The Very High Energy Sky Seen with H.E.S.S.

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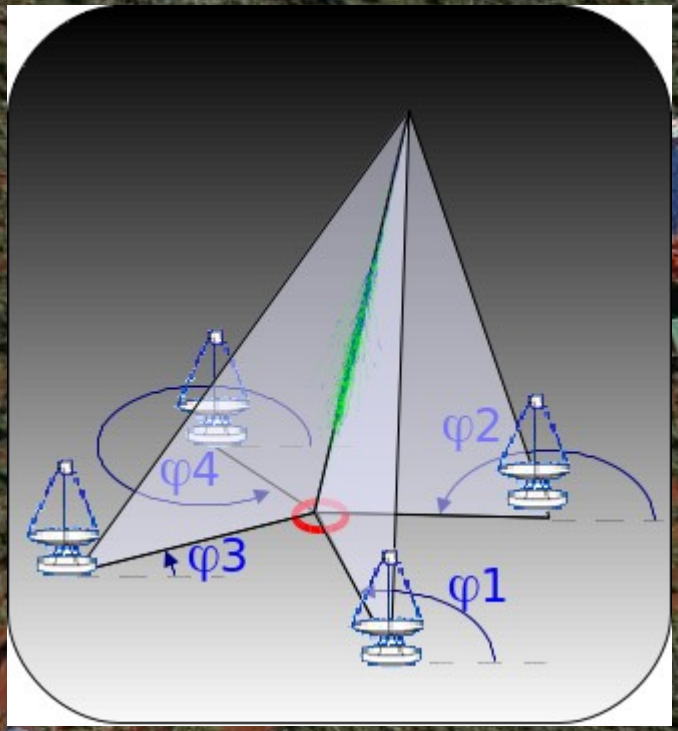
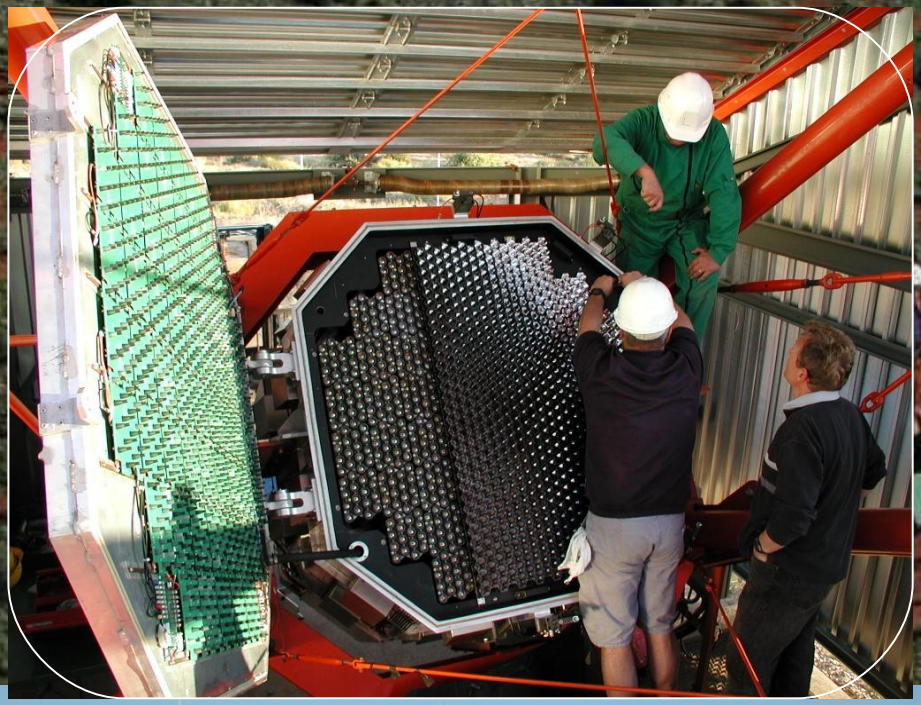
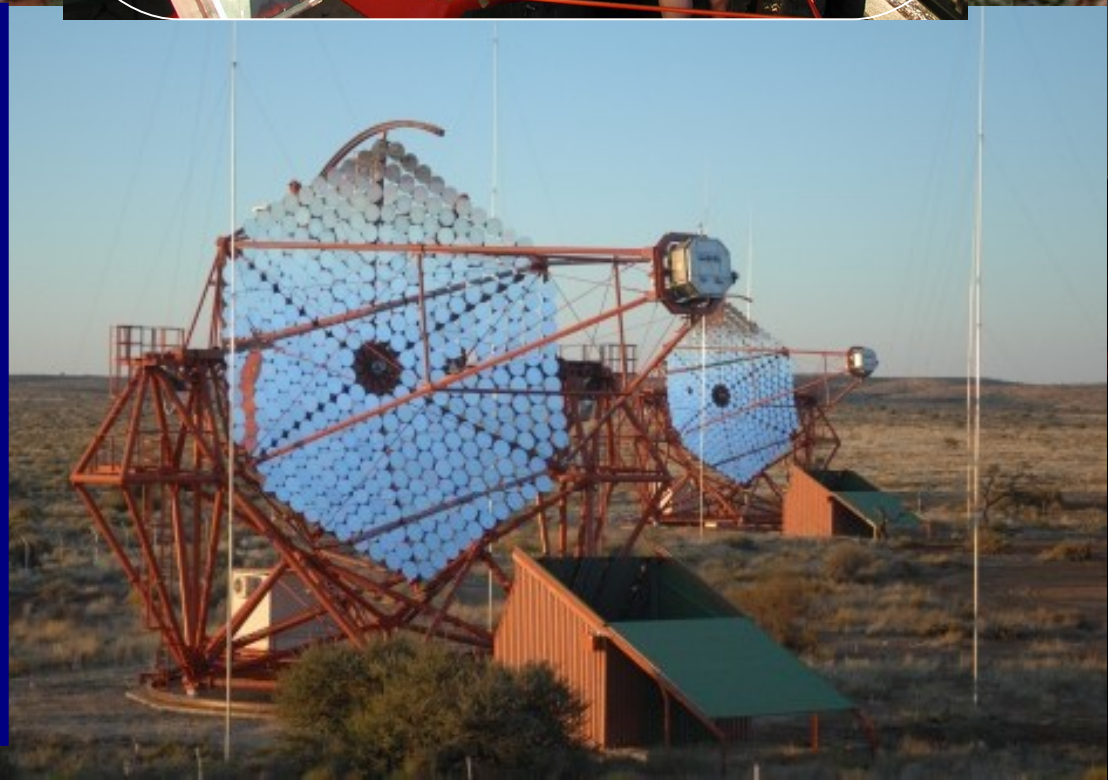
Victor HESS, 1912

H.E.S.S. in Namibia



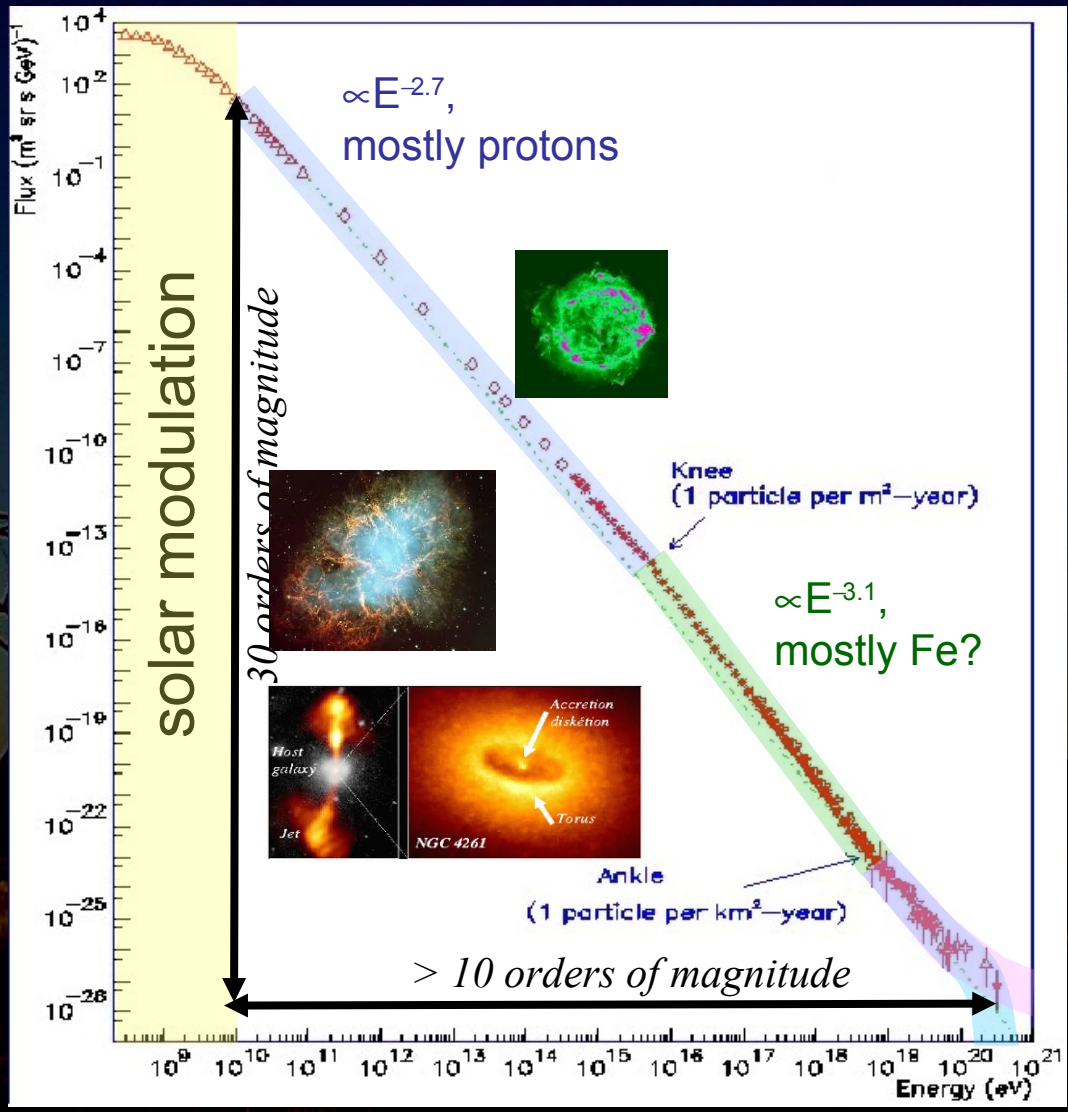


- 4 Atmospheric Cherenkov Telescopes (square of 120 m)
- 14m dishes
- 5° FOV, fine pixelisation
- (960 pixels PMTs)
- Fast electronics (1 ns sampling)
- Operating since 10/12/2003
- Threshold ⇒ 100 GeV



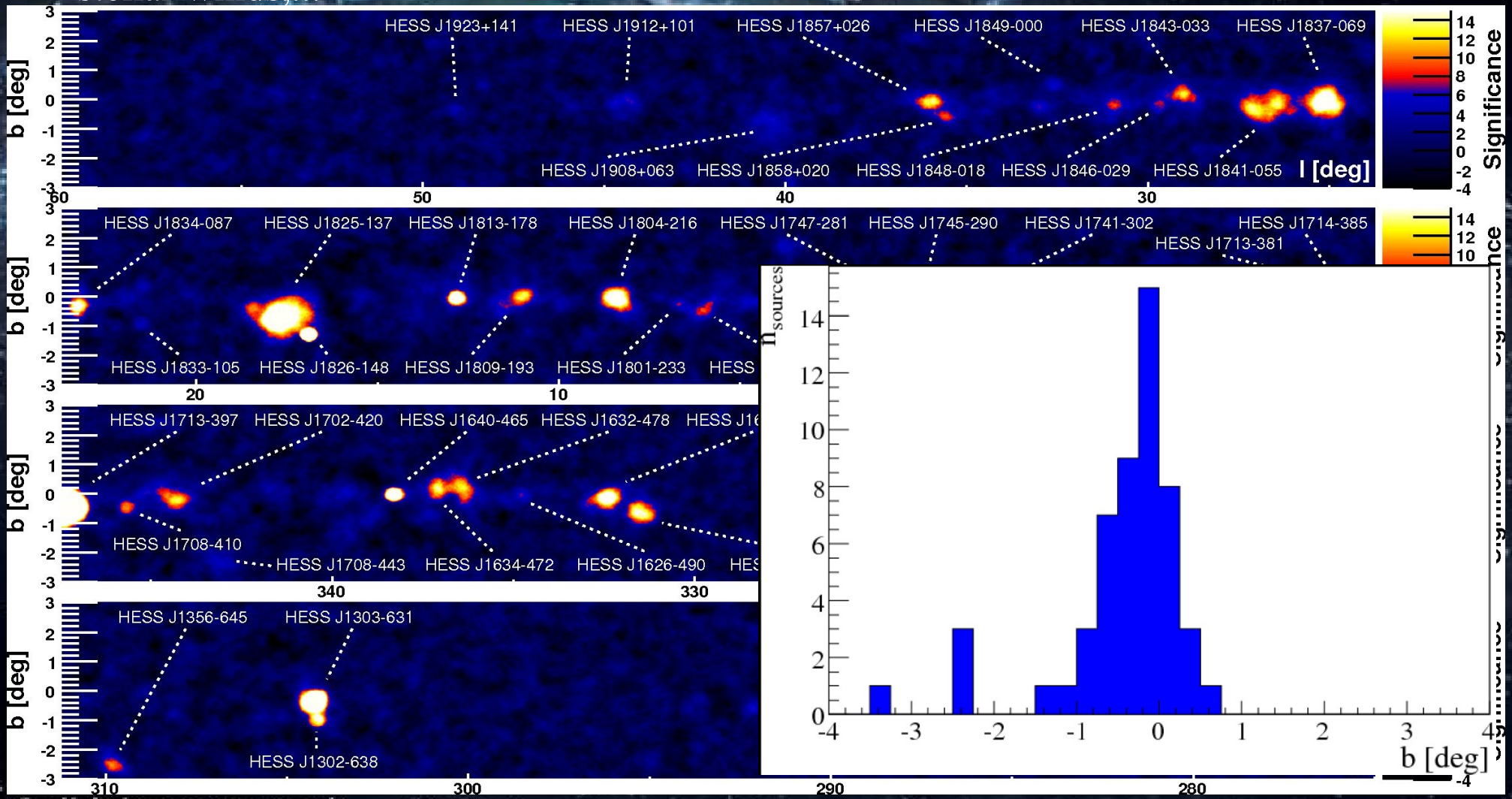
SNRs and origin of cosmic rays

- Cosmic ray problem at the origin of the field
- SNRs are believed to be the sources of CR
  - Energetics are OK (10% efficiency)
  - Robust conceptual framework (DSA)
- In the last years, many observation progresses
  - Young SNRs in TeV - Evidence for ultrarelativisitic electrons
  - Middle aged/old SNRs in GeV (Fermi)
- Open questions:
  - Up to what energy?
  - What are the dominant acceleration channels?
  - What acceleration efficiency? (CR content of SNRs)



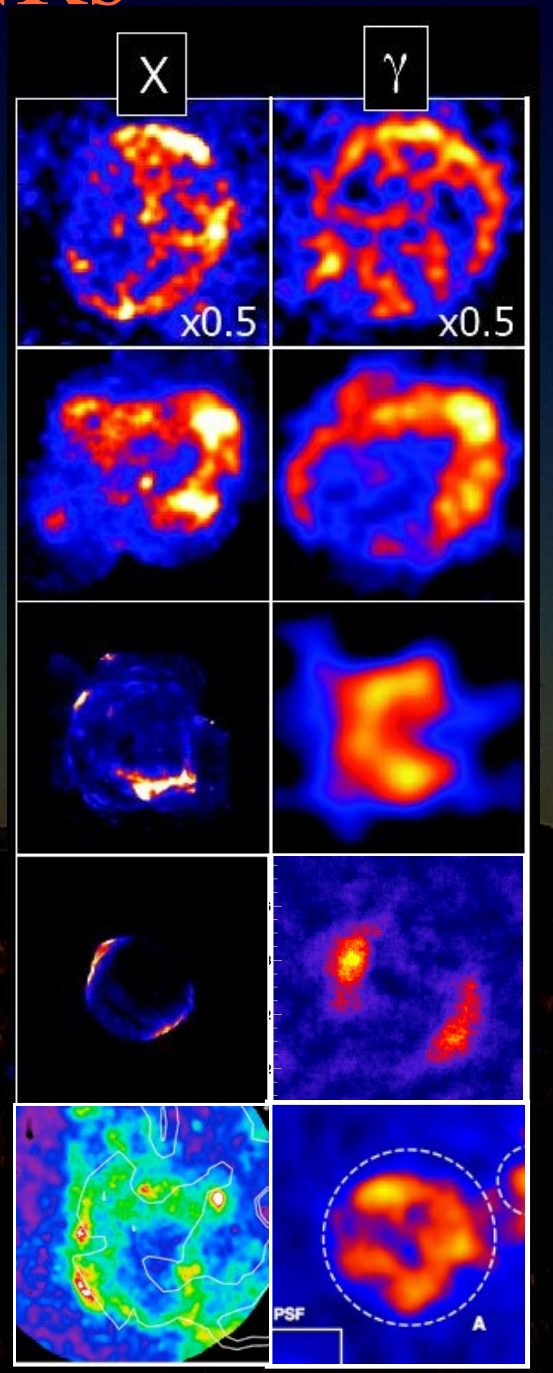
H.E.S.S. Galactic Plane Survey

Inner part of the Galaxy: |b|<3°, -80 < l < 60°, 1400 h of data + dedicated pointing
56 sources, very narrow distribution (RMS(b) ~ 0.3°)
⇒Molecular gaz scale, young sources
Population: PWN (29), SNRs (9), Binary systems (3), Dark sources, Interacting stellar winds,...



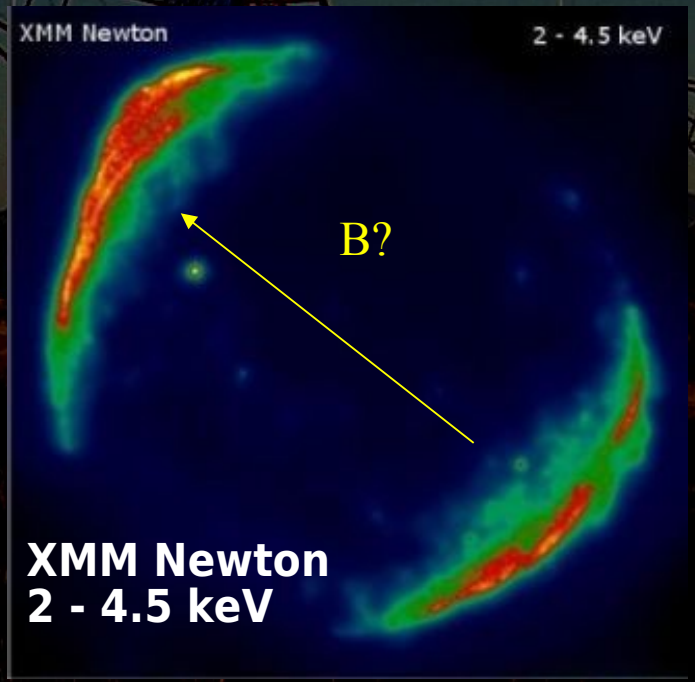
Young (TeV bright) SNRs

- 5 shell-like objects, detected in TeV gamma-rays
- Young historical SNRs
  - RX J1713.7-3946
  - Vela Junior
  - RCW 86
  - SN 1006
  - HESS J1731-347
- Unresolved:
  - Kepler (Veritas)
  - Cas A (Veritas/MAGIC)
- All show rather clear correlation with non-thermal X-ray emission
- See talk by F. Acero



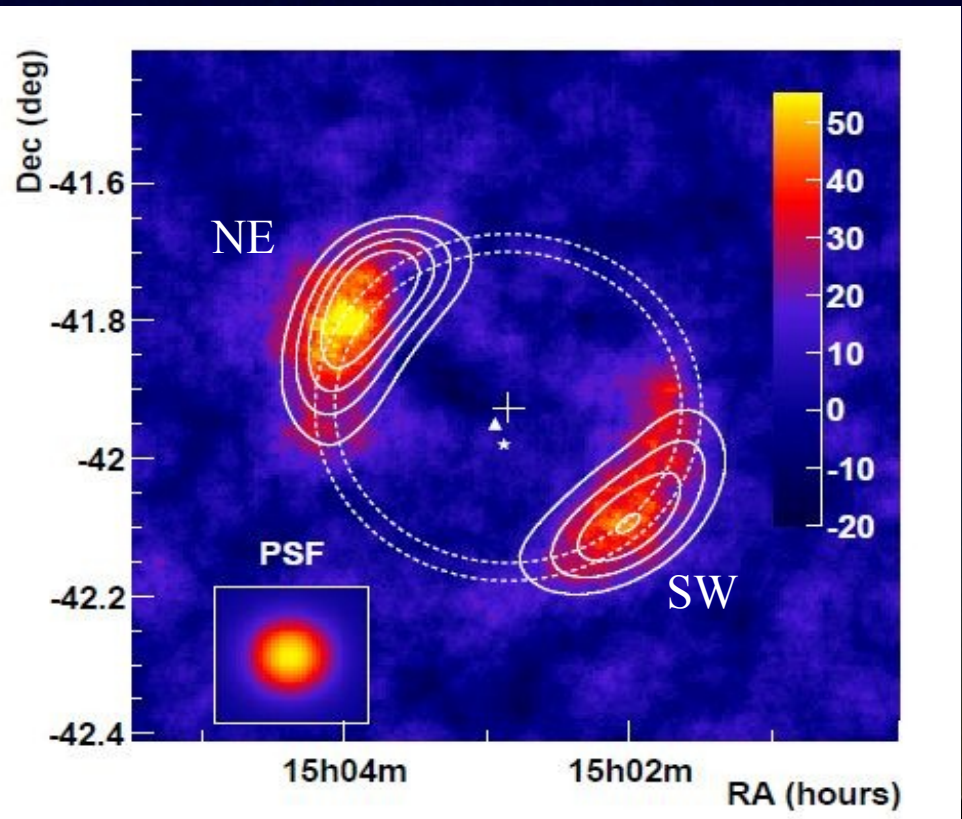
Probing acceleration mechanism
SN 1006

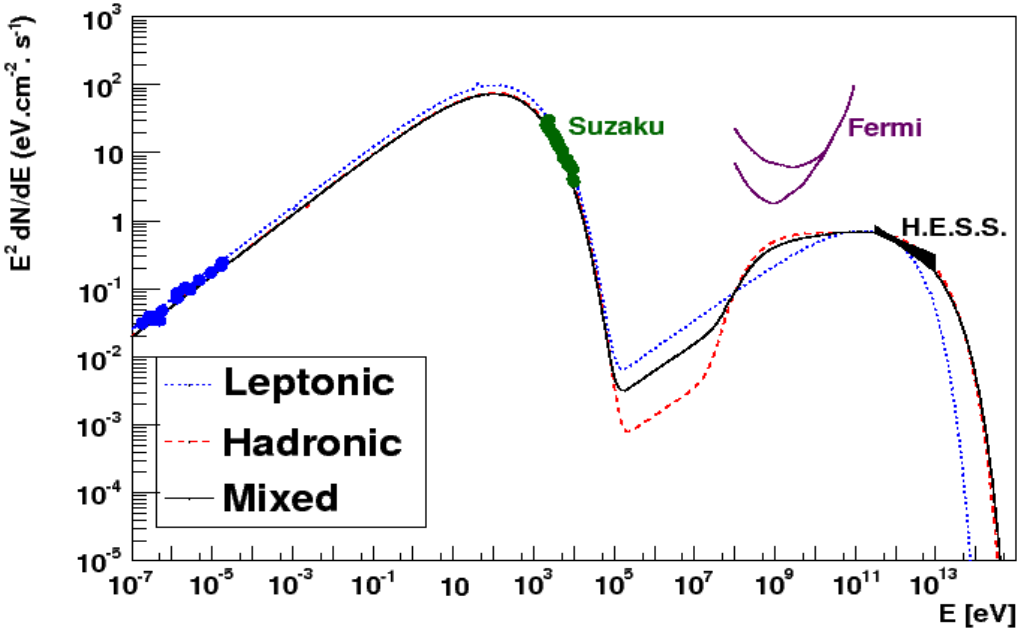
- Latest addition to young TeV SNRs, with HESS J1731-347
- Type Ia SN, distance: 2.2 kpc
- Rather uniform, low density environment (0.05 – 0.08 cm-3), 500 pc above Galactic Plane (clean, easier tests to models)
- Faint TeV source : 1% of Crab Flux, clear bipolar non-thermal morphology: plane // shock

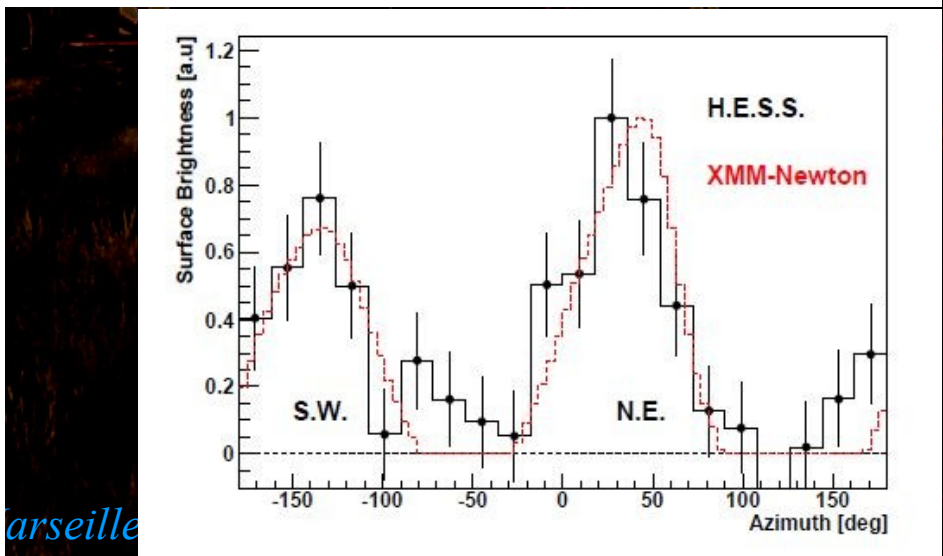


SN 1006 TeV Observations

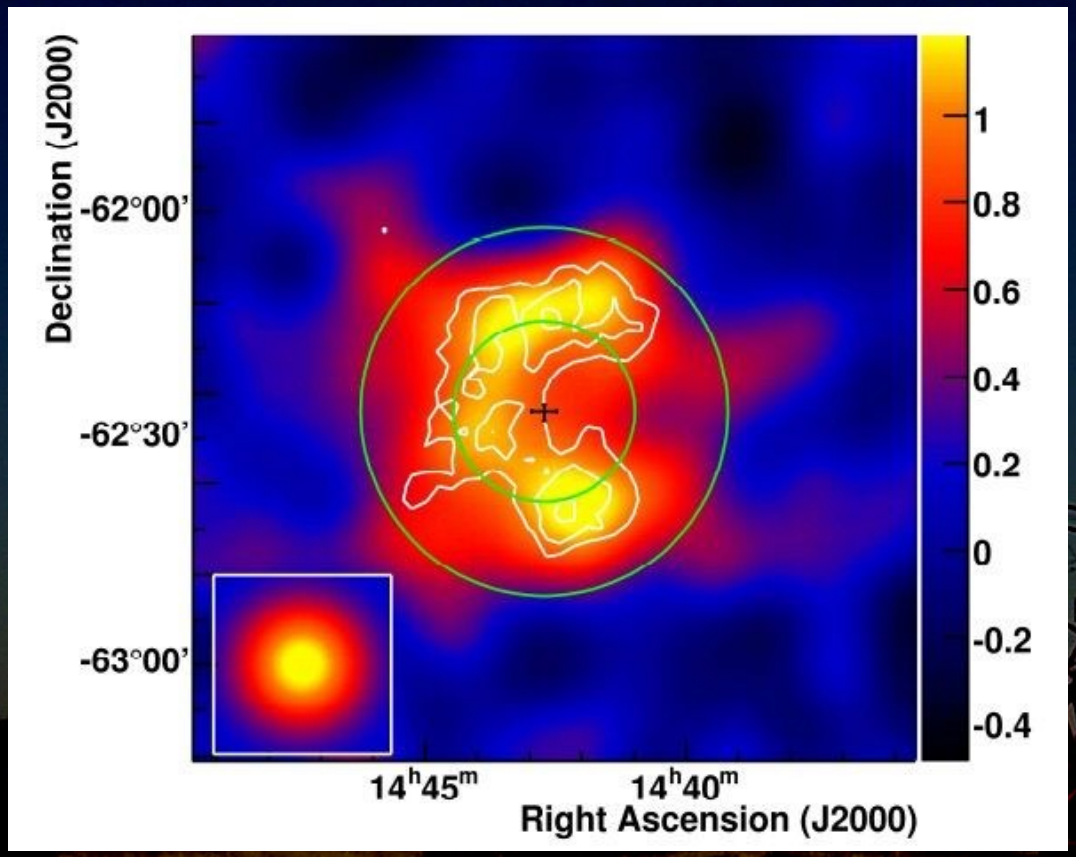
- Striking X-TeV correlation
- Mixed model gives good description of data, reasonable Wp ~ 12% WSN, B ~45 μG
- Leptonic or pure Hadronic model also possible
- In any case, energy budget dominated by protons

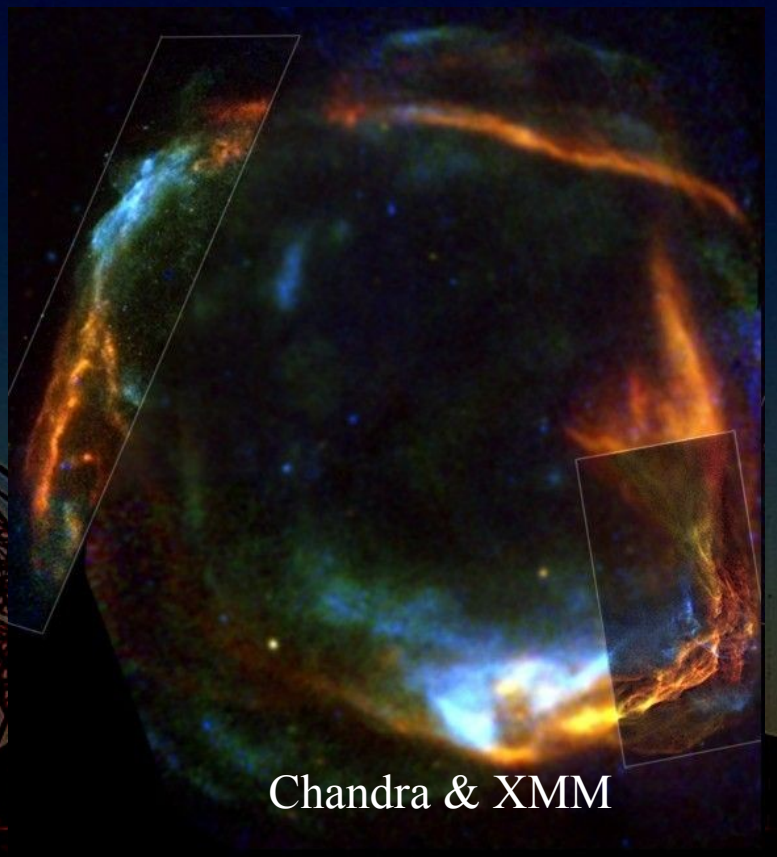






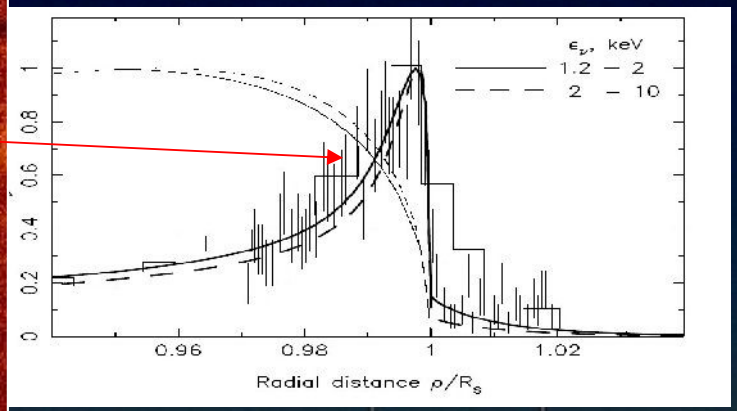
SNR acceleration efficiency: RCW 86





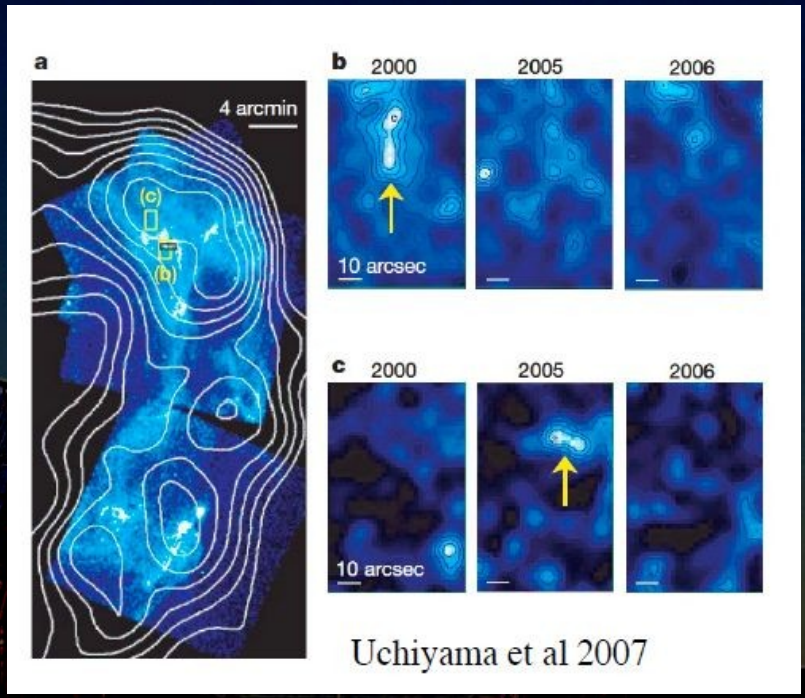
- Measured shock velocity 6000±2800 km/s (Chandra 2004,07)
- Expected post-shock gas temperature 42...70 keV *Helder et al, 2009*
- Measured post-shock temperature 2.3±0.3 keV (Hα line width)
- >50% of energy in non-thermal component (CR pressure)

Magnetic field in SNRs



Berezhko, Ksenofontov, Völk 2003
Bamba et al, 2003; Berezhko et al, 2003

Uchiyama & Aharonian, 2008

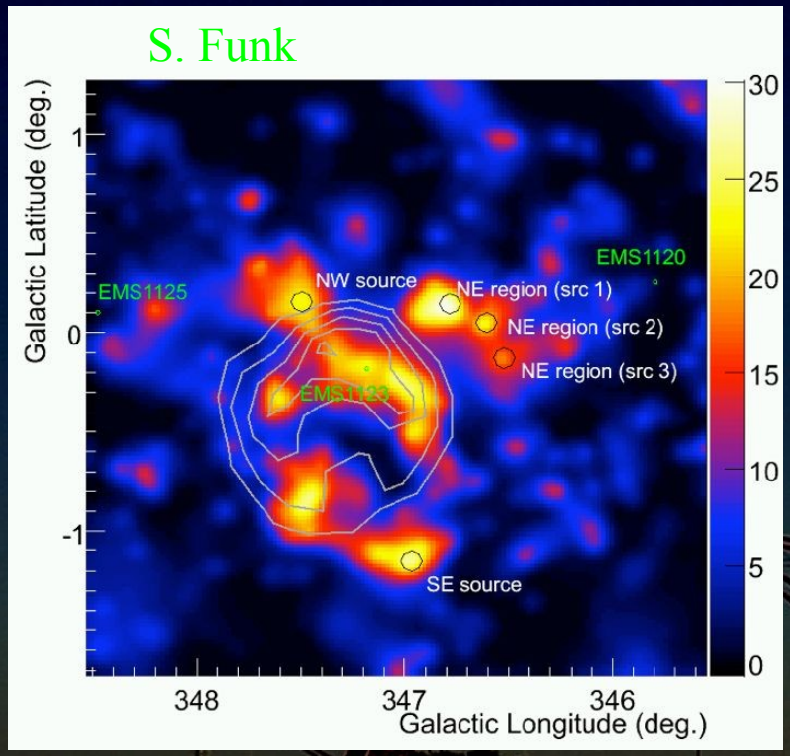


RX J1713,7-3946

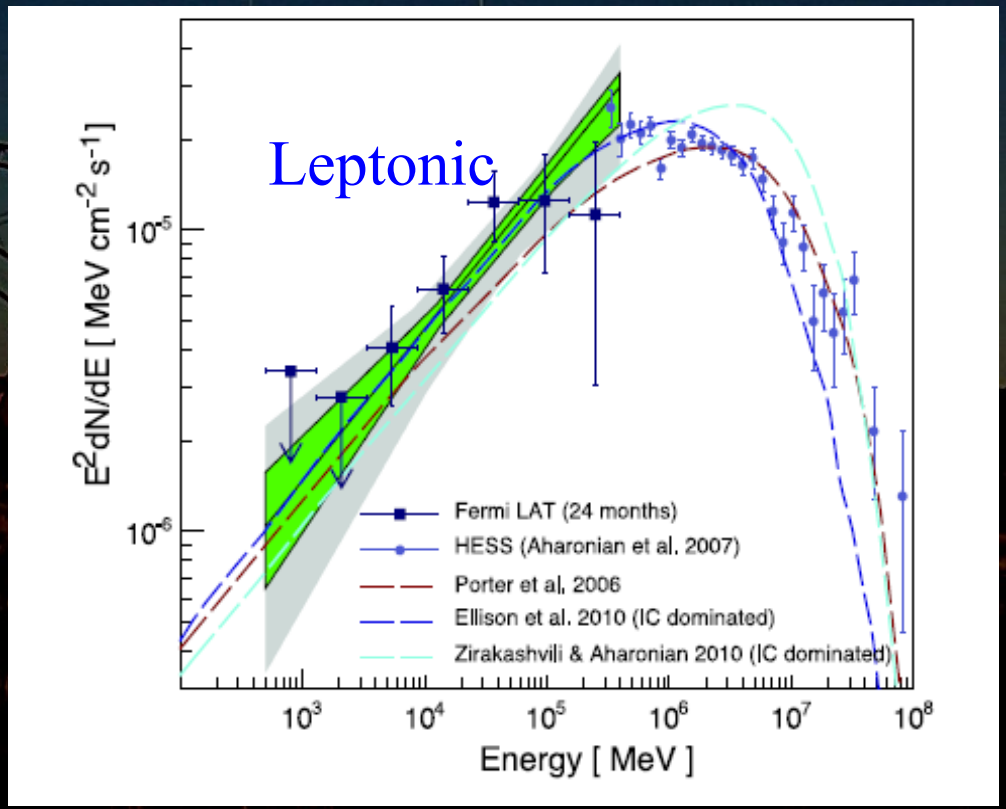
- Growing evidence for magnetic field amplification
  - Thin filaments (SN 1006, ...) indicates rapid electron cooling ⇒ B ~ 0.1 mG , but alternate explanation possible (field damping)
  - Synchrotron X-Ray variability gives new probe of B-field in SNRs

(Fast cooling) ⇒ B ~ [0.1,0.5] mG)

RX J1713.7-3946 with FERMI



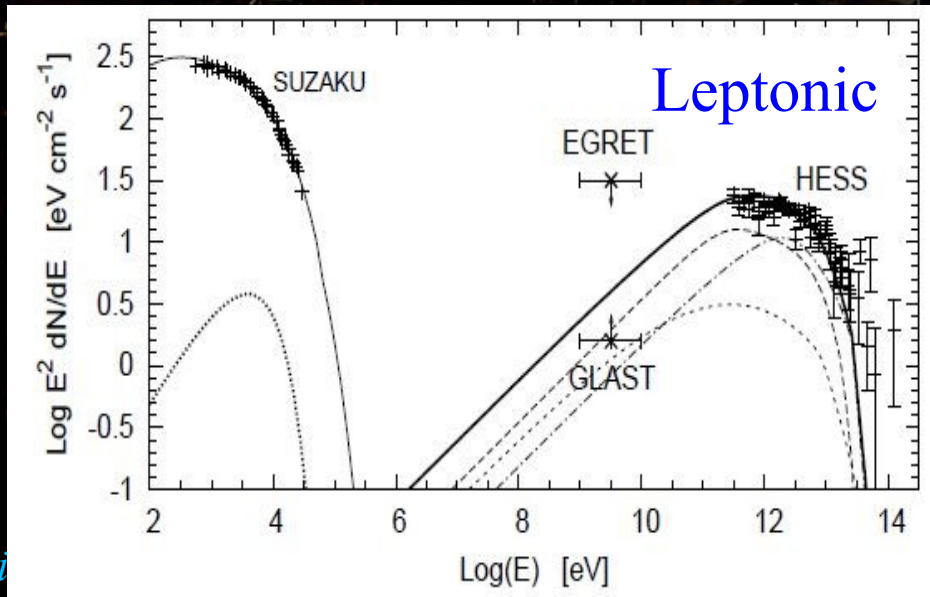
- Faint source in a complicated region
- Sources to to the north coincide with molecular material (CO and HII region)

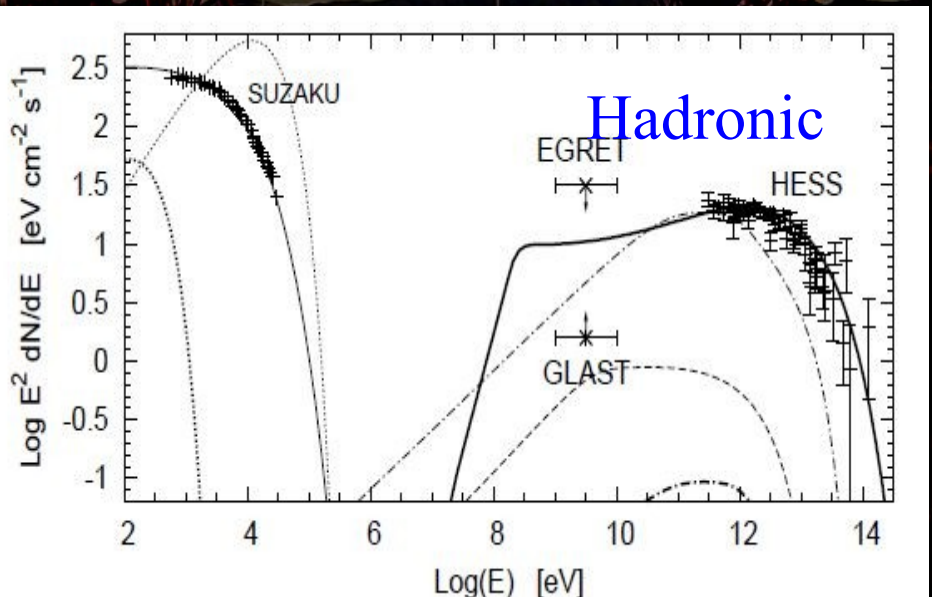


- Hard spectrum in the Fermi-LAT band: arXiv:1103.5727
- Emission from π0 difficult to accomodate

What have we learnt ?

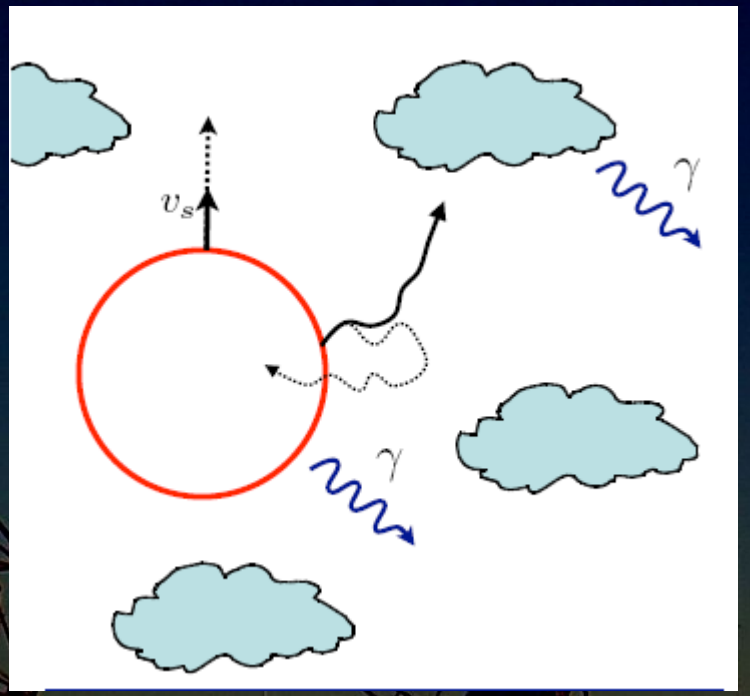
- Young SNR are proved to accelerate particles up to 100 TeV (at least)
- Efficiency can be as large as 50% (Post shock temperature, CR retroaction)
- Growing evidence for magnetic field amplification, predicted for hadron acceleration), supports acceleration of hadrons
- No definive proof concerning mechanism
  - 100 TeV difficult to reach with IC (Klein Nishina)
  - High B favours hadronic origin, B amplification as well
  - Close TeV/X correlation in favour of leptonic scenario
  - Recent Fermi paper claims it's leptonic
- Discriminating regions are GeV region (FERMI) and highest energies (CTA)

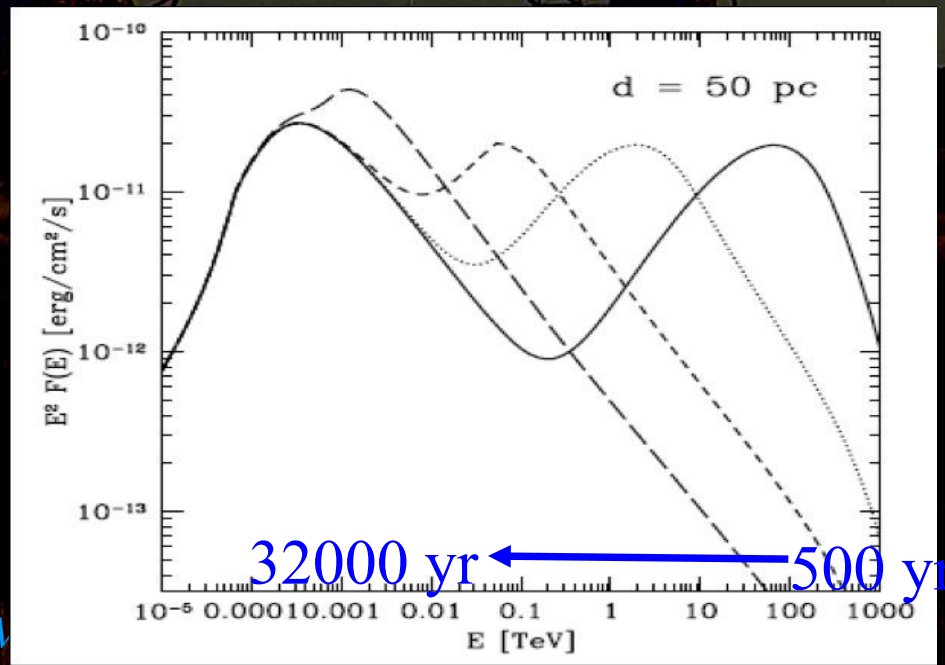




Gamma emission from molecular cloud near SNR

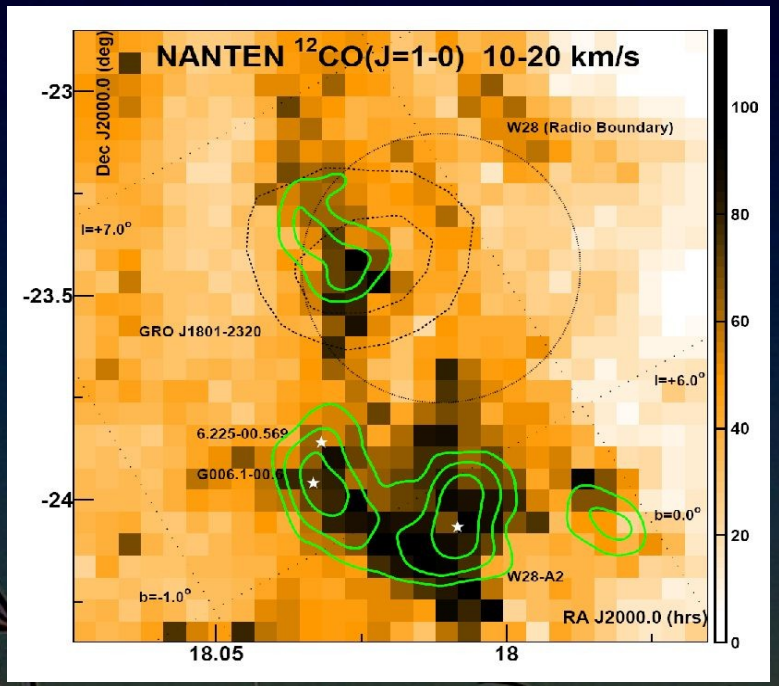
- Non-thermal emission from a molecular cloud in the proximity of a SNR: interactions of cosmic rays penetrating the cloud.
- CRs contribution from:
  - galactic background: steep spectrum, steady in time, peaks at GeV energy region;
  - runaway from SNR: hard spectrum, variable in time
  - Superposition of both: concave spectra, variable in time
- Can be use to probe CR overdensity in clouds

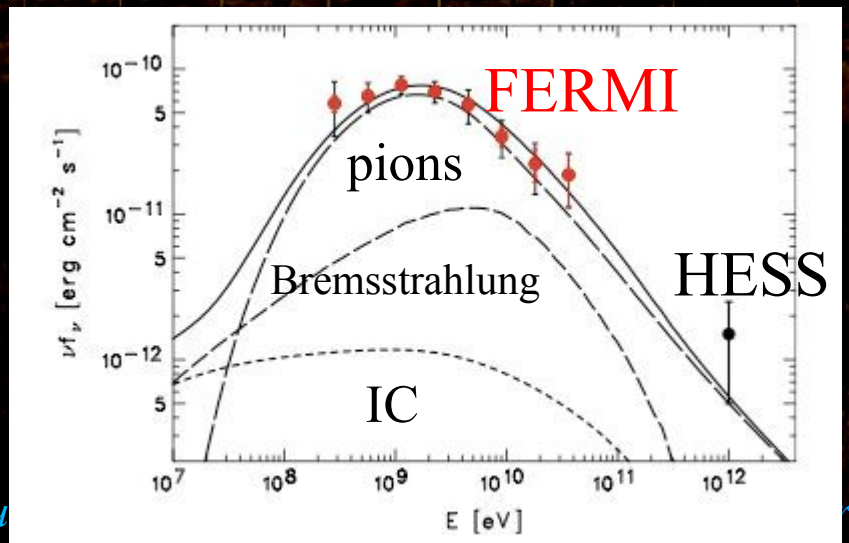


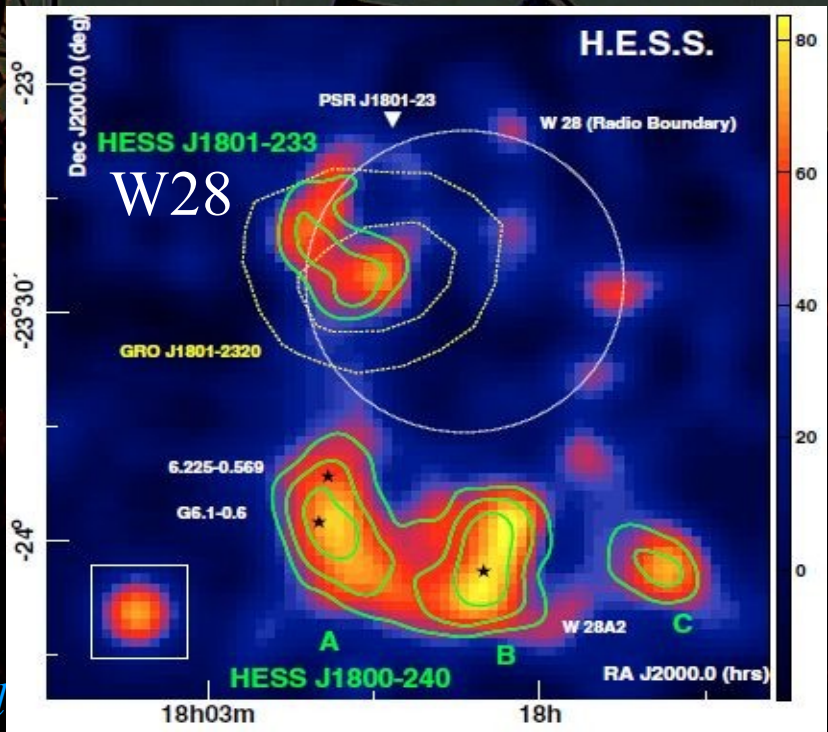


Gamma emission from molecular cloud near SNR

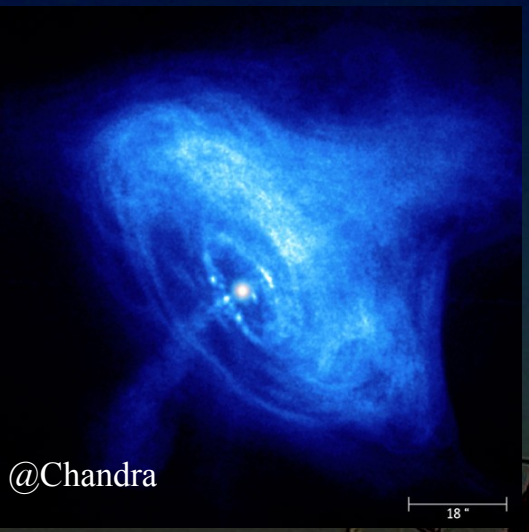
- Several cases: W28 (HESS), W51C (MAGIC), IC443, W44, HESS J1745-303, HESS J1714-385, HESS J1923+ 14 Galactic centre ridge
- W28:
  - Mixed morphology SNR, old ~35000-150000 yrs
  - Interaction of the remnant with molecular clouds seen in NANTEN CO (J=1-0); presence of OH masers, HII regions and dense molecular clouds in the South emission correlated with CO
- Strong indication of hadronic accelerators
- Overdensities of the order of 10

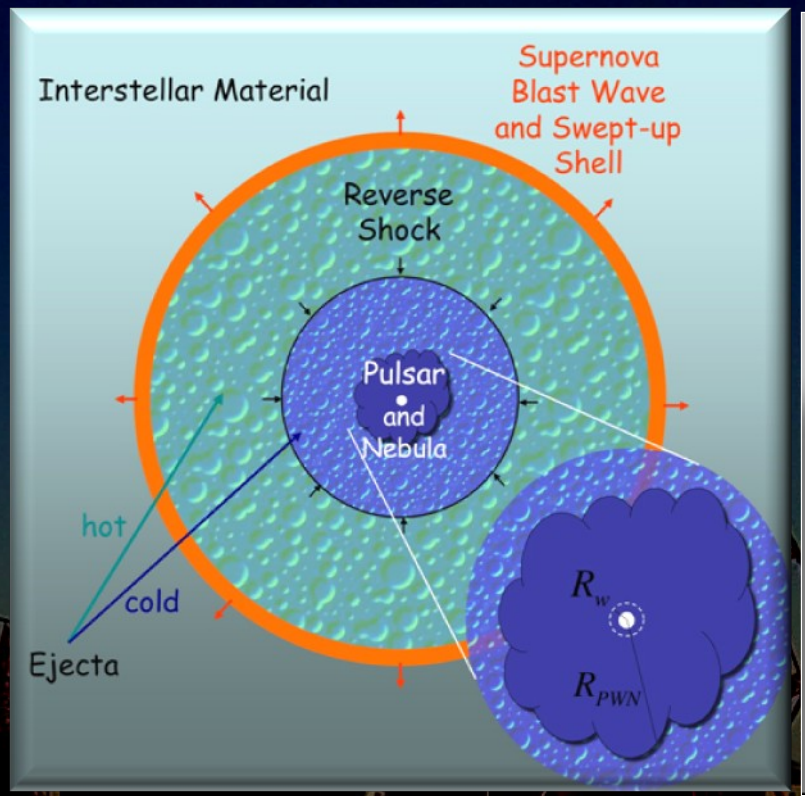


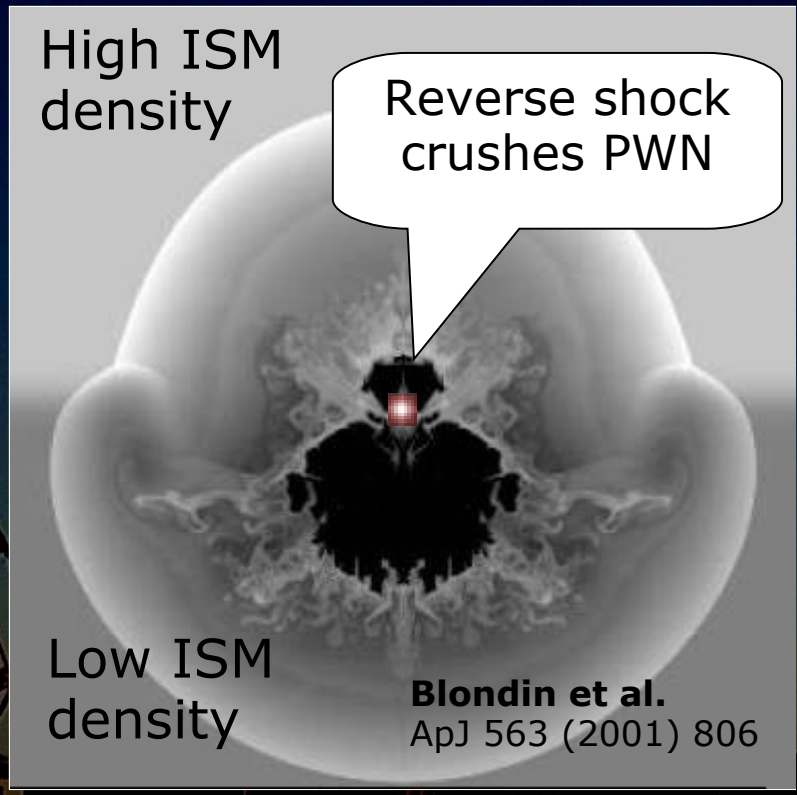




Pulsar Wind Nebulae

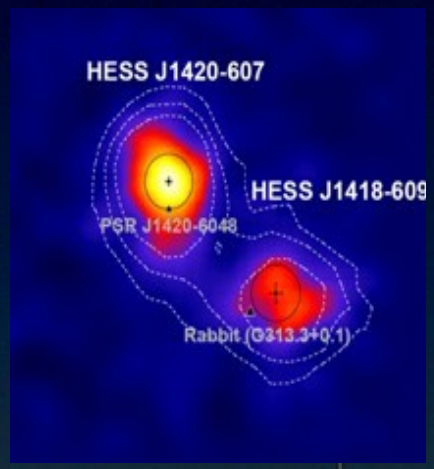


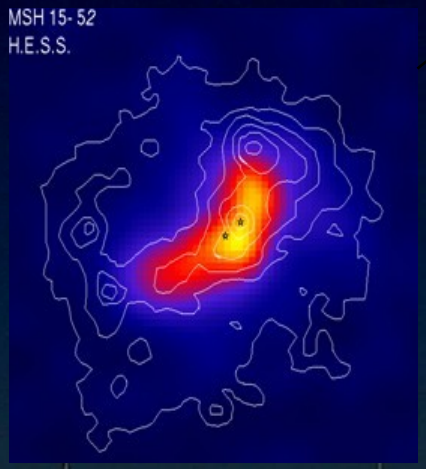


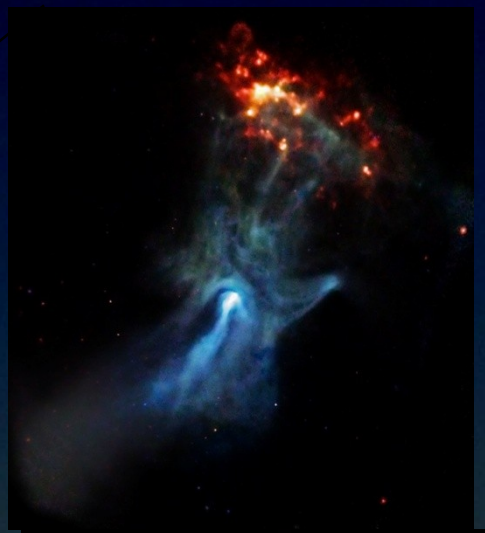


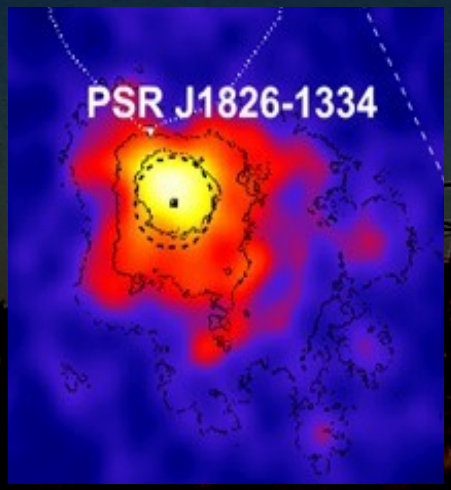
- Relativistic e^-/e^+ plasma wind driven by pulsar - confined by SNR of pulsar progenitor
  - Efficient conversion of rotation power into relativistic particles
  - Associated with young pulsars - high 'spin-down power'
  - Expansion in non-uniform medium may lead to complex morphology.

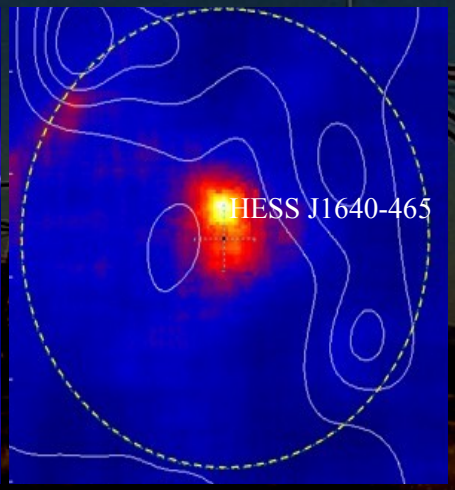
Lots of Gamma-ray PWNe

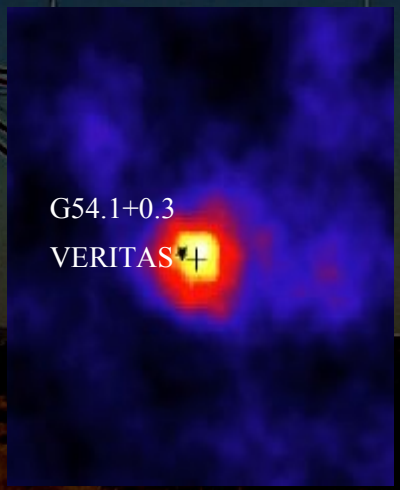


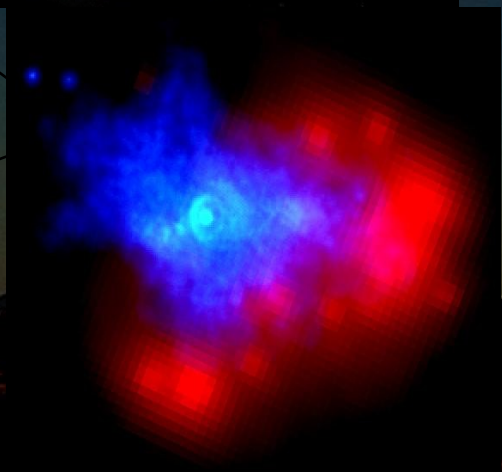








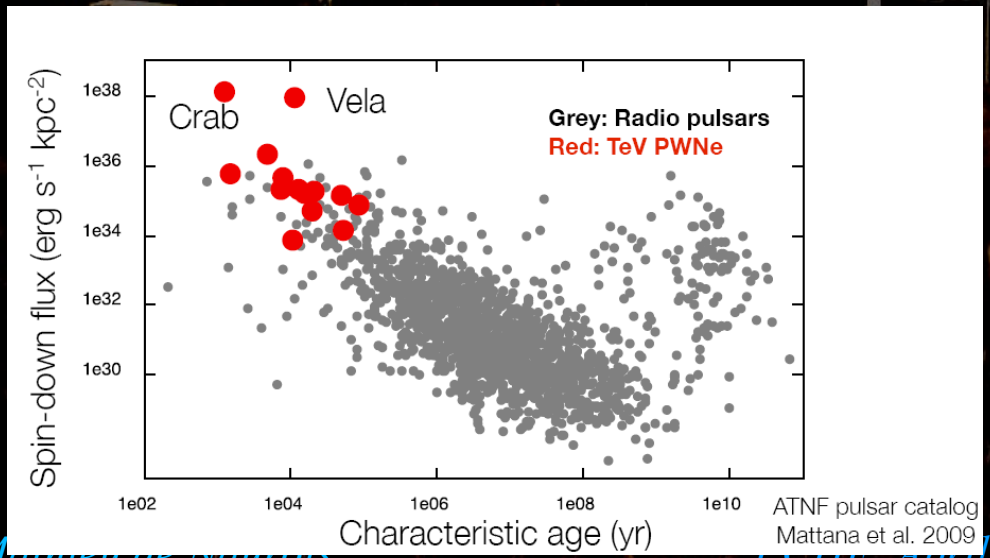


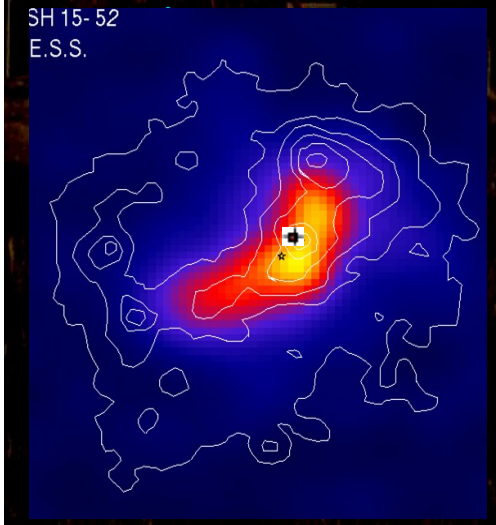


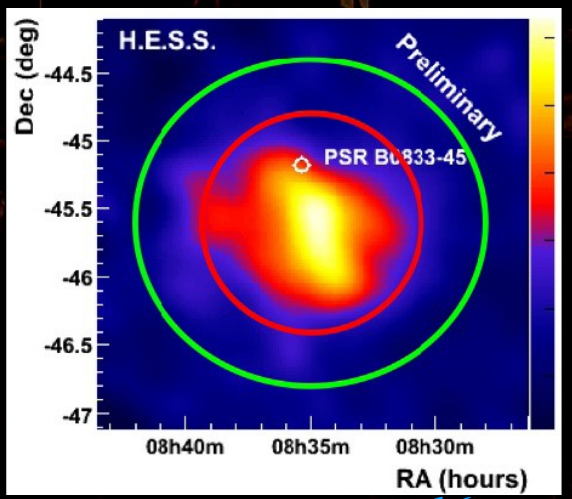
- Major galactic TeV source population, Associated with relatively young (<10^5 year old) and energetic pulsars
- Extended sources, often displaced from pulsar (expansion into inhomogenous medium)
- Generally believed that we see inverse Compton emission of 1-100 TeV electrons

Pulsar Wind Nebulae with HESS

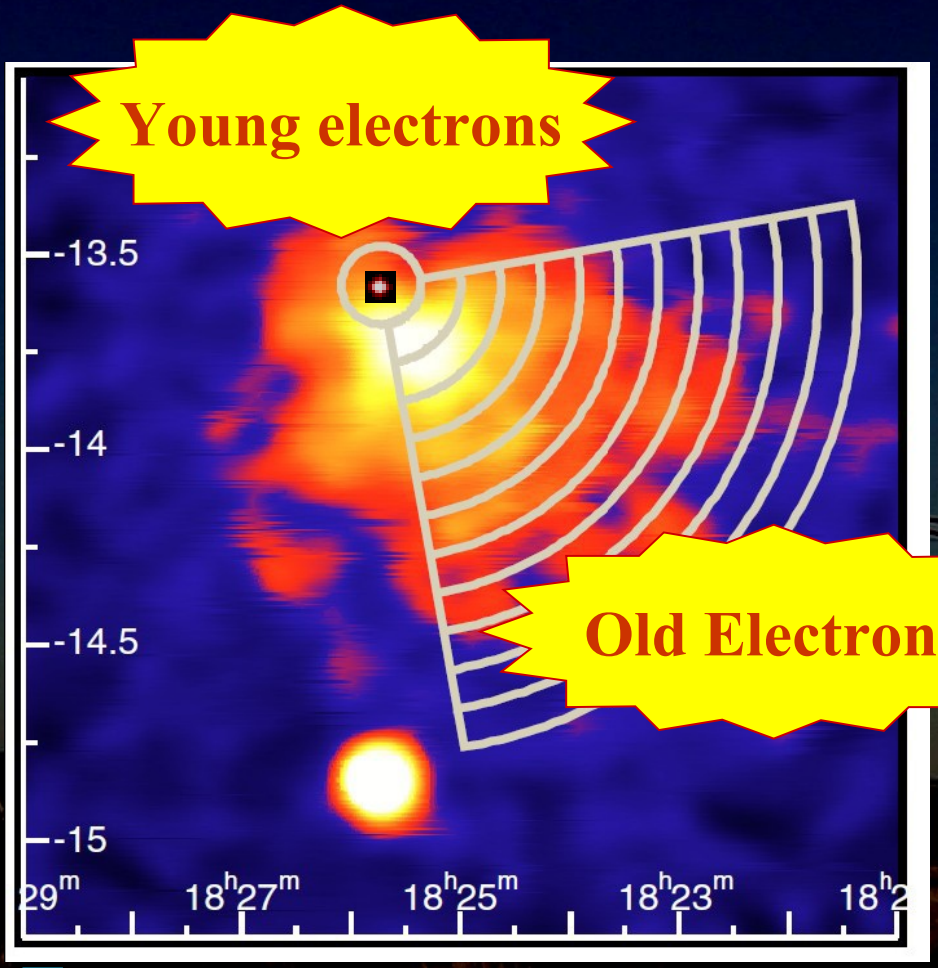
- Young PWNs: Crab Nebula, G0.9+0.1, G21.5-0.9, Kes 75, MSH 15-52,...
- Compact, generally un resolved
- Associated with relatively young (<10^5 year old) and energetic pulsars (> 10^{34} erg/s/kpc^2)
- IC emission of 1 - 100 TeV e-
- Older « offset » PWN: HESS J1825, Vela X
  - Offset can be due to reverse shock
  - VHE as extended as radio PWN (2°)
- Energy dependant morphology (HESS J1825-137, HESS J1303-631)
- First extragalactic PWN (N157B

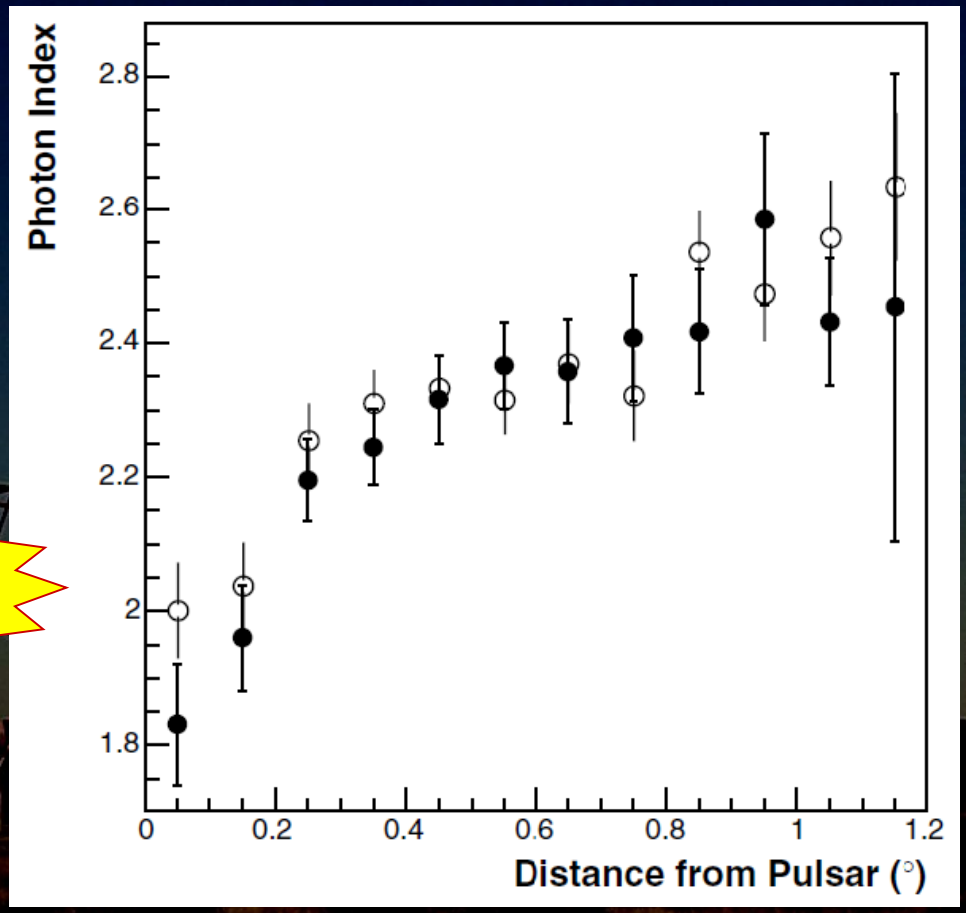






Cooling in action

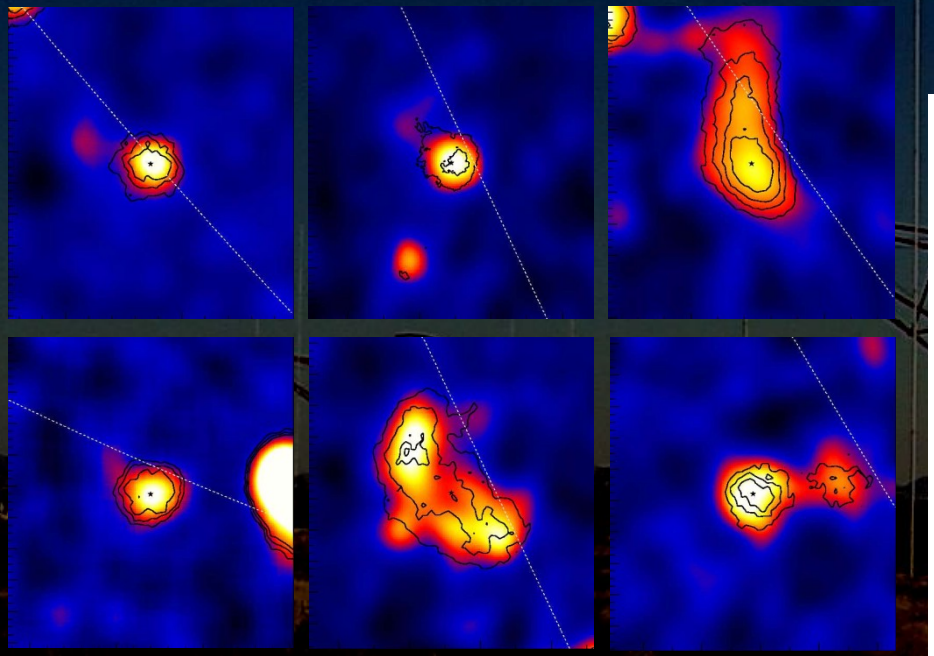




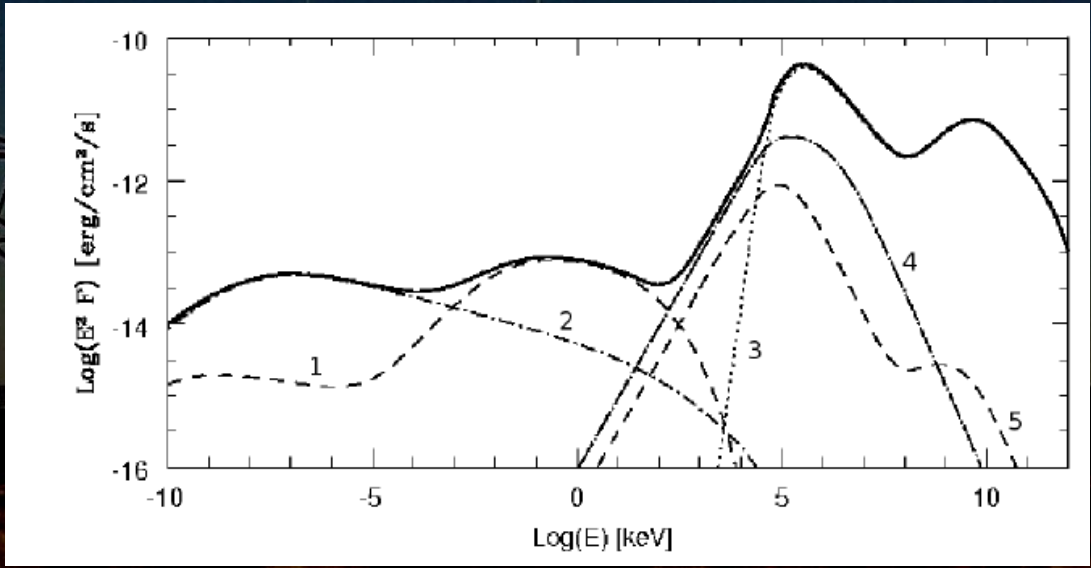
- Spectral steepening away from pulsar
- ⇒ First observation of radiative cooling of electrons, second case now (HESS J1303-631)
- Gamma Flux: ~1% of pulsar rotational energy

Dark Sources

- 50% of TeV source (same in GeV)
- Old PWN, not seen in other wavelengths?
- Old SNRs, interacting with molecular clouds?



Gabici et al, 2008

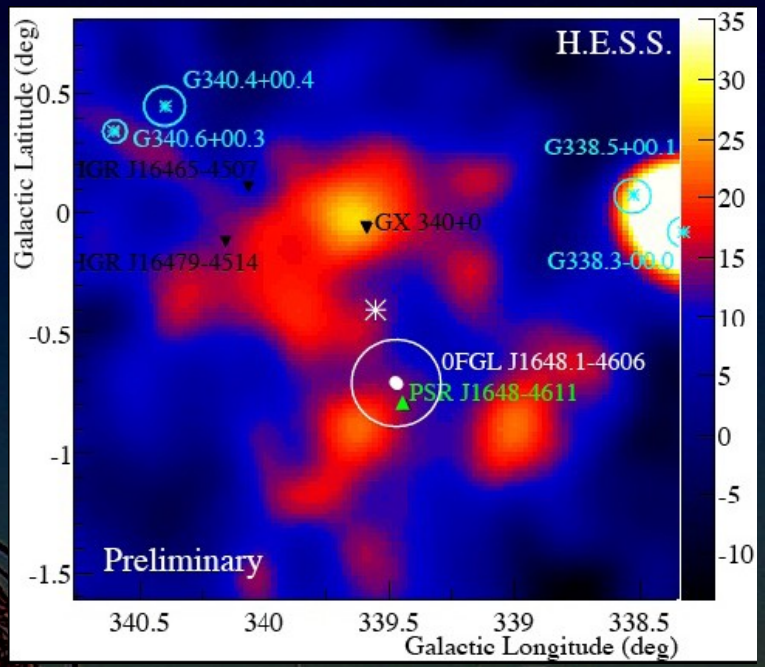


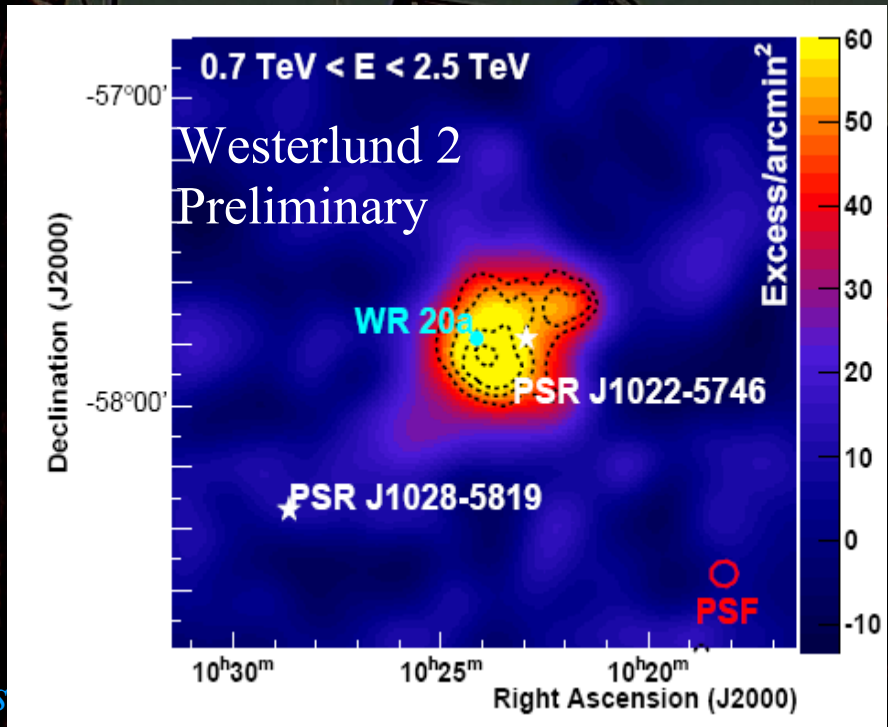
Example: broad band spectrum of cloud illuminated by SNR (2kyr)

pion decay (3), synchrotron (2) and Bremsstrahlung (4) from CR that penetrate the molecular cloud,
synchrotron (1) and Bremsstrahlung (5) from secondary e-

Massive Star Clusters

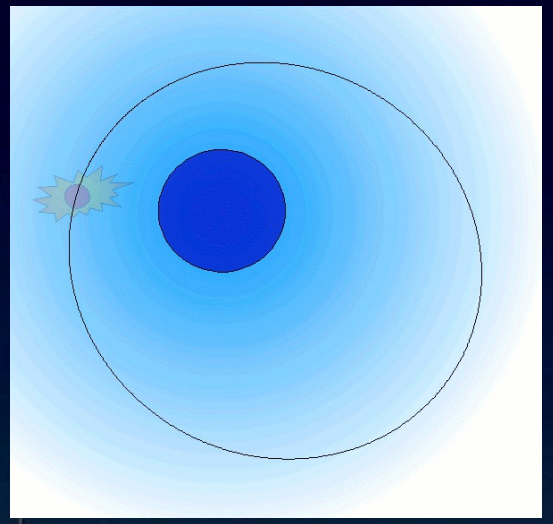
- Star forming regions, many processes:
  - SN explosions
  - Numerous binary systems ⇒ interacting stellar winds
  - Pre SN winds might blow superbubbles, collective effects might be responsible for acceleration (Parizot et al. 2004)
- Westerlund 1, Westerlund 2, HESS J1614-581, HESS J1848-018
- Westerlund 1:
  - 24 WR stars, >70% in binary systems
  - 80 blue SG stars
  - 2° extension of VHE emission, partially correlated with HI shell ⇒ Evidence for hadronic acceleration?
- Westerlund 2: bright FERMI pulsar, PWN?

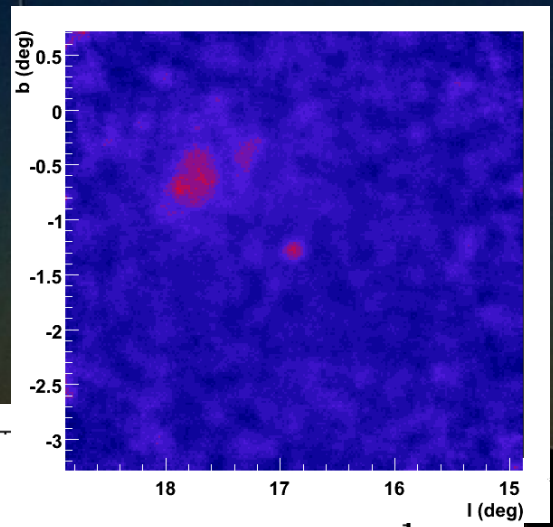


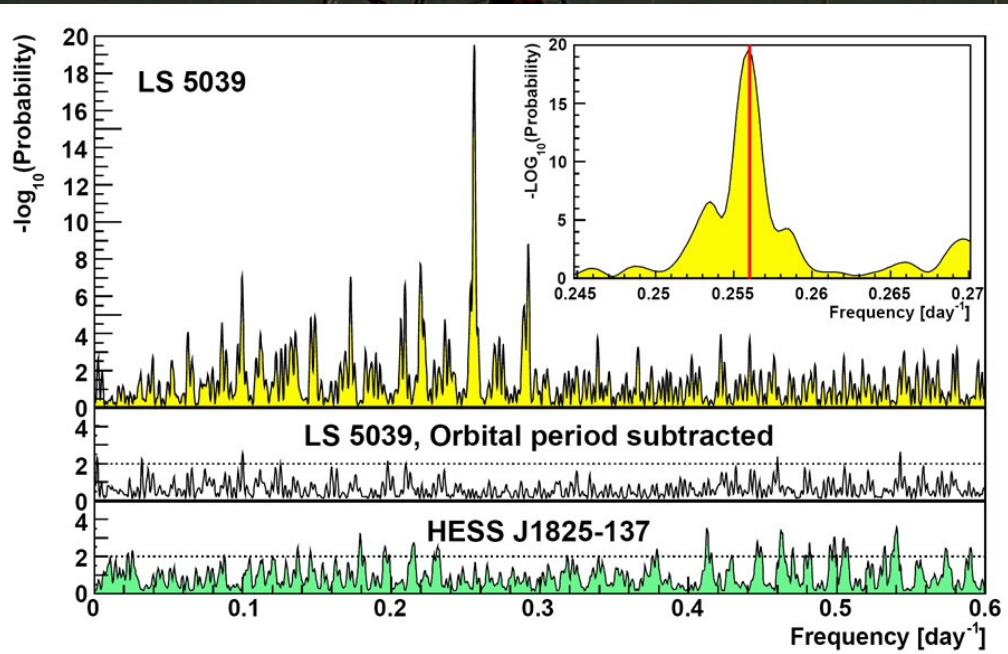


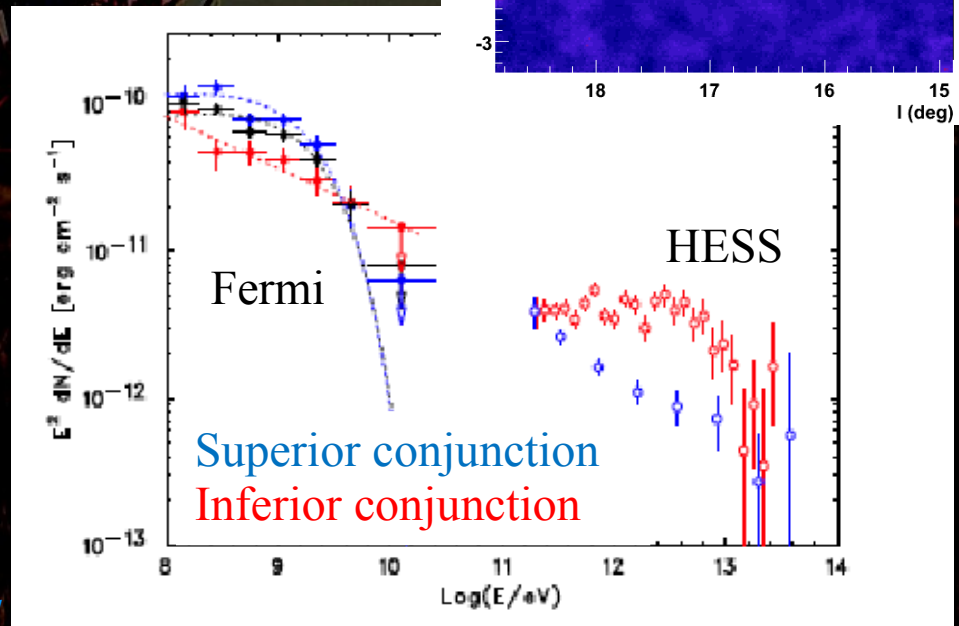
Binary Systems

- Compact object orbiting around a massive star
  - Scaled down versions of AGNs
- Additional information useful for constraining emission models:
  - LS 5039: spectral modulation at orbital phase (3.9 days)
  - Interpreted as pair creation on stellar photon field supported by FERMI / HESS anticorrelation
  - Other cases: PSR B1259-63 and recently HESS J0632+057 (period detected with swift)



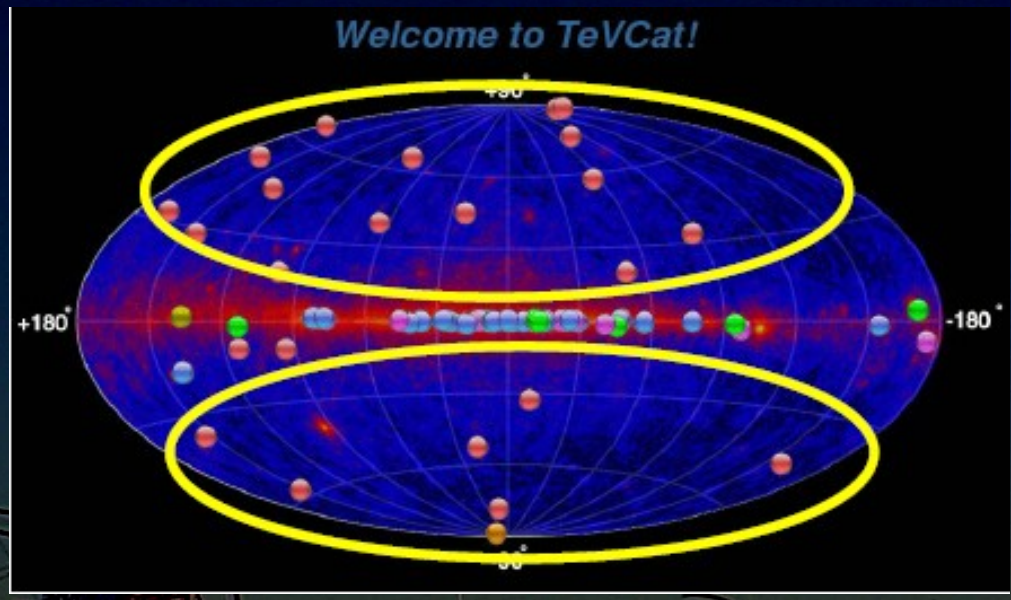


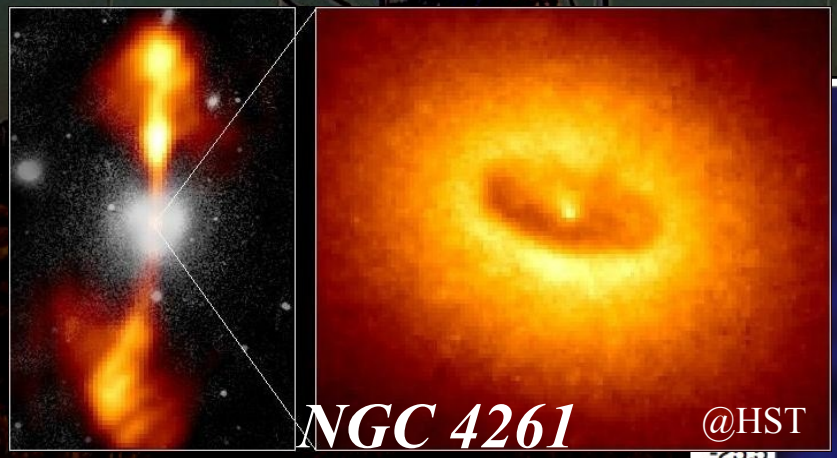


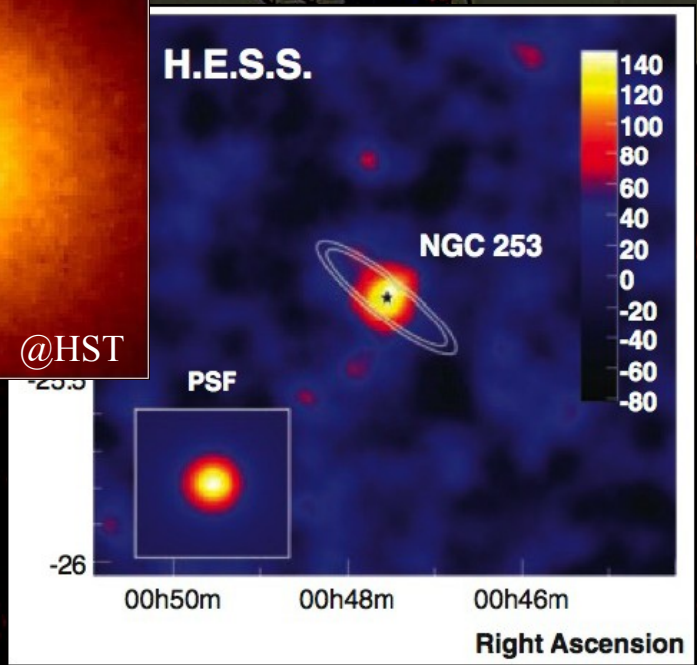


Extragalactic Sky

- TeV Blazars
- Radio Galaxies
- Starbust Galaxies

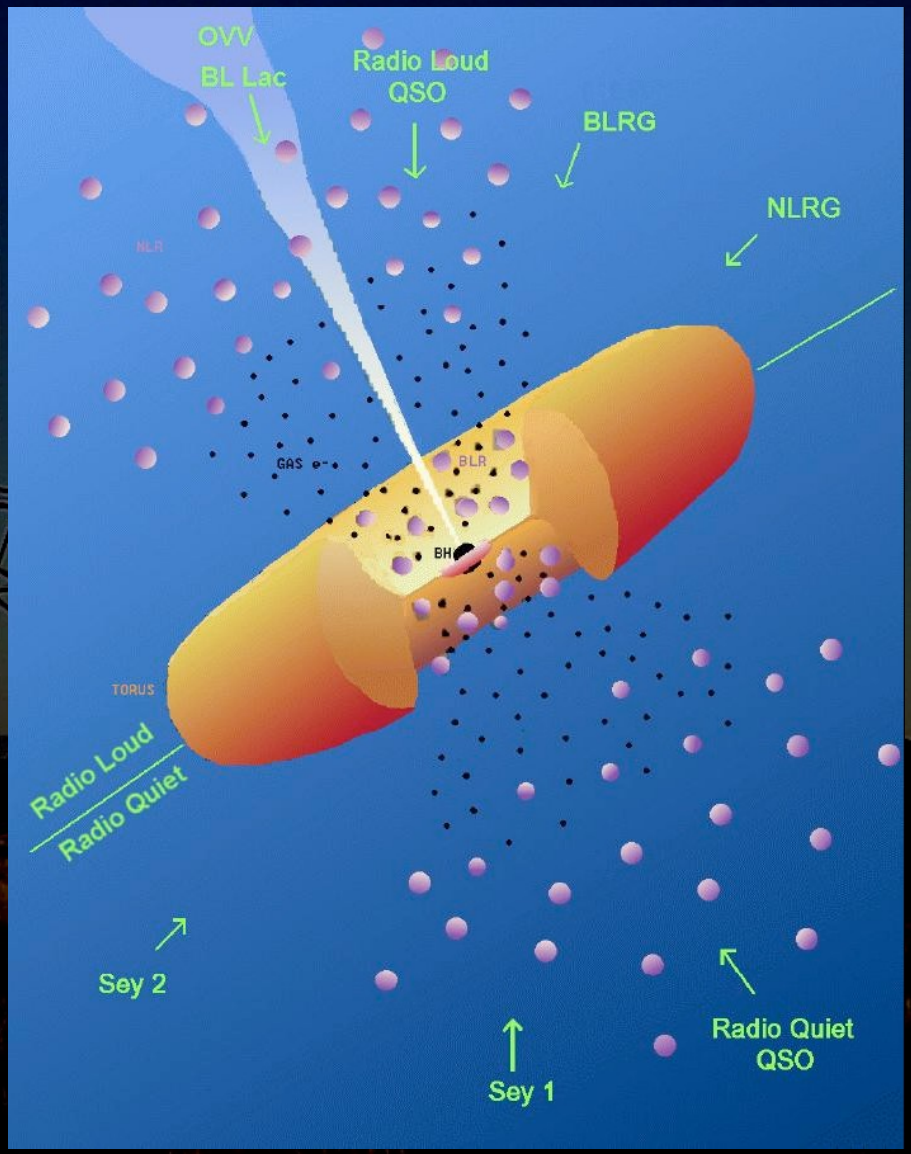




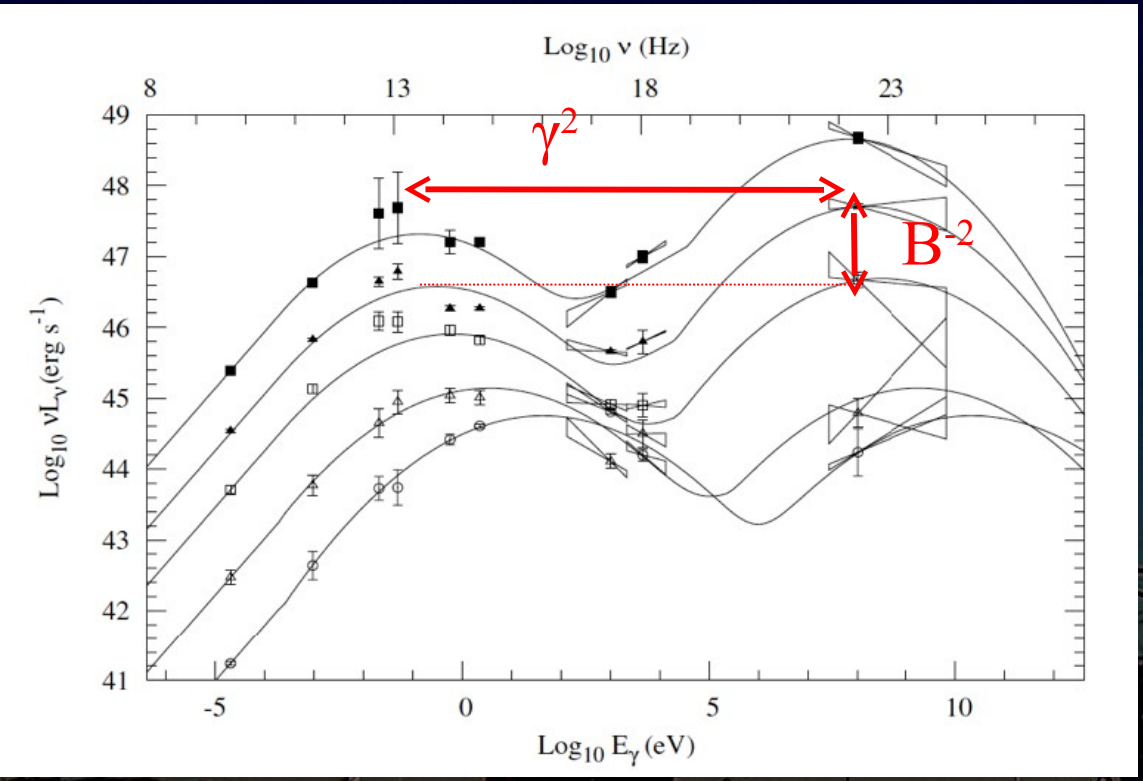


TeV Blazars

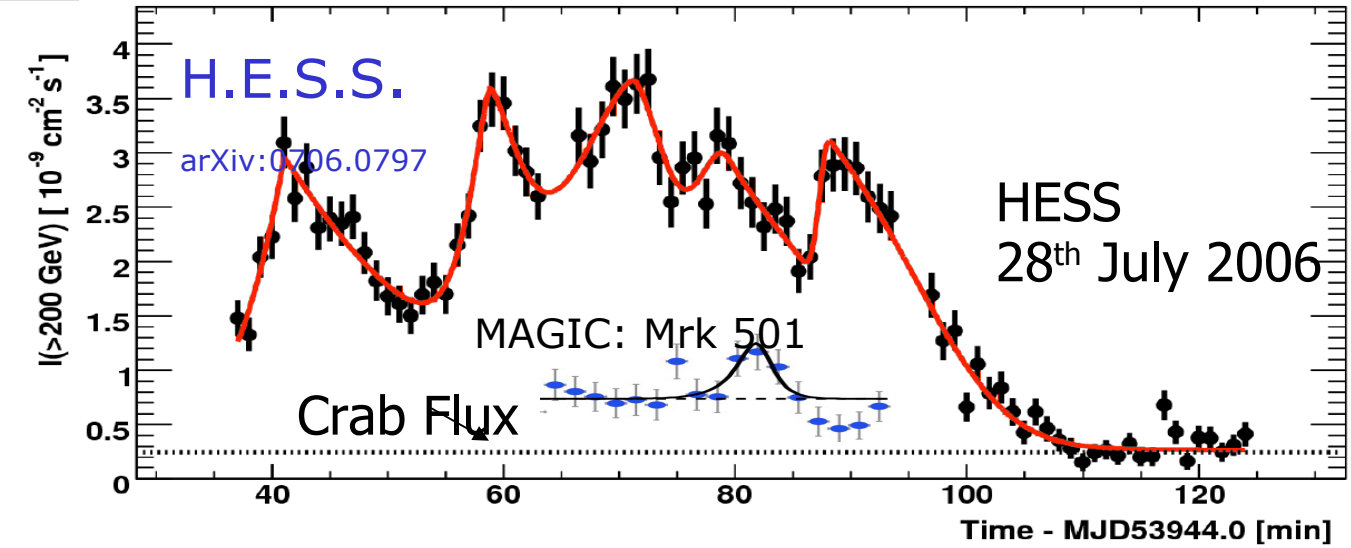
- Active Galactic Nuclei
  - Supermassive black hole surrounded by an accretion disk
  - Ultrarelativistic jets (Mpc)
  - Blazars: jets pointing towards the earth
  - Highly variable TeV emission: two model classes:
    - Leptonic
    - Hadronic (through π^0 decay)
  - Possible connection with UHECRS
- Science drivers:
  - Mechanisms of relativistic jet production
  - Blazars as probes of the extragalactic background light (EBL) through pair absorption (characteristic absorption feature)
  - Tests of Lorentz Invariance

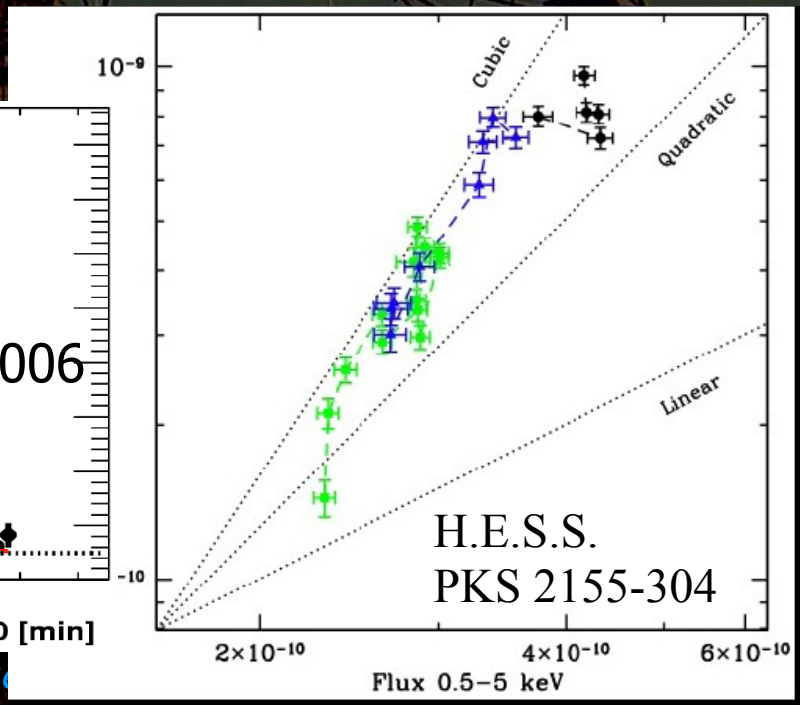


Testing models



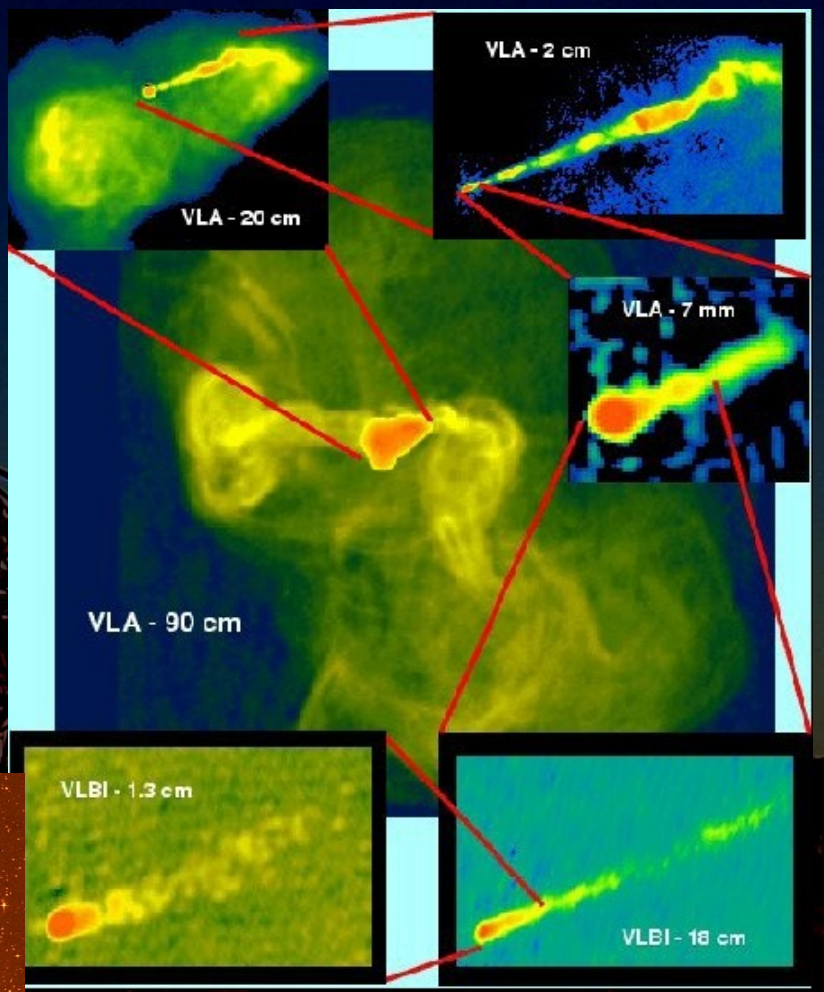
- Simple SSC Model relates Synchrotron and IC peaks (Blazar Sequence)
- Fast variability (down to 1 mn) allow precise tests: Very small emitting region << Rs
- One zone SSC excluded by F_γ/F_X ratio, correlation notalways observed
- ~ 40 TeV Blazars known

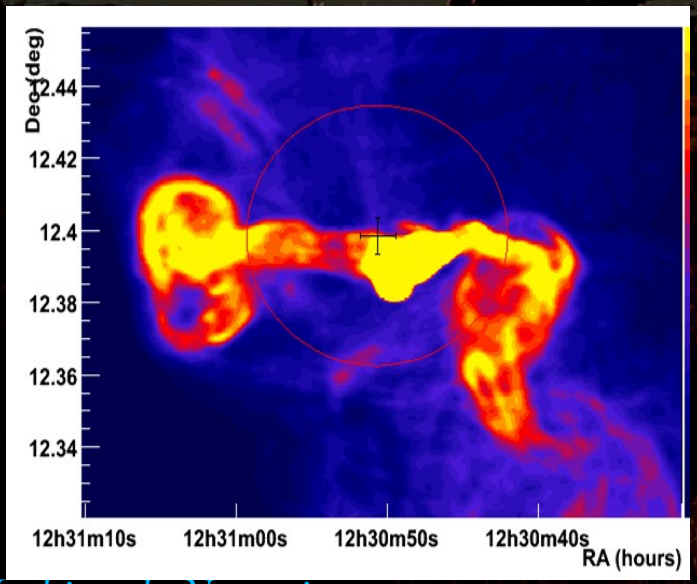


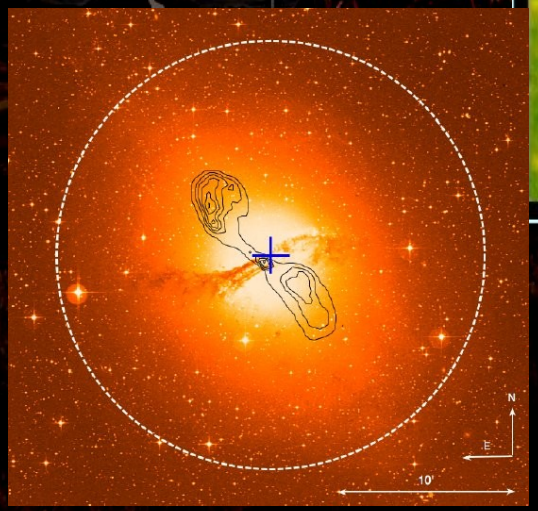


Radio Galaxies

- Radio Galaxies not seen face-on, can be very close
  - Identification of emission region
  - Less effects of relativistic beaming
- M87 (HESS, Veritas, Magic)
  - Emission (very) close to center
  - Variability on time scale of days
- Cen A (HESS), 3C 66B (MAGIC/Veritas)

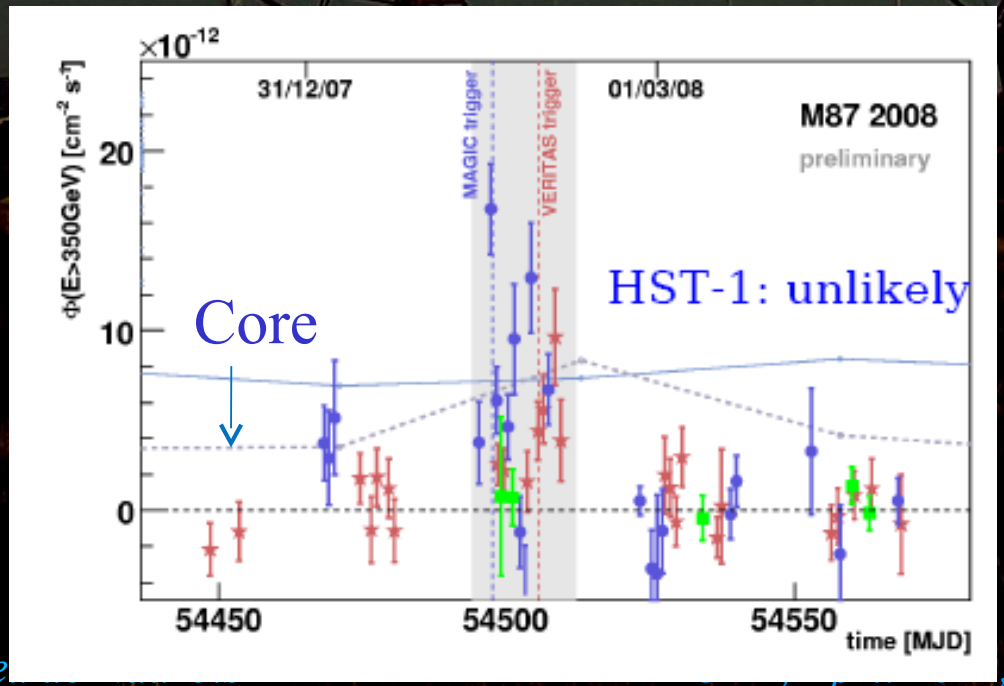


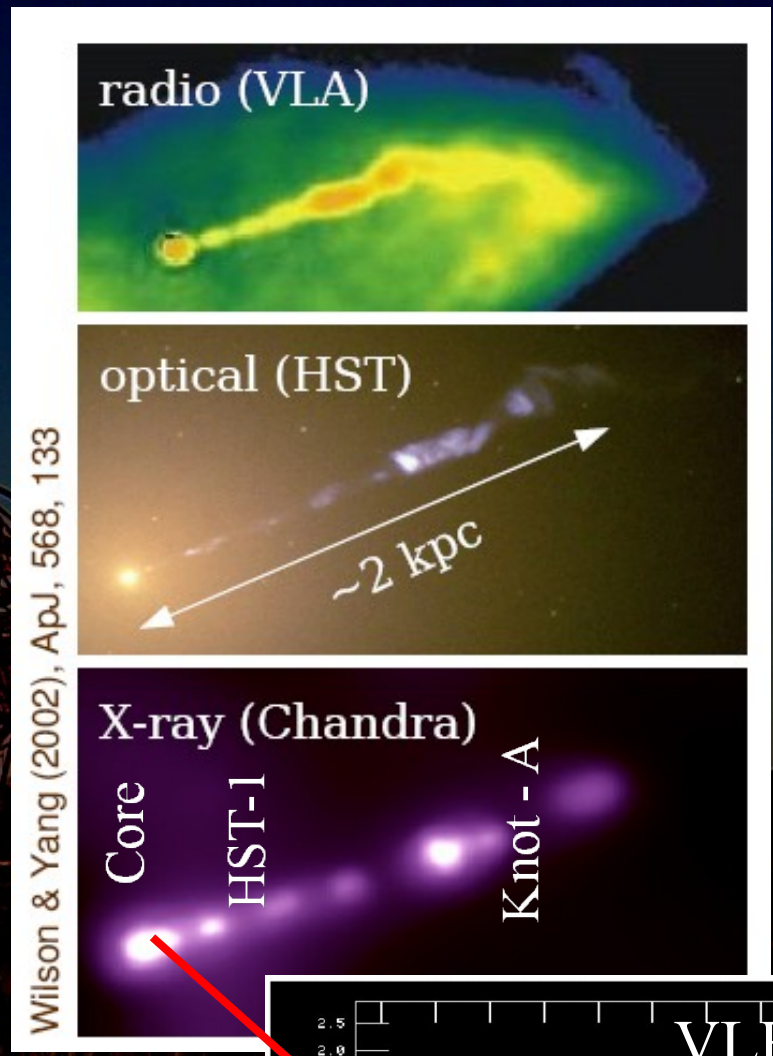


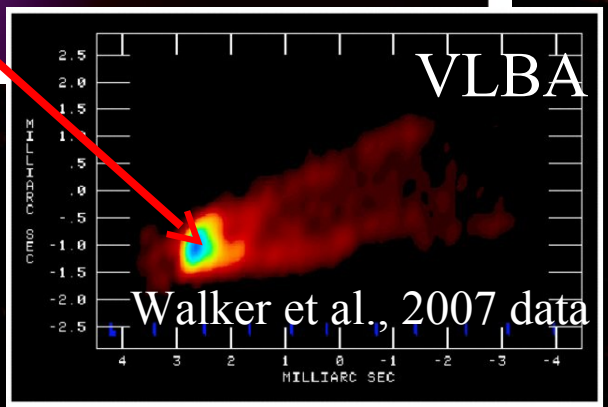


M 87 Joint campaign

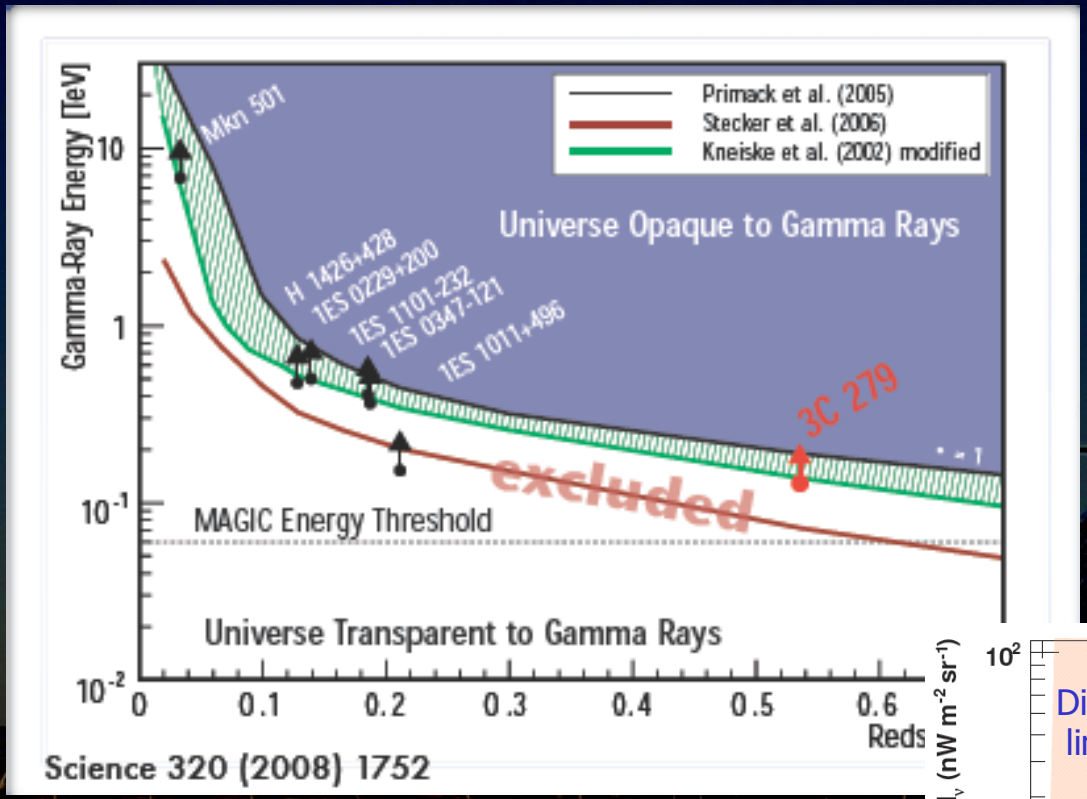
- 2007-2008 : VERITAS/MAGIC/H.E.S.S./VLBA campaign
  - VHE flare accompanied by radio flare from BH vicinity
  - HST-1 unlikely
  - VLBA resolves jet formation with 30 x 60 Schwarzschild radii

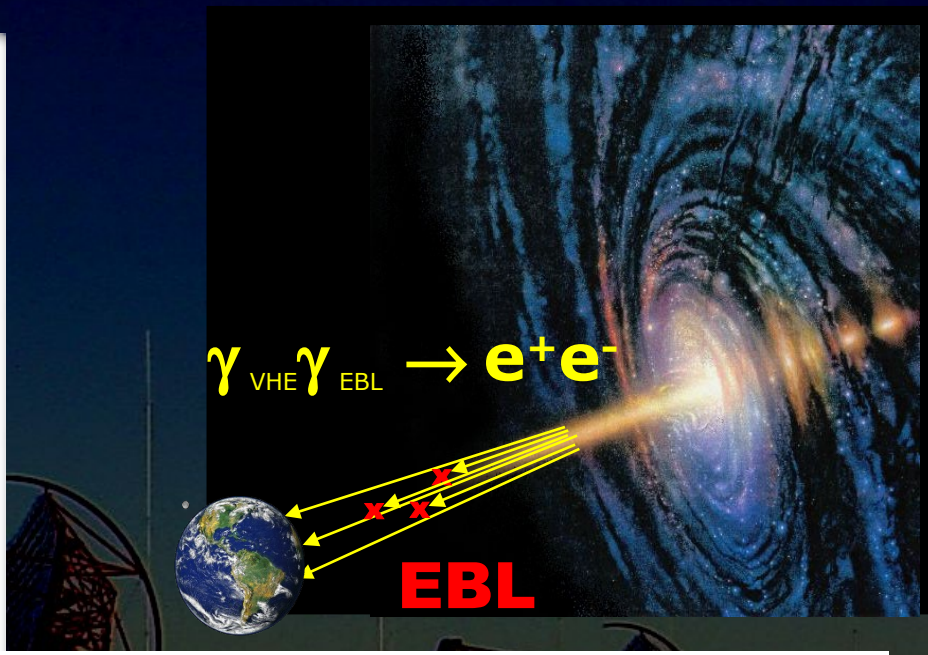


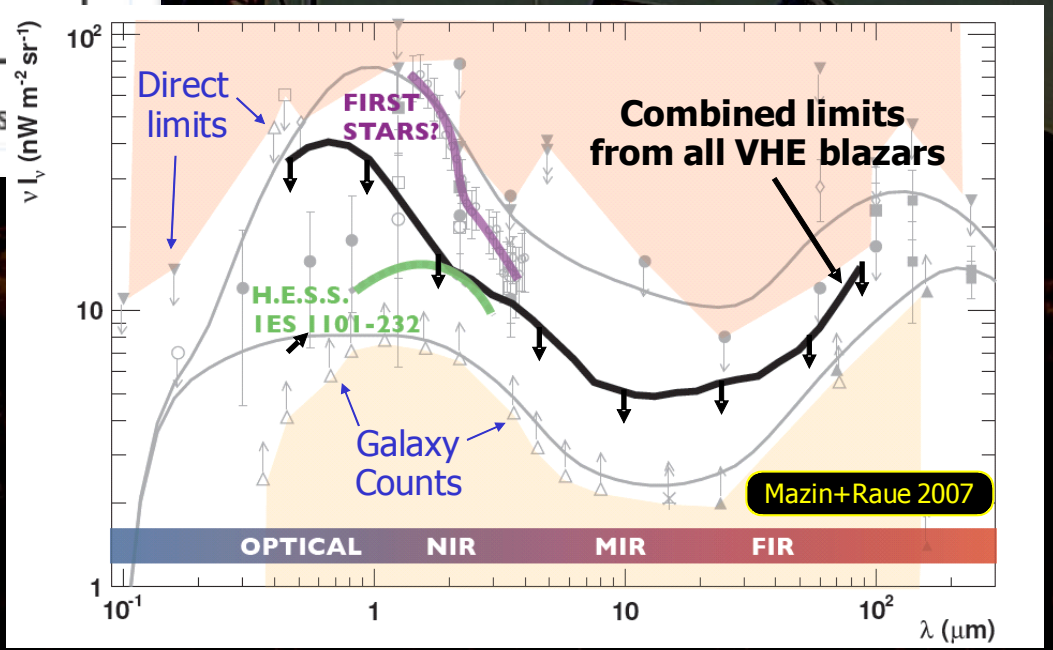




EBL Tomography







- High redshift blazars allow test of light propagation
- Recent limits on EBL close to lower limit from galaxy counts

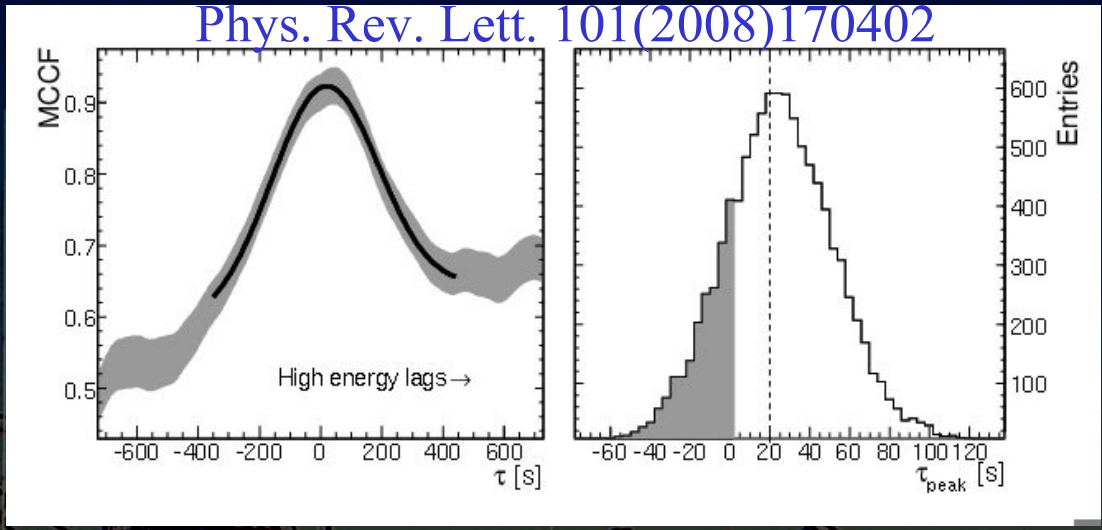
Test of Lorentz Invariance

- Search for time lags between energy bands (test of invariance of c)
- Limit: 73 s TeV^{-1} (95% CL)
- Lower limit on Quantim Gravity Scale: $E_{QG} > 0.7 \times 10^{18}$ GeV

$$c' = c\left(1 \pm \xi \frac{E}{E_P} \pm \zeta^2 \frac{E^2}{E_P^2}\right)$$

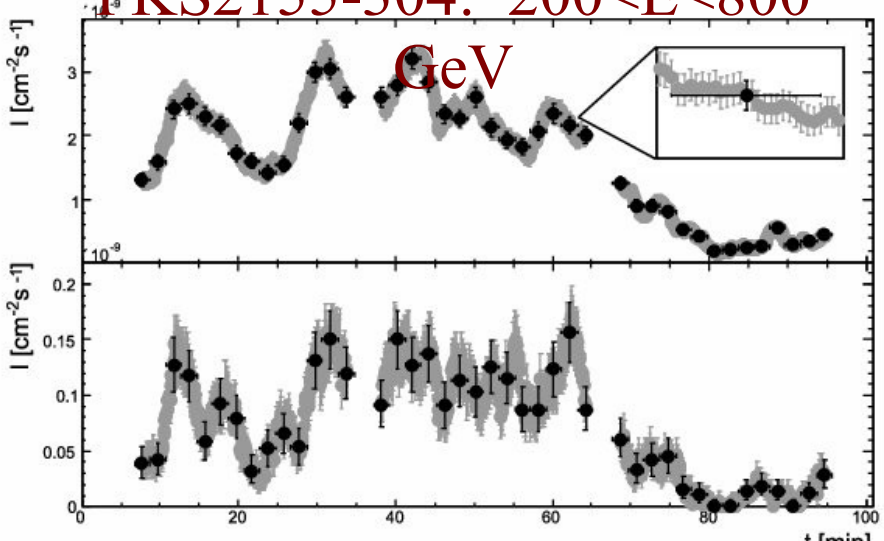
PKS2155-304: cross-correlation function vs. time lag

Phys. Rev. Lett. 101(2008)170402

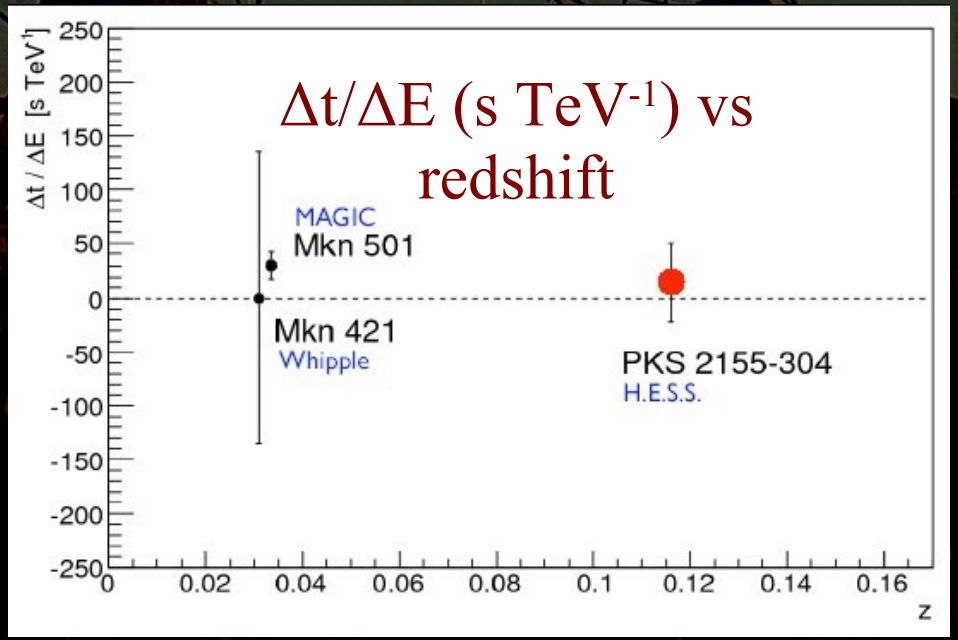


PKS2155-304: 200<E<800 GeV

PKS2155-304: E>800 GeV

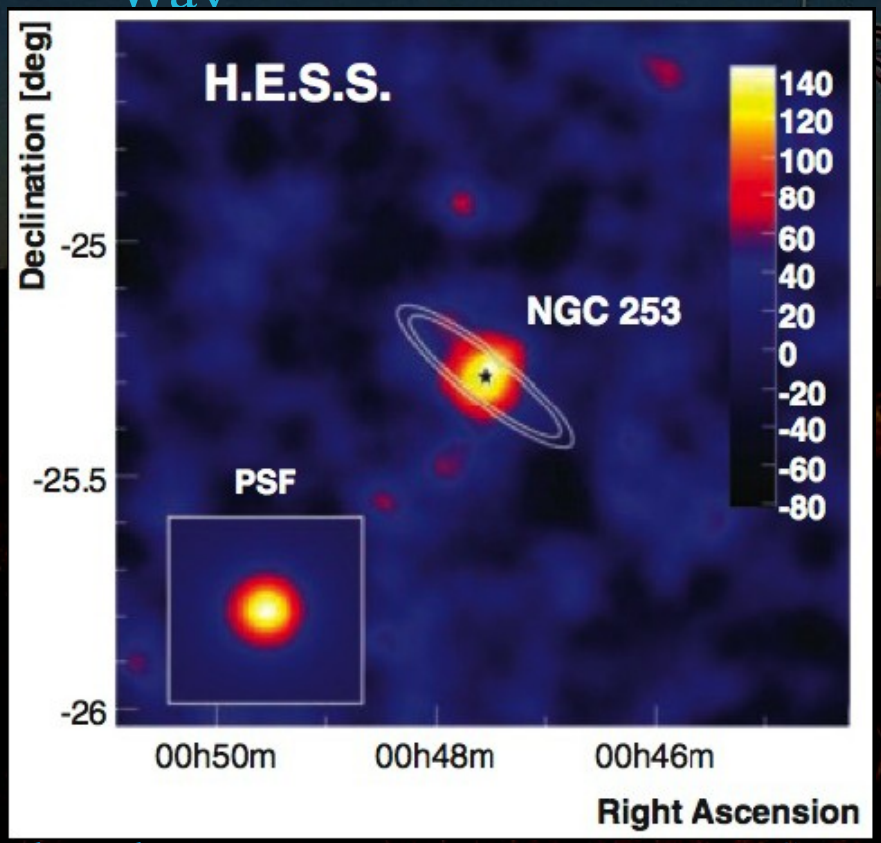


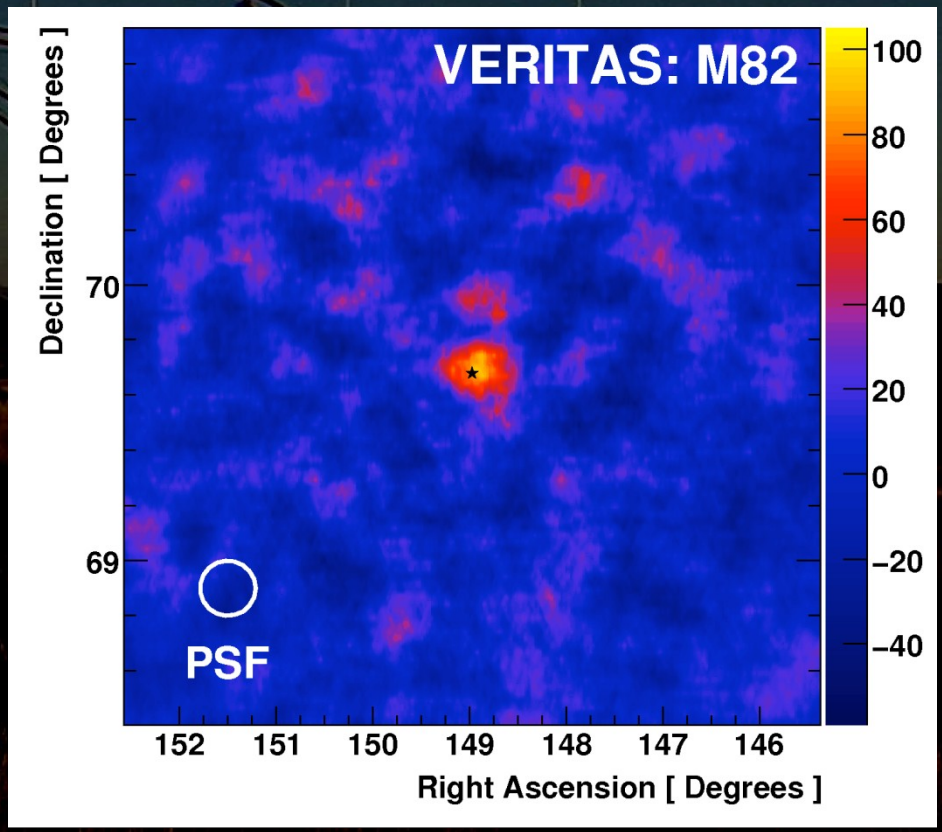
Δt/ΔE (s TeV^{-1}) vs redshift



Starburts Galaxies

- New class of sources: NGC 253 (HESS) and M82 (Veritas)
- Very deep observations (100h)
- Compact starburst region (a few 100pc) at nucleus, ~ 0.03/0.2 SN/yr
- Very high cosmic ray and gas density n~ 600/150 cm^{-3} vs ~ 1 in Milky Way



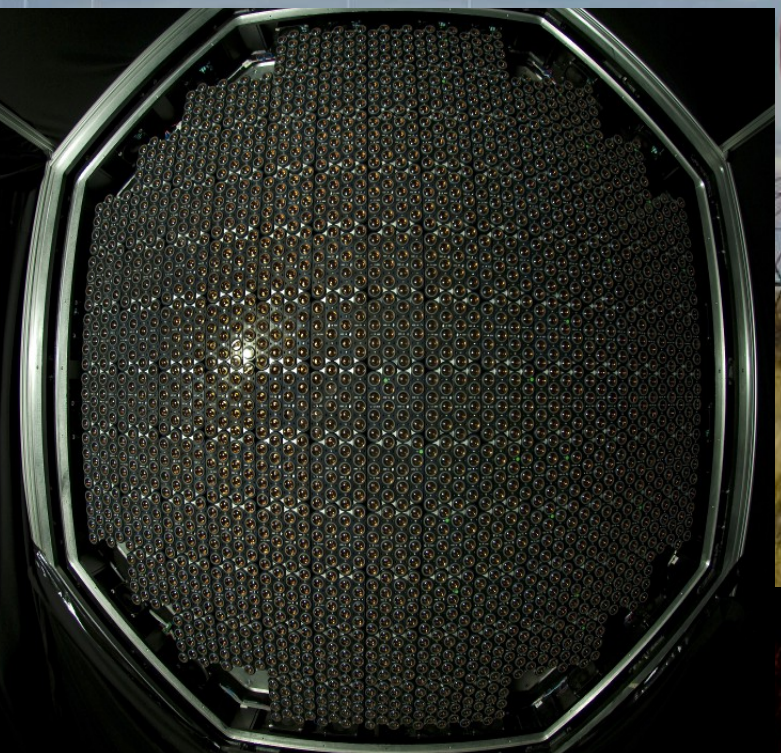


Conclusions

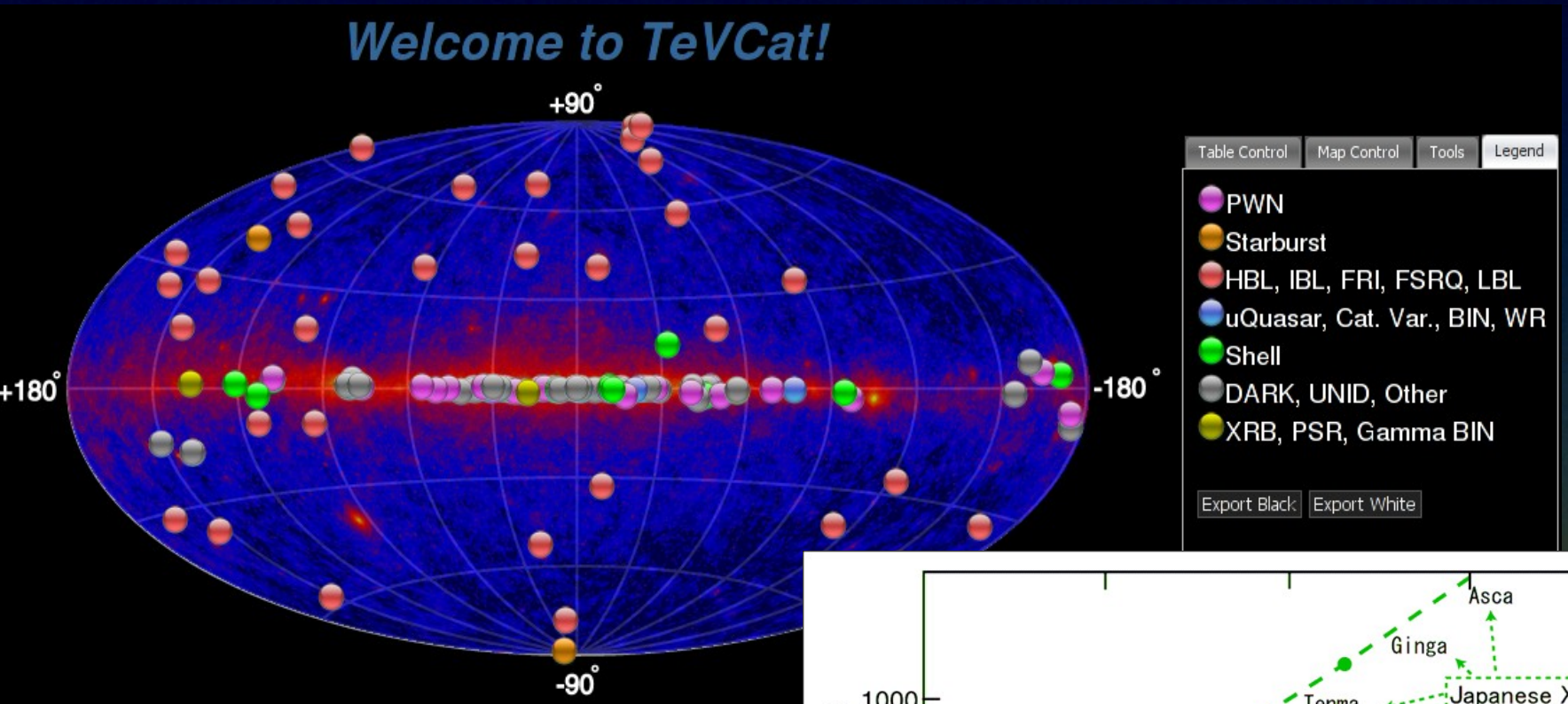
- Exploding field, major discoveries since 2003:
  - Massive flares of Active Galactic Nuclei
  - Imaged supernova remnant shells
  - Galaxy is full of VHE pulsar-wind-nebulae
  - Galactic Center Source: possible accreting SMBH
  - Binary Systems: VHE modulation
  - Diffuse gamma rays from interacting molecular
  - clouds and star-forming regions
  - Starburst Galaxies
  - Dark Accelerators
  - Extra-galactic background light constraints
  - Cosmic Ray Electron and Iron spectra
- Still exciting discoveries ahead (MAGIC-II, HESS-II, CTA)

HESS - II

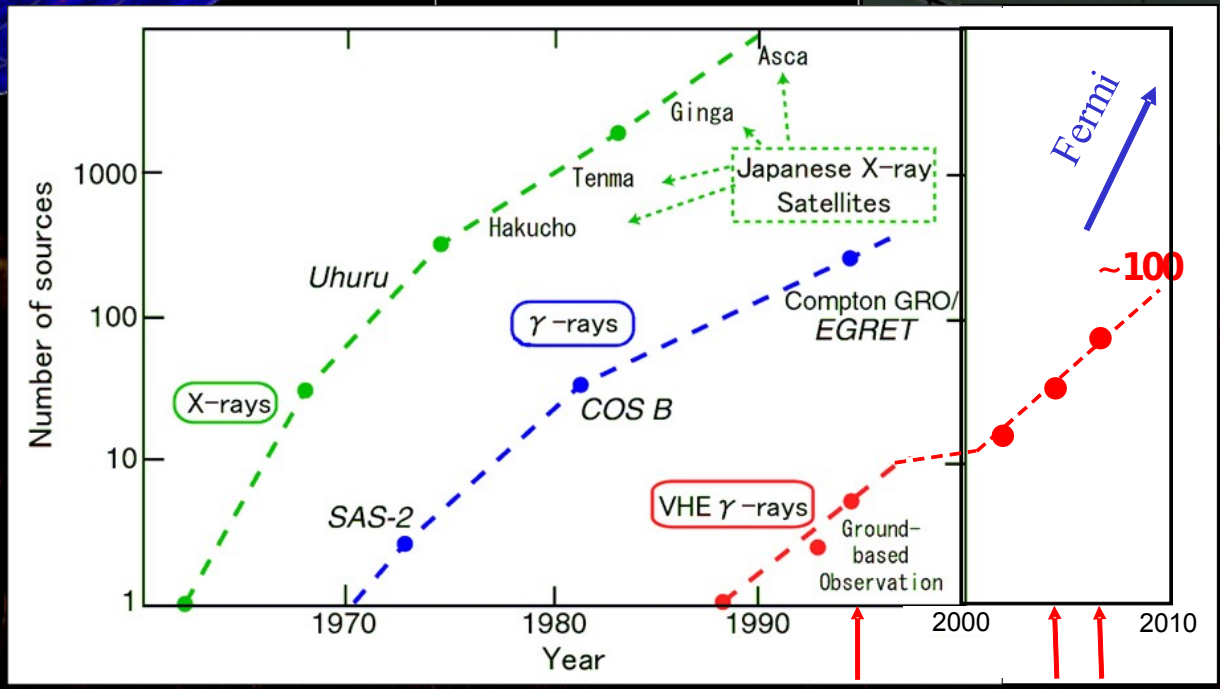
- Ongoing HESS-II construction work (restarted after many problems)
- First light fall 2011



TeV Catalogue

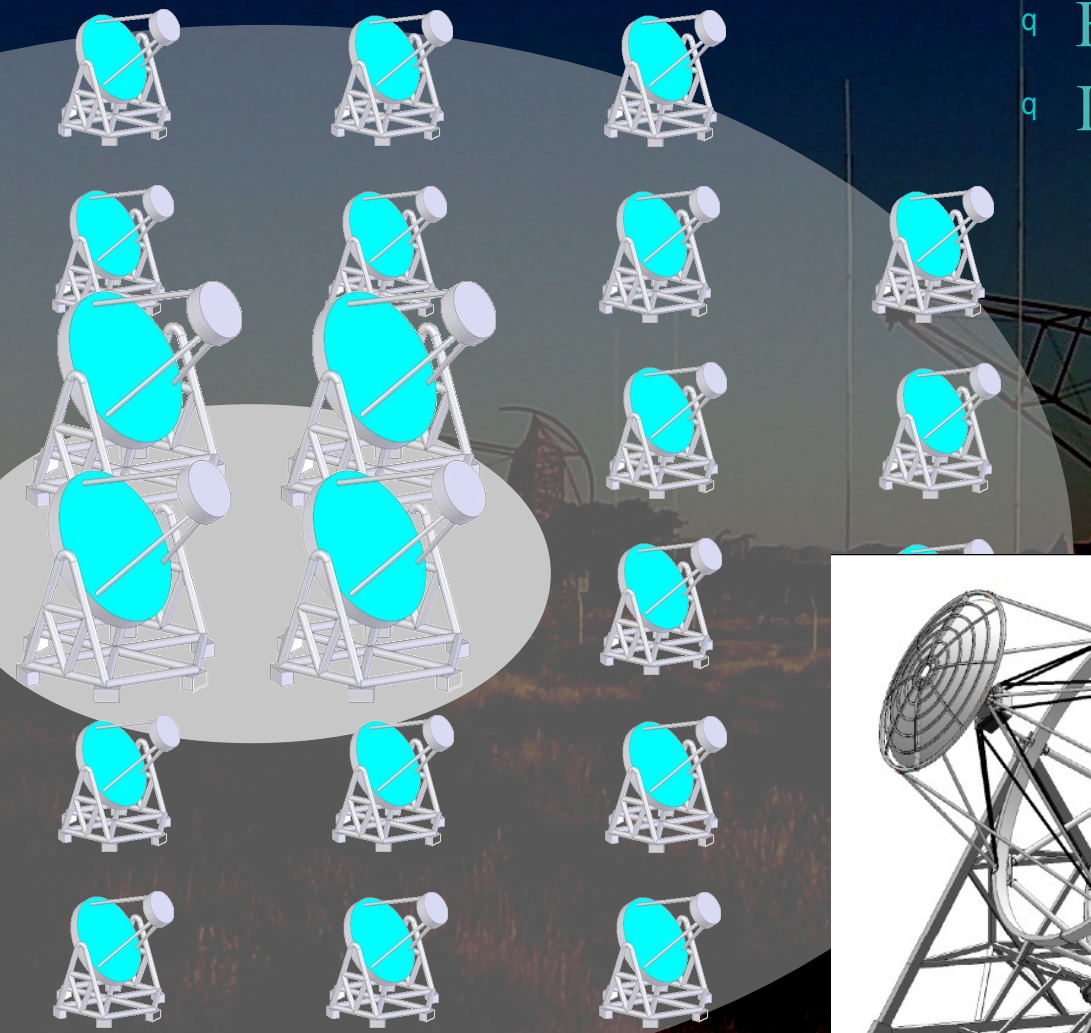


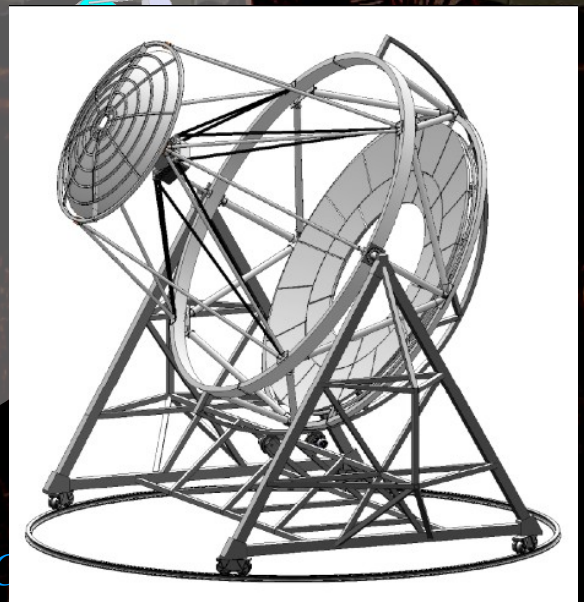
- first source in 1989,
- ~ 10 sources in 2000
- 110 sources today.

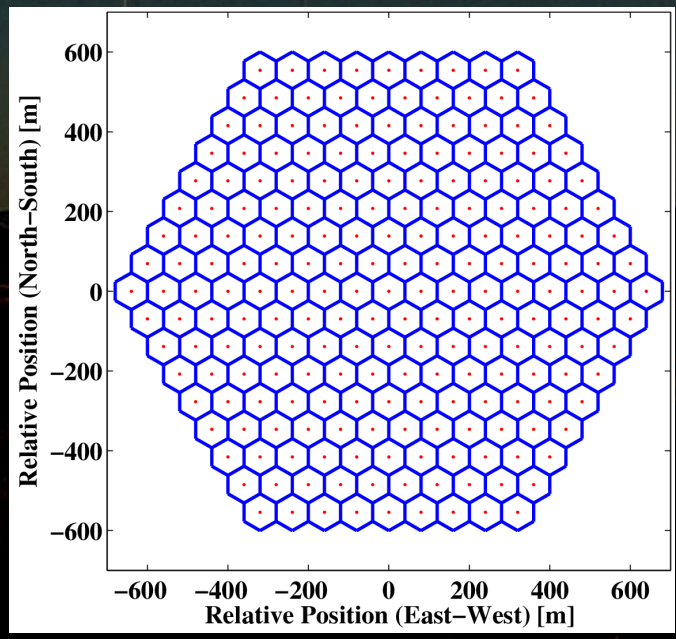


Longer term perspective (I)

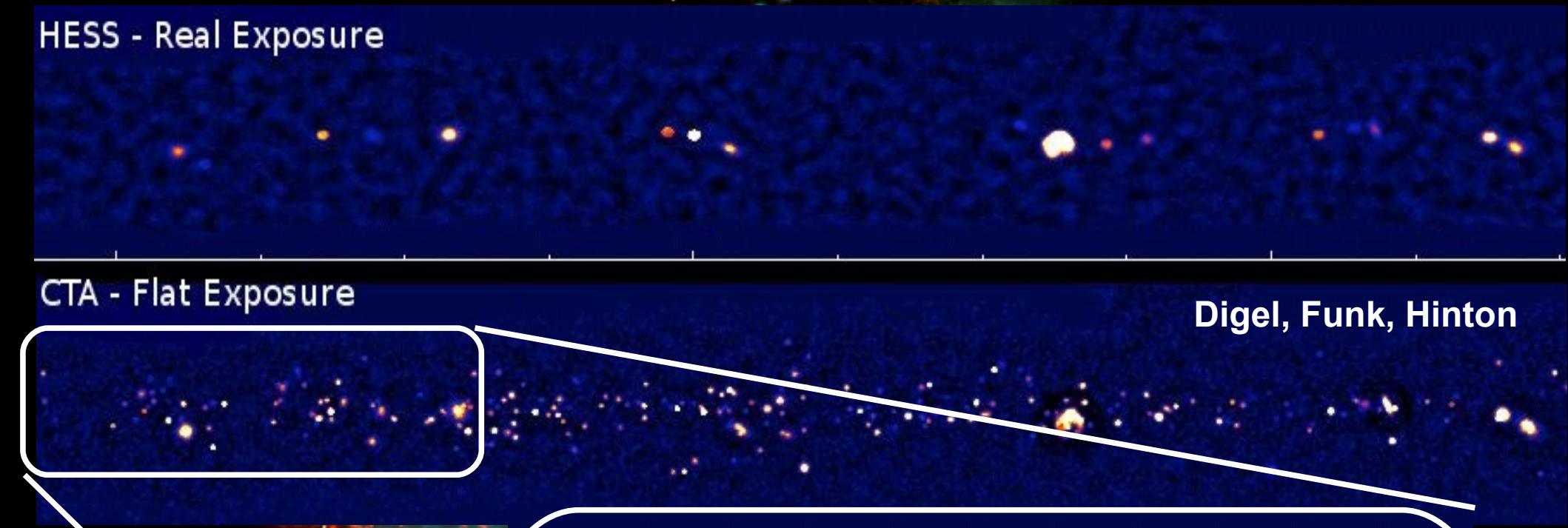
- Large observatories (CTA, AGIS)
  - > 50 telescopes
  - Factor 10 in performances
  - Increased energy coverage





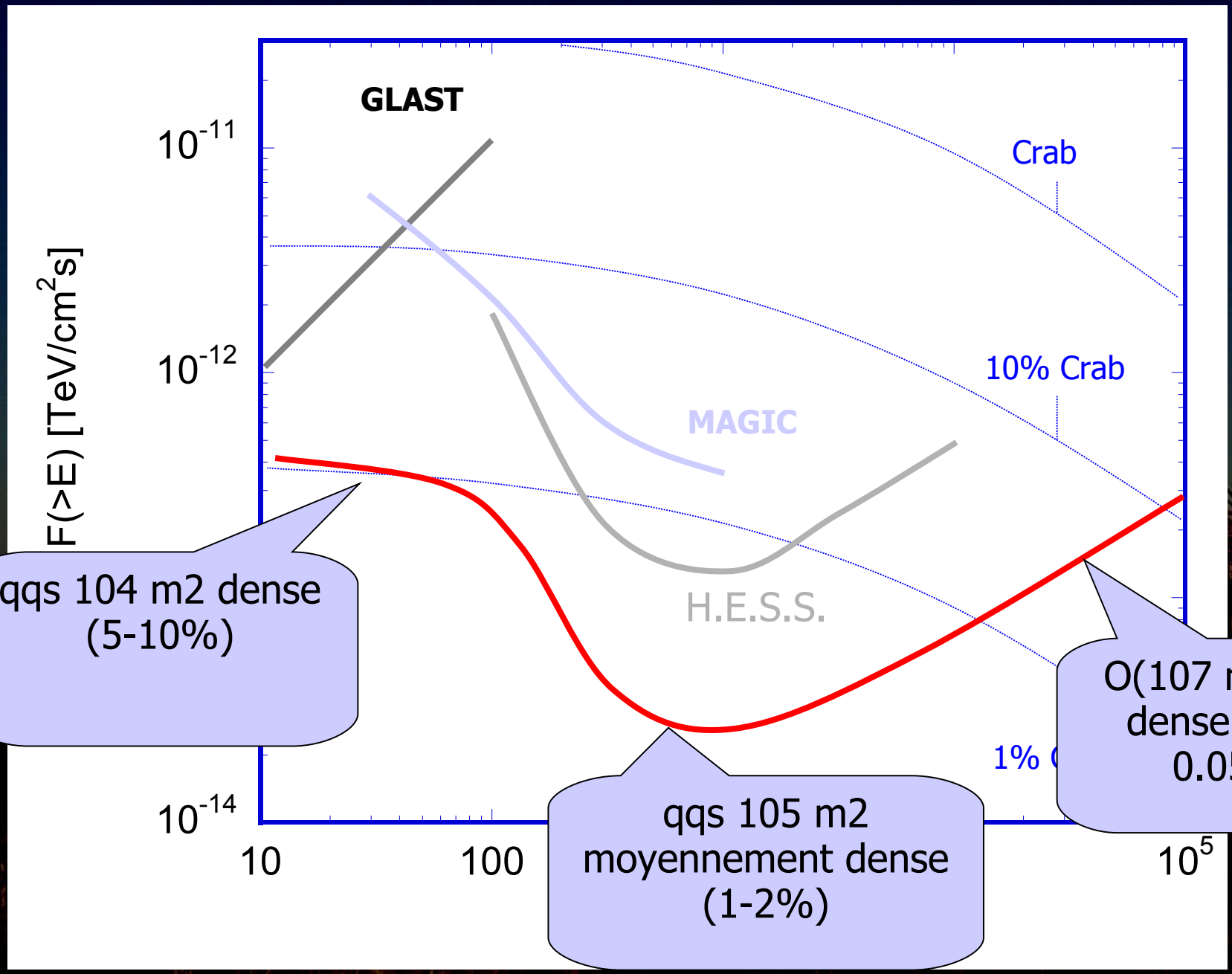


Deep TeV vision

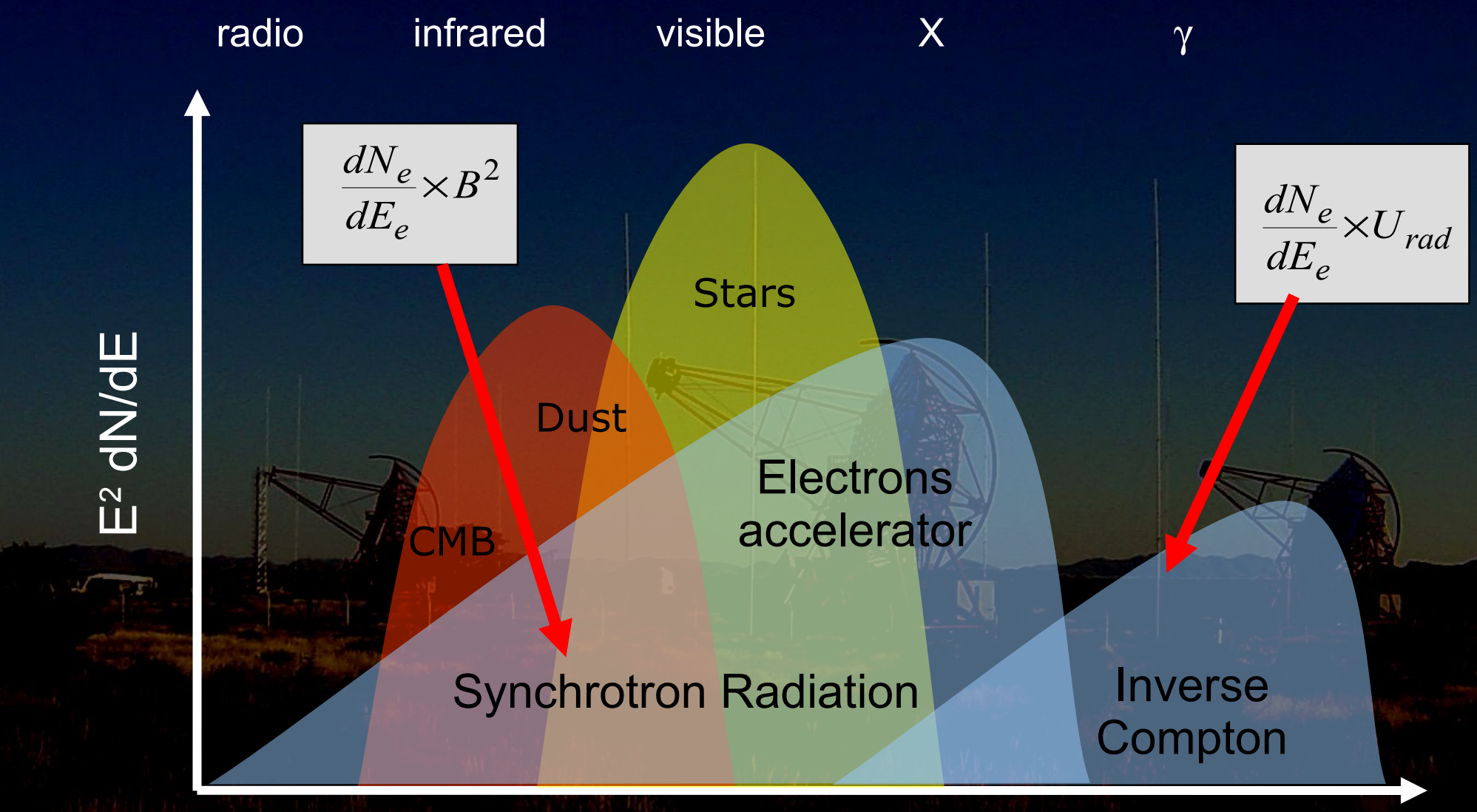


- Facteur 10 en nombre de sources…

Achievable sensitivity

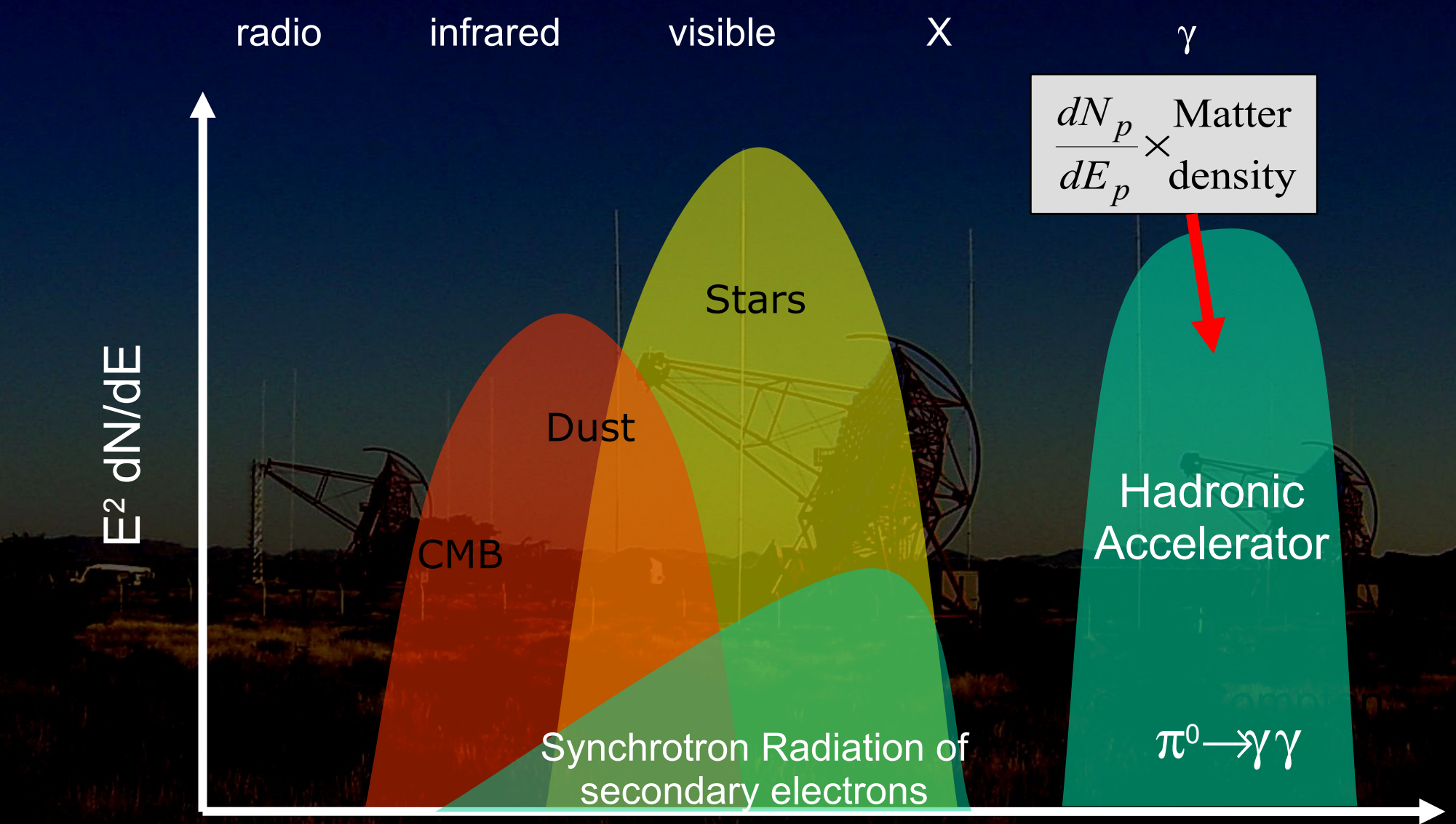


Leptonic Accelerator



- Leptonic accelerator probe photon field and magnetic field
- Ratio γ/X is a measure of B

Hadronic Accelerator



- Hadronic Accelerator Probe Matter Density
- γ Spectrum mimic underlying proton spectrum