Very-High-Energy (TeV) Observations of Pulsar Wind Nebulae and Supernova Remnants

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PWNe and SNRs in a Nutshell

possible
binary systems

black holes

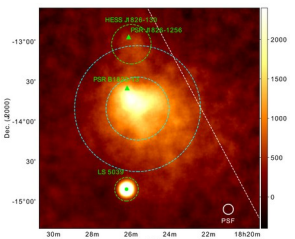
isolated neutron stars

supernova explosion
of massive star

(C) A Hitchhikers Gui
de to Space and Pla
sma Physics

core contraction

rotating neutron star
→ pulsar
surrounded by electron wind
→ pulsar wind nebula



rotation driven
$\dot{E}$ 10^{28}...10^{38} erg/s

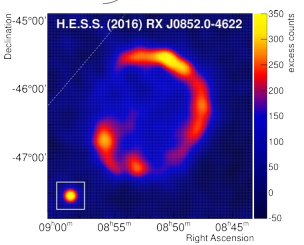
composites

expansion of outer layers

supernova type Ia

white dwarf explosion

supernova remnant

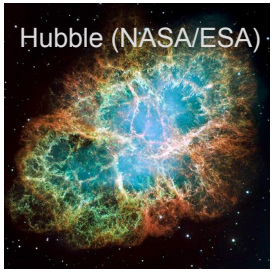


kinetic SN energy
~10^{51} erg

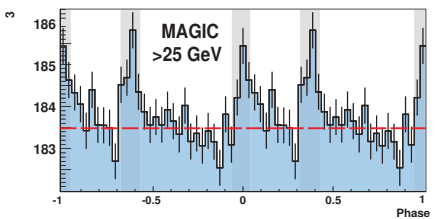
TeV Instruments

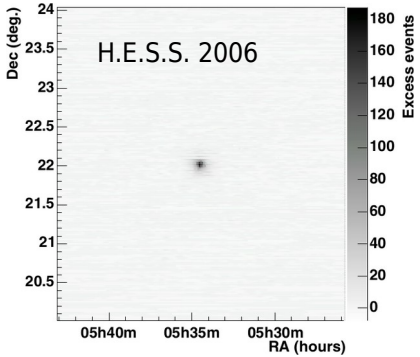
- ground based observations of atmospheric showers
- Imaging Air Cherenkov Telescopes
  - Cherenkov light in air
  - small field of view, low-duty cycle
  - detailed studies of individual sources
  - H.E.S.S., MAGIC, VERITAS
- Extensive Air Shower Arrays
  - direct detection of shower particles
  - large field of view, large duty cycle
  - population studies, large sources
  - Cherenkov light in water tanks (HAWC)
  - scintillation counters (Tibet Air Shower Array)

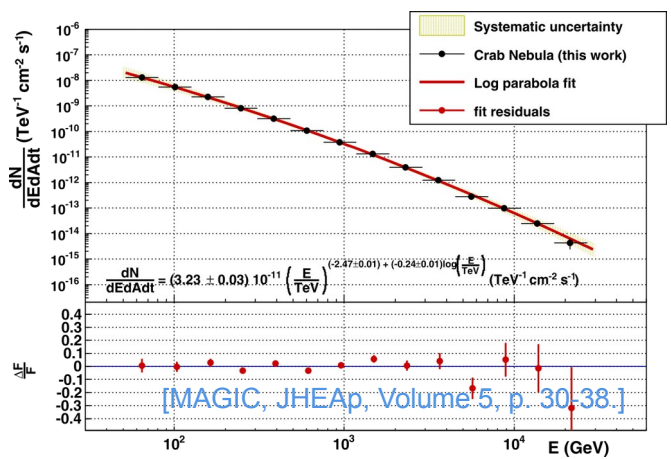
Crab Nebula: TeV Observation Timeline



- 1989, Whipple [Weekes et al. 1989 ApJ v.342, p.379]
  - 9σ detection, >0.7 TeV
- 1996, HEGRA [HEGRA Collaboration 1996 APh v. 4-3, p. 199-215]
  - 10σ detection, 1-3 TeV, power law spectrum
- 2003, Milagro [Atkins et al. ApJ v. 595, Issue 2, pp. 803-811]
  - 6.4σ, 4 TeV median energy
- 2006, H.E.S.S. [H.E.S.S. Collaboration, A&A, v. 457-3, pp.899-915]
  - ~100σ, 440 GeV – 40 TeV, spectral cut-off
- 2008, MAGIC [MAGIC Collaboration, ApJ v. 674-2, p. 1037-1055]
  - 60 GeV – 9 TeV, curved power law
- pulsed emission
  - 2008, MAGIC [MAGIC Collaboration, Science, Volume 322, Issue 5905, pp. 1221]
  - 2011, VERITAS [VERITAS Collaboration, Science 334: 69]
- > 100 TeV photons
  - 2019, Tibet [Amenomori et al. PhysRevL, v. 123, Issue 5, id.051101]
  - 2019, HAWC [HAWC Collaboration ApJ, Volume 881, Issue 2, article id. 134]
- 2020, H.E.S.S. [H.E.S.S. Collaboration, NatAs Volume 4, p. 167-173]
  - extension
- many other publications and instruments (CTA prototypes, ...)

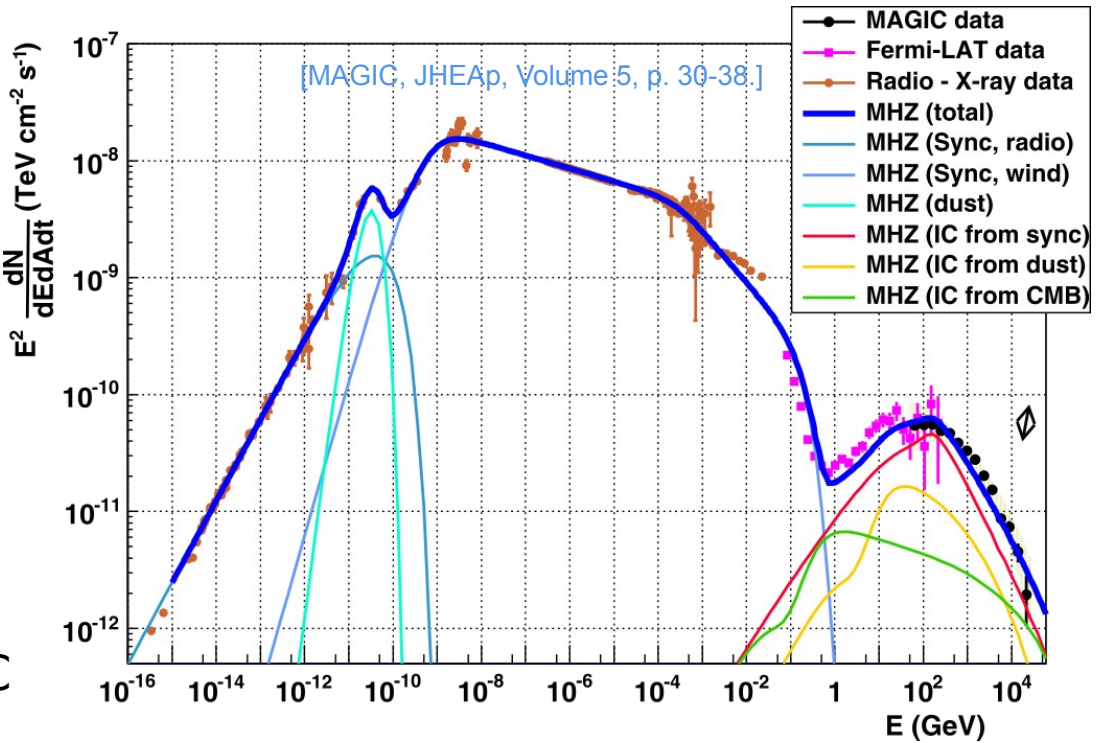






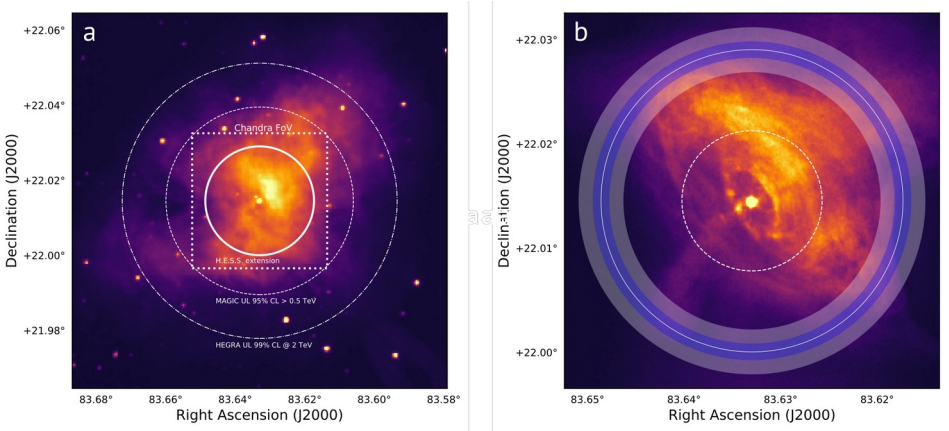
Crab Nebula

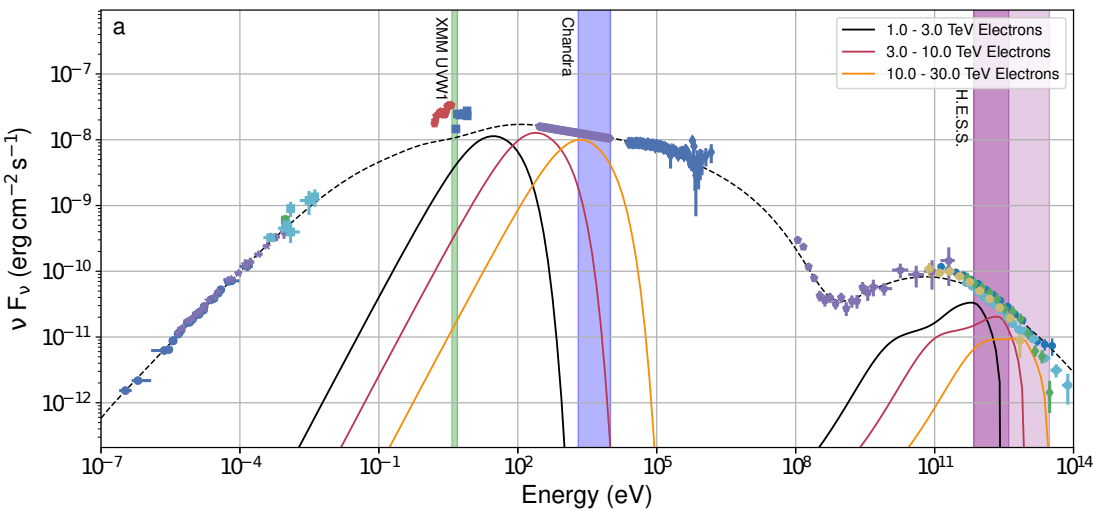
- PSR B0531+21
  - P = 33.4 ms, $\dot{P}$ =4.2×10^{-13}, $\dot{E}$ = 4.5×10^{38} erg/s, age ~1000 years
  - d = 2 kpc
- gamma-ray luminosity
  - 50 GeV – 30 TeV
  - 10^{35} erg/s (0.02% $\dot{E}$)
- Why is it so bright in TeV?
  - 2nd most luminous pulsar
  - point-like source
    - X-ray extension 50'' (0.5 pc)
  - strong synchrotron emission → SSC



Crab Nebula with H.E.S.S.

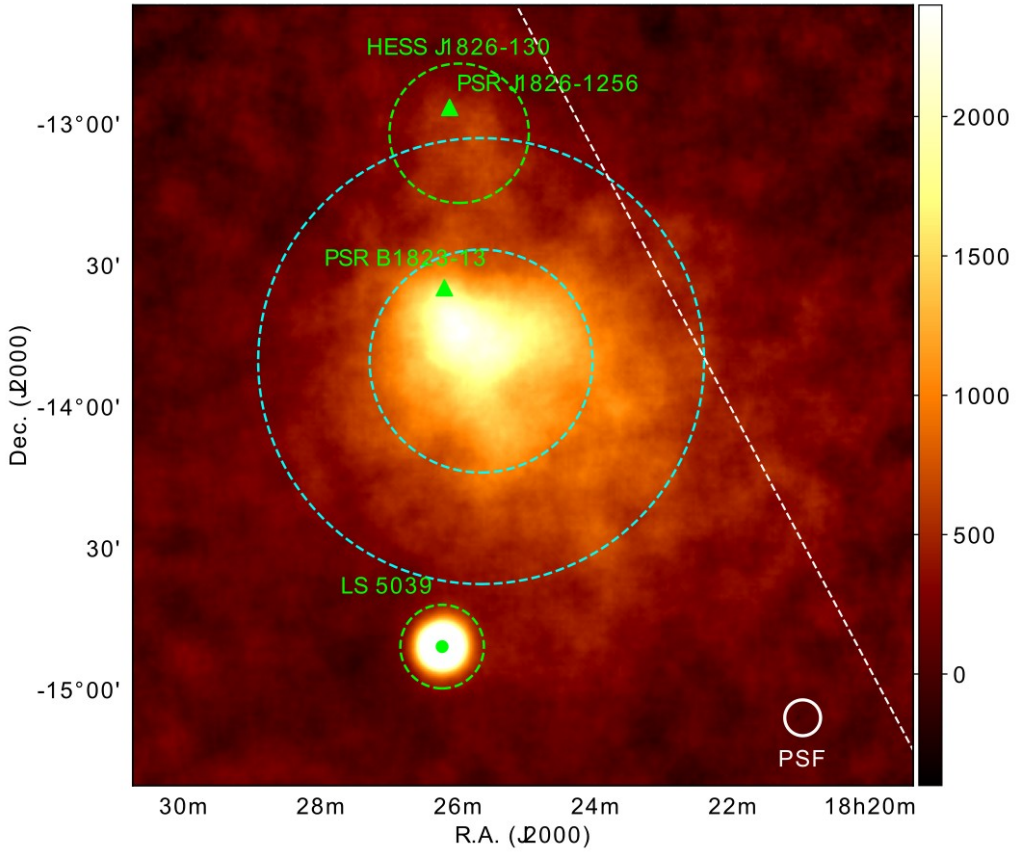
- [HESS 2020, Nat. Astron,, v, 4, p. 167-173]
- increase angular resolution
  - → simulate detector response on run-by-run basis
  - → account for detector problems, night-sky-background, ...
  - → 0.05° (68% containment)
- Crab extension 52'' (1σ of Gaussian)
  - → smaller than in UV
  - → significantly larger than in X-rays
- H.E.S.S. probes electron energies that are not well observed in synchrotron emission





HESS J1825–137

- [HESS 2019, A&A 621, A116]
- PSR B1823–13
  - → $\dot{E} = 2.8\times10^{36}$ erg/s, age 21 kyrs
  - → $d \sim 4$ kpc
- PWN at TeV
  - → ~0.8° (~56 pc)
    - larger than X-ray nebula (15')
      [Uchiyama et al., PASJ 2009, v.61, pp.S189]
    - larger than 1-100GeV nebula (0.56°)
      [Grondin et al 2011 ApJ 738 42]
  - → $L = 3.1\times10^{35}$ erg/s = 11% $\dot{E}$



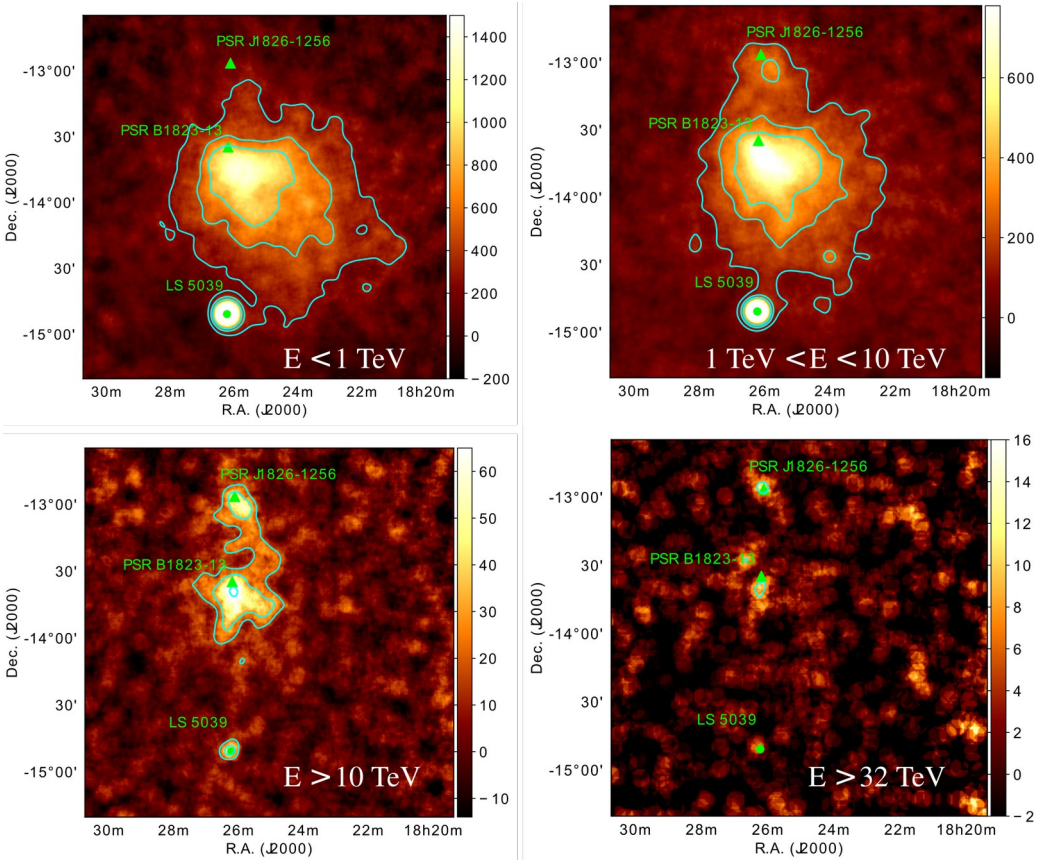
HESS J1825–137

- energy dependent morphology
  - → highest energy electrons do not travel too far away from pulsar
  - → >16 TeV photons come only from X-ray nebula

Table 3. Extent measurements as a function of energy for analyses A and B, with statistical and systematic errors.

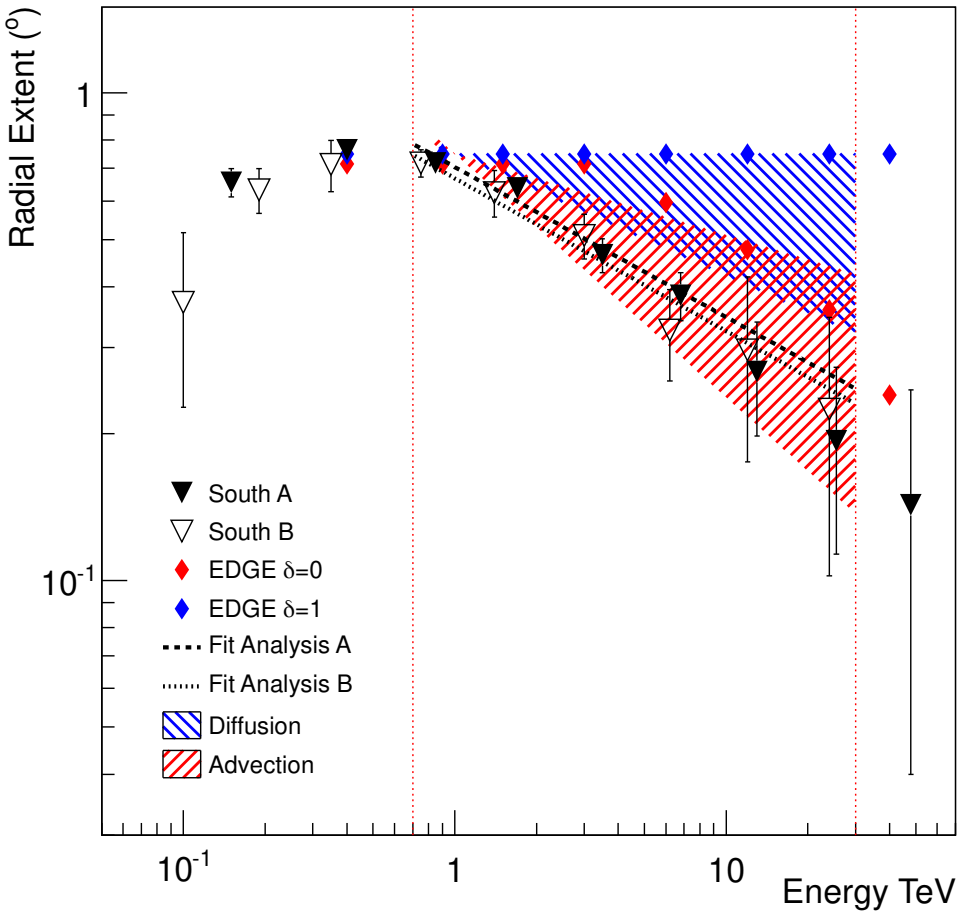
Energy range	Extent (A)	Extent (B)
<125 GeV	–	$0.37^\circ \pm 0.15^\circ \pm 0.3^\circ$
125–250 GeV	–	$0.63^\circ \pm 0.07^\circ \pm 0.07^\circ$
<250 GeV	$0.66^\circ \pm 0.04^\circ \pm 0.3^\circ$	–
250–500 GeV	$0.76^\circ \pm 0.03^\circ \pm 0.2^\circ$	$0.71^\circ \pm 0.09^\circ \pm 0.01^\circ$
500 GeV–1 TeV	$0.72^\circ \pm 0.02^\circ \pm 0.05^\circ$	$0.72^\circ \pm 0.05^\circ \pm 0.2^\circ$
1–2 TeV	$0.64^\circ \pm 0.02^\circ \pm 0.11^\circ$	$0.62^\circ \pm 0.07^\circ \pm 0.4^\circ$
2–4 TeV	$0.47^\circ \pm 0.04^\circ \pm 0.08^\circ$	$0.51^\circ \pm 0.05^\circ \pm 0.1^\circ$
4–8 TeV	$0.38^\circ \pm 0.04^\circ \pm 0.13^\circ$	$0.33^\circ \pm 0.07^\circ \pm 0.04^\circ$
8–16 TeV	$0.27^\circ \pm 0.07^\circ \pm 0.06^\circ$	$0.30^\circ \pm 0.12^\circ \pm 0.3^\circ$
>16 TeV	–	$0.22^\circ \pm 0.12^\circ \pm 0.2^\circ$
16–32 TeV	$0.19^\circ \pm 0.08^\circ \pm 0.14^\circ$	–
>32 TeV	$0.14^\circ \pm 0.1^\circ \pm 0.05^\circ$	–

X-ray nebula



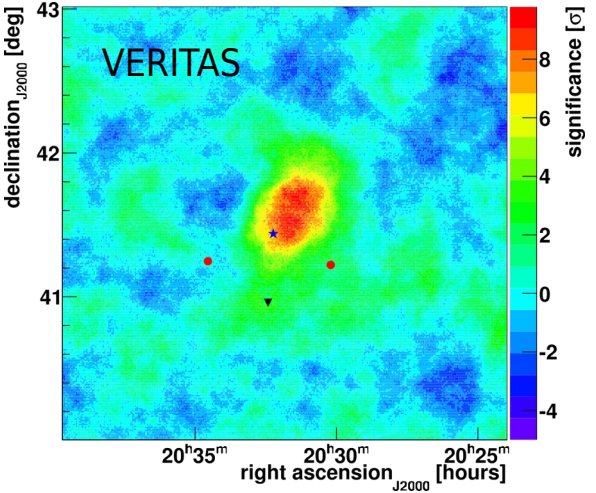
Particle Transport in HESS J1825–137

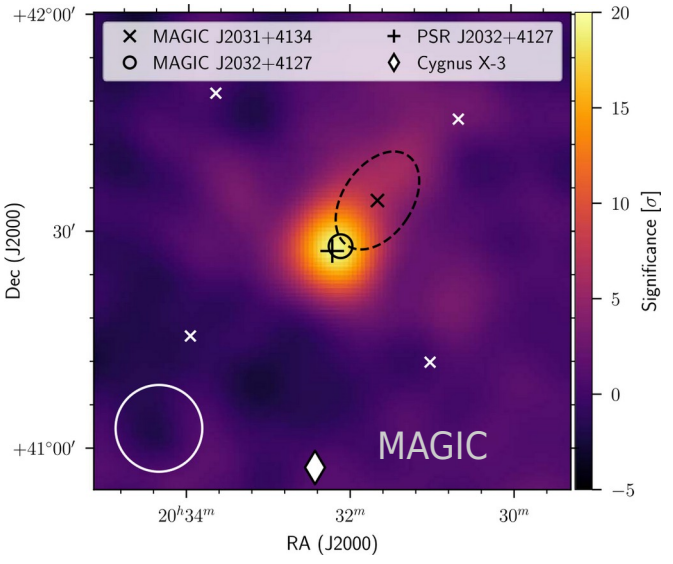
- energy dependent diffusion
  - → size would increase with energy
- diffusion and cooling
  - → maximum extend at energy where cooling time meets age
    - E_e = 4 TeV, B ≈12 μG ($B_{X\text{-rays}}$ ≈5 μG)
  - → nebula becomes smaller with energy
- advection
  - → nebula confined by ISM
  - → nebula even smaller than for diffusion
- energy-dependent morphology allows the study of the particle transport
  - → more prominent at larger distance from pulsar



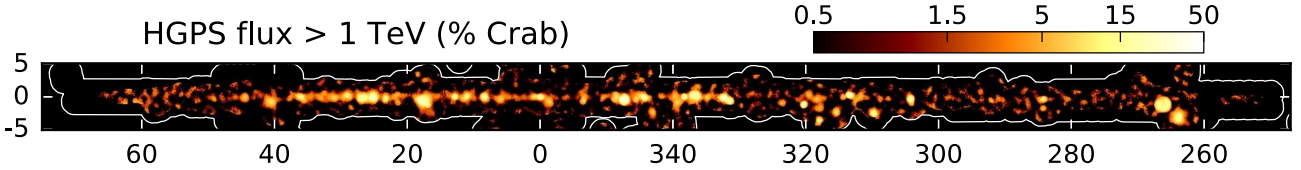
TeV J2032+4130

- first unidentified and extended TeV source
  - HEGRA [A&A, v.431, p.197-202 (2005)]
  - Whipple [A&A, v.423, p.415-419 (2004)]
  - MAGIC [ApJL, Volume 675, Issue 1, pp. L25 (2008)]
  - VERITAS [ApJ, Volume 783, Issue 1, article id. 16, 9 pp. (2014)]
- PSR J2032+4127
  - $\dot{E} = 1.5\times10^{35}$ erg/s, age 2×10^{5} years, distance 1.3 kpc
- nebula
  - TeV extension 9.5’ × 4.0’ (3.6 pc × 1.5 pc), $L \sim 0.3\%\ \dot{E}$
  - X-ray extension 12’
  - good PWN candidate
- binary system on 50-years orbit
  - detected at periastron by VERITAS and MAGIC
    - [ApJL, Volume 867, Issue 1, article id. L19, 8 pp. (2018)]
  - orbit < 200 AU
  - binary system inside a PWN (?)

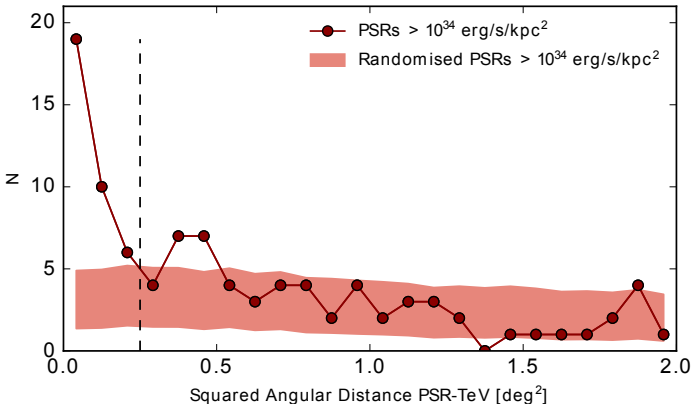


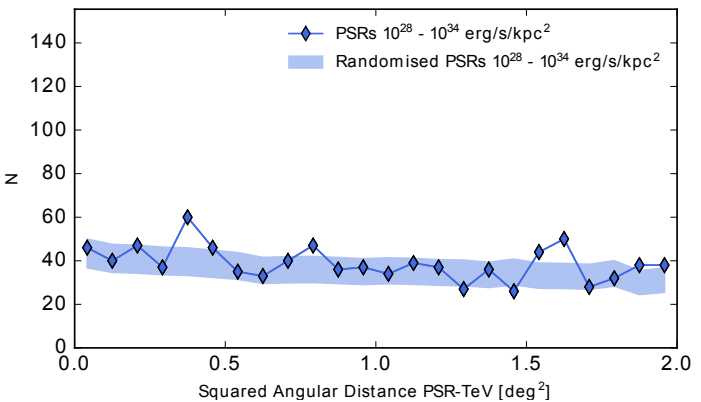


TeV PWN Population



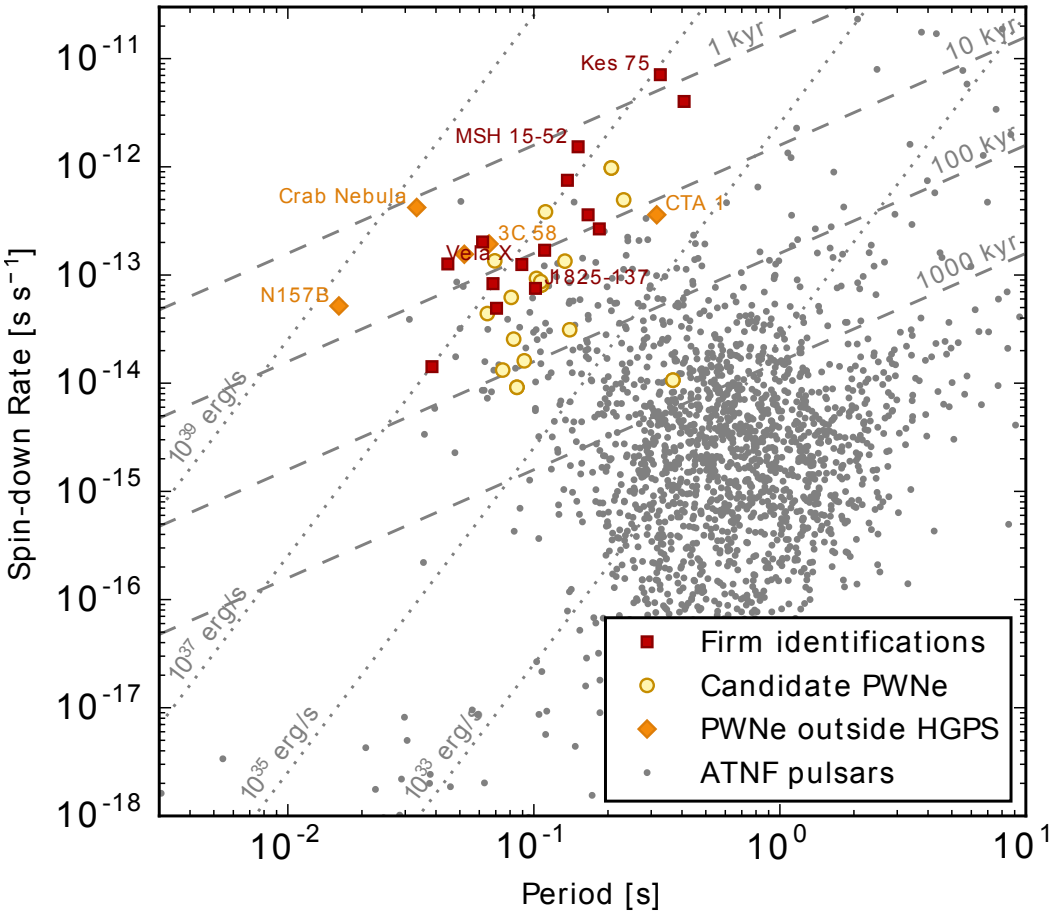
- PWN in the H.E.S.S. Galactic Plane Survey
  - → [A&A, Volume 612, id.A2, 25]
  - → correlation between pulsar and TeV emission for $\dot{E}/d^2 > 10^{34}$ erg/s/kpc^2
  - → 14 firmly identified PWN
  - → 18 PWN candidates





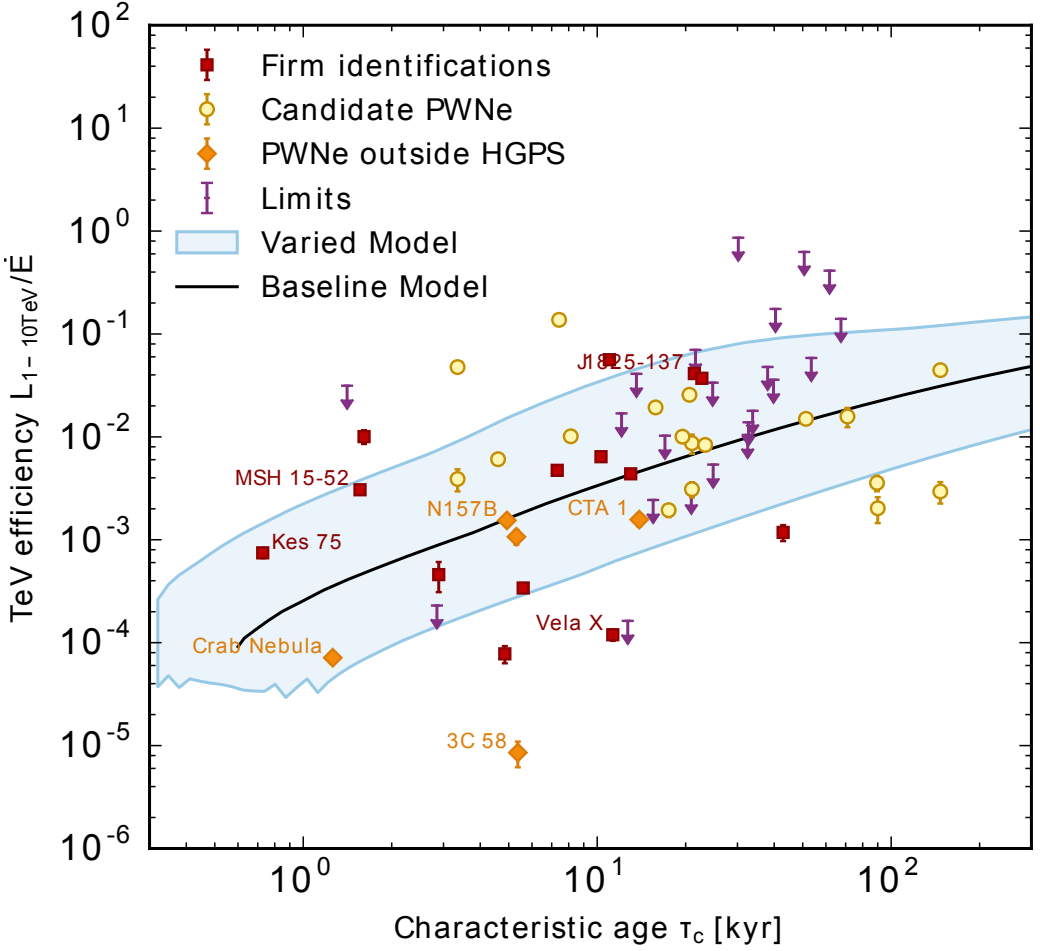
TeV PWN Population

- young, high-$\dot{E}$ pulsars
- exception
  - PSR B1742−30
    - $\dot{E} = 8.5\times10^{33}$ erg/s
    - $\tau = 5.5\times10^{5}$ years
    - $d = 200$ pc
  - 2 candidate TeV sources
    - very small: 0.2°, 0.06°
    - unlikely PWN candidates



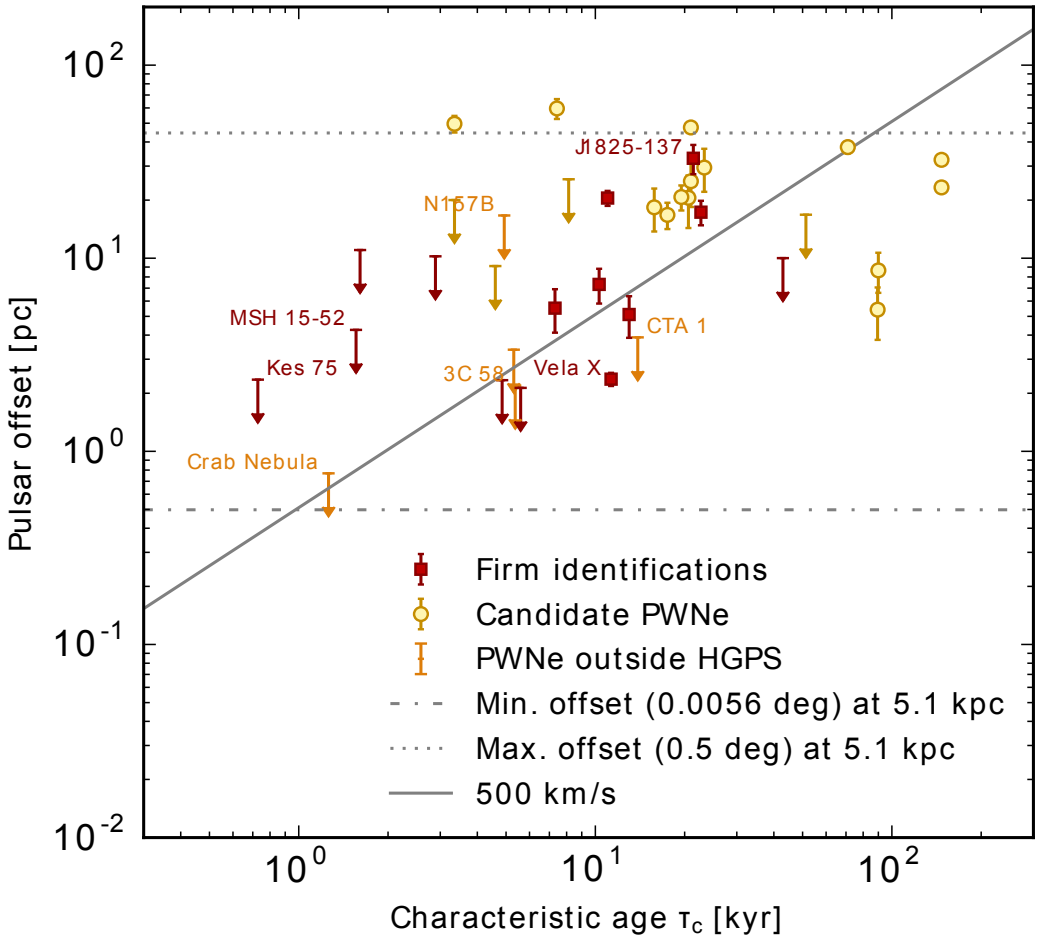
TeV PWN Population

- efficiency: $\epsilon = \frac{L_{1-10\mathrm{TeV}}}{\dot{E}}$
  - $\dot{E}$ of pulsar at present time
  - $L_{1\text{-}10\mathrm{TeV}}$ from electrons injected over life time of pulsar
- efficiency grows with age



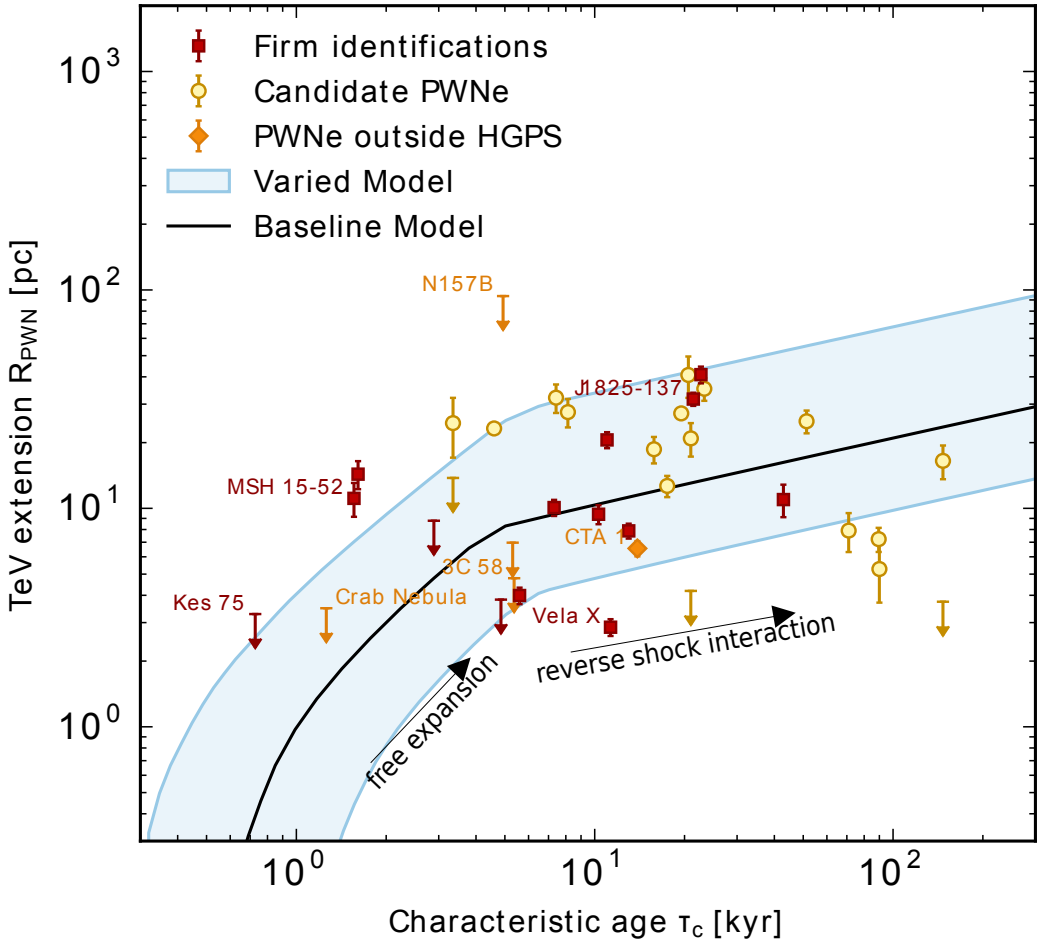
TeV PWN Population

- offset of pulsar from TeV emission centroid
- increases with age
  - → proper motion of pulsar
  - → inhomogeneous medium leads to asymmetric (“crushed”) PWN



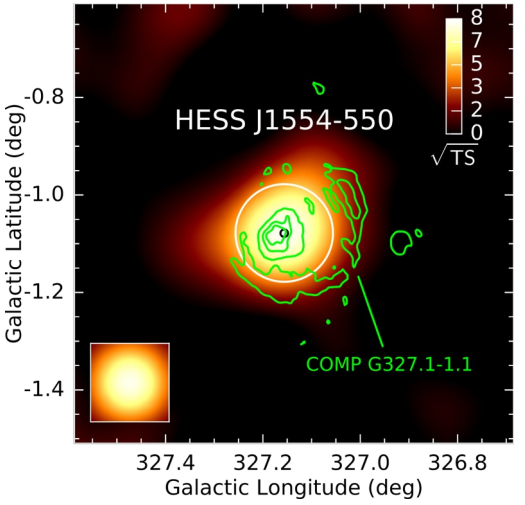
TeV PWN Population

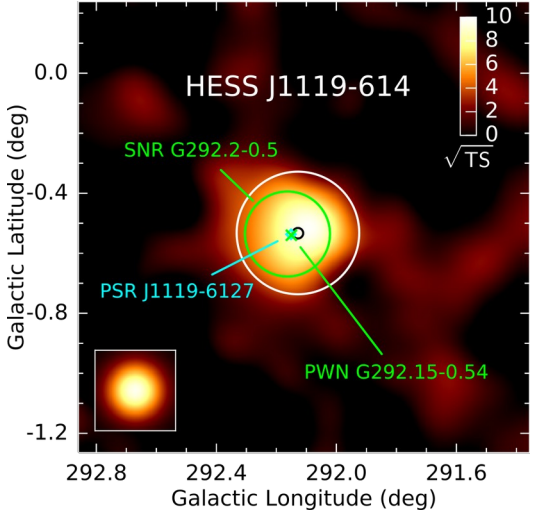
- extension of nebula increases with age



Composite Supernova Remnants

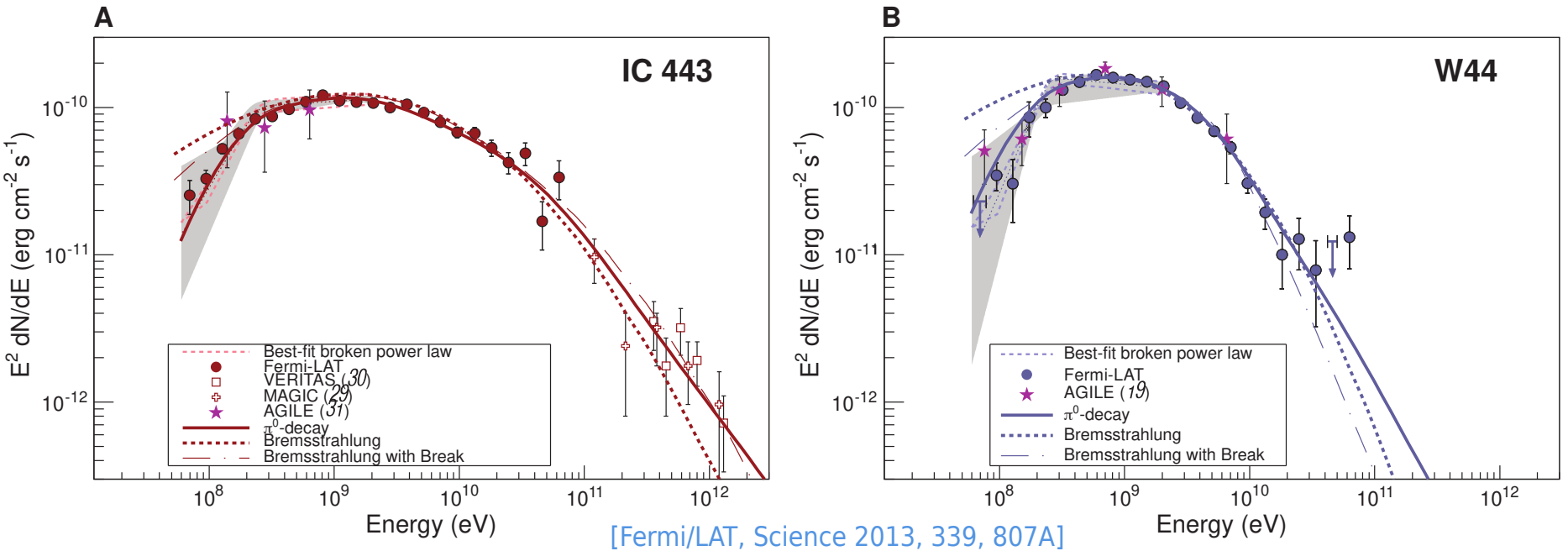
- radio/X-rays:
  PWN and SNR shell visible
- HESS J1554–550
  - → pulsar not identified
  - → TeV emission smaller then shall
    → most likely PWN emission
- HESS J1119–614
  - → PSR J1119−6127, $\dot{E} = 2.3\times10^{36}$ erg/s
  - → $d = 8.4 \pm 0.4$ kpc
  - → emission from PWN or shell?





Supernova Remnants and Cosmic Rays up to 10^{15} eV

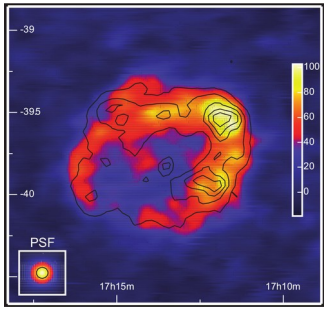
- Are SNRs the sources of Galactic CRs (protons) up to 10^{15} eV?
  - → is the emission hadronic?
  - → what is the cut-off of the spectrum?



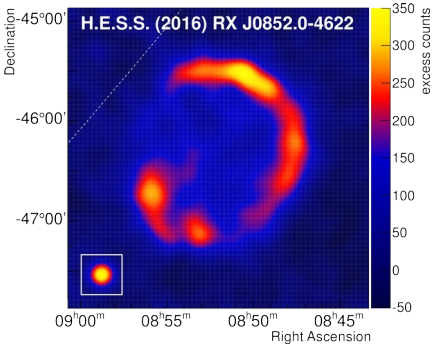
[Fermi/LAT, Science 2013, 339, 807A]

TeV SNR shells

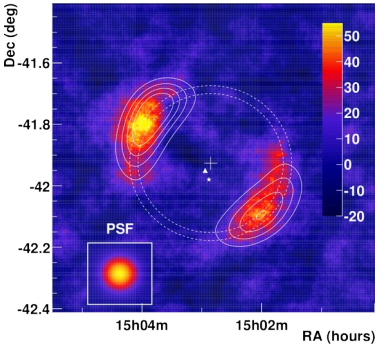
- shell-like morphology
  - → [HESS 2018, A&A, 612, 6]
  - → [HESS 2018, A&A 612, 7]
  - → [HESS 2010, A&A, 516, 62]
  - → [HESS 2018, 612, 8]
  - → [HESS 2011, A&A, 531, A81]



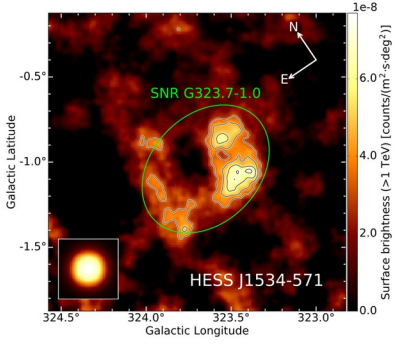
RX J1713.7–3964 (Ø 1.2°)



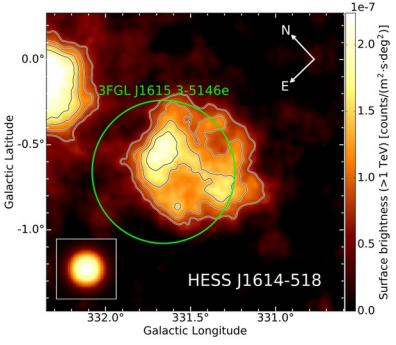
Vela Junior (Ø 2°)



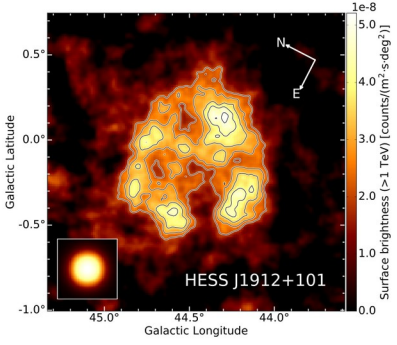
SN 1006 (Ø 0.5°)



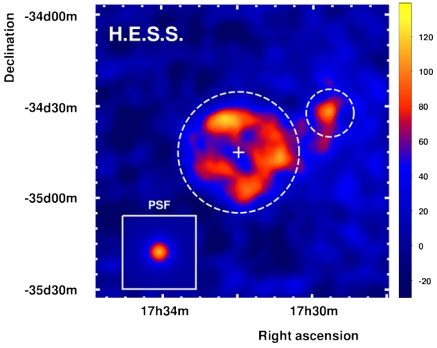
HESS J1534-571 (Ø 0.4°)



HESS J1614-518 (Ø 0.42°)



HESS J1912+101 (Ø 0.49°)



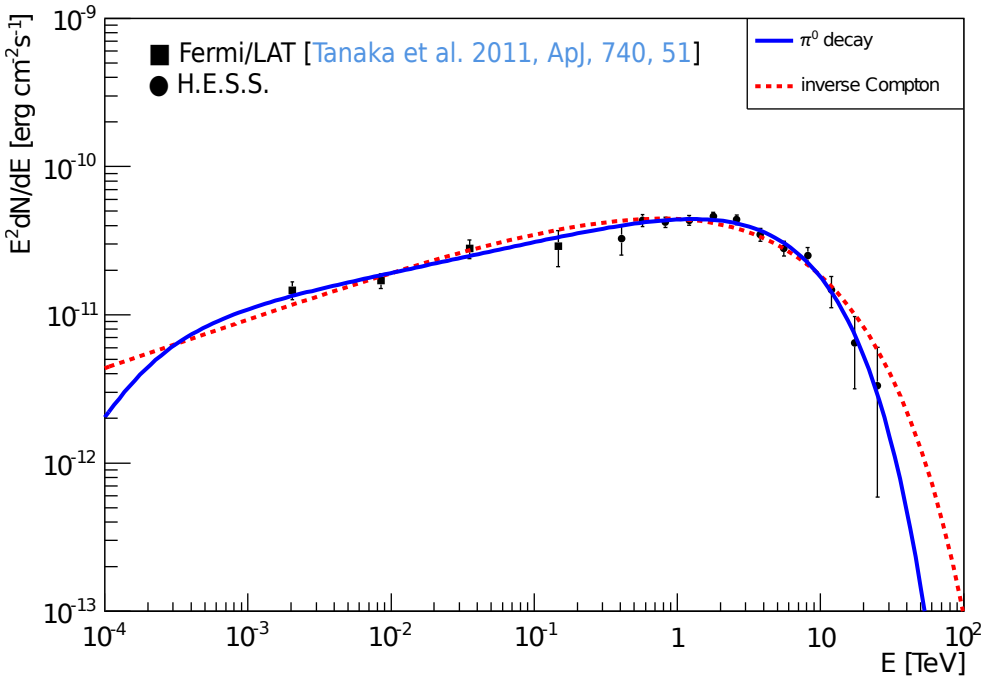
HESS J1731–347 (Ø 0.5°)

Are TeV Shells Proton Accelerators?

- example: Vela Junior
  - leptonic or hadronic scenario
  - hadronic (or mixed) scenarios need higher magnetic field (~100μG)

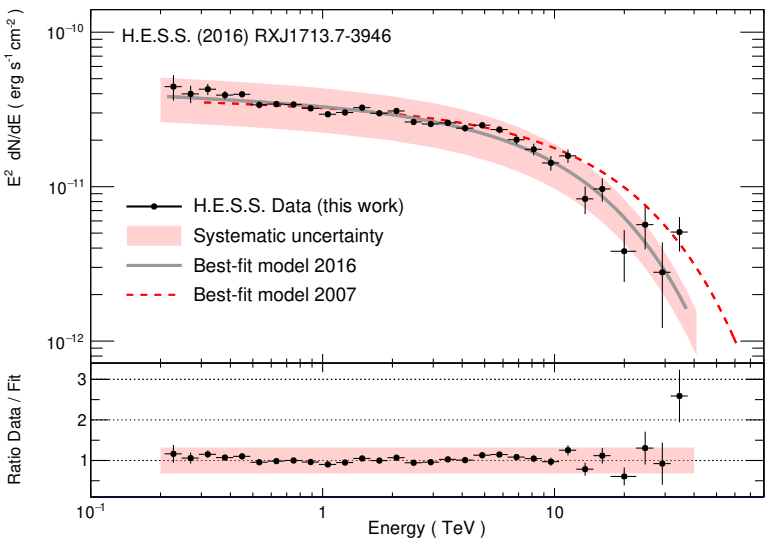
Scenario	Parameter		Value
Leptonic	$\frac{N_{0,\mathrm{e}}}{4\pi d^2}$	$[10^2\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}]$	$7.8 \pm 0.6(\pm 3.1)$
	p_{e}		$2.33 \pm 0.03(\pm 0.33)$
	$E_{\mathrm{cut,e}}$	[TeV]	$27 \pm 1(\pm 12)$
	W_{e}	$[10^{47}\ \mathrm{erg}]$	$4.1 \pm 0.3(\pm 1.7)$
Hadronic	$\frac{N_{0,\mathrm{p}}}{4\pi d^2}\,[n]^{-1}$	$[10^4\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}]$	$7.8 \pm 0.3(\pm 2.0)$
	p_{p}		$1.83 \pm 0.02(\pm 0.11)$
	$E_{\mathrm{cut,p}}$	[TeV]	$55 \pm 6(\pm 13)$
	$W_{\mathrm{p}}\,[n]^{-1}$	$[10^{49}\ \mathrm{erg}]$	$7.1 \pm 0.3(\pm 1.9)$

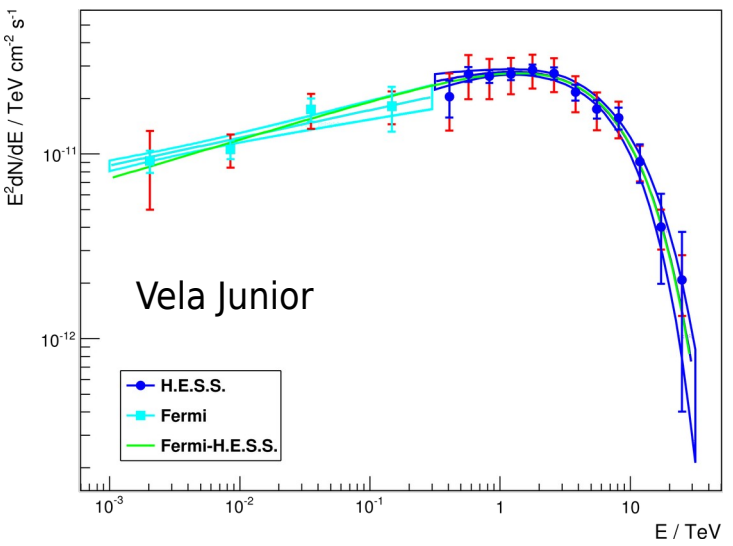
- TeV gamma-ray observations do not constrain particle type

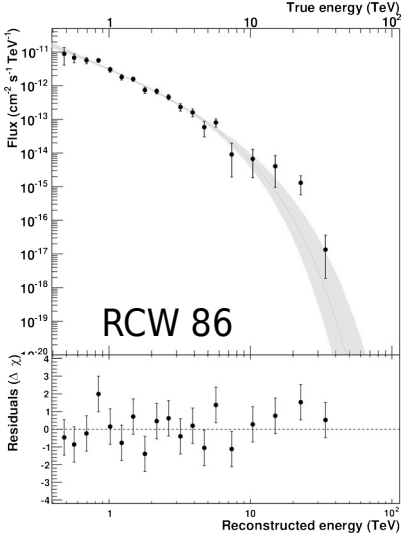


Highest Energies

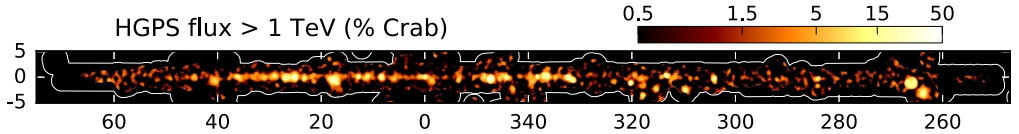
- clear detection of cut-offs (spectral indices 1.6 … 1.8)
  - → RX J1713.7–3964: 12.9 ± 1.1 TeV [HESS 2018, A&A, 612, 6]
  - → Vela Junior: 6.7 ± 1.2 TeV [HESS 2018, A&A 612, 7]
  - → RCW 86: 3.5 ± 1.2 TeV [HESS A&A 612 (2018) A4]
- only up to E_p ~ 100 TeV, Where are the PeVatrons?



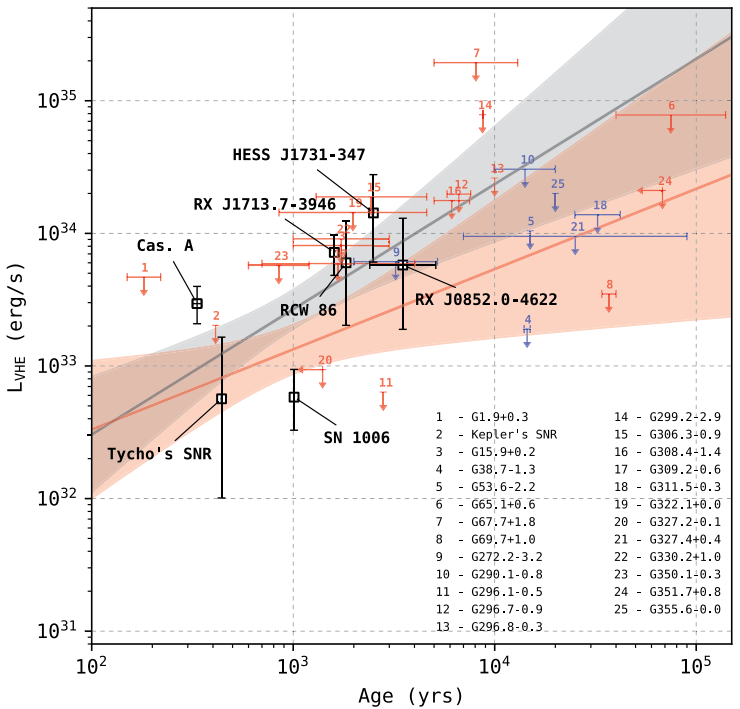


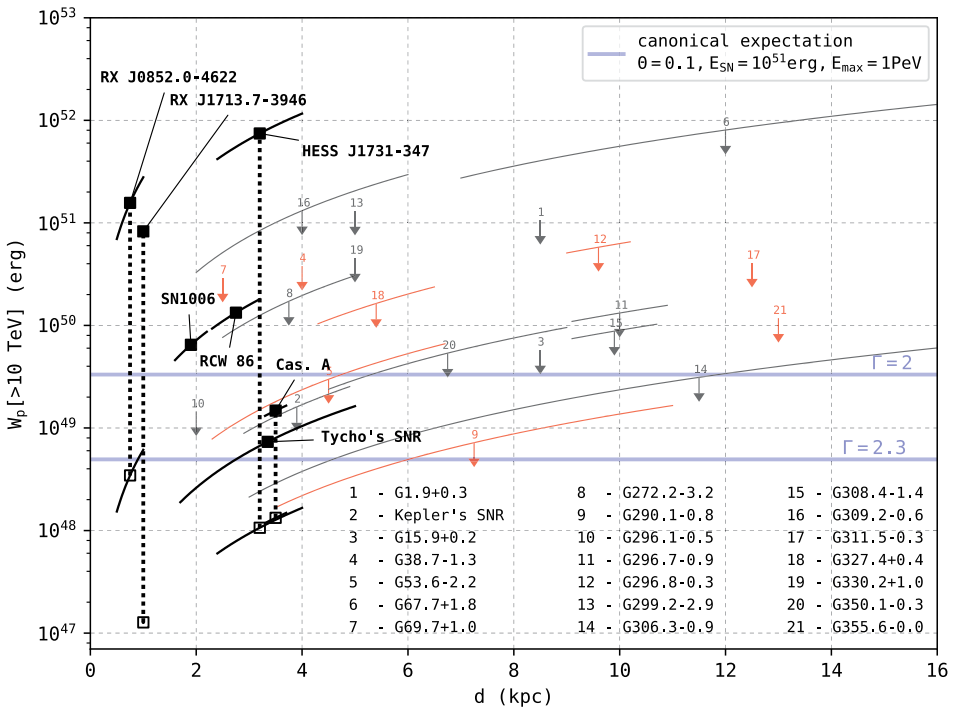


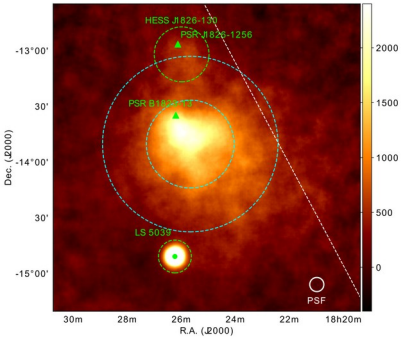
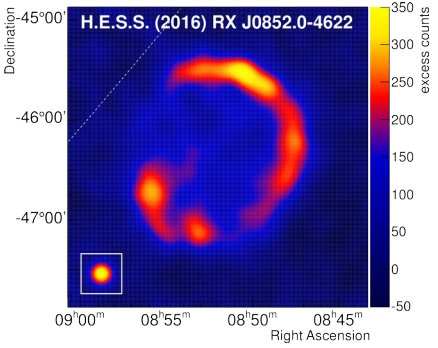
TeV SNR Population



- search for TeV emission in the HGPS survey from known SNRs
  - → [HESS 2018, A&A 612, 3]





Summary

- Pulsar Wind Nebulae
  - → largest galactic TeV source population
  - → driven by rotational energy loss of pulsar
  - → electron/positron acceleration
  - → increasing size (tens of parsecs) with increasing age (up to 100 kyr)
- Supernova Remnants
  - → rather small population
  - → driven by kinetic energy of SN explosion (10^{51} erg)
  - → electron/positron and proton acceleration
  - → resolved shells
  - → gamma-ray cut-off around 10 TeV (corresponding to 100 TeV protons)
- laboratories to study particle acceleration and propagation
- Future: Cherenkov Telescope Array
  - → higher sensitivity probes larger distances and higher energies