Friedrich-Alexander-Universität
Erlangen-Nürnberg

Galactic Astrophysics with Imaging Atmospheric Cherenkov Telescopes:

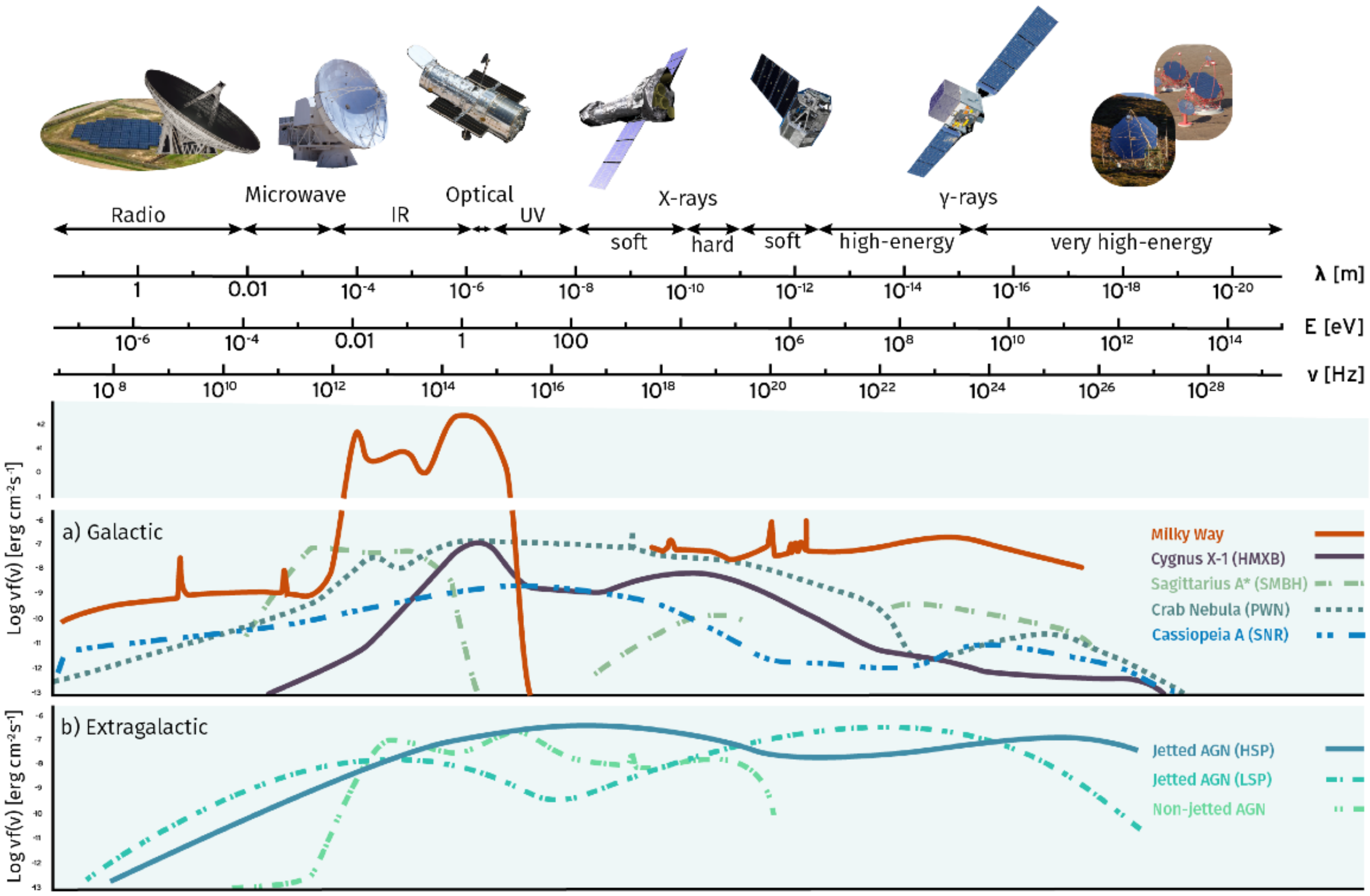
Gamma-Ray Astronomy, intensity interferometry & other radio synergies

Radio 2024

Alison Mitchell
Junior Research Group Leader
13th November 2024

Emmy Noether-Programm DFG
Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

Gamma-Ray Astronomy & Non-thermal Astrophysics



Credit: Annika Kreikenbohm, JMU Würzburg

- Very-High-Energy Gamma-rays at photon energies $E_\gamma \gtrsim 10^{11}\,\mathrm{eV}$
- Produced through non-thermal emission processes:
    - Decay of pions $\pi_0 \rightarrow \gamma + \gamma$ resulting from p-p interactions
    - Inverse Compton scattering —> energetic electrons up-scatter ambient photons e.g. CMB, IR fields…
- Gamma-rays trace energetic particles
- Gamma-ray astronomy —> insights into the origins of Cosmic Rays and particle acceleration processes

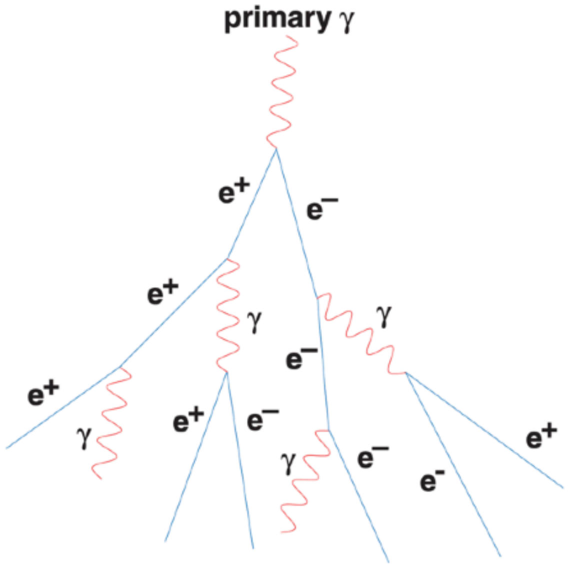
Extensive Air Showers

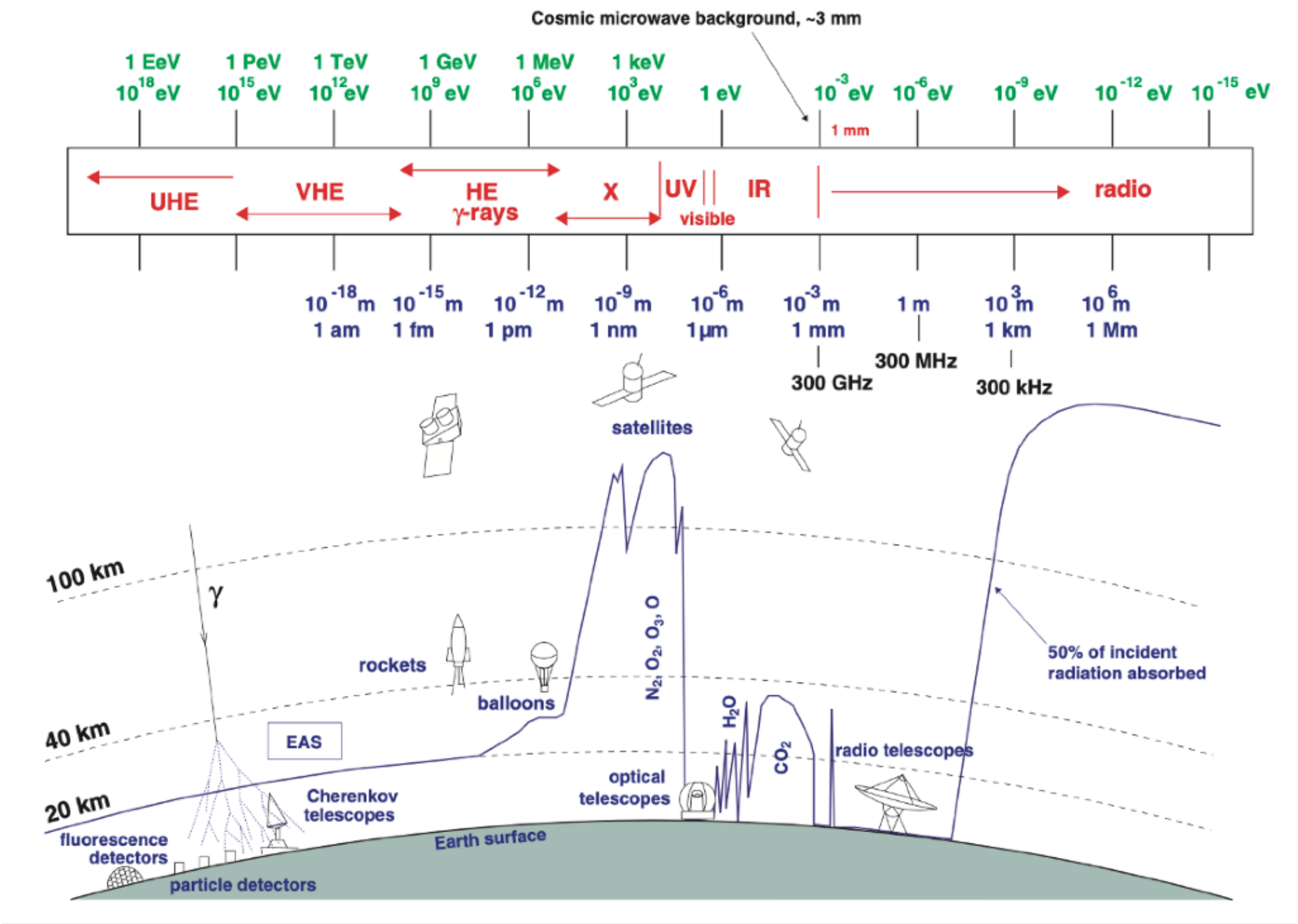
Atmosphere is opaque to gamma-rays

Collection area of satellites is too small

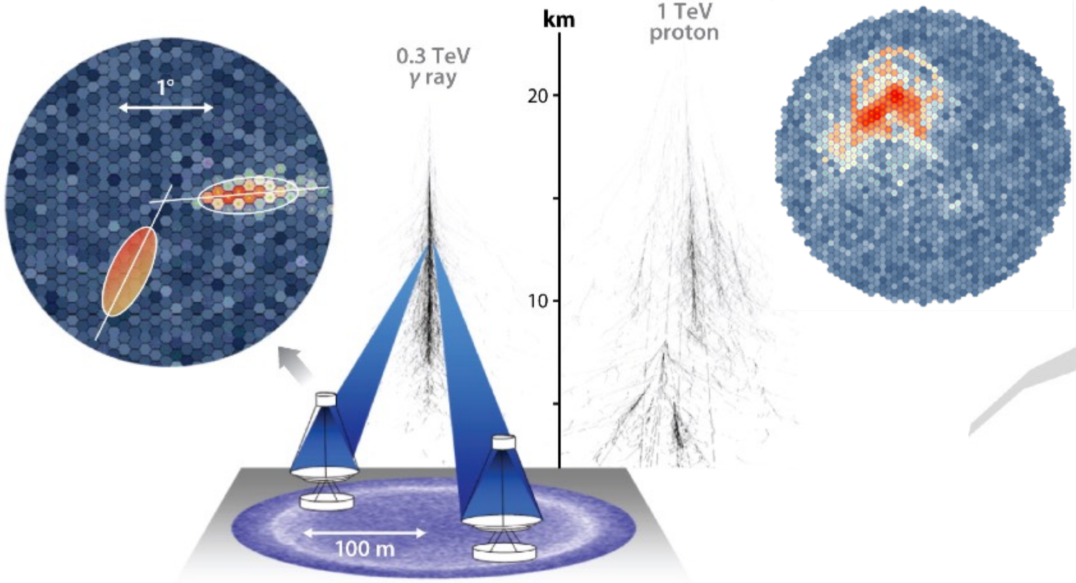
—> Use atmosphere as part of the detector:
a calorimeter

Primary gamma-rays (and cosmic rays) interact in the Earth's atmosphere inducing extensive air showers

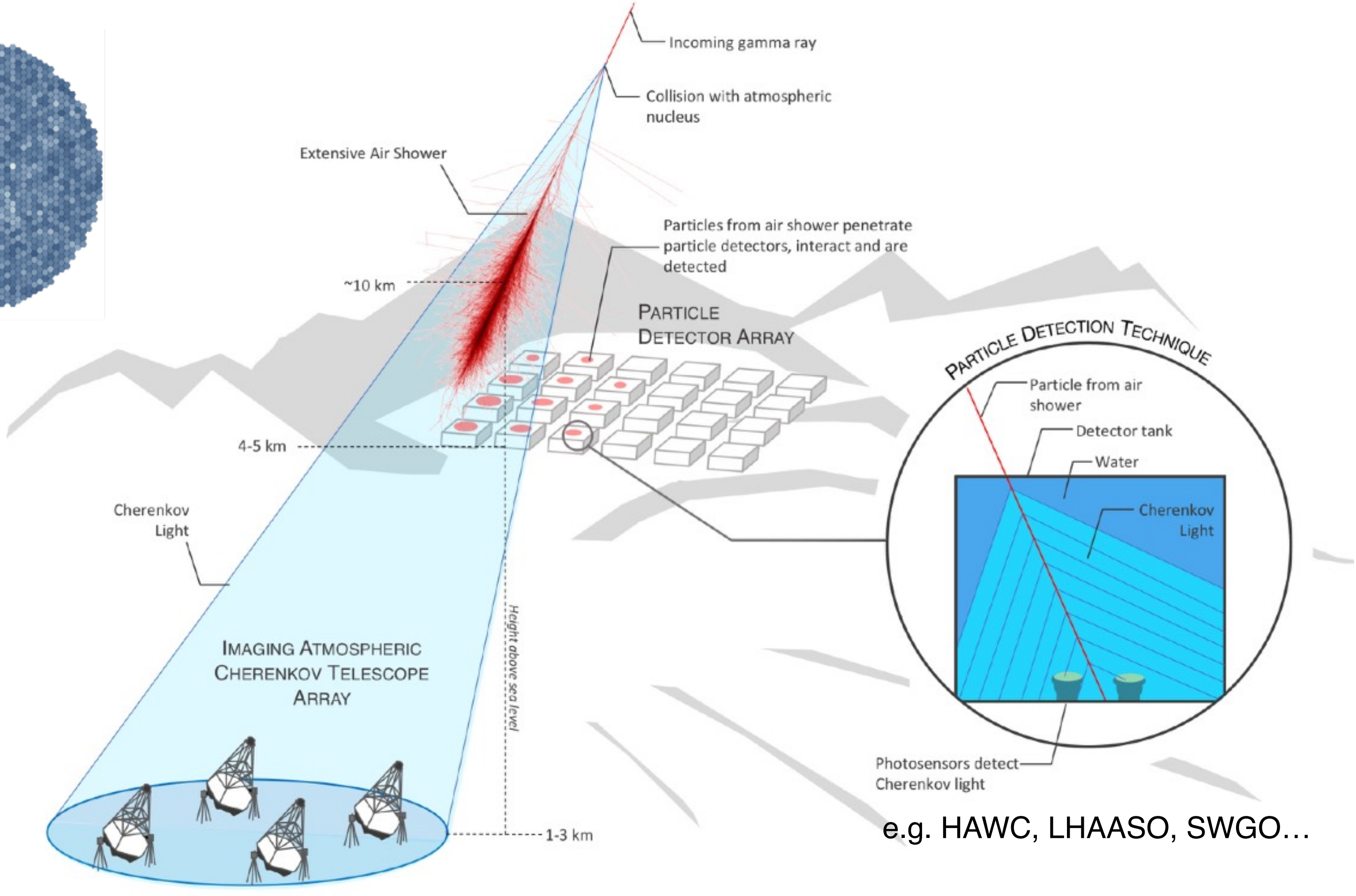




Imaging Atmospheric Cherenkov Telescopes



Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65



e.g. HAWC, LHAASO, SWGO…

Air showers are short duration ~ns —> cameras are therefore fast imaging with trigger rates ~kHz

Current Facilities

VERITAS

MAGIC

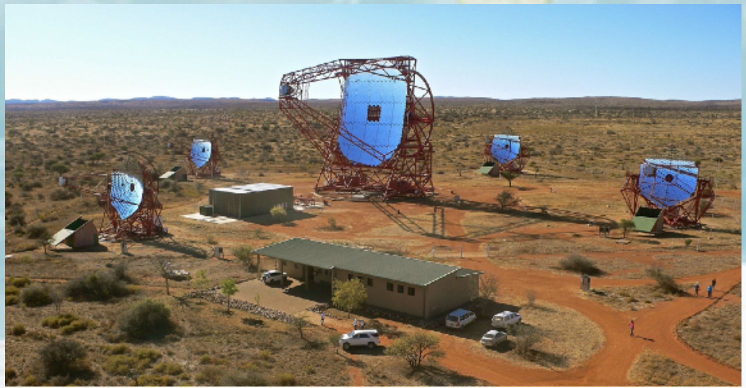
H.E.S.S.

Ideally:

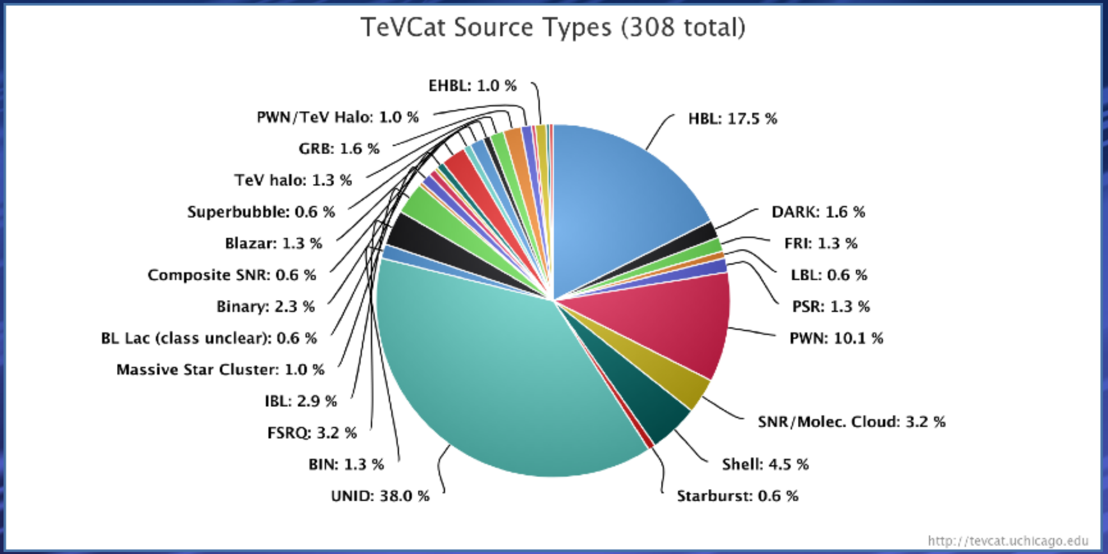
~2000m above sea level

Dark location

Dry & low magnetic field strength

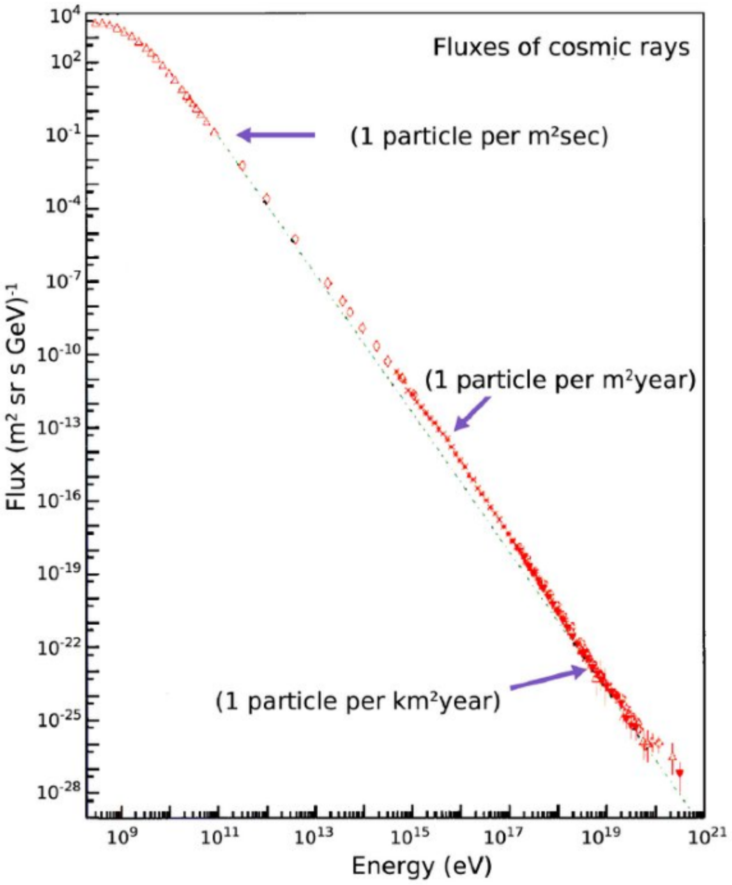


Galactic Gamma-Ray Sources

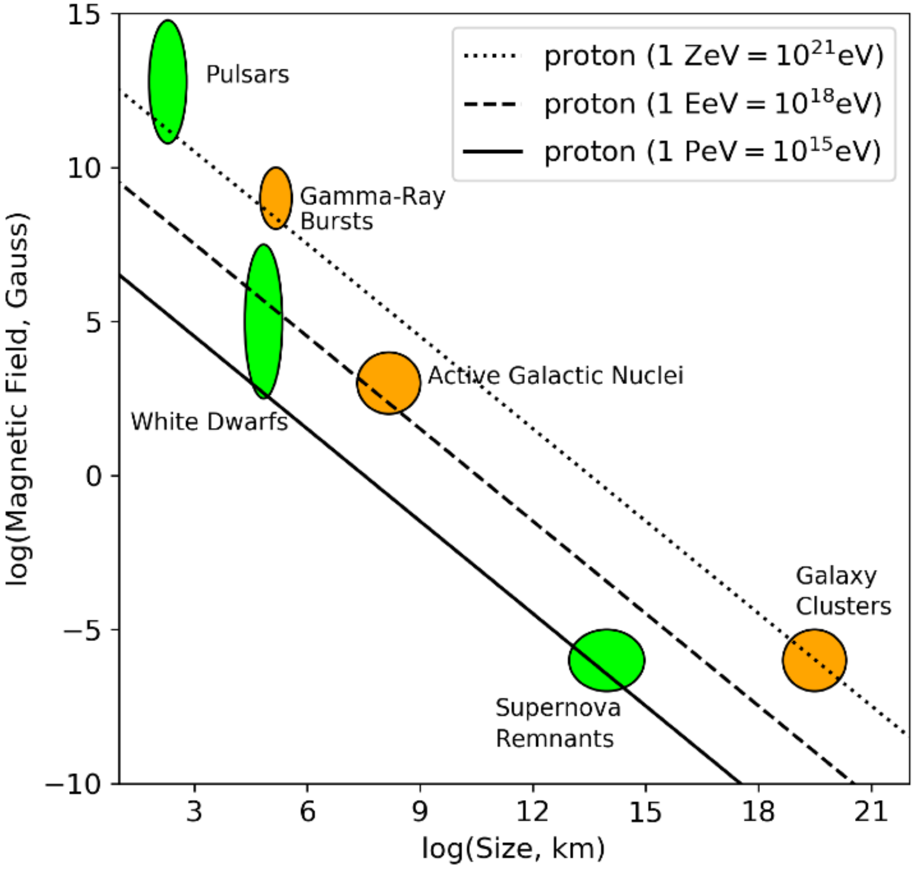


Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Cosmic Ray Spectrum
PeVatrons

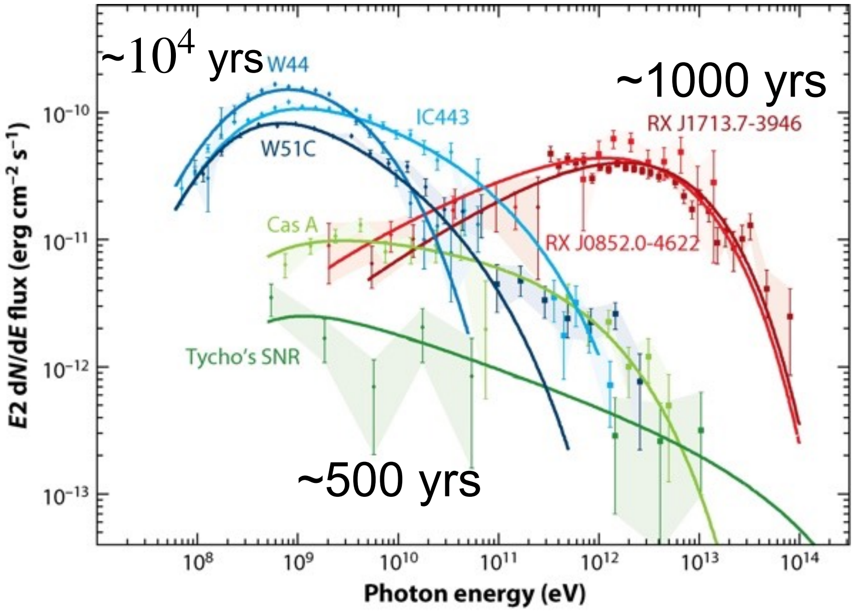


- Approximate power law spectrum $\propto E^{-3}$ over many orders of magnitude
- Change in slope "knee" at $\sim 10^{15}\,\mathrm{eV}$
- Galactic accelerators up to at least the knee —> PeVatrons
- Change in slope "ankle" at $\sim 10^{17}\,\mathrm{eV}$
- Extragalactic dominates above the ankle
- Hillas condition: $E_{\mathrm{max}} = Ze\beta cBL$

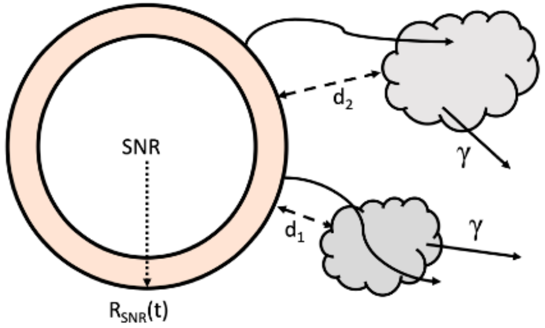


Supernova Remnants

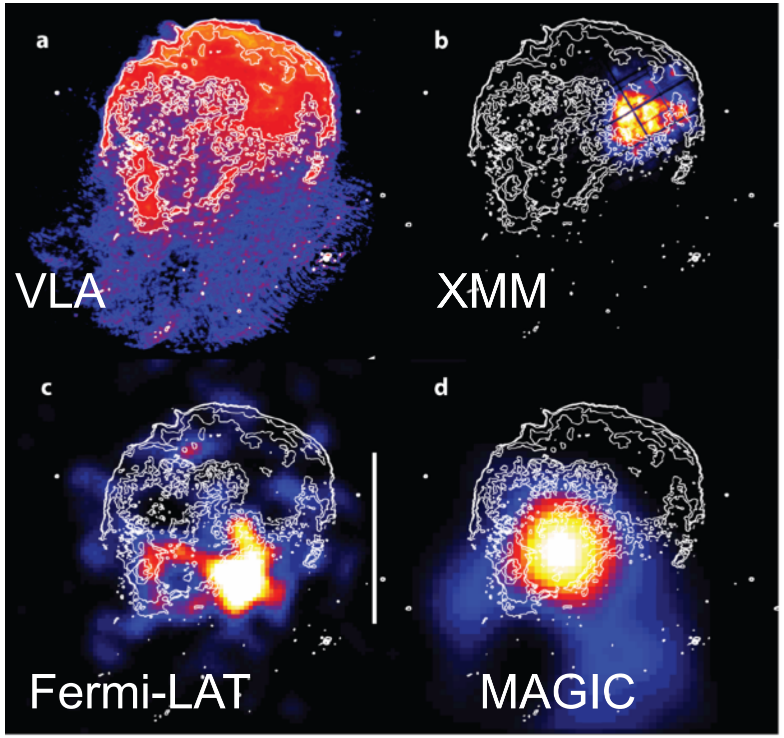
- Prime PeVatron candidates —> yet spectrum ends ~100 TeV
- Only act as PeVatrons for a short time?
- Escaping cosmic rays may illuminate nearby clouds —> detailed knowledge of clouds required!



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



IC 443



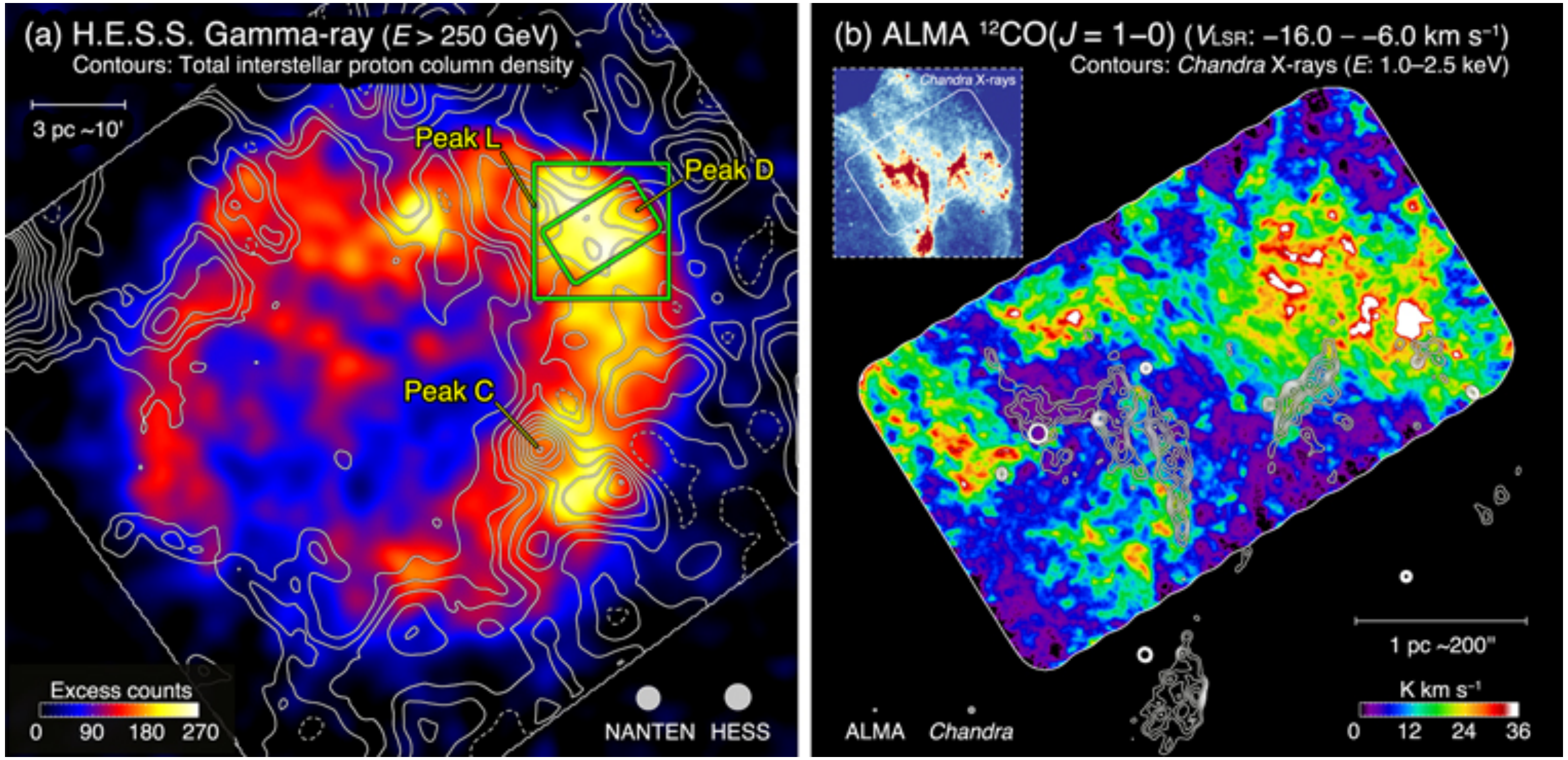
Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

Supernova Remnants

Gamma-ray emission traces shocks - particles accelerated at shock fronts.

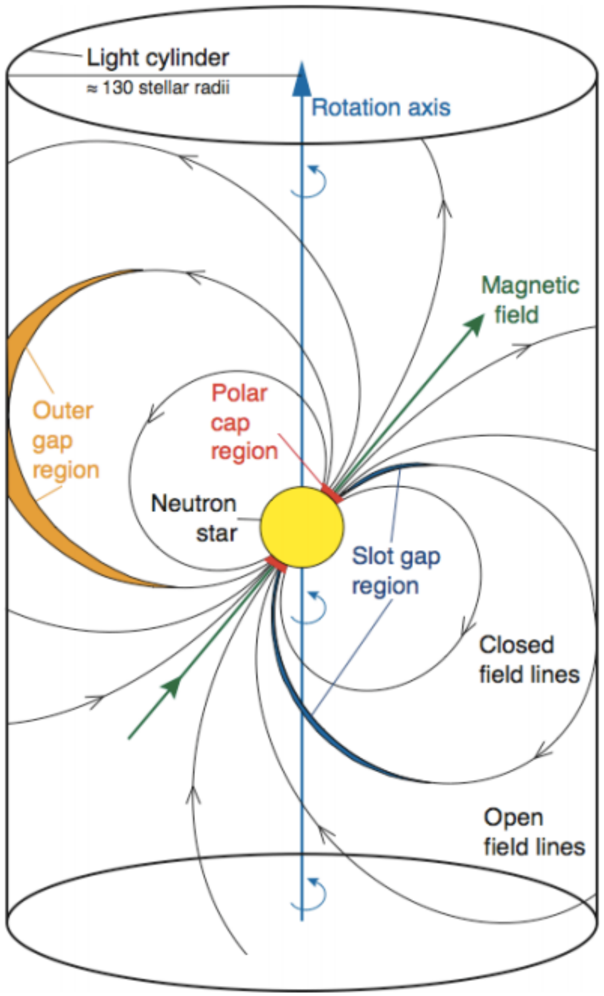
ALMA data corroborates this with evidence for cosmic ray interactions

Note the vastly different fields of view and PSFs



H. Sano *et al* 2020 *ApJL* **904** L24

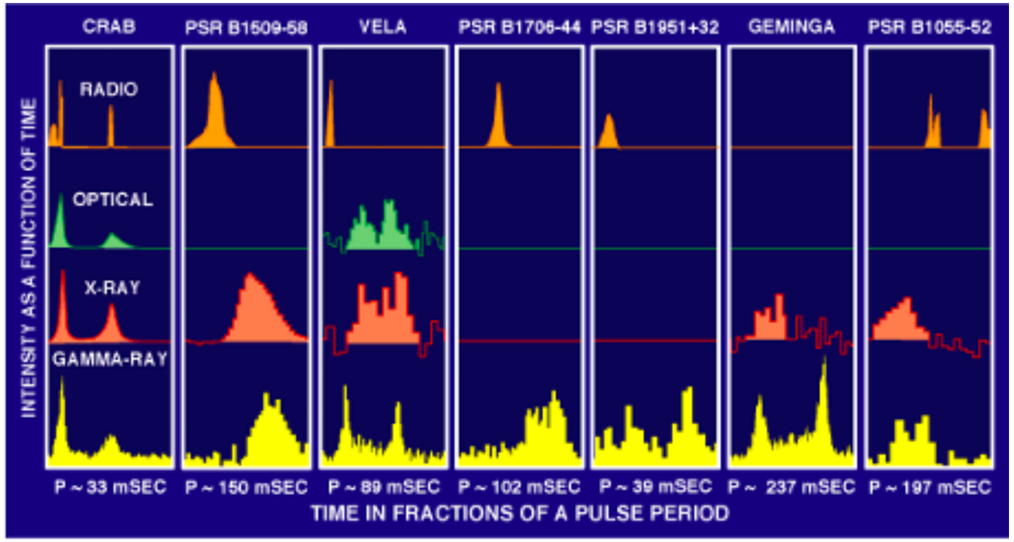
Pulsars

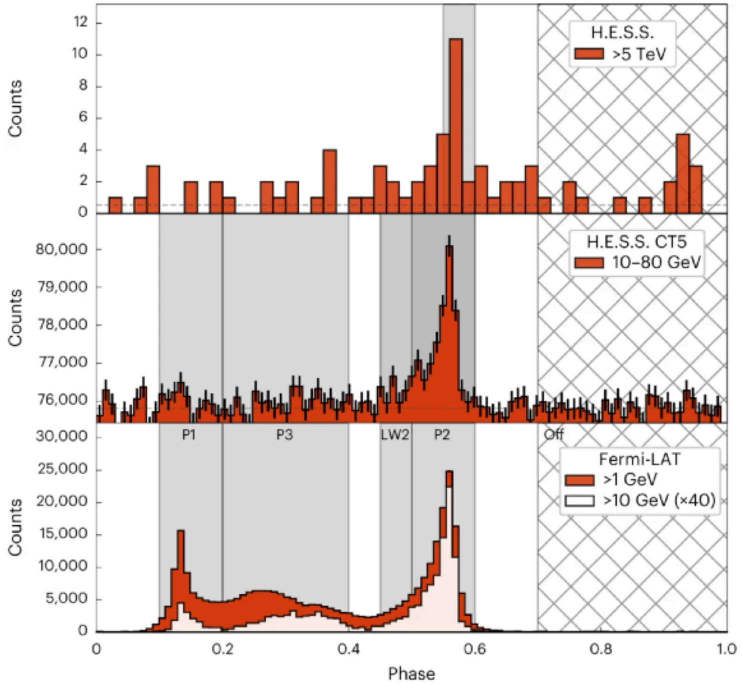


Discovered in radio, yet pulsed emission seen at different wavelengths

Several gamma-ray pulsars are radio-quiet, e.g. Geminga

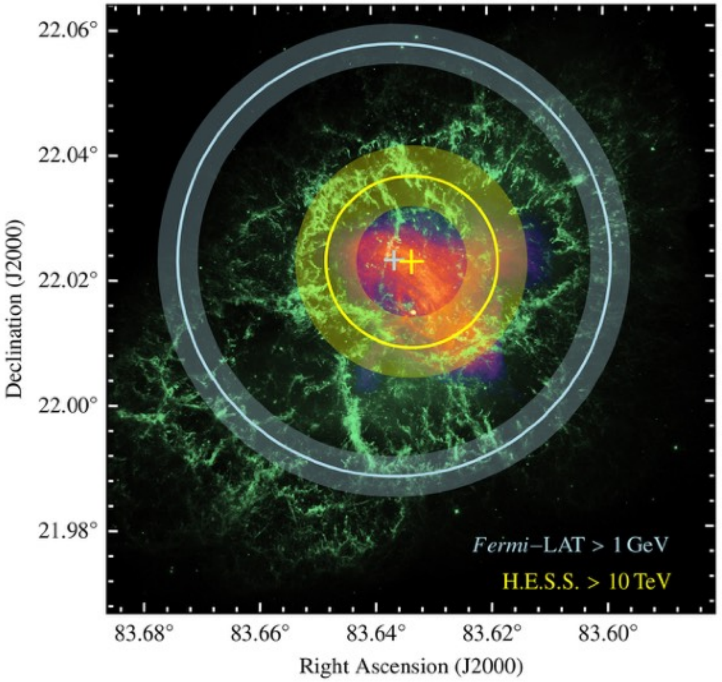
Pulsed signal from Vela reaches above 5 TeV

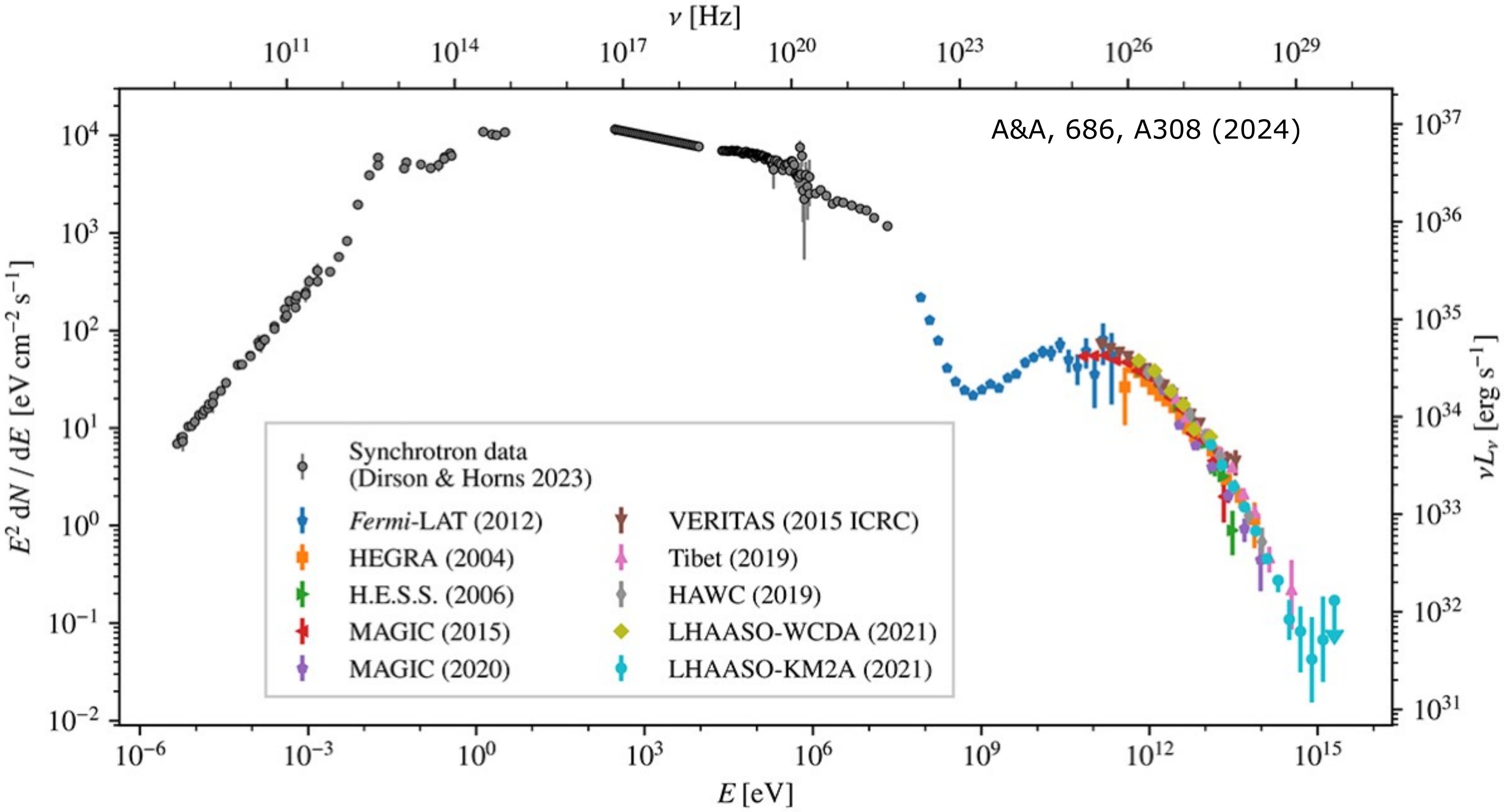




H.E.S.S. Nature Astronomy **7** 1341-1350 (2023)

The Crab Nebula (or Taurus A)





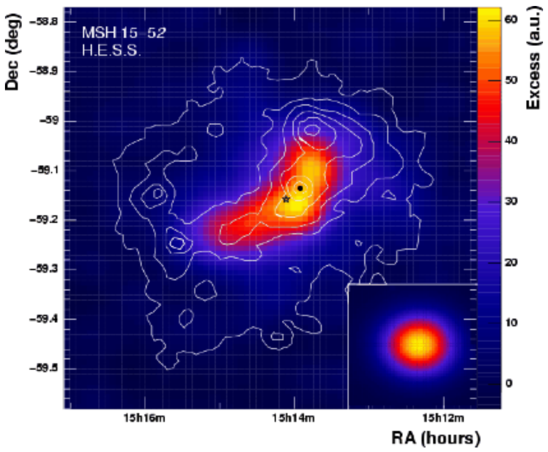
Brightest VHE gamma-ray source and the first to be discovered (Whipple, 1989)

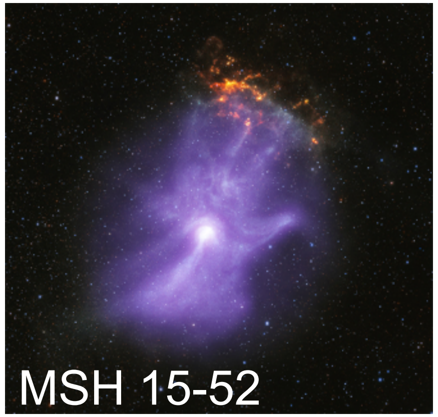
H.E.S.S. resolved the size of the TeV emission — Nature Astronomy **4**, p.167–173 (2020)

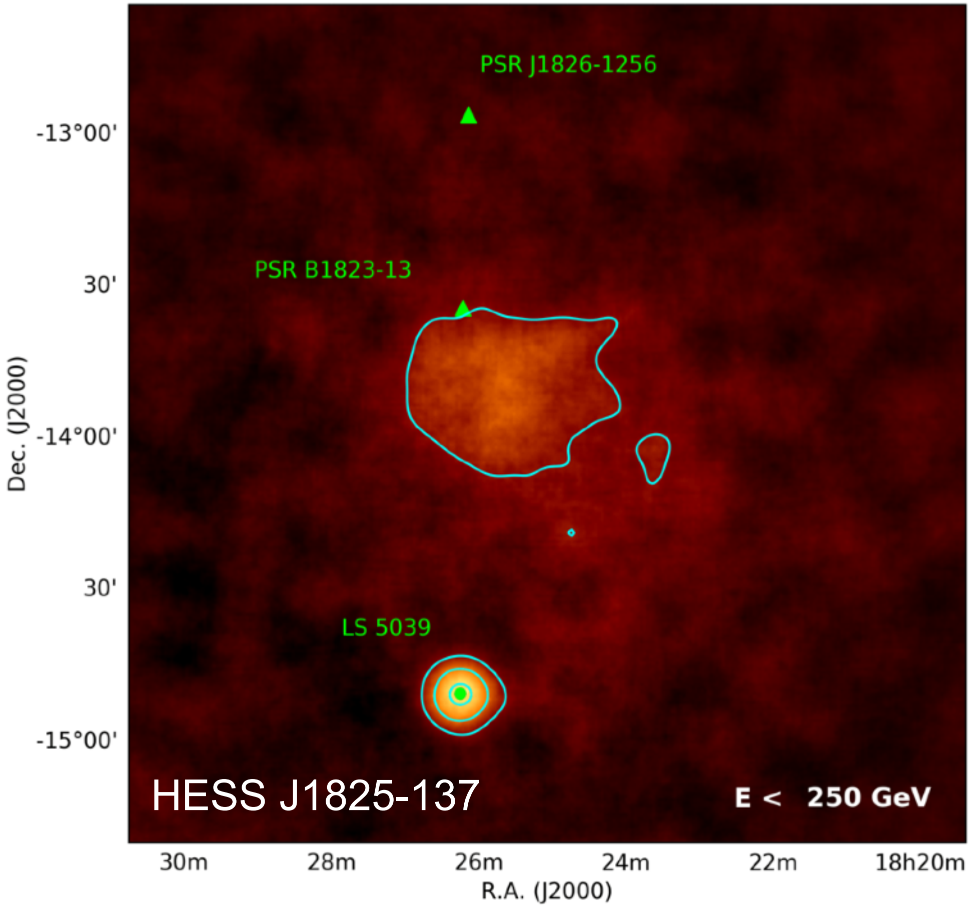
MAGIC detected TeV pulsed emission from the pulsar

Pulsar Wind Nebulae

Electrons lose energy with distance from the pulsar

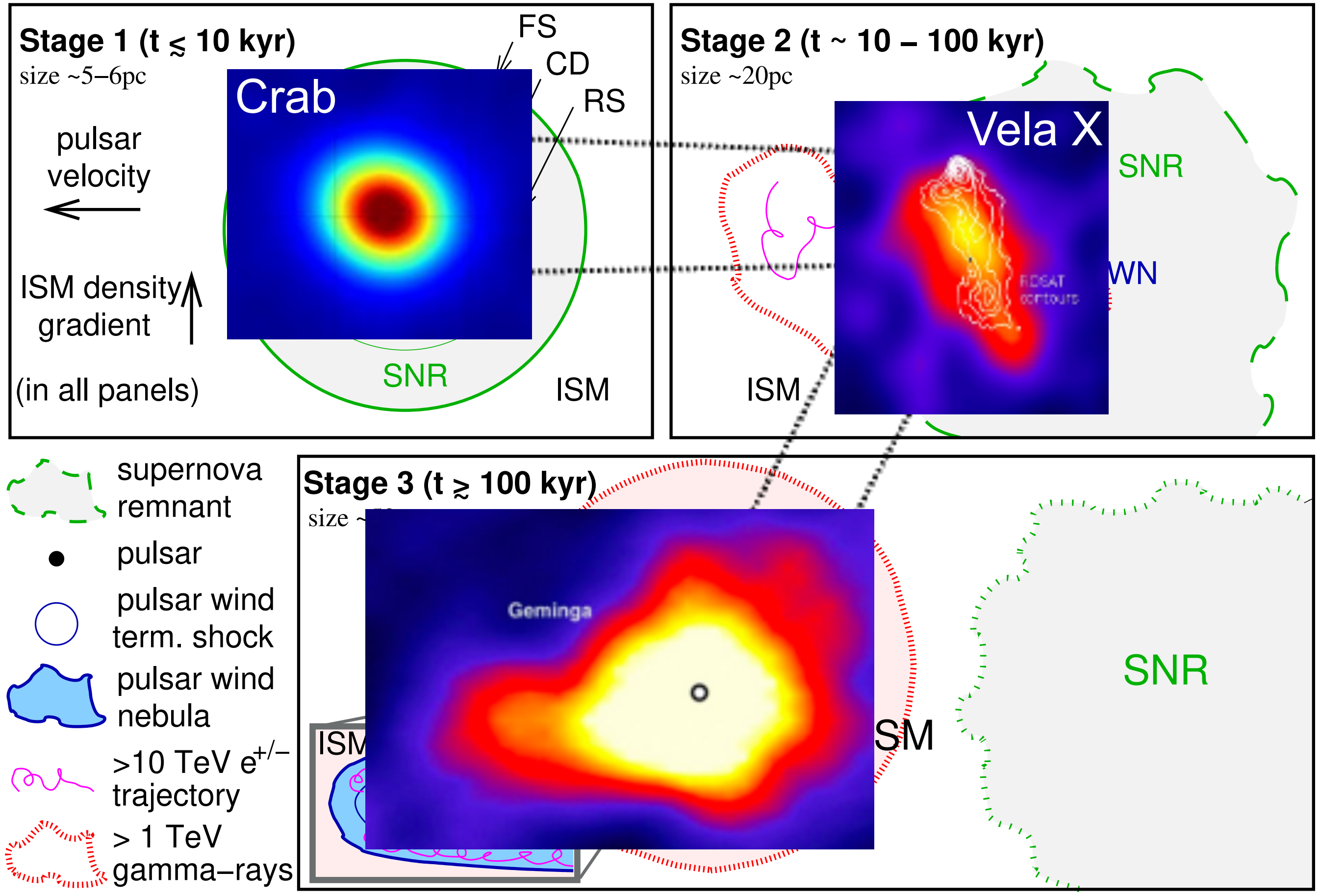




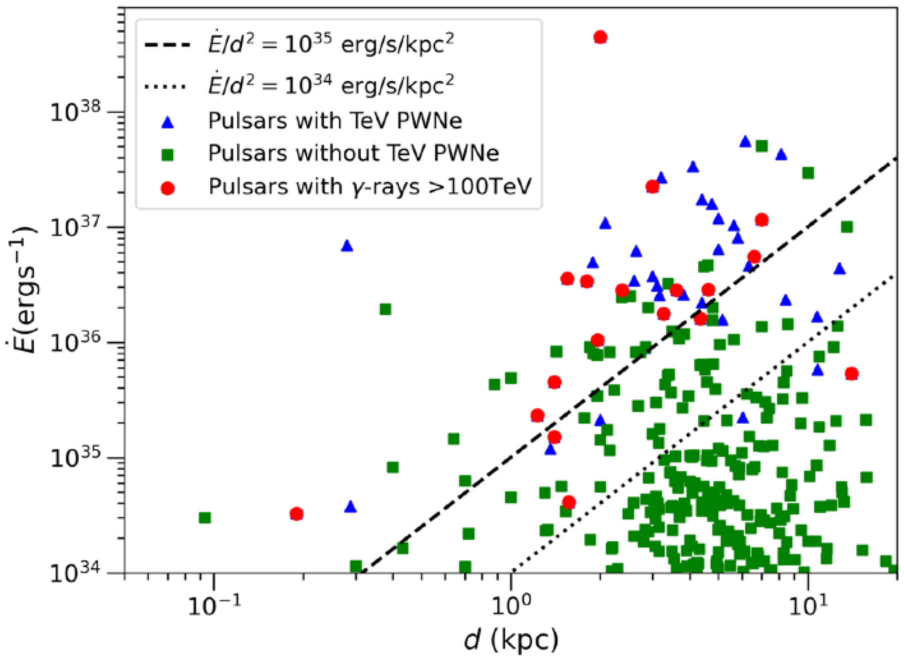


H.E.S.S. collaboration A&A **621**, A116 (2019)

Pulsar Wind Nebulae



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



AM & Gelfand, Springer (2022)

Novae

Thermonuclear outbursts from WD + companion accreting binaries

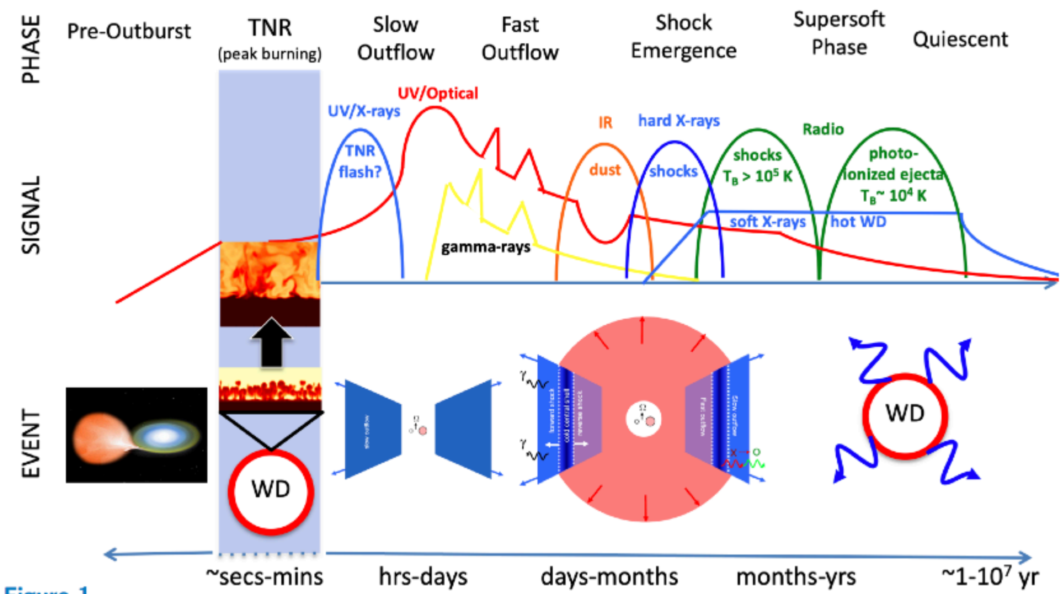
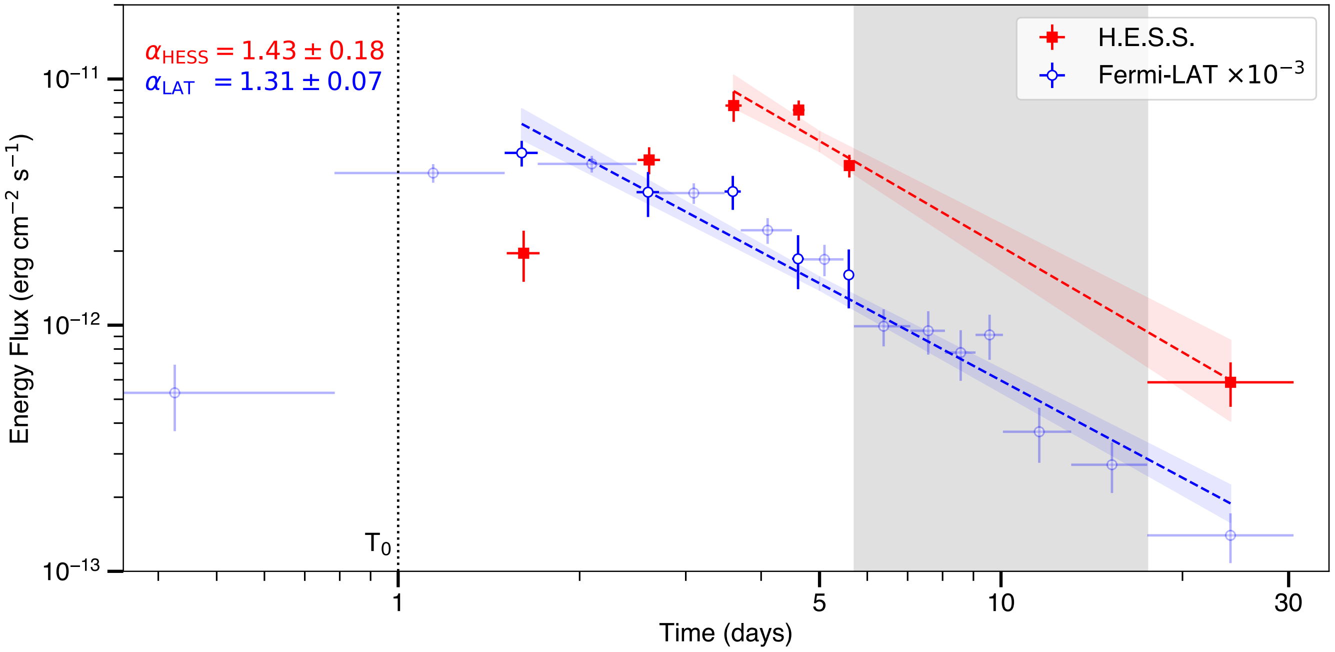


Figure 1

Schematic timeline of the physical processes and electromagnetic signals from novae. The figure includes modified images of convection/mixing during the thermonuclear runaway from Casanova et al. (2016, reproduced with permission ©ESO) and internal shocks from Metzger et al. (2015).



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

VHE (TeV) gamma-ray emission was detected from a nova for the first time in 2021: RS Ophiuchi

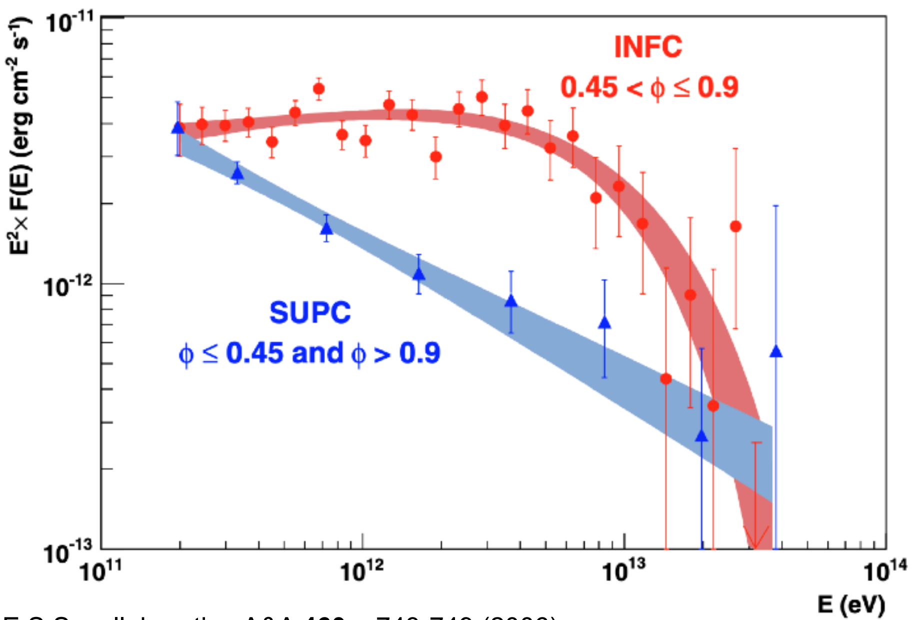
The next highly anticipated outburst is from the recurrent nova T Coronae Borealis —> due imminently

Microquasars

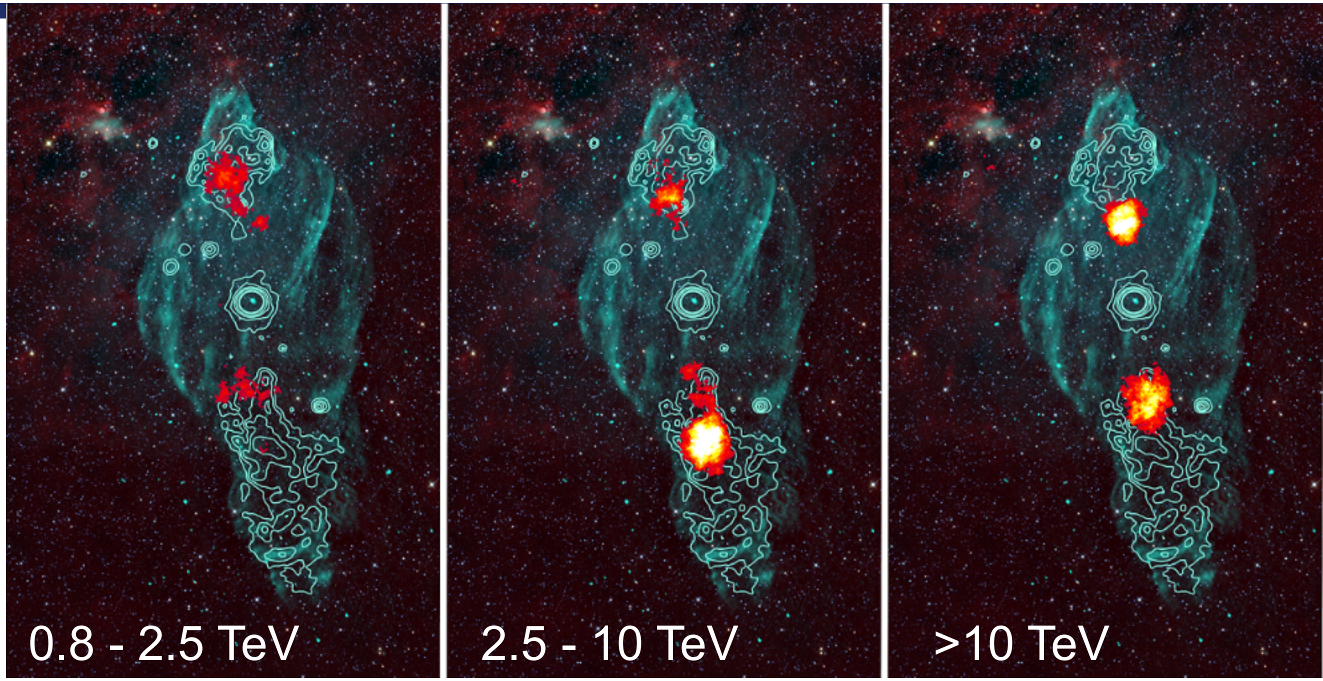
Binary systems with a stellar mass black hole & massive star producing jets

e.g. SS 433 / W50 “manatee” nebula —>

e.g. LS 5039 binary with 3.9 day orbital period

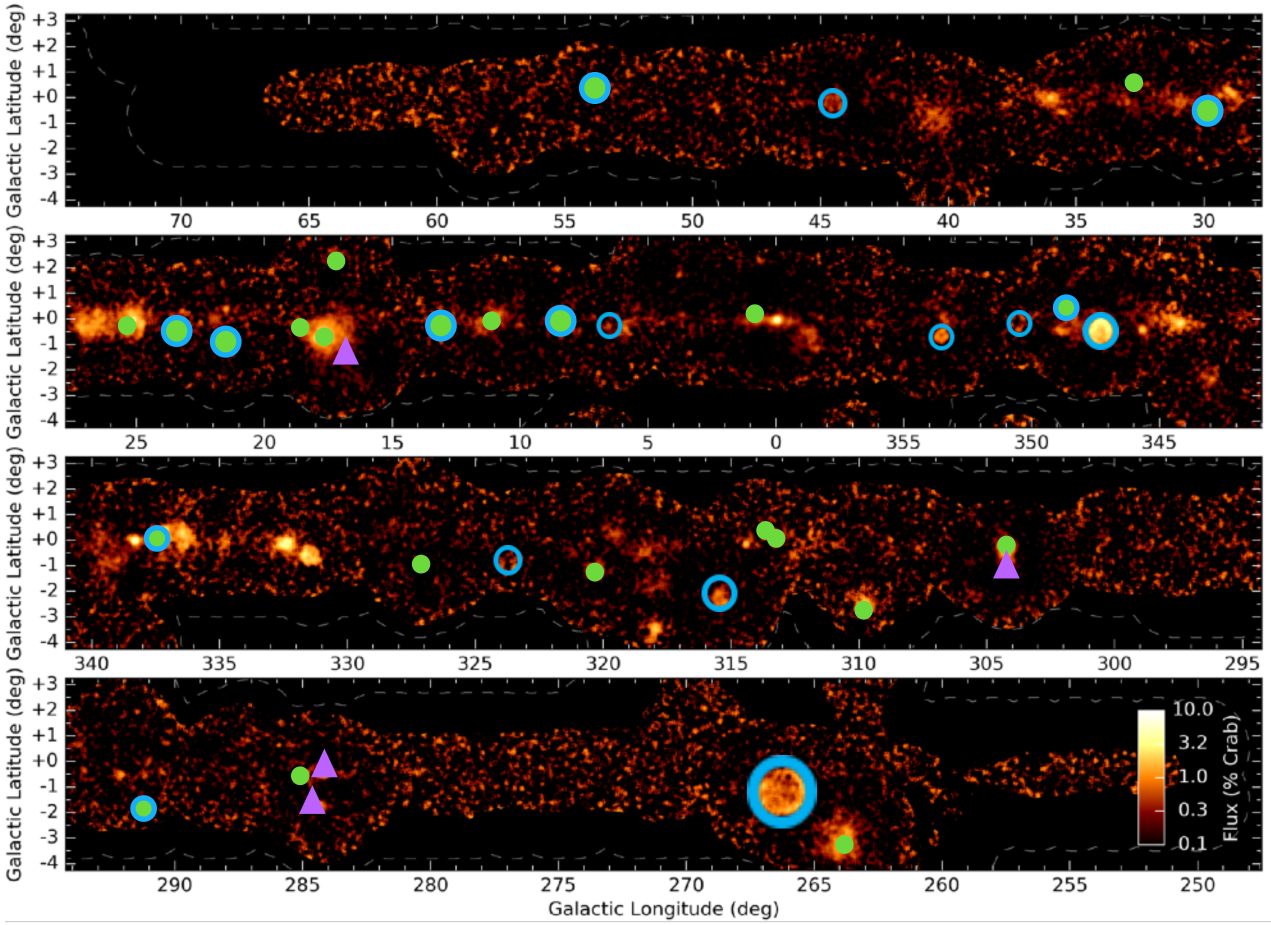


H.E.S.S. collaboration A&A **460** p.743-749 (2006)



H.E.S.S. collaboration Science **383** p.402-406 (2024)

Very-High-Energy Gamma-ray Sky

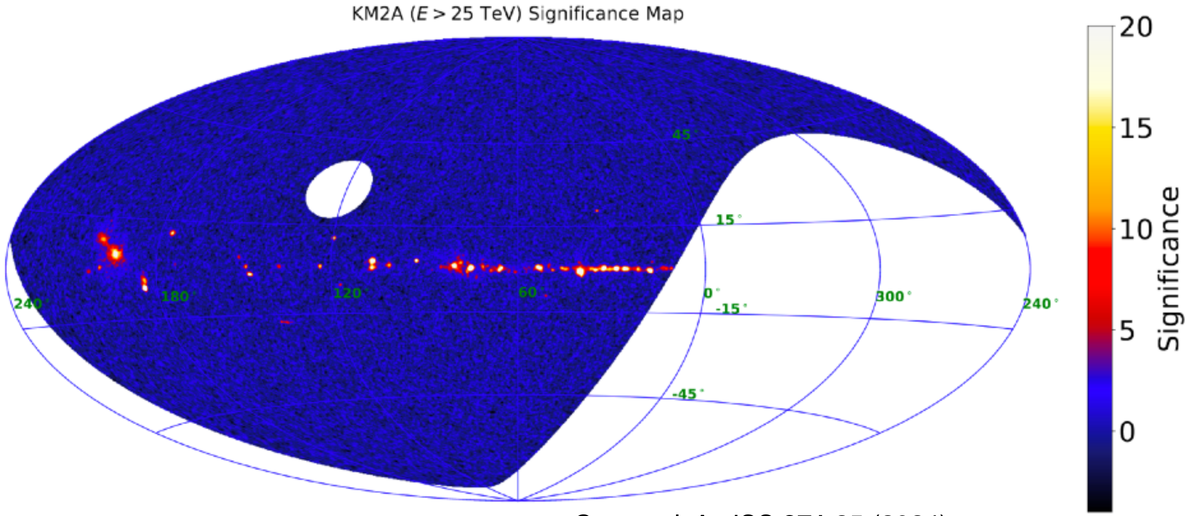


H.E.S.S. A&A **612** A1 (2018)

H.E.S.S. Galactic plane survey : 78 sources

2700 hours of observations from 2004-2013

LHAASO (particle detector array) in 2024 :
43 “ultra-high-energy” sources > 100 TeV
Highest energy photons ever ~2.5 PeV from Cygnus region



Cao et al. ApJSS **271** 25 (2024)

Galactic Centre Region

Central Molecular Zone —> Galactic Centre Ridge

HESS J1745-290 is a point-like source consistent with Sgr A*

—> formally unidentified as the emission mechanism remains unknown

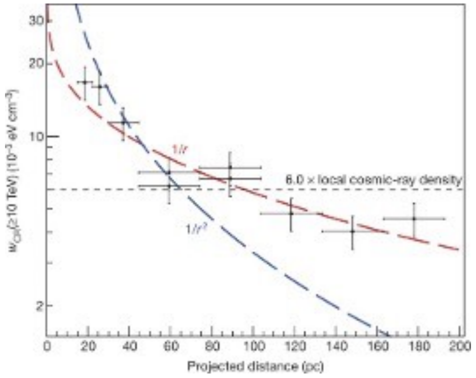
G0.9+0.1 is a compact pulsar wind nebula

Two bright point-like sources - contributions removed via modelling

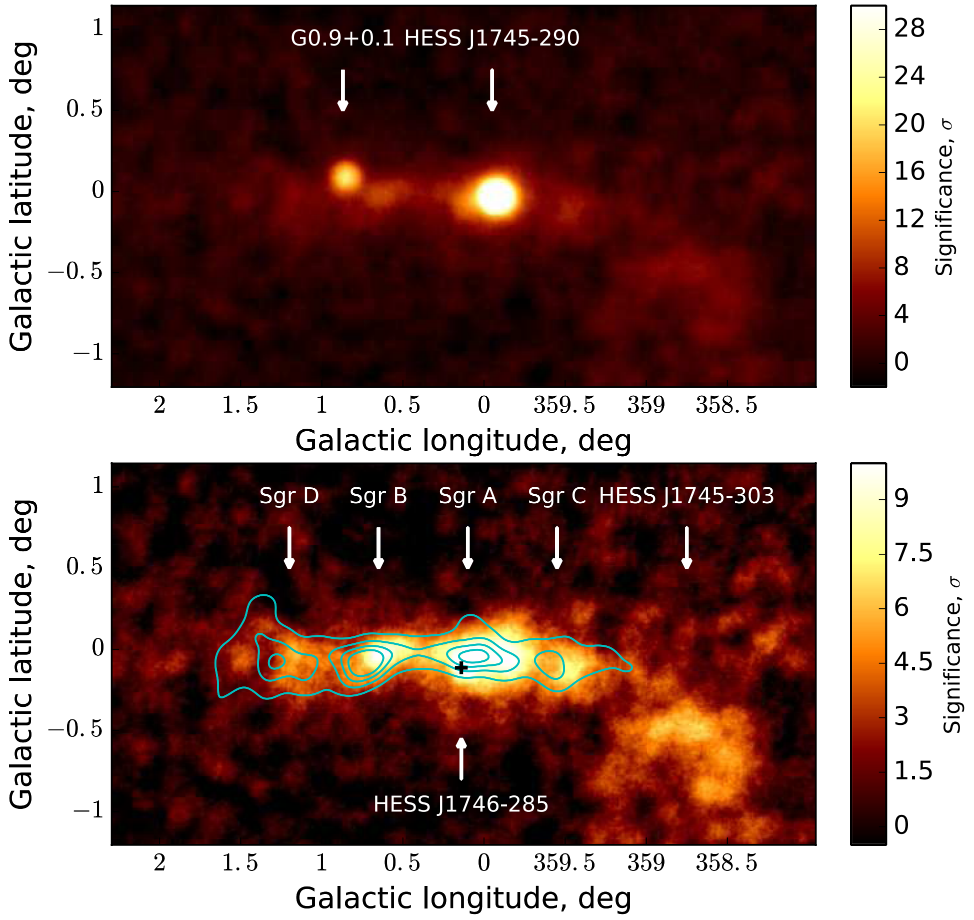
A bright ridge of emission remains, consistent with CO gas contours

—> Evidence for diffuse emission in the central 200 pc of our Galaxy

—> Cosmic Ray energy density profile implies a continuous accelerator



H.E.S.S. Collaboration, Nature **531** (2016) 476-479



HESS collaboration A&A **612**, A9 (2018

IACTs —> Optical Telescopes

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Satellite trails caught in the data

IAU : Dark and Quiet Skies; UN COPUOS (Committee on the peaceful use of outer space)

Satellite constellations are being launched in large numbers

Many of these - e.g. starlink - are (were) optically bright

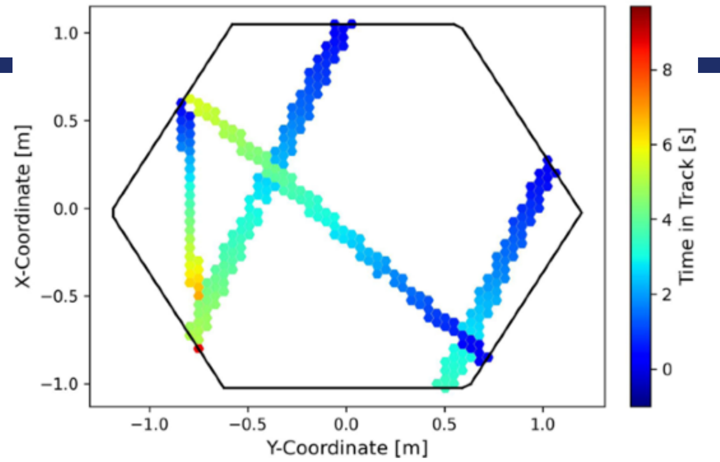
We investigated their impact on the H.E.S.S. telescopes

Fast-imaging optical telescopes

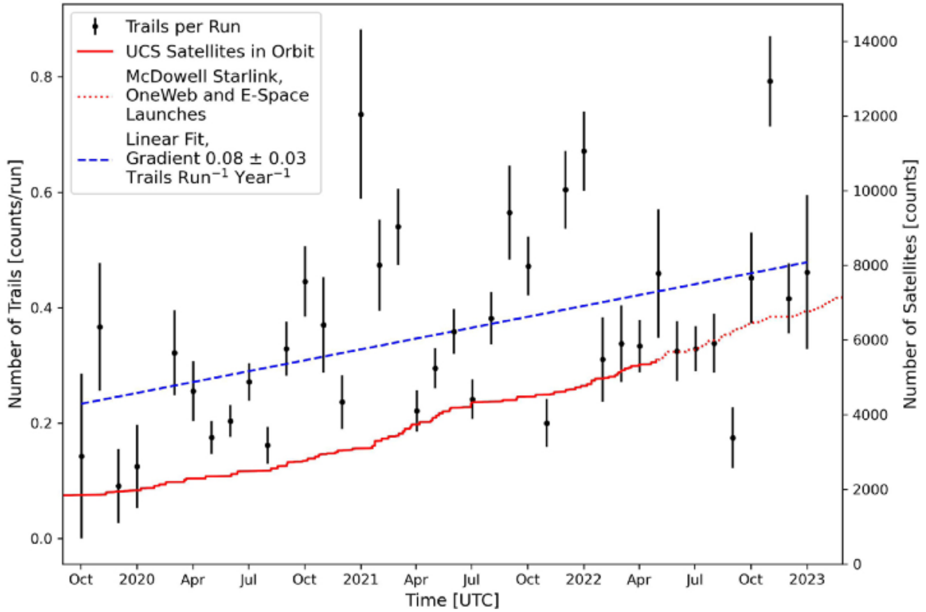
—> Small influence that can be removed from data, but measurable nonetheless

—> Rate of trails is increasing consistent with numbers launched

—> More trails at start and end of the night, and at higher zenith angle.



Lang, Spencer, AM A&A **677** A141 (2023)



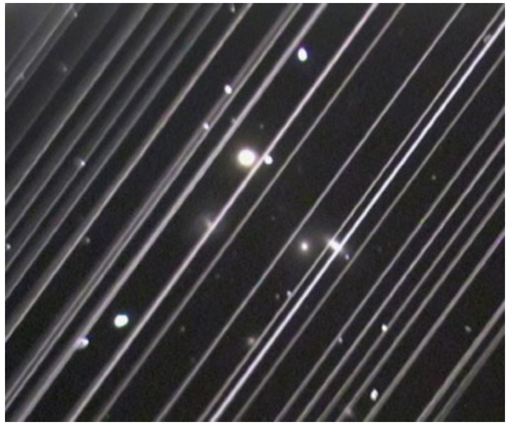
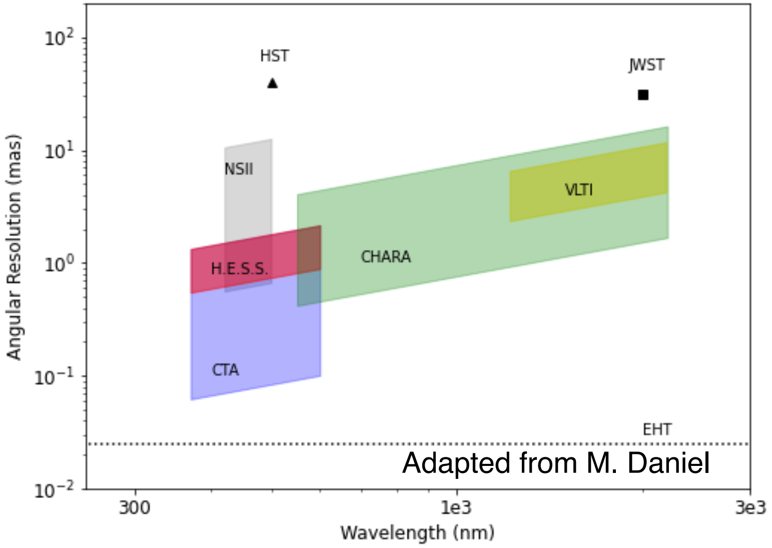


Image Credit: Victoria Girgis/Lowell Observatory

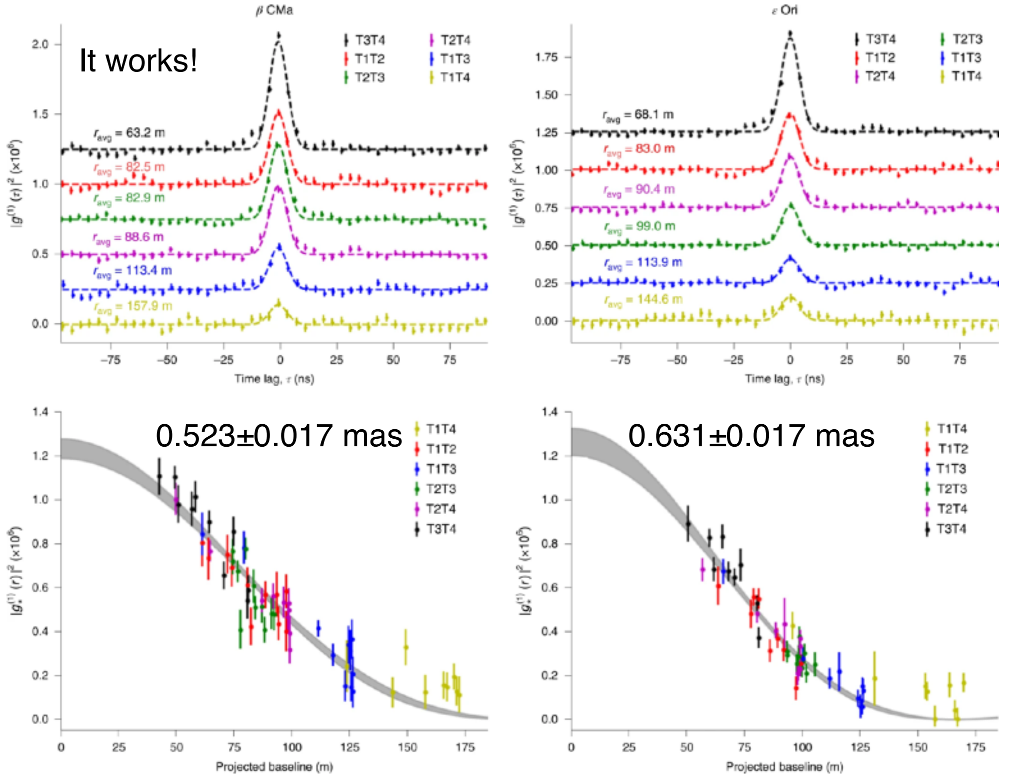
Intensity interferometry with IACTs

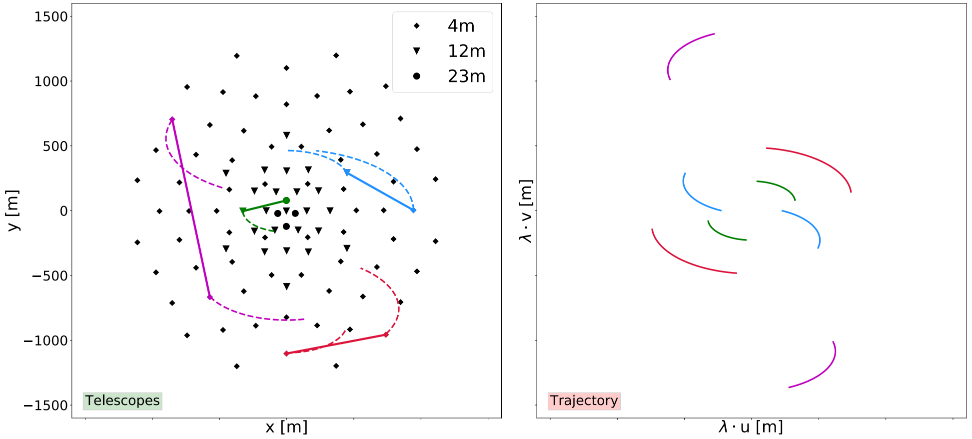


Optical telescopes in arrays separated by O(100m)
—> resolution $\sim \lambda_{\text{min}}/B_{\text{max}}$ at mas level possible at optical wavelengths

From quantum optics: chaotic light sources (e.g. thermal) will have temporally correlated photons.

Can optimise for High Photon Rates or High Time Resolution





Baumgartner et.al. MNRAS **498** (2020) 4577-4589

VERITAS, Nature Astronomy, **4**, 1164–1169 (2020)

CTAO: Cherenkov Telescope Array Observatory

Observatory

- More than 1400 scientists
- More than 200 institutes
- 31 countries

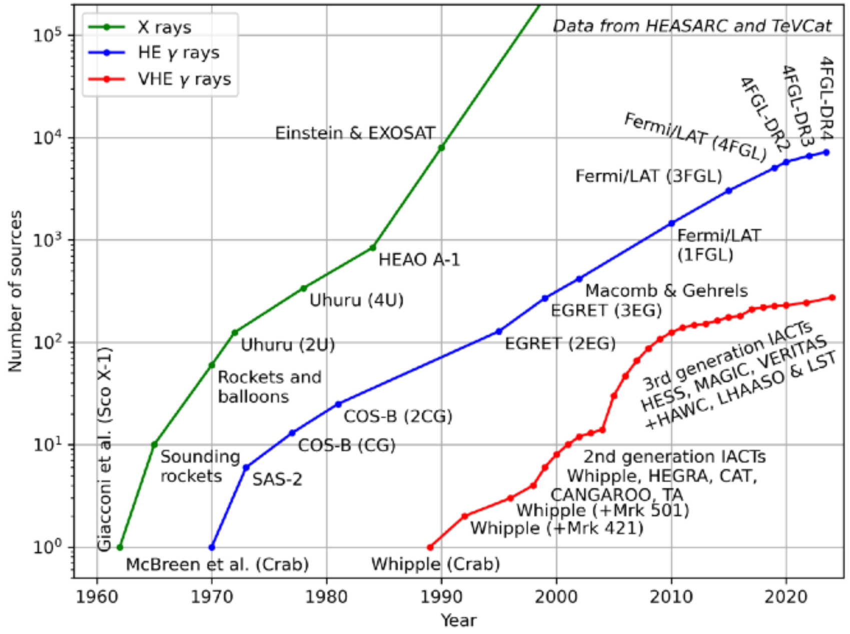
Locations:

- CTA-North:
  La Palma (Spain)
- CTA-South:
  ESO-Paranal (Chile)

Outlook to the future

Radio - Gamma-ray Synergies

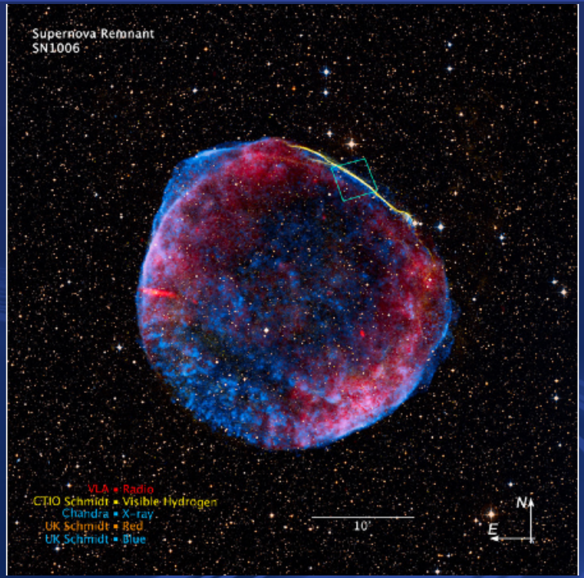
- Origins of Cosmic Rays
- Understanding particle acceleration processes
  —> shocks, jets, particle transport…
- Transient phenomena
- High resolution astronomy: u-v plane
- Unidentified & extended gamma-ray sources —> radio counterparts?
- Supernova Remnants, Pulsar Wind Nebulae, Molecular Clouds…

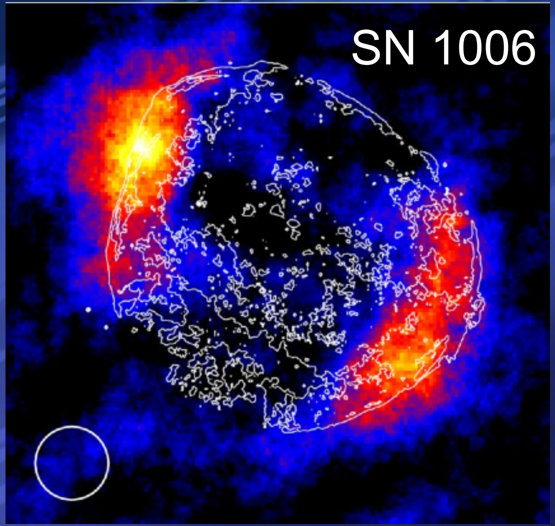


- Things I didn't mention: AGNs, GRBs, FRBs, CWBs, diffuse emission, galaxy clusters, DM searches, H0 measurements, LIV & beyond SM physics…
- Joint MWL observations —> further insights
- Major forthcoming facilities: SKAO + CTAO

Friedrich-Alexander-Universität
Erlangen-Nürnberg

Thank you for your attention
Any questions?





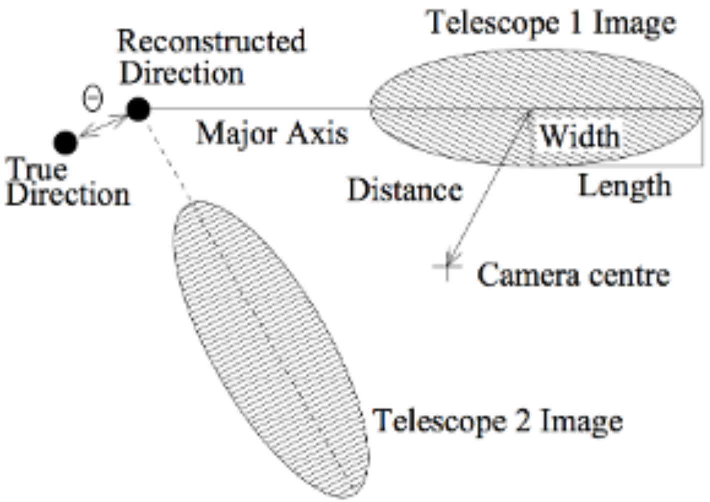
alison.mw.mitchell@fau.de

Imaging Atmospheric Cherenkov Telescopes

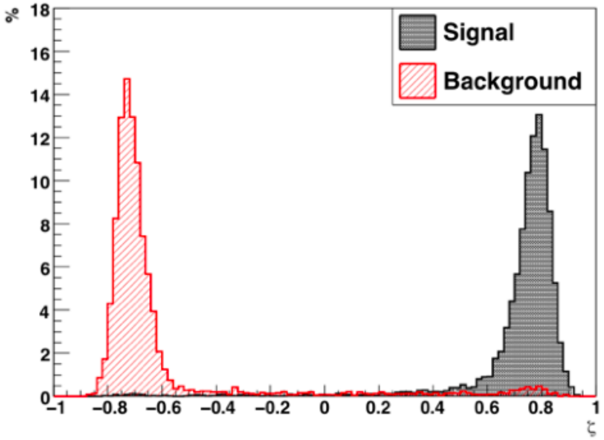
Combining images from multiple telescopes improves direction reconstruction —> better resolution

Image brightness corresponds to amount of Cherenkov light & the energy of the initial particle

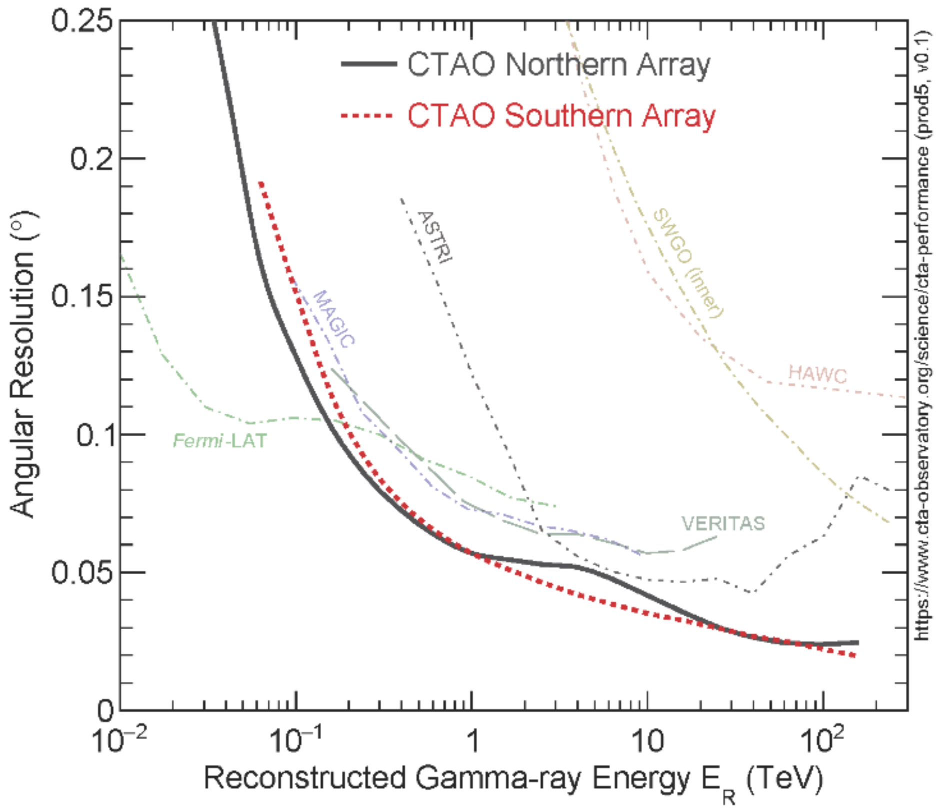
Parameterising images and using e.g. a BDT provides excellent discrimination of signal from background



H.E.S.S. collaboration A&A **457**, 899-915 (2006)



Ohm et al. Astropart. Phys. **31**, 383-391 (2009)



Cosmic Ray Spectrum

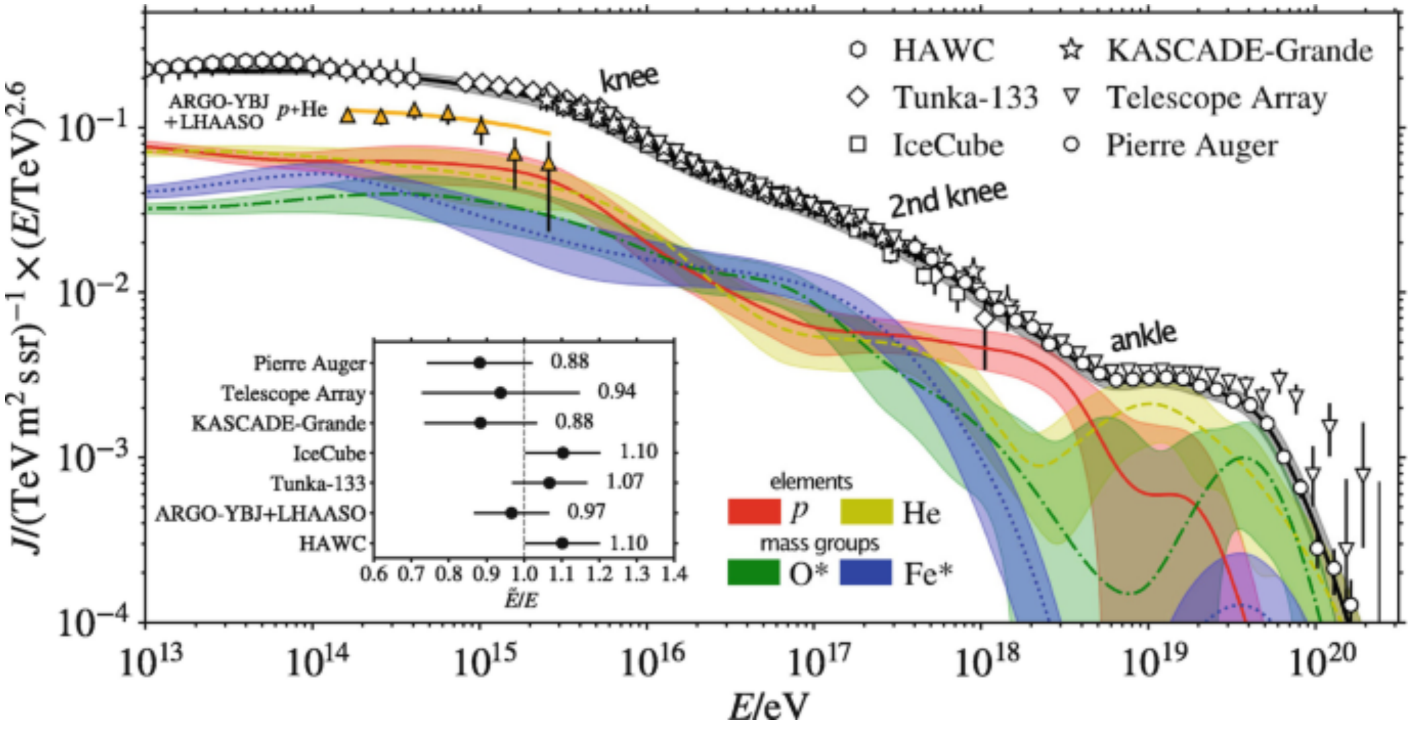
In reality, much more complex spectrum

Global spline fit to composition —>

Cosmic Ray sources should produce a hadronic (pion-decay) emission signature

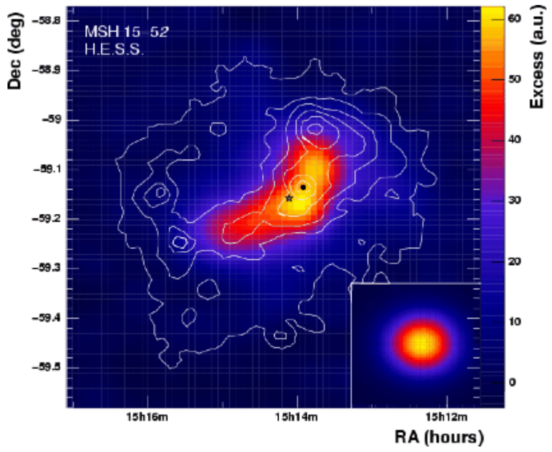
Cosmic Ray electron spectrum —>

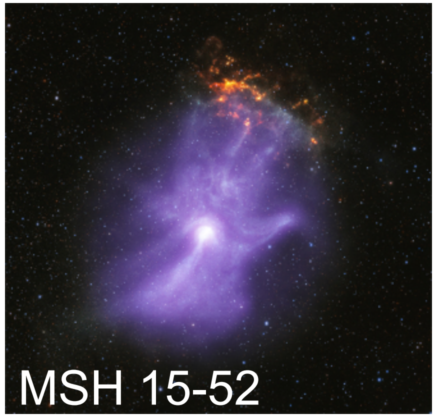
Need nearby leptonic accelerator

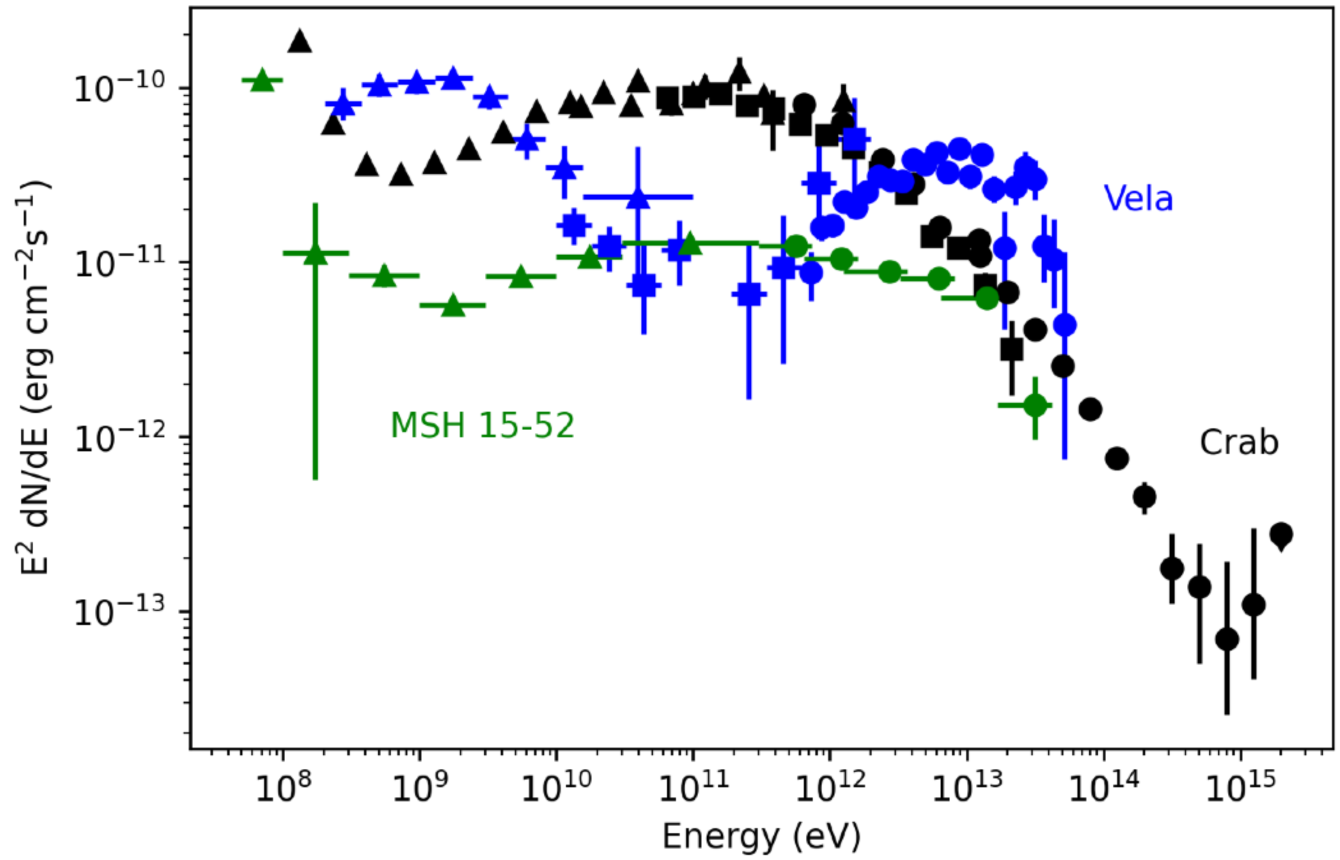


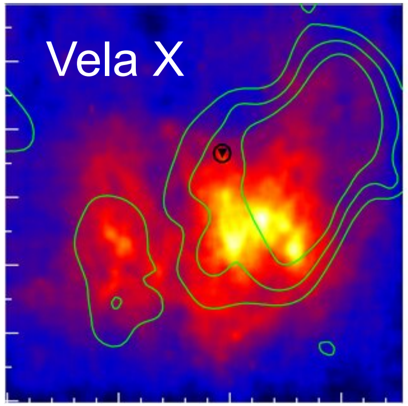
Engel & Schmidt, Springer (2021)

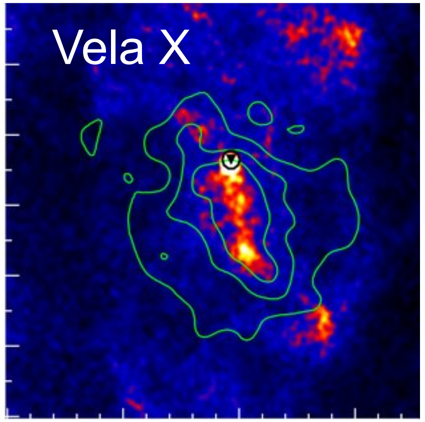
Pulsar Wind Nebulae











AM & Gelfand, Springer (2022)