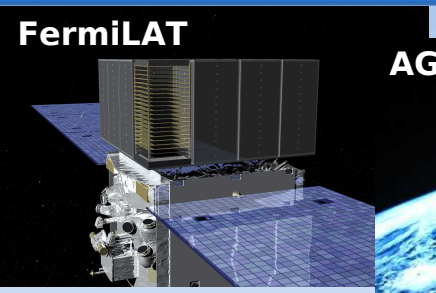
High-Energy Gamma Rays

M. Punch

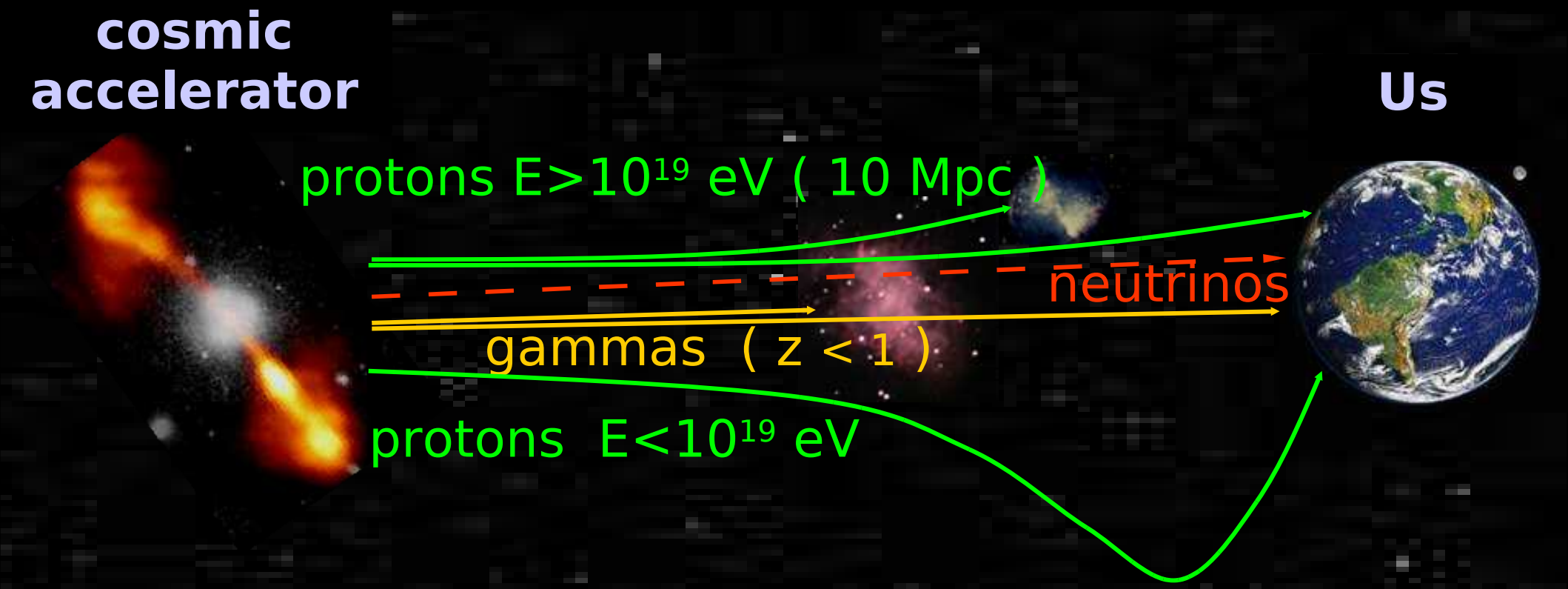
APC – CNRS/IN2P3

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

The Gamma-ray World



Multi-messenger observations of the Cosmos



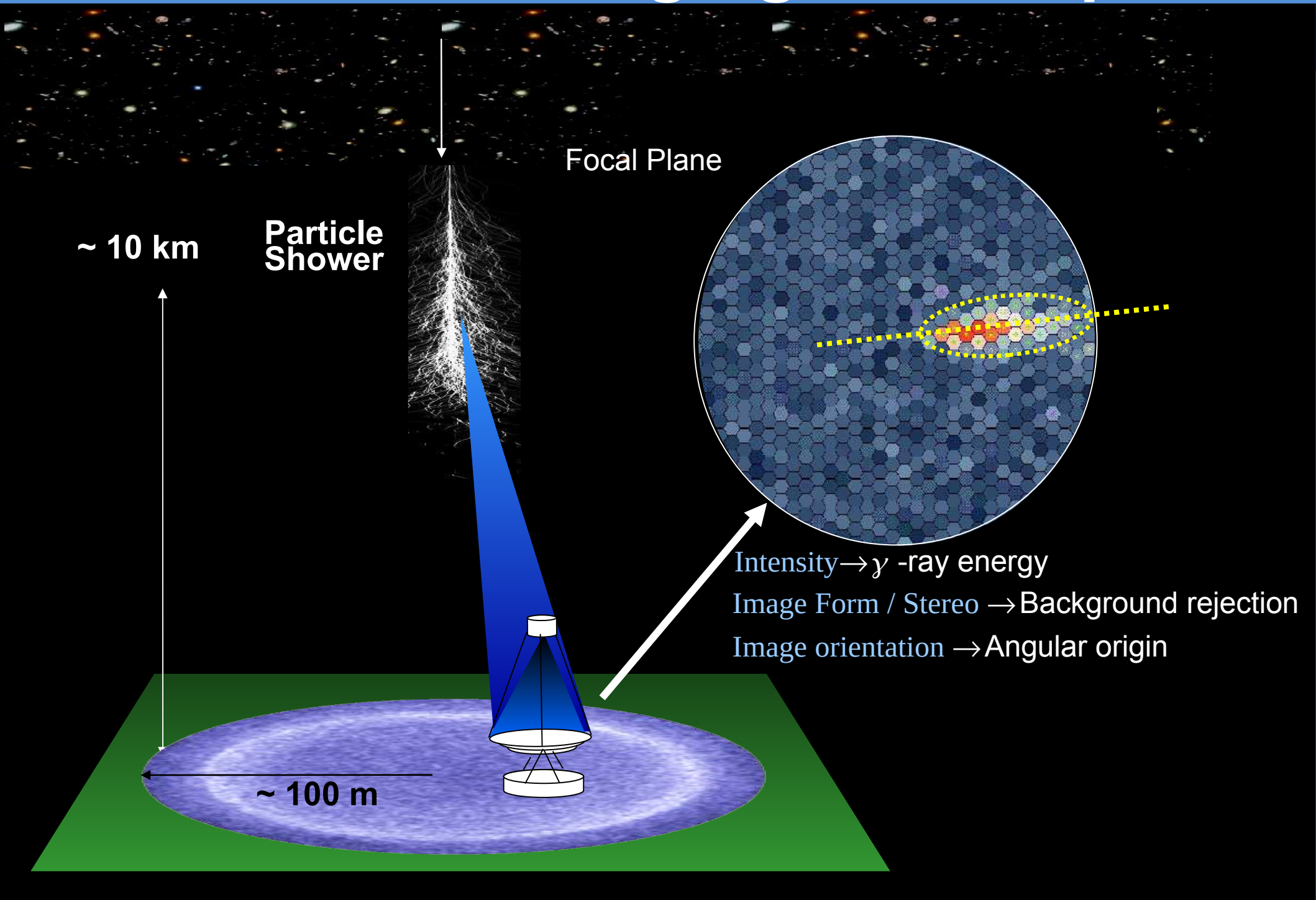
protons/nuclei: Deviated by magnetic fields, Absorbed by radiation field (GZK)

photons: Absorbed by dust & radiation field (CMB)

neutrinos: Difficult to detect

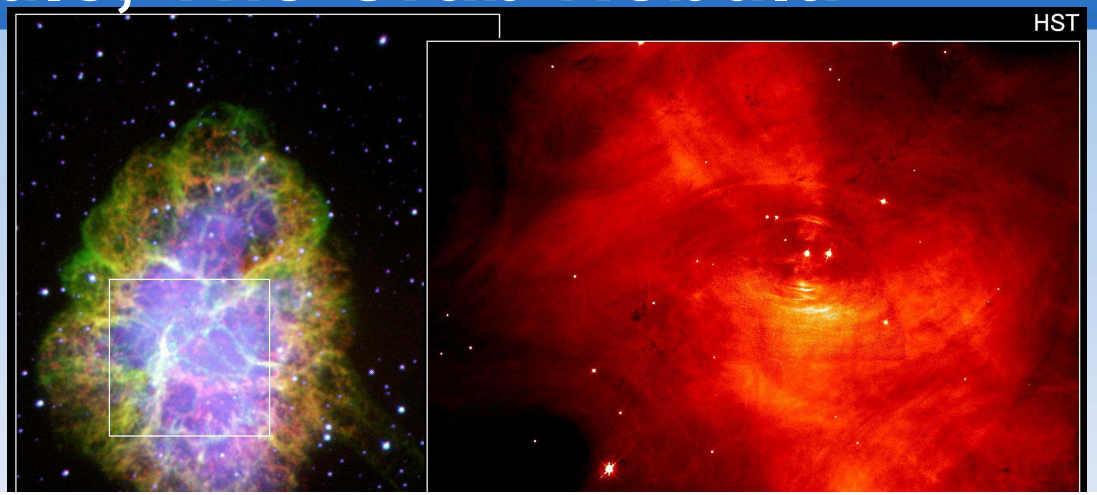
⇒ **Three "astronomies" possible...**

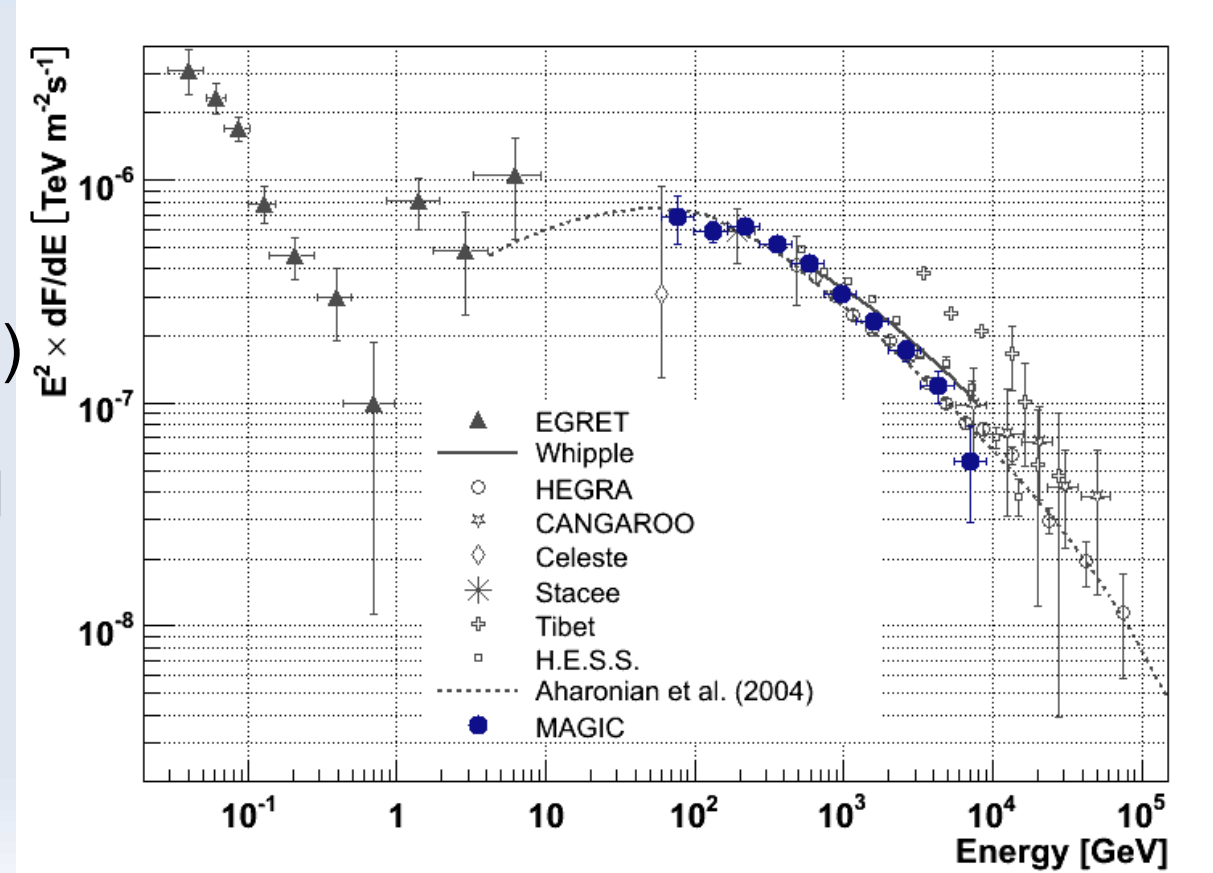
Cherenkov Imaging Technique



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)
  - ~2 σ in 50 days
  - First spectrum from ASM
- ARGO YBJ
  - 5 σ in 50 days





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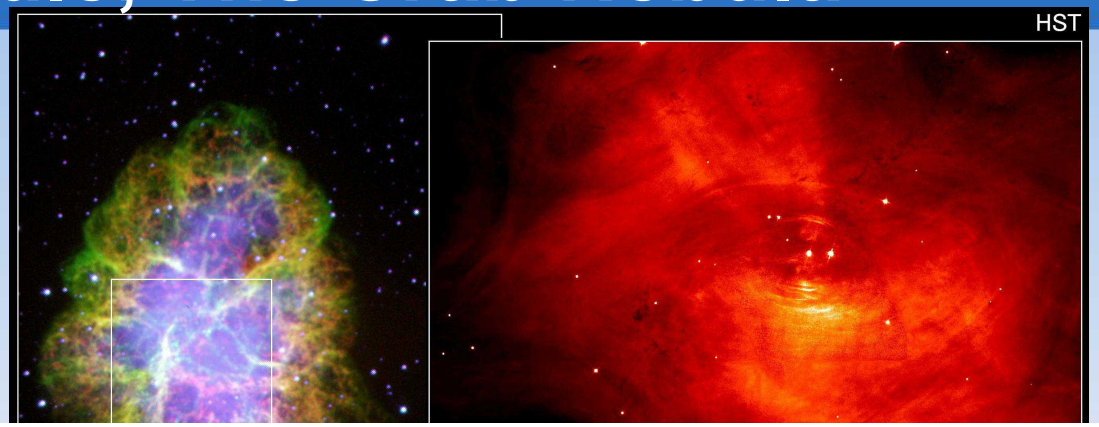
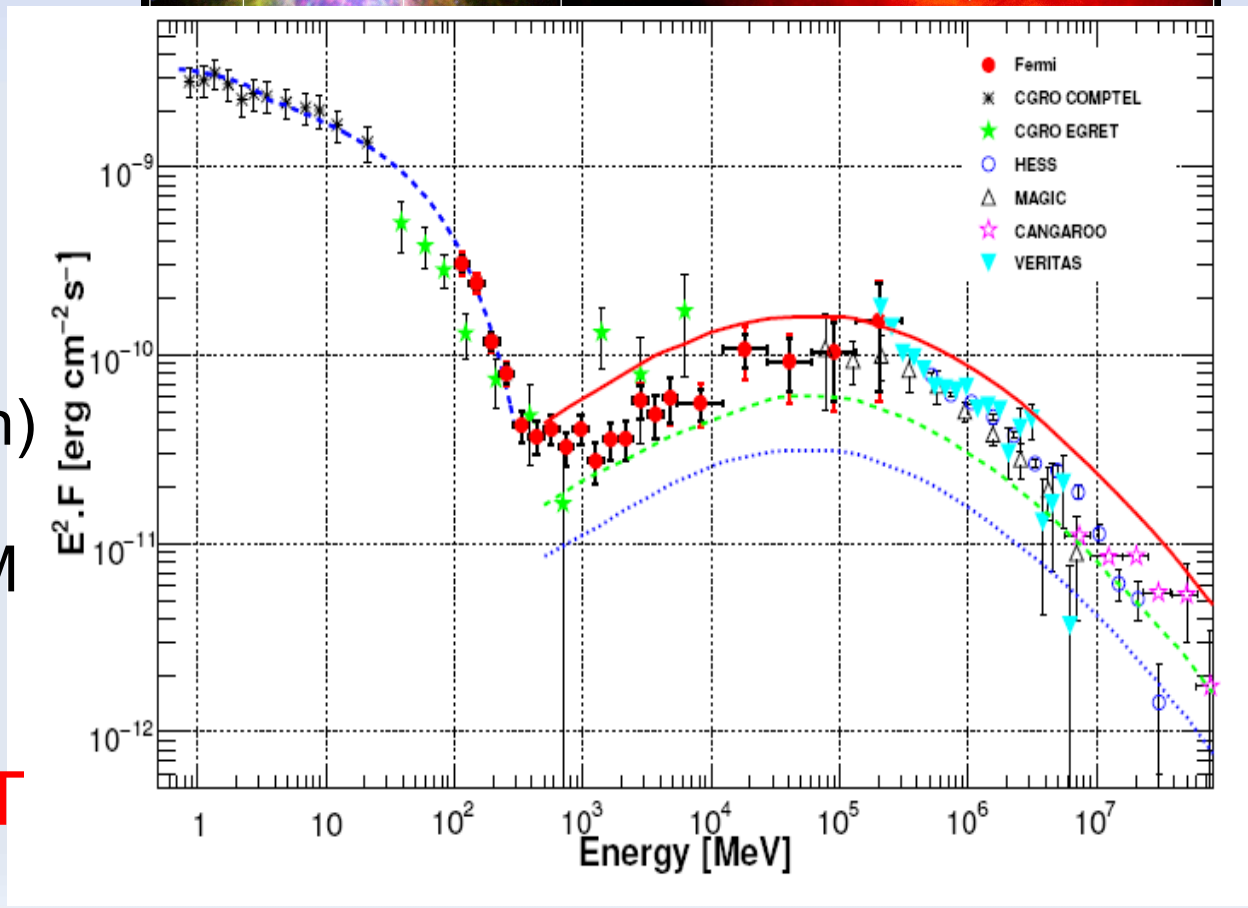
- Updated with Fermi LAT





Latest Satellite Detector: FermiLAT

Anticoincidence Detector:

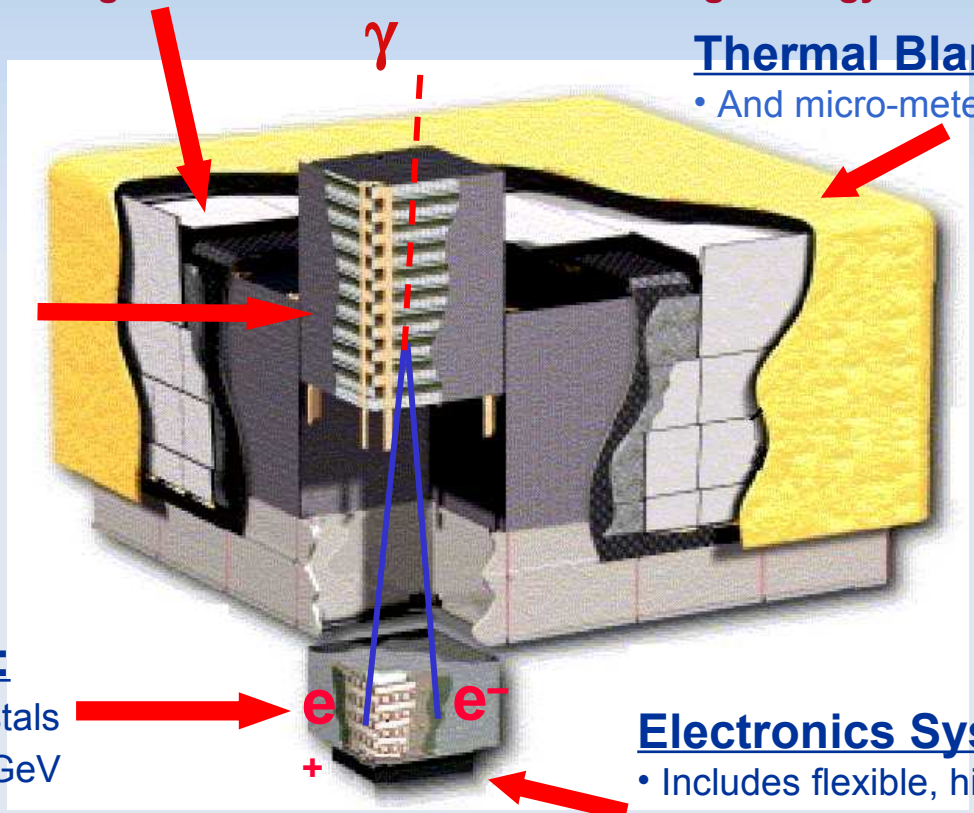
- 89 scintillator tiles
- **First step in reduction of large charged cosmic ray background**
- **Segmentation reduces self veto at high energy**

Thermal Blanket:

- And micro-meteorite shield

Overall LAT Design:

- 4x4 array of identical towers
- 3000 kg, 650 W (allocation)
- 1.8 m × 1.8 m × 1.0 m
- **20 MeV → 300 GeV**



Hodoscopic CsI Calorimeter:

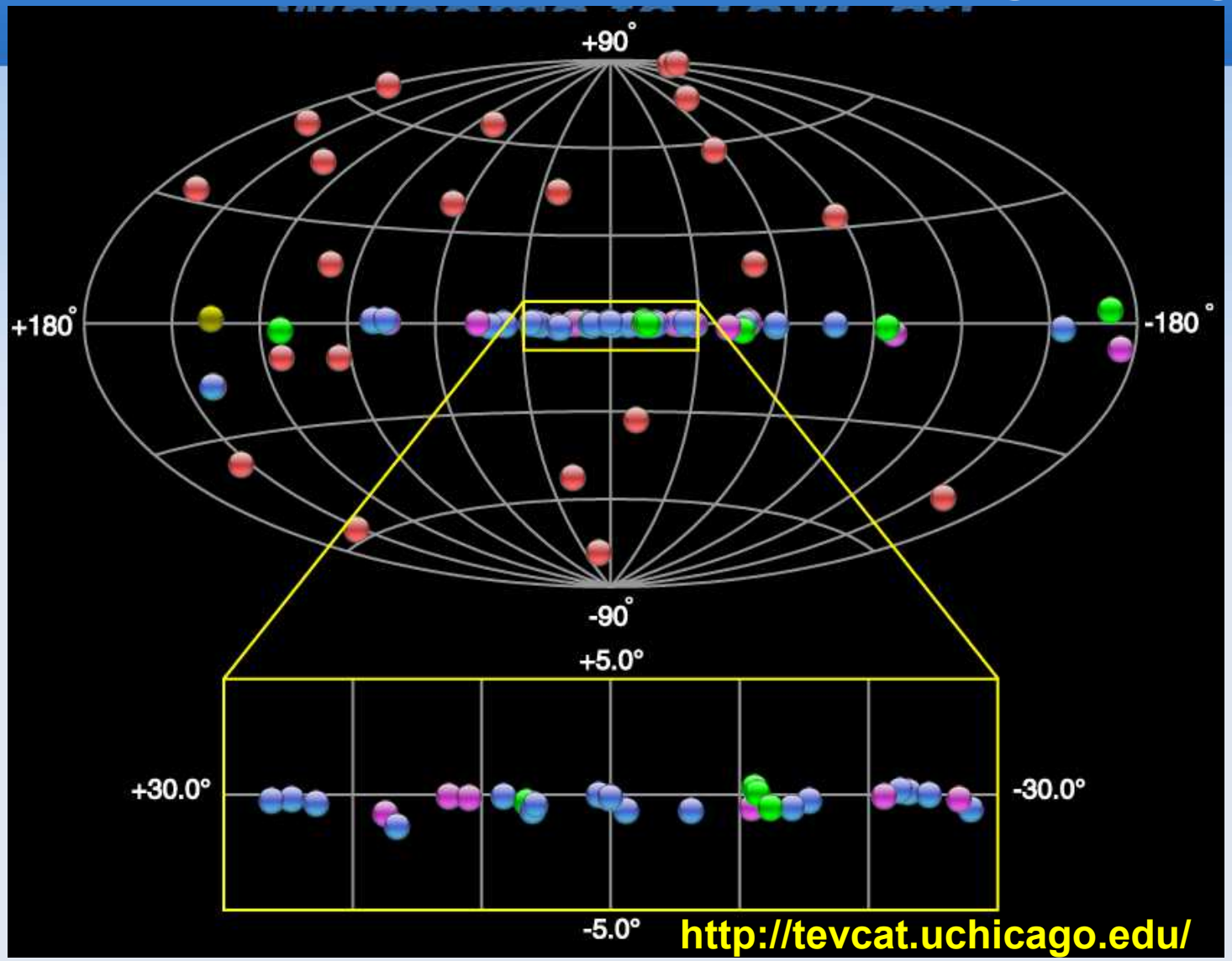
- Segmented array of 1536 CsI(Tl) crystals
- 8.5 X0: shower max contained <100 GeV
- **Measures the incident gamma energy**
- **Rejects cosmic ray backgrounds**

Electronics System:

- Includes flexible, highly-efficient, multi-level trigger

Launched 11 June 2008!

The VHE Gamma-Ray Sky



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

  Today > 60 published sources

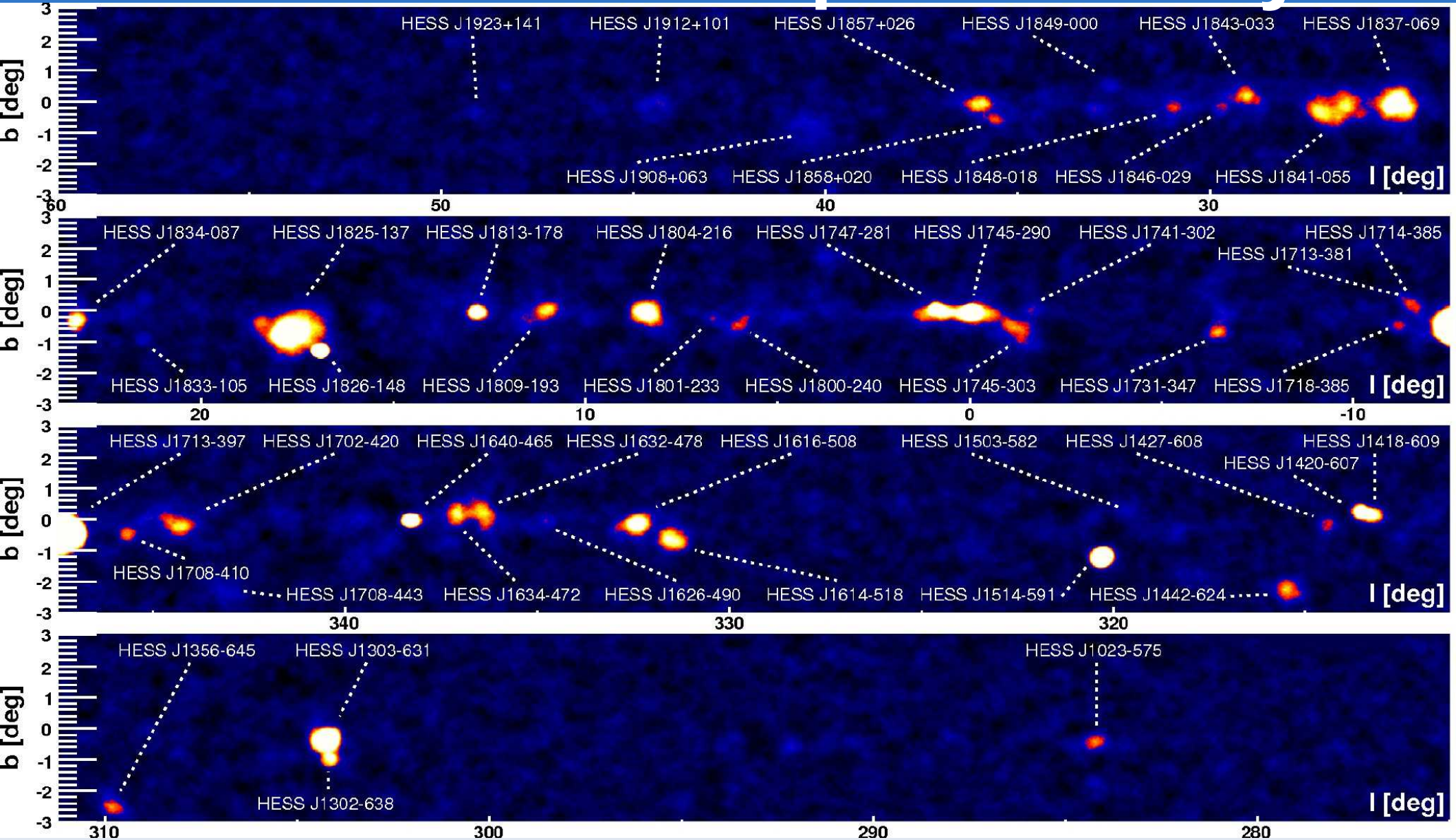
  SNRs, AGNs, Binaries, PWNs, WR, Starburst, UFOs...

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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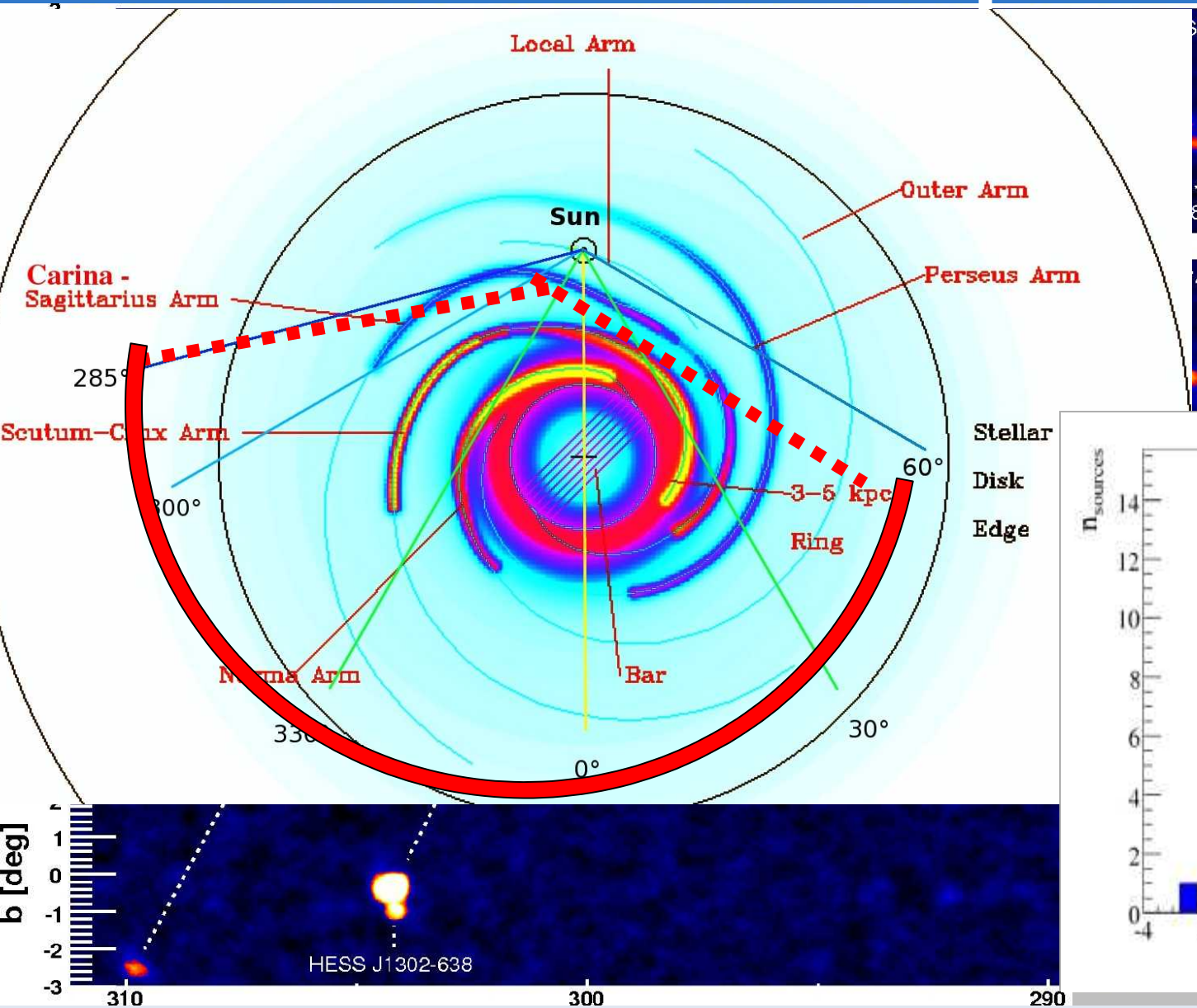

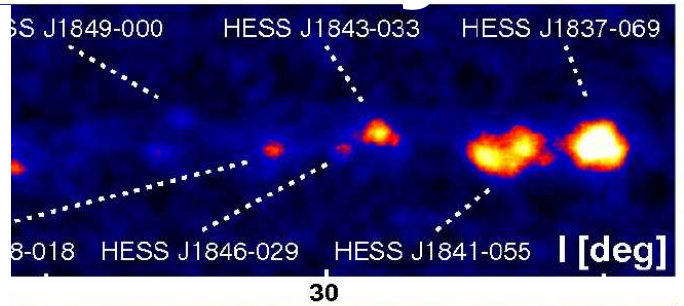

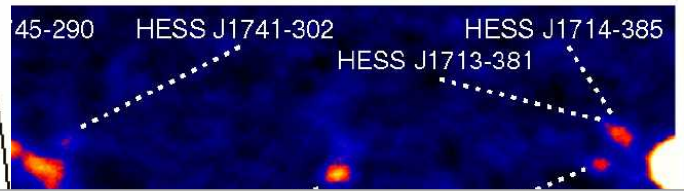

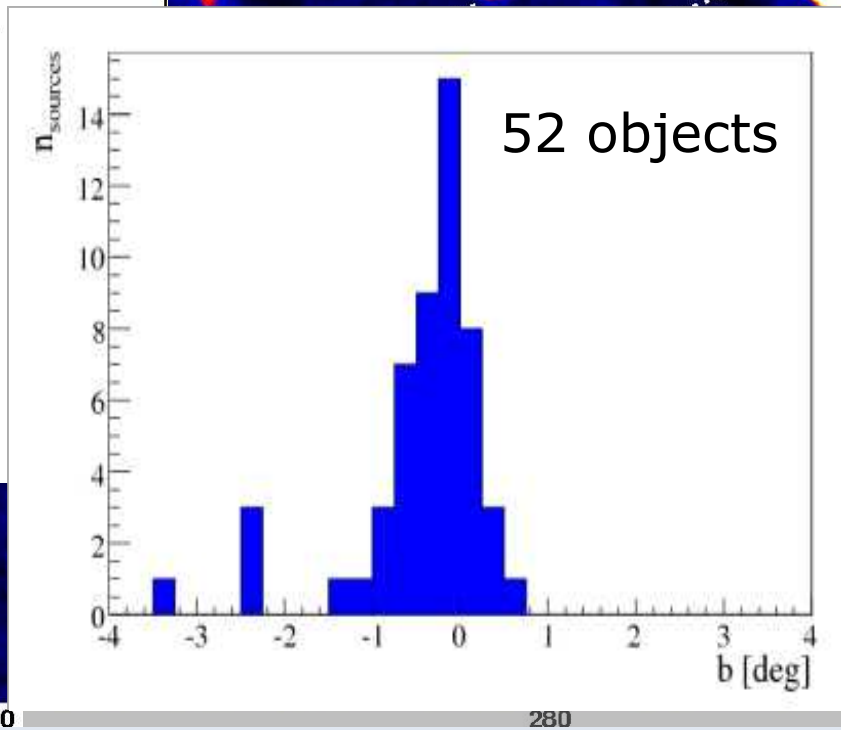

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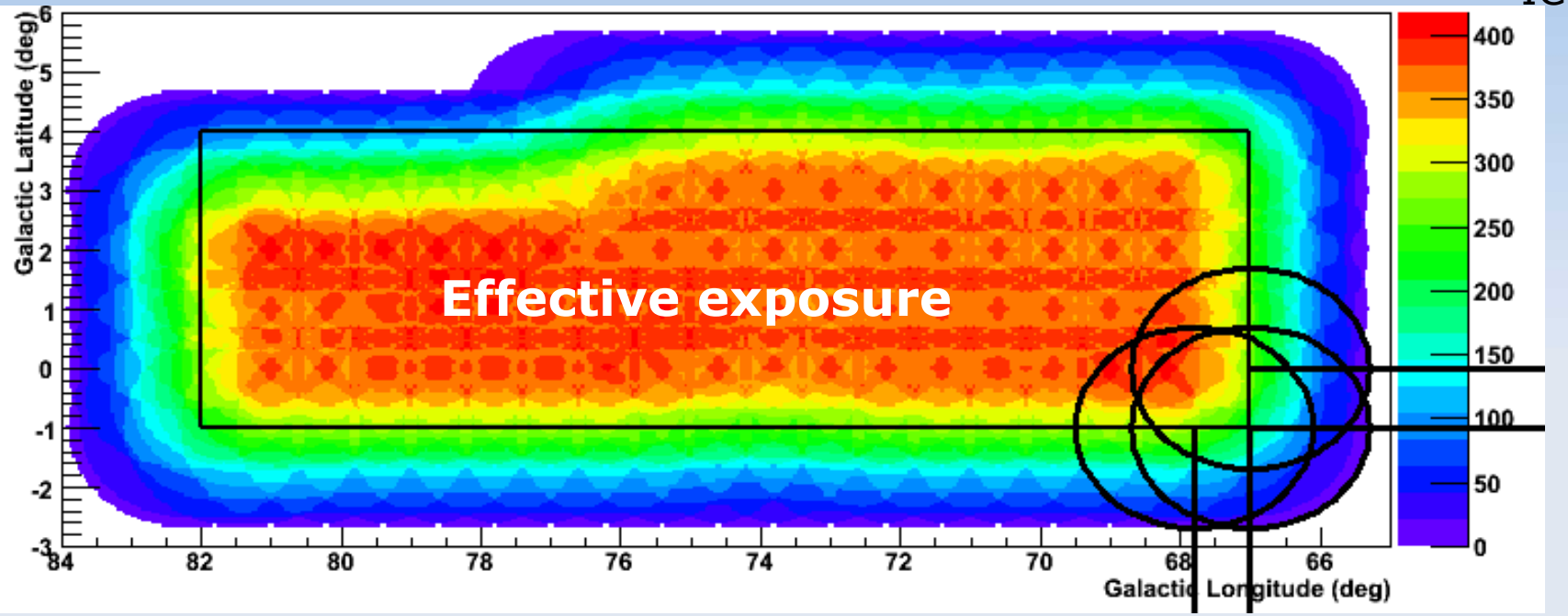
VERITAS survey of Cygnus region

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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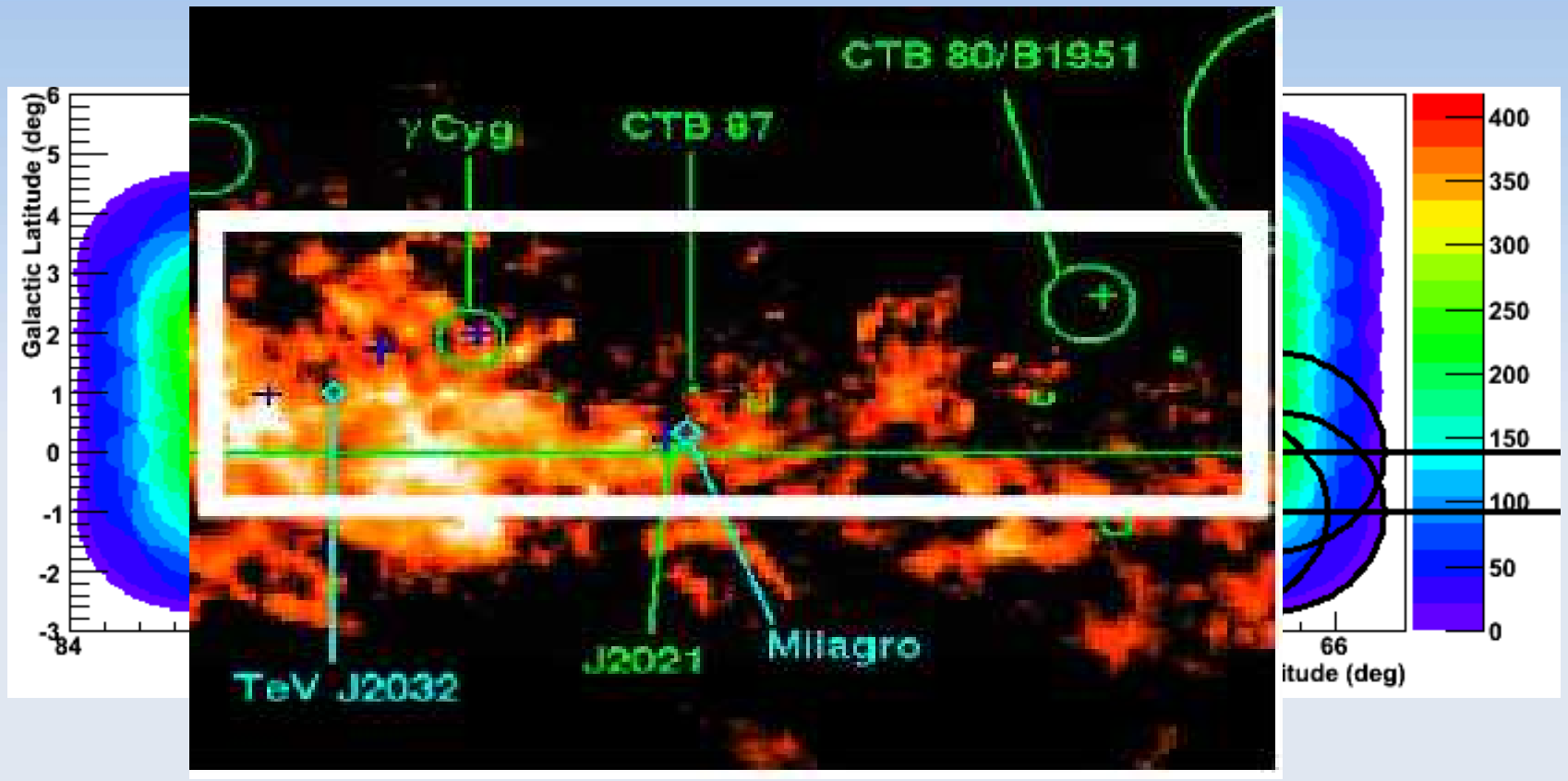

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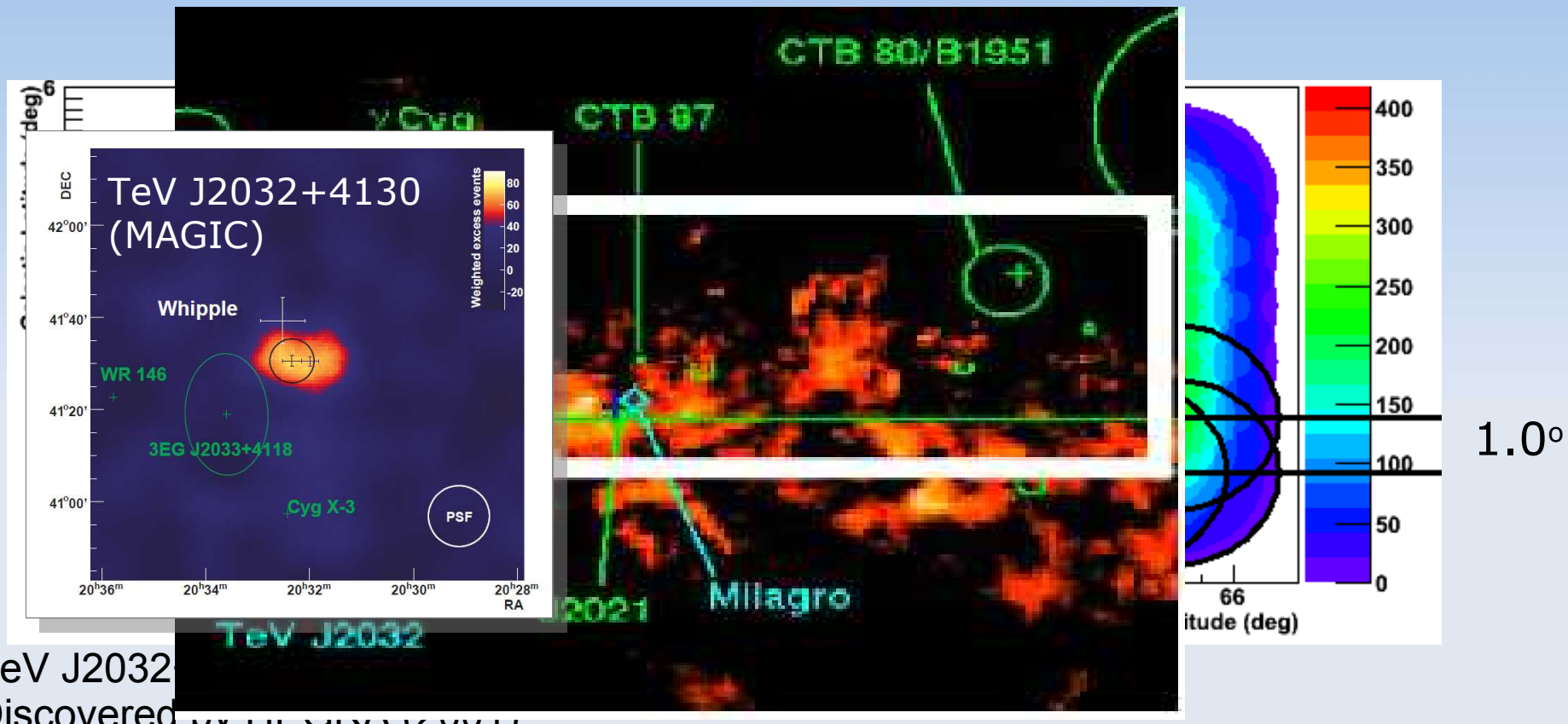

TeV J2032
Discovered by HEGRA (2001)
Confirmed by H.E.S.S./MAGIC

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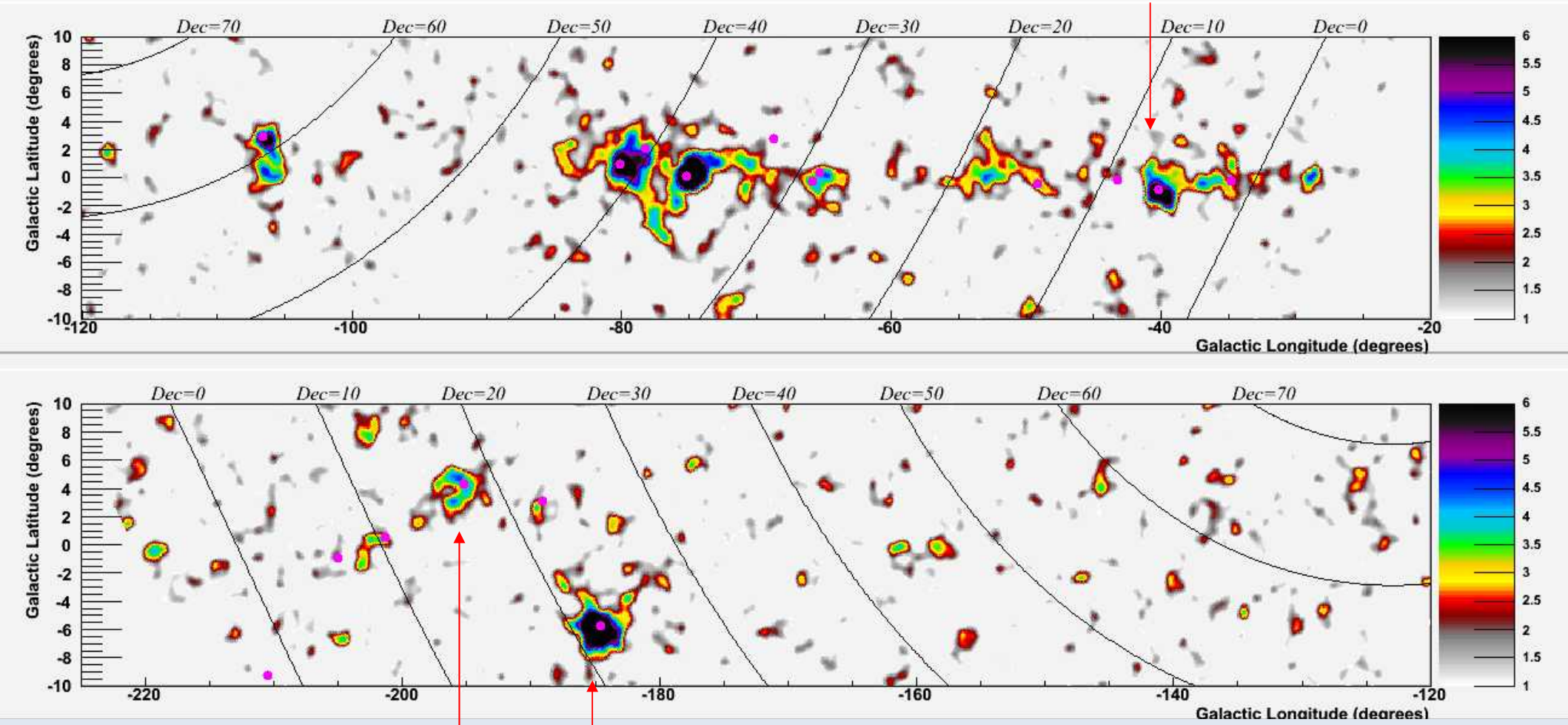
MILAGRO survey, Northern sky

Cygnus region

J1908+06

B. Dingus



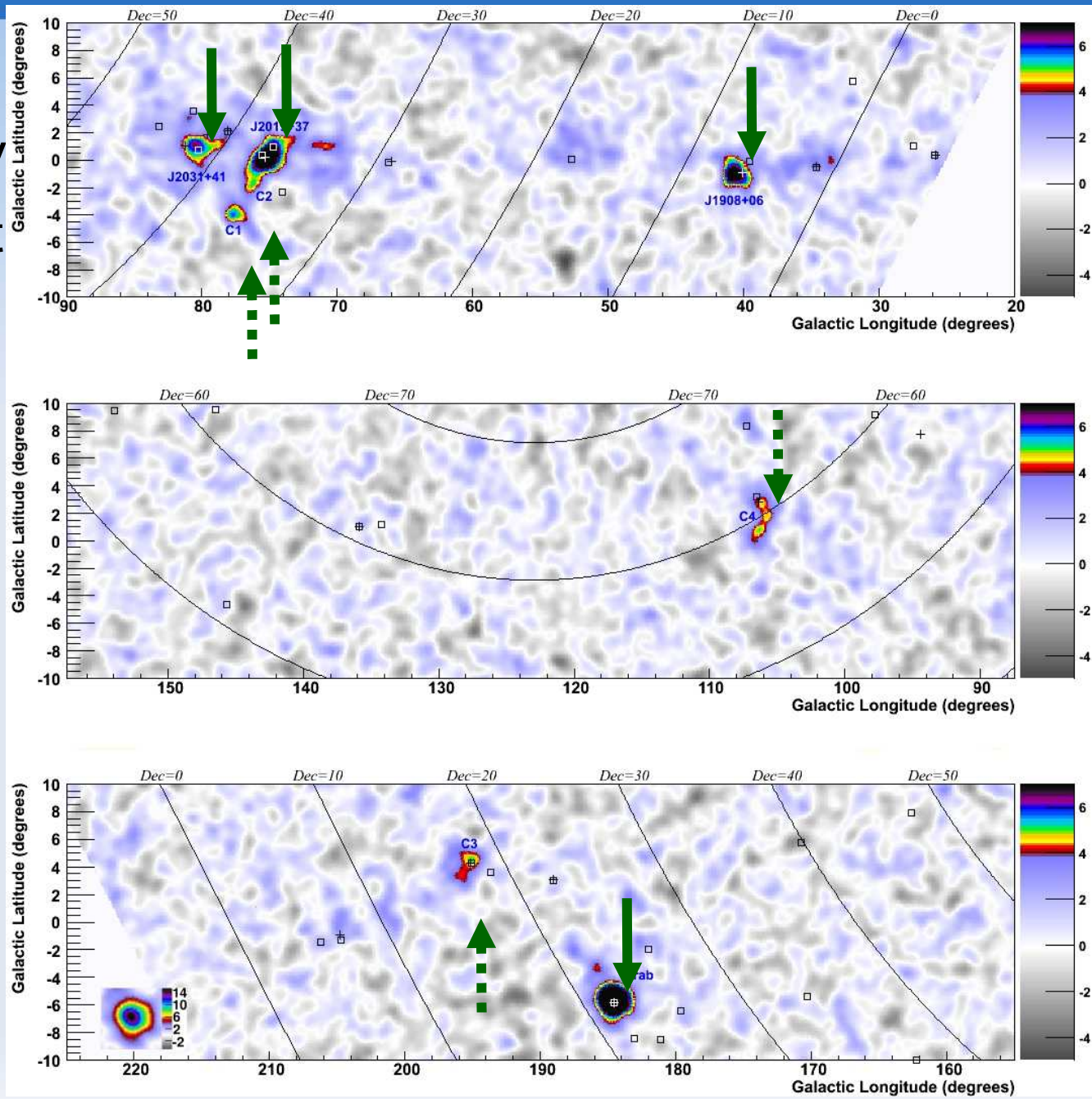
Geminga

Crab

Energy range ~5 … 100 TeV

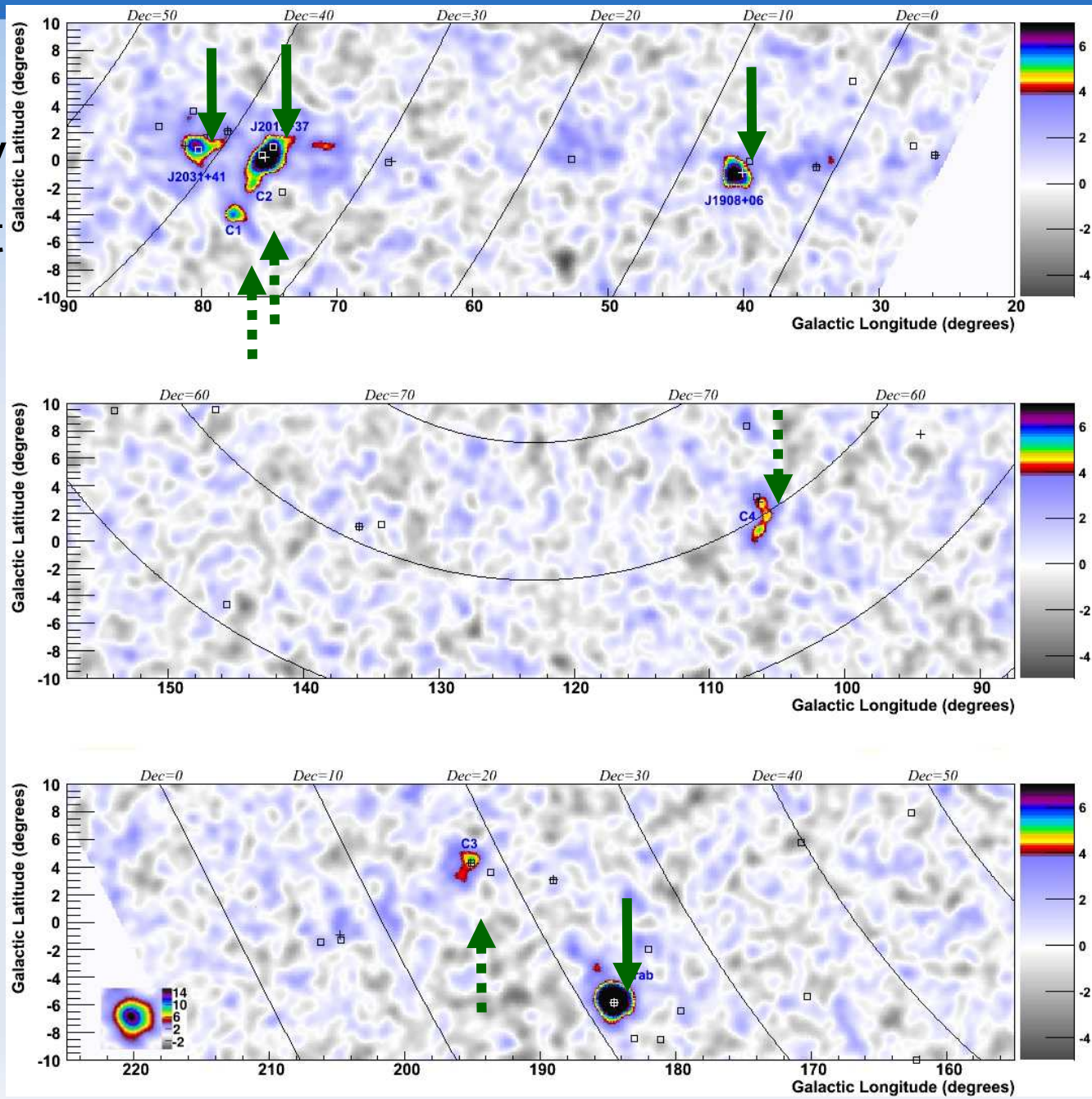
Milagro Sources and Candidates

- 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

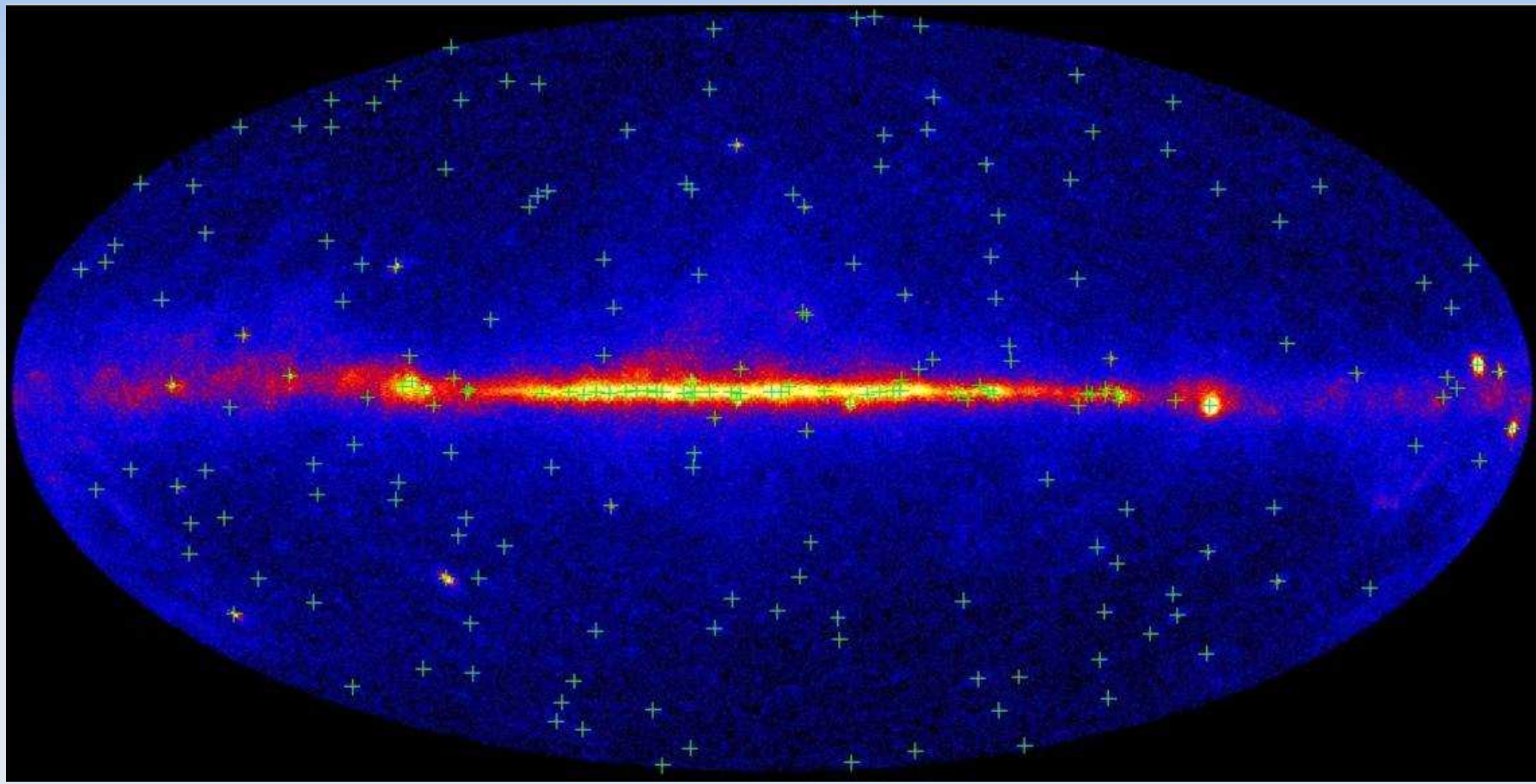


Milagro Sources and Candidates

- 7 year map
- γ /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 (>5σ that this correlation is not by chance)



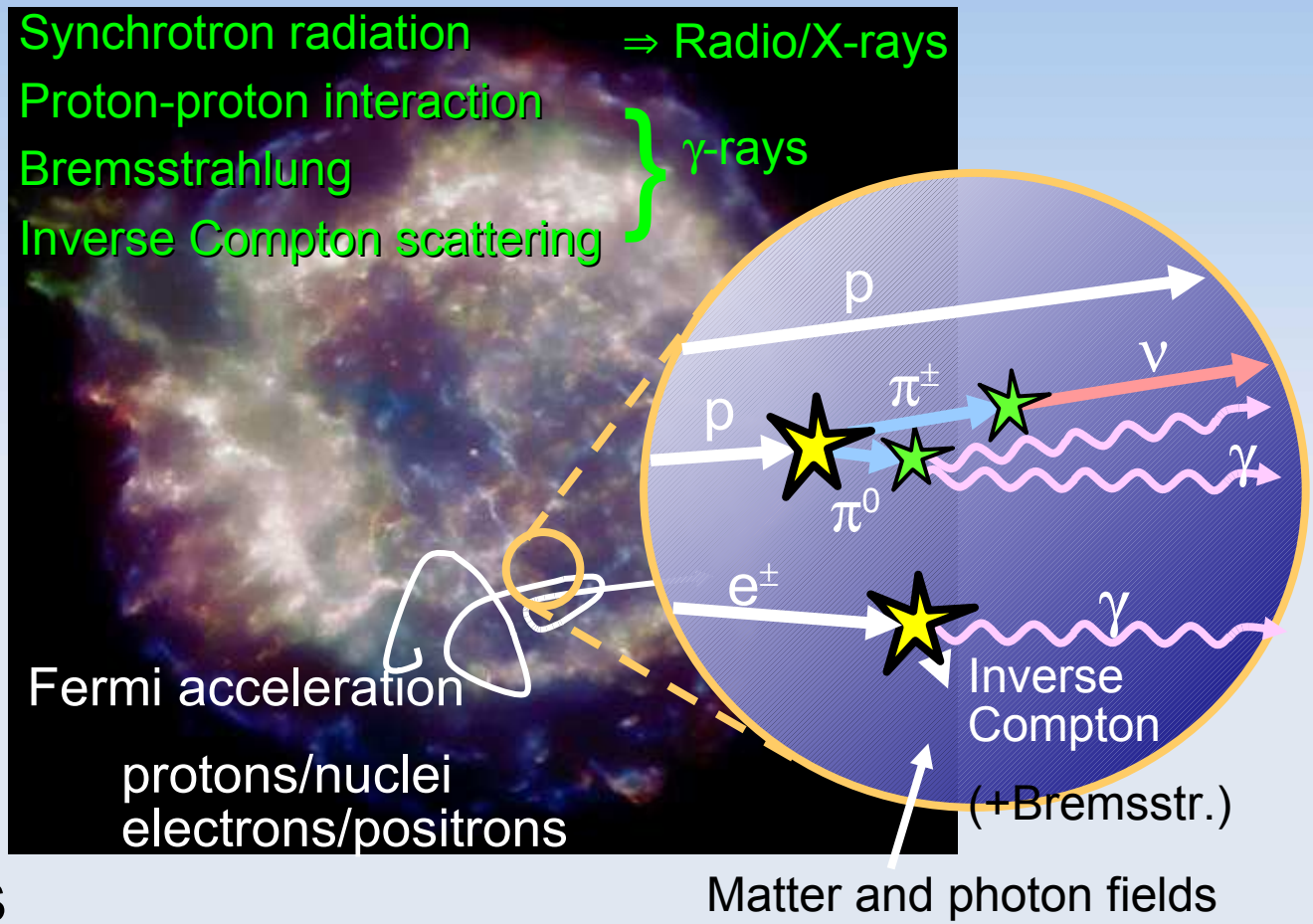
FermiLAT: 3 month High Confidence Source List BSL



- 205 sources with significance > 10σ (EGRET found fewer than 30)
- Typical 95% CL error radius is <10 arcmin
  (Abdo et al. 2009 ApJS, 183, 46)

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: $B_{shock} >> B_{ISM}$

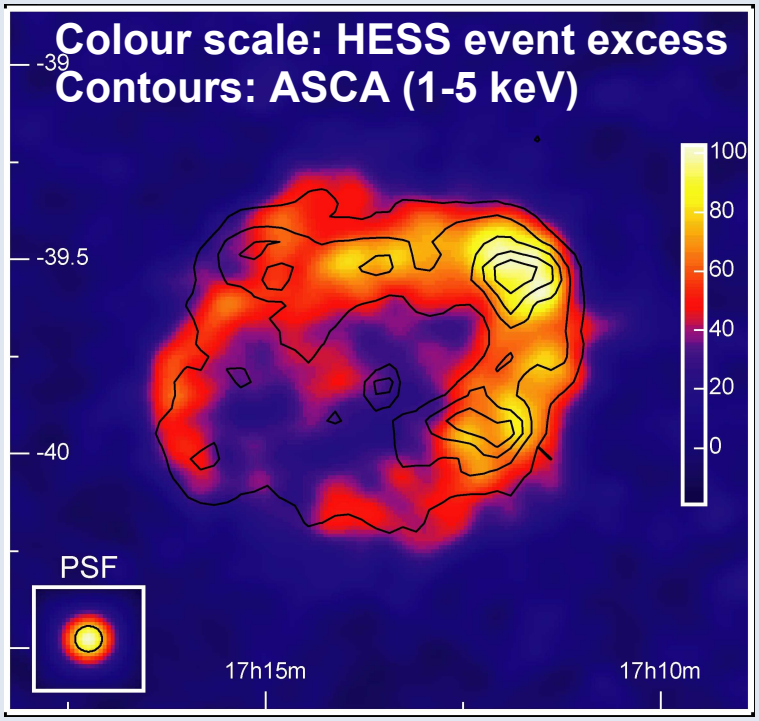


Gamma-Ray Morphology of SNRs

RX J1713.7-3946

First-ever resolved γ-ray source

Strong correlation with X-rays: ~80%



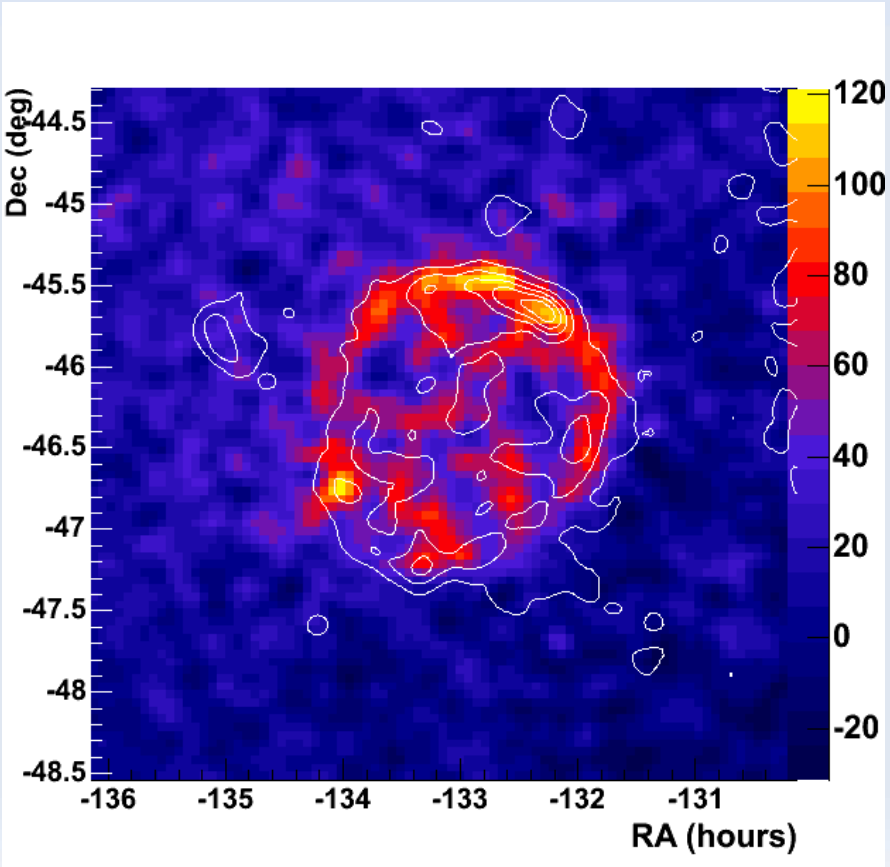
Angular resolution < 0.1°

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

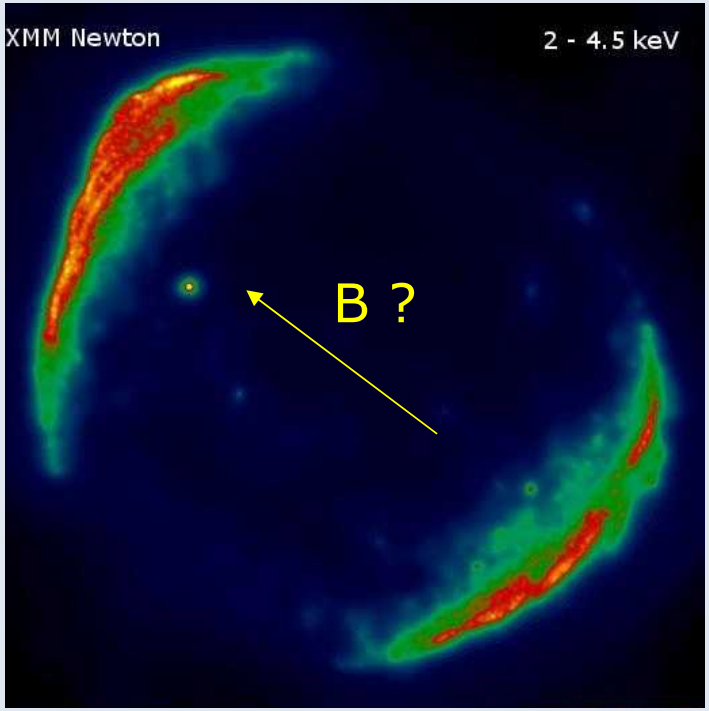
above the Galactic plane

1% Crab flux

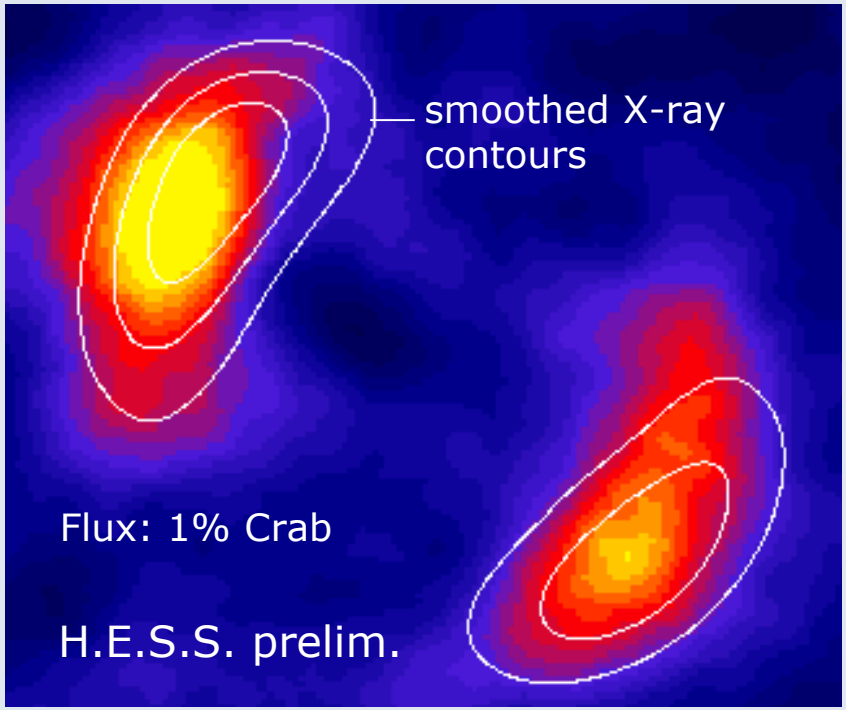
Good correlation between VHE g-rays an X-rays

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

2 – 4.5 keV X-rays



VHE γ -rays



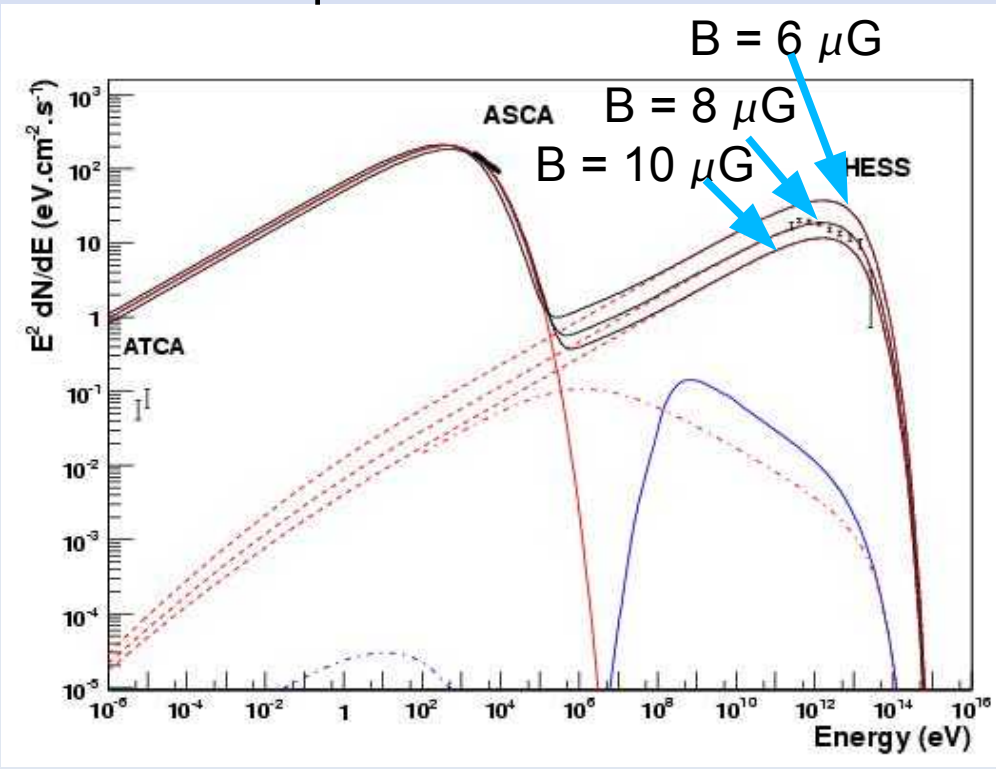
Comparison of Emission models

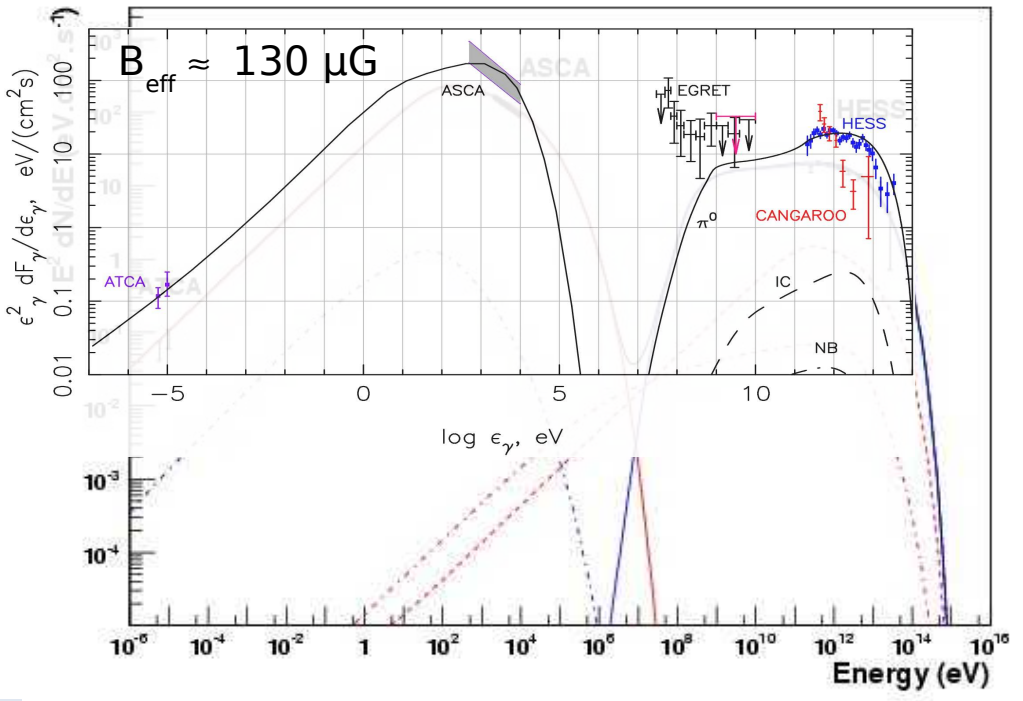
For RX J1713, γ-rays detected beyond 20 TeV ⇒ particles up to >100 TeV

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: ~ 3×10^{-2}

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

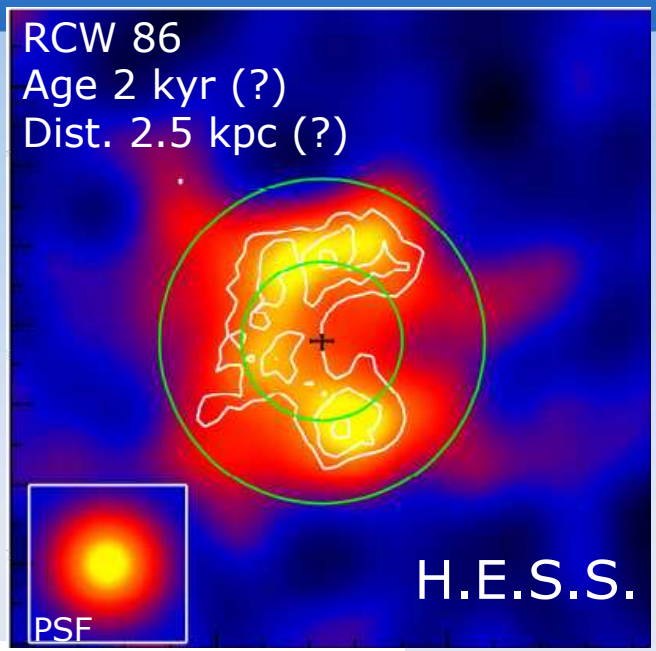




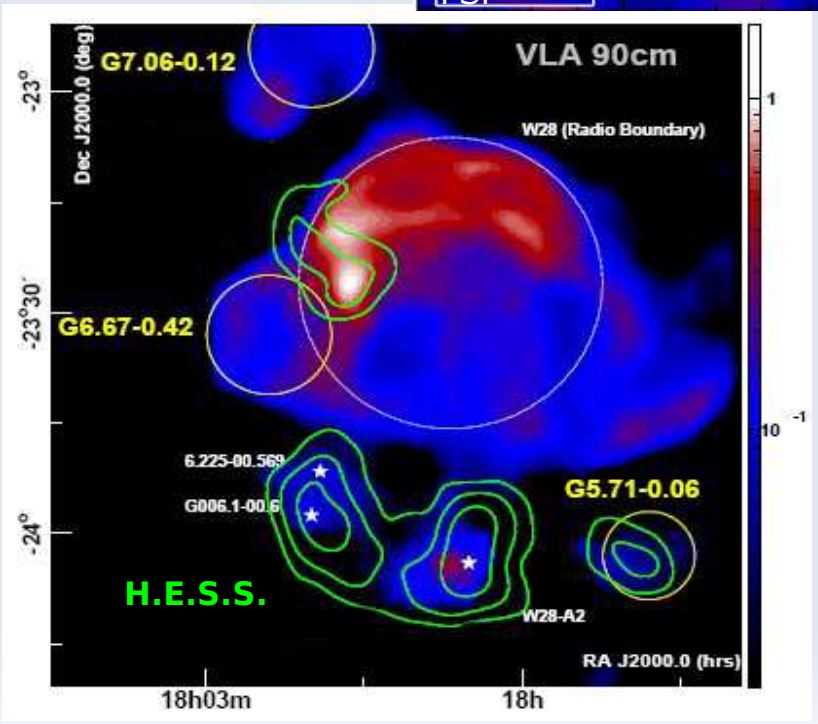
- *Leptonic scenario implies a low magnetic field*
- *Hadronic scenario requires relatively dense medium*

Other Supernova Remnants

- RCW 86, young (~1-2 ky ?) shell-type SNR
  - H.E.S.S. 9.4 σ in 30 hours, $E^{-2.5 \pm 0.1}$ spectrum
  - Probably the third TeV SNR shell

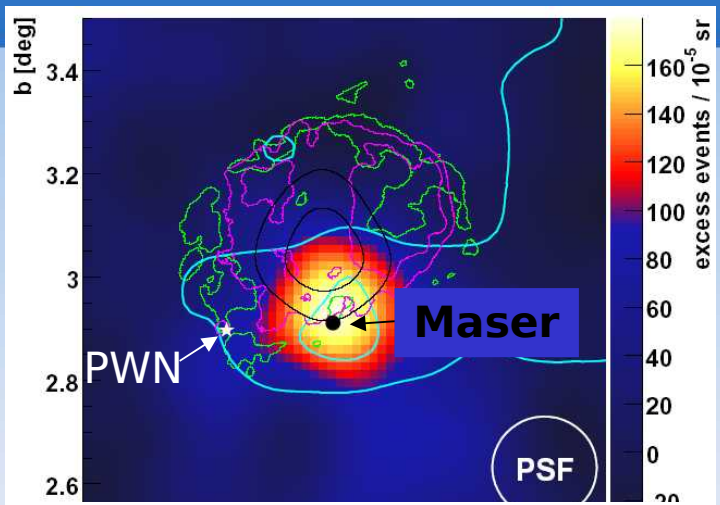


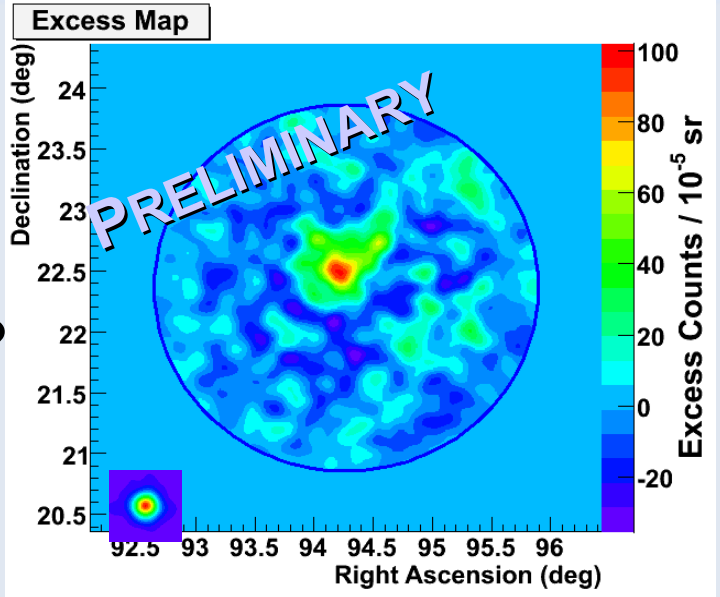
- W28, old (>10^4 year) SNR
  - H.E.S.S. TeV emission coincident with molecular clouds
  - First evidence for p-p in SNR/Cloud interactions



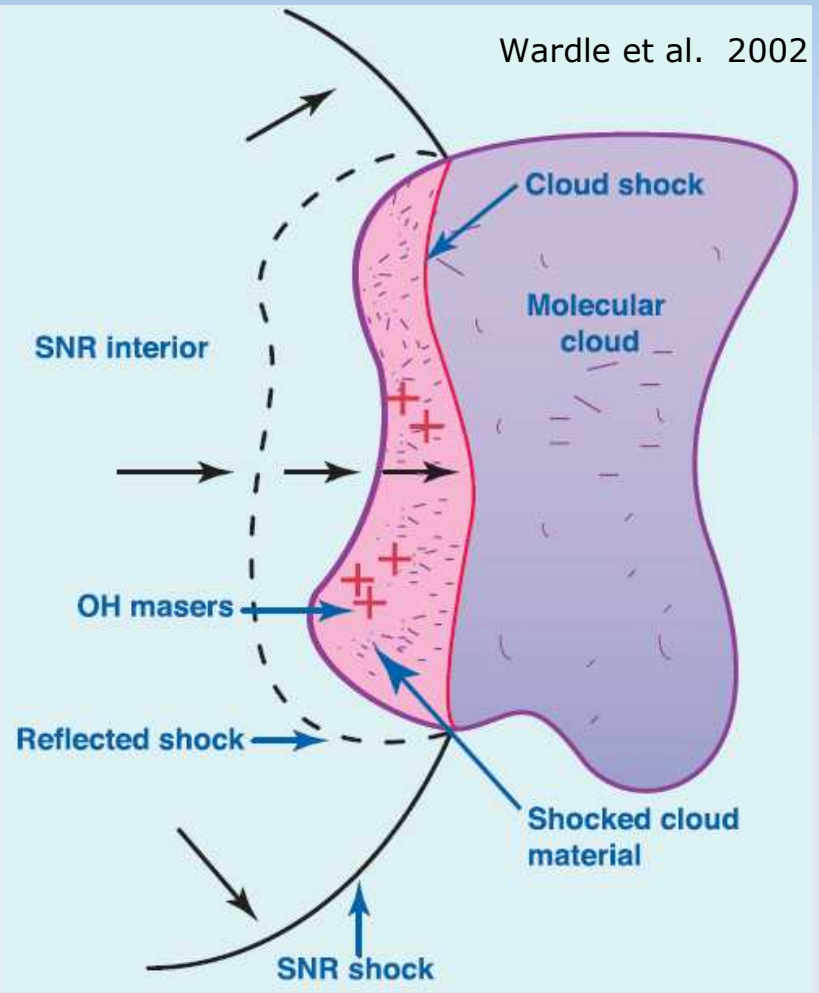
Other Supernova Remnants (2)

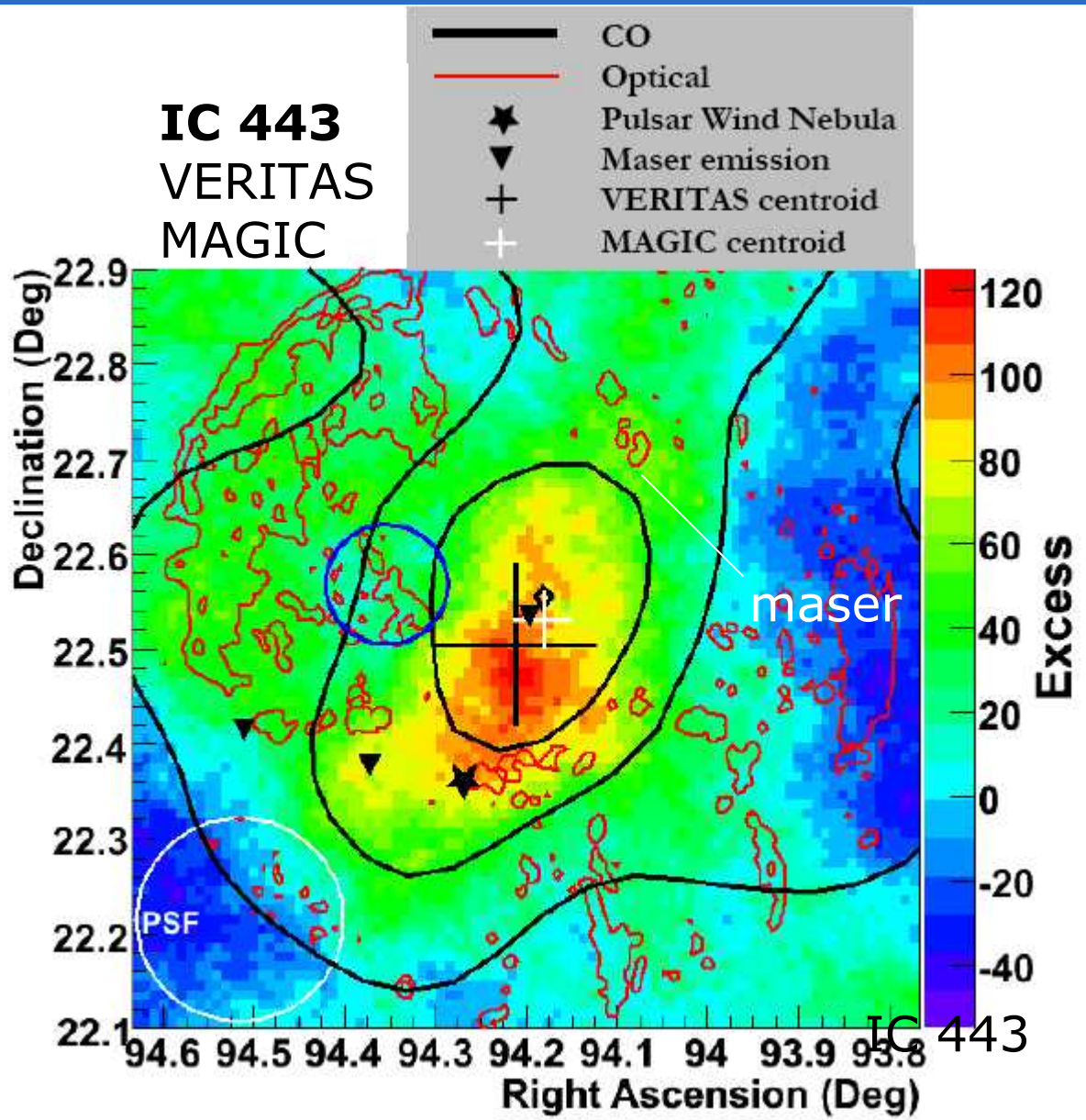
- IC433, 30kyr old, SNR
  - Maser showing shocked gas + PWN at edge of remnant
  - MAGIC 5.7σ in 29 h
    Steep spectrum $E^{-3.1 \pm 0.3}$
  - VERITAS 7.1σ in 16 h
    Consistent position
  - Position compatible with Maser
    - Interaction of SNR-accelerated hadrons?
- Cas A, young, bright radio/X-ray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



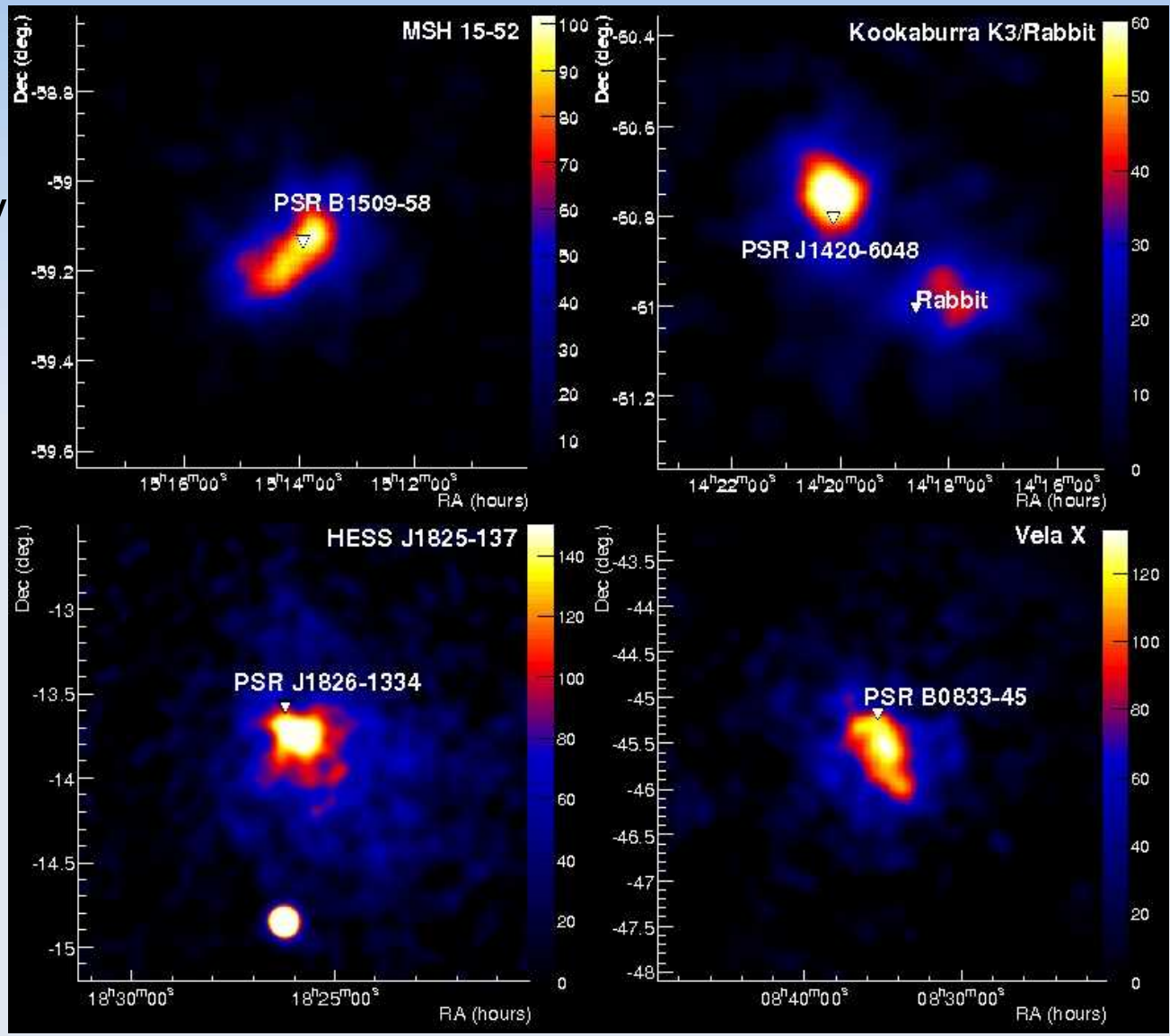


Another clue for the origin of Galactic CR ?

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

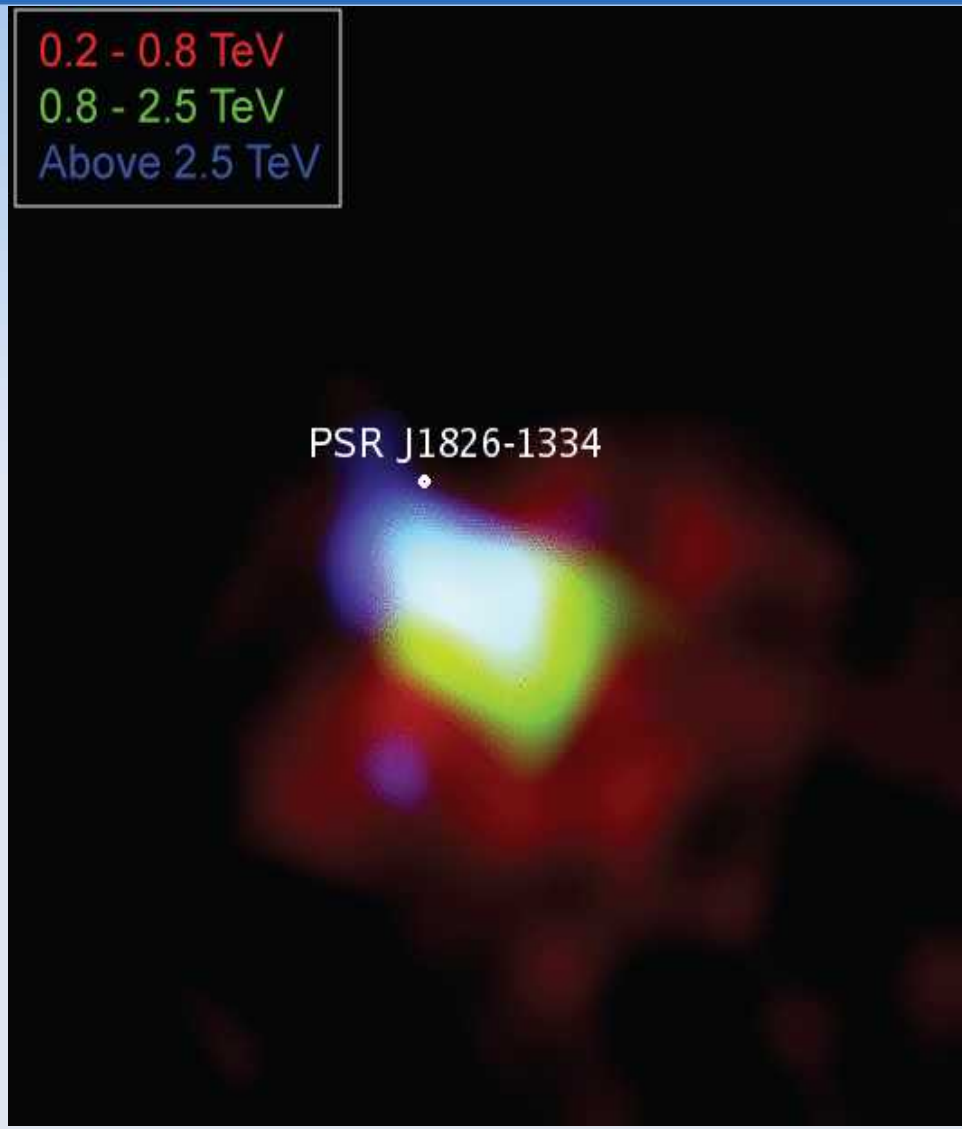
Pulsar Wind Nebulae

- 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



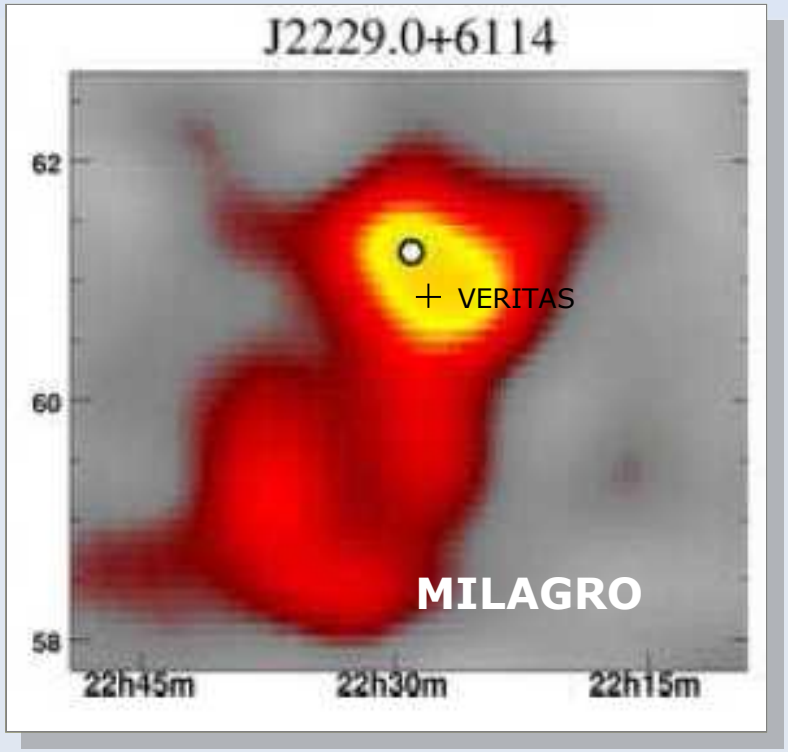
PWN Energy Dependant Morphology

- 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!

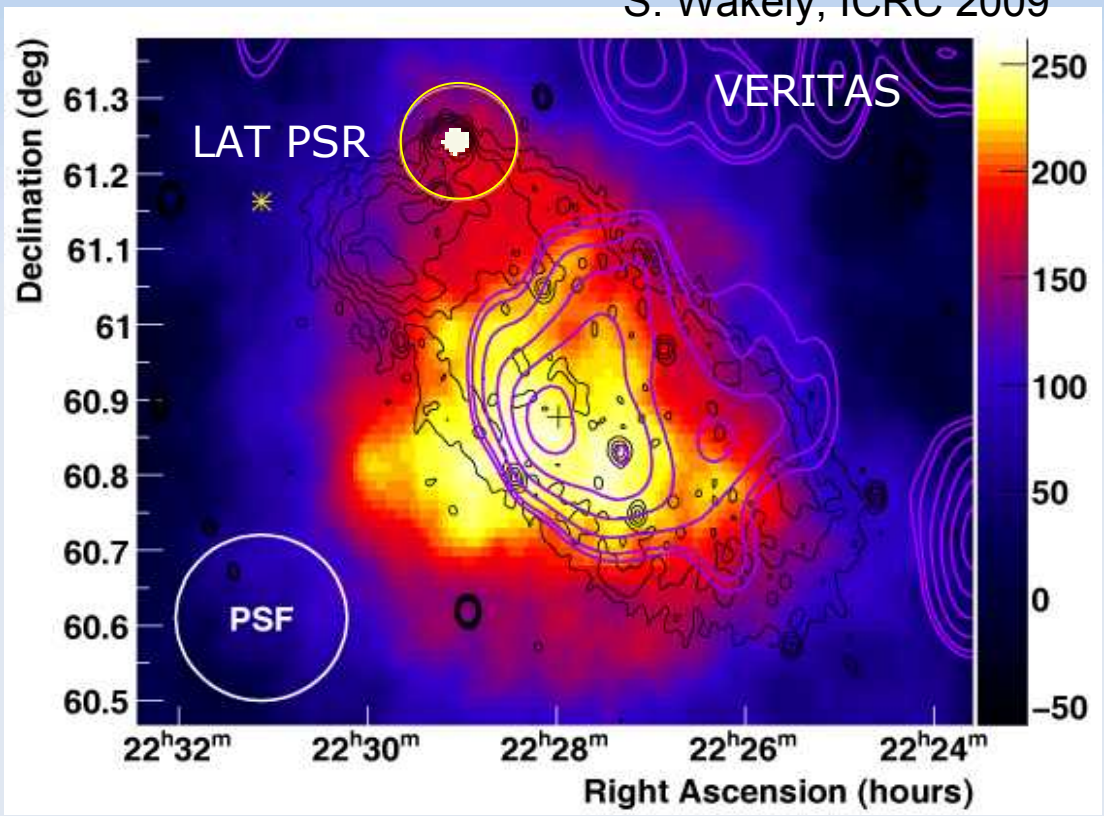


Many other VHE Pulsar Wind Nebulae

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



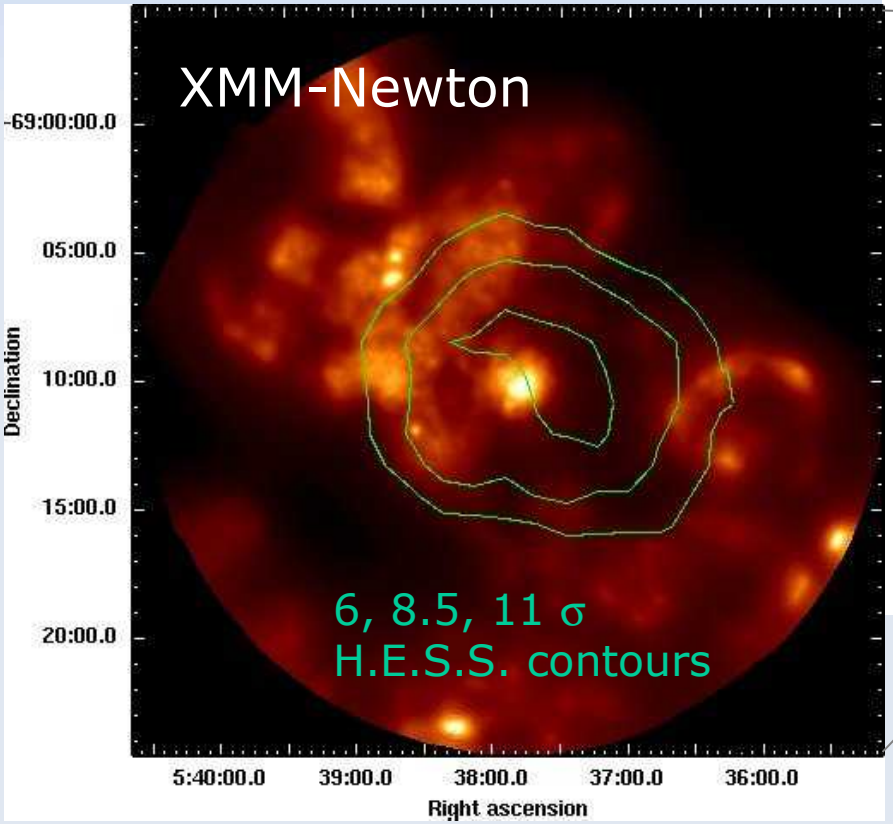
Boomerang / PSR J2229+6114
Black contours: radio, purple: CO
Also: MGRO source

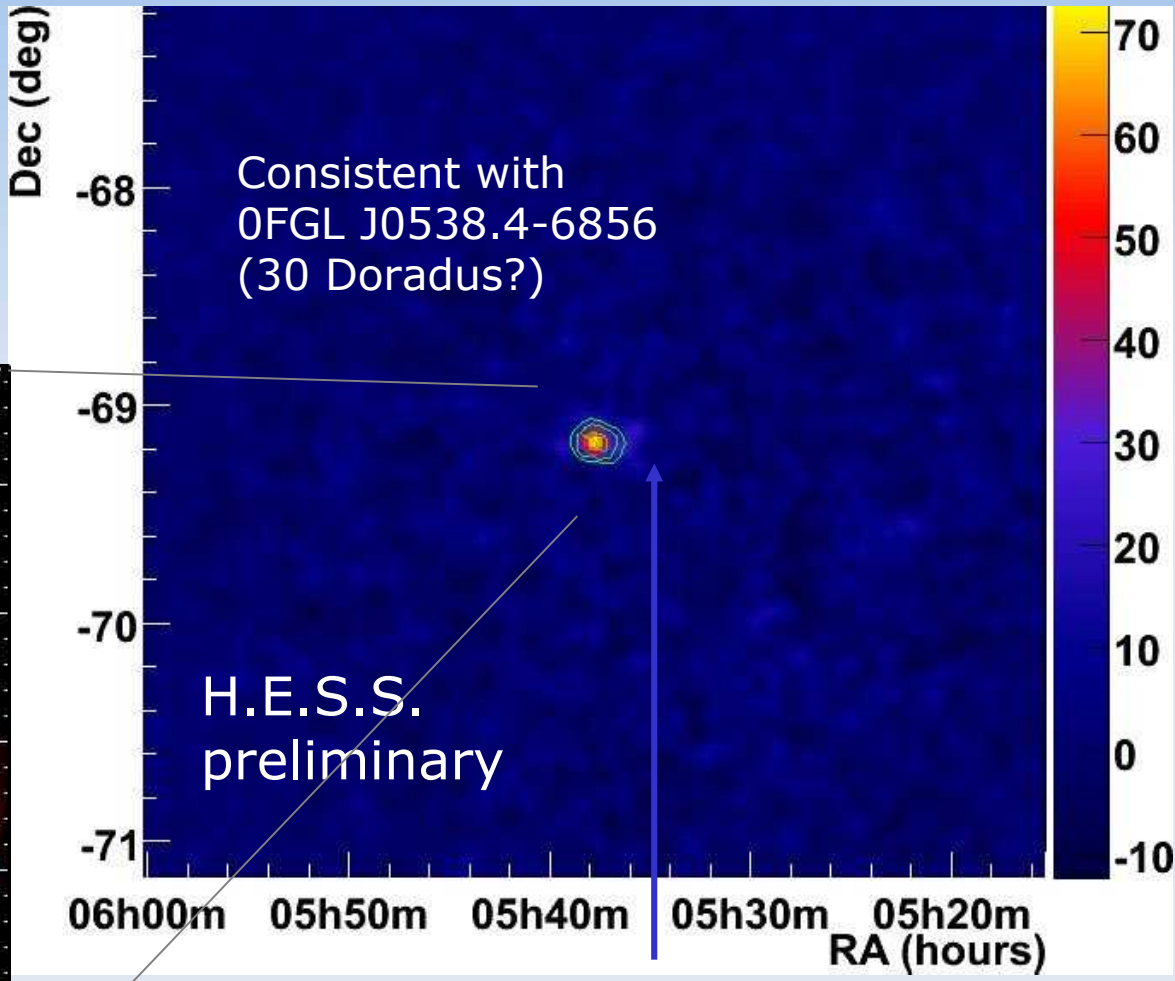
S. Wakely
ICRC 2009

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 γ -rays





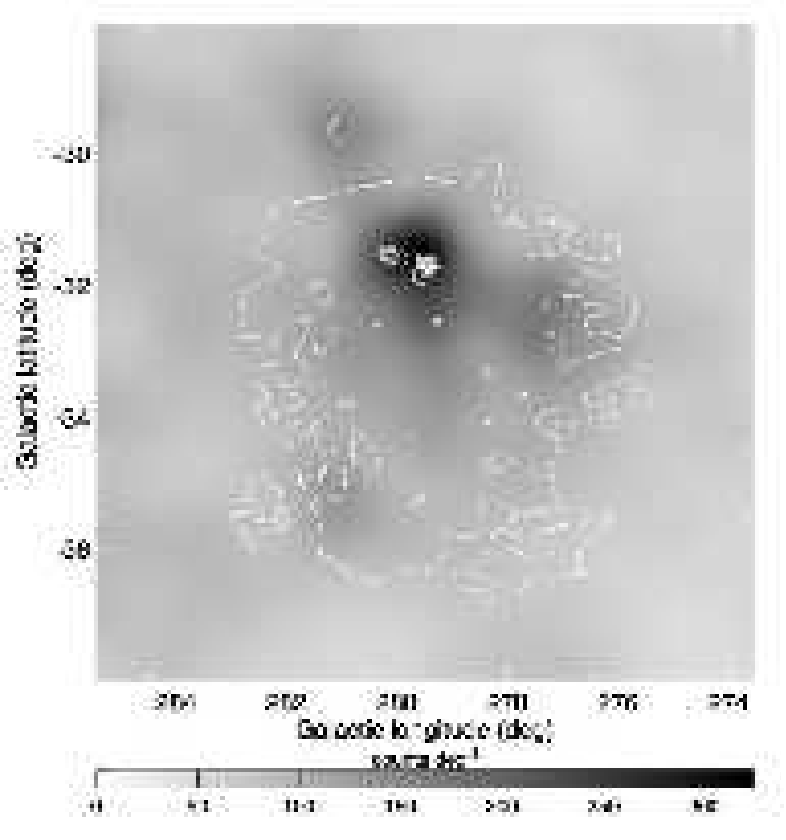
SN 1987a in FoV;
Upper limits close to predicted flux,
no detection of 30 Doradus

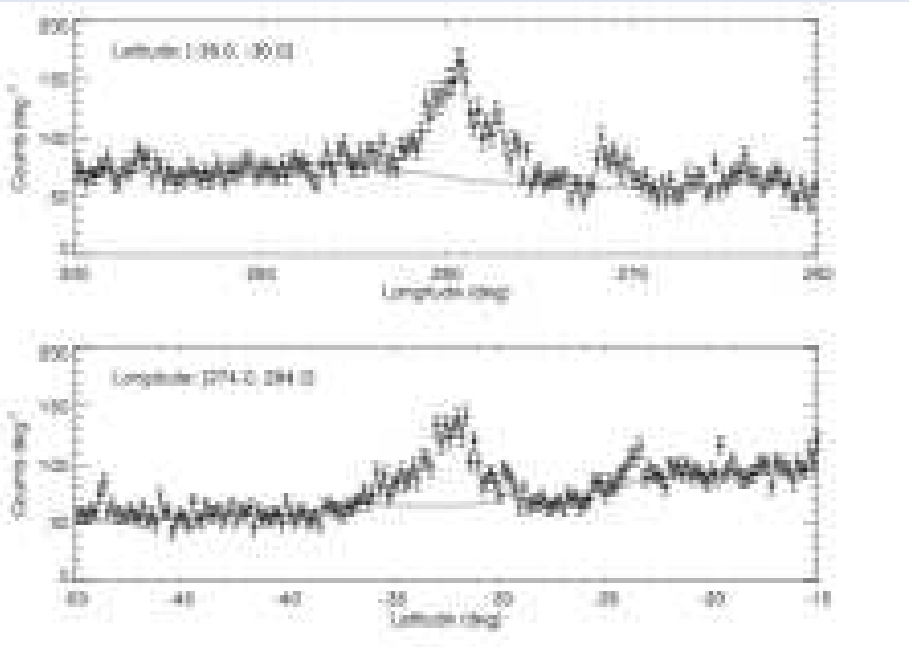
Nu. Komin
ICRC 2009

LMC seen in HE (EGRET/FermiLAT)

-HE: resolved for the first time!

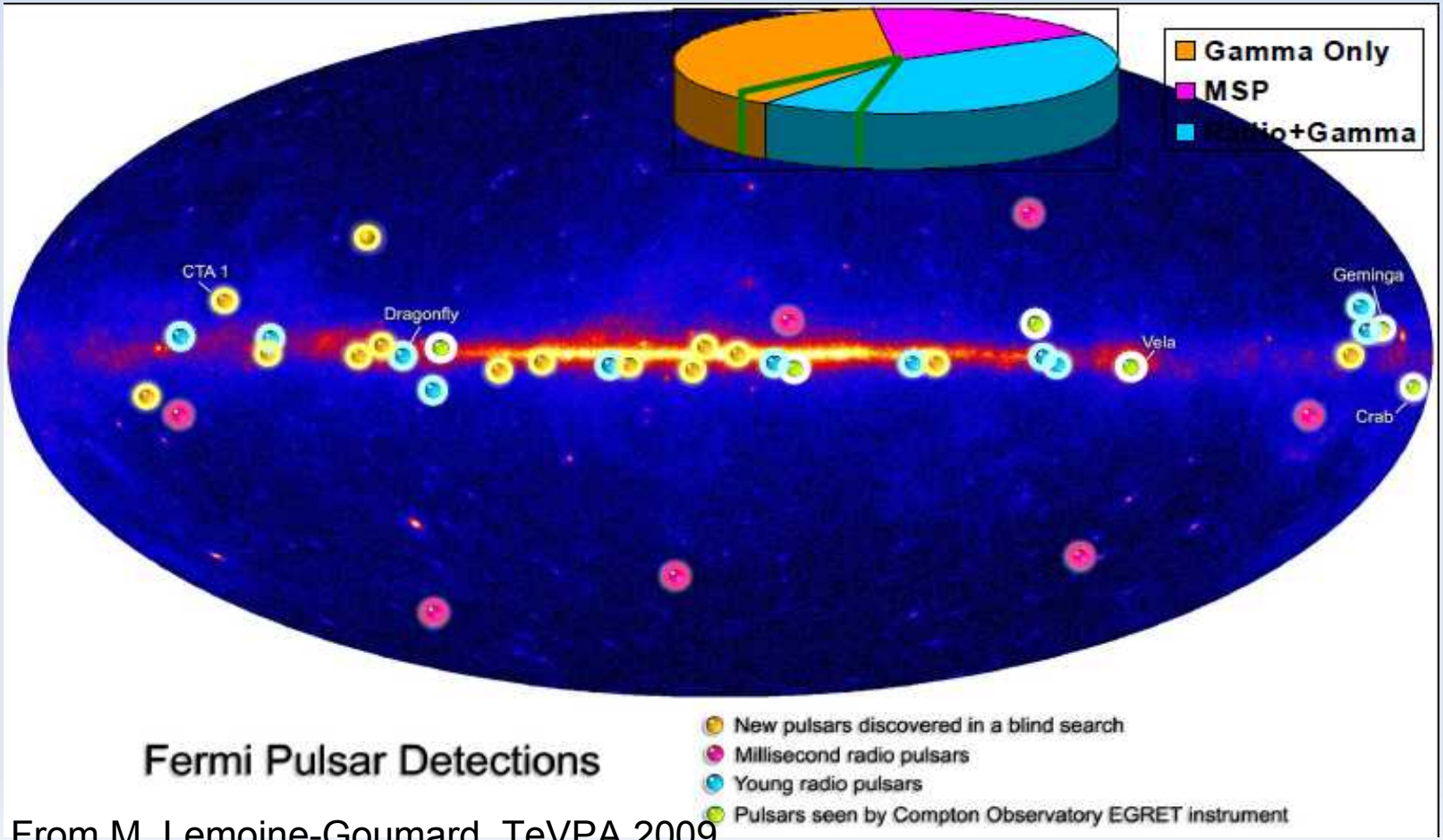
Significant part of the radiation (but not all) coming from 30 Doradus (containing SN1987A).





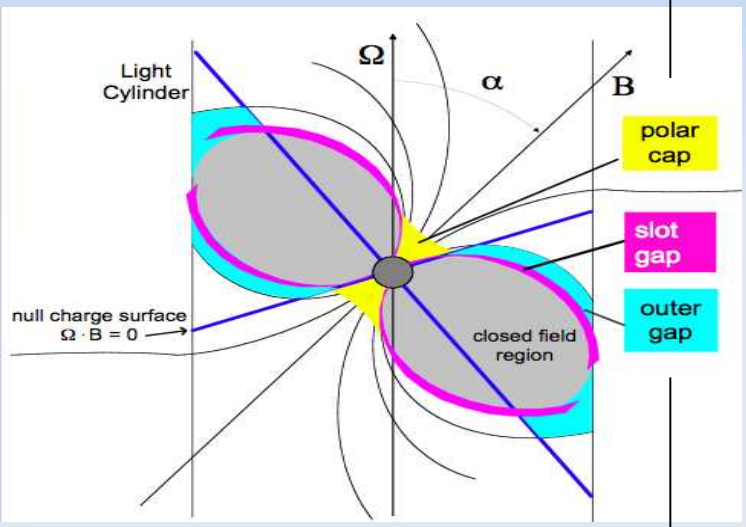
Pulsar (pulsation) detections

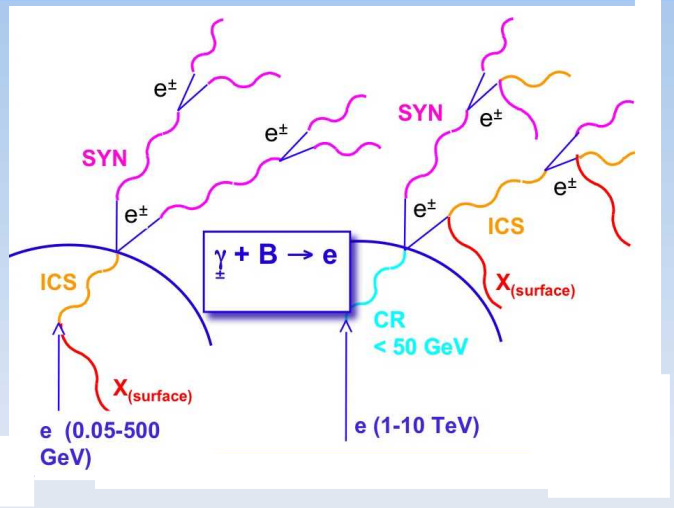
- FermiLAT is a “pulsar detection machine” !
- 46 gamma-ray pulsars !!! (6 were known previous to Fermi flight)
  - 16 previously unknown pulsars (orange).
  - Gamma-ray emission from known radio pulsars (magenta, cyan)
  - Gamma-ray emission from known or suspected gamma-ray pulsars (green)

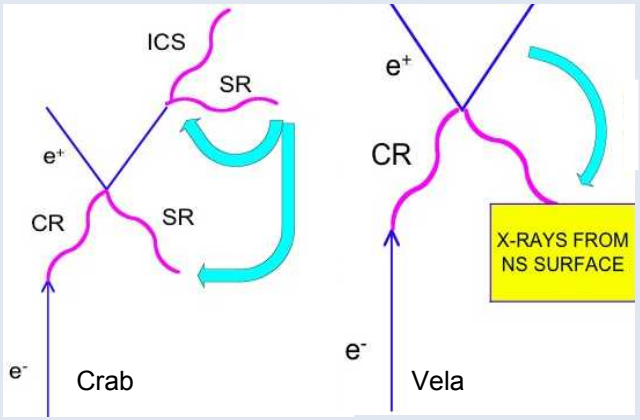


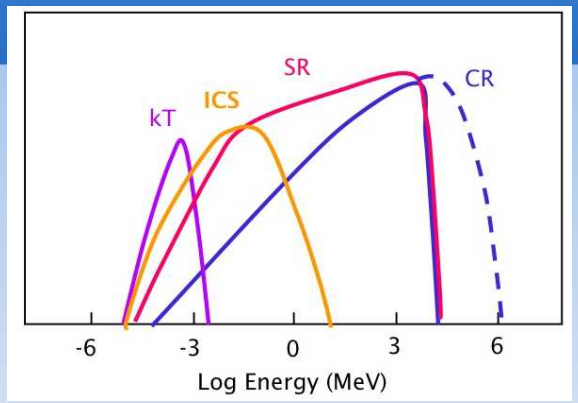
From M. Lemoine-Goumard, TeVPA 2009

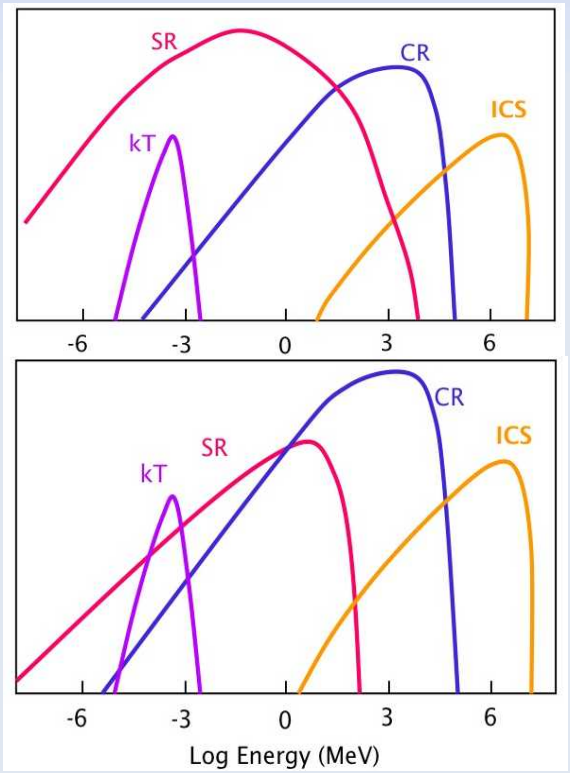
Pulsar emission, the framework











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

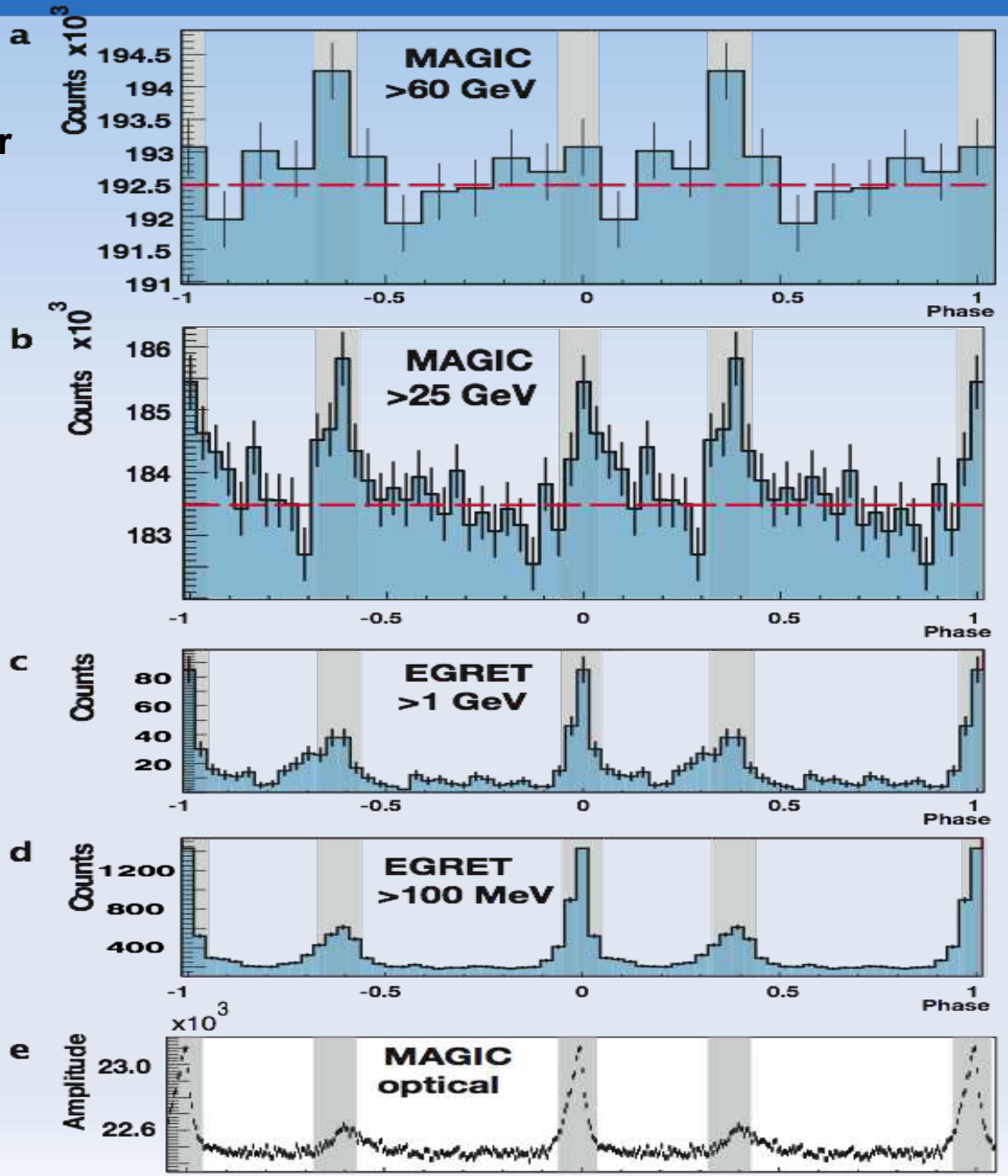
MAGIC, Science 322, 2008
using special low-energy trigger

Spectral Fit:
Power-law with an exponential cutoff

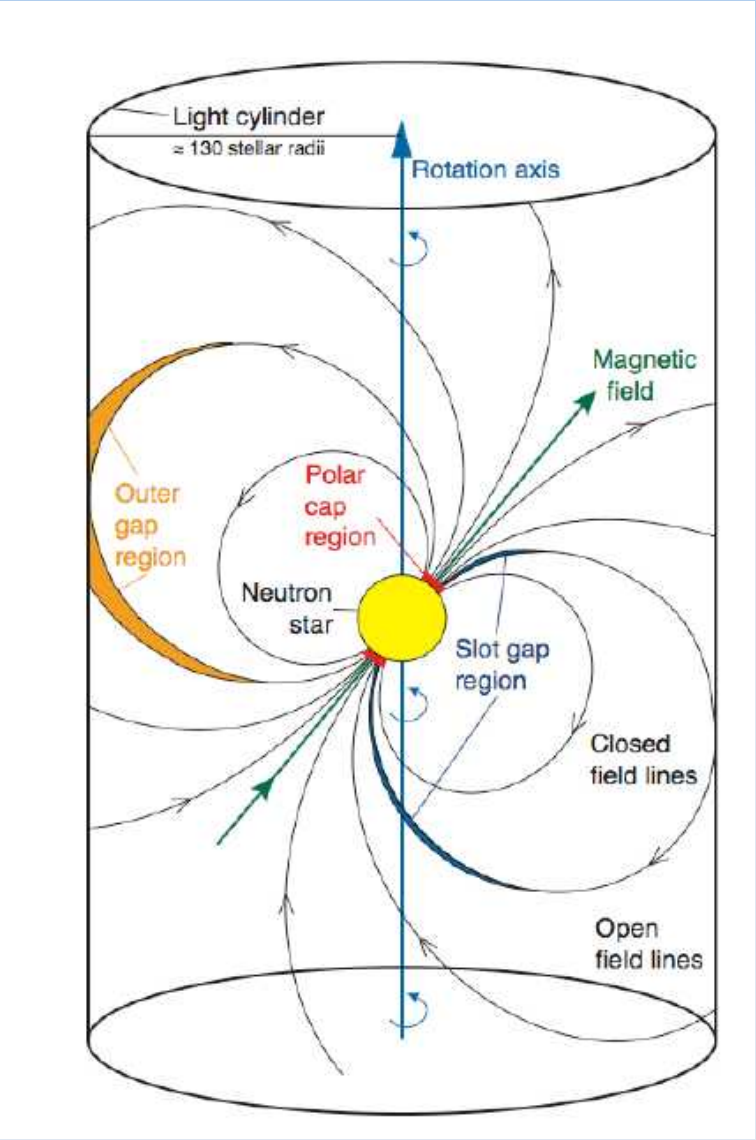
F: 8.8±1.1+2.9-1.1
M: 17.7±2.8±5

Power law with
Hyper-exponential cutoff rejected > 5σ

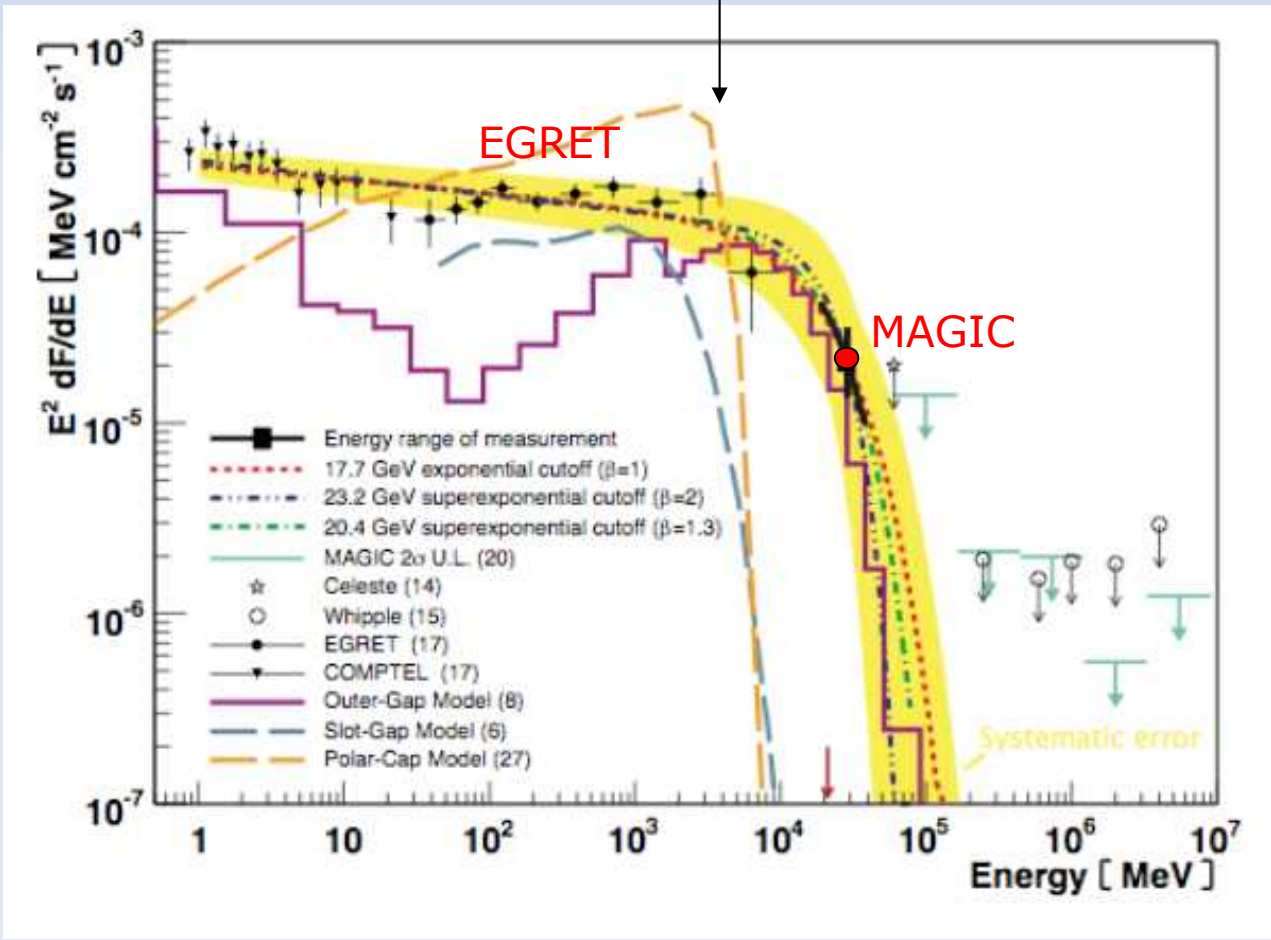
Cutoff energy limits the height of the emission (to avoid absorption) to be beyond 4 / 6 R_*



… leading to preference for outer gap model



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



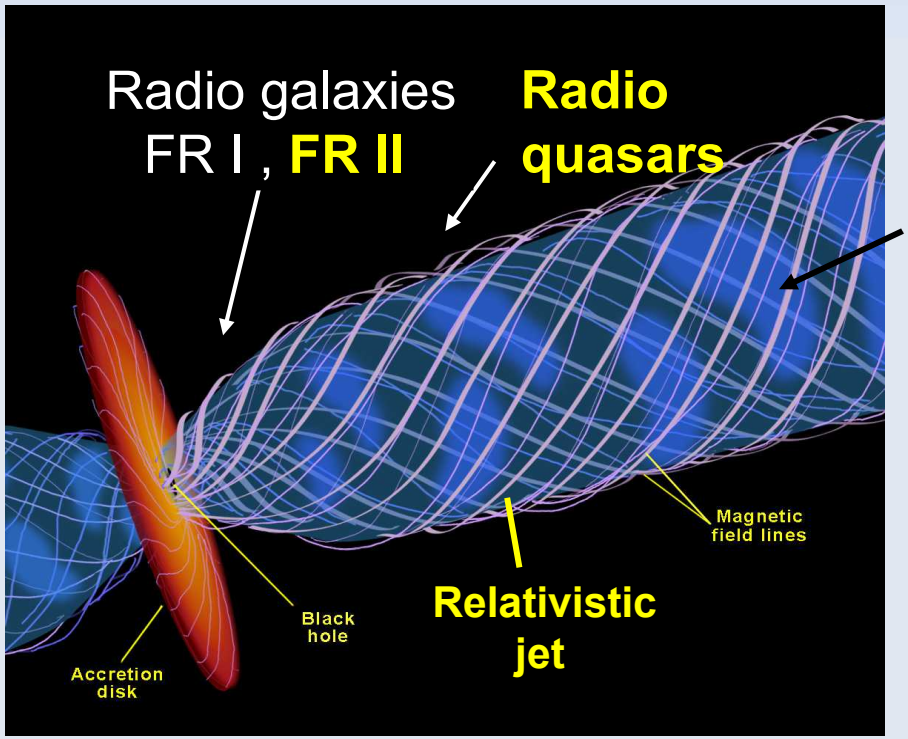
Other Galactic sources

No time to discuss !! :

- Binaries, a laboratory to study particle acceleration “periodically”:
  - LS5039, superbly measured orbital period (4day) at VHE
  - LS I +61 303 (26day)
  - PSR B1259-63, long period (3.5yrs), new results on 2nd orbit
  - Cyg X-1 awaiting confirmation
  - HESS J0632+057, a possible new candidate
  - Fermi detections of LS5039 and LS I +61 303, with anti-correlation between GeV-TeV!
- Young Stellar Clusters / star forming regions
  - containing Wolf-Rayet and OB stars
  - Emission due to collective stellar winds, colliding winds of binaries, Supernovae, Pulsar Wind Nebulae … ?

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 δ^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”

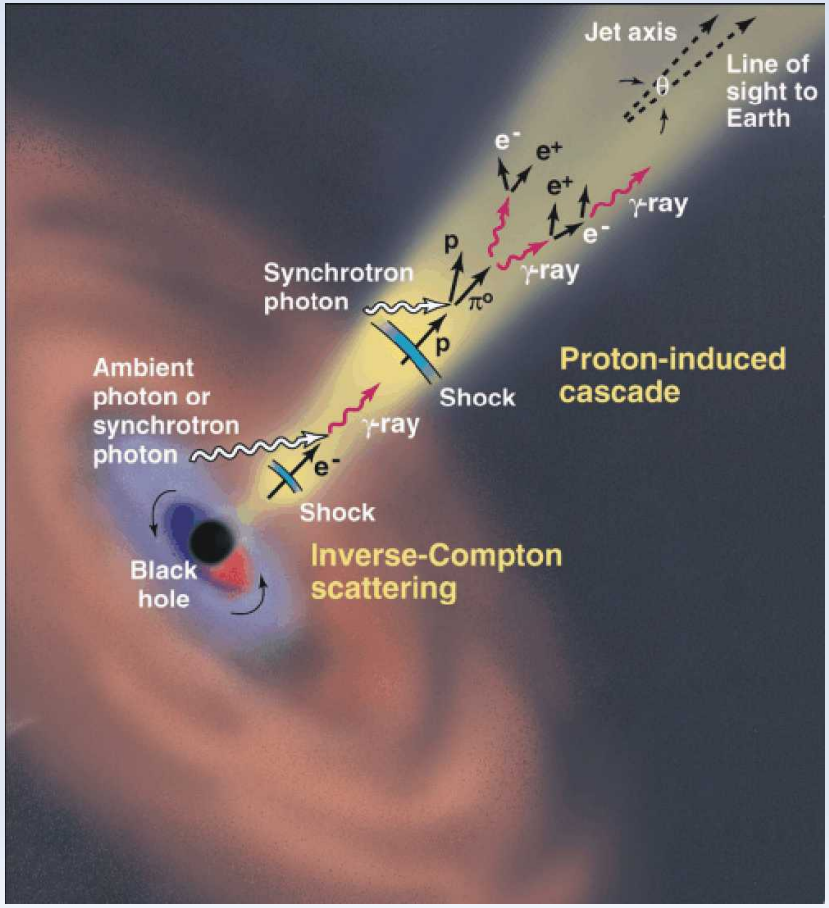
Extragalactic sources

- 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)

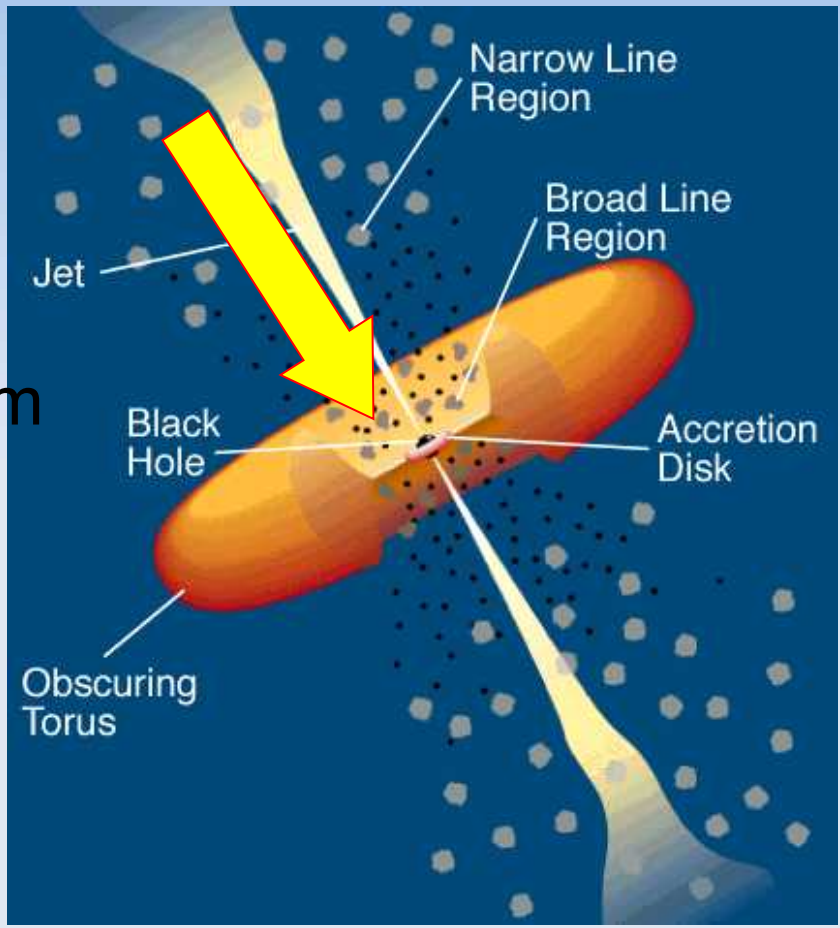
TeV variability : already seen in 18 sources (despite poor temporal coverage)

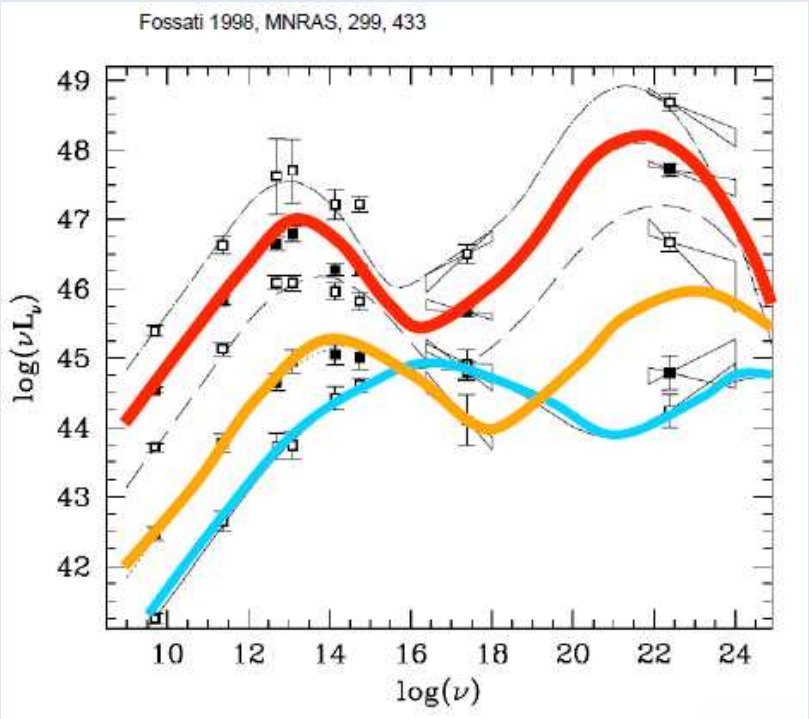
« Shortest observed time scales »

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



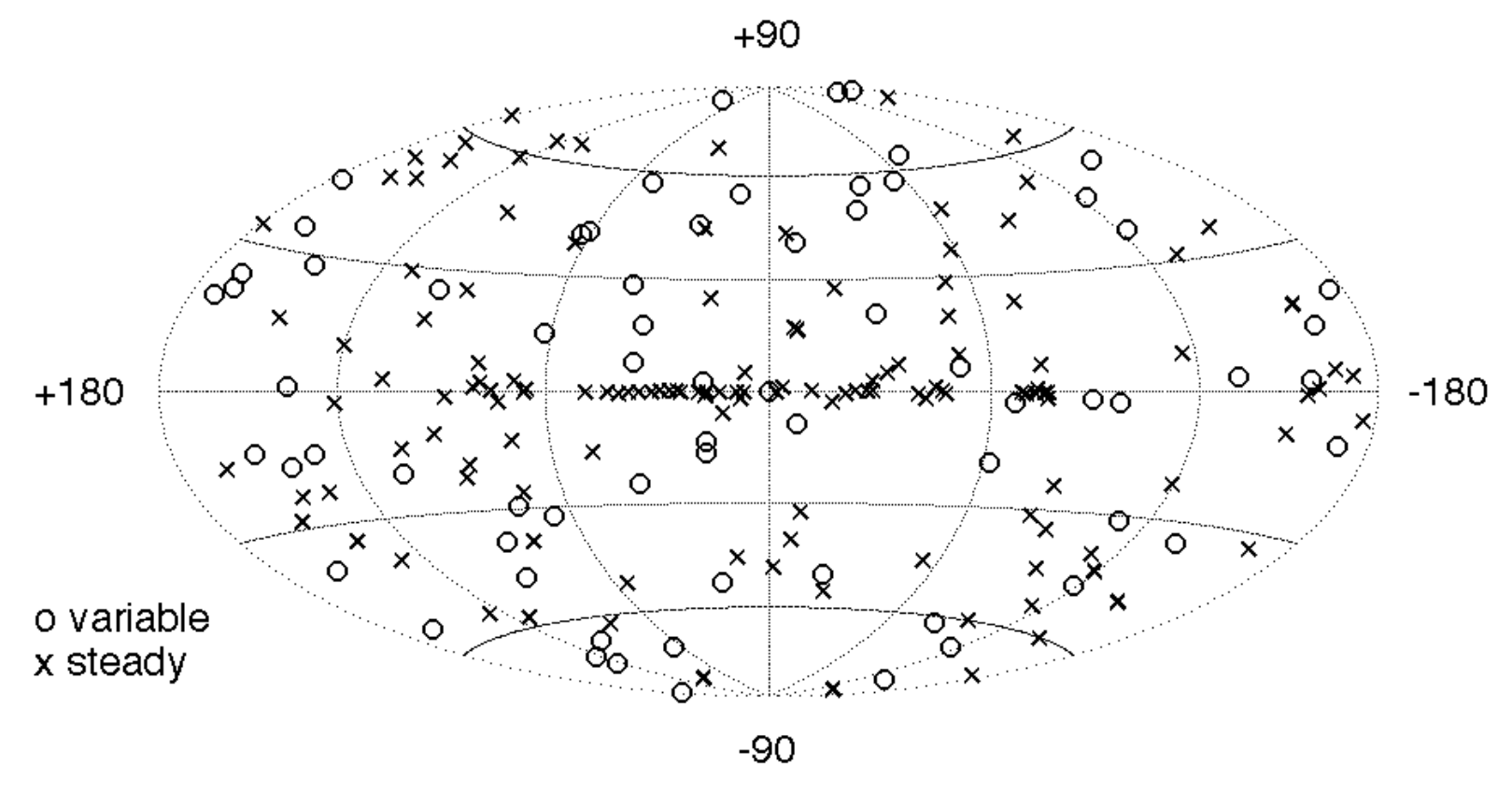


LBL:powerful, substantial external radiation fields

IBL: in between

HBL:low power, weak external radiation fields

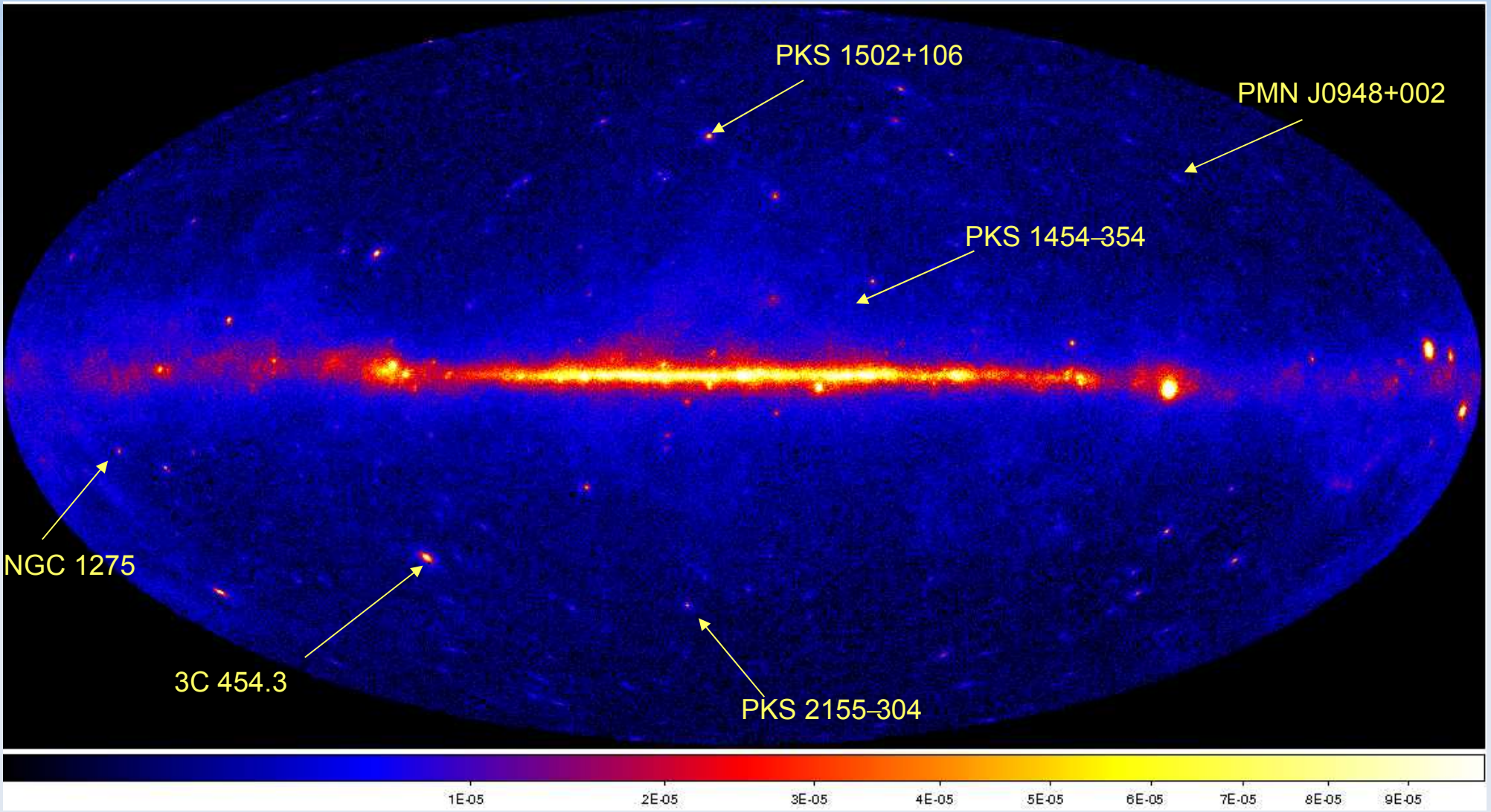
Extragalactic HE catalogue



Variable sources in the FermiLAT Bright Source List

- Based on 1 week time scales
- 68/205 show variability with probability > 99%
- Isotropic distribution ⇒ blazars

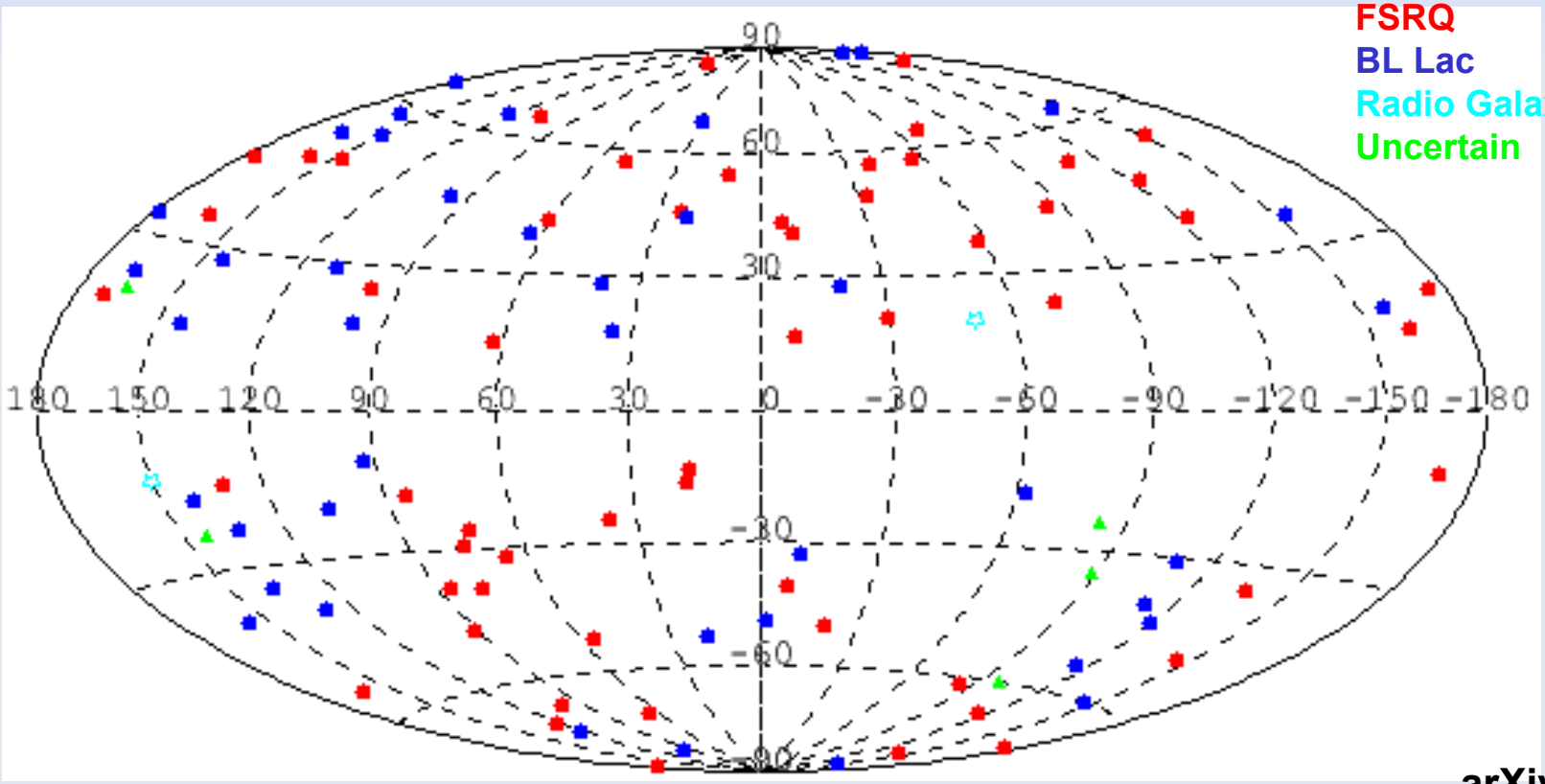
Extragalactic HE catalogue



FermiLAT skymap: Some of the brightest AGNs are clearly visible

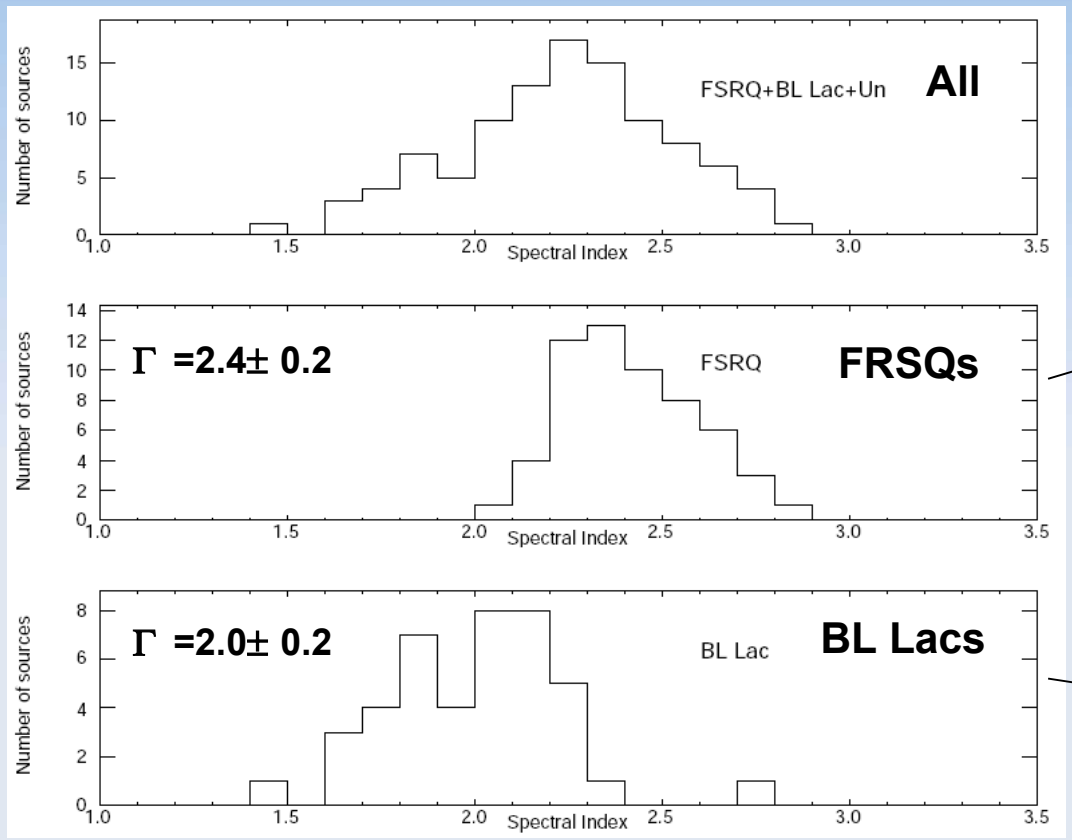
HE Blazar Population Properties

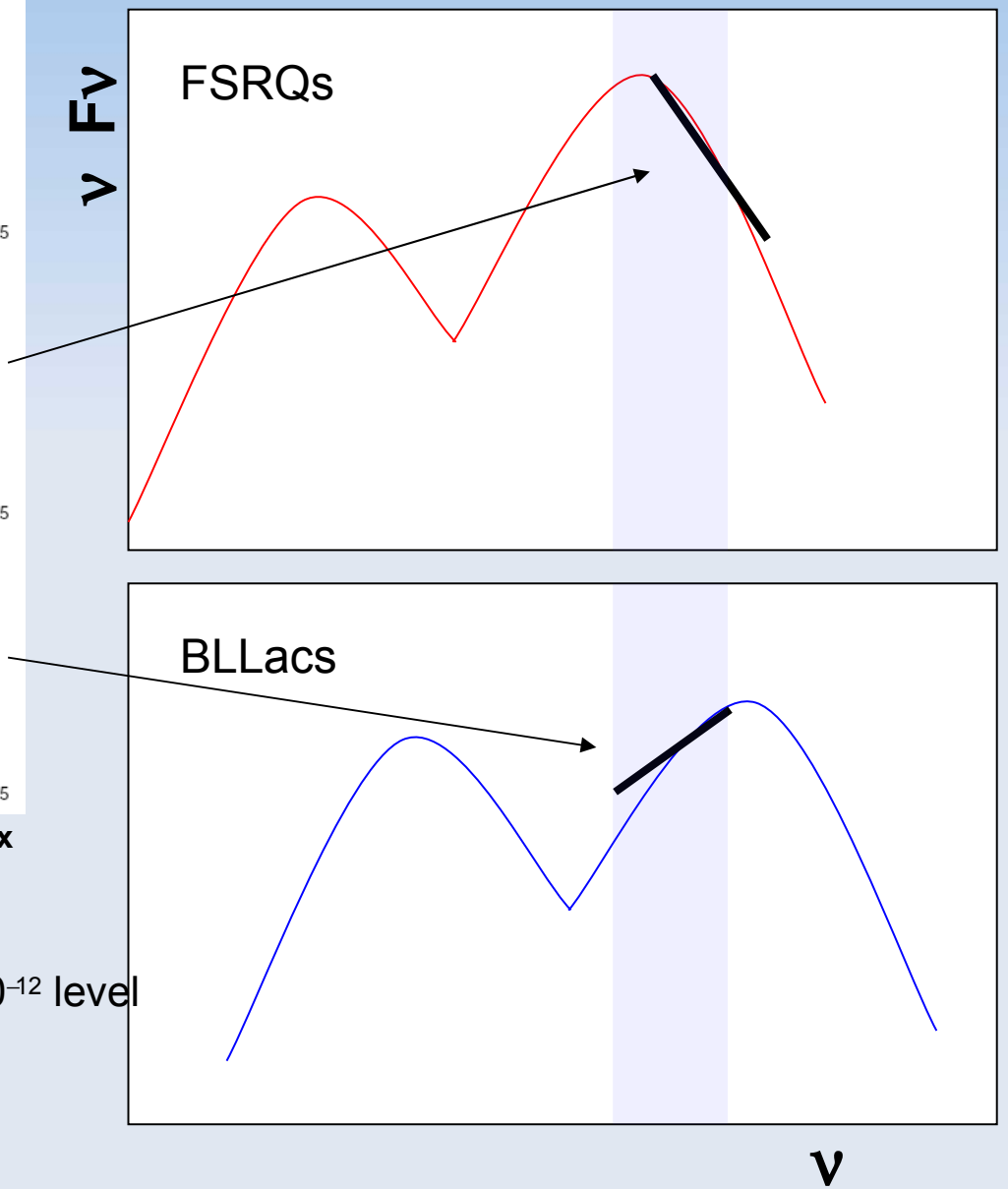
- Aug/Sep/Oct high confidence list: 205 sources with >10σ detection
- 132 with |b| > 10° (7 pulsars, 9 unid)
  - 116/125 are bright, flat spectrum radio sources
  - 58 FRSQs, 42 BL Lacs, 4 Unc., 2 radio galaxies (+10 low CL associations)
  - CRATES (all-sky radio catalogue), CGRaBS (all-sky optical spectra), BZCAT (multifreq. blazar catalogue)
  - Note also, 3 unidentified transients in Galactic plane, not associated with AGN



arXiv:0902.1559
Abdo et al, ApJ

HE Blazar Population Properties

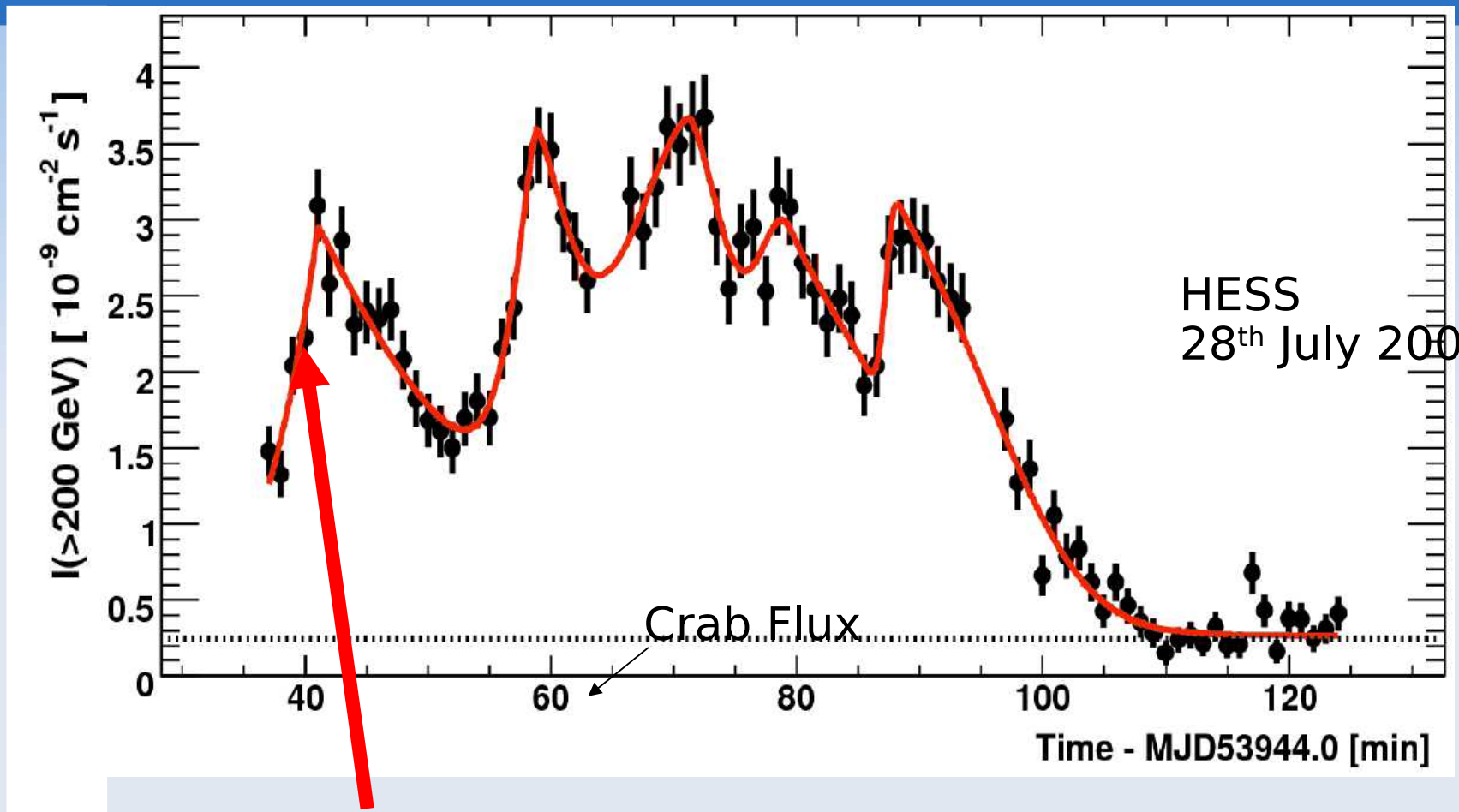




FermiLAT measurements

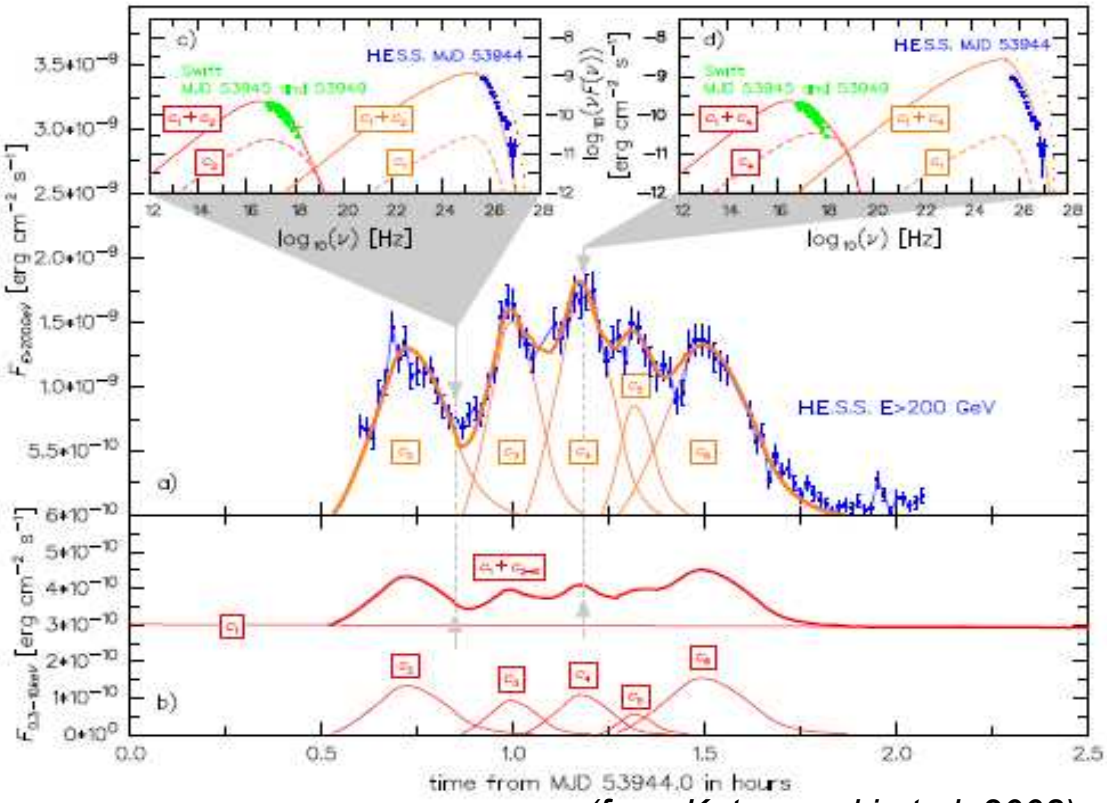
- FSRQ and BL Lac index distributions differ at 1 -10^{-12} level
- 42% BL Lac fraction (vs 23% for EGRET), 10 HBLs
- 8 TeV Blazars

VHE example: Flare From PKS 2155-304



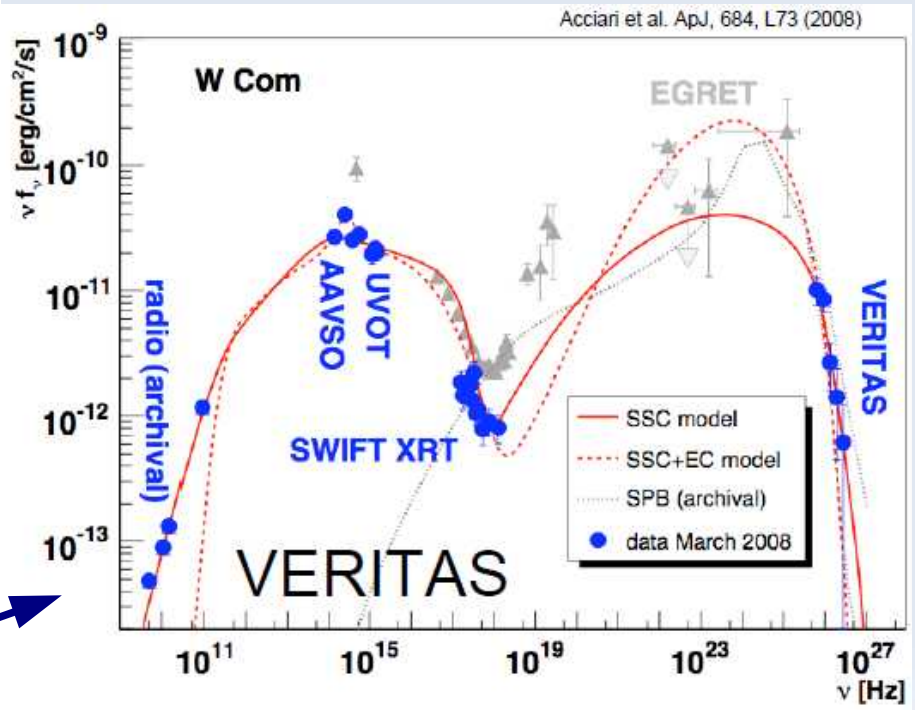
- Best measured rise-time: 173 ± 28 s
- Two orders of magnitude brighter than typical state
- Time-scale probes size of emitting region if causality applies
- Such measurements also used to test Quantum Gravity (LIV)

VHE examples: PKS 2155-304 flare, W Com



(from Katarzynski et al, 2008)

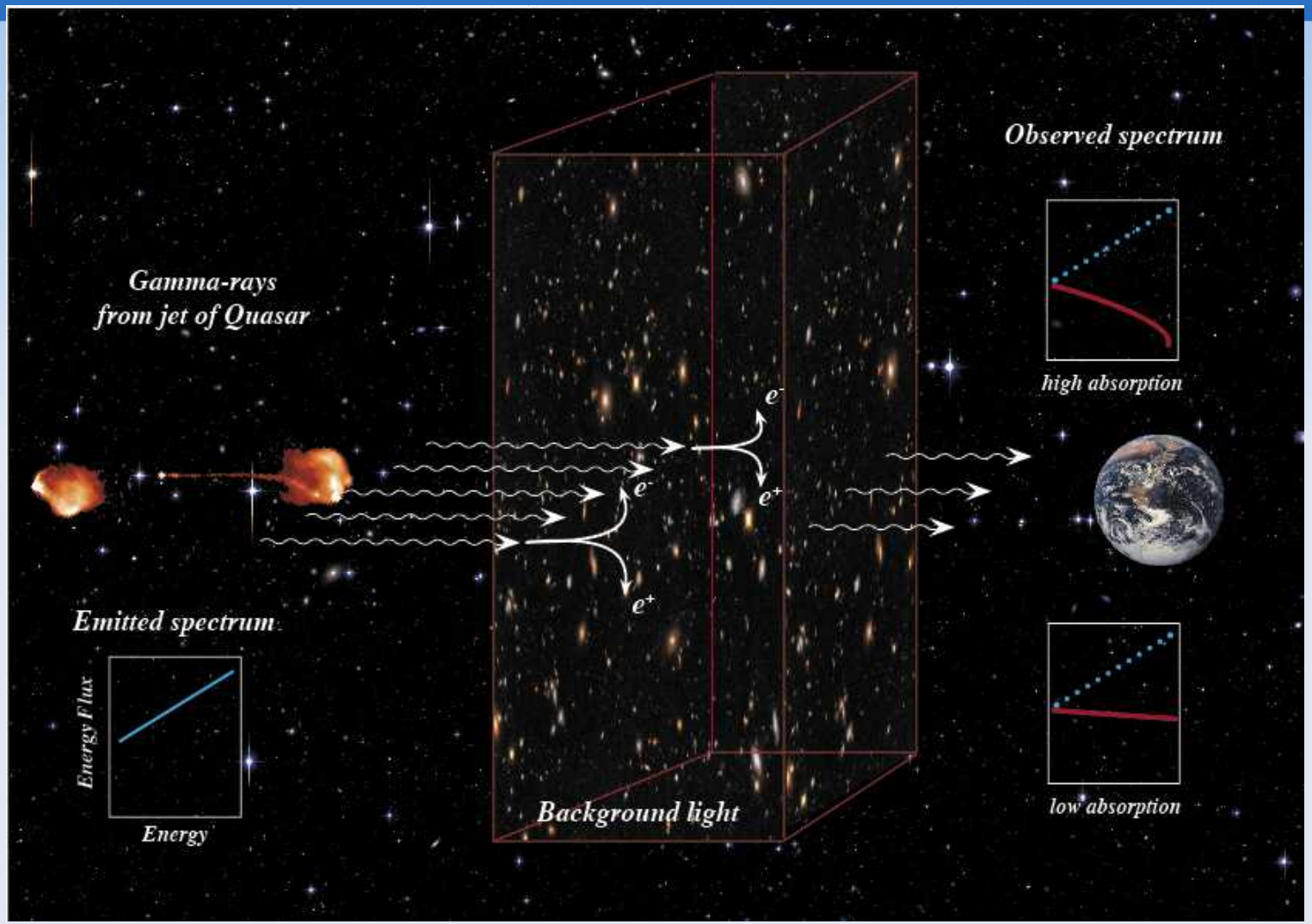
Many efforts to fit, e.g.
Example of modelling light curves and SED by time dependent SSC scenario, with 5 compact components in jet with slightly different parameters + a more extended slowly evolving component



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

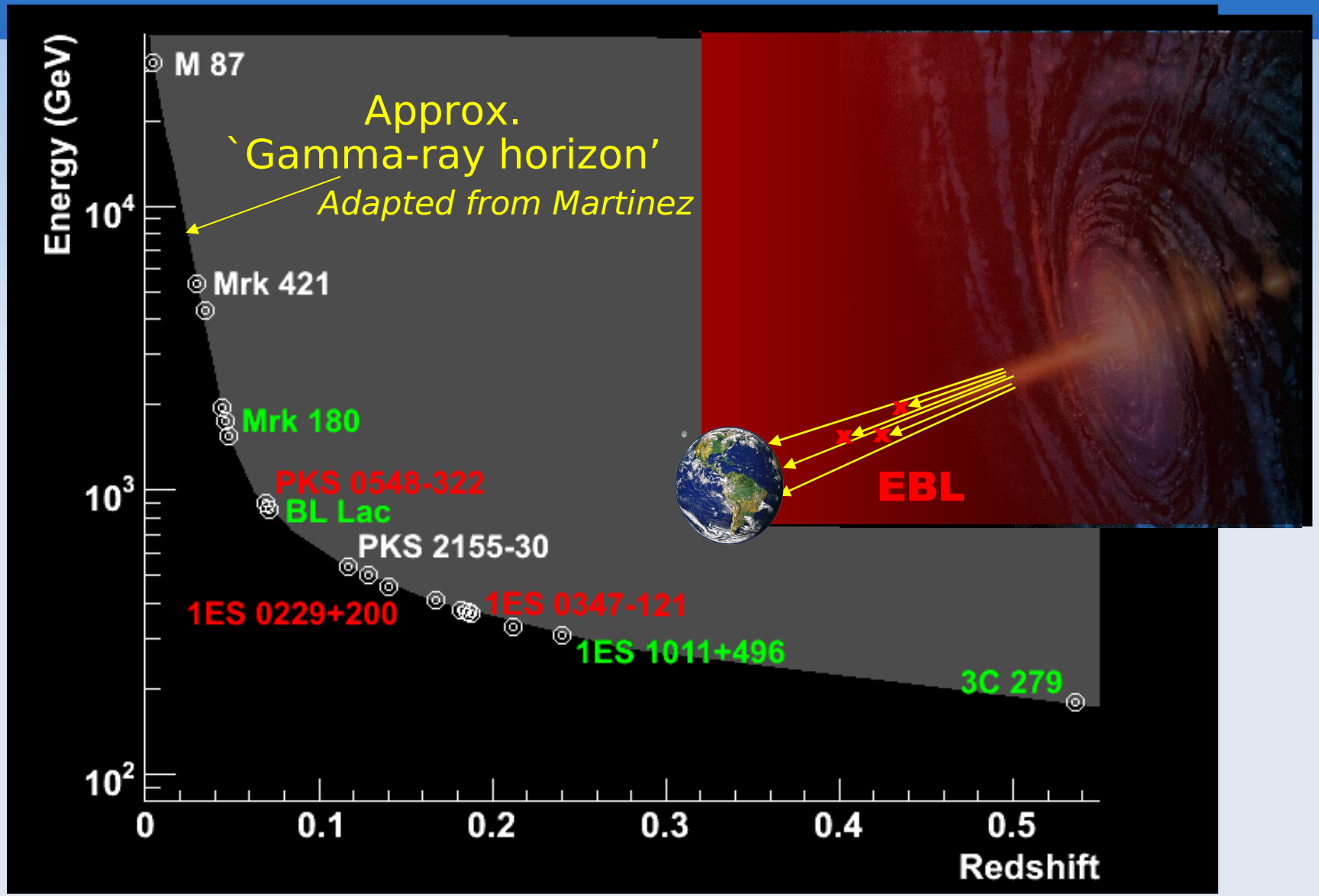
Extragalactic Background Absorption



Effect of EBL absorption:

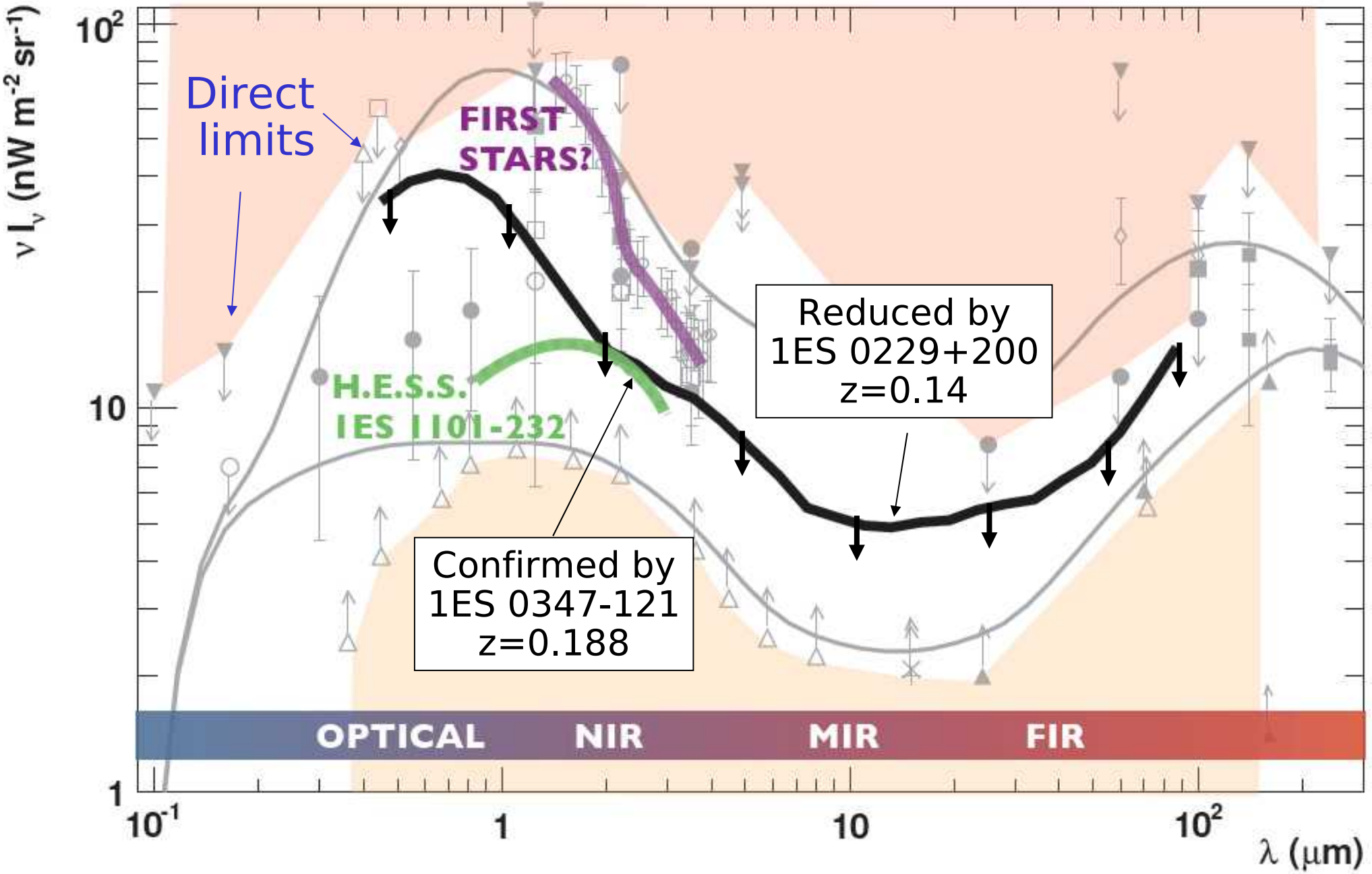
- modifies intrinsic spectral index
- introduces cut-offs or roll-overs,
- renders extremely distant sources undetectable at highest energies

Extragalactic Background Absorption



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

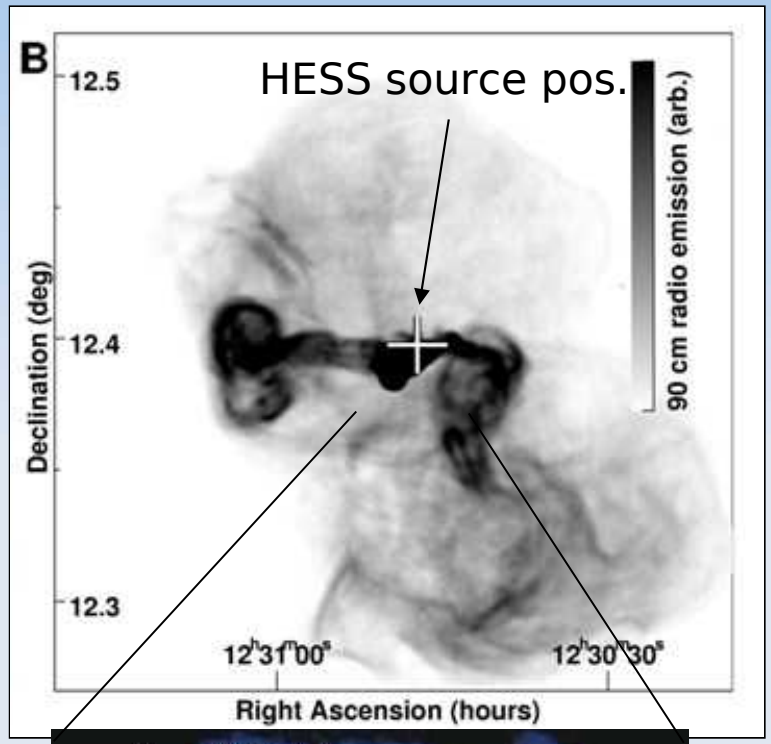
EBL Limits from VHE Spectra

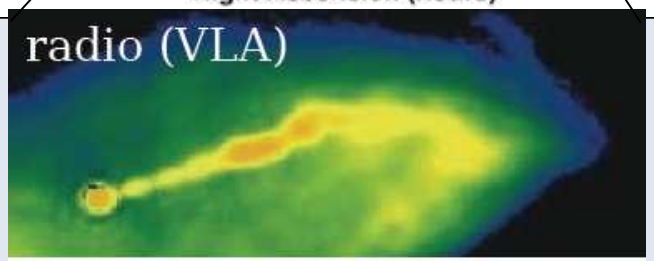


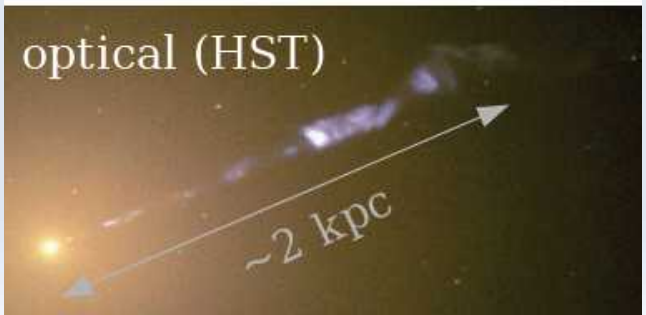
Radiogalaxy example: M 87

- 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







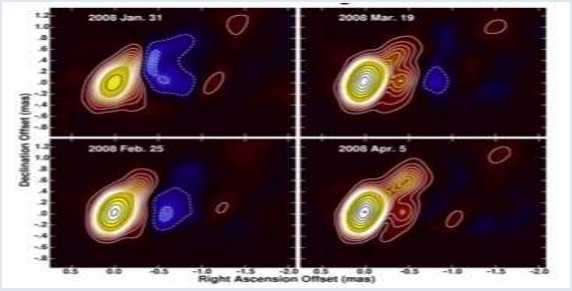
M87 joint observing campaign 2008

Joint VHE campaign:

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

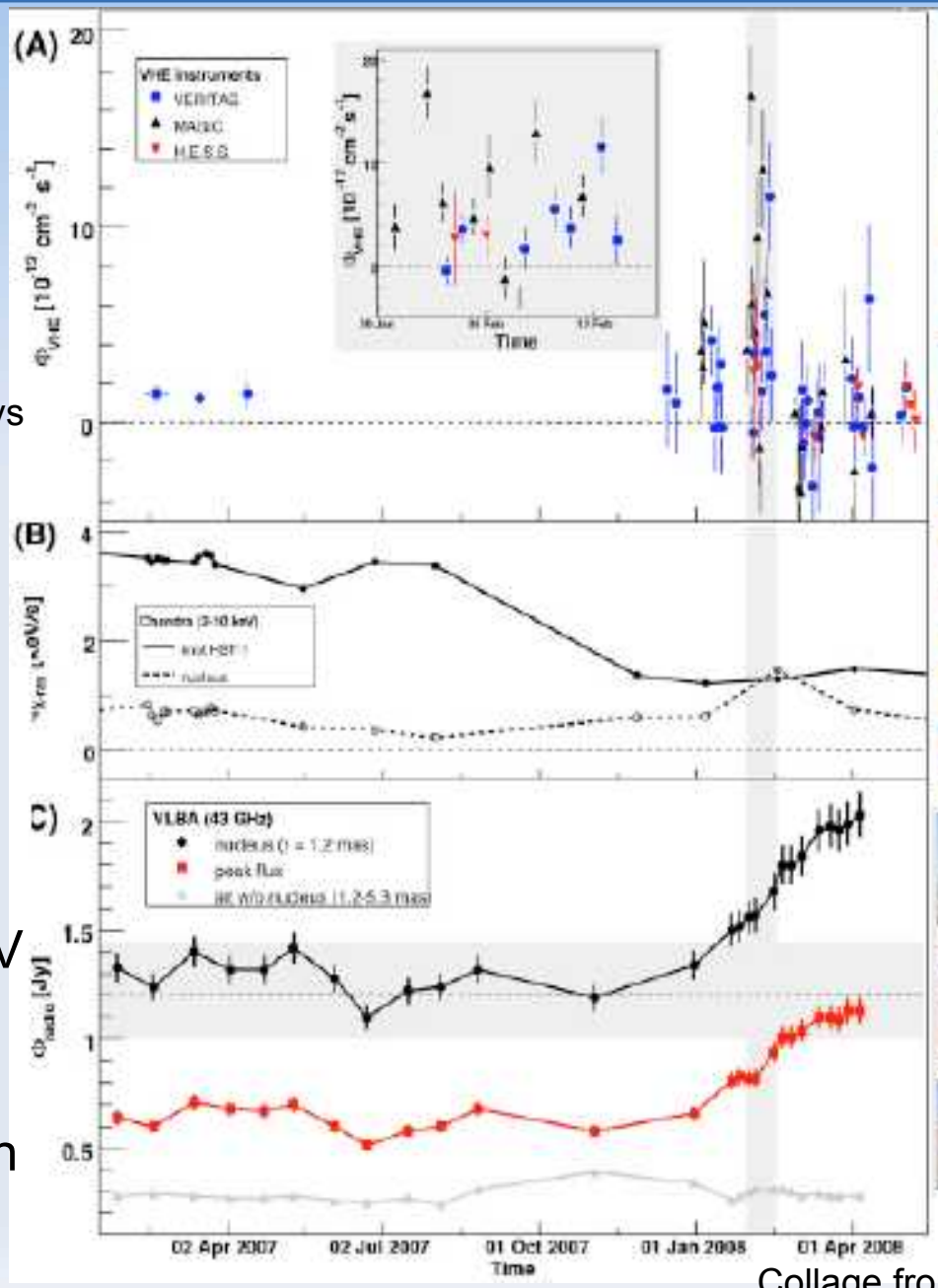
VLBA “movies”

- 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.



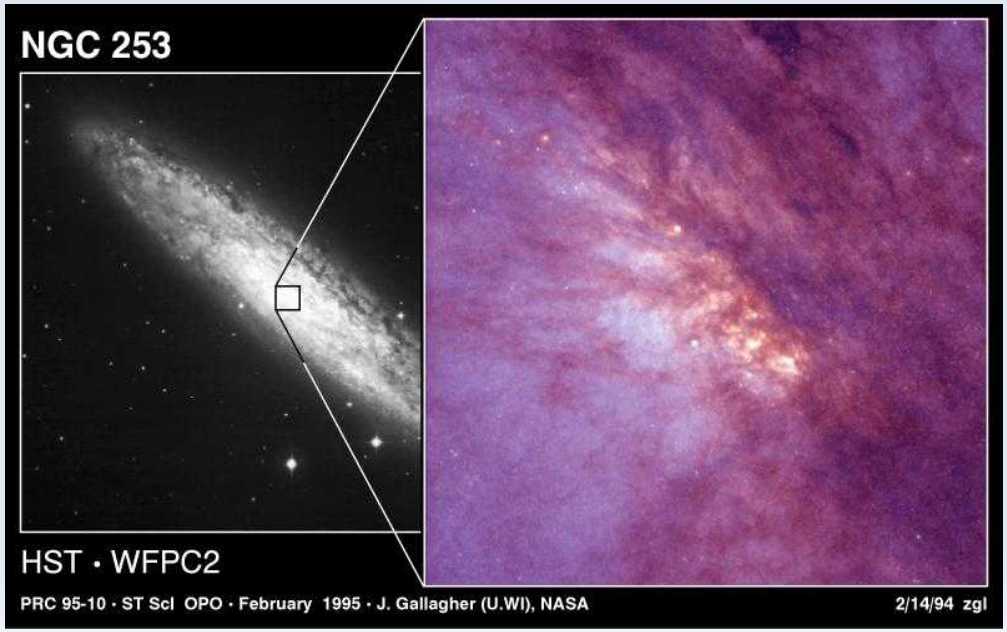
Collage from F. Krennrich, TeVPA 2009

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.
- probing paradigm that SNRs are origin of CR

- 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



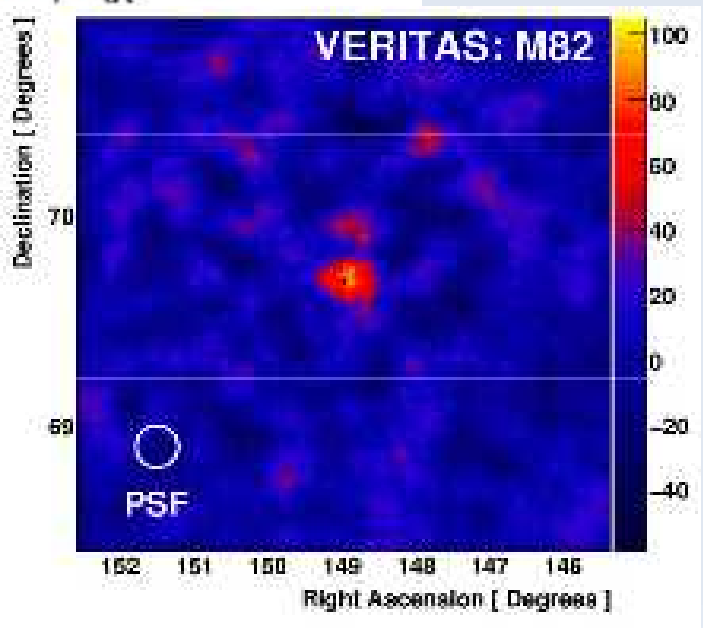
New source category: Starburst galaxies

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

$\Gamma = 2.5 \pm 0.6$

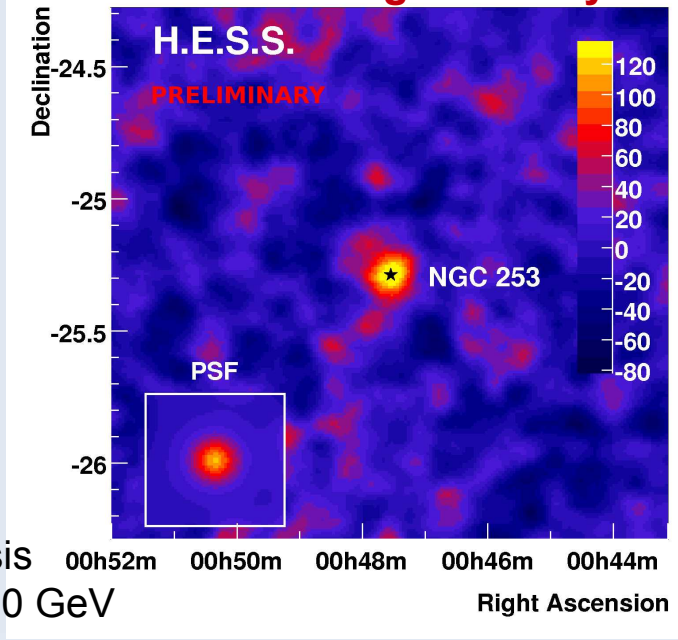


Benbow, ICRC2009

- 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

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

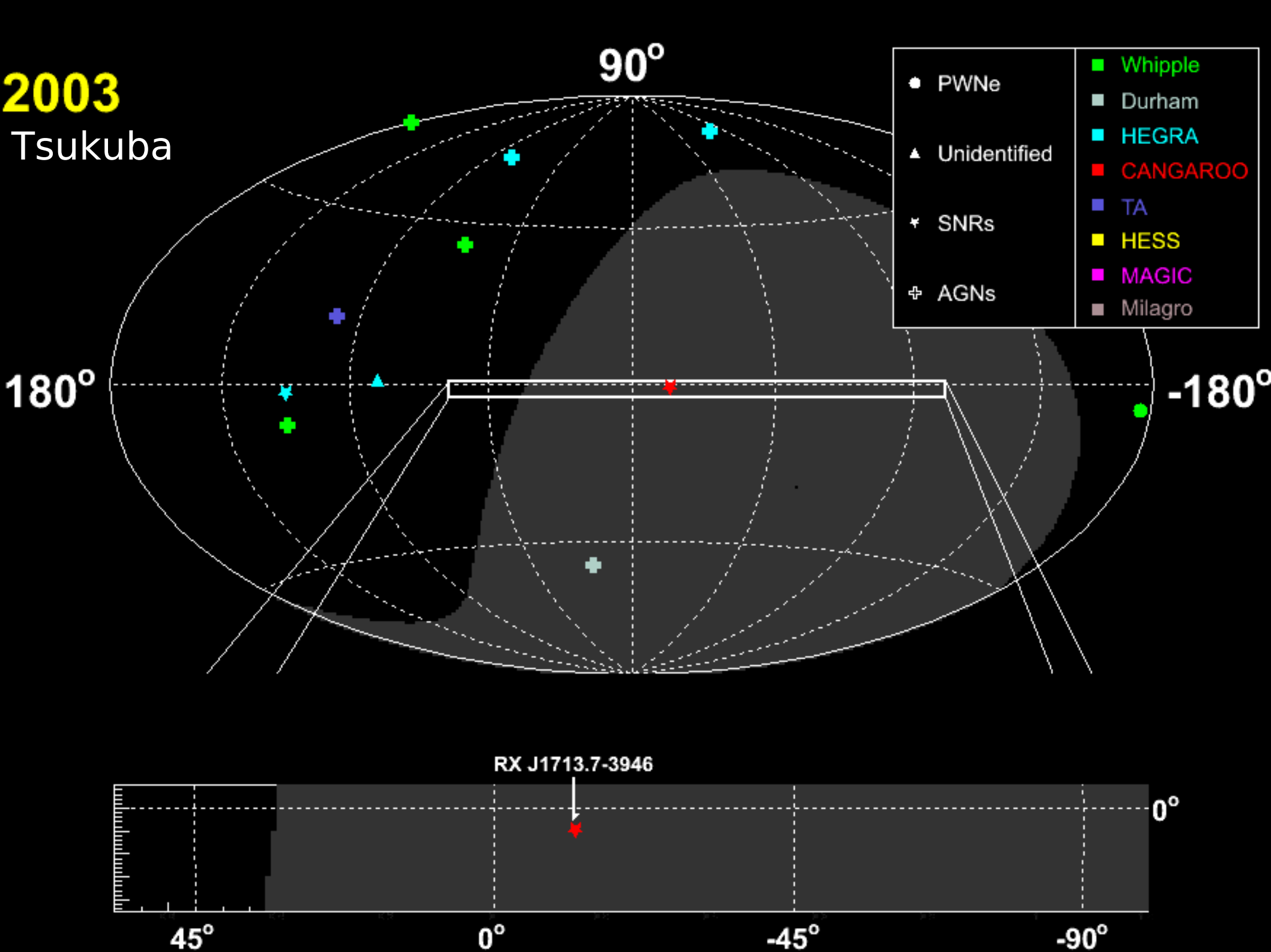
No mention of Diffuse emssion, GRBs, Dark Matter searches, etc...

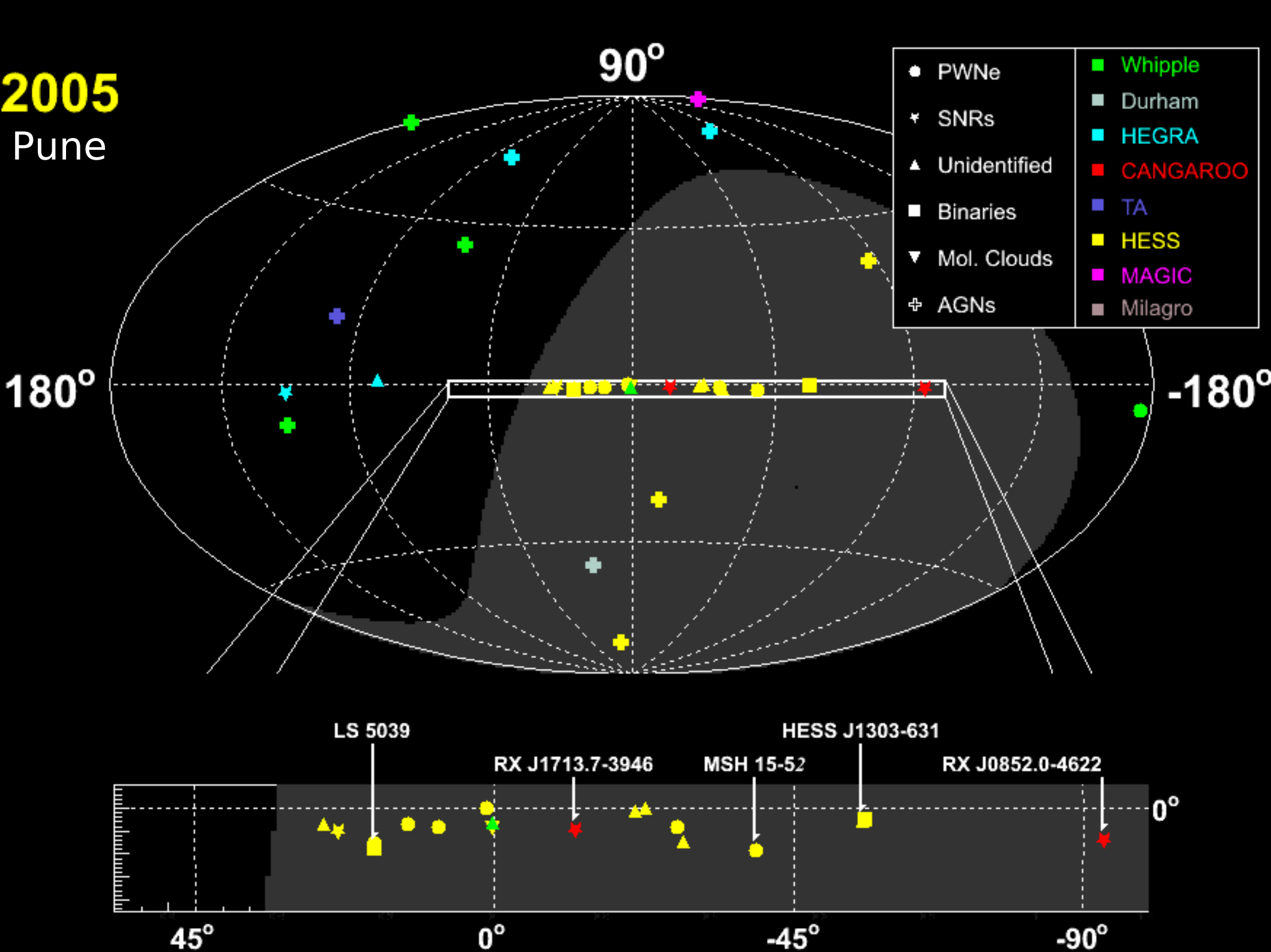
- Gamma-ray astronomy gives us a glimpse into the most energetic regions of the Universe, leading to new insights

- VHE γ -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


2003
Tsukuba
90°
180°
-180°
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°


2005
Pune
90°
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-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
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HESS
MAGIC
Milagro
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
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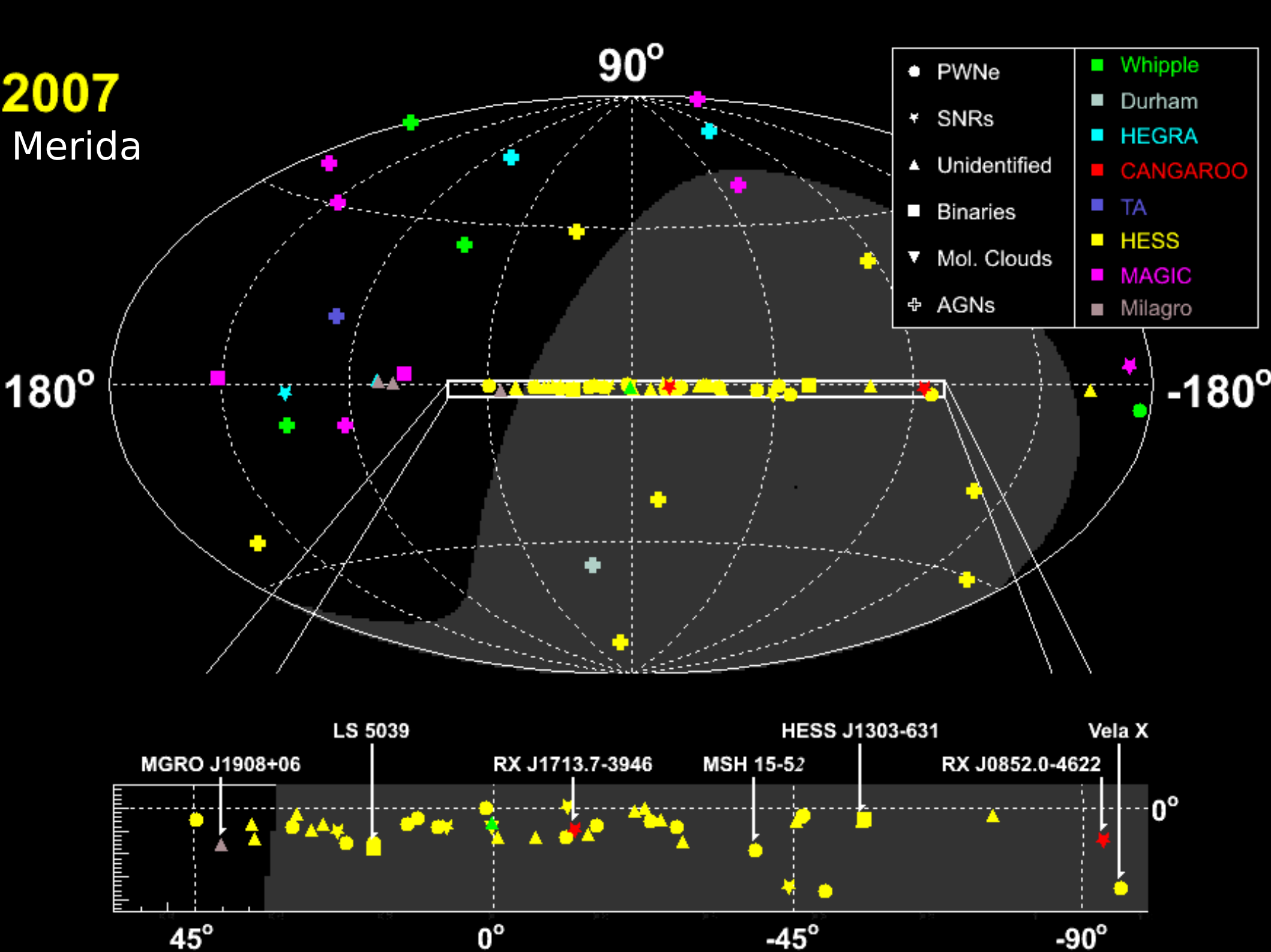
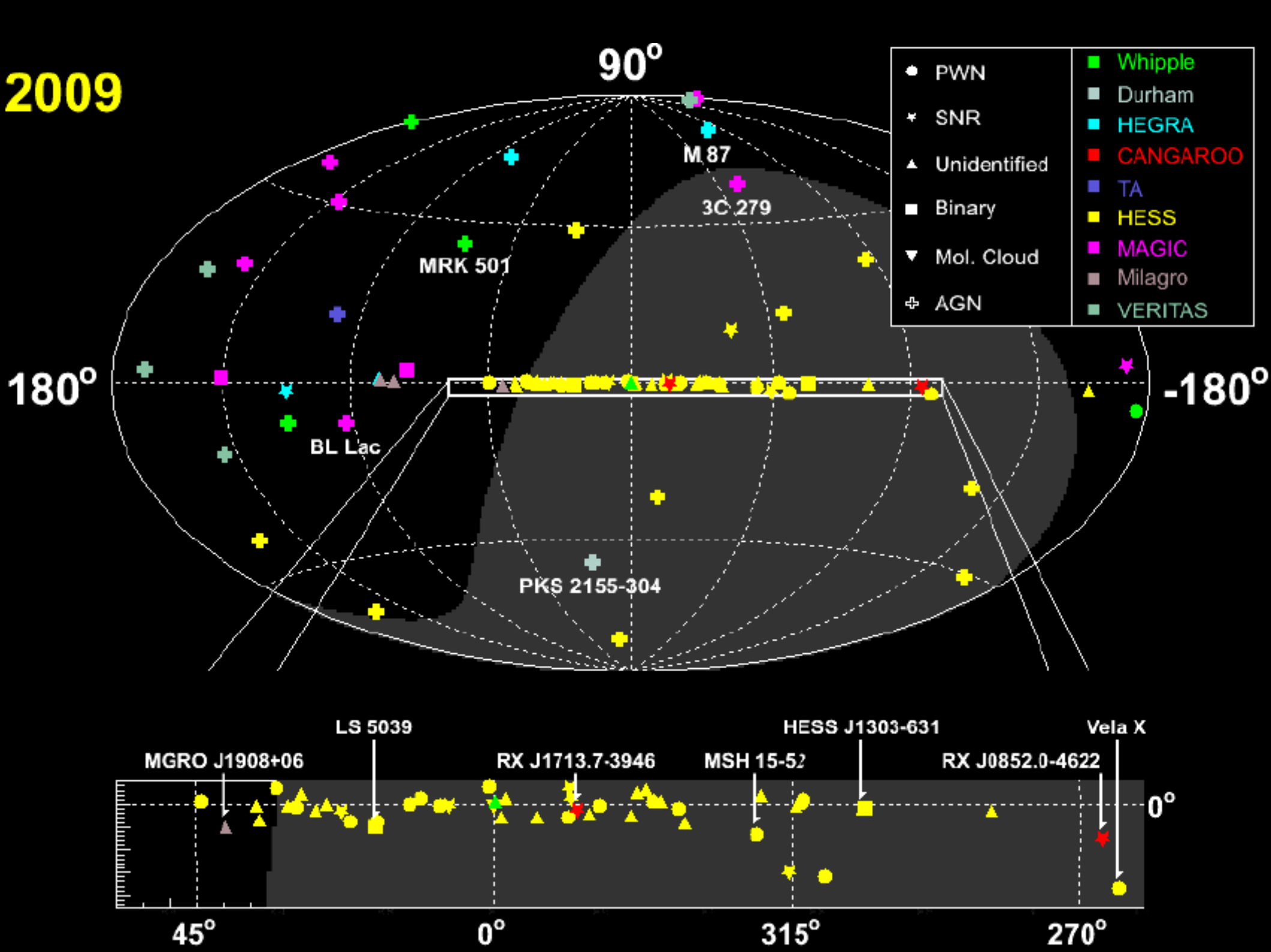
-45°
-90°


2007
Merida
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
-45°
-90°


2009
90°
180°
-180°
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
LS 5039
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
315°
270°

That's all folks...