Searching for TeV pulsar halos: revisiting the H.E.S.S. Galactic Plane Survey (work in progress)

H.E.S.S. phase II. Credits: W. Hoffman

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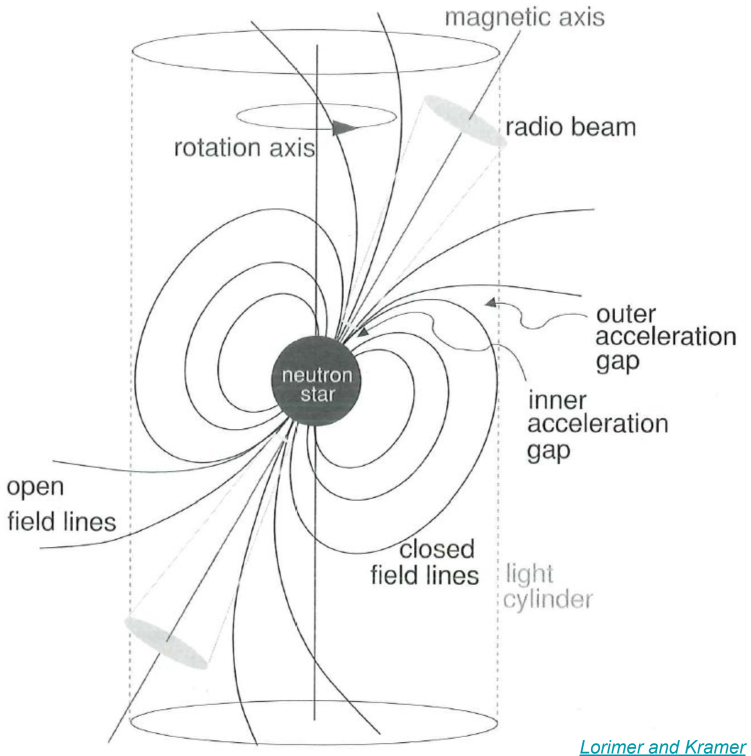
A (very) quick word on pulsars



Lorimer and Kramer 2005, p. 55

→ Type II Supernova: core collapse of a massive ~8-20 $M_{\odot}$ star, leaving behind a rapidly rotating neutron star.

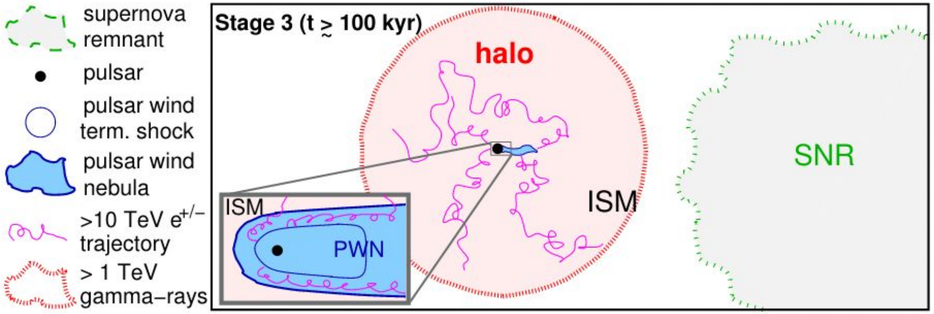
→ E_dot (erg.s^{-1}): Spin-down luminosity (total power output/loss of rotational energy).

→ Rotating magnetic field ⇒ Intense induced electric field which accelerates e^-/e^+ to relativistic energies, moving along open field lines and emitting beamed electromagnetic radiation.

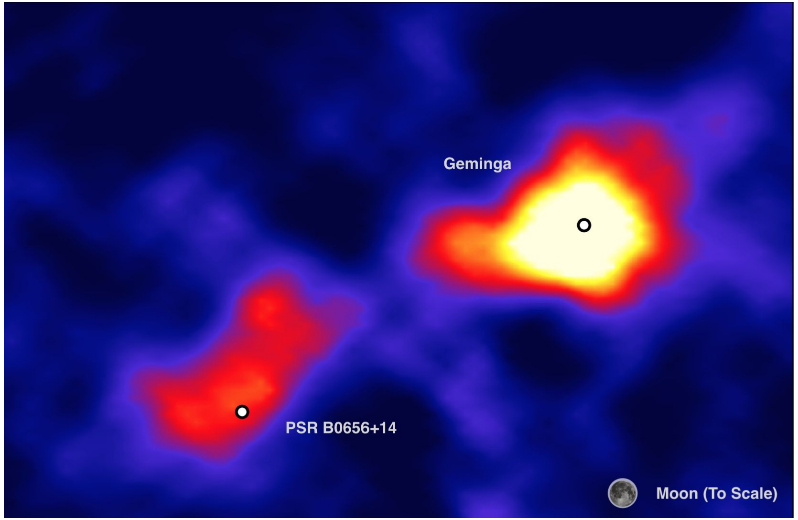
→ e^-/e^+ pair production through γ + B-field and γ-γ (pair production cascade).

→ e^-/e^+ wind outside of the magnetosphere ⇒ synchrotron radiation and inverse Compton scattering

Extended TeV emission around middle-aged pulsars



Giancinti et al. 2019



HAWC sky map of TeV emission from Geminga and its neighbor PSR B0656+14. Image: HAWC Collaboration

→ Relativistic e^+/e^- escape from the pulsar wind nebula (PWN) into the Interstellar Medium (ISM)

→ Inverse Compton interactions with ISM radiation fields and cosmic microwave background produce Very-High Energy (VHE) γ-rays

→ Slowed particle diffusion by 2-3 orders of magnitude (Abeysekara et al. 2017) over 10-100's of parsecs at 10-100's of TeV ⇒ implications on total Galactic TeV emission

TeV pulsar halo properties in Very-High Energy observations

PSR	J0633+1746 (Geminga)	B0656+14 (Monogem)	J0622+3749	J0359+5406
E_dot (erg/s)	3.3e34	3.8e34	2.7e34	1.3e36
Age (kyr)	342	111	208	75
Distance (kpc)	0.3	0.3	1.6	3.5
VHE Extension (deg)	1.16+-0.17	1.30+-0.21	0.5+-0.09	0.22+-0.05

LHAASO-WCDA results,*Cao et al. 2023*

→ TeV halos with Imaging Atmospheric Cherenkov Telescopes (IACT):

- Identified halos are too large for IACTs' field-of-view
- Outside of the H.E.S.S. Galactic Plane Survey (HGPS), but Geminga VHE emission is detected within 1° by H.E.S.S. (*H.E.S.S. collaboration 2023*).

→ Motivation:

- Can we find more pulsar halos (or candidates)? ⇒ Old PWN or TeV halo?

→ Revisiting the HGPS PWN population

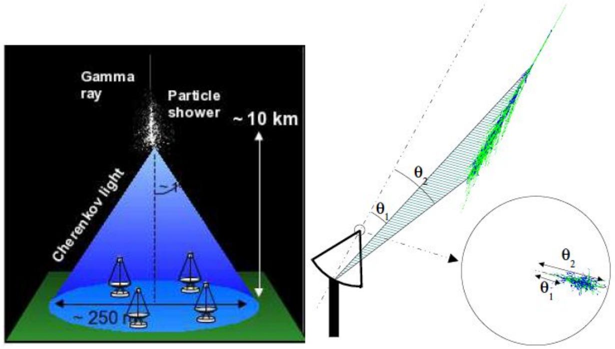
The High Energy Stereoscopic System (H.E.S.S.)

→ Array of four IACTs (12 meter mirrors) + one central 28 meter IACT installed in 2012 (HESS II phase)
→ Located in the Khomas Highland in Namibia

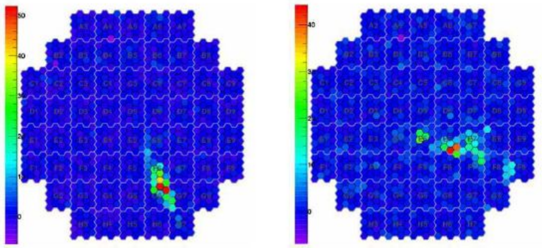
→ Detection principle: Reconstruct the direction and energy of an impinging γ-ray from Cherenkov emission of e^-/e^+ in atmospheric showers

HESS I:
- 0.2 - 100 TeV
- Field of View $\lesssim 5°$
- Ang. resolution $\lesssim 0.1°$

Atmospheric shower processes:
→ Pair production when a γ-ray interacts with Coulomb field of a nuclei
→ e^-/e^+ Bremsstrahlung
→ Pair production
→ e^-/e^+ Coulomb scattering
→ Ionization at lower energy (extinction)



Figures from *Mathieu de Naurois 2012*



Discriminate between EM and hadronic showers

The H.E.S.S. Galactic Plane Survey PWN population

The HESS Collaboration 2018b

→ Region: ℓ = 250° to 60°, $|b| \leq 3°$

→ 14 firmly identified PWNe, and 10 "highly-rated" candidates.

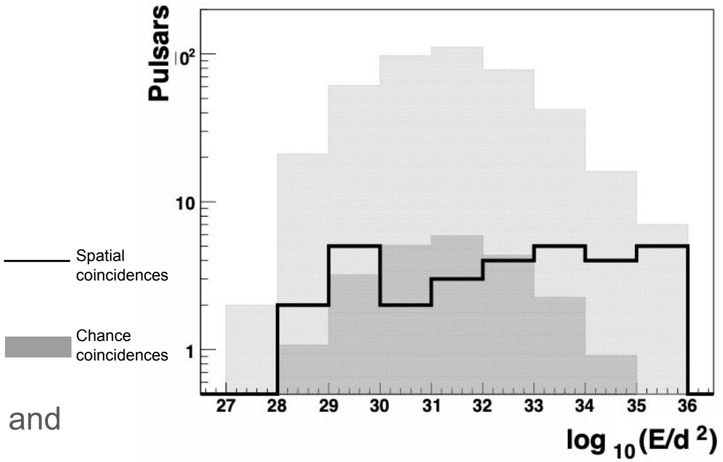
→ TeV sources observed properties: integrated photon flux, photon index
+ pulsar distance ⇒ luminosity
+ source extent (1σ extent of the symmetric 2D Gaussian sky model)

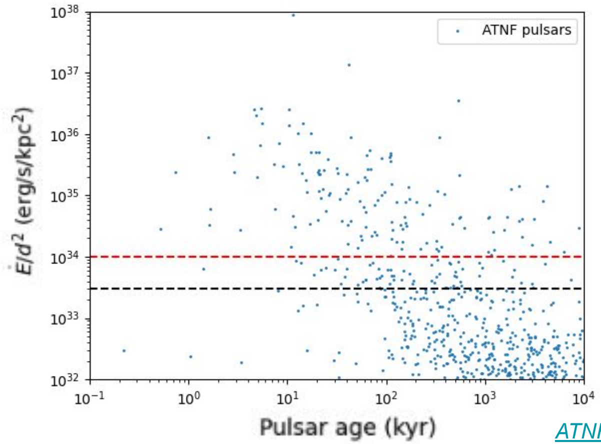
PWN leptonic evolution model:
Losses: PWN adiabatic expansion, synchrotron radiation, particle escape.
Injection: Pulsar spin-down power *E_dot(t)*
→ VHE emission via inverse Compton against the cosmic microwave background and ISM radiation fields.

Pulsar pre-selection: coincidence with HGPS components

→ *Carrigan et al. (ICRC 2008)* ⇒ rate of chance coincidences from several realisations of random pulsar samples.

→ Correlation between high spin down flux pulsars (E_dot/d^2 > 10^{34} erg.s^{-1}) and TeV sources (at ang. separation < 0.5°).

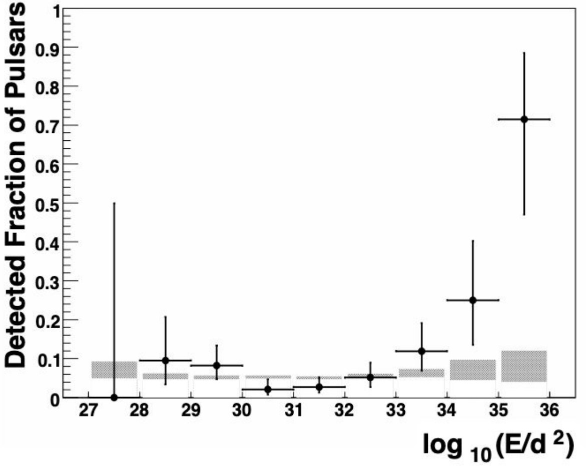




ATNF pulsar cat. v1.70

Our pre-selection Criteria:

- Ang. separation < 0.5°
- 3e33 < E_dot/d^2< 1e34
- Age < 10^4 kyr



Pulsar pre-selection: TeV halo/PWN candidates

Pulsar name	HGPS source	Offset (deg)	Extension (deg)	E_dot (erg/s)	Distance	Age	Notes
J1301-6310	J1303-631	0.18+-0.01	0.18 +-0.02	7.6e33	1.5 kpc	186 kyr	Firmly identified PWN associated with the more energetic pulsar J1301-6305
J1638-4608	J1641-463	0.49+-0.02	0.06 (u.l.)	9.4e34	4.6 kpc	86 kyr	*Eckner et al. 2023**: predicts CTA halo plain detection only
B1758-23	J1801-233	0.27	0.17 +-0.03	6.2e34	4.0 kpc	58 kyr	‖
J1841-0524	J1841-055	0.33+-0.07	0.41 +-0.03	1.0e35	4.1 kpc	30 kyr	‖
J1853-0004	J1852-000	0.35+-0.05	0.28 +-0.04	2.1e35	5.3 kpc	288 kyr	‖

*Eckner et al. 2023: Assessment of Geminga-like pulsar halo detectability in the CTA Galactic Plane Survey

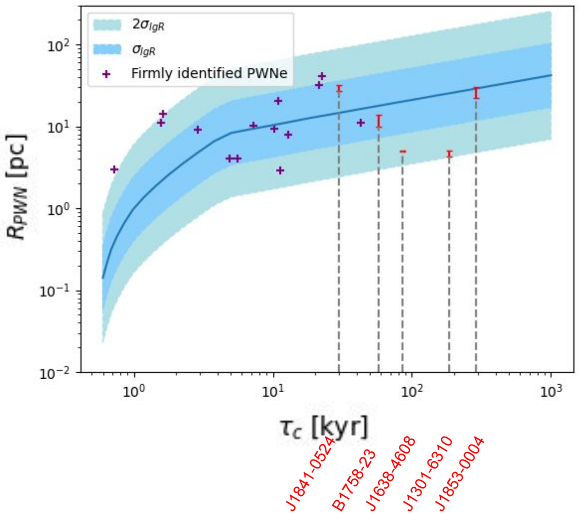
Comparison of candidates with the PWN HGPS population

Rating criteria: containment (offset < 1.5 times extension), compatibility with PWN model

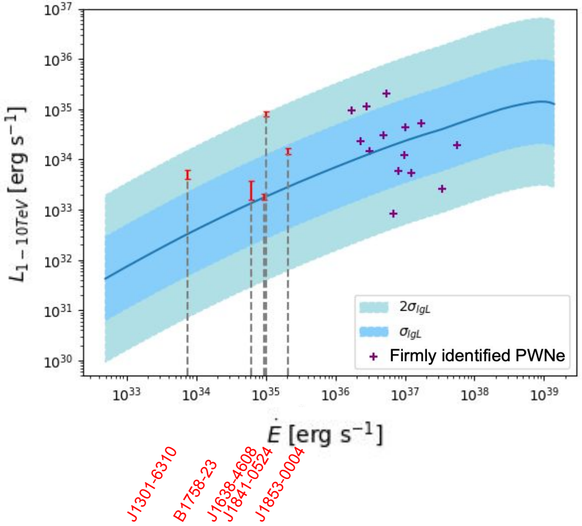
Pulsar	J1301-6310	J1638-4608	B1758-23	J1841-0524	J1853-0004
Rating	★⋆★↯	↯⋆★↯	⋆★★⋆	★★★↯	★★★★

★: fulfilled
⋆: compatible limit
↯: incompatible

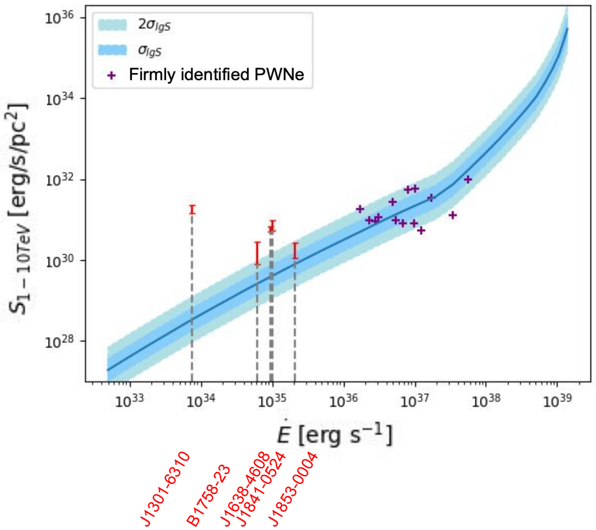
Criterion 2:



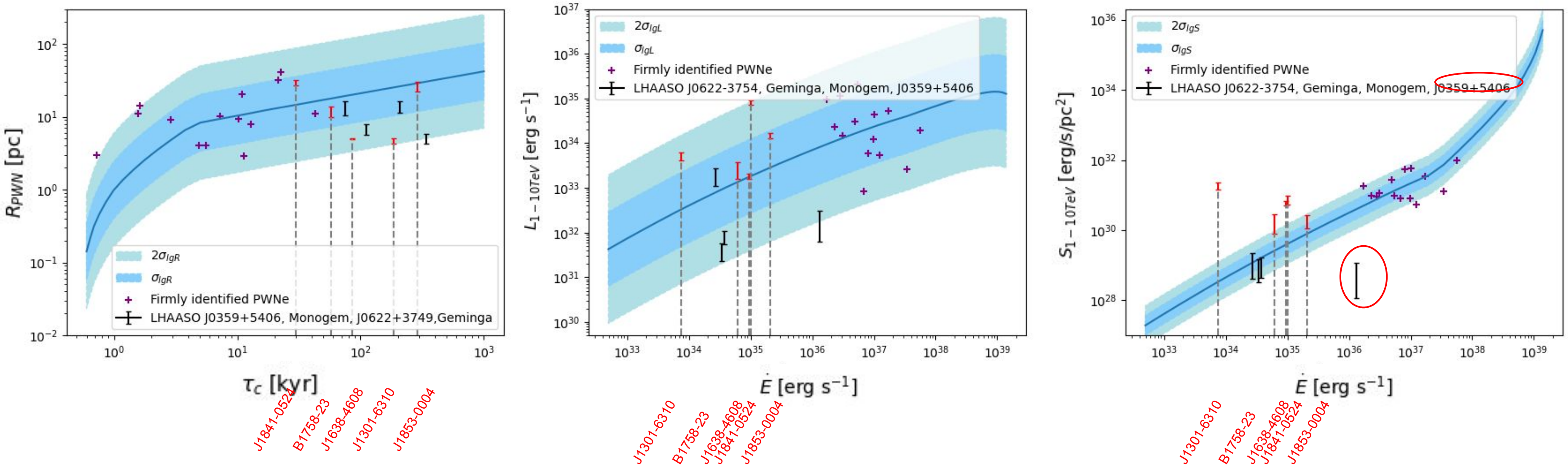
Criterion 3:



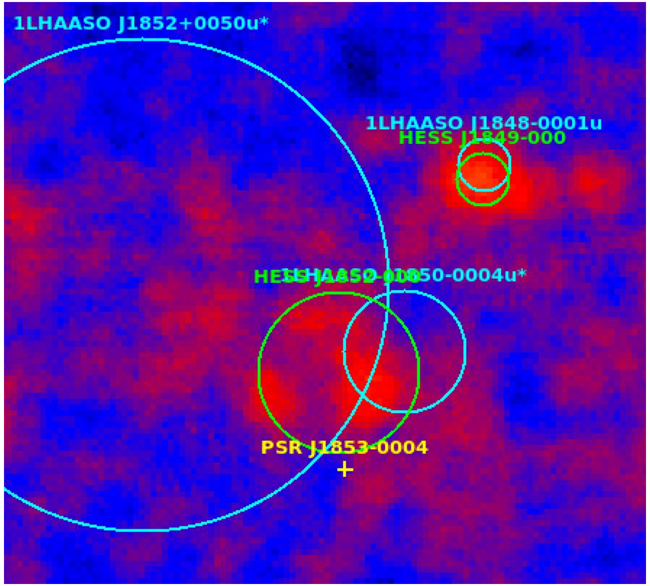
Criterion 4:



Comparison of candidates with LHAASO-WCDA TeV halo candidates

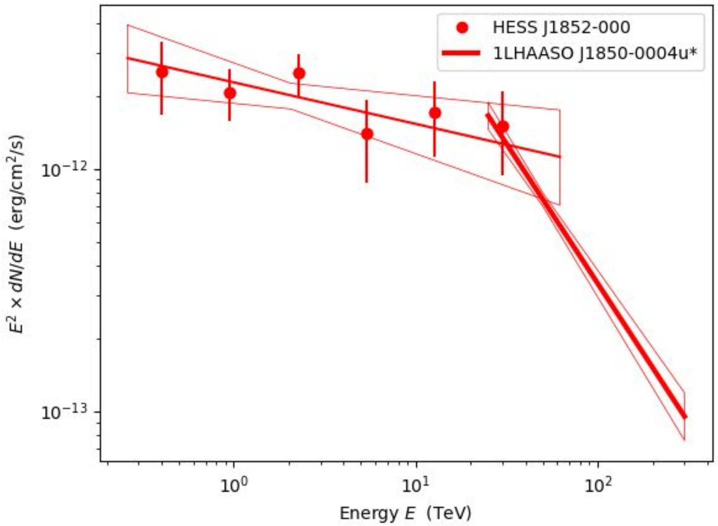


PSR J1853-000/HESS J1852-000: HGPS Significance map and LHAASO-KM2A sources



[The HESS Collaboration 2018]

Photon spectral energy distribution

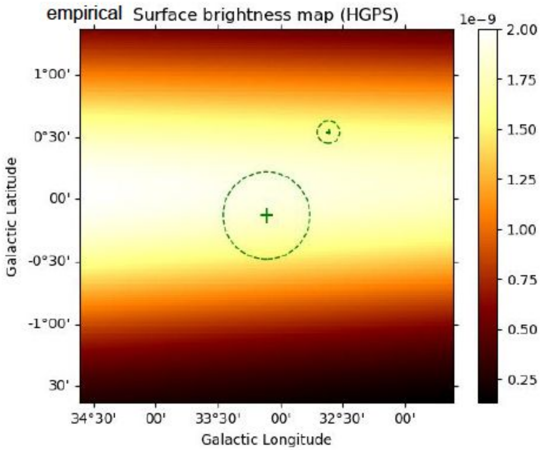


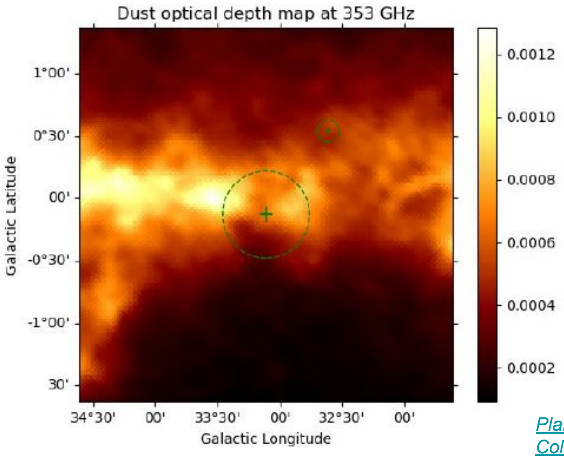
Prospects: data analysis methods with H.E.S.S.

→ Developments since the HGPS:

- New background computation methods for low latitude and source confusion scenario, and for extended sources (+ *Abdalla et al. 2021*: greater consistency between HAWC and H.E.S.S. analyses).
- Different approach to Large Scale Emission modeling (based on ISM gas tracer template maps)

HESS J1852-000 Region





Planck Collaboration XIX, 2016

→ HE counterparts (Fermi-LAT), UHE counterparts (LHAASO-KM2A) ⇒ model constraints (?)

Prospects: Particle transport model - One zone diffusion

→ $e^{\pm}$ transport, injected by point source (γ-ray emission centroid) :

- Injection : pulsar spin-down power E_dot(t)
- Losses : Inverse Compton (CMB + ISM radiation fields) and synchrotron emission
- Analytical solution for particle spatial distribution (Tang & Piran 2018, Di Mauro et al. 2018, Martin et al. 2022, Schroer et al. 2023, Osipov et al. 2020)

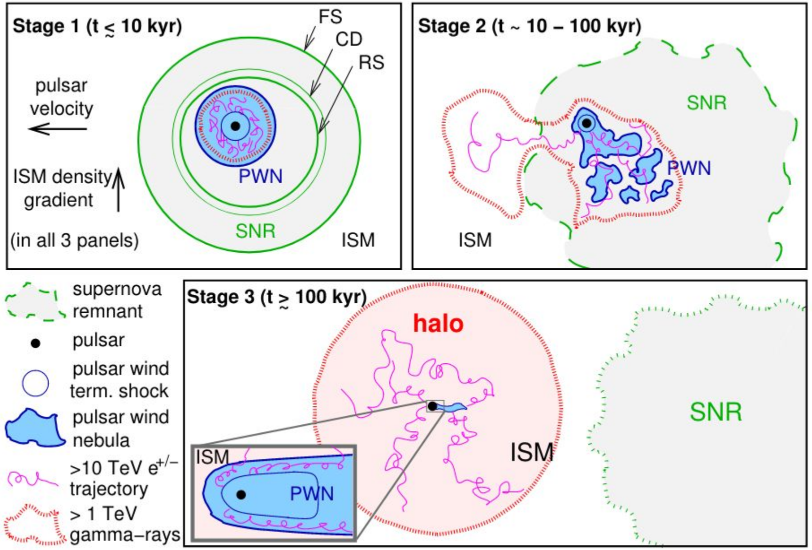
$$n(E,r,t) = \int_0^{t-t_{inj}} \frac{b(E')}{b(E)} Q(E', t-t') \mathcal{H}(r, E', t')\, dt'$$

- Photon spectrum → Compute radial profile

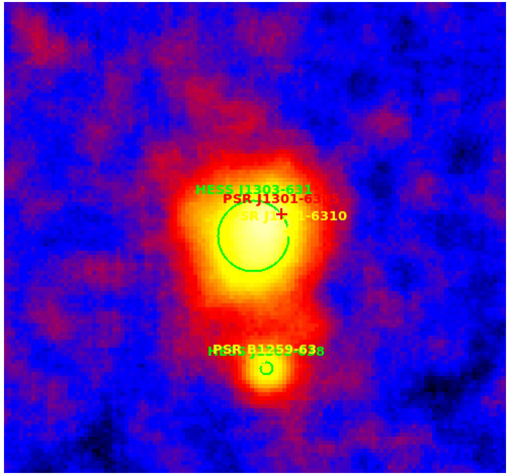
→ Free parameters : diffusion coefficient, injection efficiency, initial period

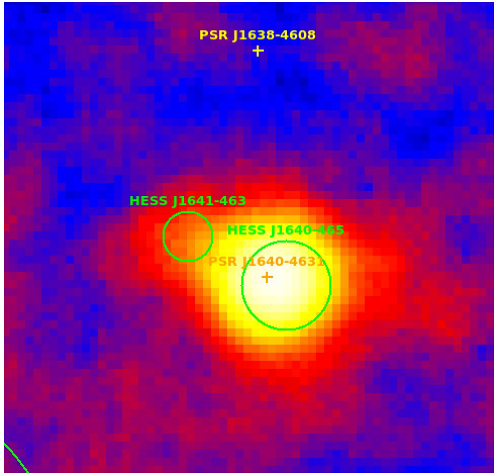
→ Pulsar proper motion: building an axisymmetric model (?)

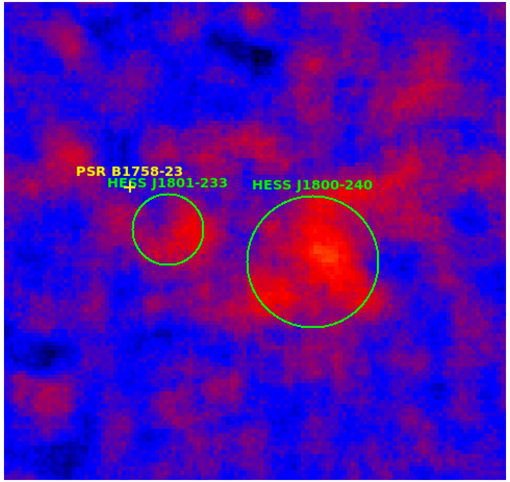
BACK UP



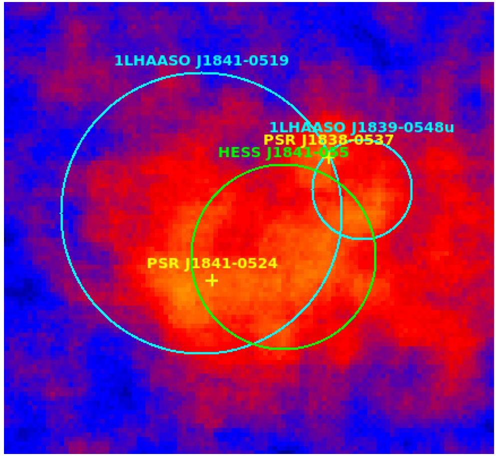
Giancinti et al. 2019

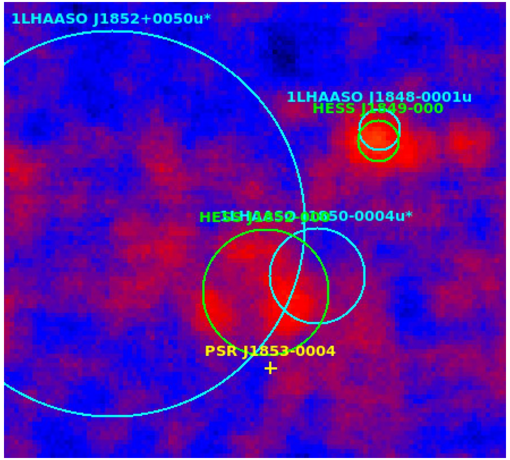


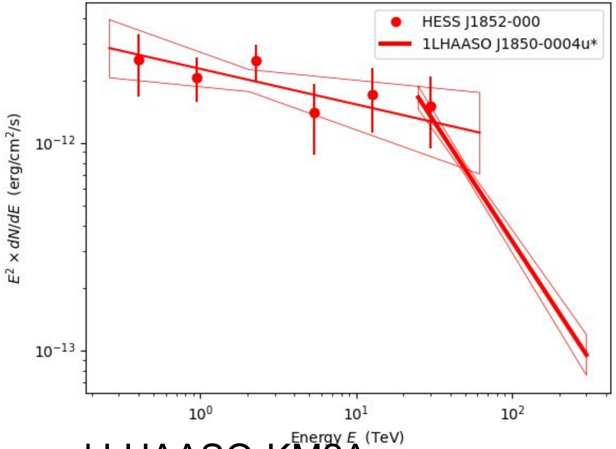




[The HESS Collaboration 2018](#)







H.E.S.S Significance maps and LHAASO-KM2A sources