Exploring Pulsar Environments at the Highest Energies

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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FRANCI Erlangen, 14/10/21

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Cosmic rays and the hunt for PeVatrons

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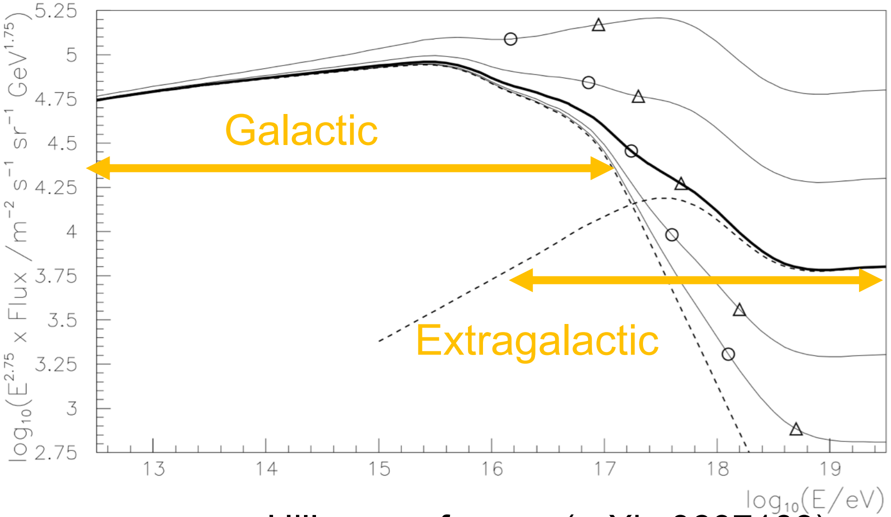
Three stages to become a cosmic ray:

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

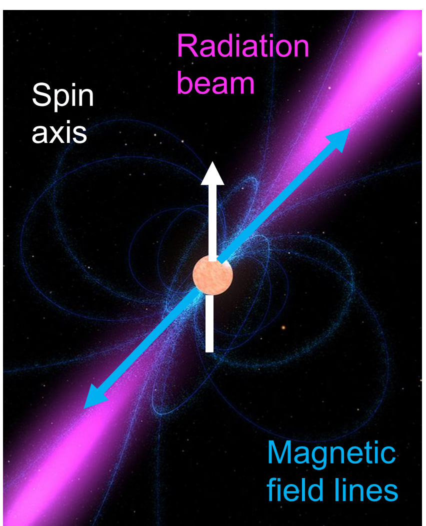
Galactic – Extragalactic transition occurs somewhere between “knee” and “ankle”

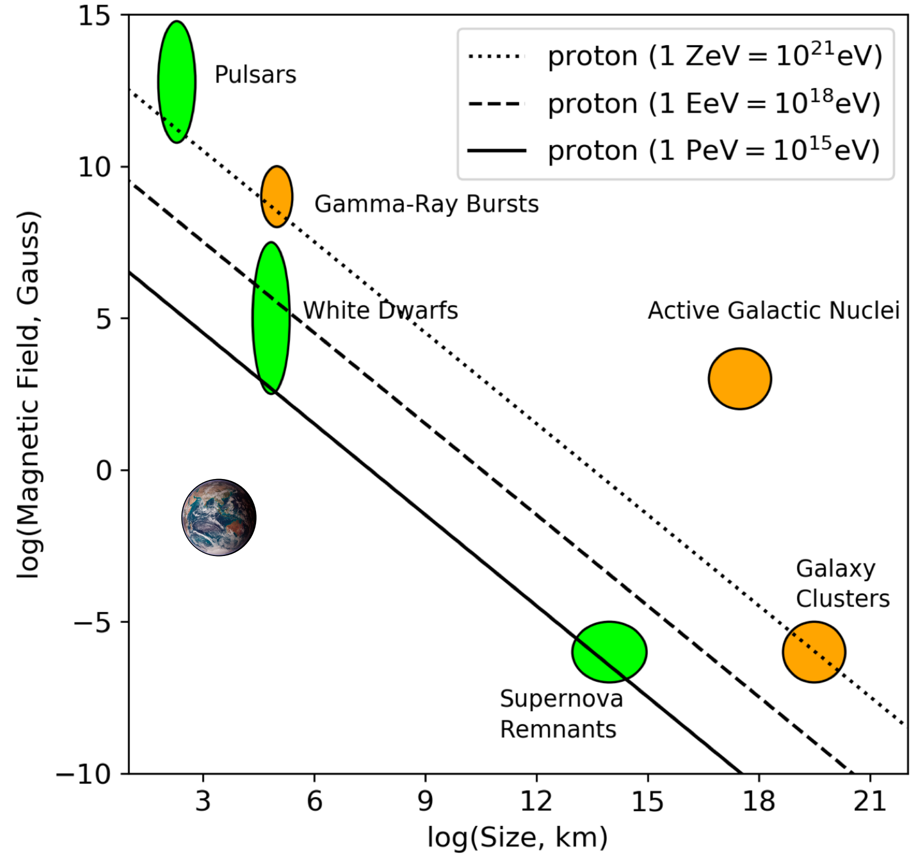


Hillas, conf. proc. (arXiv:0607109)

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?





Evolutionary stages of pulsar environments

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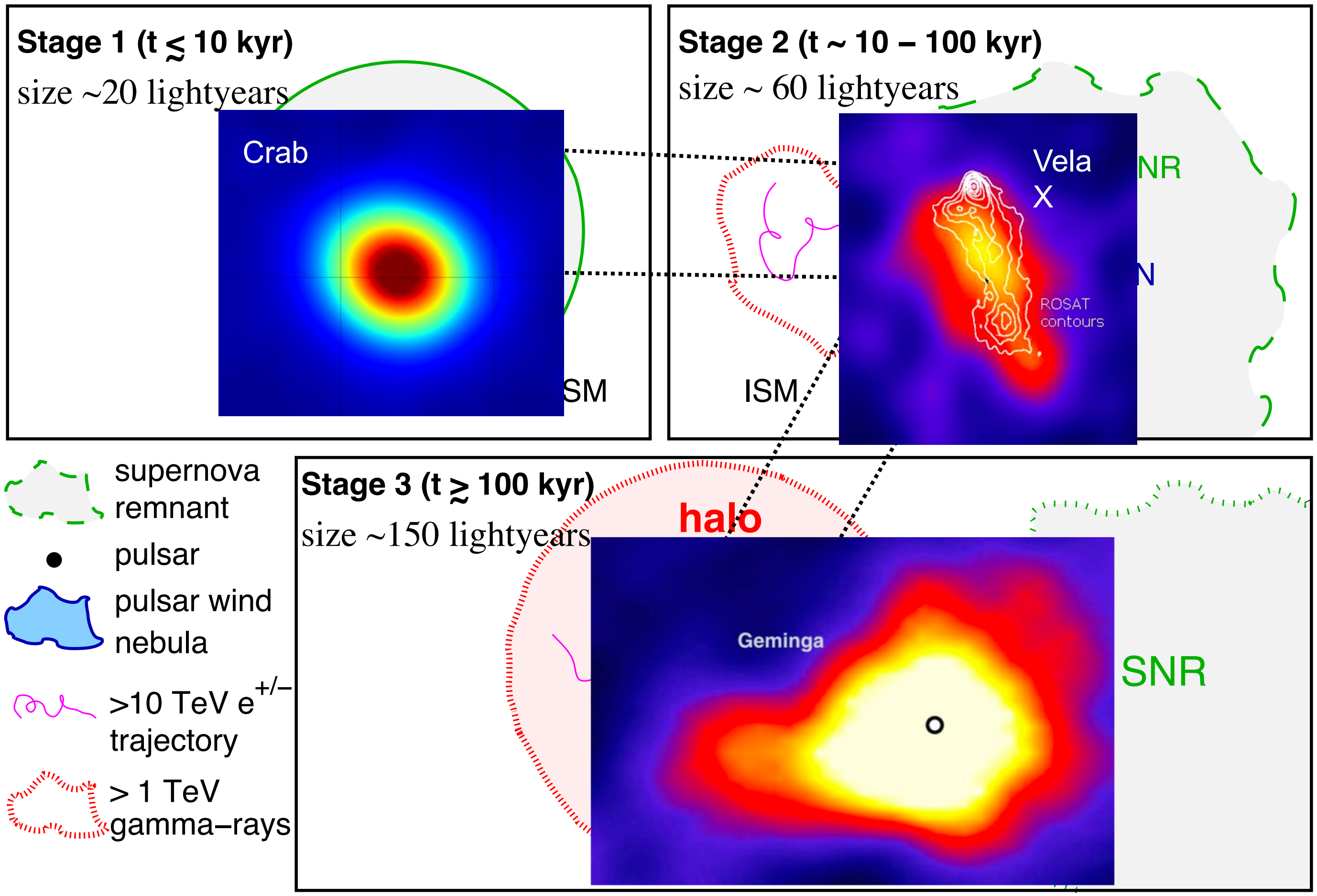


Giacinti, AM, Lopez-Coto et al, A&A **636**, A113 (2020)

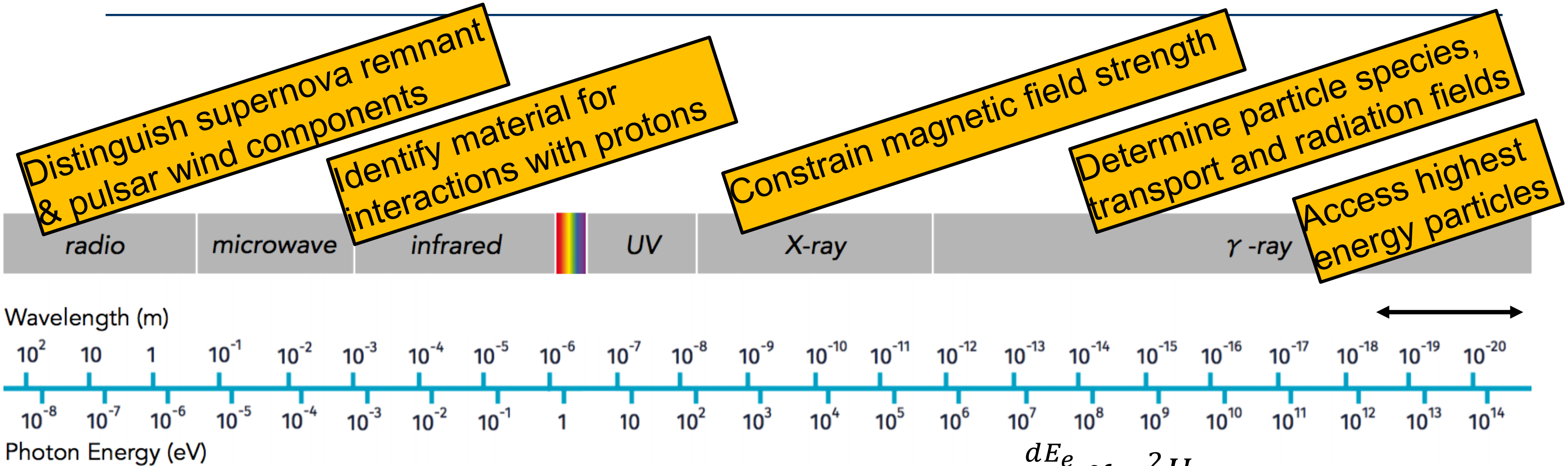
Pulsar Wind Nebulae
→ traditionally dominant sources at TeV

Pulsar Halos
→new
Particle escape into interstellar medium

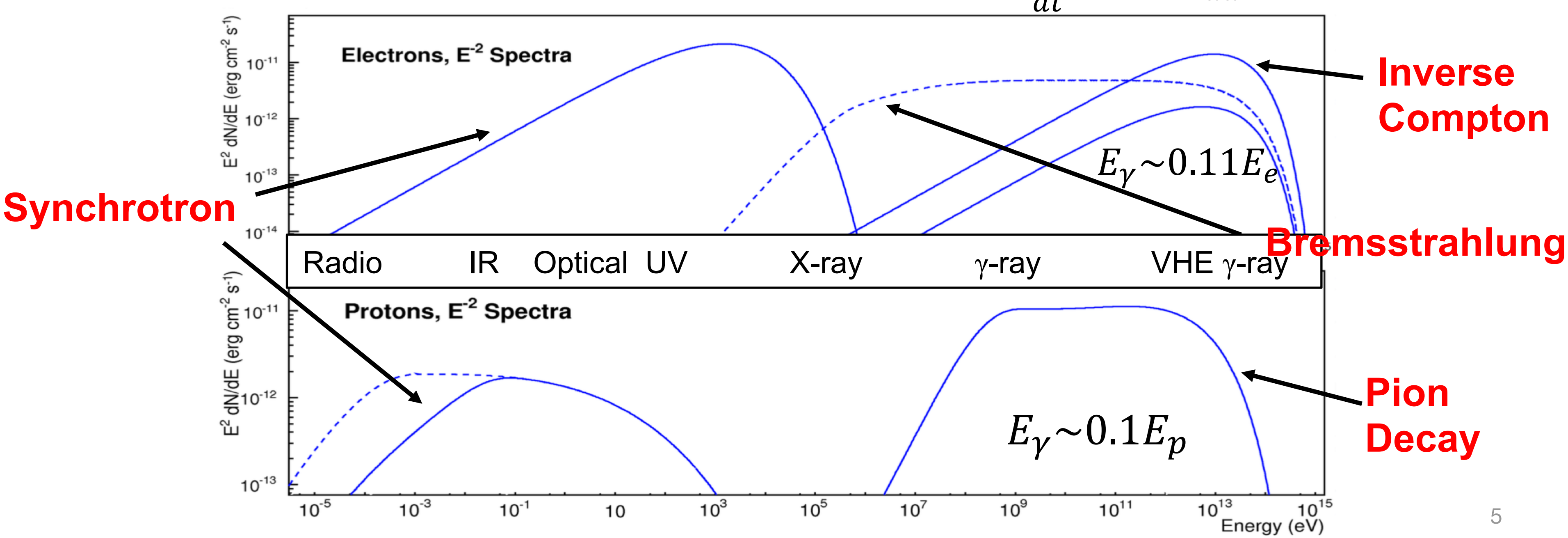
Pulsar Halos: opportunity to directly measure rate of particles (electrons / protons) escaping source and joining the sea of galactic Cosmic Rays

HAWC Collaboration, ApJ, **881** (2019) 134, HAWC Collaboration, Science **358**, (2017) 911

Multiwavelength Observations



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



Example Stage 1: Crab Nebula

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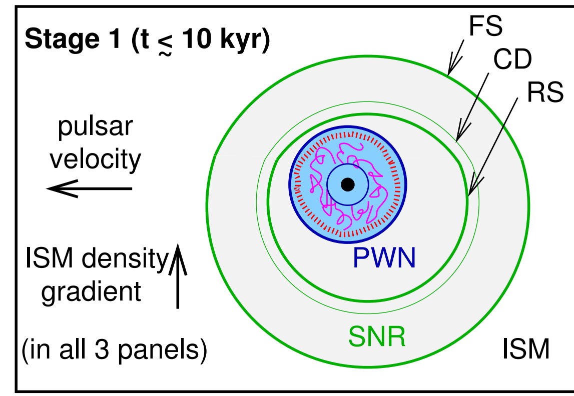
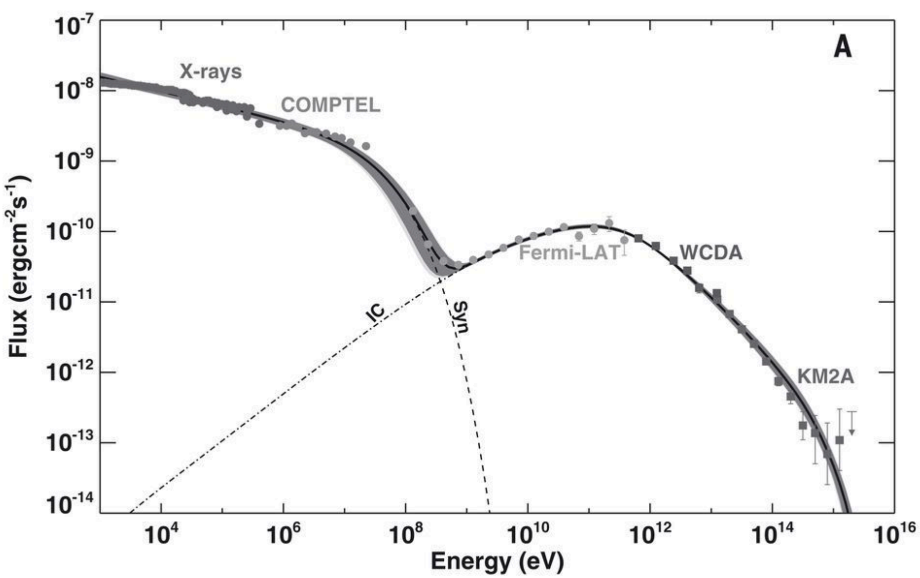
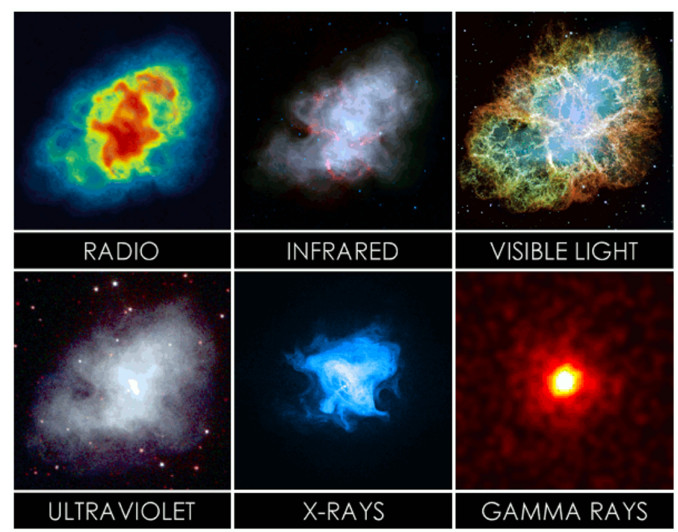
- Crab Nebula – standard candle of TeV gamma-ray astronomy

- 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



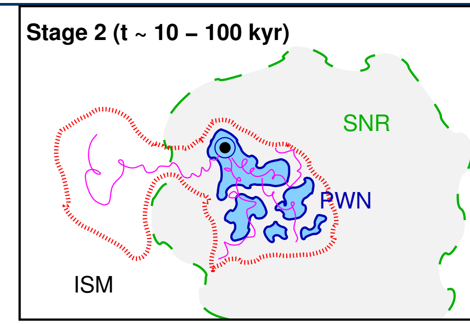


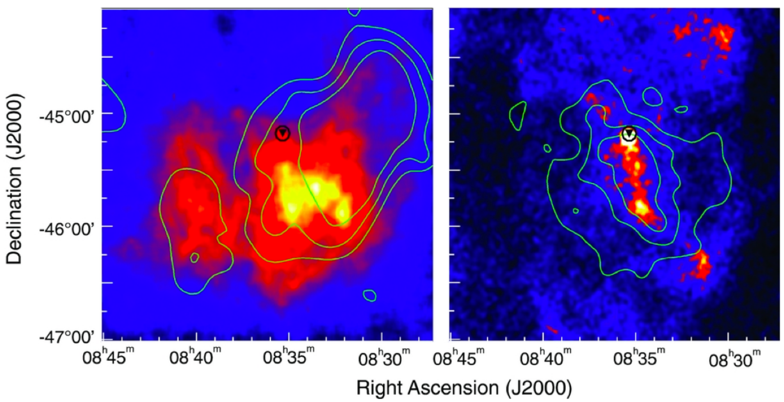


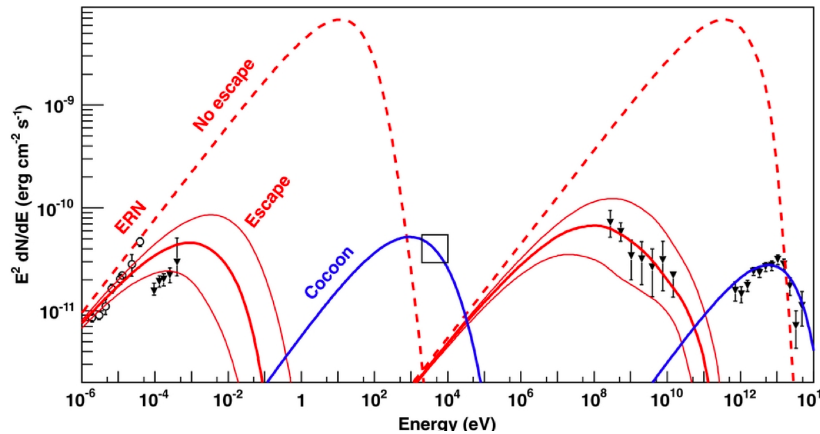
Z. Cao et al. LHAASO collaboration, Science **373**, 425-430 (2021)

Example Stage 2: Vela X

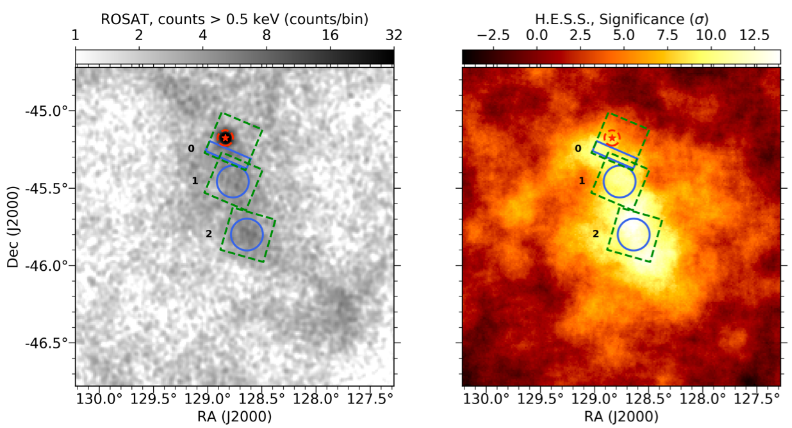
- Age = 11.3 kyr, log(Edot) = 36.84 erg/s, Distance = 0.28 kpc,
- R: radio = 12.2 pc, X-ray = 3.08 pc, TeV = 2.9 pc

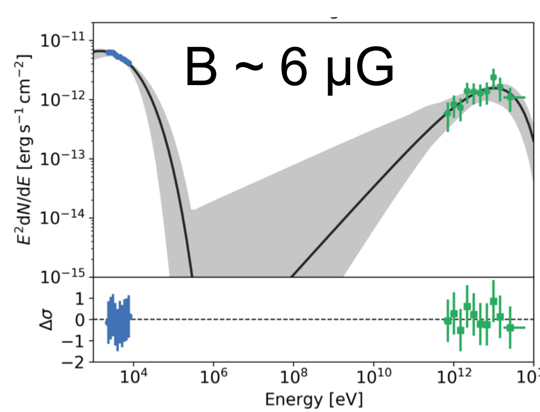






Hinton et al. ApJLett 743 (2011) L7





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

Example transition: HESS J1825-137

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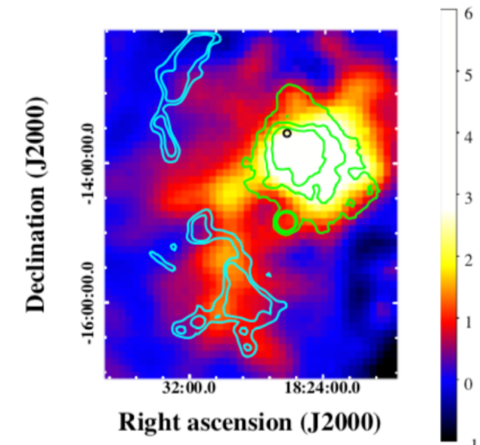
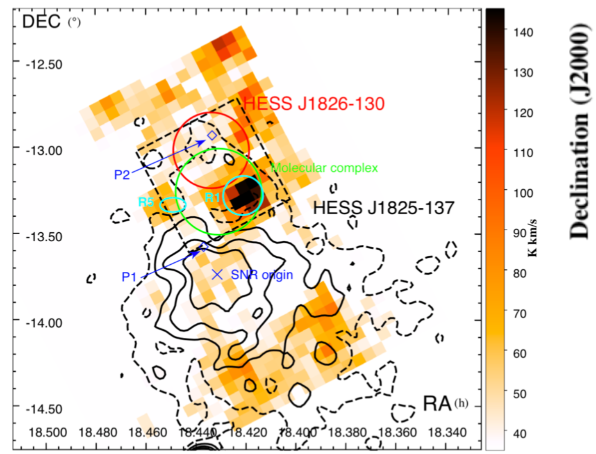
- Age = 21.4 kyr, log(Edot) = 36.45 erg/s, Distance = 3.9 kpc,
- R: radio = ? pc, X-ray = 9.1 pc, TeV = 50 pc
- strong energy dependent morphology
- bright at energies > 100 TeV

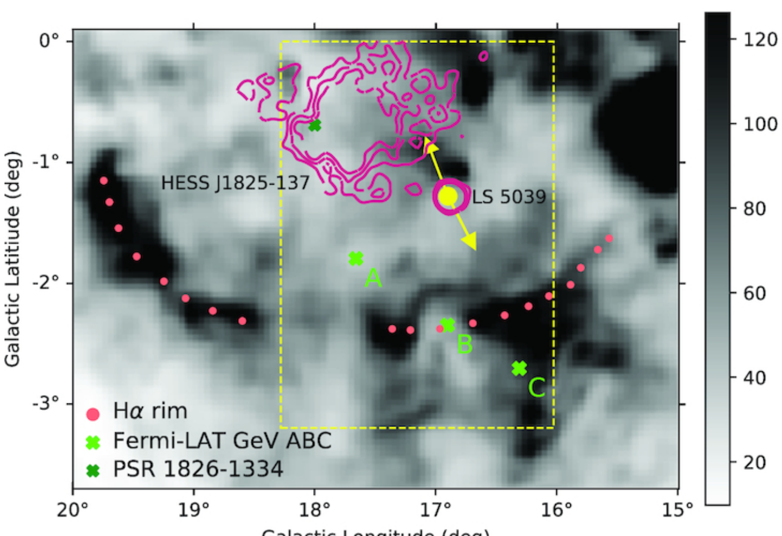
Araya et al. MNRAS **485** (2019) 1001-7

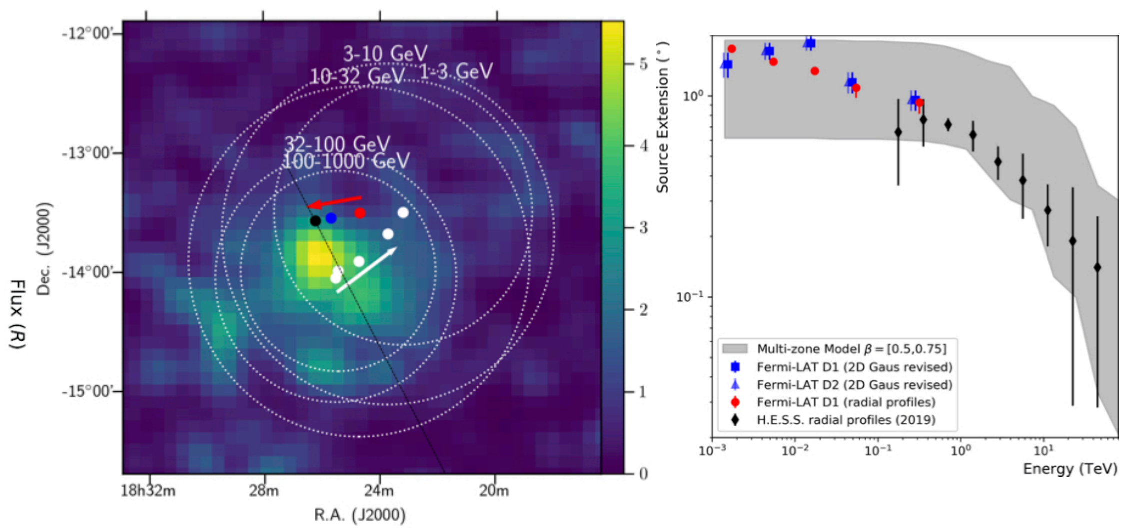


Voisin et al. MNRAS 458 (2016) 2813



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

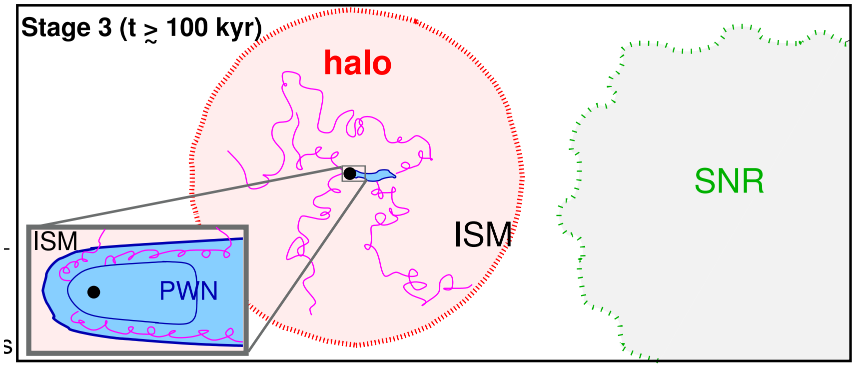




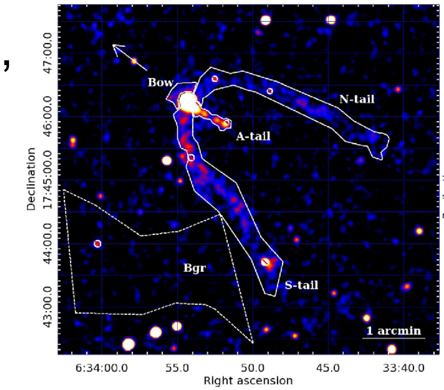
Principe et al. A&A **640** (2020) A76

Example Stage 3: Geminga

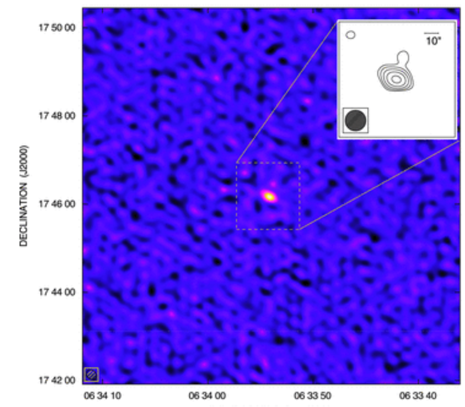
- Age = 342 kyr, log(Edot) = 34.51 erg/s, Distance = 0.25 kpc,
- R: radio = 0.01 pc, X-ray = 0.15 pc, TeV = 100 pc



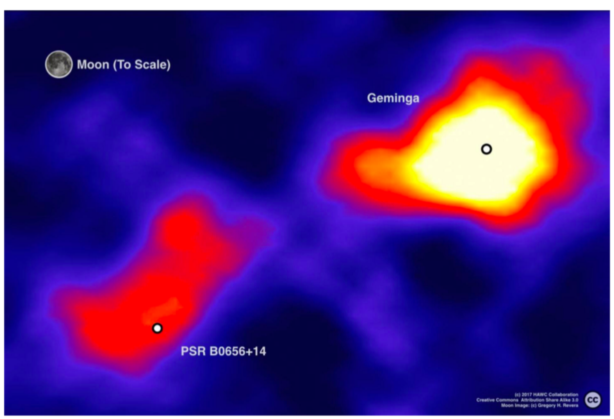
AM et al. PoS(ICRC2021)780

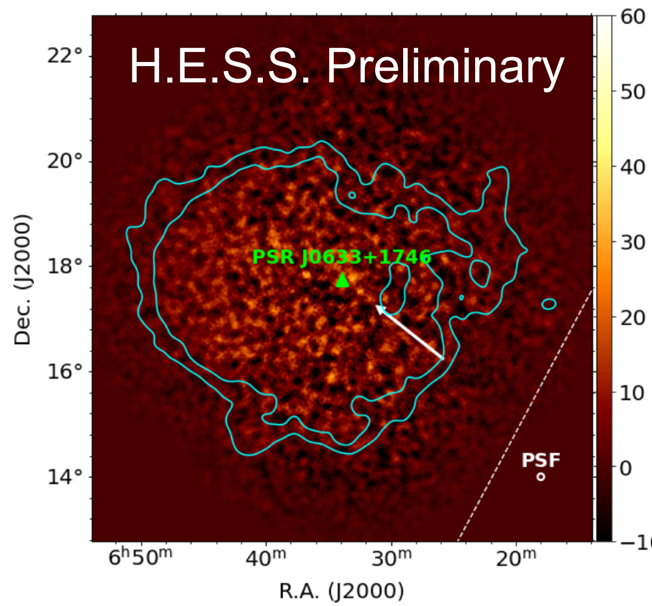


Posselt et al. ApJ 835 (2017) 66



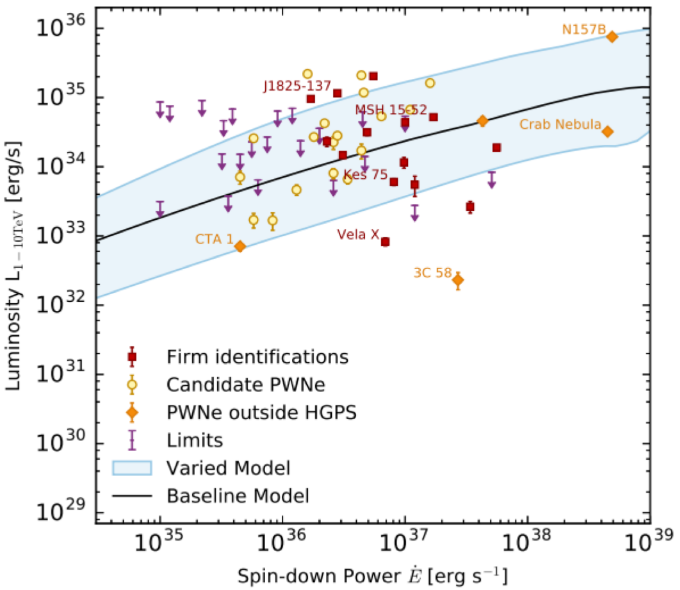
Pellizzoni et al. MNRAS 416 (2011) L45

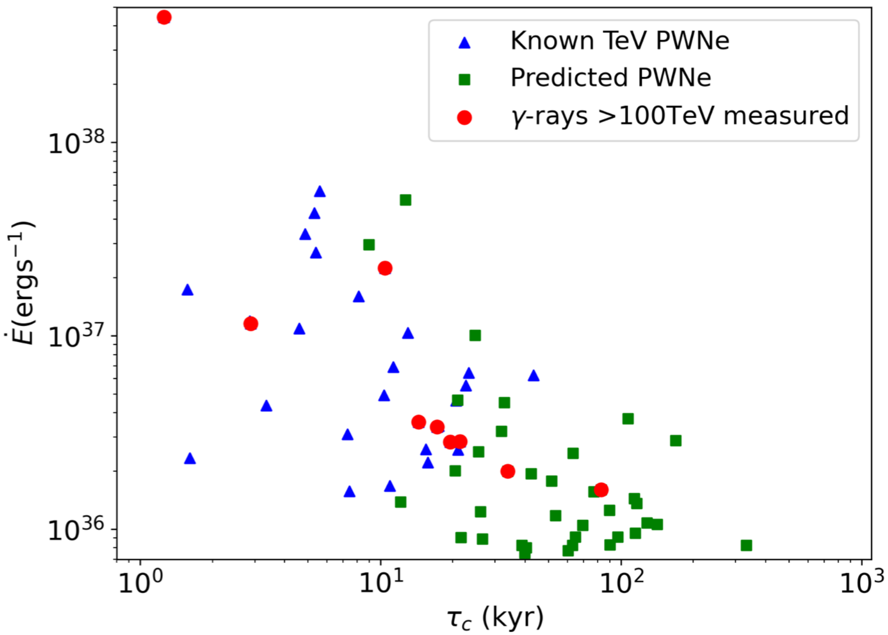


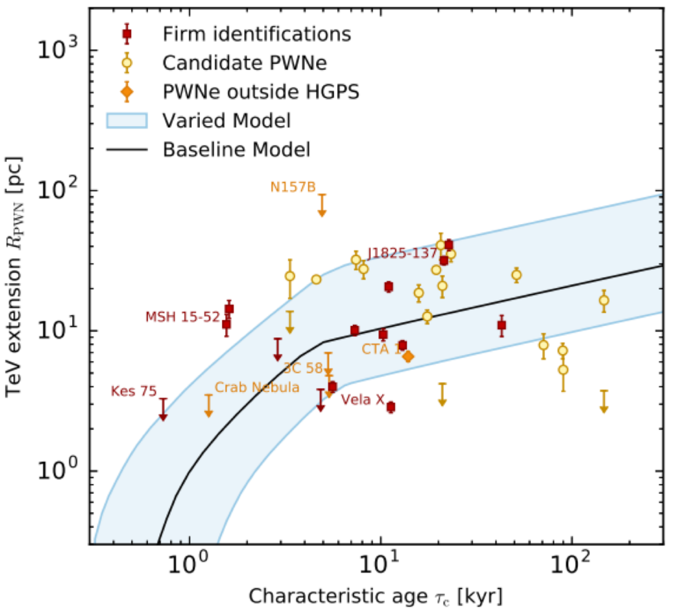


Model for evolution of pulsar wind nebulae

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





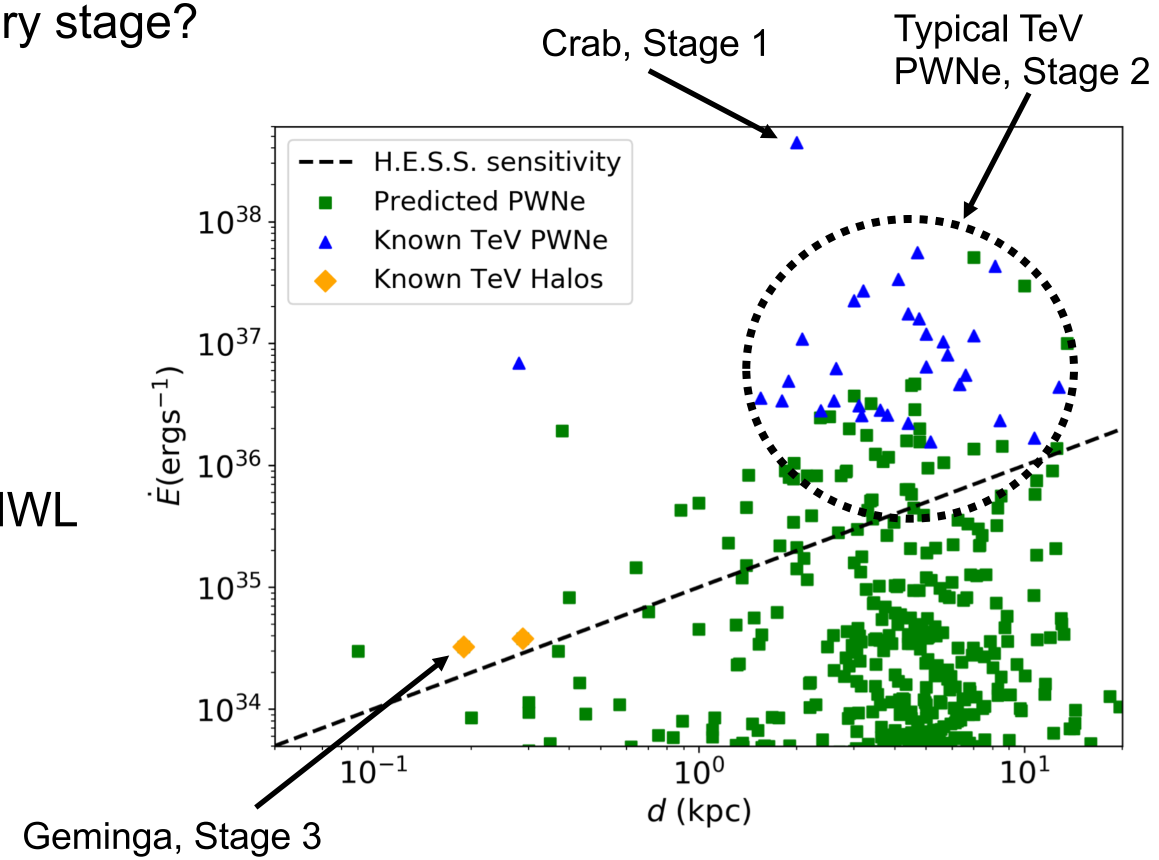


Population studies of pulsar environments

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

→ Dedicated search for more stage 3 systems in existing data with improved analysis

→ Combine TeV data with MWL observations to constrain emission models

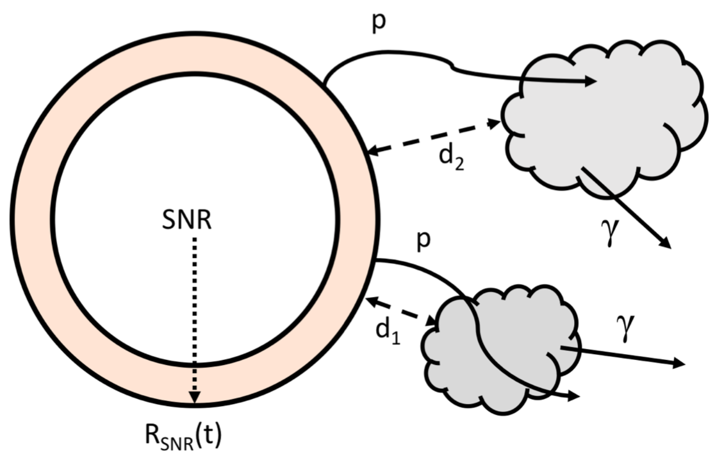


Gamma-ray signatures of cosmic rays

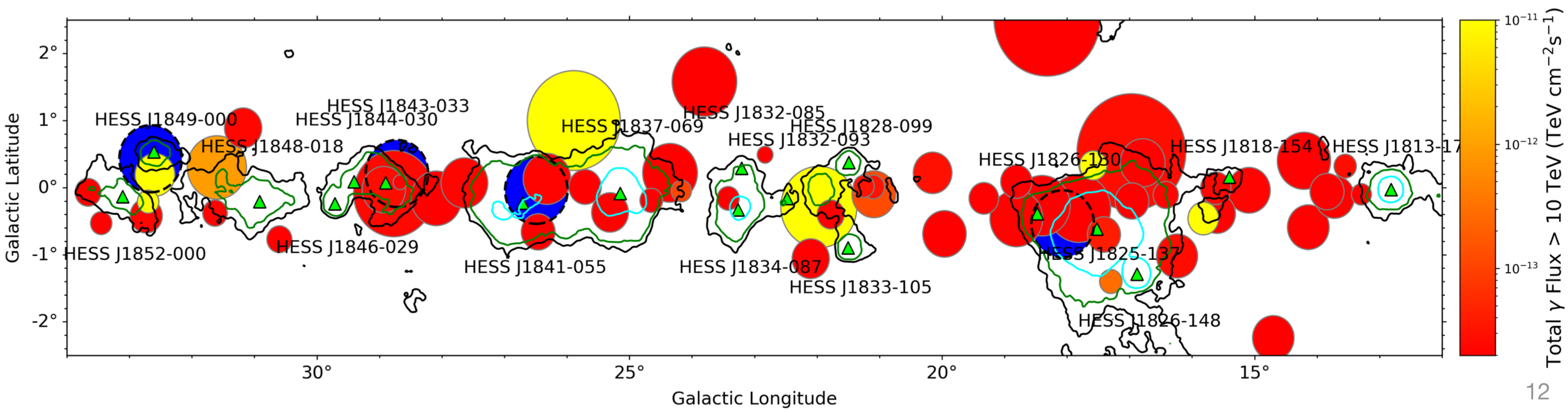
→ Protons (and heavier nuclei) escape from accelerator (SNR or Pulsar) – will interact with nearby clouds

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

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

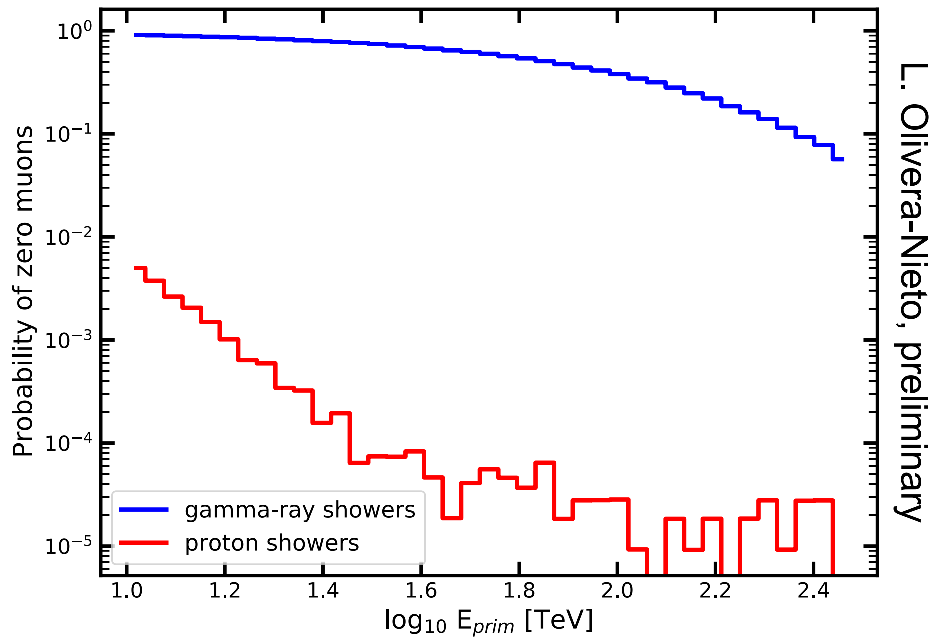


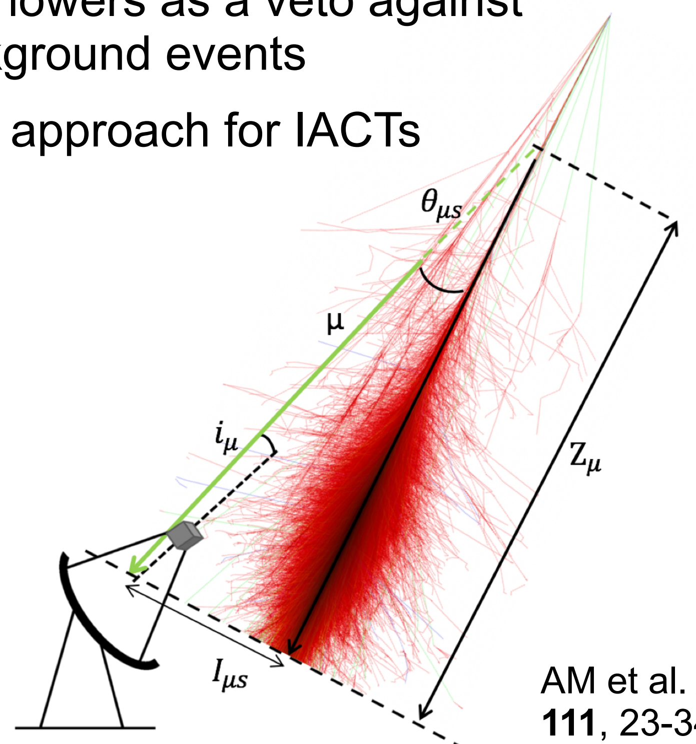
*AM et al. MNRAS **503** 3522-3539 (2021)*



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





Measure properties of muons in TeV air showers with IACTs

AM et al. Astropart. Phys. **111**, 23-34 (2019)

Open questions

1. What fraction of the PWNe population accelerate particles to PeV energies?
2. Is there evidence of hadronic as well as leptonic particle acceleration in PWNe?
3. How are energetic particles transported through pulsar environments into the ISM?
4. Are escaped particle ‘halos’ a common feature of late-stage PWNe evolution?

Aims of new group

- Improve IACT performance to extended sources and at highest energies
- Study pulsar halos (stage 3 systems) in depth
- Constrain transport of particles into Galactic CR sea
- Constrain presence of hadronic particles in pulsar environments
- MWL studies → complete picture of individual systems
- Population studies → global picture of pulsar environments

PhD & postdoc positions currently open, master & bachelor thesis opportunities

Thank you for your attention

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