Probing cosmic-ray accelerators with gamma-ray astronomy

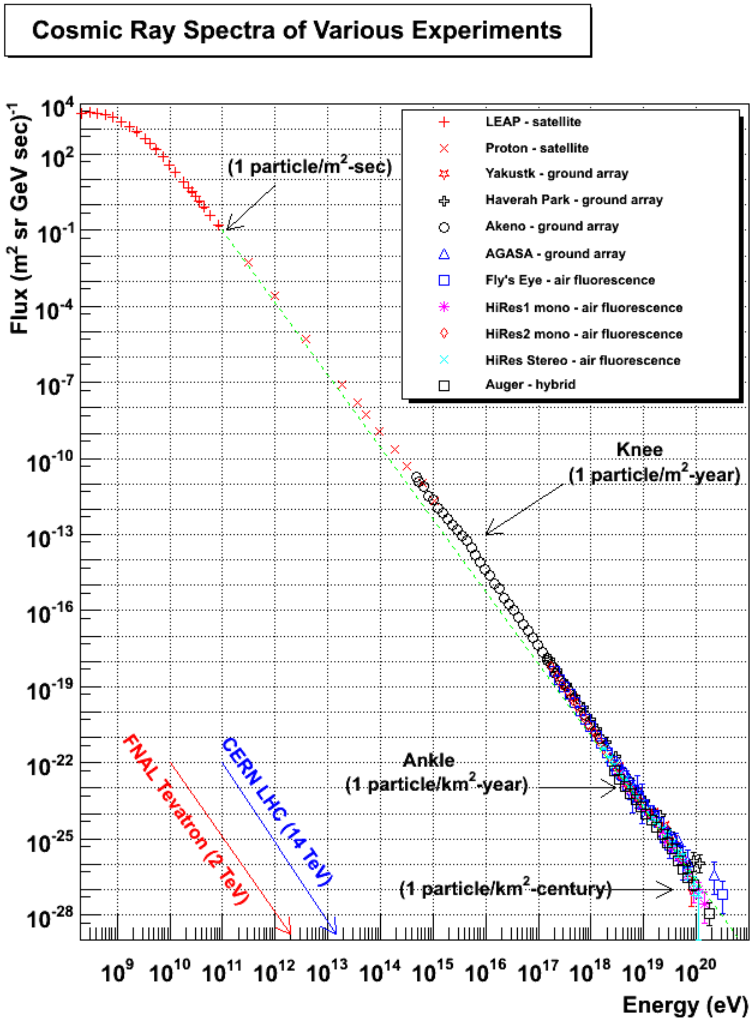
Hélène Laffon
CENBG, Université de Bordeaux

Outline

- The cosmic-ray features
- Radiative processes
- Detection techniques from GeV to TeV
- The galactic zoo
  - Supernovae remnants
  - Pulsars and their nebulae
  - Binary systems
- Searching for more accelerators: the identification process
- The future of gamma-ray astronomy: CTA
- Conclusion

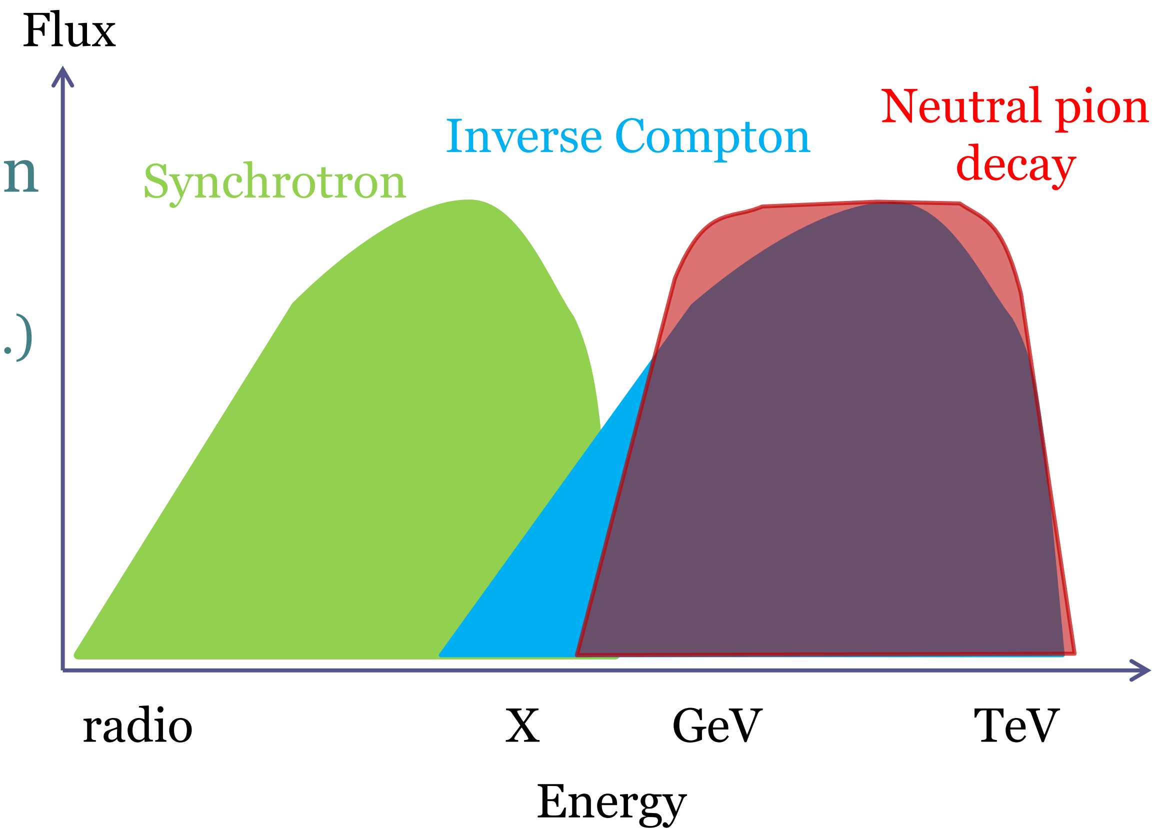
The cosmic-ray features

- 99% hadrons
- 1% electrons
- Spectrum described by a power-law over 12 decades in energy
- Charged particles are scattered by magnetic fields
- Solution: study the gamma-rays they produce



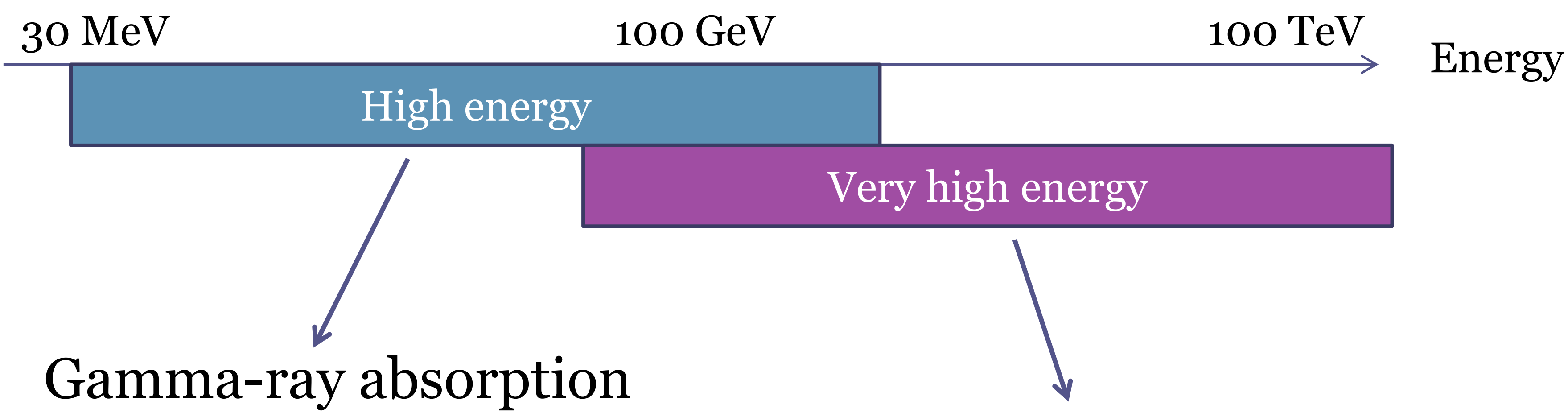
Radiative processes

- Leptonic:
  - Synchrotron emission
  - Inverse Compton scattering (CMB, CIR…)
  - Bremsstrahlung
- Hadronic:
  - Neutral pion decay $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$



Challenge: disentangle the different contributions

Detection techniques



Gamma-ray absorption in Earth's atmosphere

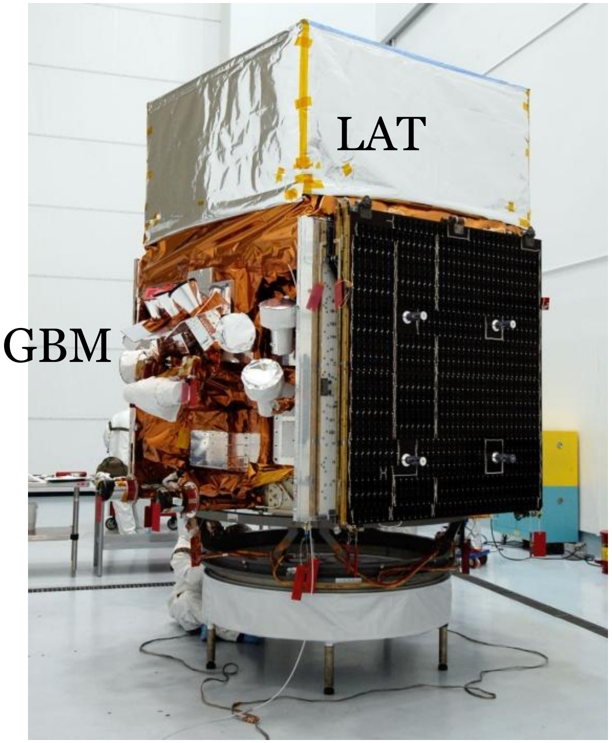
- ➢ Space experiments

Small effective area of satellites : limited flux of gamma-ray detected

- ➢ Ground-based atmospheric imaging telescopes

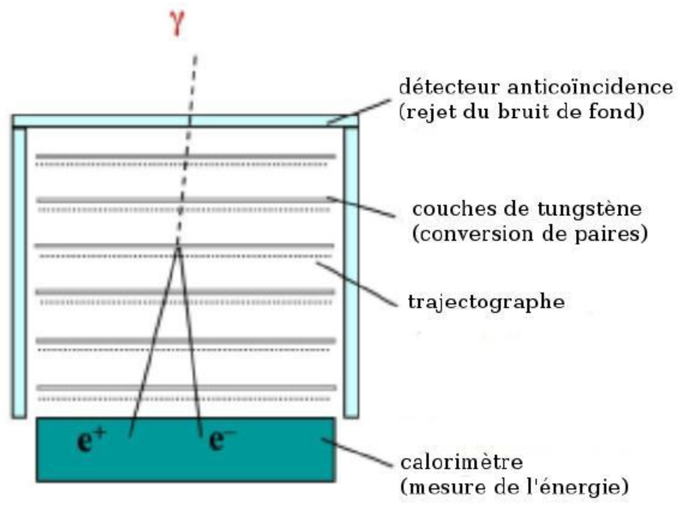
The Fermi satellite

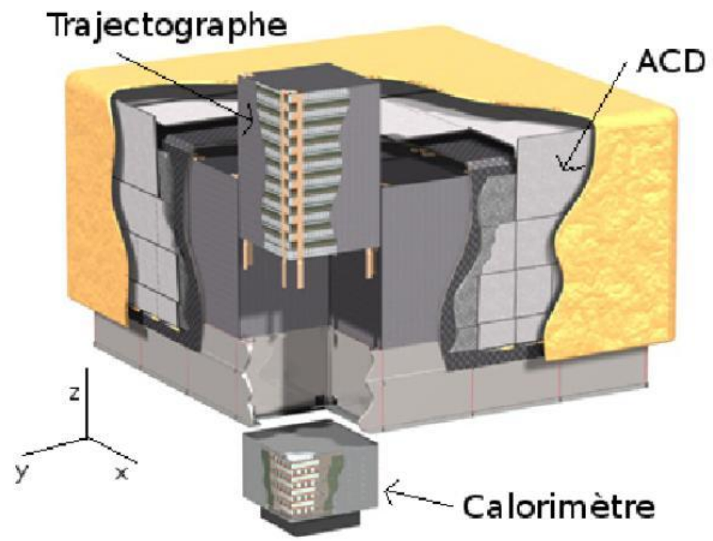
- Launched in june 2008
- 2 detectors:
  - LAT (Large Area Telescope)
  - GBM (Gamma-ray Burst Monitor)



The Fermi satellite: LAT

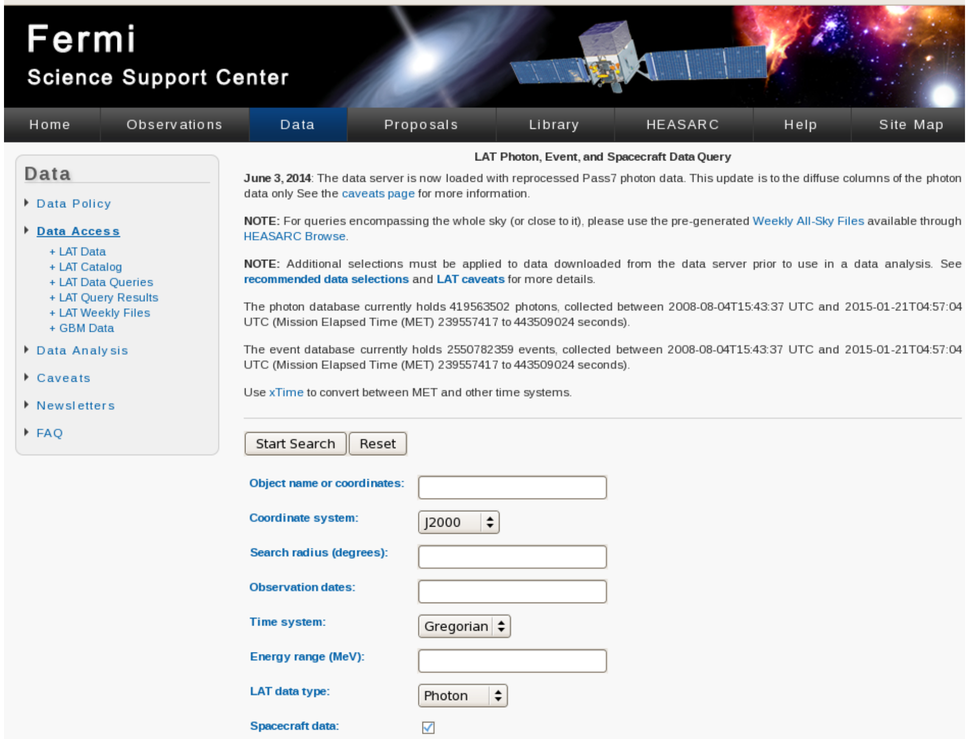
- Anti-coincidence shield to reject charged particles
- e+/e- pair creation in the tracker
  - ➢ Gamma-ray direction
- Measurement of the cascade energy in the calorimeter
  - ➢ Gamma-ray energy
- Accurate position of the satellite and precise time of arrival (<1 μs) : onboard GPS + ground radar
- Full-sky view in 3 hours



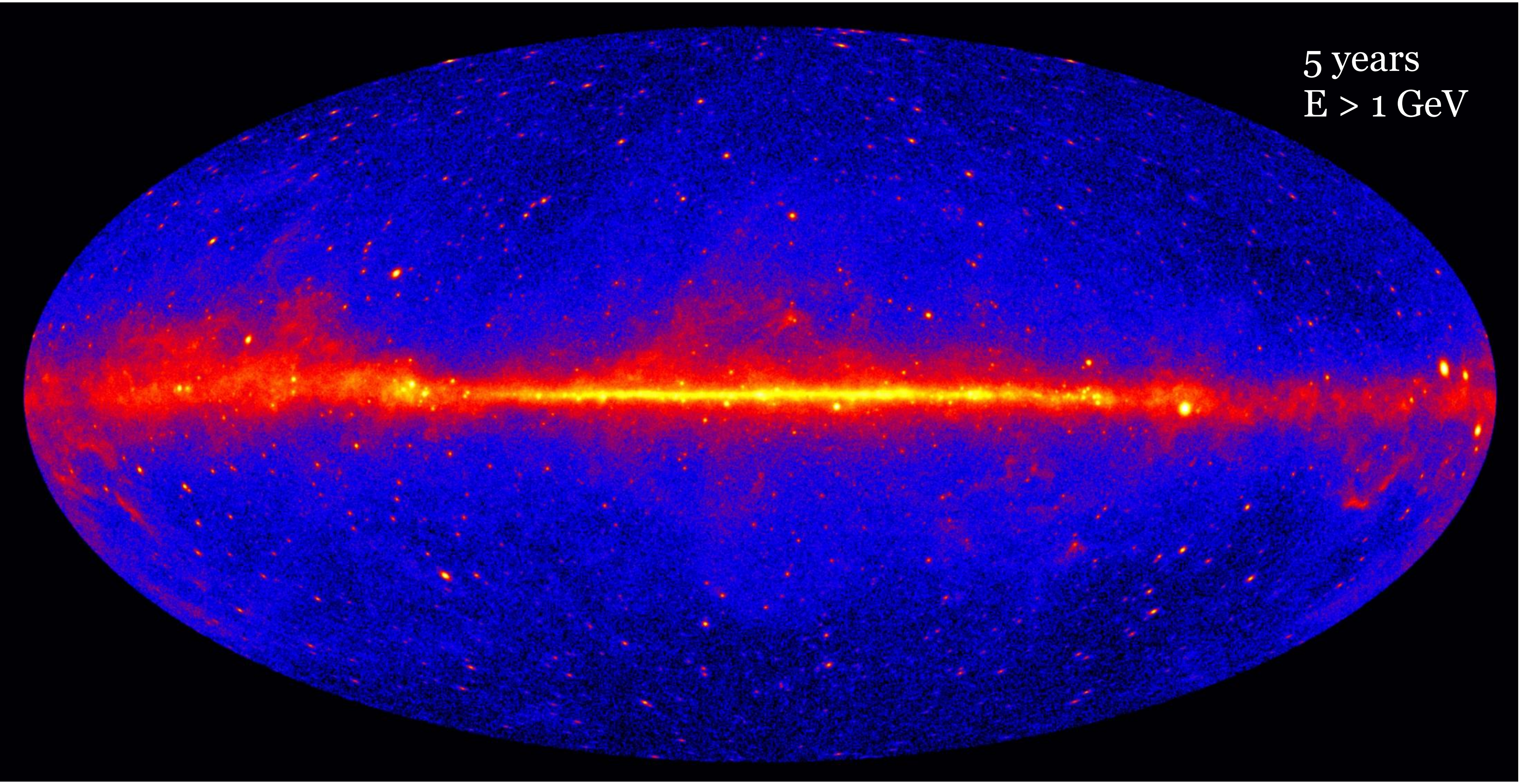


Fermi data analysis

- Public data and analysis tools available here:
  - http://fermi.gsfc.nasa.gov/ssc/data/

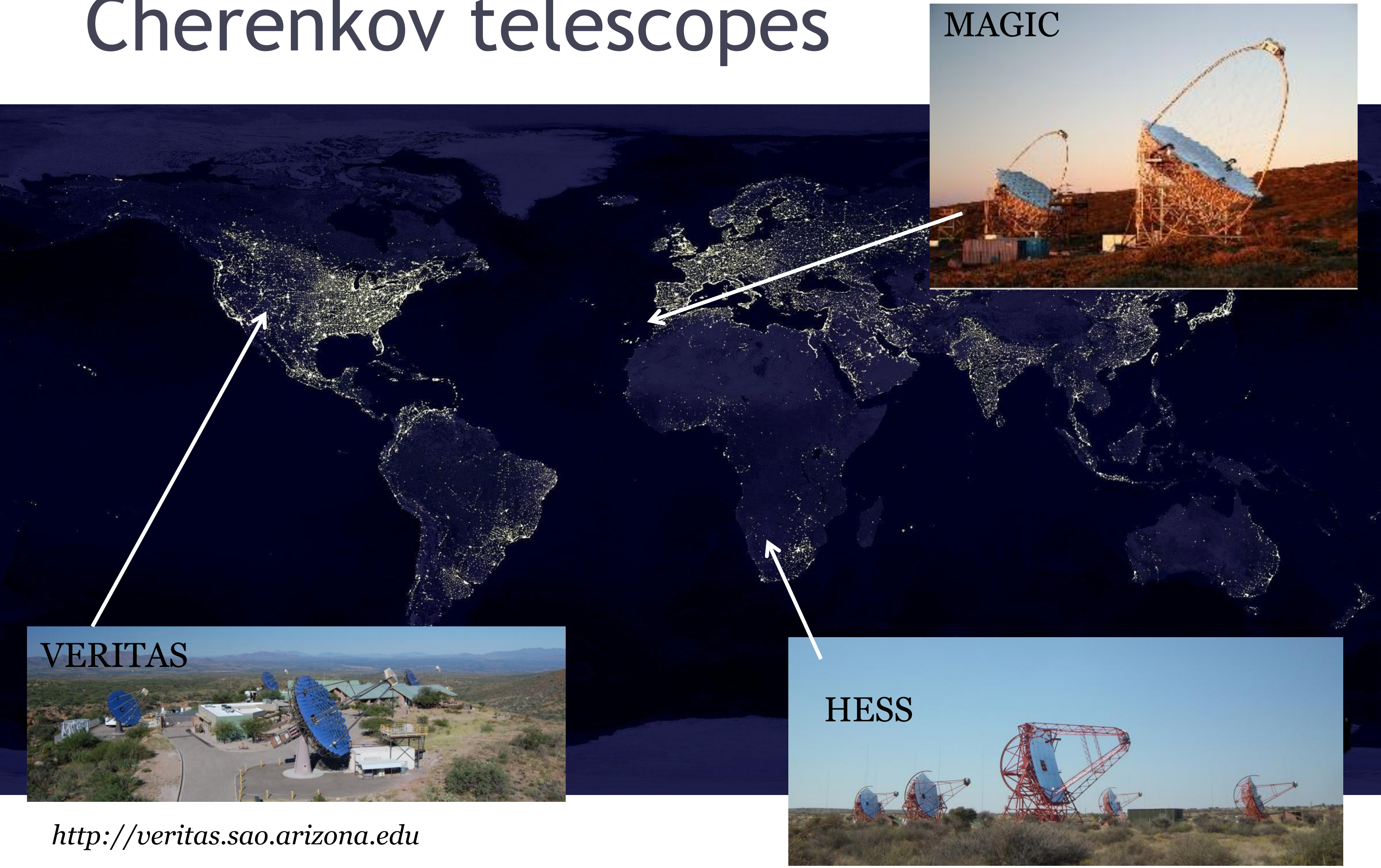


The Fermi sky



Cherenkov telescopes

http://magic.mppmu.mpg.de

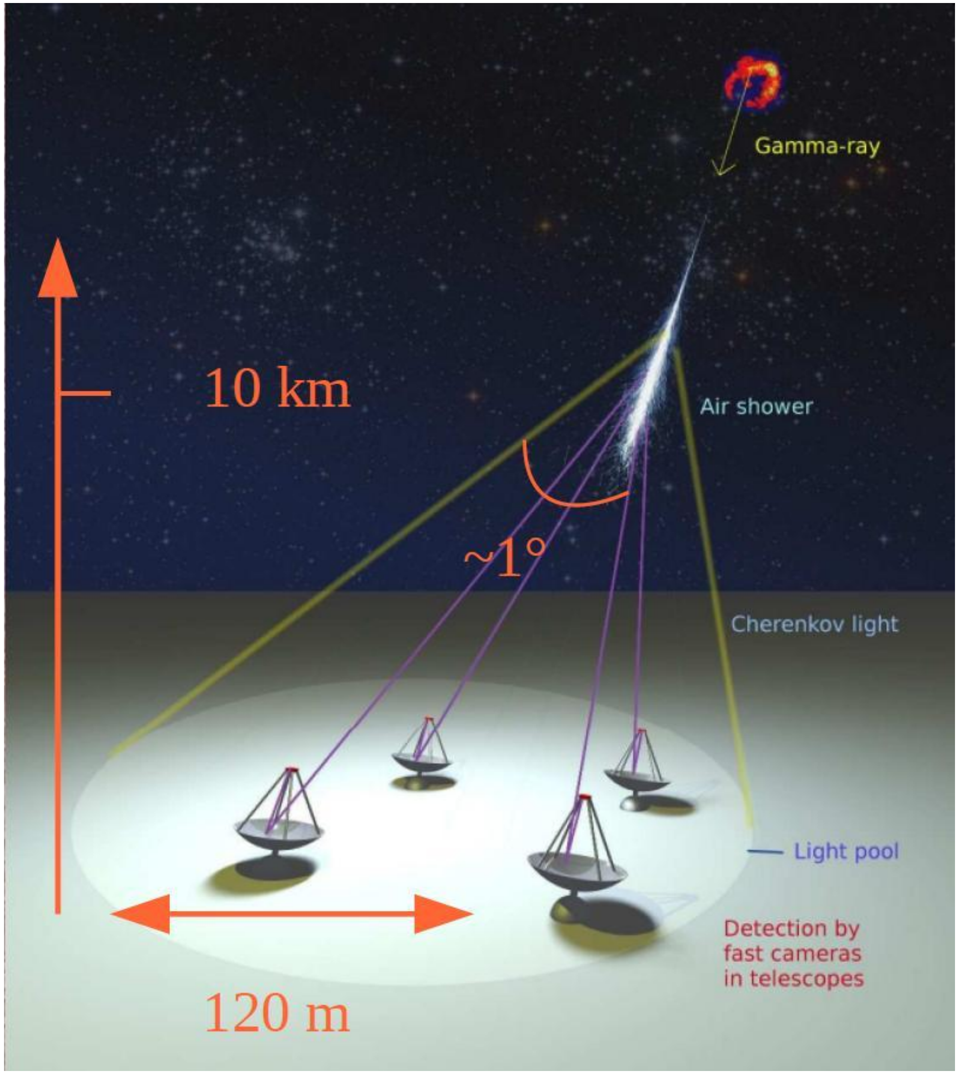


http://veritas.sao.arizona.edu

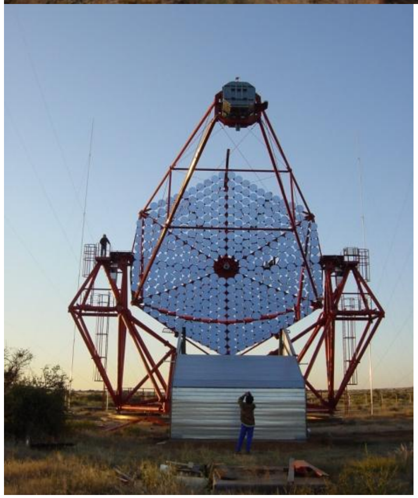
http://www.mpi-hd.mpg.de/hfm/HESS

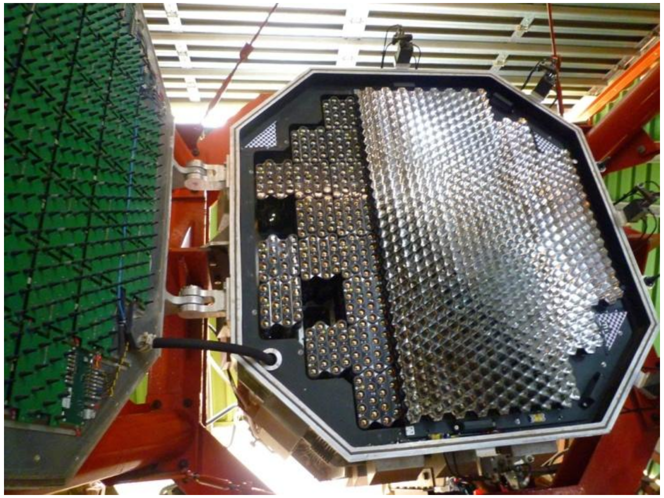
Cherenkov telescopes

- Gamma-ray interacts in atmosphere
- Air shower production
- Cherenkov light emission:
  - Optical-UV
  - ~10 ns duration
  - Max of emission ~10km for 1 TeV gamma-ray
  - Cherenkov cone ~1°
  - ~120 m ground surface covered



Cherenkov telescopes: H.E.S.S.

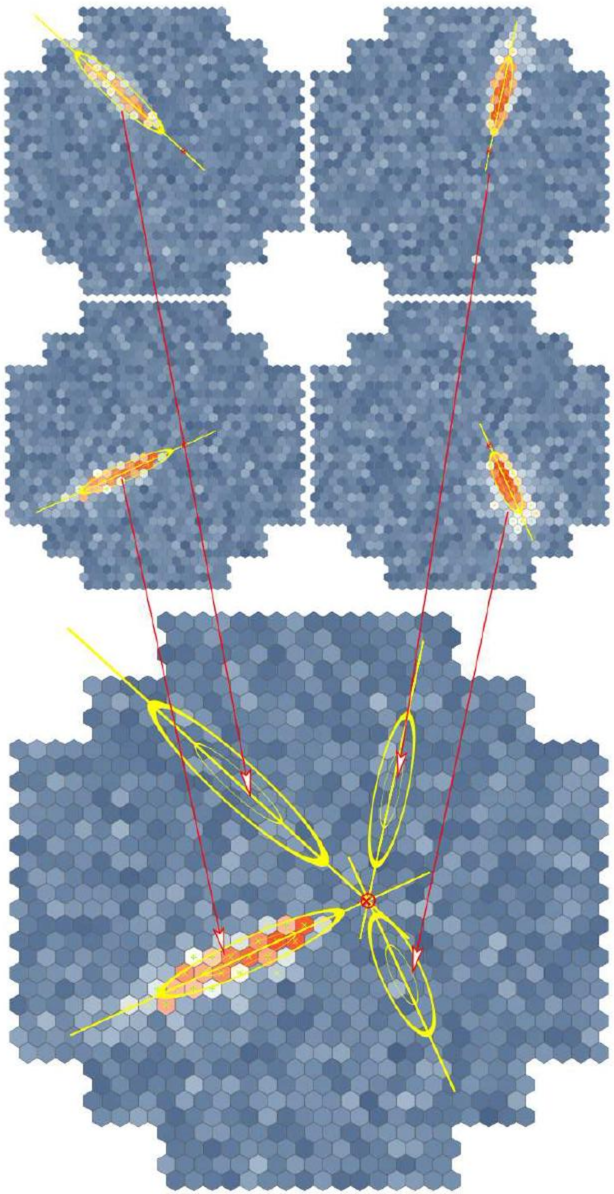




- High Energy Stereoscopic System
- 4 small telescopes
- 1 large telescope since 2012
- Namibia, 1800m altitude
- Cameras made of PMTs catch the Cherenkov light

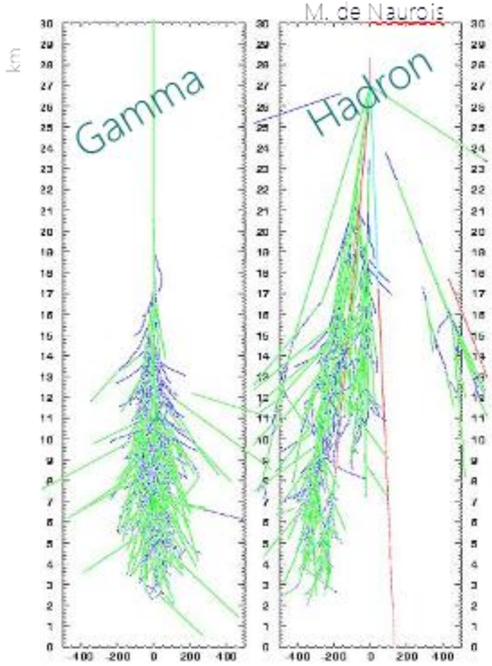
Event reconstruction

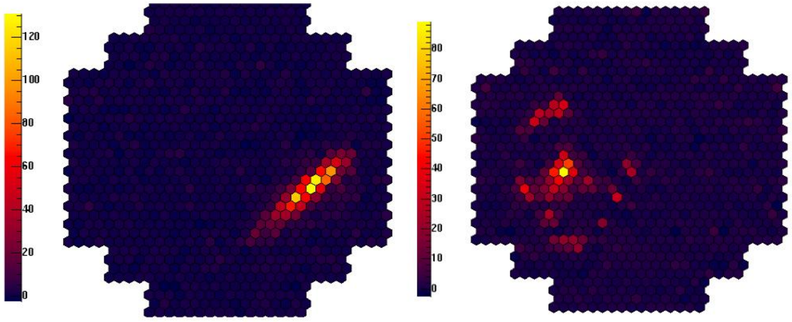
- Shower image on the cameras
  - Information on the shower intrinsic features (maximum of emission, number of Cherenkov photons, impact parameter….)
  - Information on the gamma-ray event (direction, time and energy)
- Stereoscopy allows a better reconstruction of the event’s direction
- Energy is linked to the intensity of the image and to the intrinsic parameters of the shower



Background discrimination

- Cosmic-rays (protons)
  - Hadronic showers
  - Can be discriminated with shape criteria
- Muons
  - Eliminated with stereoscopy
- Night sky background
  - Observation during darkness (no moon)
  - Fast electronics





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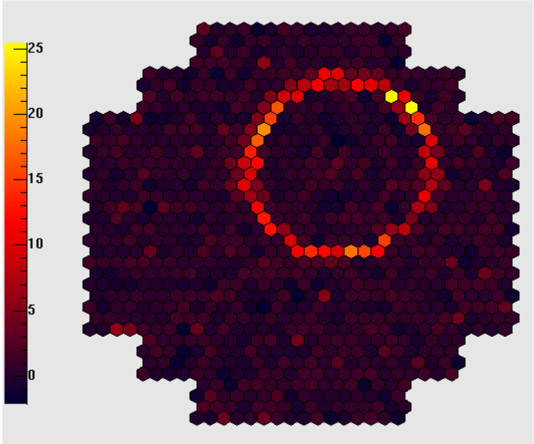

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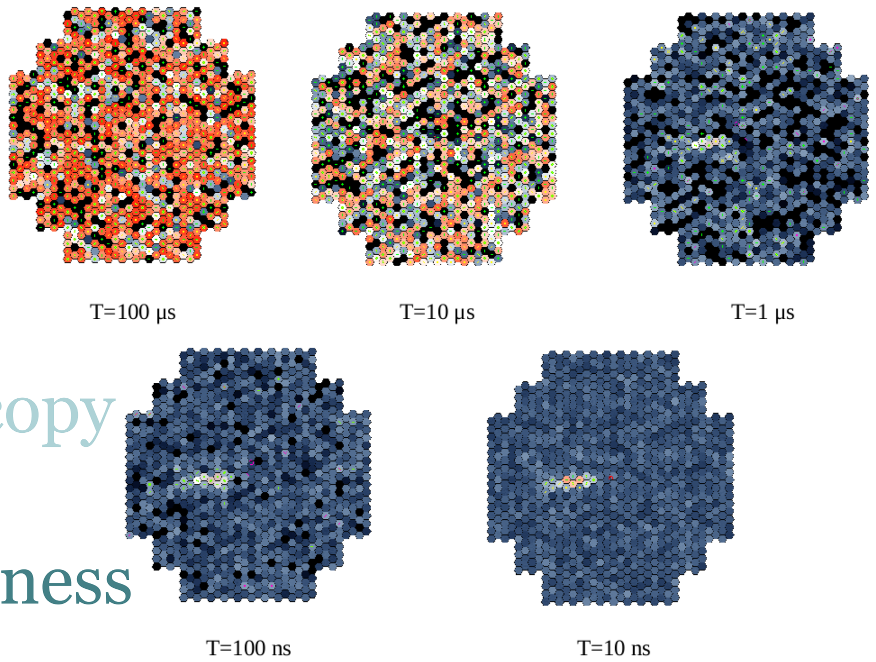
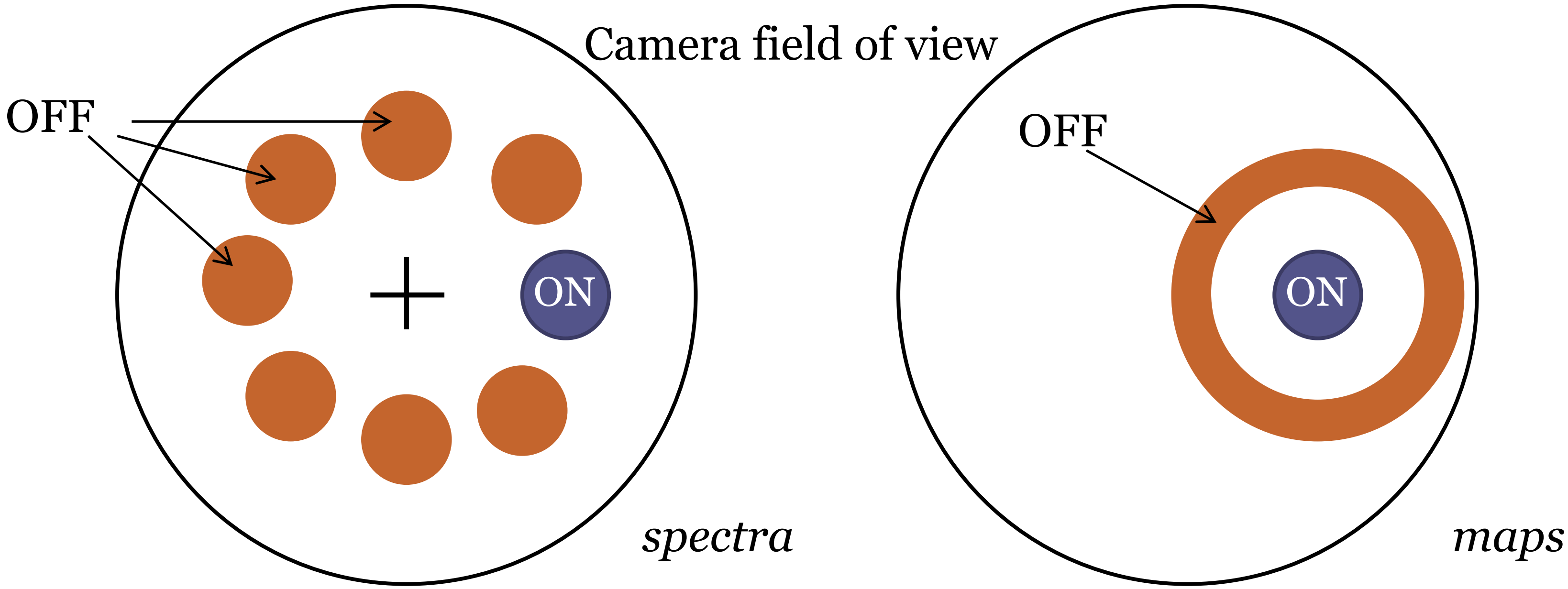
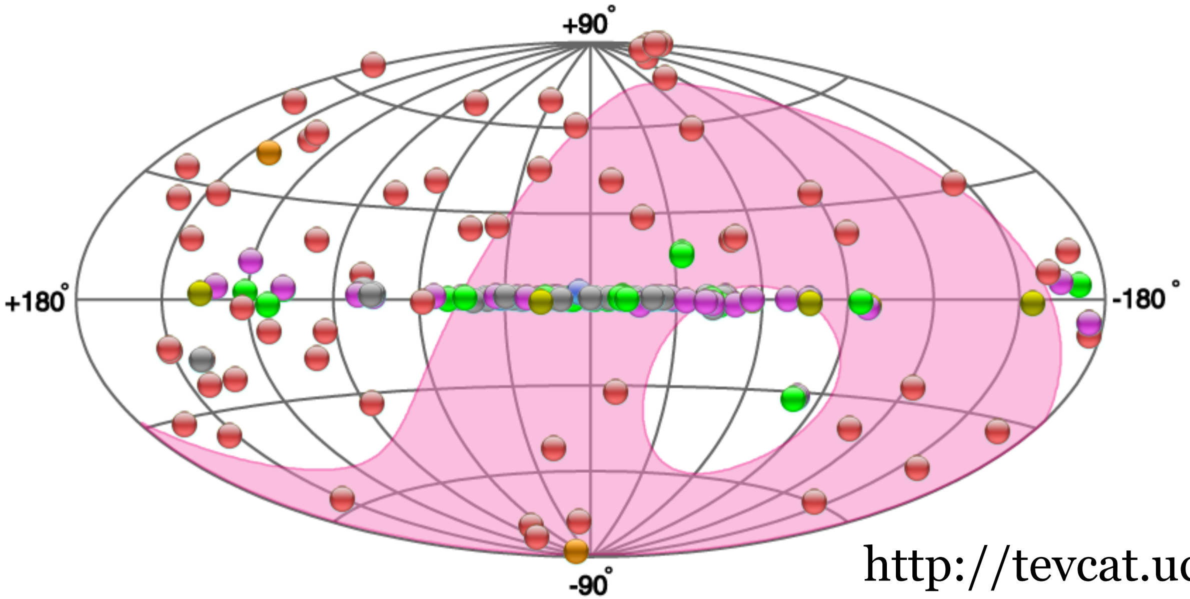


Background discrimination

- cosmic-rays (electrons) + « gamma-like »
  - Electromagnetic showers
  - Removed quantitatively (assumption of isotropy)
  - Gamma-ray sources must be removed from the region used to estimate the background



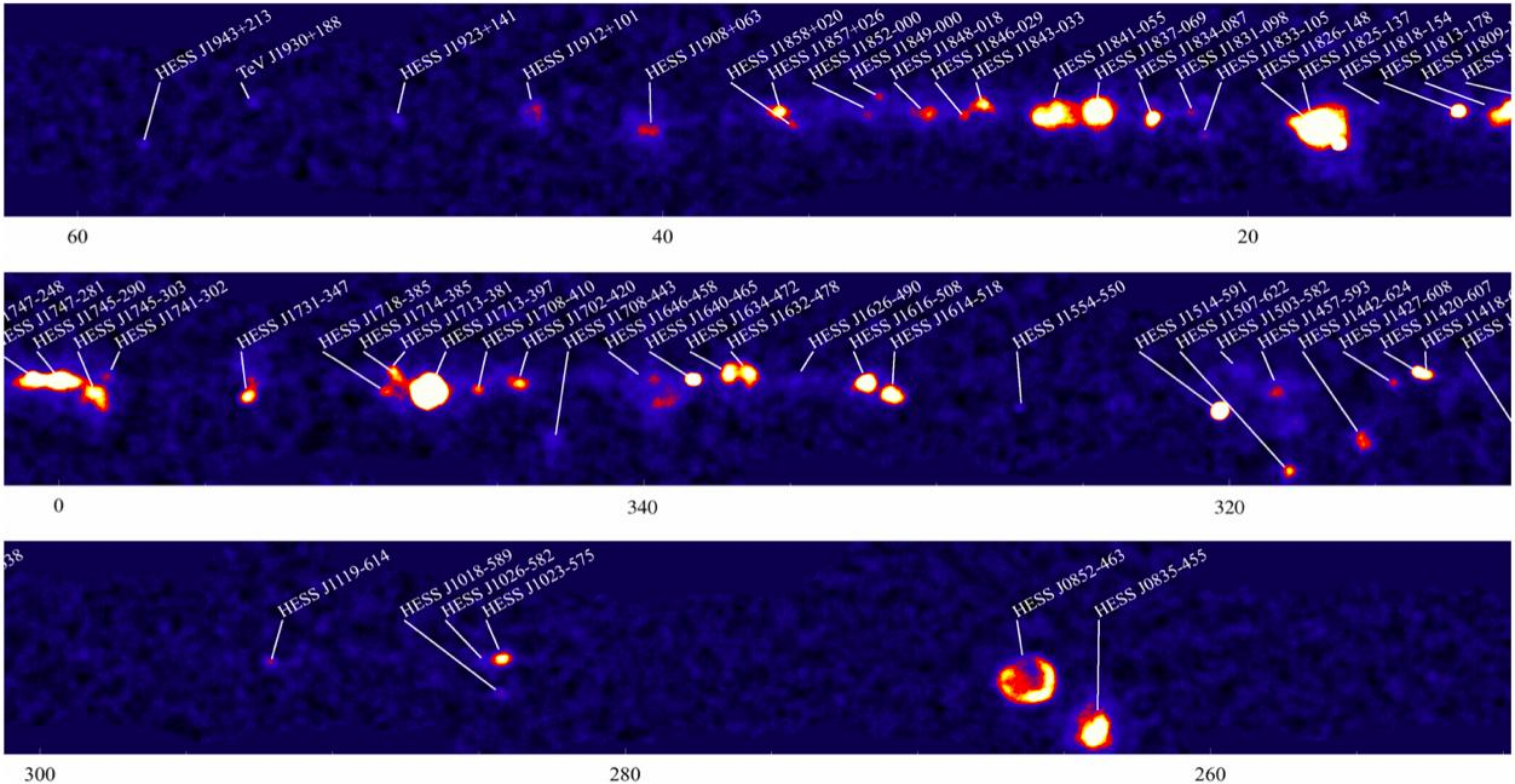
The H.E.S.S. visibility



http://tevcat.uchicago.edu/

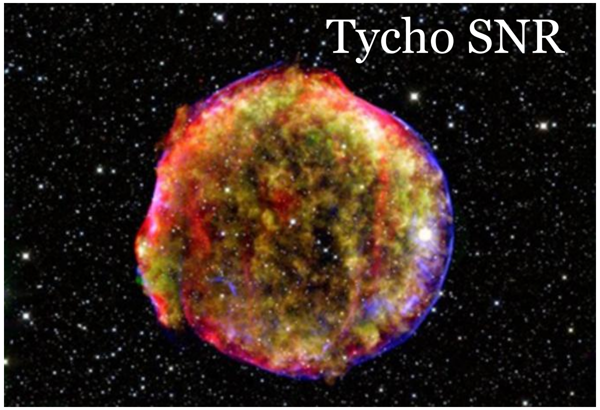
- South hemisphere gives access to the galactic center and most of the galactic plane

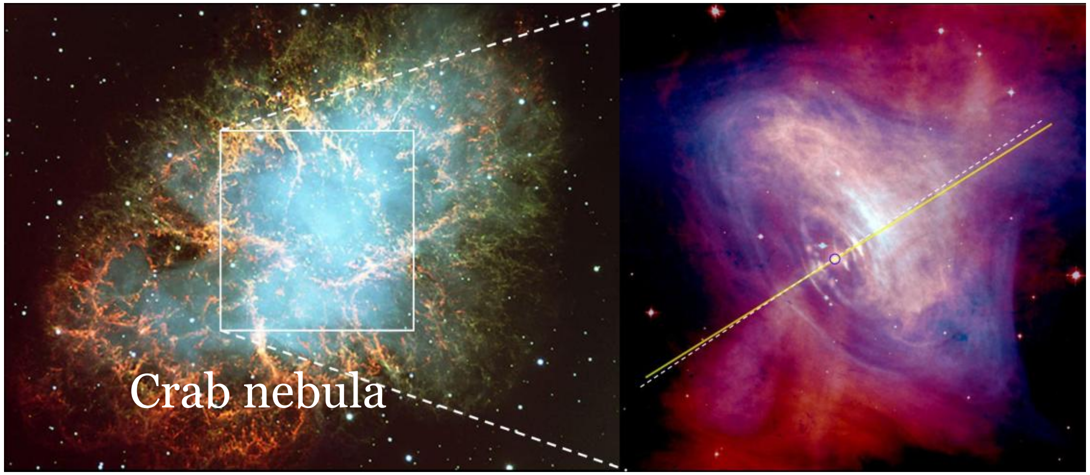
The H.E.S.S. galactic plane

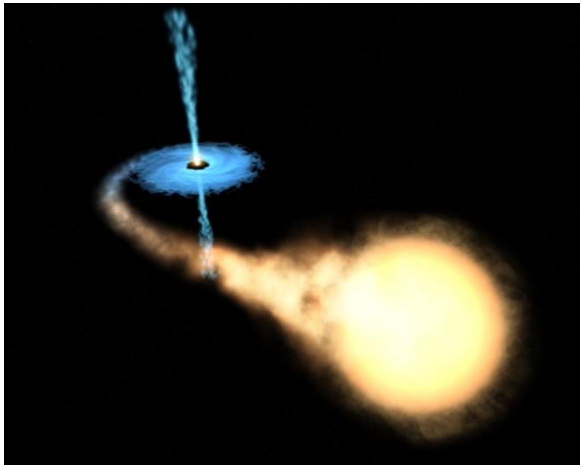


The galactic zoo:

- Supernovae remnants
- Pulsars and their nebulae
- Binary systems

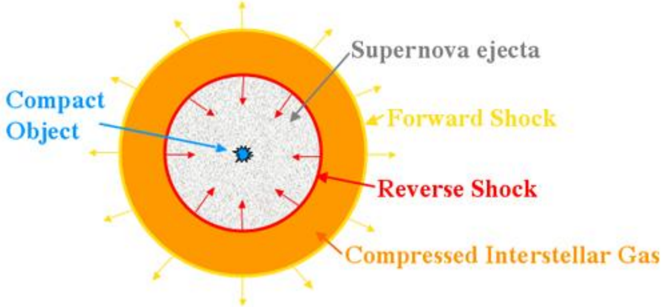






Supernovae remnants

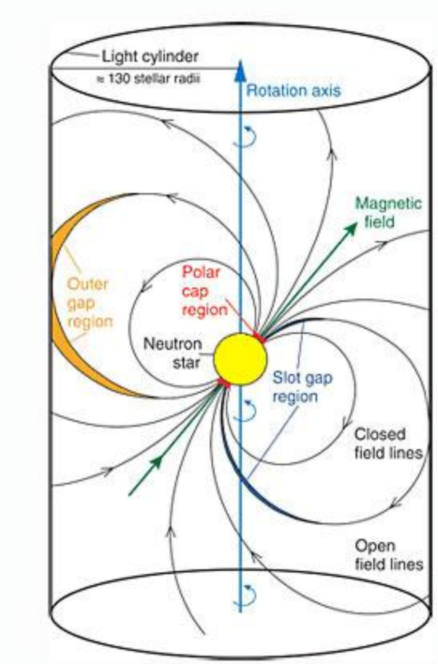
- Shock wave produced by supernova ejecta expand into the interstellar medium
  - Particle acceleration through Fermi mechanism
- 3 different stages:
  - Free expansion
  - Sedov-Taylor phase
  - Radiative phase

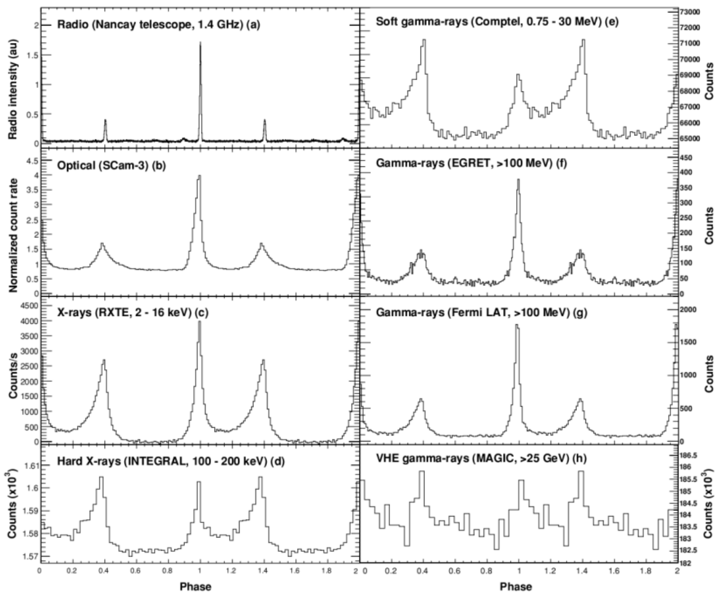


- Given the SN rate in our Galaxy and assuming that 10% of the SN energy is transferred to cosmic-rays, these objects could explain the CR spectrum up to 10^{15} eV
- ~300 objects detected in radio (Green 2014)
- Only ~20 of these are gamma-ray sources

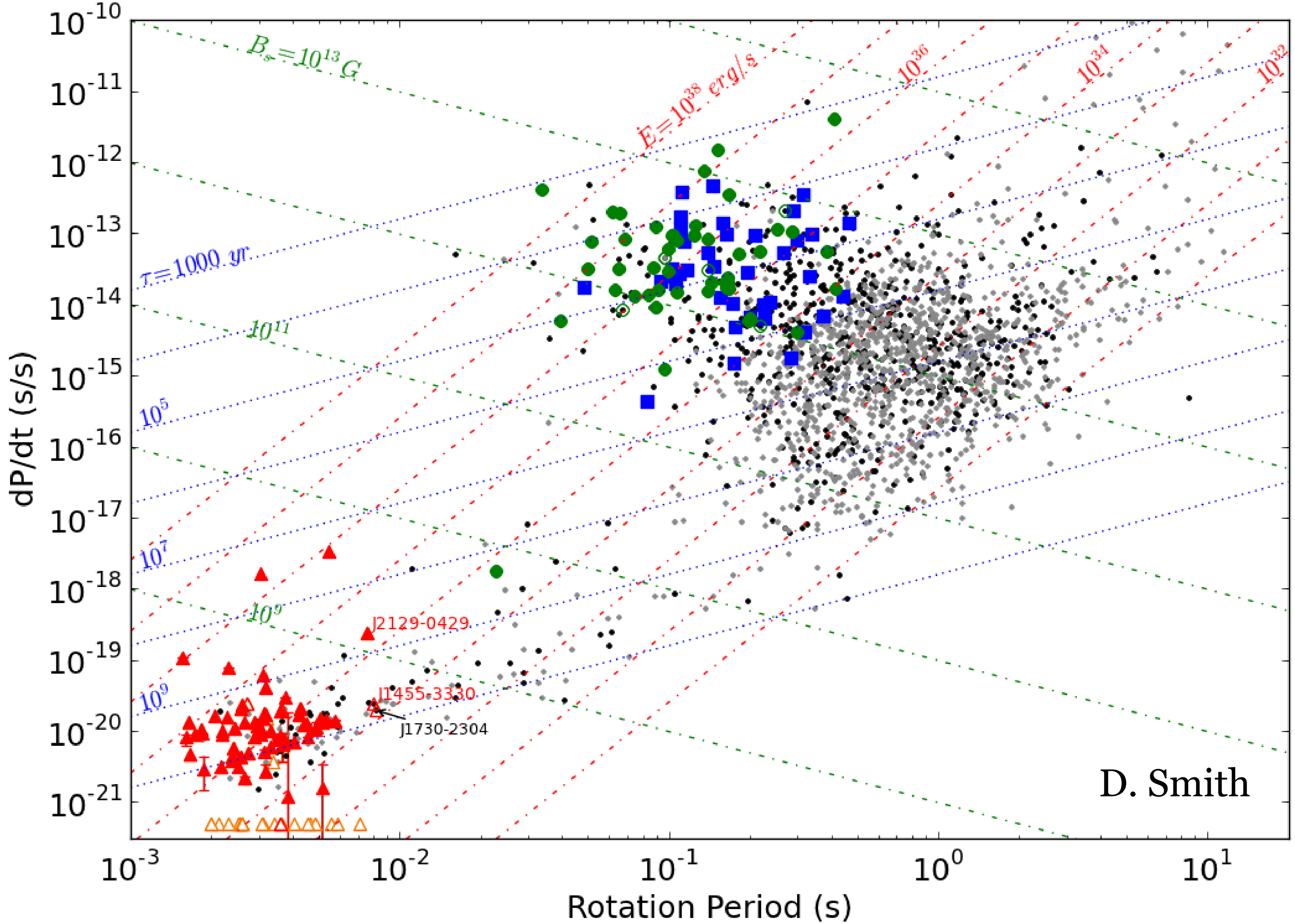
Pulsars

- Compact object with fast rotation
  - ~10 km radius
  - Period ~1 ms to 10 s
  - High magnetic field ~10^{12} G
- Particle acceleration can occur along the magnetic field lines
  - Polar cap
  - Slot gap
  - Outer gap
- Leptonic emission from radio to γ
- 2 types of pulsars: young and recycled (millisecond pulsars)



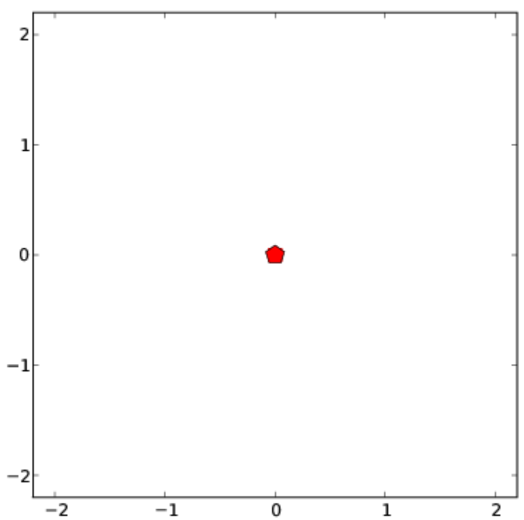


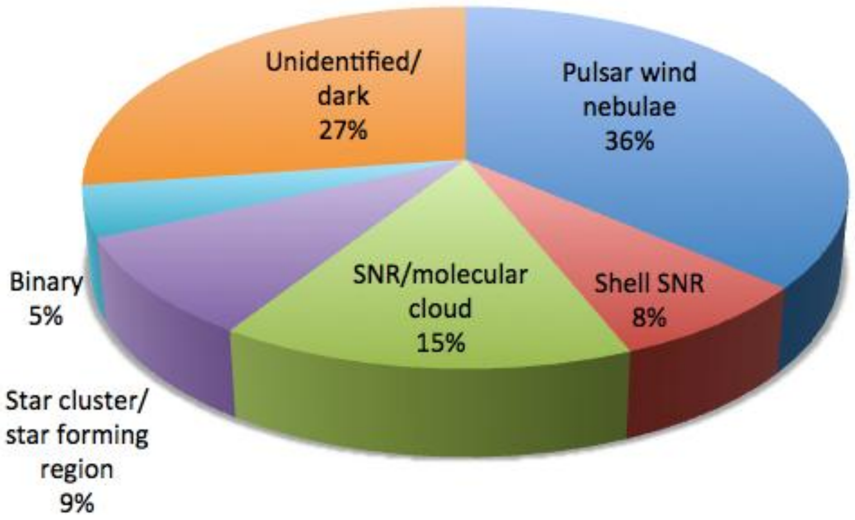
P-Pdot diagram



Pulsar wind nebulae

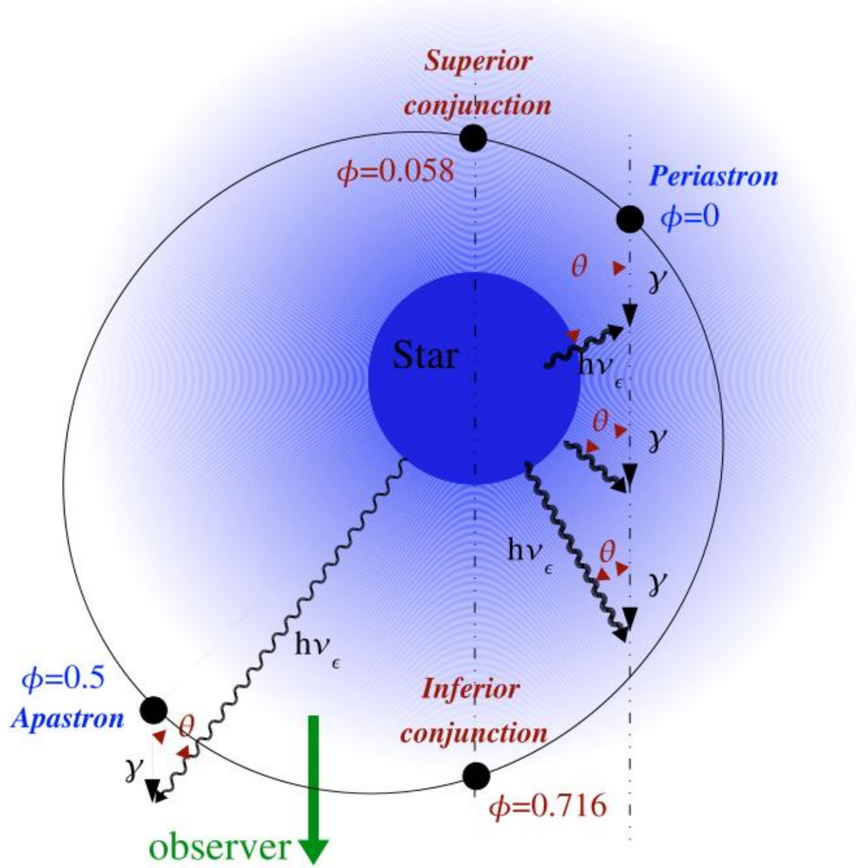
- Relativistic wind (e+/e-) produced by the pulsar fills the SNR cavity
- Leptonic emission depends on the pulsar injected power and the magnetic field
- Almost 40% of the H.E.S.S. galactic sources





Binary systems

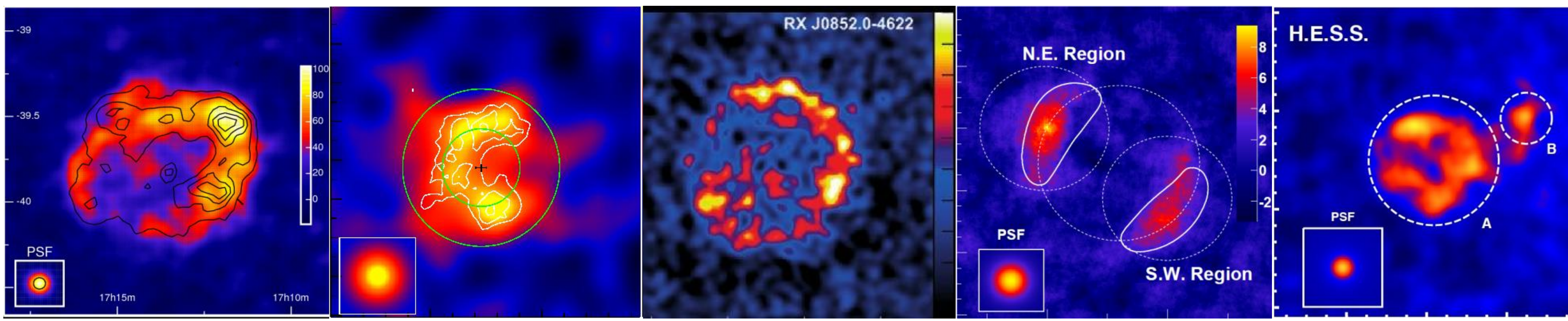
- Compact object (pulsar, black hole…) orbiting a massive star
- Particle acceleration
  - Shock waves in stellar wind interaction
  - If compact object is a pulsar, acceleration in the pulsar wind
  - In the case of a black hole (microquasar) : acceleration along the jets or at the termination shock
- Inverse Compton scattering on low-energy photons of the massive star wind →gamma-ray production
  - Depend on E_{photon}, angle between photon and electron
- Gamma-ray absorption by e+/e- pair creation
  - Depends on E_{photon} and the relative angle between the LE photon and the gamma-ray



Sketch of LS 5039 system
(Aharonian et al. 2006)

Young supernovae remnants

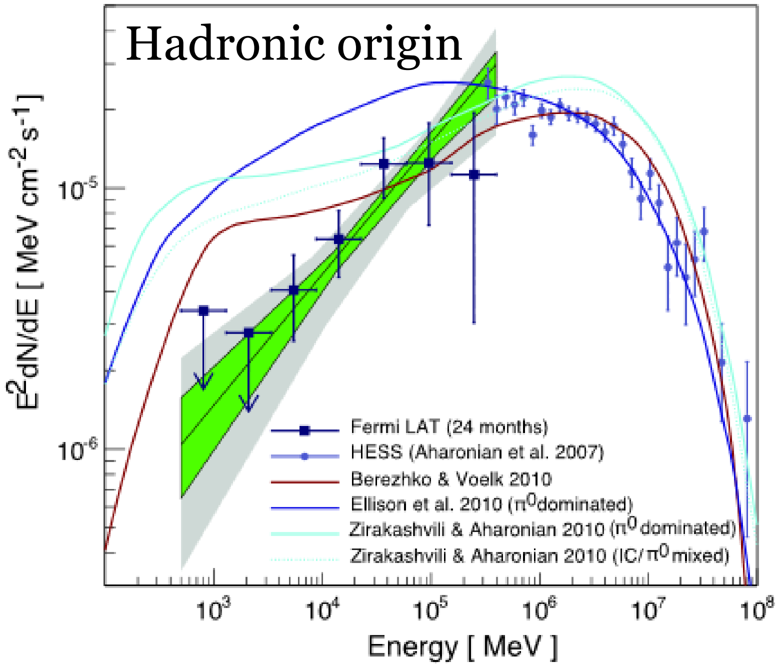
- Shell-type in gamma-rays
- A handful of objects known:

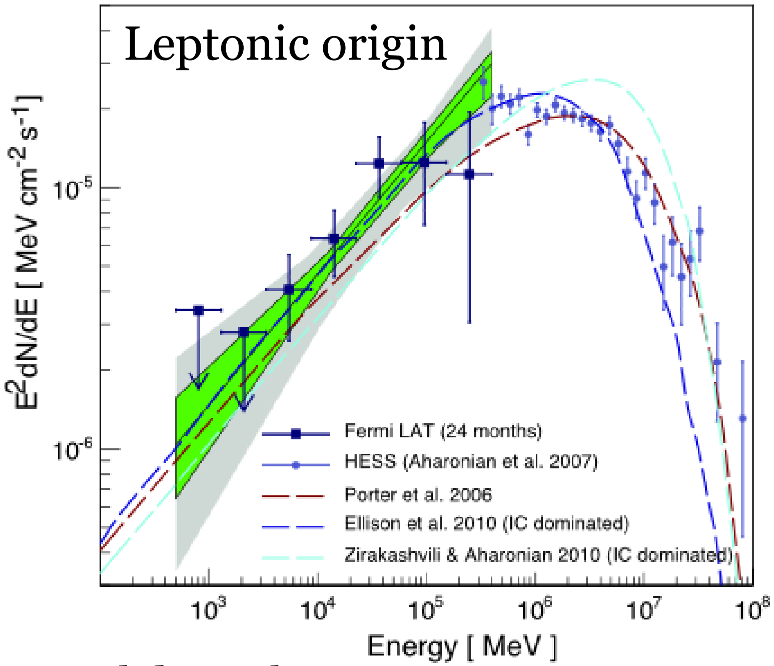


RXJ 1713	RCW 86	Vela Jr	SN 1006	HESS J1731
1.6 kyr	1.8 kyr	2-4 kyr	1009 yr	2-6 kyr
<0.02 cm^{-3}	0.01 - 1 cm^{-3}	<0.03 cm^{-3}	<0.05 cm^{-3}	<0.02 cm^{-3}

Young supernovae remnants

- Leptonic models favored
  - Hadrons are not accelerated by SNRs?
  - Not enough target material to trace them?

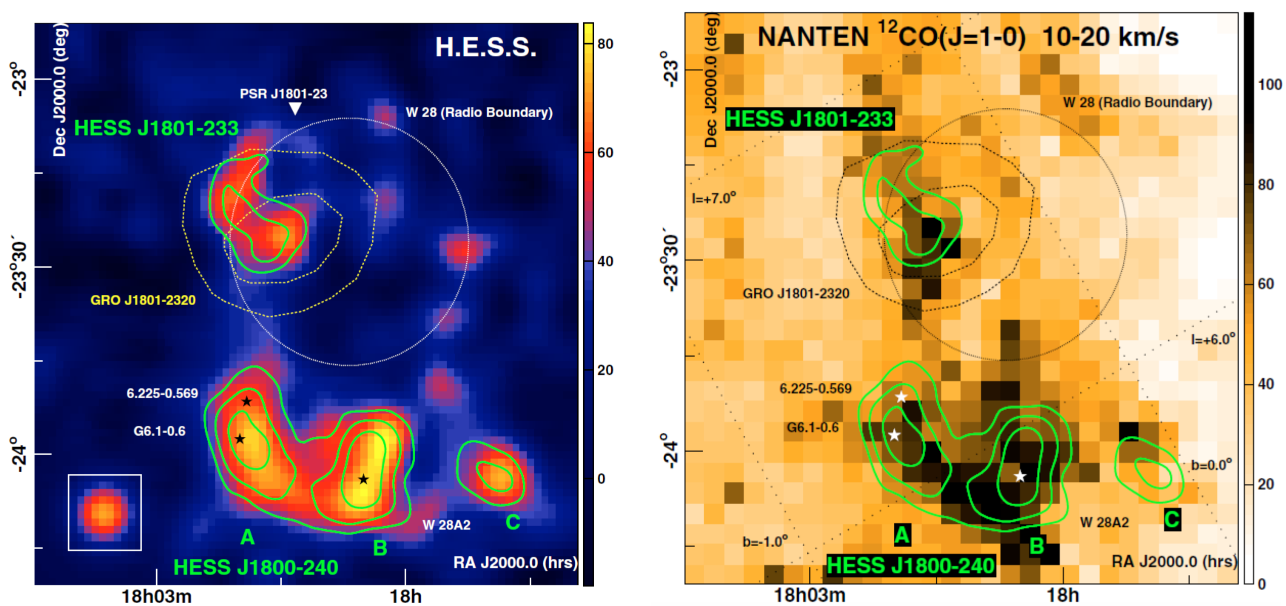




RXJ 1713.7-3946, Abdo et al. 2011

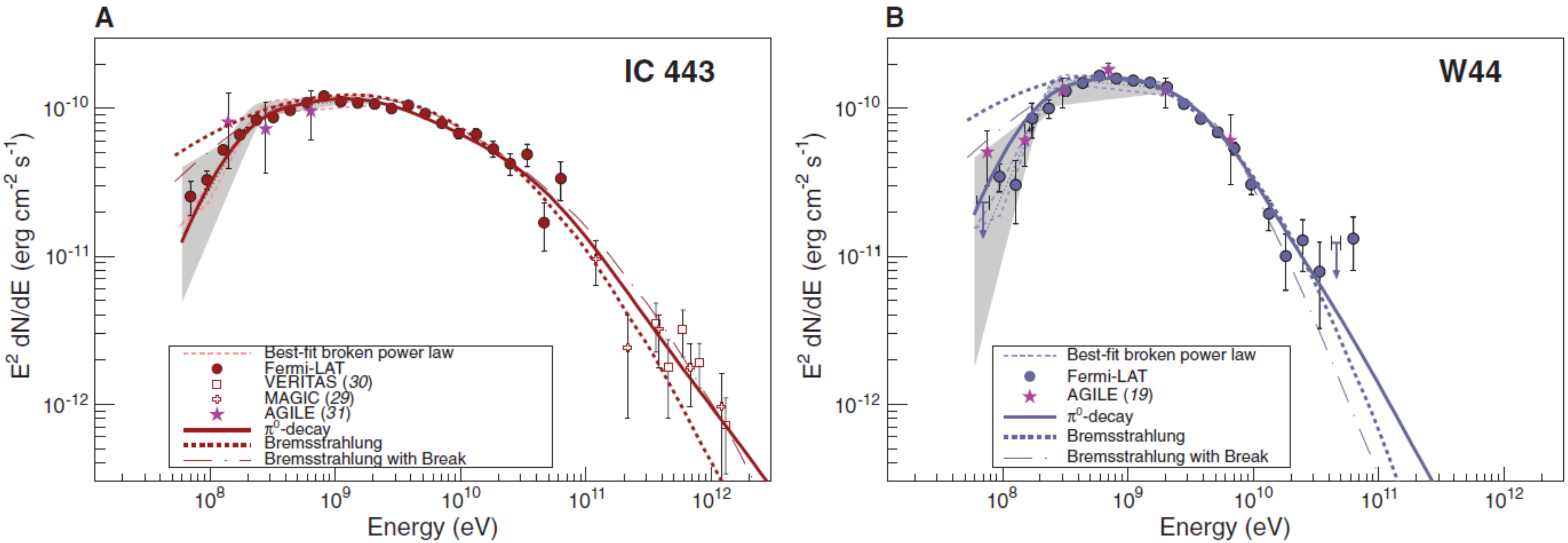
Old supernovae remnants

- Higher energy cosmic-rays escaped the remnant
- Interaction in nearby molecular clouds = targets for neutral pion production
- Example: SNR W28 (age~35-150 kyr):



Aharonian et al. 2008

First evidence for hadronic acceleration



Ackermann et al. 2013

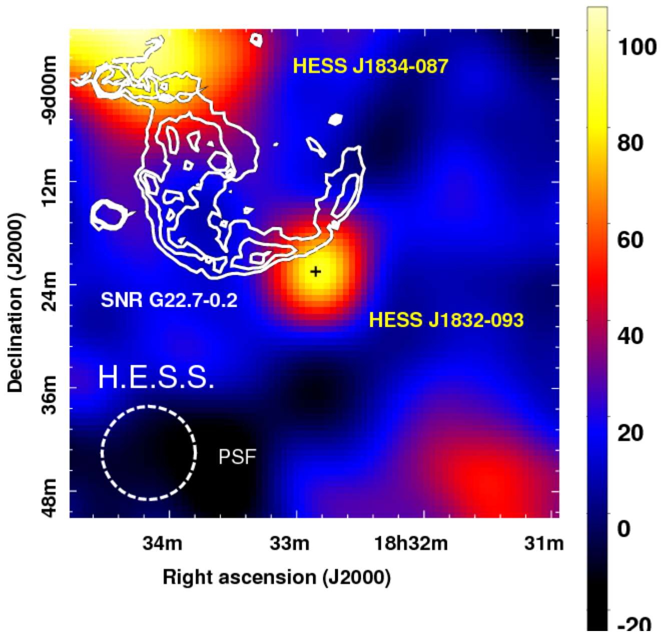
- Hadronic model favored compared to Bremsstrahlung emission
- But only for these 2 SNRs…

Searching for more hadronic accelerators: the identification process

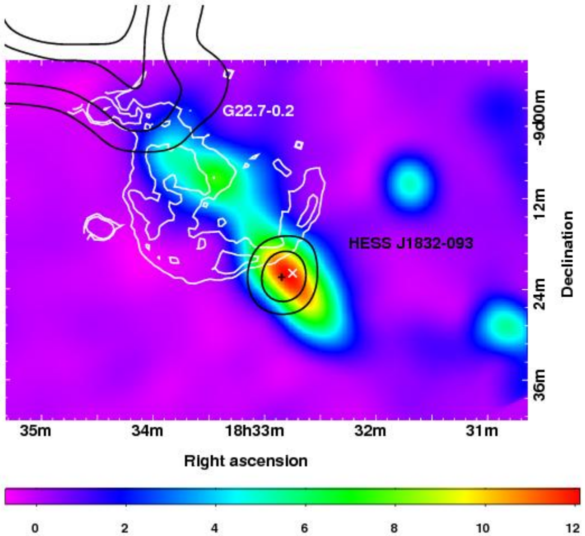
- HESS J1832-093
- HESS J1640-465 and HESS J1641-463

HESS J1832-093

- Spatially coincident with a fraction of SNR G22.7-0.2 (distance unknown, could be between 2 and 4.5 kpc)
- Flux~1.7% Crab



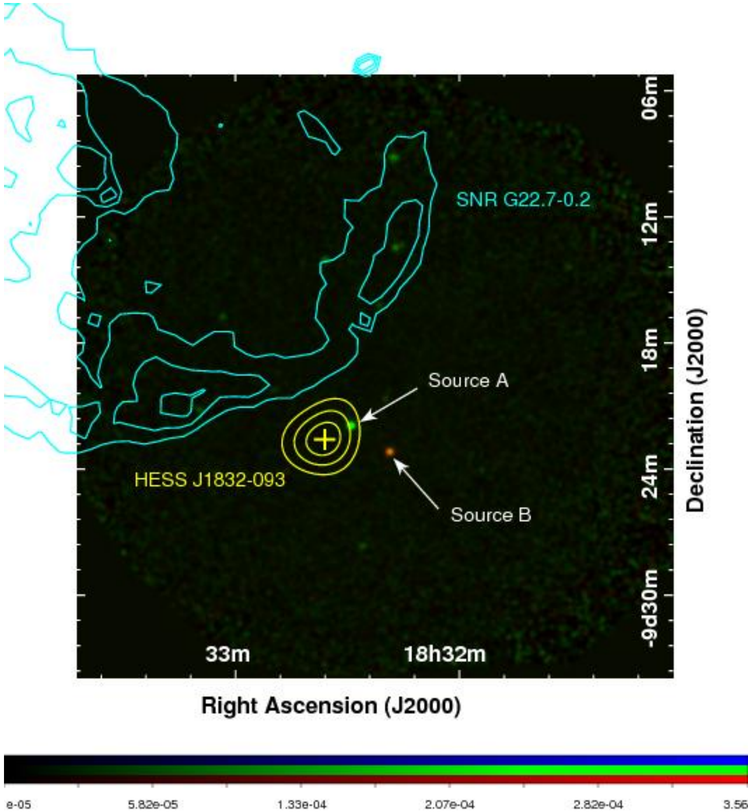
- ^{13}CO line emission observed along the line of sight
  - First interpreted as SNR/MC interaction



Laffon et al (HESS collab.) 2015

HESS J1832-093

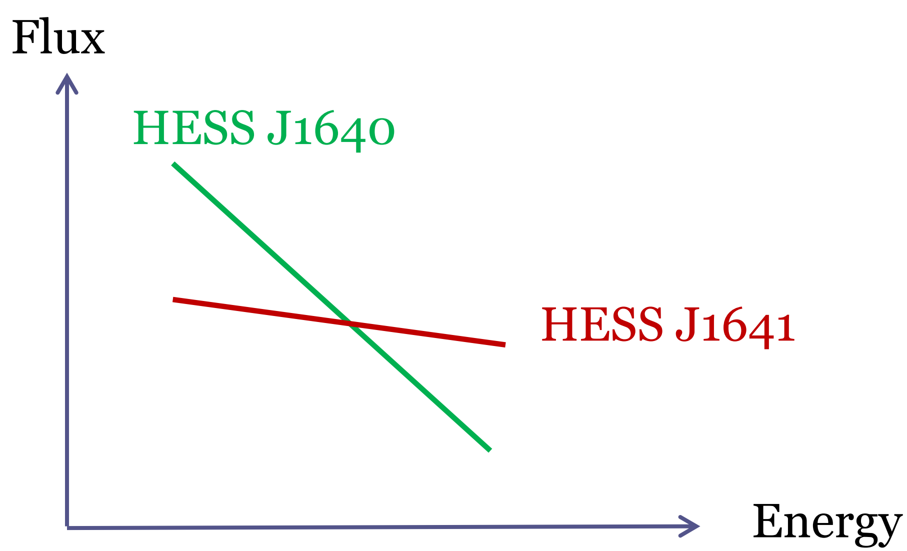
- XMM-Newton proposal
  - Discovery of point-like source with hard spectral index=$1.3^{+0.5}_{-0.4}$ → pulsar? (but no pulsations)
  - No diffuse X-ray emission
  - Estimated distance ≥5kpc using HI and CO absorption
- 2MASS source likely counterpart to the X-ray point-like source
- Underluminous X-ray PWN?
  - If pulsar: Edot~4.5×10^{37} erg s^{-1} (Li et al. 2008), Edot/d^2~6×10^{35} erg s^{-1} kpc^{-2}
  - OK to power a PWN and detectable by HESS
- Binary system?
  - Chance probability of association between IR and X-ray sources very low (2%)
  - No variability in any wavelength
- **No preferred scenario → unidentified**
- Accepted Chandra proposal to study more precisely the X-ray source



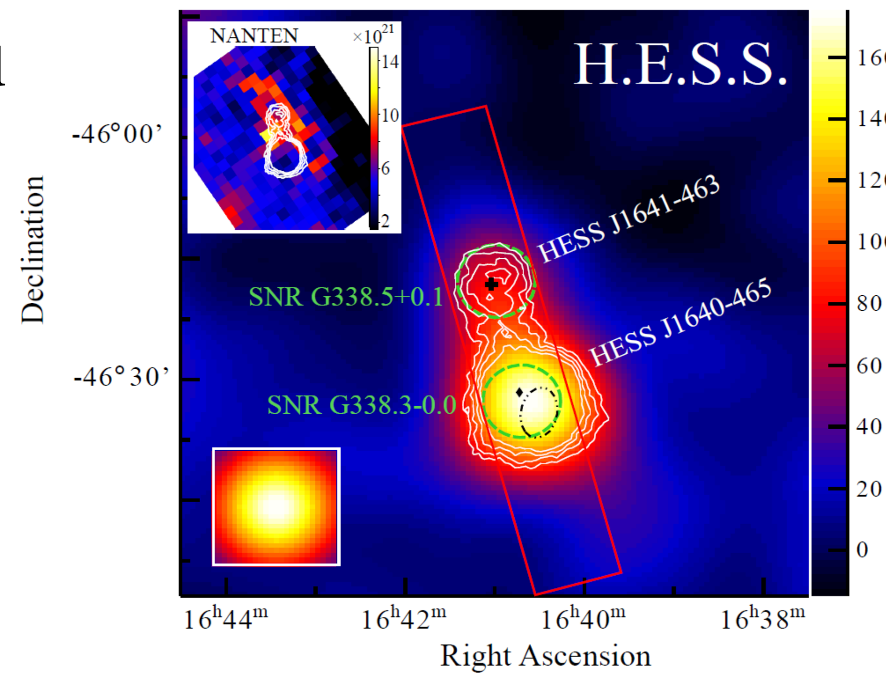
Laffon et al (HESS collab.) 2015

The case of HESSJ1640 and HESS J1641

- HESS J1640-465 is a bright H.E.S.S. source discovered in 2006
- HESS J1641-465 is 0.25° away and much fainter, discovered in 2013
- Appears only at VHE

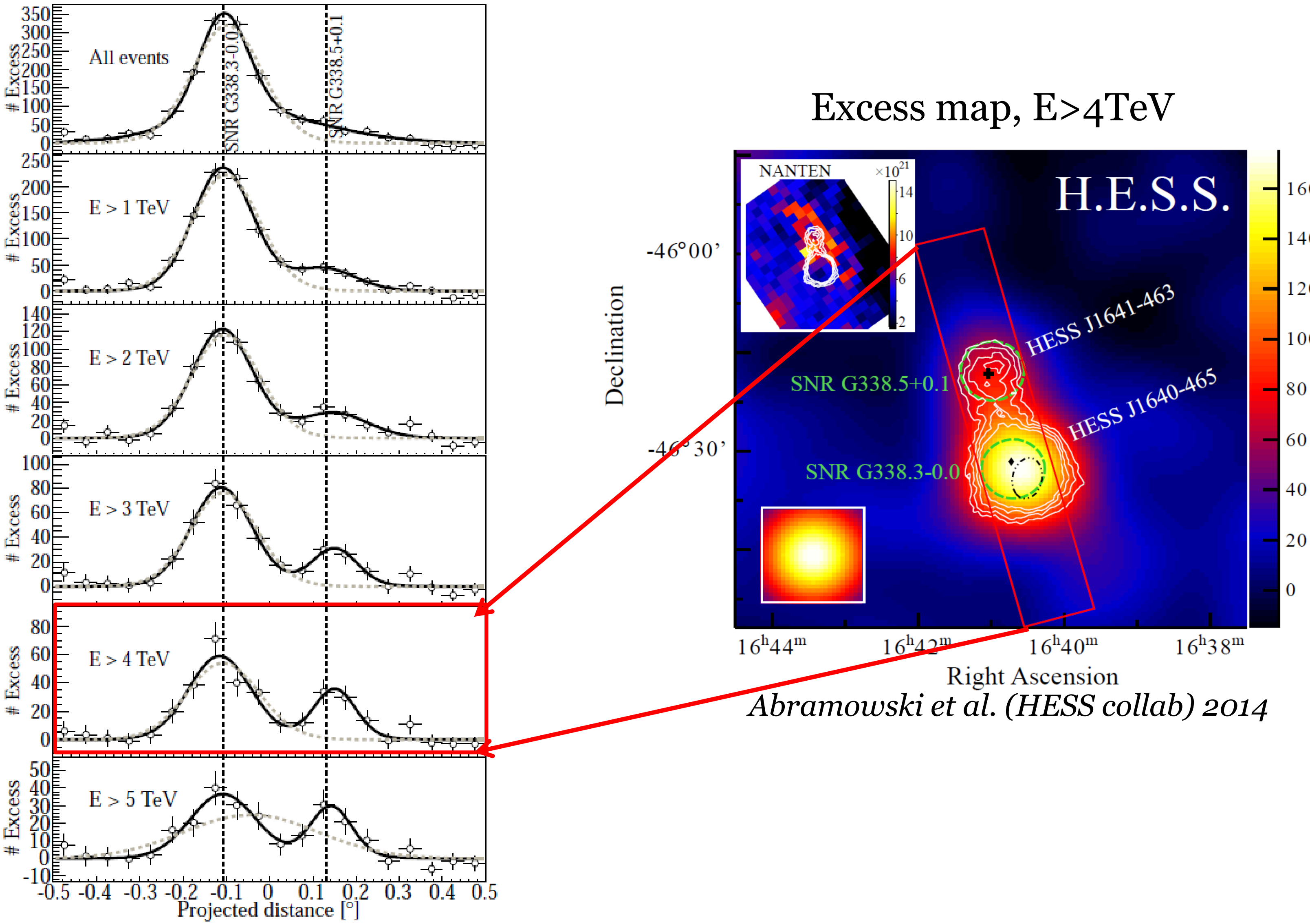


Excess map, E>4TeV



Abramowski et al. (HESS collab) 2014

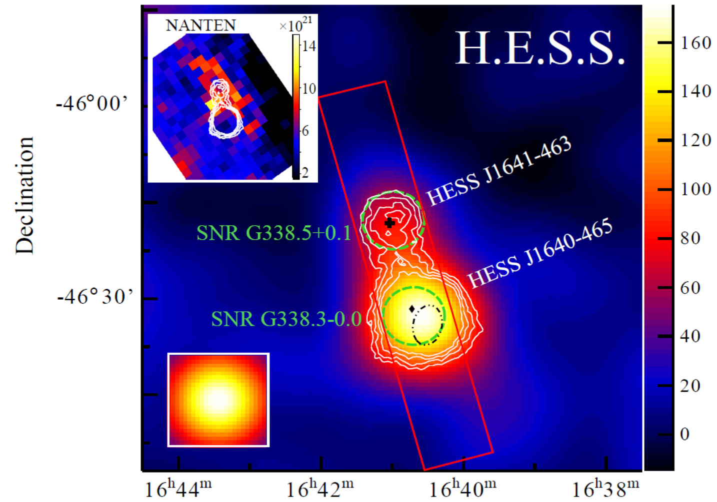
The case of HESSJ1640 and HESS J1641

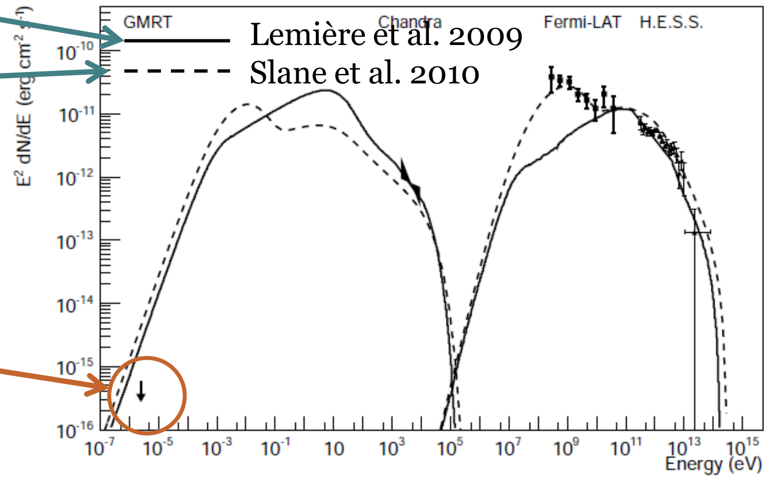


Abramowski et al. (HESS collab) 2014

The case of HESSJ1640 and HESS J1641

- **2006:** Discovery of HESSJ1640 by H.E.S.S., spatially coincident with SNR G338.3-0.0
- **2007:** X-ray PWN candidate discovered by XMM-Newton
- **2009:** Confirmation by Chandra and detection of a point-source pulsar candidate
- **2010:** Detection of GeV counterpart by Fermi: PWN modeling (leptonic)
- **2011:** New radio measurements do not show the presence of the PWN

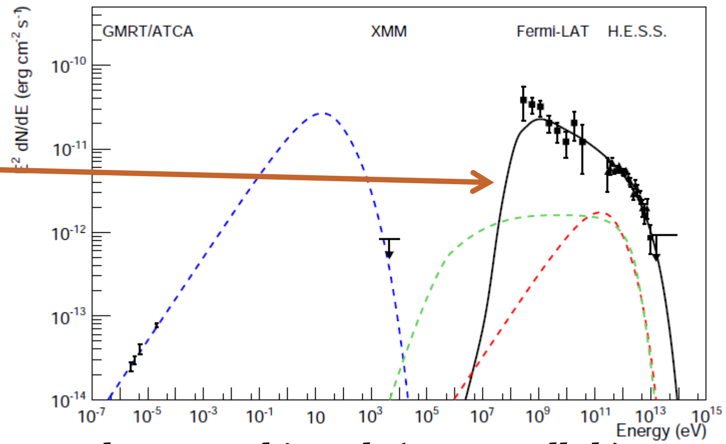




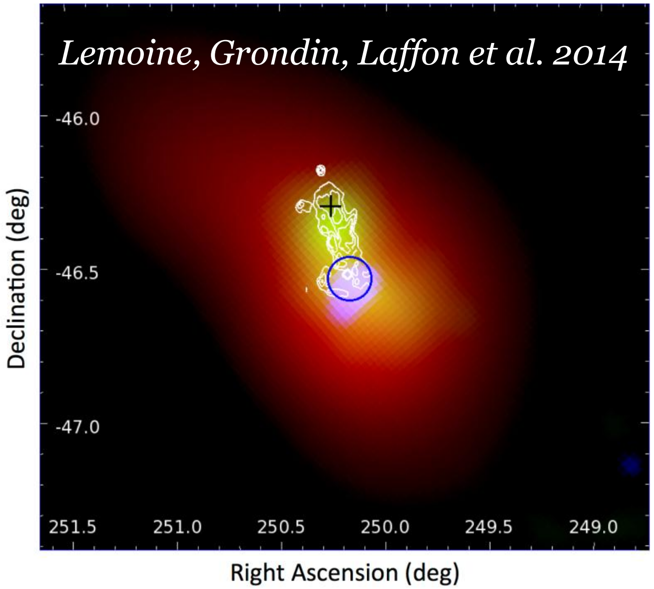
Favor hadronic models
Favor leptonic models

The case of HESSJ1640 and HESS J1641

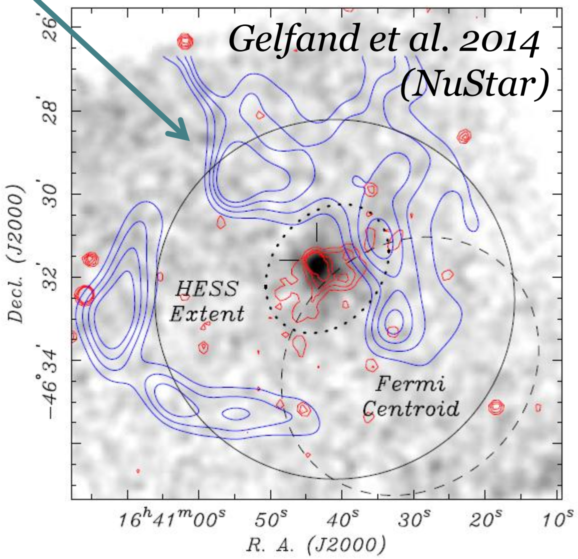
- **2013:** Discovery of HESS J1641-463
- **2014:** New hadronic model for HESS J1640-465
- **2014:** Discovery of pulsations in X-rays from the point-source pulsar candidate PSR J1640-4631
- **2014:** Discovery of HESS J1641-463 by Fermi: new spectrum for HESS J1640



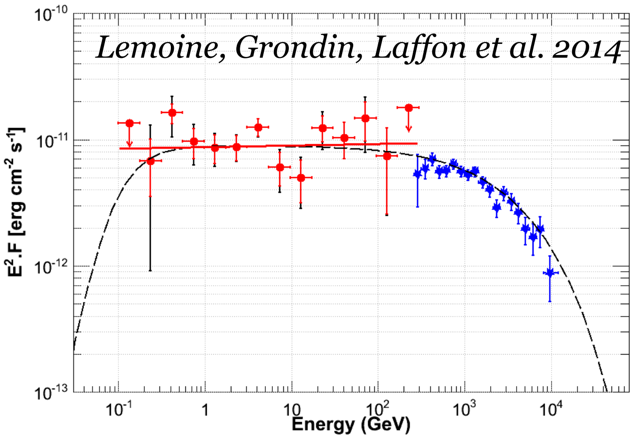
Abramowski et al. (HESS collab) 2014

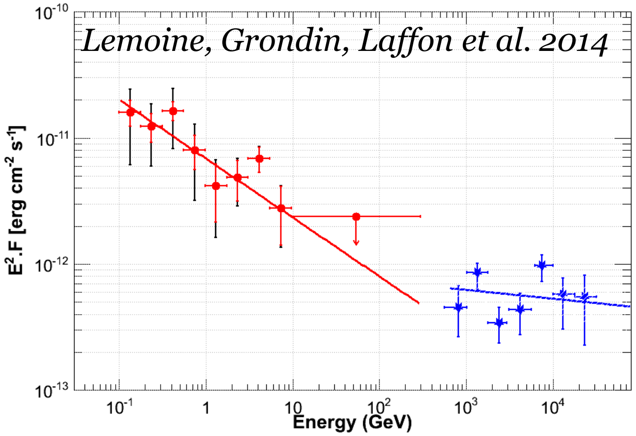


Lemoine, Grondin, Laffon et al. 2014



Gelfand et al. 2014 (NuStar)





HESS J1640-465

- Typical spectrum of SNR interacting with molecular clouds detected with Fermi
- Hadronic scenario: gamma-ray spectrum produced by π^0 decay :
  - Gas density of 150 cm^{-3}
  - Particle index of 2.0
  - Energy cutoff at 50 TeV
- 9% of supernova kinetic energy needed to reproduce the data
- But part of the Fermi flux could also be produced by either the PWN in SNR G338.3-0.0 or by PSR J1640-4631

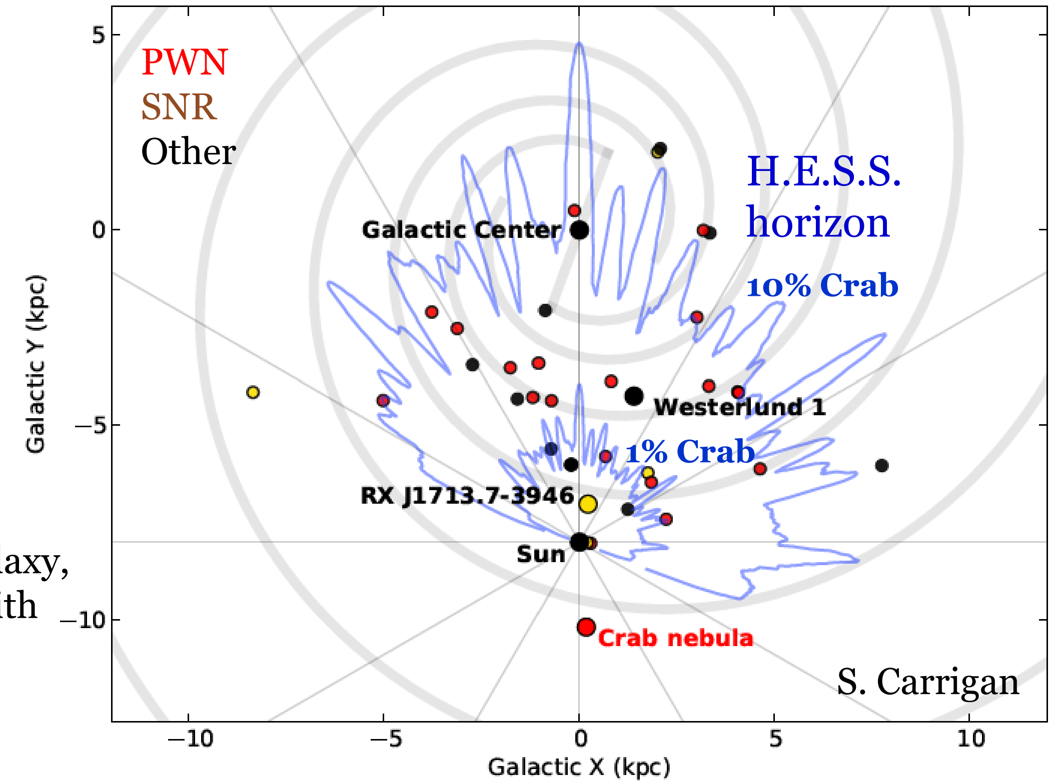
HESS J1641-463

- Unusual spectrum: 2 different mechanisms or sources for the GeV and TeV emissions?

1) Emission from a pulsar in GeV and from the associated PWN in TeV
2) Binary system
3) Hadronic origin linked to the SNRs
   - Fermi sees the shell of SNR G338.5+0.1
   - H.E.S.S. detects the runaway cosmic-rays from one of the two remnants interacting with the HII complex

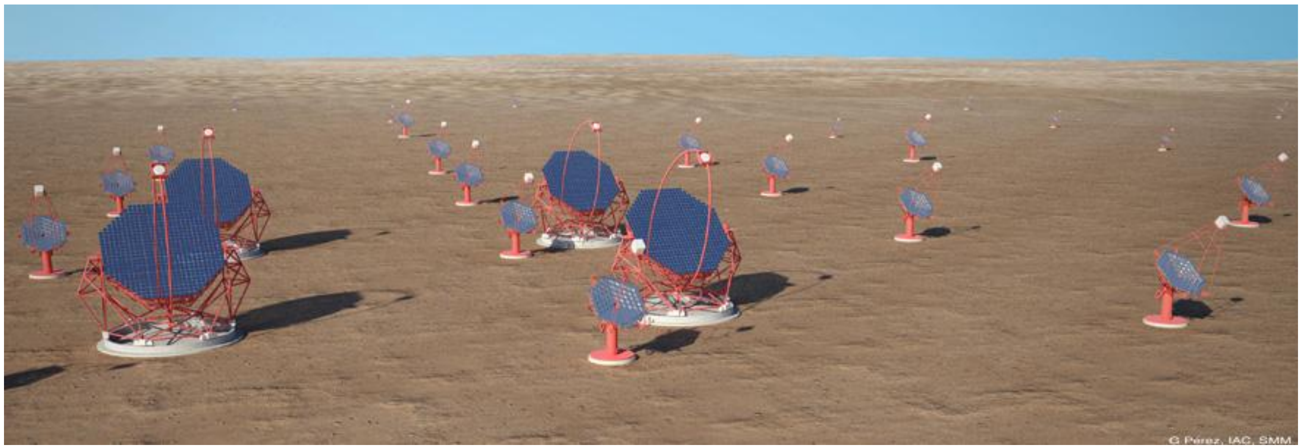
The current status of TeV astronomy

Top view of the Galaxy, H.E.S.S. sources with known distances superimposed→



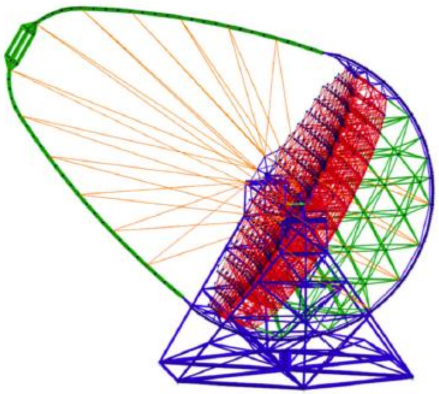
- Few sources with known distance beyond the 10% crab sensitivity line
- Small part of the Galaxy already explored
- Future instruments needed to explore deeper

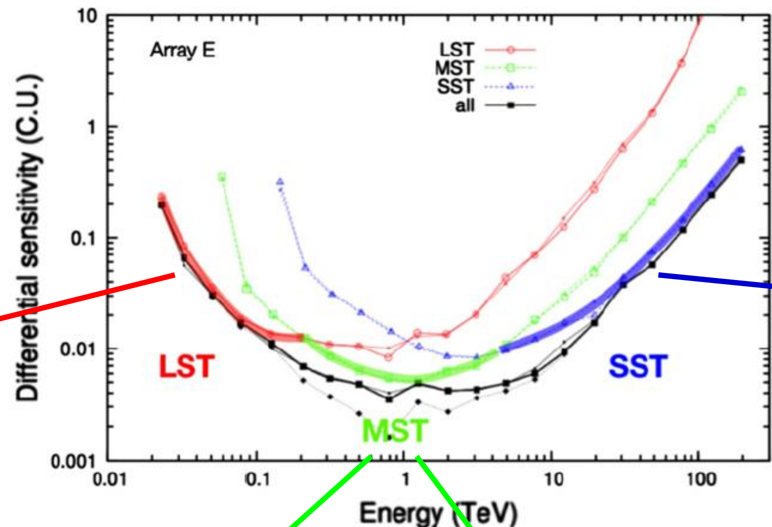
The future: CTA

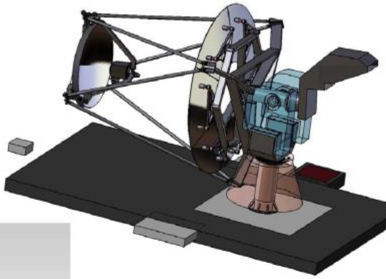


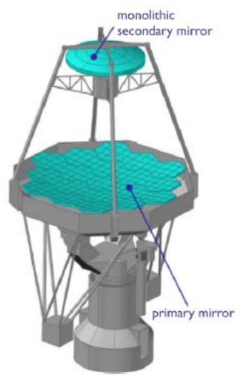
- Cherenkov Telescope Array:
  - Few large telescopes (LST)
  - Dozens of medium-sized telescopes (MST)
  - A field of small-sized telescopes (SST)
- Better sensitivity and angular resolution
- Enlarge the accessible energy range: 10 GeV -100TeV
- Number of gamma-ray sources x10

The future: CTA



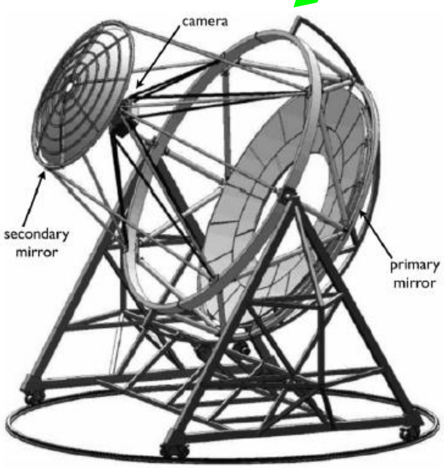


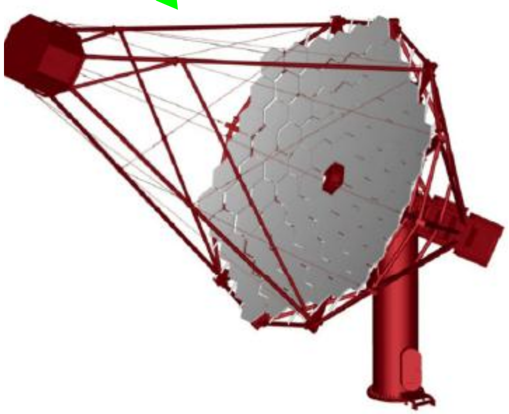




28 m, fov~4-5°

4-6 m, fov~10°

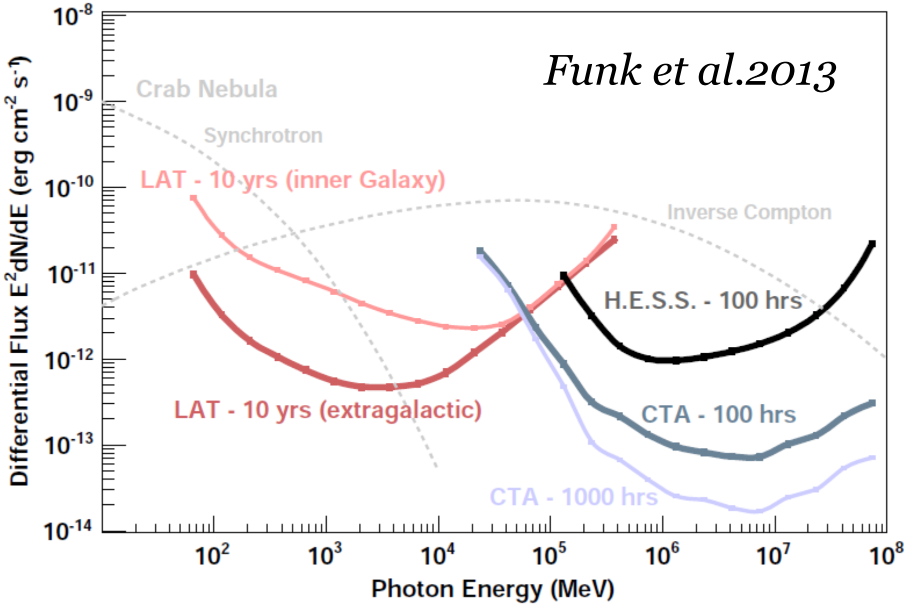


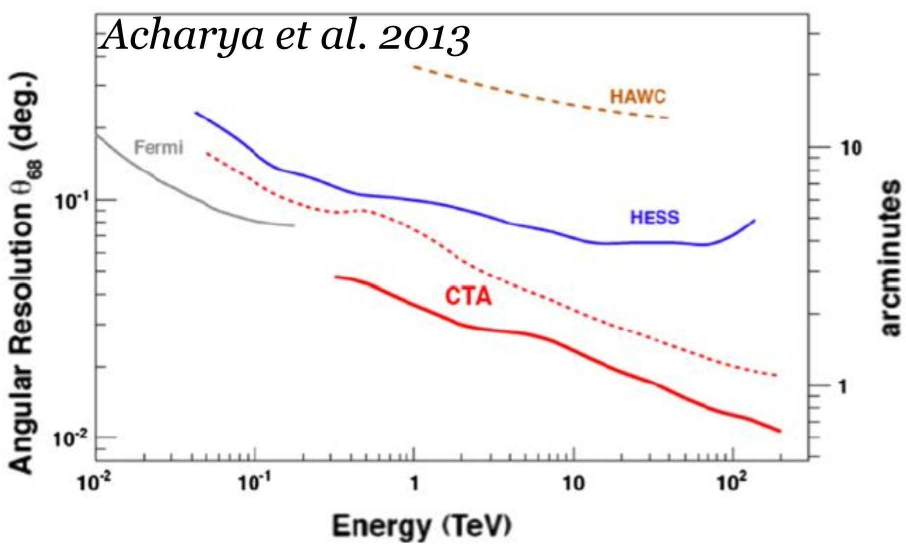


Acharya et al. 2013

10-12 m, fov~6-8°

CTA performances

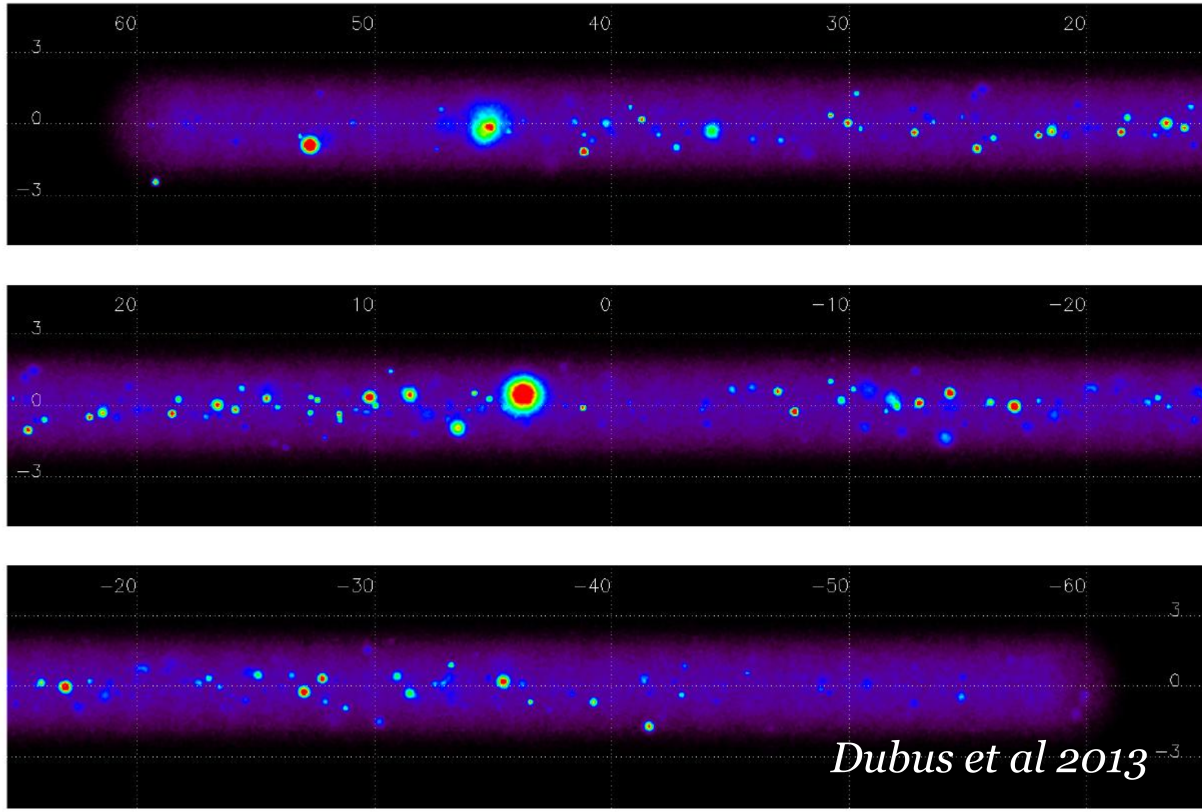




- A factor 10 in sensitivity @ 1 TeV
- A factor 2-3 in angular resolution

CTA survey

Simulation of a 240h survey along the Galactic plane with a source model dominated by pulsar wind nebulae→



- Expected number of sources x10
  - 20-70 SNRs
  - 300-600 PWNe
- Problem of source confusion
  - Ongoing investigation of Fermi-like methods to solve it

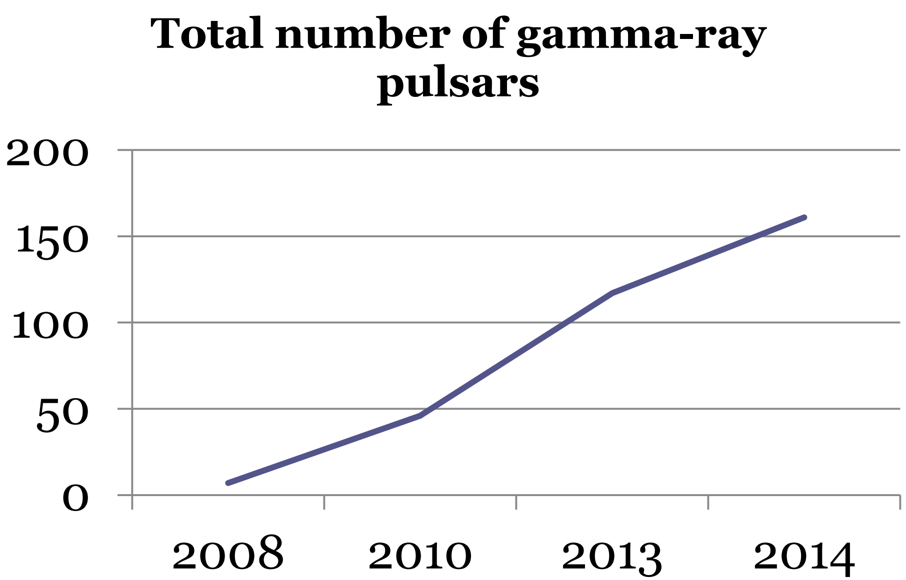
Conclusion

- **First evidence for hadronic acceleration** in SNRs but do not explain the whole CR pound
- **Non trivial processes** (lepto-hadronic scenarios, multiple accelerators…)
- **Sensitivity limit** of the current detectors does not allow to disentangle between the different scenarios
- Need more data with **better angular resolution and sensitivity**
- **Next generation instruments will (hopefully) be able to answer those questions and to explore further away our Galaxy**

Thank you for your attention!

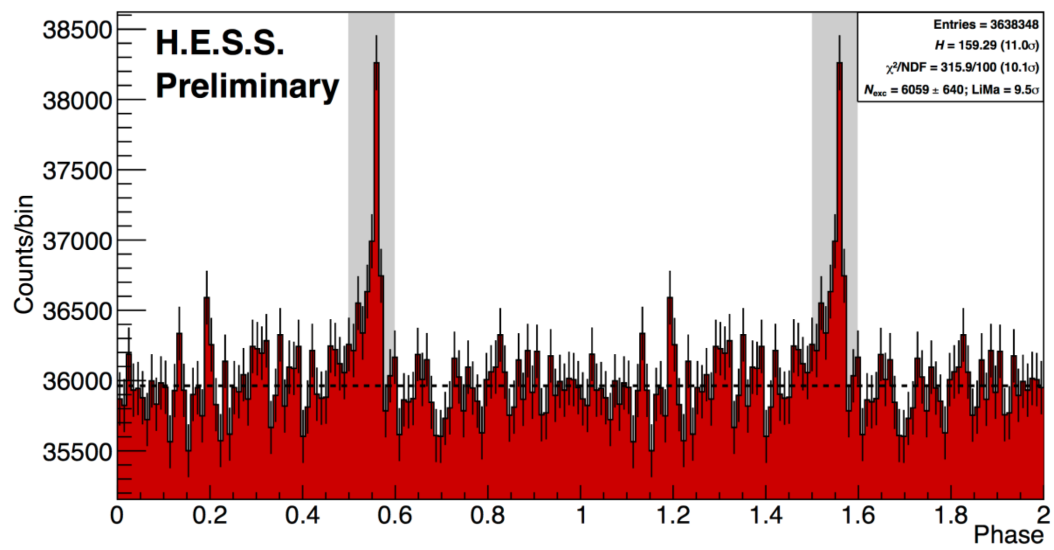
Pulsars with Fermi

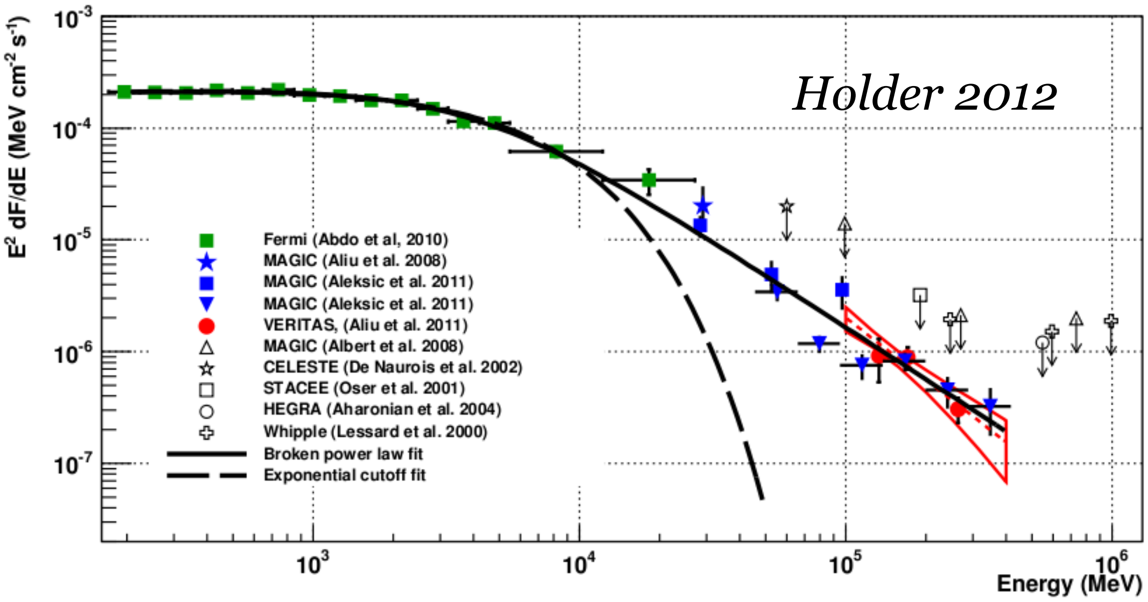
- Before Fermi only 7 pulsars seen in gamma-rays
- Now more than 160 objects : https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars
- 41 discovered in blind searches
- 120 detected thanks to radio or X-ray ephemerides



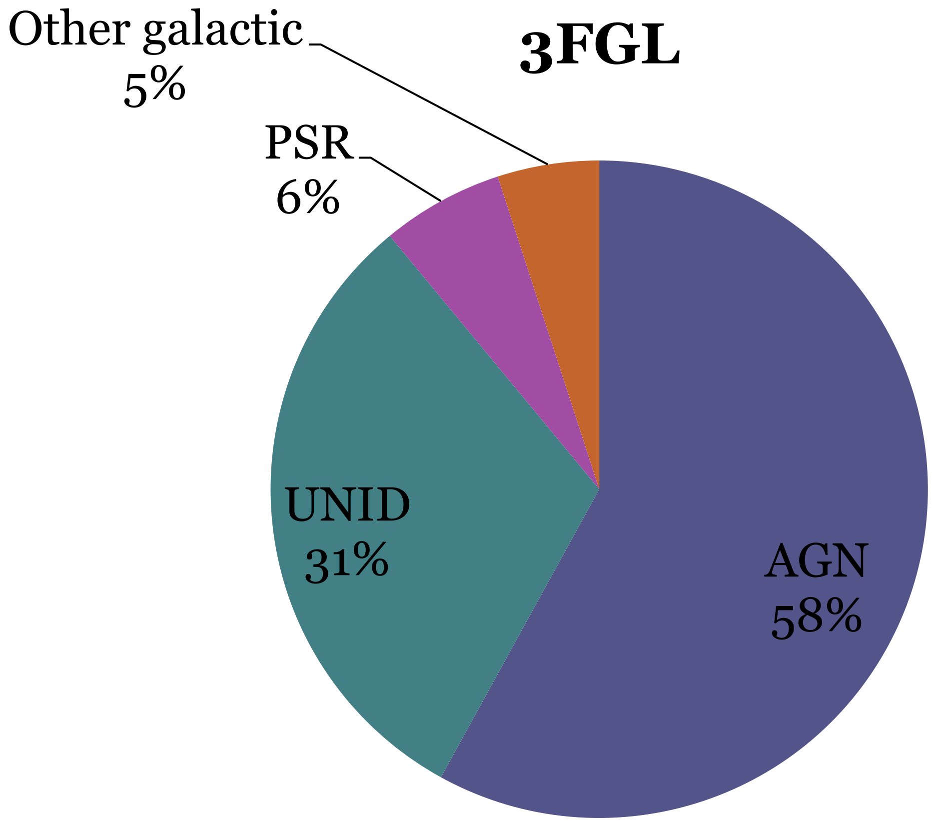
Pulsars at TeV

- Crab with MAGIC & VERITAS
- Vela with HESS 2
- Challenge the existing models



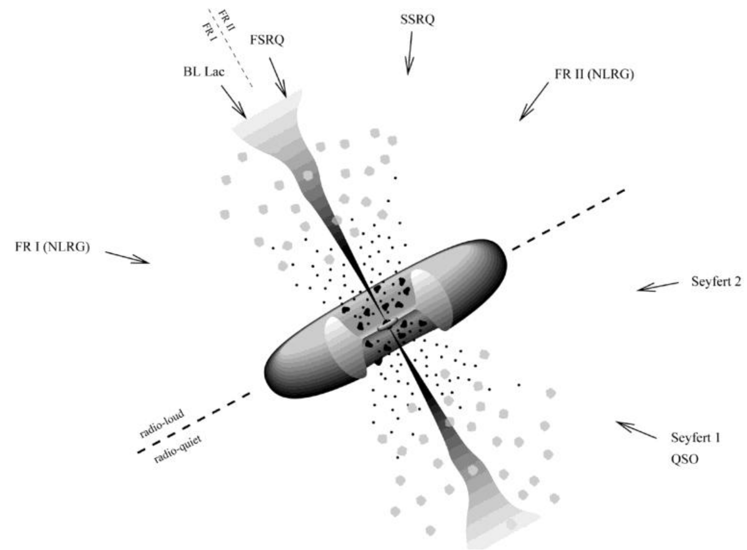


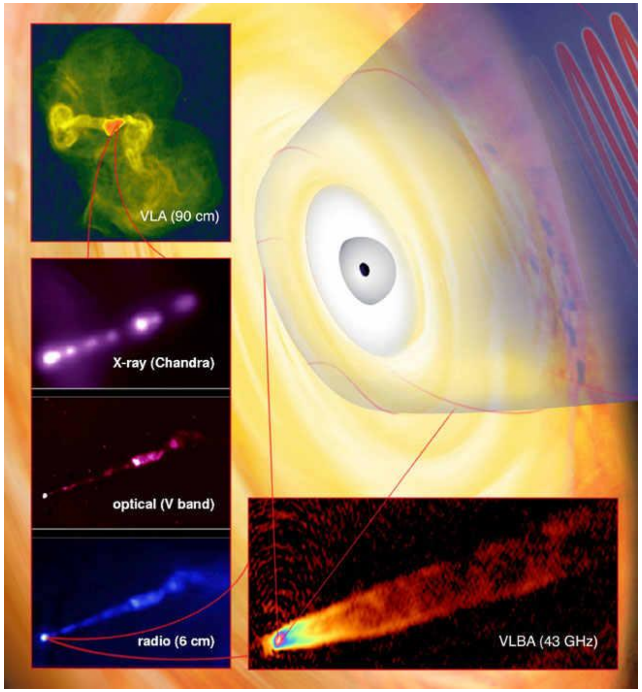
3FGL : ~3000 Fermi sources



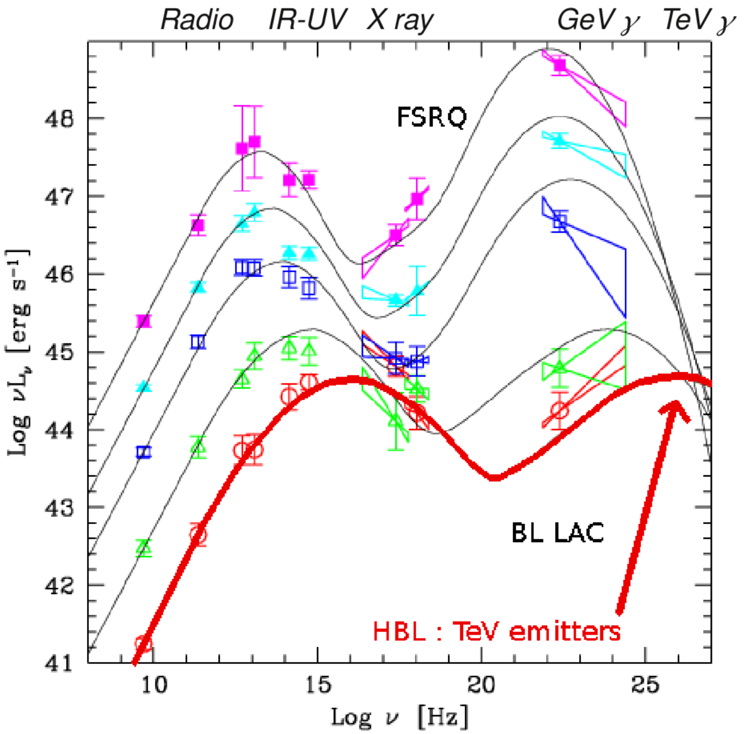
Extragalactic sources: AGN

- Active Galactic Nuclei
- Different categories depend on the observer position

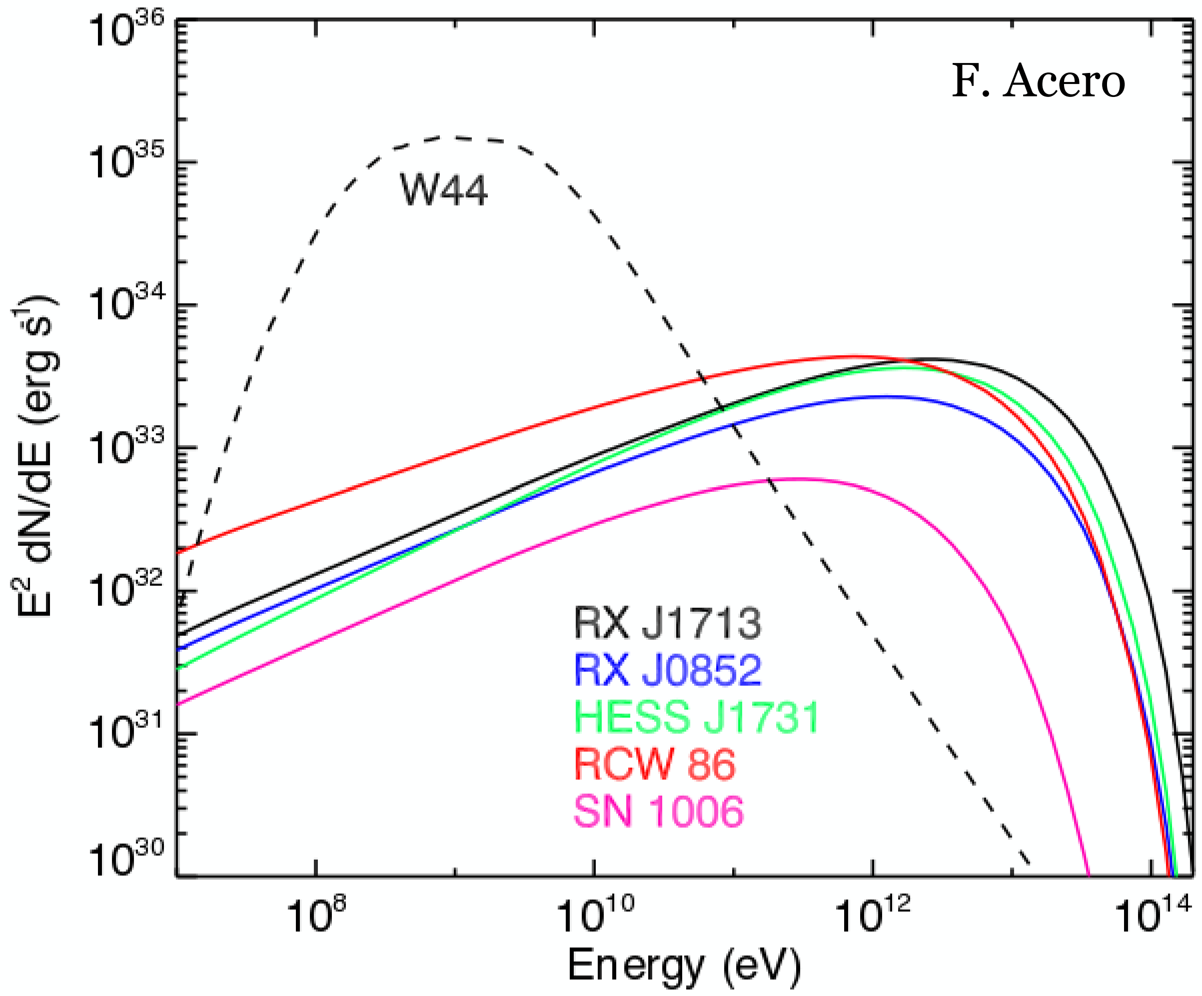




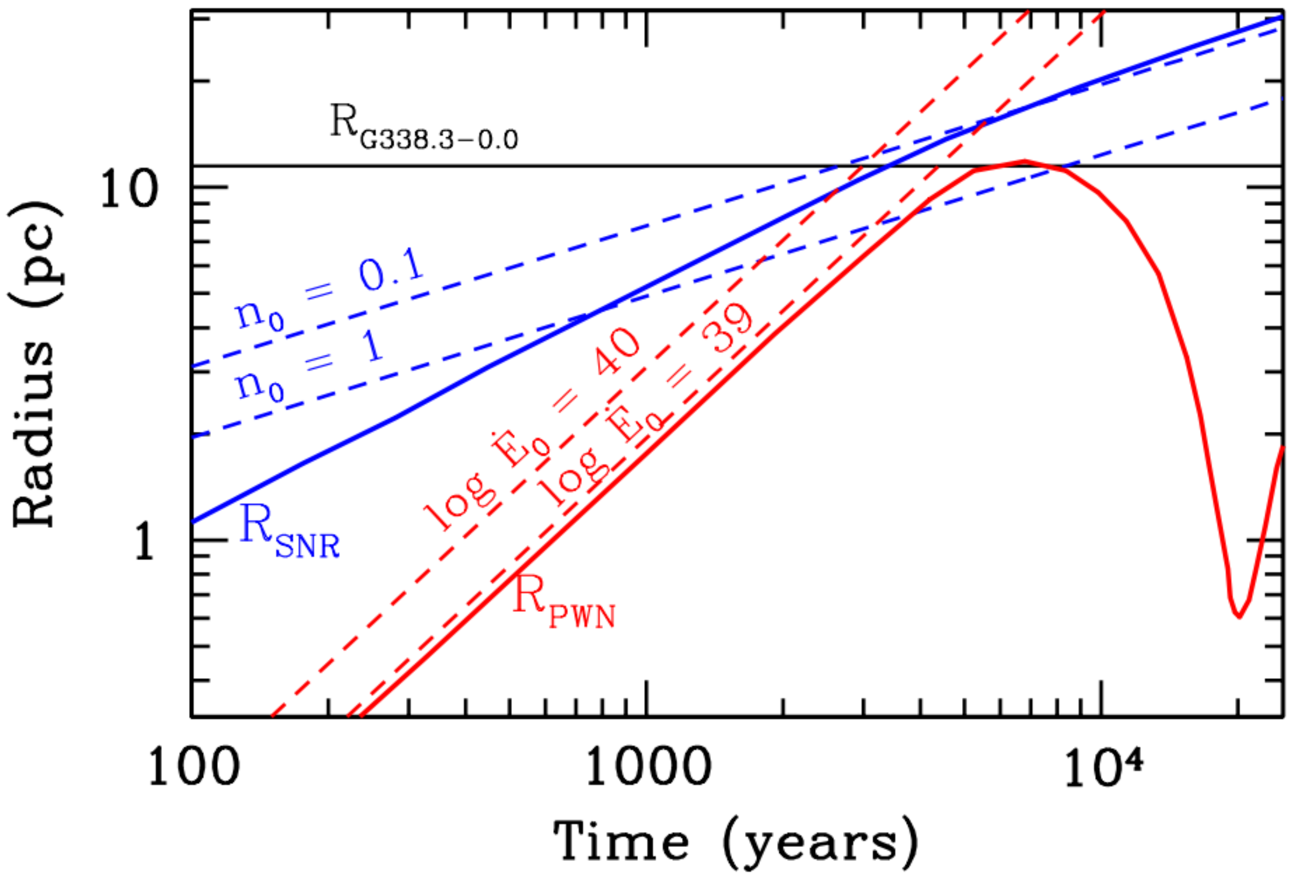
Radiogalaxy M87



SNR evolution



PWN evolution



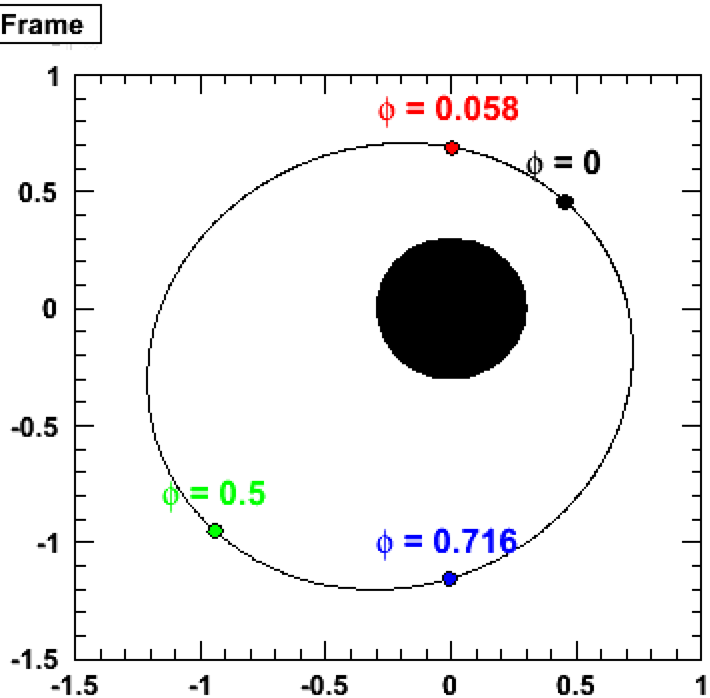
A handful of gamma-ray binary systems

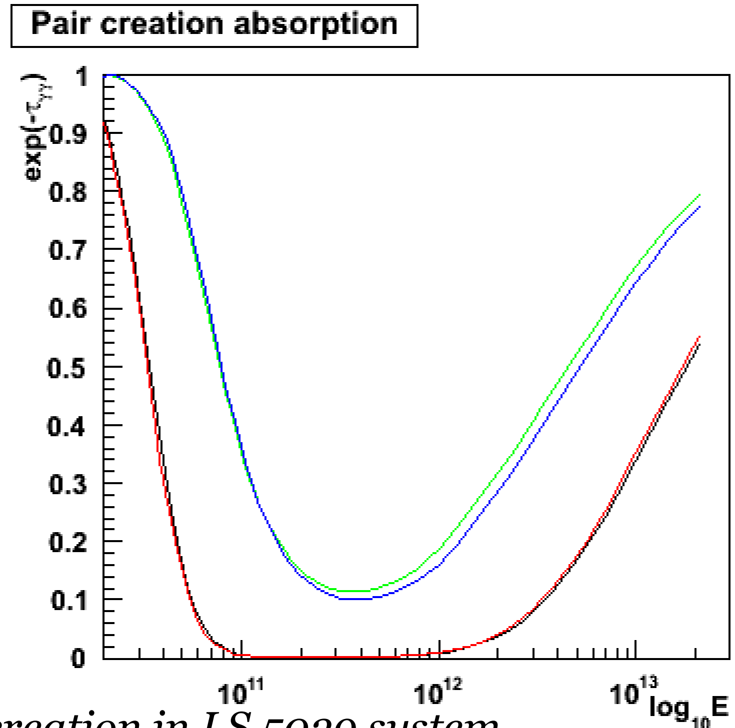
Name	PSR B1259	LS 5039	LSI+61 303	HESSJ06 32	1FGL 1018	Eta Car
Compact object	PSR	?	?	?	?	LBV
Massive star	Be	O	Be	Be	O	O or B
Orbital period	3.4 years	3.9 days	26.5 days	315 days	17 days	5.5 years
HE (<100 GeV)	yes	yes	yes	no	yes	yes
VHE (>100GeV)	yes	yes	yes	yes	yes	no

- Orbital period can vary from few days to few years
- Each object is different
- 2014: the year of binaries
  - Eta Carinae : periastron on July 26th 2014
  - PSR B1259-63 : periastron on May 5th 2014

Binary variability

- ➢Gamma-ray emission observed strongly depends on the nature of the objects, the geometry of the system and on the observer's relative position
- ➢Variable behavior expected along the orbit

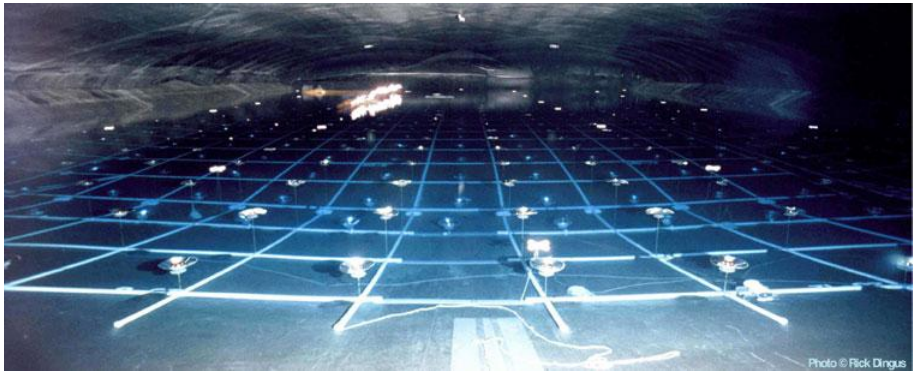




Simulation of absorption by pair creation in LS 5039 system
Credit : Christian Mariaud

Other gamma-ray detectors

- MILAGRO



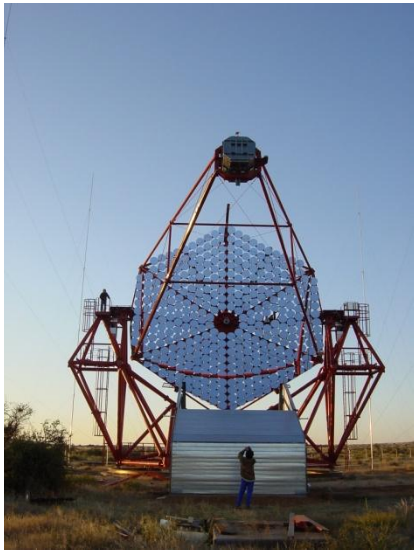
- ARGO-YBG

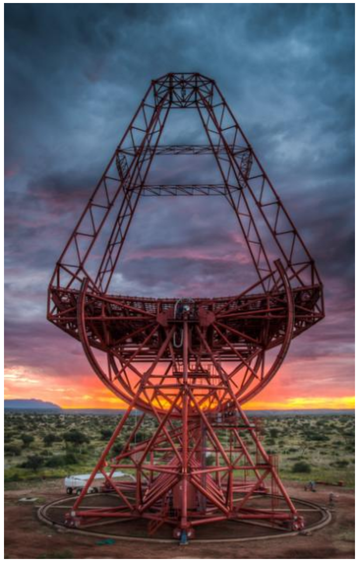
- HAWC

HESS 2

HESS vs HESS 2

	HESS I	HESS II
Dimensions	12 m	24x32 m
Mirror surface	108 m^2	614 m^2
Mirror shape	Davies-Cotton	Parabolic
Number of PMTs	960	2048
Total Weight	60 tons	580 tons





Exclusion regions

- Double-threshold system applied to significance maps
- Definition of signal regions
- Smoothing -> Exclusion