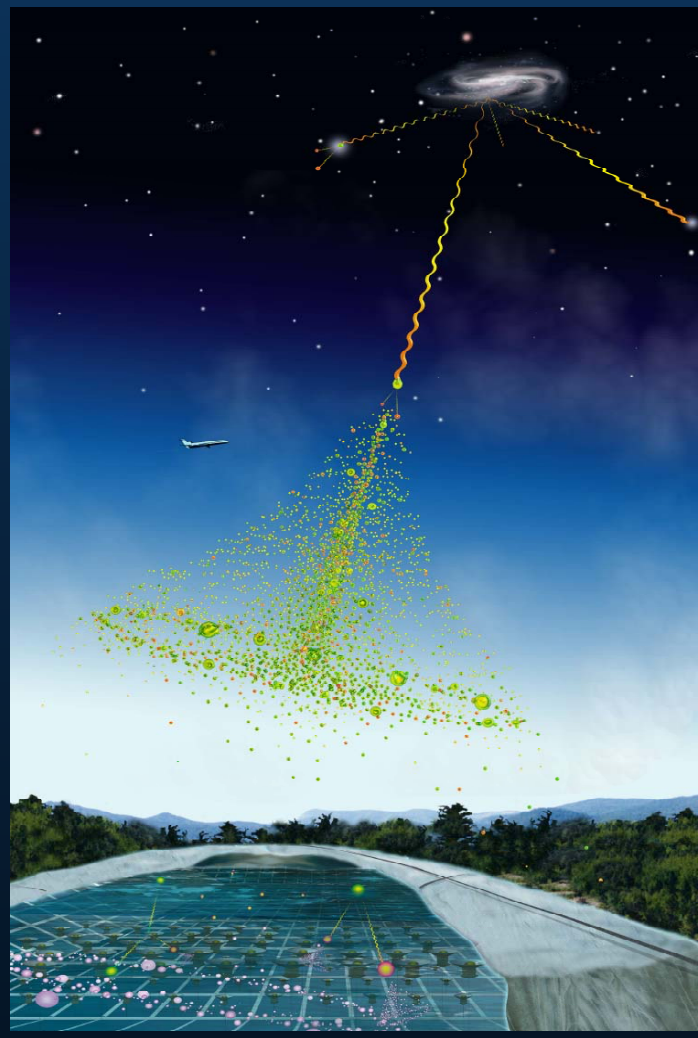
- Good angular resolution (0.05-0.1°)
- Low duty cycle (~15%)
- Detect Crab-like source in ~30 seconds (H.E.S.S.), 1% Crab in 25 hours

Experiments: Non-imaging air shower detectors

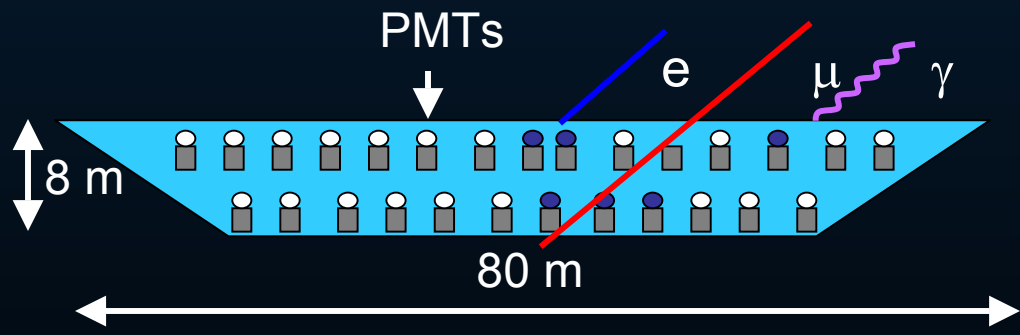


Experimental Technique

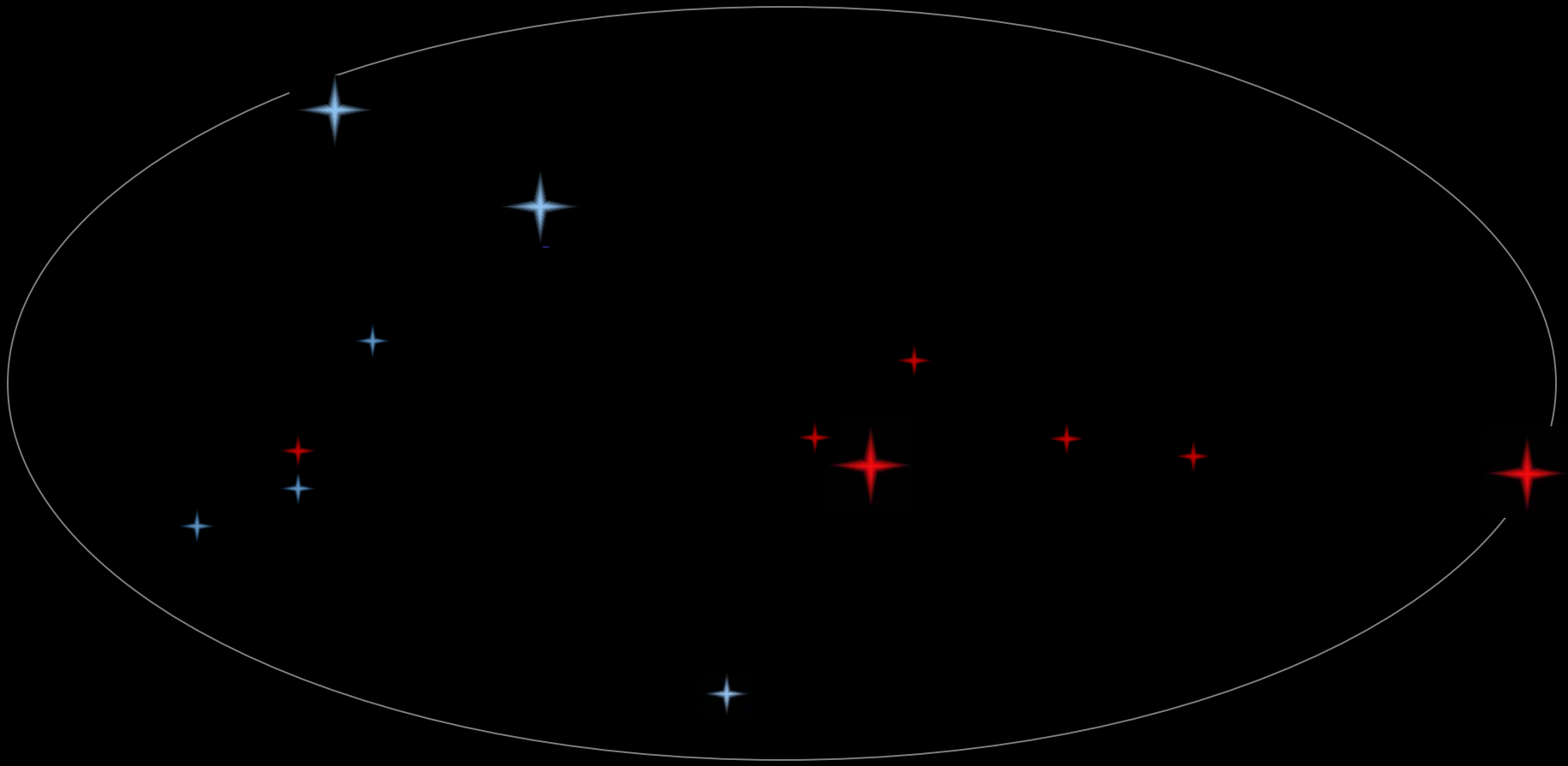
- Only northern hemisphere covered
- Variety of experimental techniques
- Water Cherenkov (MILAGRO) or RPCs+Scintillators (ARGO, Tibet AS)
- Large field of view (~2 sr)
- High duty cycle (>90%)
- Higher energy threshold (> few TeV)
- Angular resolution ~1°
- Detect Crab Nebula in ~3 months



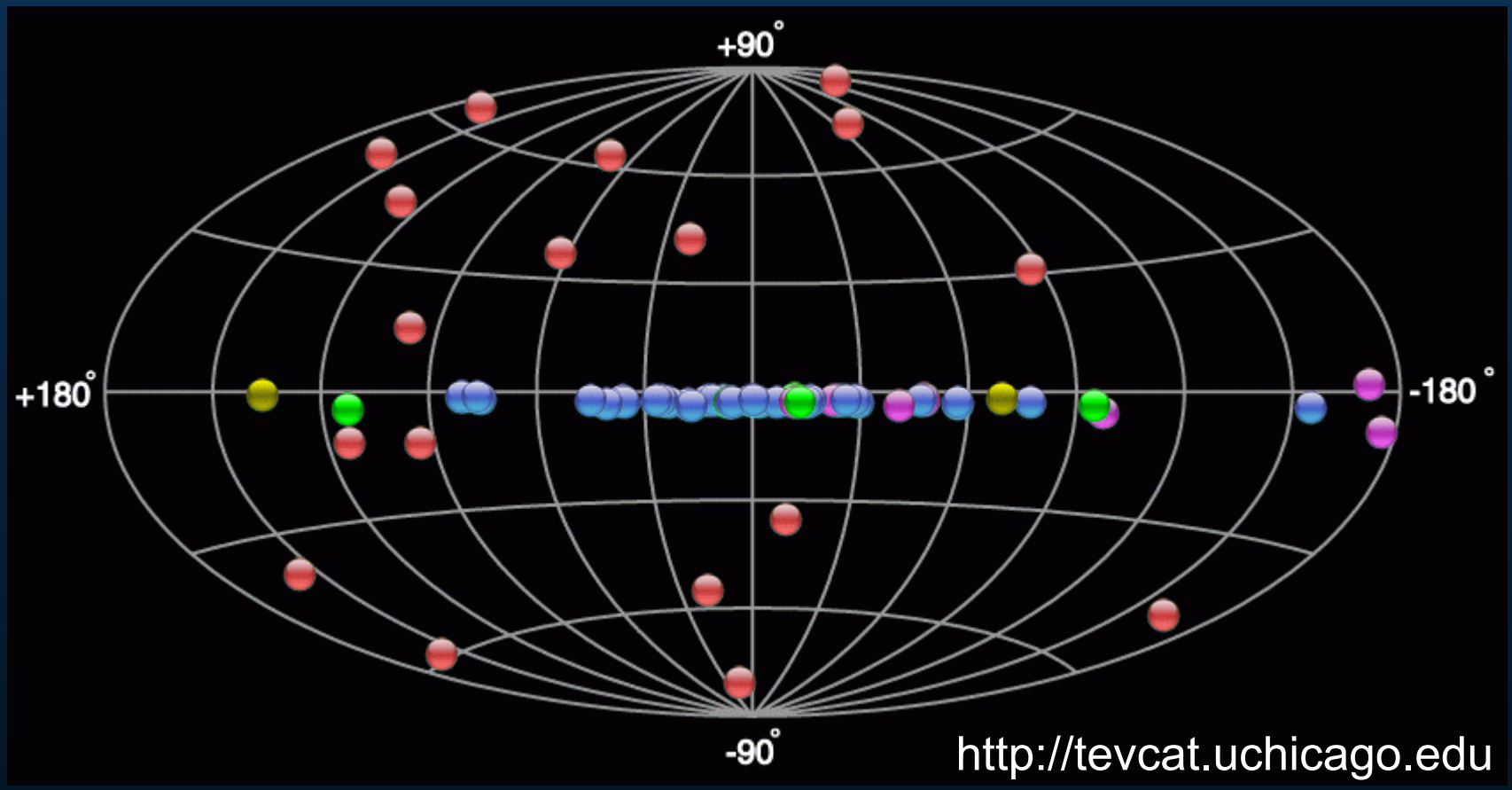
Milagro



The TeV Sky in 2004



The TeV Sky in 2008



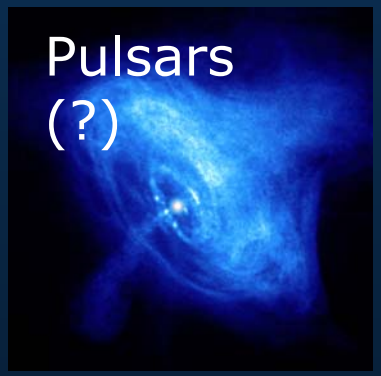
- ~70 sources, ~50 of them galactic
- ~2/3 of all sources discovered by H.E.S.S., ~7% contributions from MAGIC and Whipple

Galactic Targets

Supernova Remnants (~6)

Pulsar Wind Nebulae (~10)

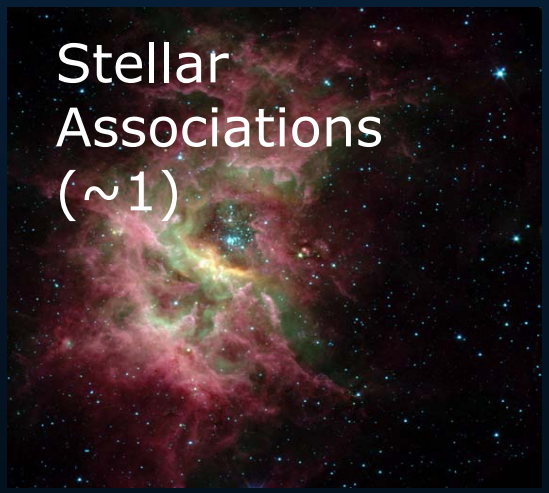
Pulsars (?)



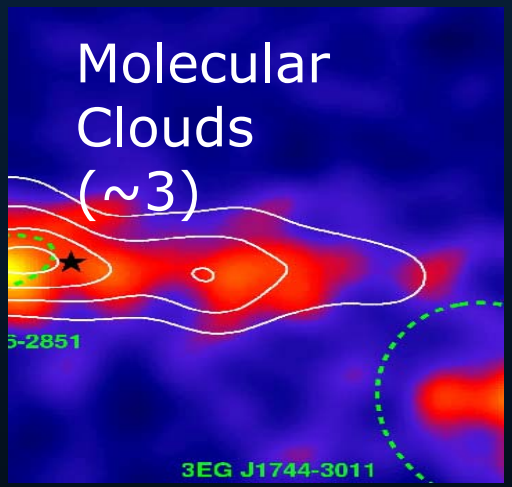
Dwarf Galaxies (0)

TeV binaries (4)

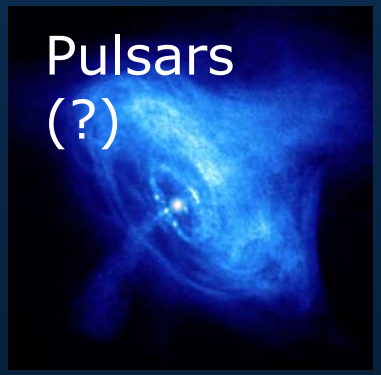
Stellar Associations (~1)



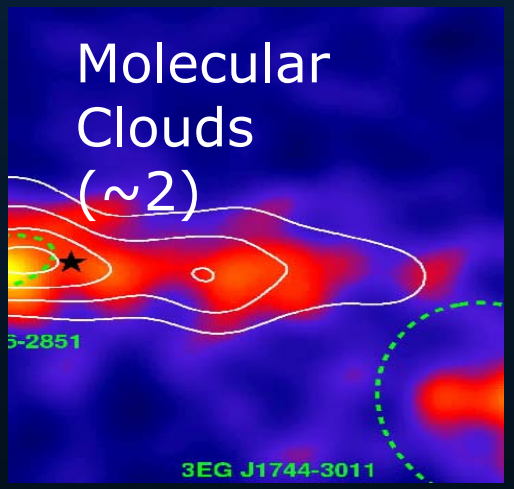
Molecular Clouds (~3)



Galactic Targets



TeV
binaries
(4)



Extragalactic Targets

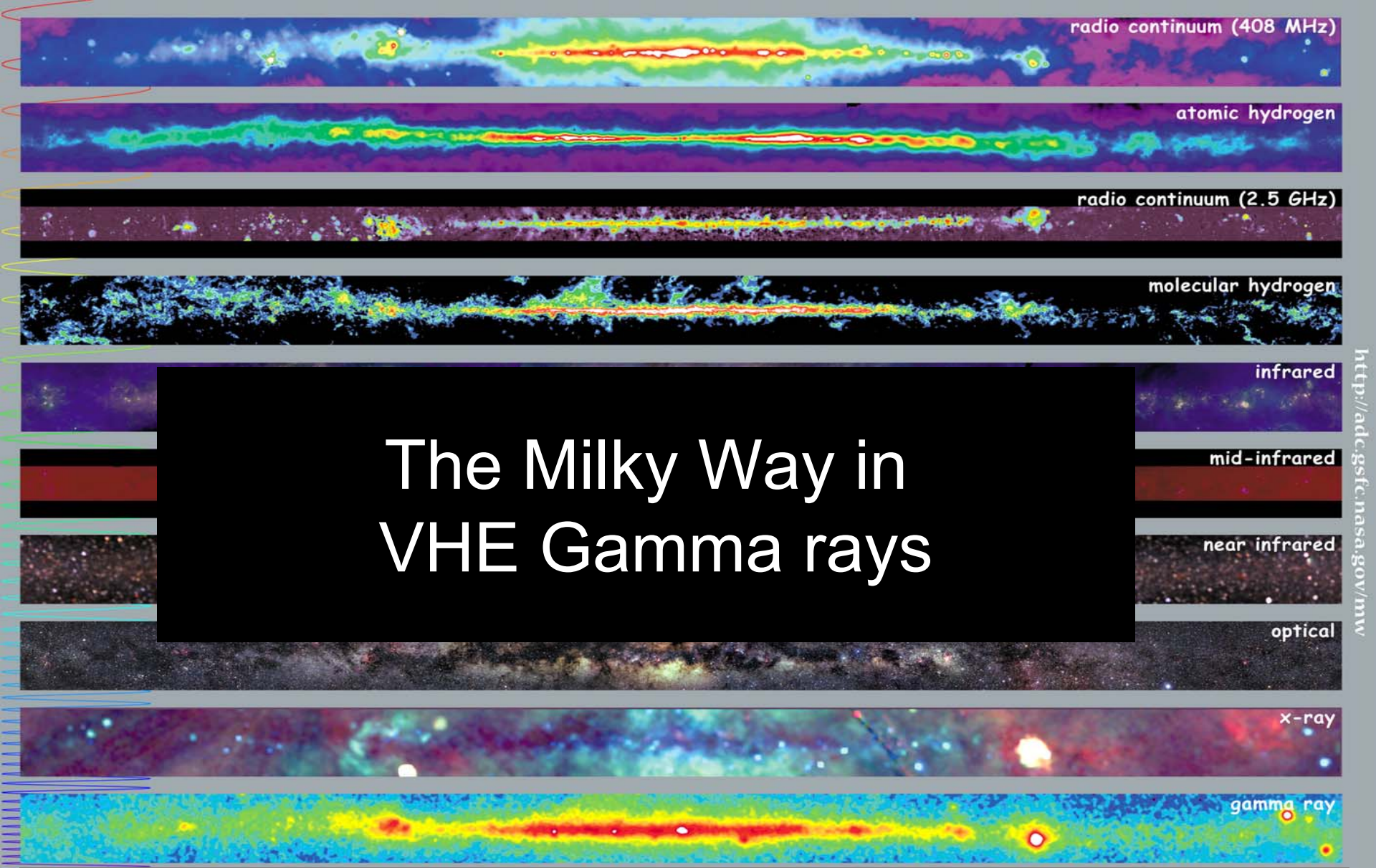
Active Galactic Nuclei (~20)

Gamma-ray bursts (0)

Starbust Galaxies (0)

Virgo Galaxy Cluster (X-ray)

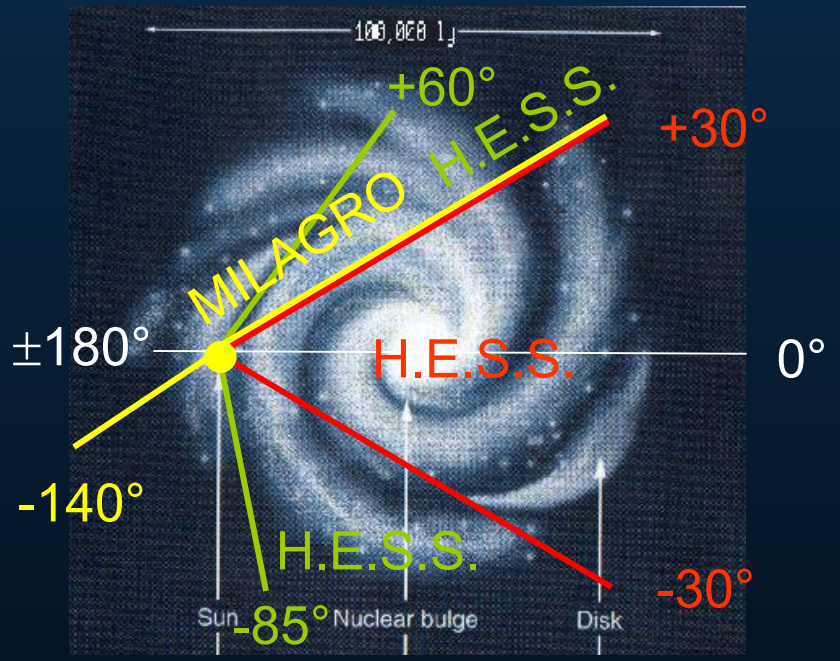
Galaxy Clusters (0)



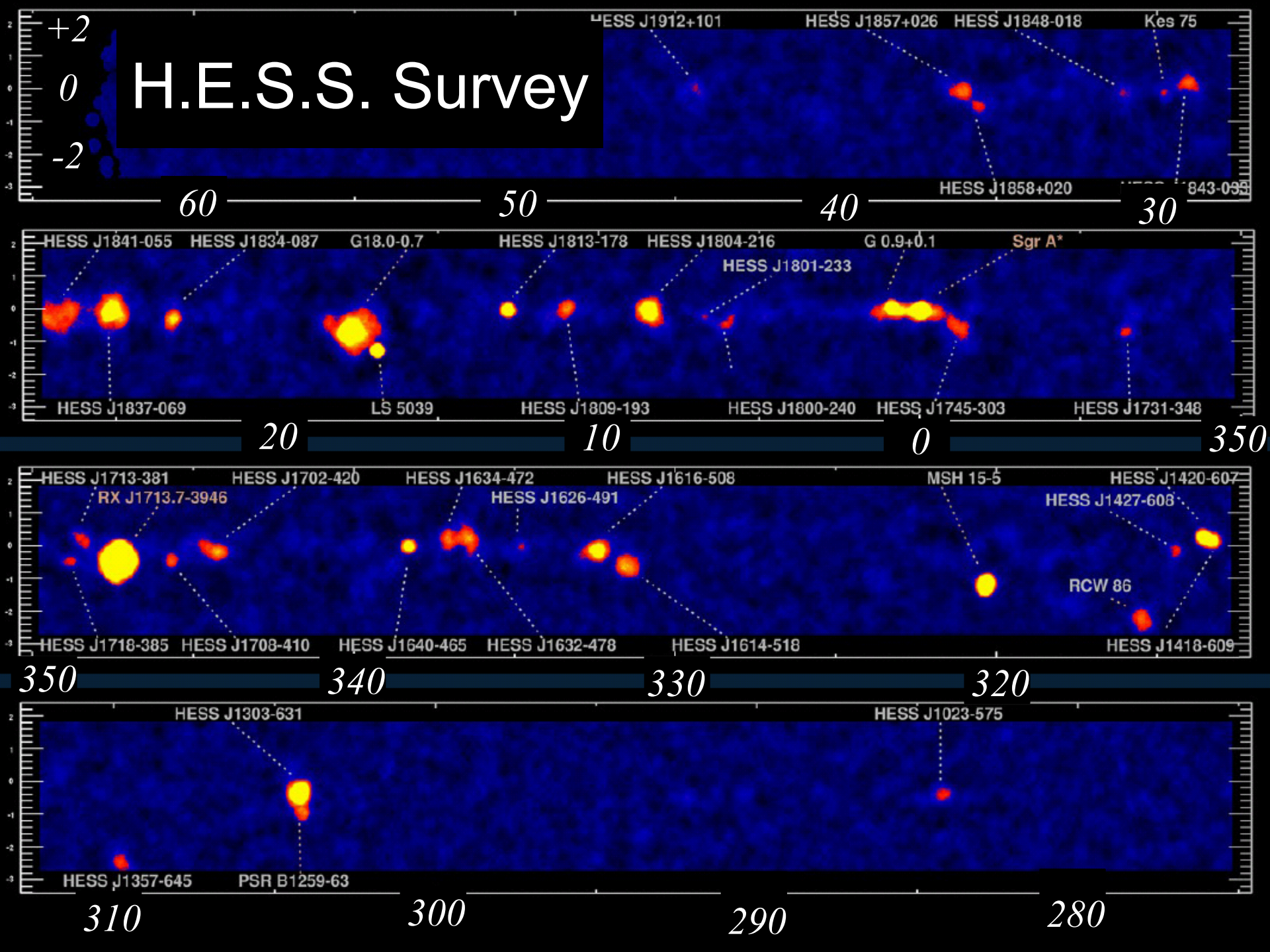
The Milky Way in VHE Gamma rays

?

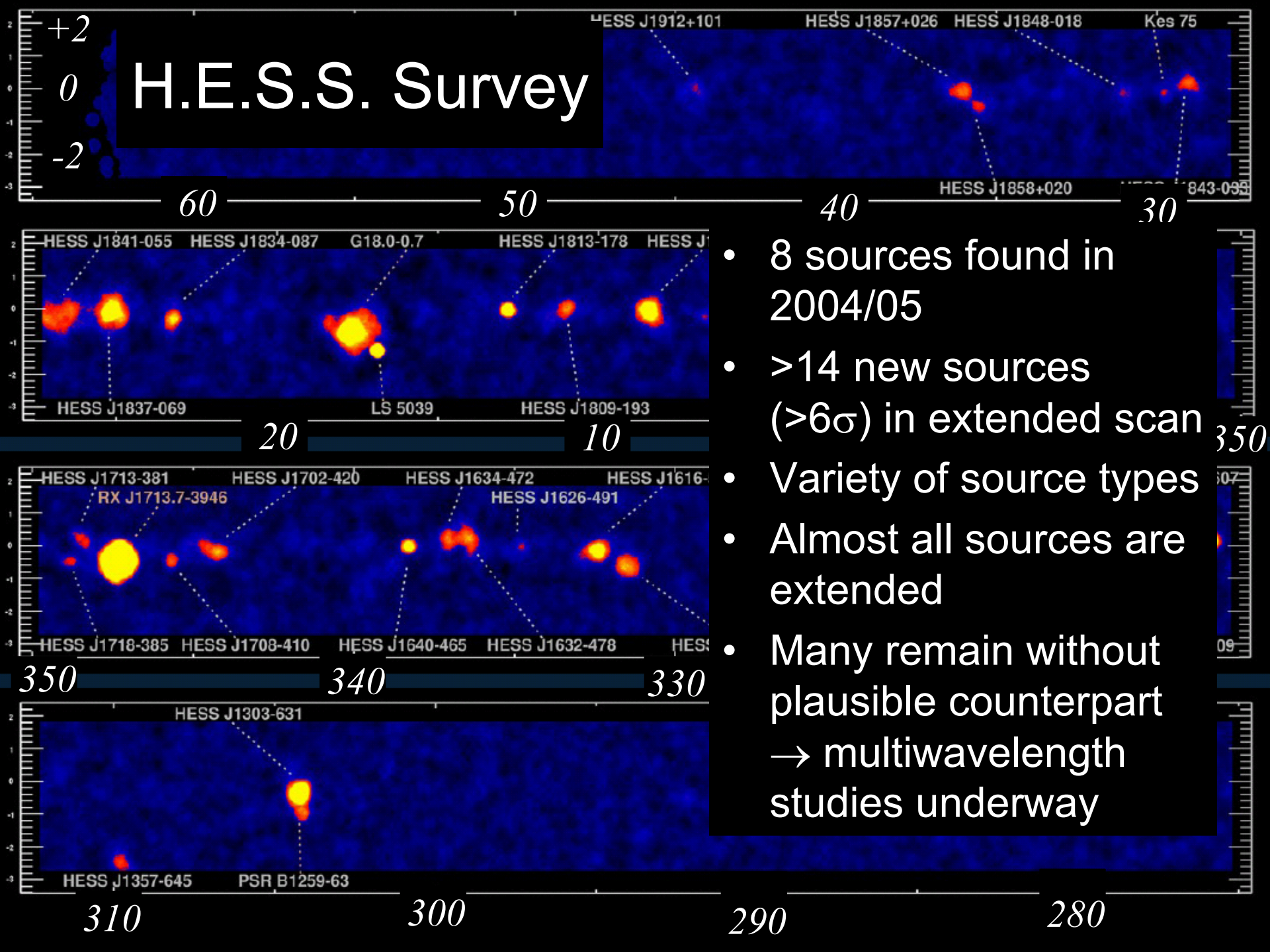
Surveys of the Galactic Plane



- H.E.S.S. 2004-2005 (inner galaxy)
  - b = ± 2° (expected source distribution)
- H.E.S.S. 2005-2007
  - Extended to b = ± 3°
- Milagro 2000-2007
  - b = ± 10° (zenith angle)
- Overlap in 30-60° longitude window
- H.E.S.S. Sensitivity: few % Crab
- Milagro sensitivity factor 10 worse than H.E.S.S. → detections, but no energy spectra


H.E.S.S. Survey
+2
0
-2
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
60
50
40
30
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
HESS J1801-233
G 0.9+0.1
Sgr A*
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
350
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-5
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
HESS J1357-645
PSR B1259-63
310
300
290
280

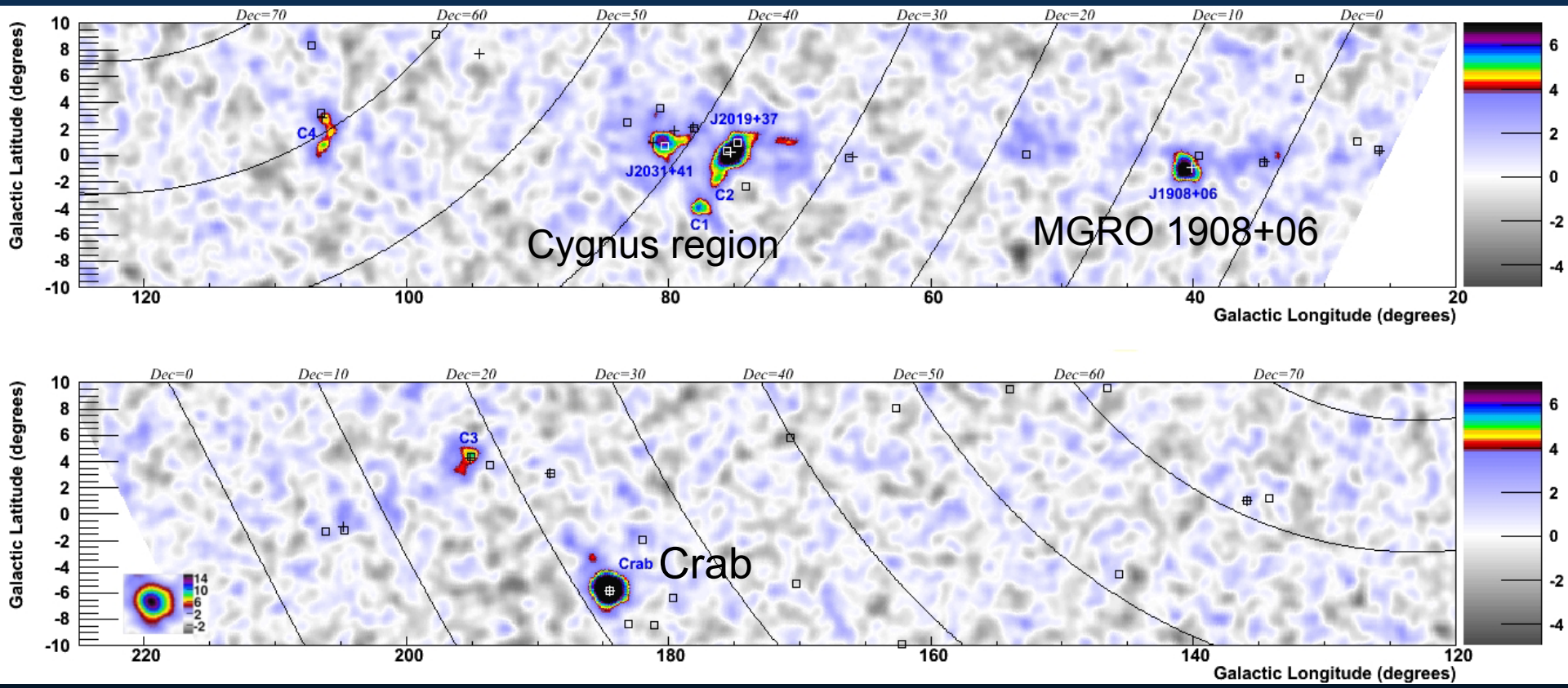
H.E.S.S. Survey



- 8 sources found in 2004/05
- >14 new sources (>6σ) in extended scan
- Variety of source types
- Almost all sources are extended
- Many remain without plausible counterpart → multiwavelength studies underway

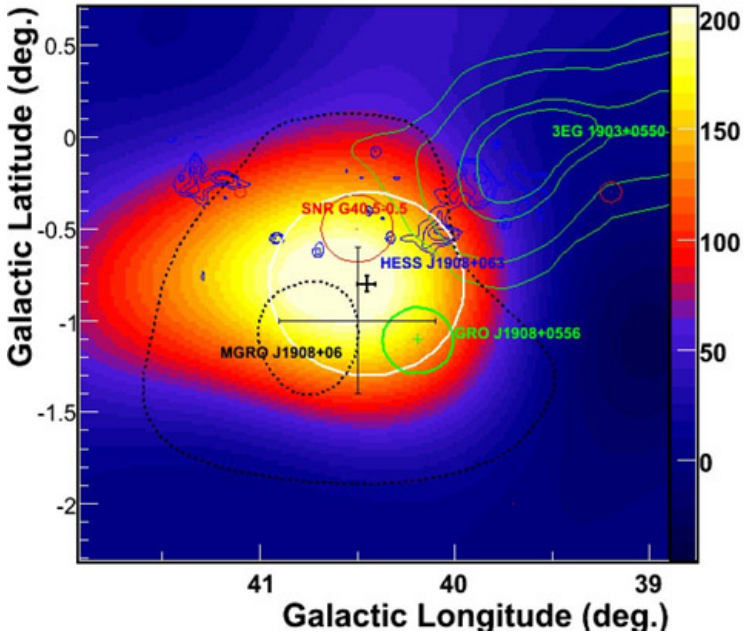
Milagro Survey

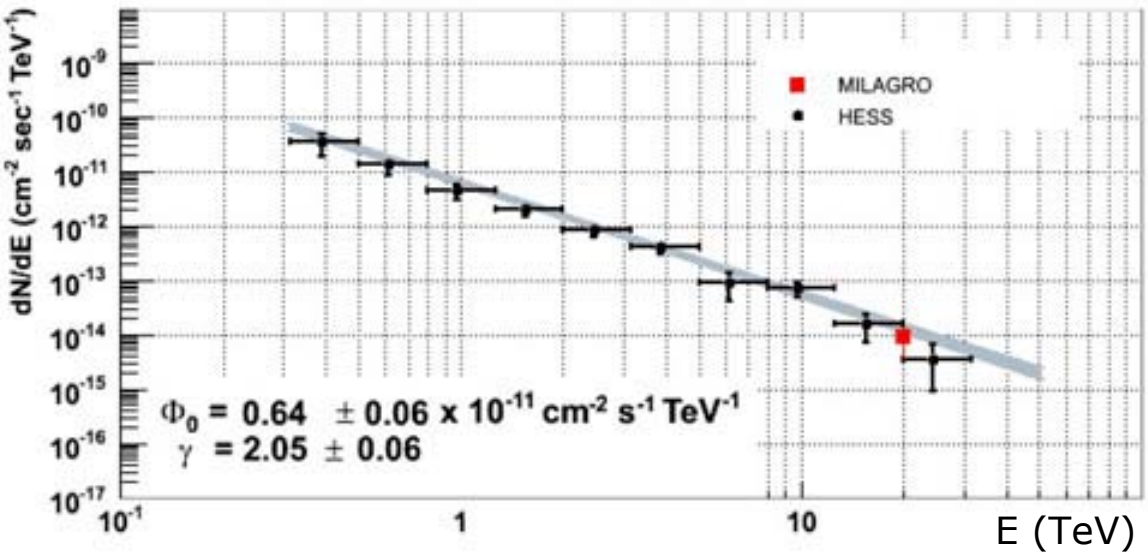
Abdo, et al. ApJ Lett 2007



- 6.5 years of live-time
- Crab nebula plus 7 sources, 3 of which are significant after accounting for trials

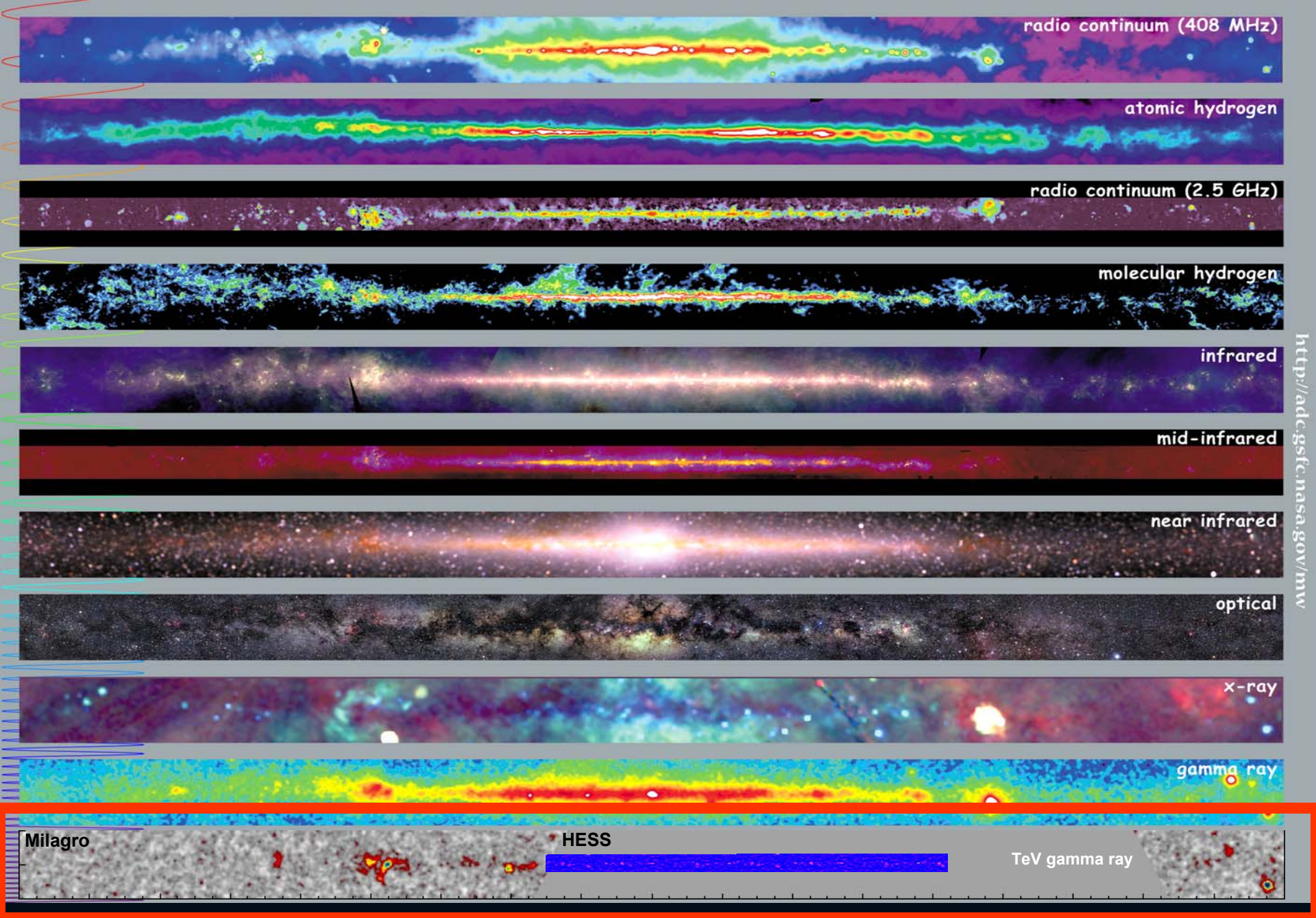
MGRO 1908+06 = HESS J1908+063



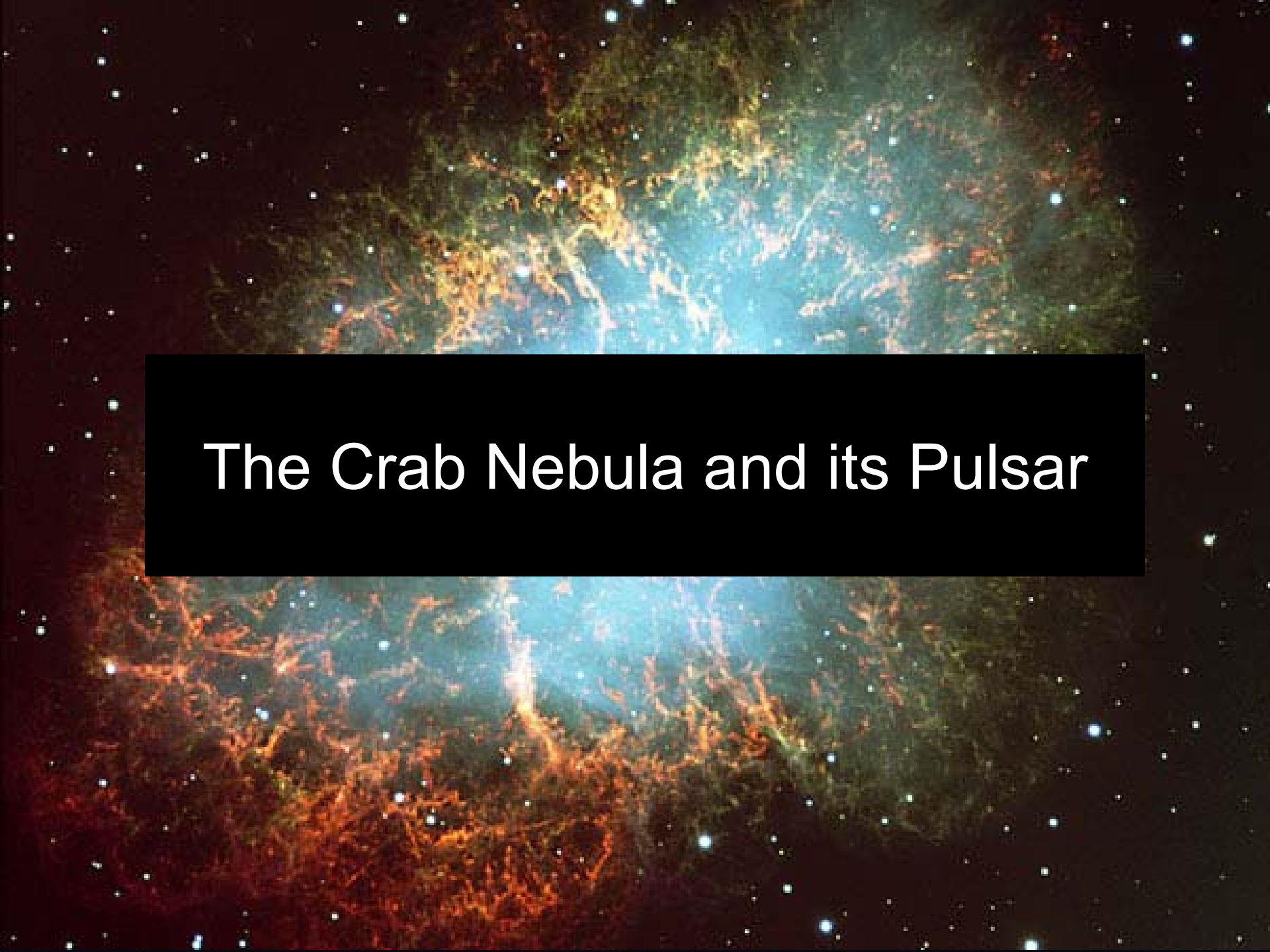


15 h of data, 5.7σ, 14% Crab

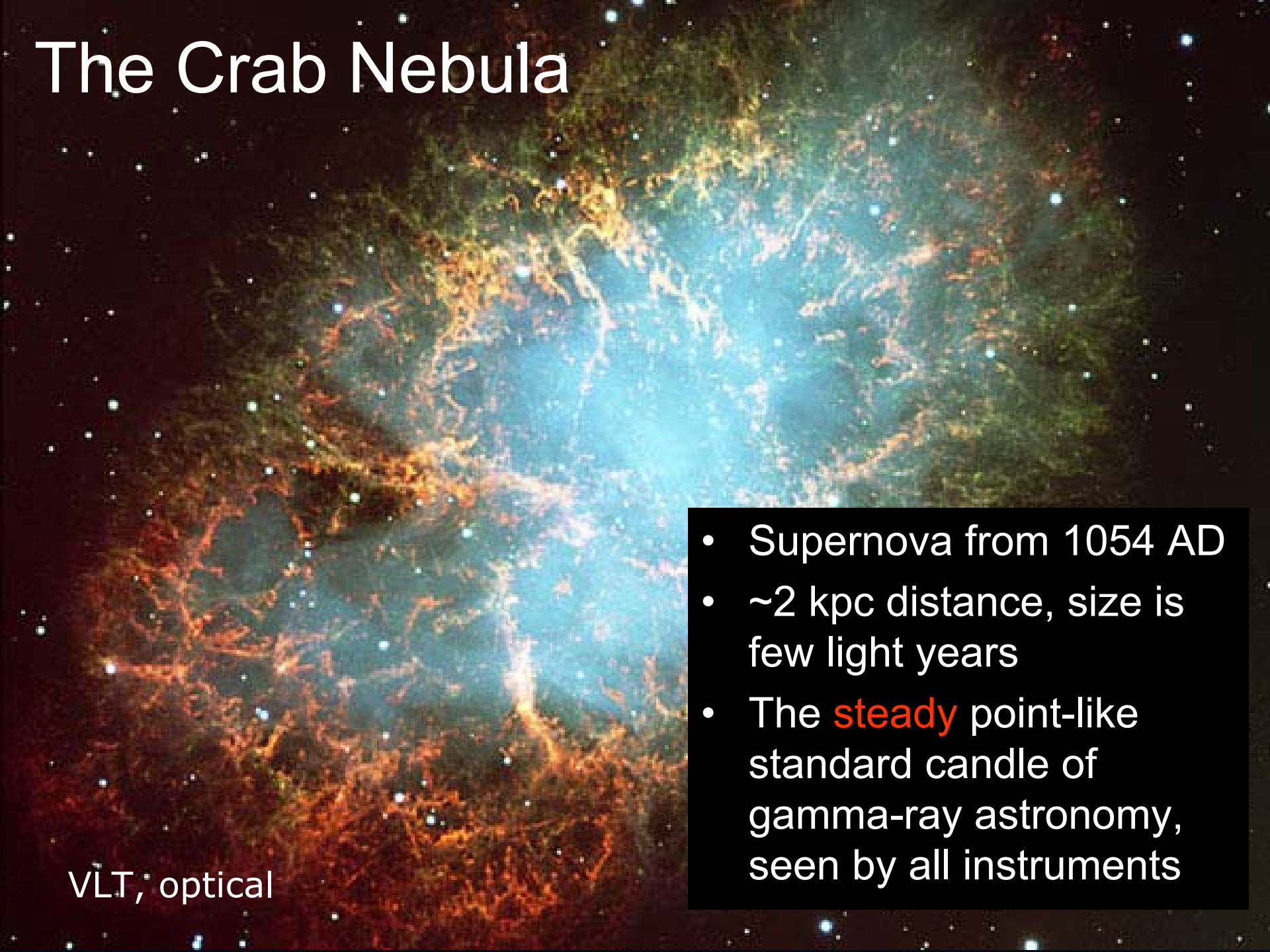
- Positional coincidence of H.E.S.S. and Milagro source
- Is the source a SNR + molecular clouds?
- Surveys and sources start overlapping



A picture of the Galaxy at VHE energies emerges!


The Crab Nebula and its Pulsar

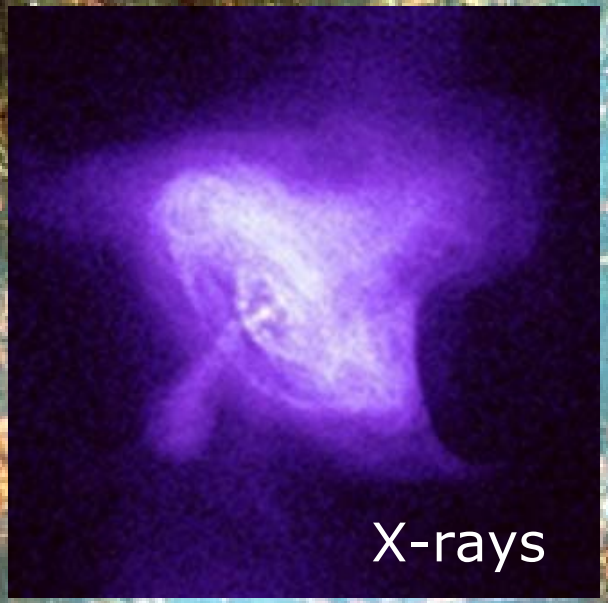
The Crab Nebula

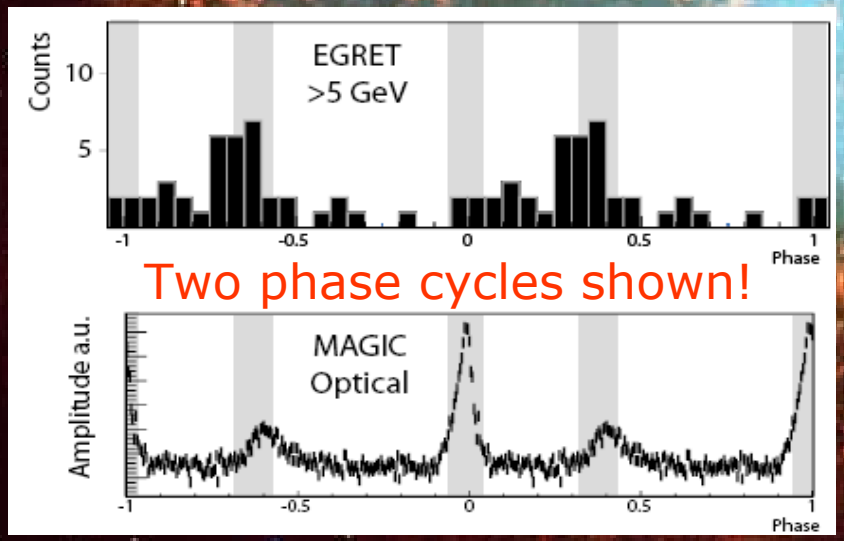


- Supernova from 1054 AD
- ~2 kpc distance, size is few light years
- The steady point-like standard candle of gamma-ray astronomy, seen by all instruments

VLT, optical

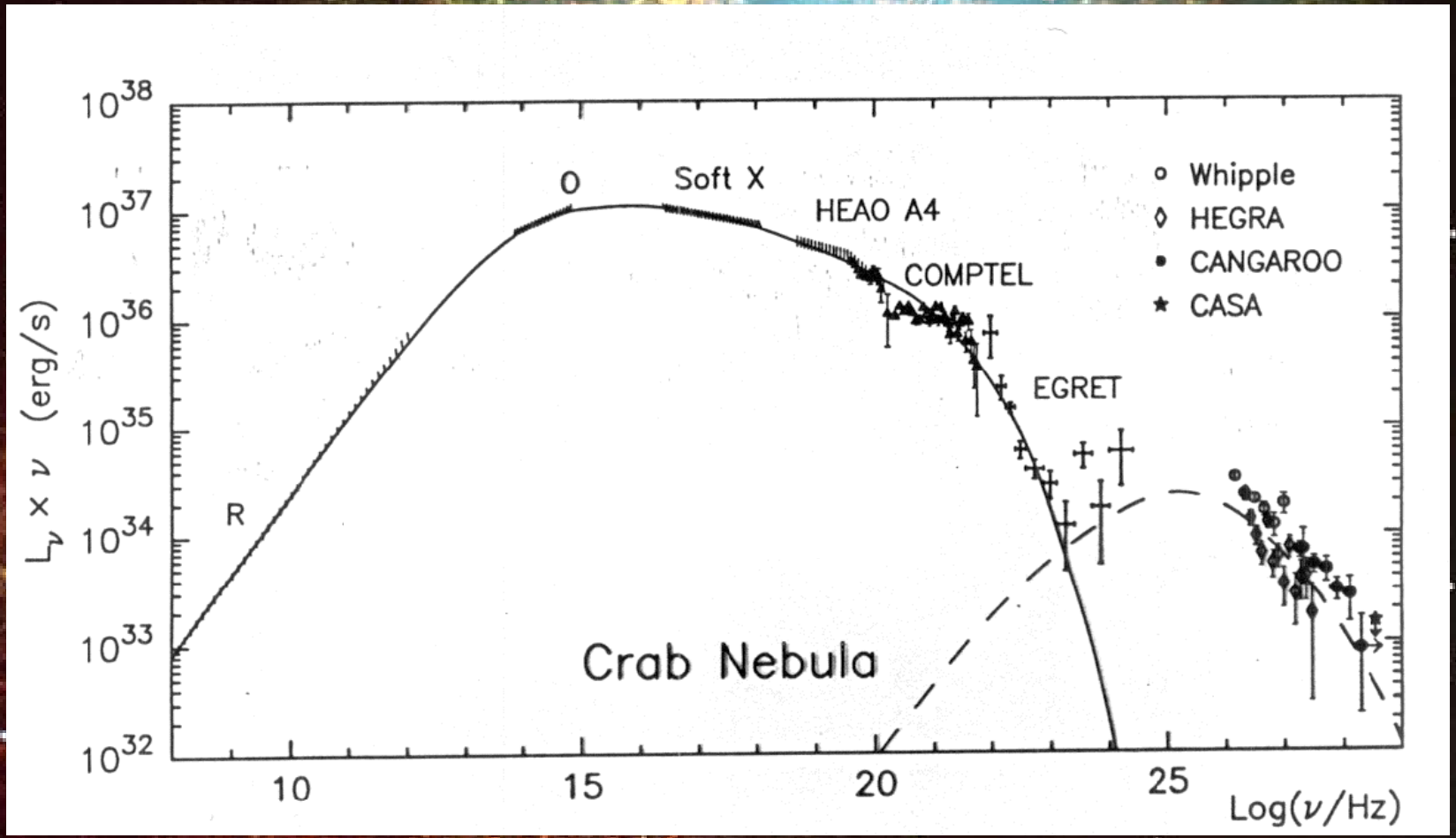
The Crab Nebula and its Pulsar





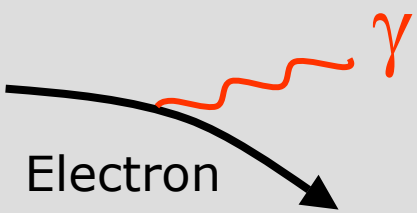
- 33 ms Pulsar
- Pulsed emission seen at optical, radio, X-ray and gamma (EGRET) frequencies but not yet in VHE gammas

Steady emission from the PWN

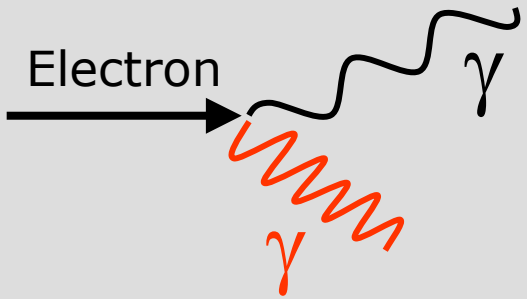


Steady emission from the PWN

Synchrotron radiation

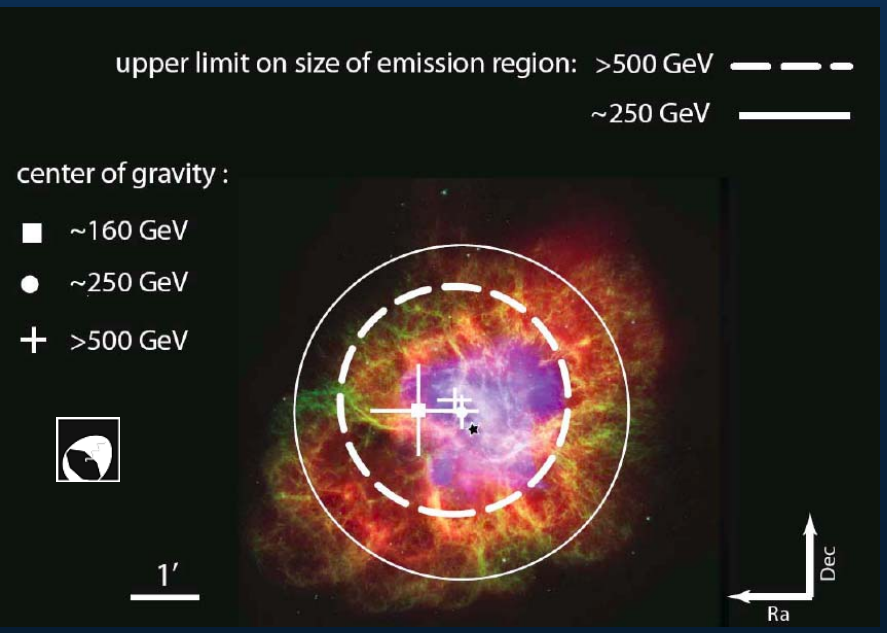


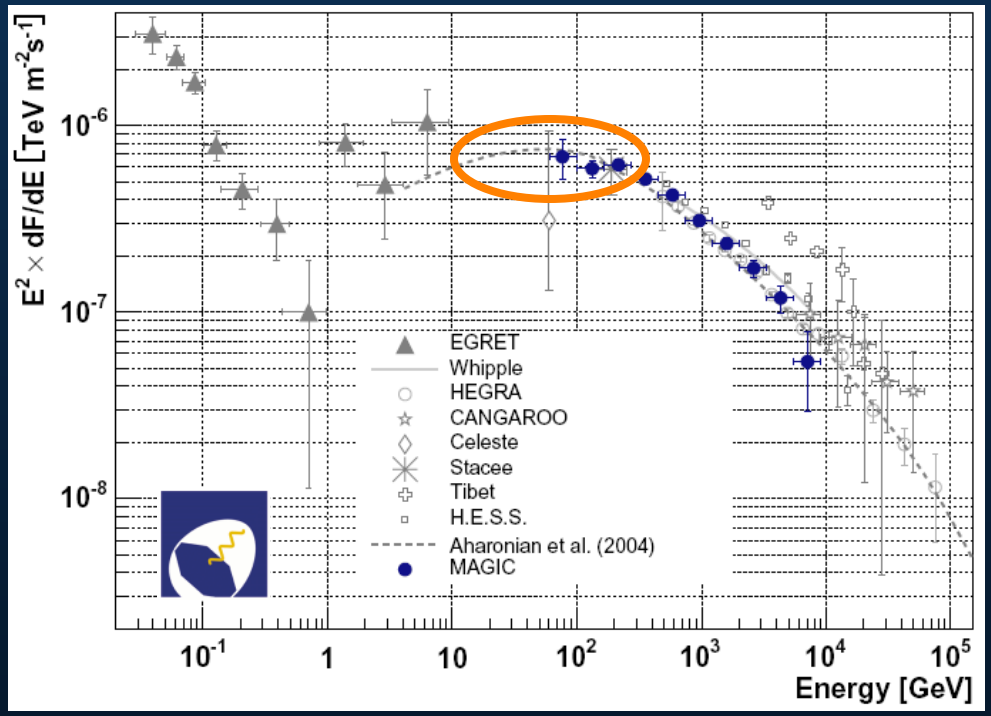
Inverse Compton scattering



Steady emission from the PWN

MAGIC Collab.,
ApJ 674 (2008) 1037

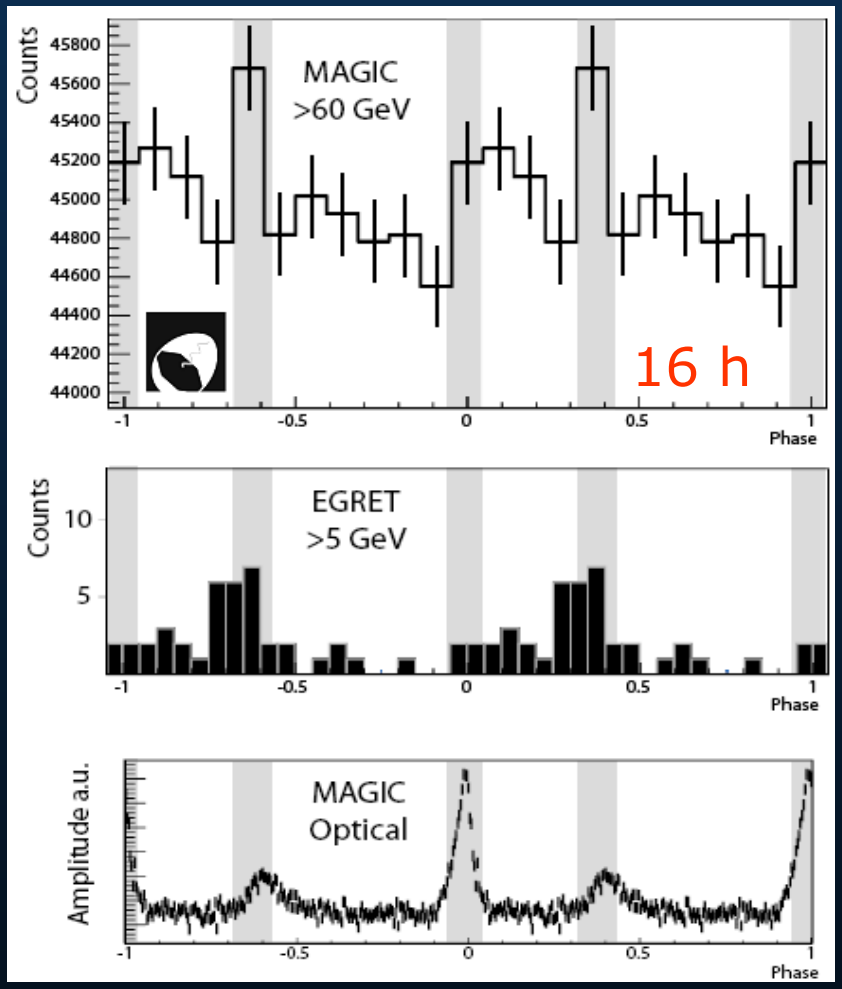




- MAGIC measured spectrum down to 60 GeV
- Energy spectrum well described by IC emission
- IC peak estimated at 77 GeV

Pulsed Emission from the Pulsar

- First hint (2.9σ) from 16 h of data at EGRET position
- 22 h of data (Oct 07-Feb 08) with dedicated trigger (E_{thr} from 50-60 to 25 GeV)
- Recorded 8500 pulsed photons (6.4σ)



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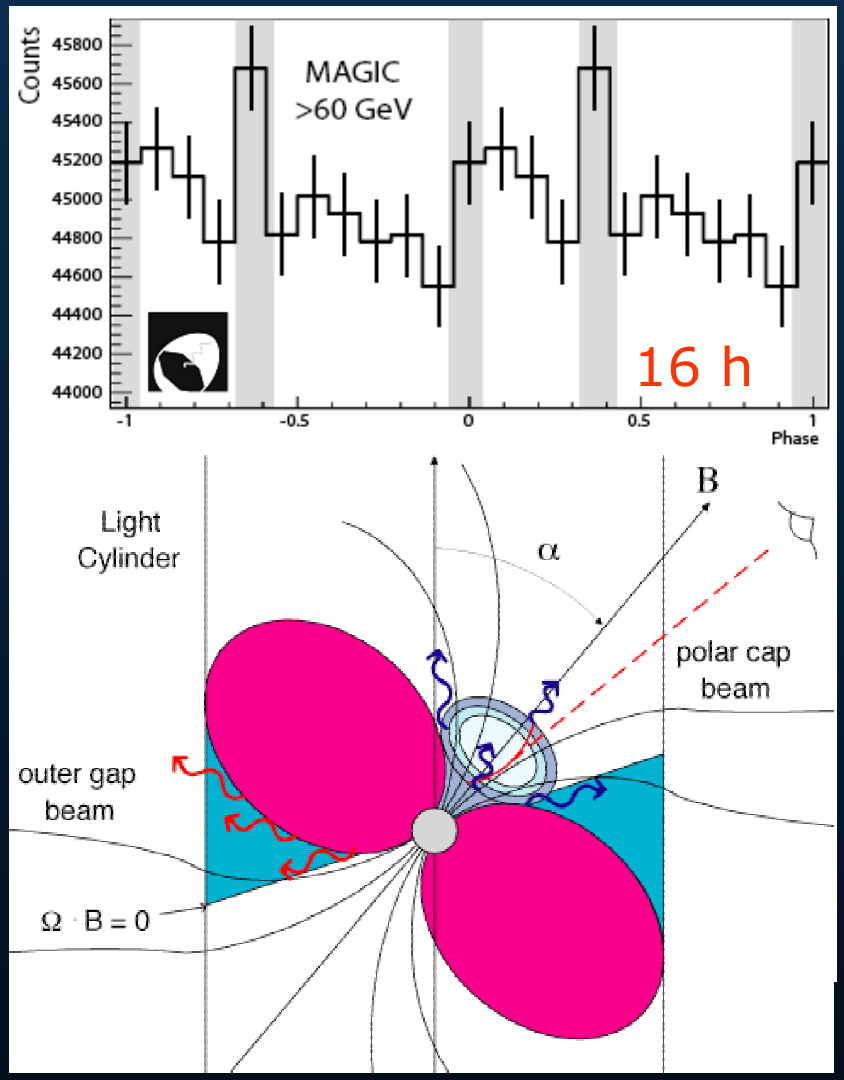
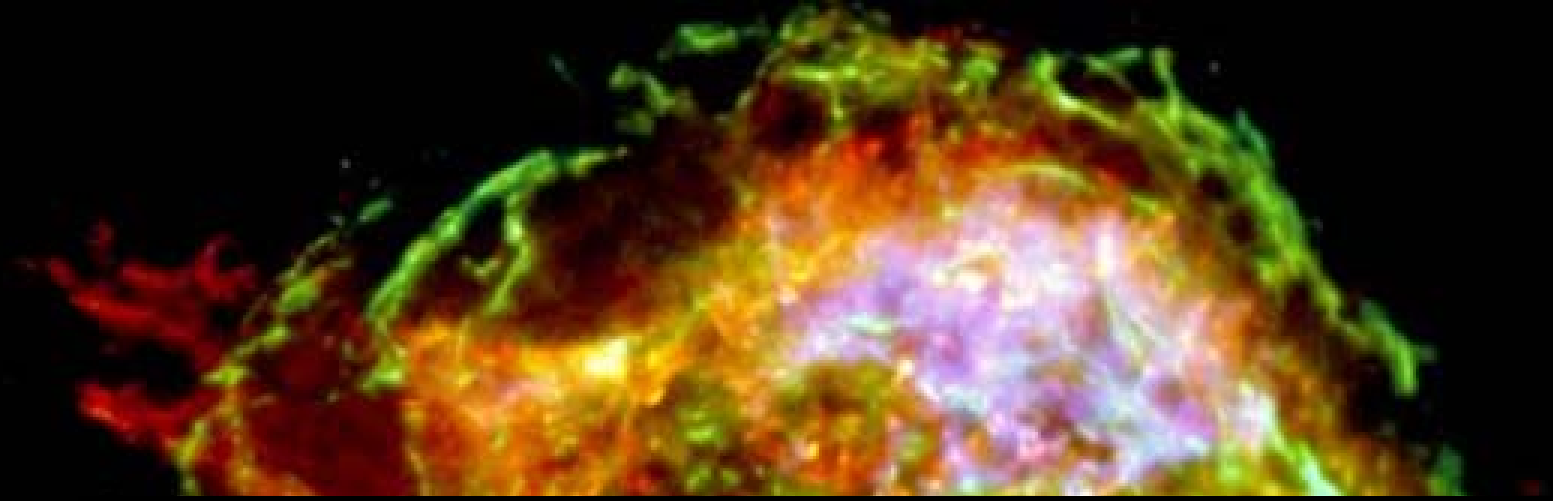
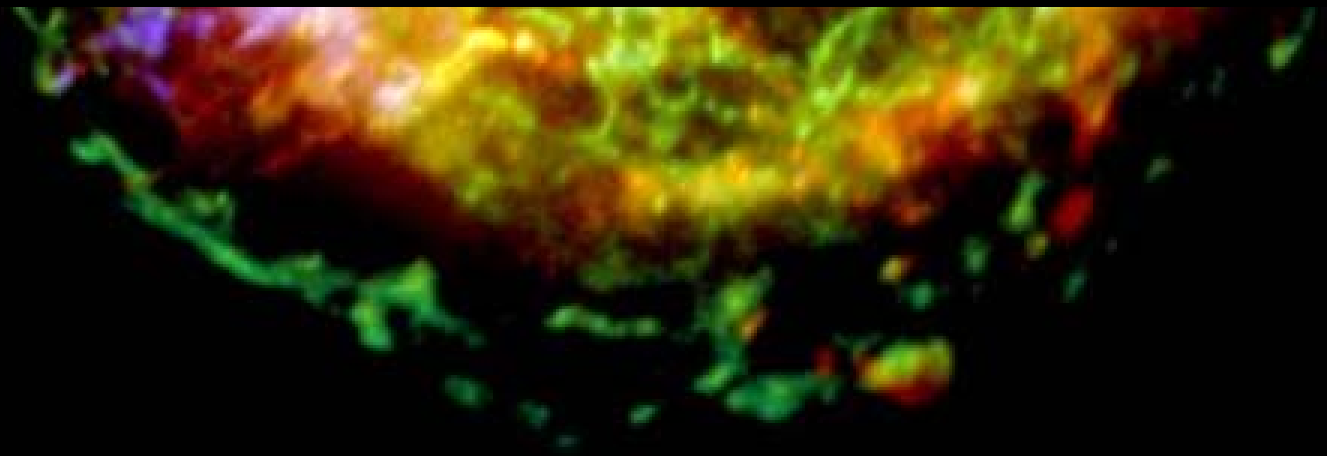
- Recorded 8500 pulsed photons (6.4σ)
- Important input for understanding of acceleration mechanisms in pulsar magnetosphere

First measurement of pulsed emission from a pulsar at VHE energies!



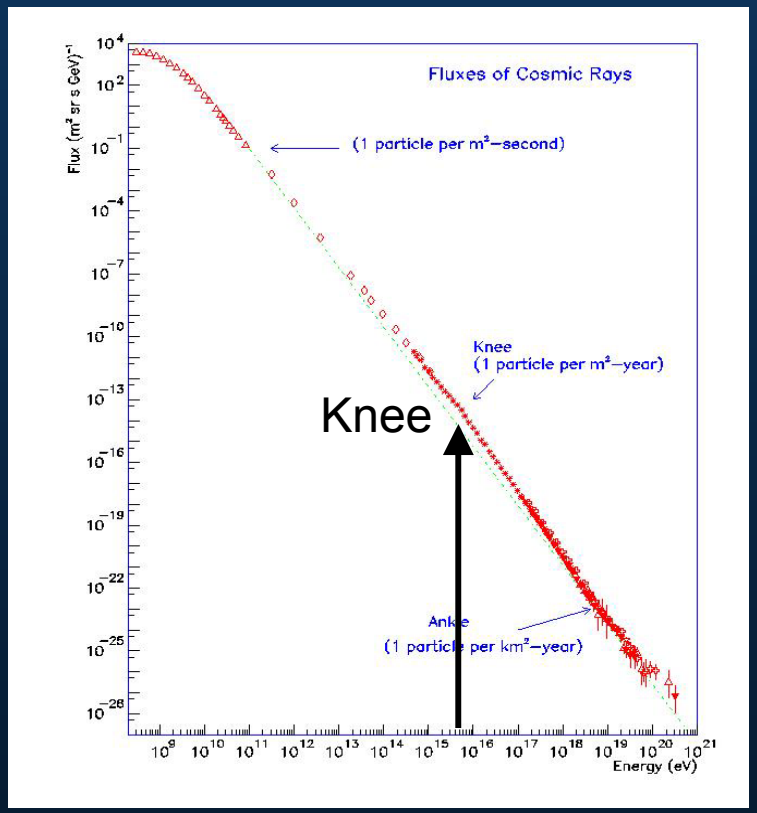


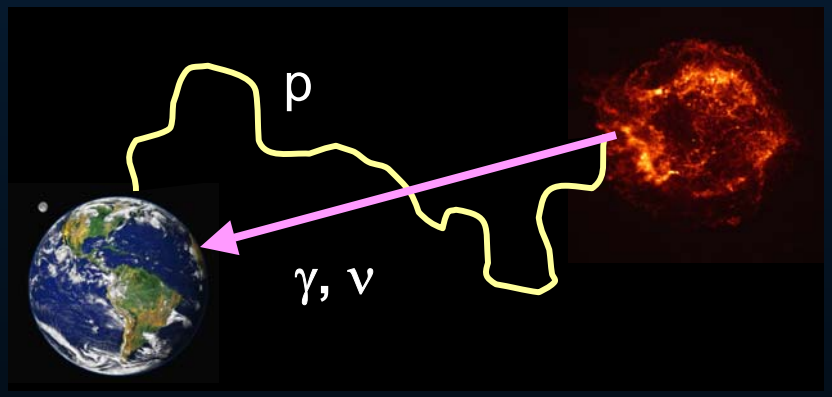
Are supernova remnants the sources of cosmic rays?



Cosmic Ray (CR) Accelerators

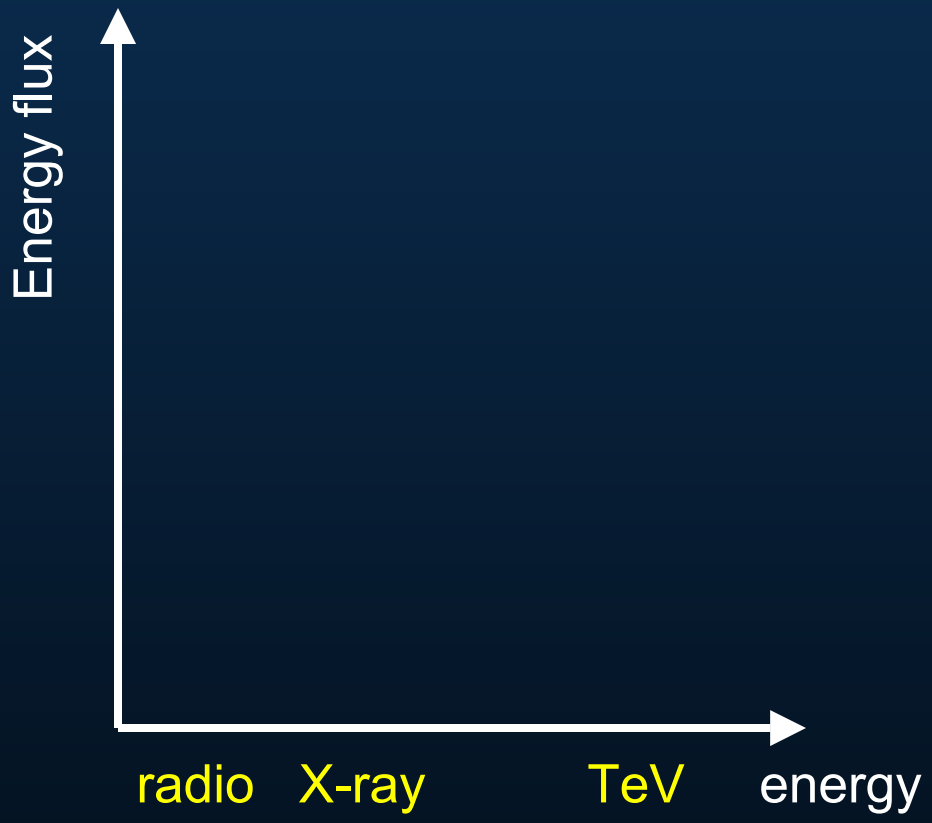
- Knee is thought to mark transition from galactic to extragalactic CRs
- Are extragalactic CRs related to Active Galactic Nuclei? ($\rightarrow$ recent AUGER results)
- Supernova remnants are thought to be accelerators of galactic CRs
- Secondary gamma-rays point back to source!





SNRs as Cosmic Ray Accelerators

- Large energy release
  - $(dE/dt)_{SN} = 10 \cdot (dE/dt)_{CR}$
- Diffuse shock acceleration (DSA) in SNR shell
- Efficiency O(10%)
- Need to prove that protons are accelerated, too



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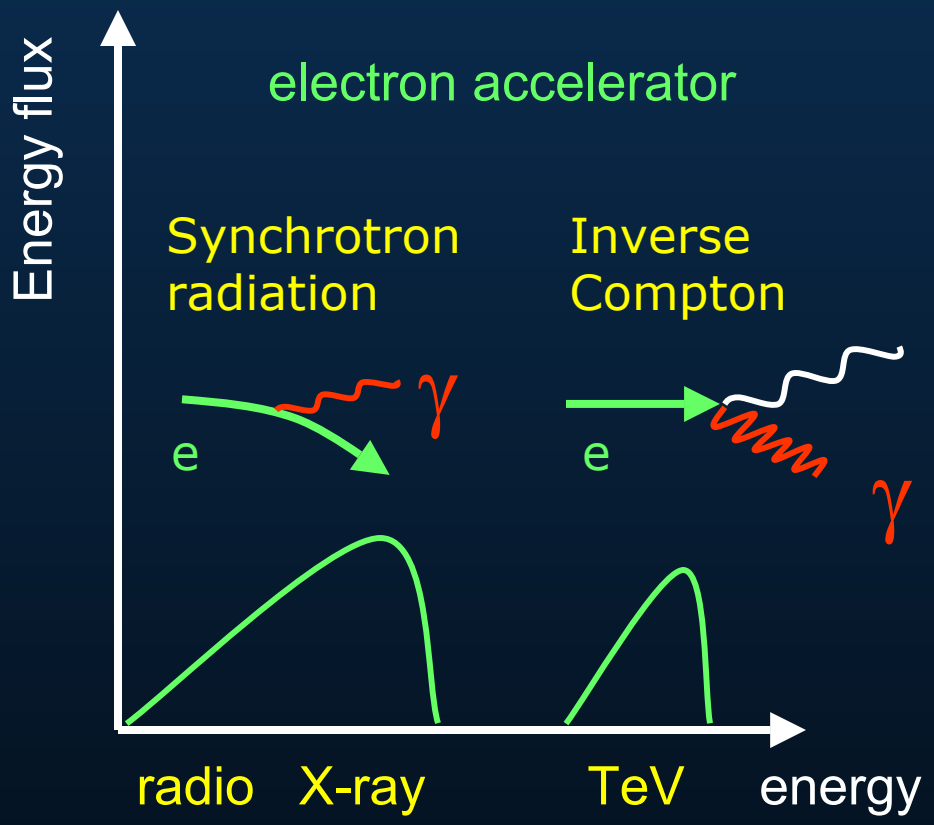

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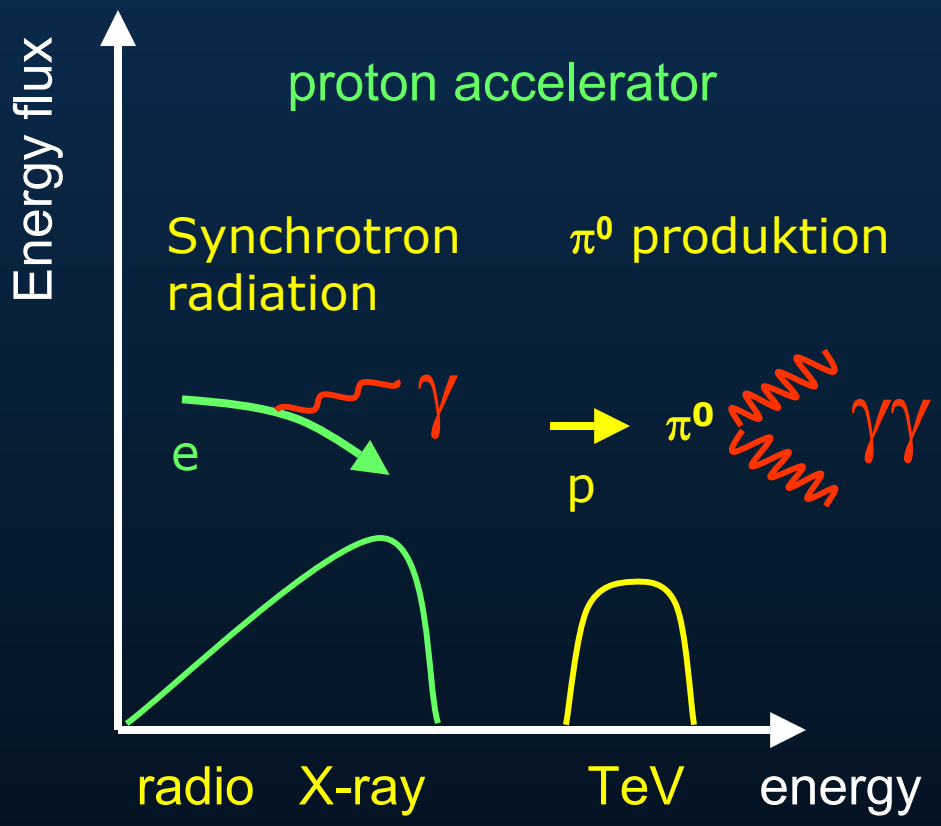
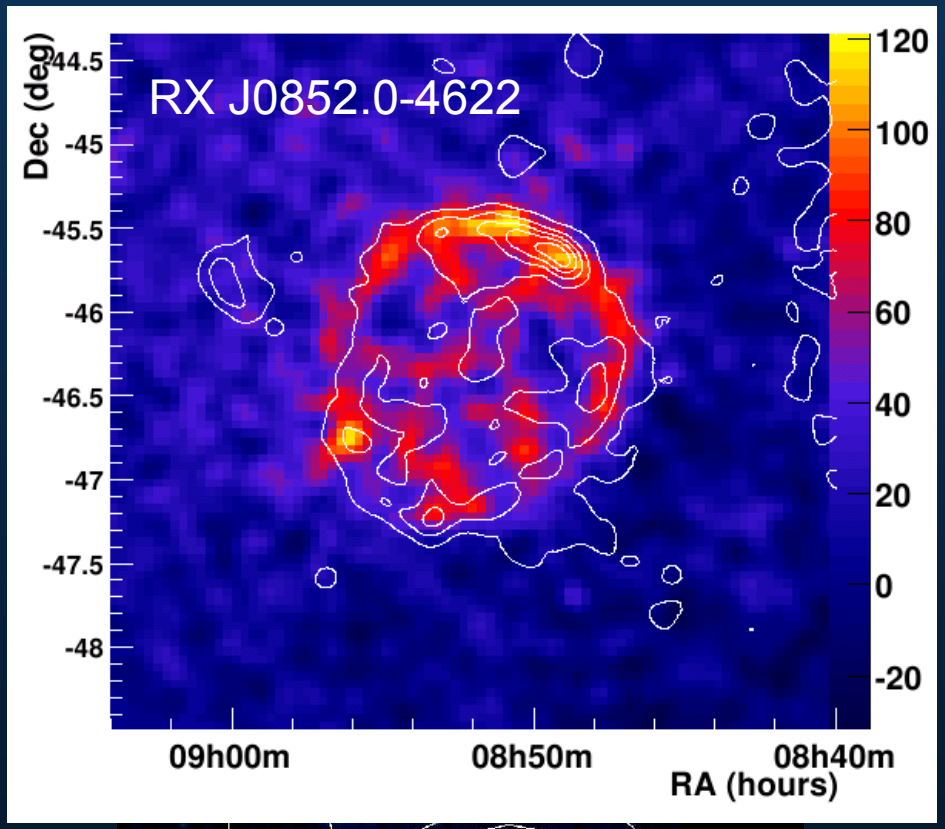
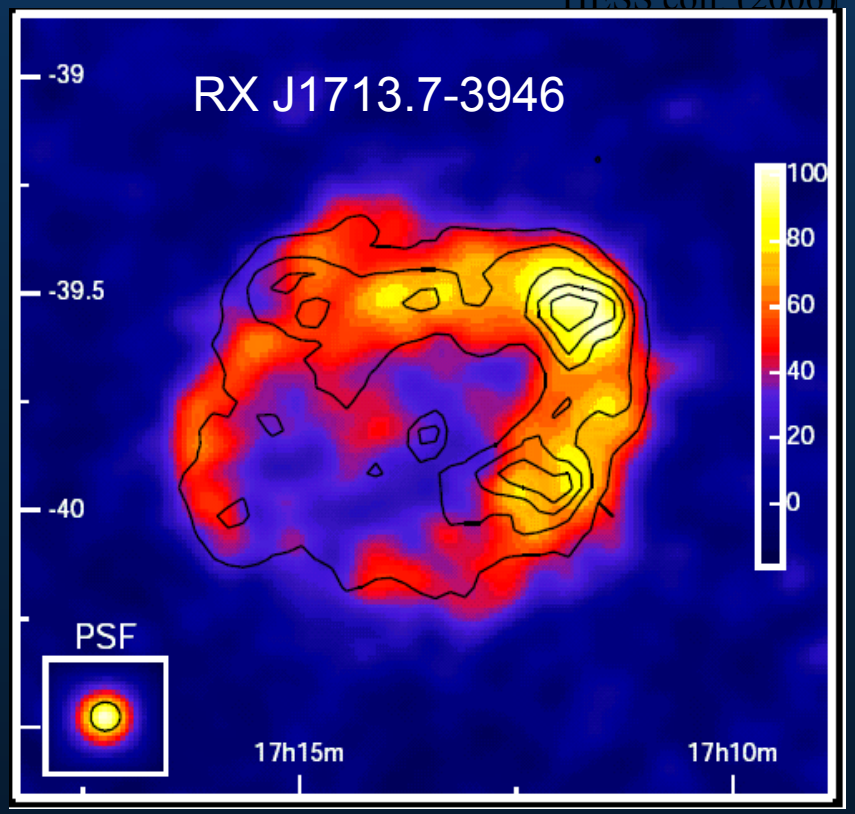
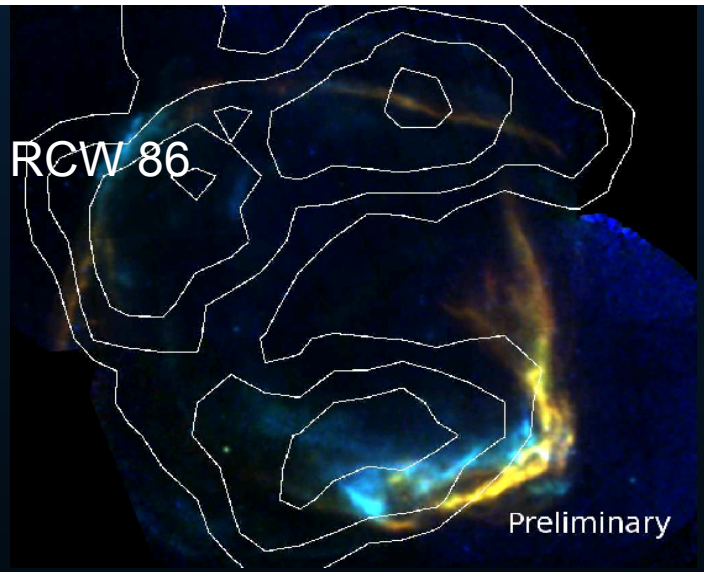


HESS coll. (2006)

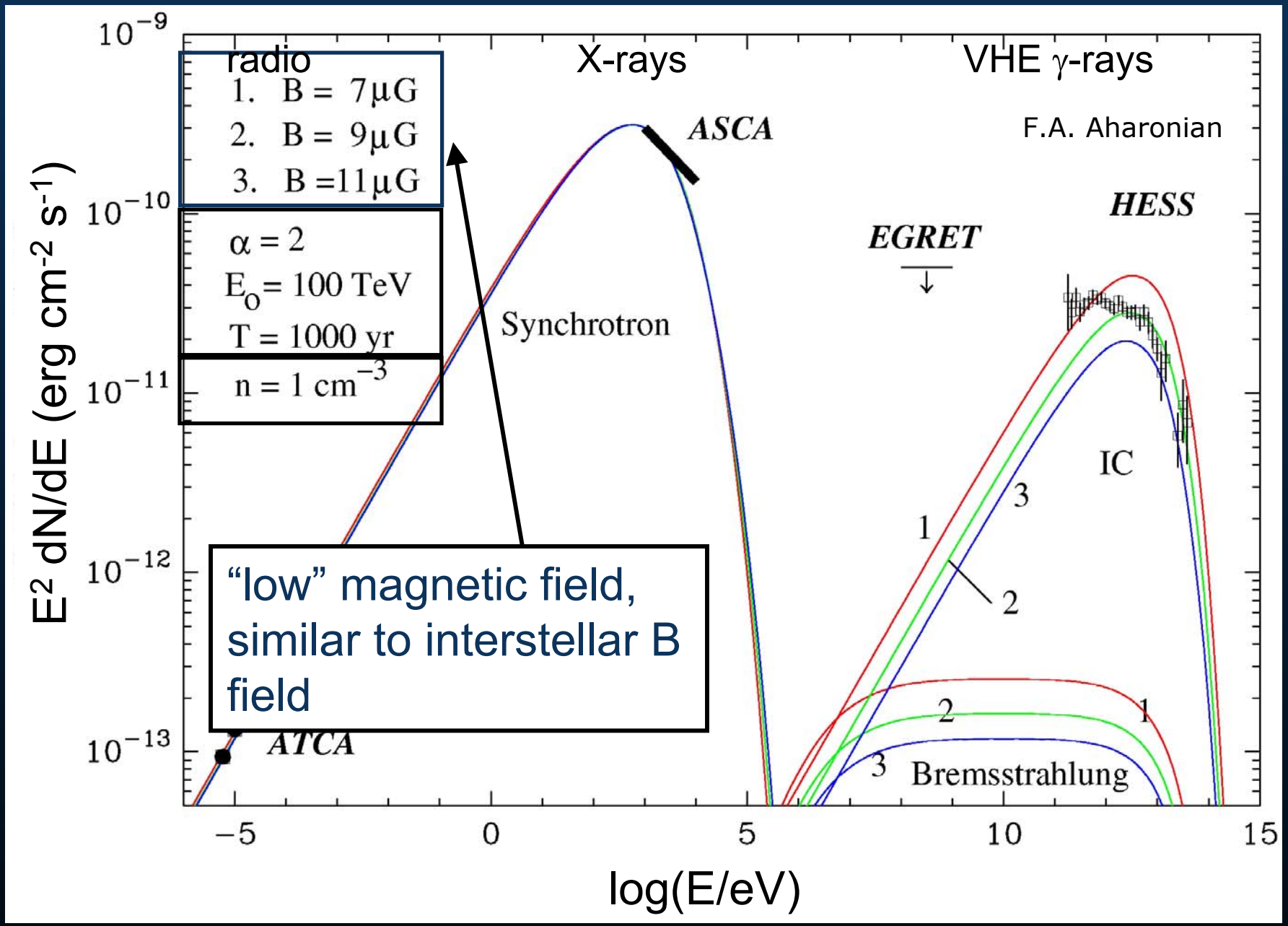




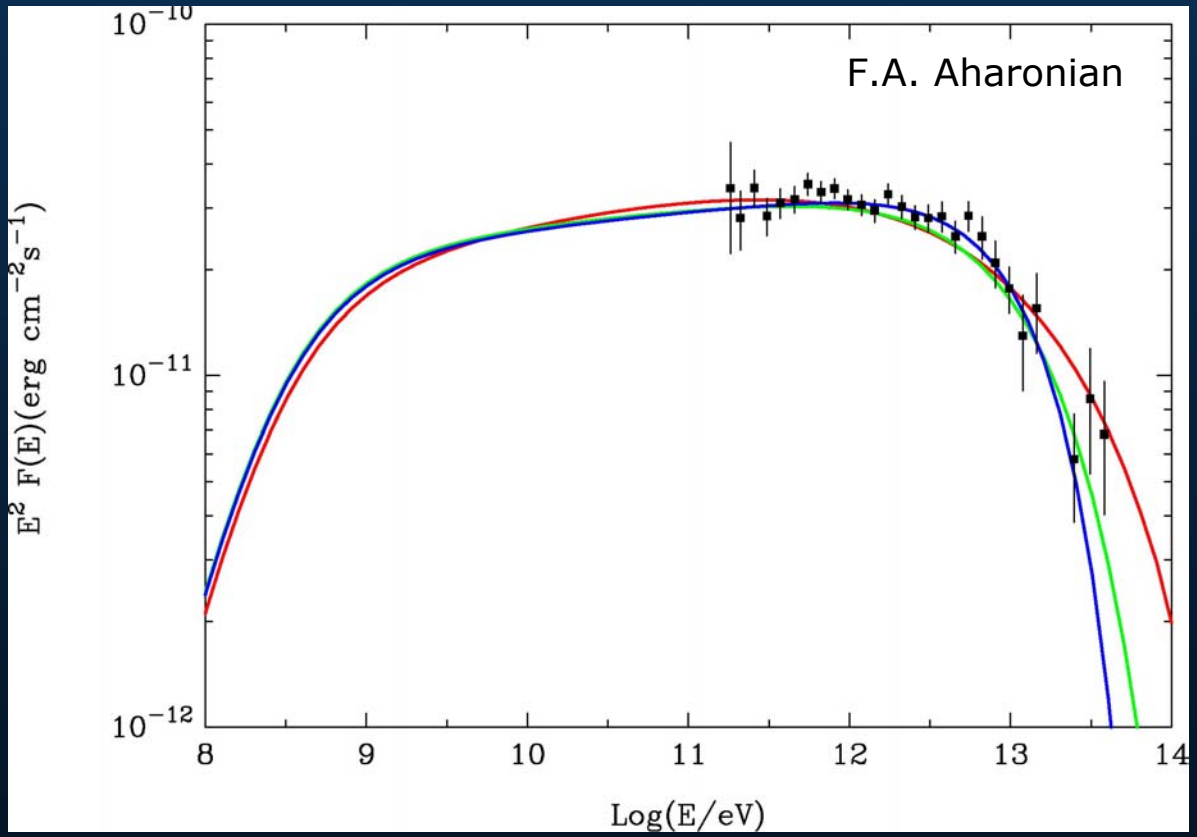


- Detection of 3 shell-type SNRs by H.E.S.S.
- H.E.S.S. limits for 3 other SNRs
  - Tycho, Kepler, SN 1006
- Apparent correlation with X-rays

Electron accelerator

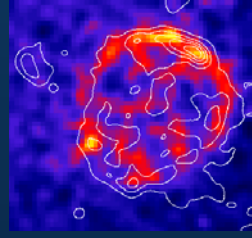


Proton accelerator

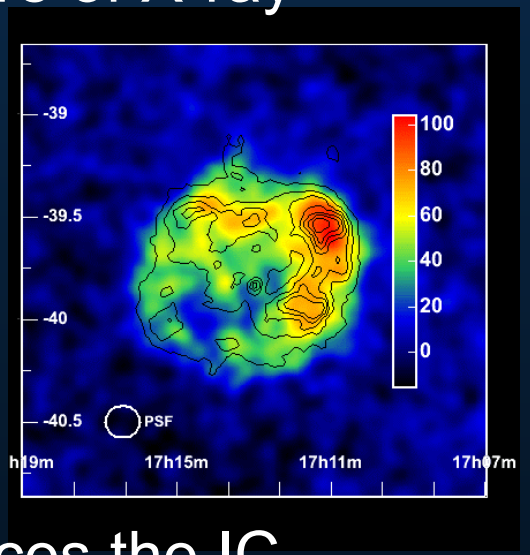


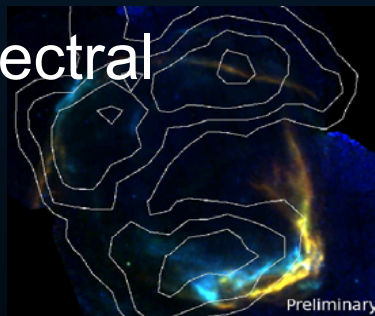
- Continuous proton injection over 1000 years
- Injection spectrum: power law, index ~2
- Different cutoff shapes

Implications



- SNR shock waves accelerate particles to O(100 TeV)
- The low B field found in electronic models is at odds with DSA and probably also with the fine structure of X-ray filaments
- Open questions:
  - Can we judge from so few sources?
  - Are really protons accelerated?
  - Does acceleration efficiency match?
  - Maximum energy consistens with knee?
- Around 100 TeV (where Klein-Nishina reduces the IC efficiency), current IACTs run out of statistics
- GLAST and low-energy IACTs might measure spectral shape < 50 GeV

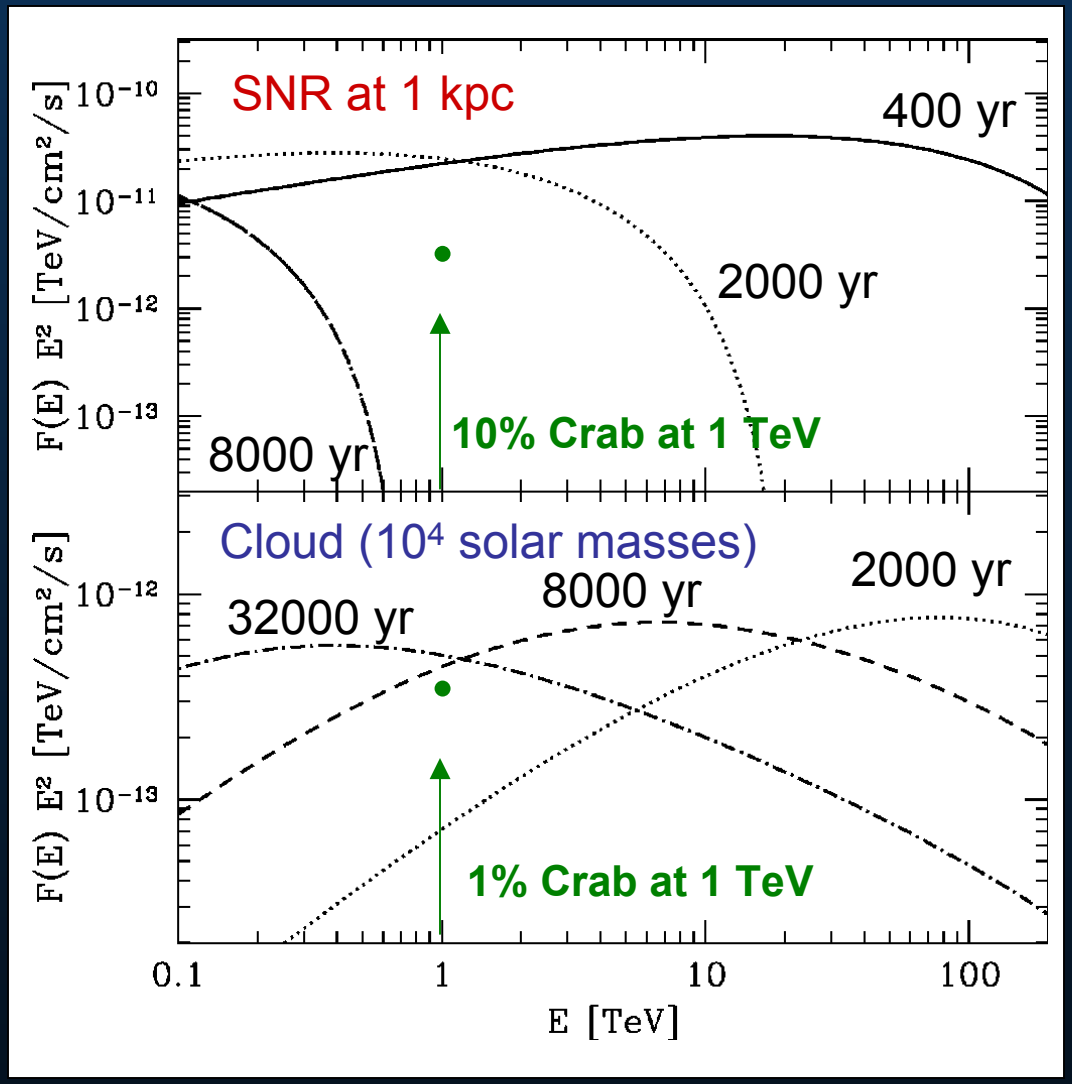




Meanwhile...

- Only relatively young SNRs (up to Sedov phase) can shock-accelerate to particles to PeV energies
- Electrons suffer from stronger energy losses (→gone earlier)
- Neighbouring molecular clouds might be illuminated by escaping protons
- Look for SNR-cloud association and inspect older SNRs

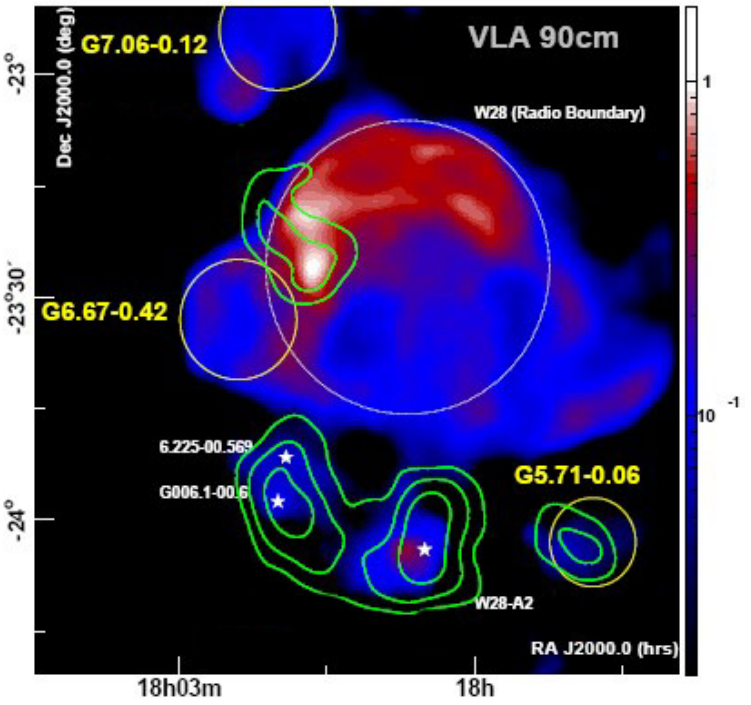
Gabici & Aharonian 2007

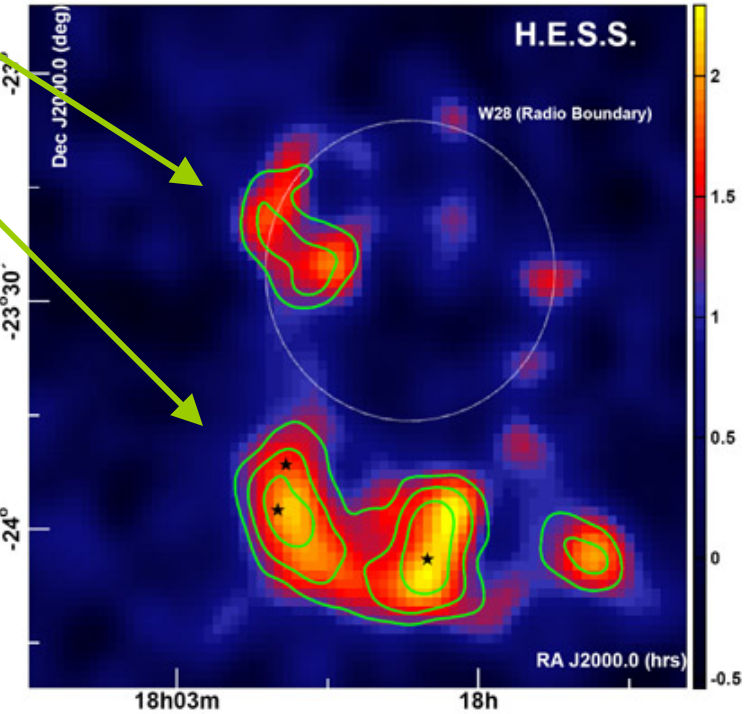


Will discuss two examples... (W28, IC443)

The SNR W28

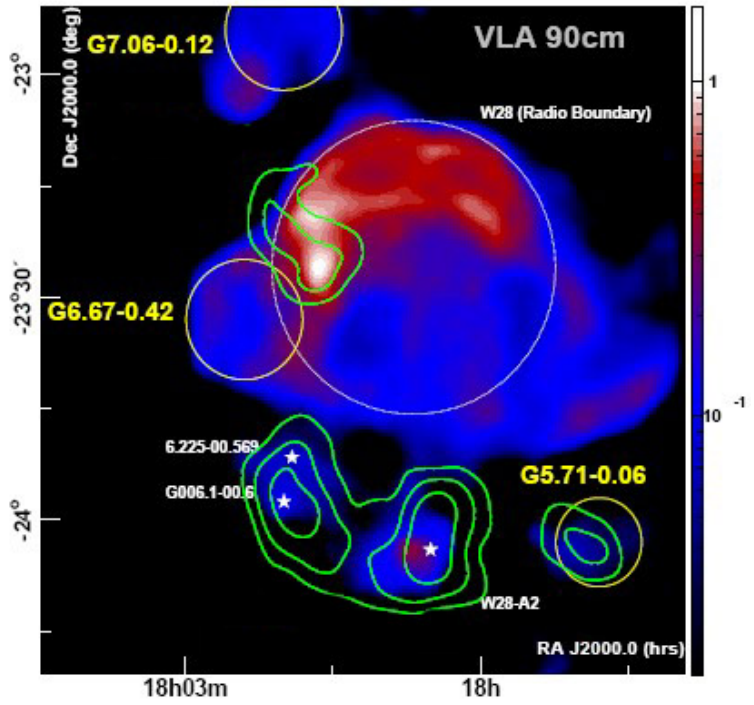
- Rather old SNR (35-150 kyears)
- H.E.S.S. Observations:
  - One source coinciding with shell
  - Sources to the south of W28

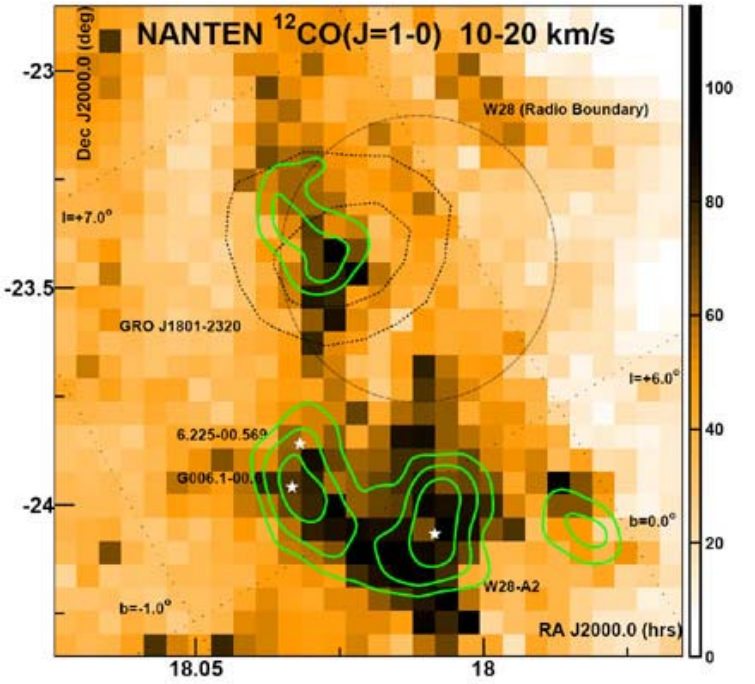


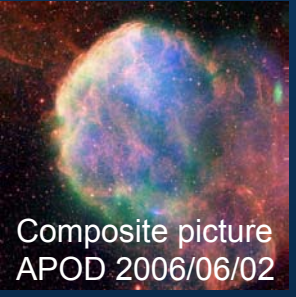


The SNR W28

- Rather old SNR (35-150 kyears)
- H.E.S.S. Observations:
  - One source coinciding with shell
  - Sources to the south of W28
- NANTEN radio observations indicate the presence of molecular clouds at the kinematic distance of W28
- Evident correlation

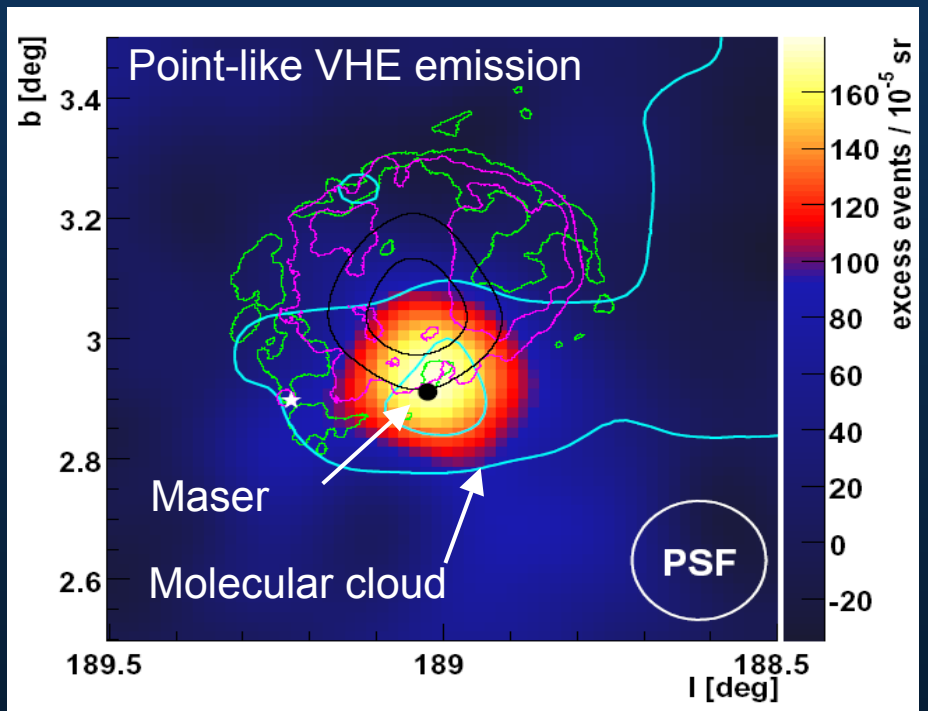


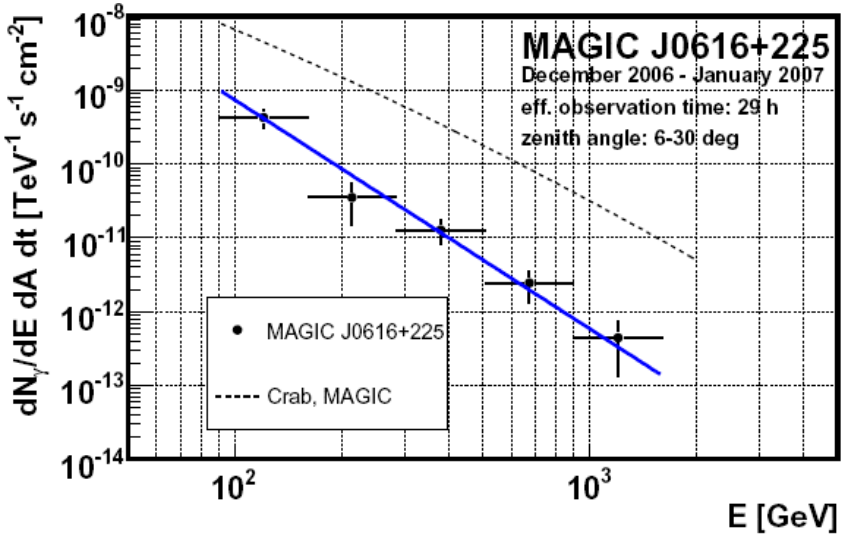




SNR IC 443

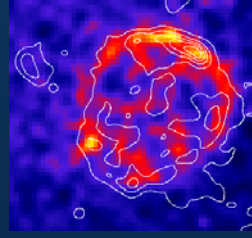
- Asymmetric shell type SNR at 1.5 kpc
- Point-like source MAGIC J0616+225 (~6σ)
- Coincident with maser emission and high-density molecular cloud
- γ-ray emission from π^0 generated in molecular cloud by CRs accelerated in IC443 ?



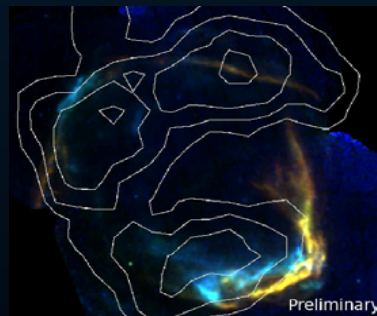


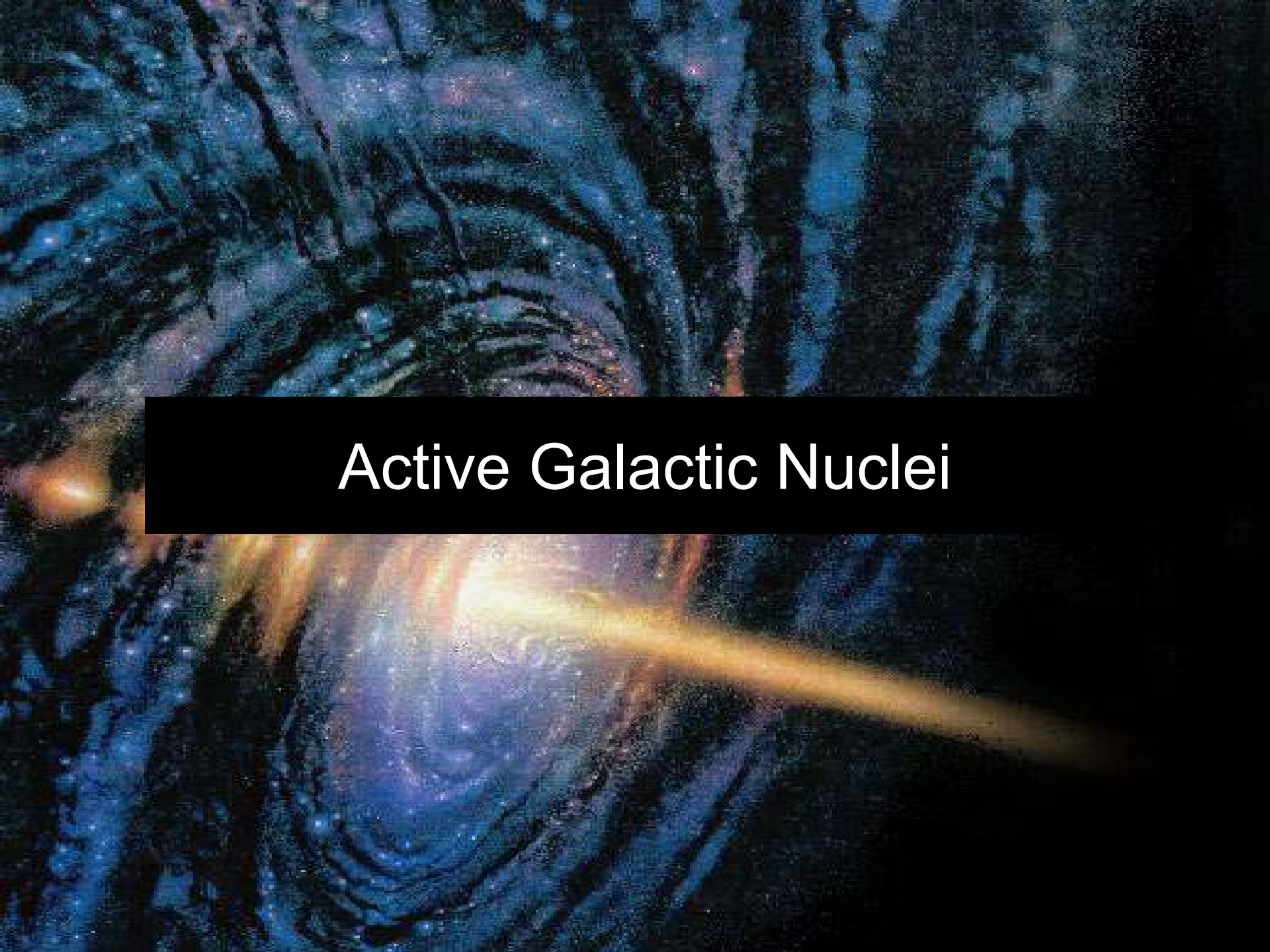
Γ=3.1±0.3, 6.5% Crab above 0.1 TeV

SNR Summary



- Proving the SNR origin of hadronic CRs is a multi-wavelength (radio, X-ray, gamma, VHE gamma) puzzle game!
- There is evidence for SNR-molecular cloud association and generation of π^0 decay photons in older SNRs
- Substantial uncertainties on important parameters (SNR age, distance; matter density) do often not allow to exclude alternative explanations
- Will probably need better instruments for a final answer
  - Wider coverage at lower and higher photon energies for longer lever arm in spectra
  - Better sensitivity to boost source statistics





Active Galactic Nuclei

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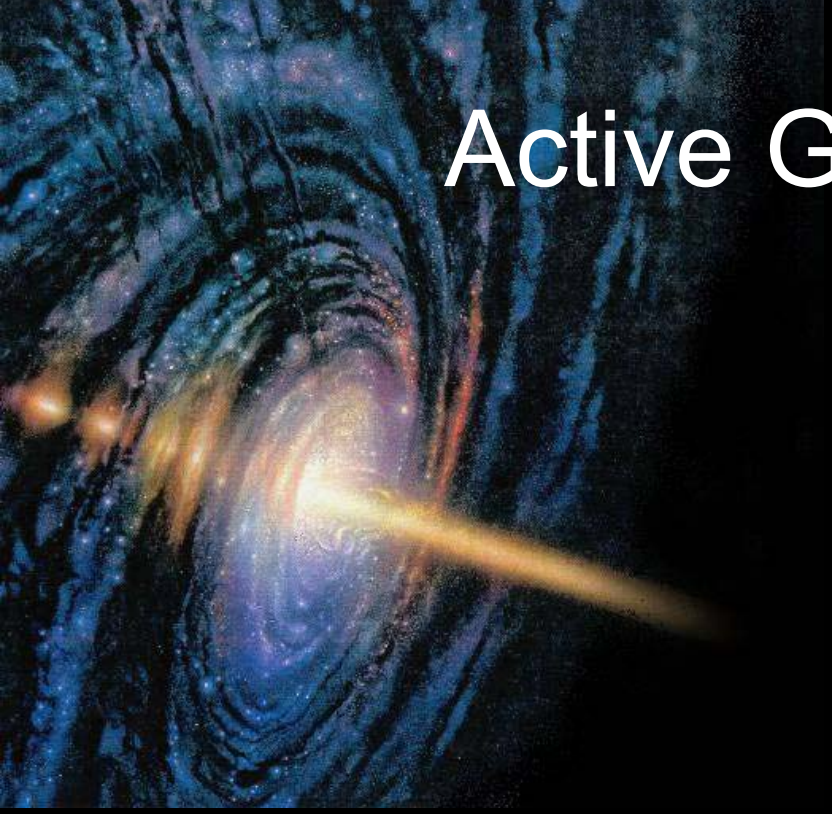


Active Galactic Nuclei

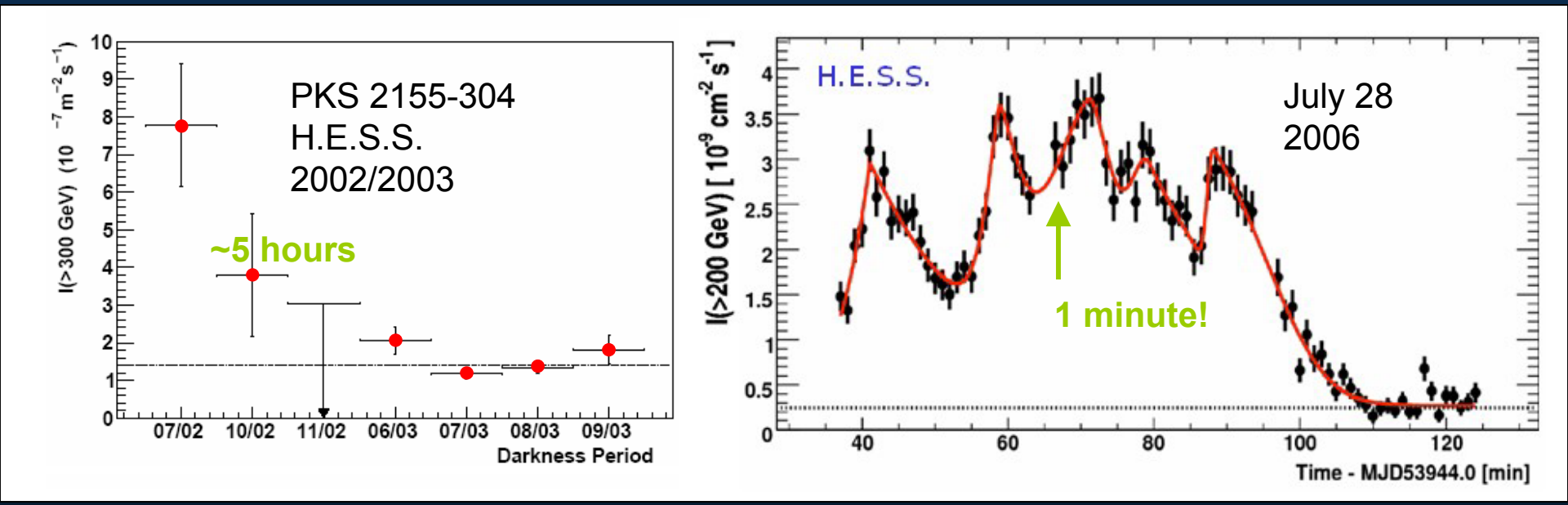
- Supermassive black holes, $M \approx 10^9\, M_\odot$
- Accretion disc with relativistic jet

Blazar: Jet towards Earth

- Doppler-boost of emission $\rightarrow$ High luminosity, TeV γ-radiation

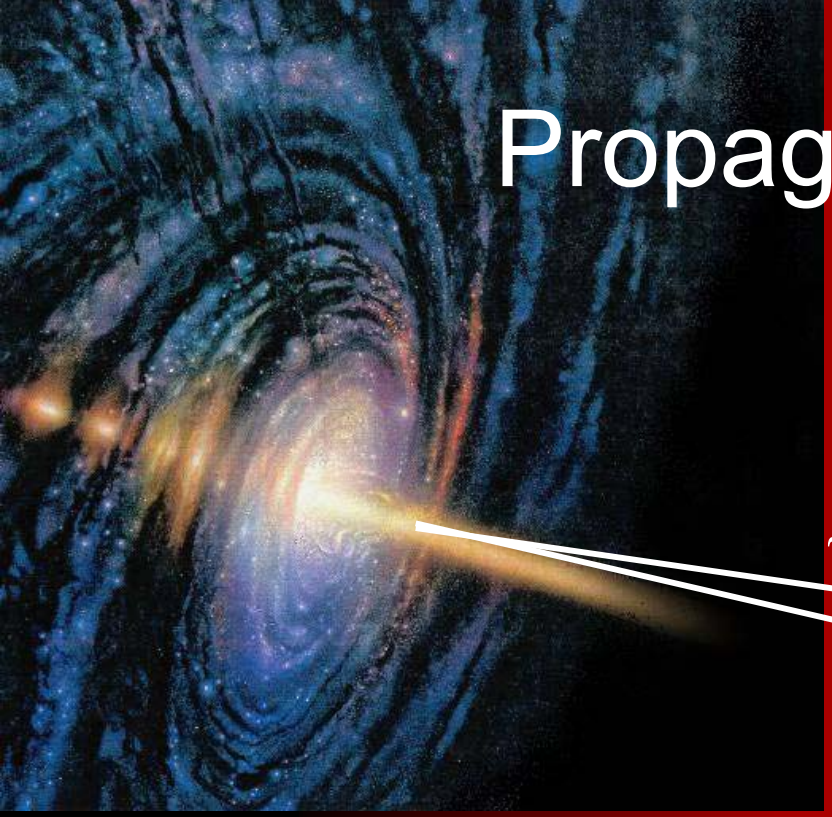
AGN Emission Processes

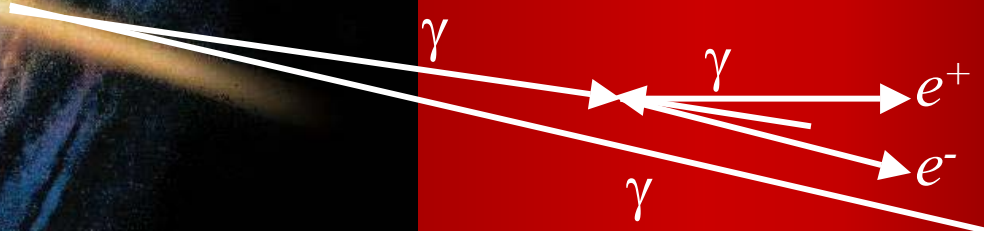
Aharonian et al., ApJ 664 (2007) L71



- Detection of spectacular flares: 15x Crab flux, 100x higher than low-state flux
- Fast rise times (~100 s) limit size of emission region
- Important input for emission scenarios

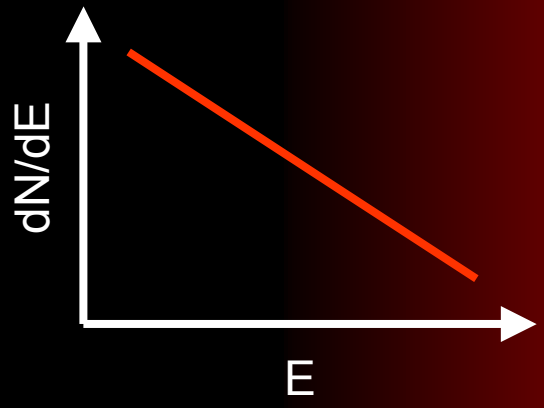
Propagation Effects



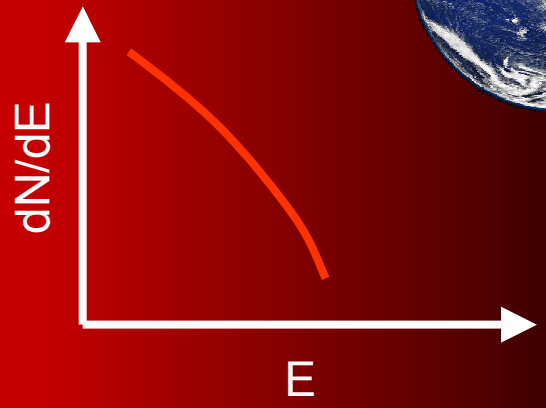


Absorption in extragalactic background light (EGBL)

$\gamma(\text{TeV}) + \gamma(\text{IR}) \rightarrow e^+e^-$

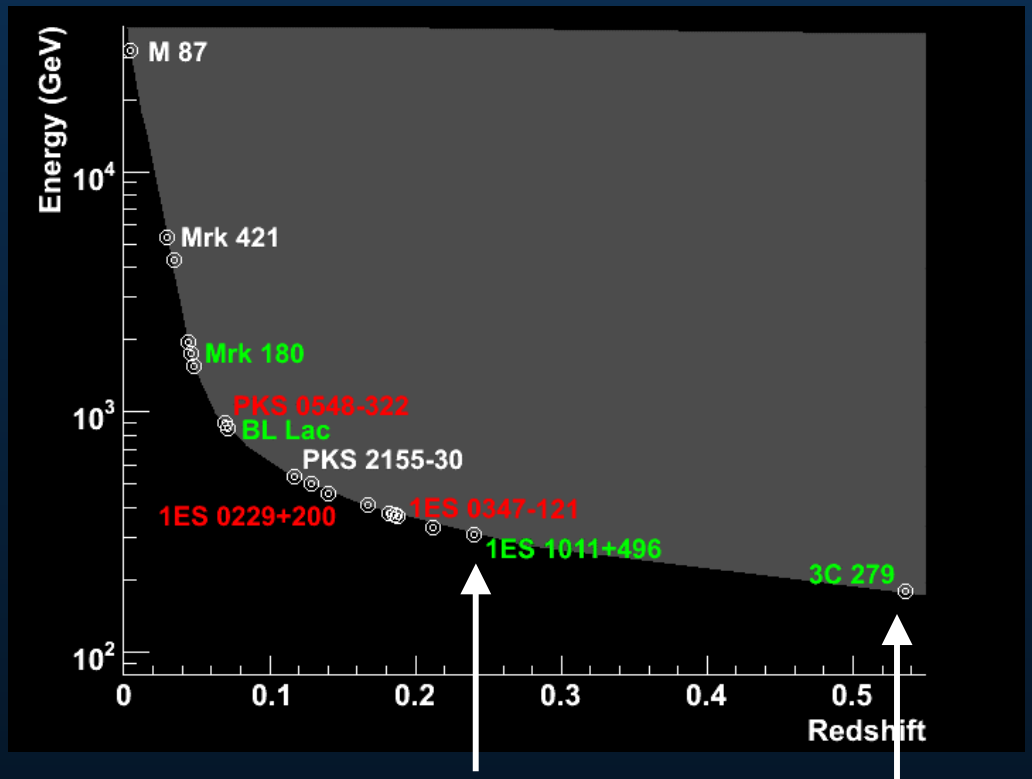


Physics of compact objects and relativistic jets



Study of the EGBL → Cosmology

New AGN at high redshift



1ES1011+496 (z=0.212)

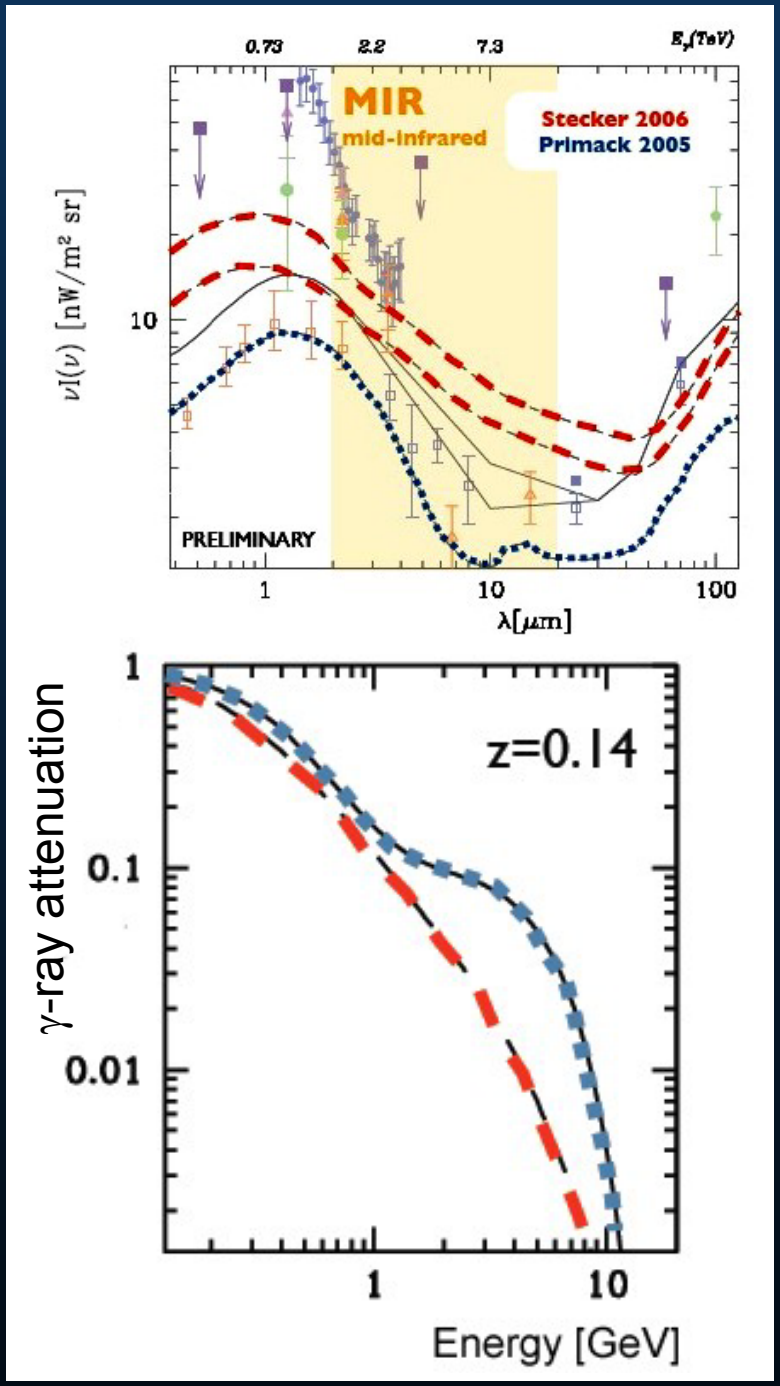
3C279 (z=0.538)

- AGN are being discovered at a rate of O(4 per year)
- Need many AGN at same z to study source effects
- Need AGN at high z where impact of propagation effects is strongest
- Magic detected the two AGN with highest redshift
- Major step in z

Why do we see a source as distant as 3C 279 at all?

EGBL limits

- Measured AGN spectra + cosmological model + assumption on intrinsic spectra = Test of cosmological model
- New AGN discovered by H.E.S.S. (1ES 0229+200, z=0.14)
- Spectrum indicates that Universe is more transparent in the 2-20 μm window
- Disfavours models with high mid-IR flux
- High-z sources will impose stronger constraints!



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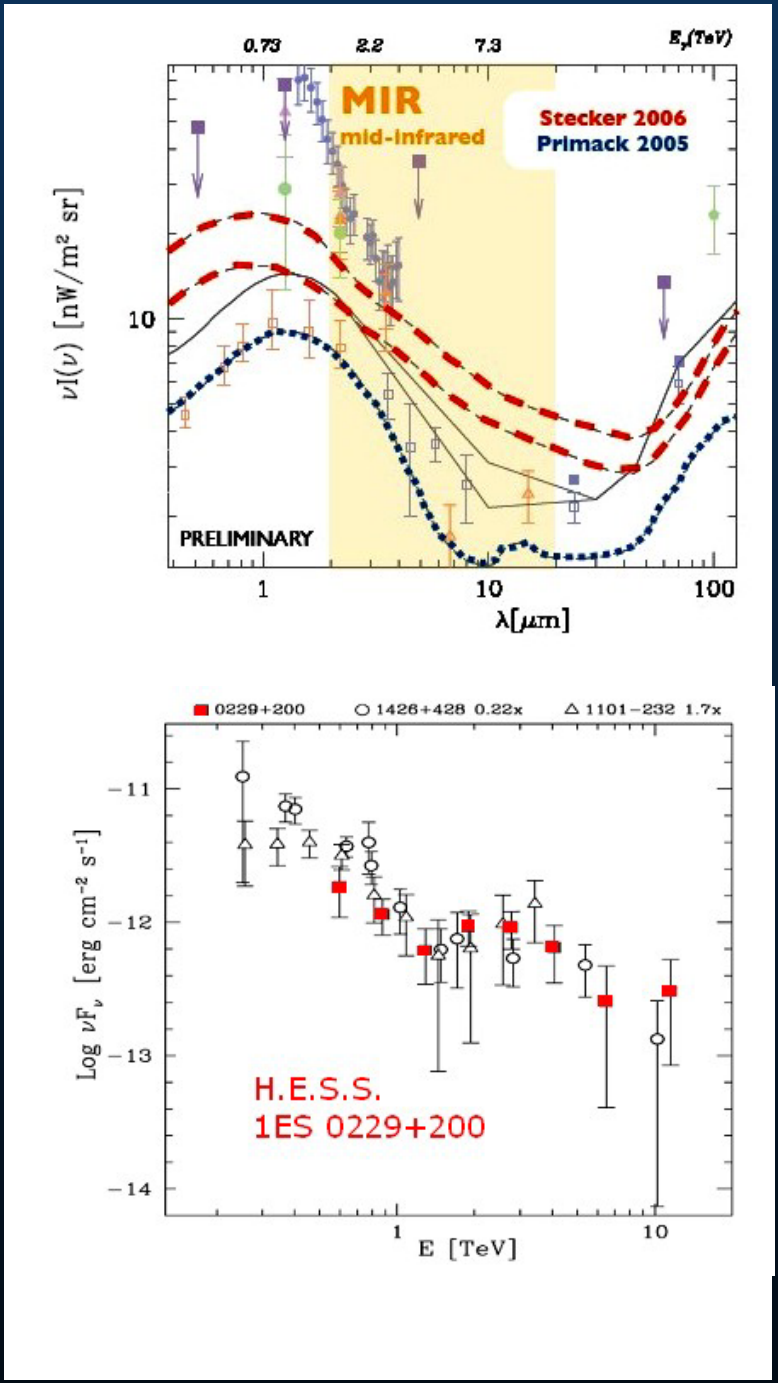


Summary

- H.E.S.S., MAGIC and VERITAS are running for source number 100; regular observations between 60 GeV and some 10 TeV at few % Crab sensitivity
- A picture of the Milky Way in VHE gamma-rays is emerging
- There is quite some evidence for SNRs as cosmic-ray sources
- VHE gamma-ray astronomy addresses fundamental questions ranging from electrodynamics (pulsar magnetospheres) to cosmology (AGN)
- Expect a lot from overlap with GLAST and studies of the AUGER anisotropies

Outlook

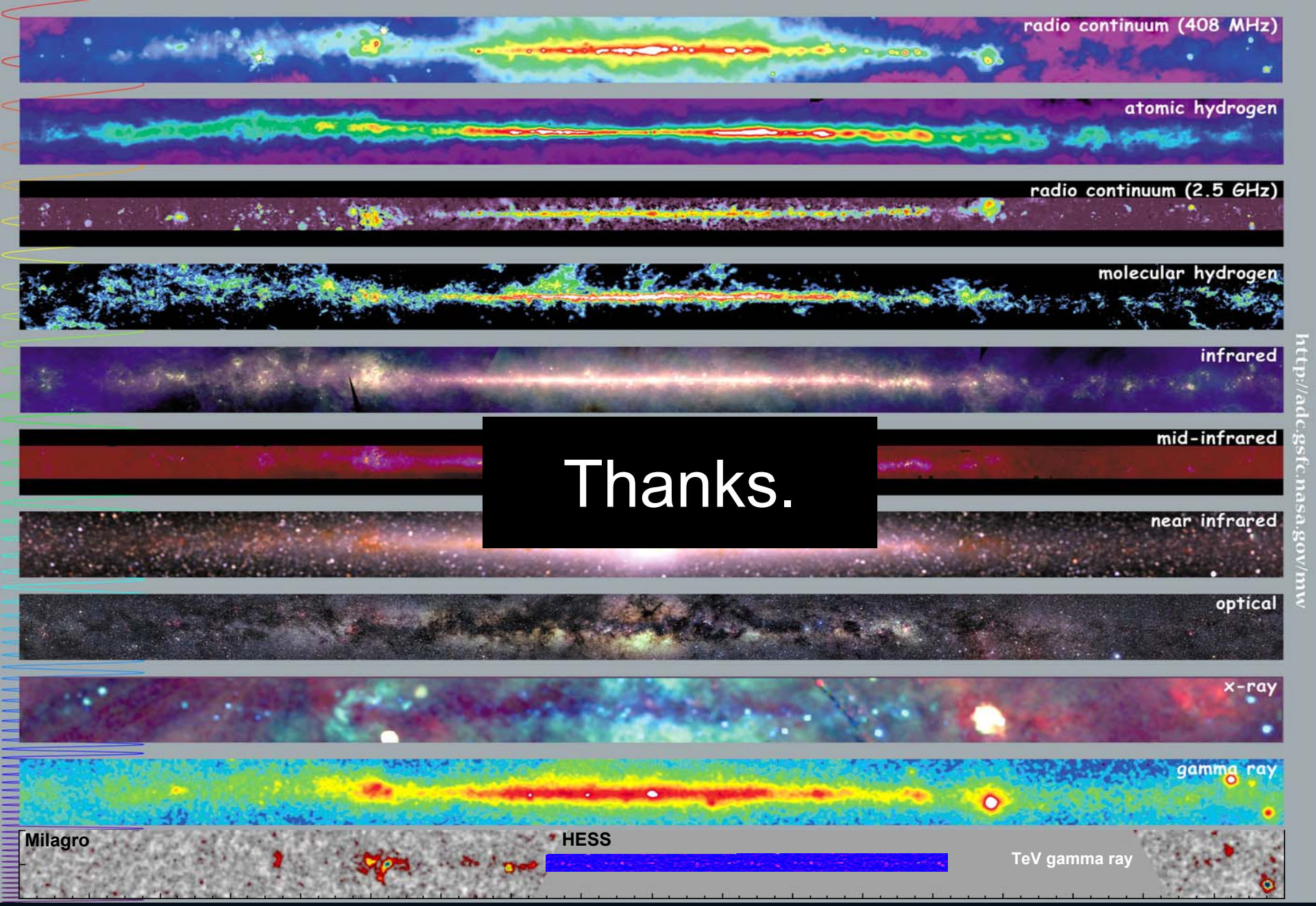
H.E.S.S. II
Mid 2009
→ Lower threshold (~25 GeV)

(montage)

MAGIC II
Inauguration Sep 21, 2008
→ stereoscopic

(Feb 2008)

- Longer-term future (>2010)
  - CTA Observatory (factor 10 in sensitivity)
  - AGIS
  - HAWC (10-15x more sensitive than Milagro)



Thanks.

VHE γ-rays have opened a new window on the sky!