Highlights of TeV Astrophysics

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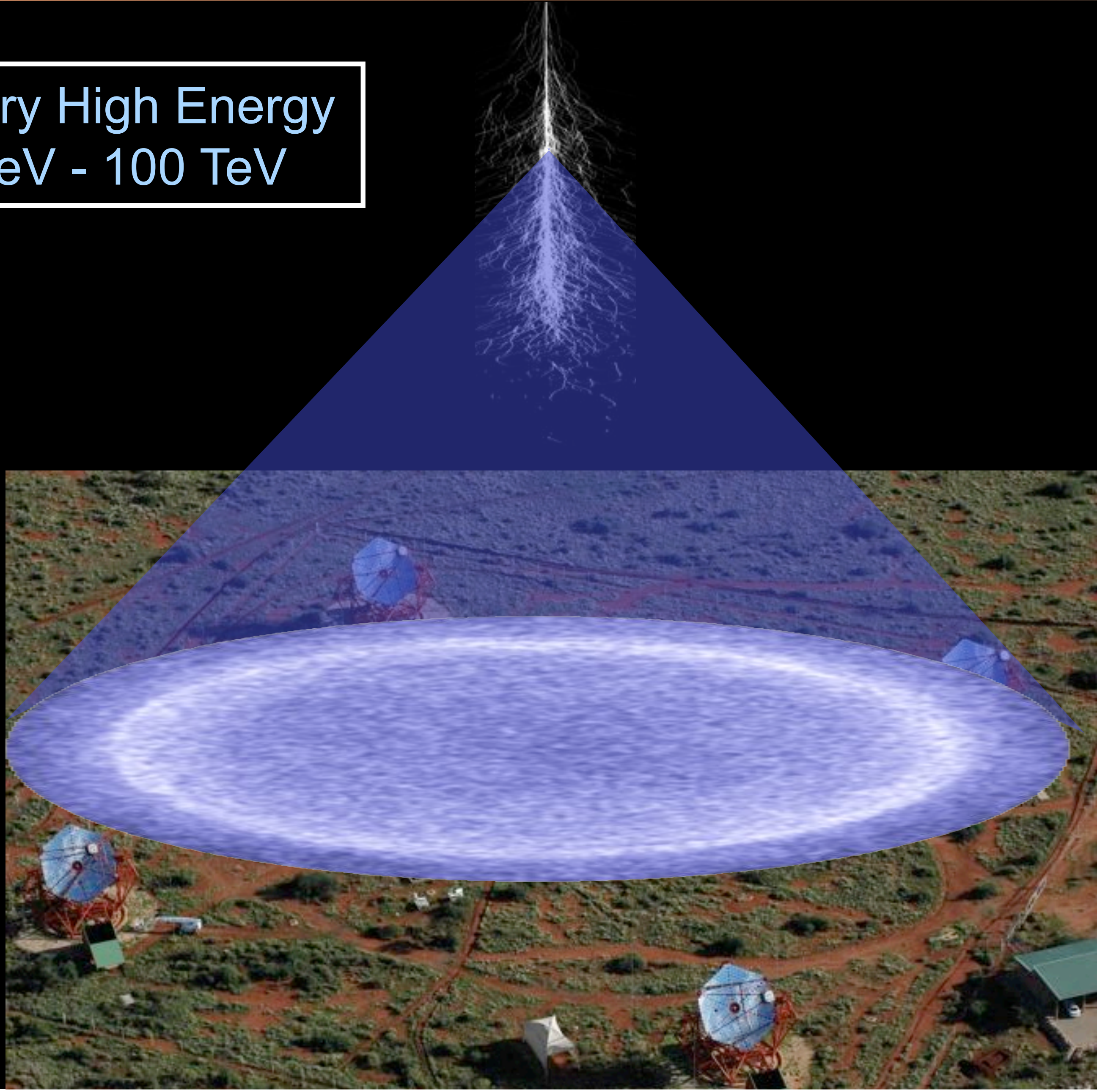
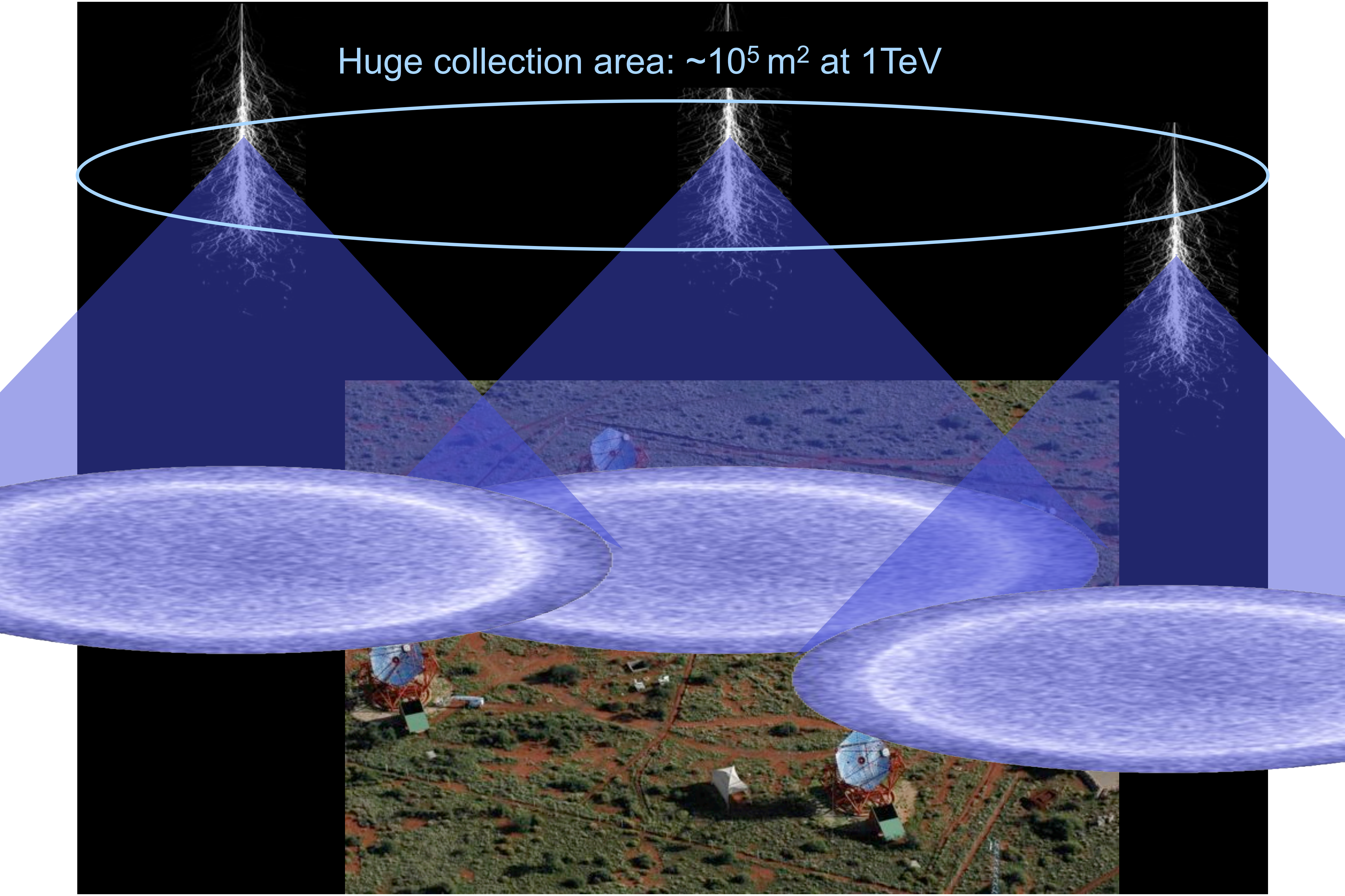
Experimental High Energy Astrophysics: Challenges for the new Decade, Tübingen, July 15-16 2010

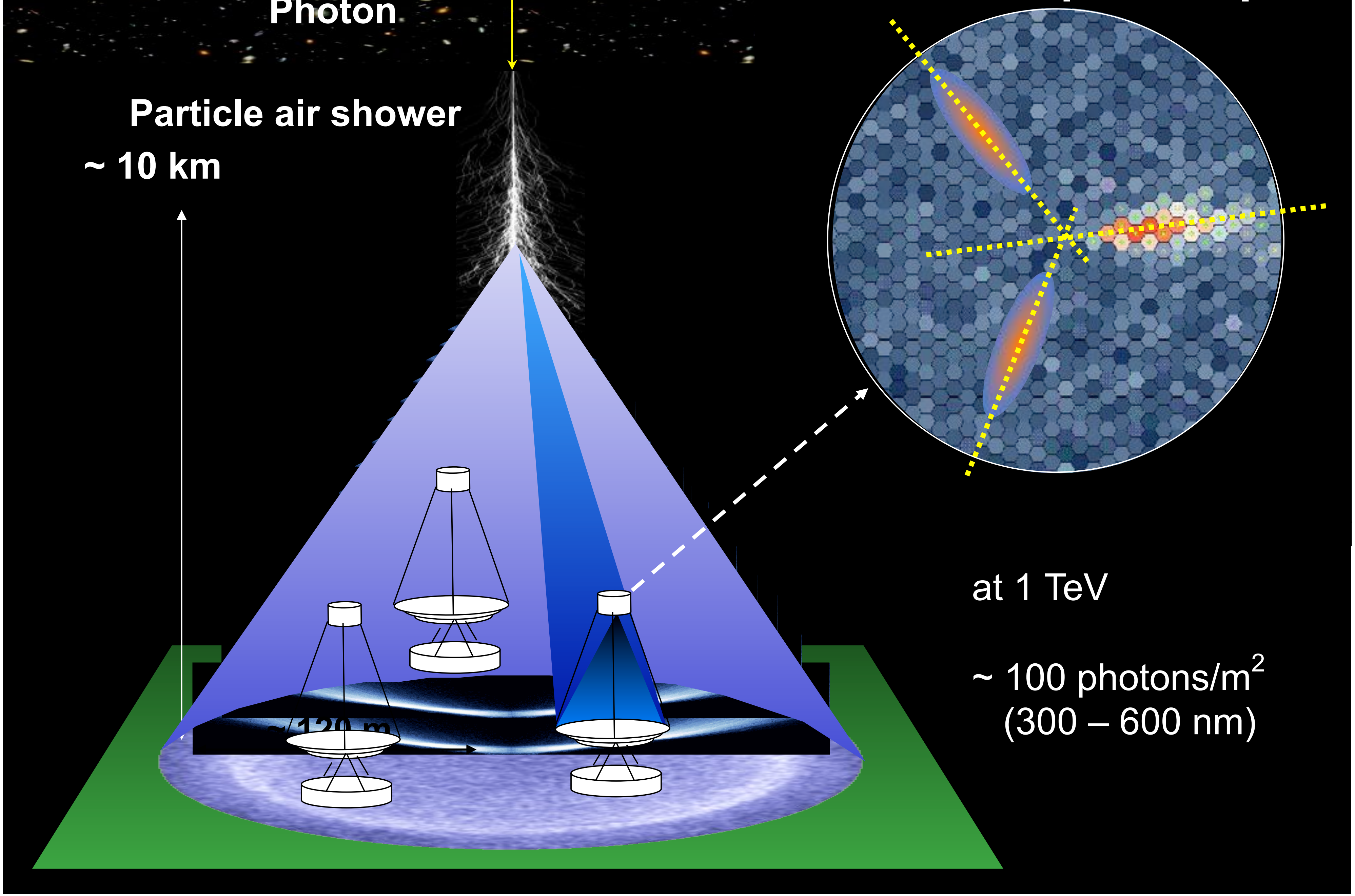
The current generation of VHE instruments

VHE: Very High Energy
100 GeV - 100 TeV

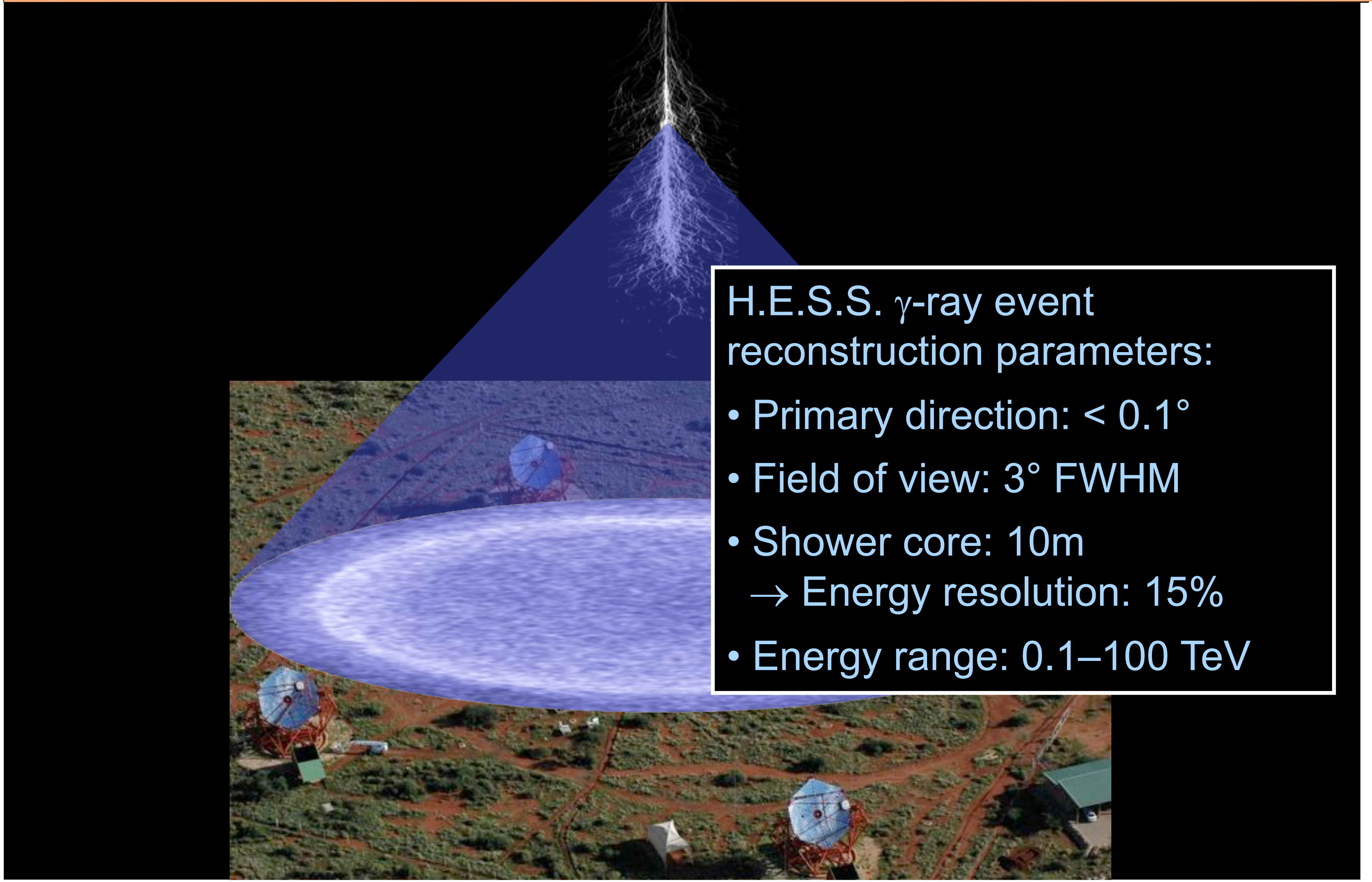



Huge collection area: ~10^5 m^2 at 1TeV

Detection principle



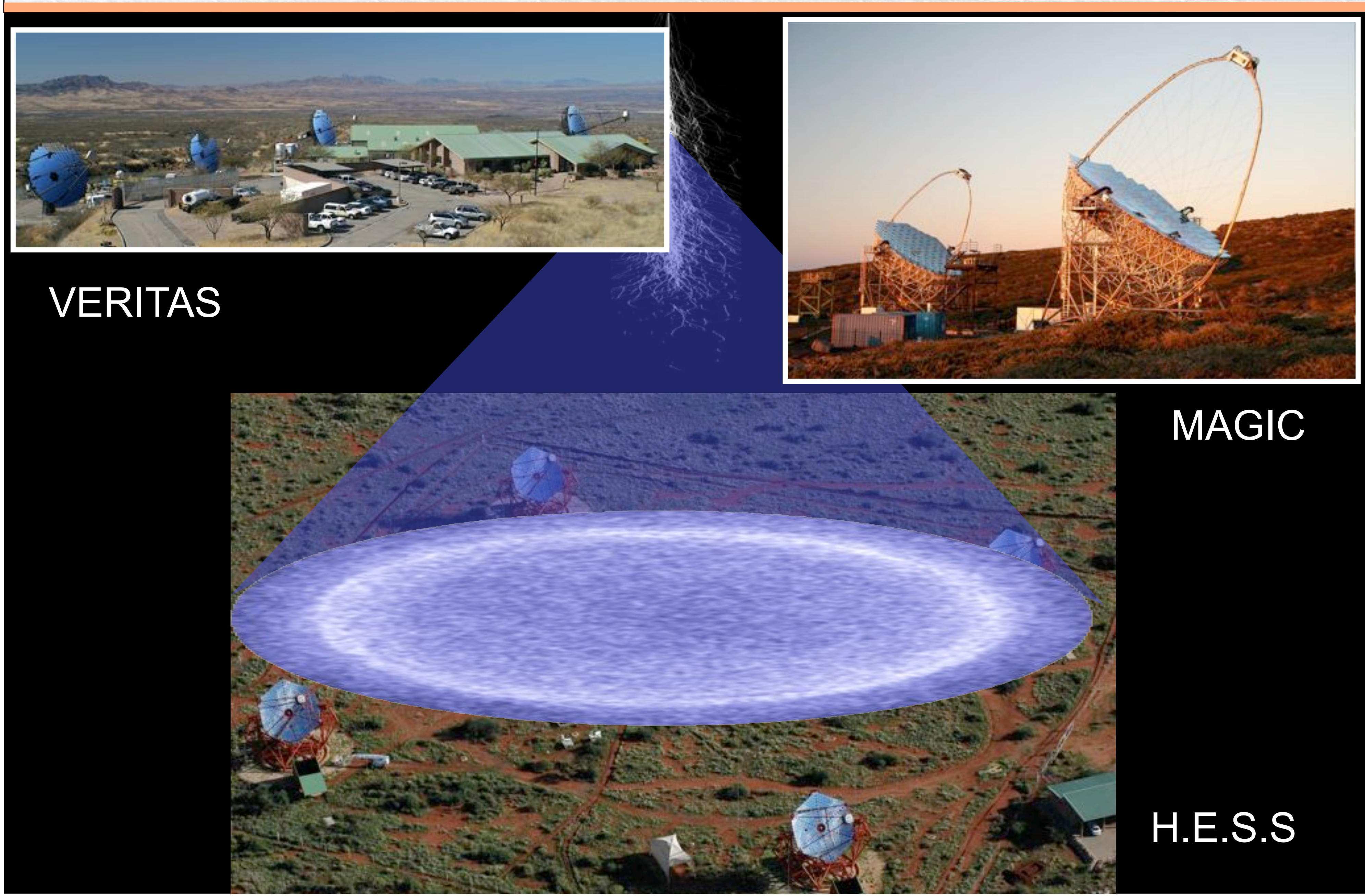
The current generation of VHE instruments



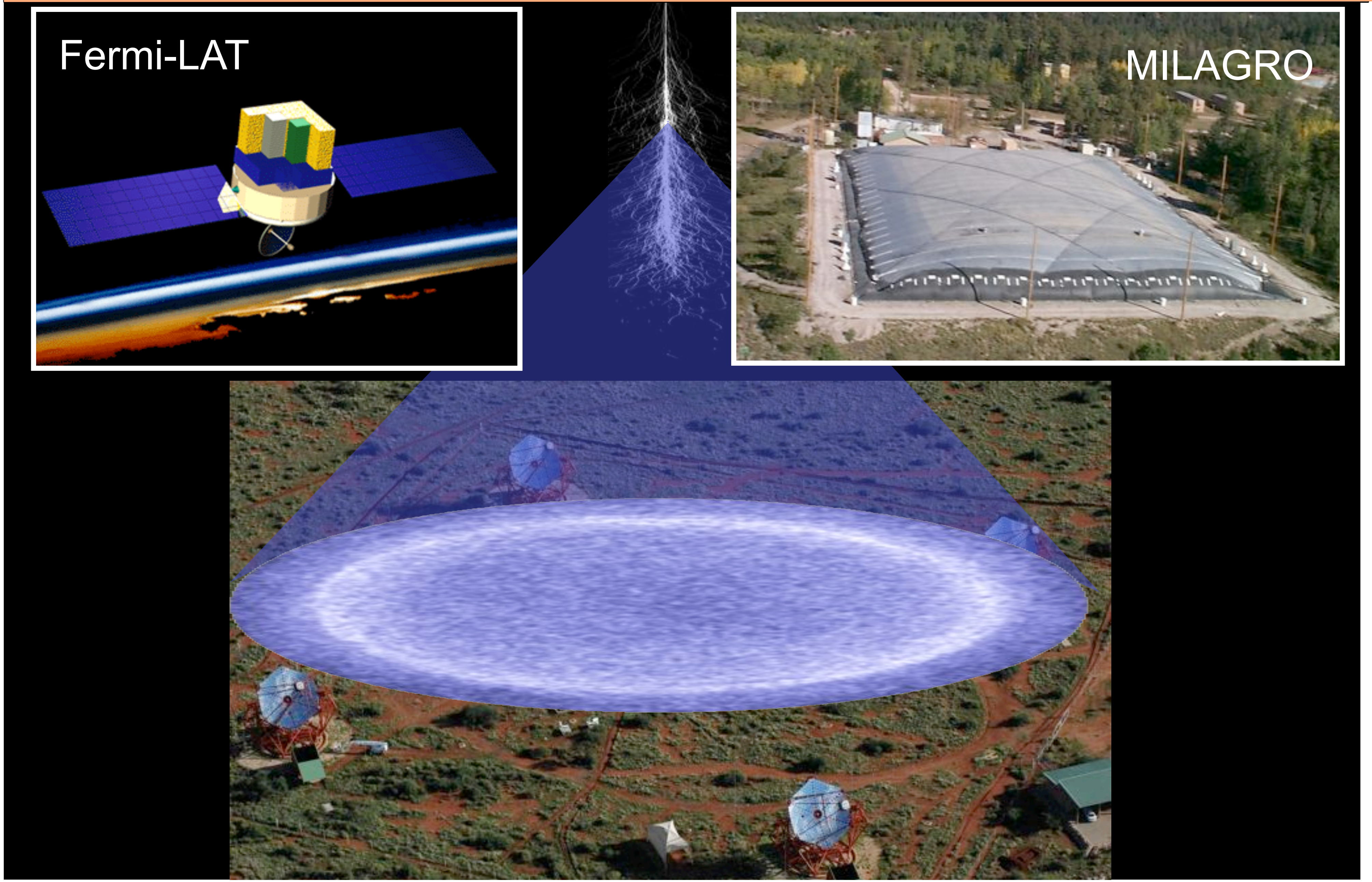
H.E.S.S. γ-ray event reconstruction parameters:

- Primary direction: < 0.1°
- Field of view: 3° FWHM
- Shower core: 10m
  → Energy resolution: 15%
- Energy range: 0.1–100 TeV

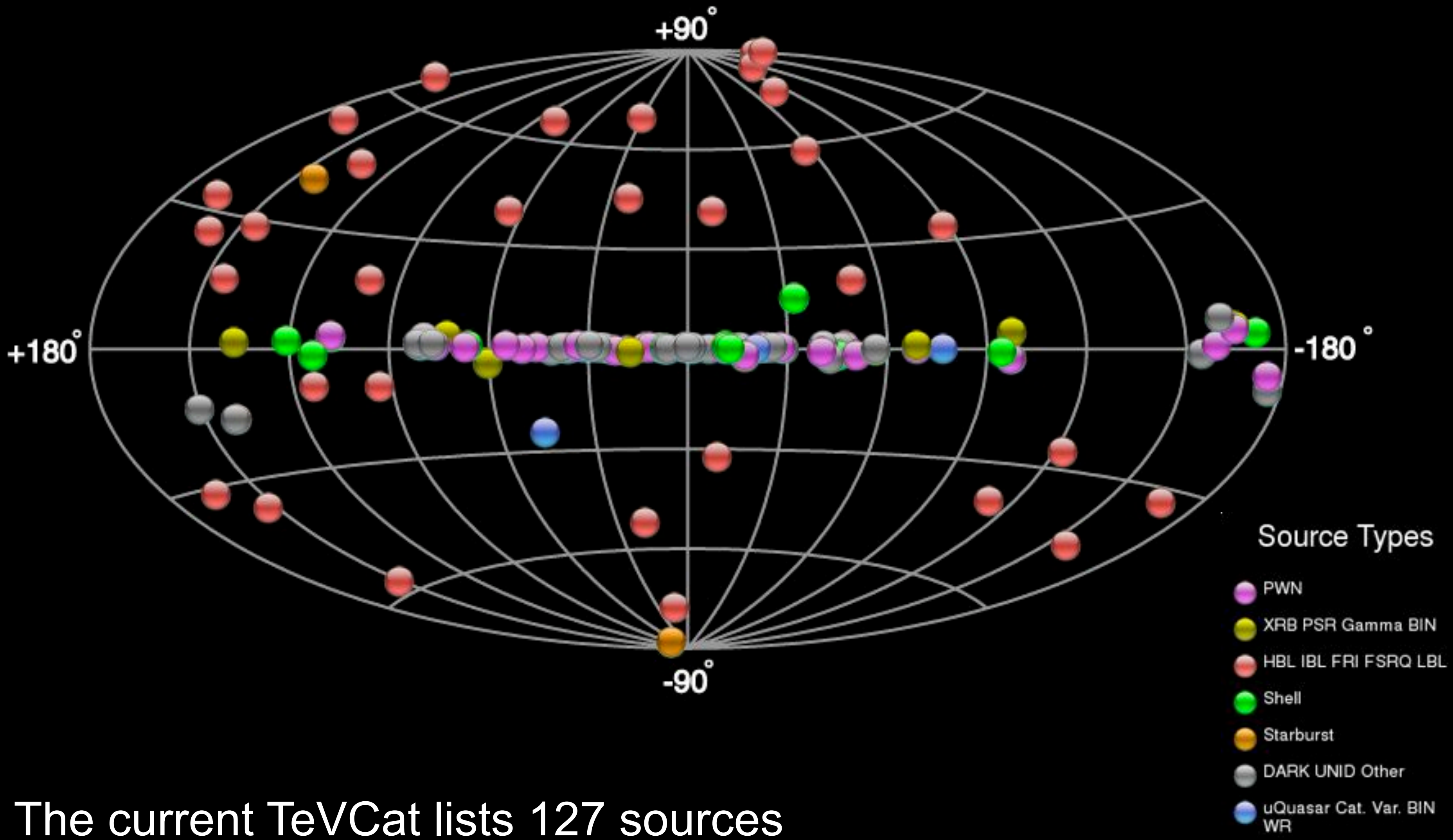
The current generation of VHE instruments



The current generation of VHE instruments



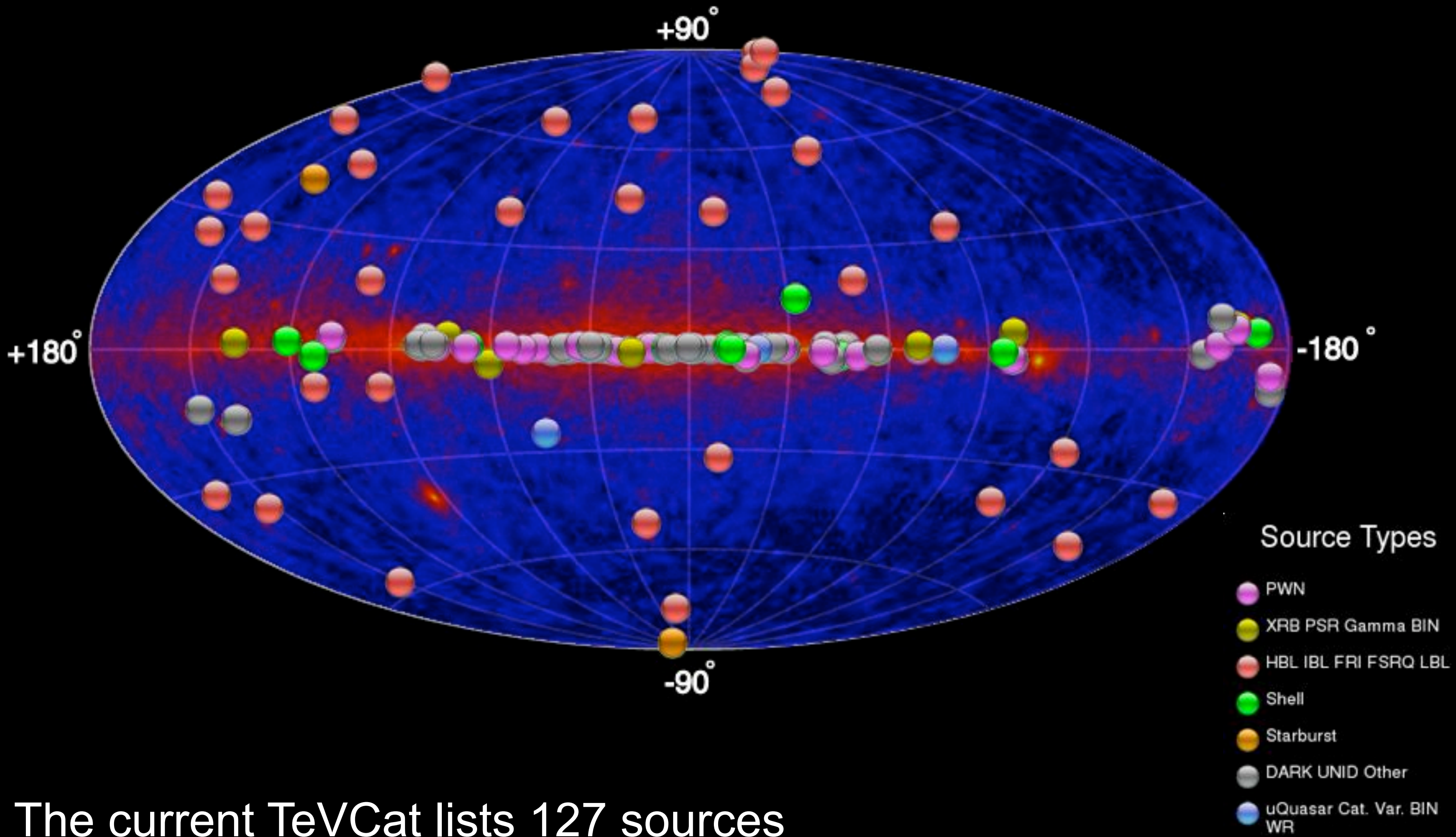
Maybe the biggest highlight: lots of TeV sources



The current TeVCat lists 127 sources

Image Credit: http://tevcat.uchicago.edu/

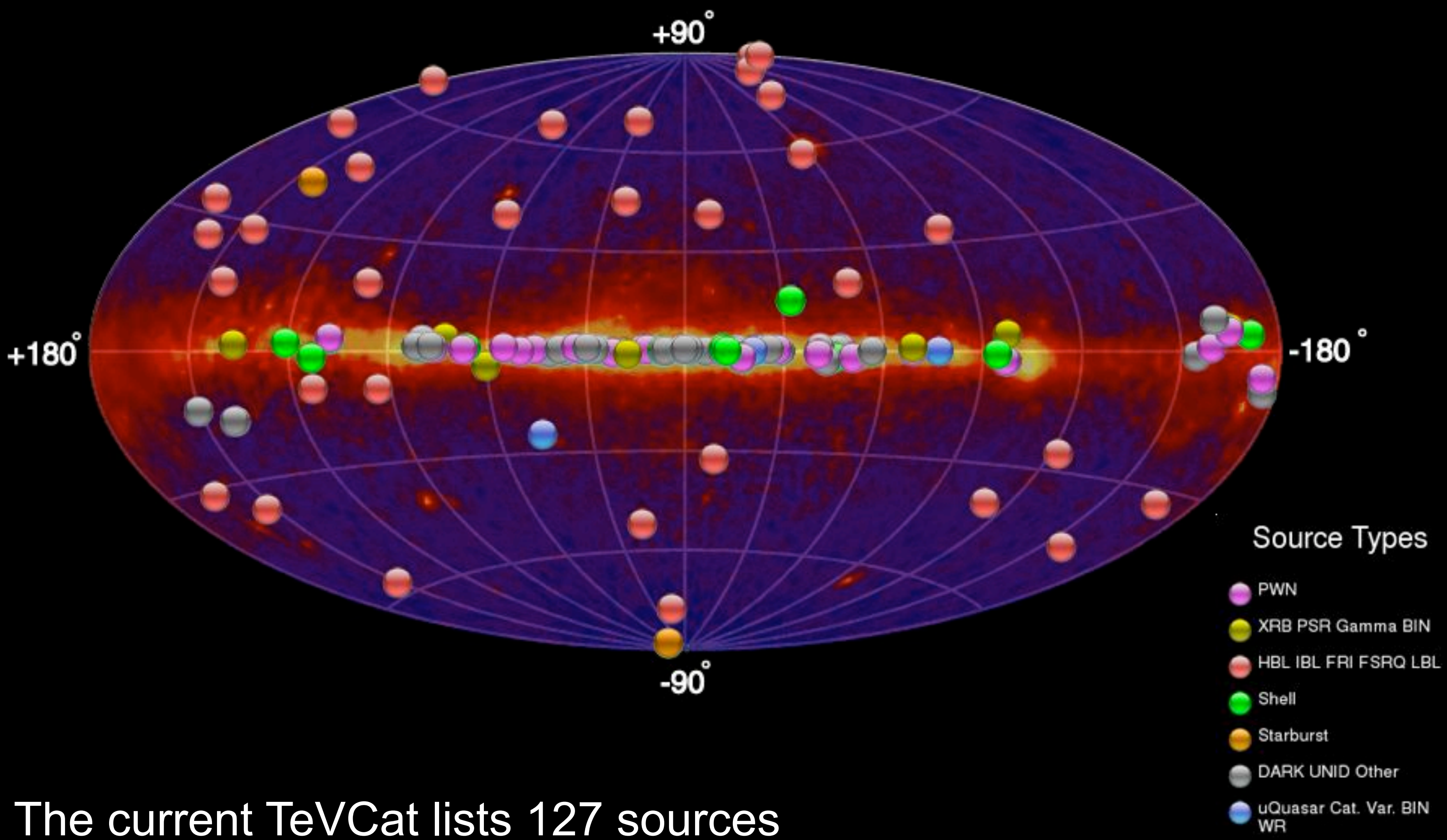
Maybe the biggest highlight: lots of TeV sources



The current TeVCat lists 127 sources
Compare to Fermi-LAT ...

Image Credit: http://tevcat.uchicago.edu/

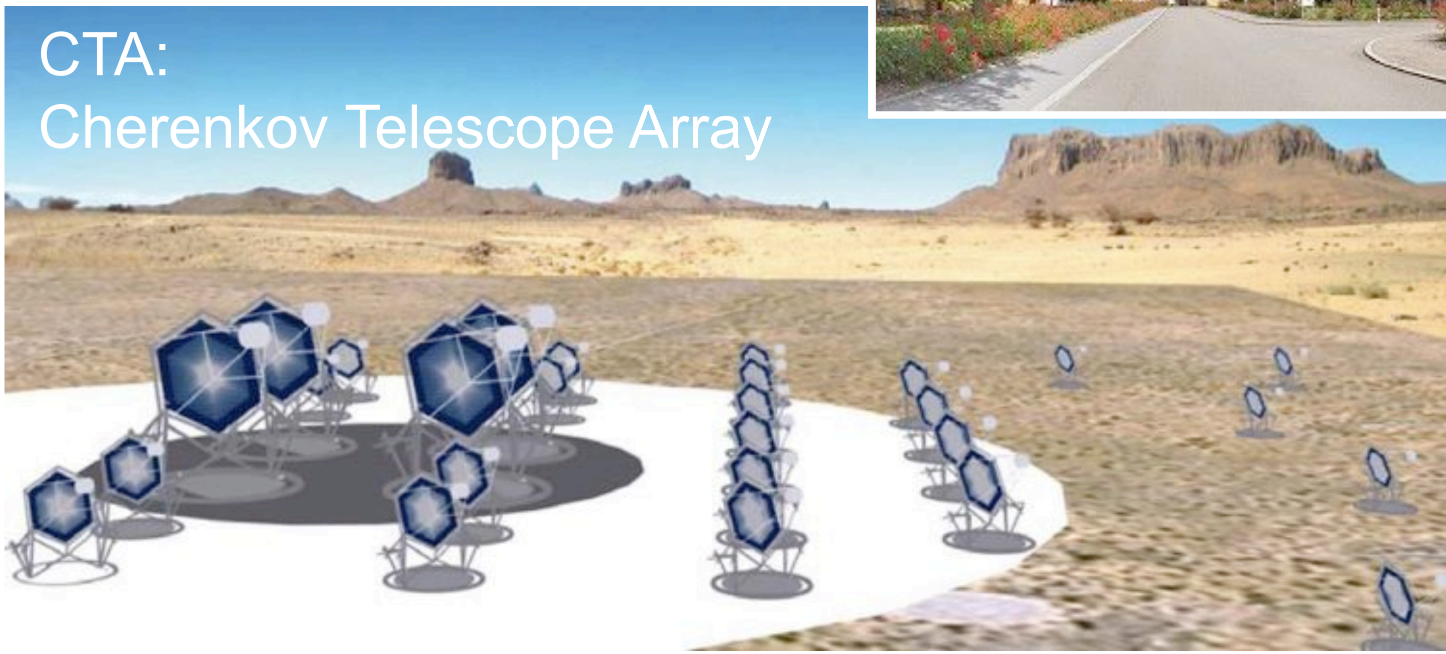
Maybe the biggest highlight: lots of TeV sources

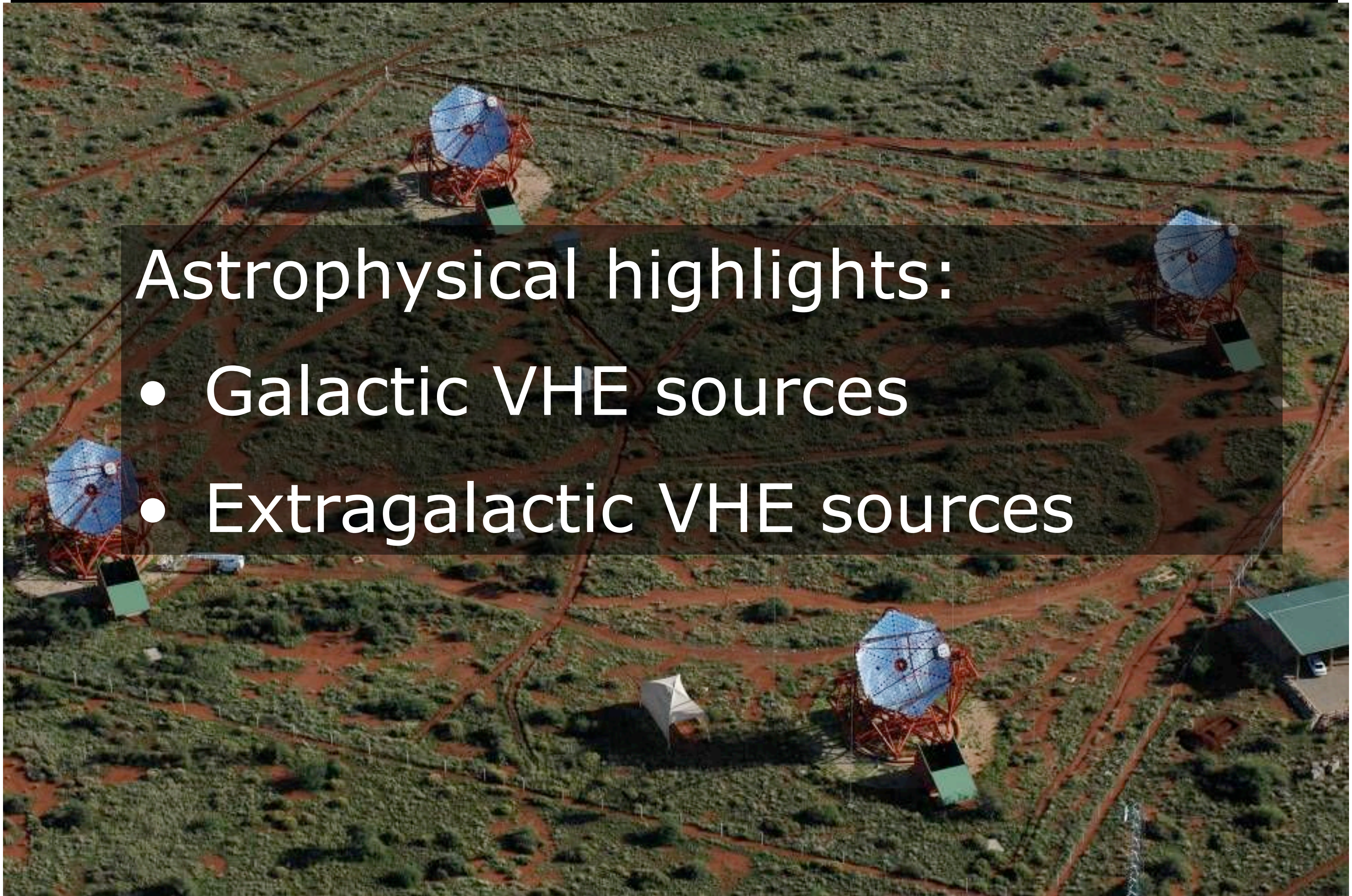


The current TeVCat lists 127 sources
Compare to EGRET onboard CGRO ...

Image Credit: http://tevcat.uchicago.edu/

Conclusion

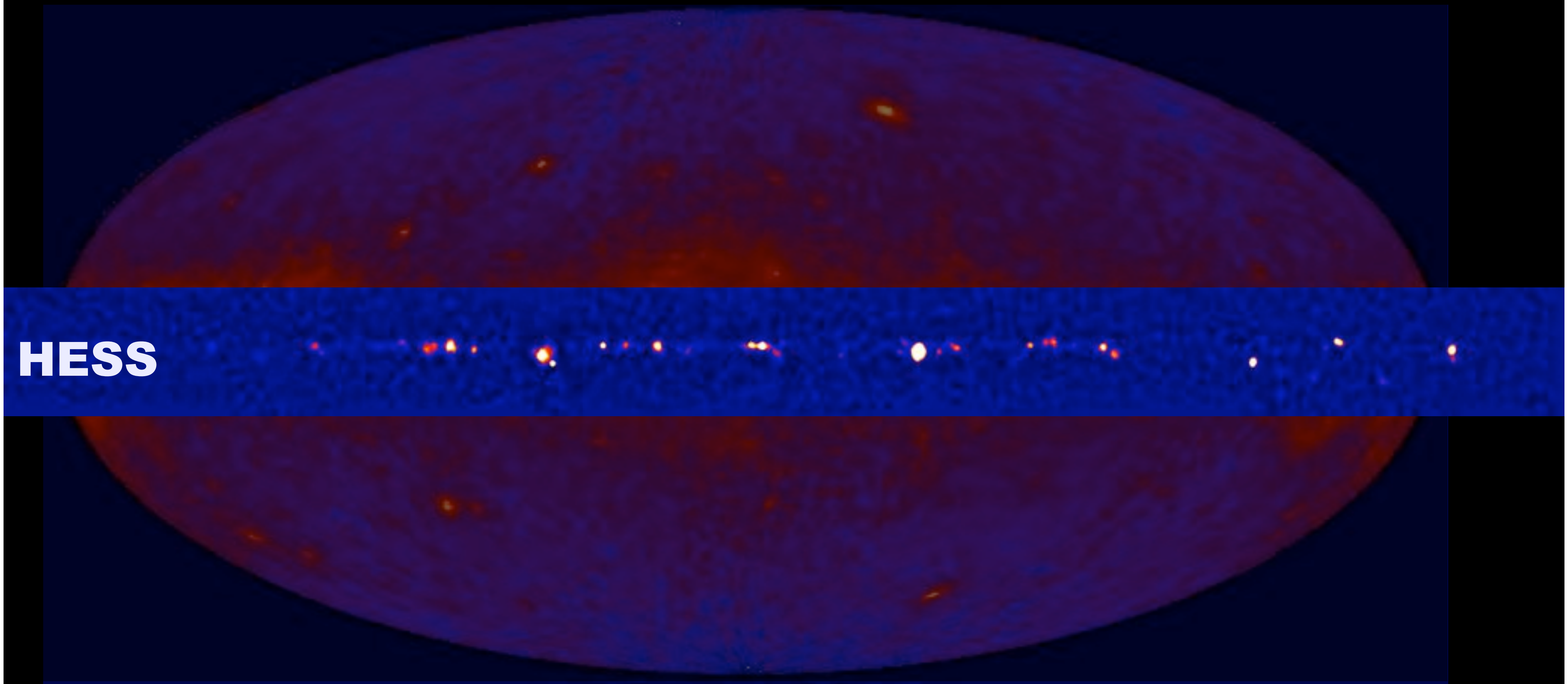




Astrophysical highlights:

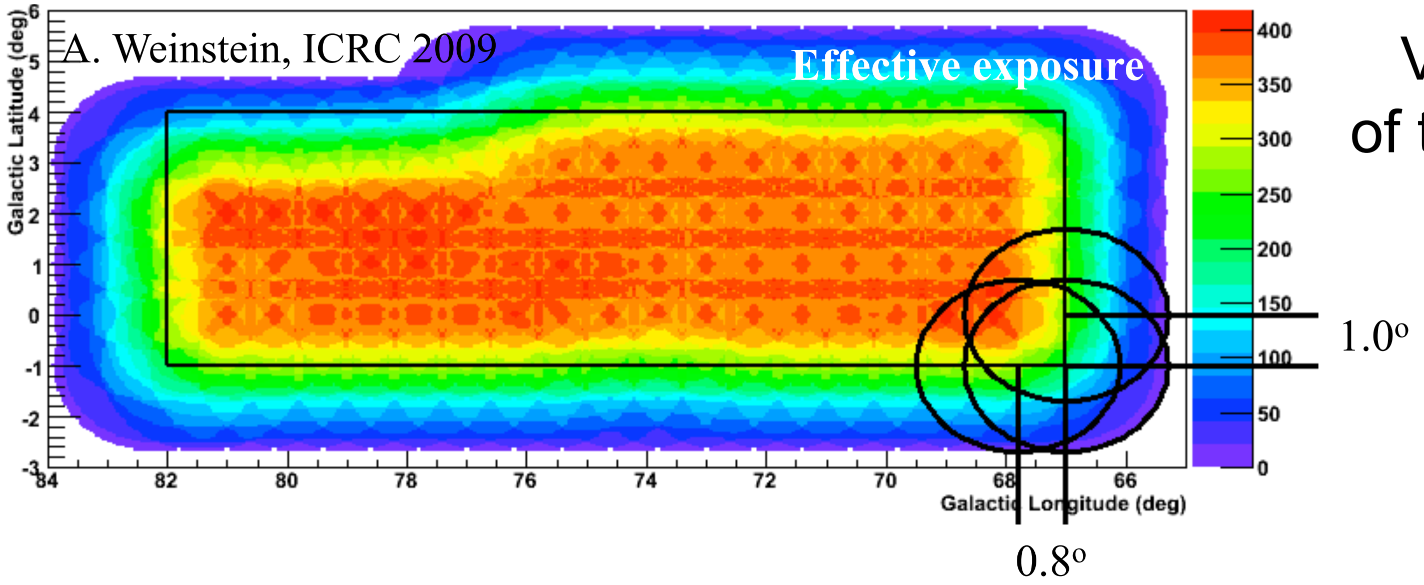
- Galactic VHE sources
- Extragalactic VHE sources

Very High Energy γ-rays: Surveys

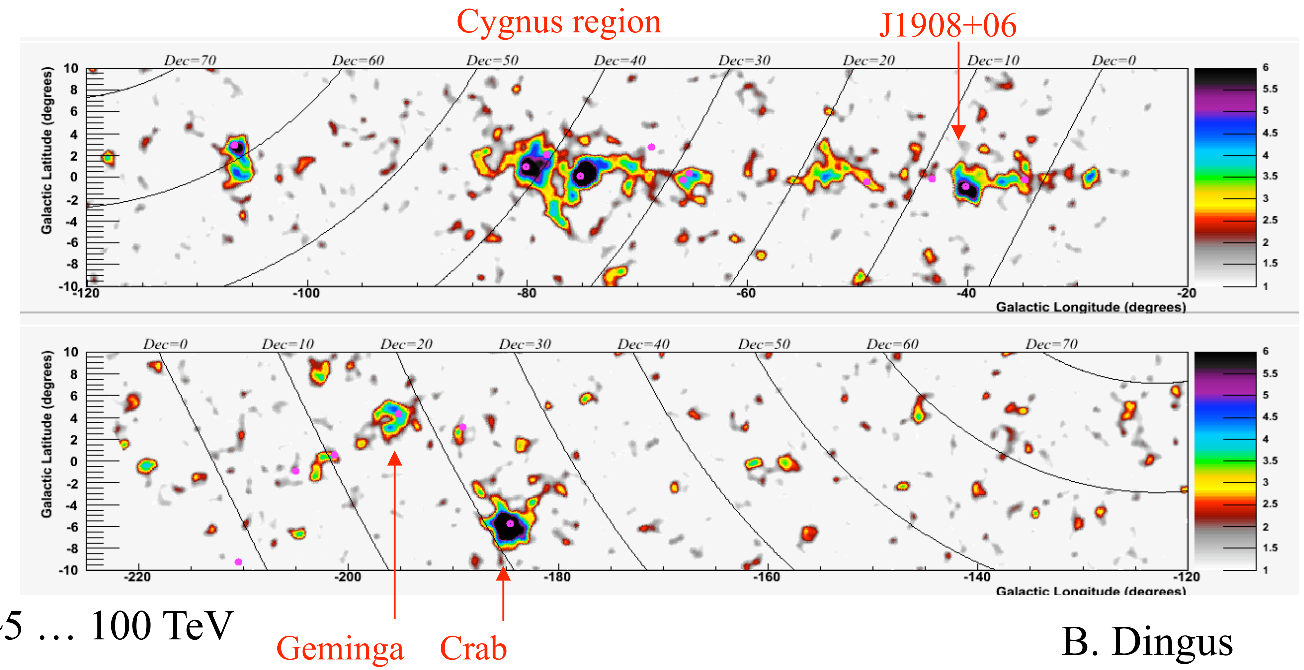


- Dominated by sources
- sources cluster at b=0° ⇒ Galactic, some kpc distance
- View on the highest (particle and γ-ray) energies

Very High Energy γ-rays: Surveys



VERITAS Survey
of the Cygnus region



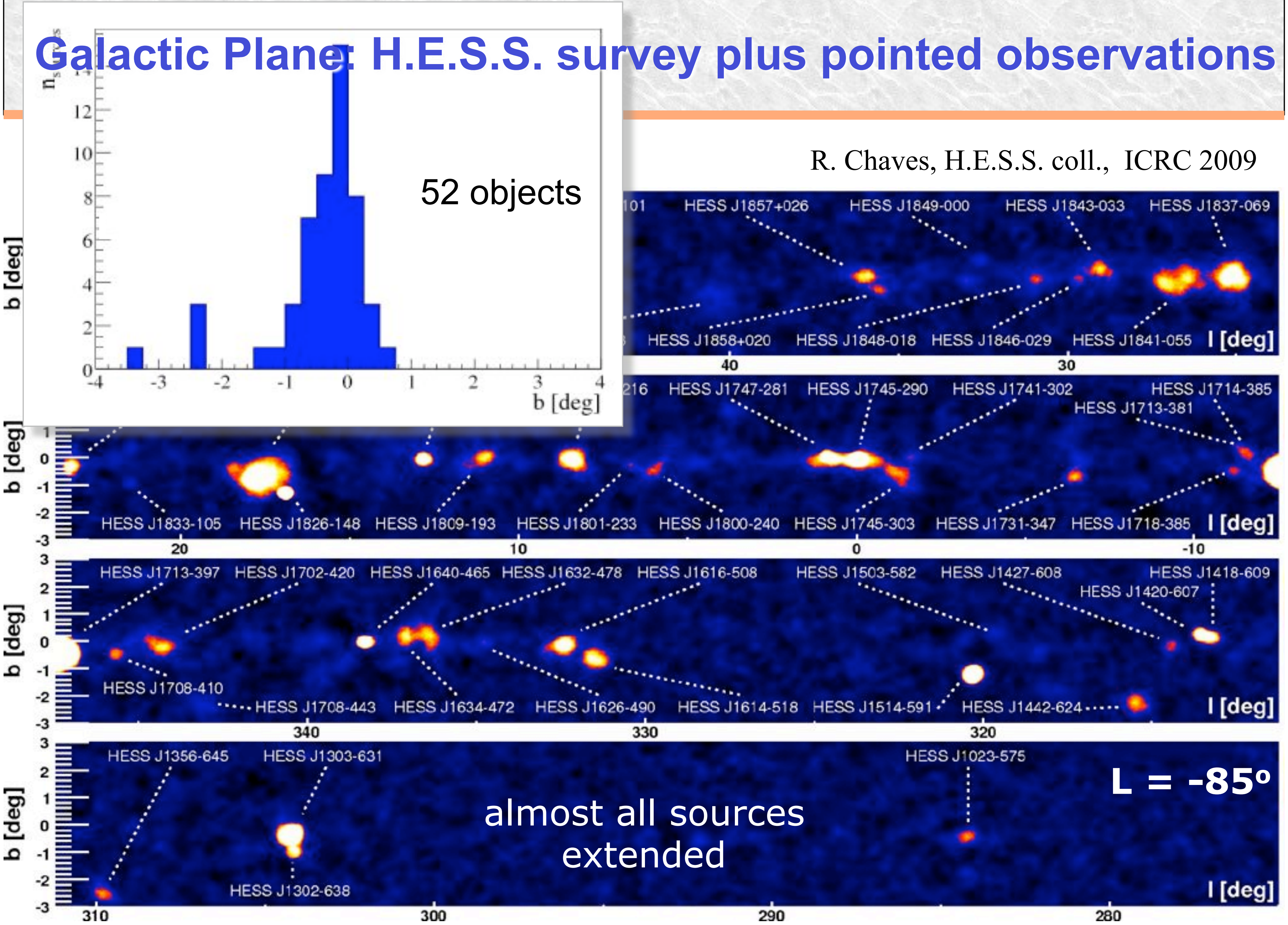
MILAGRO Survey
of the Northern Sky

Energy range ~5 … 100 TeV

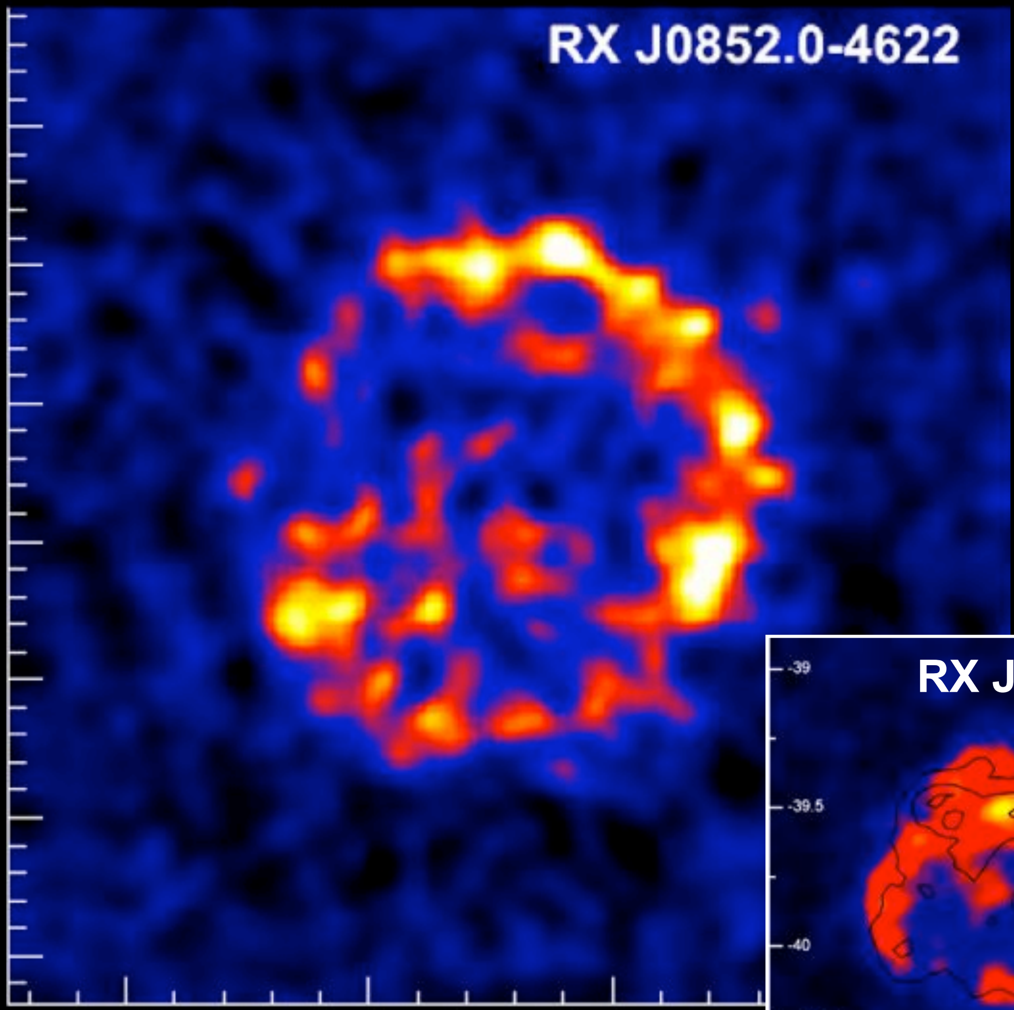
B. Dingus

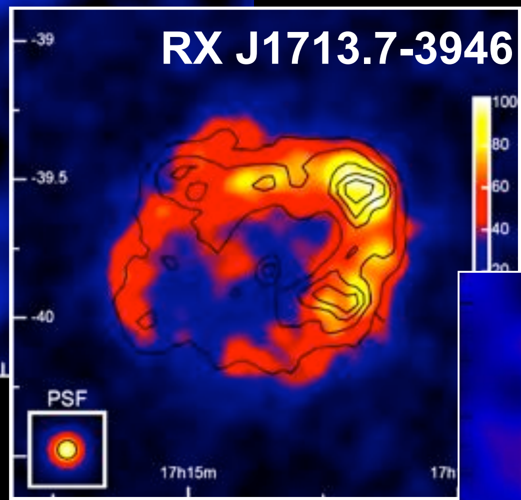
Galactic Plane: H.E.S.S. survey plus pointed observations

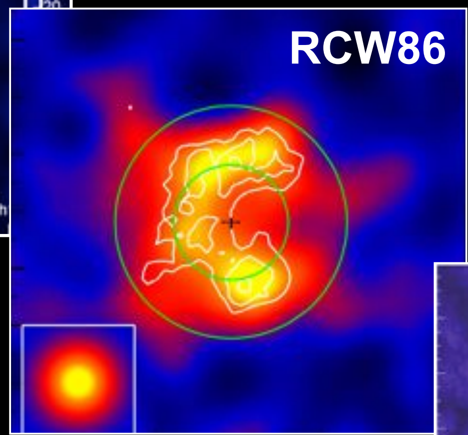
R. Chaves, H.E.S.S. coll., ICRC 2009

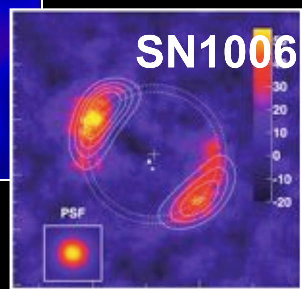


Resolved shell-type supernova remnants in the VHE band



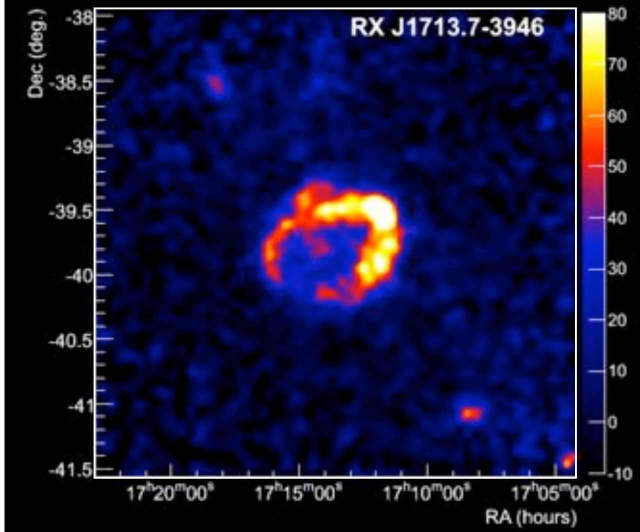


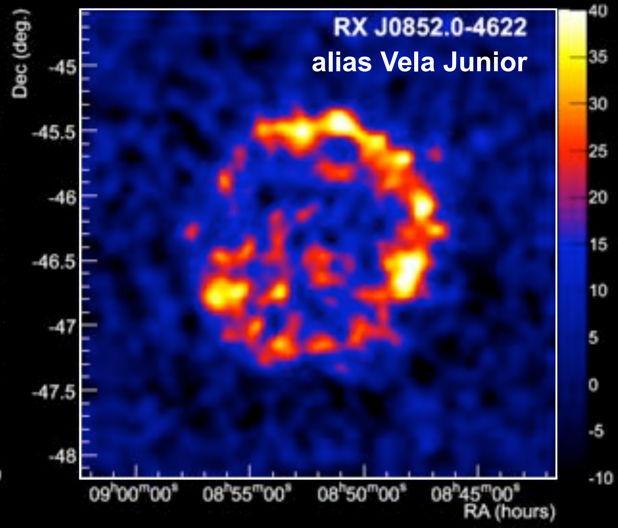




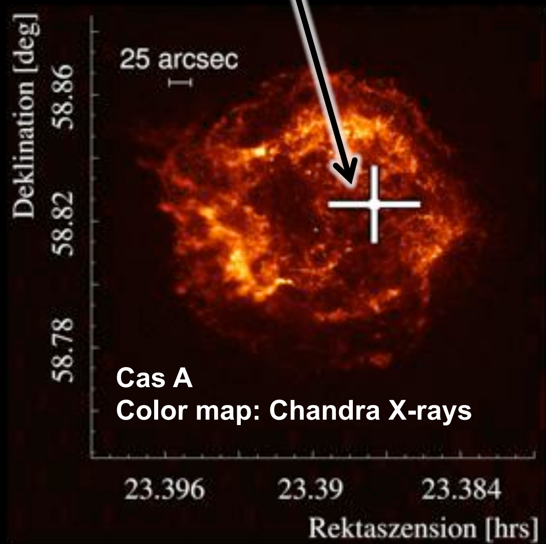
roughly to scale

Young SNR shells resolved in TeV

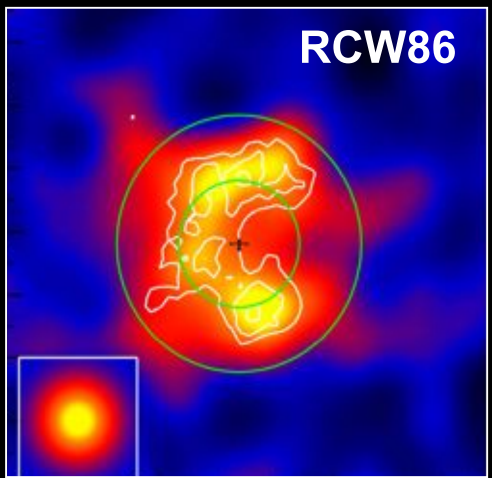


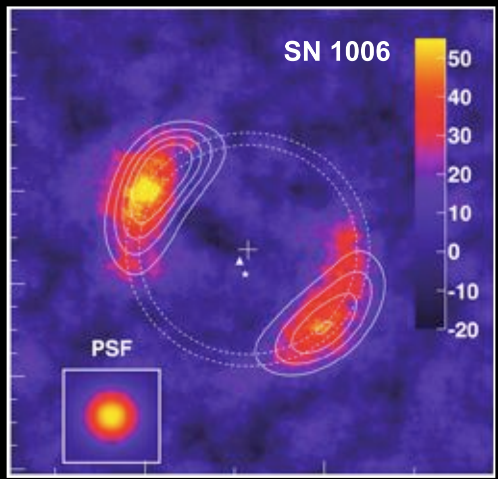


+ Cassiopeia A
(HEGRA coll., MAGIC coll., VERITAS coll.)



unresolved in TeV, but almost certainly dominated by shell emission

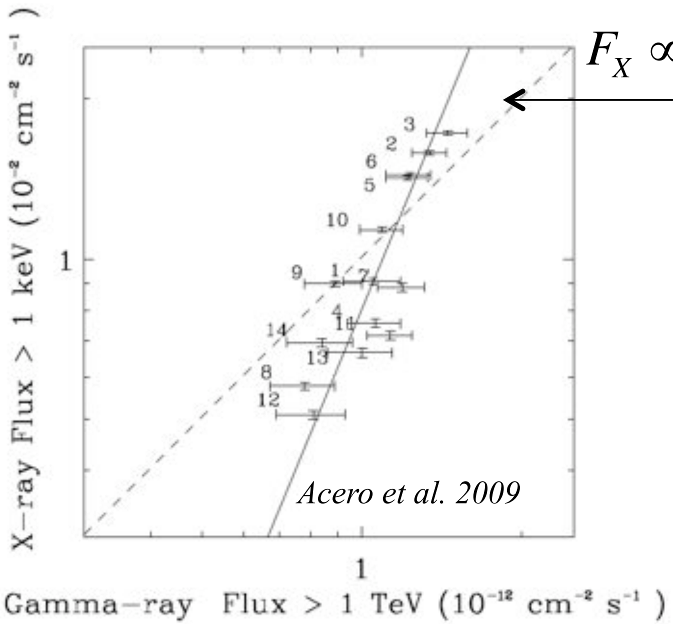




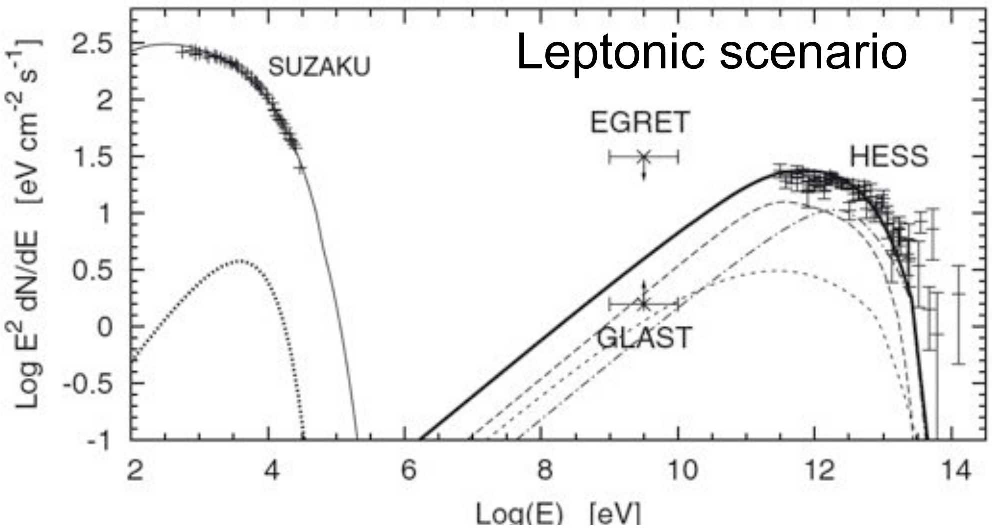
+ recent discovery of TeV emission from Tycho's SNR (VERITAS coll.), but shell dominance not (yet?) clear

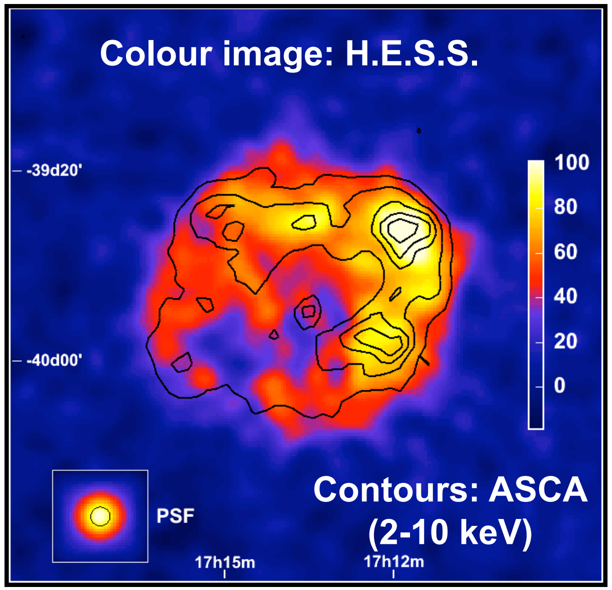
A little bit of shell SNR physics: RXJ 1713.7-3946

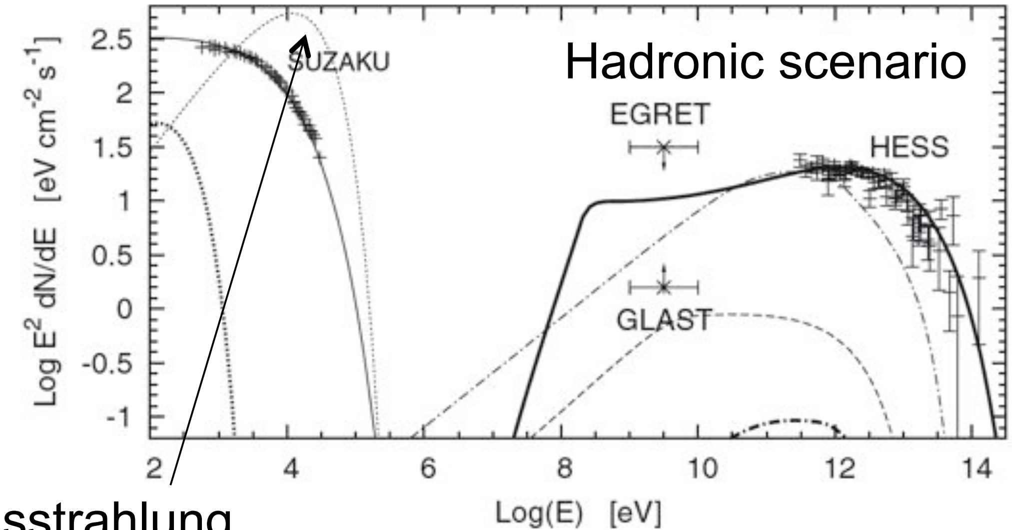
$F_X \propto F_\gamma^{2.41\pm0.55}$ favours leptonic origin (?)



Morlino et al. 2009



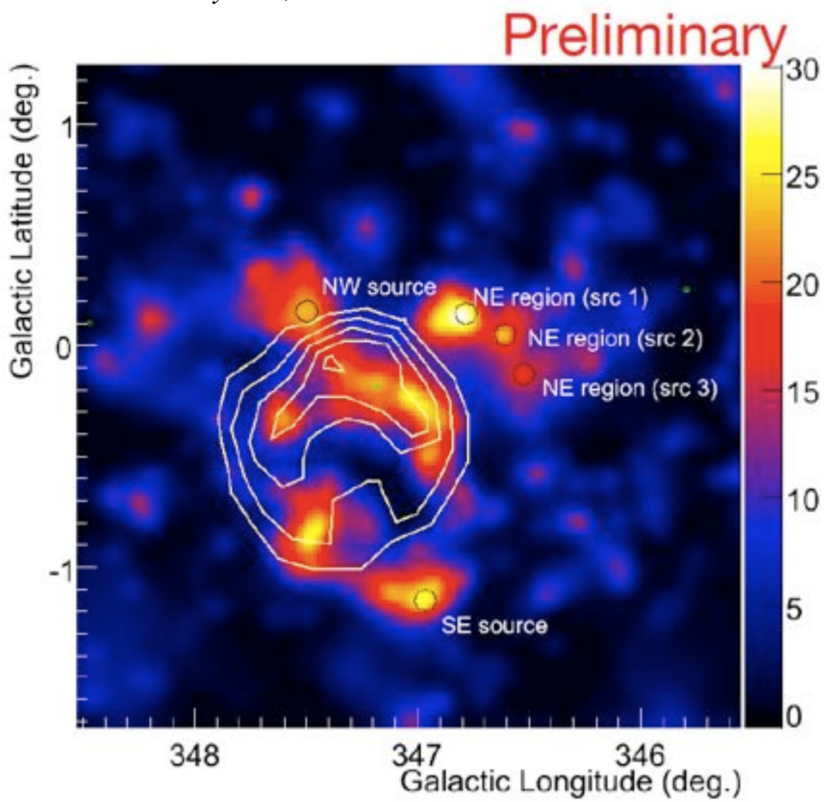


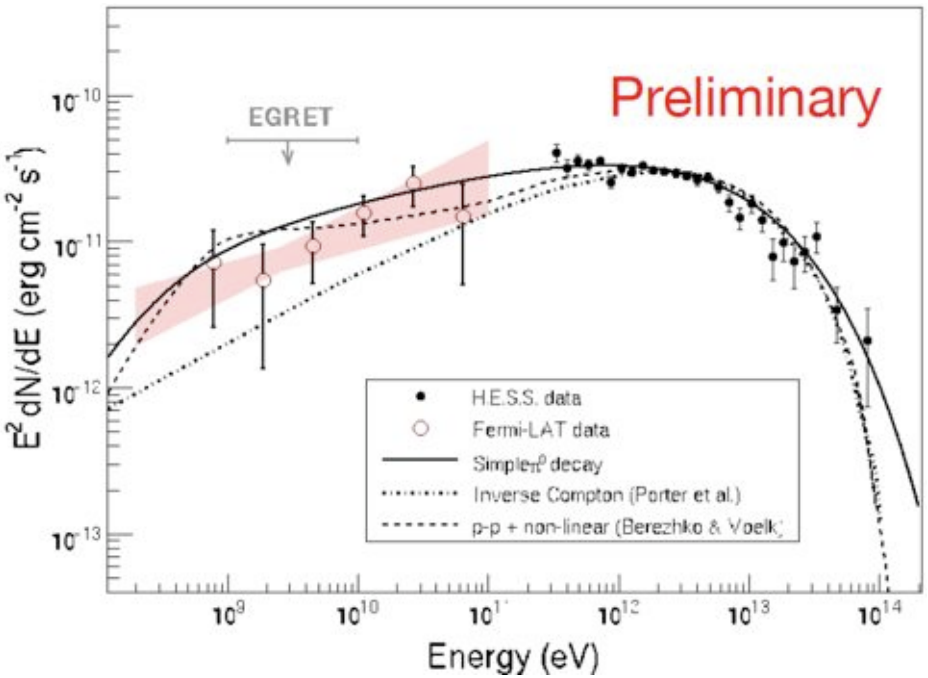


bremsstrahlung

The next piece in the puzzle: Fermi observations of RXJ 1713.7-3946

Funk/Uchiyama, Fermi coll.

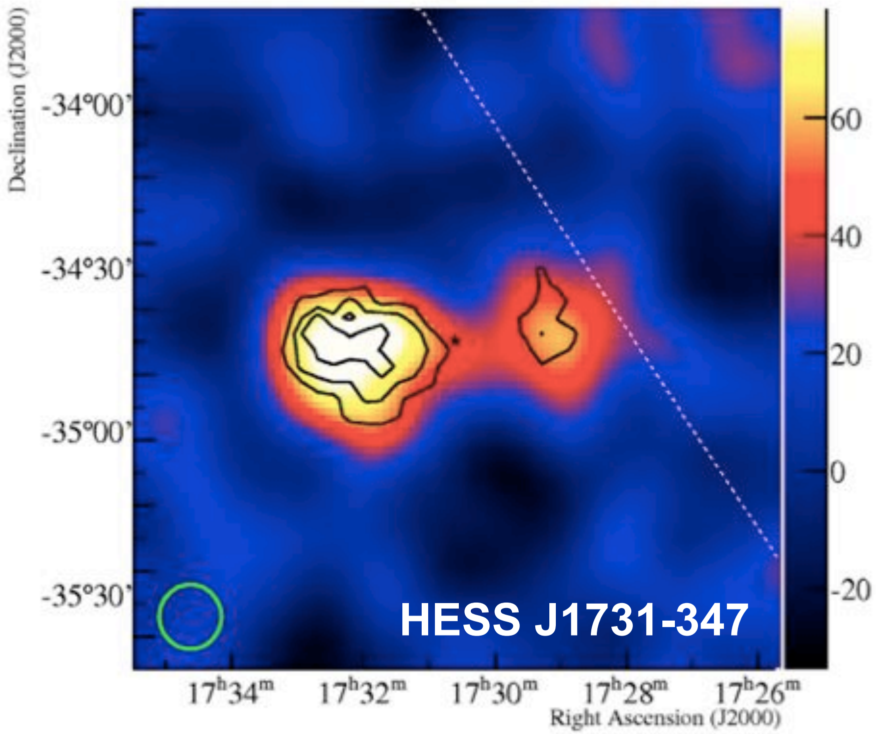


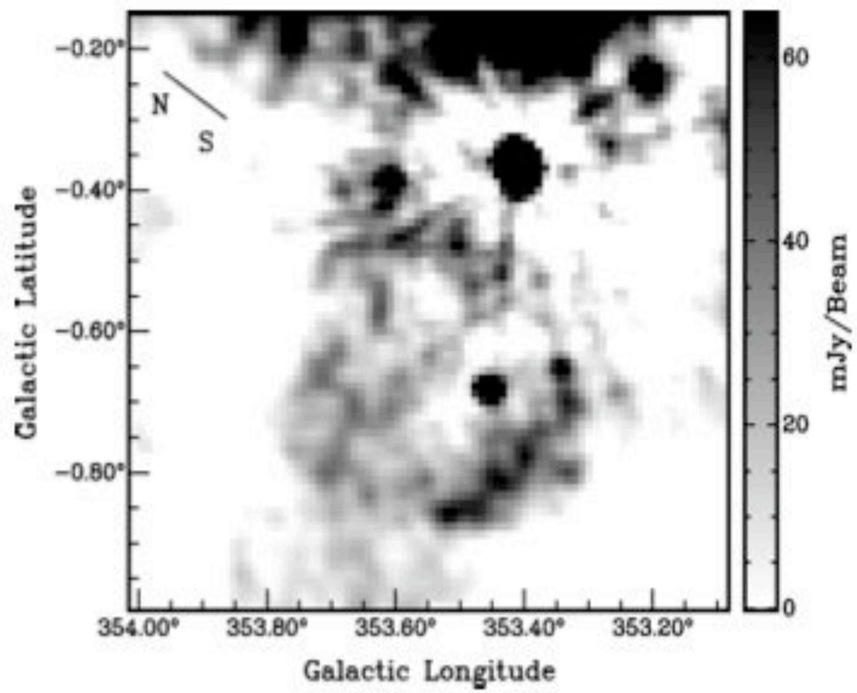


HESS J1731-347: the only shell discovered so far (first) in VHE

HESS collaboration, A&A 2008:
~14 hours lifetime

Tian et al., ApJ 2008



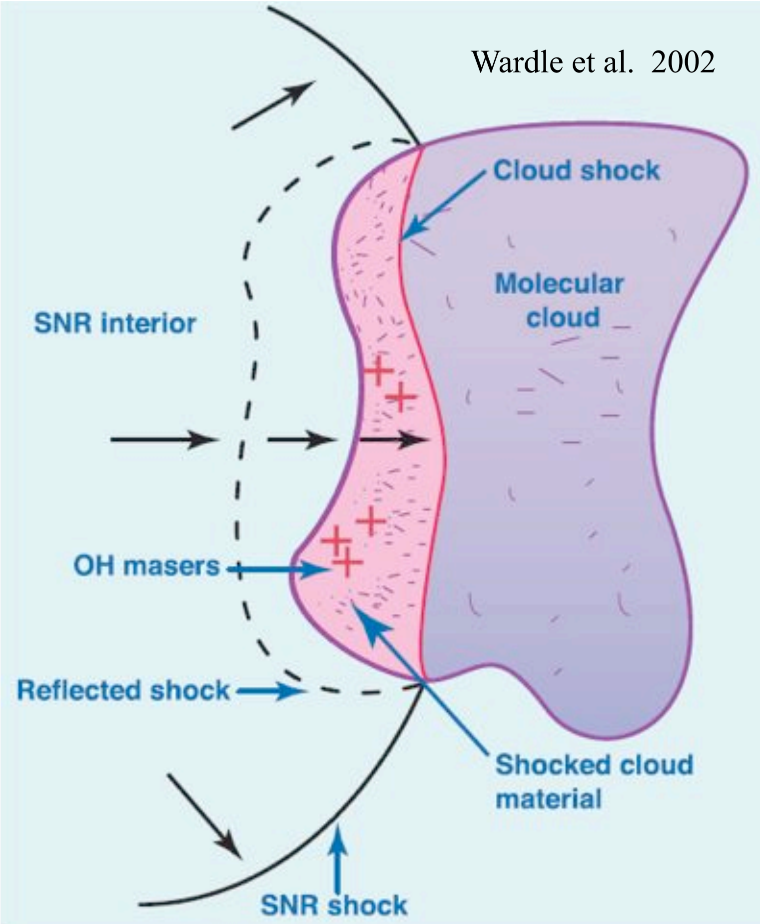


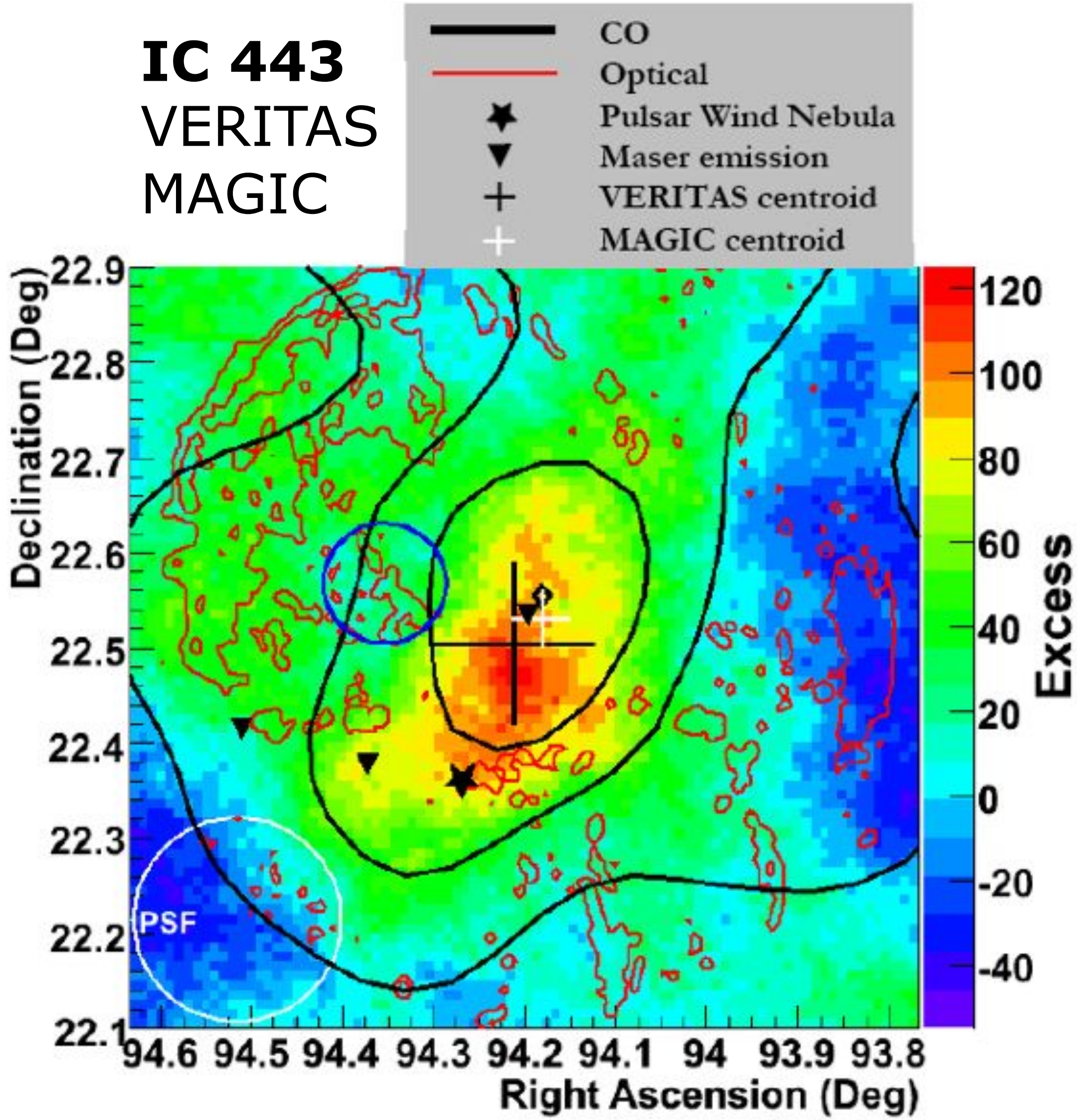
Color map: H.E.S.S. γ-ray excess
Contours: H.E.S.S. significance

B&W map: ATCA 1.4 GHz

(more data underway to confirm shell in TeV)

SNRs interacting with molecular clouds: better tracers for CR protons?

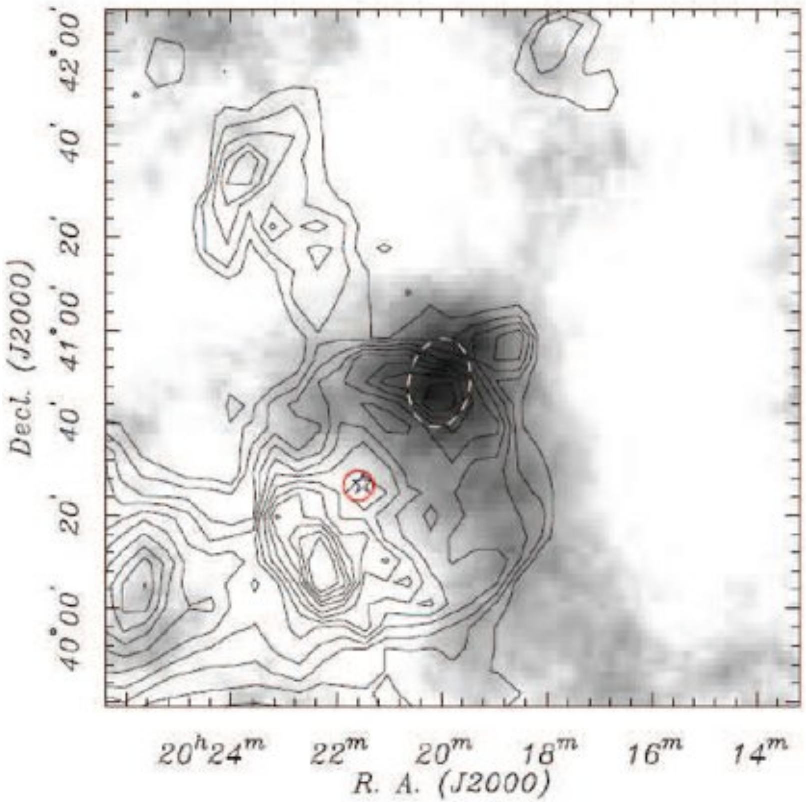




SNRs interacting with molecular clouds: better tracers for CR protons?

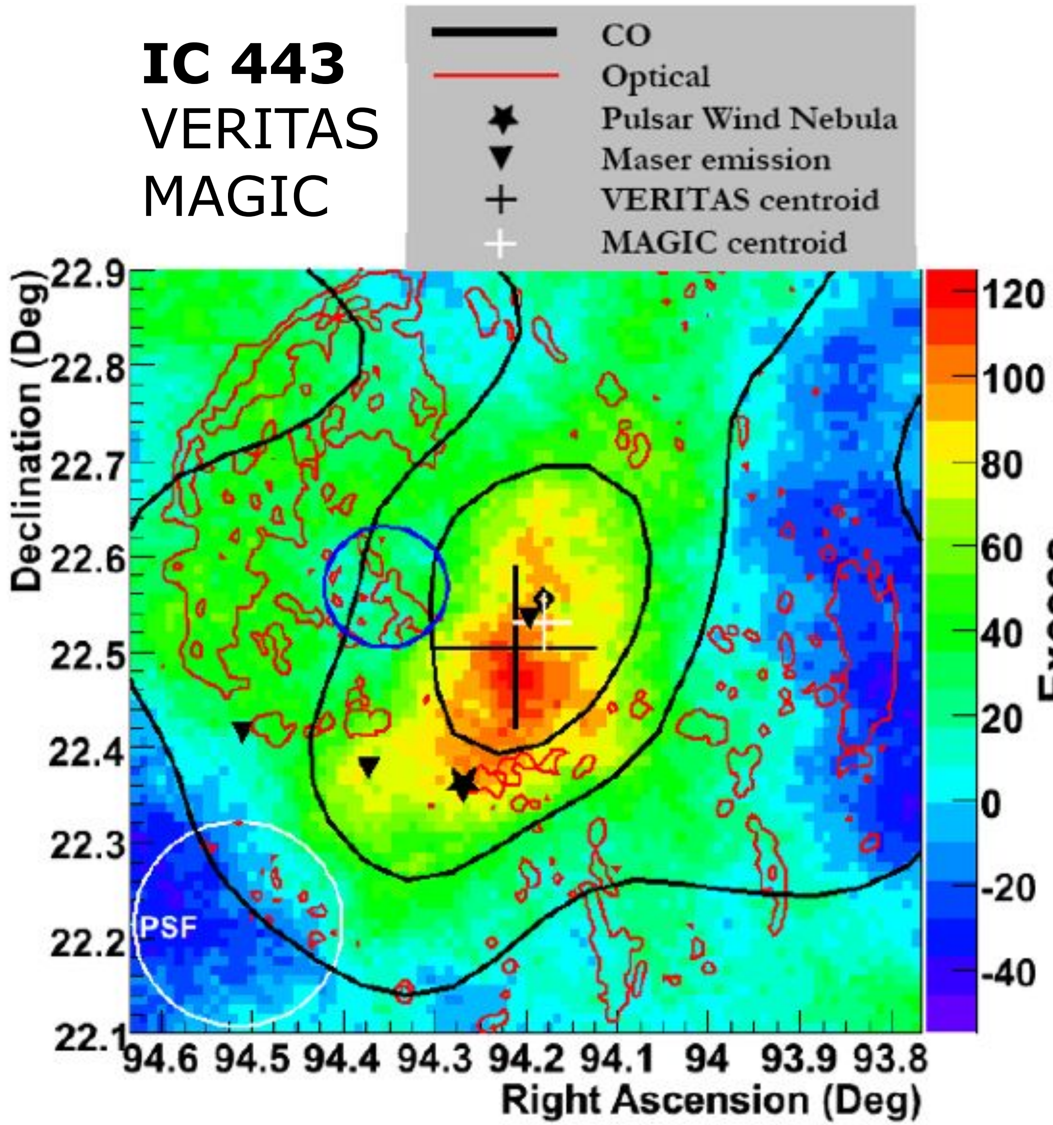
γ-Cyg (G78.2+2.1)
VERITAS

Contours: radio continuum



Weinstein et al. 2009

IC 443
VERITAS
MAGIC

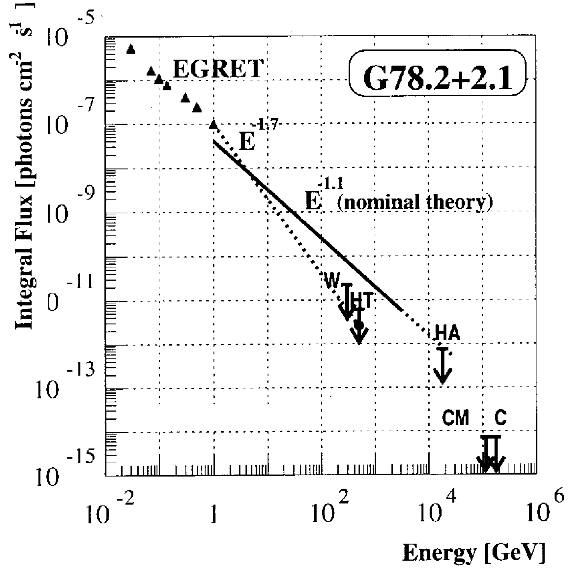


Already a piece of historical research

Candidates:

Shell type SNRs, well in Sedov phase

interacting with molecular cloud



Results:

EGRET (<1 GeV): IC 443, γ–Cygni, ...

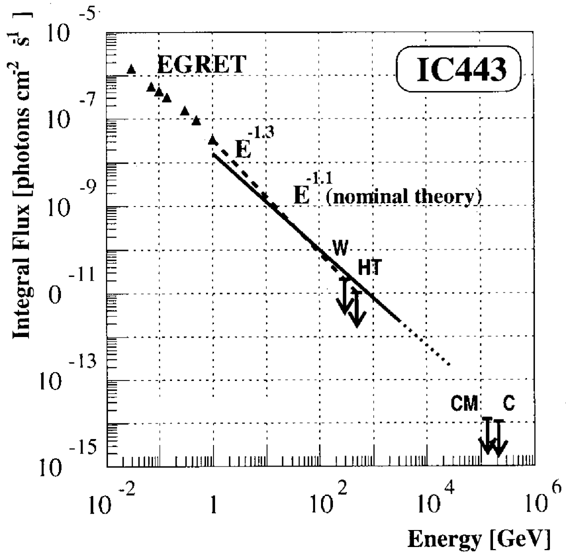
Esposito et al (1996)

Whipple (> 300 GeV): upper limits

Buckley et al. (1997/98)

HEGRA (> 500 GeV): upper limits

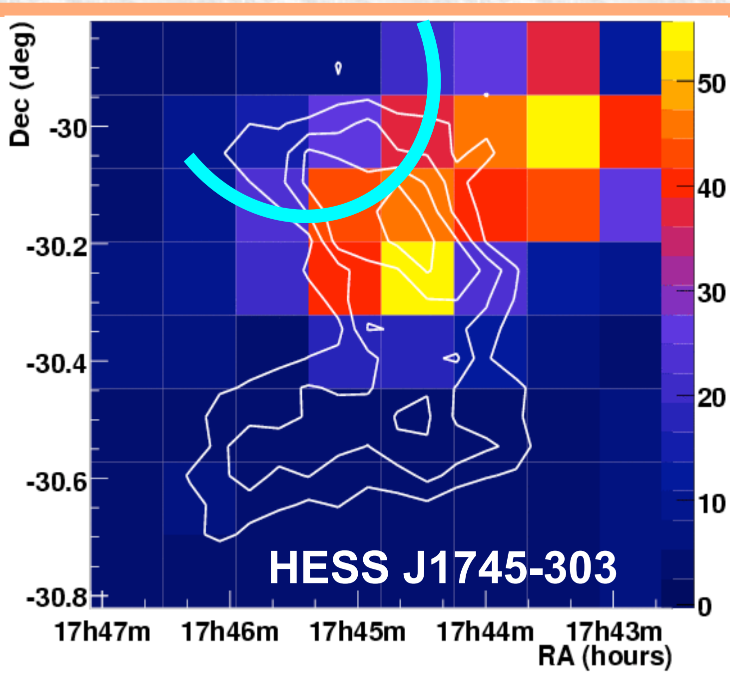
Heß et al. (1997)

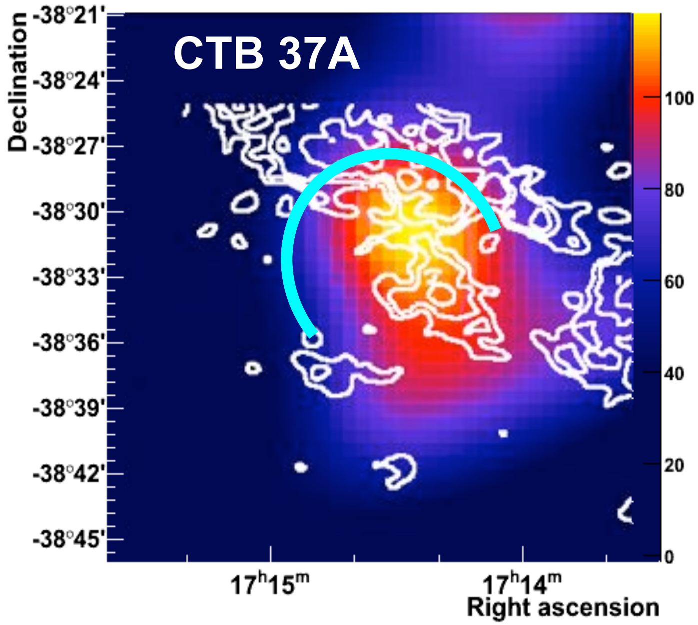


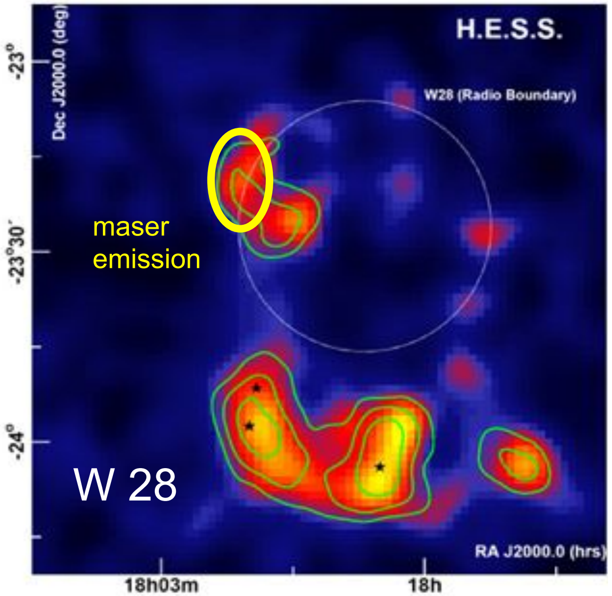
Völk, Krüger Park 1997

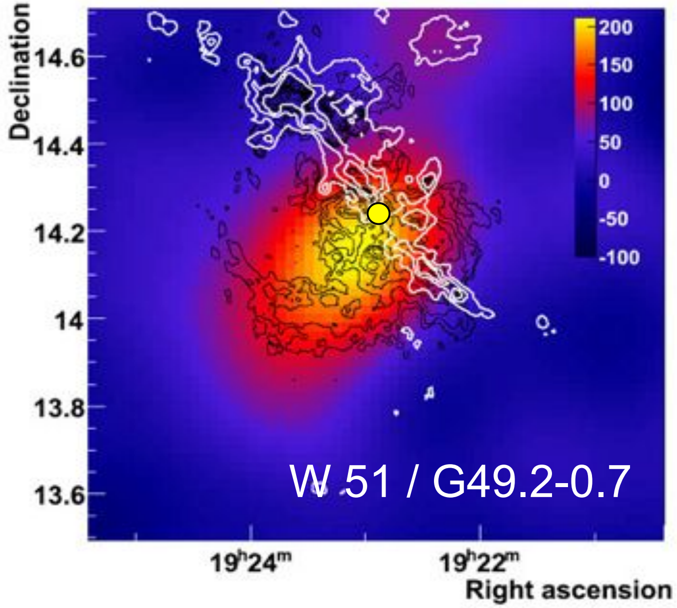
astro–ph 9711204

SNR interacting with molecular clouds: H.E.S.S. results





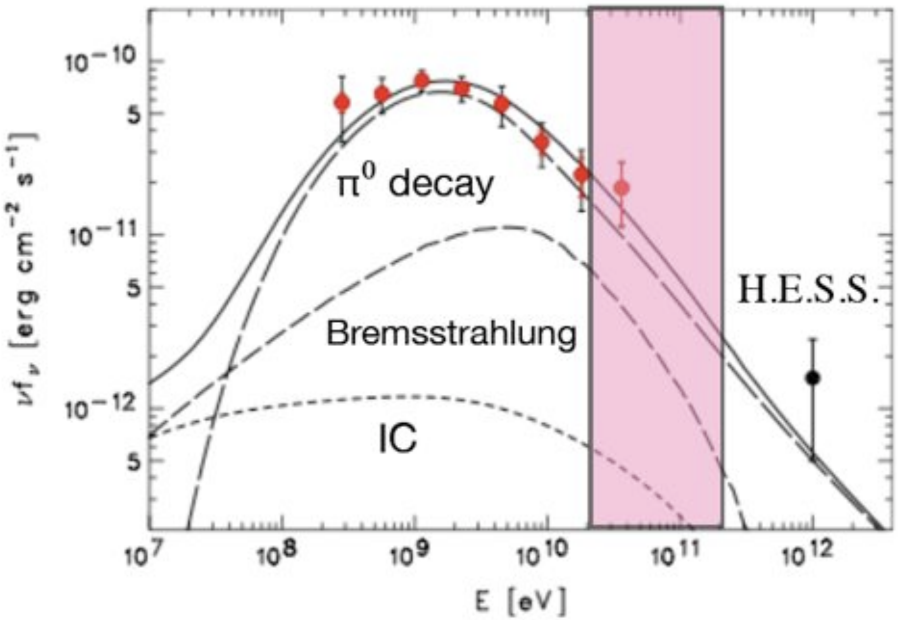




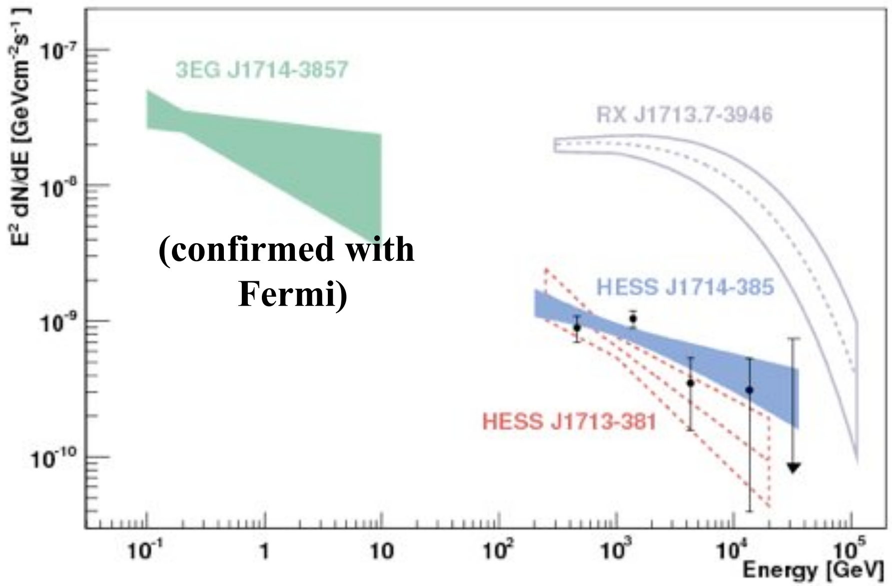
HESS coll., ICRC 2009

Problems with the SNR-MC interactions

W51C — Fermi team 2010



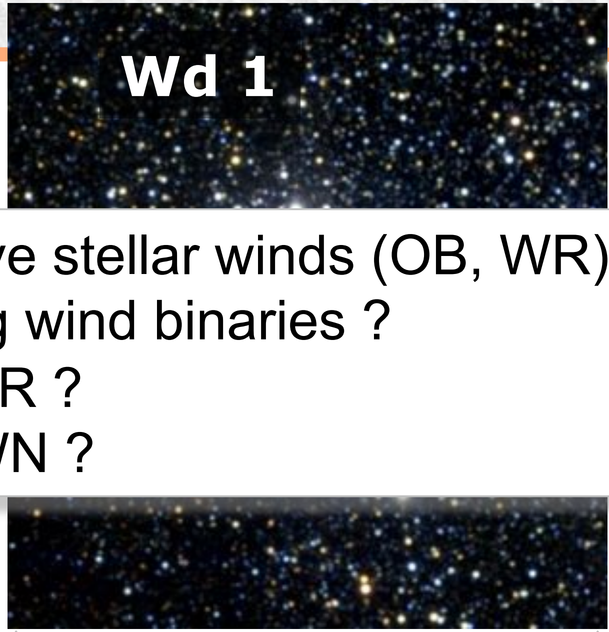
HESS coll. 2008 — **CTB 37A**

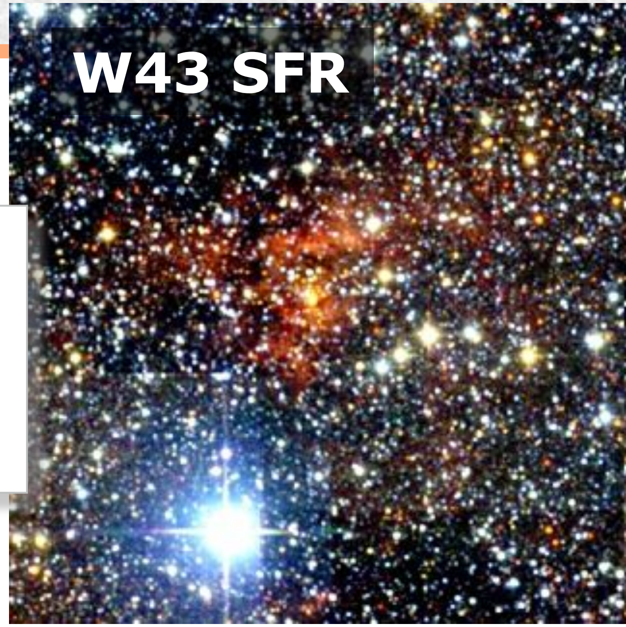


+ hadronic scenario plausible (energetics precludes IC scenario)

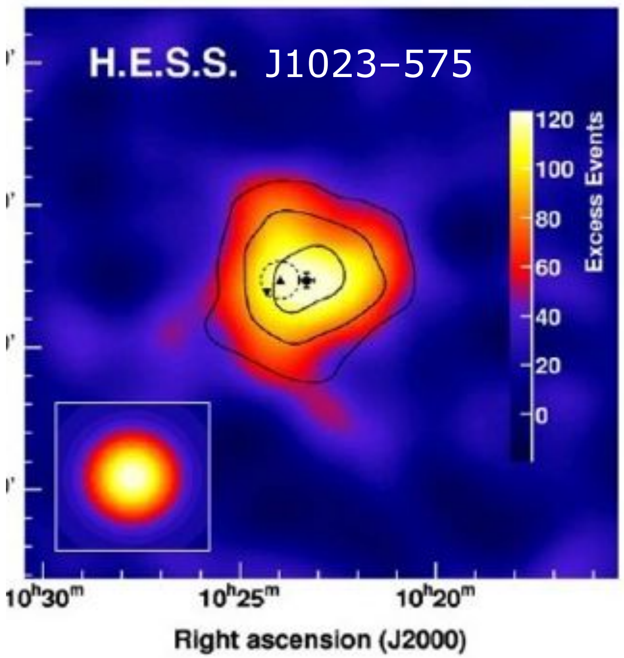
+ but: are we happy with the hadronic spectrum implied (low E-cutoff)?
+ and: high B-field from masers (0.2 - 0.6mG)
→ X-ray emission from secondary electrons expected (but not seen yet)

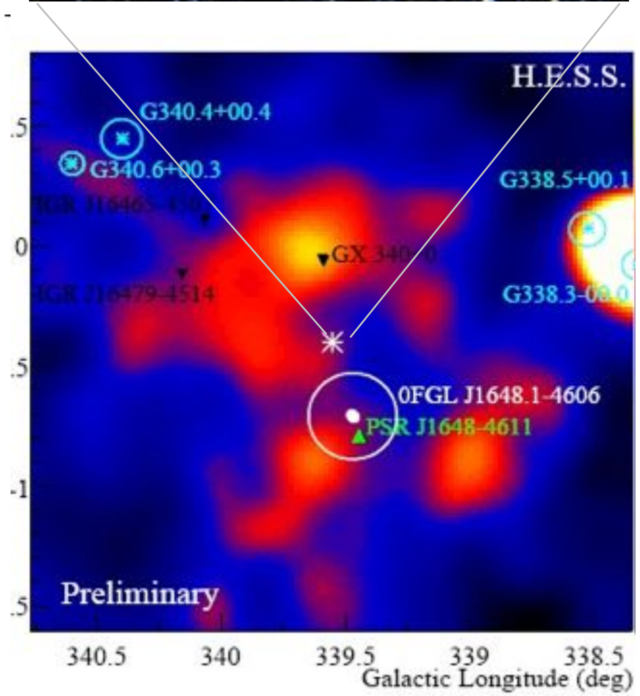
Young stellar clusters / star forming regions

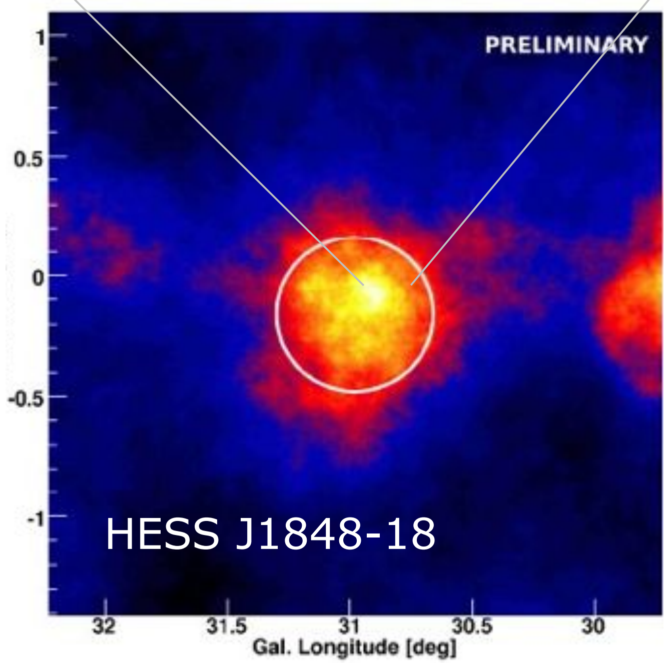




Collective stellar winds (OB, WR) ?
Colliding wind binaries ?
First SNR ?
First PWN ?





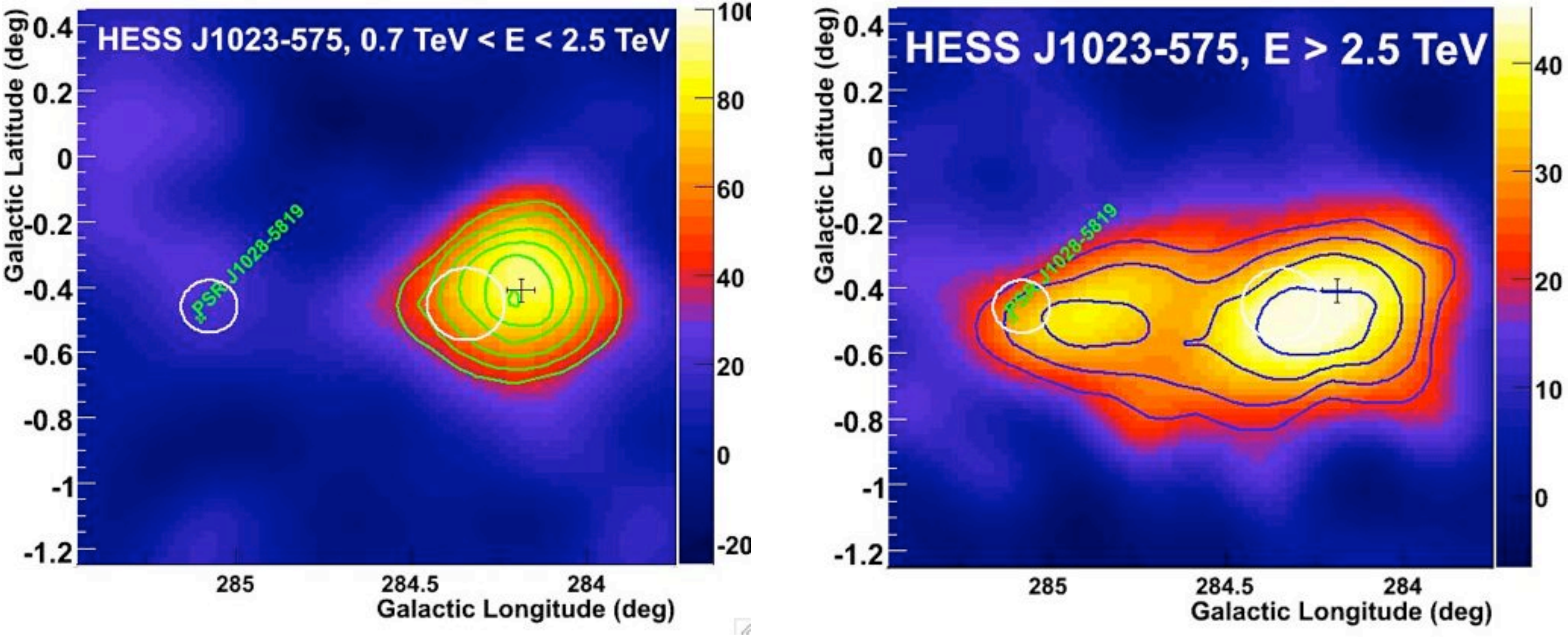


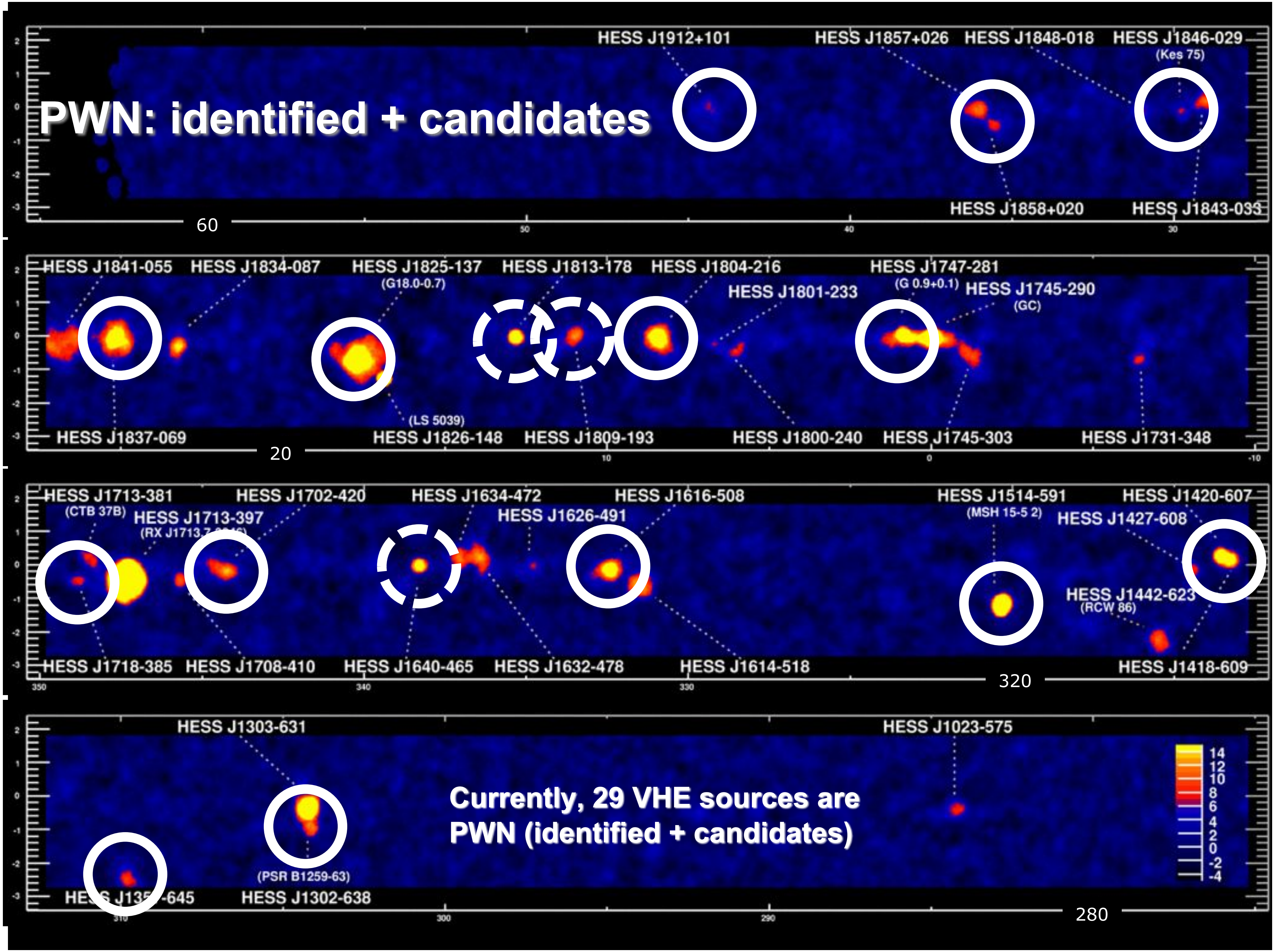
Complex source morphologies

E. de Ona Wilhelmi
ICRC 2009

one of several instances where complex sources decompose into multiple objects

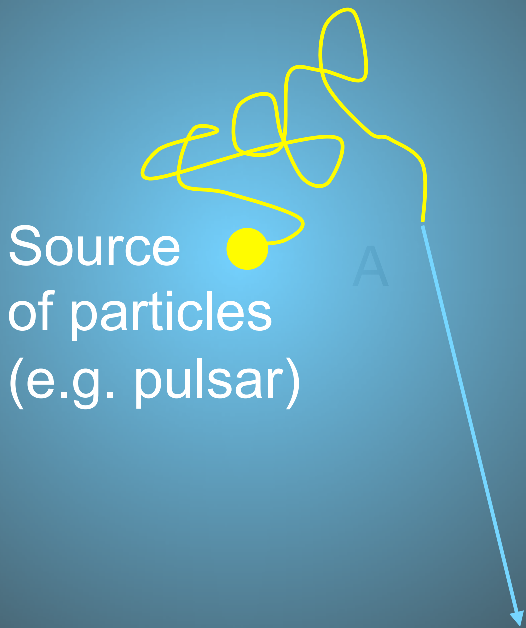
HESS J1023-575:
Combination of a hard source, compatible with PSR J1028-5819, 0FGL J1028.6-5817)
and a softer source (Wd 2, OFGL J1024.0-5754)





PWN: identified + candidates
HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1801-233
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
(CTB 37B)
HESS J1713-397
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1420-607
HESS J1427-608
HESS J1442-623
(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
(PSR B1259-63)
HESS J1302-638
Currently, 29 VHE sources are PWN (identified + candidates)
14
12
10
8
6
4
2
0
-2
-4
310
300
290
280

Source sizes & shapes → identification



For uniform distribution of targets, **γ-rays probe particle distribution**

Typical lifetime of electrons is 10s of kyr, of protons 100s of kyr

▶ **range 10s of pc, unless confined by strong magnetic fields or radiative losses**

▶ **typically large & diffuse sources**

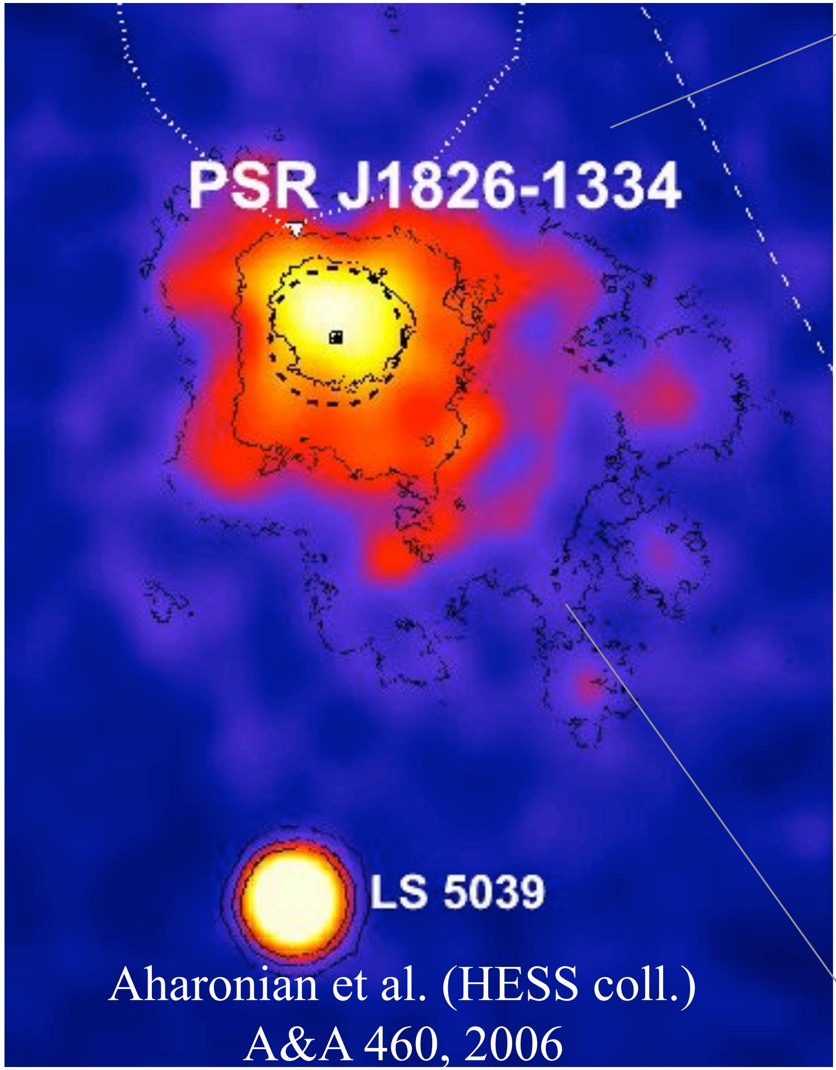
▶ **electrons are more effective radiators**

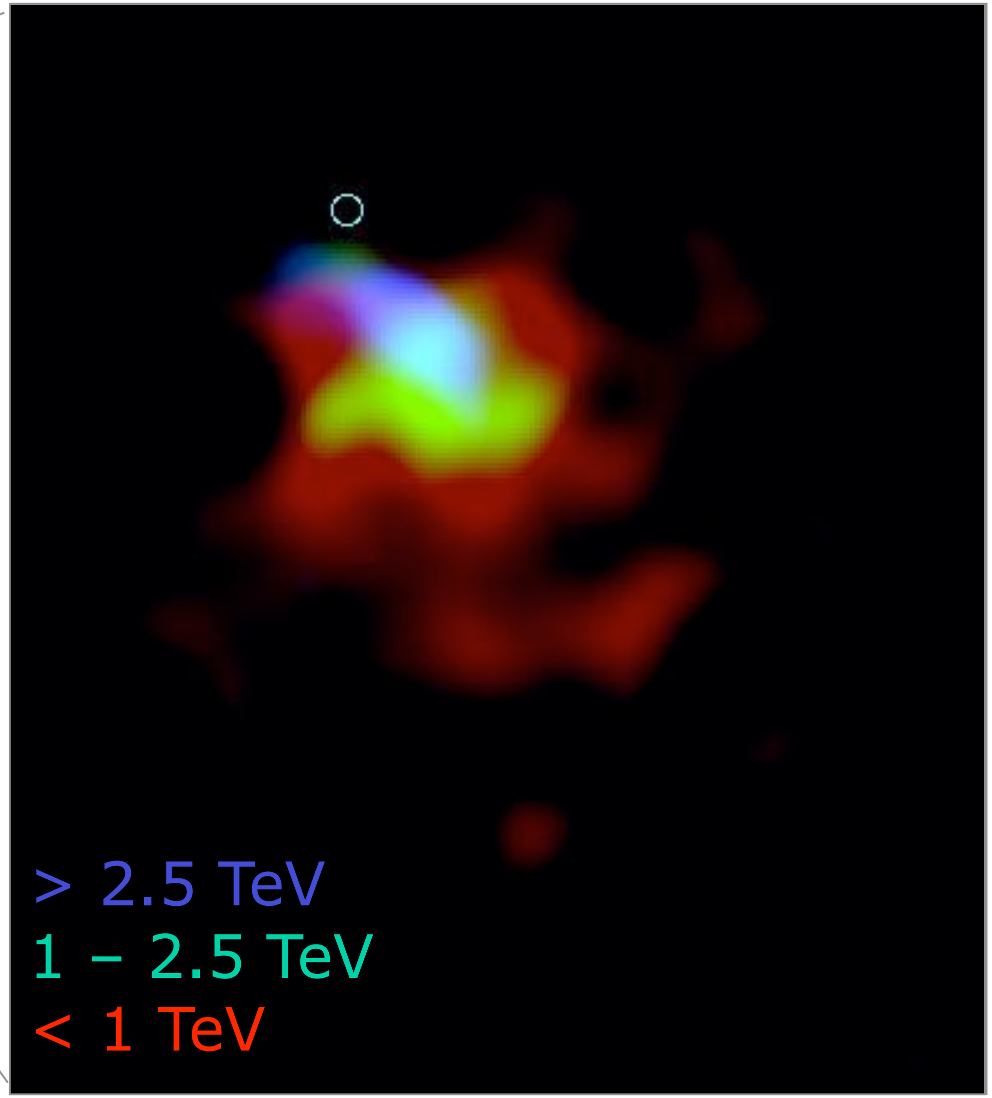
Target “material”:
Gas for π^o production by protons
CMB, IR, optical for IC upscattering of electrons

After W. Hofmann

The standard “relic” pulsar wind nebula candle

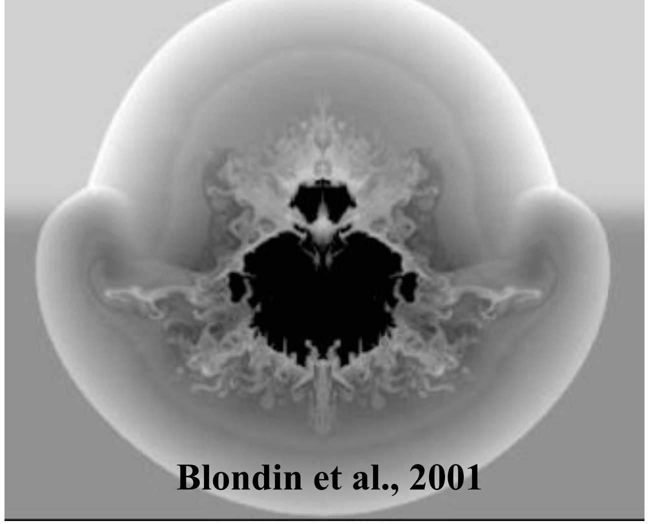
HESS J1825-137:
Identification (mainly) by TeV spectral imaging



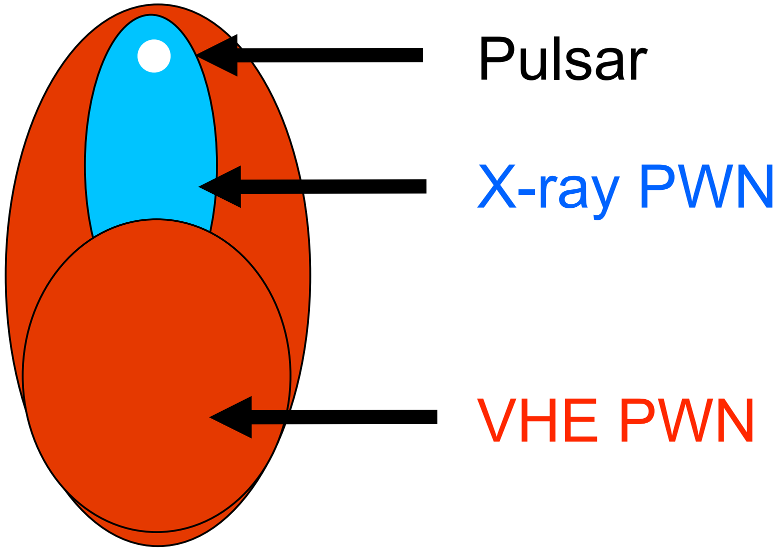


Asymmetric VHE Pulsar Wind Nebulae

"Crushed Plerions"



Offset VHE PWN

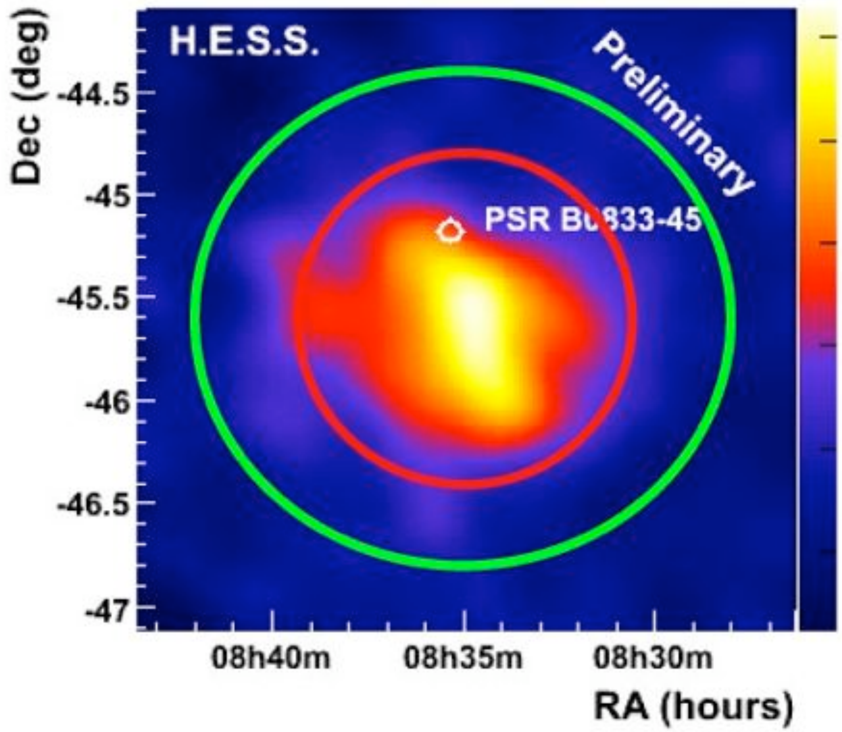


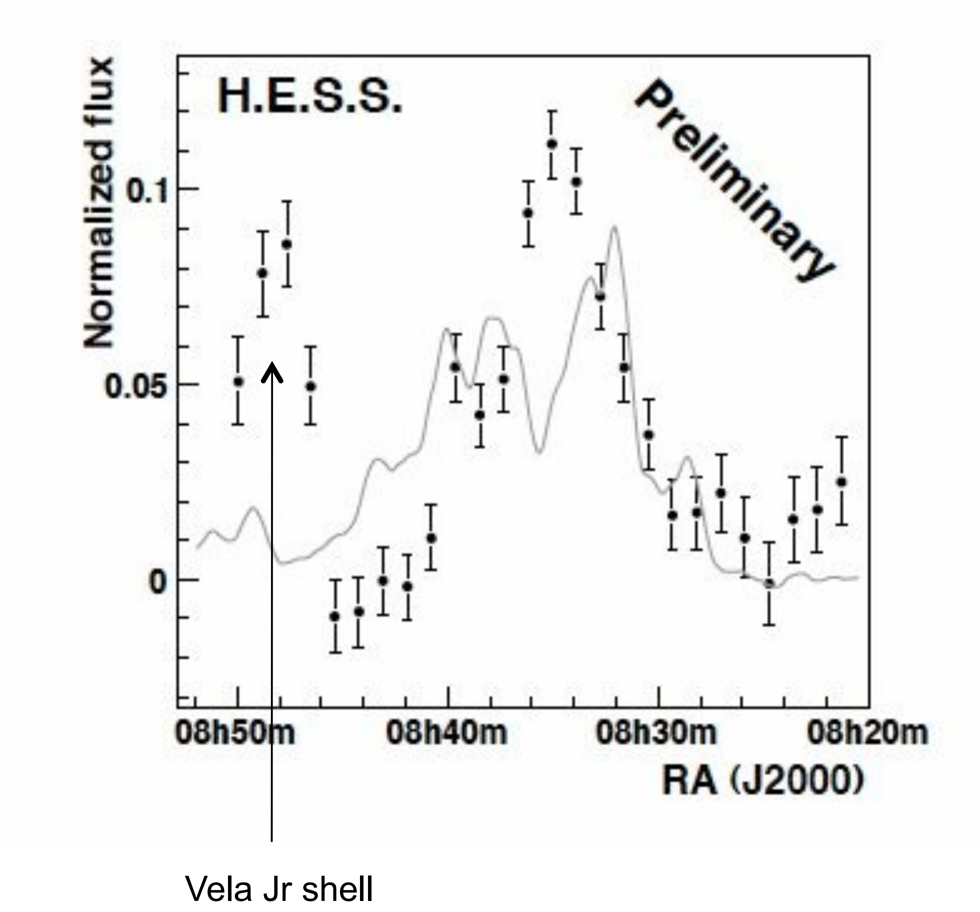
+ IC electron lifetime larger than synchrotron lifetime
+ larger particle injection efficiency in the past

Or pulsar proper motion/ ram pressure?

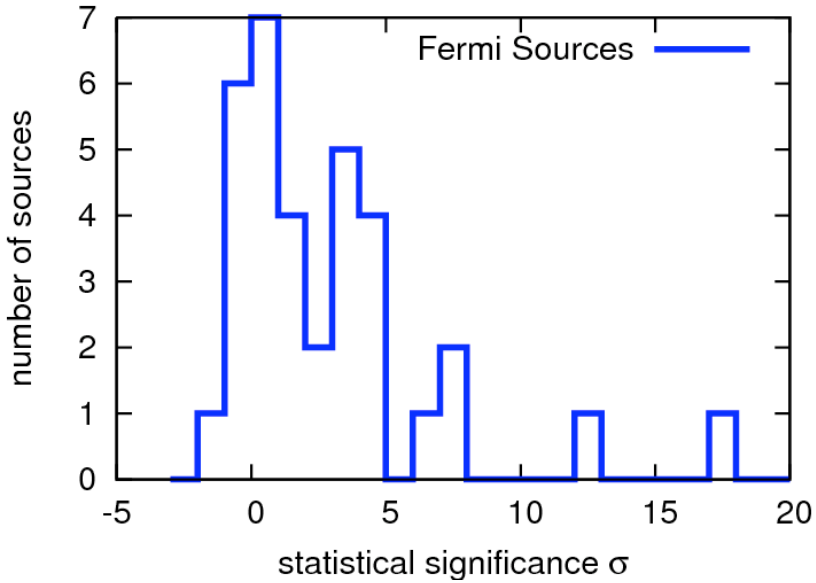
Among the most extended PWNe: Vela X

F. Dubois, ICRC 2009
HESS SOM 03/2010





Pulsars in HE vs. VHE

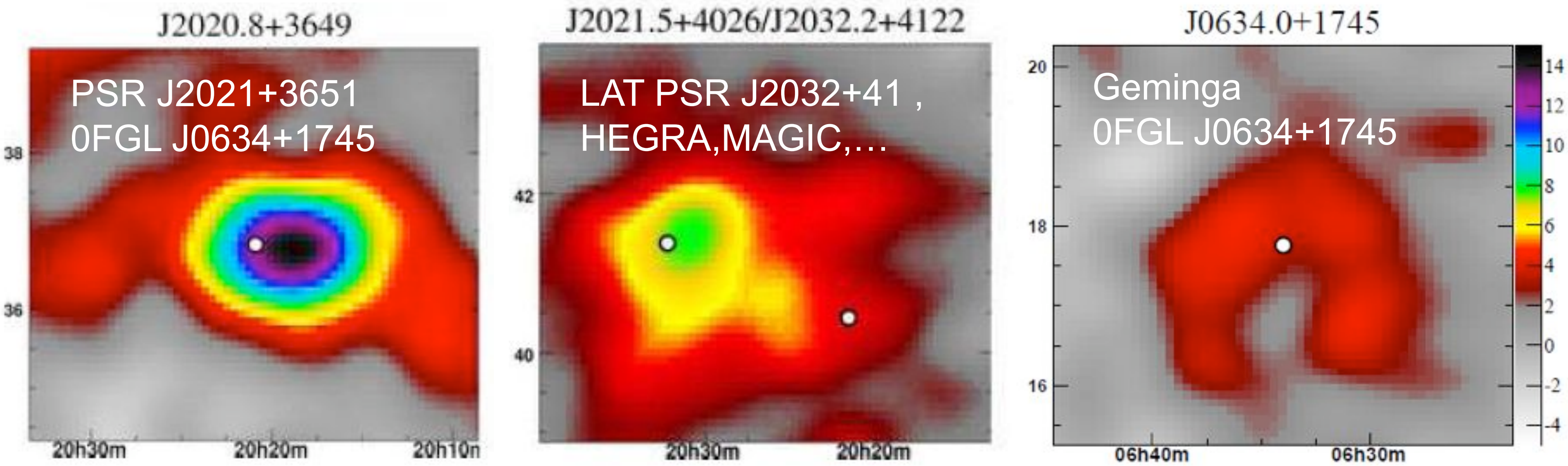


14 of 34 Fermi Bright Sources in Milagro FoV have >3σ

9 of 16 LAT PSR have >3σ

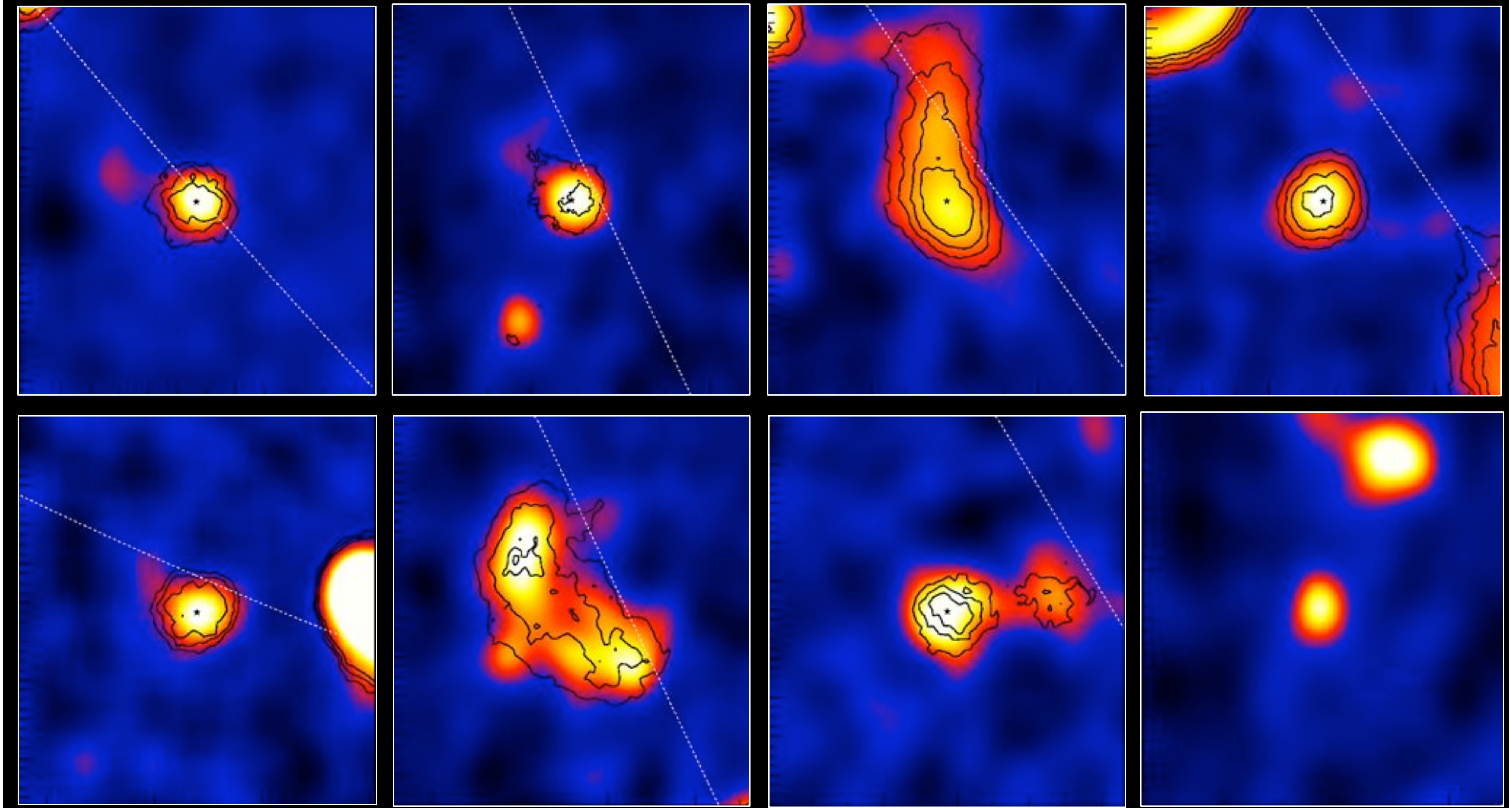
➔ Most strong PSR extend into Multi-TeV regime (via PWNe)

Abdo et al., ApJL, 2009



"Dark" TeV sources?

only a fraction of the H.E.S.S. survey sources is already identified



"Dark" TeV sources?

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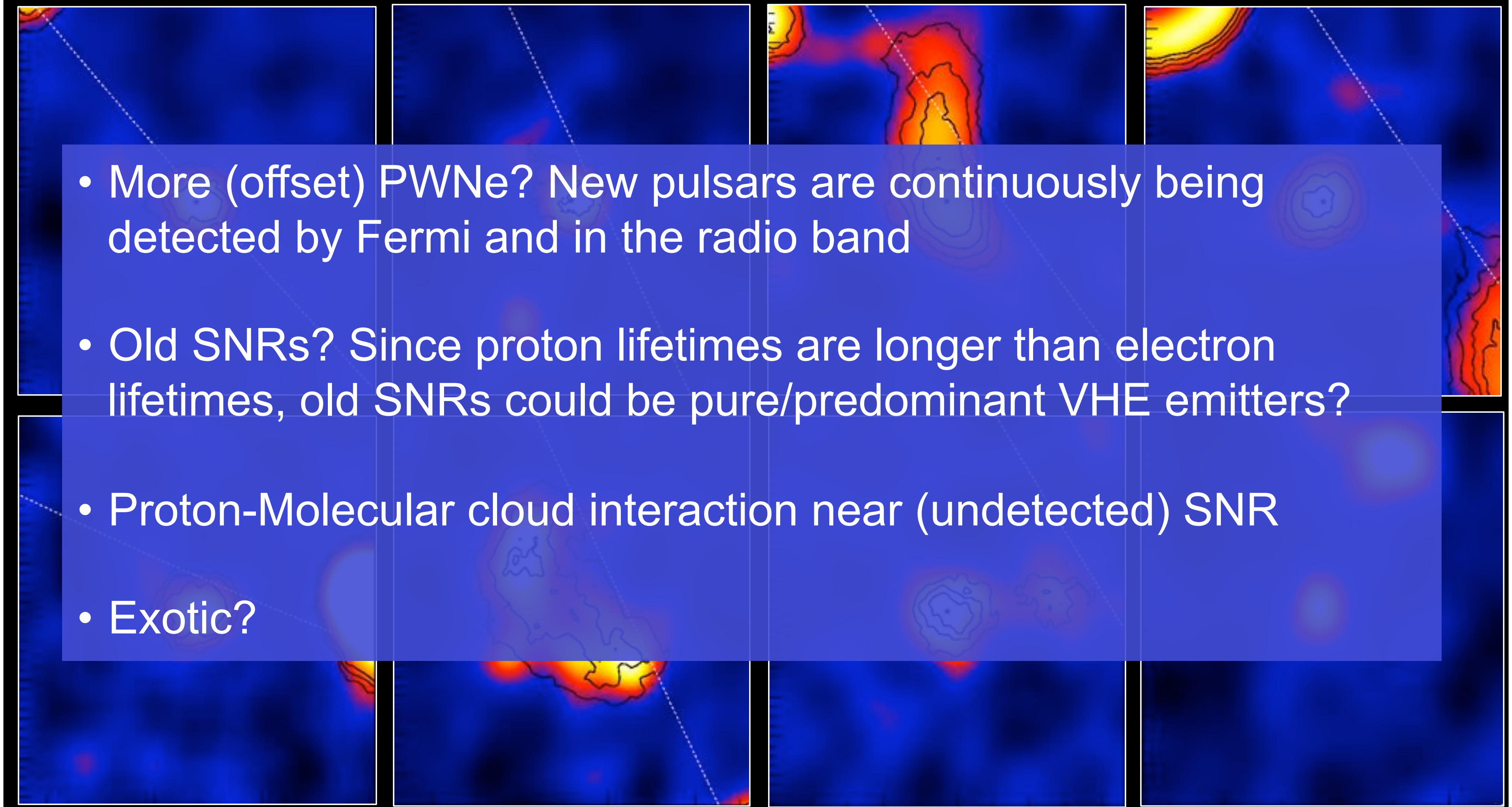
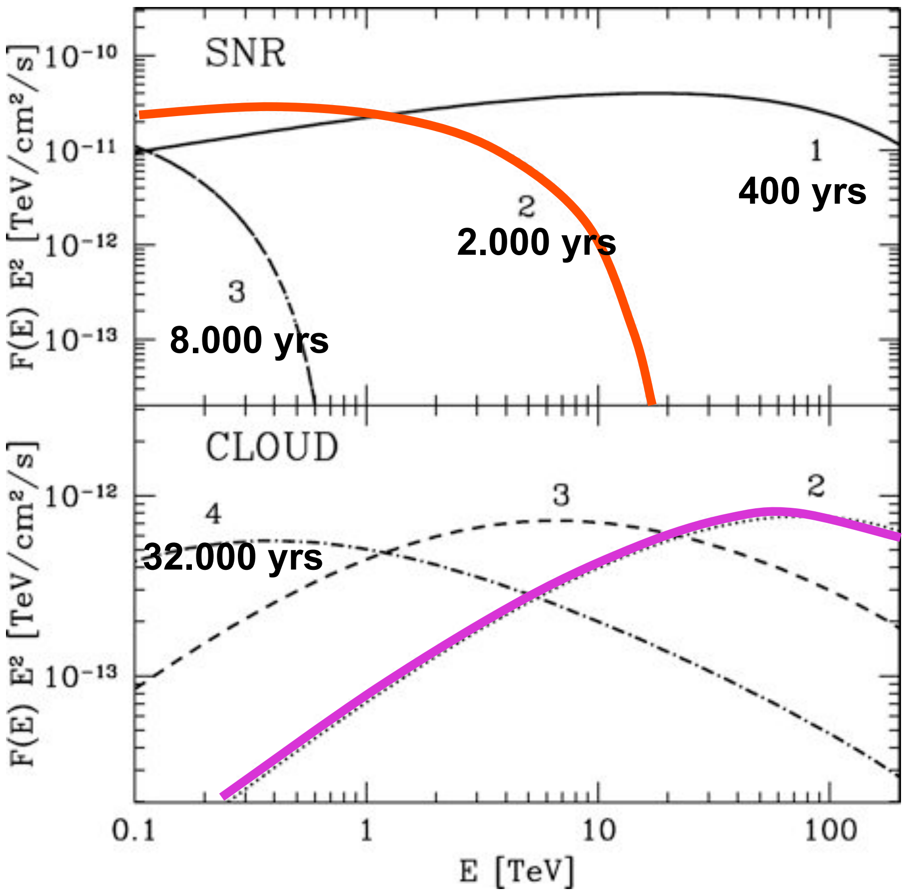
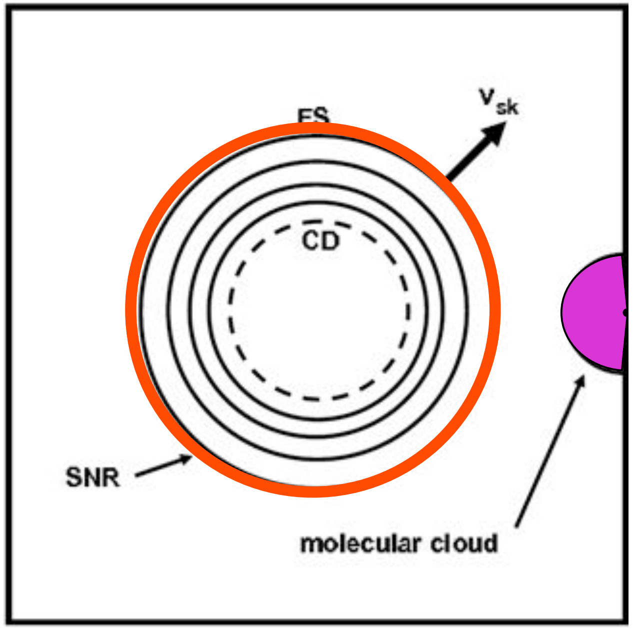


- More (offset) PWNe? New pulsars are continuously being detected by Fermi and in the radio band
- Old SNRs? Since proton lifetimes are longer than electron lifetimes, old SNRs could be pure/predominant VHE emitters?
- Proton-Molecular cloud interaction near (undetected) SNR
- Exotic?

Molecular clouds illuminated by SNRs



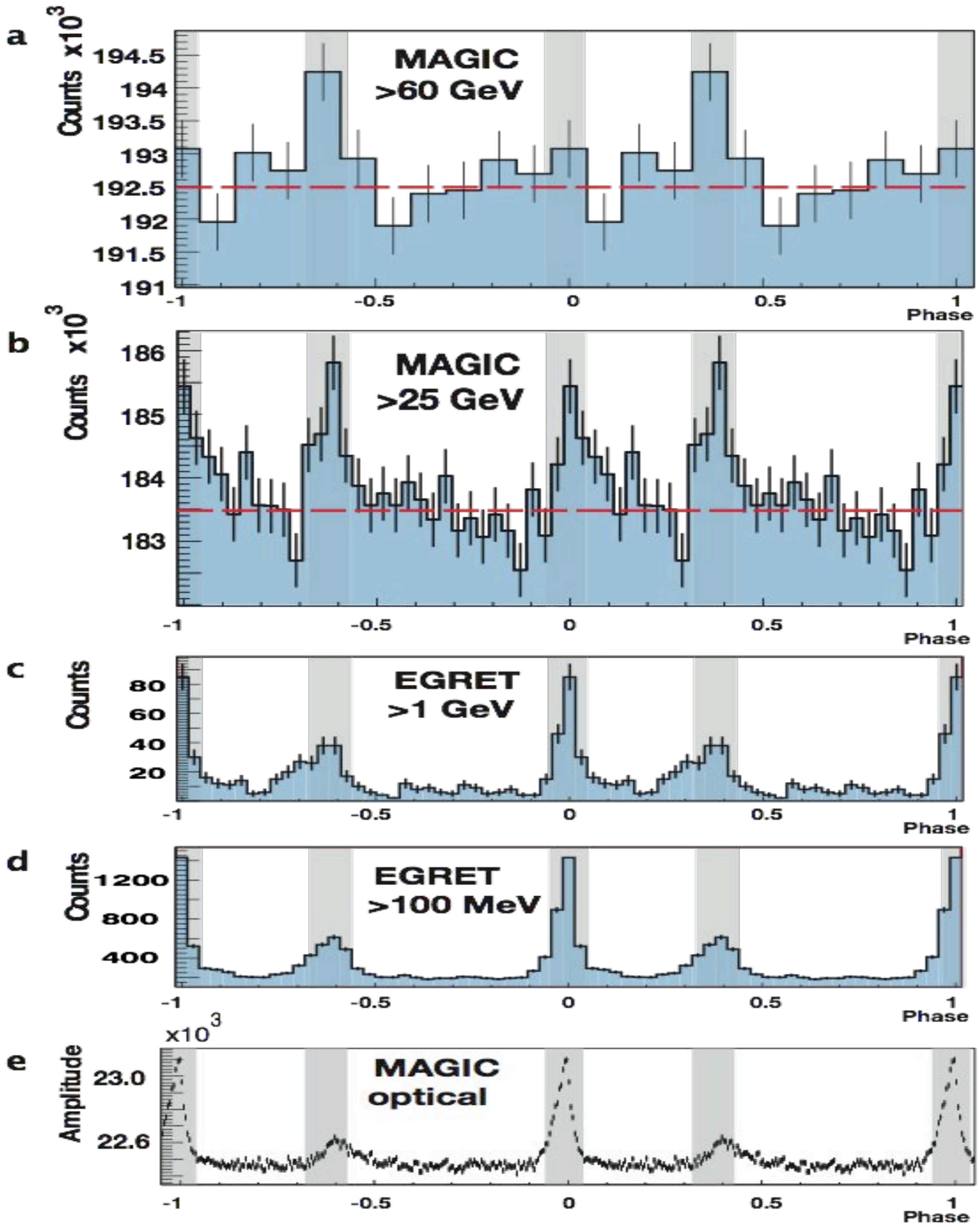


sketch from Lee et al., ApJ 686, 2008

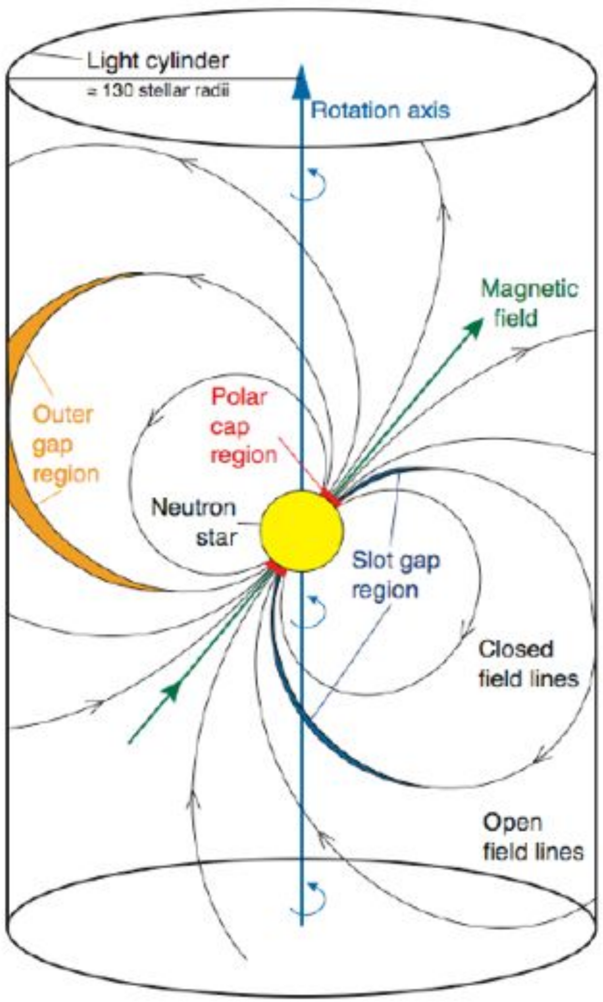
Gabici & A haronian, ApJ 665, 2007
see also Yamazaki et al. 2006, Lee et al. 2008

First ground-based detection of pulsed emission from a pulsar

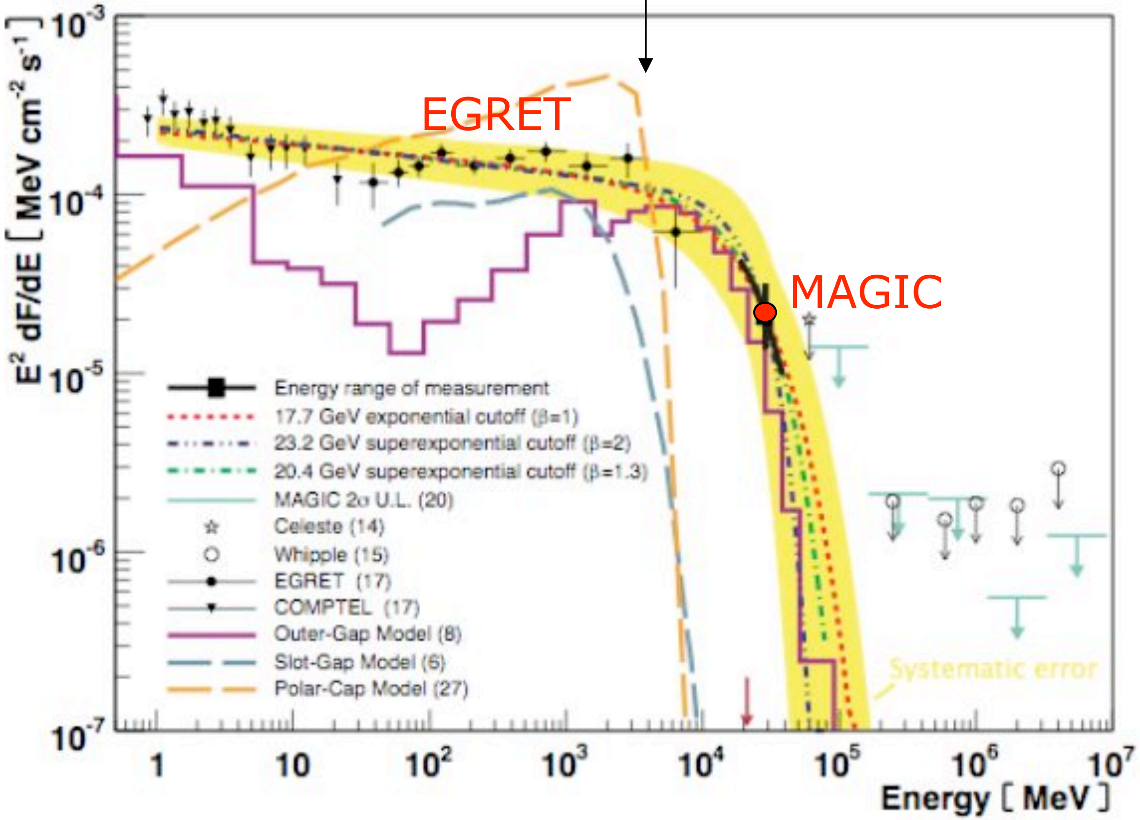
MAGIC, Science 322, 2008
using special low-energy trigger



Origin of pulsed emission: outer gap



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



Gamma-ray binaries

H.E.S.S.

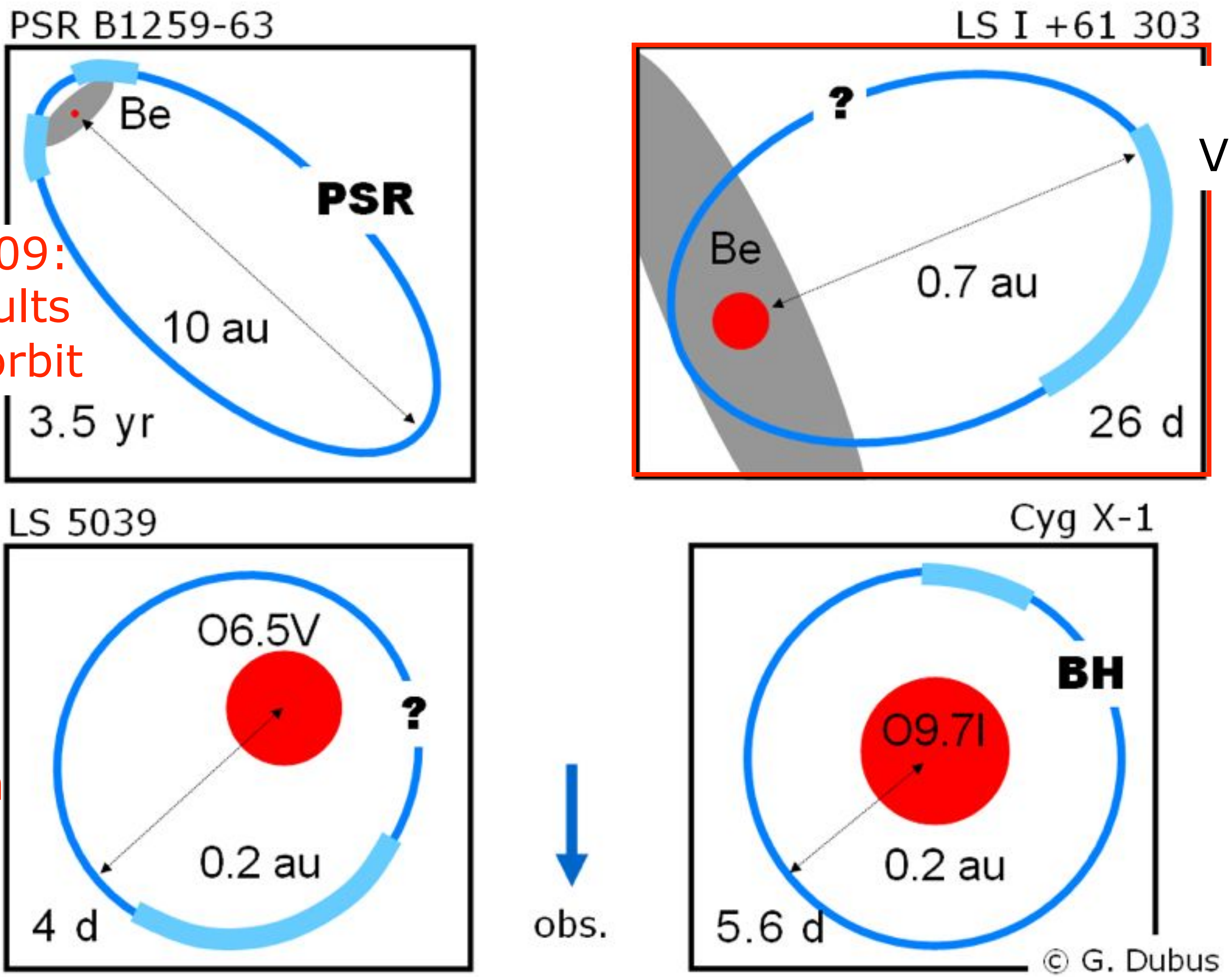
ICRC 2009:
New results
on 2nd orbit

MAGIC
VERITAS

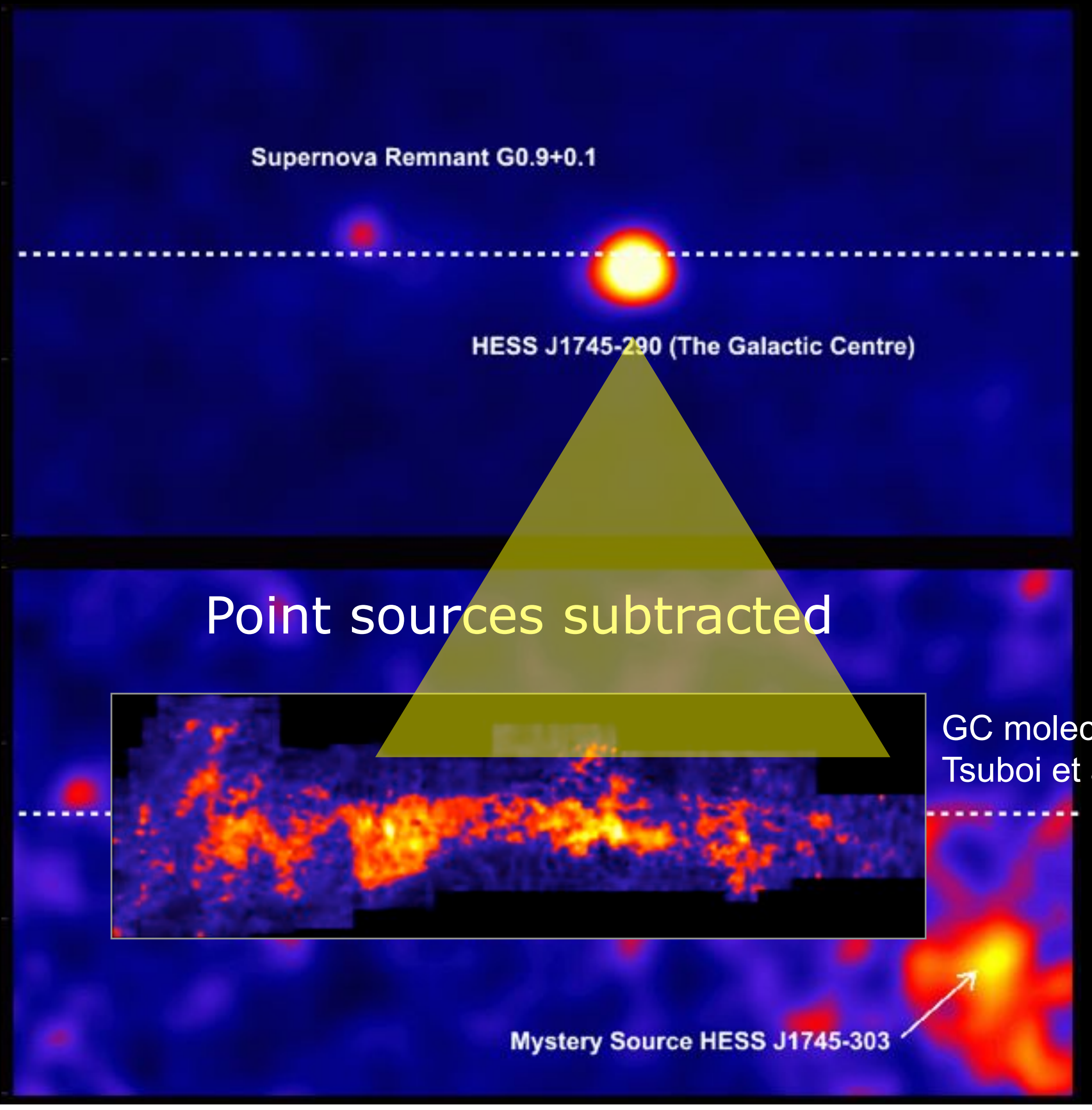
H.E.S.S.

Periodic
emission

MAGIC



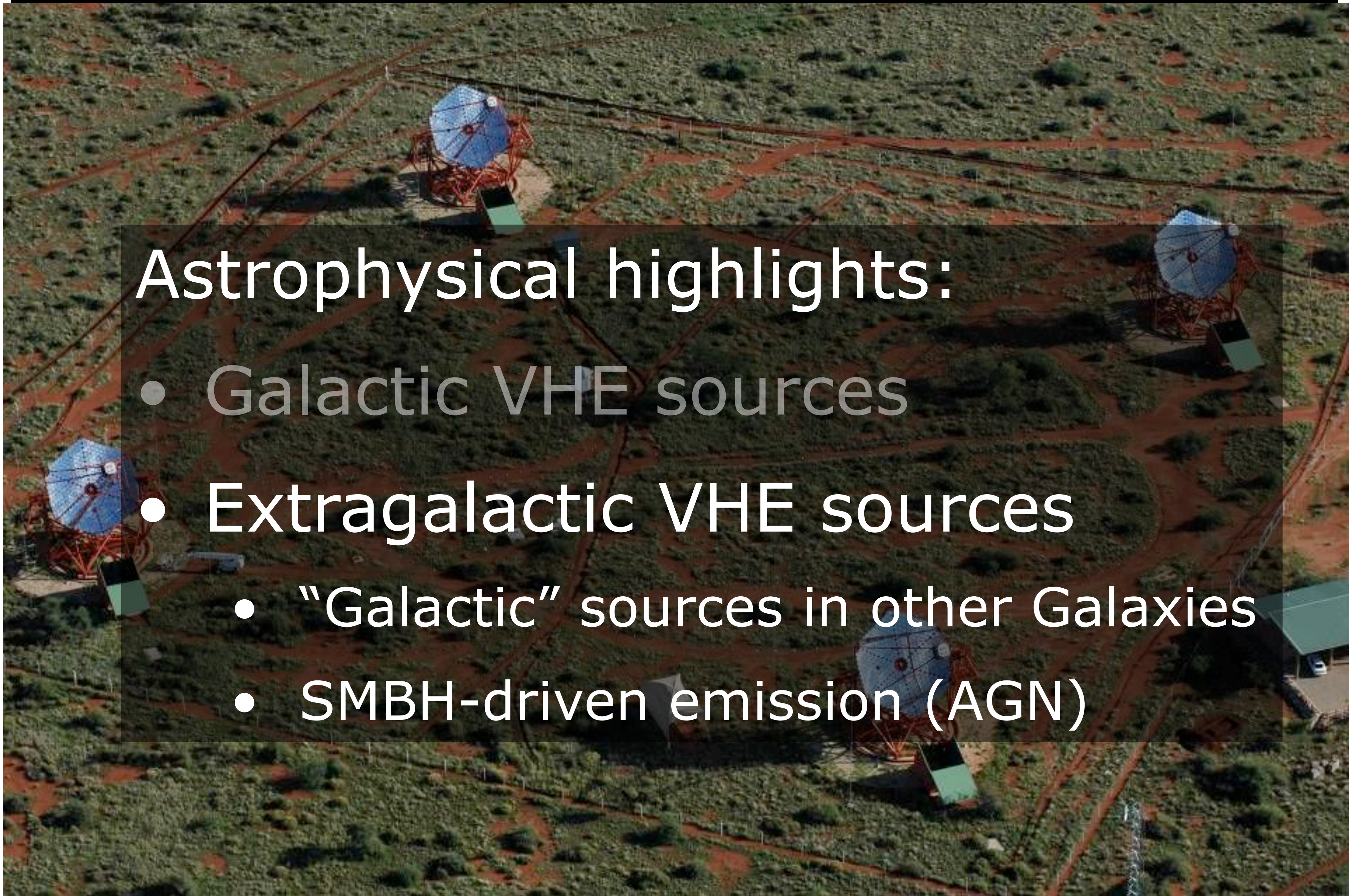
The center of our Galaxy



HESS collaboration
Nature
Feb. 2006

Galactic plane

GC molecular clouds
Tsuboi et al. 1999



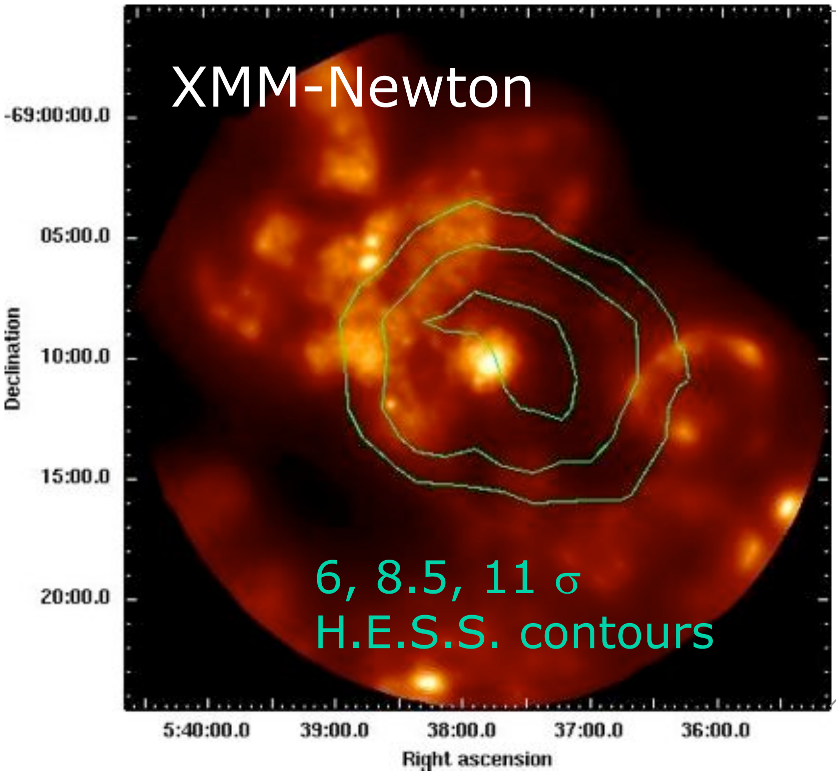
Astrophysical highlights:

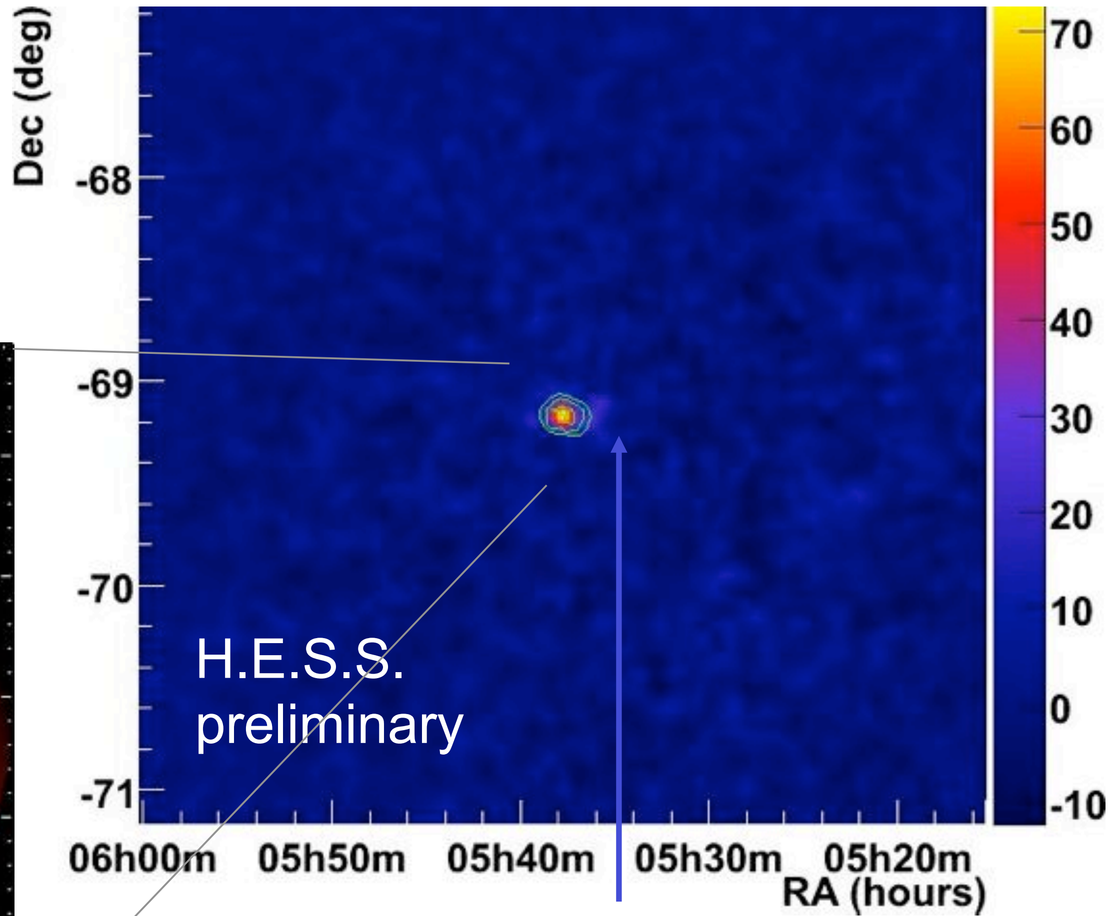
- Galactic VHE sources
- Extragalactic VHE sources
  - “Galactic” sources in other Galaxies
  - SMBH-driven emission (AGN)

The most distant TeV PWN (?): N 157B / PSR J0537-6910 in LMC

Nu. Komin, ICRC 2009

About 1% of pulsar spin-down luminosity (5×10^{38} ergs/s) visible in 1-10 TeV γ-rays



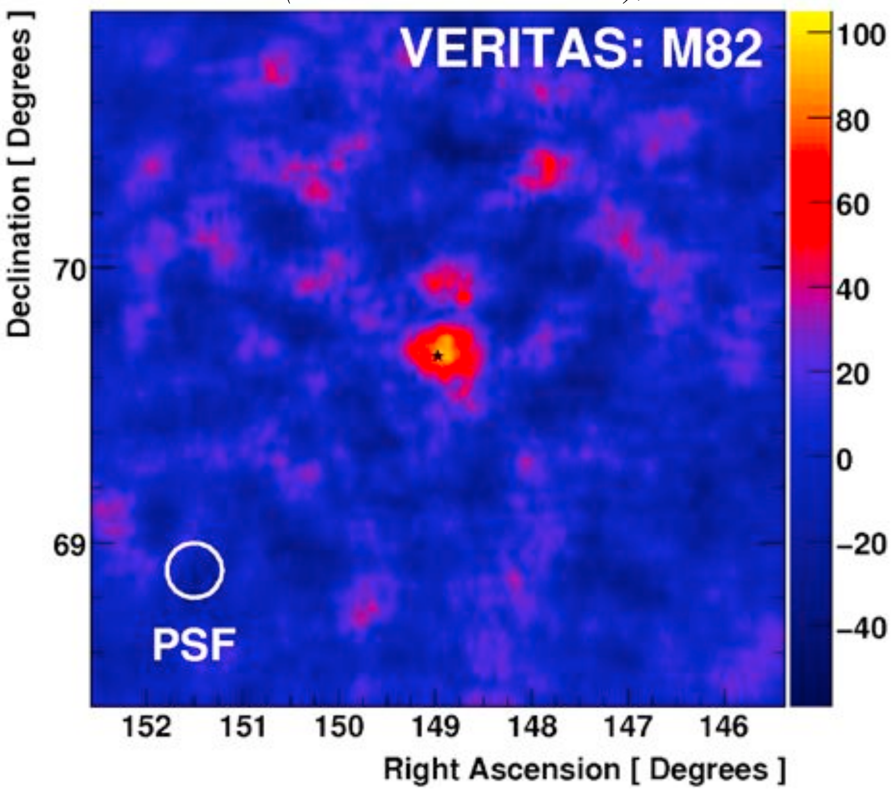


SN 1987a in FoV
upper limits close to predicted TeV flux

M82, NGC 253: TeV detections ...

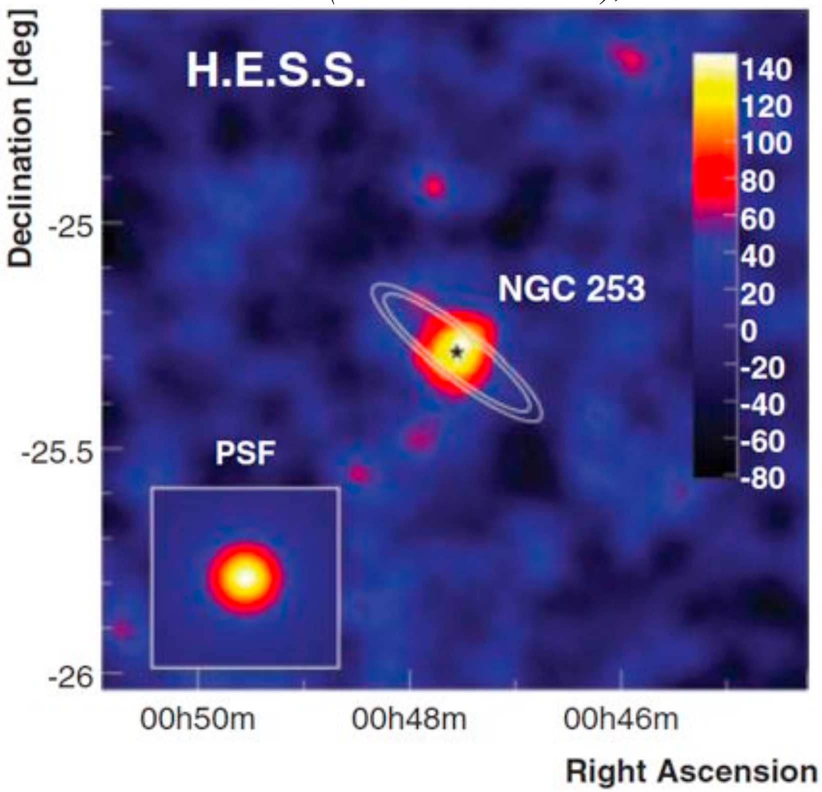
... at the very sensitivity limit of current TeV detectors

Acciari et al (VERITAS collaboration), Nature 2009



- 4.8 σ detection, 137 hrs
- Consistent with star burst core, but optical galaxy not resolvable (<psf)
- 91 Photons, 1/1.5 hrs
- $F(E>700\text{ GeV}) = 3.7 \times 10^{-13}\text{ cm}^{-2}\text{s}^{-1}$, 0.9% Crab

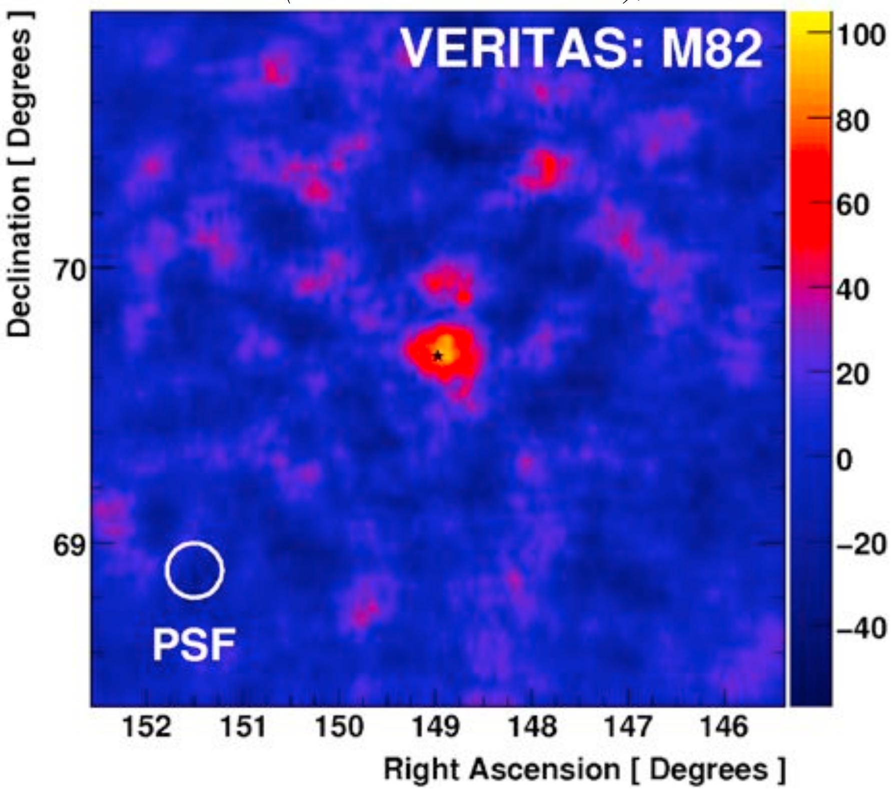
Aharonian et al. (HESS collabortion), Science 2009



- 5.2 σ detection, 119 hrs
- Emission from star burst core, not from disk
- 247 Photons, 2 / hrs
- $F(E>220\text{ GeV}) = 5.5 \times 10^{-13}\text{ cm}^{-2}\text{s}^{-1}$, 0.3% Crab

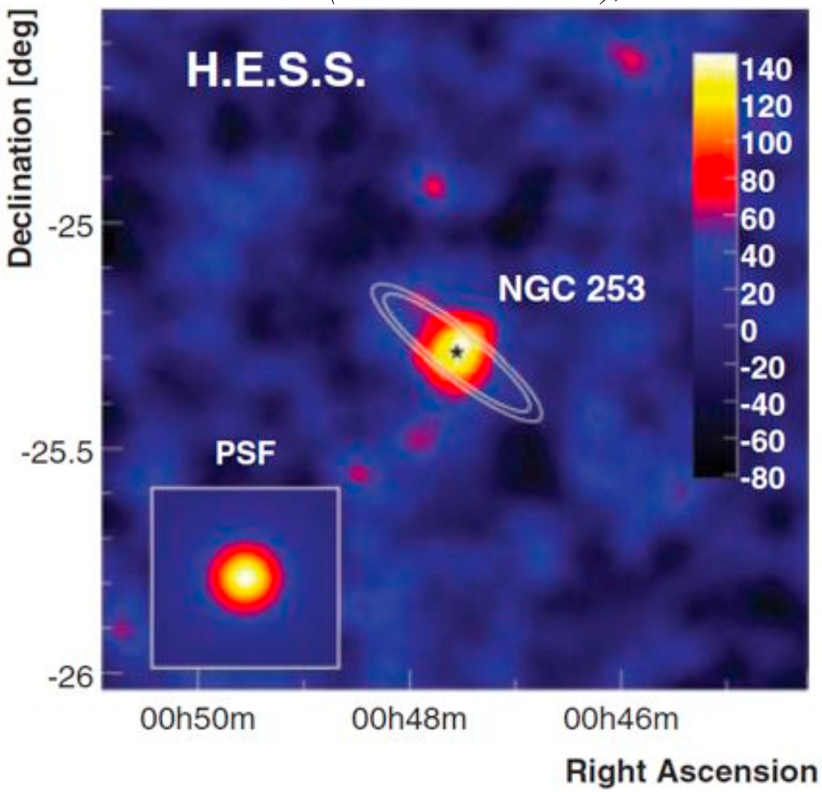
M82, NGC 253: TeV detections ...

Acciari et al (VERITAS collaboration), Nature 2009



CR density 250 eV / cm3
-> 500 × higher than in our Galaxy

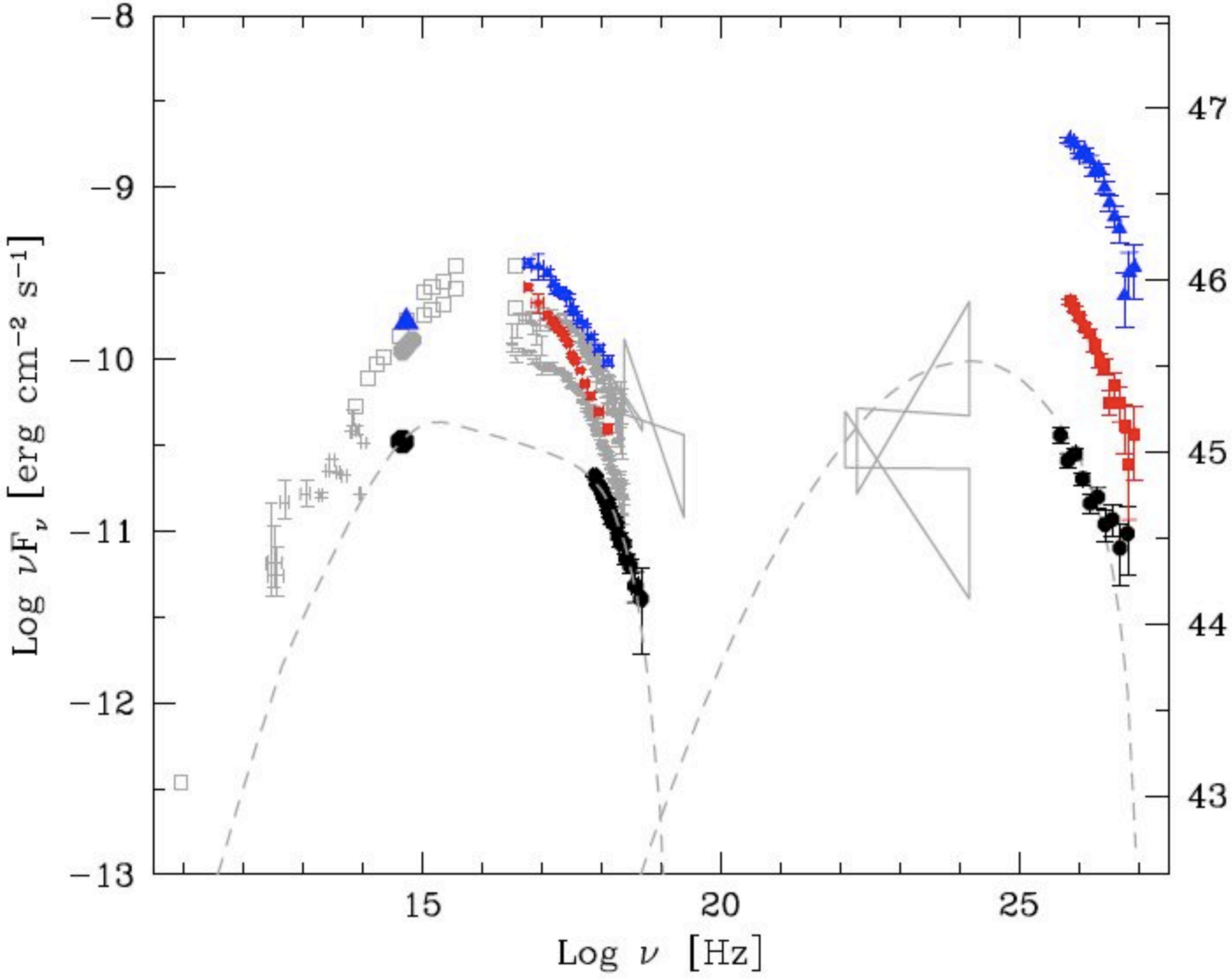
Aharonian et al. (HESS collabortion), Science 2009



-> 2000 × higher than in our Galaxy
(or 1400 higher than in the Galactic center region)

PKS 2155-304: Compton dominance

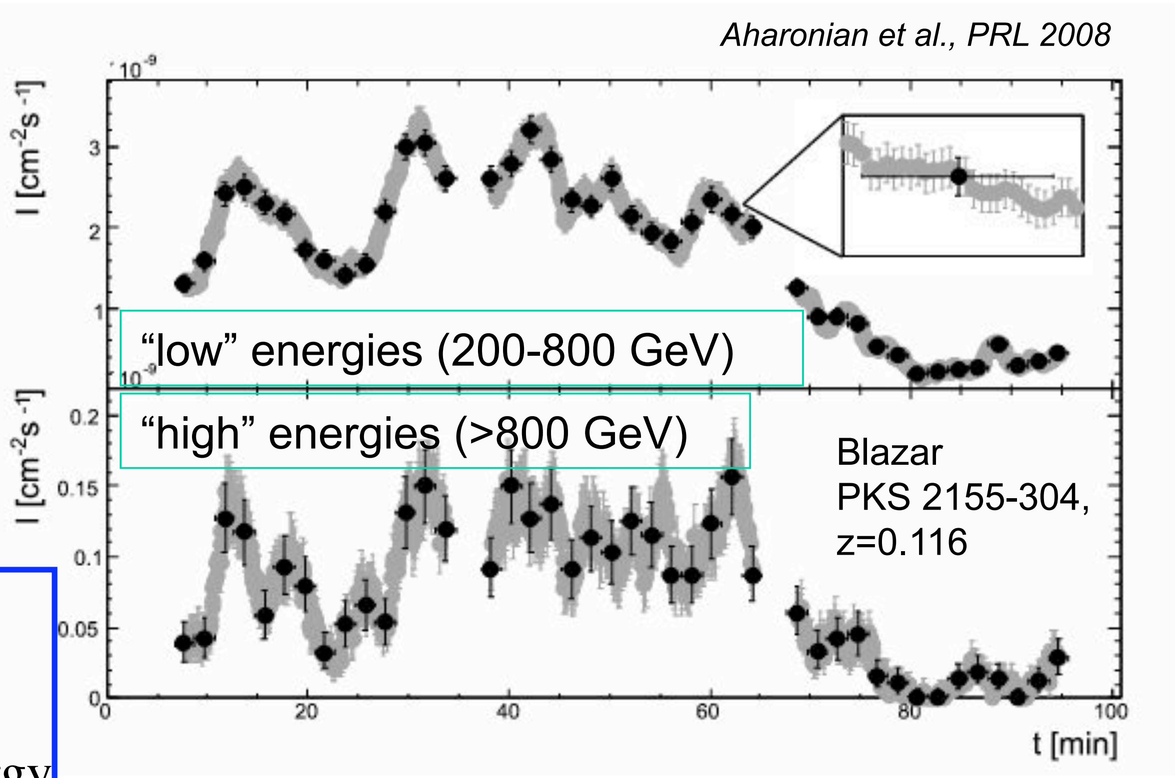
HESS collaboration, 2009



Blazars as extragalactic probes

Verification that the speed of light is not energy-dependent

- Einstein's postulate:
  "c is independent of the state of motion of the emitting body"
- Verification through time-of-flight measurements:
  Energy dependence predicted in models that go beyond Einstein's postulate
- Substantial effects possible for cosmological sources



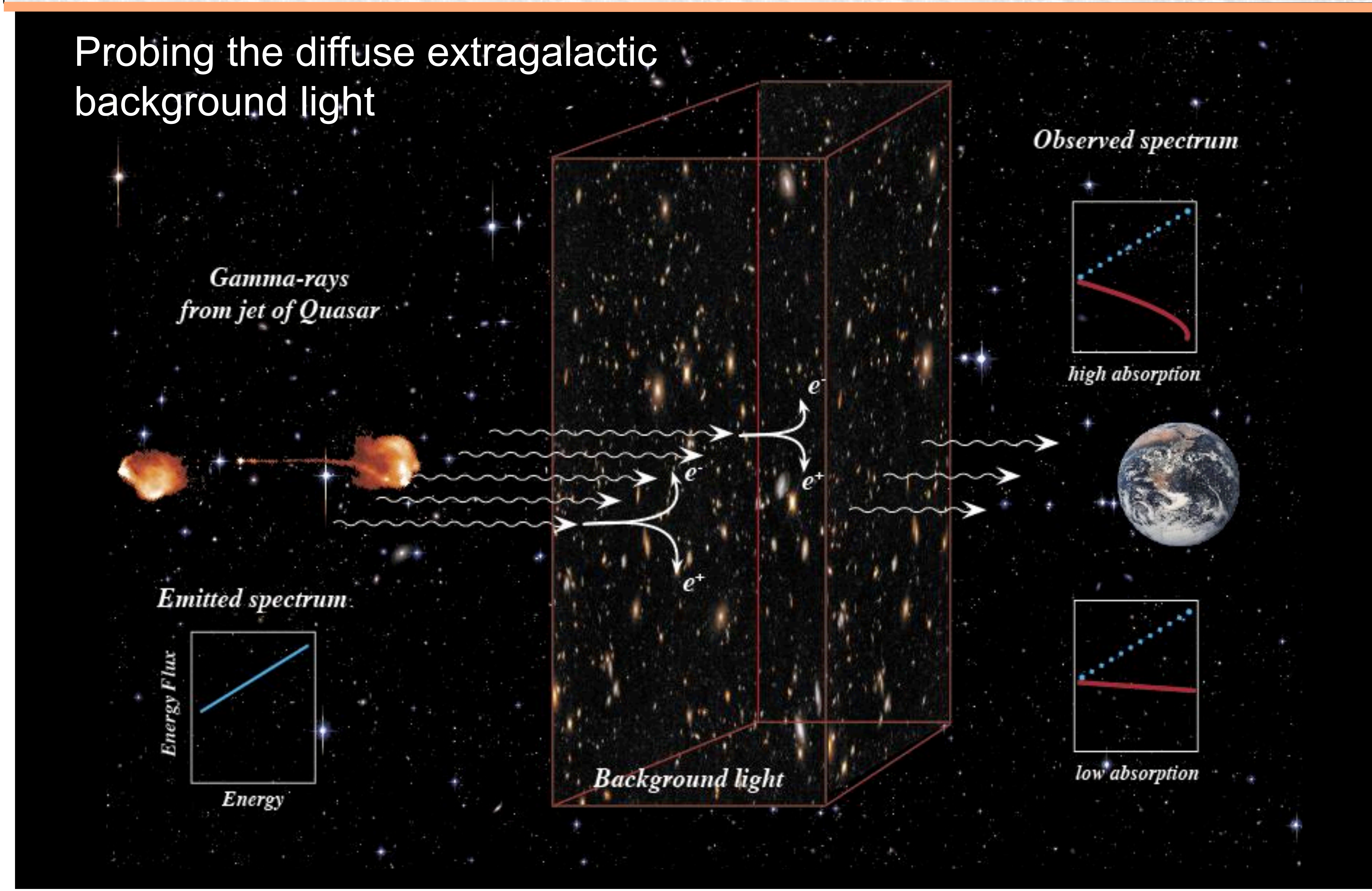
$$c' = c\left(1 + \xi \frac{E}{E_P} + \zeta \frac{E^2}{E_P^2}\right) \quad \text{(Ansatz)}$$

$$E_p = 1.22 \times 10^{19}\,\text{GeV} \ : \ \text{Planck energy}$$

- Absence of time delay -> upper limits on the energy dependence of c
- If effect was present -> worry also about source-intrinsic effects, sample of sources would then help
- Other sources that can be used: gamma-ray bursts

Blazars as extragalactic probes

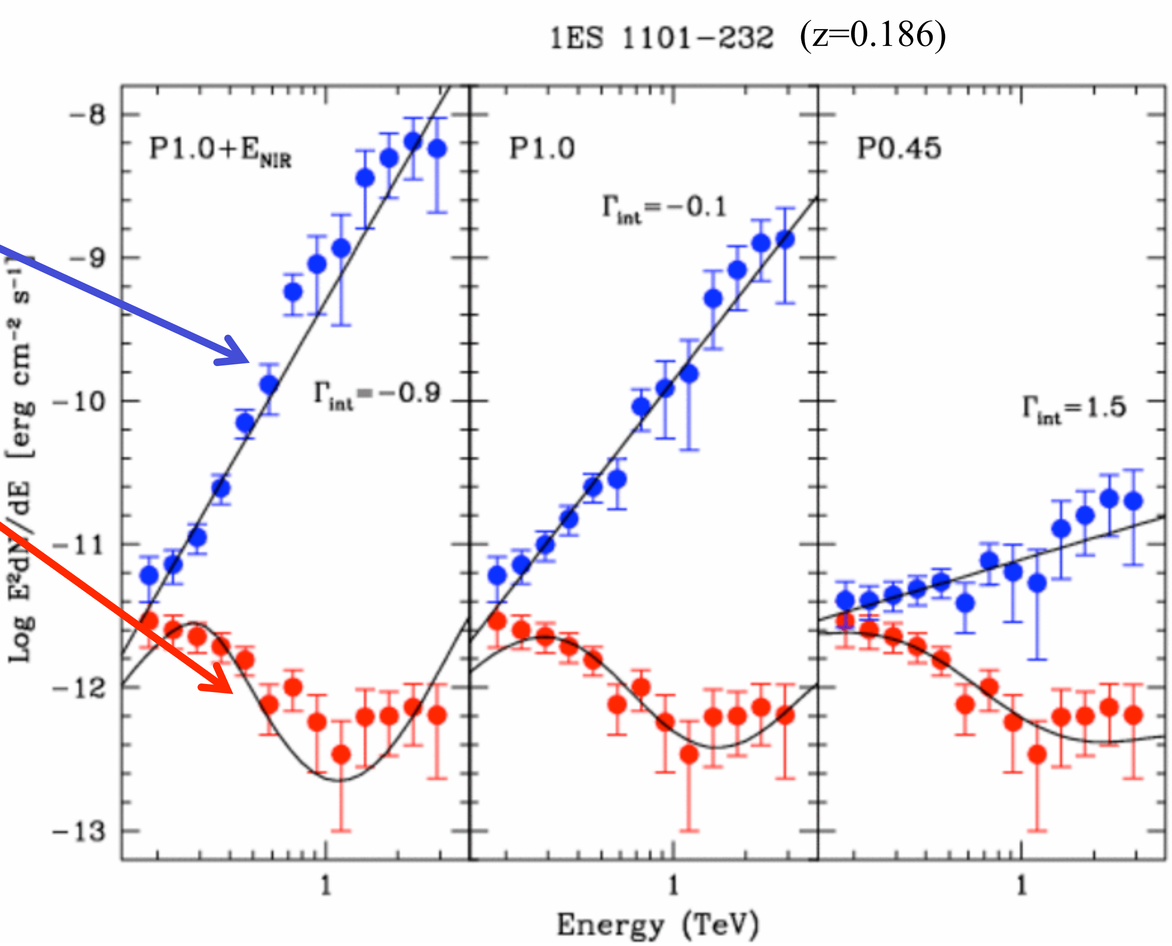
Probing the diffuse extragalactic background light



Blazars as extragalactic probes

Probing the diffuse extragalactic background light

$$F_{\mathrm{obs}}(E) = F_{\mathrm{int}}(E) \cdot e^{-\tau(E)}$$



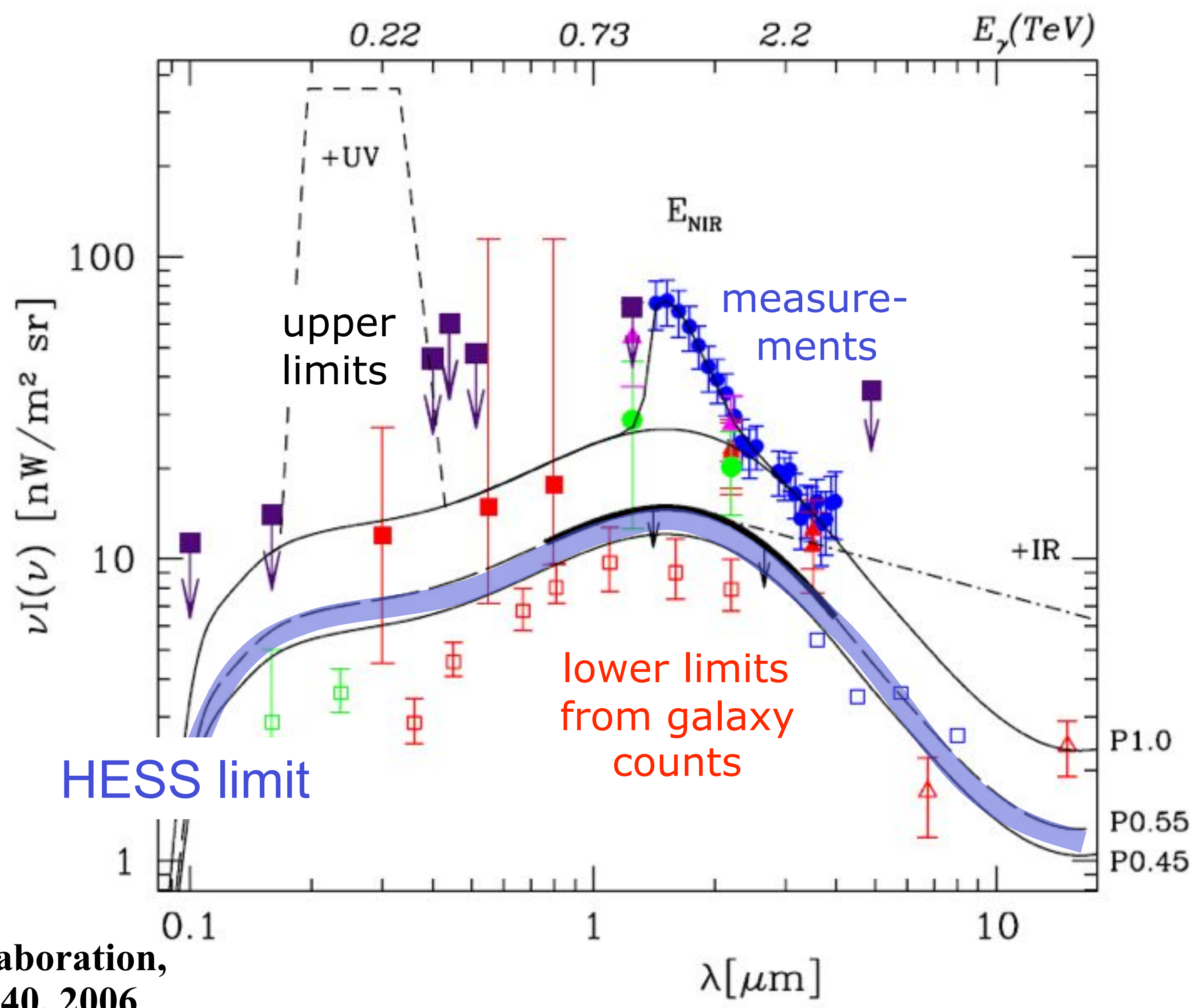
Characteristic absorbing photon's wavelength

$$\lambda^{*} \approx 1.4 \left(\frac{E_{\gamma}}{1\ \mathrm{TeV}} \right) \mu\mathrm{m}$$

-> with TeV photons from AGN,
infrared background fields are probed

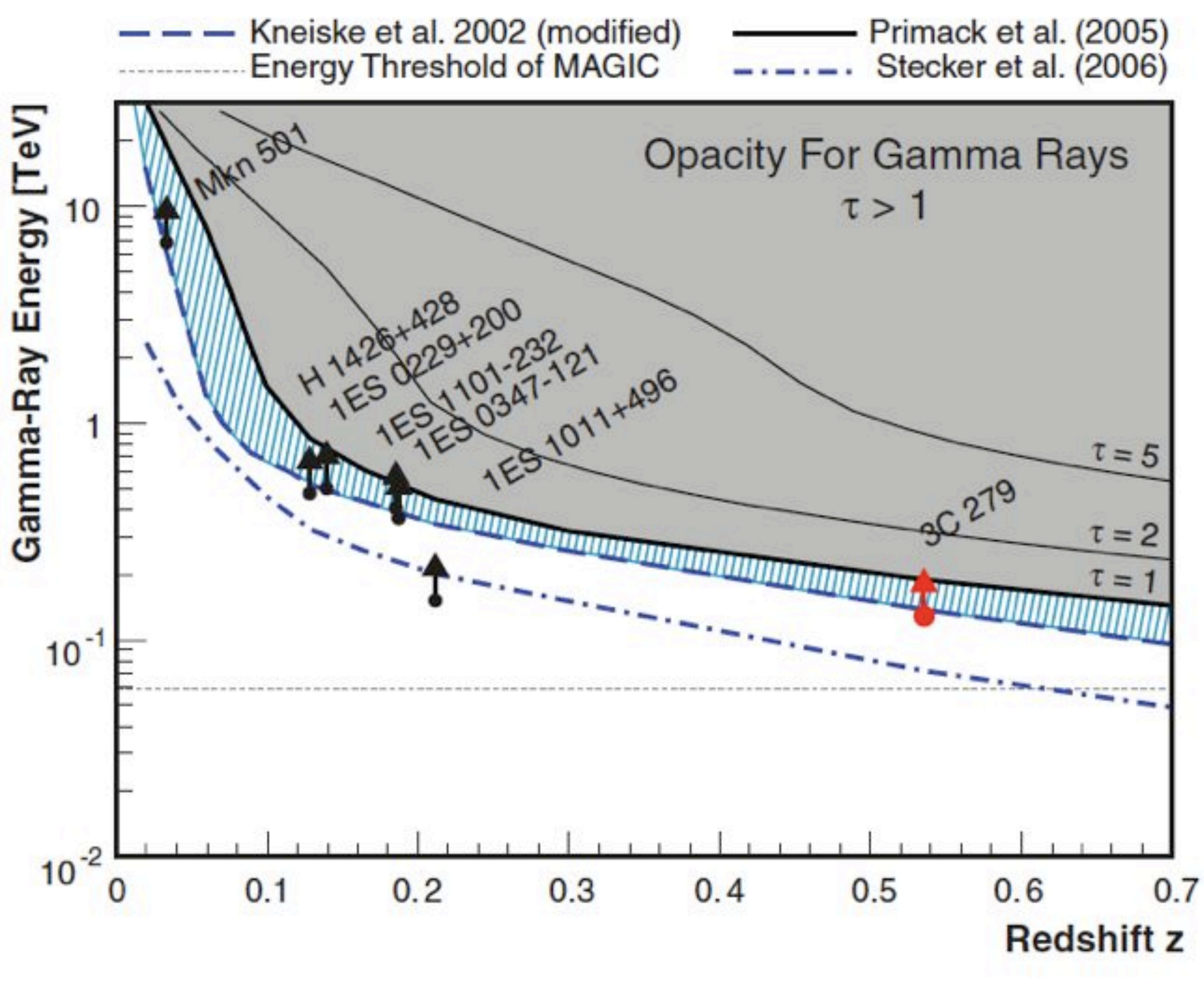
Aharonian et al., Nature 2006

EBL limit from HESS



HESS collaboration,
Nature 440, 2006

Towards a redshift breakthrough



MAGIC collaboration. Science 2008

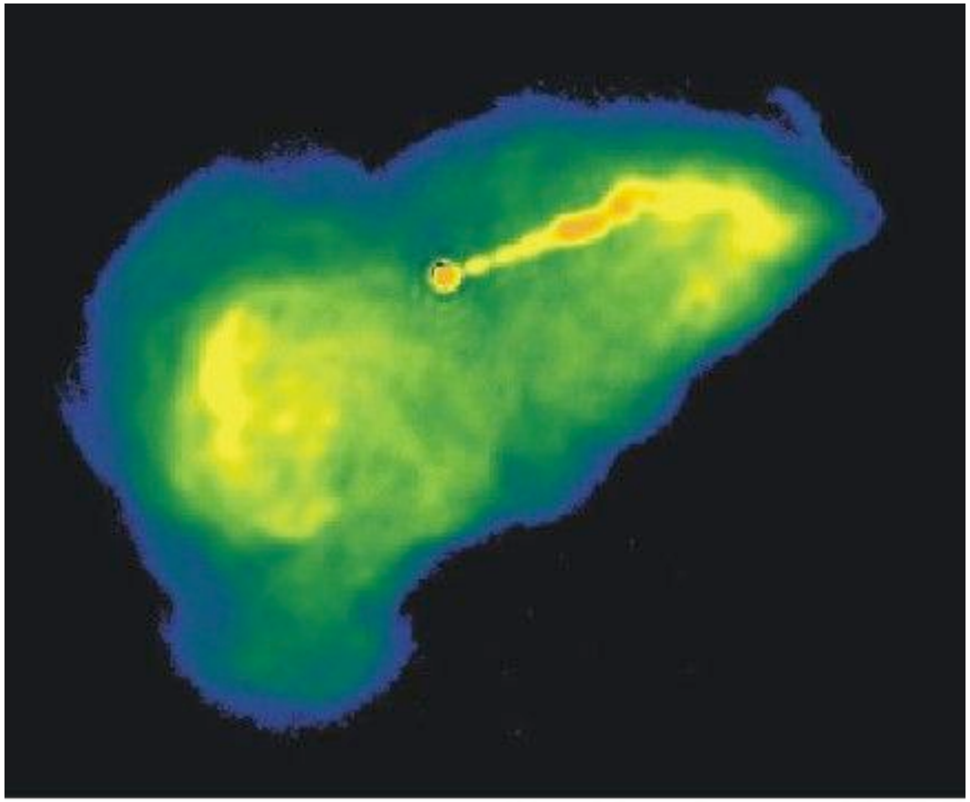
Good news:

1. The universe is much more transparent to TeV γ-rays than thought ten years ago
2. Not only BL Lacs but also FSRQ are seen in TeV γ-rays (3C 279, PKS 1510-089, 4C+21.35)
3. And: also radio galaxies…

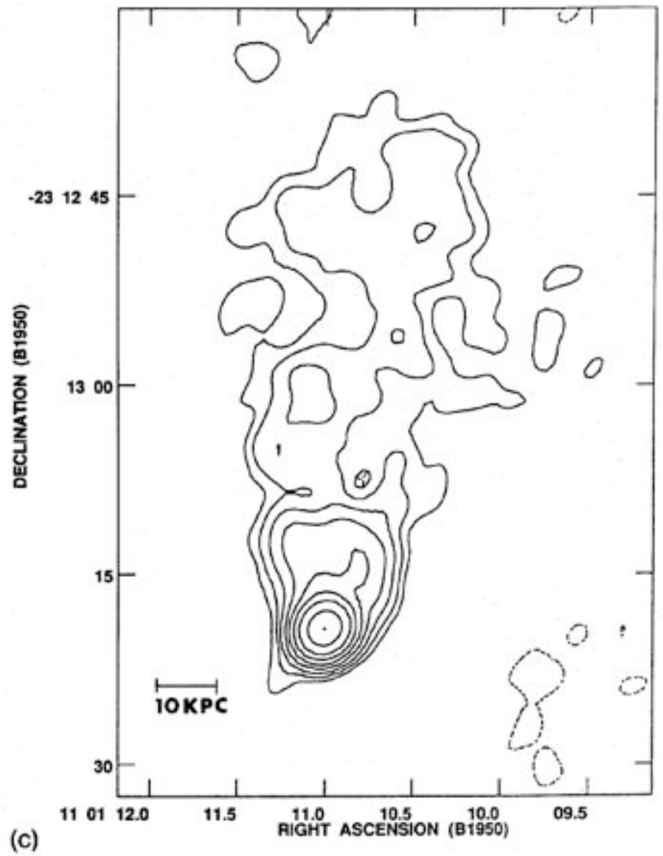
FRI Radio Galaxies: The parent population of blazars

M 87: a "misaligned" blazar

(1ES 1101-232: head-on view on the collimated jet)

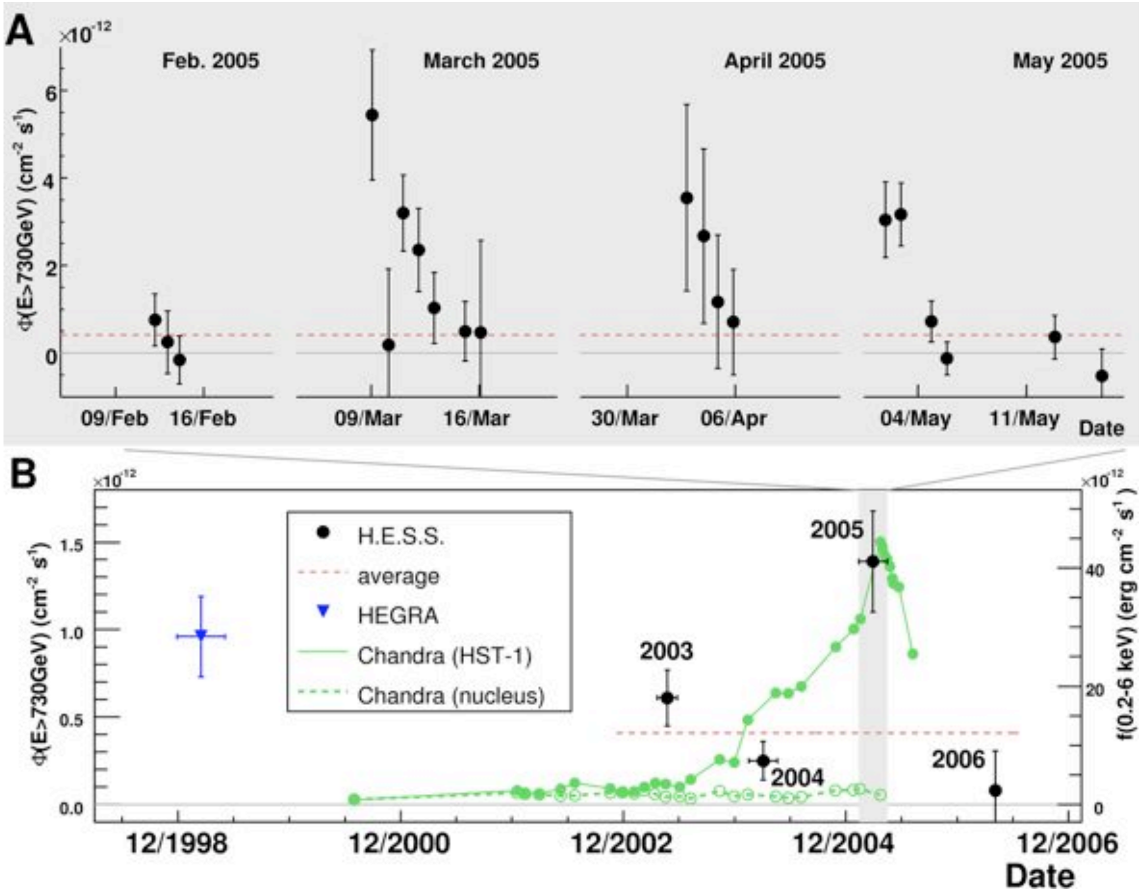


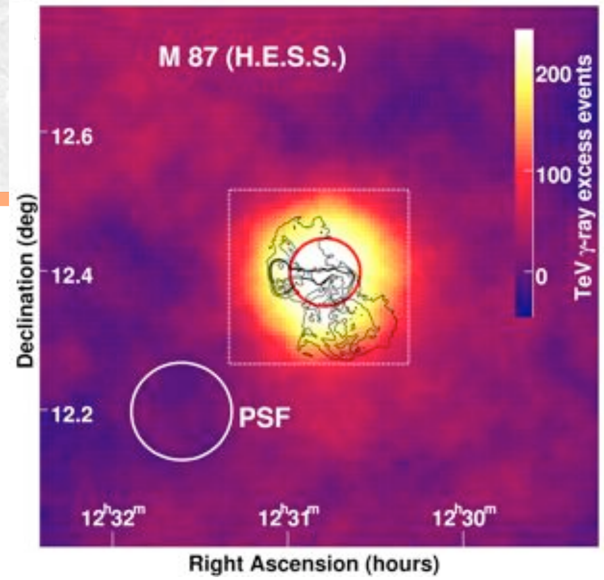
F. Owen, NRAO, with J. Biretta, STScI, & J. Eilek, NMIMT



VLA, 1.4 GHz

The radio galaxy M 87

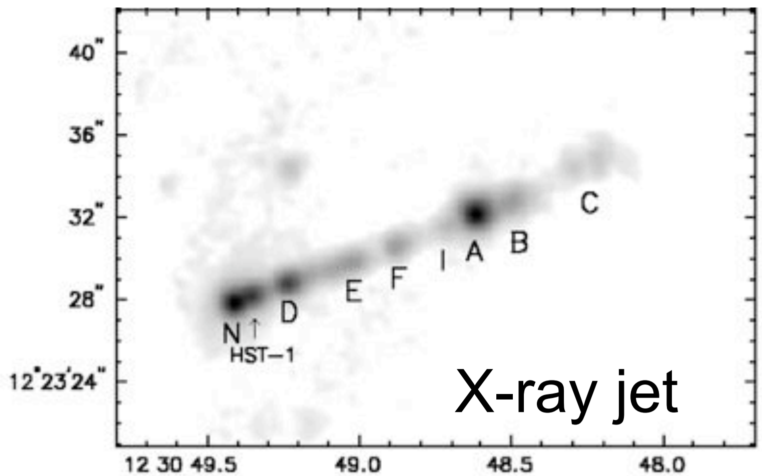




HESS collaboration,
Science 314, 2006

Variability
→ radiation close to the BH likely
(HST 1 not excluded but difficult)

Hard VHE spectrum
→ challenges off-axis blazar scenarios



Conclusion (again)