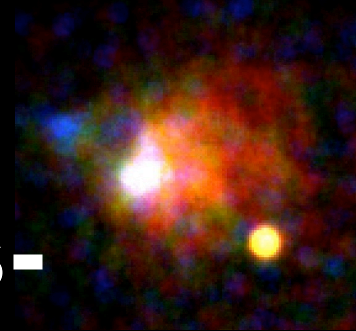
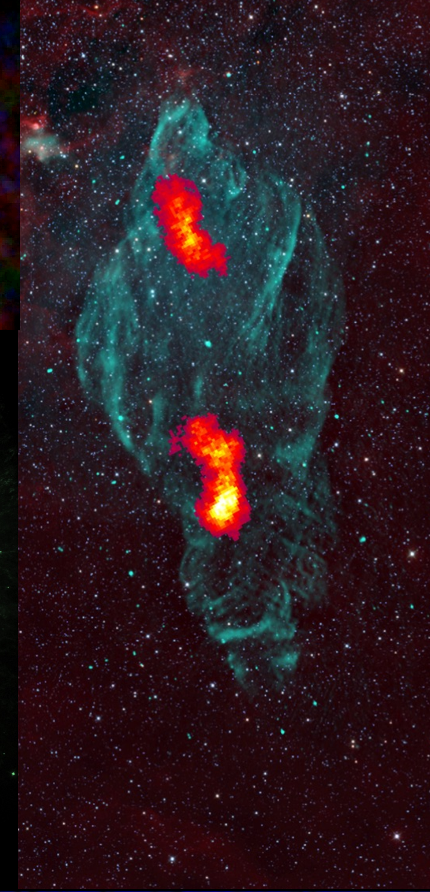
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

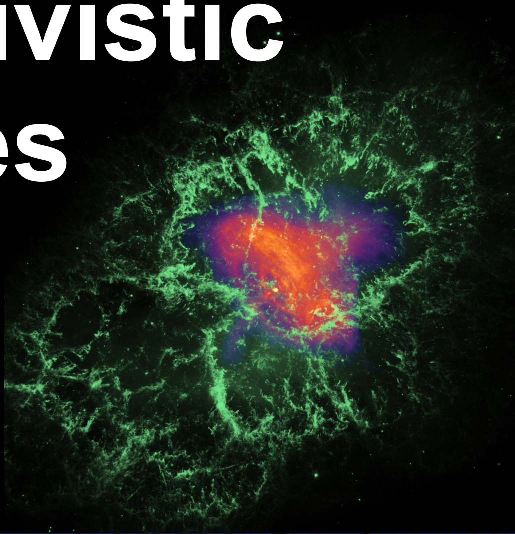
Texas Symposium

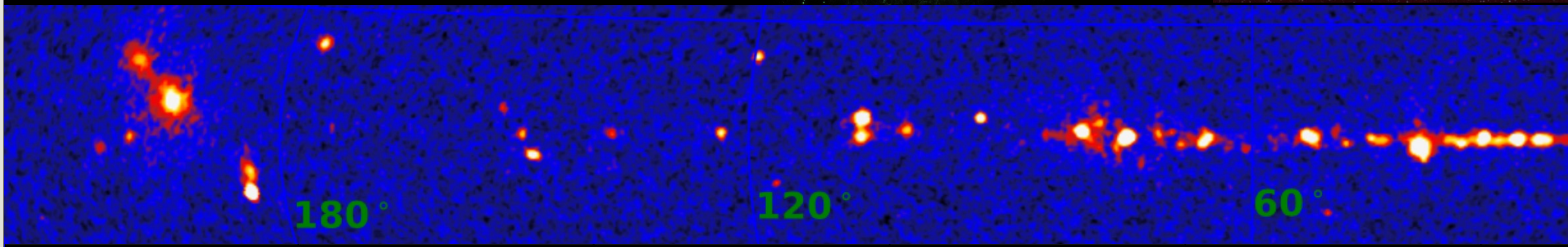
VHE-UHE Gammas-rays from Relativistic Galactic Sources

Jim Hinton, MPIK, Heidelberg









Acceleration at relativistic shocks

$B_{\mu G} L_{pc} > 2E_{15}/Z\beta$

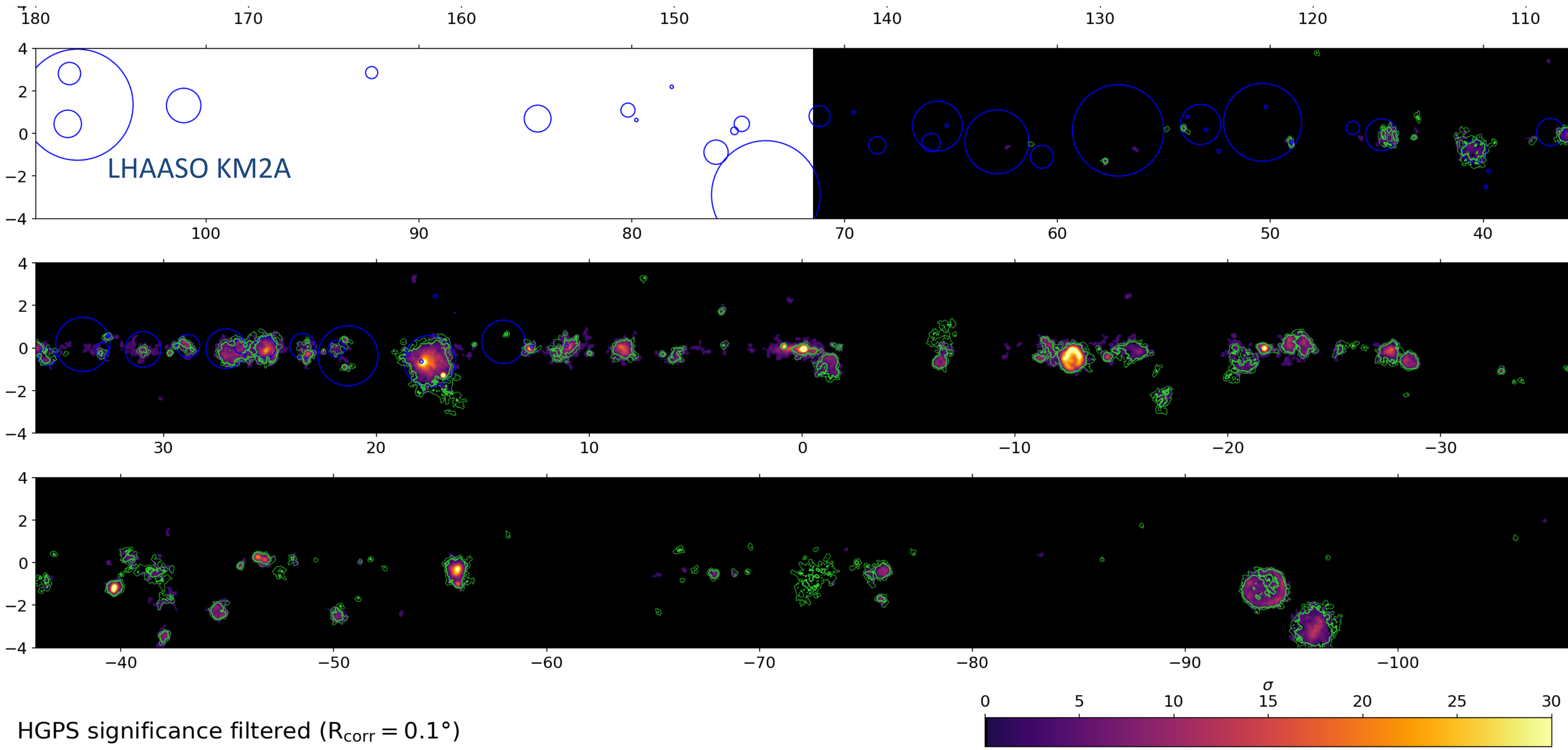
- v~c raises maximum energy (Hillas criterion)
  - and acceleration rate, higher E_{max} for cooling-limited electrons
- Observed to be highly efficient accelerators
  - AGN (blazars, inner jets, - e.g. Cen A HESS+Chandra)
  - GRBs (prompt and **afterglow** – e.g. GRB190829A,GRB221009A)
  - Longstanding theoretical challenge to match the observed effectiveness of relativistic shocks over a wide range of conditions – but much recent progress (e.g. Huang, Reville, Kirk, Giacinti MNRAS 2023)
- BUT the usual suspects for **Galactic** cosmic ray acceleration are **non-relativistic** systems
  - Supernova remnants, termination shocks of massive stellar clusters ++
  - Why? Energetics and apparent lack of protons and nuclei accelerated in the most prominent Galactic relativistic systems
- None-the-less relativistic objects dominate the VHE-UHE gamma-ray sky – in particular Pulsar Wind Nebulae
  - But now also microquasars

Gamma-ray emission

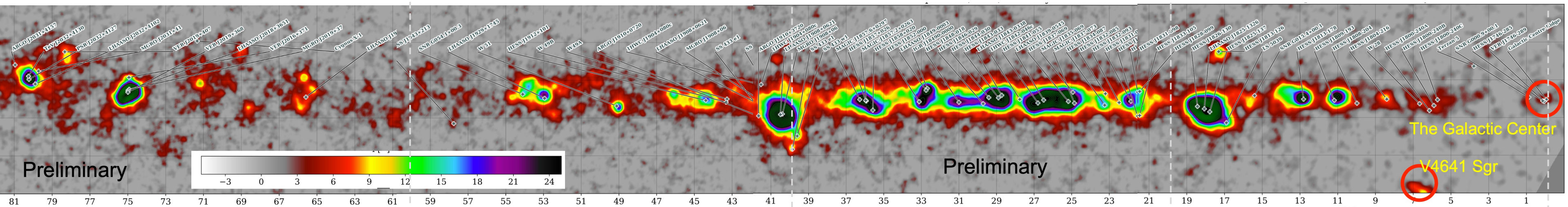
- Very High (0.1-100 TeV) and UHE (0.1-10 PeV) emission dominated by Inverse Compton or 'p-p' (nucleus-nucleus) emission
- Inverse Compton emission efficient if magnetic fields rather low …
  - e.g. typical ISM rather than very close to compact sources
  - p-p emission requires a substantial target as well as proton acceleration $t_{pp} \sim 3 \cdot 10^7$ (1 cm^{-3}/n) years
- Transport?
  - Very easy for bulk flow to beat diffusion in relativistic systems
- Typical cooling time of relativistic electrons
  - $t_{sync,IC} \sim 10^3 (E_e/100\ \mathrm{TeV})^{-1}$ years
- Transport on this timescale
  - Advection: 300 pc (v/c) $(E_e/100\ \mathrm{TeV})^{-1}$ → E-dep. gamma-ray morphology
  - Diffusion: 9 pc $(D/10^{28}\ \mathrm{cm^2/s})^{0.5} (E_e/100\ \mathrm{TeV})^{(\delta-1)/2}$

VHE/UHE Galaxy

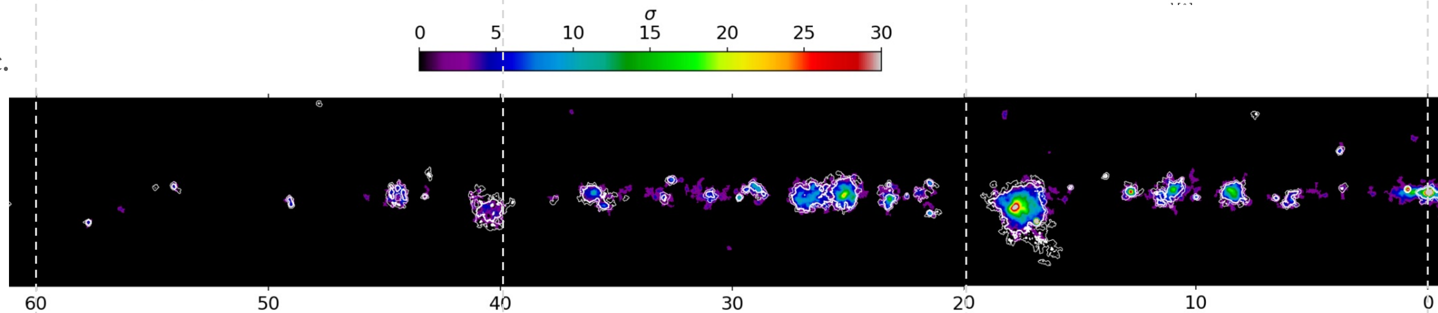
- Updated HESS Galactic Plane Survey
  - Quentin Remy et al (Proc. ICRC 2023)
- +LHAASO KM2A sources
  - Catalog 2023

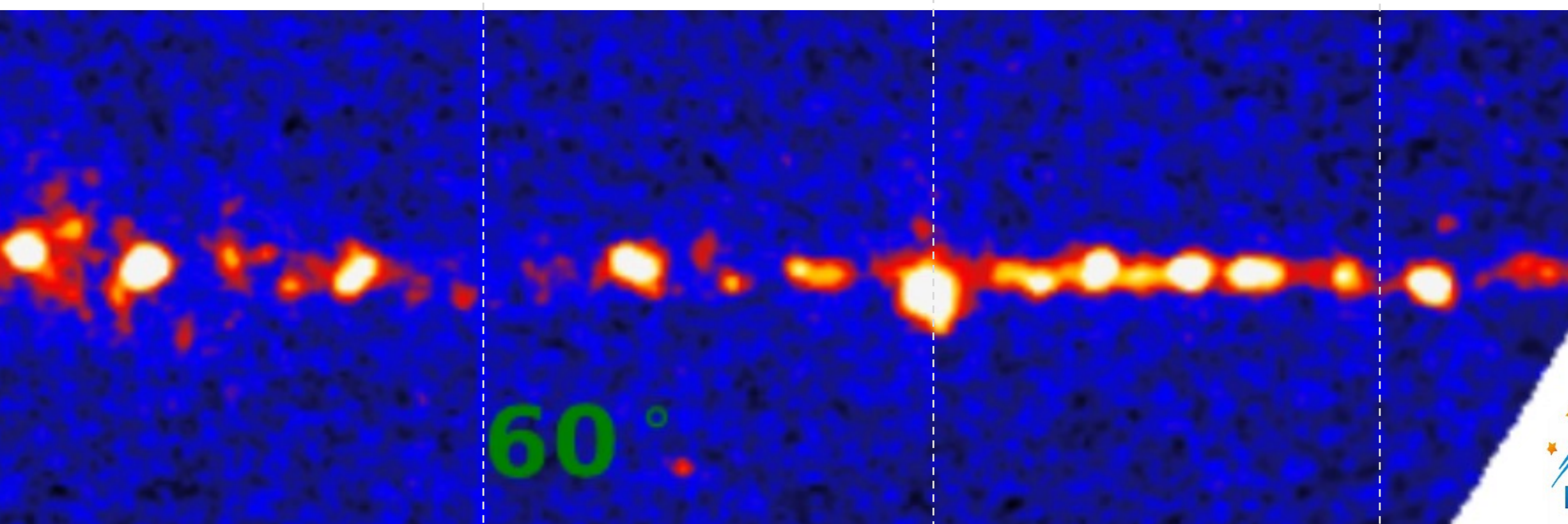


- Pass 5 prelim. Goodman Gamma2022



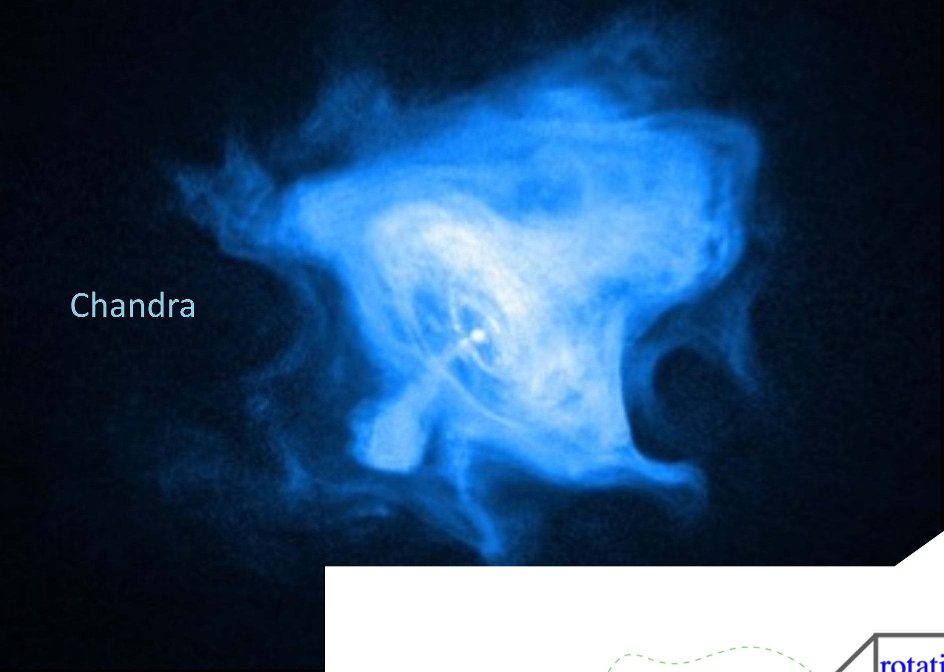
- Remy et al (Proc. ICRC 2023)

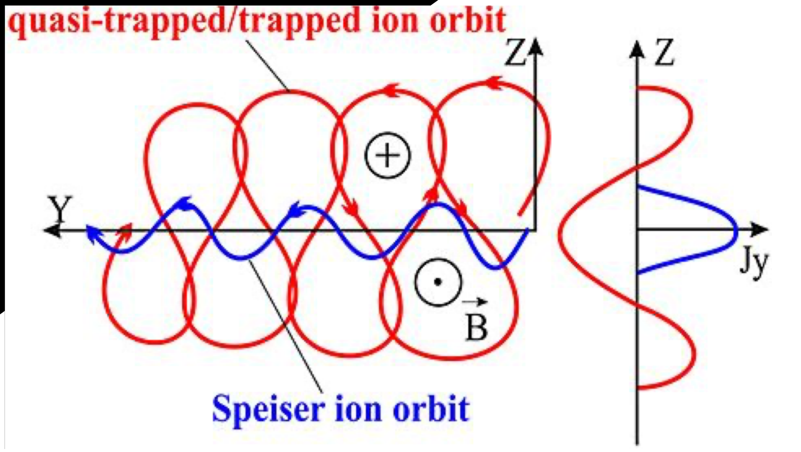


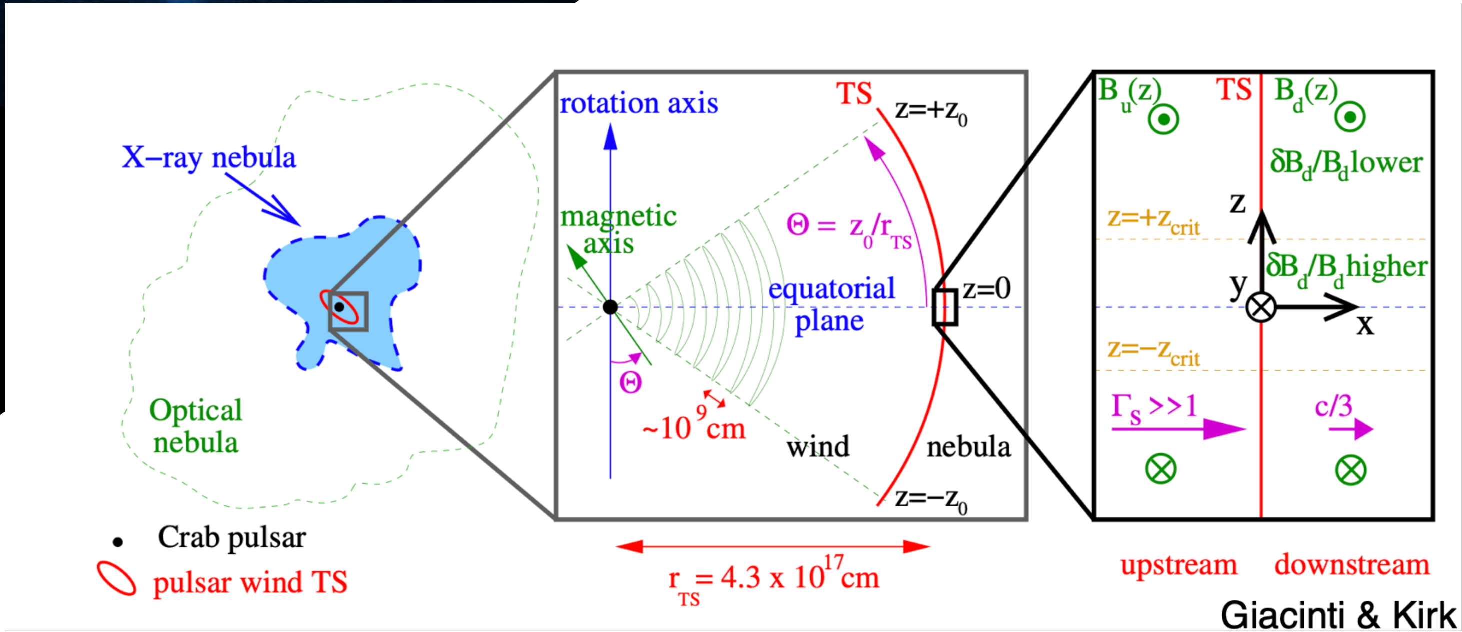


- 1st LHAASO Catalogue : KM2A

Pulsar Wind Nebulae



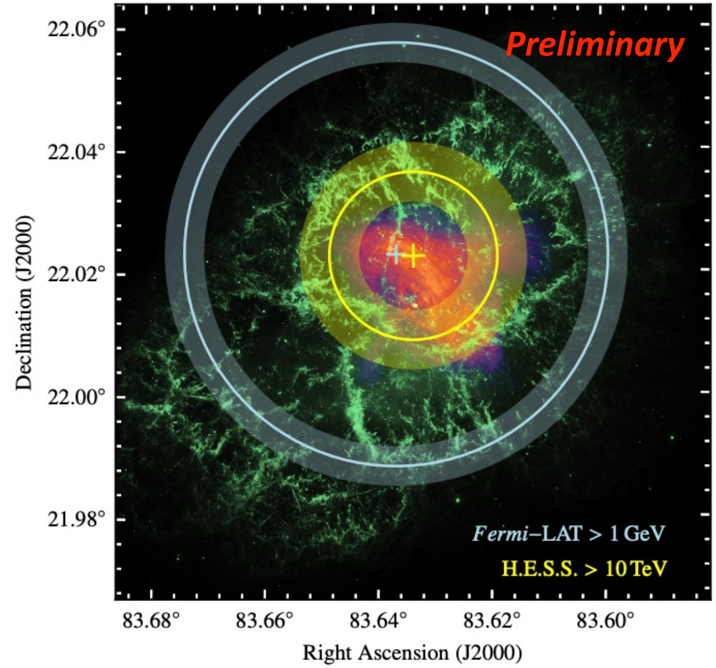


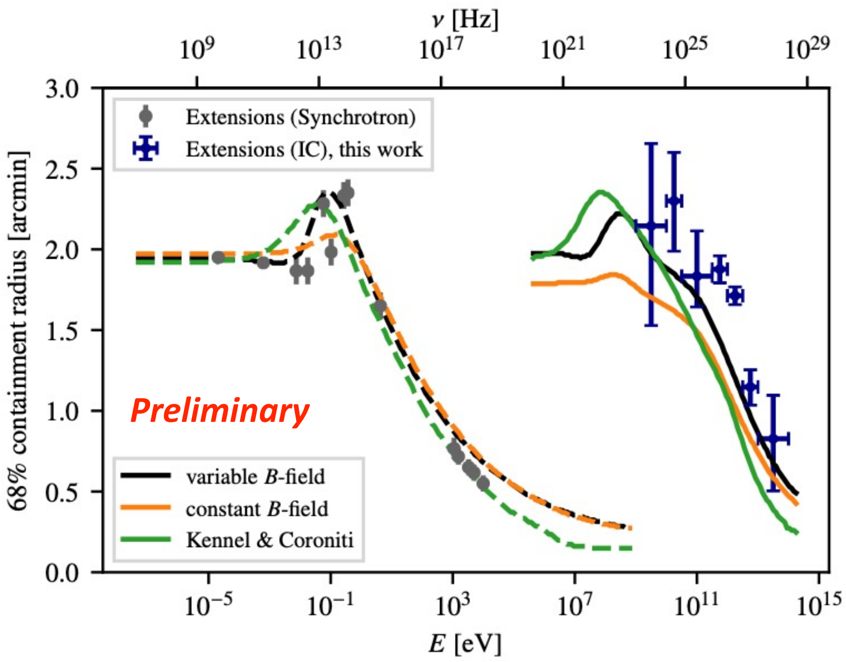


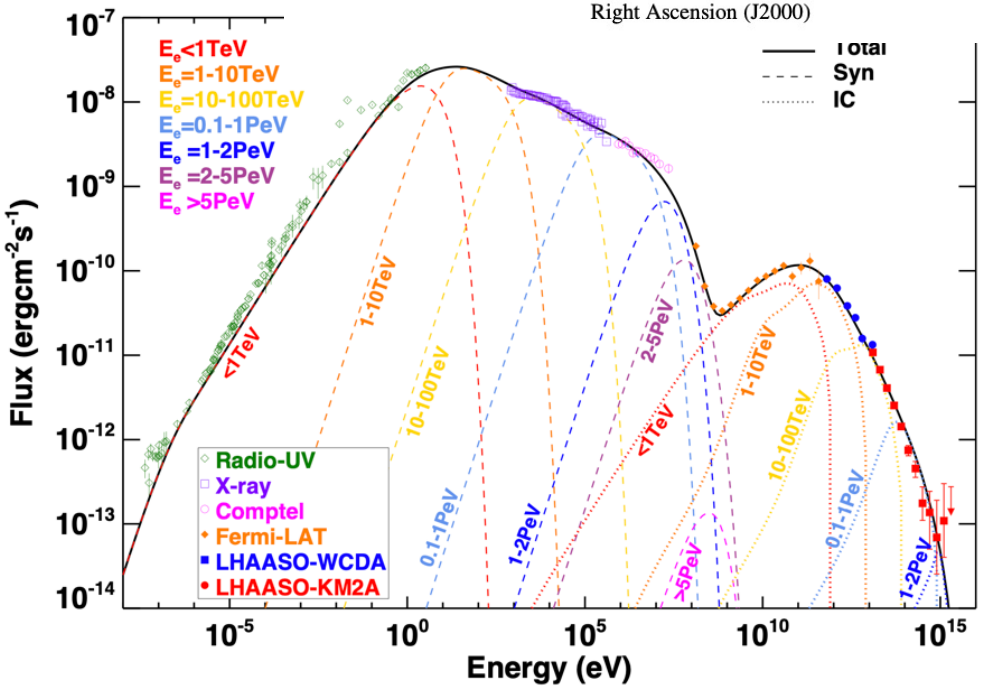
Giacinti & Kirk (2018)

The Crab Nebula

- Strongly energy-dependent size
  - In synchrotron and IC components
  - E.g. Mohrmann TeVPA 2023
- Extension of SED to PeV: LHAASO 202

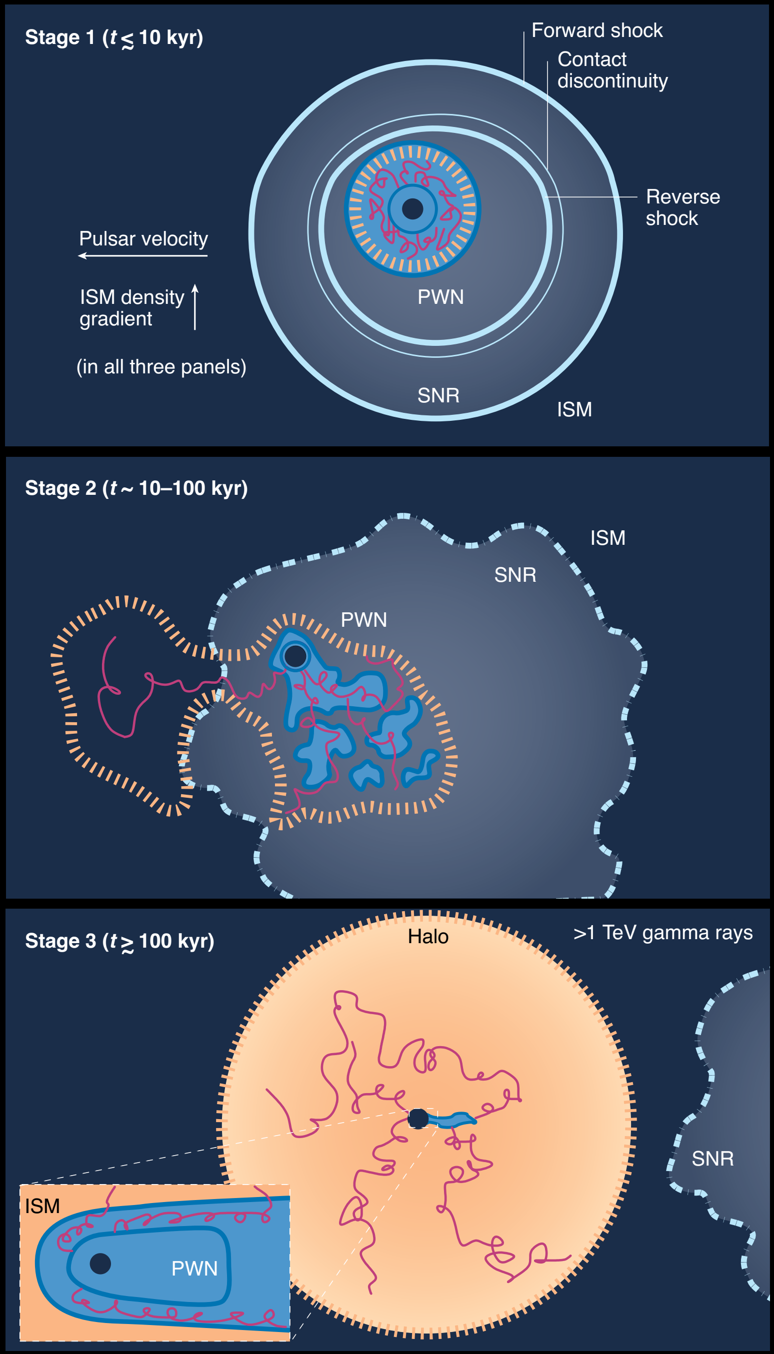






PWN Evolution

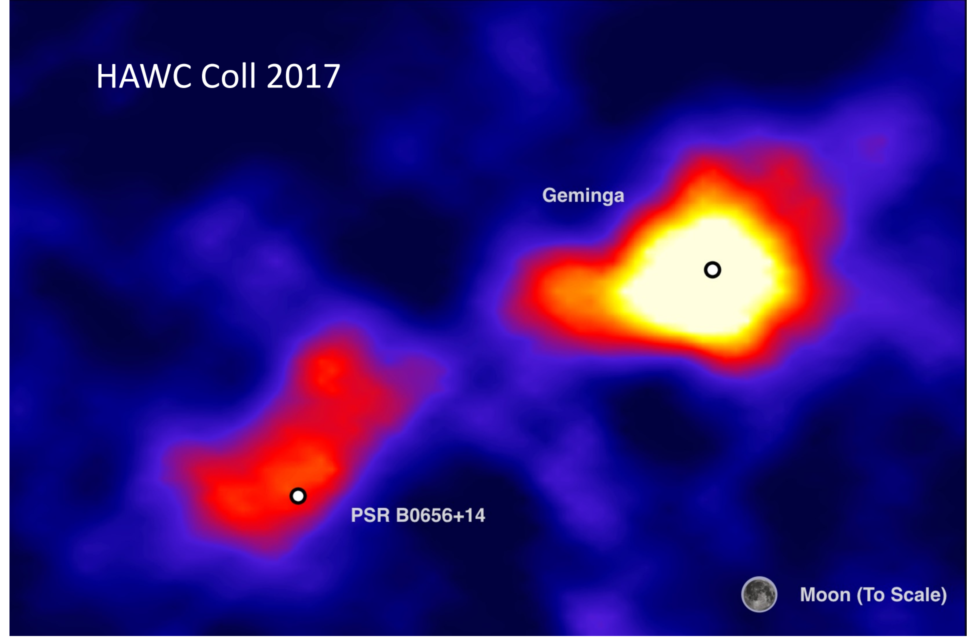
- Early phase
  - Powerful wind of very young pulsar - free expansion
- Interaction with reverse shock of supernova remnant
  - Material starts to mix
  - Particle escape becomes possible
- Bow shock phase outside SNR
  - PWN leaves SNR due to natal kick velocity, lower power, older systems with much more limited zone of influence

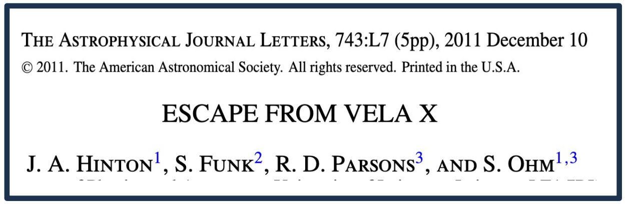


López-Coto et al Nature Astron. 6, 199 (2022)
Adpated from Giacinti et al A&A 636, A113 (2020)

Escape/Halos

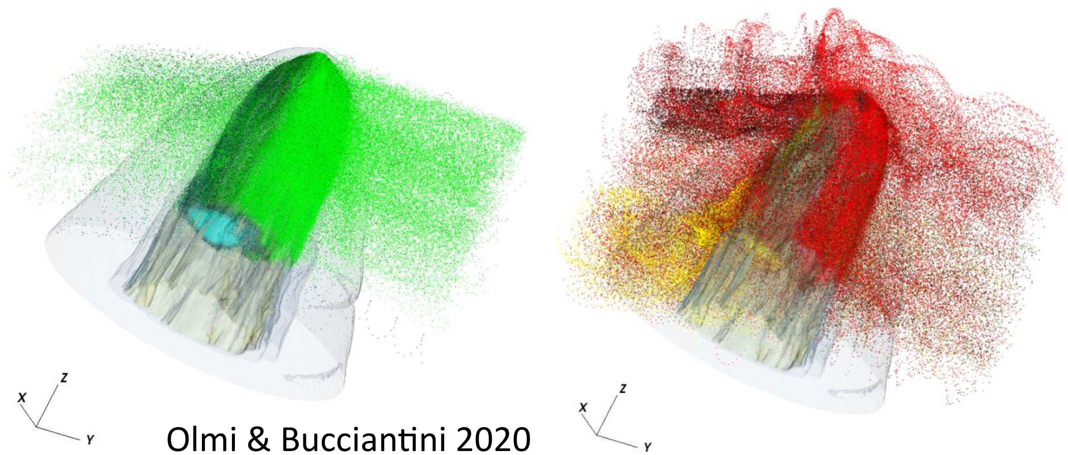
- Evidence for escaping electrons, e.g.
  - Missing TeV-emitting electrons in the Vela-X ERN
  - Positrons in the local cosmic rays (AMS+)
  - Gamma-ray halos (HAWC +)
- BUT
  - Escape is a complex time and energy dep. Process
  - Escaped = in the ISM




THE ASTROPHYSICAL JOURNAL LETTERS, 743:L7 (5pp), 2011 December 10

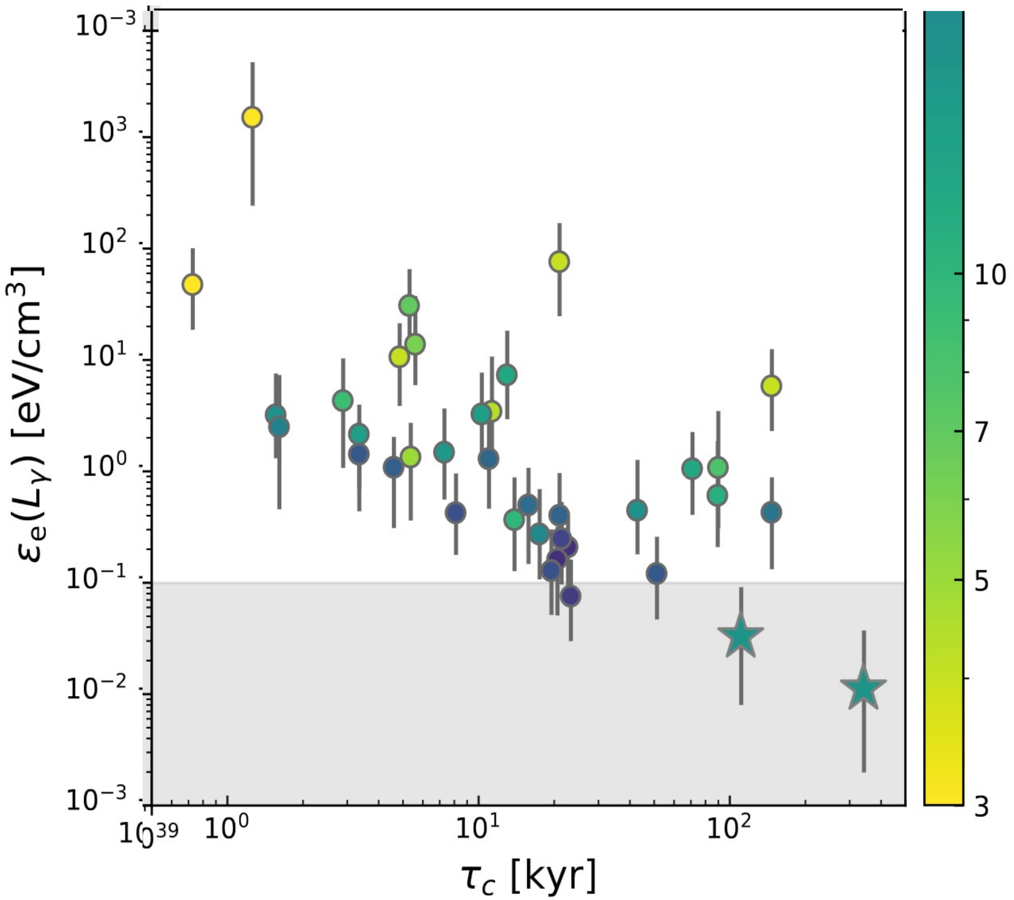
ESCAPE FROM VELA X

J. A. HINTON[1], S. FUNK[2], R. D. PARSONS[3], AND S. OHM[1,3]

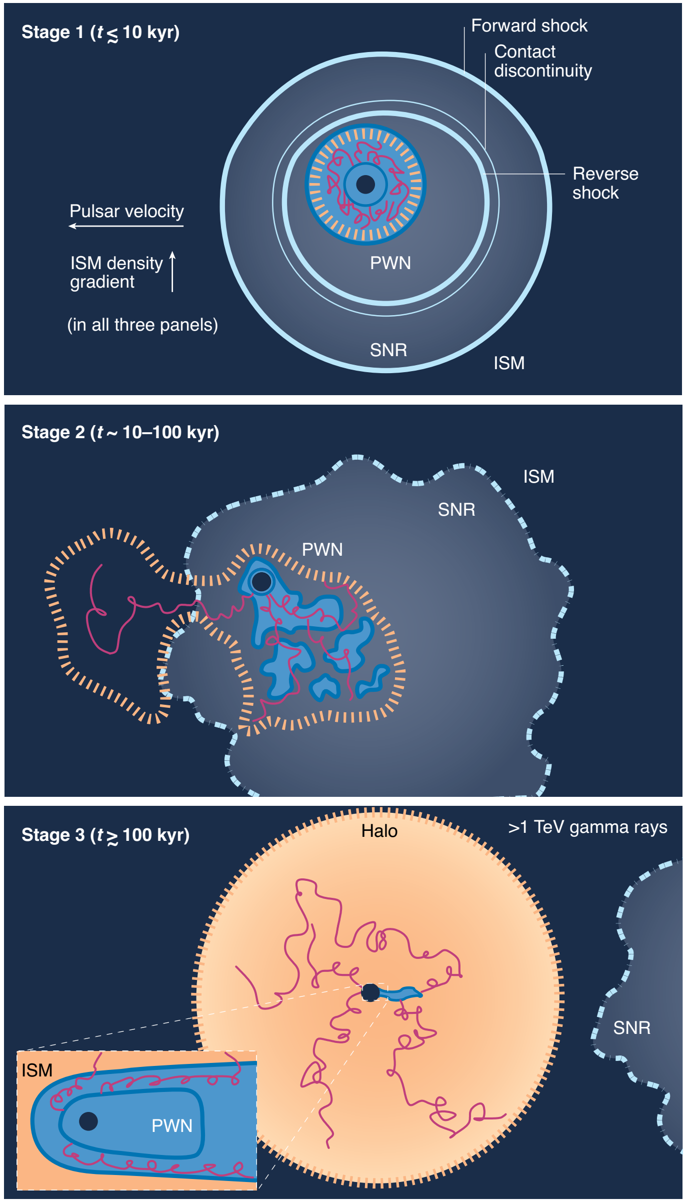


Olmi & Bucciantini 2020

Escape/Halos

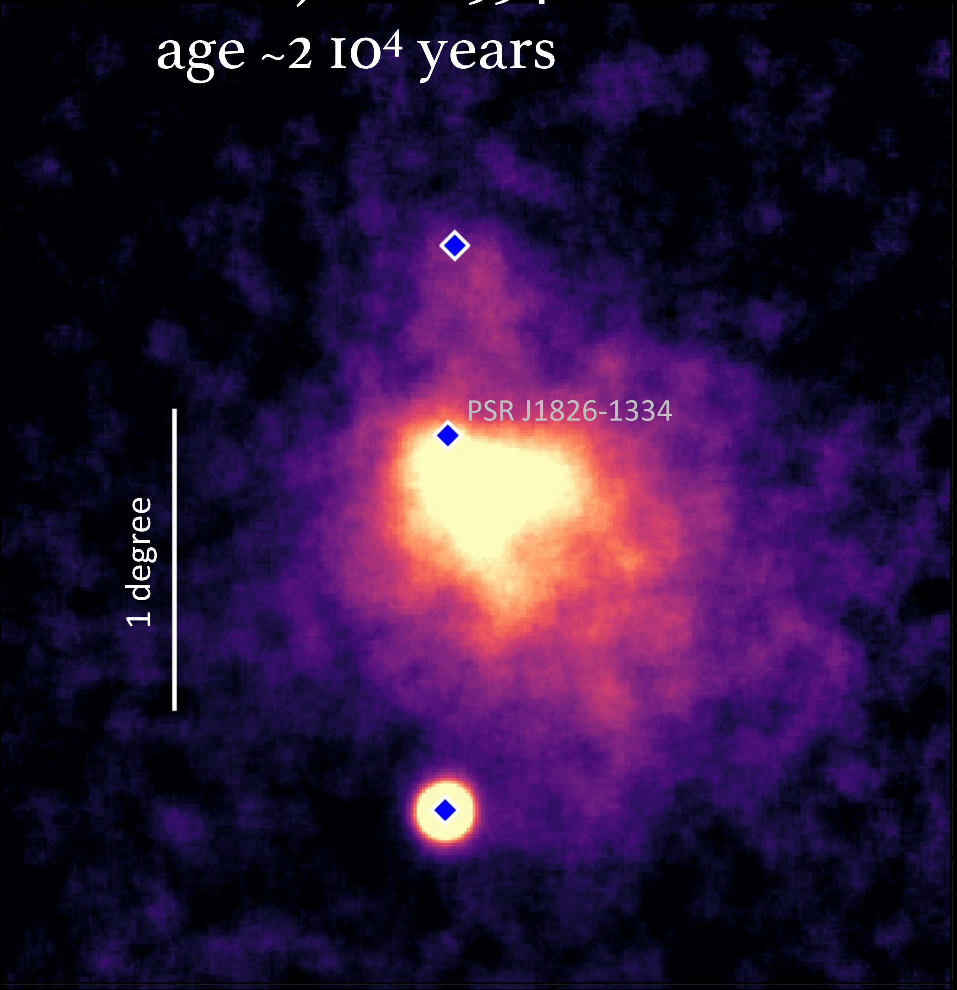


Giacinti et al A&A 636, A113 (2020)

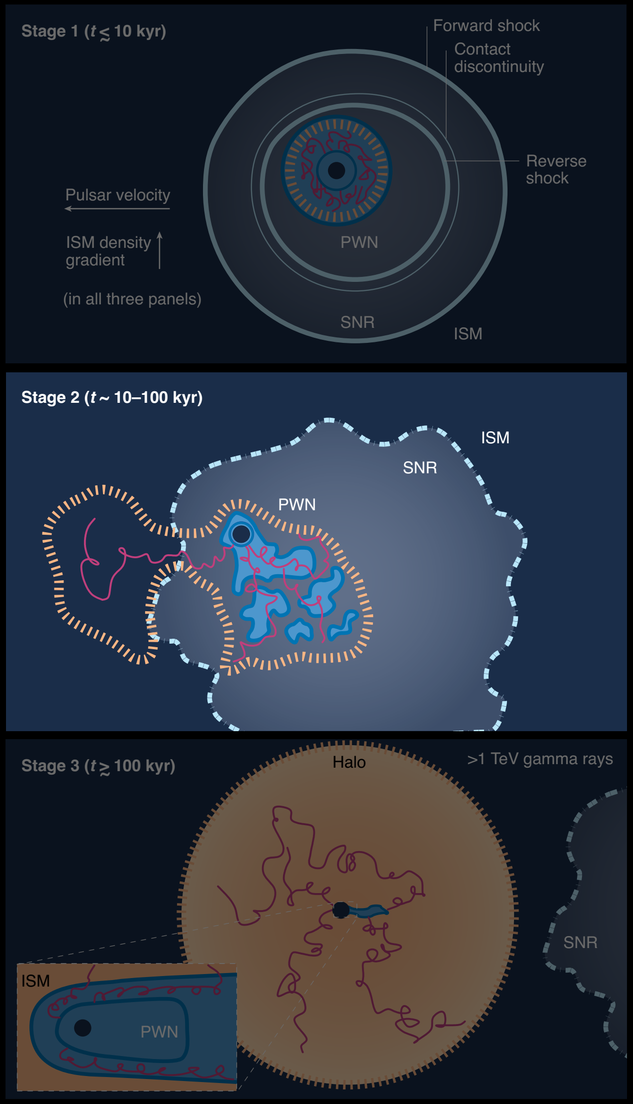


HESS J1825-137

- PSR J1826-1334 characteristic age ~2 10⁴ years



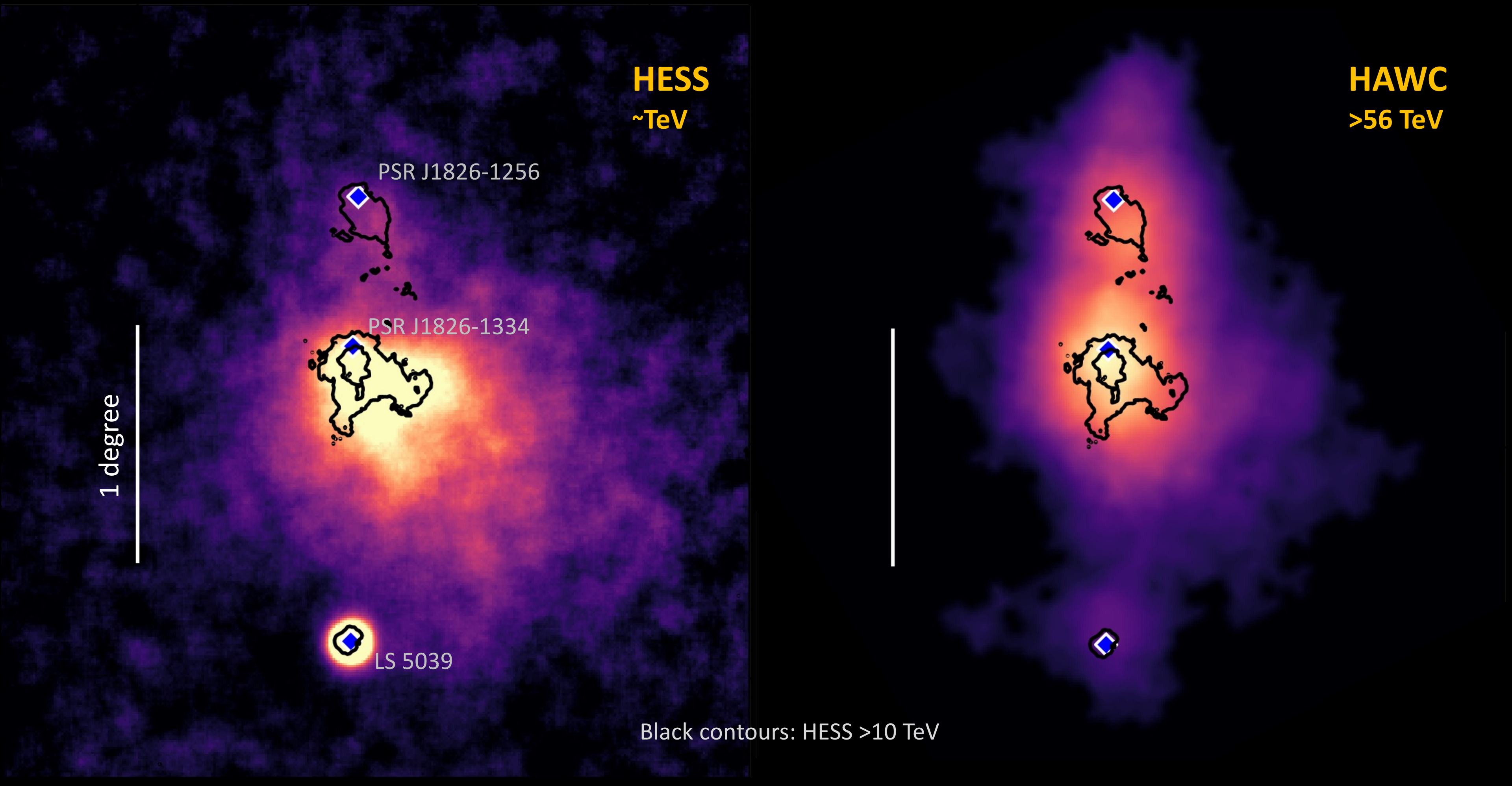
?



HESS J1825-137

Data from HESS Coll. A&A 621, A116 (2019)

HAWC Coll Prelim. Goksu et al TeVPA 2023

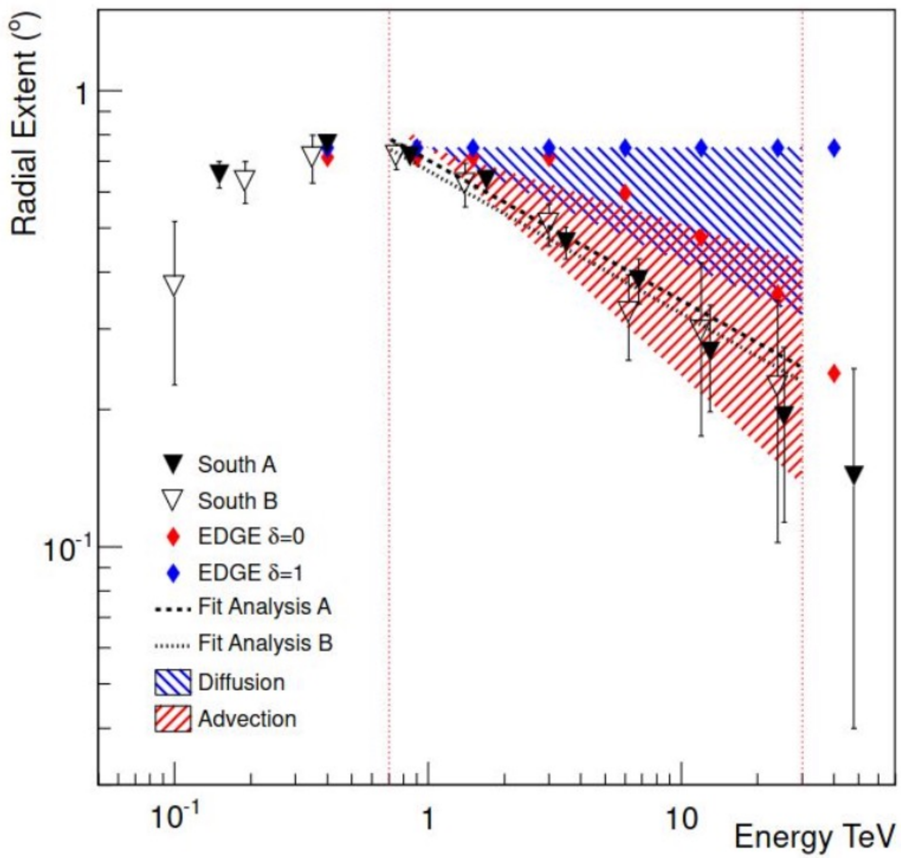


Black contours: HESS >10 TeV

HESS J1825-137

Fermi-LAT,
Principe et al.
2020

HESS Coll. A&A 621, A116 (2019)



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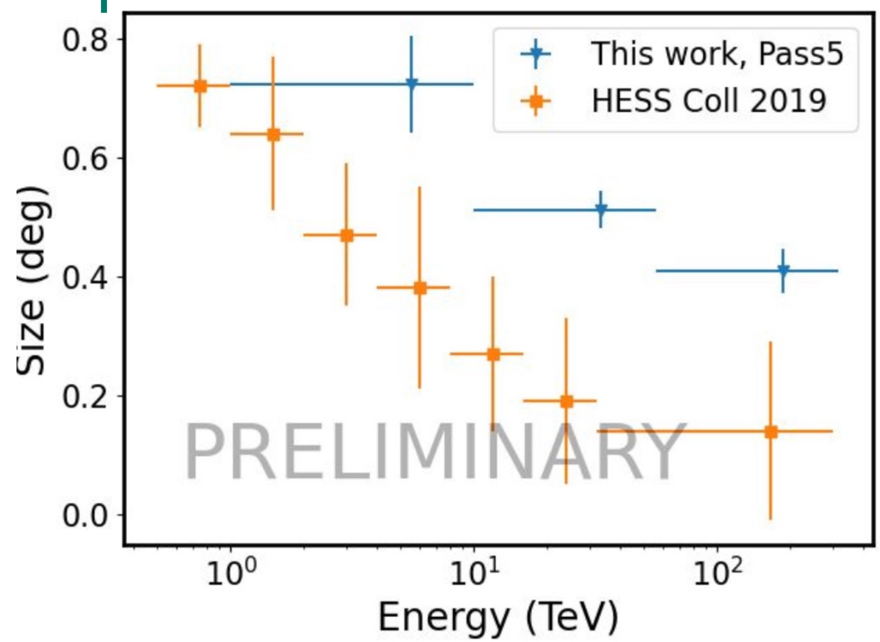
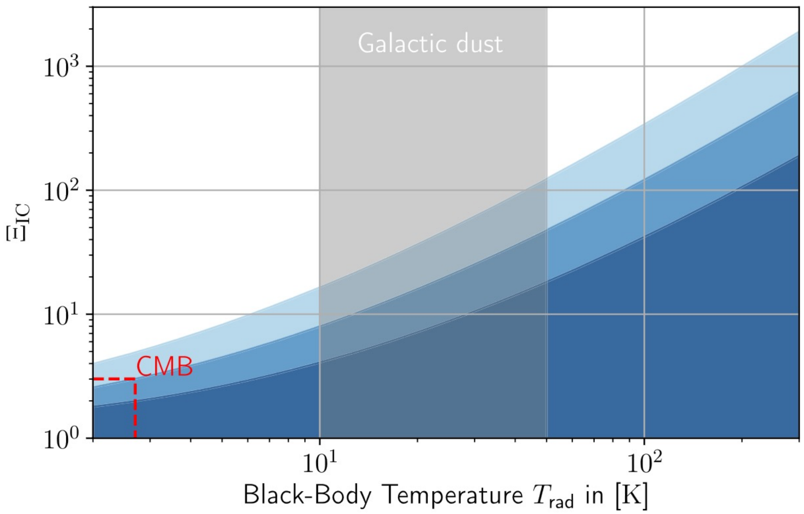
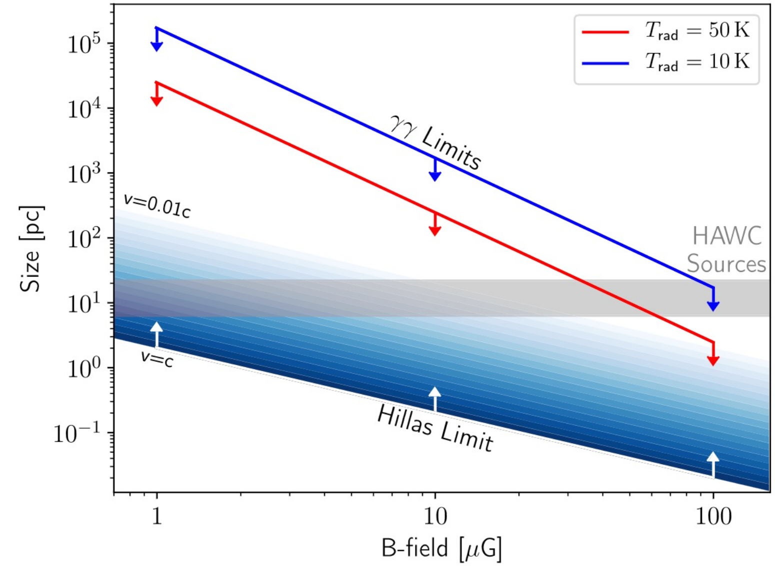


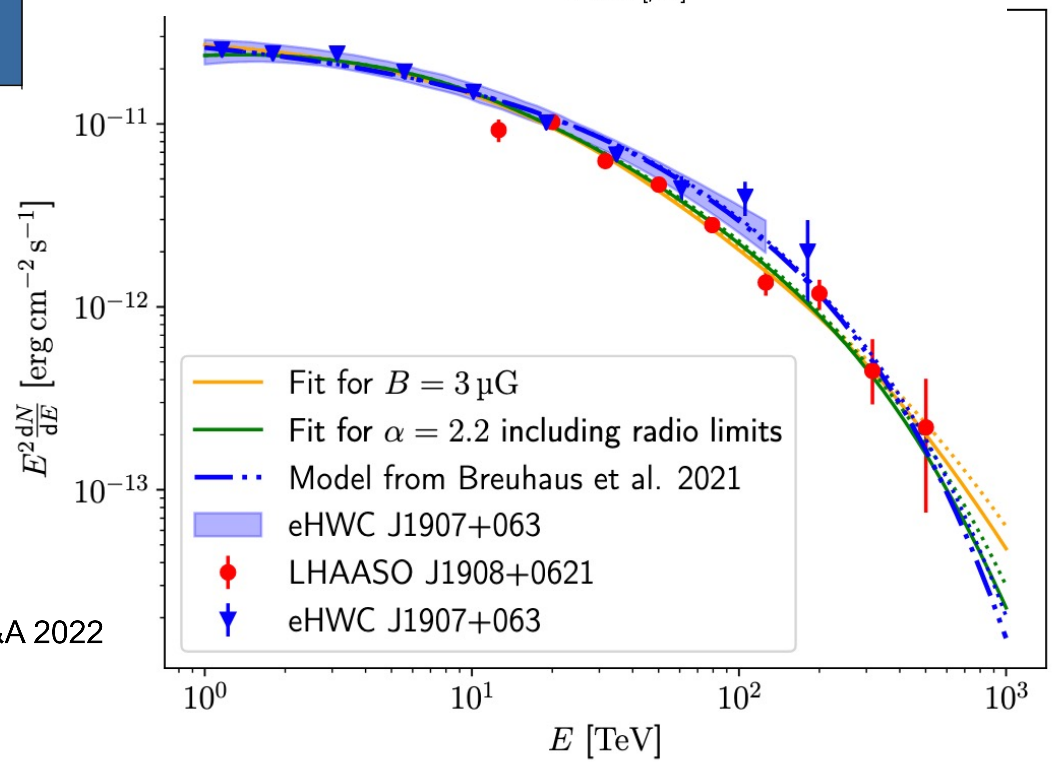
A **Python** package for **gamma-ray** astronomy

Spectra?

Breuhaus et al ApJ 2021

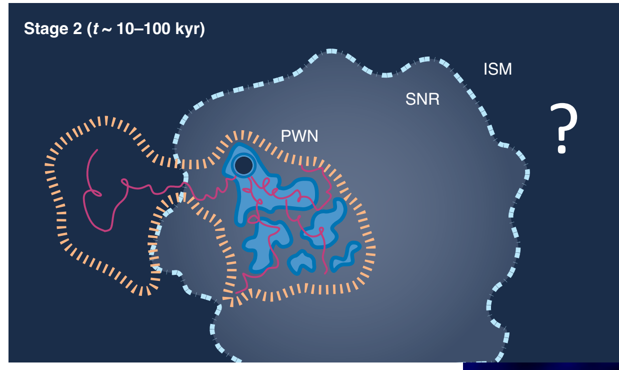


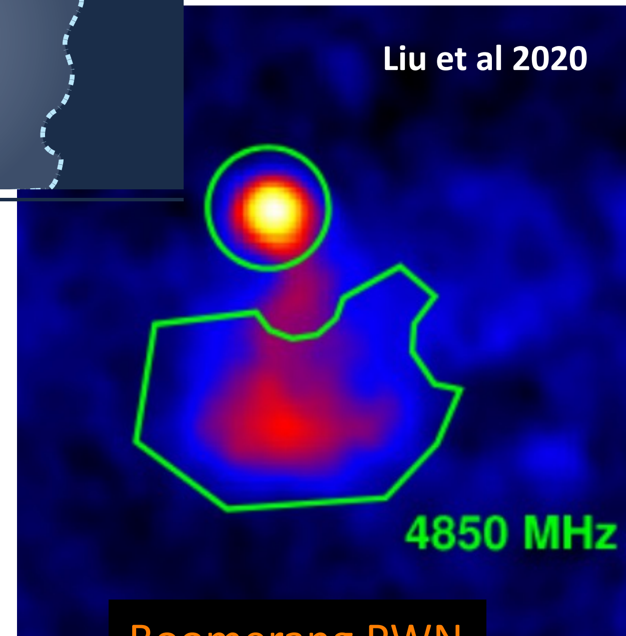


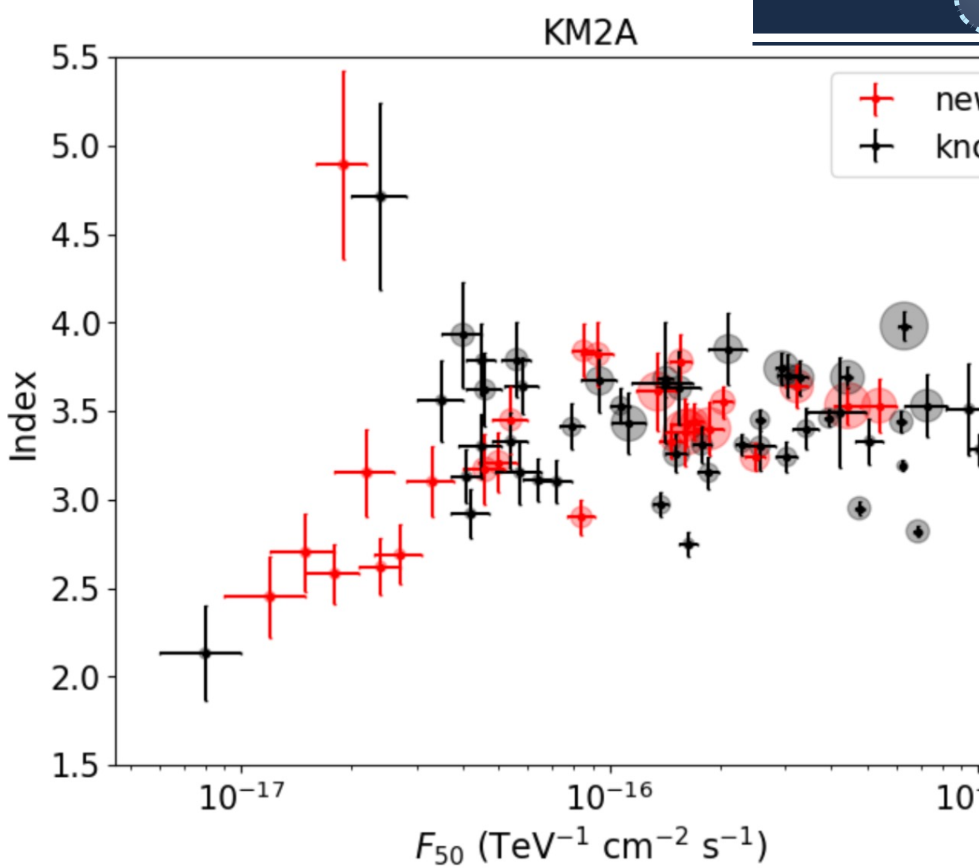


Breuhaus, Reville, Hinton A&A 2022

Spectra?

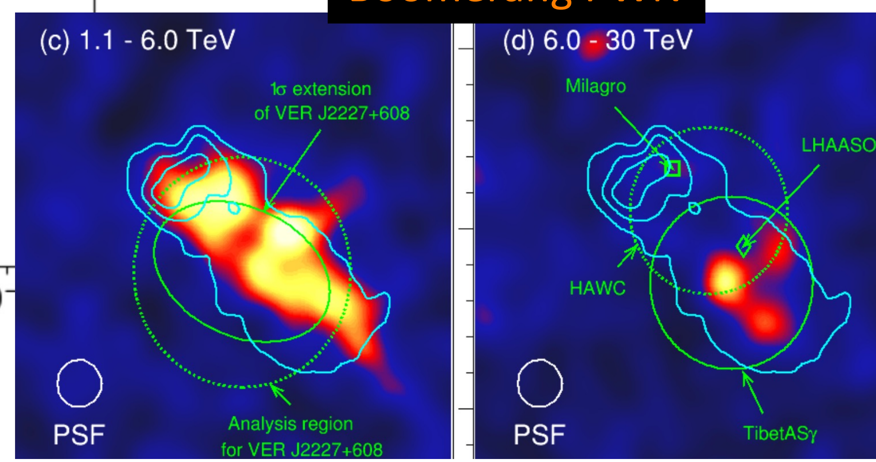






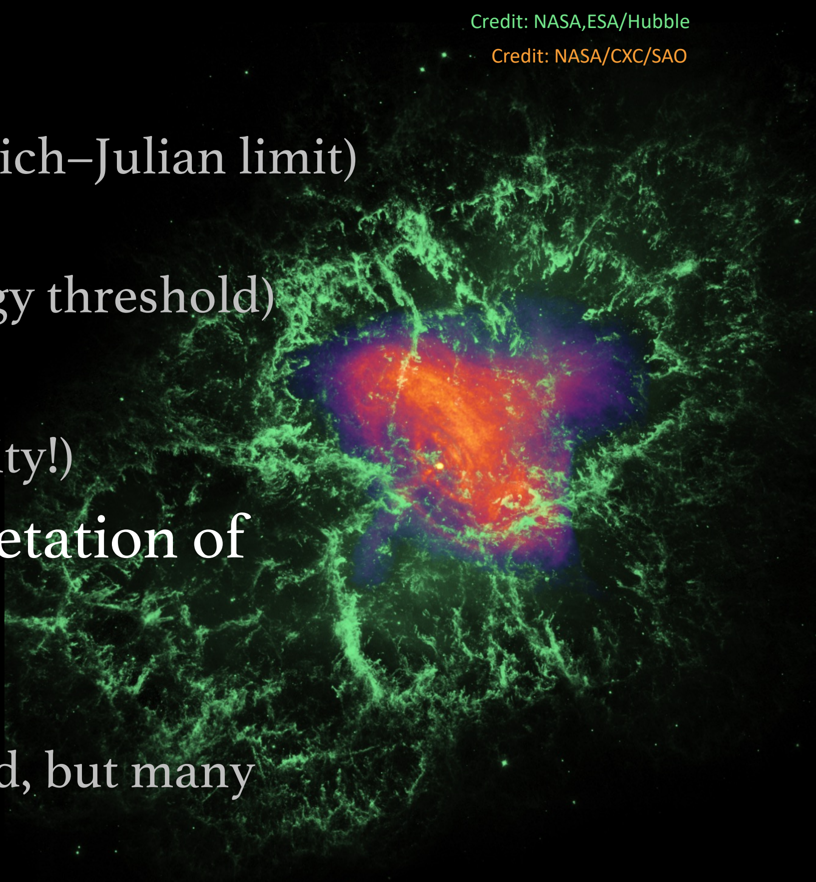
First LHAASO Catalogue 2023

Boomerang PWN



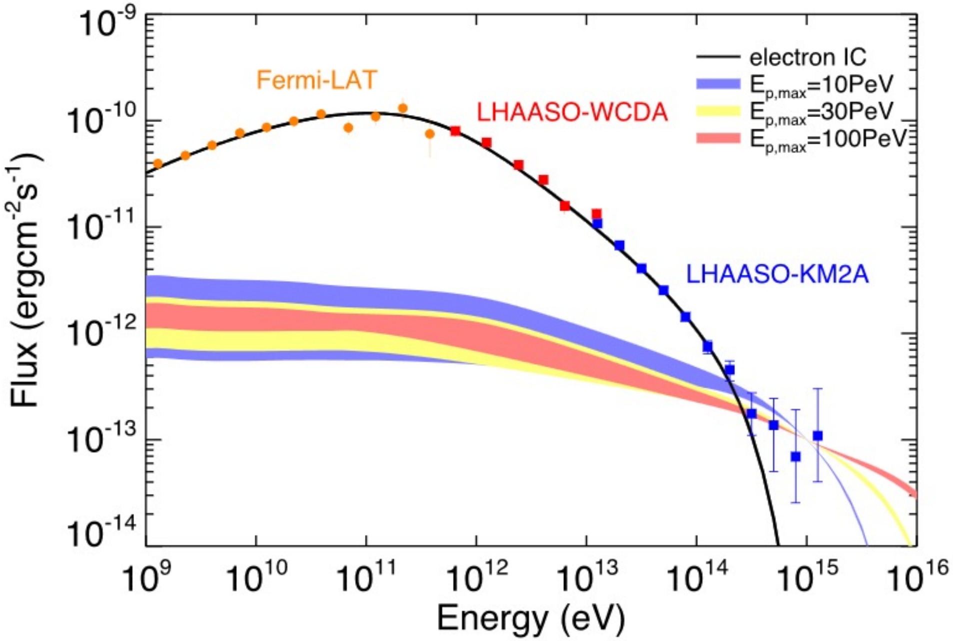
MAGIC Coll. 2022

Protons in PWN

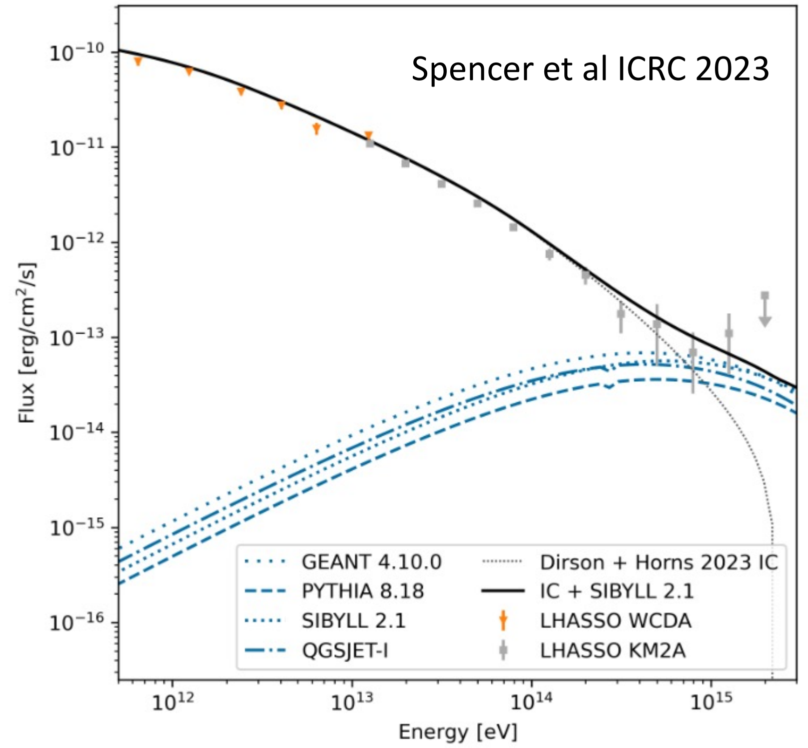


- Must reach the acceleration site
  - Ions present in unshocked wind (Goldreich–Julian limit) or
  - make it in from outside (minimum energy threshold)
- Must reach target material
  - and interact in sufficient numbers (density!)
- Great care must be taken in interpretation of much lower energy data
  - Complex (star forming!) regions
  - p-p often dominates over IC in GeV band, but many accelerators to GeV, few to PeV
- Change in UHE morphology as smoking gun

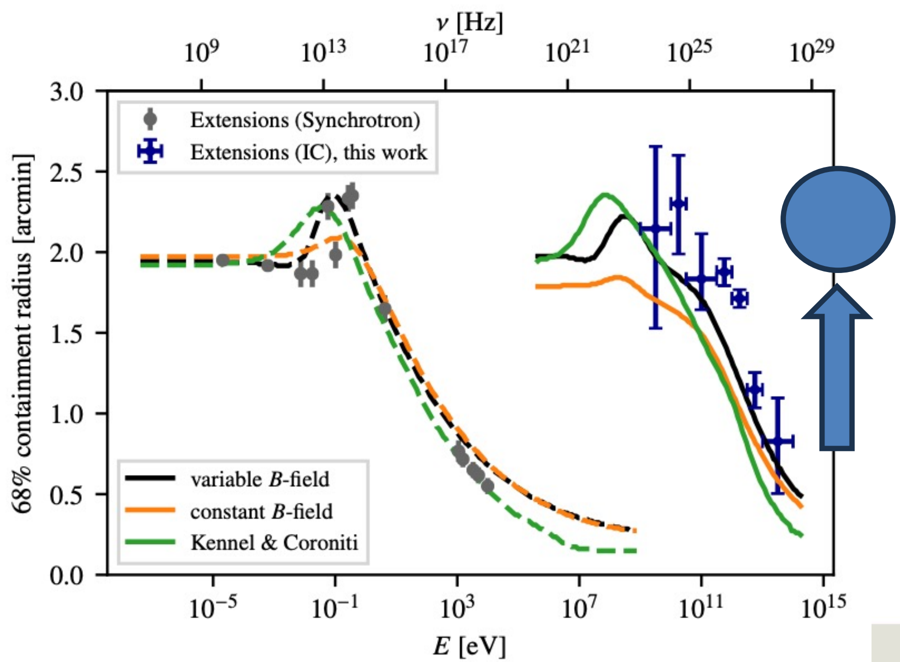
Liu & Wang ApJ 2021

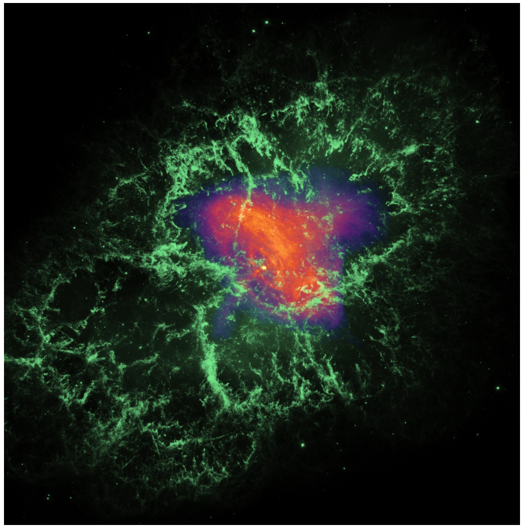


Spencer et al ICRC 2023



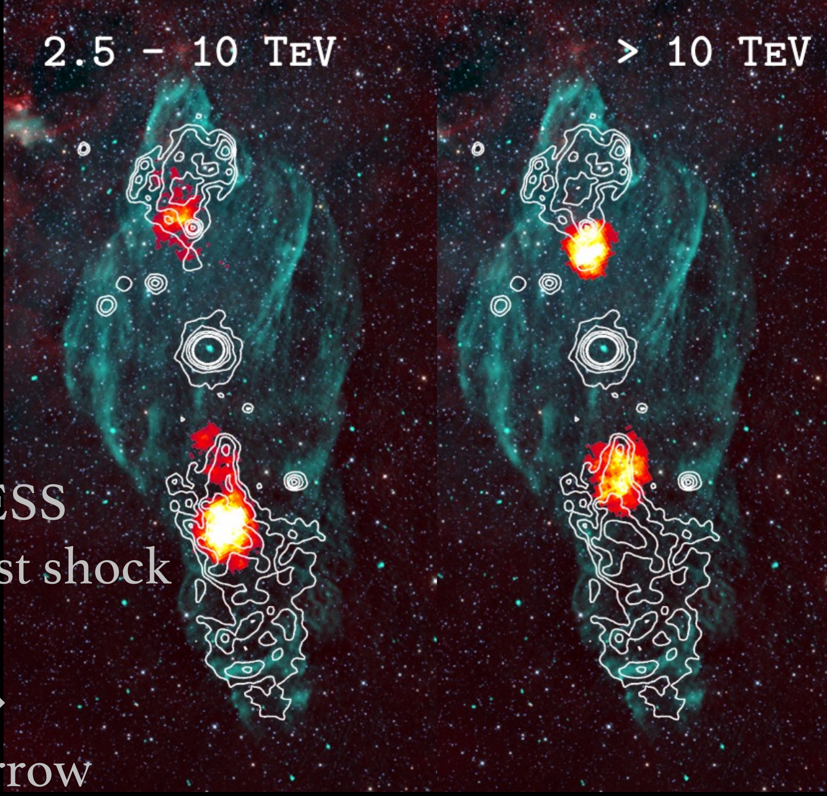
Mohrmann+ ICRC 2023



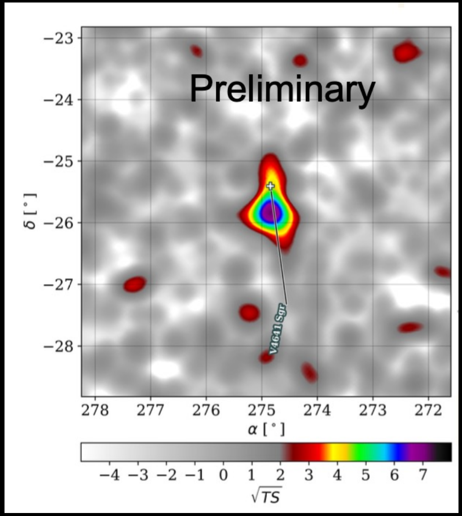


Microquasars

Olivera/HESS
Coll ICRC 2023

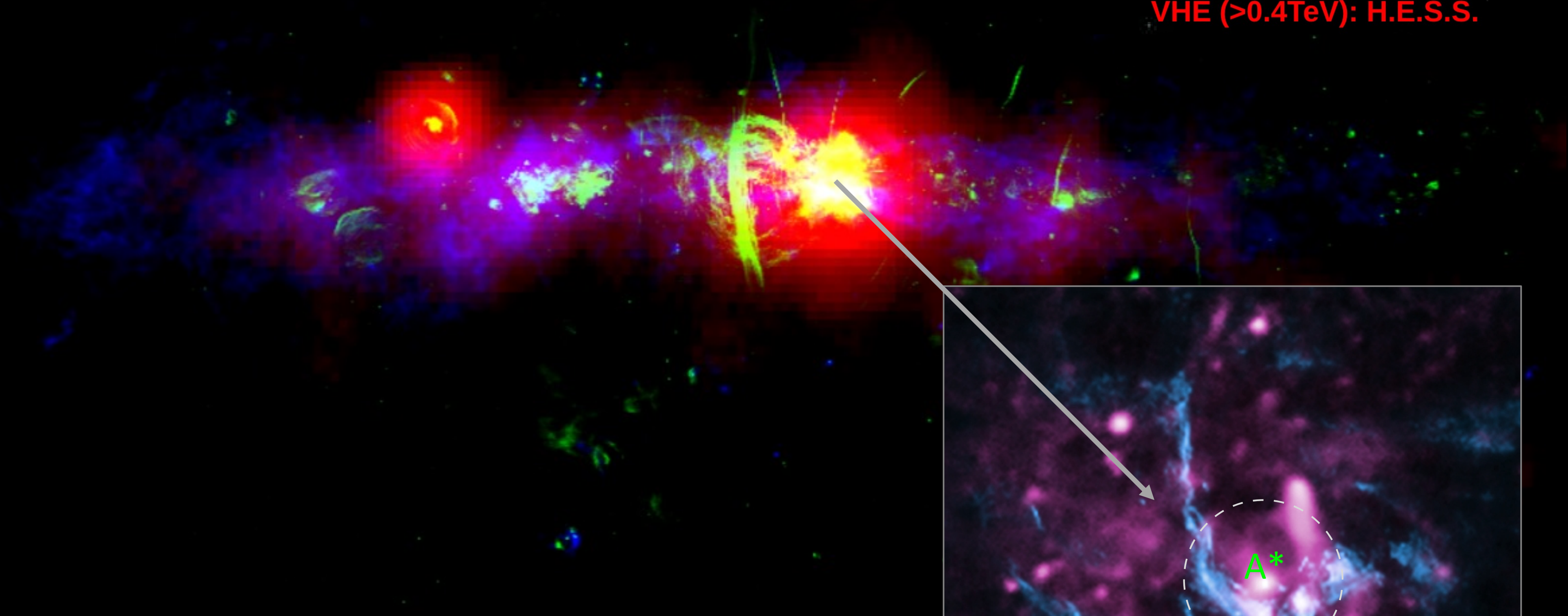


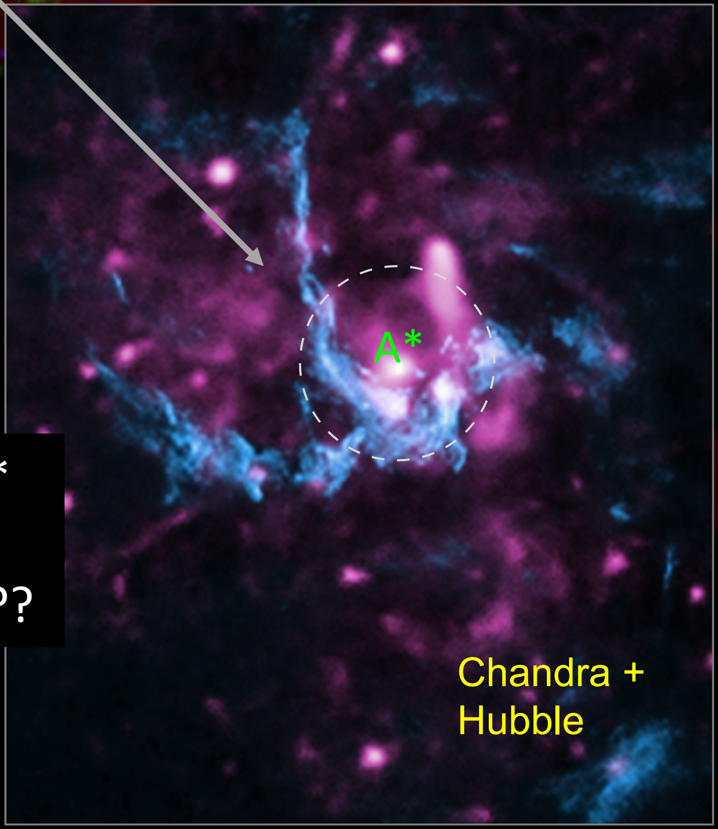
- SS433
  - VHE detection HAWC Coll. 2018
  - Energy dependent morphology with HESS clearly indicates cooling electrons in post shock flow
  - HESS Coll. 2024 Accepted by Science → Presentation Laura Olivera-Nieto tomorrow
- Known hadronic jet
  - V. likely PeV proton accelerator – but no p-p signature→ low densities
  - And this is a very rare/unusual object…
  - Now also V 4641 Sgr HAWC → emerging population?



Goodman/HAWC
Coll Gamma2022

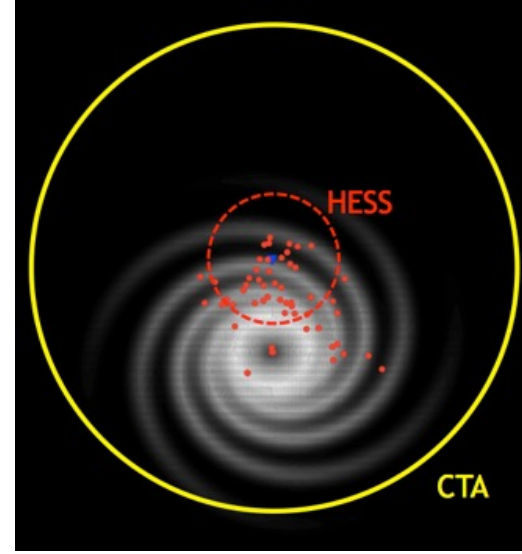
Sgr A* ?





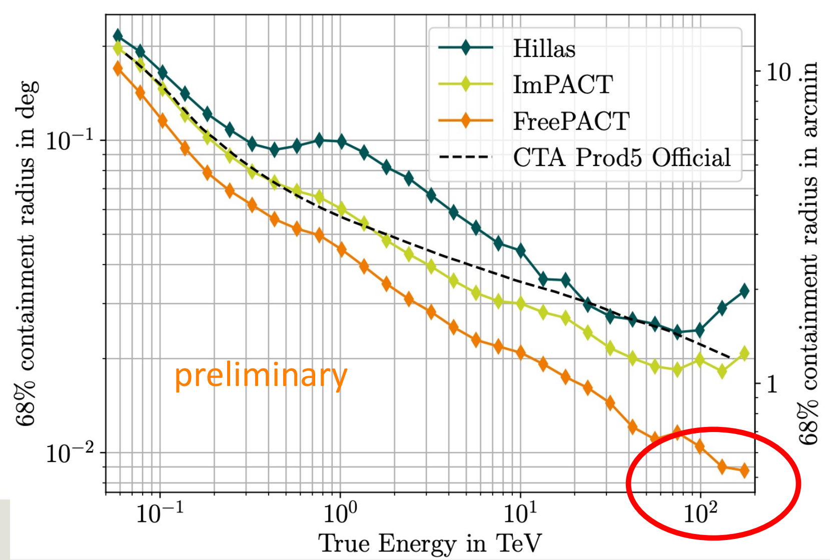
Point-like TeV source coincident (within 10”) of A*
‘Excess’ diffuse emission in CMZ
Hidden jet? ‘Magnetospheric’? Central cluster ????

Observational prospects

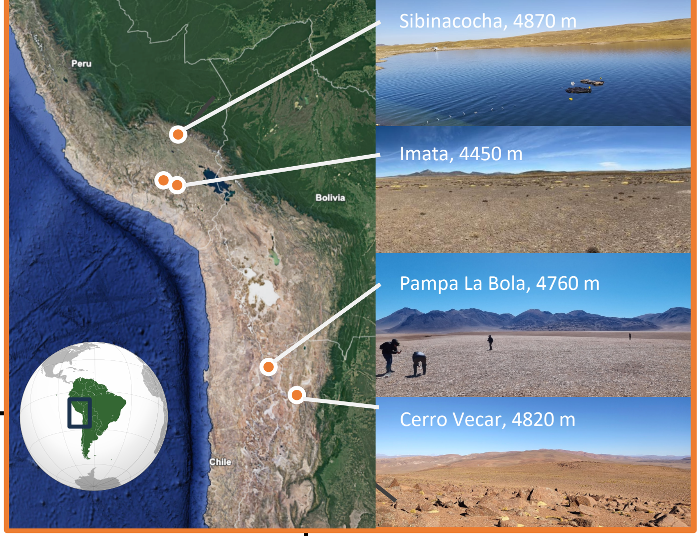


- Populations
  - Separation of evolutionary and environmental effects only possible with a larger sample: ALL powerful young pulsars in MW detectable with CTA as PWN
  - An emerging microquasar population?
- UHE gamma-ray observations
  - Extremely good angular resolution (30 arcseconds!) at UHE looks possible with CTA South (Schwefer, Parsons and Hinton in prep.)
  - UHE sensitivity of SWGO – aiming for LHAASO/KM2A level – for the inner galaxy…

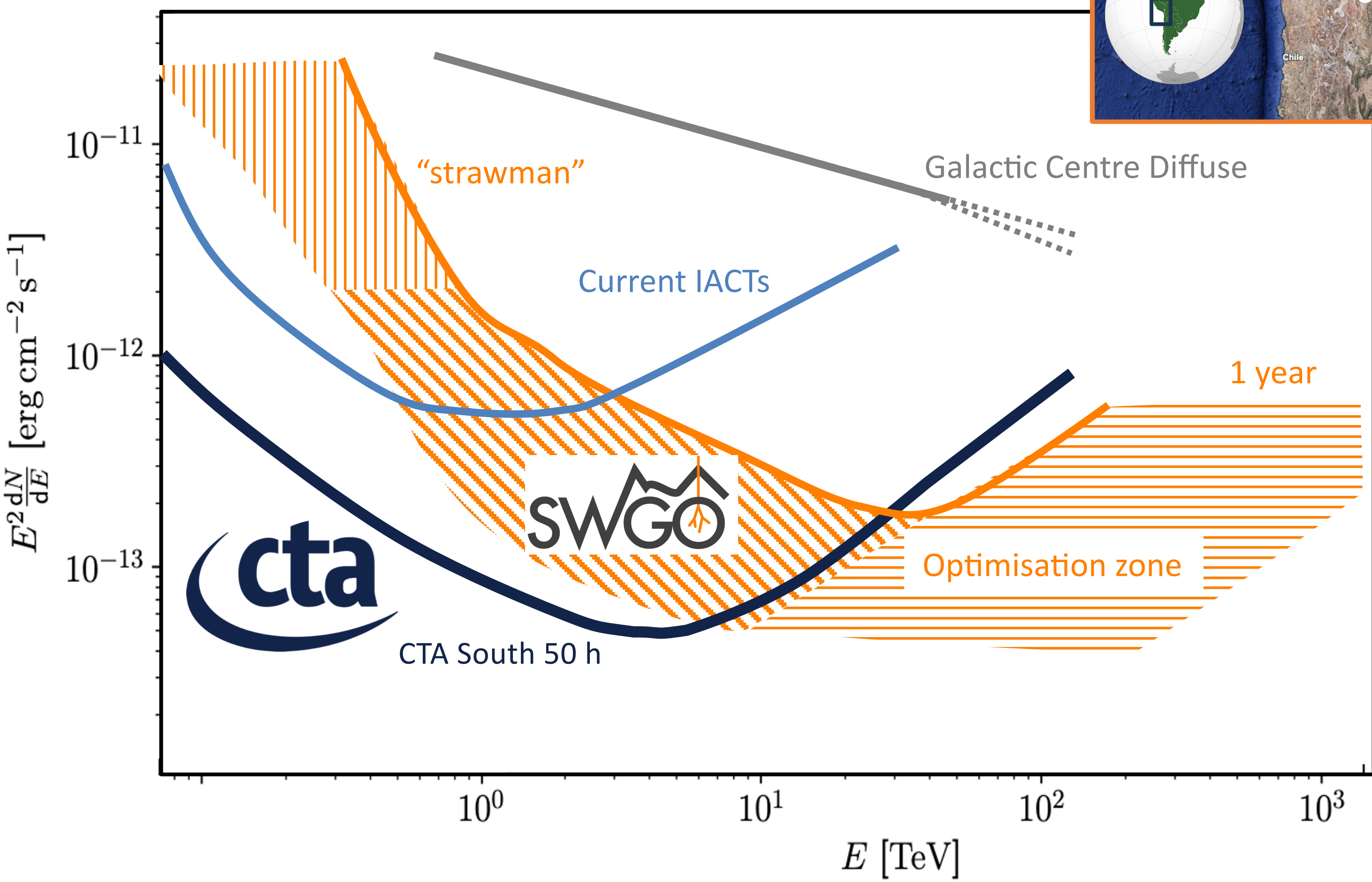
First CTA and/or SWGO data from 2027+



SWGO
2024: Site & Technology Choices
2026+: Engineering Array



Point-source differential sensitivity (5 bins per decade, 5 sigma)



Summary

- Galactic relativistic systems play a major role in non-thermal astrophysics
  - Even if they likely do not dominate CR (proton) flux at any energy – they serve as laboratory for systems on much larger scales
  - Dominant source class at VHE-UHE: PWN
- Key elements
  - Still uncertain physics of acceleration and post-shock propagation
  - Escape of particles from post-shock 'nebulae'
  - Circumstances and locations of acceleration of protons and nuclei
- Excellent observational opportunities at VHE/UHE
  - Common toolkit and combined analysis (gammapy!)
  - Energy-dependent morphology always expected in these systems – within reach of current instruments – but in danger of being missed
  - New generation of instruments CTA and SWGO coming 'soon' !