Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Are galactic ultra-high-energy gamma-ray sources active or passive?

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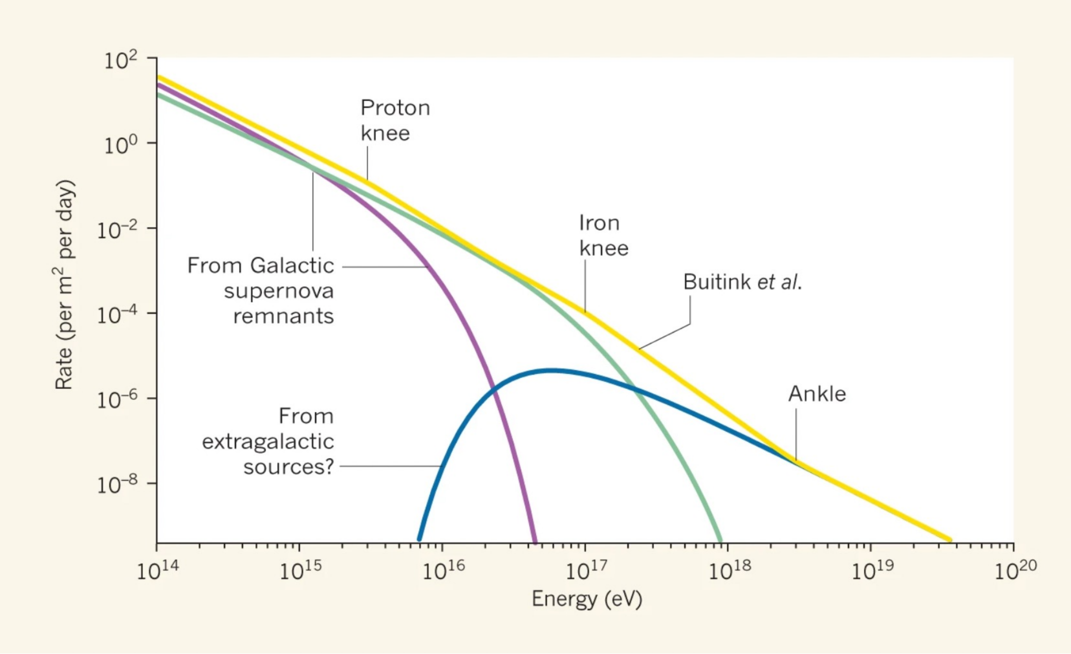
Cosmic Ray sources

Transition between galactic and extragalactic accelerators starts at ~10^{15}eV and ends at the ankle ~10^{18}eV.

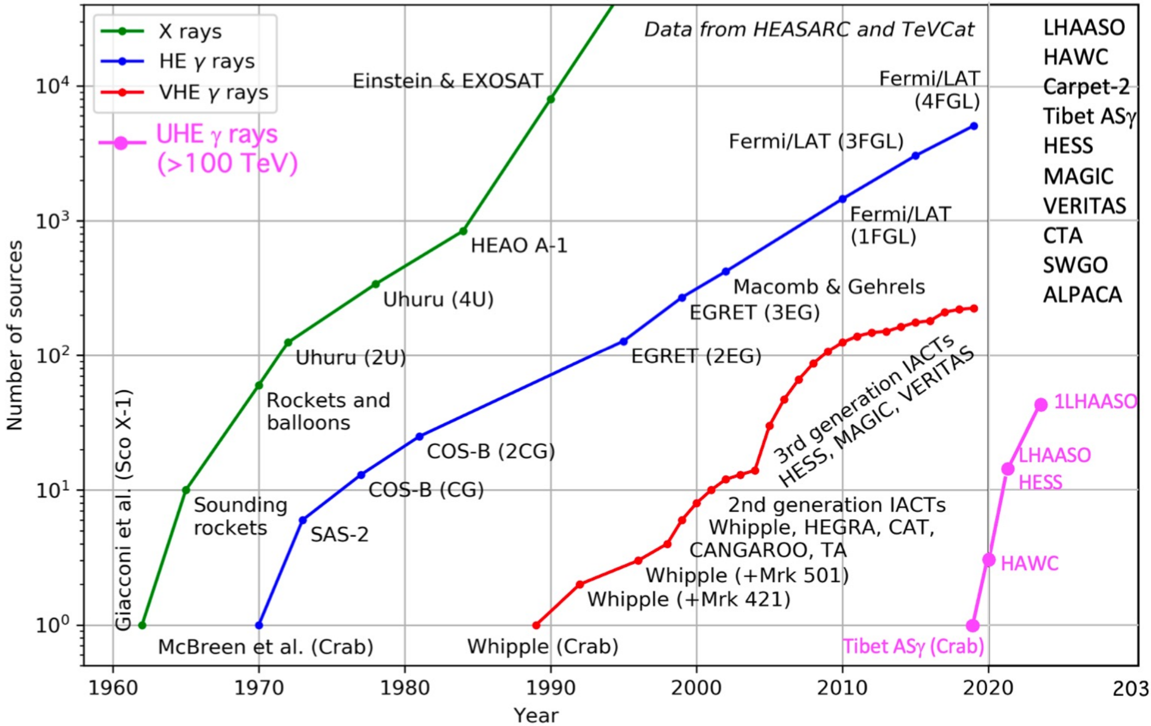
Recent growth in the number of known sources at UHE (≥100 TeV) - mainly thanks to HAWC & LHAASO

“PeVatrons” = accelerators of particles to energies ≥ 10^{15} eV



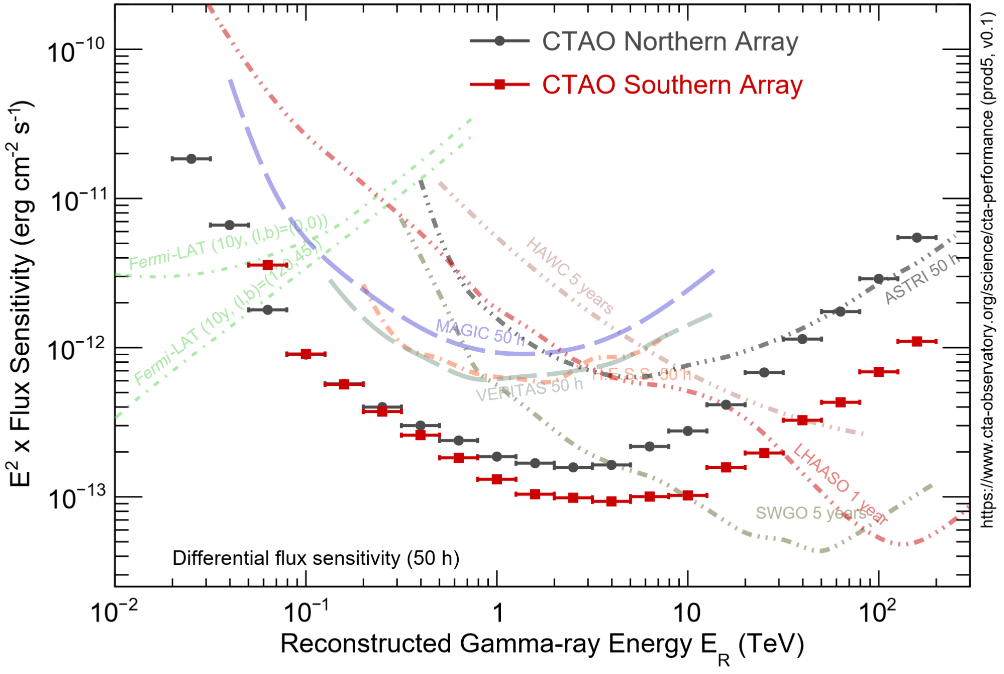
Taylor, Nature **531** 43-44 (2016)

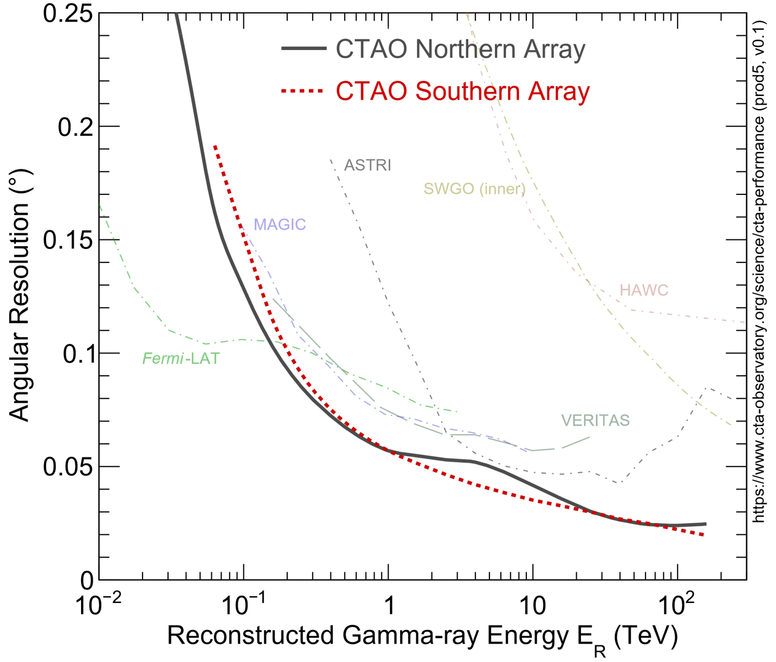
Kifune plot (Credit: Stephen Fegan) + UHE γ rays



Complementary Gamma-ray Facilities

Gamma-rays – a signature of high energy particle interactions





Different techniques → different performance.
Trade-off between sensitivity and resolution

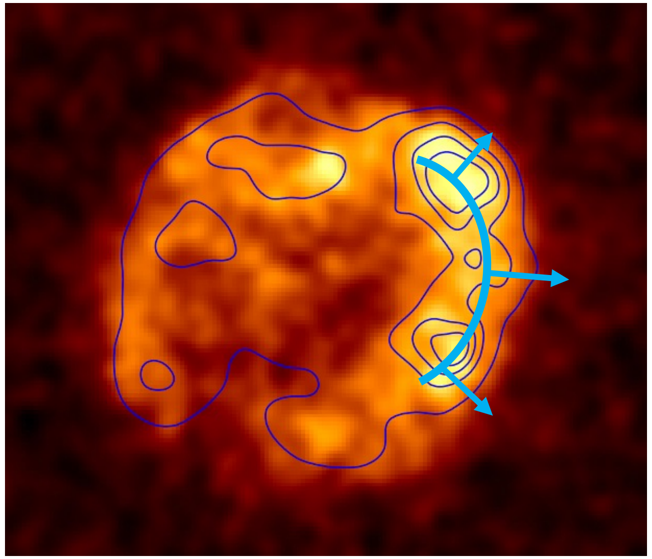
https://www.cta-observatory.org/science/ctao-performance/

Funk & Hinton, Astropart Phys 43 (348-355), 2013

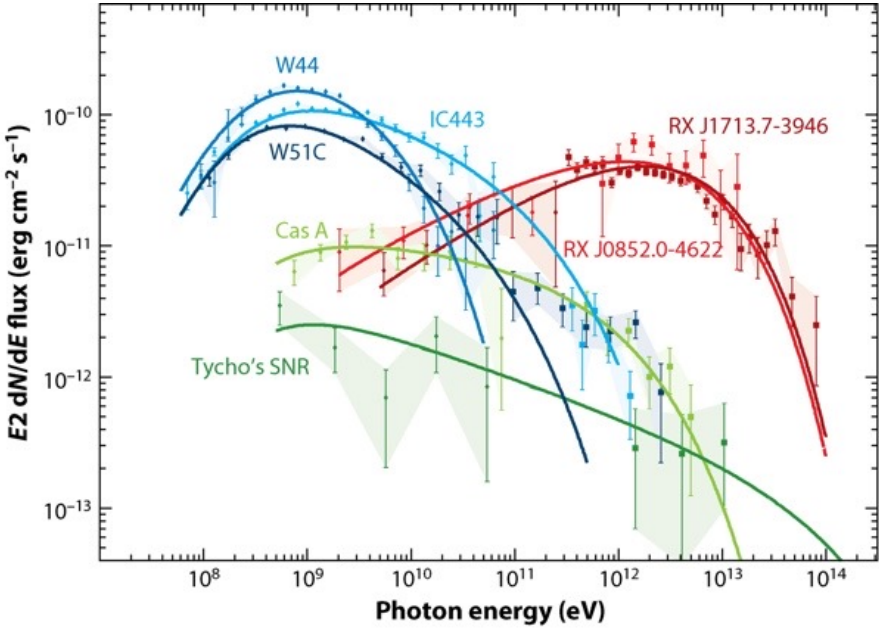
Supernova Remnants

- Acceleration at shock fronts of SNRs:
  - ~10^{51} erg per SN explosion
  - ~10% into proton / CR acceleration
  - ~ 3 events per century in Milky Way

→ Would be sufficient to power Cosmic Rays



- Cosmic rays: deflected by magnetic fields
- Interactions produce neutral messengers: gamma-rays & neutrinos point to source
- Motivation for gamma-ray astronomy
  → high energy particles



Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

LHAASO PeVatrons

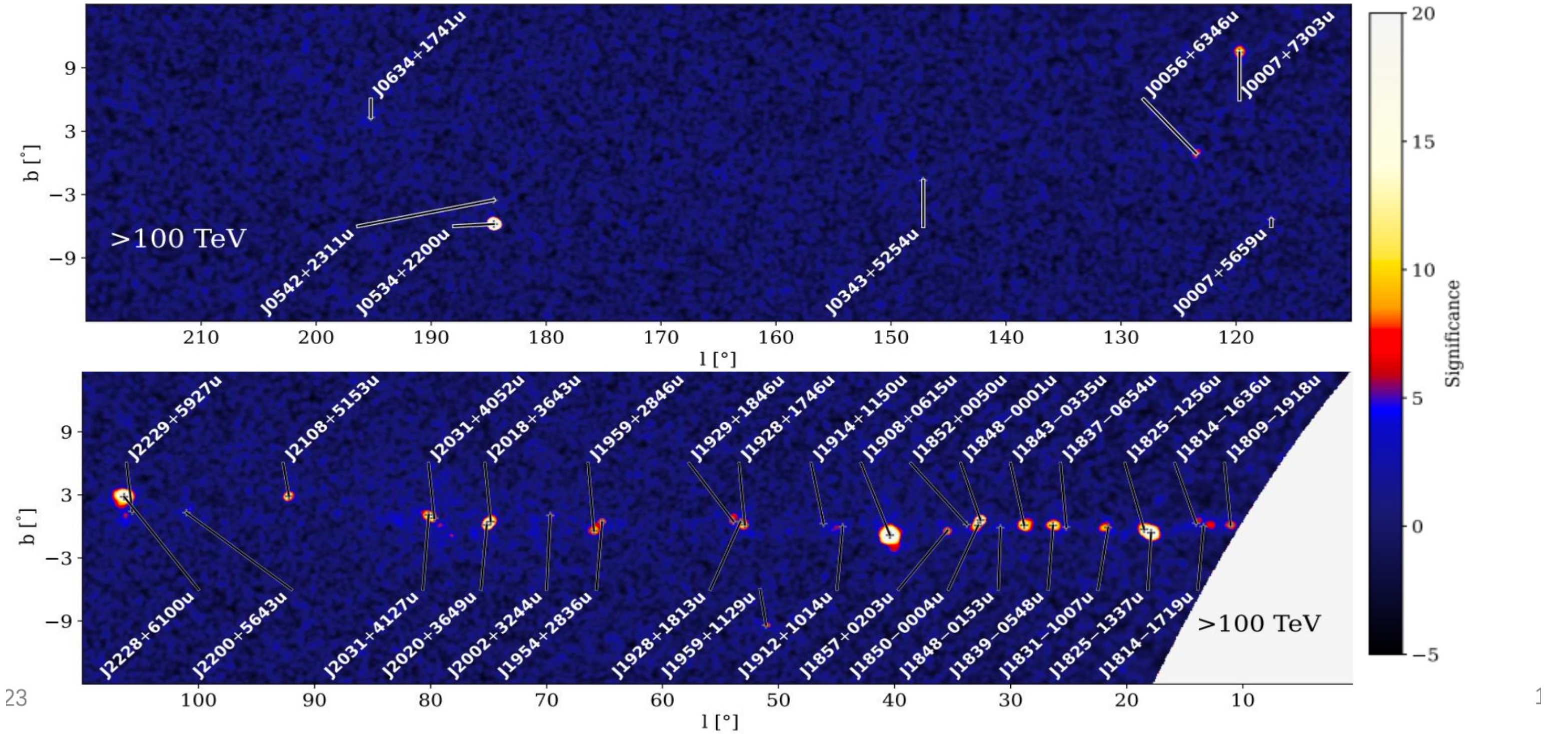
Wu & Chen ICRC2023, 010

1st LHAASO catalogue: arXiv:2305.17030 (accepted in ApJS)

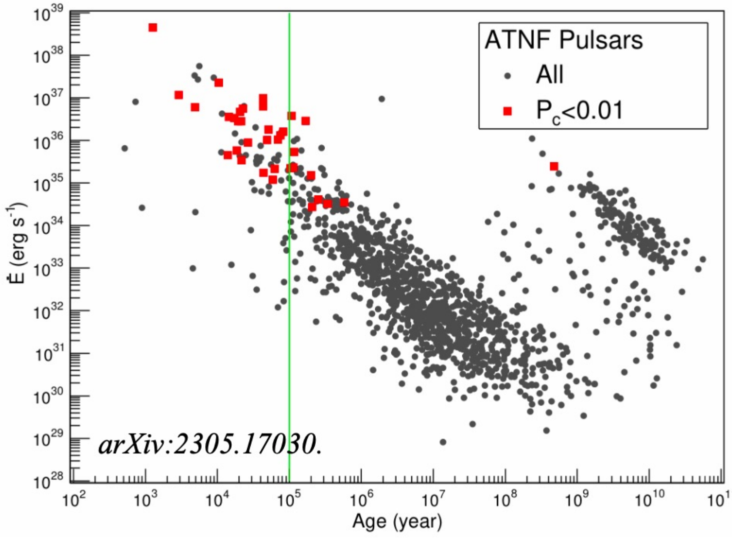
Several different source classes detected above 100 TeV!

Including PWNe, SNRs, stellar clusters...and unidentified sources

- **E>100 TeV, 43 sources were detected with significance above 4σ.**



- Among the 35 1stLHAASO sources with pulsar associations, **22** are labeled as UHE sources.



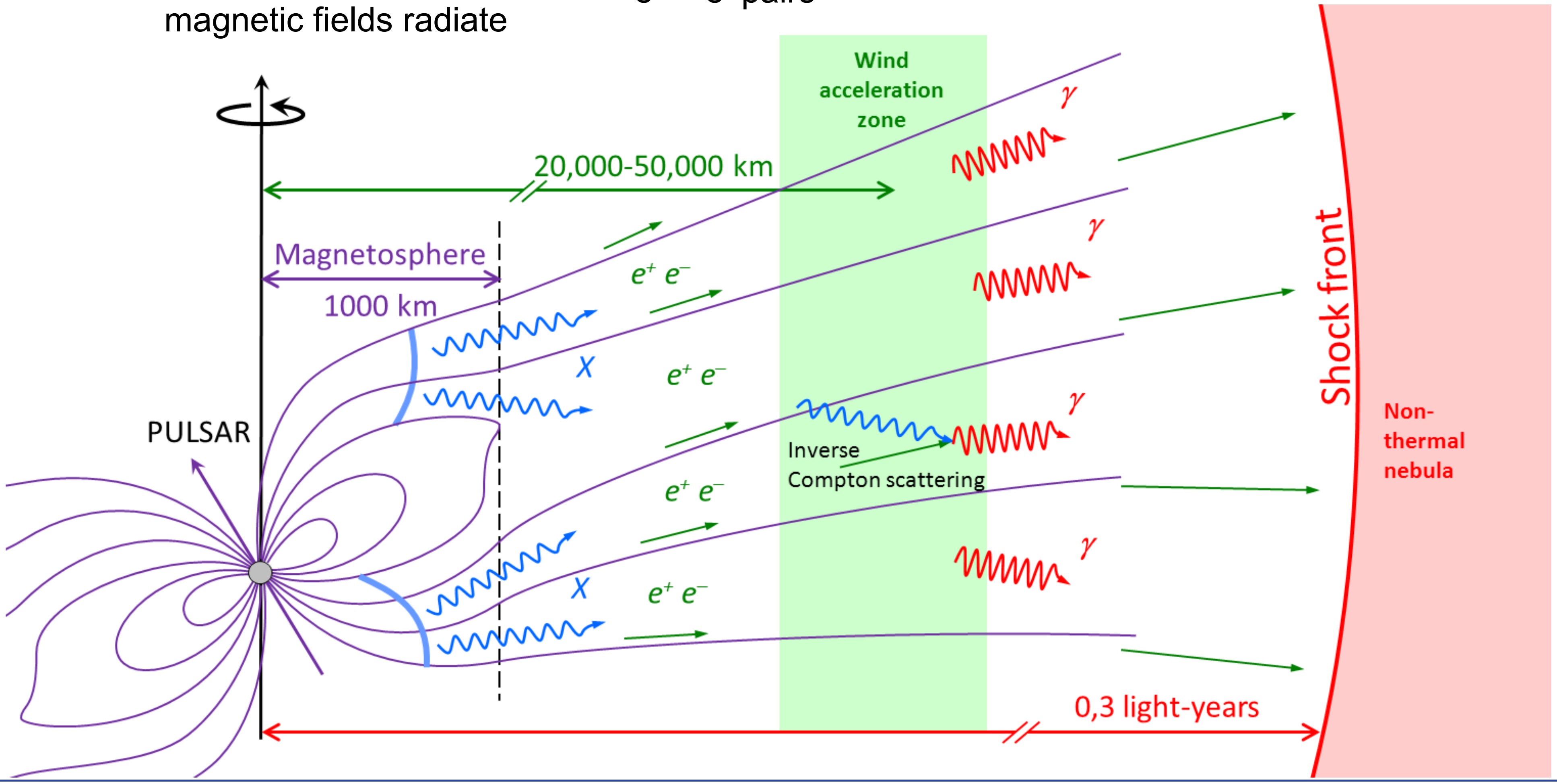
Pulsar environments

Pulsar – Pulsar Wind – Pulsar Wind Nebula

→ Charged particles accelerated in magnetic fields radiate

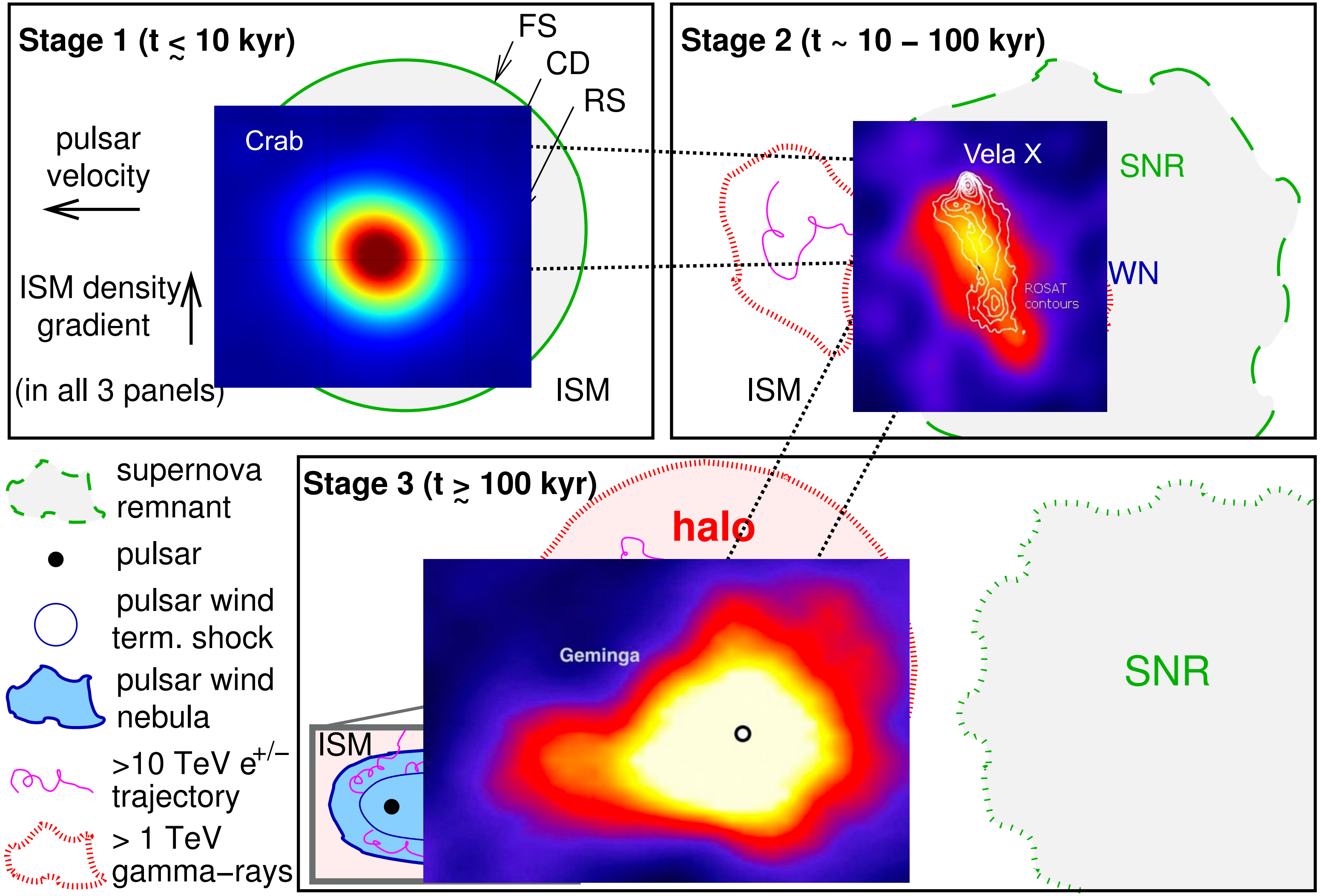
→ Radiation produces $e^+ - e^-$ pairs

Nebula of high energy particles → Mainly $e^\pm$



Evolutionary stages of pulsar environments

Leptonically dominated sources

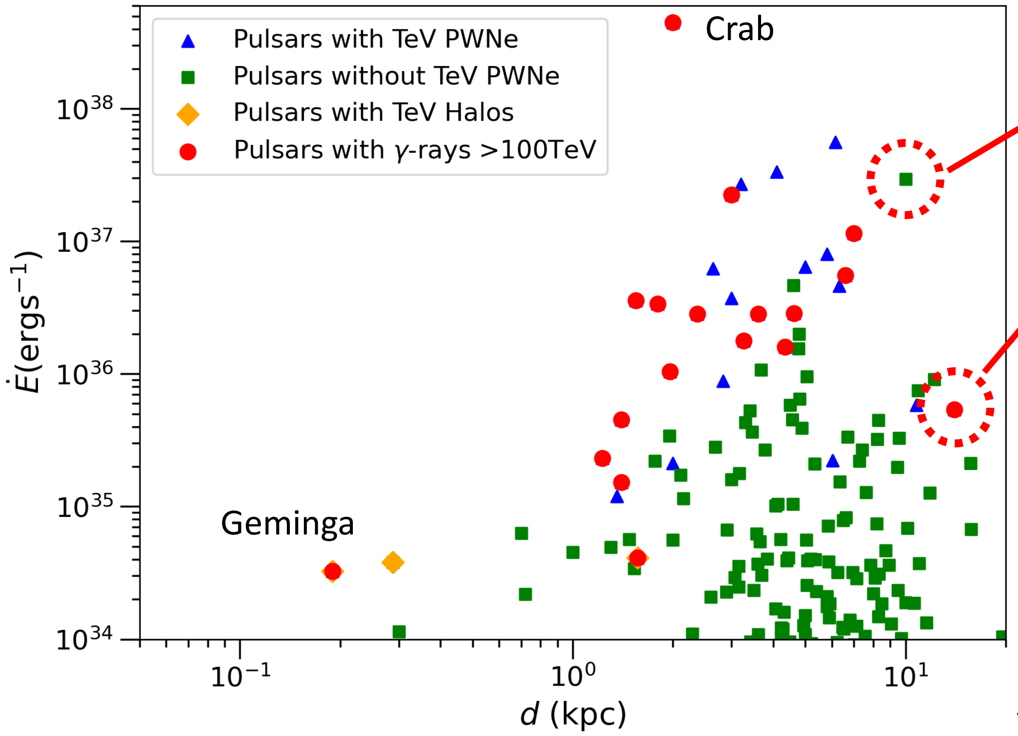


Pulsar Wind Nebulae (PWN)

→ **Pulsar Halos**

Giacinti, AM, Lopez-Coto et al, A&A **636**, A113 (2020)

Pulsar-powered PeVatrons?



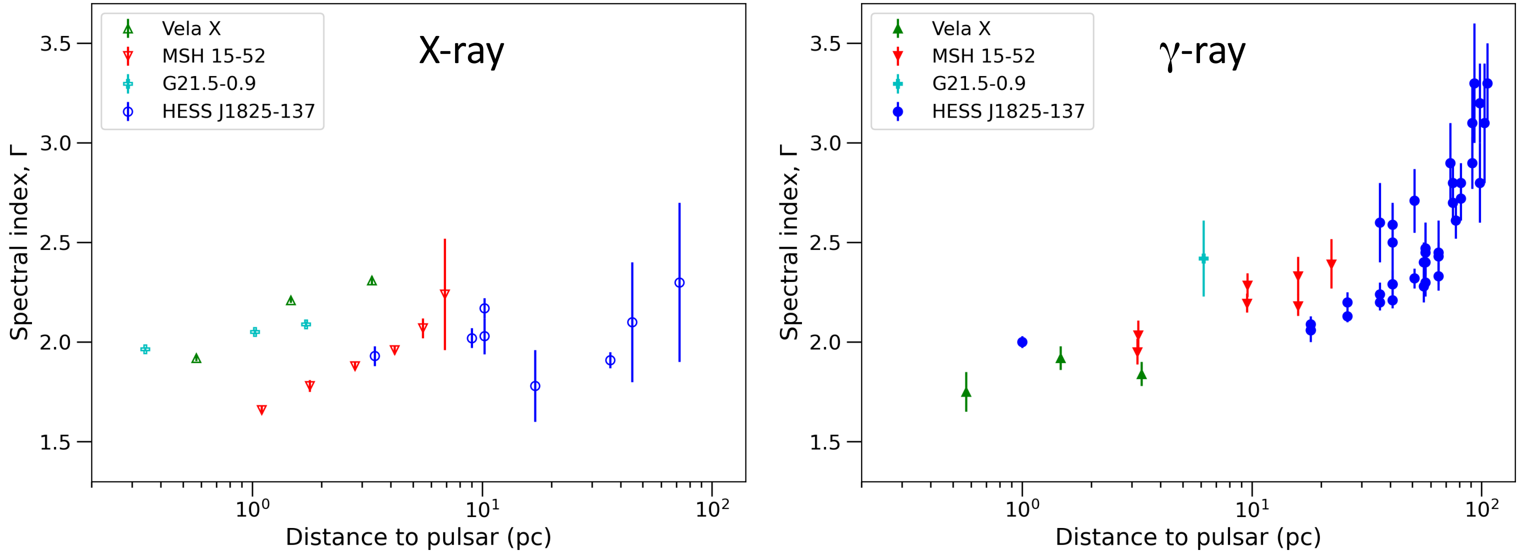
Why not PSR J2022+3842, with 3 x 10^{37} erg/s ?

Is PSR J1915+1150 exceptional? Is distance correct?

Common feature: spectral index increasing with distance from pulsar

→ electron transport and cooling

→ leptonically dominant sources

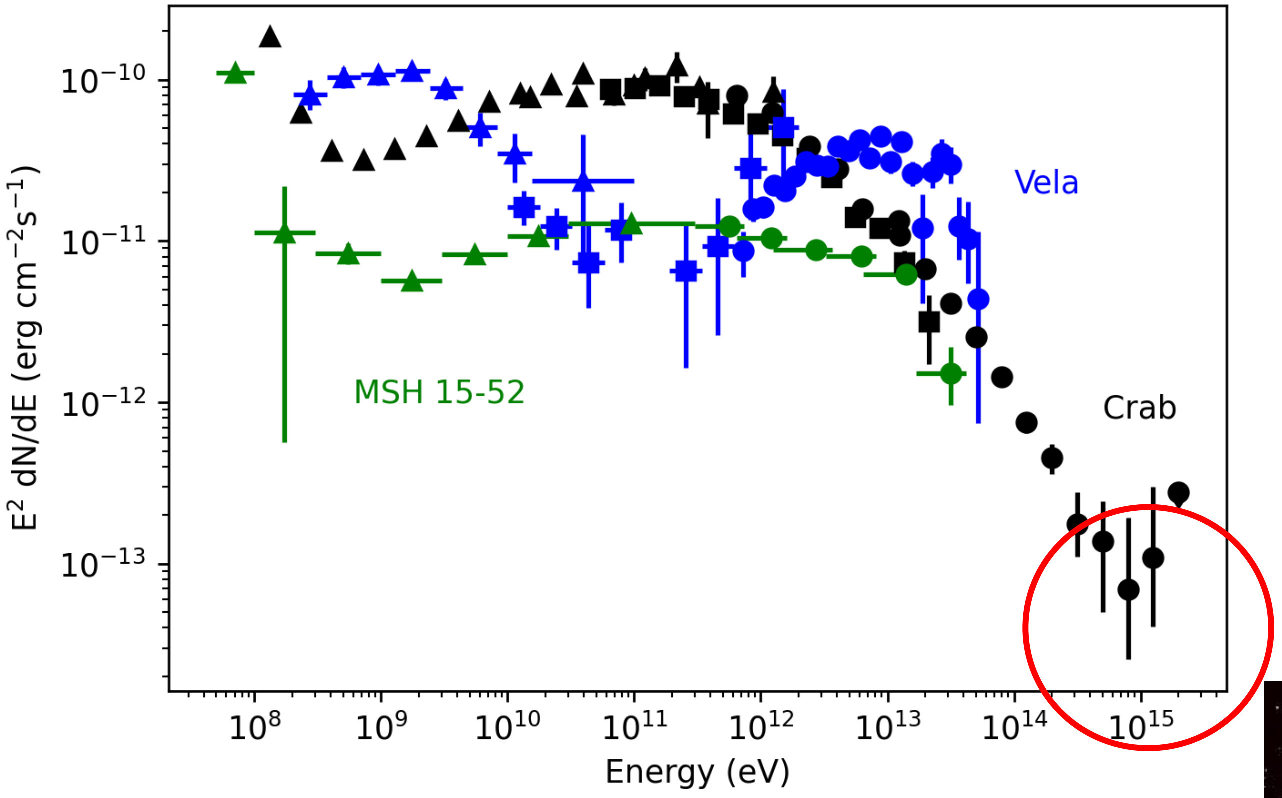


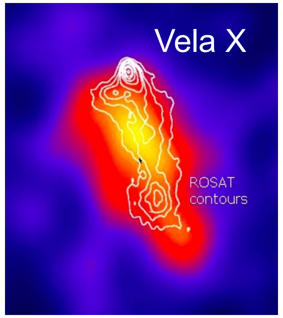
AM & Gelfand, Springer, 2022

Most highly energetic pulsars within the LHAASO visibility region now have associated TeV emission.

A couple of interesting exceptions

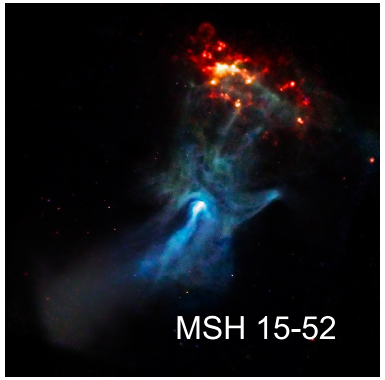
Pulsar Wind Nebulae

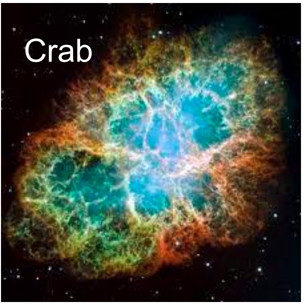




Age: 11.3 kyr
Edot: 6.9x10^{36} erg/s
Distance: 0.28 kpc

Age: 1.57 kyr
Edot: 1.7x10^{37} erg/s
Distance: 4.4 kpc



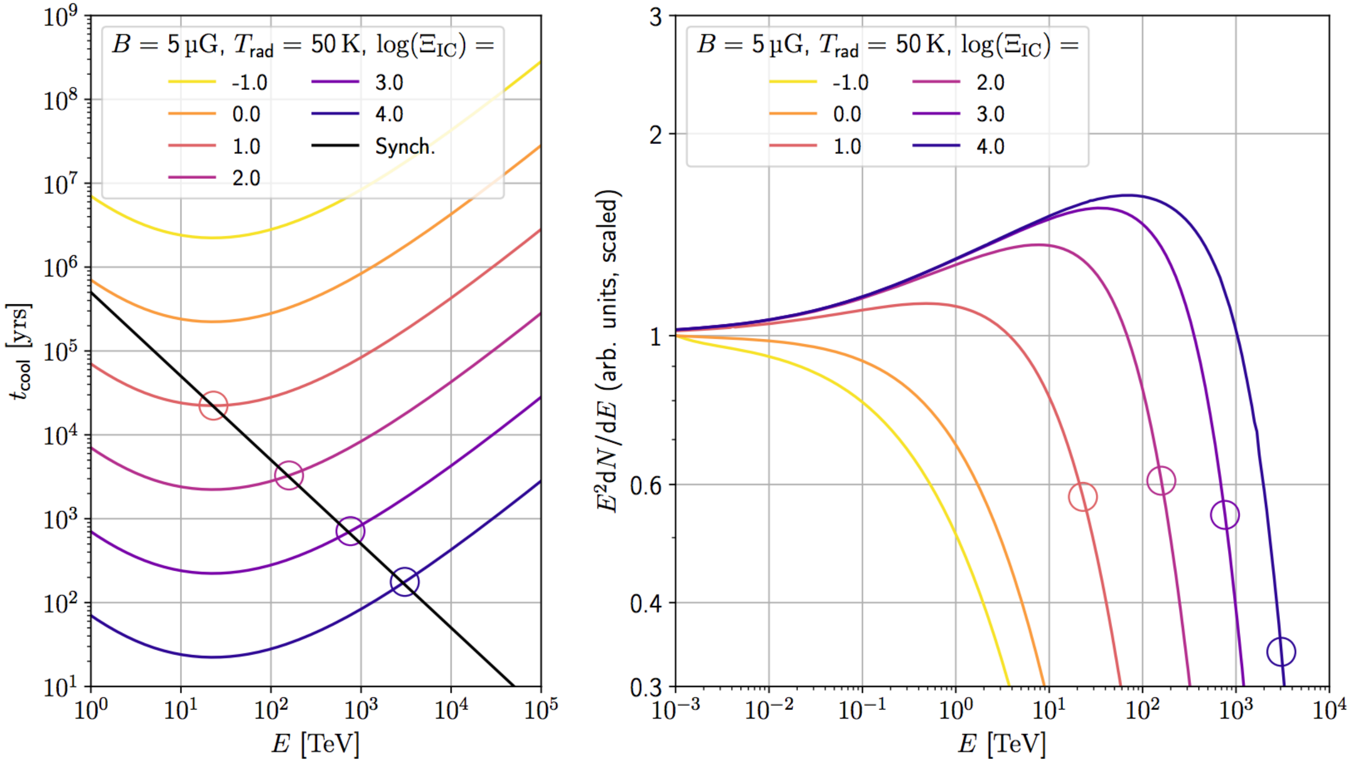


Age: 0.94 kyr
Edot: 4.5x10^{38} erg/s
Distance: 2 kpc

UHE leptonic emission & Klein-Nishina effect

$$\Xi_{IC} \equiv {}^{U_{rad}}/_{U_B}$$

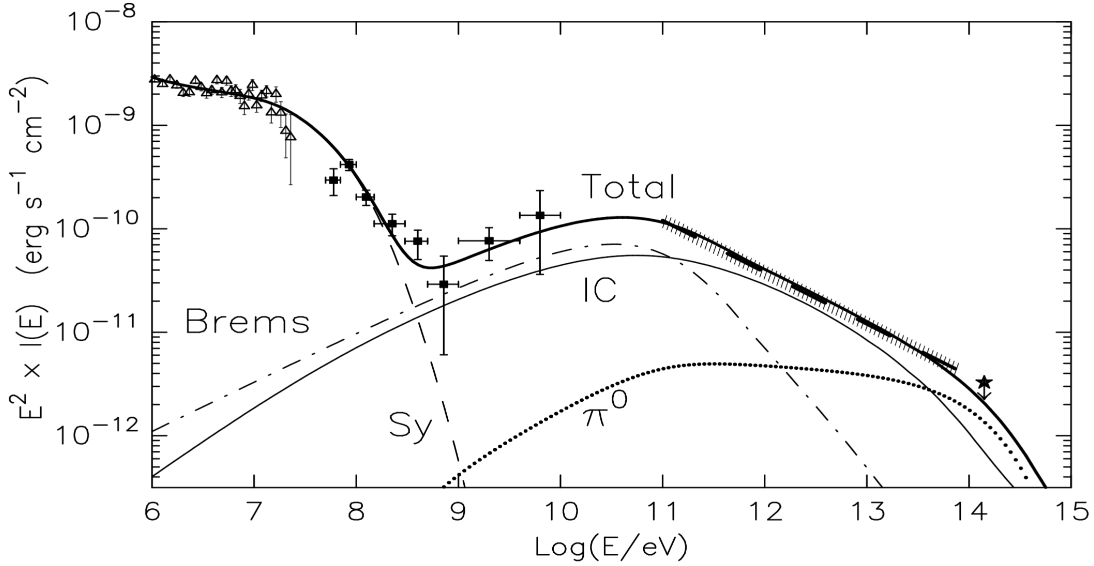
- In high radiation environments, $U_{rad} >> U_B$, synchrotron cooling dominates over IC losses, even into Klein-Nishina regime.
- Inverse Compton cross-section is suppressed
- Resulting spectrum is harder/ higher energy cut-off
- Leptonic spectra can be observed up to PeV energies



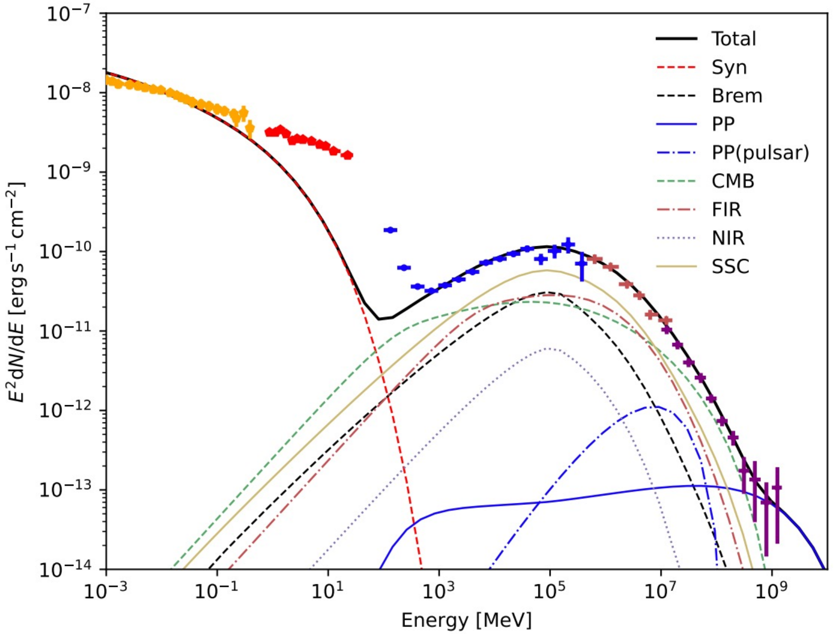
Breuhaus et al. ApJL **908** L49 (2021)

Klein-Nishina cut-off → sub-dominant hadronic component

Crab nebula:
A sub-dominant hadronic component could be revealed at the highest energies, beyond the Klein-Nishina cut-off



Aharonian & Atoyan, proc. "Neutron Stars and Pulsars" 439 (1998)



Nie et al, ApJ 924, 42 (2022)

Q: How could hadrons reach high energies in the environment of the Crab PWN?

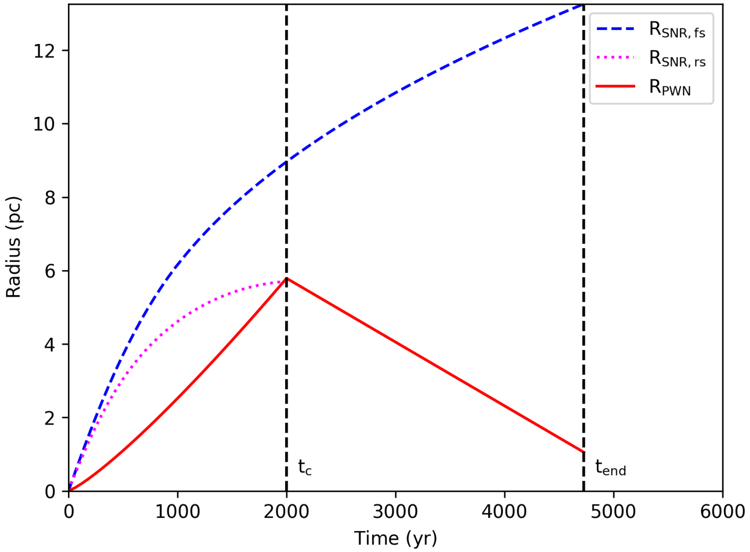
Acceleration of hadrons in PWNe?

Reinjection of particles from the reservoir within the supernova remnant

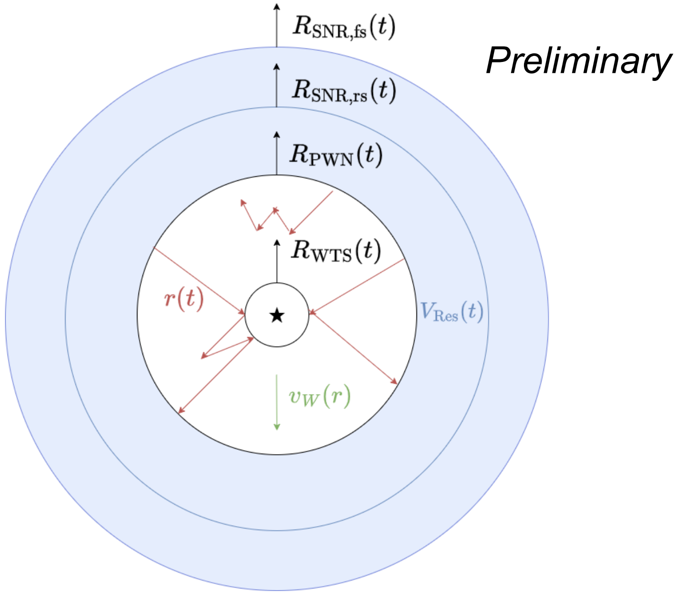
Further hadronic particle acceleration at the pulsar wind termination shock

Particle tracking simulations

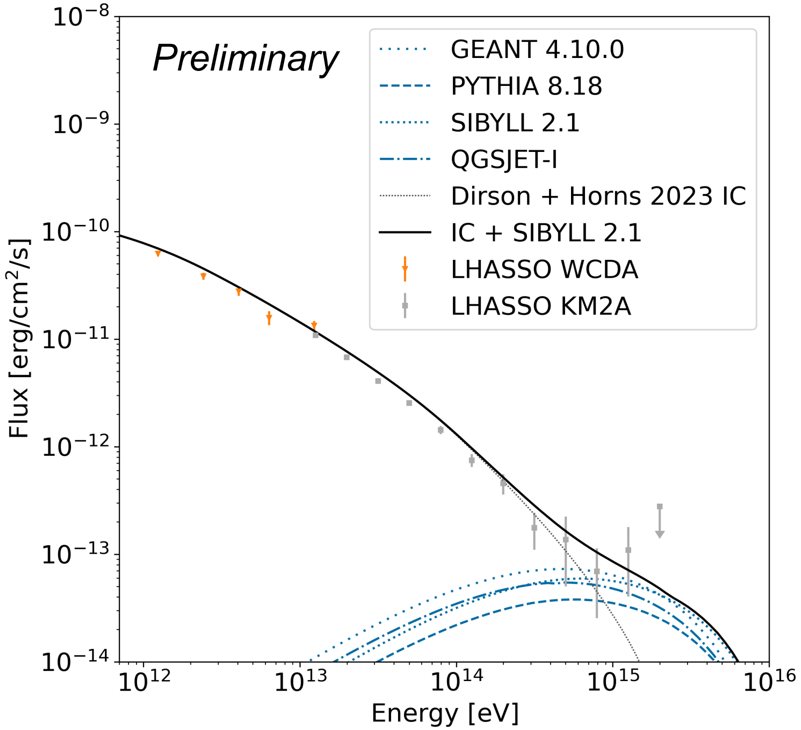
Assume Bohm diffusion inwards, outward advection with the wind, and an energy gain of factor 2 per shock crossing

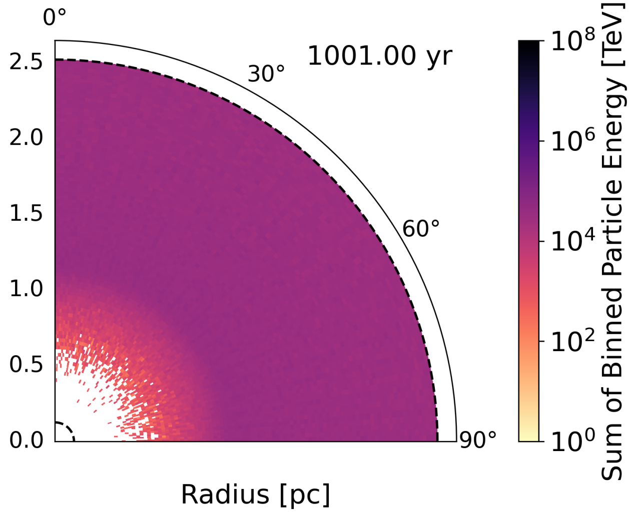


After Ohira et al, MNRAS **478**, 926-931 (2018)



S. Spencer, AM, B. Reville (ICRC2023)





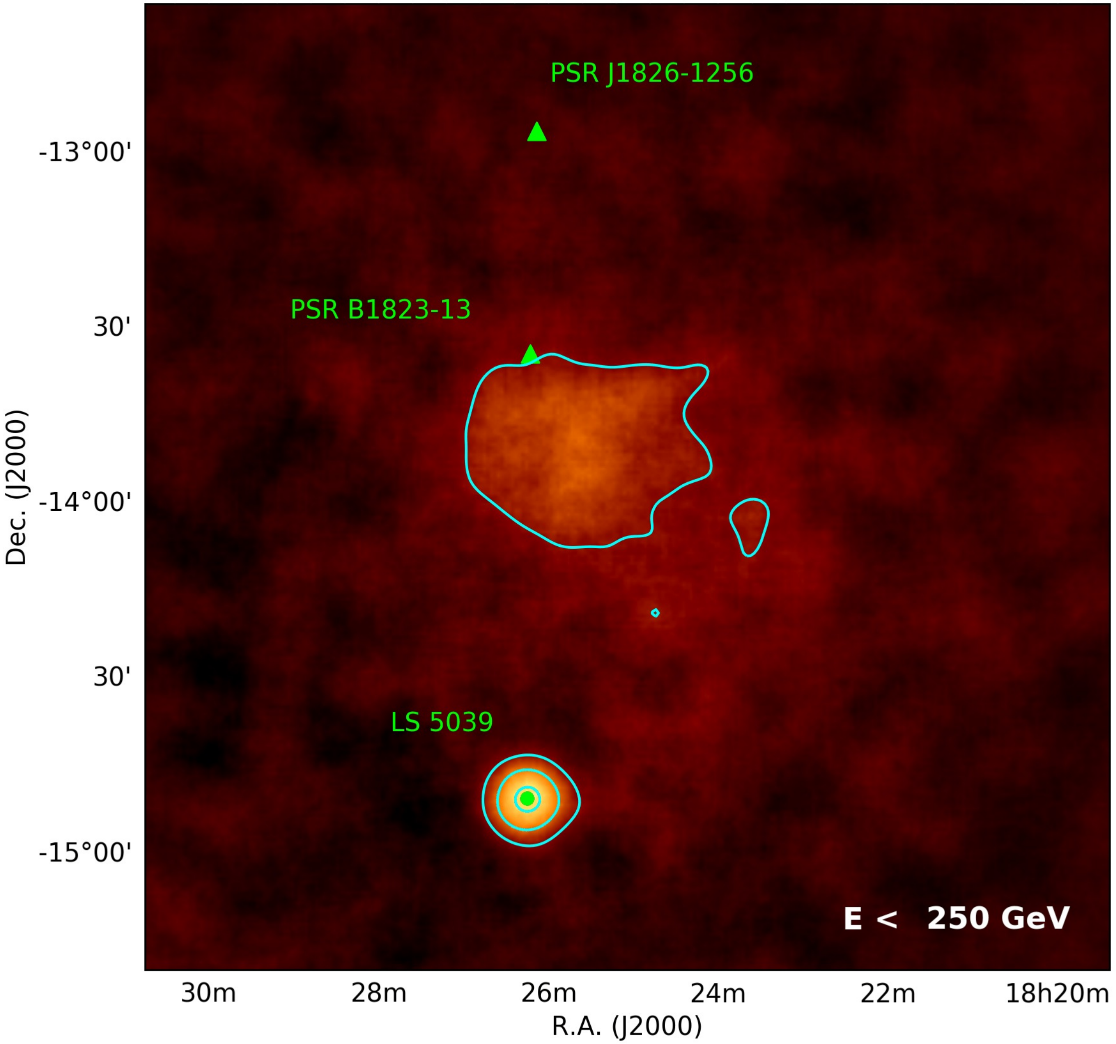
Example transition: HESS J1825-137

Pulsar Wind Nebula → Pulsar Halo

Age: 21.4 kyr

Edot: 2.8x10^{36} erg/s

Distance: 3.9 kpc



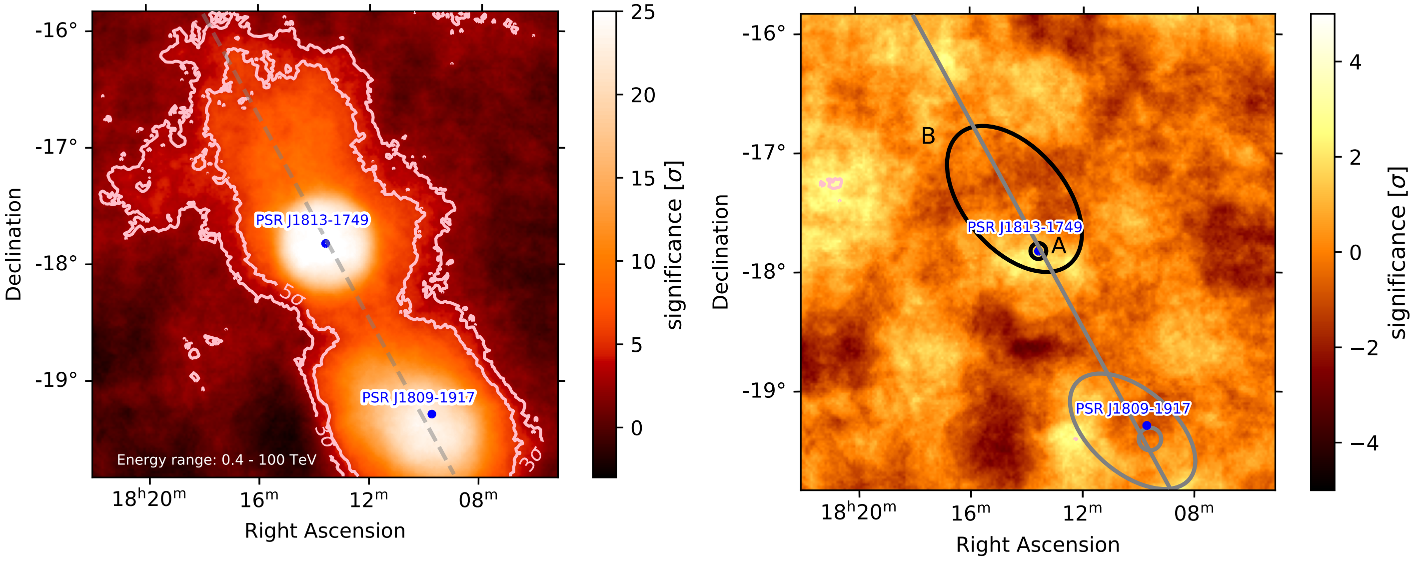
H.E.S.S. collaboration et al. A&A **621** (2019) A116

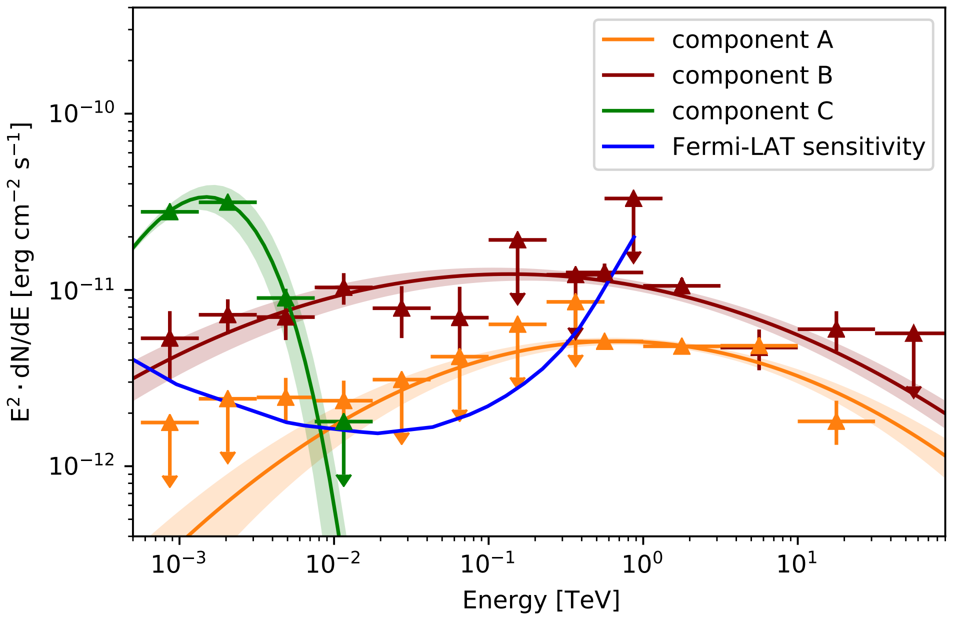
Example transition: HESS J1813-178

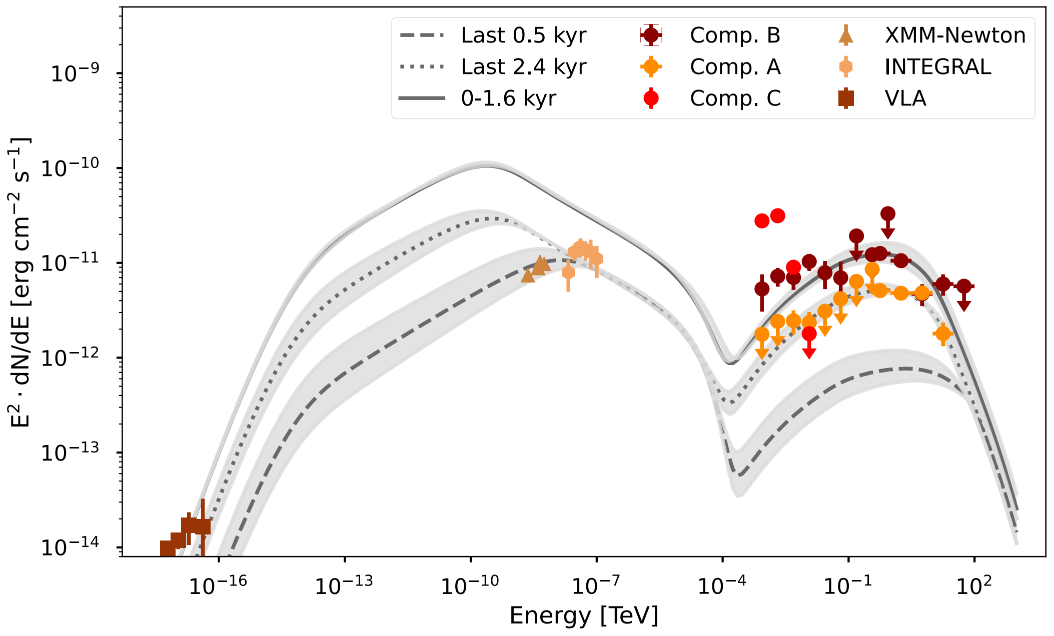
Joint fit to Fermi-LAT and H.E.S.S. data yielded a core component A and extended component B

Modelled as electron populations of different ages released from the pulsar

Energy density is PWN-like and halo-like respectively







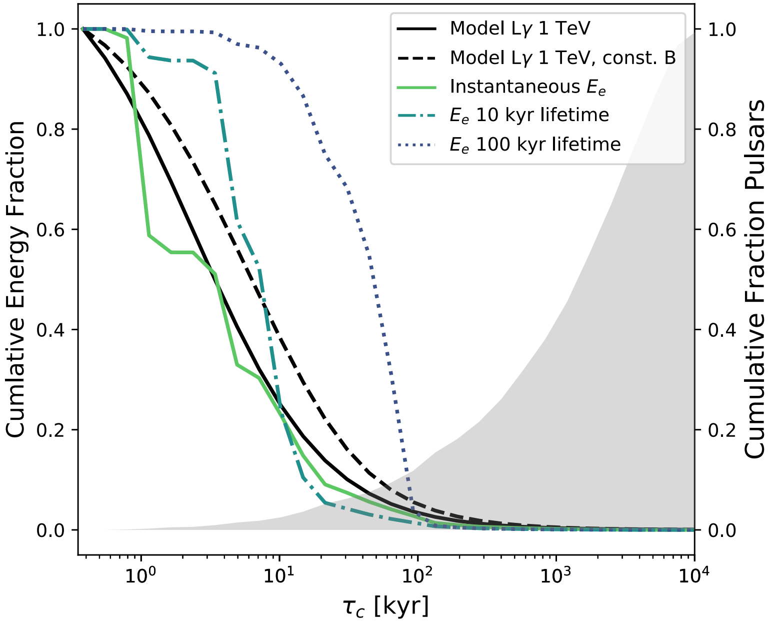
T. Wach, H.E.S.S. (A&A submitted)

Pulsar halo energy density

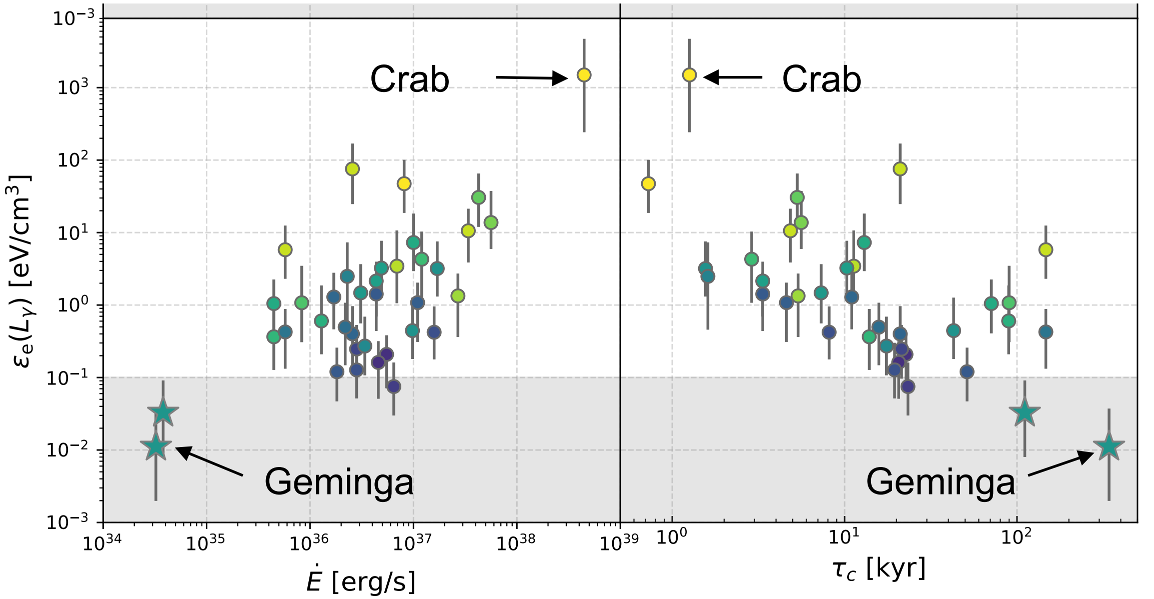
How to distinguish between the nebula and halo components?

→ Non-thermal gamma-ray emission extending beyond the canonical X-ray nebula e.g. Sudoh et al, PhysRev D 100, (2019) 043016

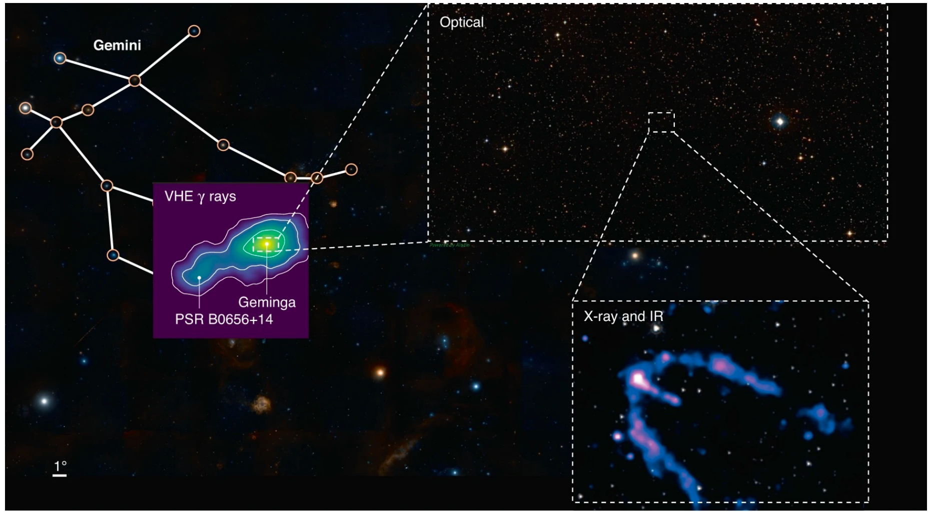
→ Particle (electron) energy density – a region in which the energy density due to the pulsar no longer dominates above ISM e.g. Giacinti et al, A&A 636, A113 (2020)



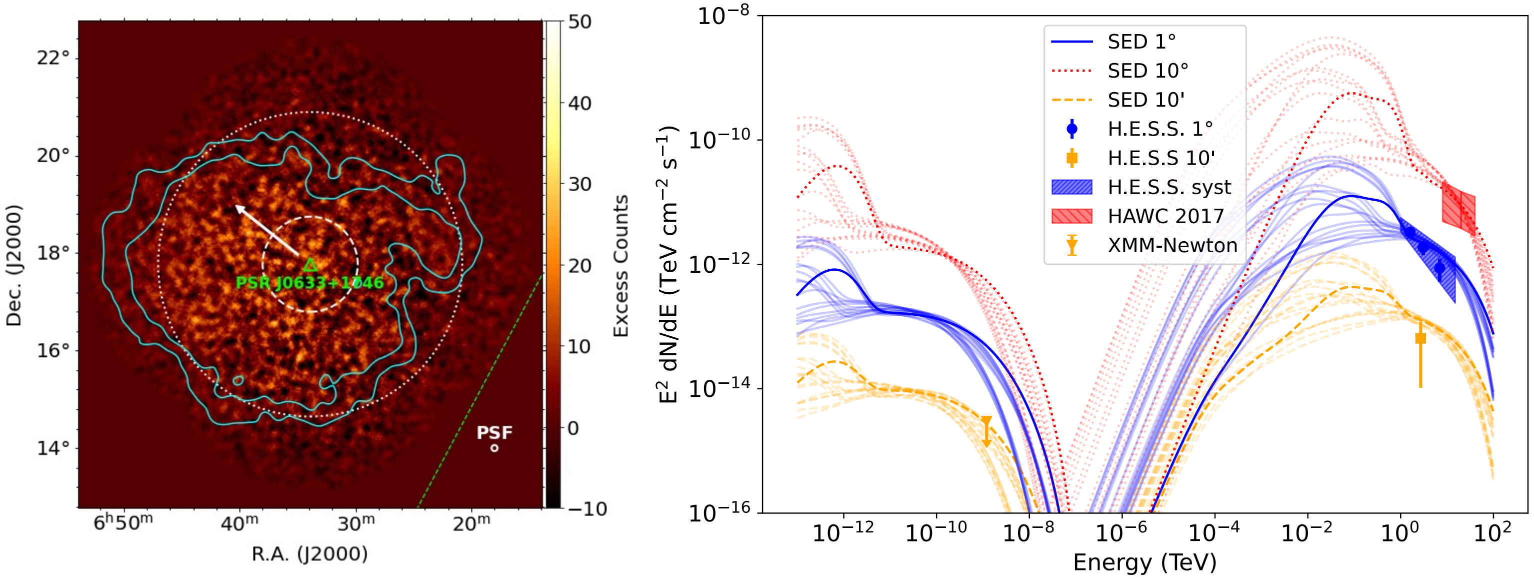
Giacinti et al, A&A 636, A113 (2020)



Electron diffusion in the Geminga halo



Lopez-Coto et al. Nat. Ast. **6** (2022) 199-206



H.E.S.S. Collaboration A&A **673** (2023) A148

- VHE gamma-ray emission size >> X-ray size
- Emission profile indicates diffusion coefficient normalisation far below the Galactic average
  → not expected for particles escaped into the ISM
- H.E.S.S. results can be consistently described with MWL data under a slow diffusion model

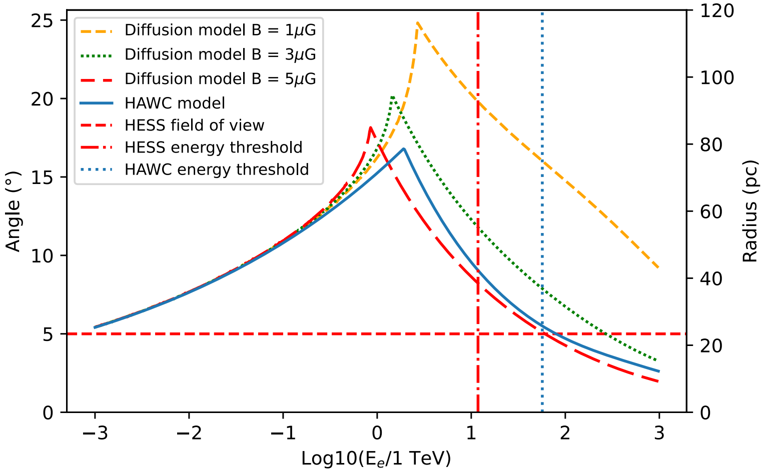
Diffusion modelling of the Geminga pulsar halo

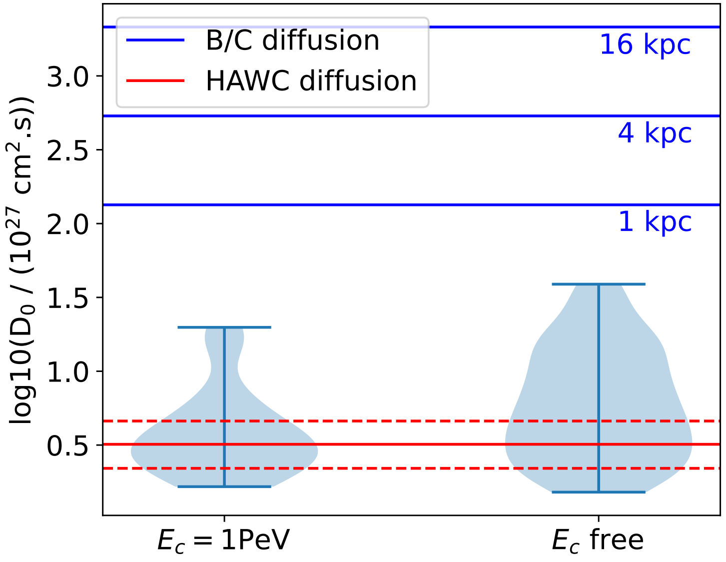
- Model of continuous electron injection by the pulsar and diffusion through the halo
- Peak diffusion radius corresponds to the age of the system via electron cooling losses
- Parameter scan: varied n, δ, α, η, B & E_c
  → 243 possible combinations

- Diffusion Coefficient normalisations significantly below galactic average values are preferred

$$D(E_e) = D_0(E_e/10\,GeV)^{\delta}$$

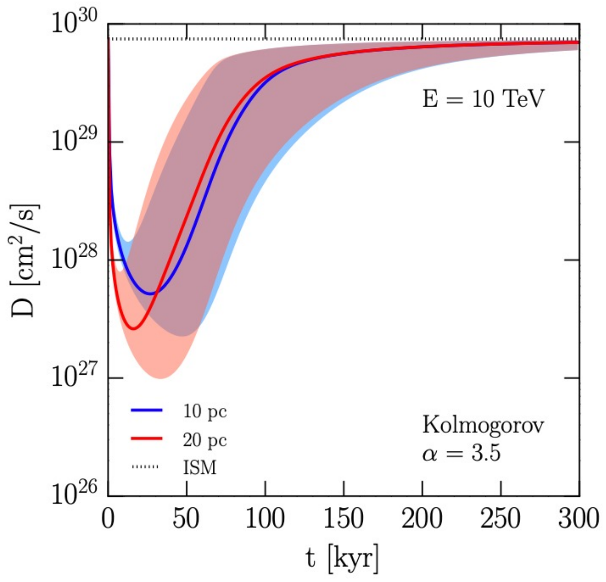
$$r_d = 2\sqrt{D(E_e)t_E} \quad \text{(S6).}$$



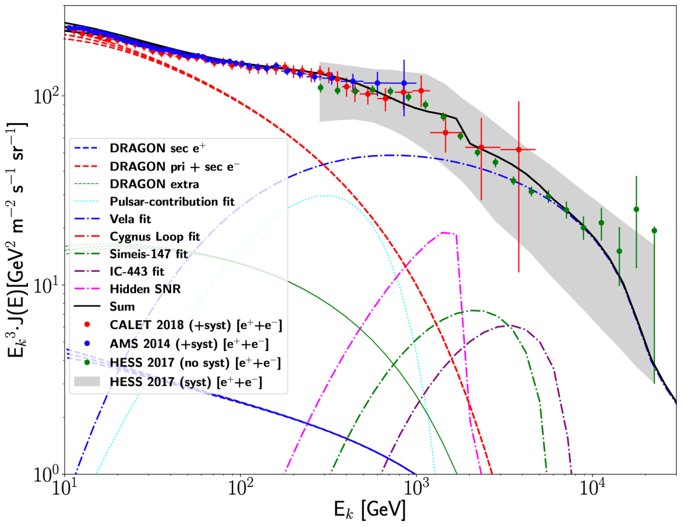


Cosmic Ray Electron Spectrum

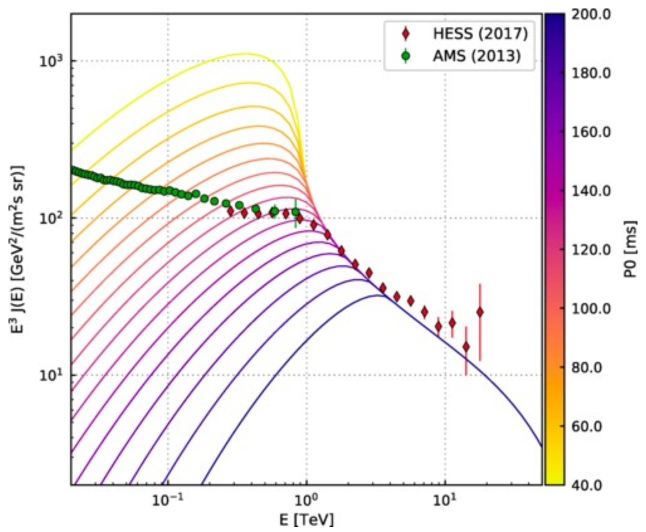
- Recent measurements of slow diffusion in vicinity of nearby accelerator
- Generally, need a local source contribution to explain the high energy CR electron spectrum
- Either the diffusion coefficient recovers to galactic values, or there is another local source contributing
- Nature unclear: local SNR, local pulsar....



Evoli et al PRD **98**, 063017 (2018)



Fornieri et al. JCAP **02** (2020) 009



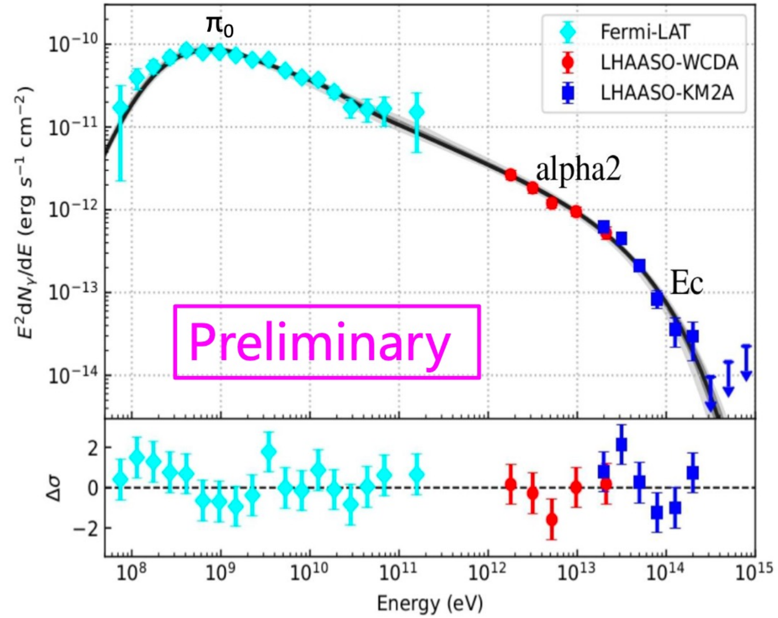
Lopez-Coto et al. PRL **121** (2018) 251106

Supernova Remnants

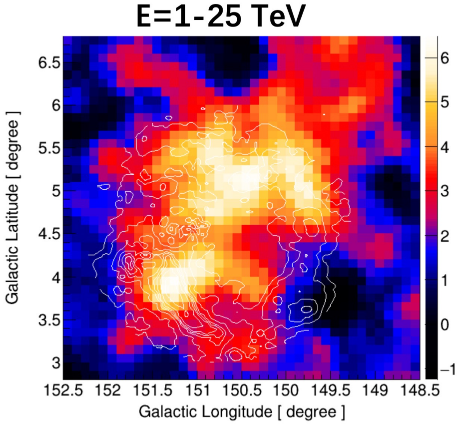
Supernova Remnant PeVatrons

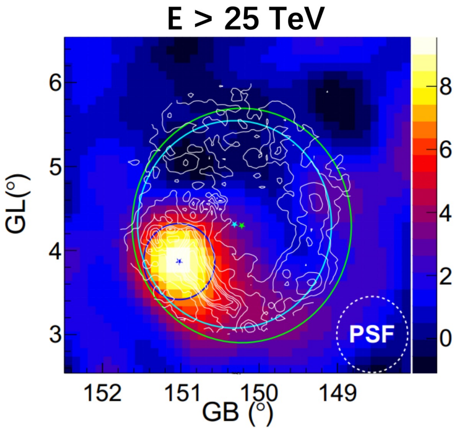
Recent results

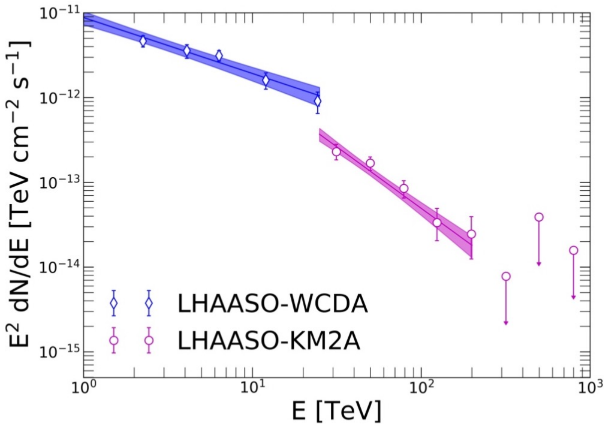
SNR W51C → spectrum reaching 300 TeV (Fang et al. ICRC2023, 957)
→ PeVatron or interacting with a molecular cloud?



SNR G150.3+4.5 = potentially a PWN on top of an SNR shell
(Fermi-LAT analysis – Devin et al 2020)
Suggest either SNR + PWN or SNR + clouds (Zeng et al. ICRC2023, 606)





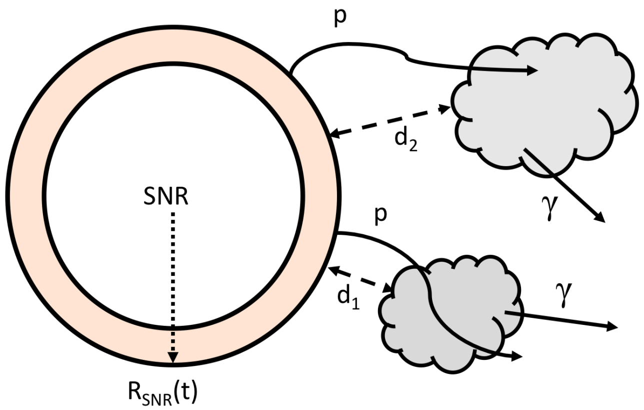


Illuminating molecular clouds?

Cosmic ray accelerators can only accelerate up to (roughly) the Hillas limit

The most energetic cosmic rays will, however, be able to escape the source

They may propagate through the intervening medium to interact with molecular clouds



Gamma-ray emission from clouds can hence act as **a probe of past PeVatron activity**

→ We should even **anticipate a new population of (passive) sources – illuminated clouds – emerging at the highest gamma-ray energies**

→ Spectrum of particles arriving at the cloud is **much harder** than the spectrum at the accelerator

* Not always straightforward, turbulence can complicate how well CRs can traverse a cloud...etc.

SNR + Cloud Model: particle and gamma-ray flux

Assume: particle flux from an impulsive accelerator, $\alpha = 2$ (Aharonian & Atoyan '96)

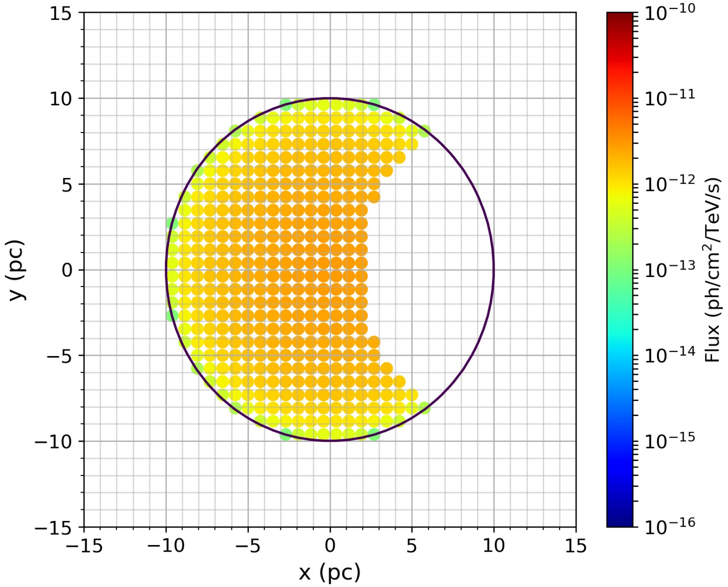
$$f(E,r,t) \approx f_0 \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_d^3} \exp\left(-\frac{(\alpha-1)t}{\tau_{pp}} - \frac{R^2}{R_d^2}\right)$$

Gamma-ray flux Φ_γ produced by interactions with a target cloud (Kelner et al 2006)

$$\Phi_\gamma(E_\gamma) = c n_H \int_{E_\gamma}^{\infty} \sigma_{\rm inel}(E_p) f(E_p,r,t) F_\gamma\left(\frac{E_\gamma}{E_p}, E_p\right) \frac{dE_p}{E_p}$$

Assuming particles fully traverse cloud, observable flux is normalised based on the cloud volume.

Otherwise, a cell-based integration is performed over the partial cloud volume that the particles have traversed.



Model: SNR evolution and particle escape

Particles of different energies are released at different times during the evolution of the SNR.

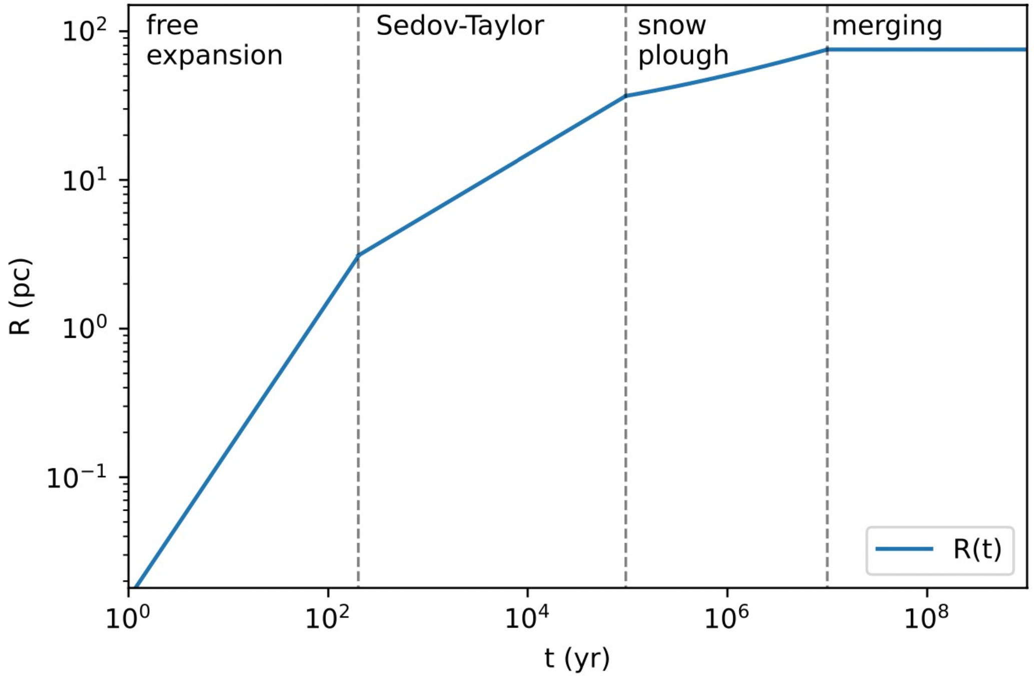
$$t_{\rm esc} = t_{\rm sed} \left(\frac{p}{p_M} \right)^{-1/\beta} \ \ {\rm yr}$$

Assume all SNR considered to be in the Sedov-Taylor phase
(~ 100yr – 50kyr), Sedov time = 1.6kyr (type II), β = 2.5

Meanwhile, the SNR radius also expands.

$$R_{\rm SNR}(t) = 0.31 \left(\frac{(E_{SN}/10^{51}{\rm erg})}{(n/1{\rm cm}^{-3})(\mu_1/1.4)} \right)^{1/5} (t/{\rm yr})^{2/5} \ \ {\rm pc}$$

Then:
- diffuse through ISM to reach cloud
- particle interactions with cloud

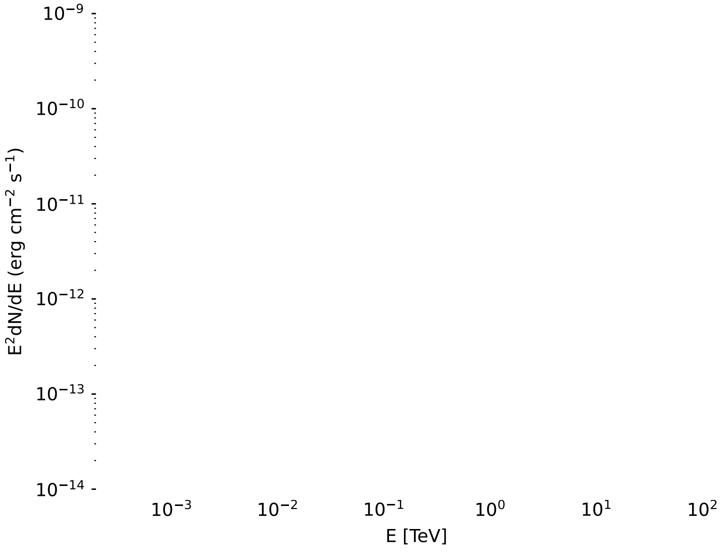


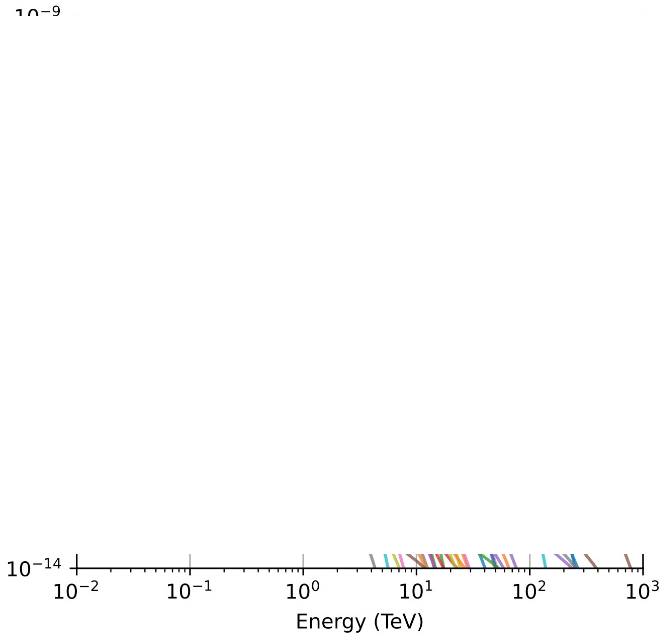
SNRs as PeVatrons

If all SNRs act as PeVatrons for a short time (i.e. Emax at the Sedov time), how many should be detectable now?

Explore parameter phase space of model

Fit to data where possible (e.g. SN 1006, RX J1713...)





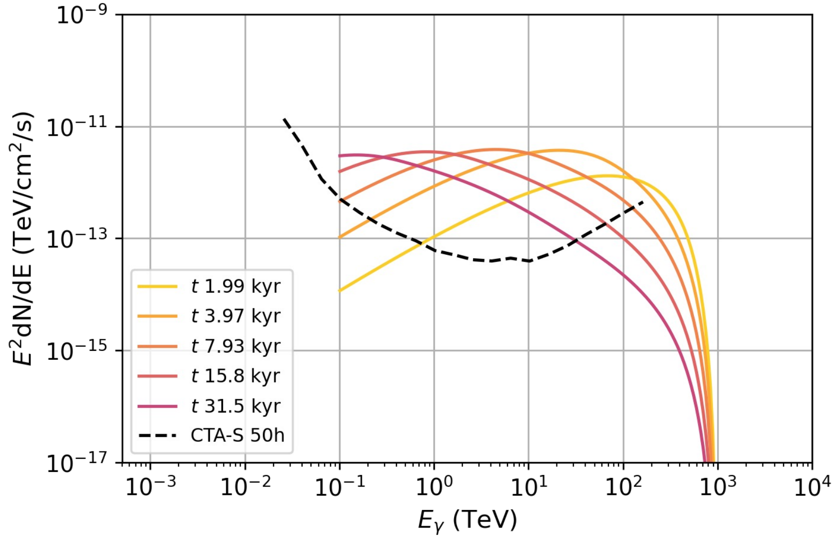
N. Scharrer, V. Joshi, AM

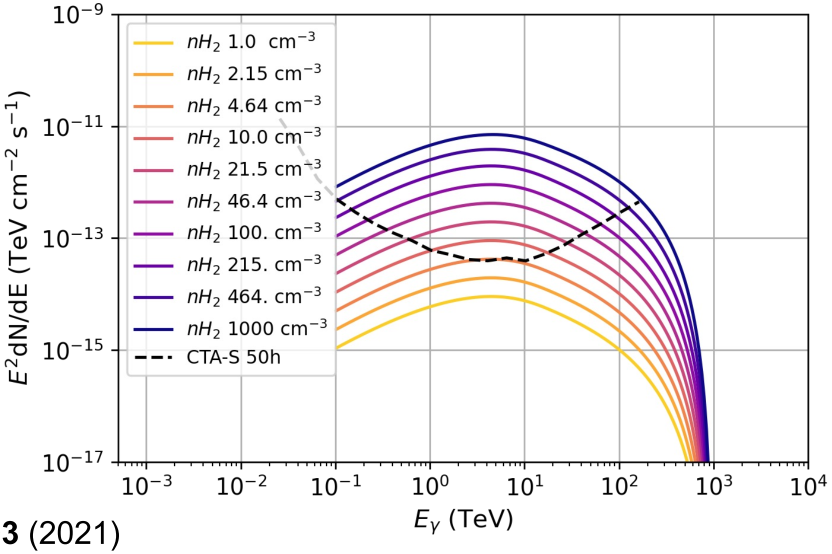
Once particles have been accelerated by the SNR:
- diffuse through ISM to reach cloud
- particle interactions with cloud

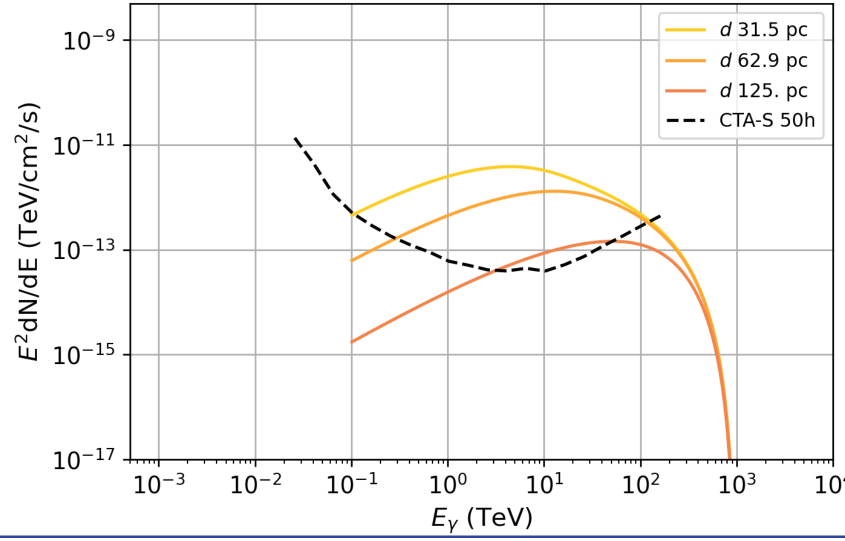
Cloud – SNR properties: example spectra

Primary variables (aside from model assumptions) are:

- SNR age (t): peak shifts to lower energies for older SNRs
- Cloud density (n): higher density = more flux
- SNR-cloud separation distance (d):
  it takes more time for lower energy particles to arrive







AM, Rowell, Celli, Einecke MNRAS **503** (2021)

Clouds in the Galactic Plane: γ-rays above 10 TeV

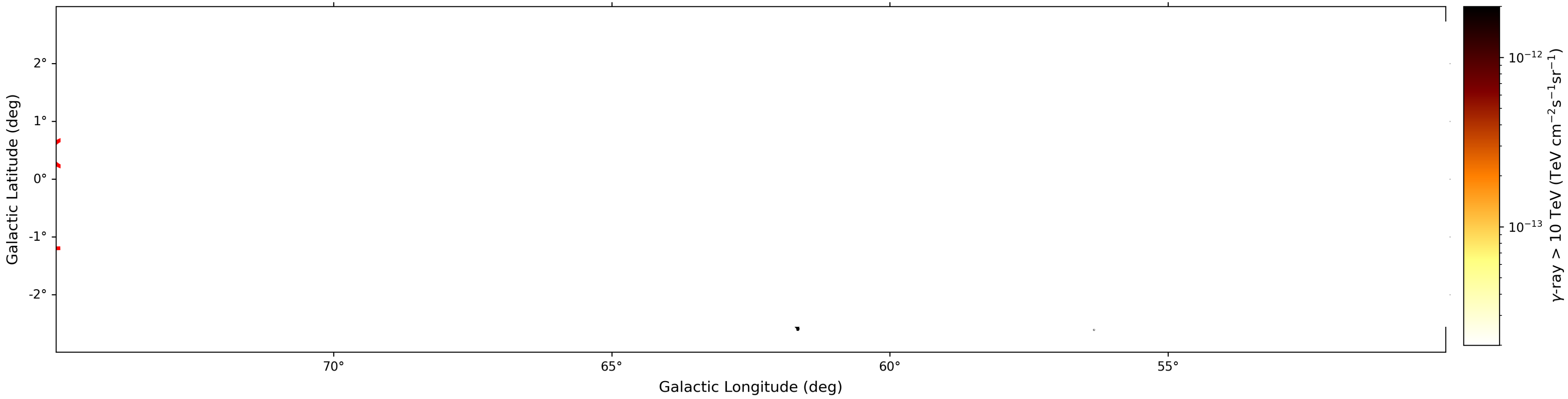
Contours from HGPS sources.

Detectable clouds illuminated by SNRs with colour-scale integral flux.

(Dame CO data, Miville-Deschenes 2017 & SNRCat.)

LHAASO sources with red circles, solid = UHE with emission > 100 TeV

(first LHAASO catalogue, Cao et al. 2023)



Clouds in the Galactic Plane: γ-rays above 10 TeV

Contours from HGPS sources.

Detectable clouds illuminated by SNRs with colour-scale integral flux.

(Dame CO data, Miville-Deschenes 2017 & SNRCat.)

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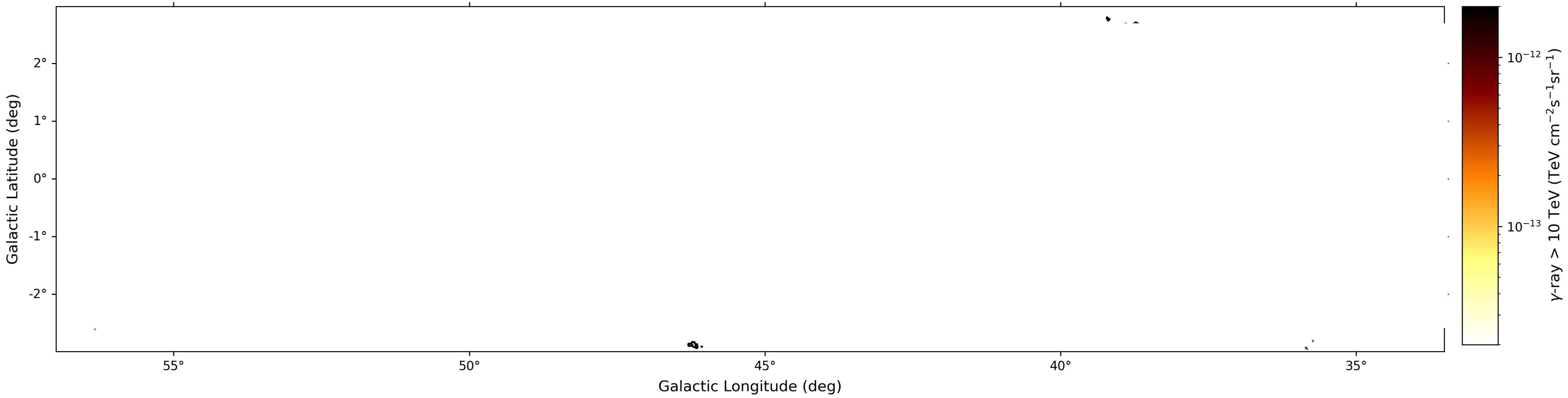

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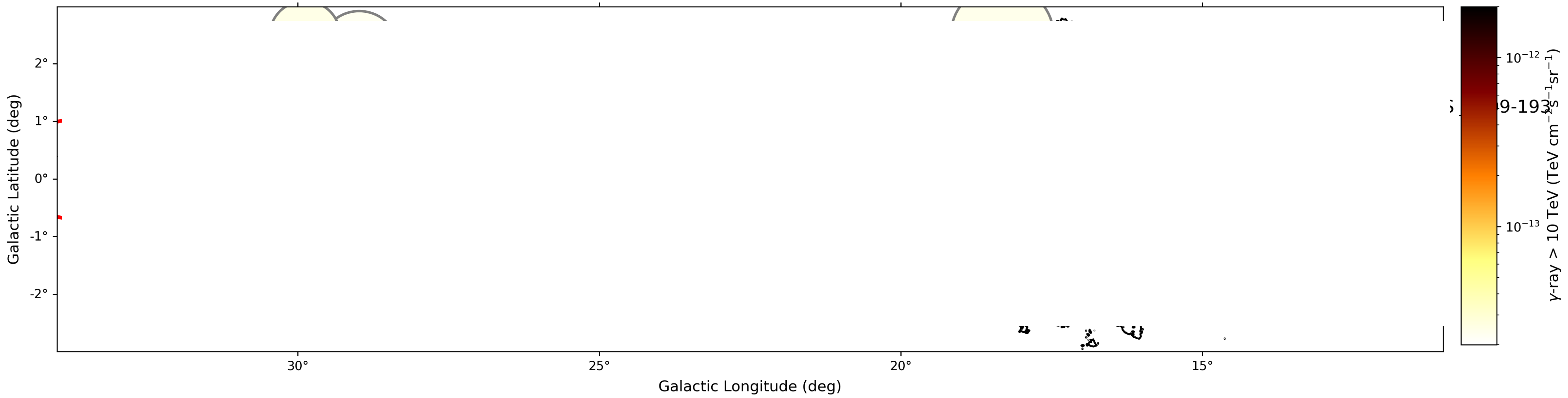
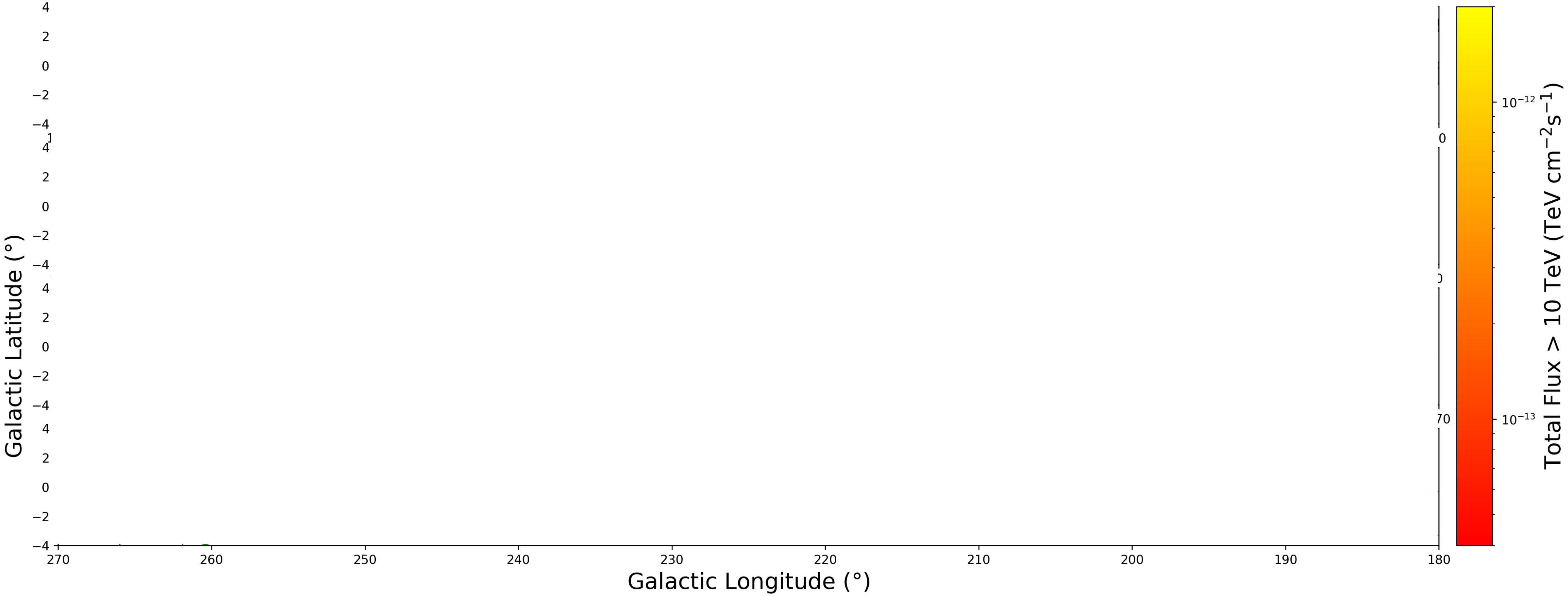


SNR – illuminated clouds along the (full) galactic plane

What about the illumination of clouds by SNRs along the whole plane?

Note – limited by coverage of non-uniform surveys

Search systematically for coincidences along the galactic plane



LHAASO J2108+5157

An intriguing dark source, discovered at UHE (Cao et al. Nature 2021)

Coincident with a molecular cloud, yet no clear accelerator nearby

HAWC detection, Veritas upper limits (Kumar et al, ICRC2023, 941)
Fermi-LAT detection

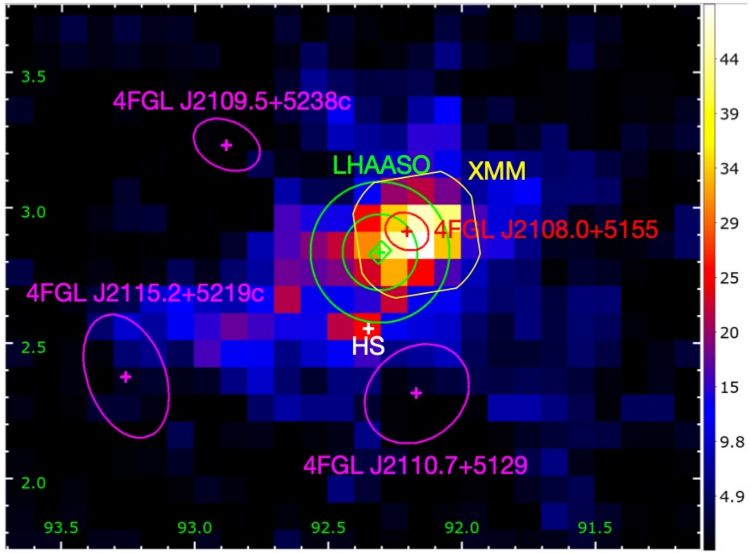
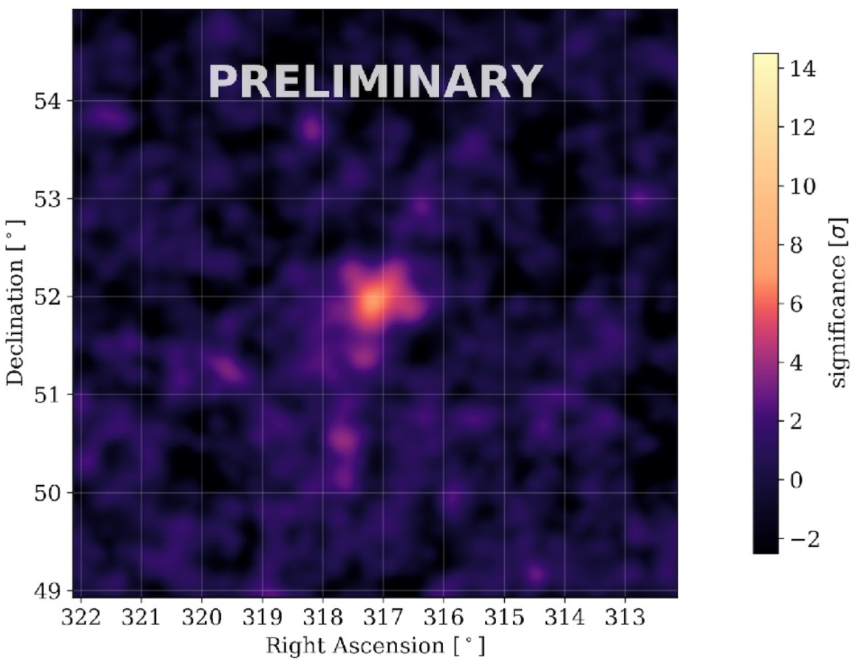
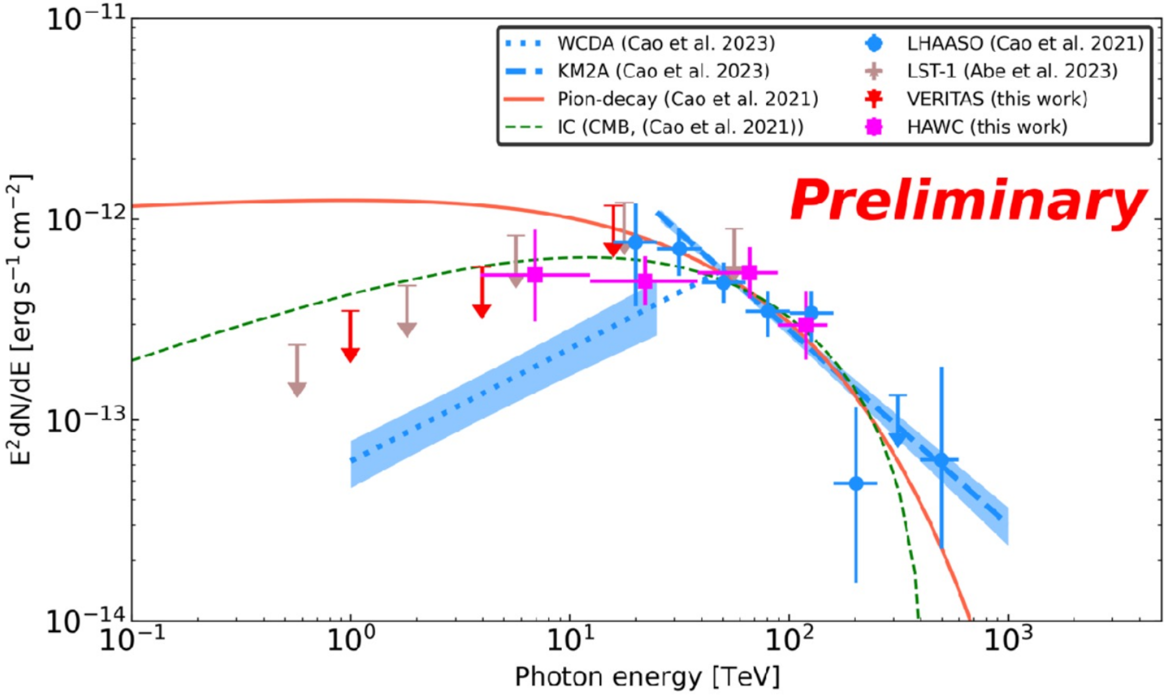


Figure 2: *Fermi*-LAT TS map above 2 GeV





If LHAASO J2108+5157 is a cloud illuminated by an SNR…
…what properties should the SNR have?

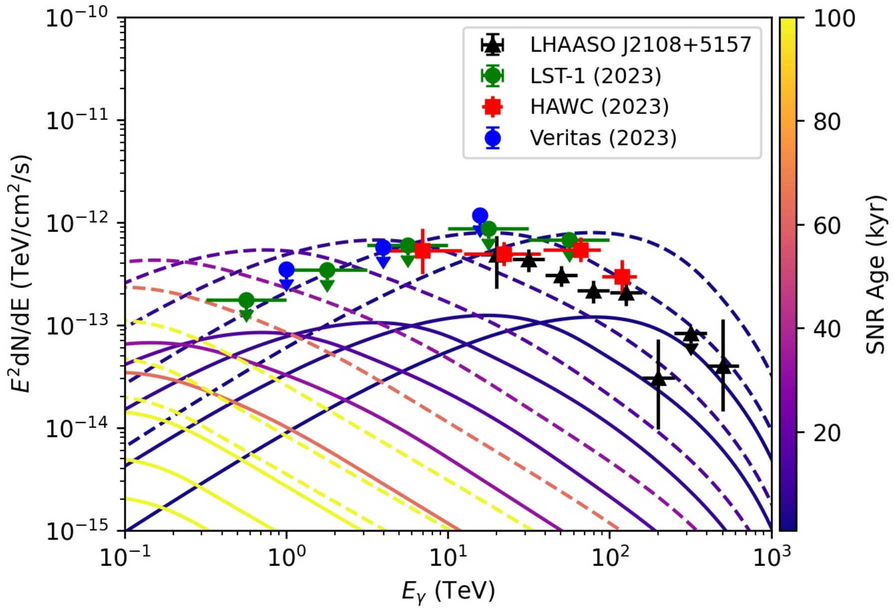
Two molecular clouds coincident with this enigmatic dark source.

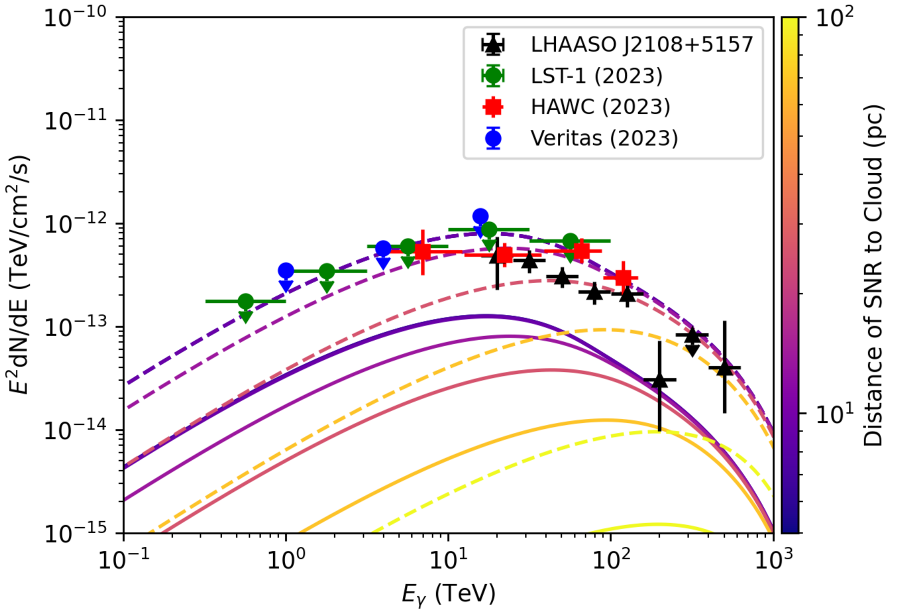
Could be a not-yet-discovered SNR in the vicinity?

- Properties of the clouds are known
- Fix cloud properties and scan possible SNR properties
- Type II SN (also done for type IA)
  Top: fixed cloud-SNR distance 24 pc
  Bottom: fixed SNR age 4 kyr
  Solid lines – MML
  Dashed lines = FKT

Cloud	MML[2017]4607	FKT[2022]
(l (deg), b (deg))	(92.272, 2.775)	(92.4, 3.2)
d (kpc)	3.28	1.7 ± 0.6
n (cm^{-3})	30	37 ± 14
Size (deg)	0.5	1.1 ± 0.2

Miville-Deschênes et al. ApJ (2017)
de la Fuente et al. PASJ (2022)





AM A&A (2023) arXiv:2310.18007

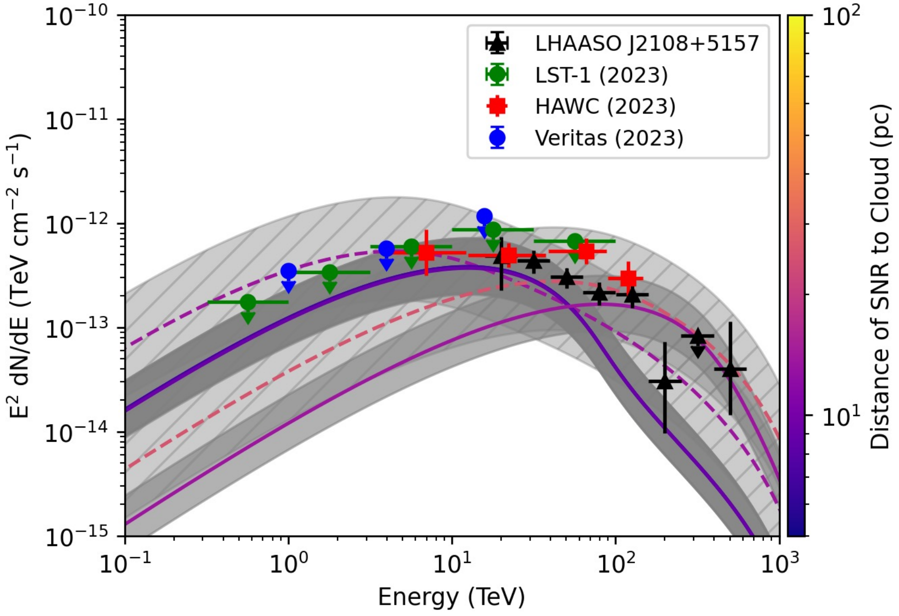
Best matching models to data

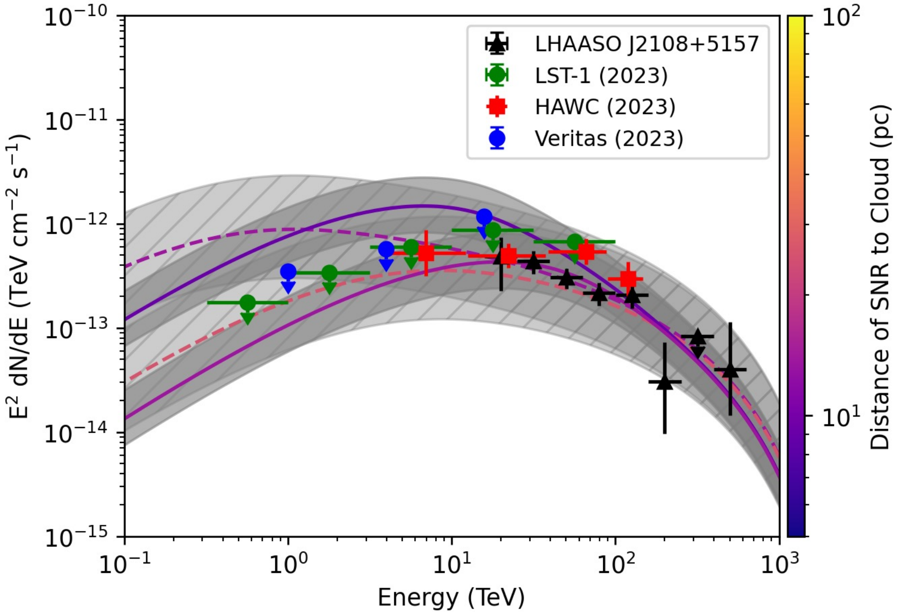
Adopt for the two clouds “MML[2017]4607” (solid) and “FKT[2022]” (dashed) the models that best match the data

Vary properties of the cloud according to the quoted uncertainties in measured parameters (or ~10% minimum uncertainty assumed)

What are the resulting uncertainty bands?
(Left for type II, right type Ia)

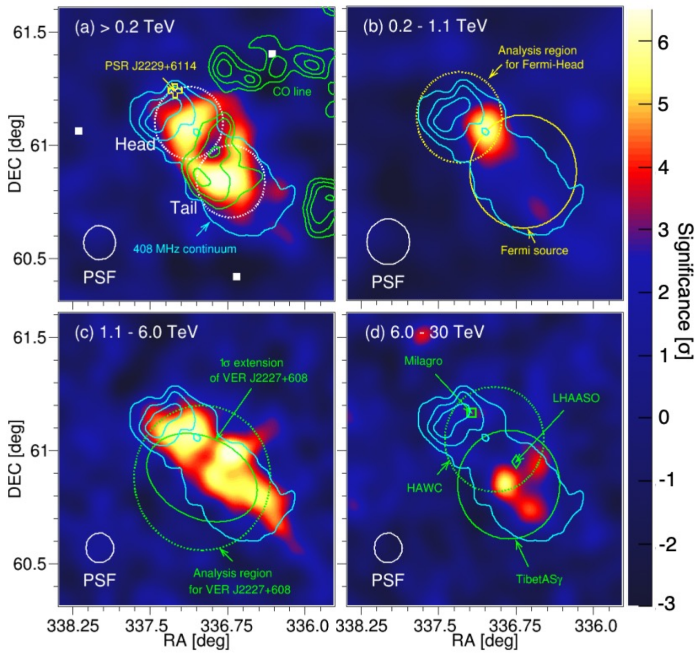
Cloud	t (kyr)	Δd (pc)	SN type	χ^2
MML[2017]4607	1	37	Ia	5.1
FKT[2022]	4	37 *	Ia	6.7
FKT[2022]	4	57	Ia	9.2
FKT[2022]	4	57	II	15.5
FKT[2022]	8	24 **	II	17.0
MML[2017]4607	4	24 **	II	24.4
MML[2017]4607	2	37	II	25.0
MML[2017]4607	1	24	Ia	28.2





AM A&A (2023) arXiv:2310.18007

Other potential SNR + cloud interaction systems



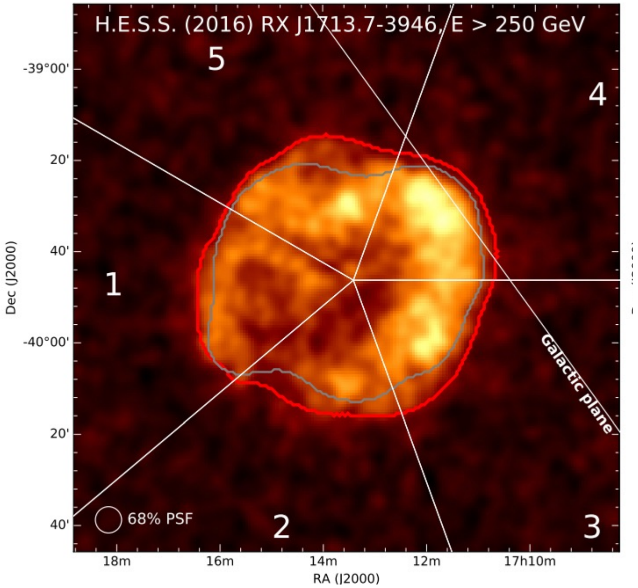
MAGIC collaboration, A&A **671**, A12 (2023)

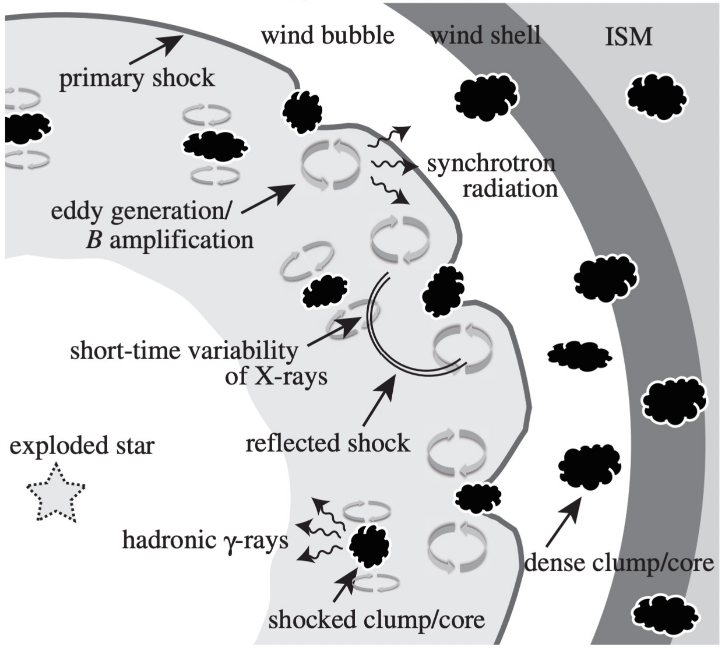
Within the first LHAASO catalogue, 7 sources are dark, 8 have only gamma-ray (GeV) counterparts.
At least two cases could indicate escaping CRs → but further follow-up studies are needed

SNR G106.3+2.7 & the Boomerang nebula
Complex region containing SNR, PWN with energetic pulsar, and molecular material
→ Many recent publications!

RX J1713.7-3946
Evidence for gamma-rays extending beyond the X-ray shell and shock interaction with molecular material (CO, HI) surrounding the SNR

...and several others.
(e.g. HESS J1731-347...)





HESS collaboration A&A **612**, A6 (2018)

Inoue et al. ApJ **744**, 71 (2012)

White Dwarfs?

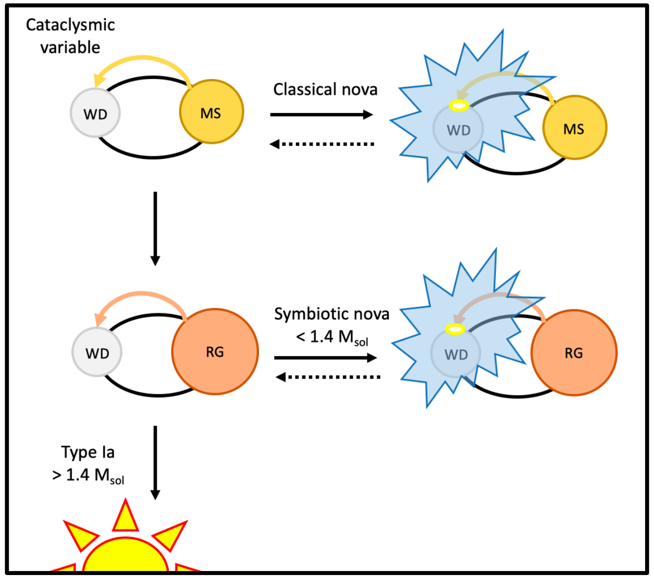
White dwarfs in binary systems → Novae

– outbursts from accreting binary systems (White Dwarf + massive donor)

Recurrent Novae → multiple observed outbursts

Nuclear fusion ignited on surface of white dwarf → thermonuclear explosion

Dramatic increase in optical brightness → Typical optical duration weeks to months



RS Ophiuchi in 2021:

H.E.S.S. collaboration, Science **376** (2022) 77-80

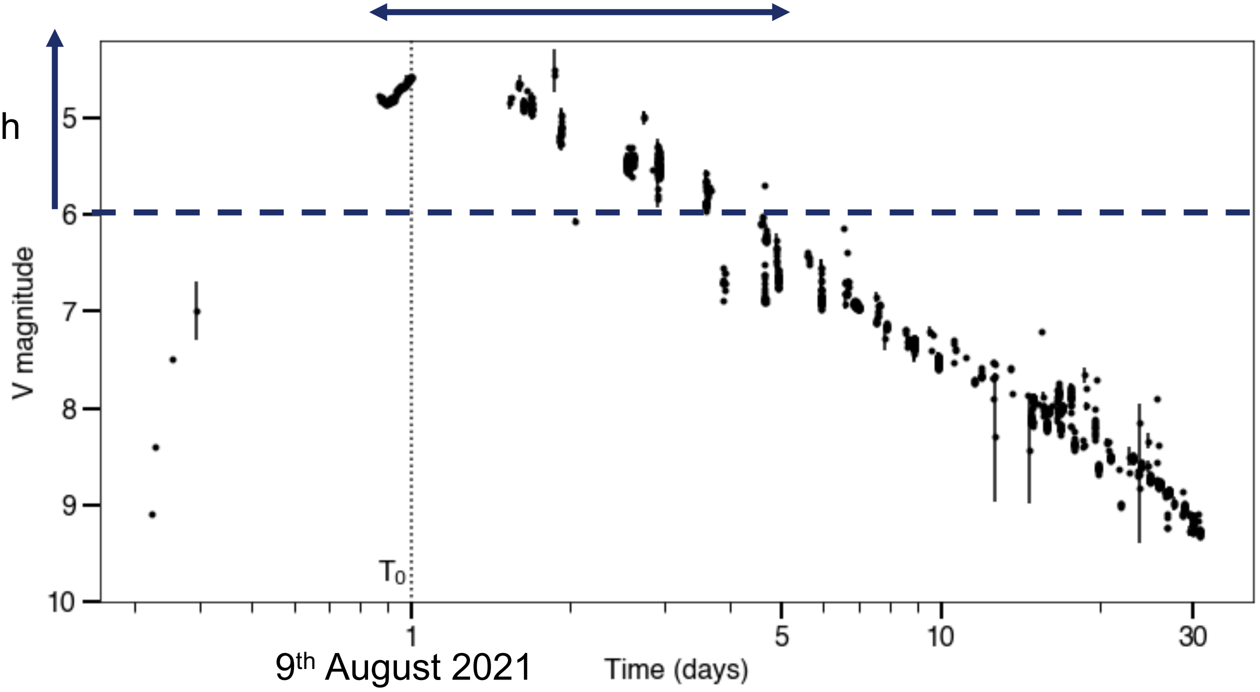
MAGIC collaboration, Nature Astronomy **6** (2022) 689-697

First Nova in VHE gamma-rays: RS Ophiuchi in 2021

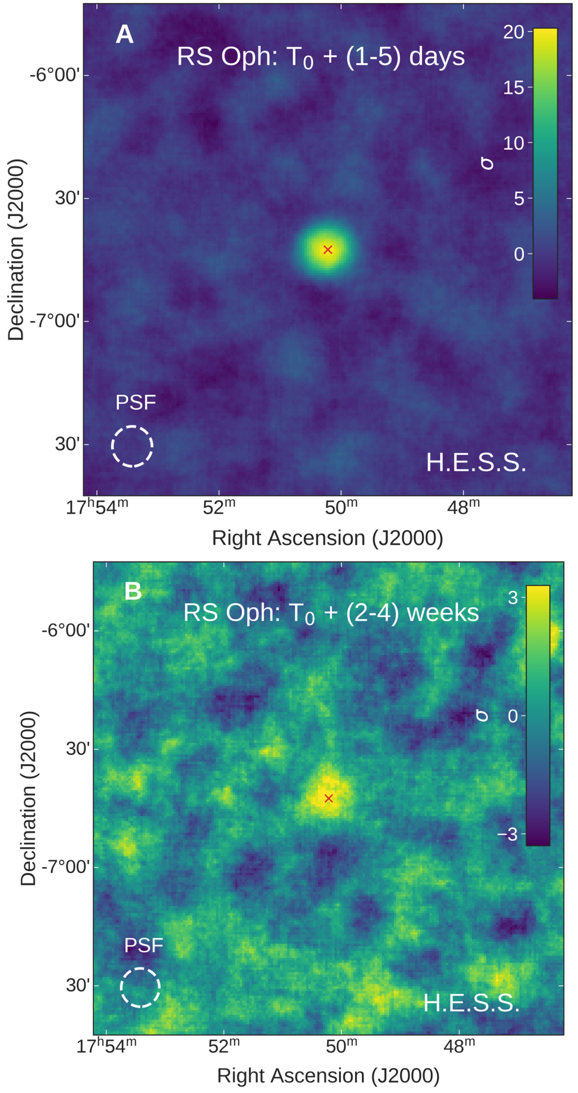
- →Binary system comprised of white dwarf and red giant at about 1.4 kpc
- → Explosions observed since 1898 : most recently in 12th February 2006 and **8th August 2021**
- → Detected by IACTs in VHE gamma-rays over days to weeks
- → Factor 100x higher energy reached than seen in other novae

8. -- 13. August 2021

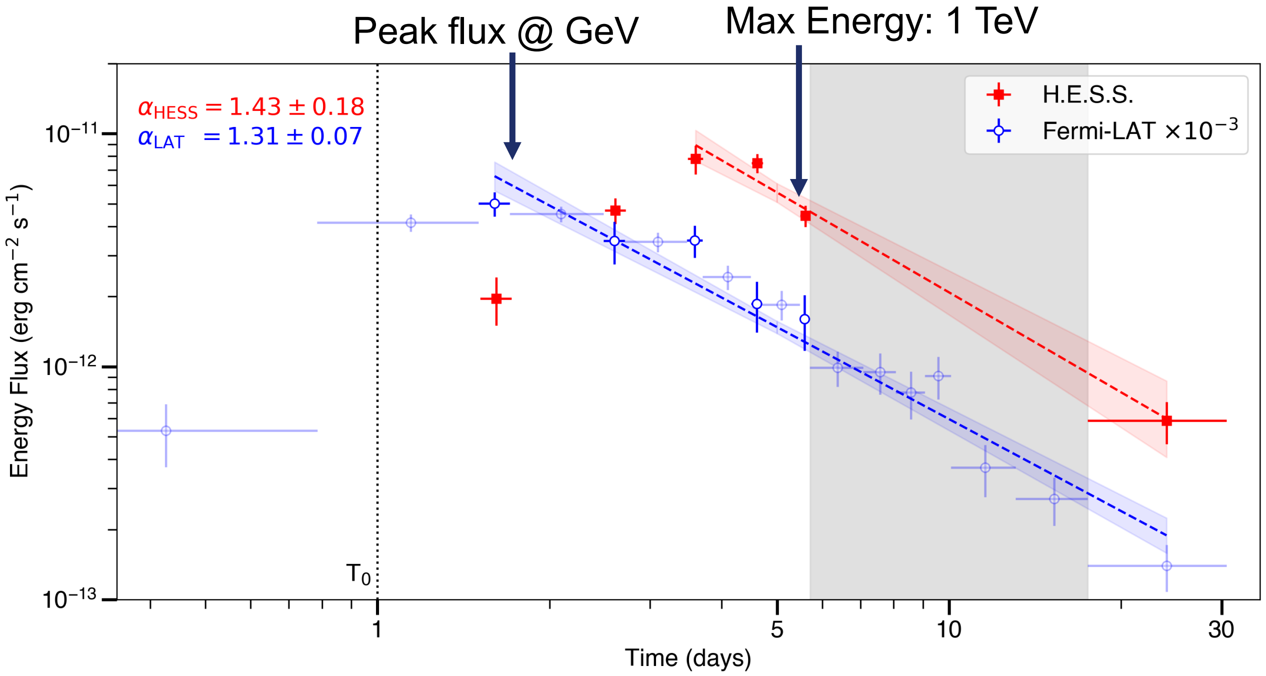
Range visible with the naked eye



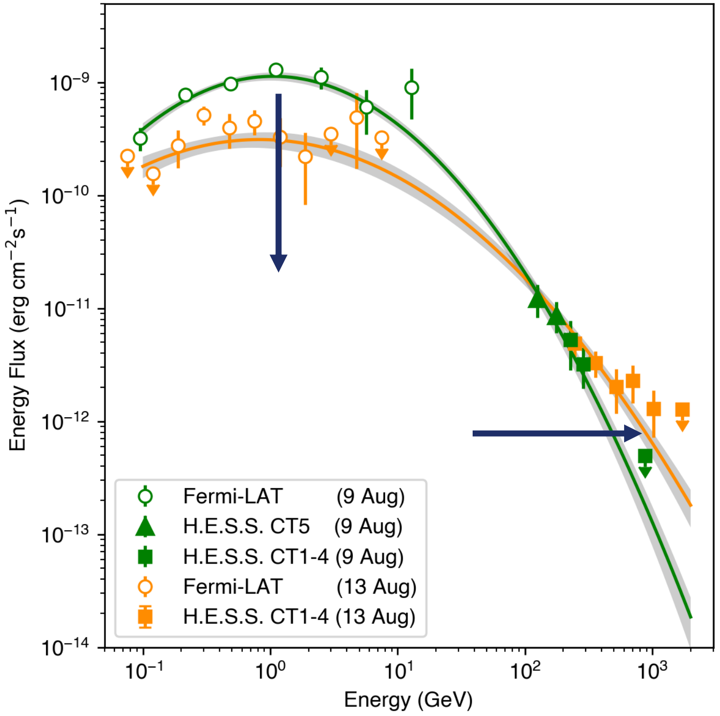
9th August 2021



RS Ophiuchi: gamma-ray evolution


Peak flux @ GeV

Max Energy: 1 TeV



Theoretical limit max energy for Diffusive shock acceleration reached

- → It takes time to reach the maximum energy
- → Necessary efficiency is reached in nature!
- → If efficiency scales up to supernovae, results support supernovae as the origin of galactic cosmic rays.

A new type of Cosmic Ray accelerator

Next one → T Coronae Borealis?

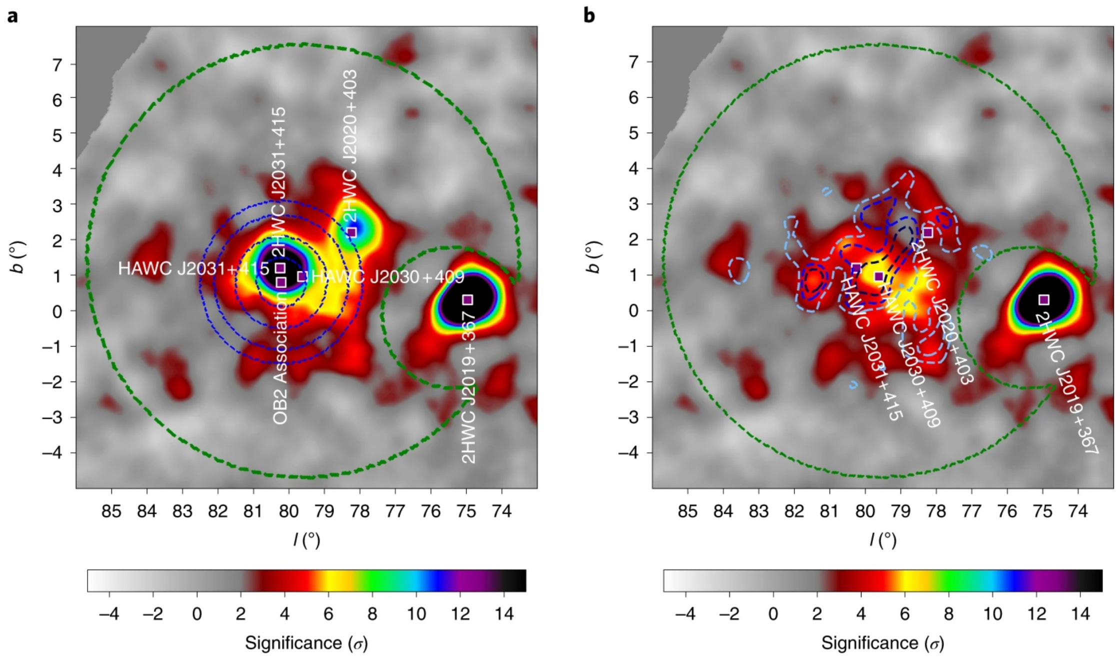
Expected in 2024, likely to be bright → Watch this space...

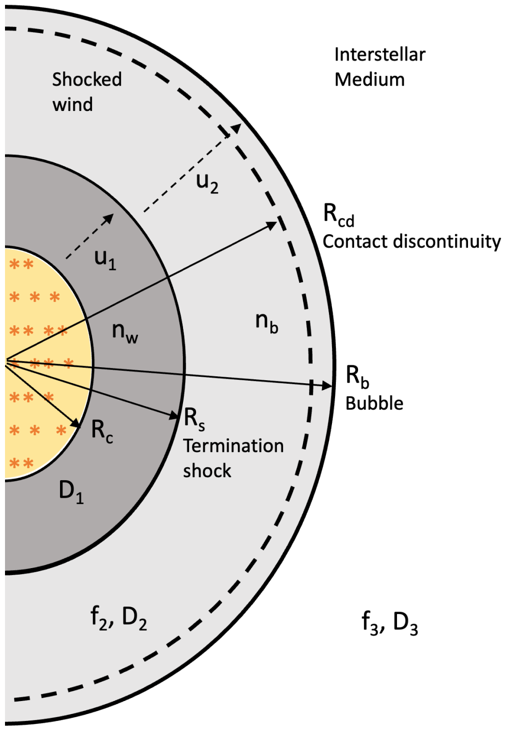
Stellar Clusters

Stellar Clusters

(see talk by S. Celli)

- Collective stellar winds drive a shock in the interstellar medium
- Requires typically young stellar clusters / massive star forming regions
- Highest energy photon measured to date: 1.42 ± 0.13 PeV → from Cygnus region?
  LHAASO J2032+4102 (Cao et al. Nature **594** (2021) 33-36)
- HAWC Cygnus cocoon (Nature Astro. **5** (2021) 465-471)



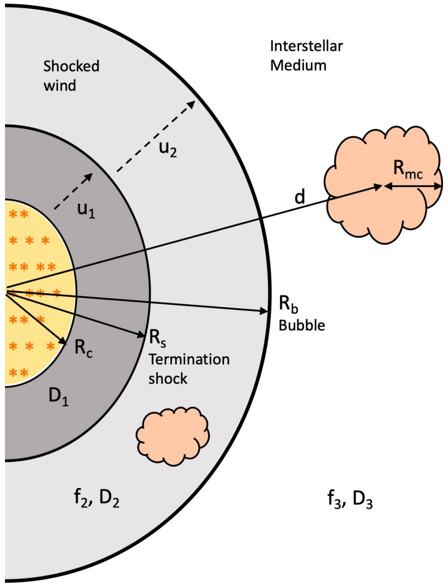


Q: Which stellar clusters are the most promising PeVatron candidates?

Model from Morlino et al. MNRAS **504** (2021) 6096-6105

Which stellar clusters are PeVatrons?

- Most promising clusters identified based on Gaia catalogue
- Caveat: cluster bubbles have a large angular size (1º - 10º)
  → low surface brightness
- Next:
  → use molecular cloud catalogues to identify those in the vicinity of stellar clusters that are promising targets for hadronic interactions
  → predict gamma-ray flux (enhancement) from these clouds.



S. Celli, AM, A. Specovius, G. Morlino, S. Menchiari (ICRC2023)

Are galactic UHE gamma-ray sources active or passive?

- Many more sources and source classes now known above 100 TeV than anticipated
- Highest energy particles are among the earliest to escape from the vicinity of the **active** accelerator
- These particles may traverse across the intervening medium to interact with nearby **passive** interstellar clouds

Implications:
→ Expect a population of passive sources emerging at the highest energies that are illuminated by nearby active accelerators.

→ Expect that many accelerators (especially SNRs) are only active PeVatrons for a brief period of their lifetime, and may not be exhibiting PeVatron activity now

→ Can search instead for evidence of past PeVatron activity via passive targets.

Some sources may be active accelerators, but many could be passively illuminated by nearby accelerators or galactic CRs.

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Thank you for your attention

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