Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

The Evolution of Pulsar Environments at TeV Energies

Alison Mitchell
TU Dortmund seminar 05/05/22

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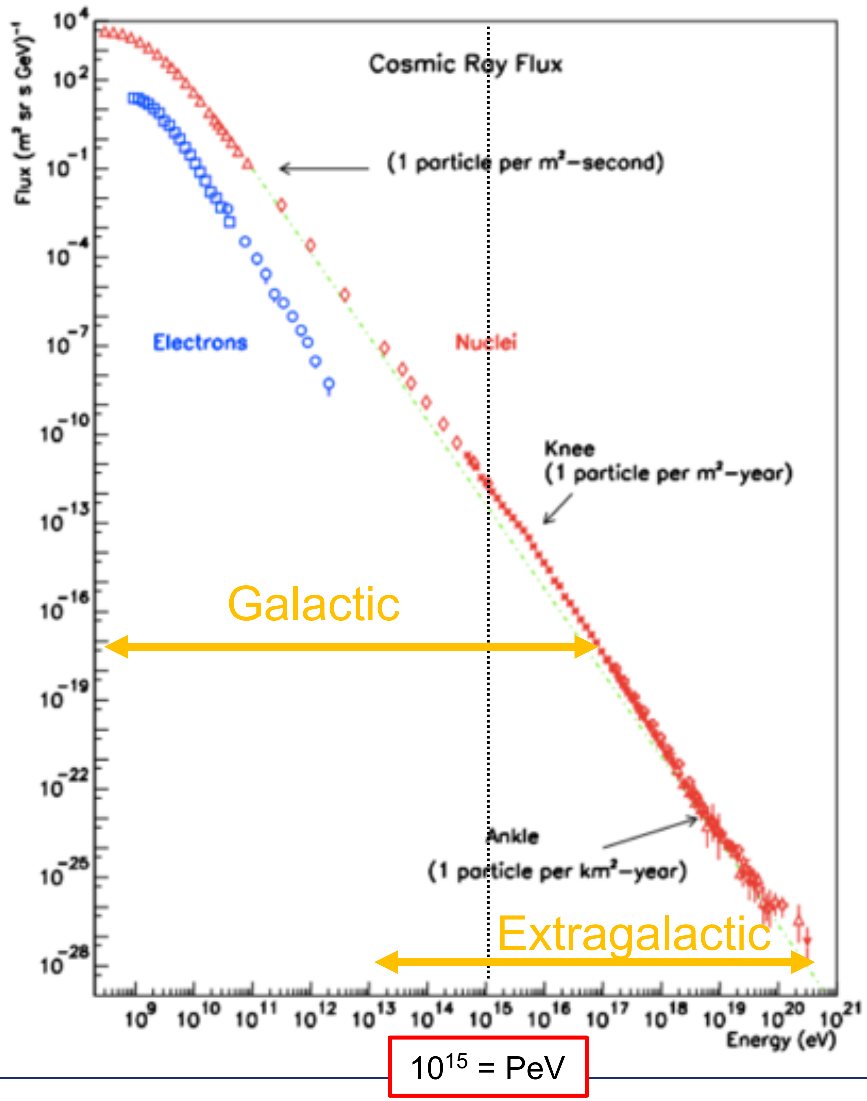
The All-particle Cosmic Ray Spectrum

- High Energy particles from space, up to 10^{20} eV
- p, He, C, N, O, Fe… e^-, e^+ …

<u>Why are Cosmic Rays important?</u>

- Highest energy particles in nature
- Central component of our Galaxy; comparable energy budget to starlight, dust, magnetic fields…
- Interact and feedback on environment
  → affect Galactic structure



Cosmic rays and the hunt for PeVatrons

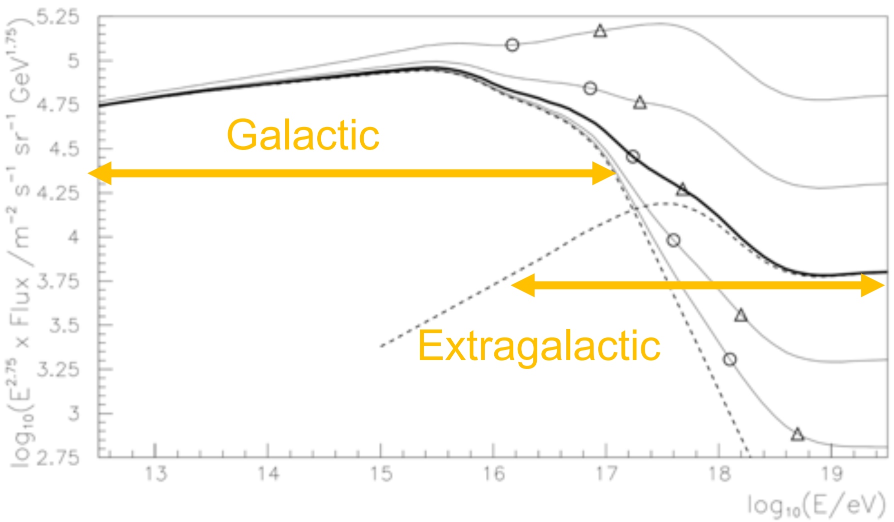
Three stages to become a cosmic ray:

1. Acceleration within sources (injection spectrum)
2. Escape from sources (energy loss processes)
3. Propagation through interstellar medium (ISM)

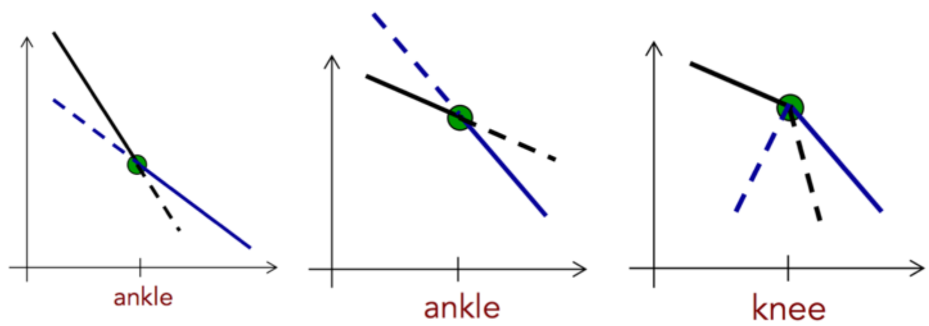
→ Each step modifies the spectral shape

$$f_{accn} \neq f_{esc} \neq f_{galCR}$$

Galactic – Extragalactic transition occurs somewhere between "knee" ($\sim 10^{15}$eV) and "ankle" ($\sim 10^{18}$eV)



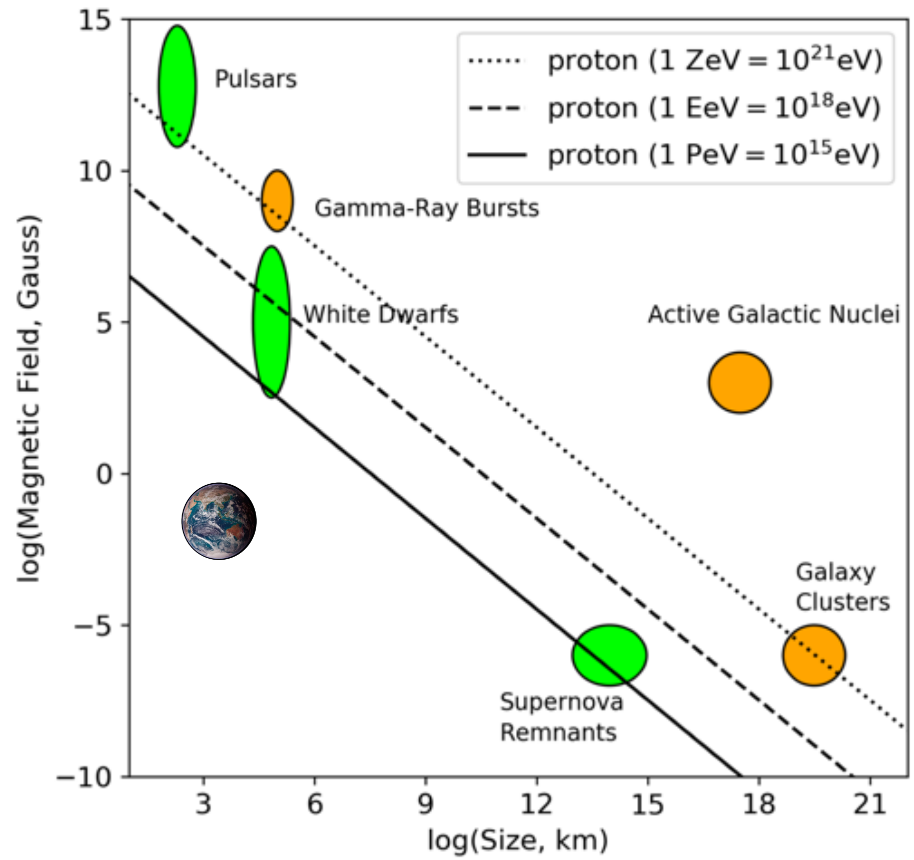
Hillas, conf. proc. (arXiv:0607109)

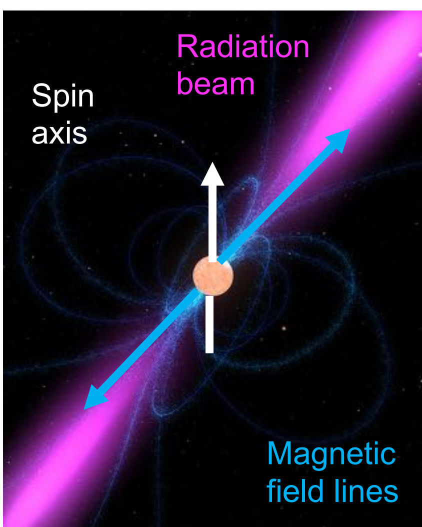


E. Parizot

The origin of Galactic cosmic rays?

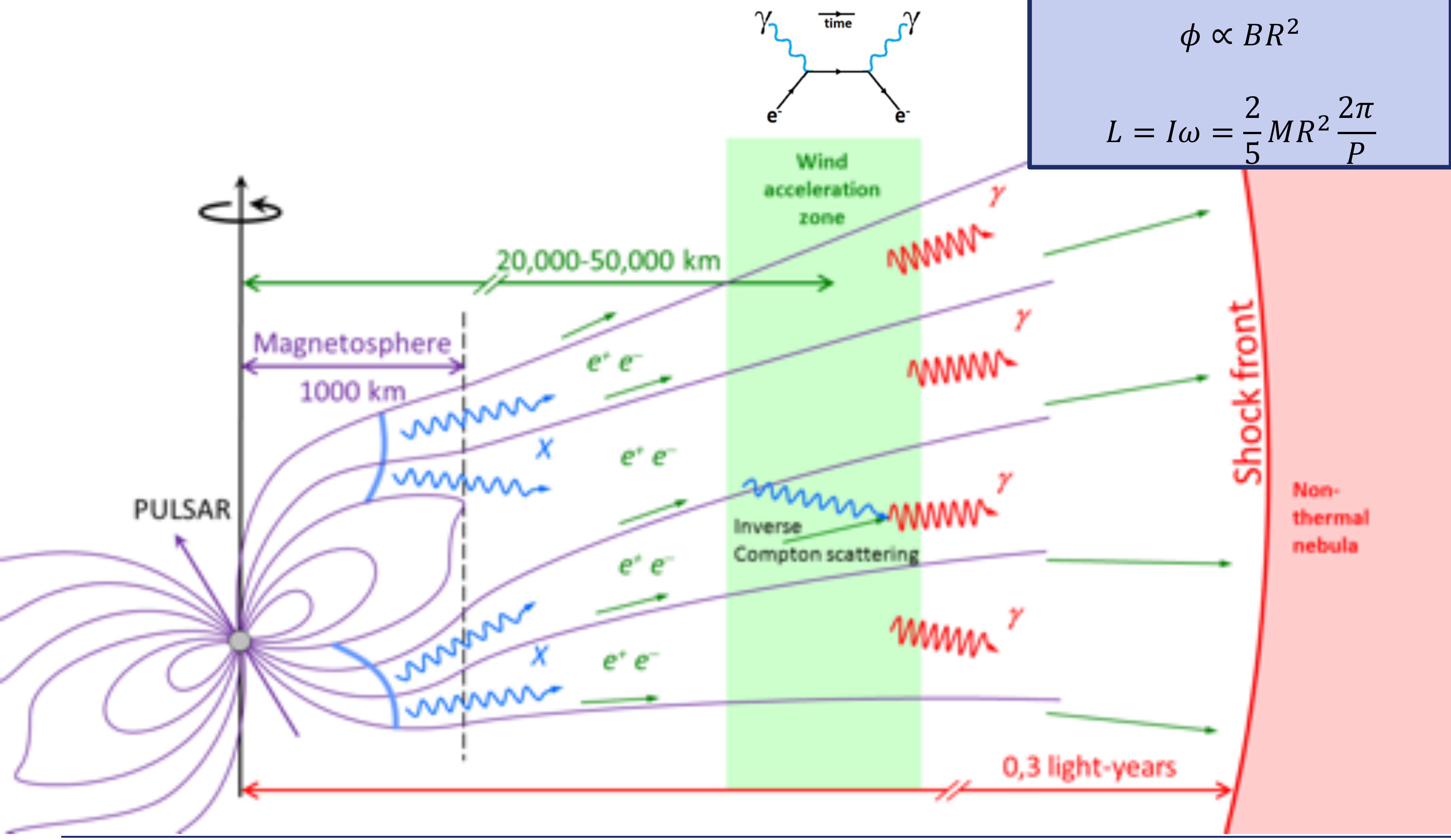
- Supernova Remnants as prime candidates
- Difficult to reach 10^{15} eV
- Shift to other PeVatron candidates
    - Stellar clusters → particle acceleration due to wind & shock interactions?
    - Pulsars → acceleration of ions as well as $e^{+} - e^{-}$ pairs?
    - Shock mixing from SNRs in pulsar environments?





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

Pulsar – Pulsar Wind – Pulsar Wind Nebula

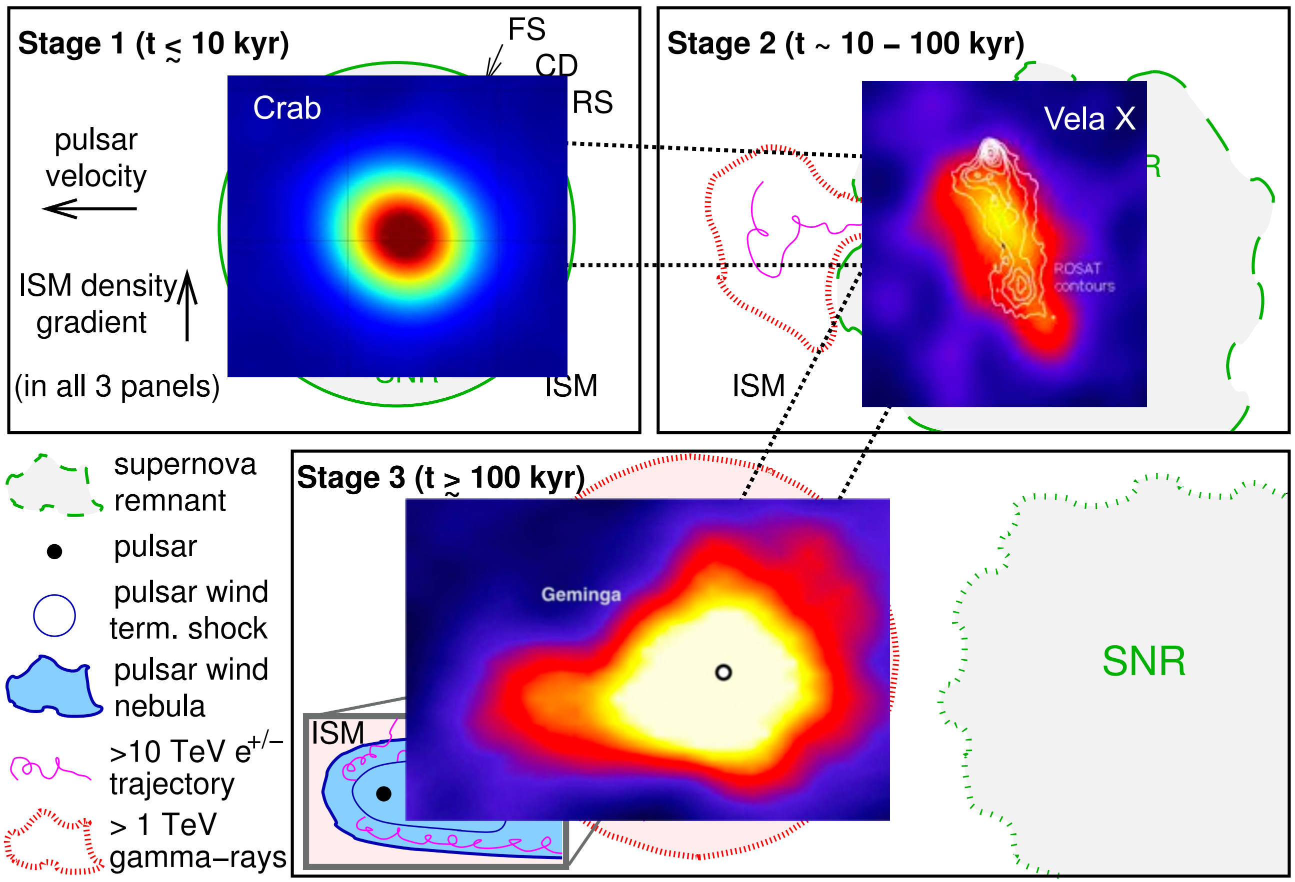


Conserved during collapse:

$$\phi \propto BR^2$$

$$L = I\omega = \frac{2}{5} MR^2 \frac{2\pi}{P}$$

Evolutionary stages of pulsar environments



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

Pulsar Wind Nebulae
→ traditionally dominant sources at TeV

Pulsar Halos
→new
Particle escape into interstellar medium

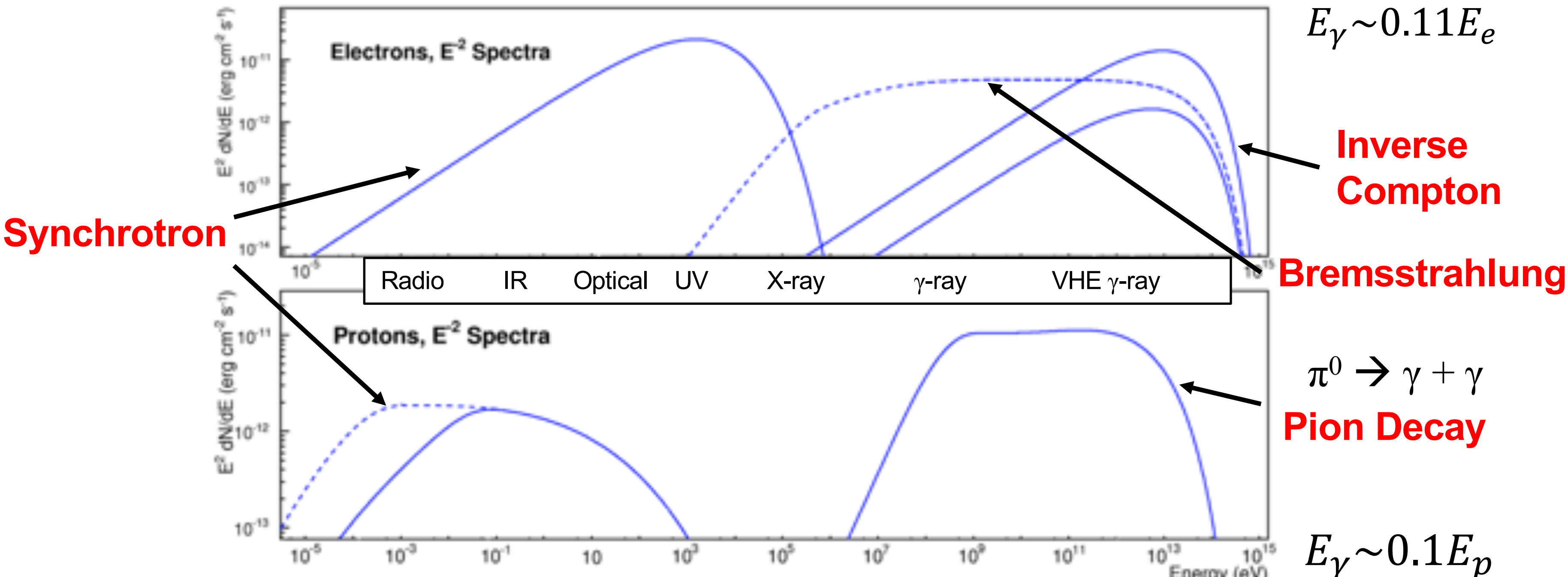
Pulsar Halos: opportunity to directly measure rate of particles (electrons / protons) escaping source and joining the sea of galactic Cosmic Rays

Very-High-Energy Gamma-ray Astronomy

Gamma-ray Emission Mechanisms

$$-\frac{dE_e}{dt} \propto \gamma^2 U_{rad}$$

$$E_\gamma \sim 0.11 E_e$$



Hinton & Hofmann (2009)

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

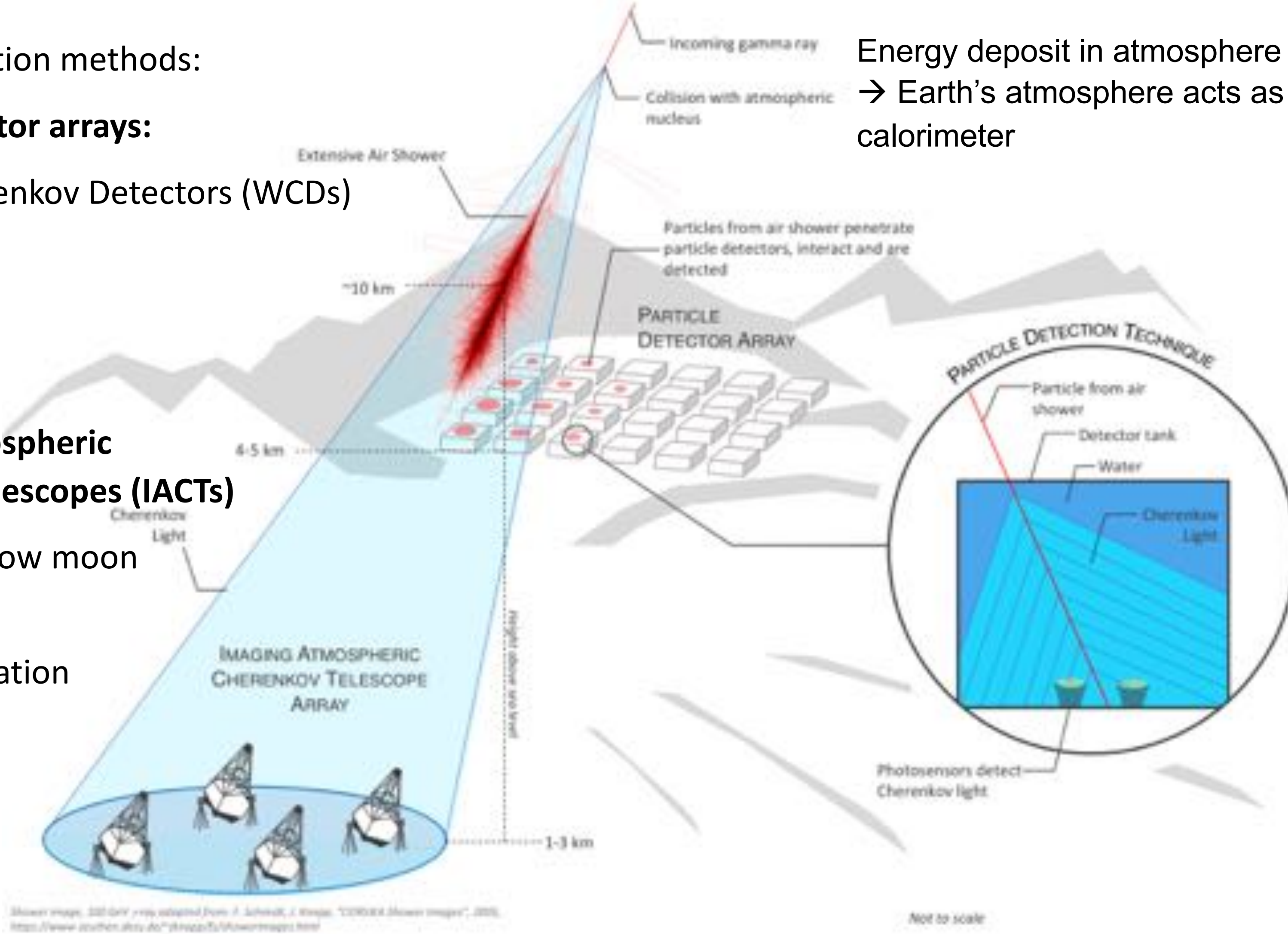
$$E_\gamma \sim 0.1 E_p$$

Detection Techniques for Very-High-Energy gamma-rays

Two main detection methods:

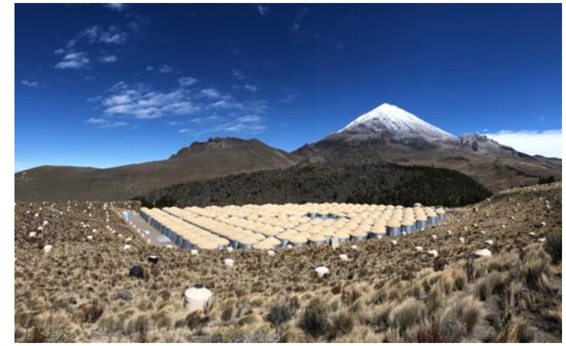
- **Particle detector arrays:**
  - Water Cherenkov Detectors (WCDs)
  - Scintillators
  - Up to 24/7
- **Imaging Atmospheric Cherenkov Telescopes (IACTs)**
  - Night only, low moon
- ...or a combination

Energy deposit in atmosphere
→ Earth's atmosphere acts as a calorimeter

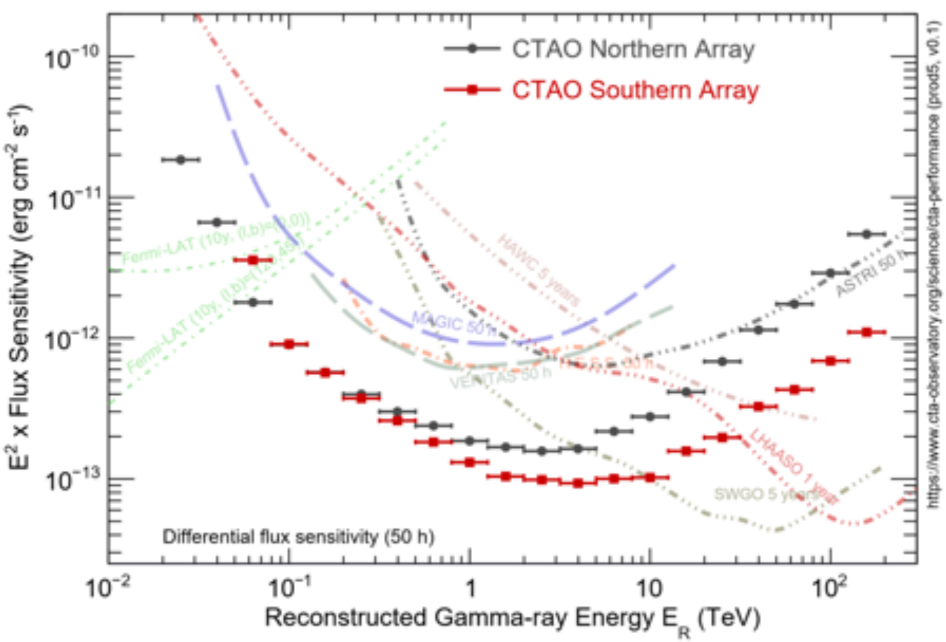


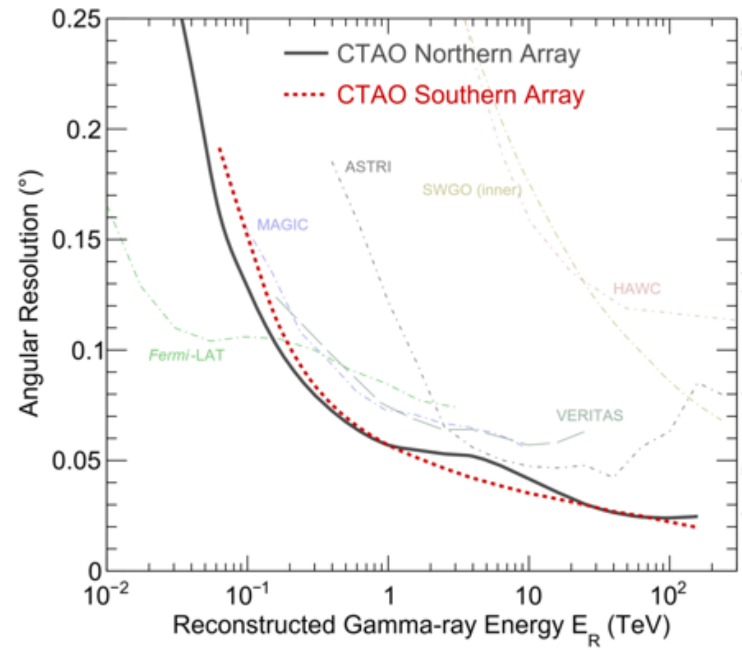
https://www.swgo.org/SWGOWiki/doku.php

Complementary Facilities



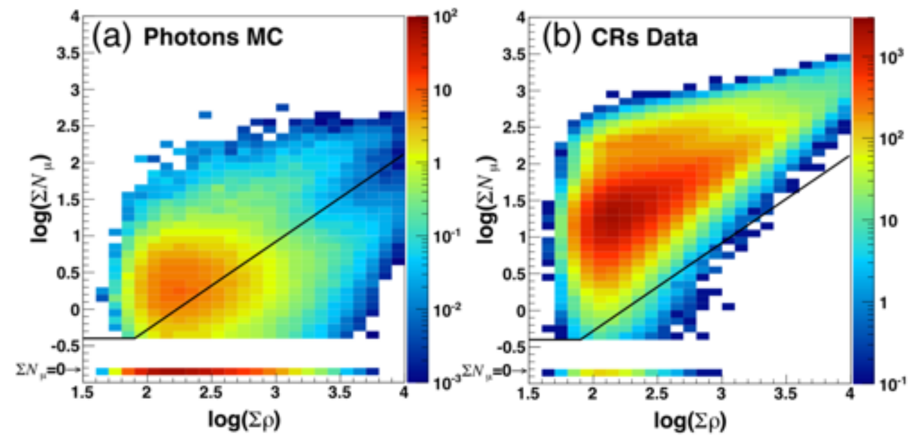
Different techniques → different performance



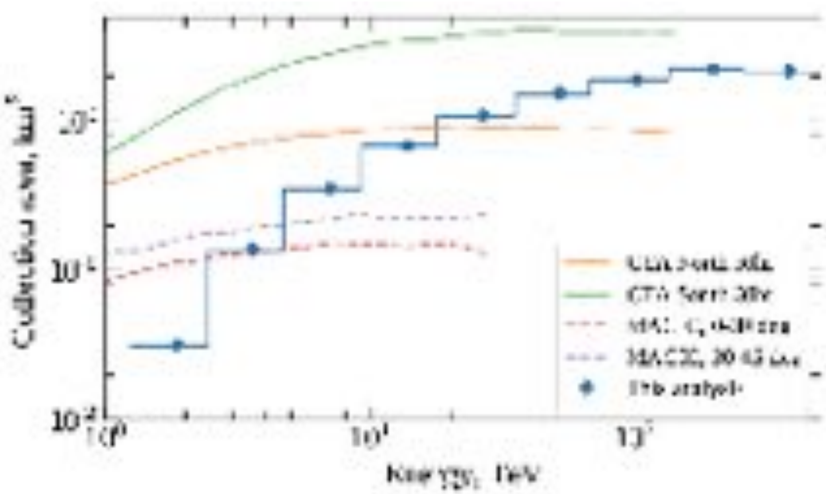


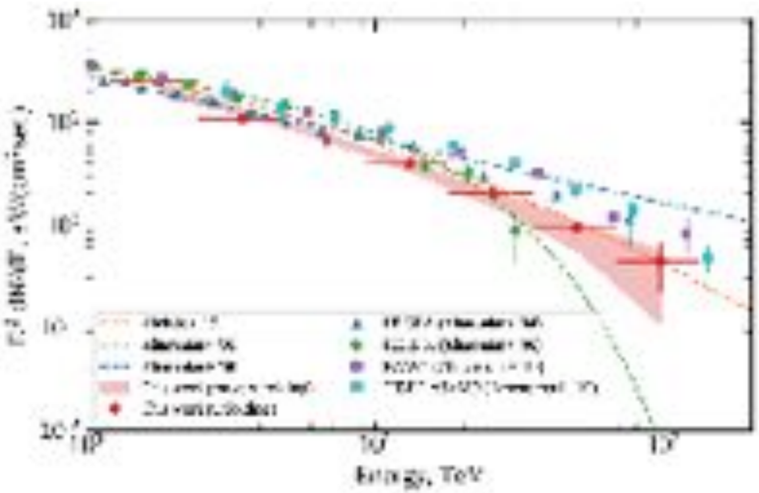
High Energy performance improvements

- Background rejection by muon tagging key for Water Cherenkov Facilities (LHAASO and Tibet ASγ)
- Potential improvements in background rejection using muon tagging in IACTs
- Very Large Zenith Angle Observations
  → increase collection area at highest energies



Gamma Survival ratio : ~90% by MC sim (>100 TeV)
CR Survival ratio : ~10^{-3} (>100 TeV)



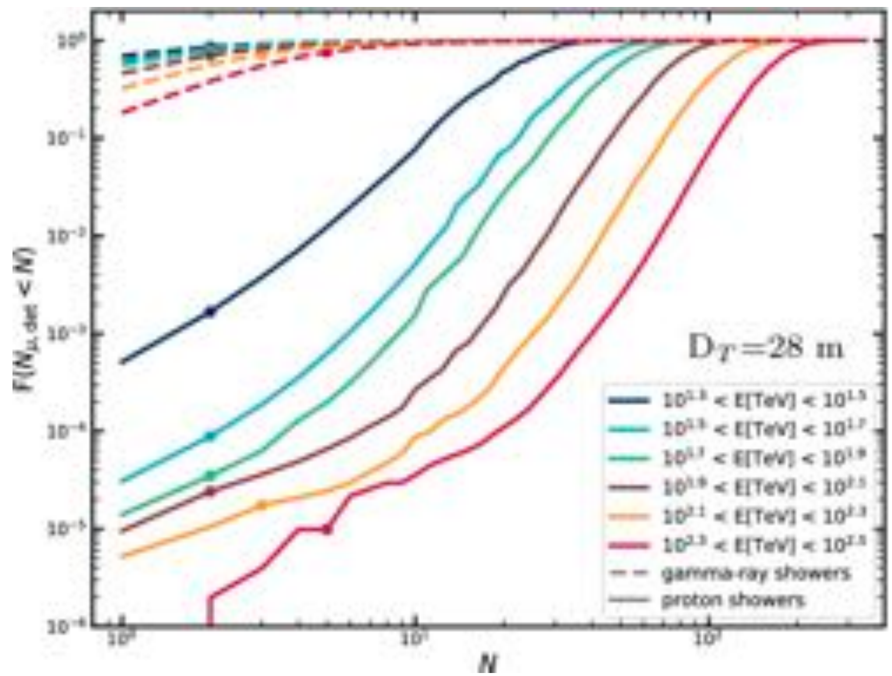


MAGIC collaboration A&A 635 (2020) A158

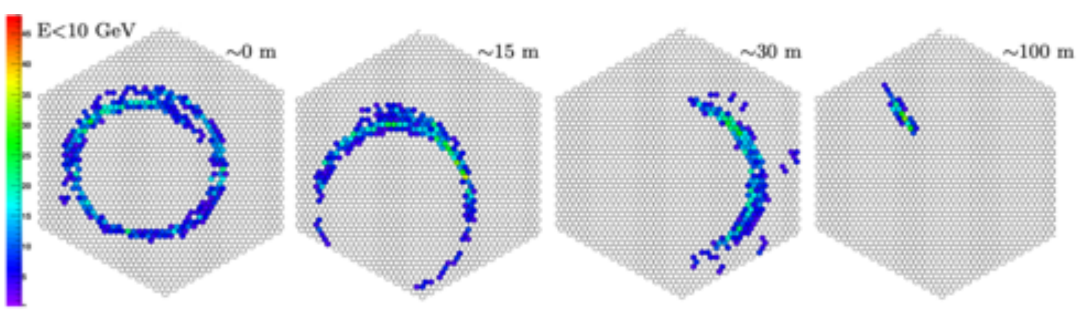
Muons and hadronic air showers

Muons as a tool for background rejection

- Limiting factor for detection of extended halos:
  Background of cosmic ray air shower events
- Improving background rejection improves sensitivity
- Use muons from proton initiated air showers as a veto against background events
- New approach for IACTs



L. Olivera-Nieto et al., EPJC **81** 1101 (2021)



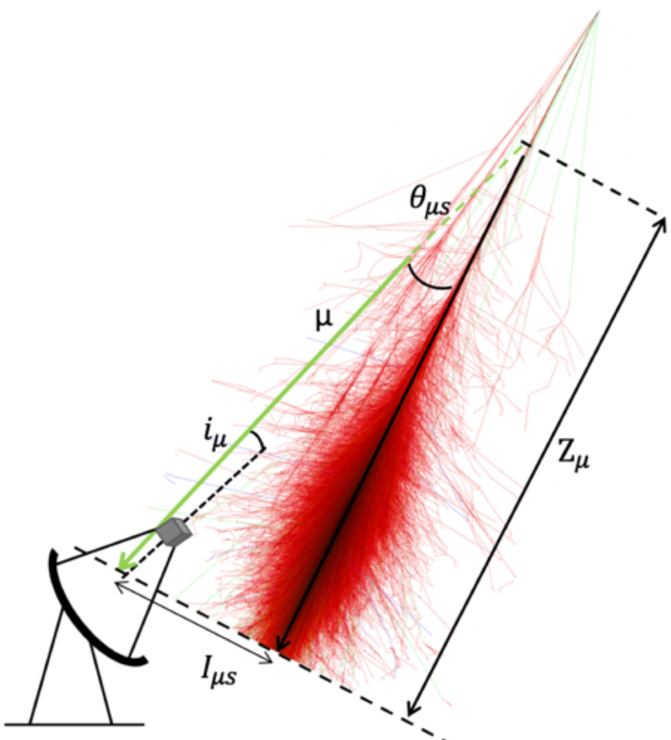
Muons form characteristically ring-shaped images
→ when passing through the mirror dish
Flag muons caught in shower images to veto events

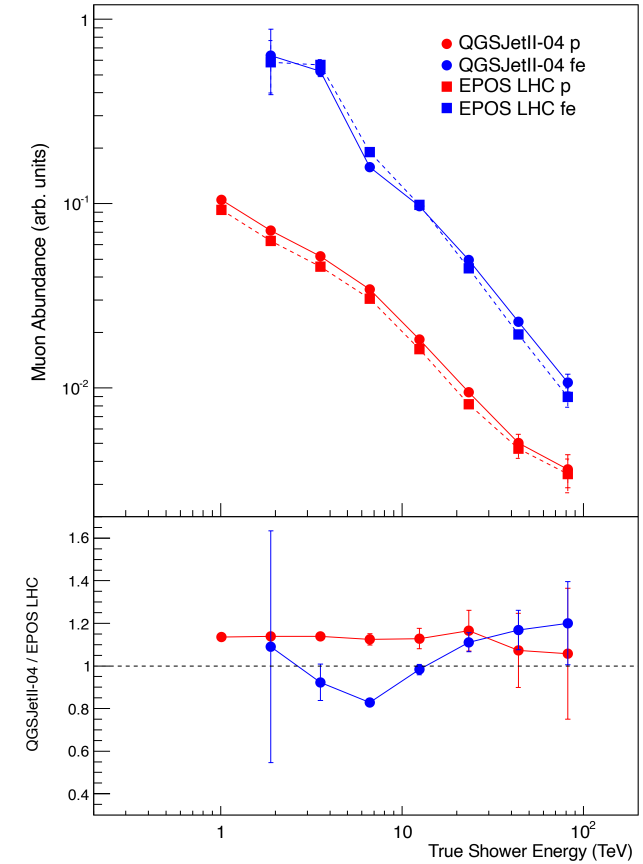
Muon measurements with IACTs

Measure properties of muons in TeV air showers with IACTs:

Muon Rate, lateral distribution, production height...

Well-known discrepancy between simulations and data above ~10^{15} eV

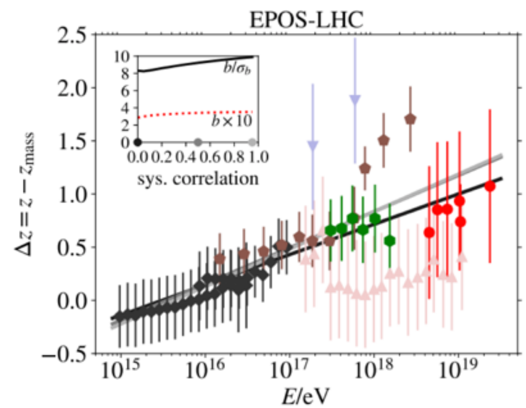




AM, Dembinski, Parsons Astroparticle Physics, 111, 23-34 (2019)

Measuring properties of muons in EAS

Muon deficit in simulations of hadronic Extensive Air Showers compared to measurements.

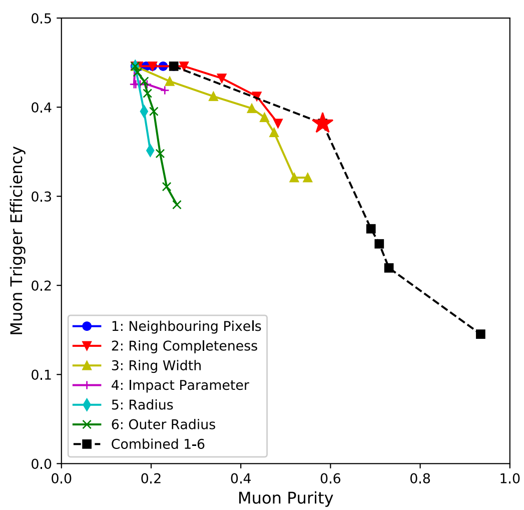


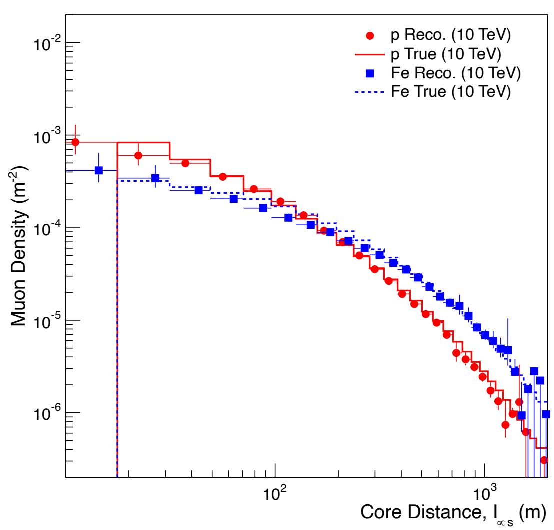
Results confirmed as atound 8 sigma deviation in a combined analysis across multiple experiments

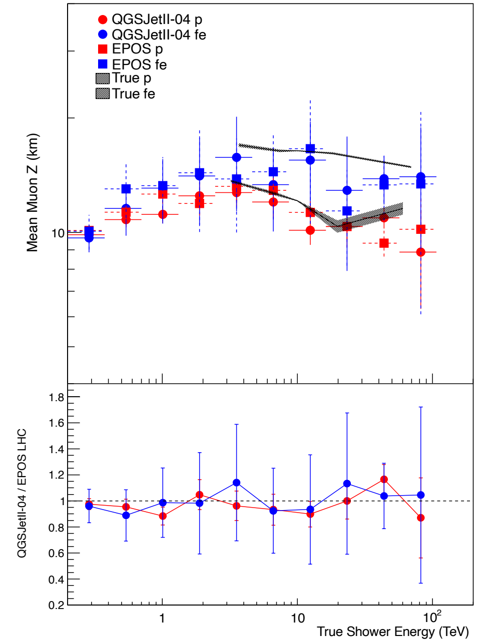
Dembinski et al, UHECR 2018 EPJ Web of Conferences 210, 02004, 2019

Plenty of potential to improve approach

→ Make a first measurement in the TeV range







AM, Dembinski, Parsons Astroparticle Physics, 111, 23-34 (2019)

Hadronic Interaction Model Uncertainties

Understanding performance of VHE gamma-ray instruments relies on simulations

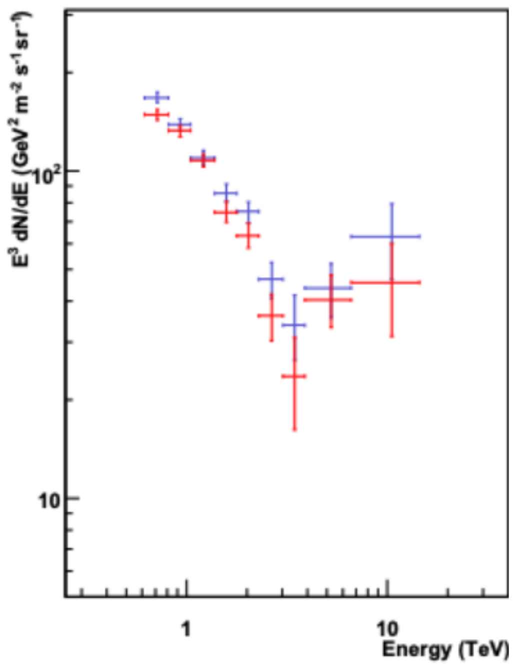
Air shower simulations generated with different hadronic interaction models

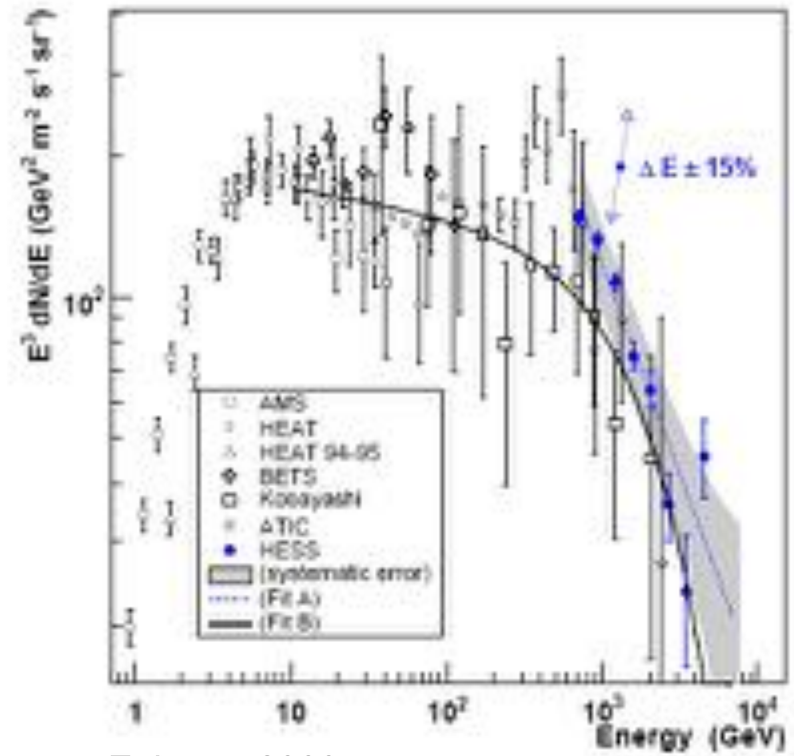
Can affect and change results / interpretation → especially for Cosmic Ray measurements

Example:
Electron spectrum

Local pulsars may contribute to the high energy CR electron spectrum

Improvements in hadronic interaction model uncertainties
→ more accurate physics interpretations



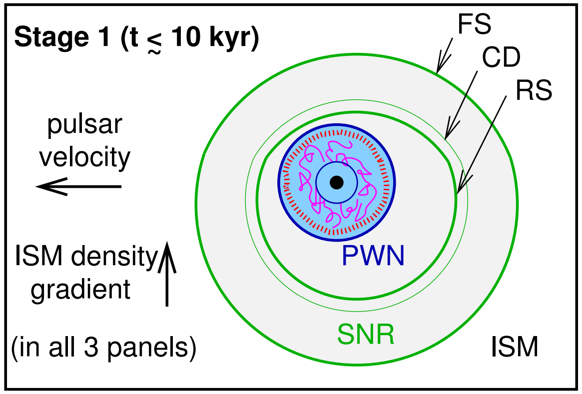


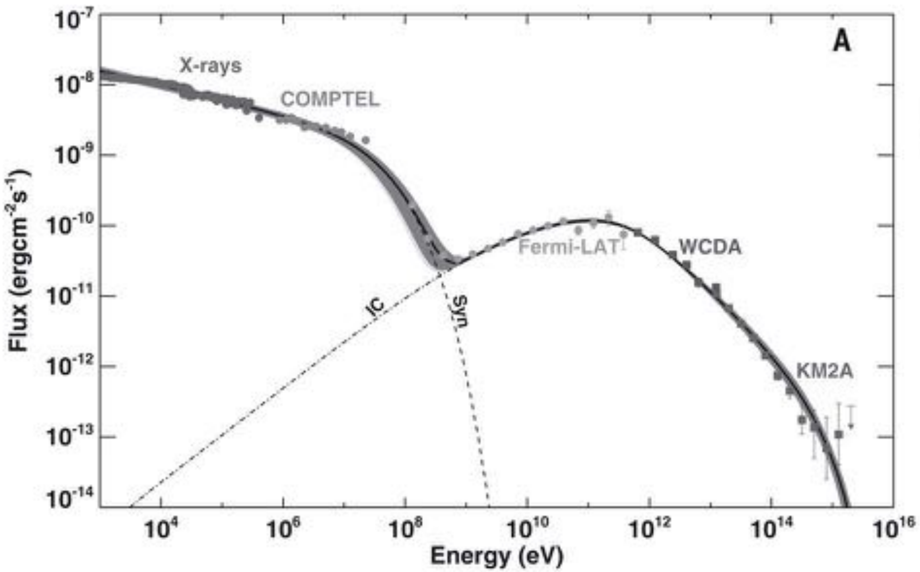
Egberts, 2009

Example pulsar environments

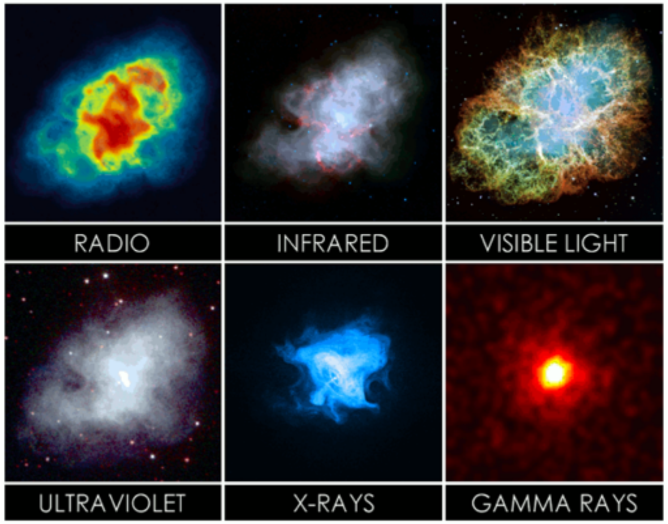
Example Stage 1: Crab Nebula

- Crab Nebula – standard candle of TeV gamma-ray astronomy
- Age = 0.94 kyr, log(Edot) = 38.65 erg/s, Distance = 2 kpc,
- R: radio = 2.8 pc, X-ray = 0.24 pc, TeV ≤ 3 pc
- Gamma-ray flares, resolved TeV extent
- Emission > 100 TeV





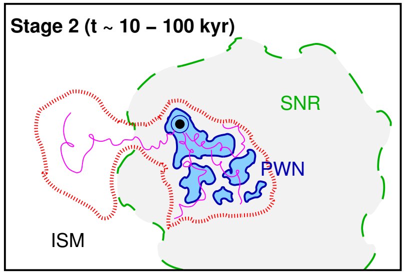
Z. Cao et al. LHAASO collaboration, Science **373**, 425-430 (2021)

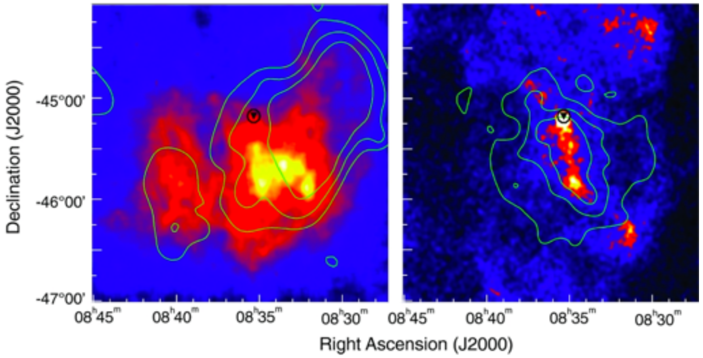


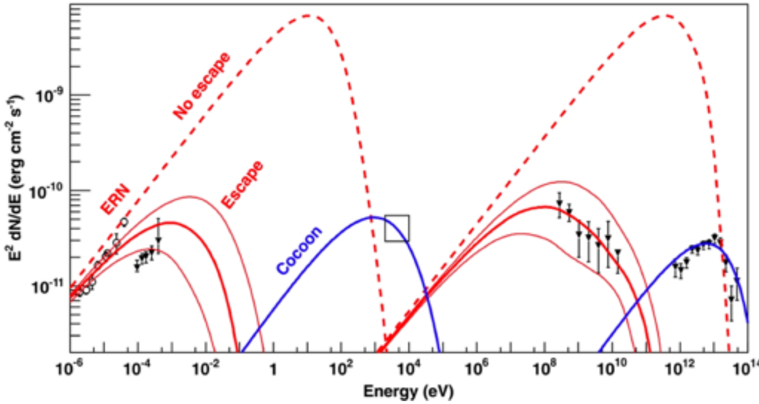
18

Example Stage 2: Vela X

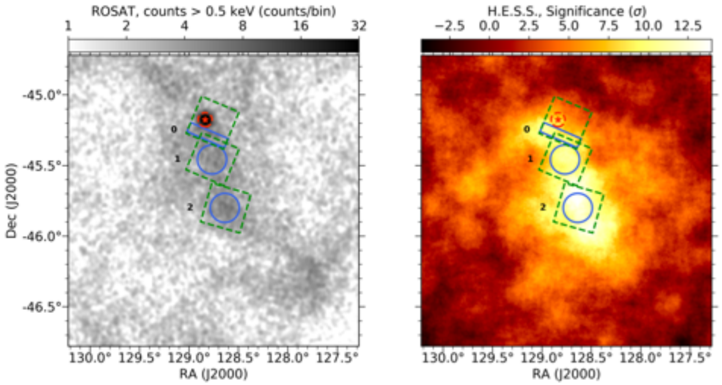
- Age = 11.3 kyr, log(Edot) = 36.84 erg/s, Distance = 0.28 kpc,
- R: radio = 12.2 pc, X-ray = 3.08 pc, TeV = 2.9 pc

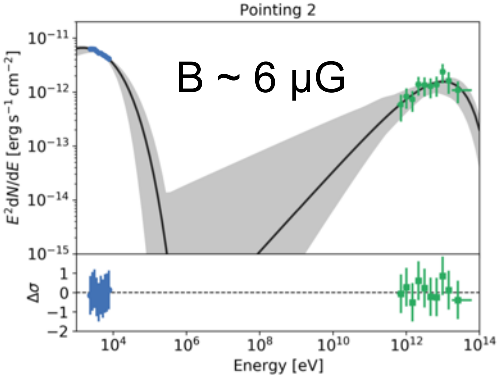






Hinton et al. ApJLett 743 (2011) L7

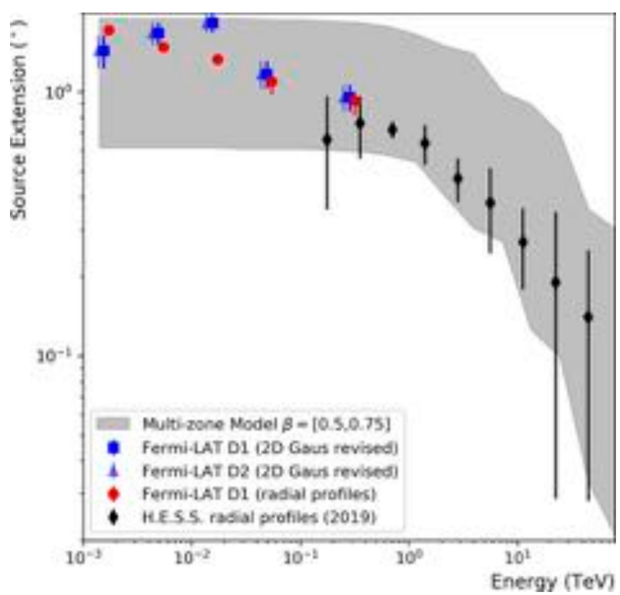




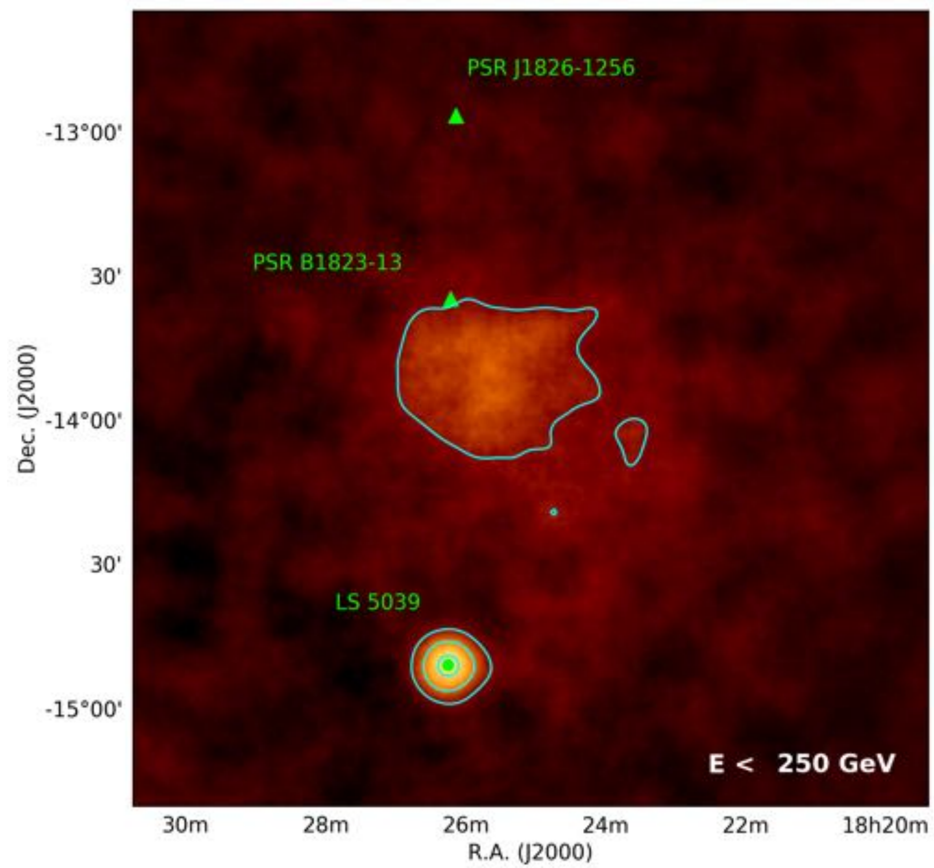
H.E.S.S. Collaboration, A&A 627, (2019) A100

Example transition: HESS J1825-137

- Age = 21.4 kyr, log(Edot) = 36.45 erg/s, Distance = 3.9 kpc,
- R: radio = ? pc, X-ray = 9.1 pc, TeV = 50 pc
- strong energy dependent morphology
- bright at energies > 100 TeV



Principe et al. A&A **640** (2020) A76

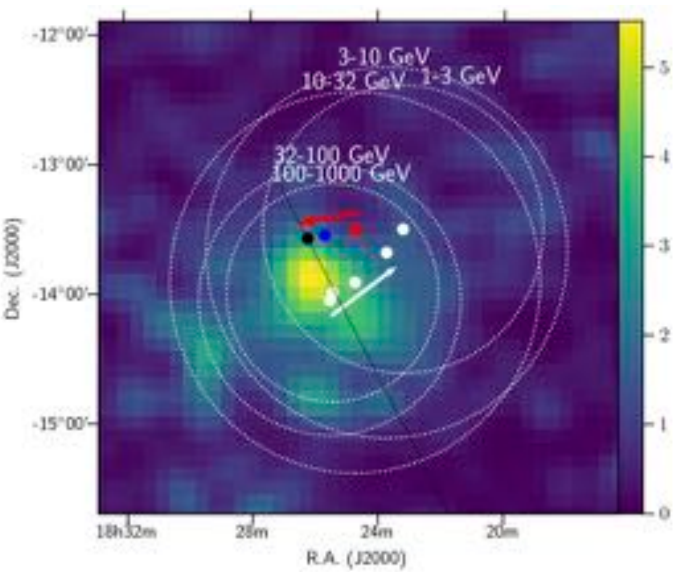


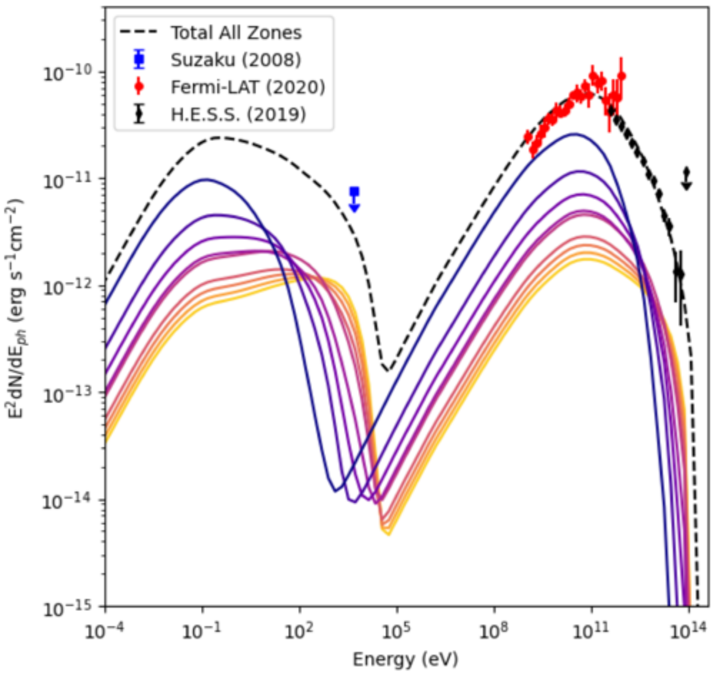
H.E.S.S. collaboration et al. A&A **621** (2019) A116

Example transition: HESS J1825-137

Particle evolution and transport

- Age = 21.4 kyr, log(Edot) = 36.45 erg/s, Distance = 3.9 kpc,
- R: radio = ? pc, X-ray = 9.1 pc, TeV = 50 pc
- strong energy dependent morphology
- bright at energies > 100 TeV





Principe et al. A&A **640** (2020) A76

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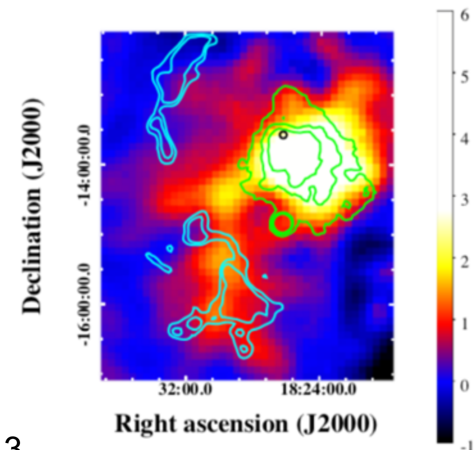
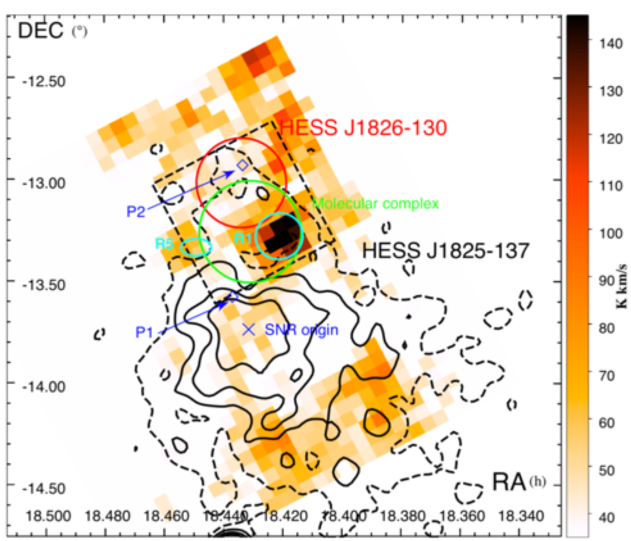
- strong energy dependent morphology
- bright at energies > 100 TeV

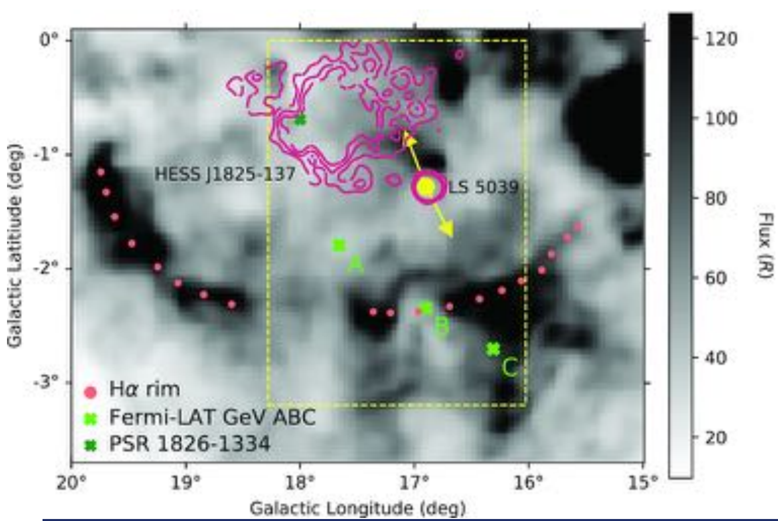
Araya et al. MNRAS **485** (2019) 1001-7



Voisin et al. MNRAS 458 (2016) 2813



Collins et al, MNRAS **504**, 1840-1853 (2021)



HAWC J1825-134

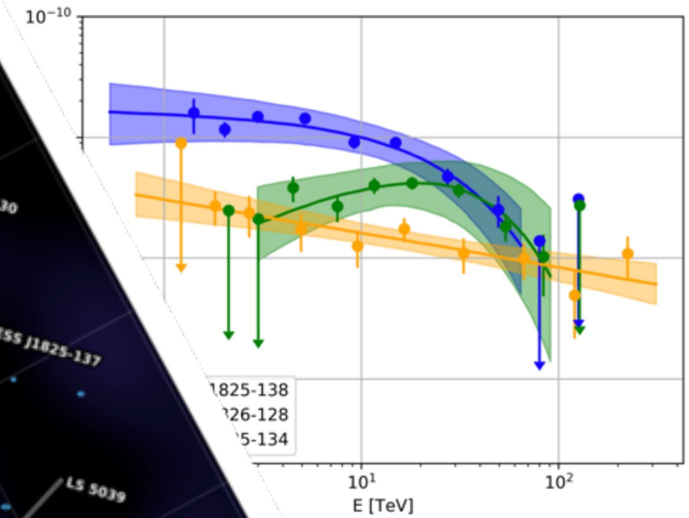
HAWC Collaboration, arXiv:2012.15275

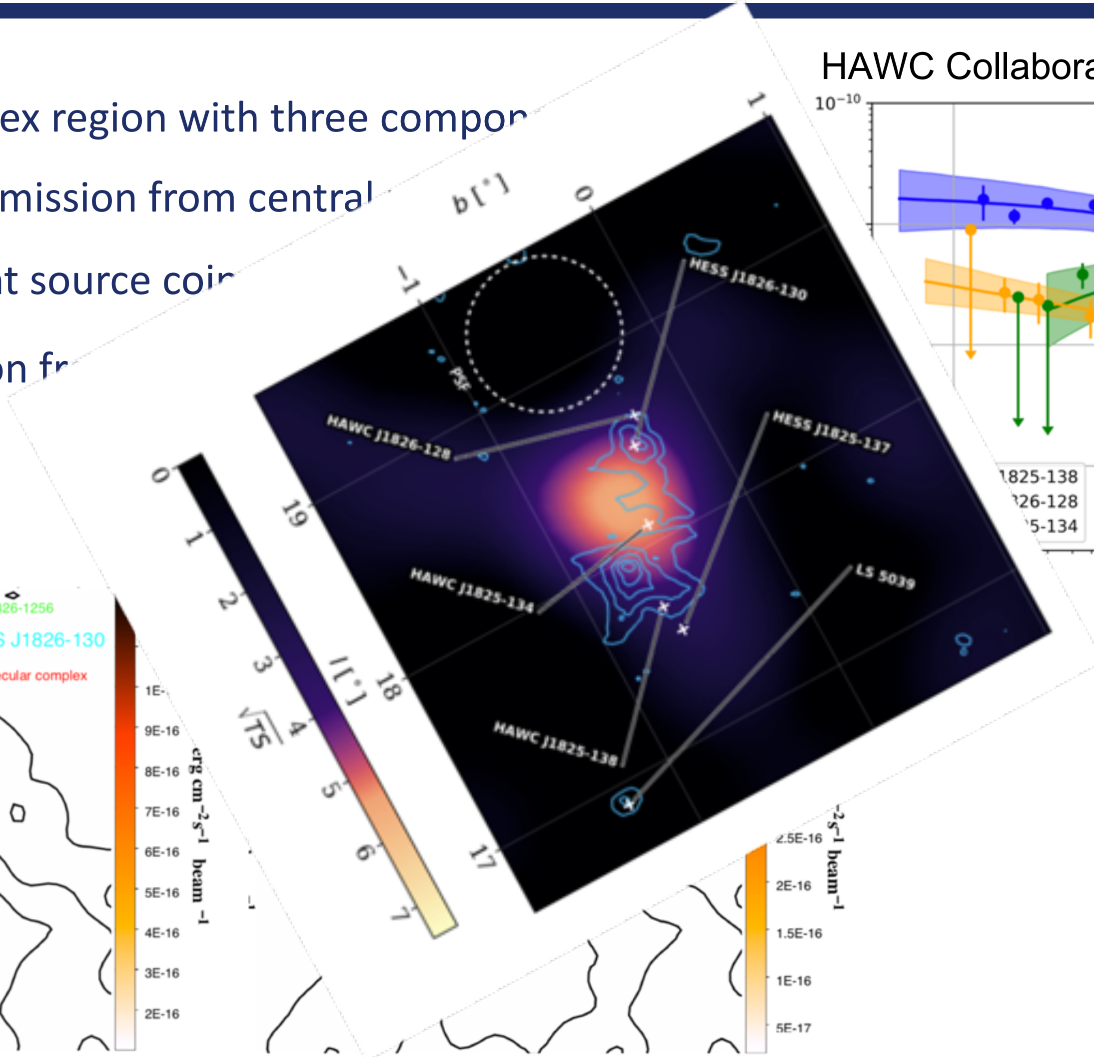
Joint fit of complex region with three compon

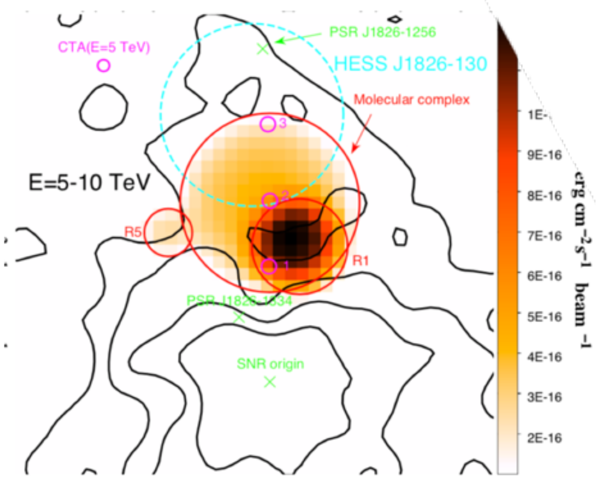
Highest energy emission from central

New independent source coi

Hadronic emission fr







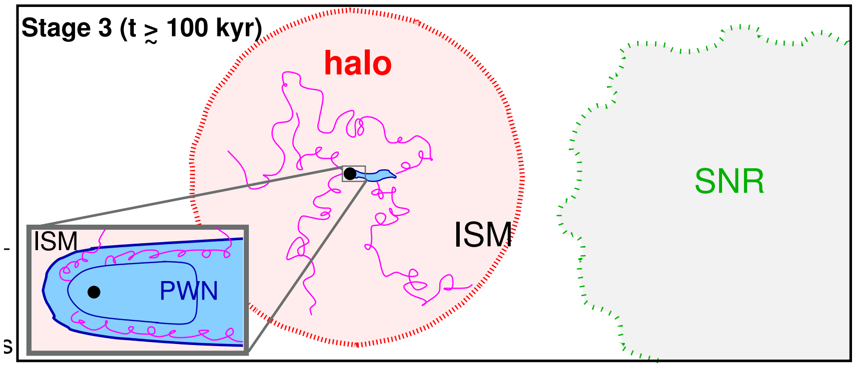
Hadronic, impulsive, SNR

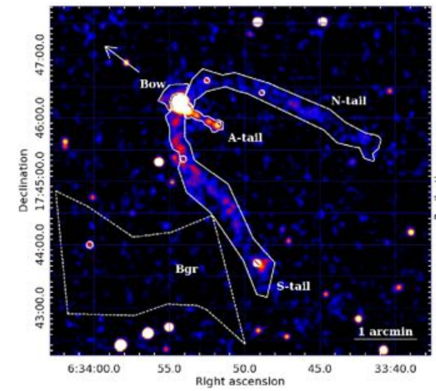
Hadronic, continuous, PWN

Voisin PhD thesis 2017

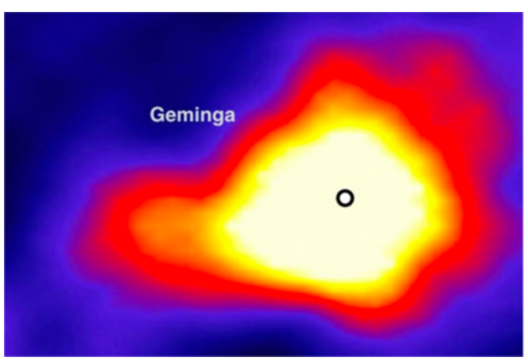
Example Stage 3: Geminga

- Age = 342 kyr, log(Edot) = 34.51 erg/s, Distance = 0.25 kpc,
- R: radio = 0.01 pc, X-ray = 0.15 pc, TeV = 100 pc

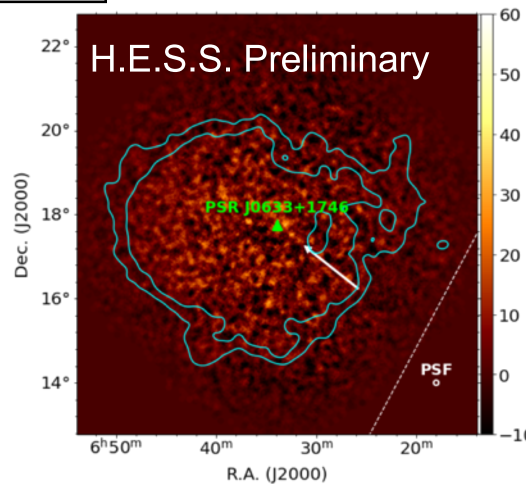




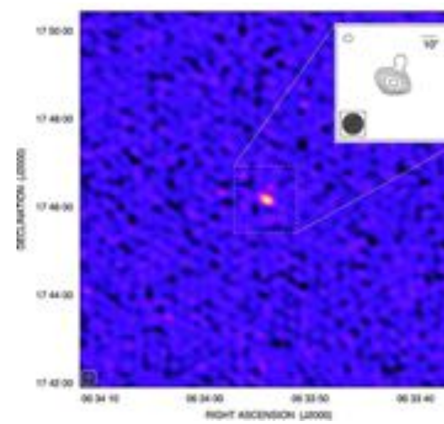
Posselt et al. ApJ 835 (2017) 66



HAWC Collaboration, Science **358**, (2017) 911



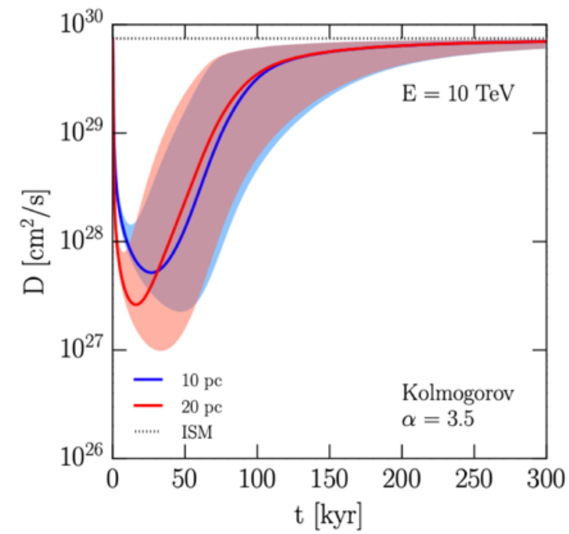
AM et al. PoS(ICRC2021)780



Pellizzoni et al. MNRAS 416 (2011) L45

Particle Transport – Diffusion in the ISM

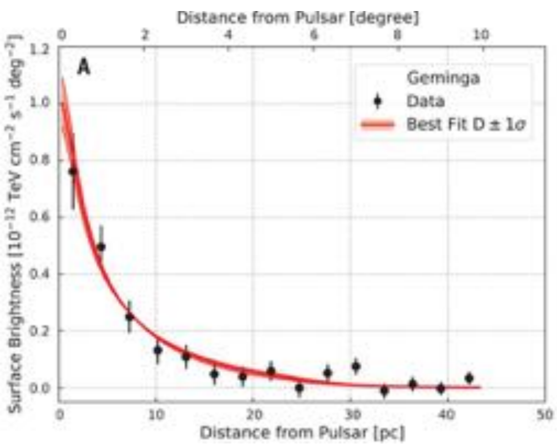
Evoli et al PRD **98**, 063017 (2018)

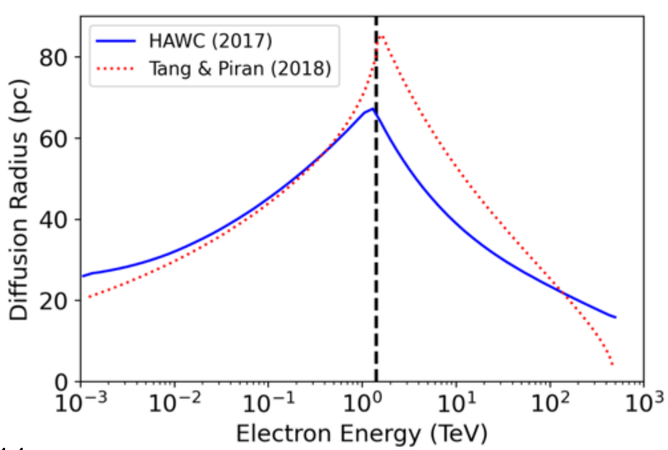


Diffusion much slower than Galactic Average (from B/C ratio)
→ tension with pulsars as an explanation for the CR e- spectrum?

Possible solutions:

- Diffusion only slow/inhibited within halo region (CR self-generated turbulence)
- Unidentified nearby source?
- ...





HAWC Collaboration, Science **358**, (2017) 911

Careful!

Diffusion slow in halos – escaped particles

Diffusion slow in PWNe – trapped particles

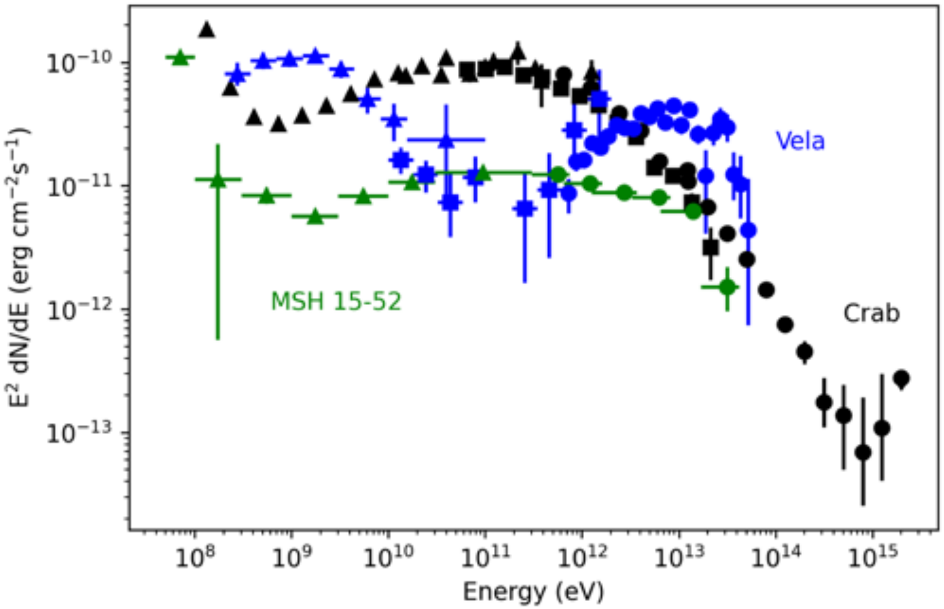
General Properties of Pulsar Wind Nebulae

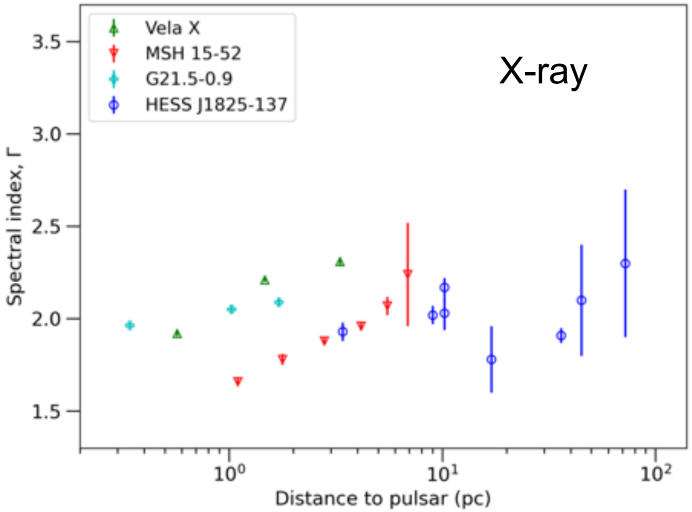
Energy-dependent morphology

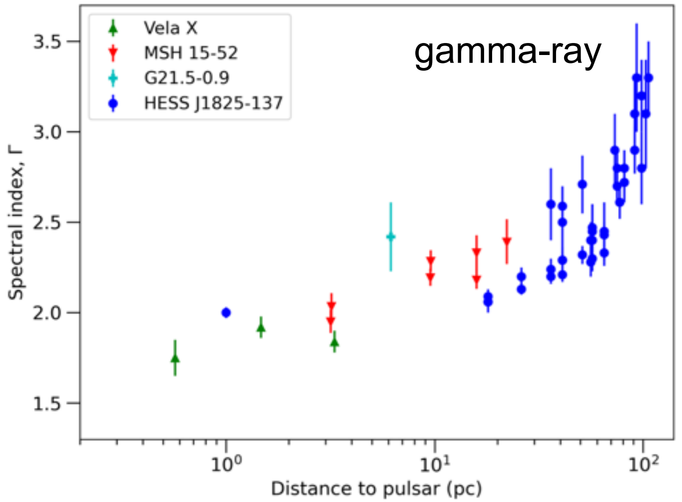
→ Due to cooling losses as particles are transported away from pulsar (seen in X-ray and gamma-ray)

Spectral Energy Distribution

→ Leptonically dominated, inverse Compton



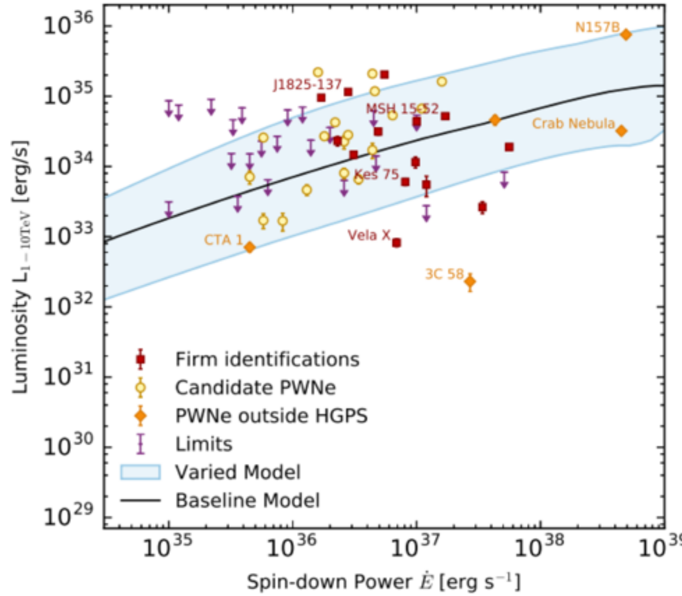




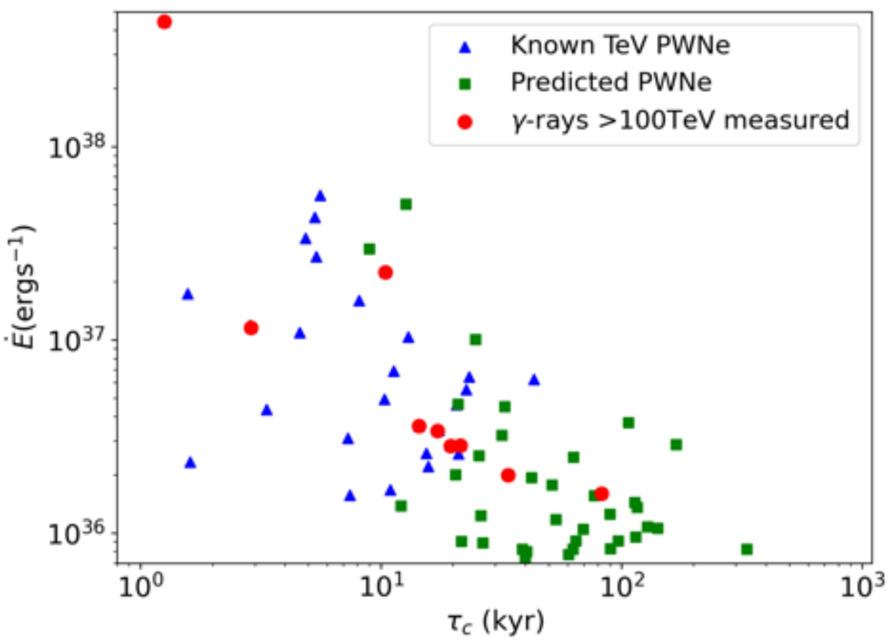
Pulsar population and the gamma-ray sky

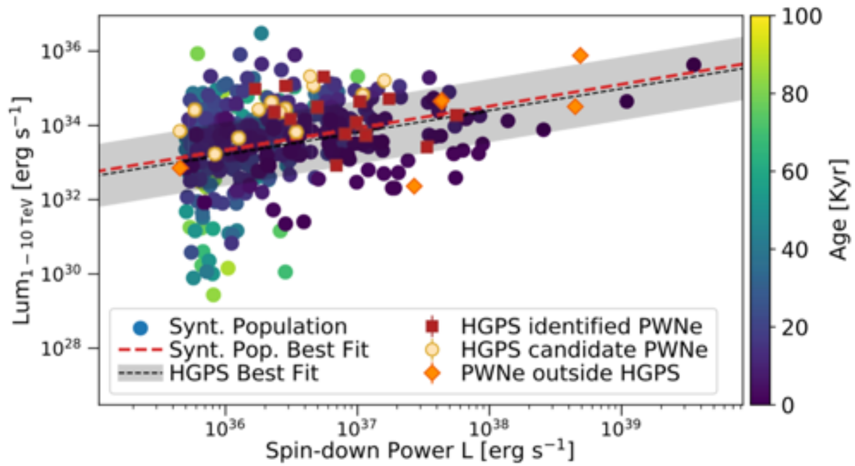
Model for evolution of pulsar wind nebulae

- Adopt baseline model from HESS PWN population paper
- Predict PWNe around pulsars listed in ATNF



H.E.S.S. collaboration A&A 612, A2 (2018)





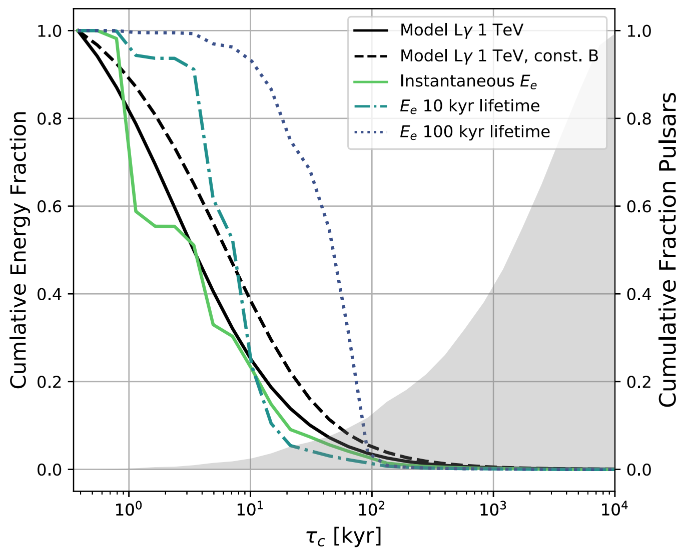
Fiori et al MNRAS 511, 1439-53 (2022)

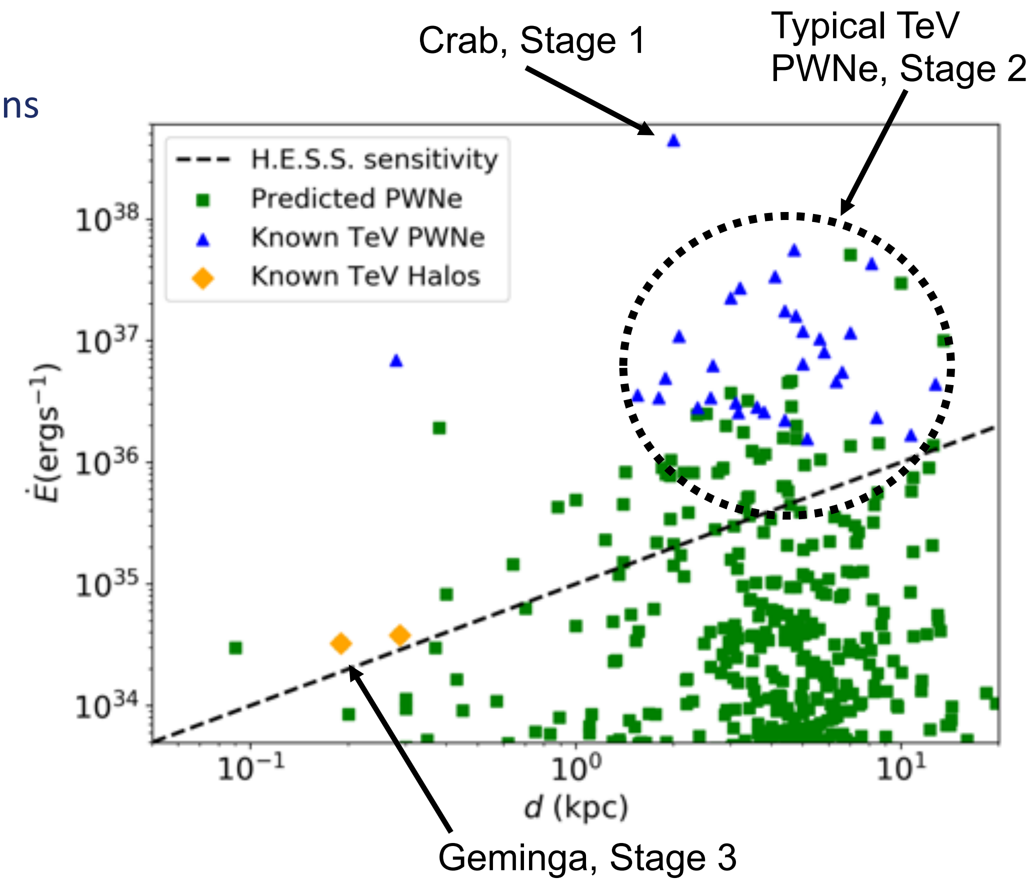
Population studies of pulsar environments

1. Variation with evolutionary stage?
2. Particle transport mechanism?
3. Evidence of proton acceleration?

→ Combine TeV data with MWL observations to constrain emission models

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





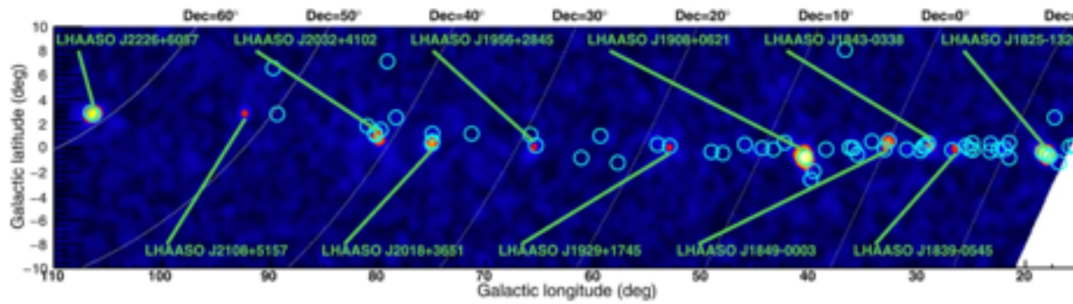
Current halo fraction low – might be a large number of low flux, diffuse halos

Highest energy gamma-ray sky > 100 TeV

- Sky maps by LHAASO, Tibet-ASγ and HAWC:
- $E_\gamma > 100$ TeV ($E_p \sim 1$ PeV; $E_e \sim 183$ TeV) → ~12 sources

Source	Location (l,b)	Detected > 100 TeV by	Possible Origin
Crab Nebula	(184.557, -5.784)	HAWC, MAGIC, LHAASO, Tibet-ASγ	PSR
HESS J1702-420	(344.304, -0.184)	H.E.S.S.	?
Galactic Centre	(0-1.2, -0.1– +0.1)	H.E.S.S.	SMBH?
eHWC J1825-134	(18.116, -0.46)	HAWC, LHAASO	PSR
LHAASO J1839-0545	(26.49, -0.04)	LHAASO	PSR
LHAASO J1843-0338	(28.722, 0.21)	LHAASO	SNR
LHAASO J1849-0003	(32.655, 0.43)	LHAASO	PSR, YMC
eHWC J1907+063	(40.401, -0.70)	HAWC, LHAASO	SNR, PSR
LHAASO J1929+1745	(52.94, 0.04)	LHAASO	PSR, SNR
LHAASO J1956+2845	(65.58, 0.10)	LHAASO	PSR, SNR
eHWC J2019+368	(75.017, 0.283)	HAWC, LHAASO	PSR, H II/YMC
LHAASO J2032+4102	(79.89, 0.79)	LHAASO	YMC, PSR, SNR?
LHAASO J2108+5157	(92.28, 2.87)	LHAASO	?
TeV J2227+609	(106.259, 2.73)	Tibet-ASγ, LHAASO	SNR, PSRs

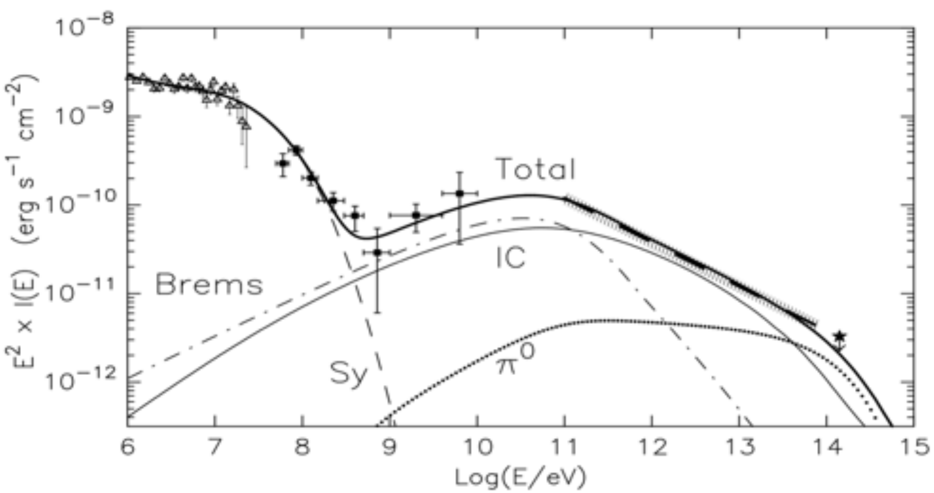
- Most associated with pulsars
- "But pulsars implies e^+ & e^-, not protons / nuclei…"
  → is this assumption true?



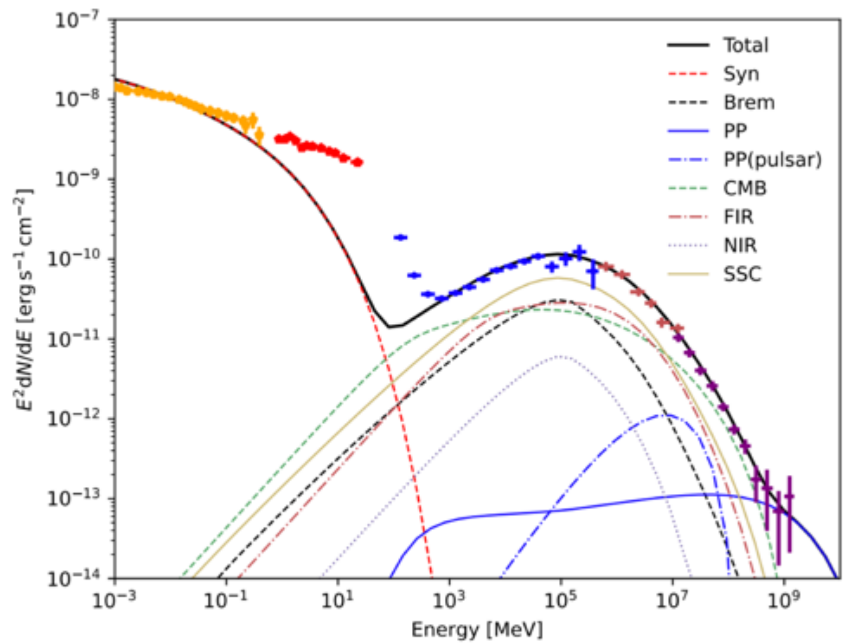
Klein-Nishina cut-off → sub-dominant hadronic component

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

Cf J1908 → also above 100 TeV
→ tentative neutrino association : hadronic smoking gun



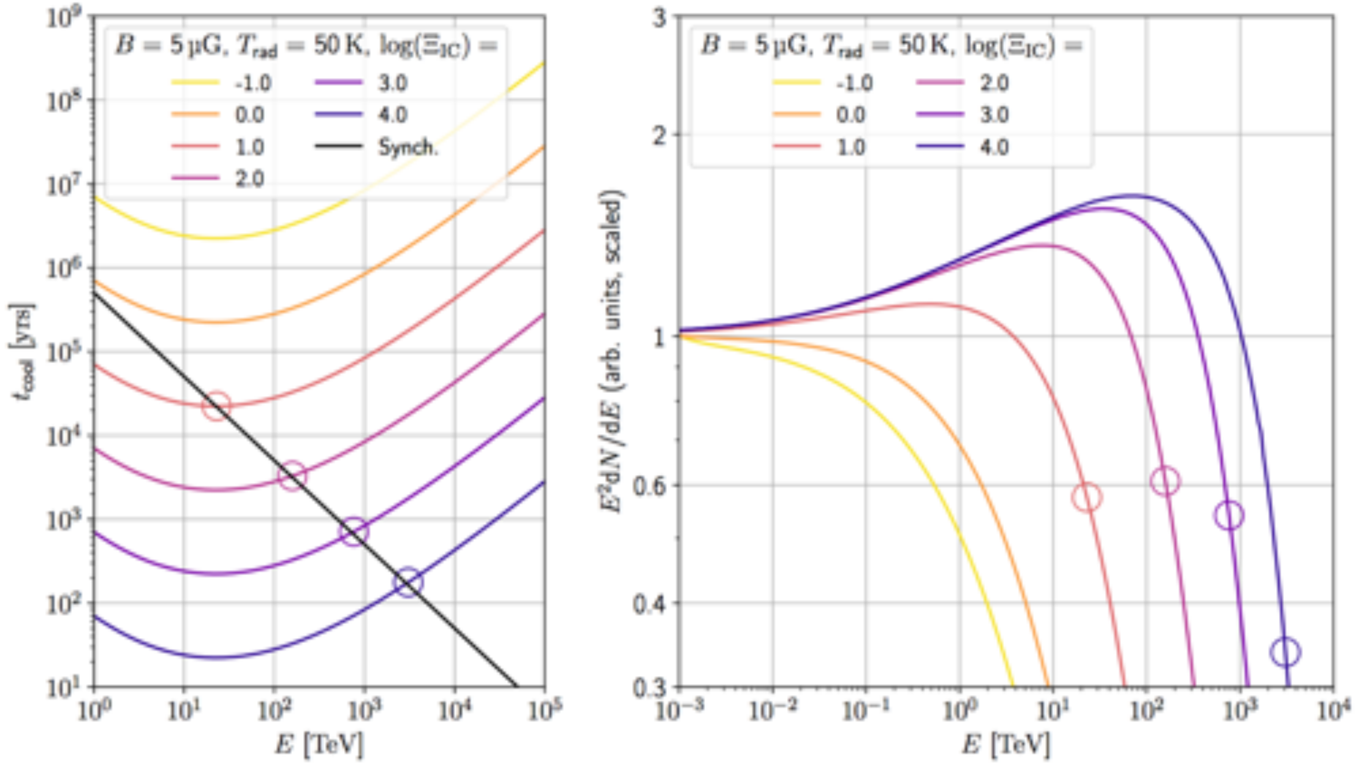
Aharonian & Atoyan, proc. “Neutron Stars and Pulsars” 439 (1998)



Nie et al, ApJ 924, 42 (2022)

UHE leptonic emission & Klein-Nishina effect

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



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

- In high radiation environments, synchrotron cooling dominates over IC losses, even into Klein-Nishina regime. (IC cross-section suppressed)
- Resulting spectrum is harder / cut-off at higher energies.
- Leptonic spectra out to PeV energies can be observed

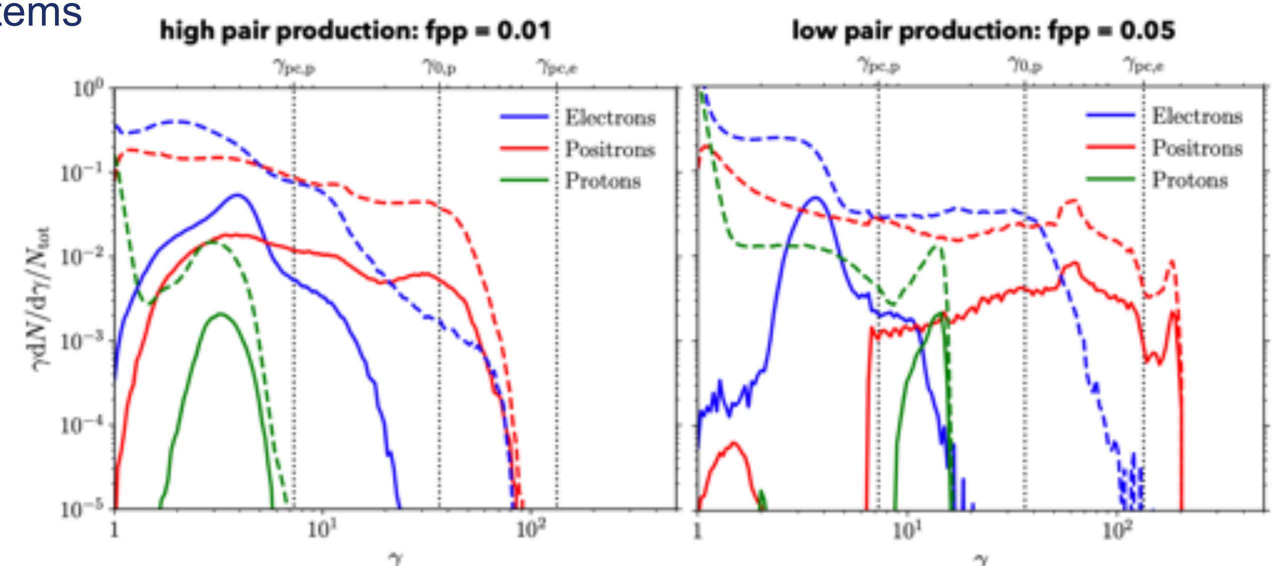
Hadronic particle acceleration in PWN environments?

1. Extraction of nuclei from pulsar surface and ion acceleration; mixed composition enters pulsar wind. e.g. Kotera et al., JCAP 08, 26 (2015)

   Ions can carry up to 20% of energy, acceleration at termination shock, e.g. Lemoine, Kotera & Pétri, JCAP 07, 16 (2015)

   Max ion energy and injection depends on pair-production multiplicity
   → Powerful, young systems

Dashed lines: total, solid lines: escaping

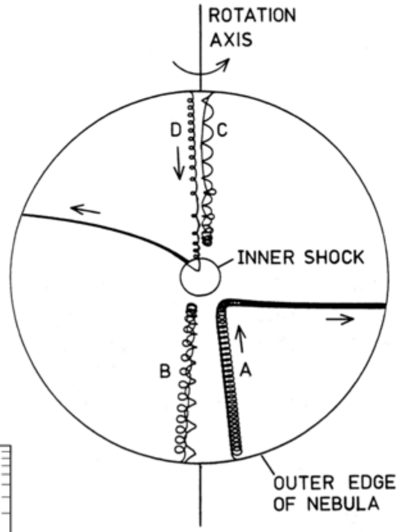


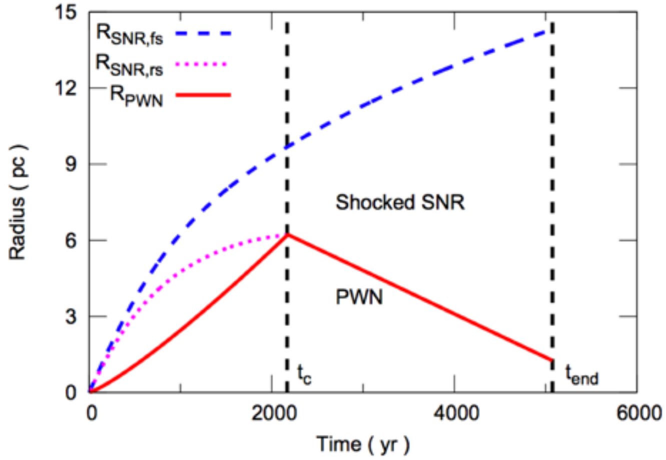
C. Guepin, CRSIG (2022)

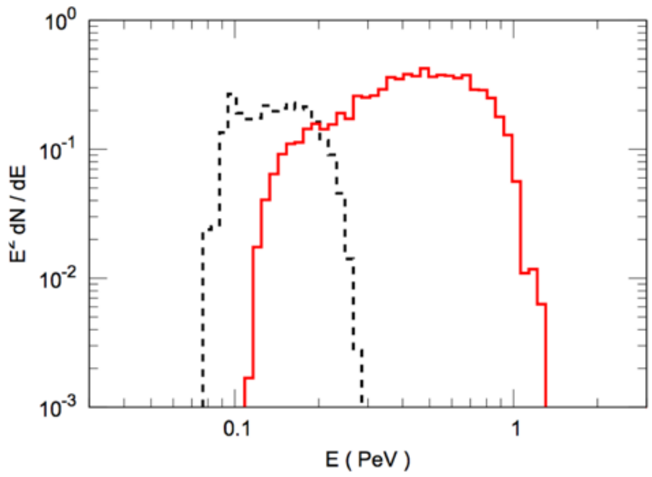
Hadronic particle acceleration in PWN environments?

1. Extraction of nuclei from pulsar surface and ion acceleration; mixed composition enters pulsar wind. e.g. Kotera et al., JCAP 08, 26 (2015)

2. Particle reacceleration in shock mixing between SNR reverse and PWN forward shock.
e.g. Ohira et al, MNRAS 478 (2018) 926; Lucek & Bell MNRAS **268** (1994) 581-594
→ Middle aged / evolved systems







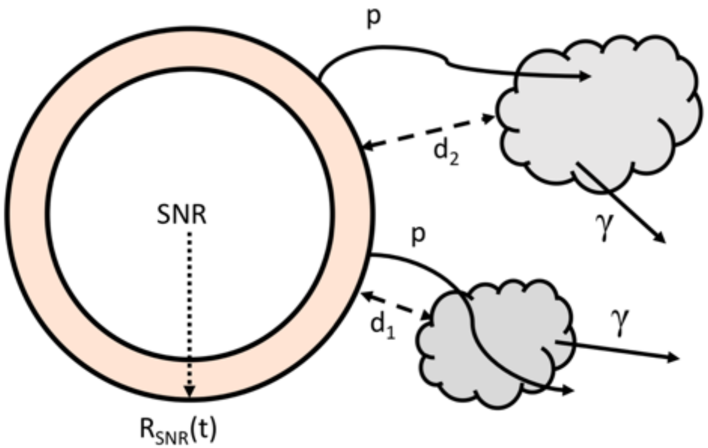
If CR knee forms from source confinement, then evidence of > PeV particles will not be located at the accelerator, but nearby → Molecular Clouds?

Gamma-ray signatures of cosmic rays

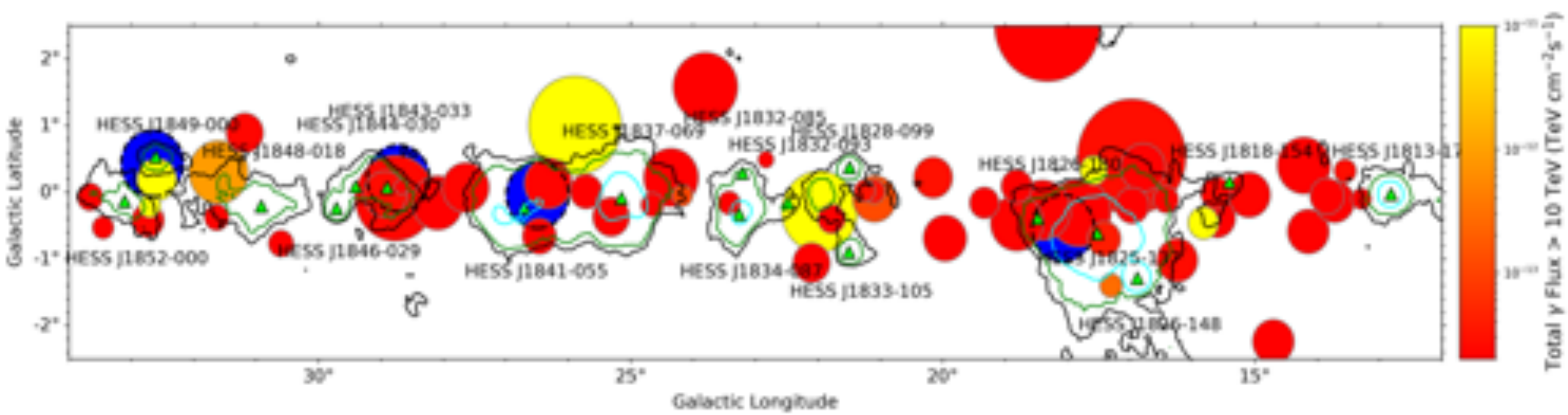
→Protons (and heavier nuclei) escape from accelerator (SNR or Pulsar) – will interact with nearby clouds

→Predict and search for gamma-rays from clouds identified in radio

→Can use clouds in vicinity of pulsars and SNRs to probe escape of protons and constrain their presence



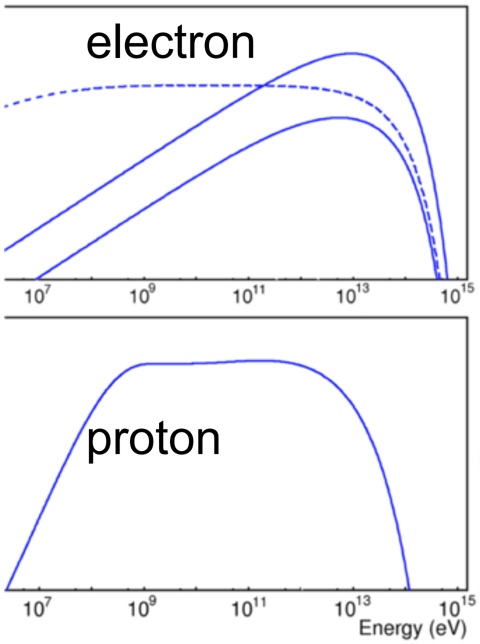
AM et al. MNRAS ***503*** *3522-3539 (2021)*



Evidence for a pulsar contribution to Galactic Cosmic Rays?

Spectral evidence:

- GeV spectral index ~2
- Clear pion-decay cut-off
- Second component at very high energies
- Emission reaching 100 TeV



Morphological evidence:

- Cosmic ray illumination of nearby clouds
- Enhanced gamma-ray emission with dense gas

Open Questions

1. Which particle species are accelerated – leptonic or hadronic?
   → Search for spectral and morphological indicators
   → e.g. pion-decay bump, correlation with dense gas

2. How are particles transported through the surrounding medium?
   → Test for energy-dependent morphology
   → Characterise radial emission profile with transport models (diffusion / advection)

3. What is the maximum energy limit for particle acceleration in pulsar environments?
   → Sky-maps at $E \geq 100$ TeV
   → Evidence for escaped energetic particles?

Friedrich-Alexander-Universität
Erlangen-Nürnberg

Thank you for your attention

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