Friedrich-Alexander-Universität
Erlangen-Nürnberg

Erlangen Centre for Astroparticle Physics

Gamma-ray insights into the origins of galactic Cosmic Rays

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Junior Research Group Leader

DESY seminar, 24/11/2023

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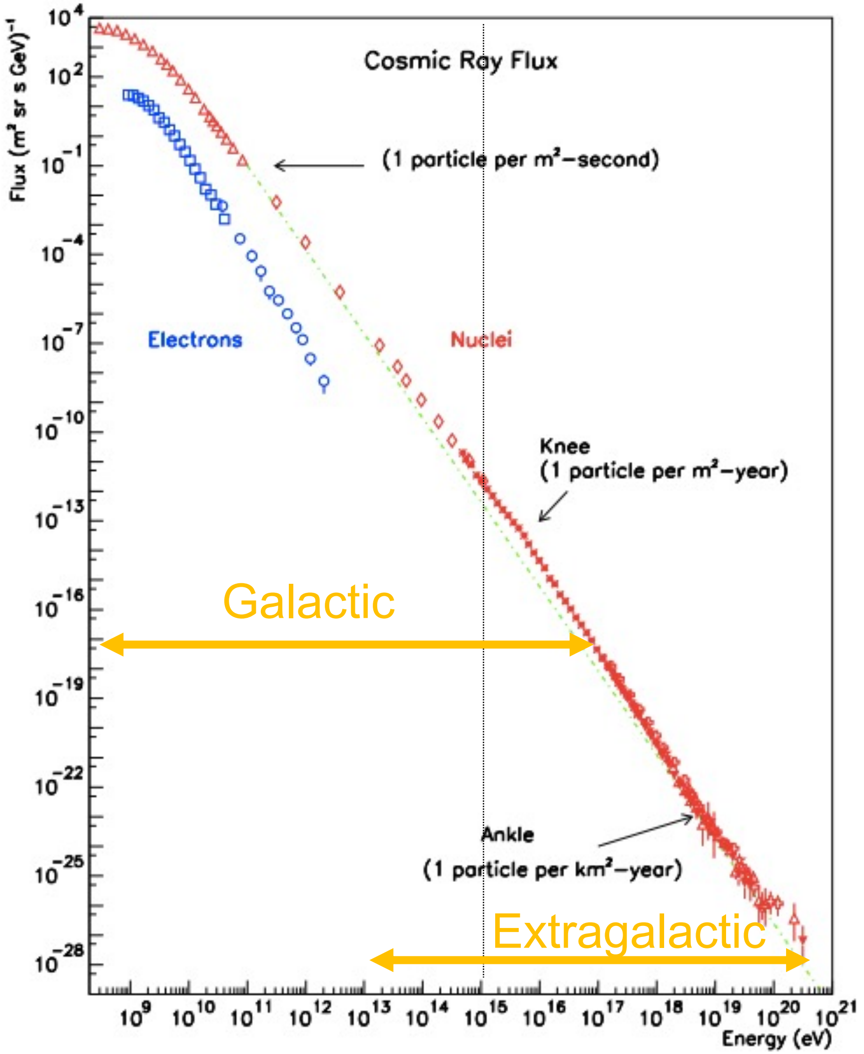
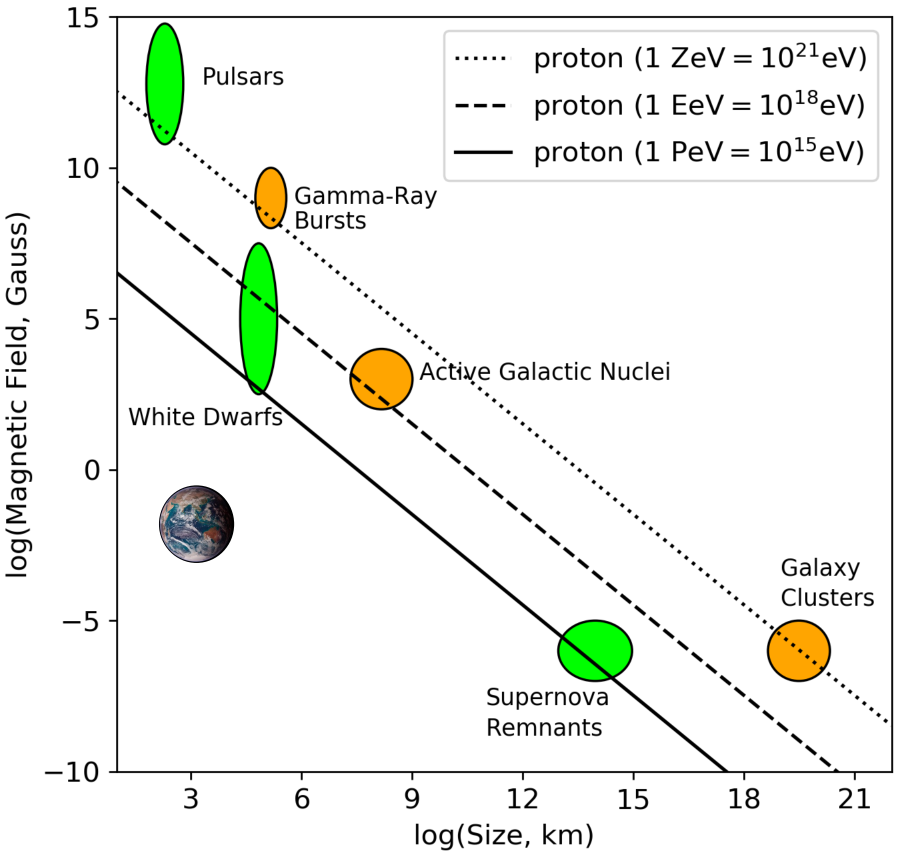
German Research Foundation

Cosmic Ray sources



- Transition from galactic to extragalactic between "knee" at 10^{15} eV and "ankle" at 10^{18} eV
- Central component of our Galaxy – energy density comparable to starlight, dust, magnetic fields...
- "PeVatrons" = accelerators of particles to energies ≥ 10^{15} eV



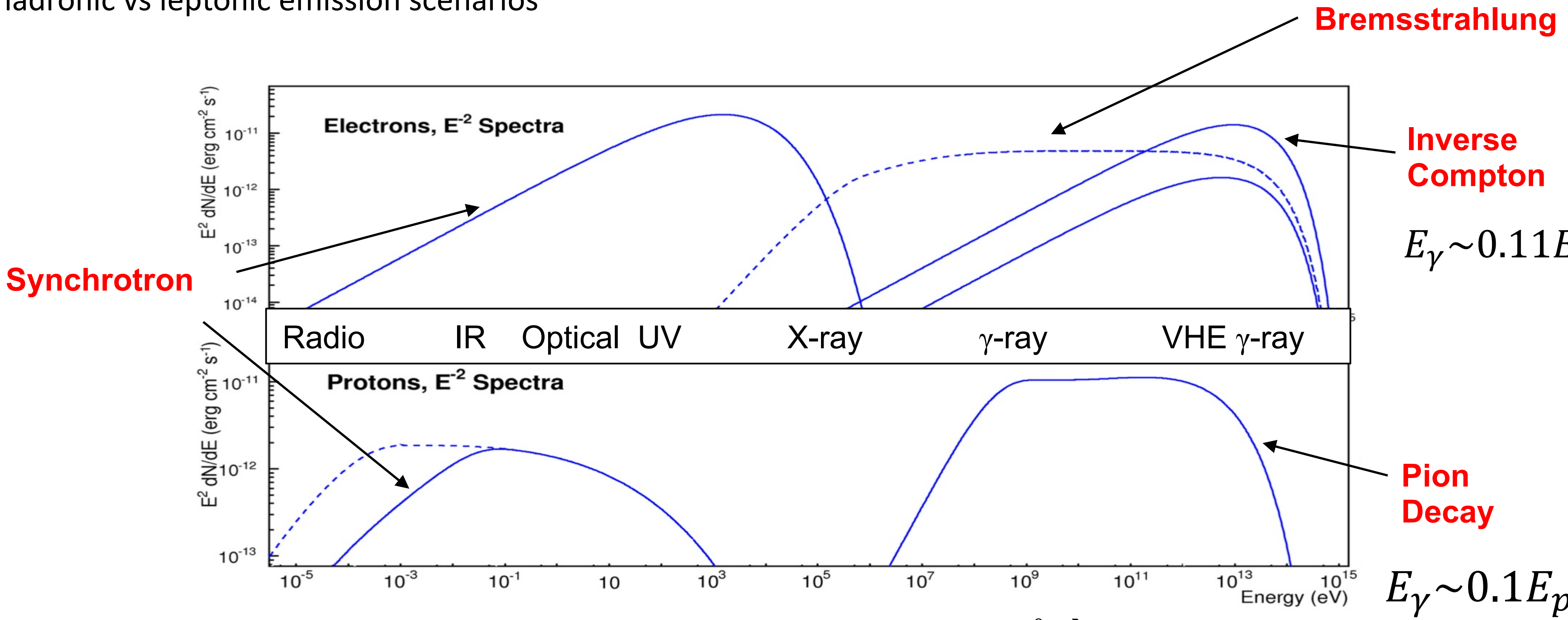
$$E_{\max} = Ze\beta cBL$$

Very-High-Energy Gamma-ray Astronomy

Gamma-ray emission mechanisms

Searching for the origins of hadronic cosmic rays

→ Constrain hadronic vs leptonic emission scenarios



$E_\gamma \sim 0.11 E_e$

$E_\gamma \sim 0.1 E_p$

$\pi^0 \rightarrow \gamma + \gamma$

Target molecular material for hadronic interactions?

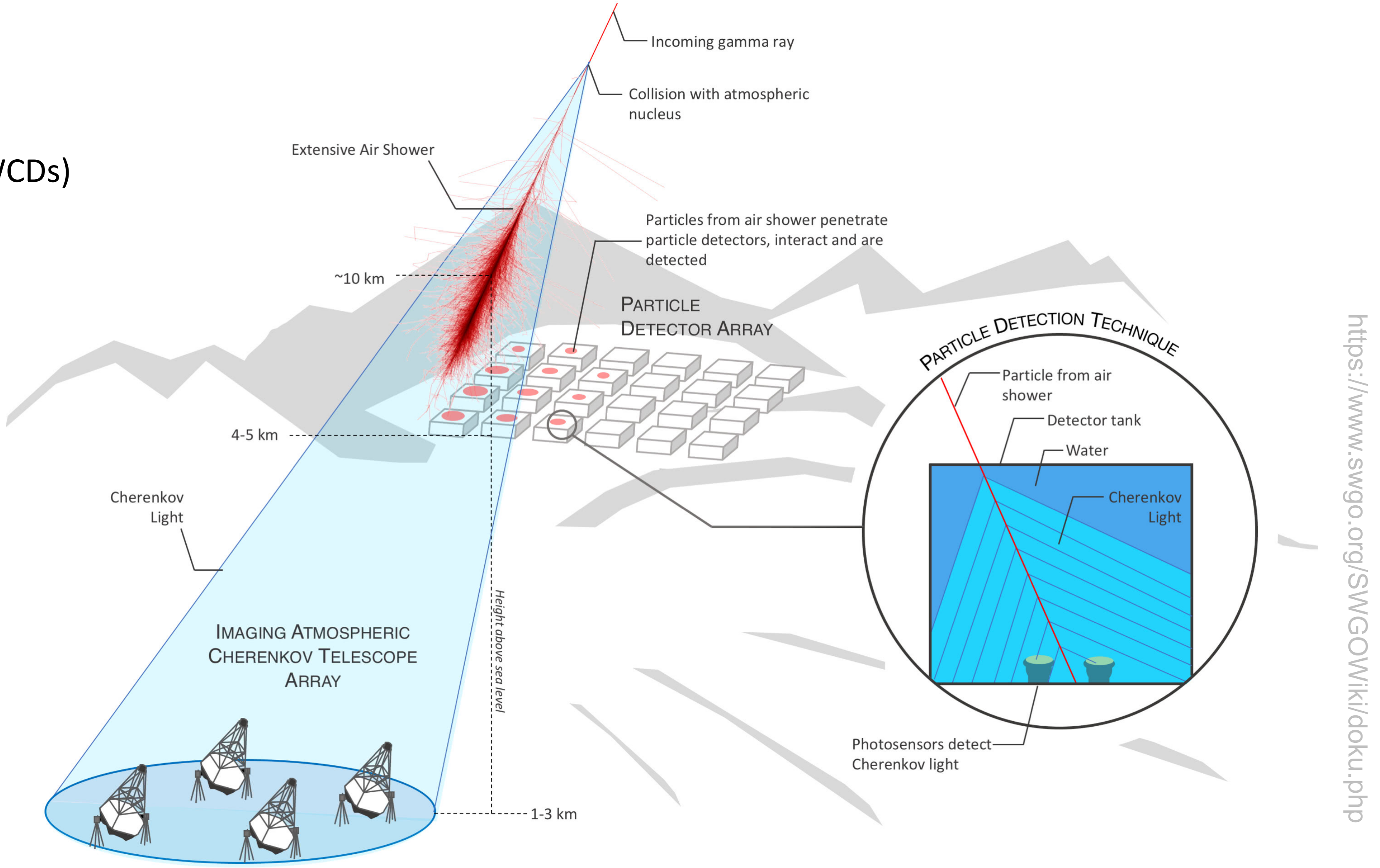
Coincident neutrinos as a smoking gun?

$\pi^+ \rightarrow \mu^+ + \nu_\mu\ ,\ \ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

Detection Techniques for Very-High-Energy gamma-rays

Two main detection methods:

- **Particle detector arrays:**
  - Water Cherenkov Detectors (WCDs)
  - Up to 24/7
- **Imaging Atmospheric Cherenkov Telescopes (IACTs)**
  - Night only, low moon
- ...or a combination



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Not to scale

Complementary Gamma-ray Facilities

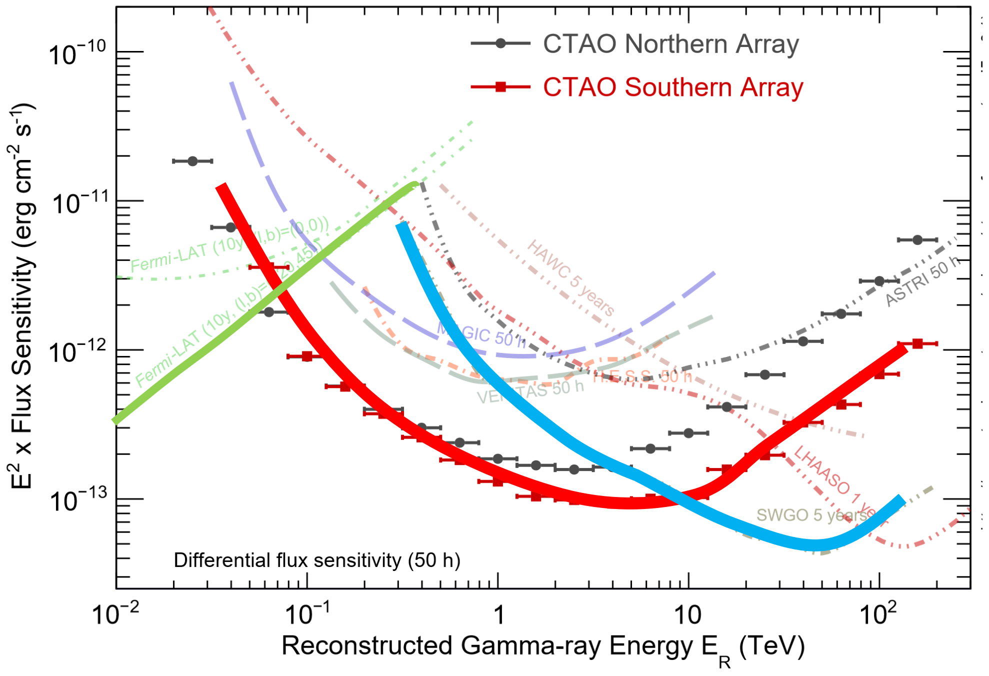
Different techniques → different performance.
Trade-off between sensitivity and resolution

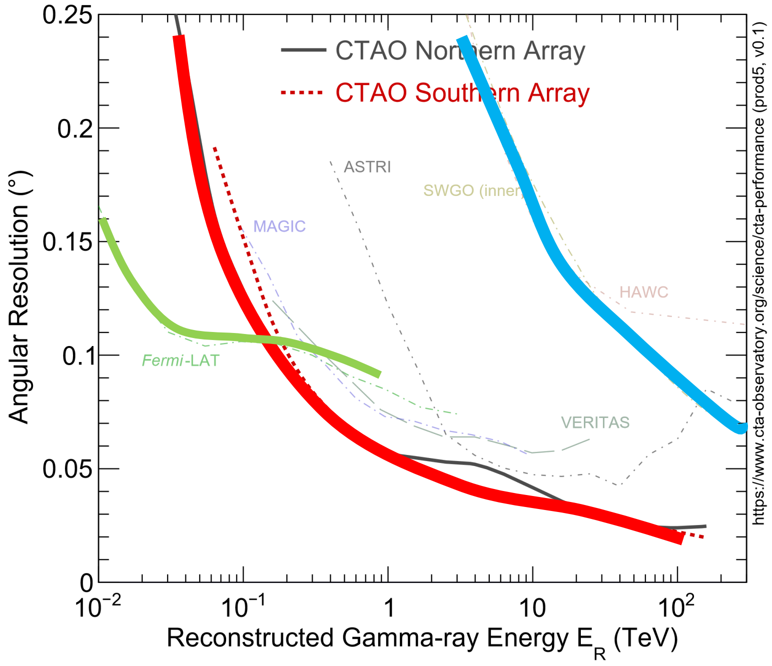
IACTs

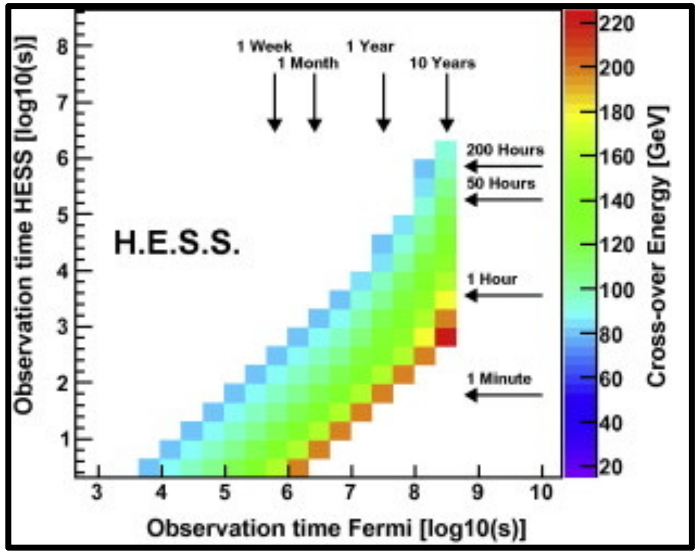
WCDs

Satellite

Cross-over energy depends on exposure (and zenith angle, instrumentation...)





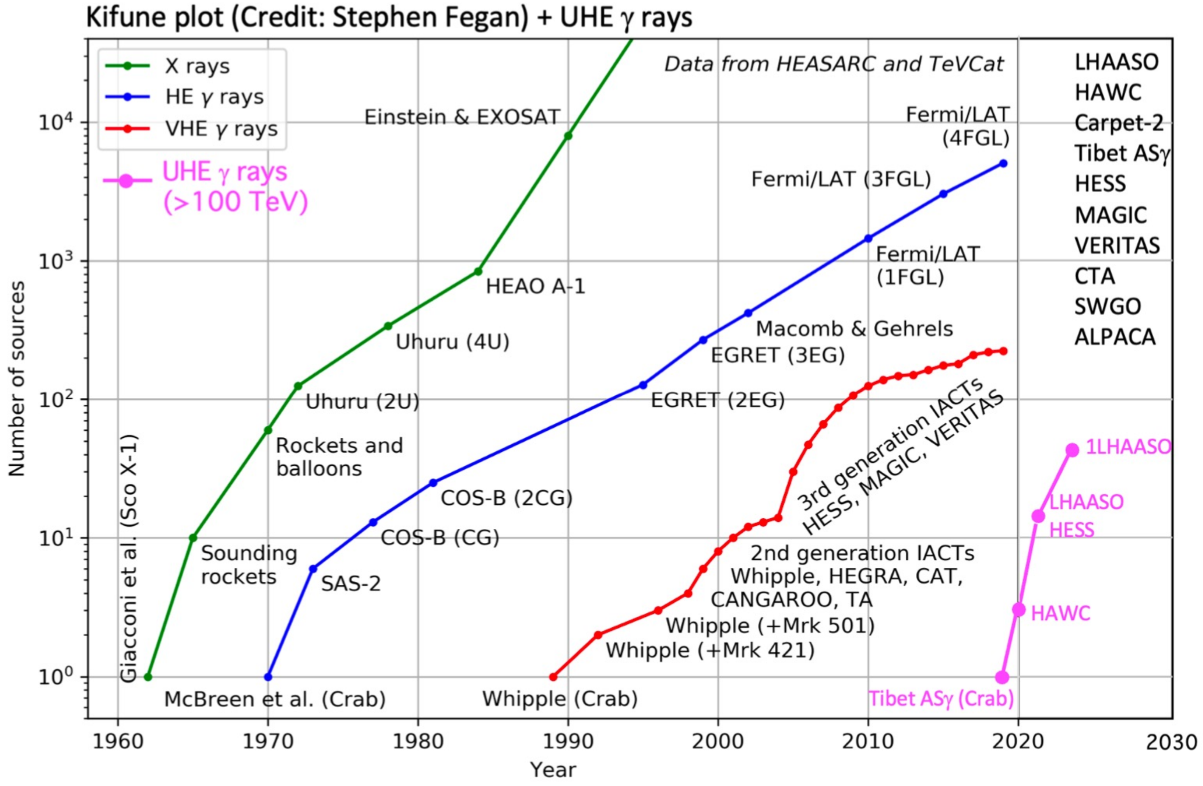


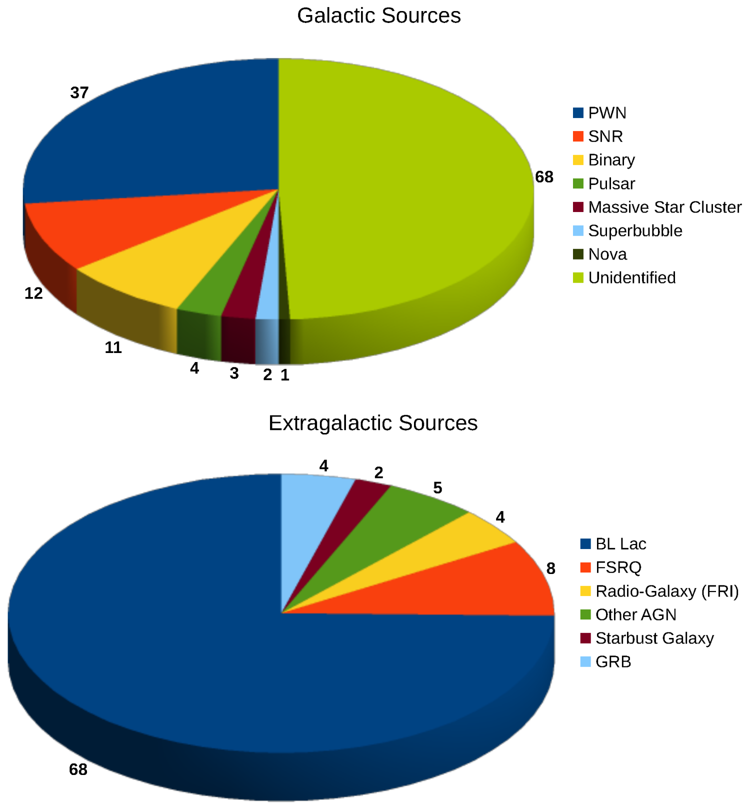
https://www.cta-observatory.org/science/ctao-performance/

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

Gamma-ray sources

Within the last few years, massive growth in the number of known sources at UHE (≥100 TeV) (mainly thanks to HAWC & LHAASO)



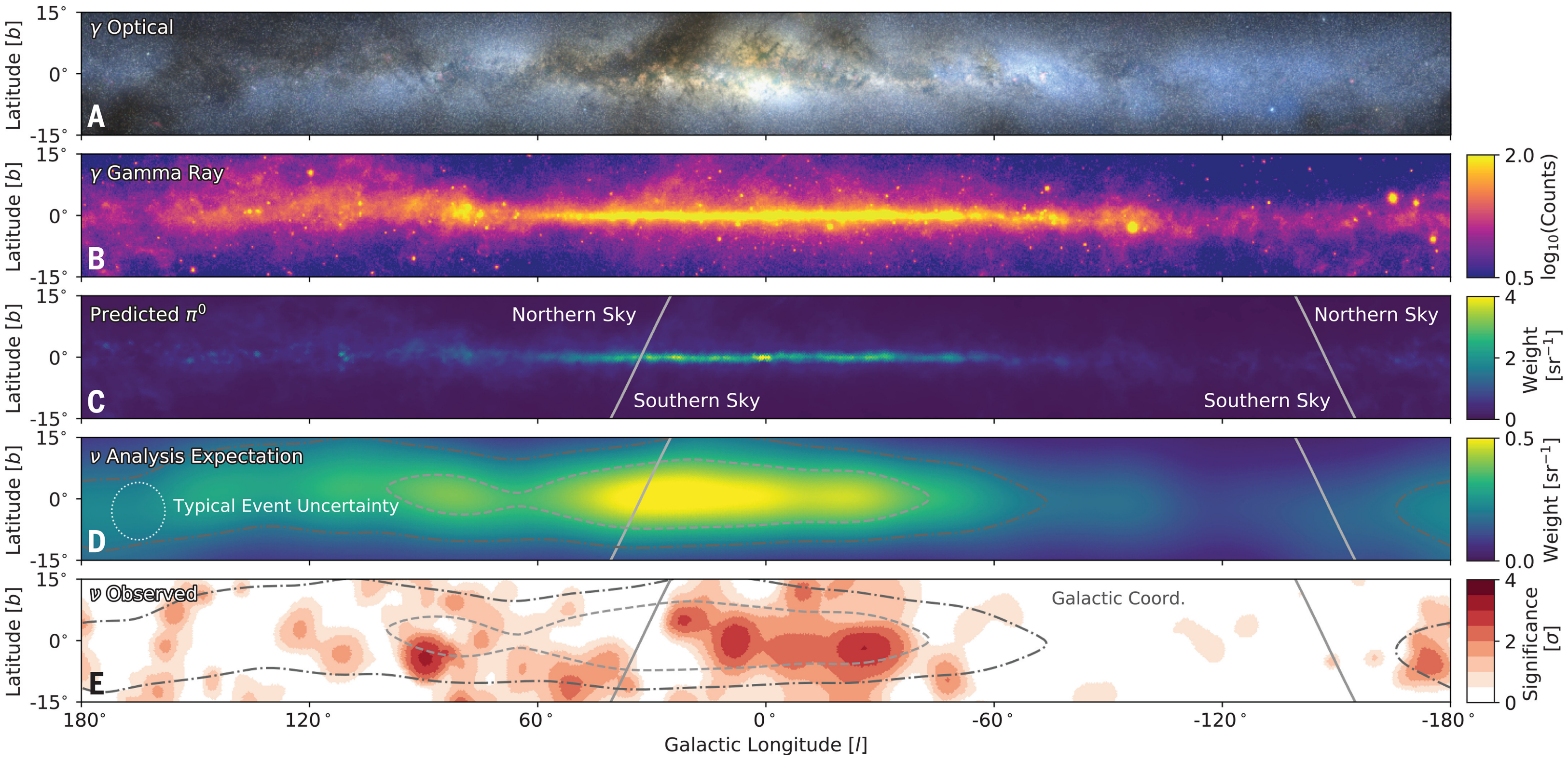


Neutrinos – a hadronic smoking gun

Detection of the Galactic Plane in neutrinos – at 4.5σ in 10 years of IceCube data (June 2023)

No significant associations with known VHE gamma-ray sources (yet)

IceCube Collaboration Science **380** (2023) 1338-1343

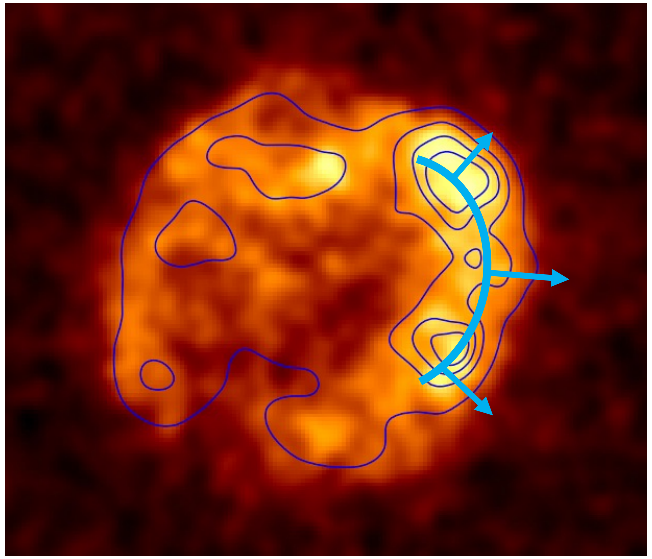


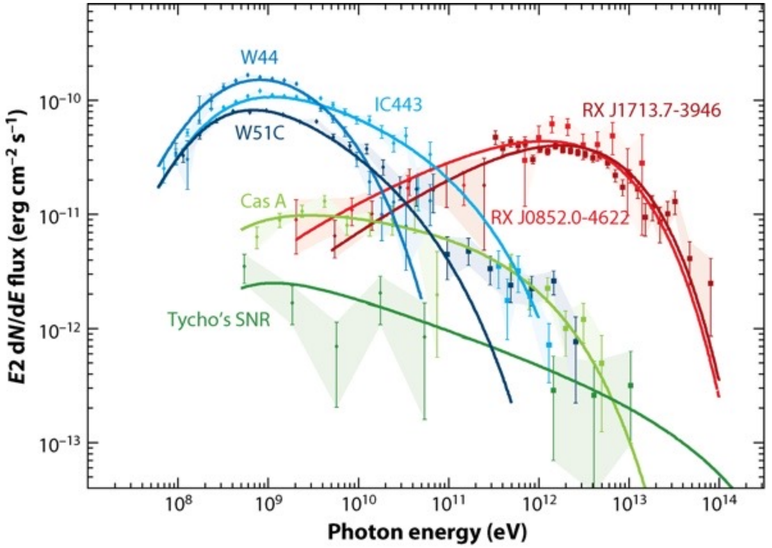
Supernova Remnants

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

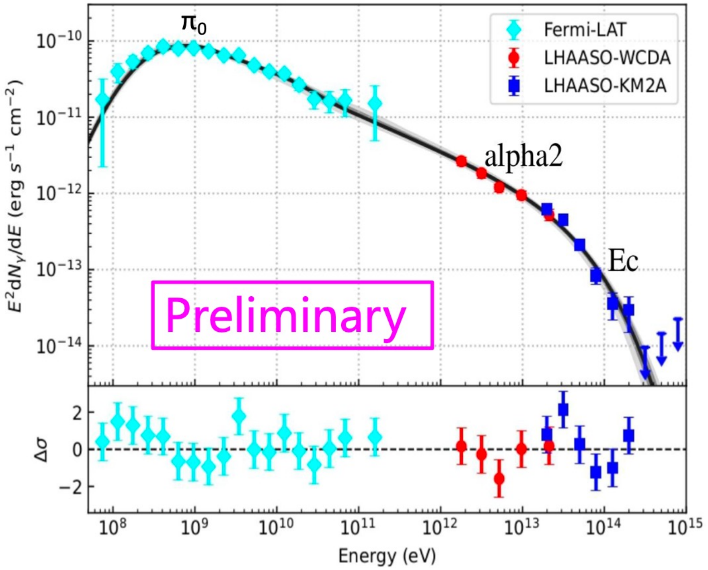




Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

However, few SNRs seem to reach PeV energies.

Recent results show ≥ 100 TeV emission from SNRs W51C and G150.3+4.5 (tbc)

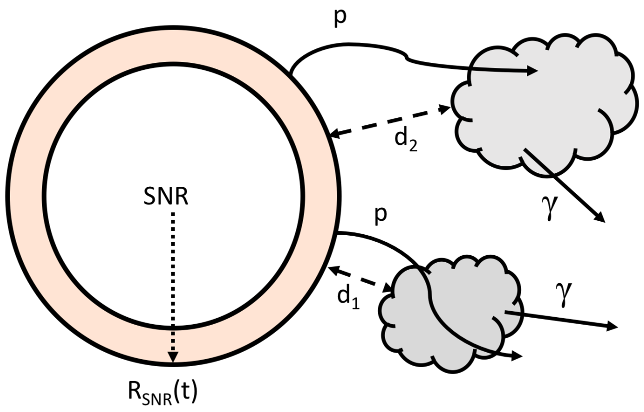


Illuminating molecular clouds?

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)

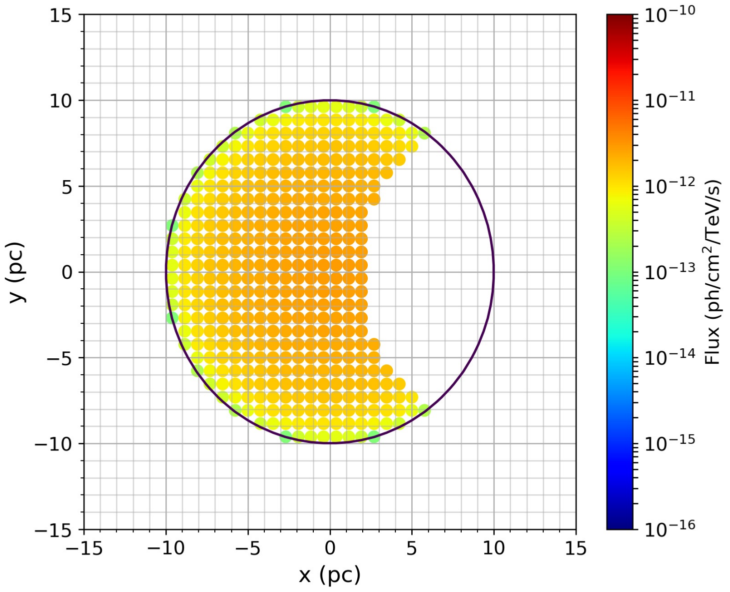
$$f(E,r,t) \approx f_0 \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_d^3} \exp\left(-\frac{(\alpha-1)t}{\tau_{pp}} - \frac{R^2}{R_d^2}\right)$$

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

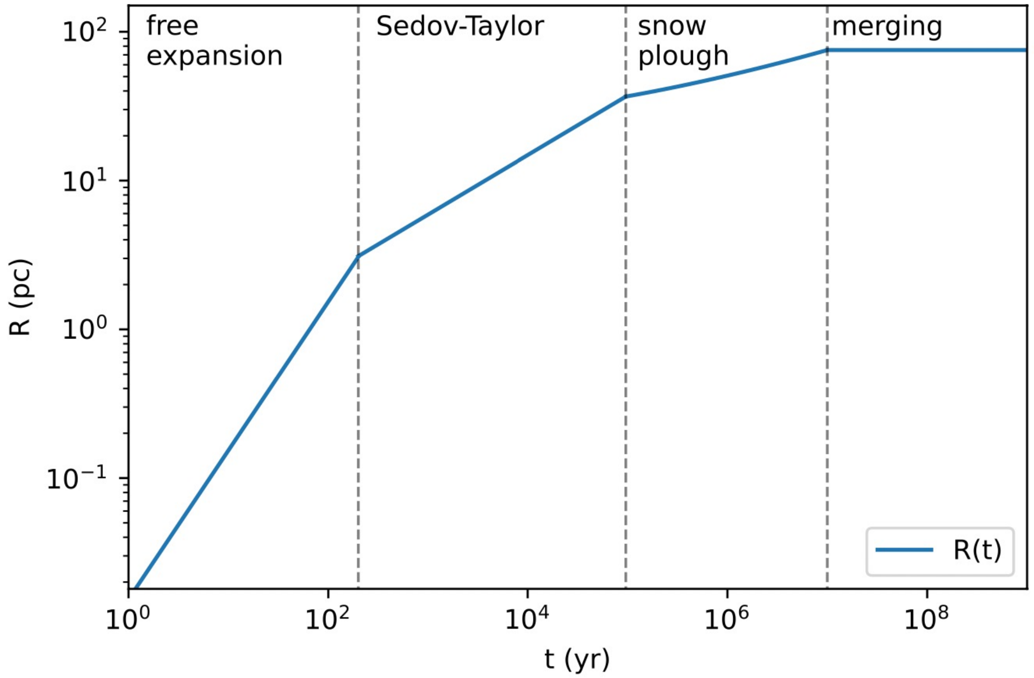
Particles of different energies are released at different times during the evolution of the SNR.

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

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.

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



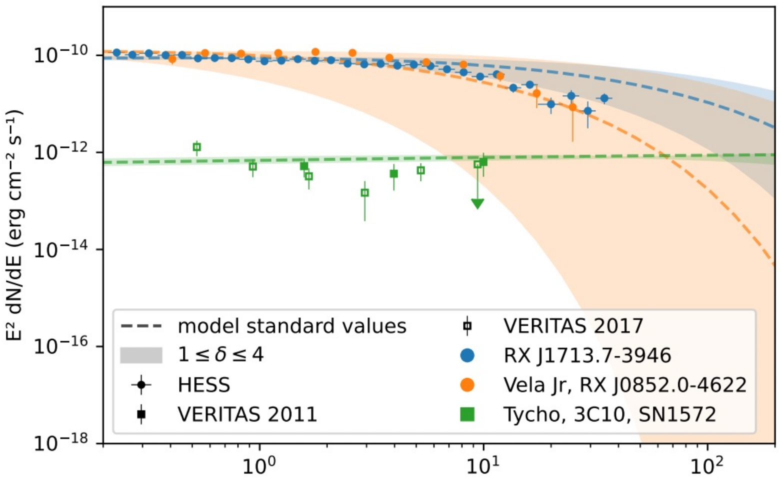
N. Scharrer

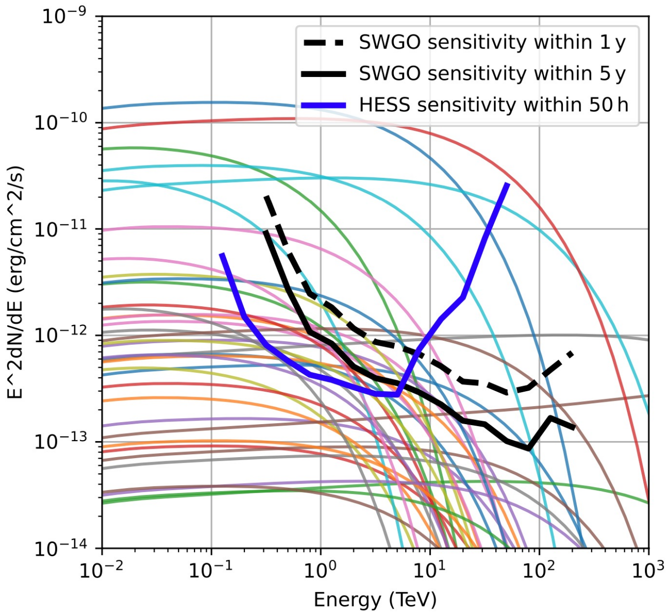
SNRs as PeVatrons

If all SNRs act as PeVatrons for a short time, how many should be detectable now?

Explore parameter phase space of model

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



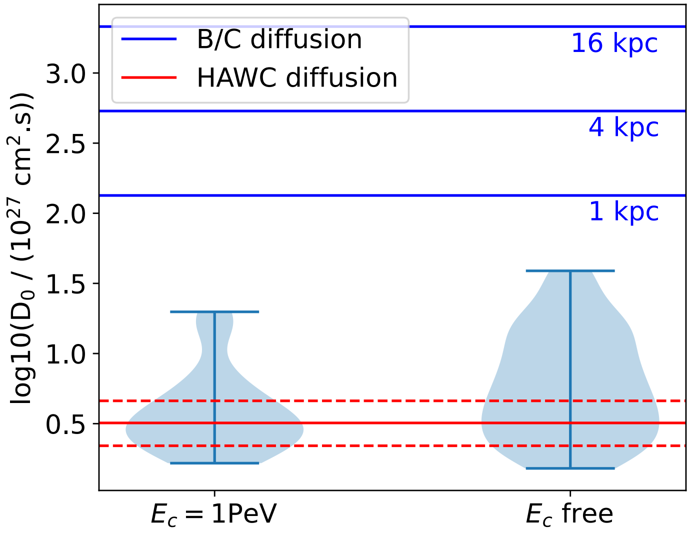


N. Scharrer, V. Joshi, AM

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

Model: Diffusion Properties

- Diffusion radius R_d , simplifies in the ISM to: $R_d = 2\sqrt{D(E)t}$
- Diffusion Coefficient D_0 tested with *fast* and ***slow*** values: $$D(E) = \chi D_0 \left(\frac{E_p(\mathrm{GeV})}{B(n)/3\mu\mathrm{G}} \right)^{\delta}$$
- $D_0 = 3{\times}10^{27}\,\mathrm{cm}^2$ /s at 1 GeV , and a factor 10 slower.
  With δ = 0.5 and χ = 0.05 (cloud) or 1 (ISM)
- Slow diffusion value adopted → in general, suppressed in the vicinity of powerful accelerators due to CR turbulence
- Example: diffusion normalisation as determined from data around the Geminga pulsar (D_0 at 100 TeV)

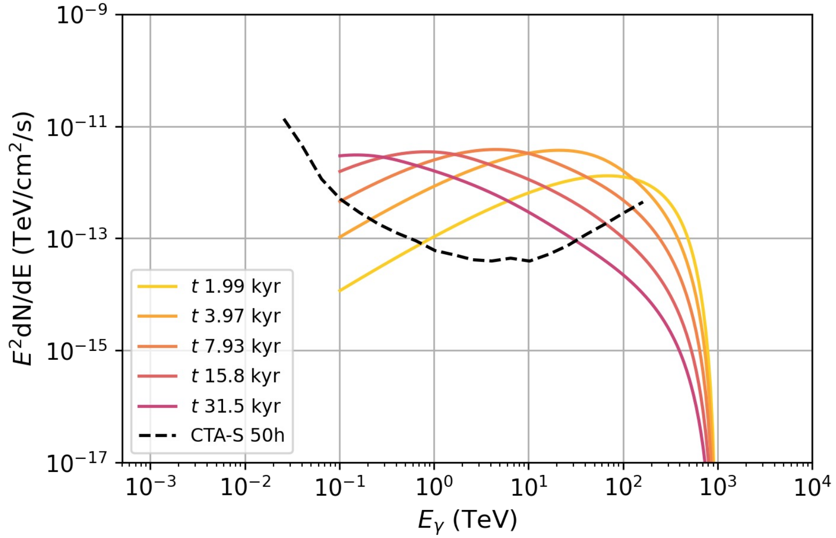


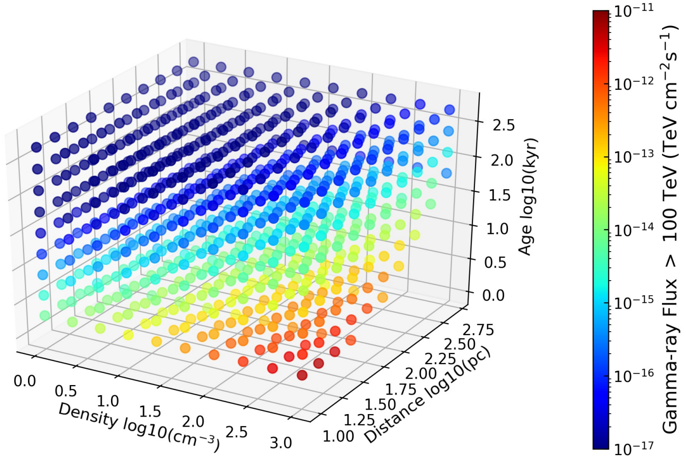
H.E.S.S. collaboration A&A **673** A148 (2023)

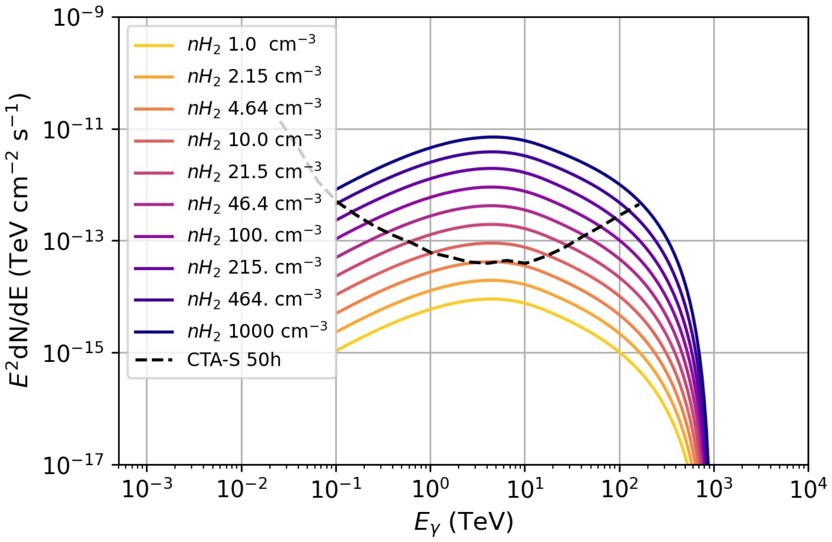
Cloud – SNR properties: example spectra

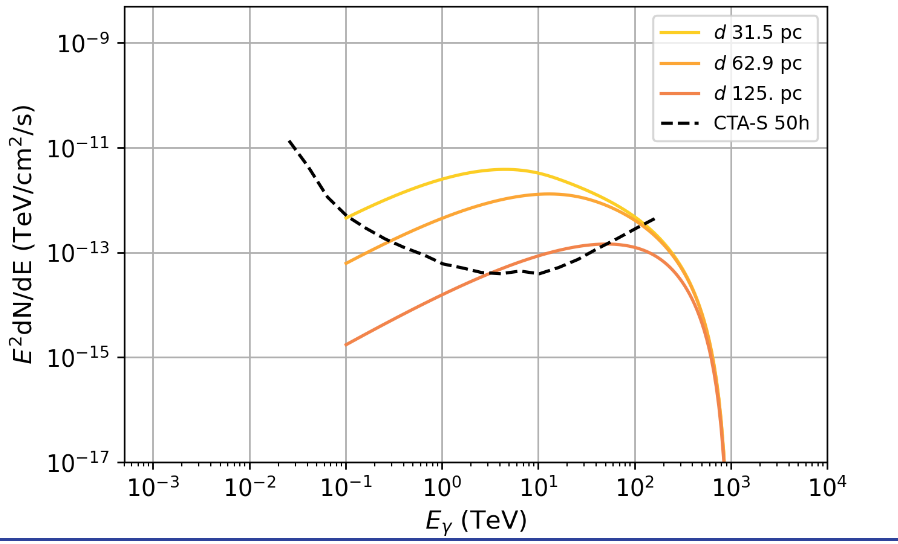
Primary variables (aside from model assumptions) are:

- 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









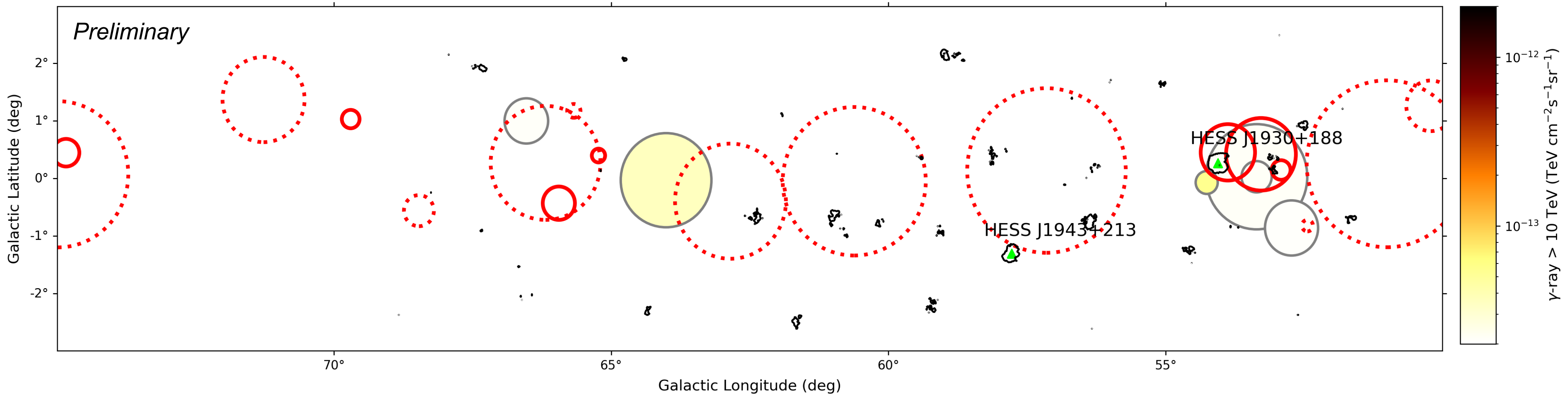
AM, Rowell, Celli, Einecke MNRAS **503** (2021)

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)



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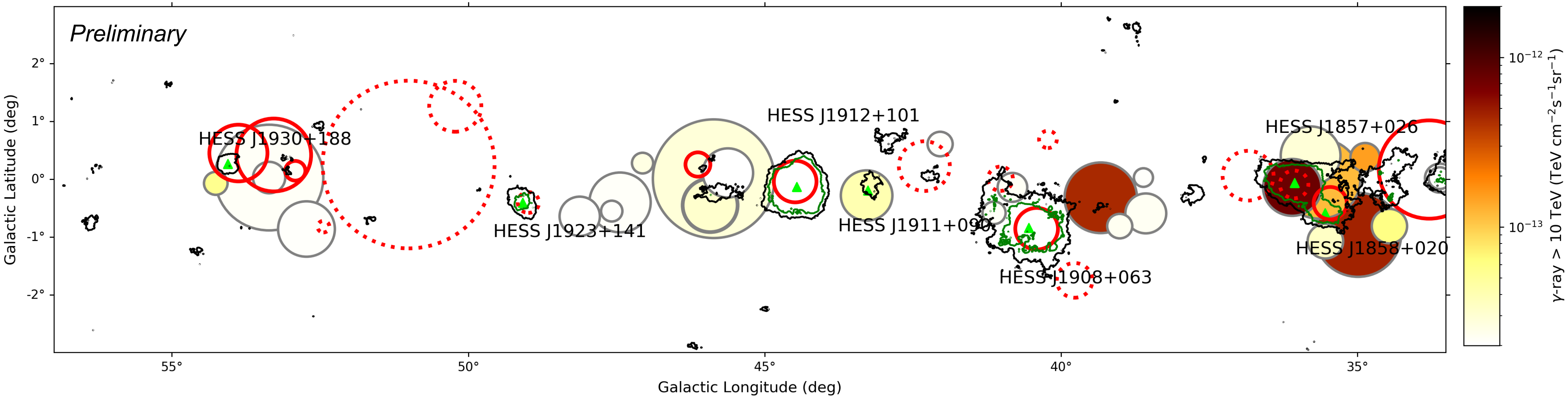

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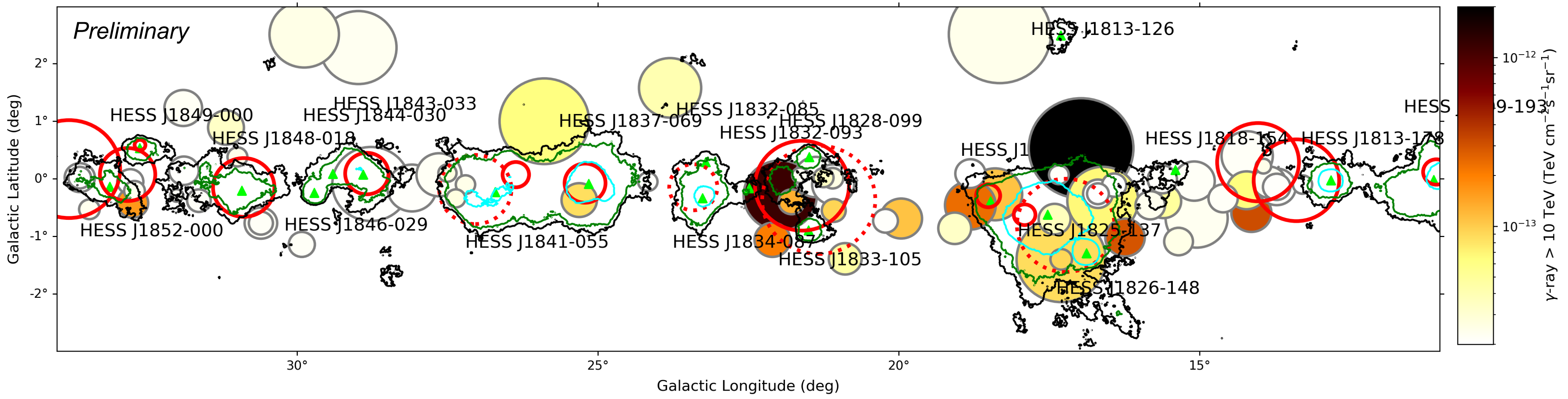
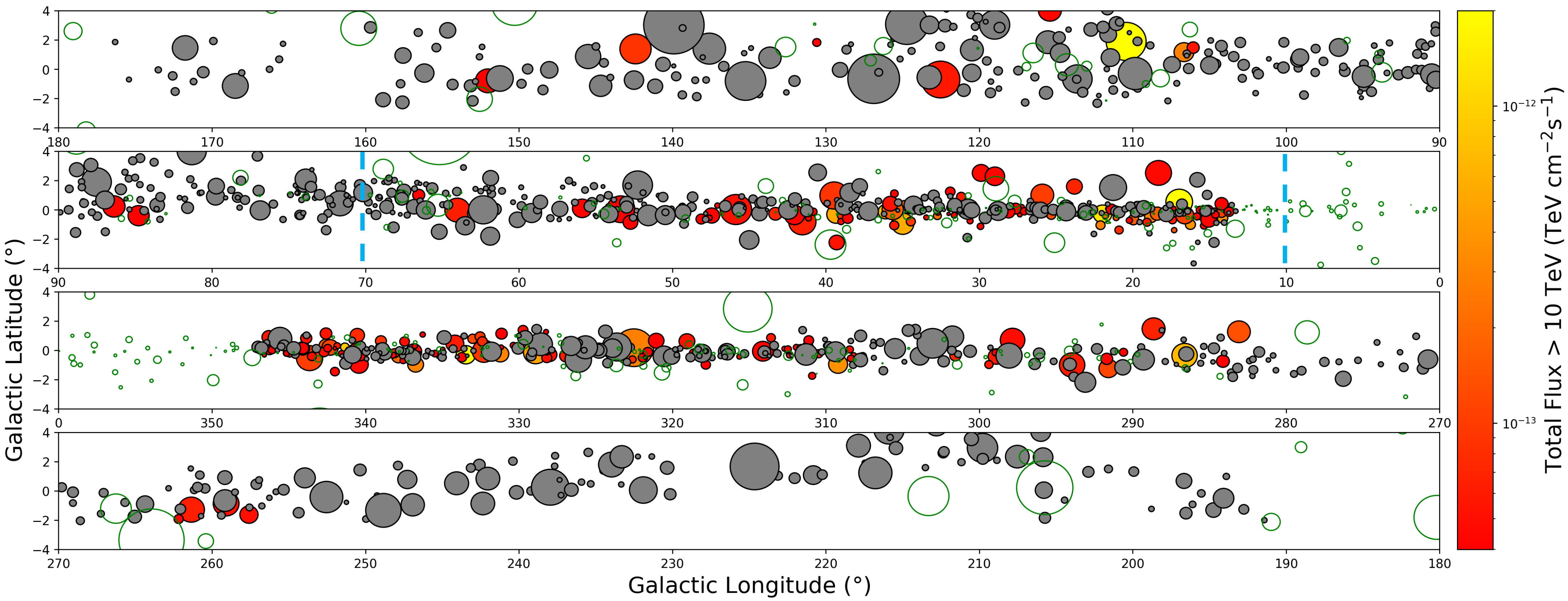


SNR – illuminated clouds along the (full) galactic plane

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

Search systematically for coincidences along the galactic plane

Note – limited by coverage of non-uniform surveys



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

UHE dark source: LHAASO J2108+5157

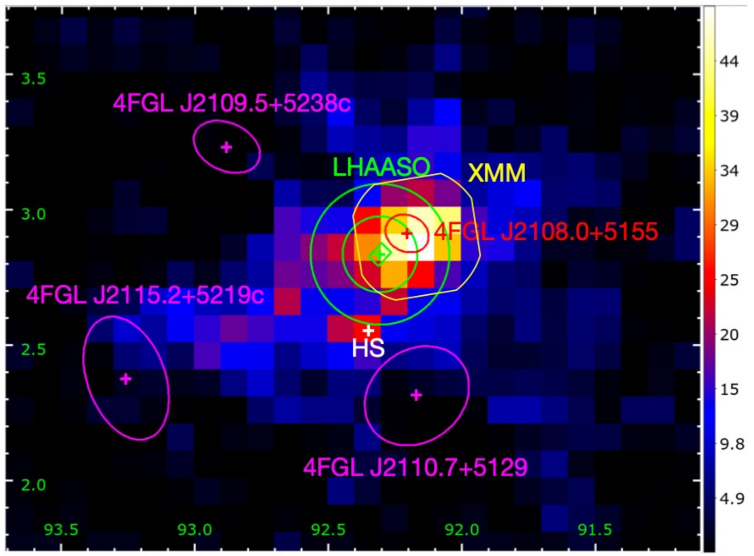
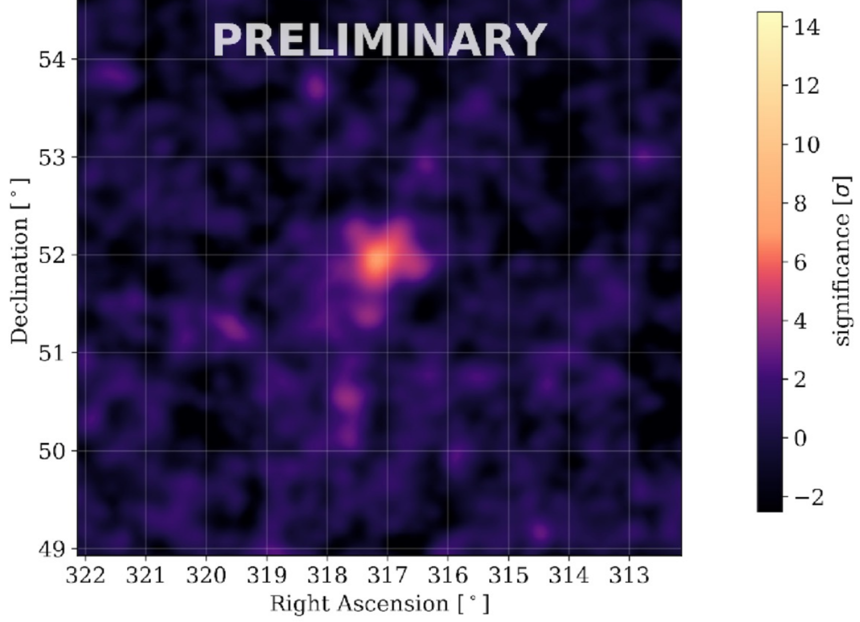


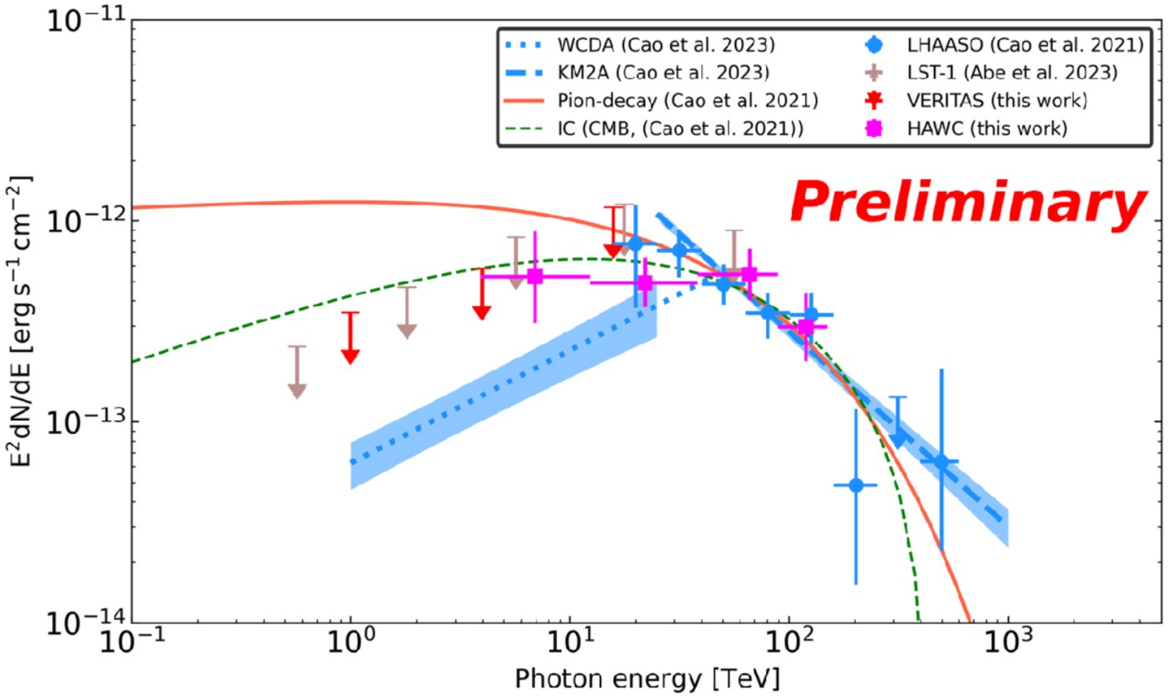
Figure 2: *Fermi*-LAT TS map above 2 GeV

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





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.

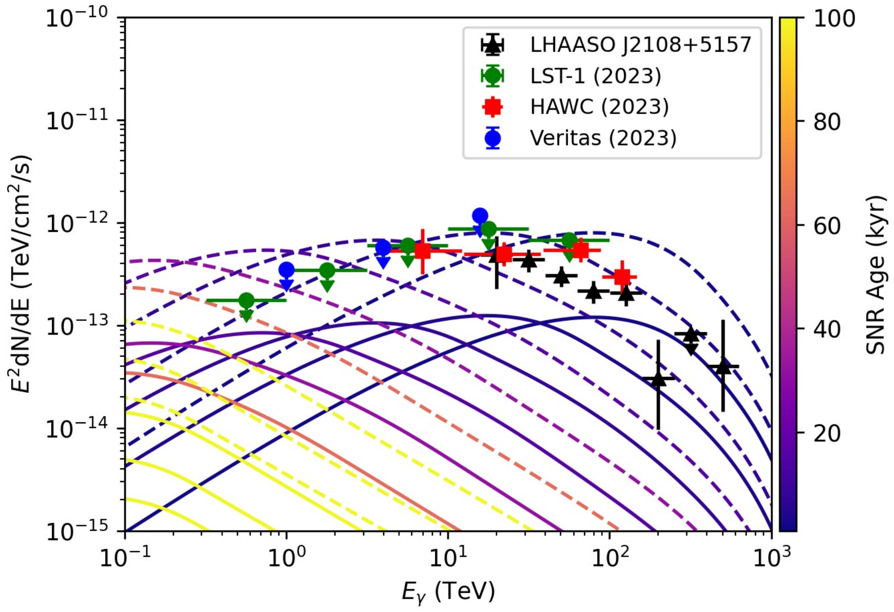
Recent survey by ASKAP (different sky region)
→ large number of low surface brightness SNRs found in radio
(survey field 7º x 6º with 7 known SNRs and 7 candidates
→ 13 new candidates found)

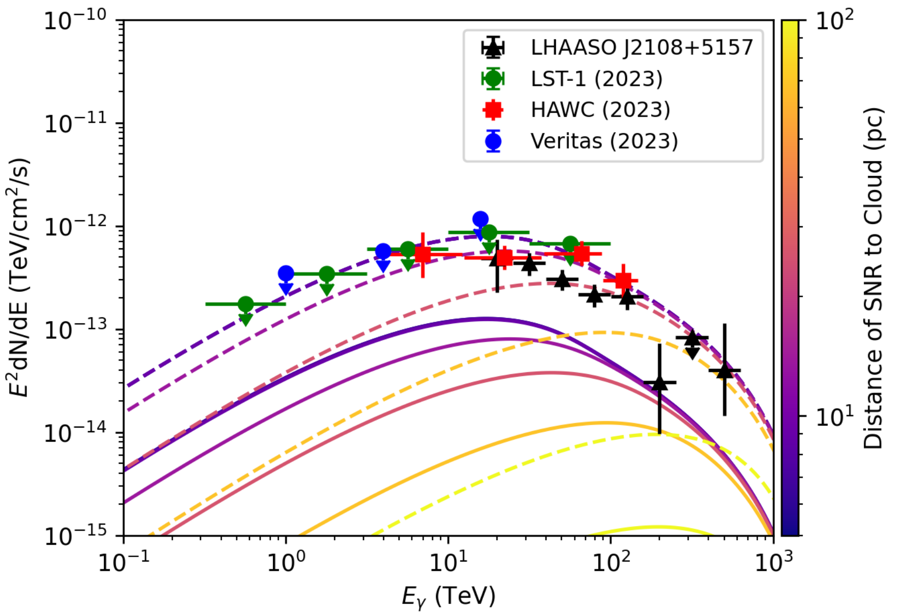
Could be a not-yet-discovered SNR in the vicinity?

- 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

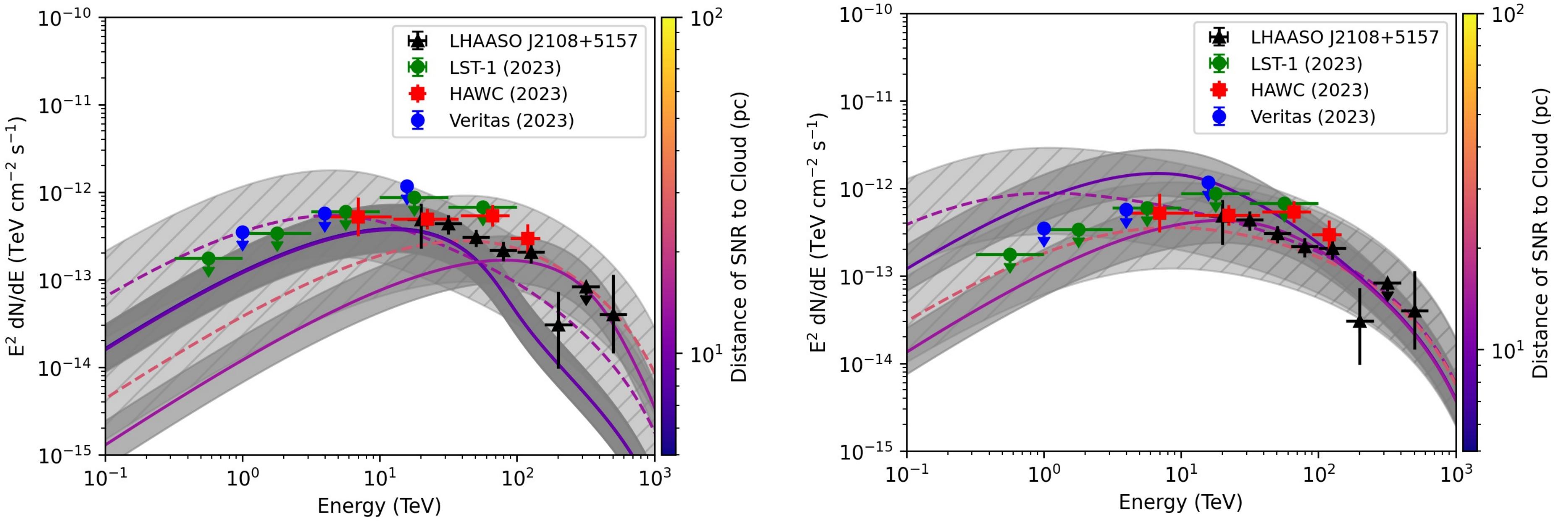
Best matching models to data

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

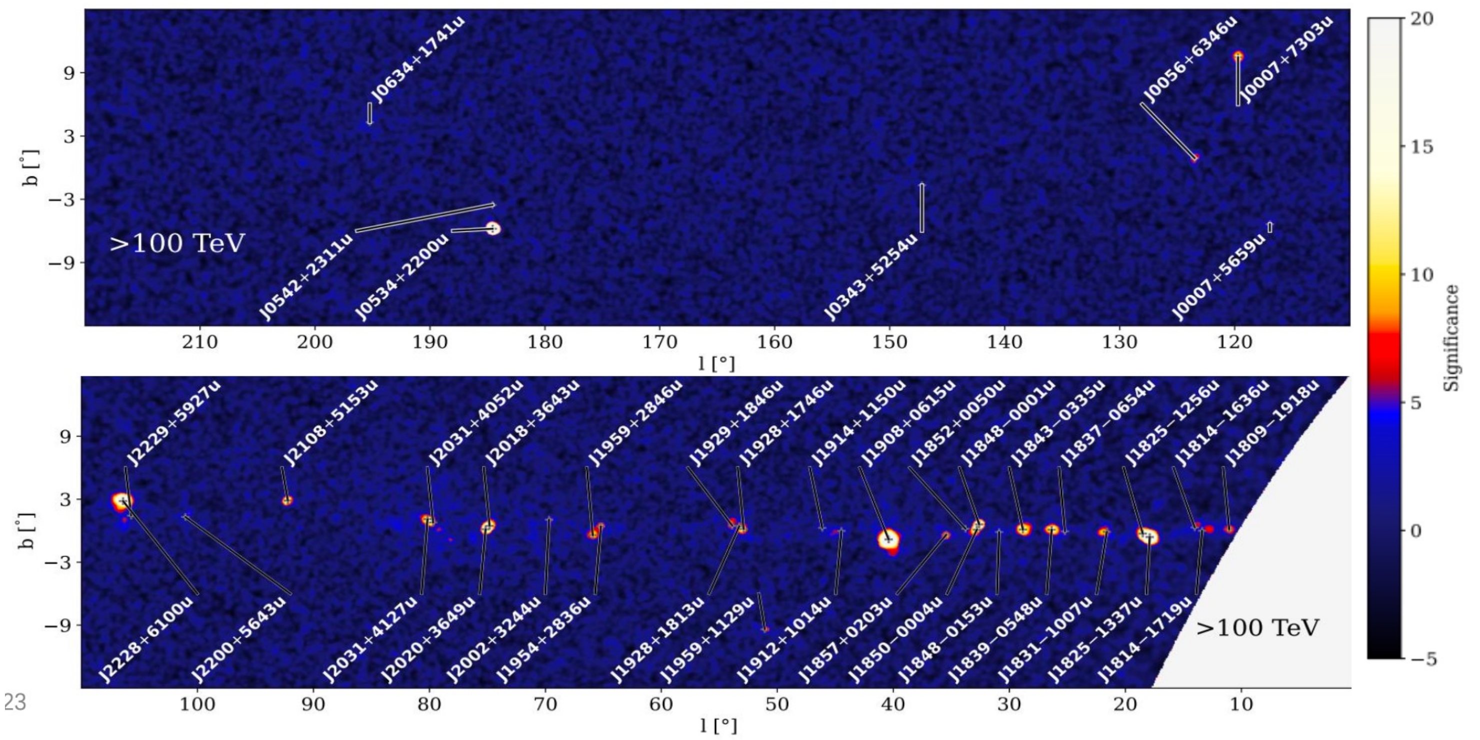
LHAASO PeVatrons

1st LHAASO catalogue: arXiv:2305.17030

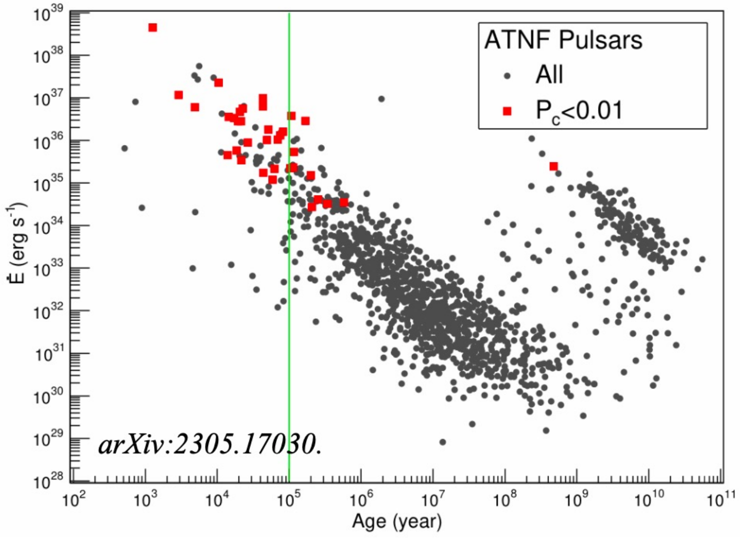
Several different source classes detected above 100 TeV!

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

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

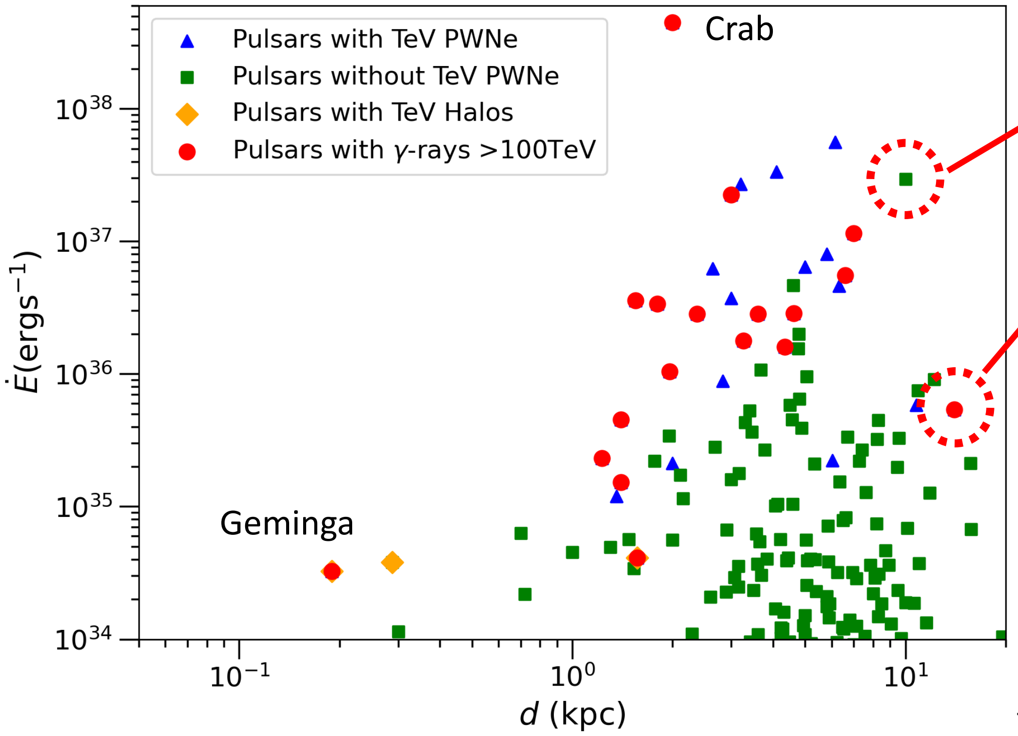


- Among the 35 1stLHAASO sources with pulsar associations, **22** are labeled as UHE sources.



Pulsar environments

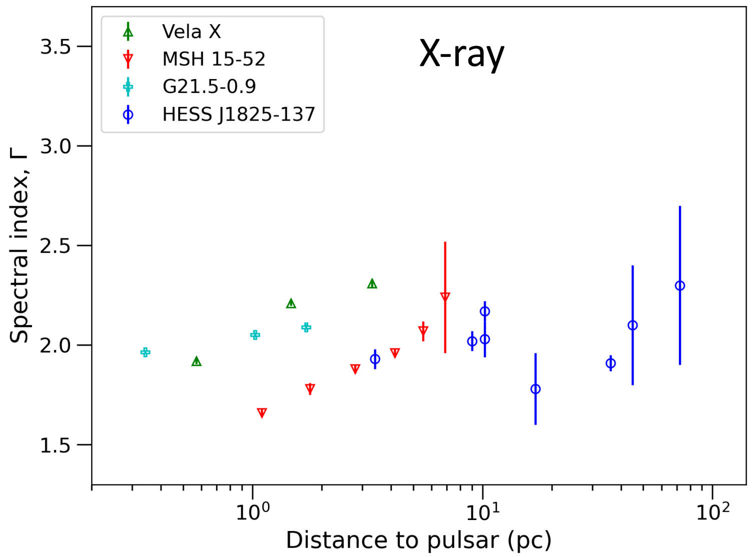
Pulsar-powered PeVatrons?

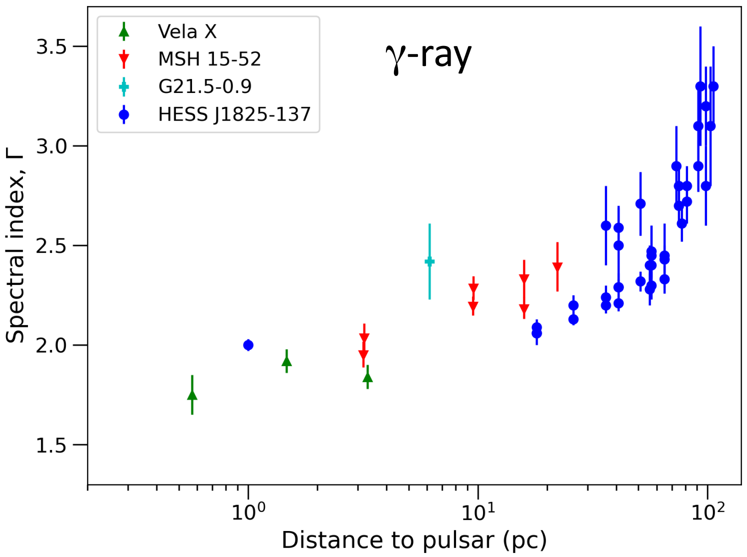


Why not PSR J2022+3842, with 3 x 10^{37} erg/s ?

Is PSR J1915+1150 exceptional? Is distance correct?

Common feature: spectral index increasing with distance from pulsar
→ electron transport and cooling
→ leptonically dominant sources





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

A couple of interesting exceptions

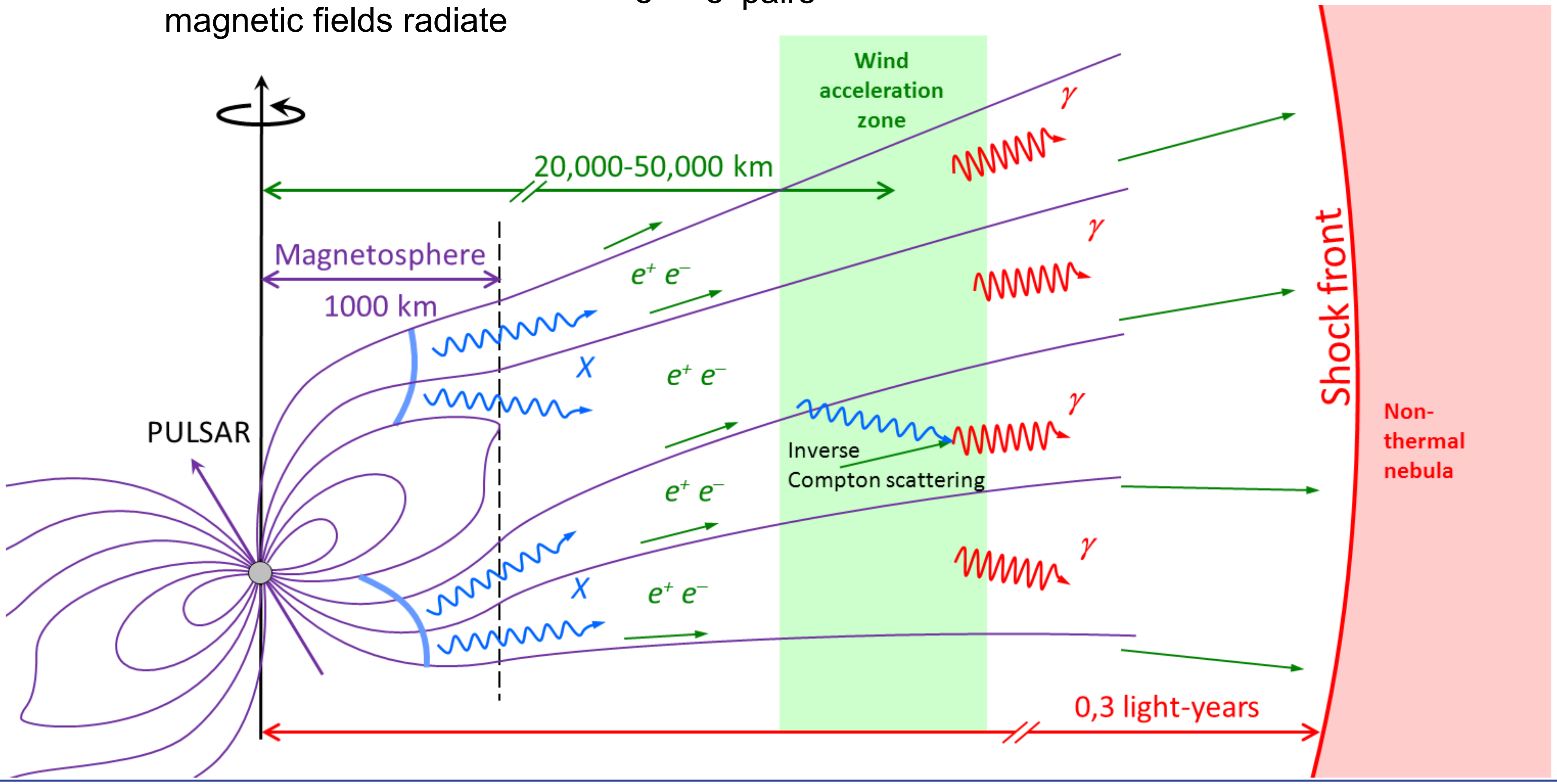
AM & Gelfand, Springer, 2022

Pulsar – Pulsar Wind – Pulsar Wind Nebula

→ Charged particles accelerated in magnetic fields radiate

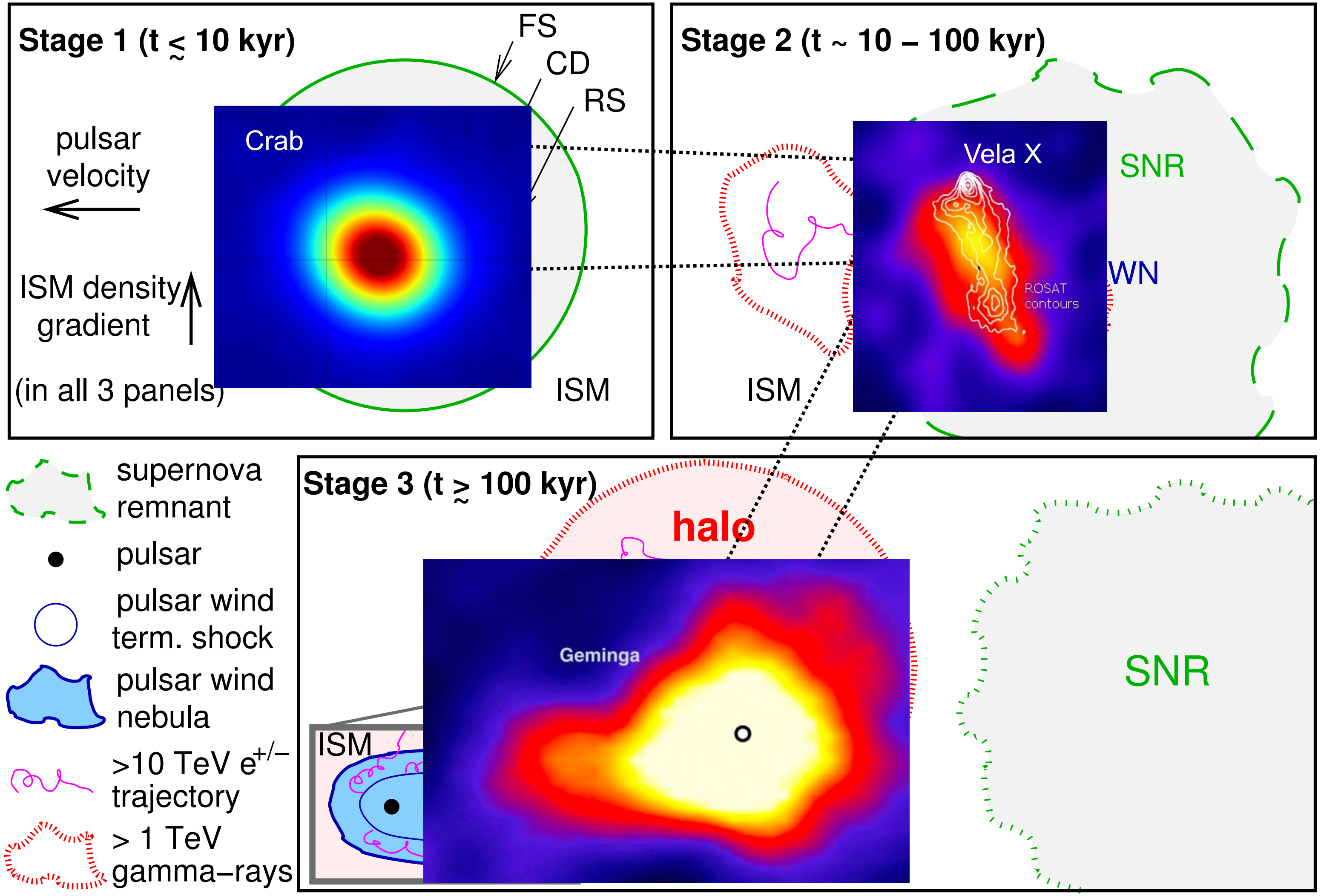
→ Radiation produces $e^+ - e^-$ pairs

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



Evolutionary stages of pulsar environments

Leptonically dominated sources

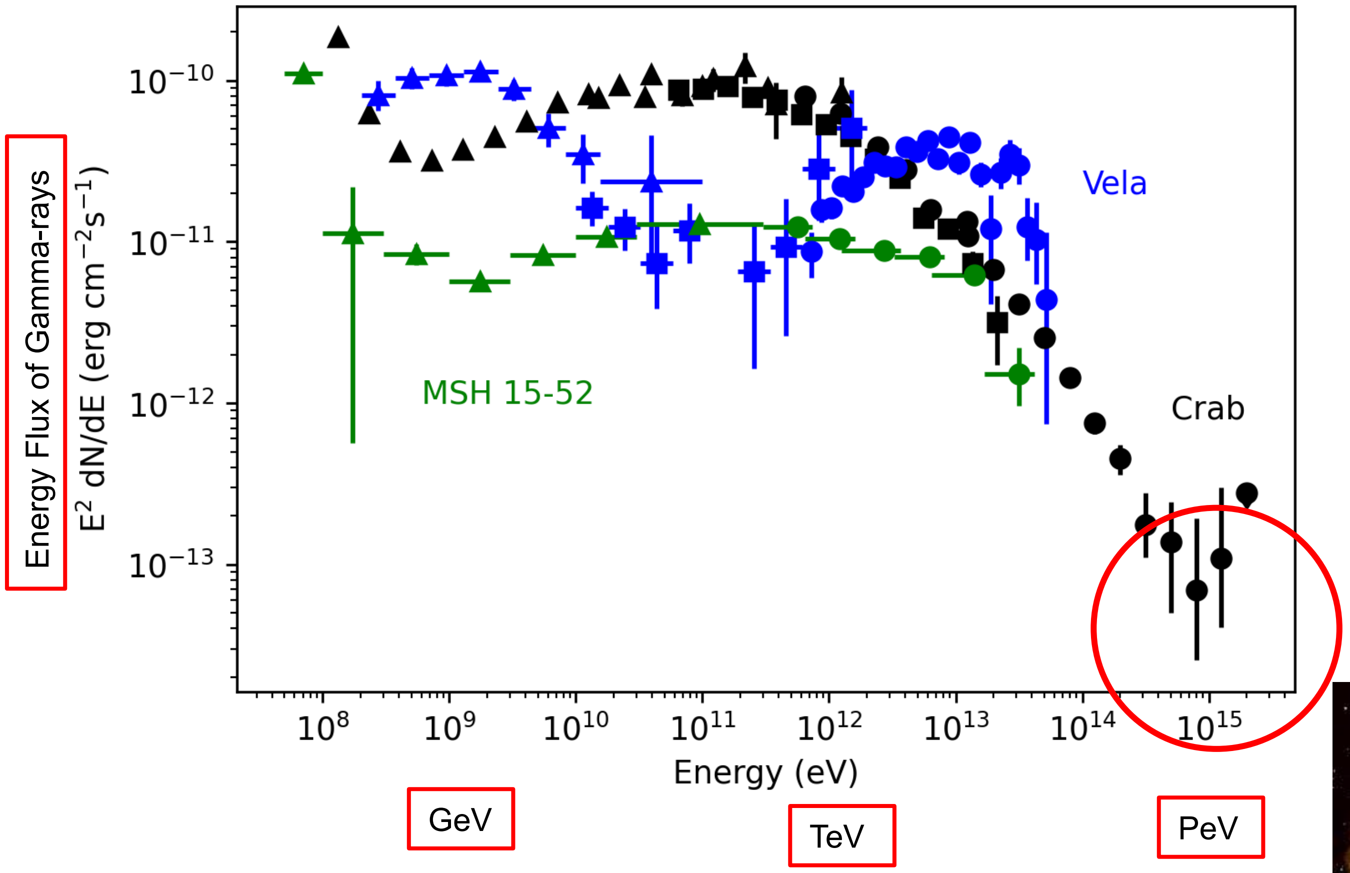


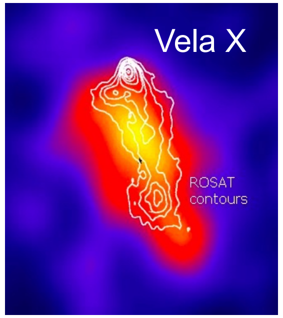
Pulsar Wind Nebulae (PWN)

→ Pulsar Halos

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

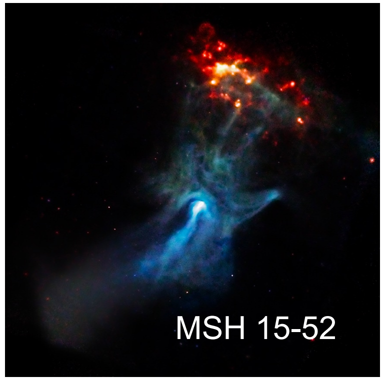
Pulsar Wind Nebulae

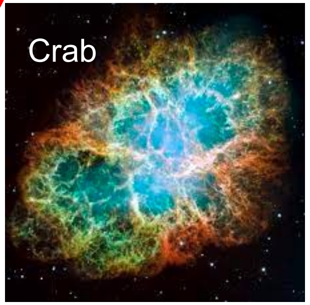




Age: 11.3 kyr
Energy output:
6.9×10^{36} erg/s
Distance: 0.28 kpc

Age: 1.57 kyr
Energy output:
1.7×10^{37} erg/s
Distance: 4.4 kpc



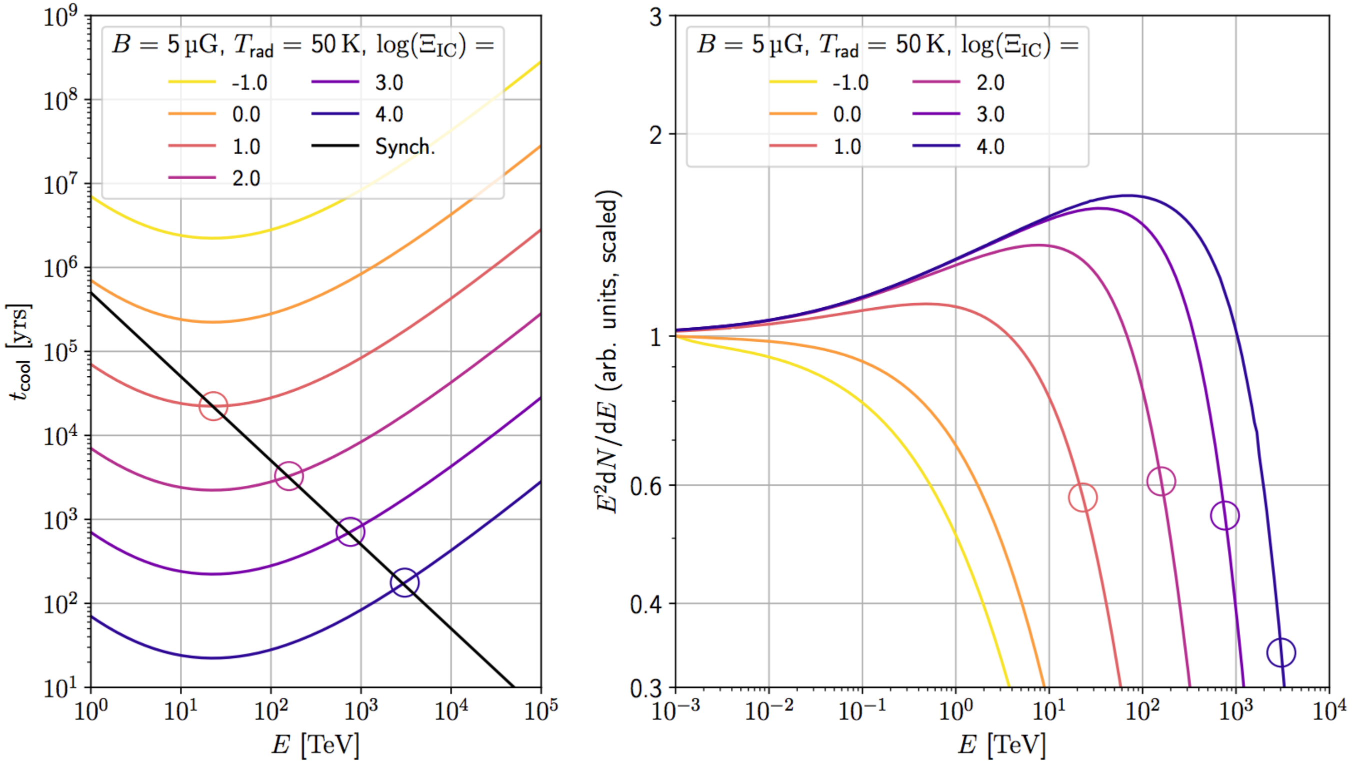


Age: 0.94 kyr
Energy output:
4.5×10^{38} erg/s
Distance: 2 kpc

UHE leptonic emission & Klein-Nishina effect

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

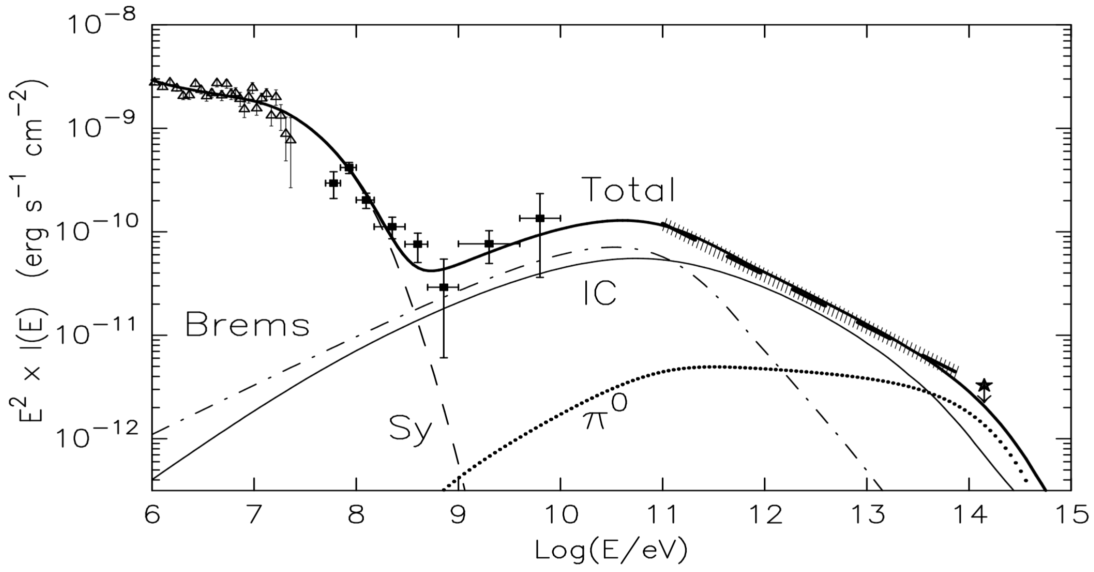
- In high radiation environments, $U_{rad} >> U_B$, synchrotron cooling dominates over IC losses, even into Klein-Nishina regime. (IC cross-section suppressed)
- Resulting spectrum is harder, i.e. cut-off is less pronounced.
- Leptonic spectra out to PeV energies can be observed



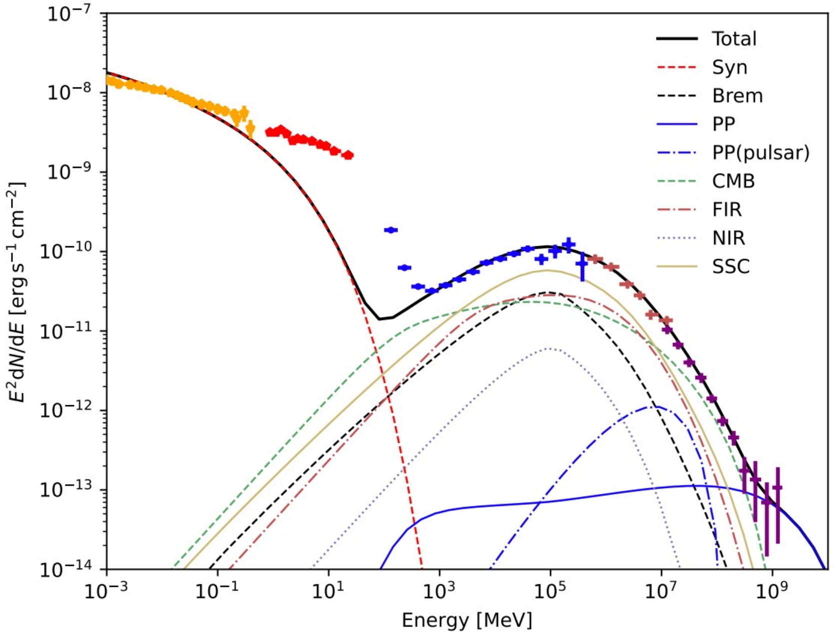
Breuhaus et al. ApJL **908** L49 (2021)

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

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?

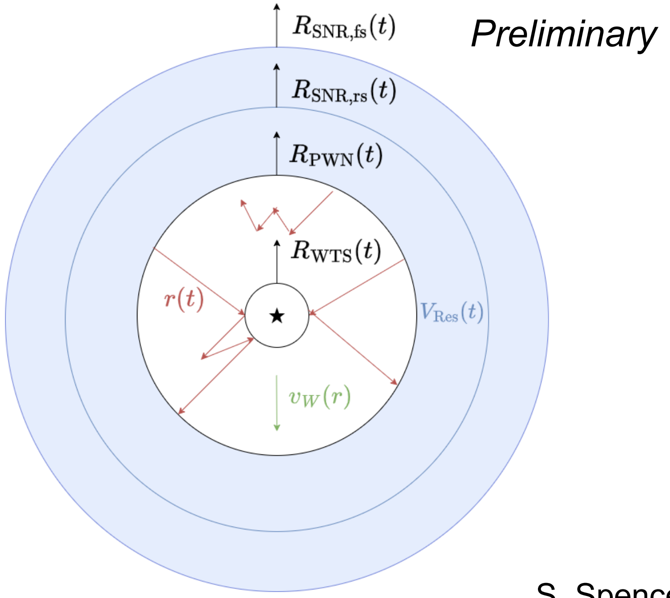
Acceleration of hadrons in PWNe?

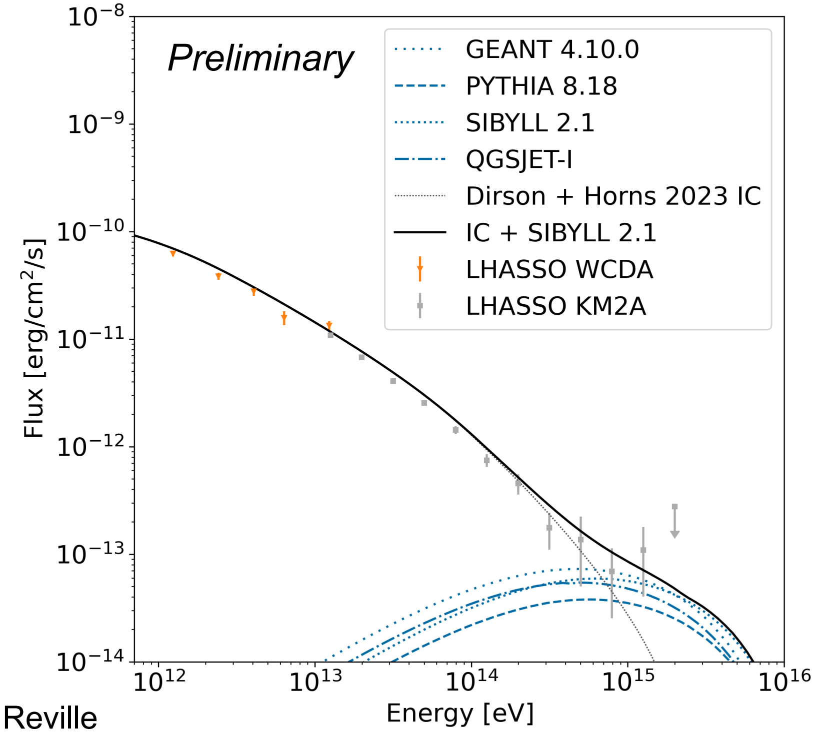
Reinjection of particles from the reservoir within the supernova remnant

Further hadronic particle acceleration at the pulsar wind termination shock

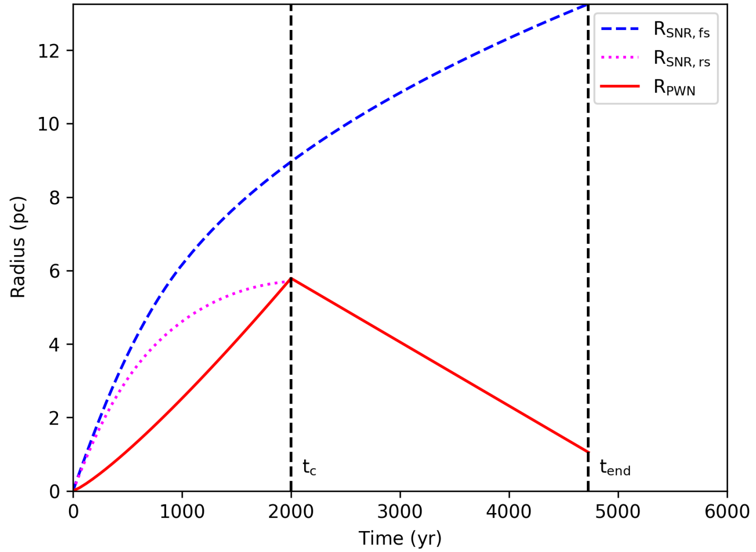
Particle tracking simulations

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

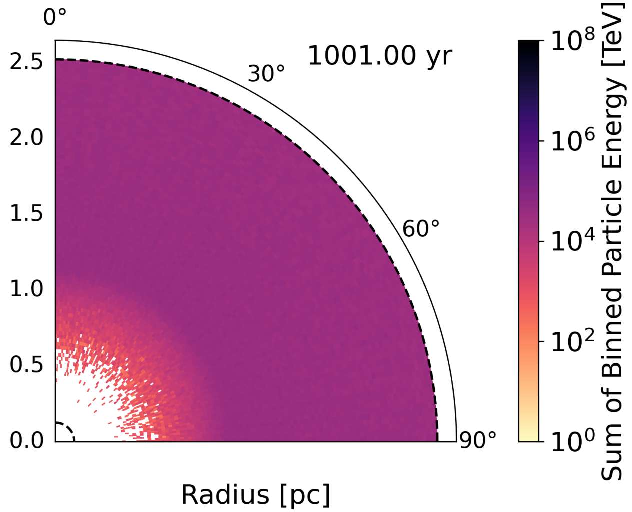




S. Spencer, AM, B. Reville (ICRC2023)



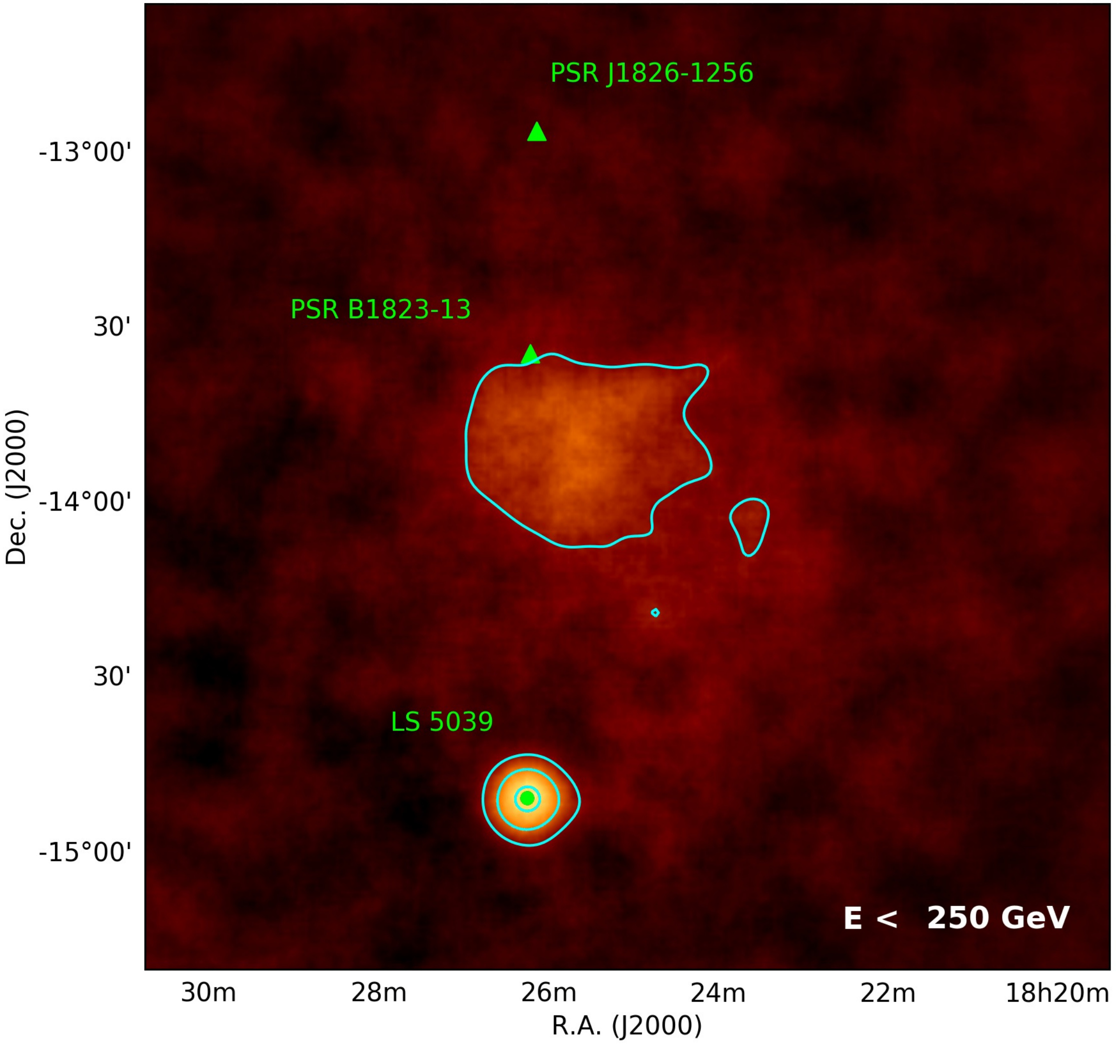
After Ohira et al, MNRAS **478**, 926-931 (2018)



Example transition: HESS J1825-137

Pulsar Wind Nebula → Pulsar Halo

Age: 21.4 kyr
Energy output:
2.8x10^{36} erg/s
Distance: 3.9 kpc



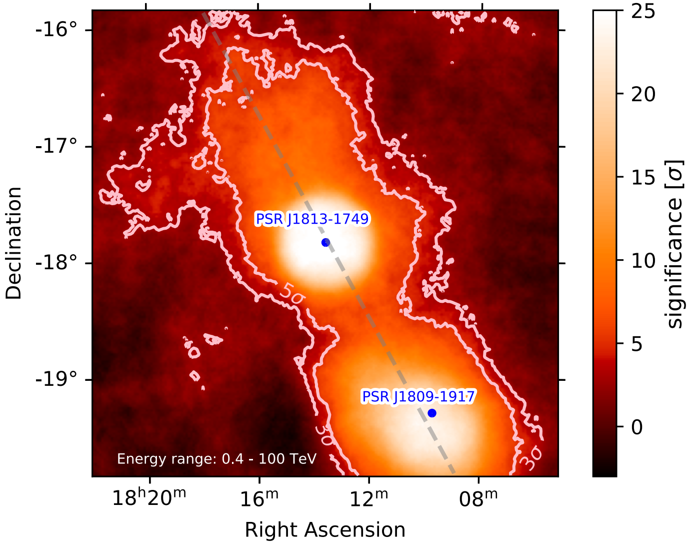
H.E.S.S. collaboration et al. A&A **621** (2019) A116

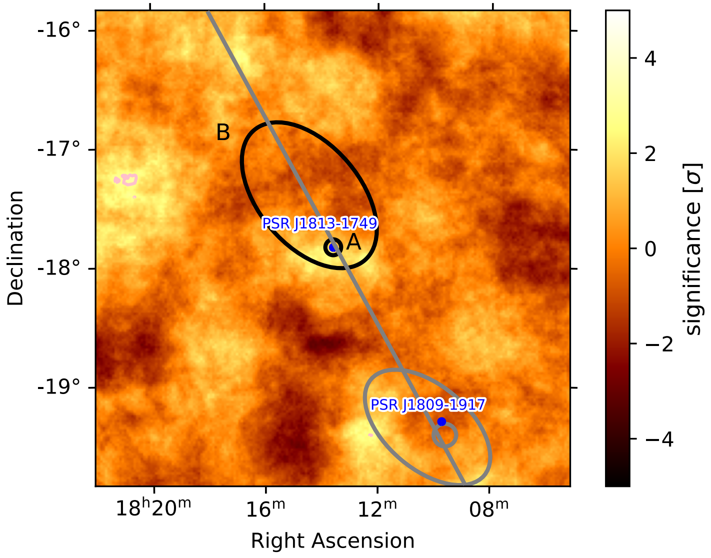
Example transition: HESS J1813-178

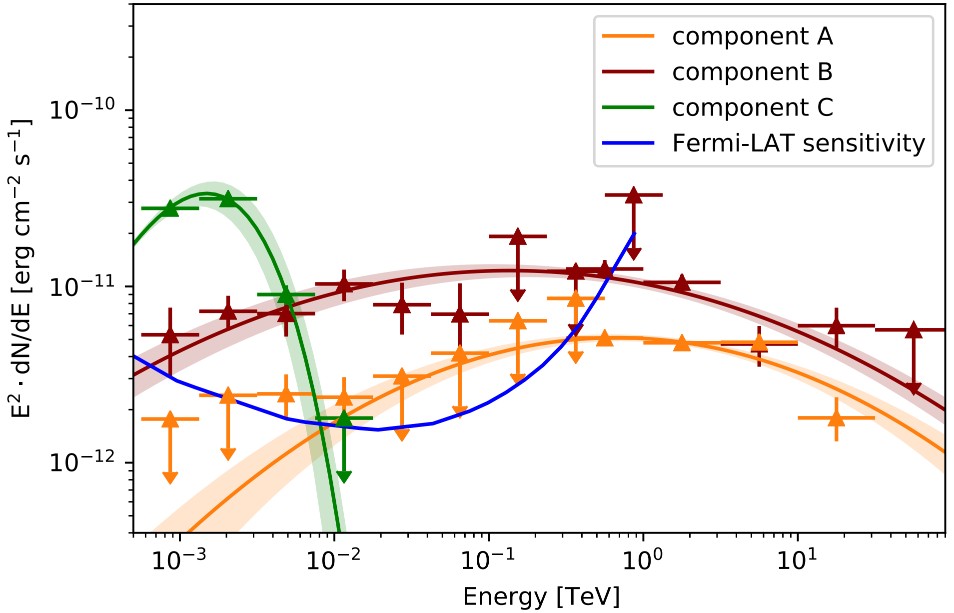
Joint fit to Fermi-LAT and H.E.S.S. data yielded a core component A and extended component B

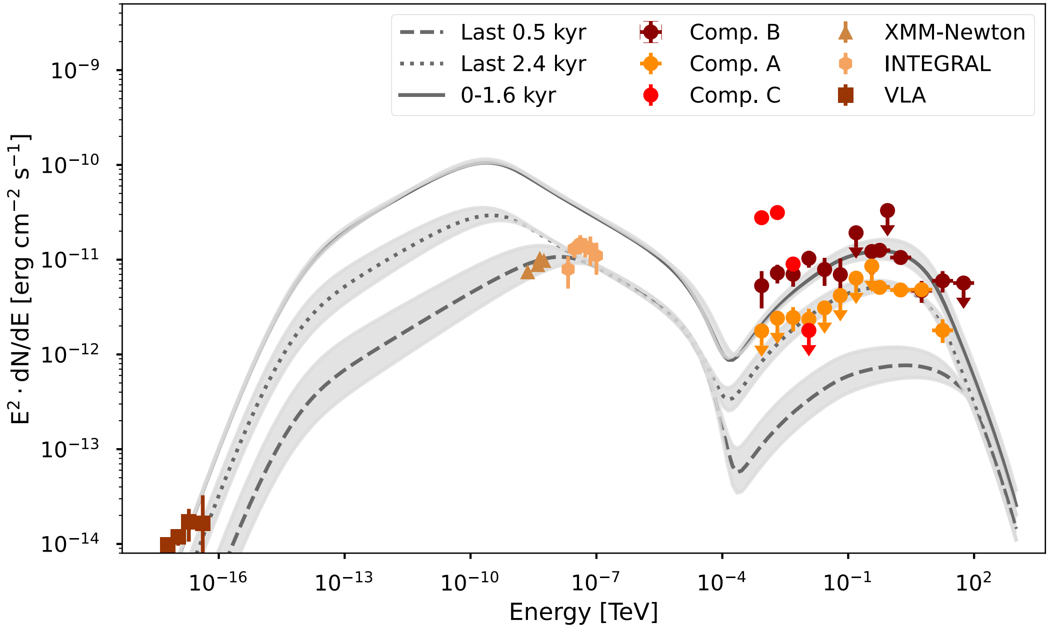
Modelled as electron populations of different ages released from the pulsar

Energy density is PWN-like and halo-like respectively



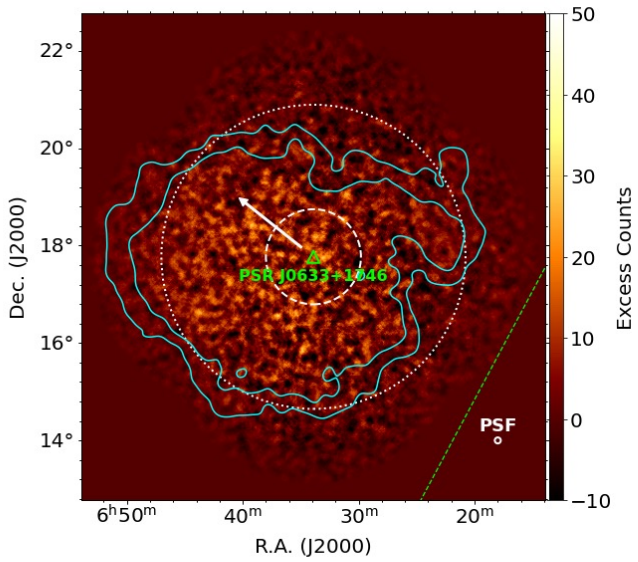




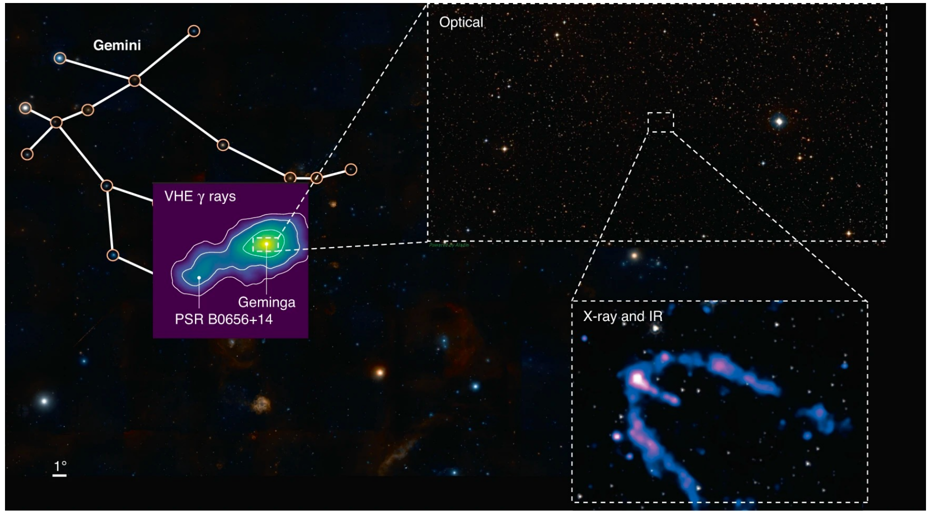


T. Wach, H.E.S.S. (ICRC2023)

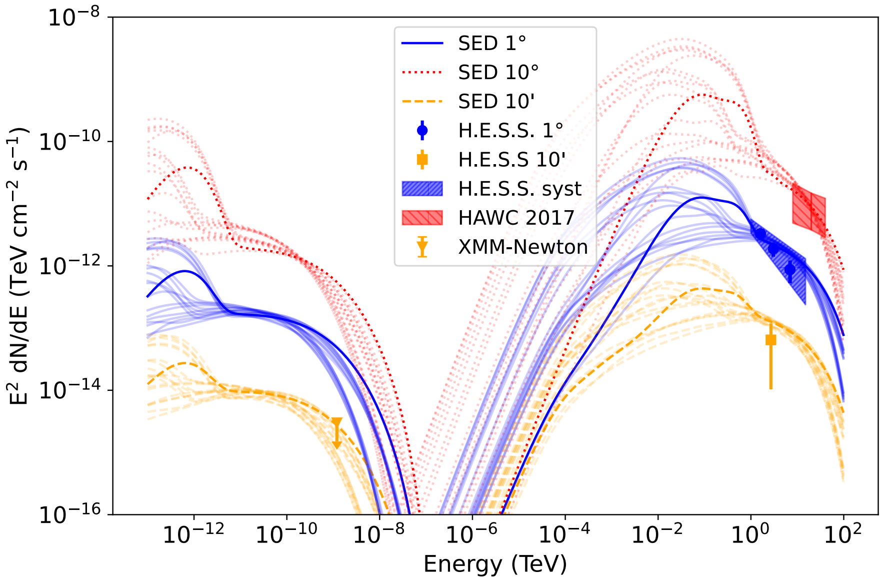
Electron diffusion in the Geminga halo



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



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



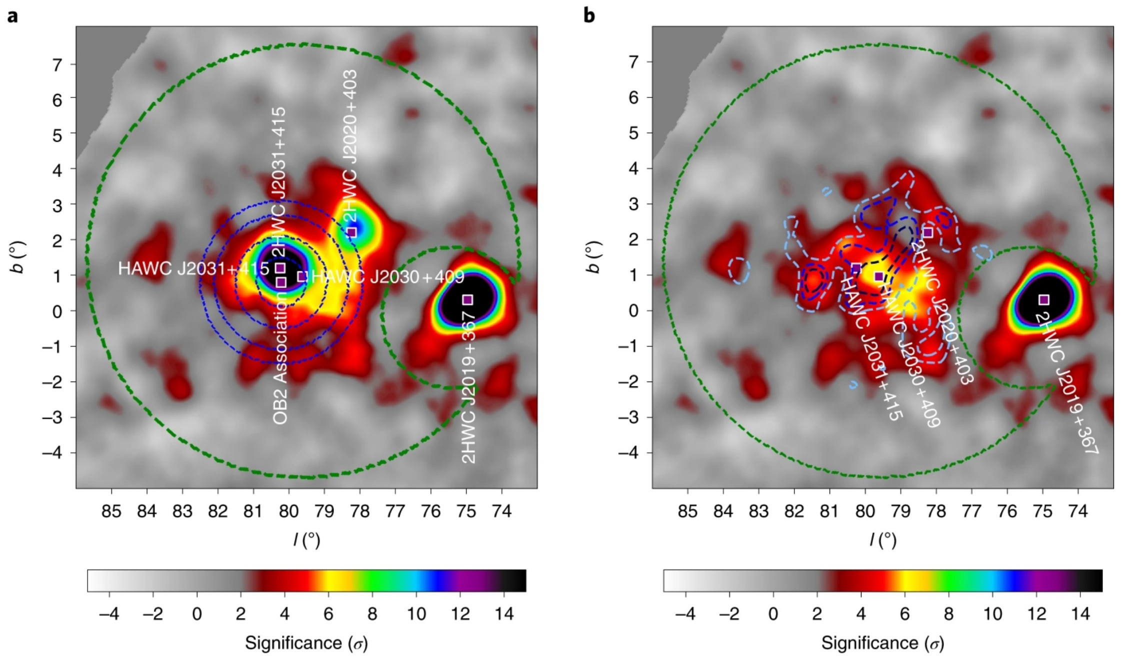
H.E.S.S. Collaboration A&A **673** (2023) A148

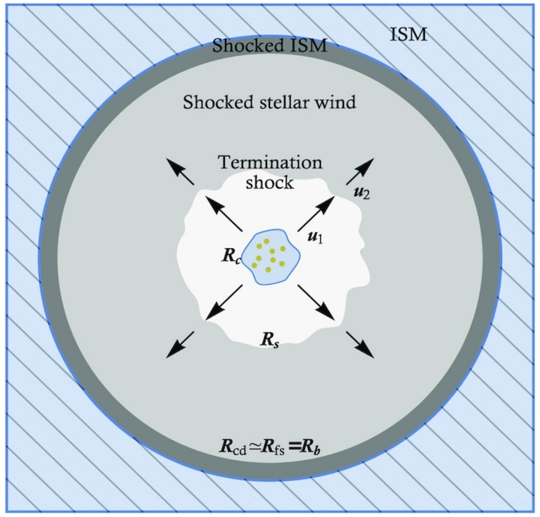
- VHE gamma-ray emission size >> X-ray size
- Emission profile indicates diffusion coefficient normalisation far below the Galactic average
  → not expected for particles escaped into the ISM
- H.E.S.S. results can be consistently described with MWL data under a slow diffusion model

Stellar Clusters

Stellar Clusters

- 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)



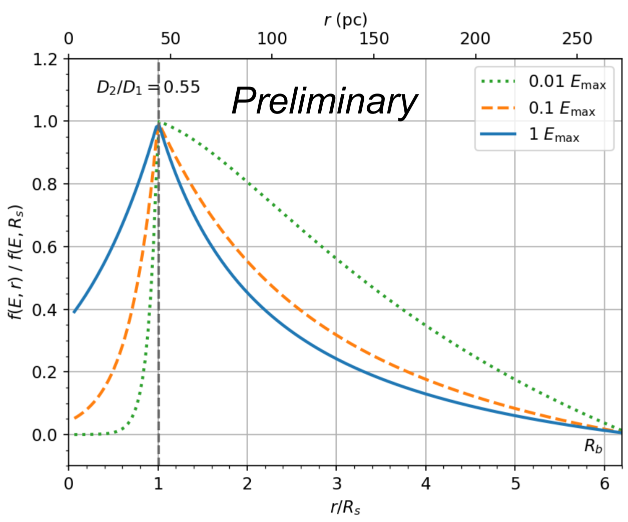


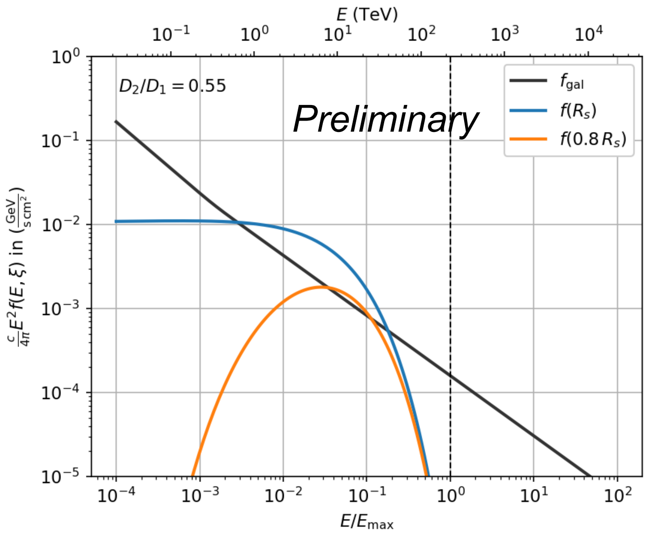
Morlino et al. MNRAS **504** (2021) 6096-6105

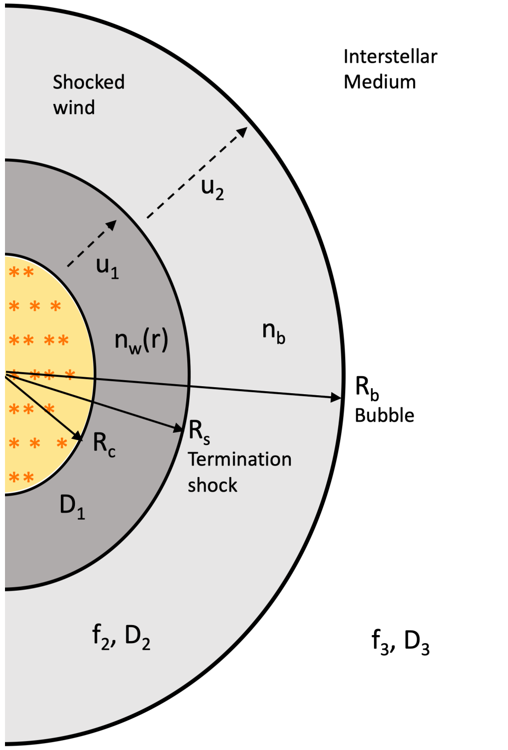
Q: Which stellar clusters are the most promising PeVatron candidates?

Which stellar clusters are PeVatrons?

- Wind termination shock and cluster bubble radii depend strongly on wind luminosity (mass loss rate, wind velocity) and age
- Young, massive clusters are favoured
- We use GaiaDR2 catalogue of star clusters & select those with age ≤ 30 Myr
- Include the contribution of the galactic CR sea in the total particle distribution







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

$$f_2(r,p) = f_s(p)e^{\alpha(r)}\frac{1+\beta(e^{\alpha(R_b)}e^{-\alpha(r)}-1)}{1+\beta(e^{\alpha(R_b)}-1)} + f_{\rm Gal}(p)\frac{\beta\left(e^{\alpha(r)}-1\right)}{1+\beta(e^{\alpha(R_b)}-1)}$$

$$\alpha(r,p) = \frac{u_2 R_s}{D_2(p)}\left(1-\frac{R_s}{r}\right)$$

$$\beta(p) = \frac{D_3(p)R_b}{u_2 R_s^2}$$

Stellar cluster model: luminosity and radii

- Estimate radii – need mass-loss rate and wind luminosity
- Can be estimated from the combined contribution of individual stars in the cluster
- Mass-loss rate per star and stellar wind velocity can be estimated via analytical expressions
- All unknowns can be expressed in terms of the **mass**.
  → How to estimate the mass?

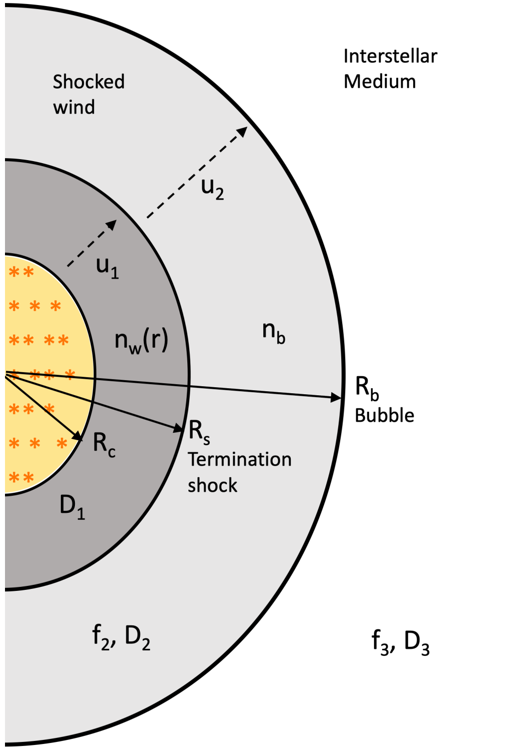
$$R_s(t) = 48.6 \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-0.3} \left(\frac{\dot{M}_c}{10^{-4} \mathrm{M}_\odot \mathrm{yr}^{-1}}\right)^{0.3} \left(\frac{v_{w,c}}{1000\,\mathrm{km\,s}^{-1}}\right)^{0.1} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.4} \mathrm{pc}$$

$$R_b(t) = 174 \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-0.2} \left(\frac{L_{w,c}}{10^{37}\,\mathrm{erg\,s}^{-1}}\right)^{0.2} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.6} \mathrm{pc}$$

$$L_{c,w} = \frac{1}{2}\dot{M}_c v_{w,c}^2 = \frac{1}{2} \frac{\left(\int_{M_{min}}^{M_{max}} \xi(M)\dot{M}_s(M) v_{w,s}(M) dM\right)^2}{\int_{M_{min}}^{M_{max}} \xi(M)\dot{M}_s(M) dM}$$

$$v_{w,s}(M) = C(T_{eff}) \sqrt{\frac{2G_N M}{R_s(M)}\left(1 - \frac{L_s(M)}{L_{Edd}(M)}\right)}$$

$$\dot{M}_s(M) \simeq 9.55 \times 10^{-15} \left(\frac{L_s(M)}{L_\odot}\right)^{1.24} \left(\frac{M}{M_\odot}\right)^{0.16} \left(\frac{R_s(M)}{R_\odot}\right)^{0.81} \frac{\mathrm{M}_\odot}{\mathrm{yr}},$$



How to estimate the mass of a stellar cluster

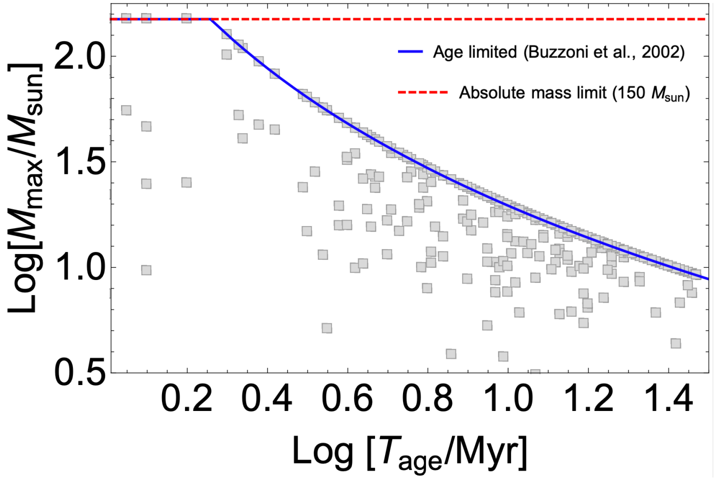
1. Extract the number and magnitude of observed member stars, as well as extinction
2. Obtain the minimum and maximum observed G-band magnitude (i.e. completeness range), via the stellar magnitude distribution
3. Convert magnitudes into a maximum and minimum stellar luminosity, via bolometric and extinction corrections
4. Assume the mass-luminosity relation of main sequence stars to obtain the M_{min} and M_{max} of observed stars
5. Derive the normalisation of the stellar mass function needed to reproduce the number of observed stars within the given (complete) mass range.

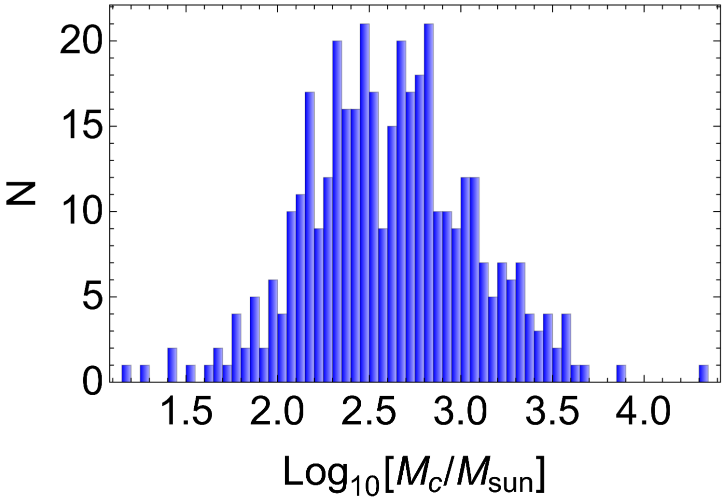
$$N^* = \int_{M^*_{\rm min}}^{M^*_{\rm max}} \xi(M)\, dM$$

6. Use this normalisation in an integral of the IMF from 0.08 M_{sun} to M_{max}(T) , the maximum stellar mass allowed by the cluster age, to derive the total cluster mass.

$$M_{\rm c} = \int_{M_{\rm min}}^{M_{\rm max}} \xi(M) M\, dM$$

It works! But likely only as a lower bound.

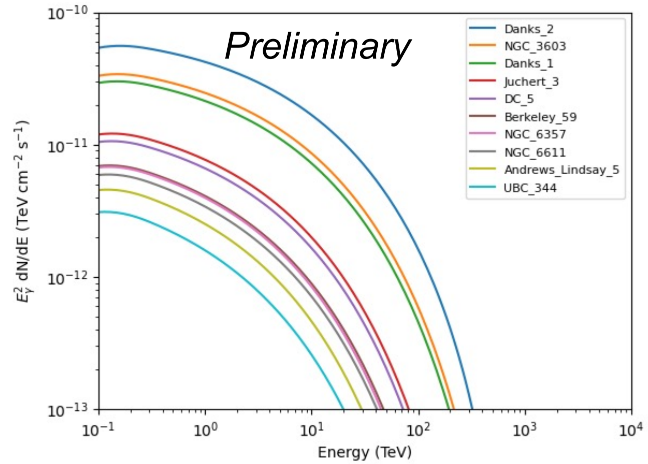


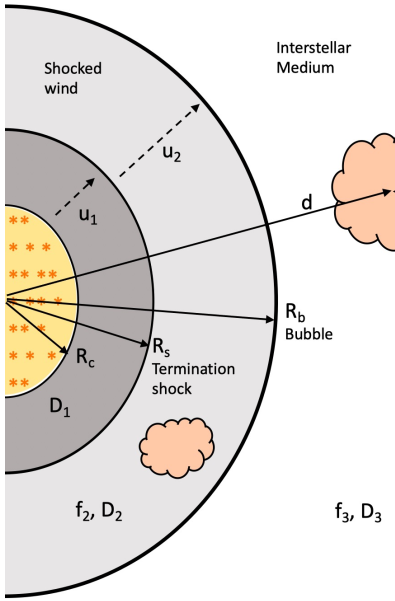


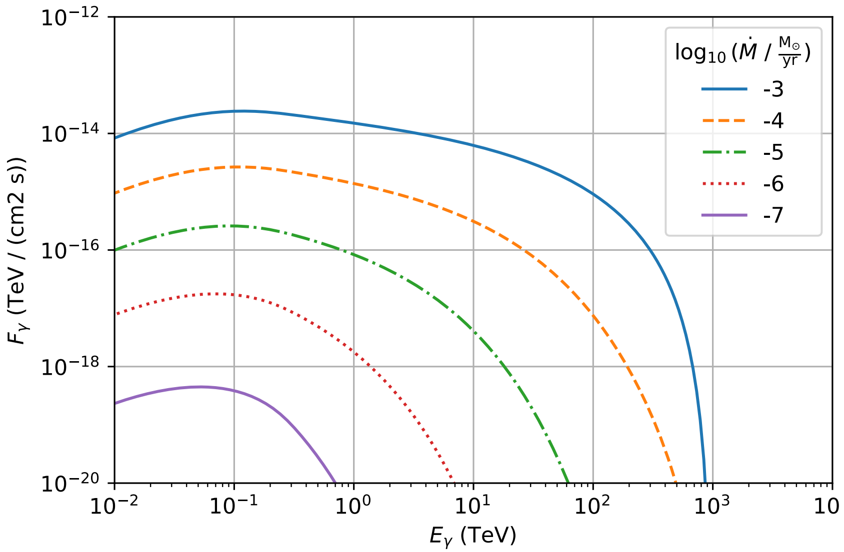
S. Celli, A. Specovius, S. Menchiari, AM, G. Morlino arXiv:2311.09089

Which stellar clusters are PeVatrons?

- Example: most promising ten clusters identified
- Caveat: cluster bubbles have a large angular size (1º - 10º)
  → low surface brightness
- Second part:
  → 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.







	Cluster	GLON (°)	GLAT (°)	Age (Myr)	Distance (kpc)	R_s (pc)	R_b (pc)	R_b (°)	F_γ (> 1 TeV) (TeV cm^{-2} s^{-1})	F_γ^{ul} (> 1 TeV) (TeV cm^{-2} s^{-1})	E_{max} (PeV)
1	Danks 2	305.390	0.089	2.0	2.2	45.8	181	4.63	8.5e-11	1.2e-12	5.0
2	NGC 3603	291.624	-0.518	1.0	7.2	32.5	115	0.92	4.6e-11	2.4e-12	3.36
3	Danks 1	305.342	0.074	1.0	1.9	31.6	113	3.45	3.9e-11	1.3e-12	3.11
4	Juchert 3	40.354	-0.701	1.0	1.5	25.7	98	3.80	1.2e-11	8.3e-12	1.80
5	DC 5	286.795	-0.502	1.1	4.4	[illegible]	103	1.33	1.0e-11	3.6e-12	1.70
6	Berkeley 59	118.230	5.019	1.3	1.0	24.5	[illegible]	[illegible]	5.9e-12	–	1.35
7	NGC 6357	353.166	0.890	1.0	1.8	22.6	90	2.92	5.7e-12	3.7e-12	1.28
8	NGC 6611	16.962	0.811	2.1	1.6	28.5	134	4.66	4.8e-12	2.4e-12	1.30
9	Andrews Lindsay 5	27.733	-0.667	1.0	2.3	20.7	85	2.14	3.4e-12	3.1e-12	1.01
10	UBC 344	18.354	1.820	3.5	1.9	30.3	159	4.74	2.0e-12	2.3e-12	0.90

Preliminary

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

White Dwarfs?

White dwarfs in binary systems
→ Novae

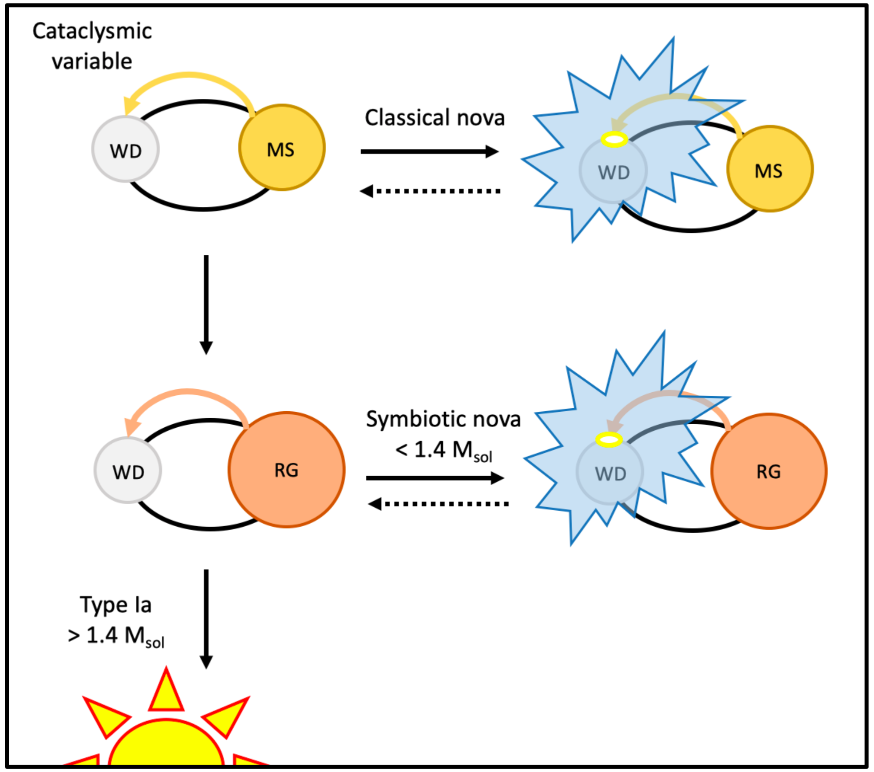
– outbursts from accreting binary systems
(White Dwarf + massive donor)

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



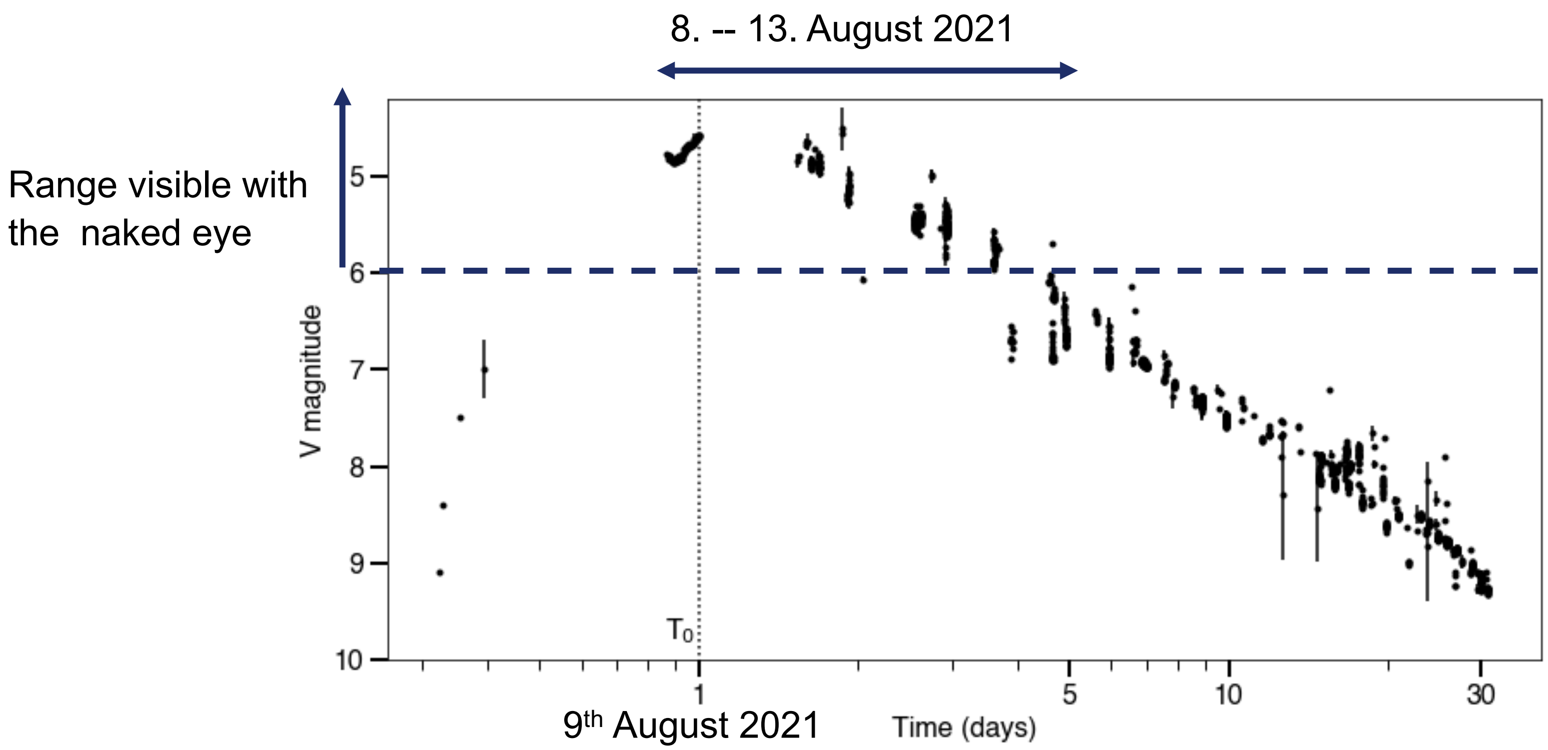
First Nova in VHE gamma-rays: RS Ophiuchi in 2021

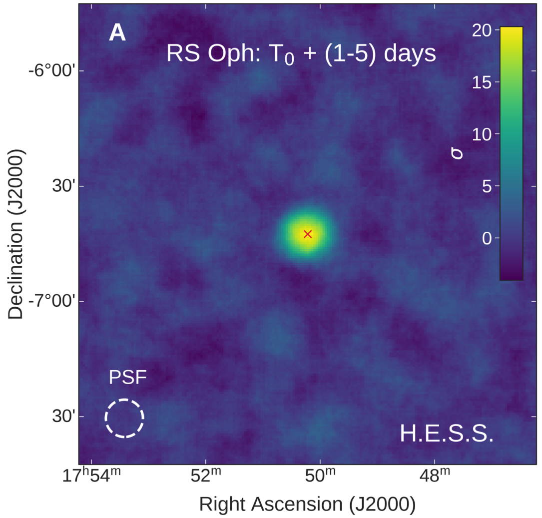
→Binary system comprised of white dwarf and red giant at about 1.4 kpc

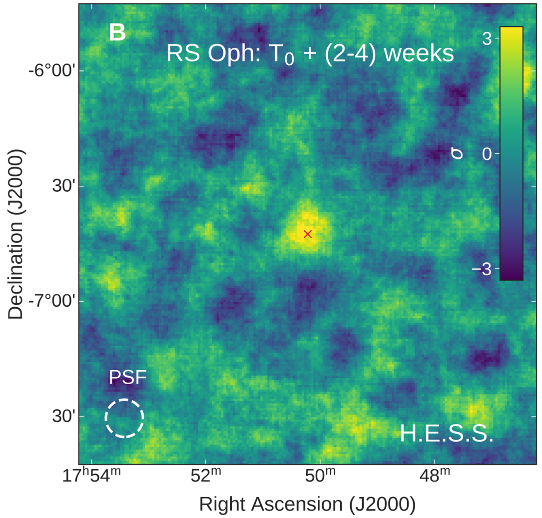
→ Explosions observed since 1898 : most recently in 12th February 2006 and **8th August 2021**

→ Detected by IACTs in VHE gamma-rays over days to weeks

→ Factor 100x higher energy reached than seen in other novae

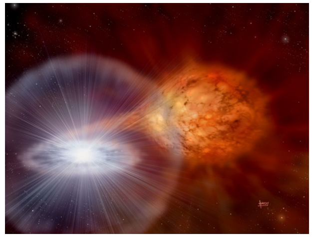


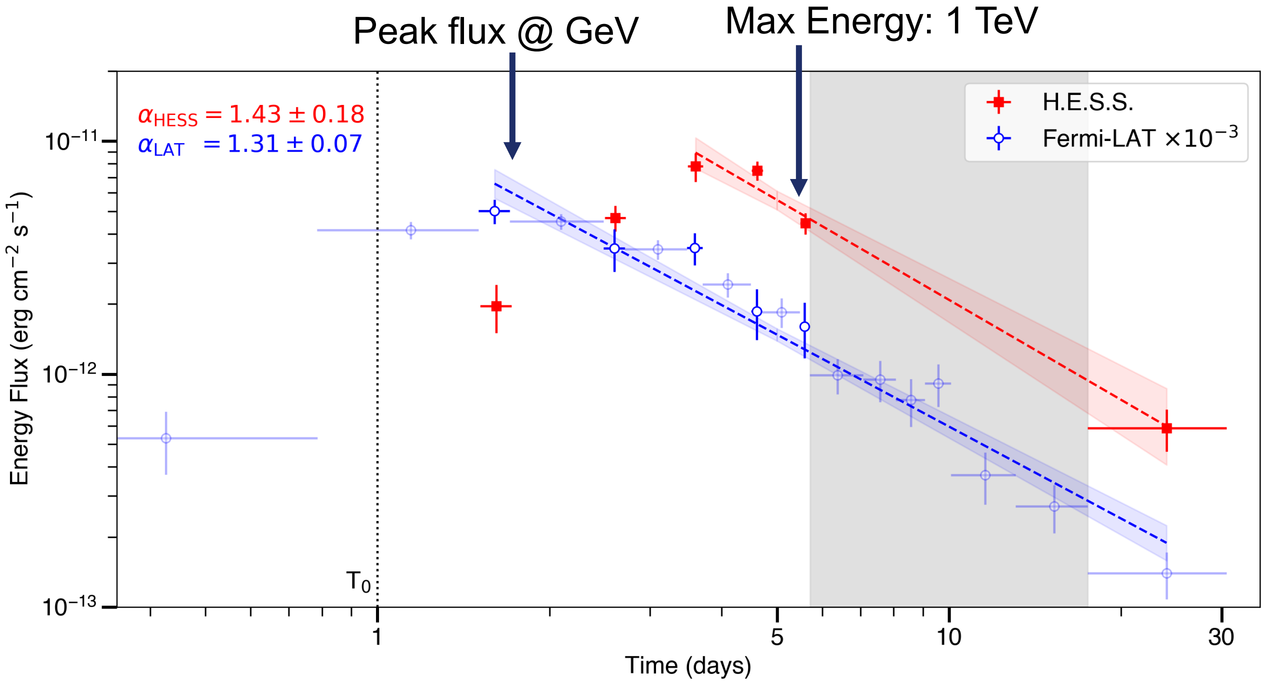


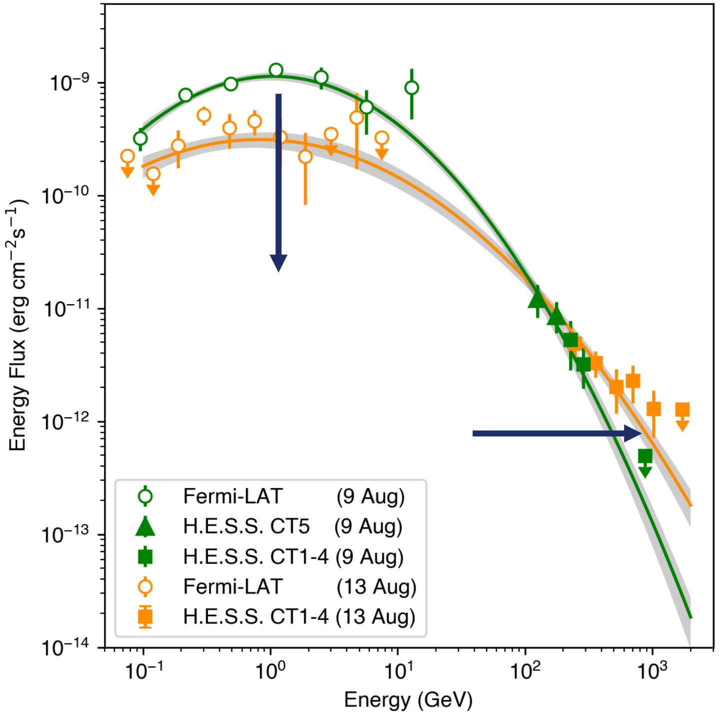


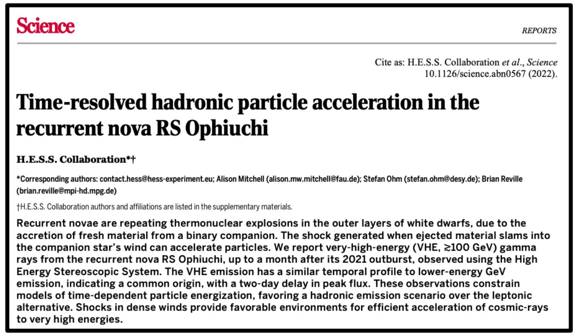
RS Ophiuchi: gamma-ray evolution

https://www.science.org/doi/10.1126/science.abn0567









Science REPORTS

Cite as: H.E.S.S. Collaboration *et al.*, *Science* 10.1126/science.abn0567 (2022).

Time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi

H.E.S.S. Collaboration*†

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†H.E.S.S. Collaboration authors and affiliations are listed in the supplementary materials.

Recurrent novae are repeating thermonuclear explosions in the outer layers of white dwarfs, due to the accretion of fresh material from a binary companion. The shock generated when ejected material slams into the companion star's wind can accelerate particles. We report very-high-energy (VHE, ≳100 GeV) gamma rays from the recurrent nova RS Ophiuchi, up to a month after its 2021 outburst, observed using the High Energy Stereoscopic System. The VHE emission has a similar temporal profile to lower-energy GeV emission, indicating a common origin, with a two-day delay in peak flux. These observations constrain models of time-dependent particle energization, favoring a hadronic emission scenario over the leptonic alternative. Shocks in dense winds provide favorable environments for efficient acceleration of cosmic-rays to very high energies.

A new type of Cosmic Ray accelerator

Next one → T Coronae Borealis?

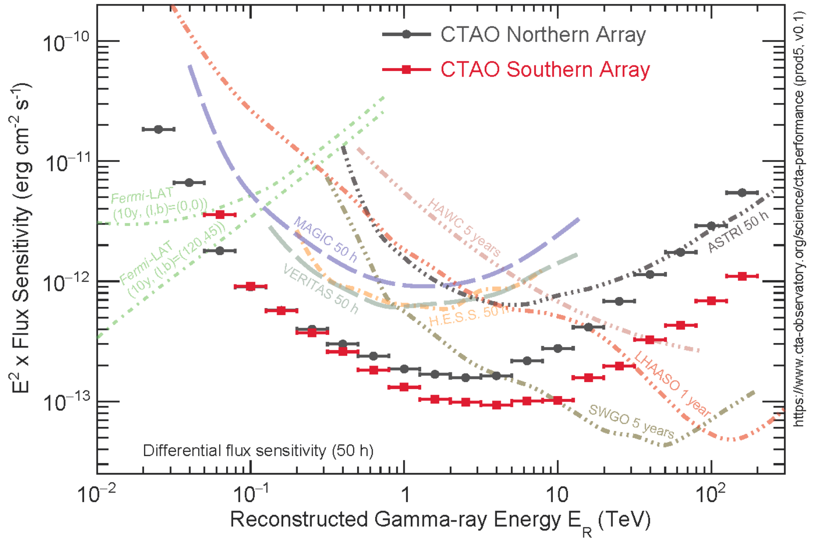
Expected in 2024, likely to be bright → Watch this space...

What next?

Future facilities and future challenges

Forthcoming → CTAO (IACT) in North and South, SWGO (WCD)

ASTRI: array on Tenerife
ALPACA: survey instrument in Bolivia
LHAASO extension: addition of 32 IACTs at LHAASO site (9.6º)



Major challenges:

→ Source confusion in the galactic plane

→ Source identification and association

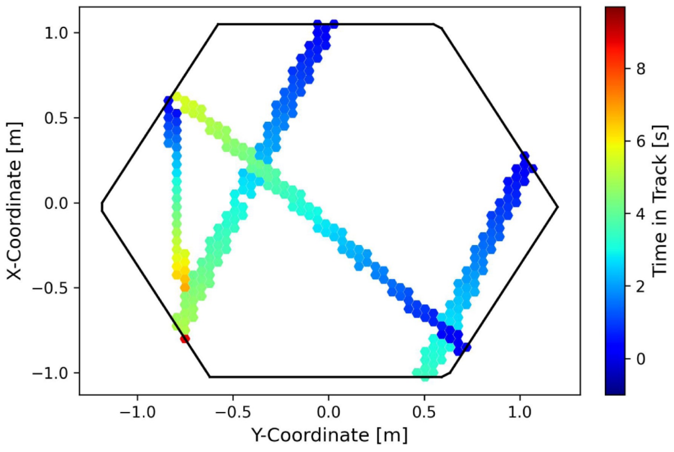
→ Joint modelling of MWL / MM observations

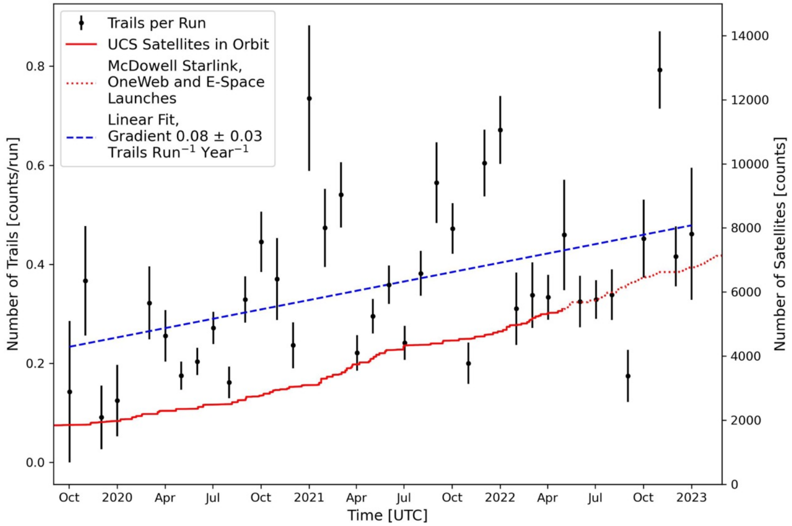
→ Multi-instrument fitting & calibration

→ Rapid response to transients

→ Robustness to observation conditions

→ Big data & powerful computing approaches





T. Lang, S. Spencer, AM, A&A 677, A141 (2023)

Summary and Outlook

Many sources and source classes are emerging at UHE – beyond expectations.
Many associated with pulsars.

New source classes also emerging – novae, microquasars

Highest energy particles are earliest to escape from accelerator
→ traverse across the intervening medium to interact with nearby molecular clouds

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

→ Expect that many accelerators act as PeVatrons for a brief period only

→ Can search instead for evidence of past PeVatron activity.

Lots to study and unanswered questions in galactic gamma-ray astronomy!

Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS → Erlangen Centre for Astroparticle Physics

FAU

Thank you for your attention

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DFG Deutsche Forschungsgemeinschaft

DFG project number: 452934793

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DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Effect of satellite trails on H.E.S.S. data

Using an On-Off approach for the duration of a satellite transit across the camera

Find an increase in low amplitude events → usually excluded by threshold cuts

Nevertheless may become significant for specific analyses

More trails occur at the beginning and end of the night, and at high zenith angles (expected trend).

Other IACTs should perform similar studies to assess the impact of satellite trails on different camera designs and from different locations.