Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Updates from Gamma-Rays

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FAU Erlangen-Nürnberg

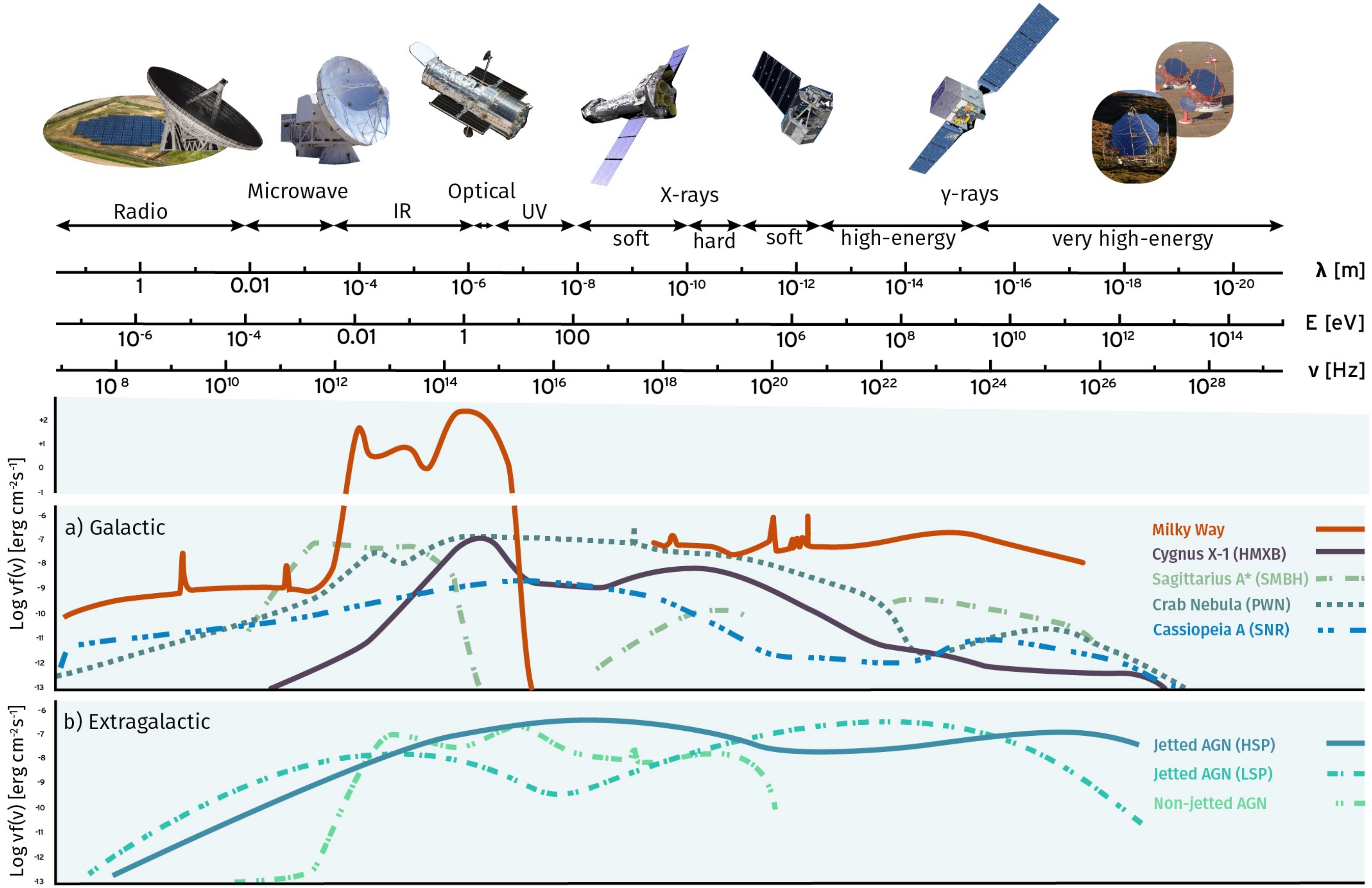
Synergies in nonthermal astrophysics in Southern Africa
29/07/24

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

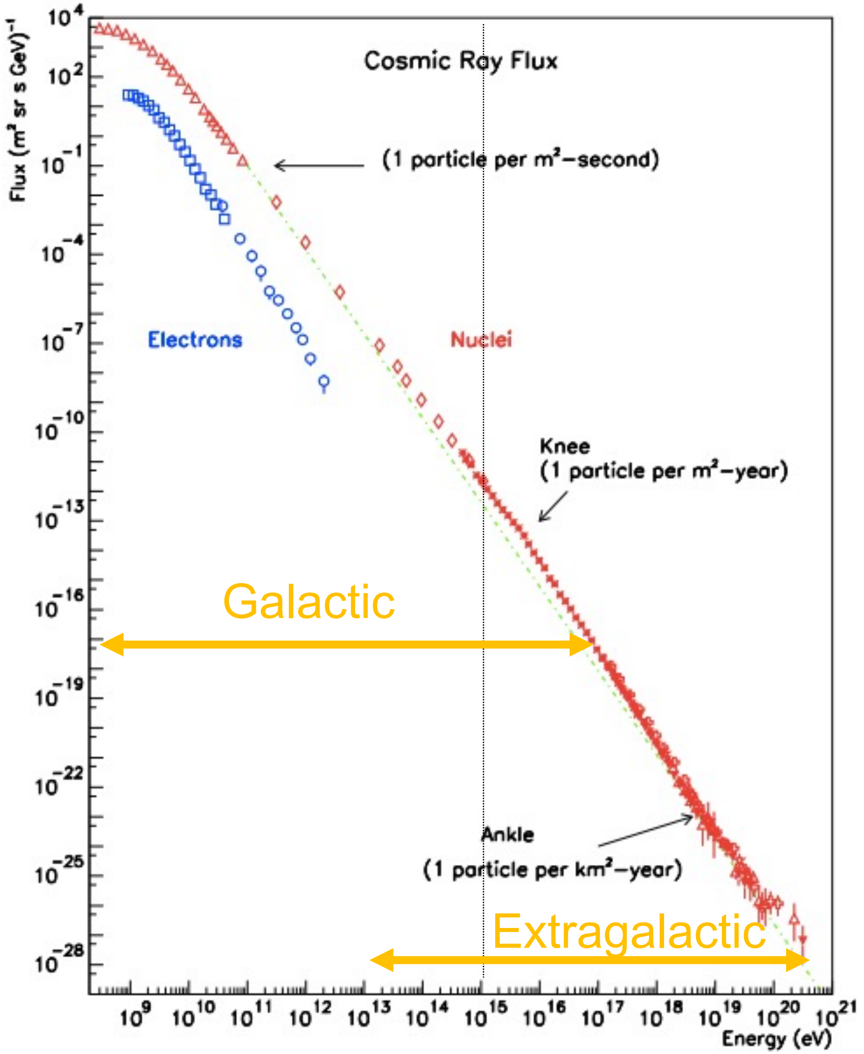
Gamma-ray Astronomy

Non-thermal Astrophysics



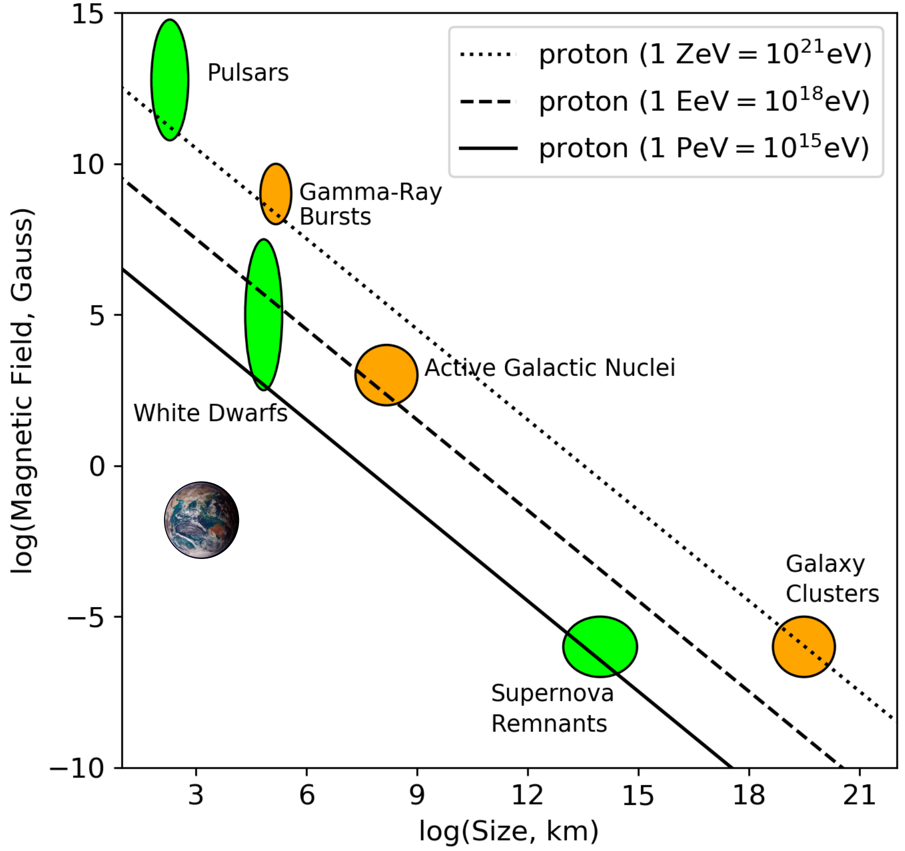
Credit: Annika Kreikenbohm, JMU Würzburg

The origin of Cosmic Rays?



– Cosmic Rays – highest energy particles in nature, up to 10^{20} eV

– "PeVatrons" = accelerators of particles to energies ≥ 10^{15} eV



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

Supernova Remnants

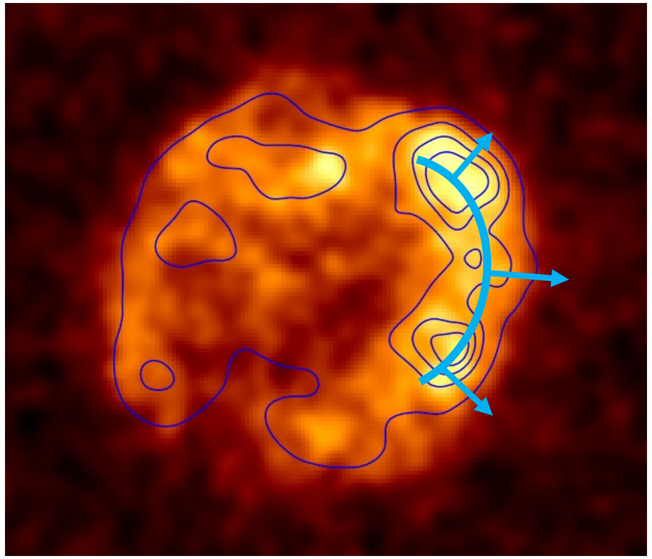
– Acceleration at shock fronts of SNRs:

  – ~10^{51} erg per SN explosion

  – ~10% into proton / CR acceleration

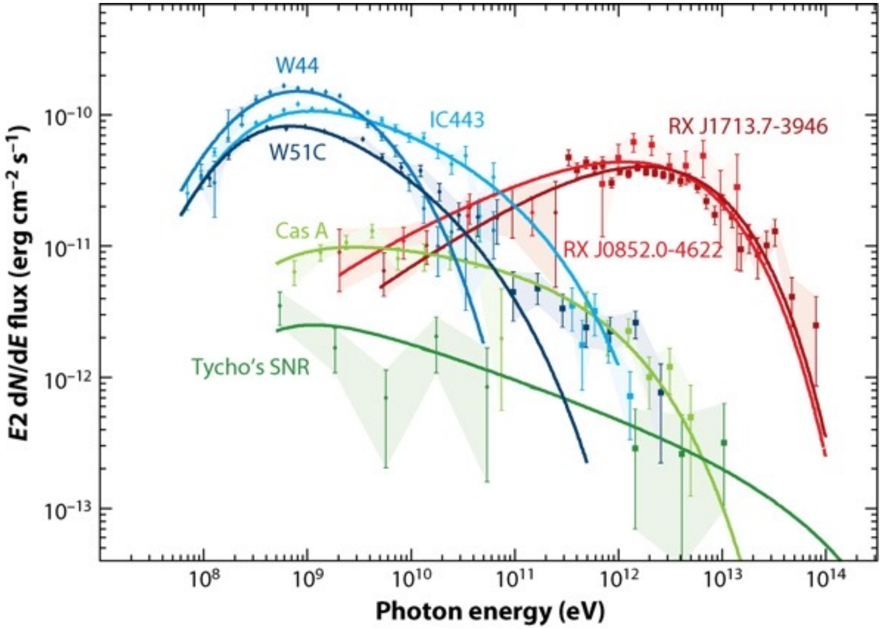
  – ~ 3 events per century in Milky Way

→ Would be sufficient to power Cosmic Rays



- Cosmic rays: deflected by magnetic fields
- Interactions produce neutral messengers: gamma-rays & neutrinos point to source
- Motivation for gamma-ray astronomy
  → high energy particles

1 erg = 10^{-7} J = 0.62 TeV

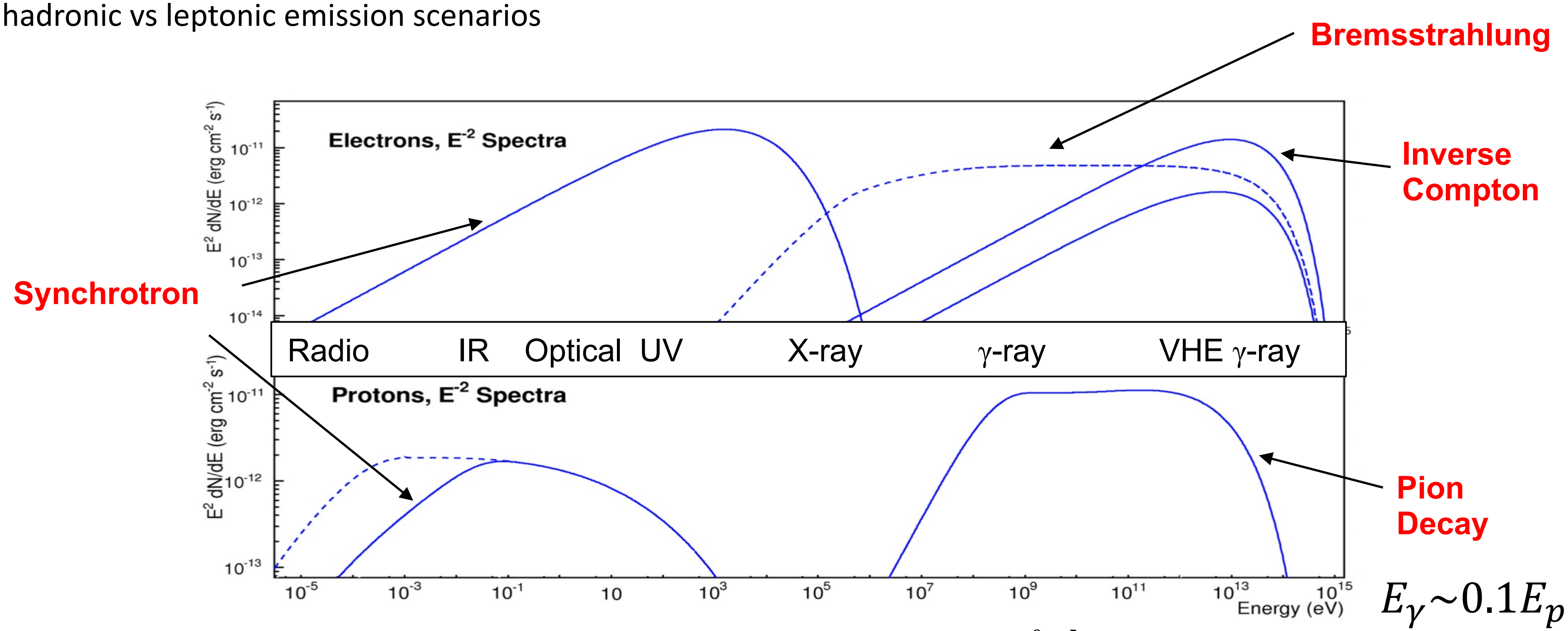


Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

Gamma-ray emission mechanisms

Searching for the origins of hadronic cosmic rays

→ Constrain hadronic vs leptonic emission scenarios



$E_\gamma \sim 0.1 E_p$

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

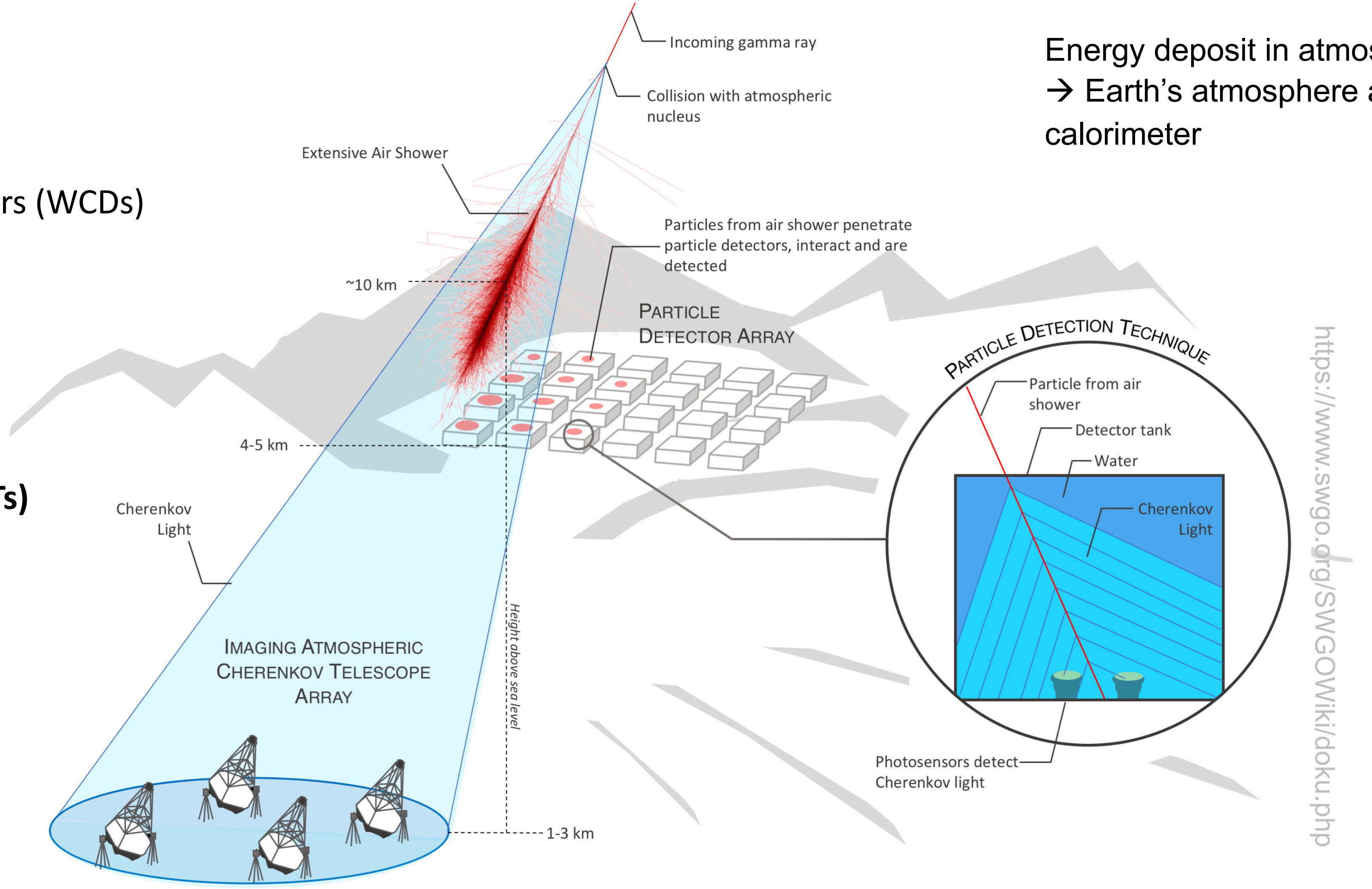
Target molecular material for hadronic interactions?

Coincident neutrinos as a smoking gun?

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 moonlight



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

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

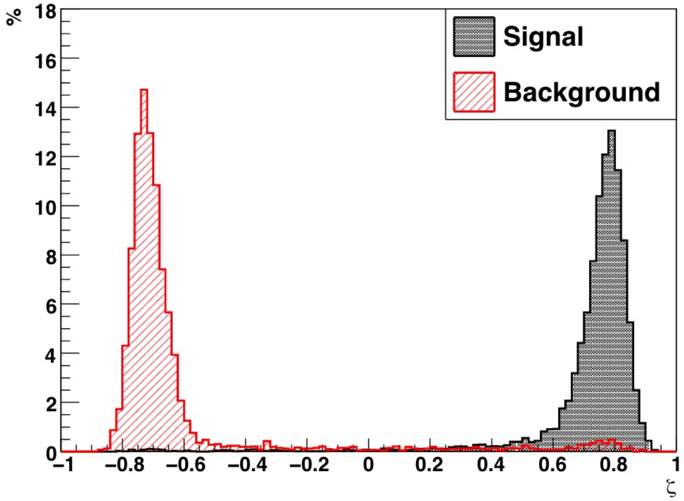
Imaging Atmospheric Cherenkov Technique

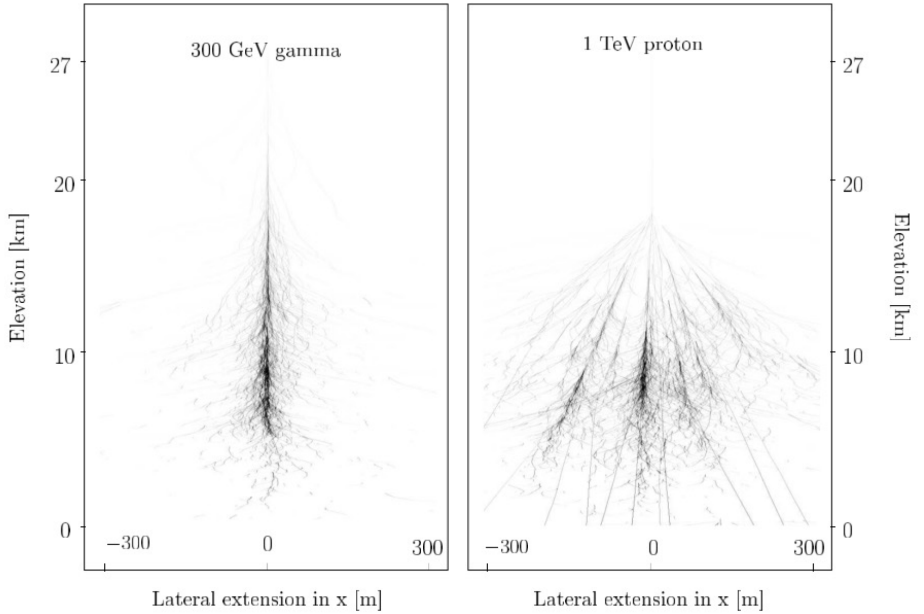
Extensive Air Shower detection

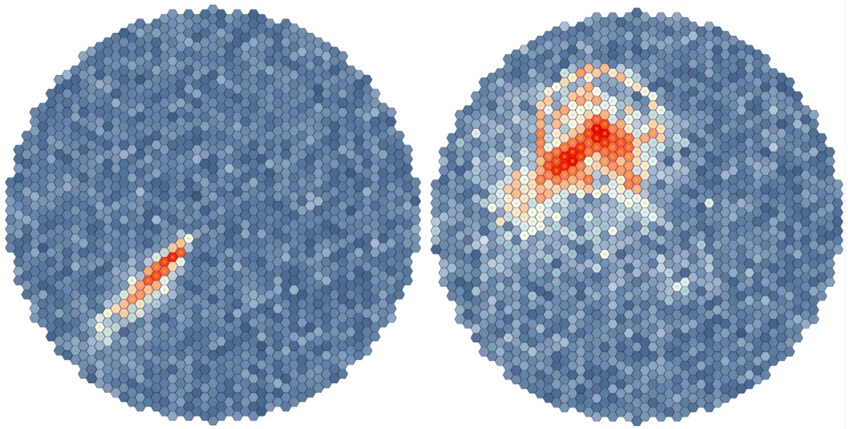
Key aspect: ability to distinguish gamma-ray initiated EAS from hadronic EAS background

Advances:
→ Hillas parameters
→ Boosted decision trees
→ Deep learning approaches, muon tagging, event classes....

Limitations:
Neural network highly sensitive to environmental conditions
(e.g. NSB, atmosphere...)
→ computationally expensive re-training?
hadronic interaction model uncertainties







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

Complementary Facilities

Complementary Facilities

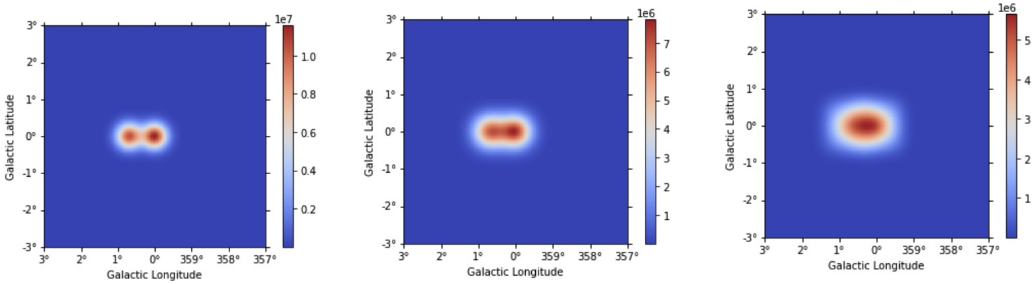
Different techniques → different performance

IACTs

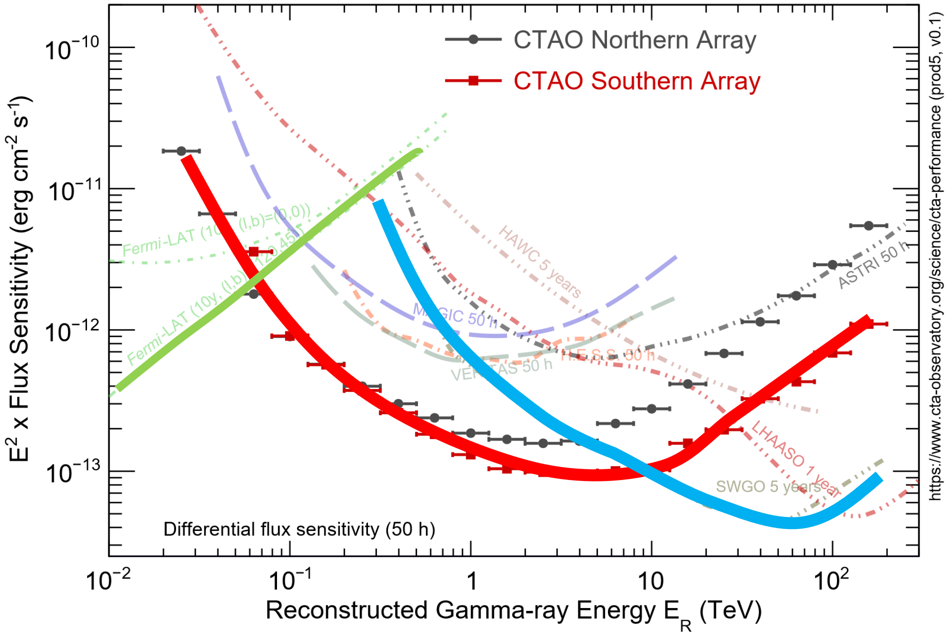
WCDs

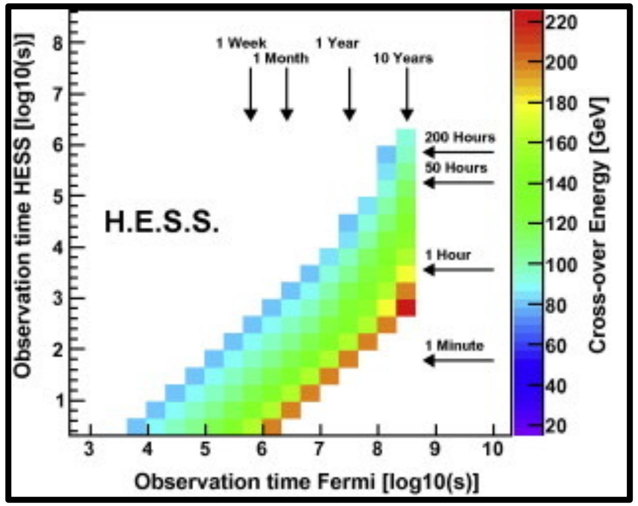
Satellite

Cross-over energy depends on exposure

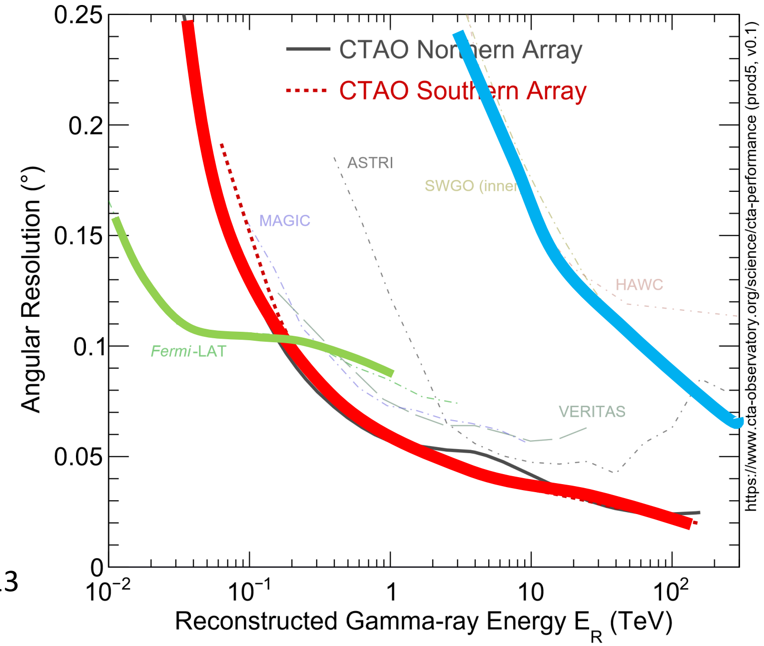


Angular resolution deteriorating



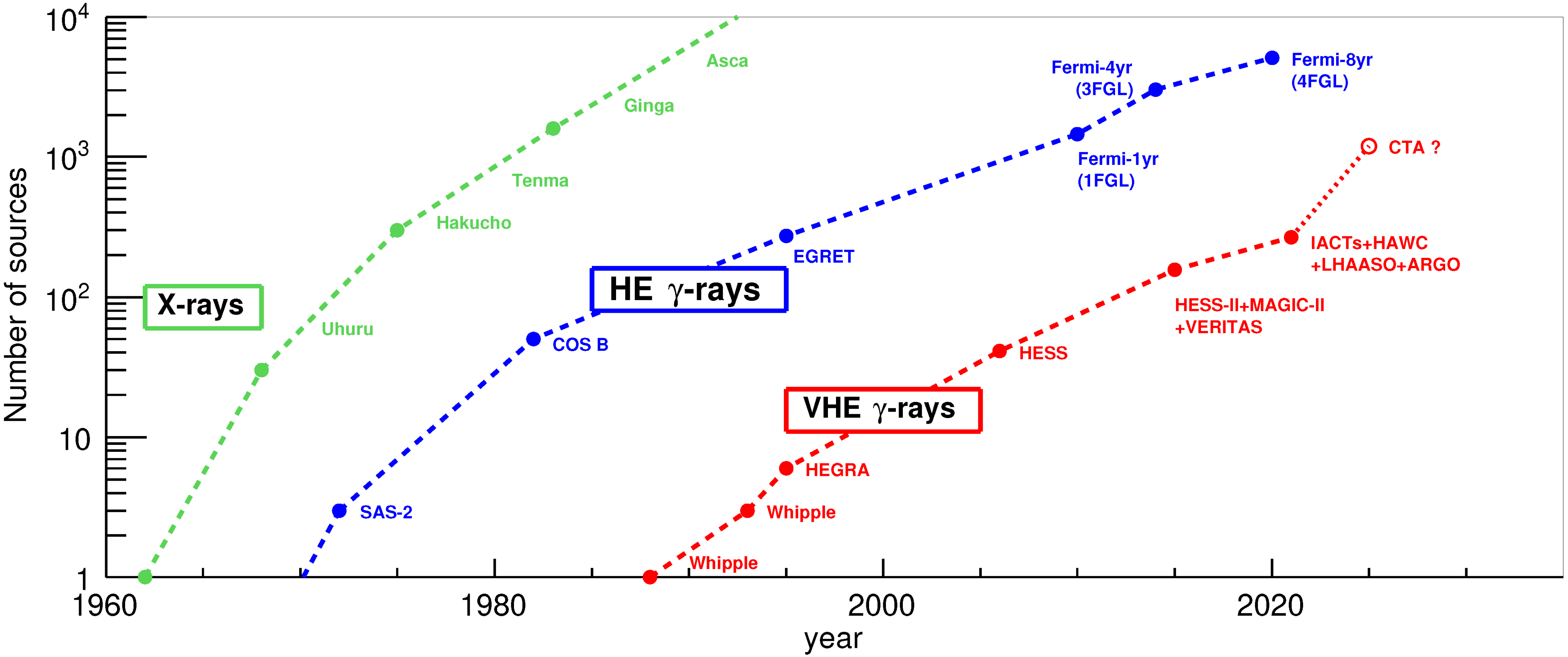


Funk & Hinton, Astropart Phys 43 (348-355), 2013



https://www.cta-observatory.org/science/ctao-performance/ , E. de Oña Wilhelmi+

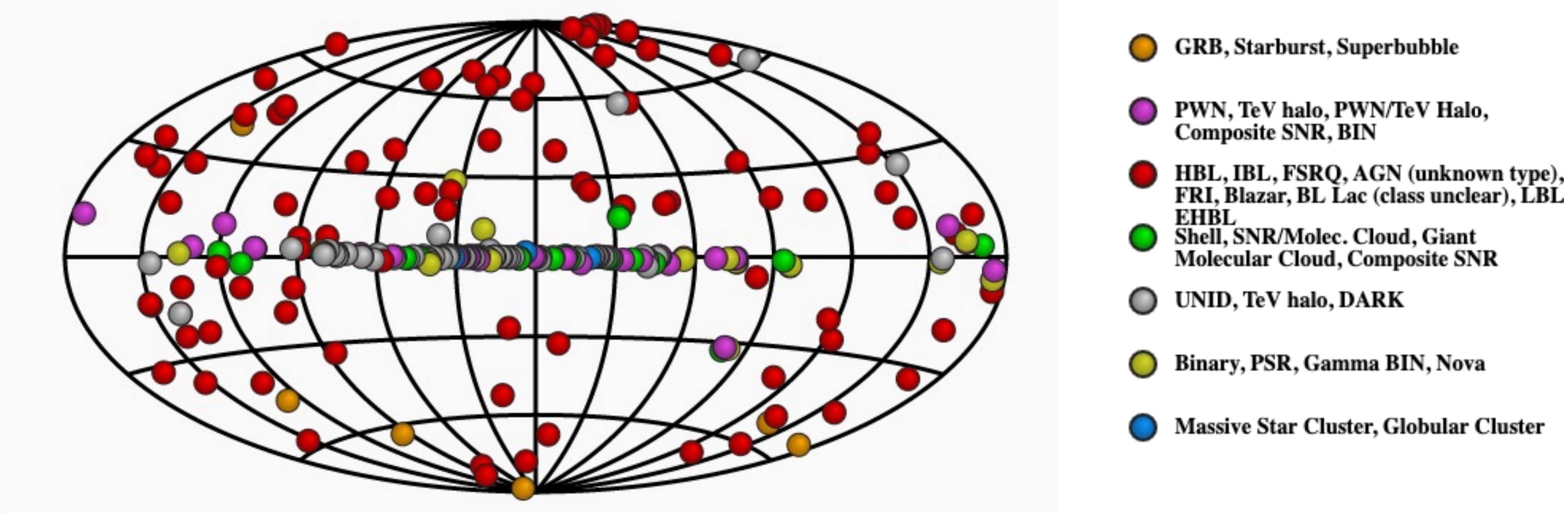
Development of VHE gamma-ray astronomy



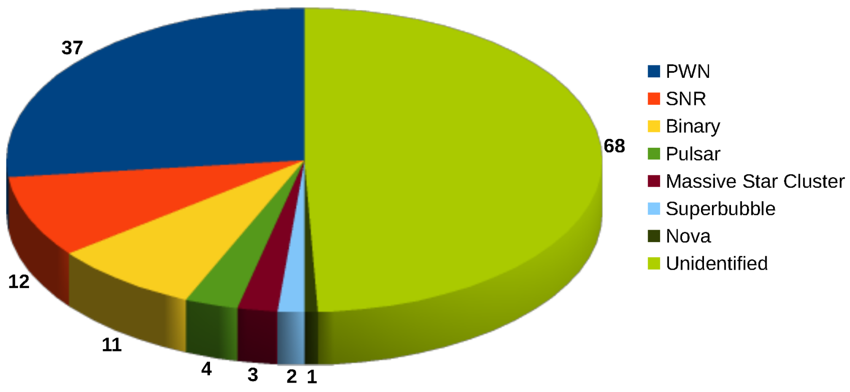
de Naurois Universe **7** (2021) 421

Very High Energy Gamma-ray Sky

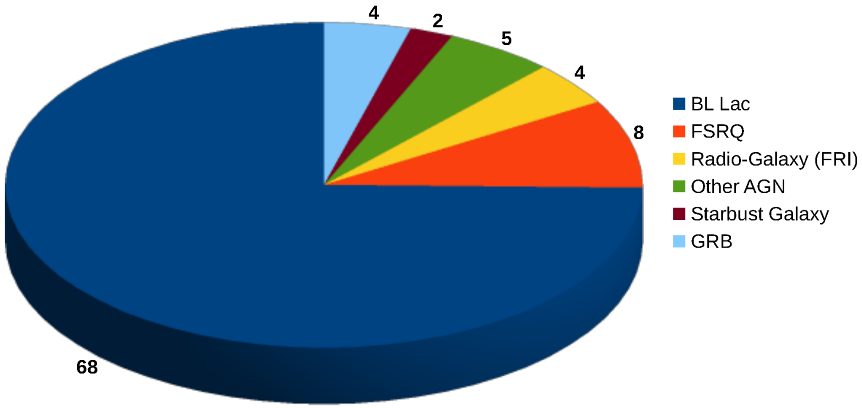
de Naurois Universe **7** (2021) 421
http://tevcat2.uchicago.edu/



Galactic Sources

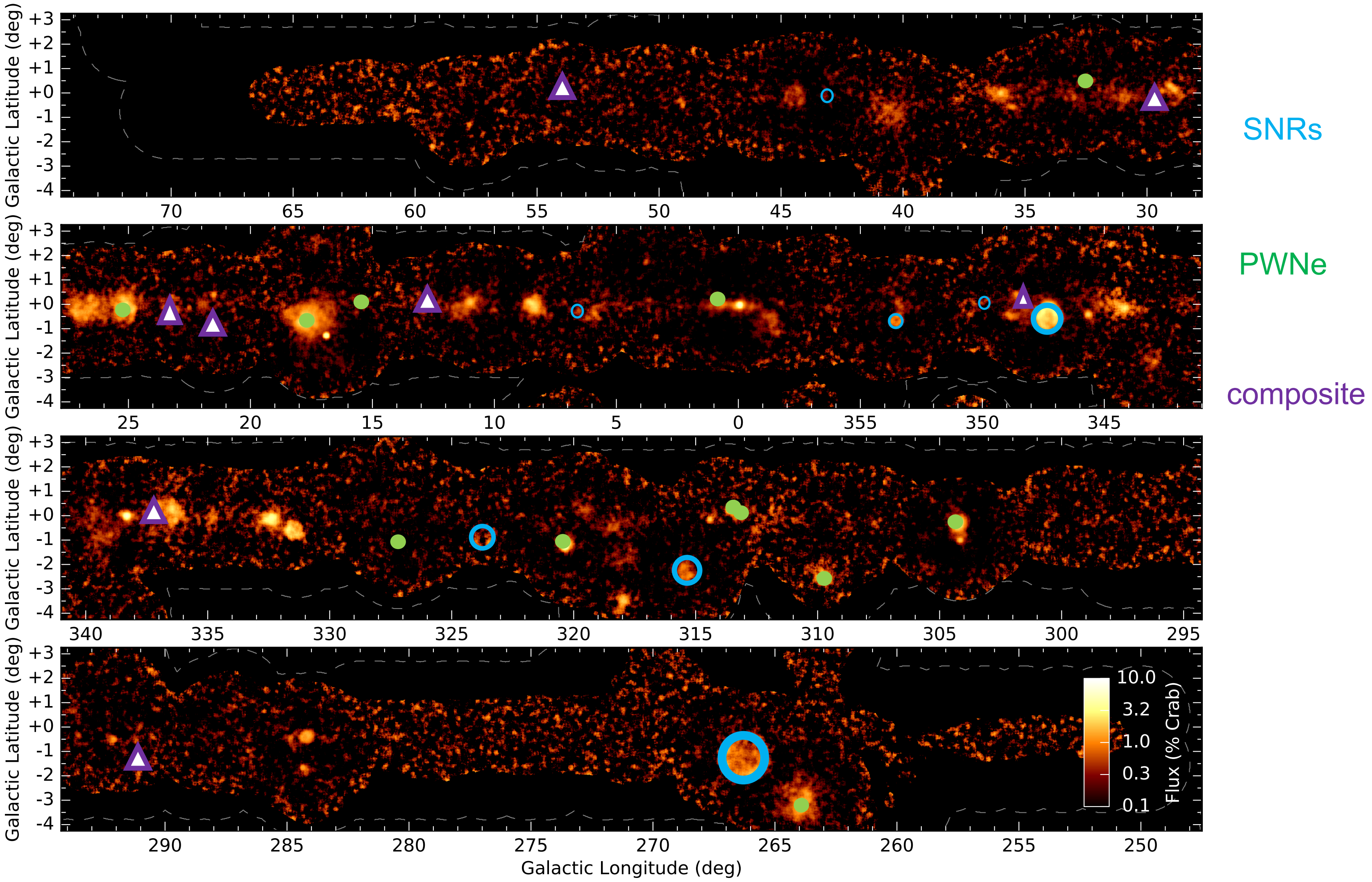


Extragalactic Sources



Very High Energy Gamma-ray Sky

H.E.S.S. Galactic Plane Survey

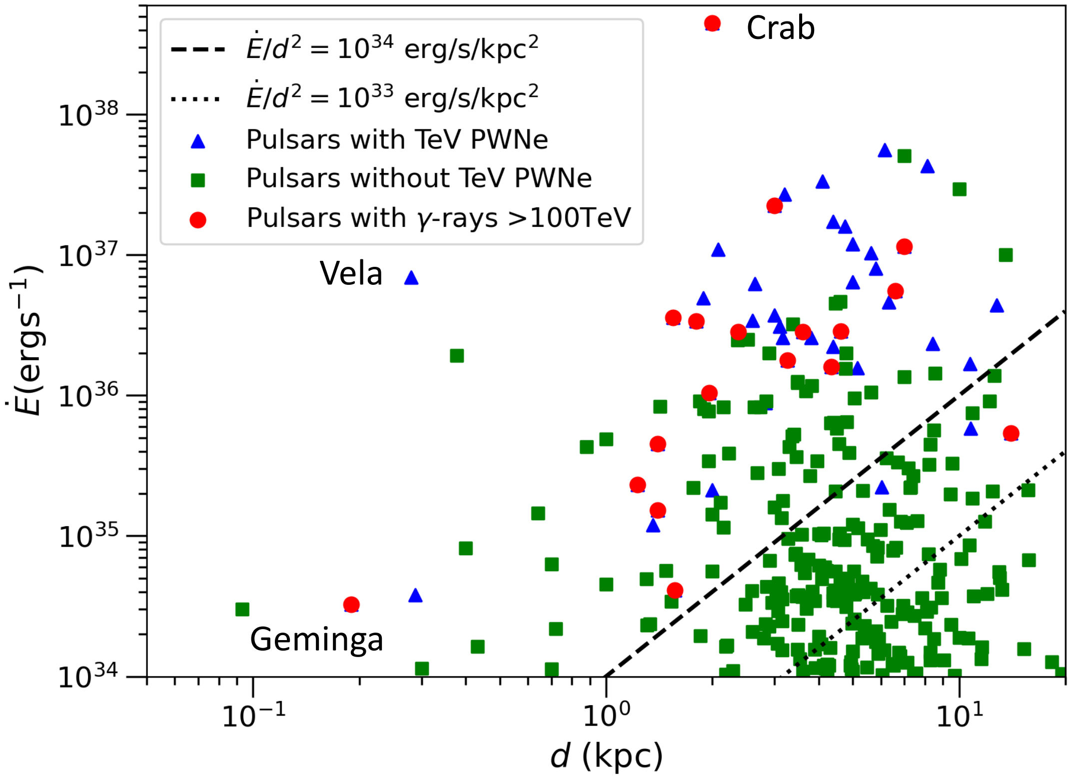


Energetic pulsar environments

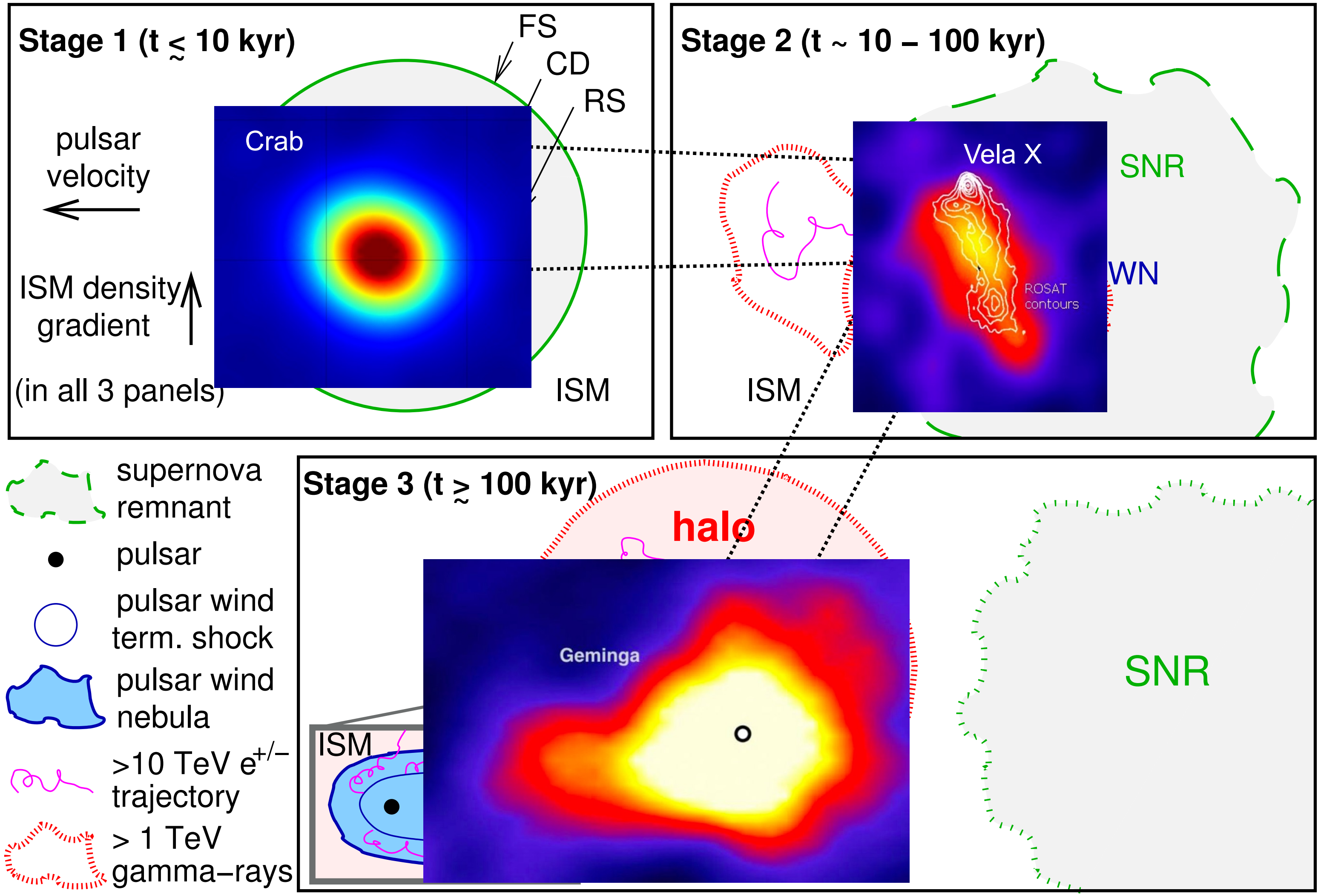
Pulsars listed in the ATNF

More energetic or closer pulsars dominate TeV detections

Some outliers – likely poor distance estimate or misattributed



Evolutionary stages of pulsar environments



Pulsar Wind Nebulae (PWN)

→ **Pulsar Halos**

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

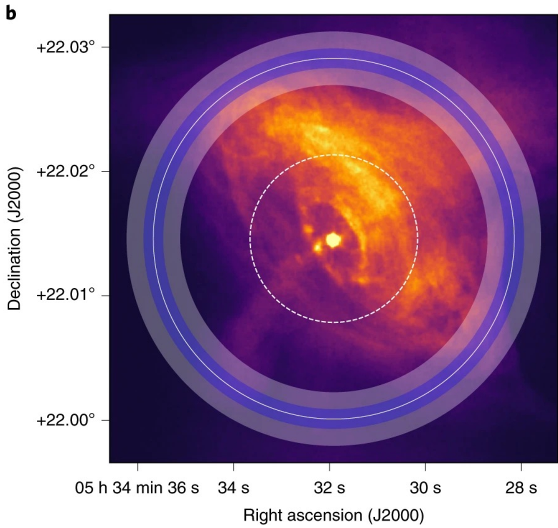
Crab Nebula

Pulsar Wind Nebula – "Standard candle" of TeV gamma-ray astronomy

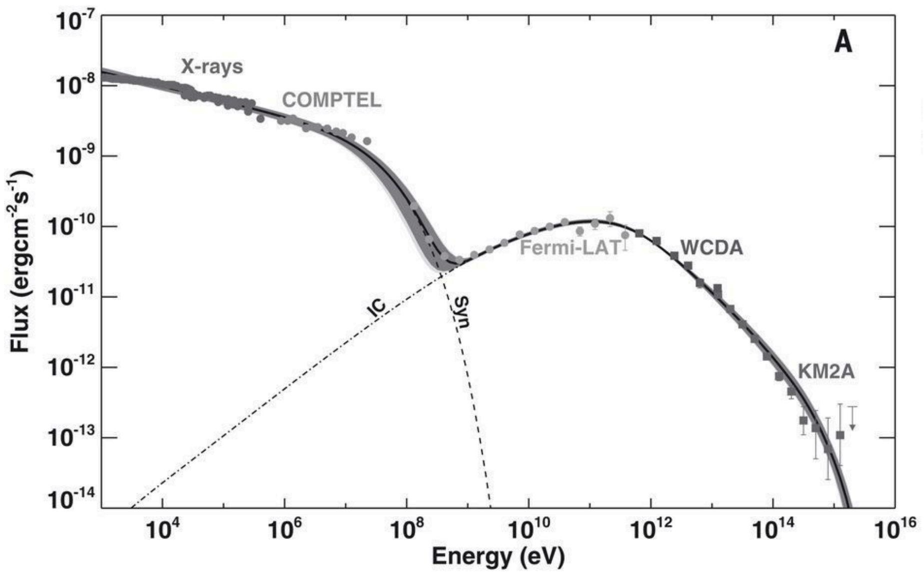
- First TeV source: Whipple 1989
- Highest energy photons > 1 PeV
- Brightest VHE gamma-ray source → "Crab" units
- t = 0.94 kyr, $\dot{E}$ = 4.5x10^{38} erg/s, d = 2 kpc

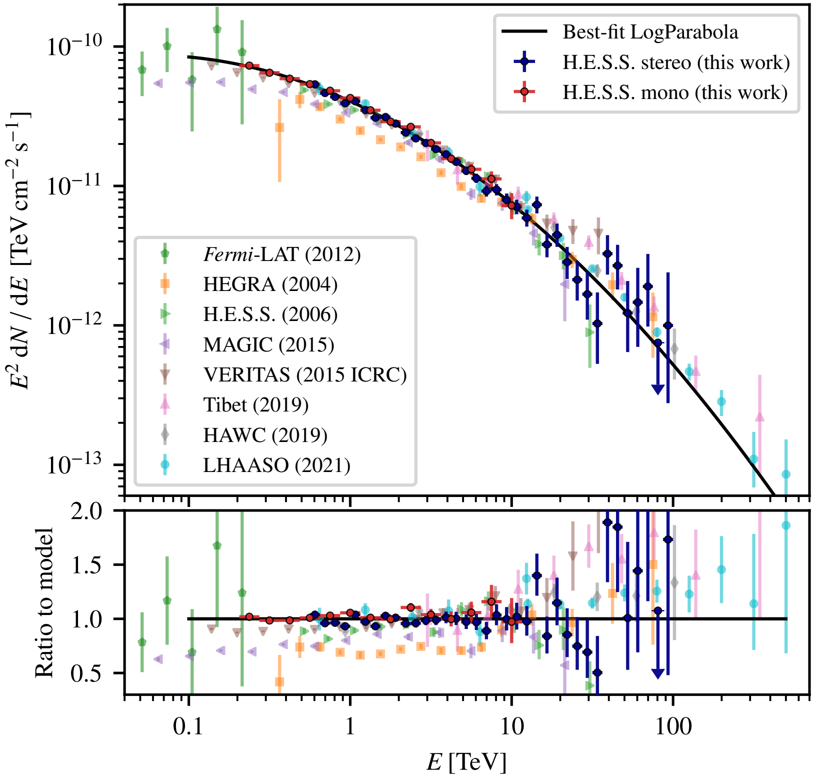
VHE extension: 52"

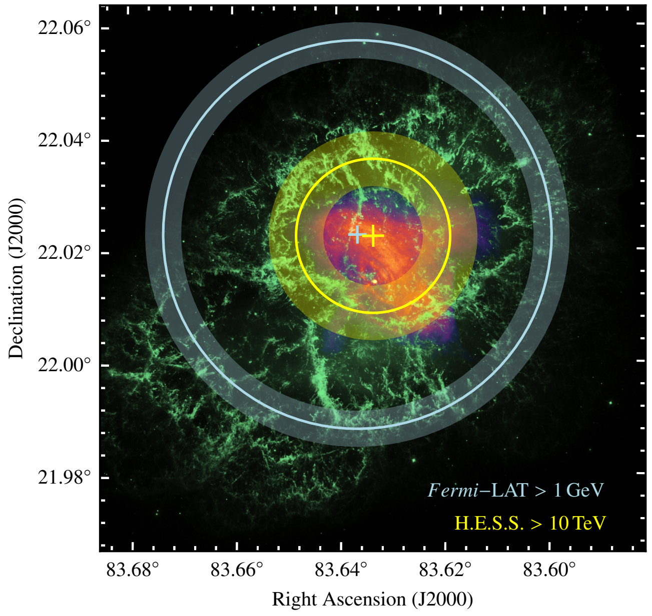
H.E.S.S. collaboration,
Nature Ast. **4**, 167-173 (2020)



Joint Fermi & HESS analysis
A&A **686** (2024) A308





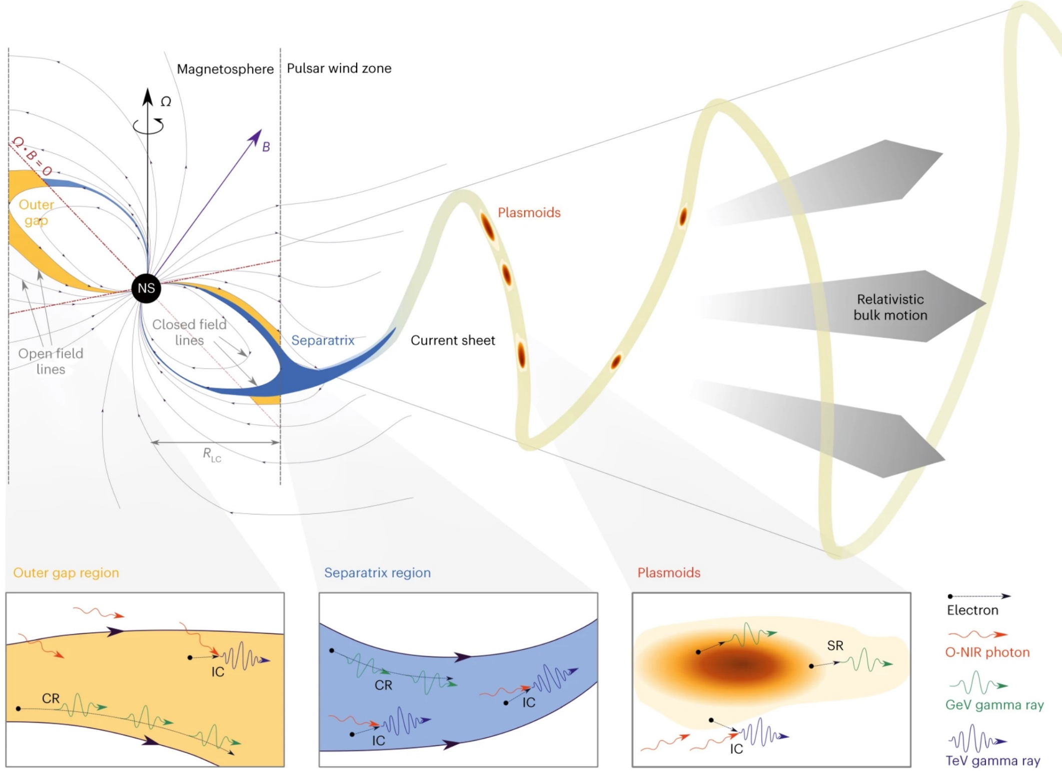


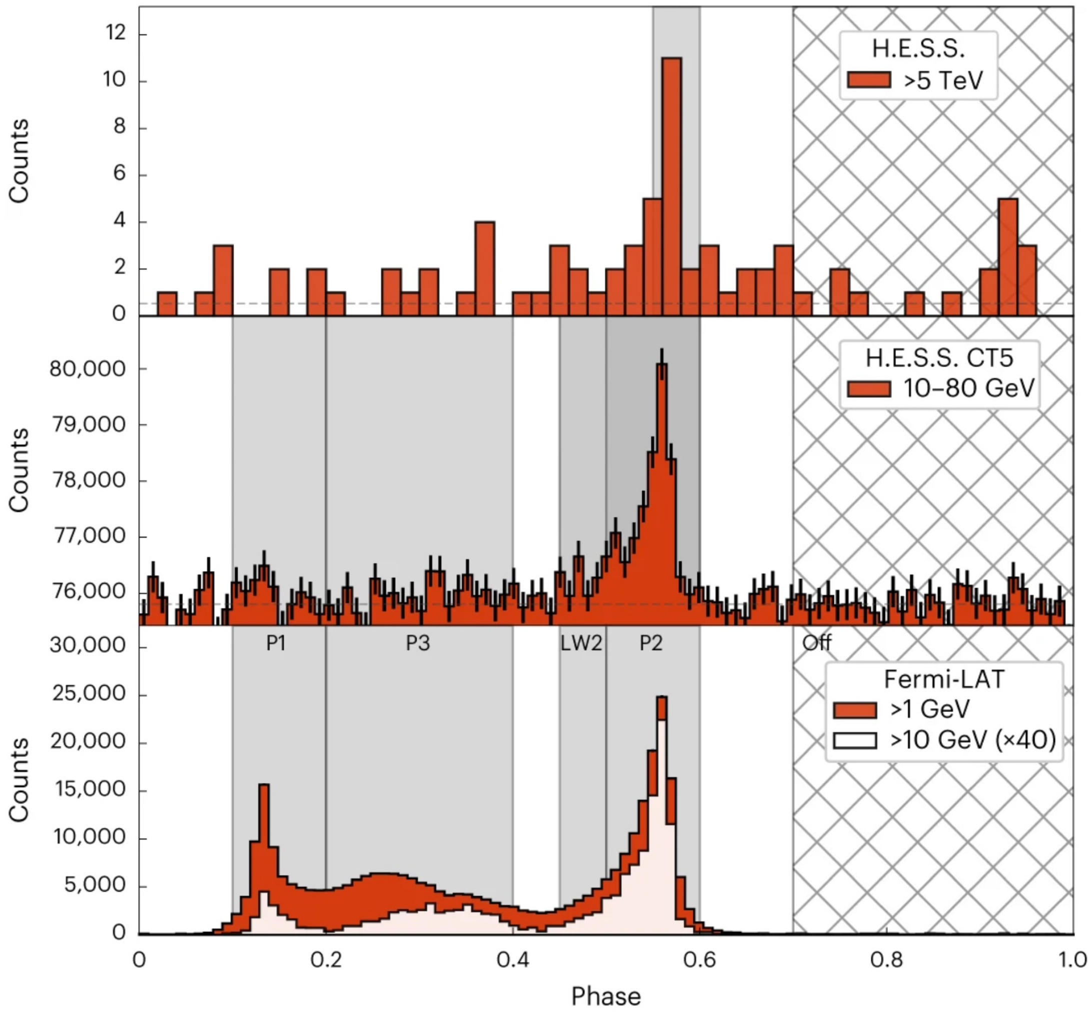
Z. Cao et al. LHAASO collaboration, Science **373**, 425-430 (2021)

Vela Pulsar

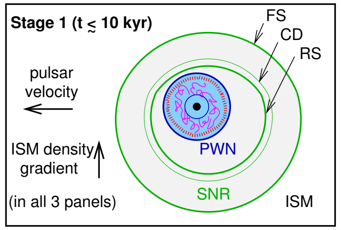
H.E.S.S. collaboration, Nature Astronomy, **7**, 1341-1350 (2023)

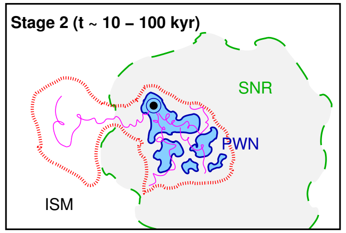
- Pulsed emission detected up to 20 TeV
- Predominantly from the P2 pulse
- t = 11 kyr, $\dot{E}$ = 7x10^{36} erg/s, d = 287 pc



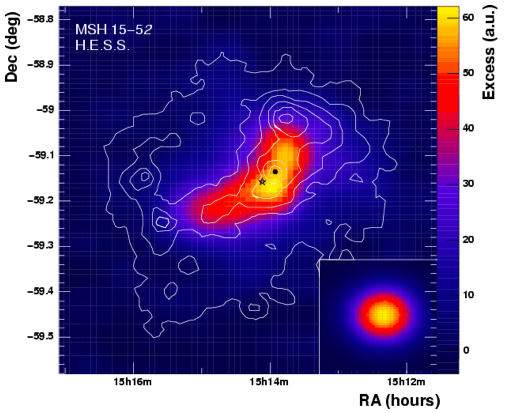


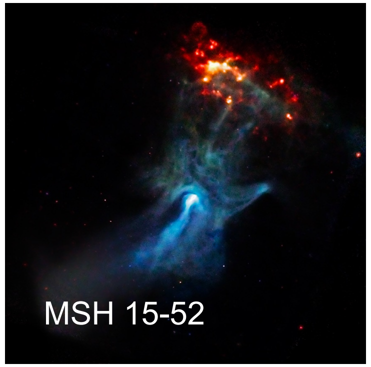
Pulsar Wind Nebulae

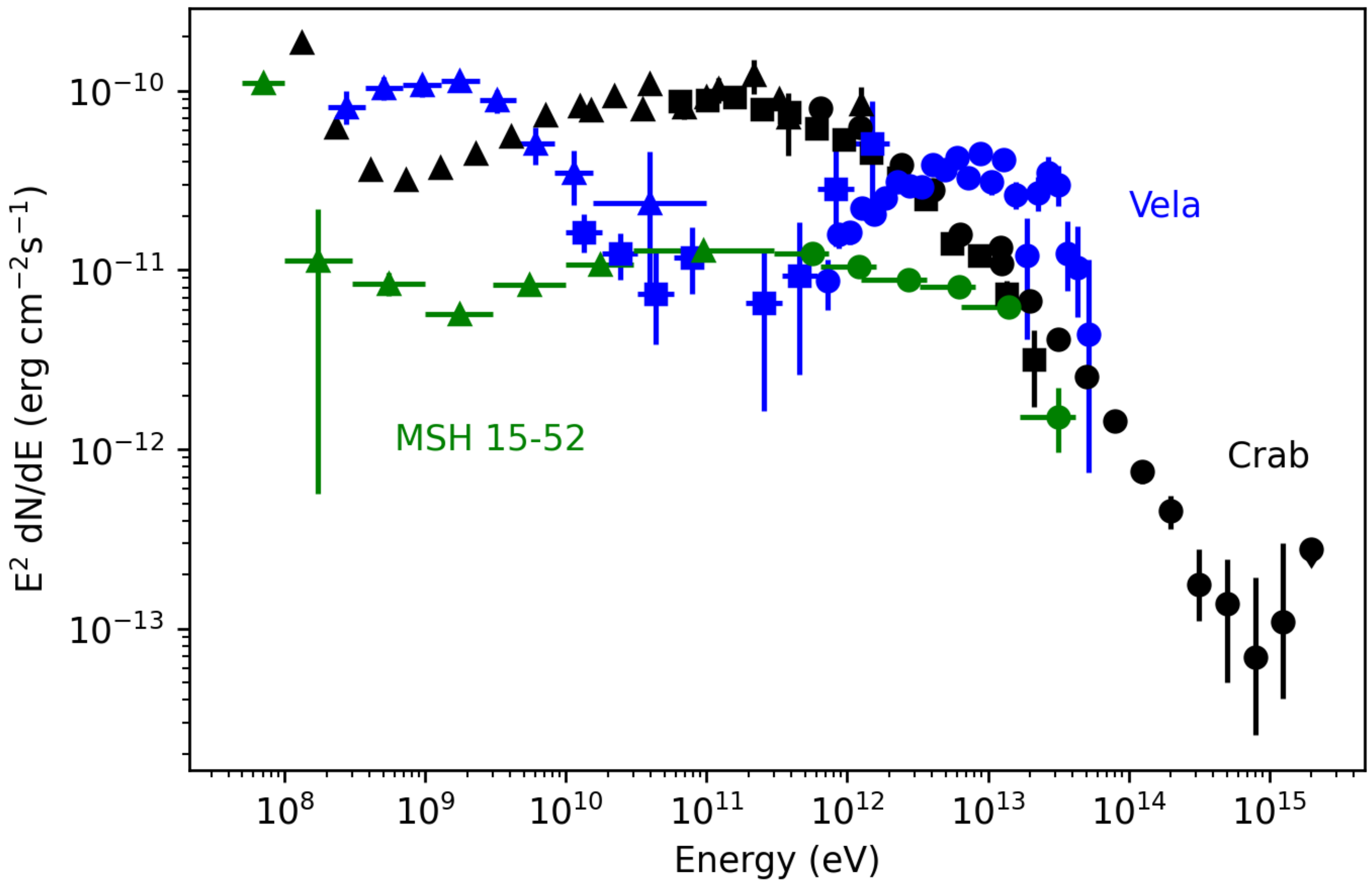


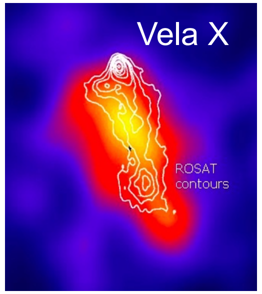


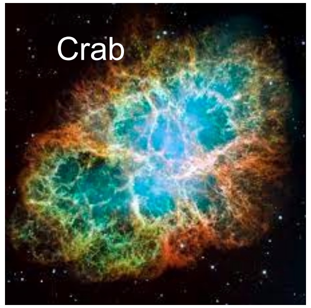
- Most numerous source class in the VHE gamma-ray sky

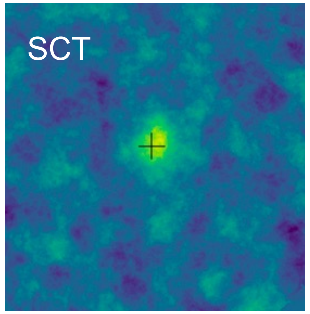






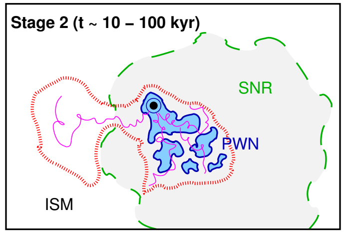


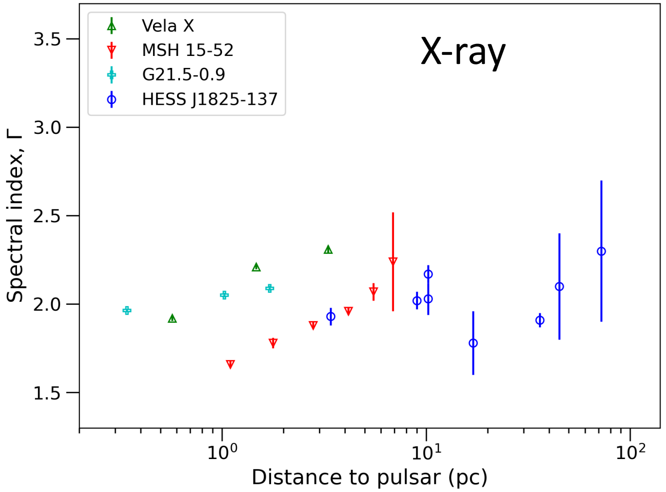


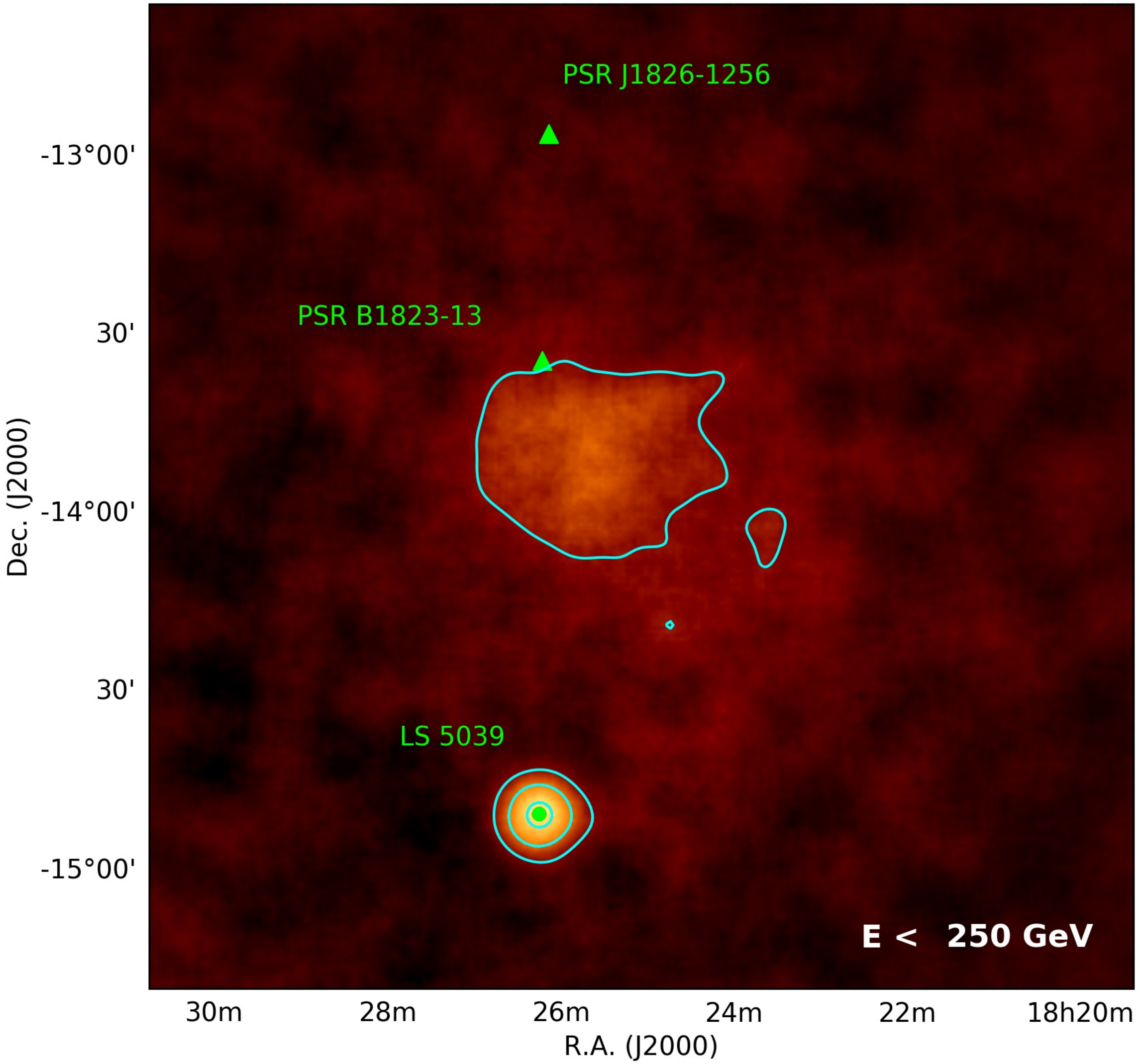


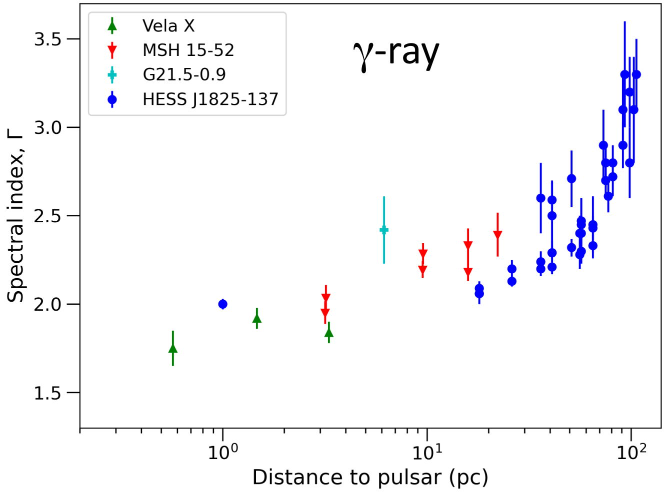
A&A **435**, L17-L20 (2005) https://news.ucsc.edu/2020/06/crab-nebula.html

Pulsar Wind Nebulae





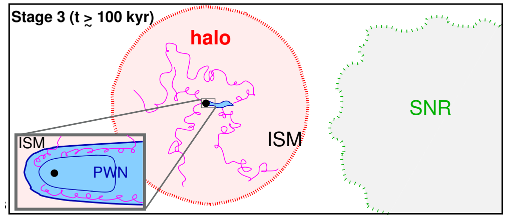




AM & Gelfand, Springer, 2022

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

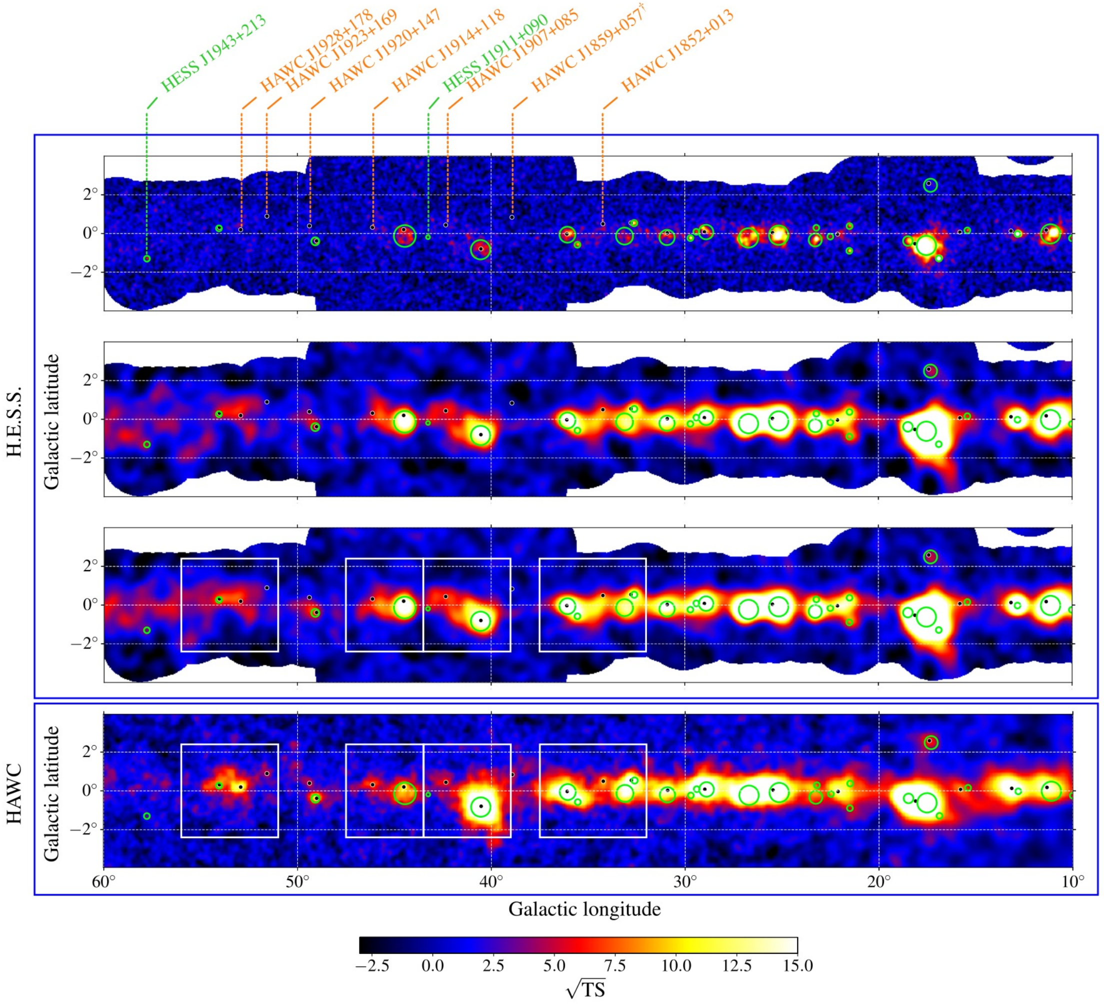
Pulsar halos: e.g. Geminga



- First identified at TeV energies by Water Cherenkov Detector HAWC
  Larger field-of-view → less angular size bias

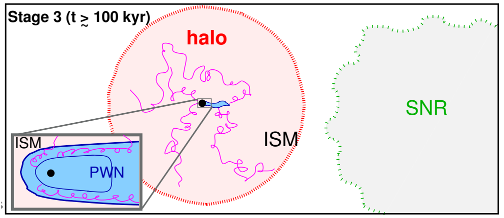
- IACTs such as H.E.S.S. have since put effort into improving analysis sensitivity to extended sources

  - Consistent view of the Galactic Plane (H.E.S.S. & HAWC, ApJ, **917**, 2021, 6)
    → several extended sources seen by HAWC now detected in H.E.S.S. data



H.E.S.S. & HAWC Collaborations, ApJ **917** (2021) 6

Pulsar halos: e.g. Geminga



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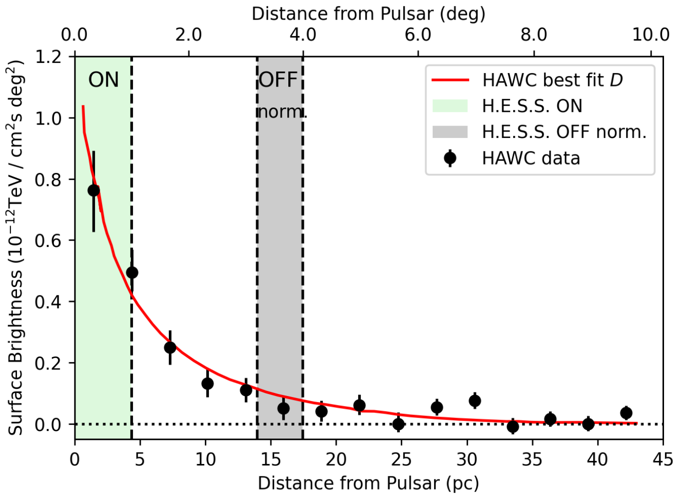
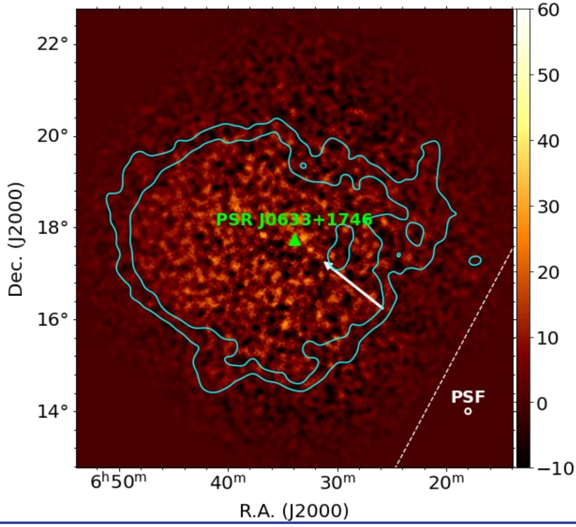
    → several extended sources seen by HAWC now detected in H.E.S.S. data

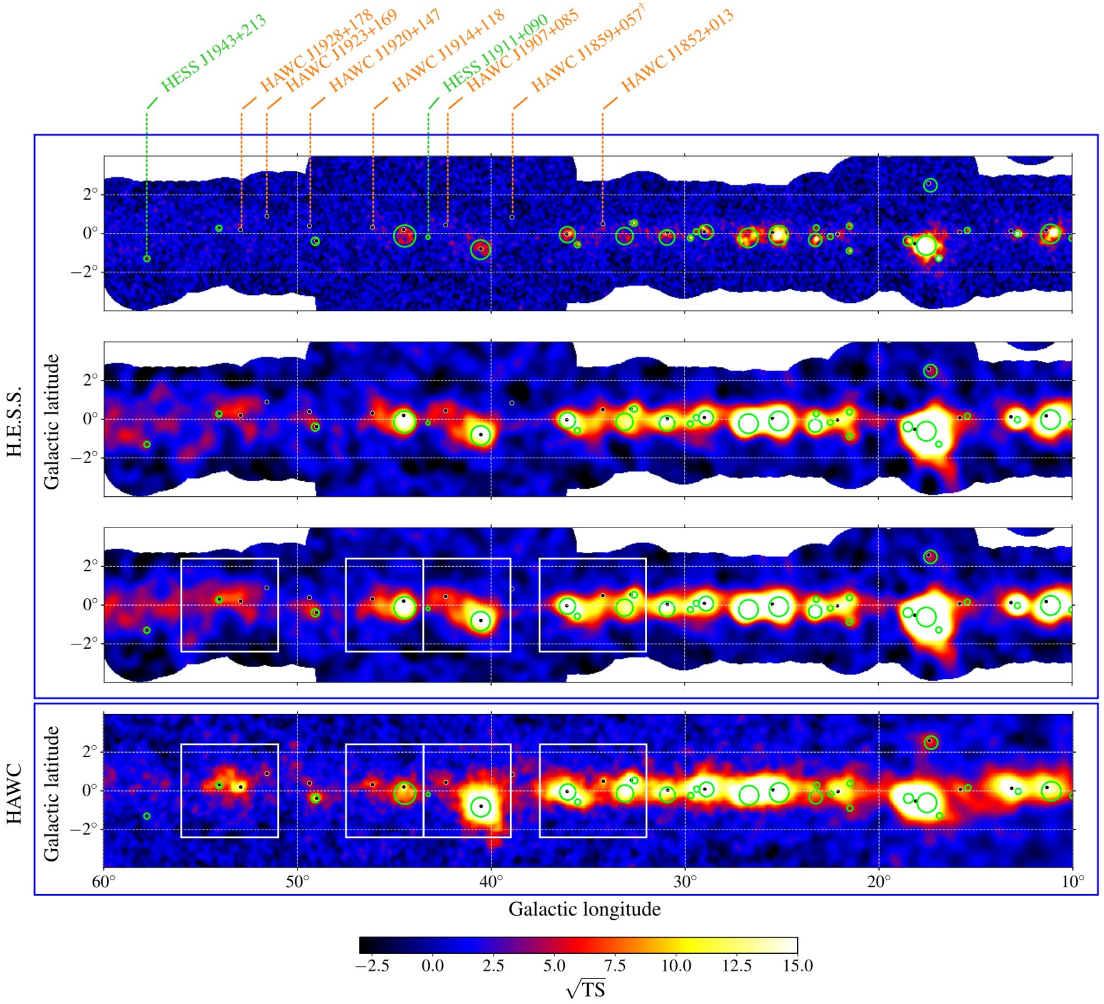
  - Detection of the canonical halo around the Geminga pulsar

  - t = 342 kyr, $\dot{E}$ = 3.2x10^{34} erg/s, d = 0.25 kpc





HESS A&A (2023)

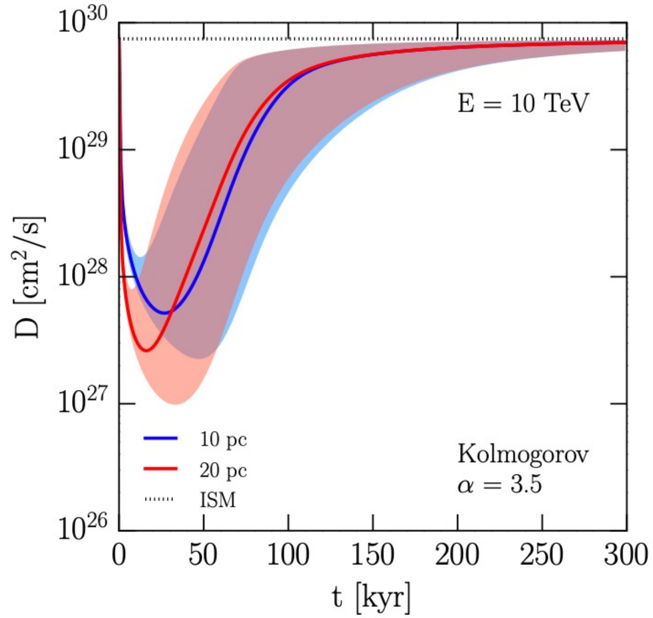


H.E.S.S. & HAWC Collaborations, ApJ **917** (2021) 6

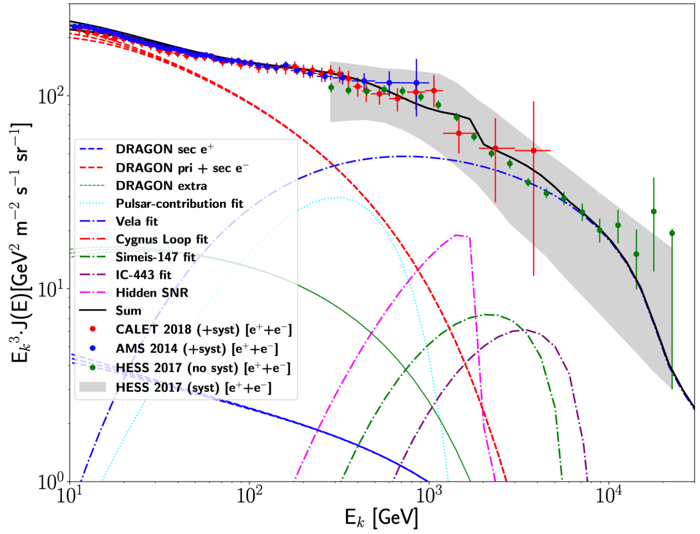
Cosmic Ray Electron Spectrum

- Recent measurements of slow diffusion in accelerator vicinity
- Generally need a local source contribution to explain the high energy CR electron spectrum
- Nature unclear: local SNR, local pulsar....

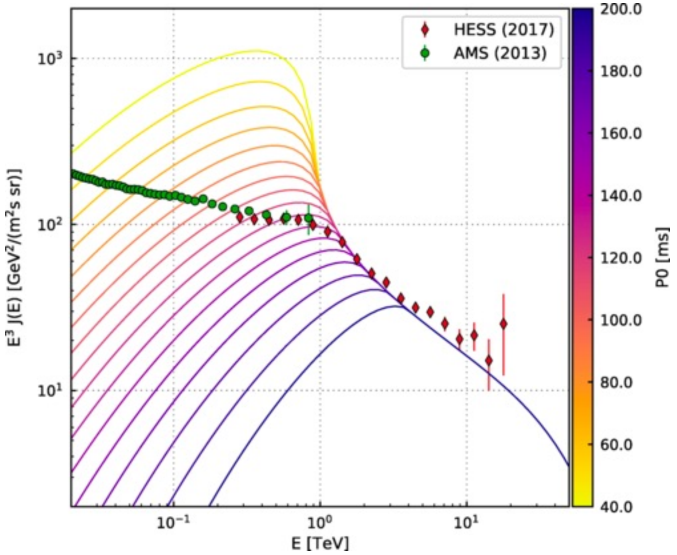
ΔE ± 15% due to hadronic interaction model uncertainties



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



Fornieri et al. JCAP **02** (2020) 009



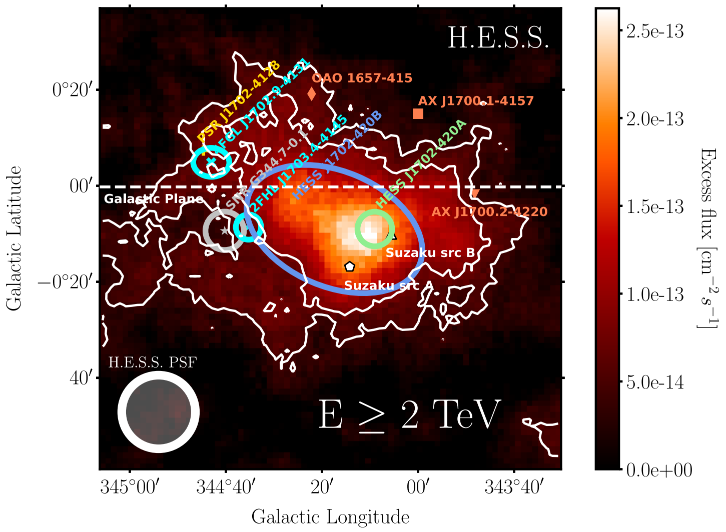
Lopez-Coto et al. PRL **121** (2018) 251106

PeVatron candidates

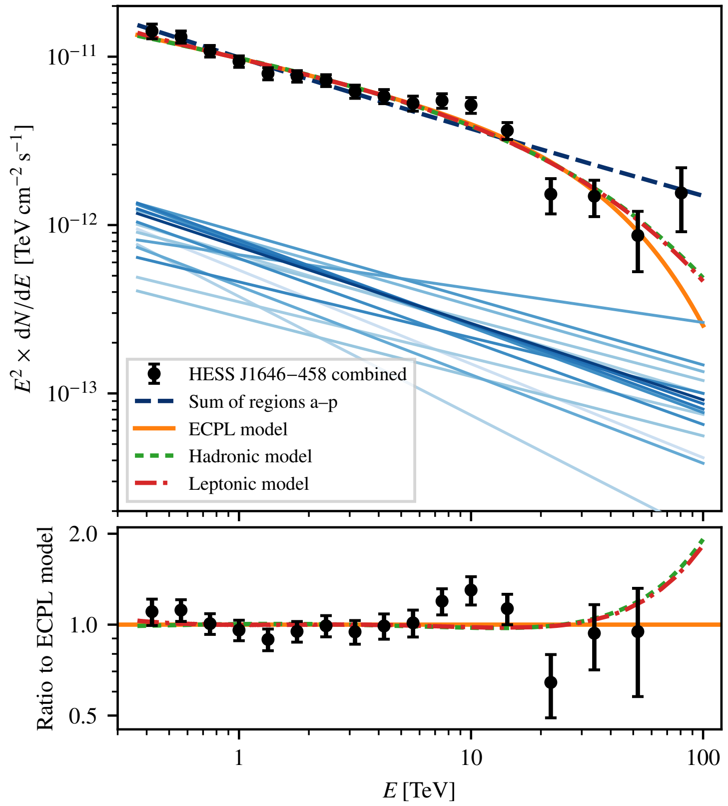
Supernova Remnants, Stellar Clusters...

Search for origins of Galactic Cosmic Rays:
-- supernova remnants?
-- Galactic Centre region?
-- stellar clusters?
-- escaping CRs interacting with clouds?
-- Unidentified sources?

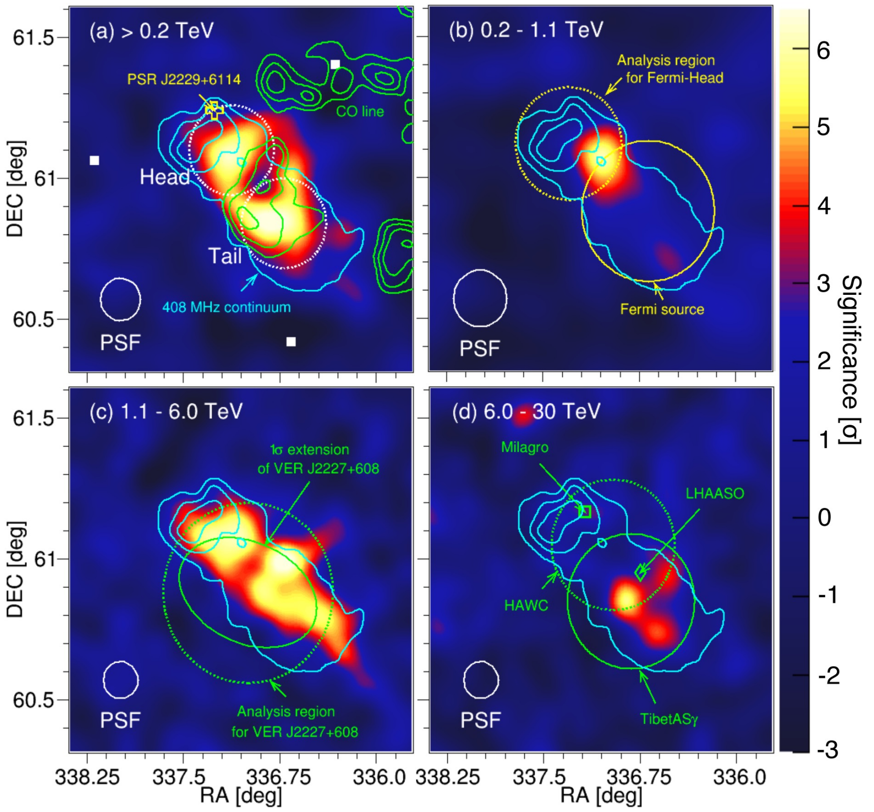
HESS J1702-420



H.E.S.S. Collaboration A&A **653** A152 (2021)

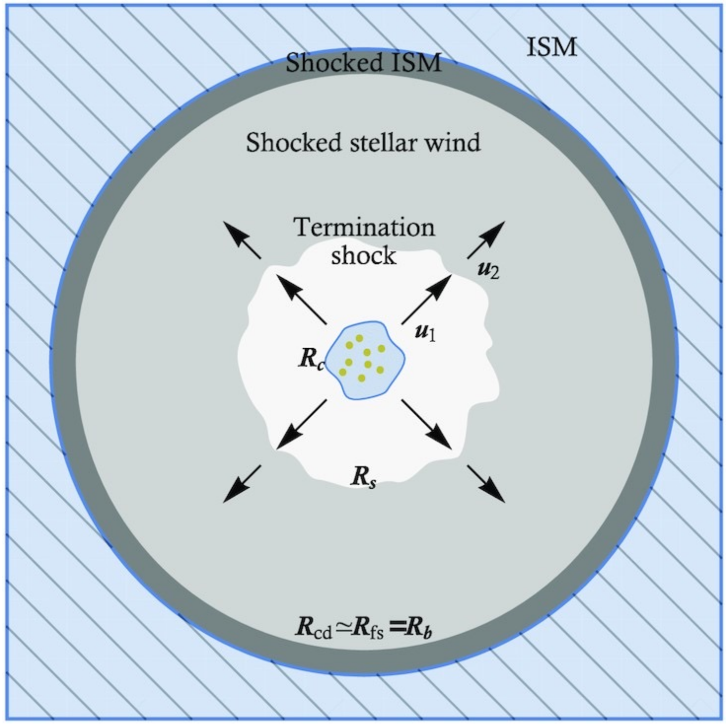


Westerlund 1
HESS Collaboration A&A **666** A124 (2022)



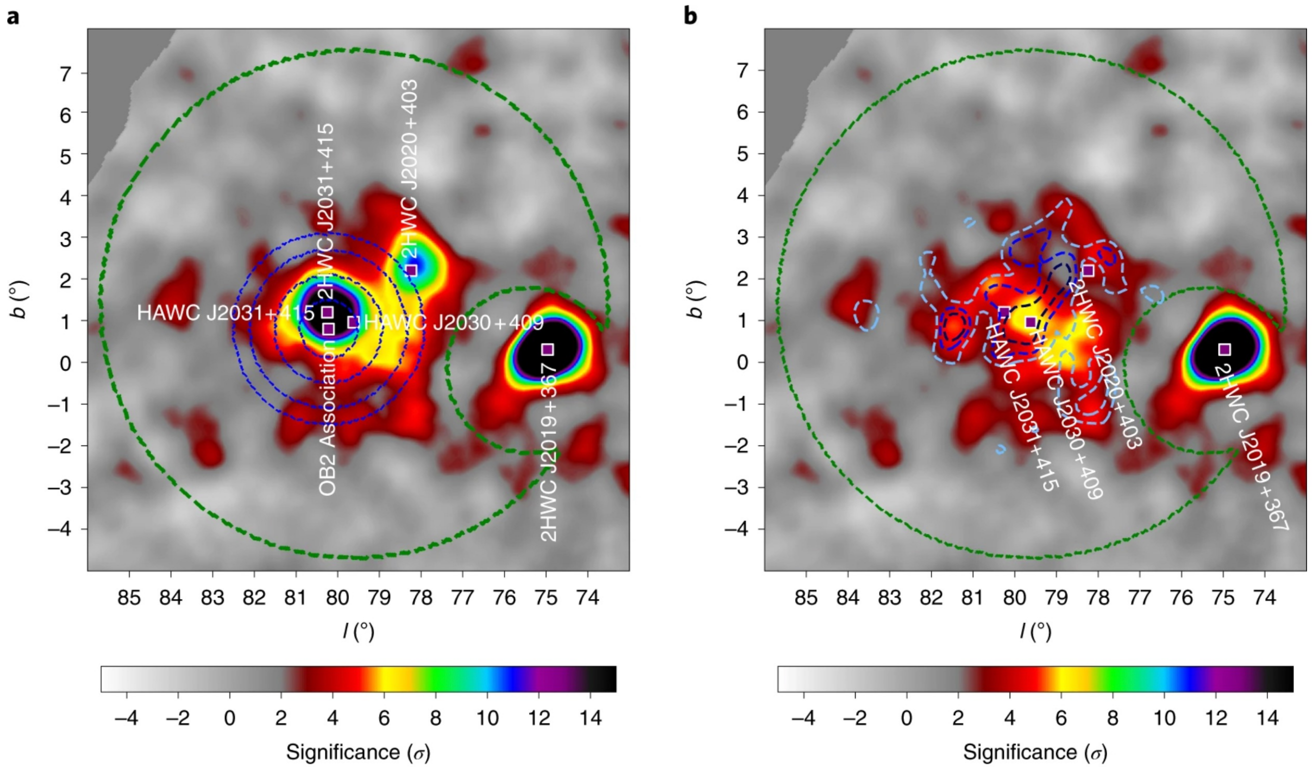
G106.3+2.7 / Boomerang nebula
MAGIC collaboration A&A **671**, A12 (2023)

Stellar Clusters and Cygnus Superbubble



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

- 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)

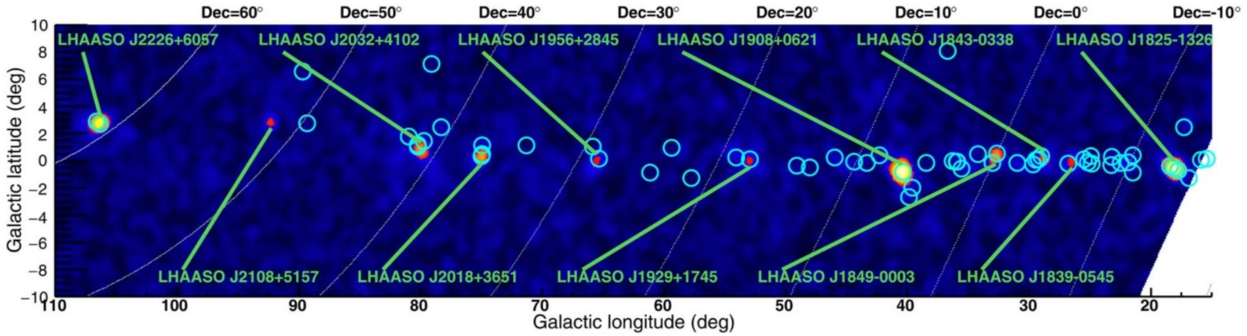


Highest energy gamma-ray sky > 100 TeV

- Sky maps by LHAASO, Tibet-ASγ and HAWC:
- $E_\gamma > 100$ TeV ($E_p \sim 1$ PeV; $E_e \sim 183$ TeV)
  → ~12 sources
- Cao et al. Nature **594** (2021) 33-36

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

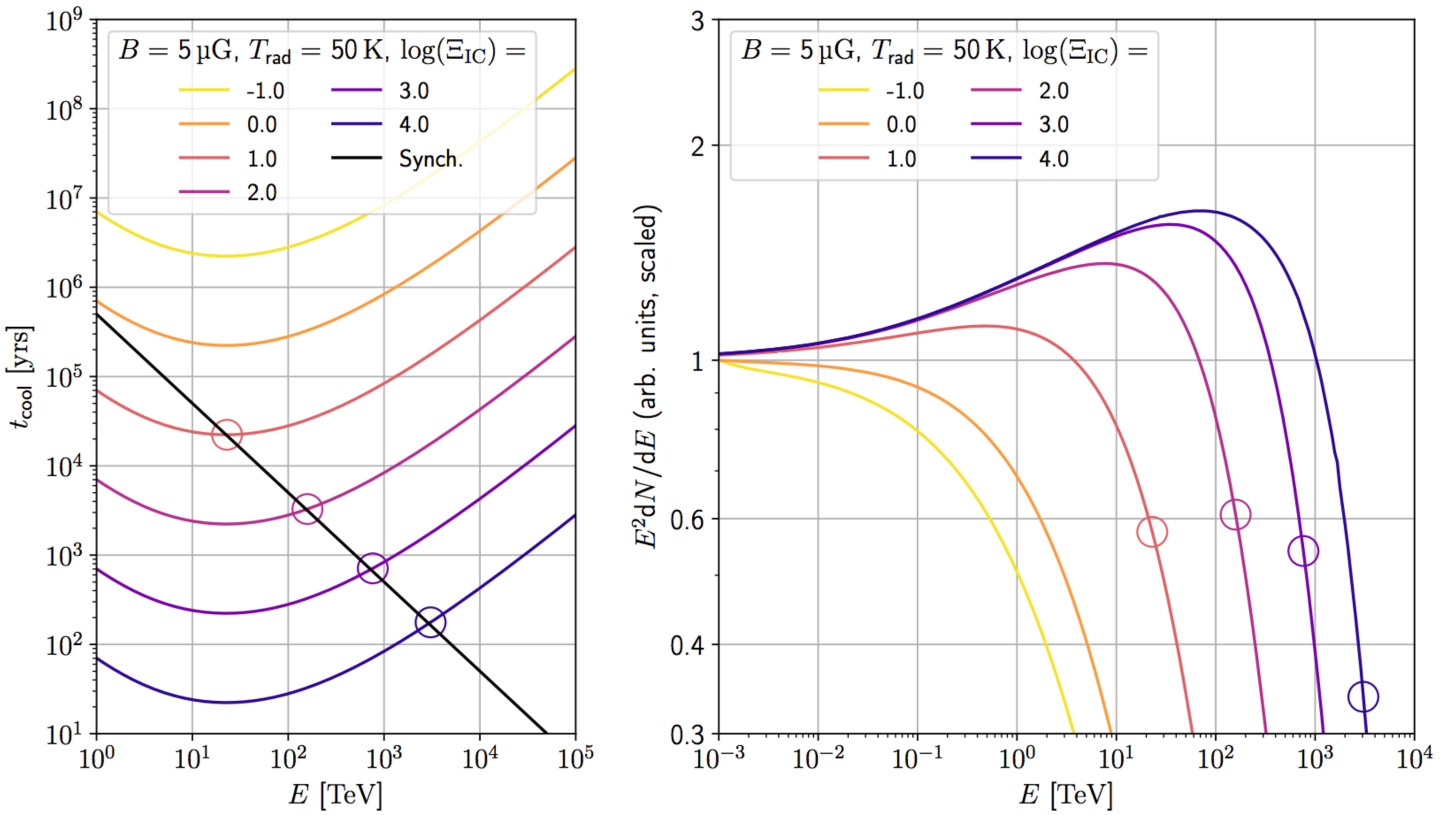
- Most associated with pulsars
- Generally, pulsars are associated with leptonic emission (e^+ & e^-)



UHE leptonic emission & Klein-Nishina effect

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

- 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 is less pronounced.
- Leptonic spectra out to PeV energies can be observed



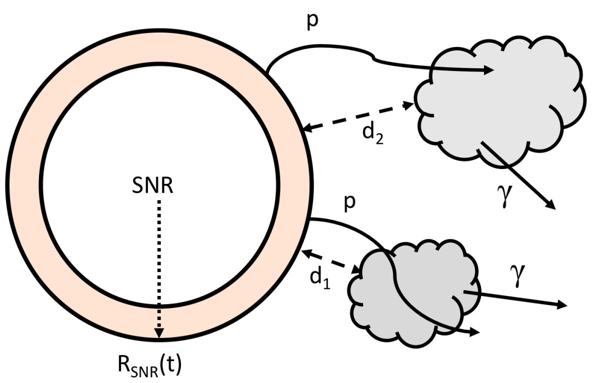
Breuhaus et al. ApJL **908** L49 (2021)

Gamma-ray signatures of cosmic rays

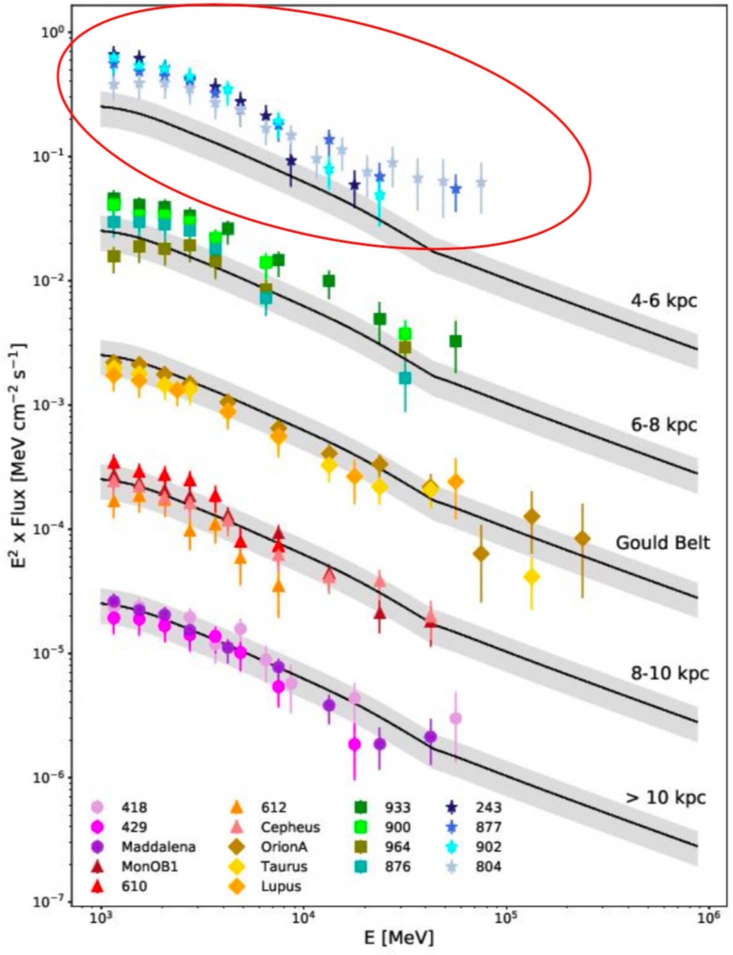
→Protons (and heavier nuclei) escape from accelerator – will interact with nearby clouds

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

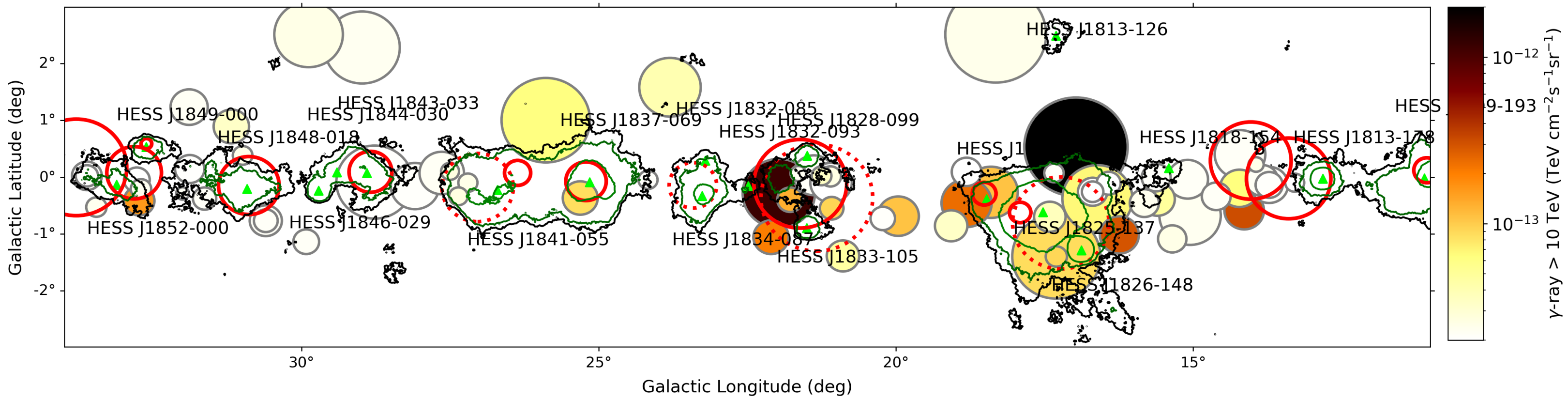
→Can use clouds in vicinity of accelerators to probe escape of protons and constrain their presence



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



Aharonian et al, PRD **101**, 083018 (2020)

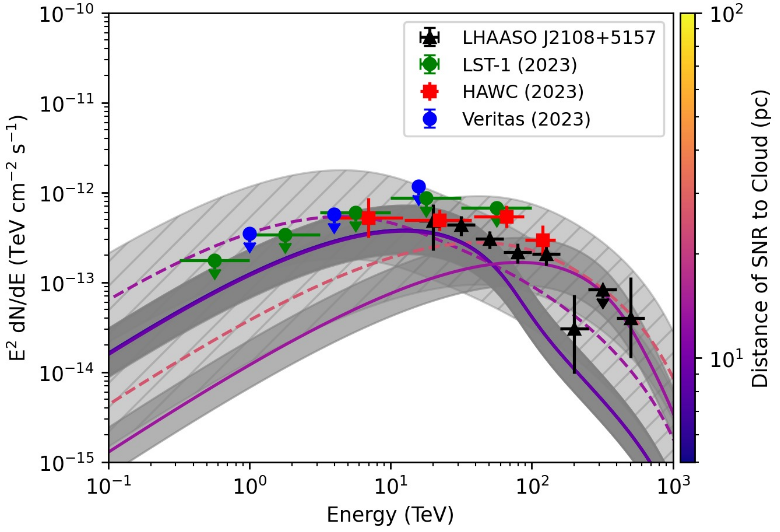


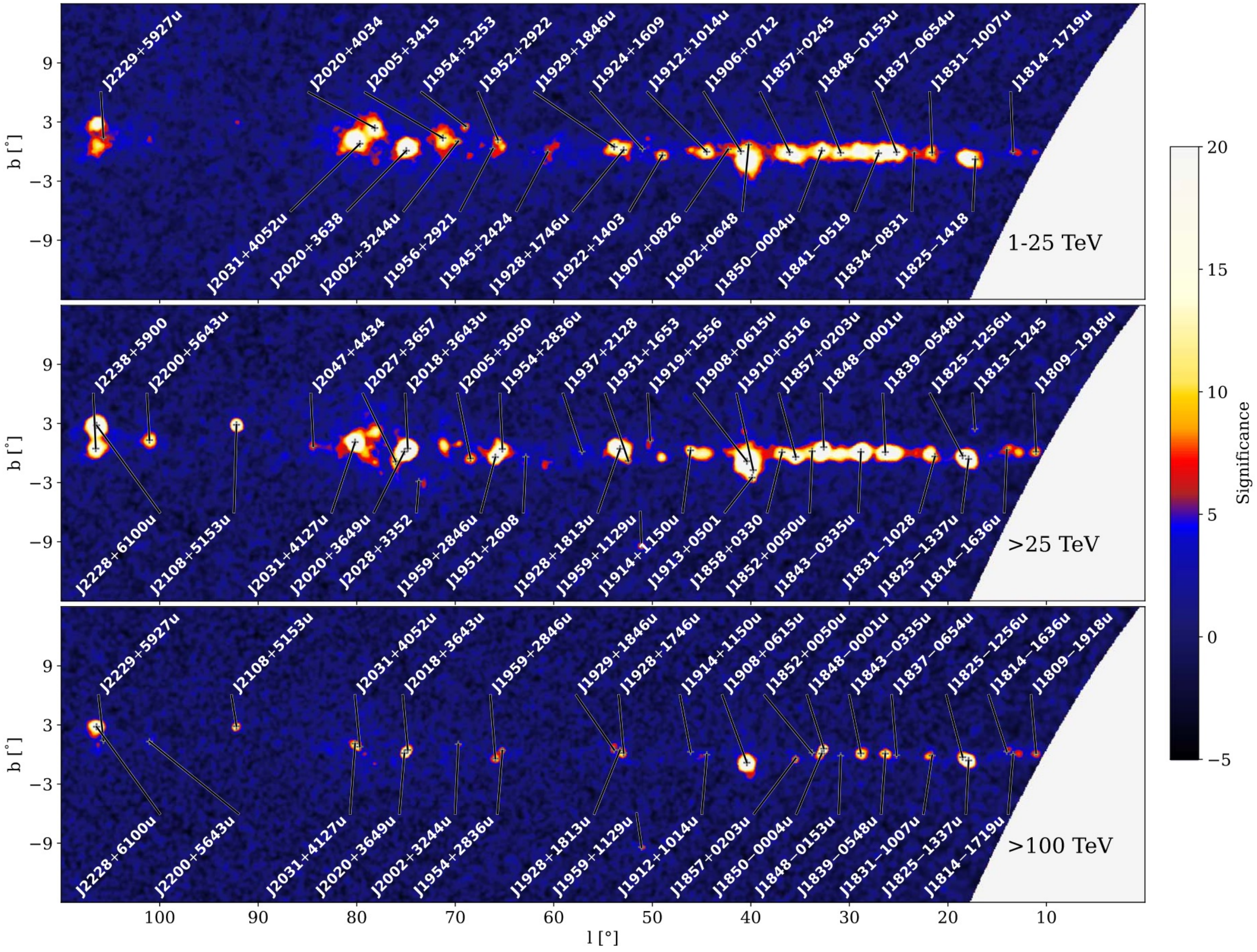
Unidentified Ultra-High-Energy sources

1LHAASO catalogue

- In the first LHAASO catalogue – many unidentified sources in the galactic plane
- No known accelerator as counterpart
- However – often molecular cloud as counterpart
- Example: LHAASO J2108+5157
- Constrain properties of molecular clouds → scan parameter space to constrain potential SNR properties

AM A&A **684** A66 (2024)





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

Binary Systems: Microquasars, Colliding wind binaries...

Gamma-ray emitting binaries:

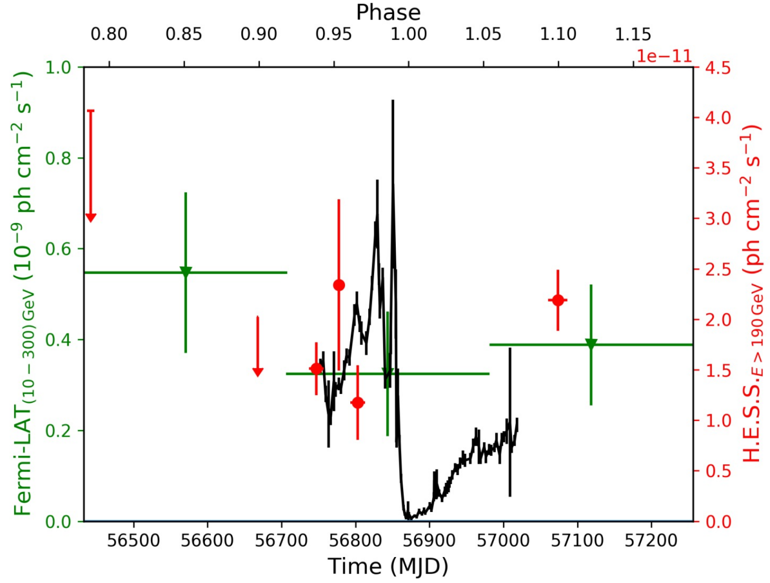
→ Colliding Wind Binaries

→ Gamma-ray binaries

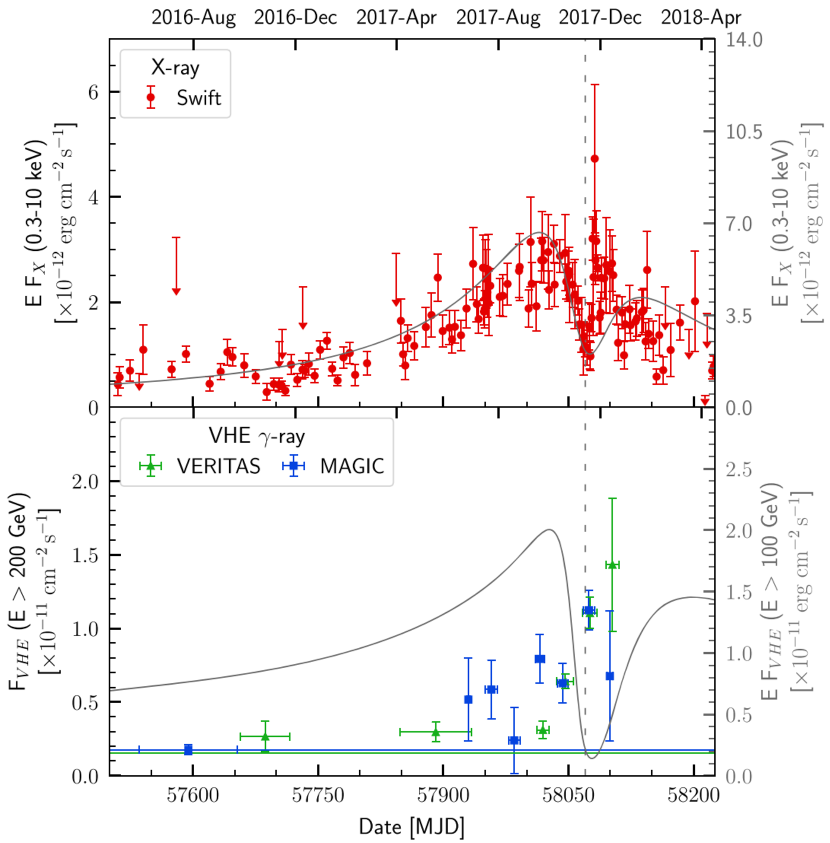
→ Microquasars (solar mass BHs)

→ Novae

Eta Carinae: P ~5.5yr



PSR J2032+4127/Be: P ~50yr



H.E.S.S. Collaboration A&A **635** A167 (2020)

MAGIC & VERITAS Collaborations ApJ **867** L19 (2018)

Energy-dependent emission from the jets of SS433

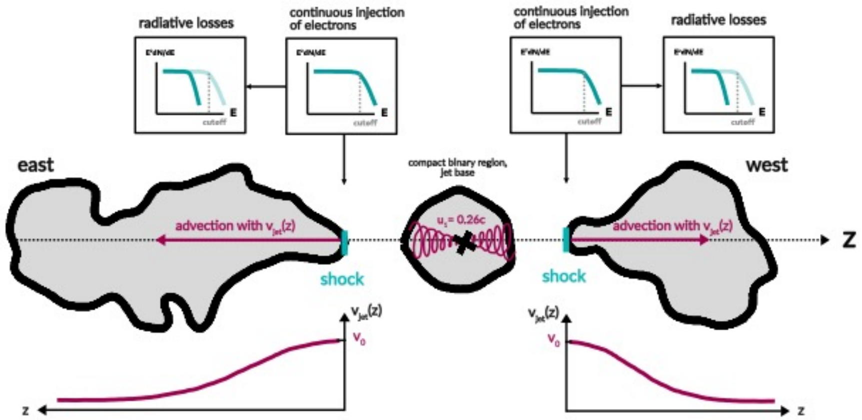
H.E.S.S. Collaboration, Science, **383**, p. 402-406 (2024)

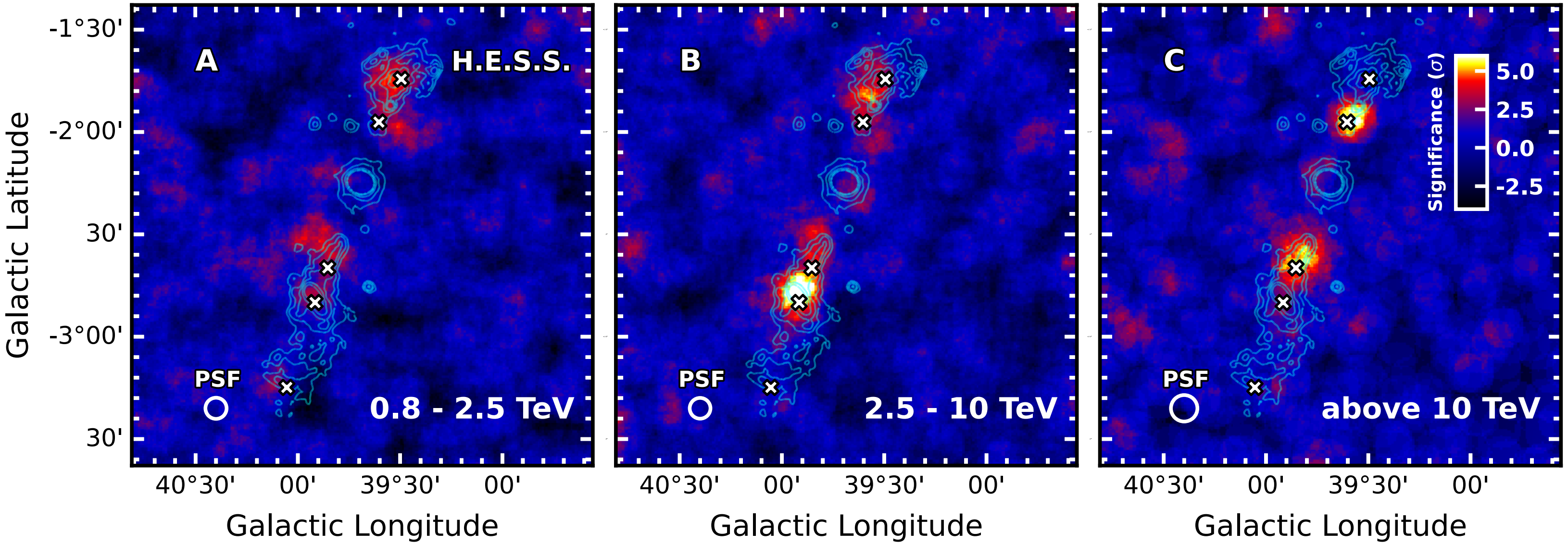
SS 433 microquasar producing powerful jets

H.E.S.S. detection of emission from the outer jets

Indications for an energy-dependence of the emission along the jets

Constrains the particle launch velocity to (0.08 ±0.03)c





Stellar Novae

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

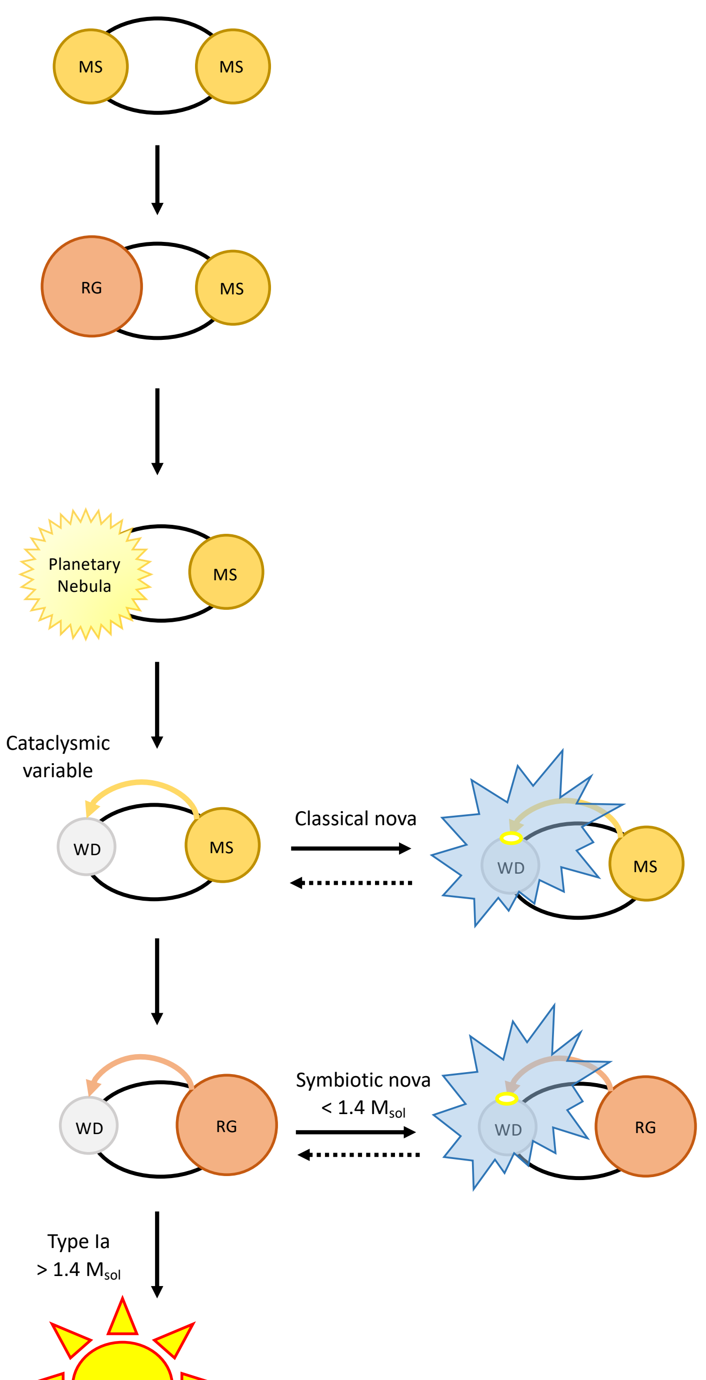
- (Classical) Novae → outbursts from cataclysmic variables
- Symbiotic Novae → red giant / "evolved" donor star
- Recurrent Novae → multiple observed outbursts
- Dwarf Novae → mini-outbursts (not thermonuclear)

Thermonuclear explosion ignited on surface of white dwarf

Increase in optical brightness $\Delta m_v \sim 8$ to 15

Typical optical duration weeks to months

$$E_{\max} = 1.5 |Z| \left(\frac{\xi_{\rm esc}}{0.01} \right) \left(\frac{\dot{M} / v_{\rm wind}}{10^{11}\ {\rm kg\ m^{-1}}} \right)^{1/2} \left(\frac{u_{\rm sh}}{5000\ {\rm km\ s^{-1}}} \right)^{2}\ {\rm TeV}$$



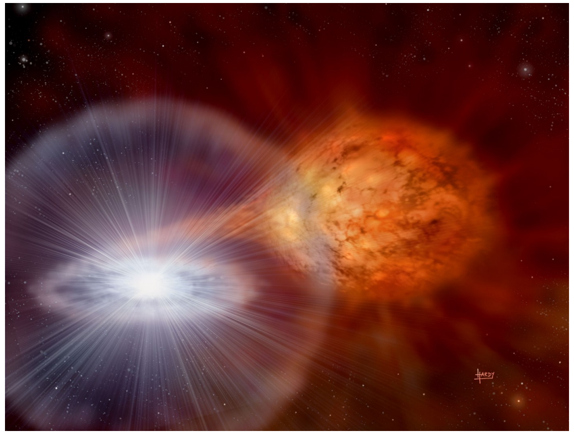
First Nova in VHE gamma-rays: RS Ophiuchi

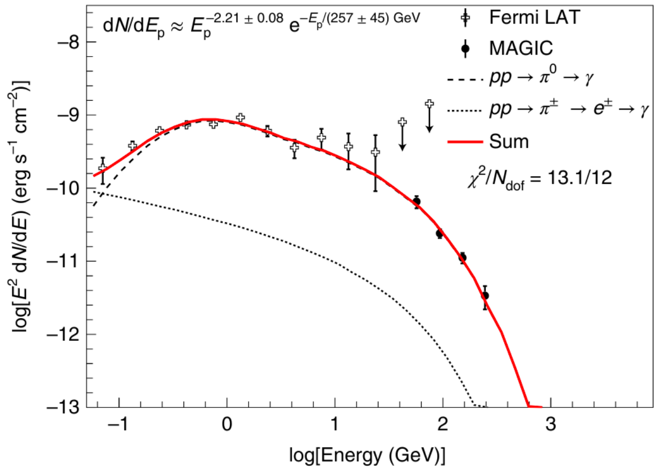
Binary of white dwarf and red giant

- Binary system comprised of white dwarf and red giant at ~1.4 kpc distance
- Semi-regular explosions observed since 1898
- Last two: 12th February 2006 and **8th August 2021** reaching $m_v = 4.6$ (cf quiet state $m_v = 12.5$)

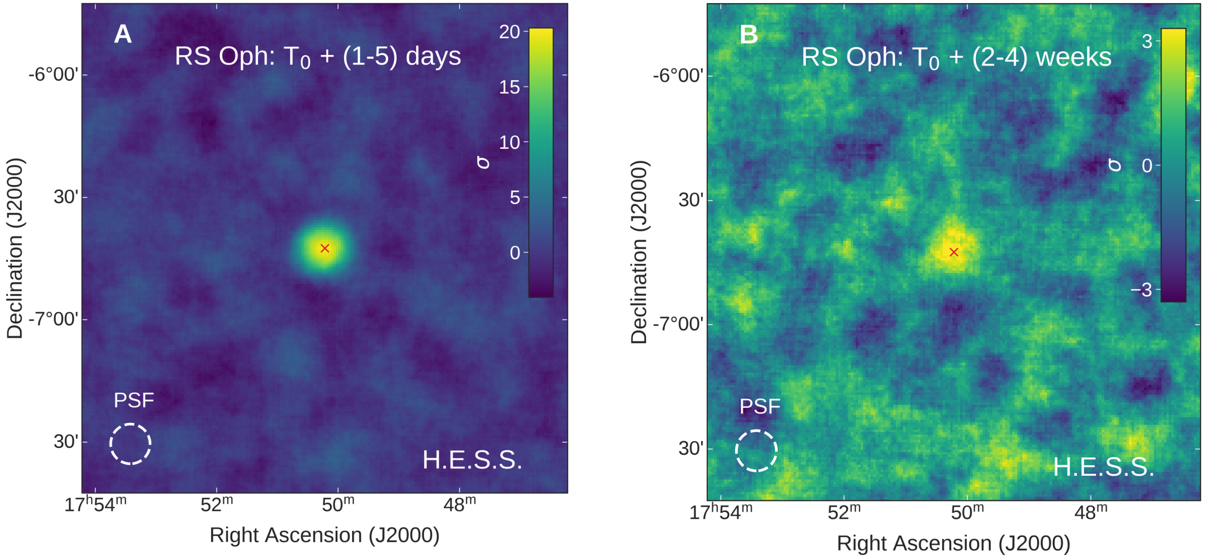
→ Detected by H.E.S.S., MAGIC and LST in VHE gamma-rays (Atel 14844)

Hadronic scenario preferred





MAGIC collaboration
Nat. Astr. **6** (2022) 689-697



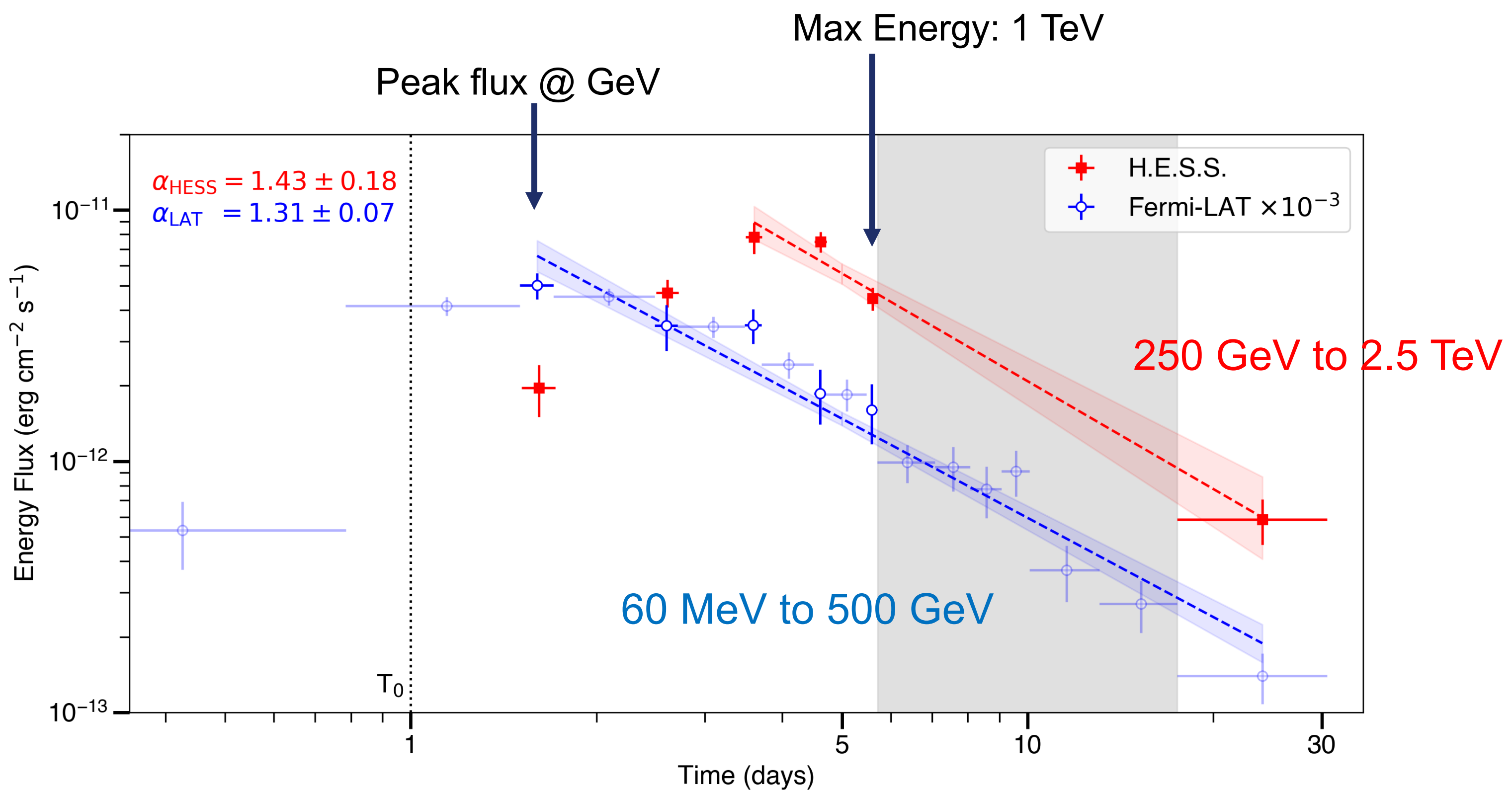
H.E.S.S. collaboration Science **376** (2022) 77-80

Gamma-ray flux decay

Optical peak occurred at T_0 = 59435.25 (MJD)

VHE gamma-ray flux peak seen by H.E.S.S. is delayed with respect to Fermi-LAT

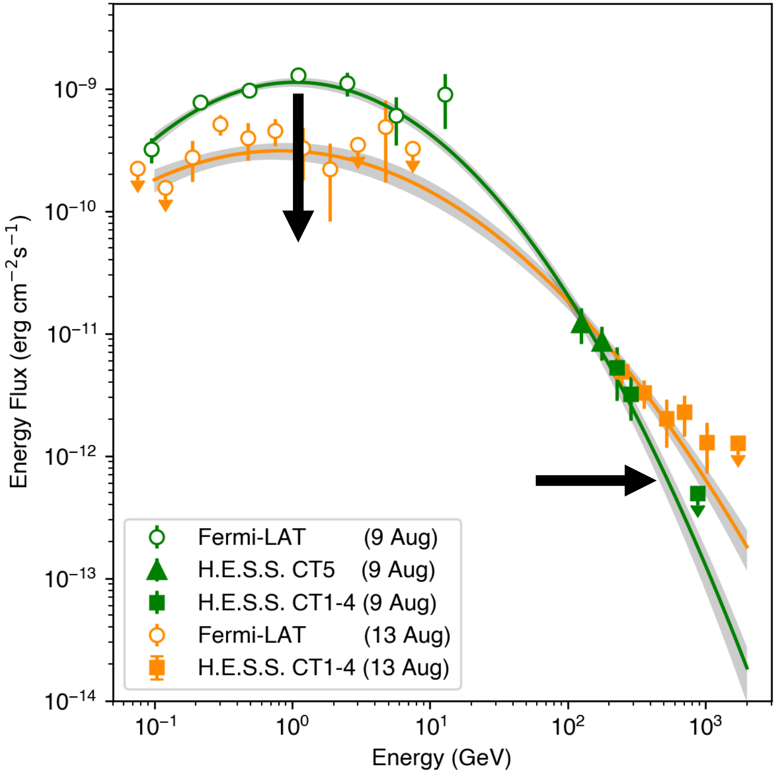
Consistent decay slope after peak flux is attained



It takes time to reach the theoretical maximum energy

Either: cooling limited (leptonic)

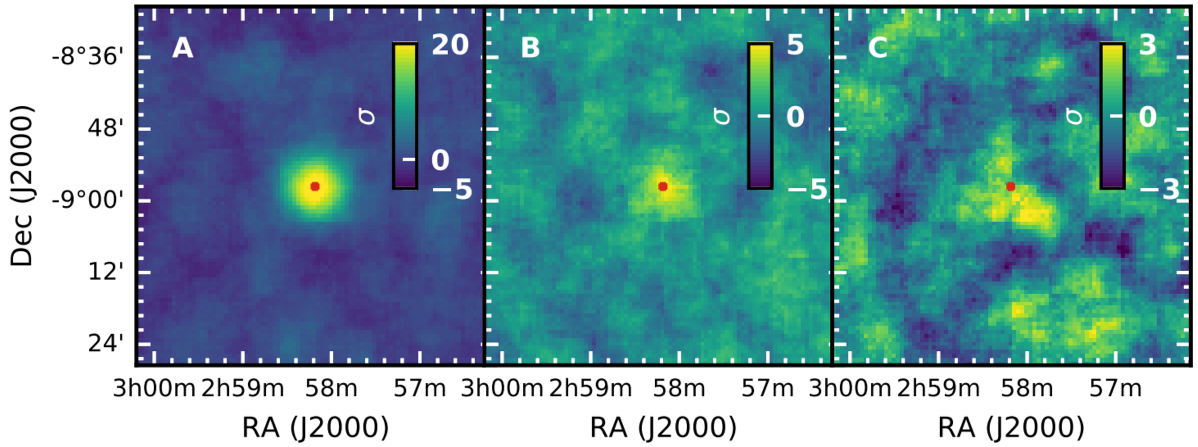
Or: confinement limited (hadronic)
until particles become sufficiently energetic to escape the shock

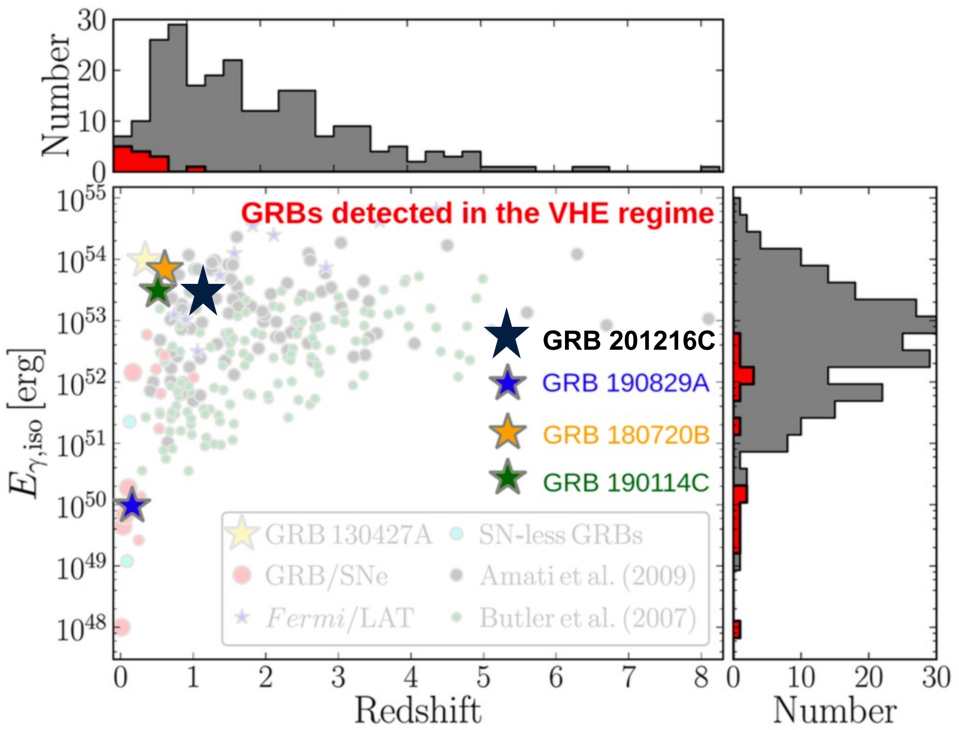


Transients: Gamma-Ray Bursts

First four VHE GRBs detected by H.E.S.S. & MAGIC between 2018 – 2020 (long GRBs, detected during afterglow phase)

- GRB 180720B, z ~ 0.654 (H.E.S.S.)
- GRB 190114C, z ~ 0.4245 (MAGIC)
- GRB 190829A, z ~ 0.08 (H.E.S.S.)
- GRB 201216C, z ~ 1.1 (MAGIC)





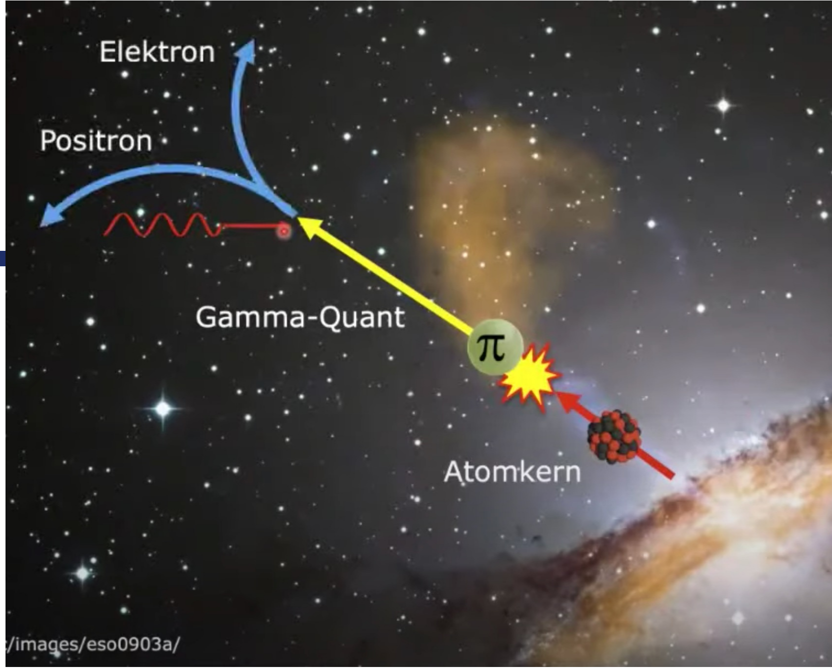
Large distances z ≥ 1 → severe attenuation due to the Extragalactic background light

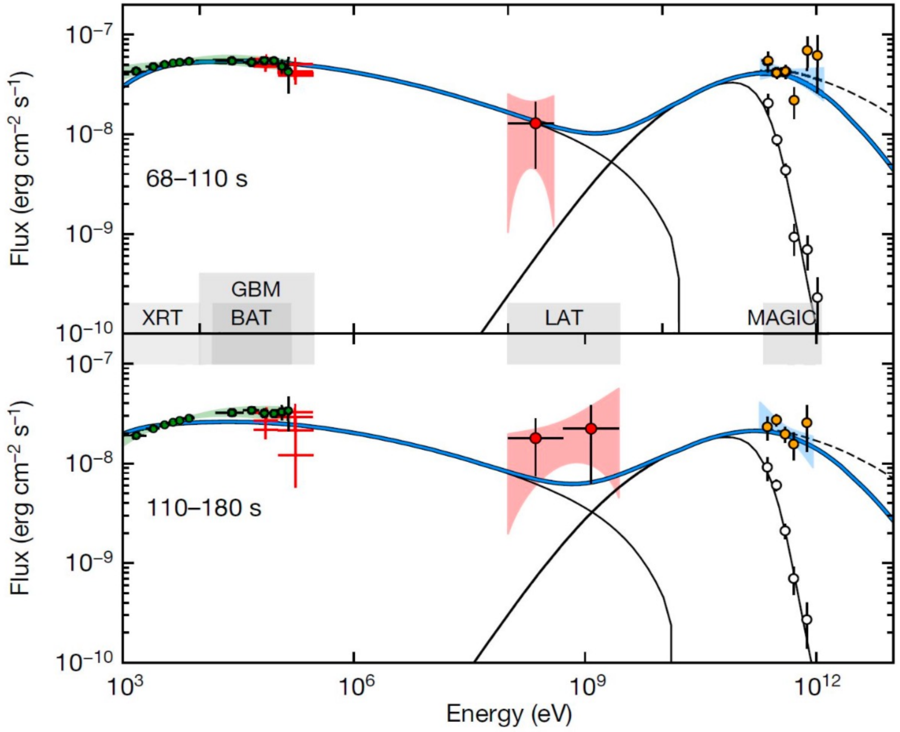
Interactions with EBL → strongly attenuated spectra

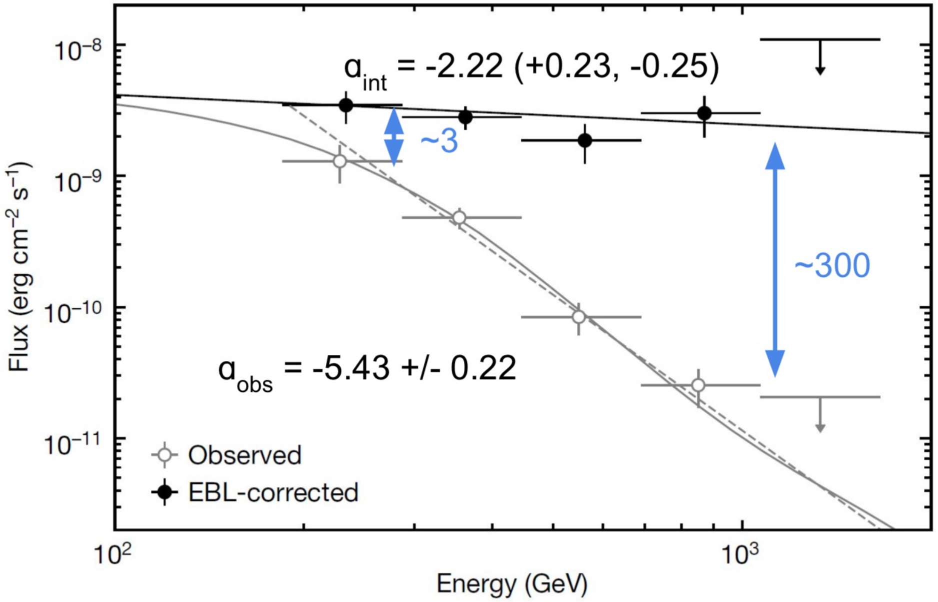
H.E.S.S. collaboration Science **372** (2021) 1081-5

GRB 190114C and EBL absorption

- Synchrotron self-Compton (SSC) component: Necessary or not?
- Absorption by Extragalactic Background Light (EBL)
  → large uncertainties on models
  → Need to correct spectrum

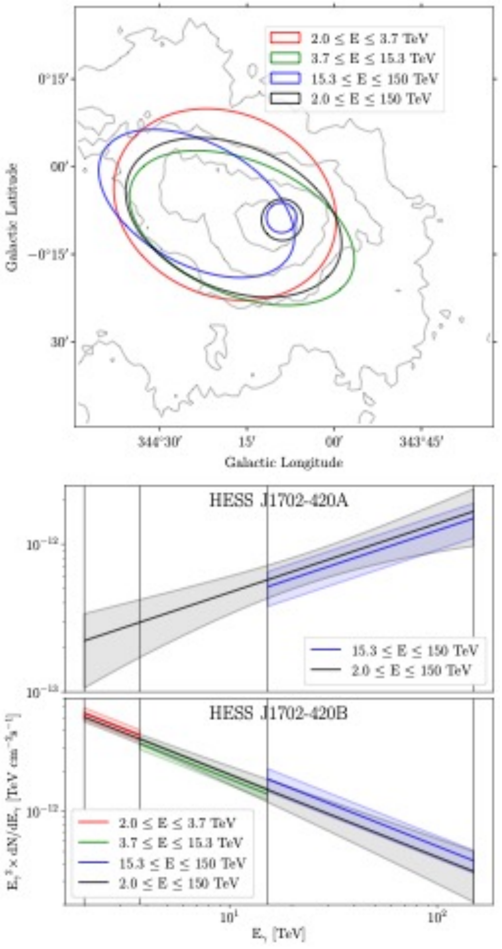






Gammapy (γπ) and 3D analysis approaches

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



HESS Collaboration A&A **653** (2021) A152

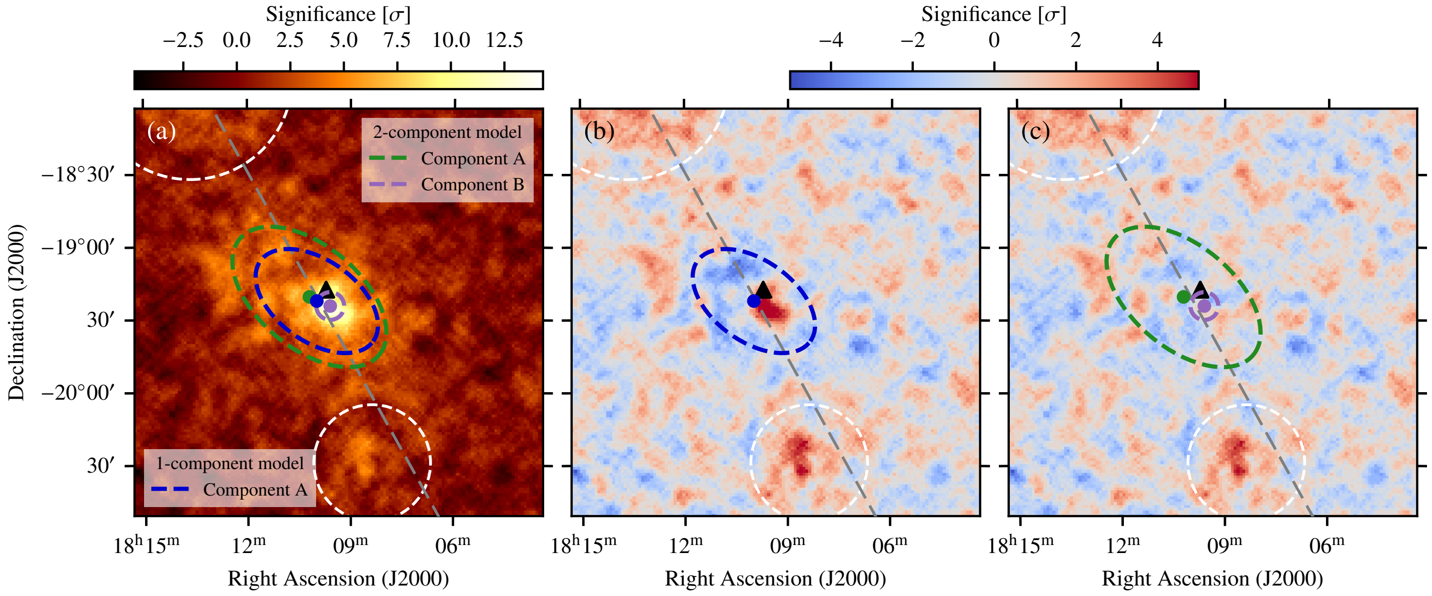
3D analysis fitting:

→ enabling multiple components to be simultaneously fit in spatial and energy dimensions

Especially powerful for studies of complex regions or sources with complex morphology

Examples: HESS J1702-420, HESS J1809-193...

https://gammapy.org/

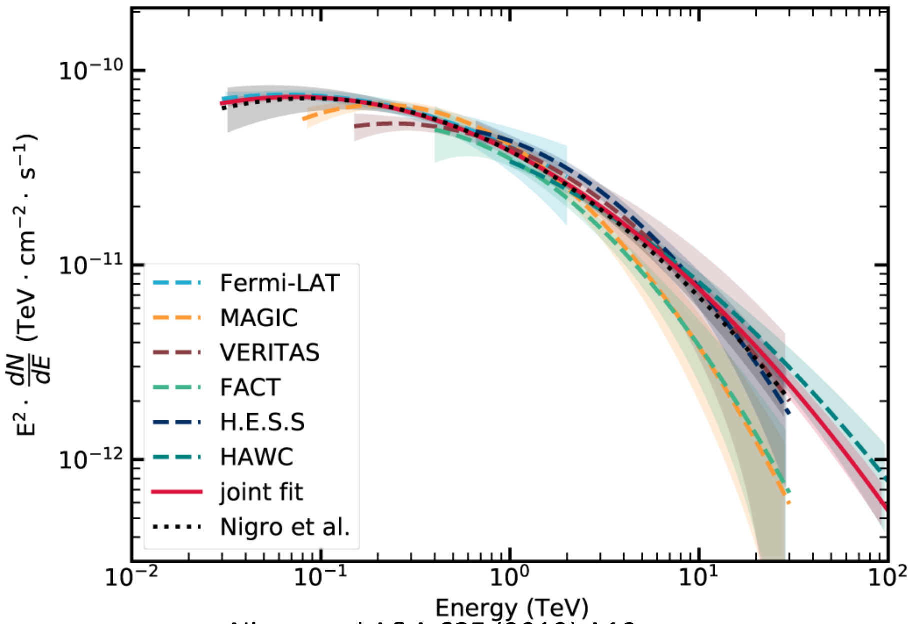


HESS Collaboration A&A **672** (2023) A103

Multi-instrument joint analyses

Common formats enable data from multiple instruments to be analysed simultaneously (GADF: gamma-astro-data-formats)

e.g. Multi-instrument fit to the Crab nebula spectrum: calibration source for VHE gamma-rays

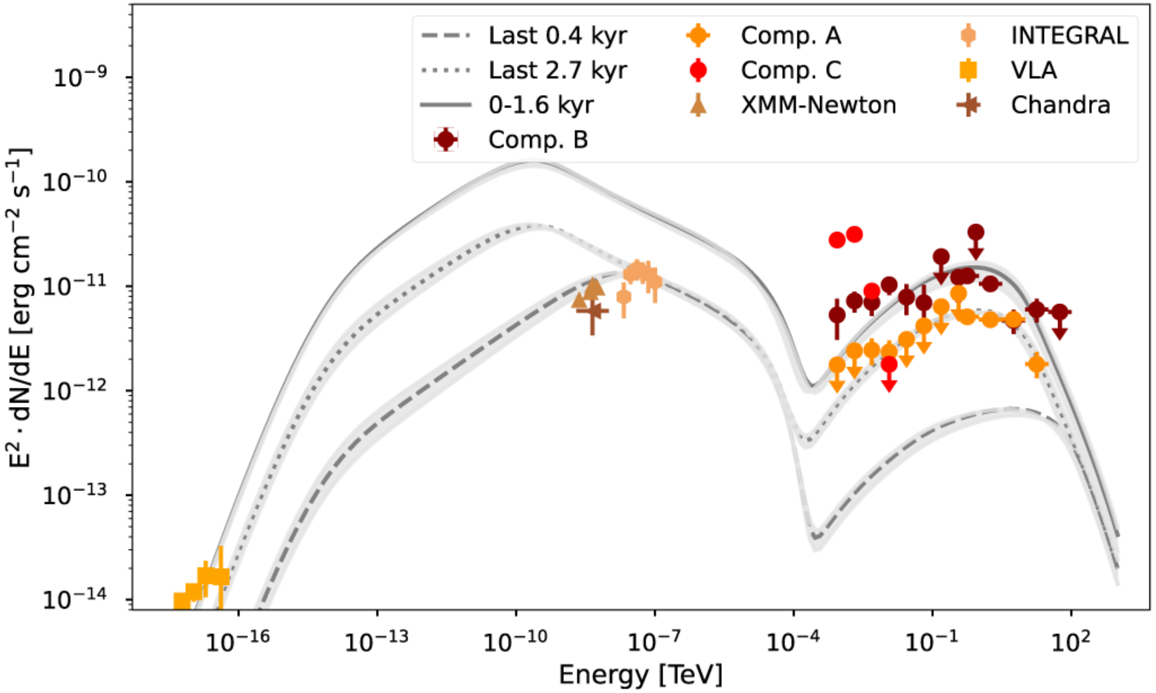


Nigro et al A&A **625** (2019) A10

HAWC collaboration A&A **667** (2022) A36

Simultaneous 3D fitting of data from multiple instruments e.g. Fermi-LAT and H.E.S.S. for HESS J1813-178

H.E.S.S. collaboration A&A **686** (2024) A149

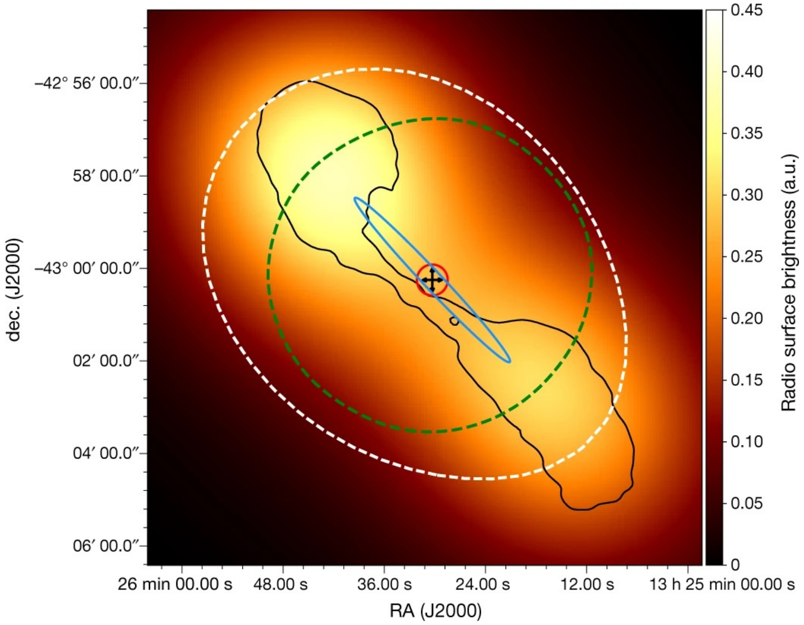


Active Galactic Nuclei: flaring activity, neutrinos?

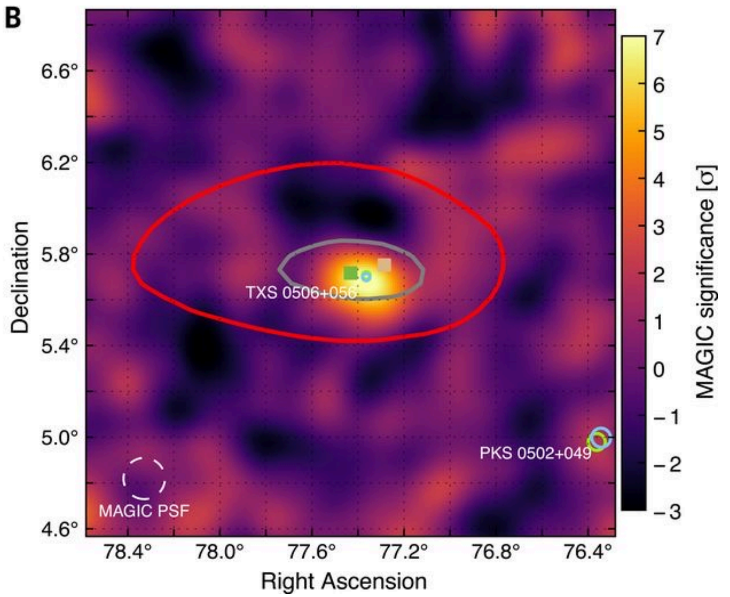
Majority of extragalactic sources – blazars

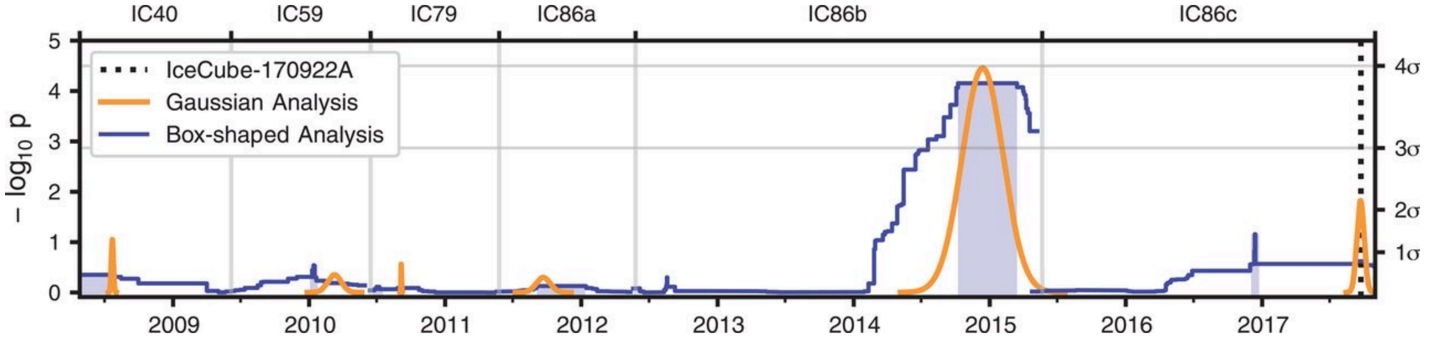
First indications of a neutrino source: TXS 0506+056 (z=0.3365)
Associated gamma-ray detection of flaring activity by Fermi-LAT & MAGIC
Chance coincidence disfavoured at ~3 sigma → **Multi-messenger astronomy**

Resolving extension of Centaurus A jets ≥ 2.2 kpc



H.E.S.S. collaboration Nature **582** (2020) 356-359





Science **361** (2018) eaat1378 Science **361** (2018) 147-151

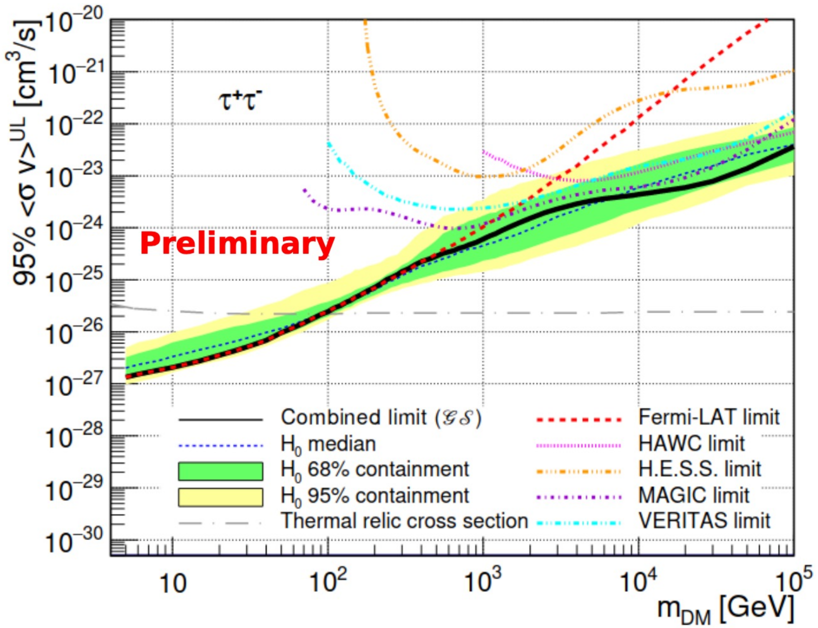
Searching for Dark Matter

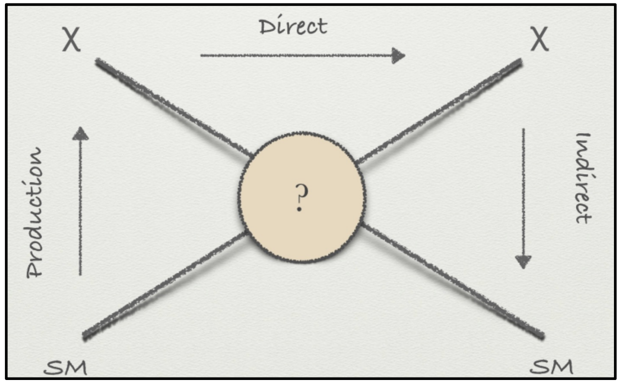
Dark Matter upper limits from observations of dwarf spheroidal galaxies

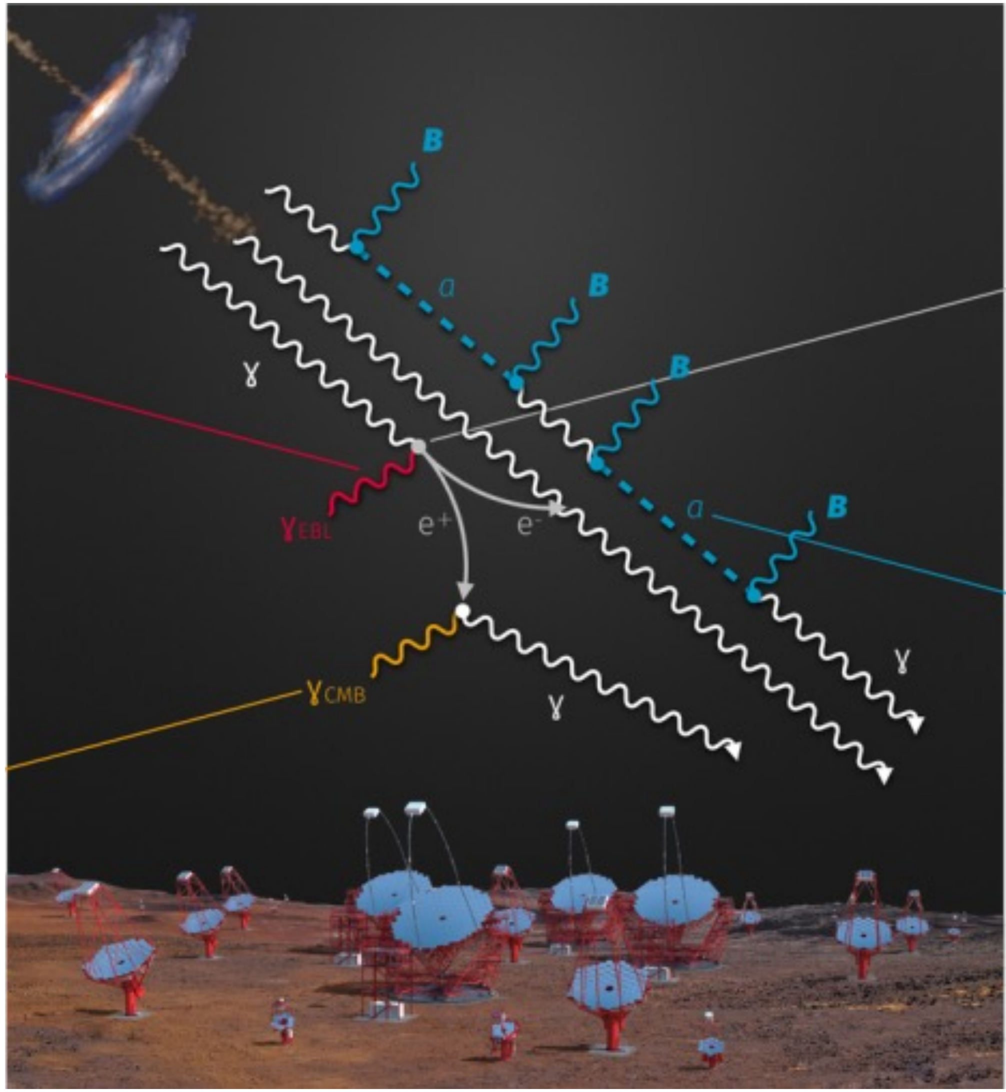
Combined likelihood more constraining

Other targets: Galactic centre, Galaxy clusters...

Other DM candidates: Axions → modify gamma-ray spectrum via a boost at high energies / reduction in EBL absorption







Kerszberg, Gamma2022

Biteau & Meyer https://www.cta-observatory.org/what-propogation-of-energetic-light-can-tell-us/

Future for IACTs

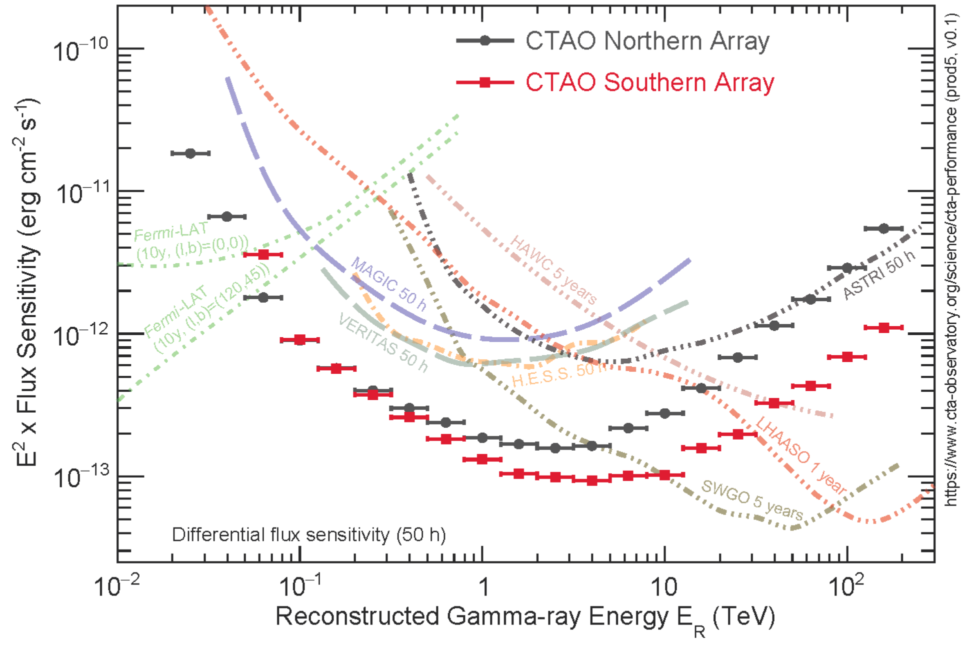
Current generation IACTs continue to make discoveries

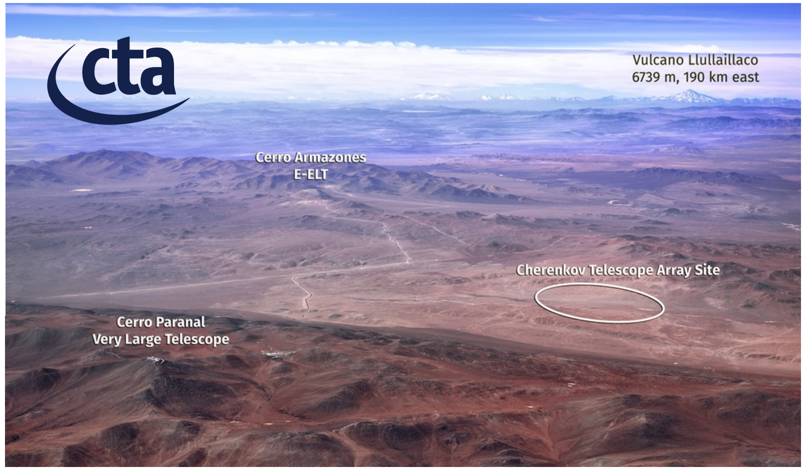
→ New source classes at TeV energies

First alert from a CTA telescope:
LST detects flaring activity from BL Lacertae (Atel 14783, 2021)

Forthcoming IACT facilities:

→ CTA-North La Palma, Spain
→ CTA-South Paranal, Chile
→ ASTRI mini-array Tenerife,





Strengths of IACTs:

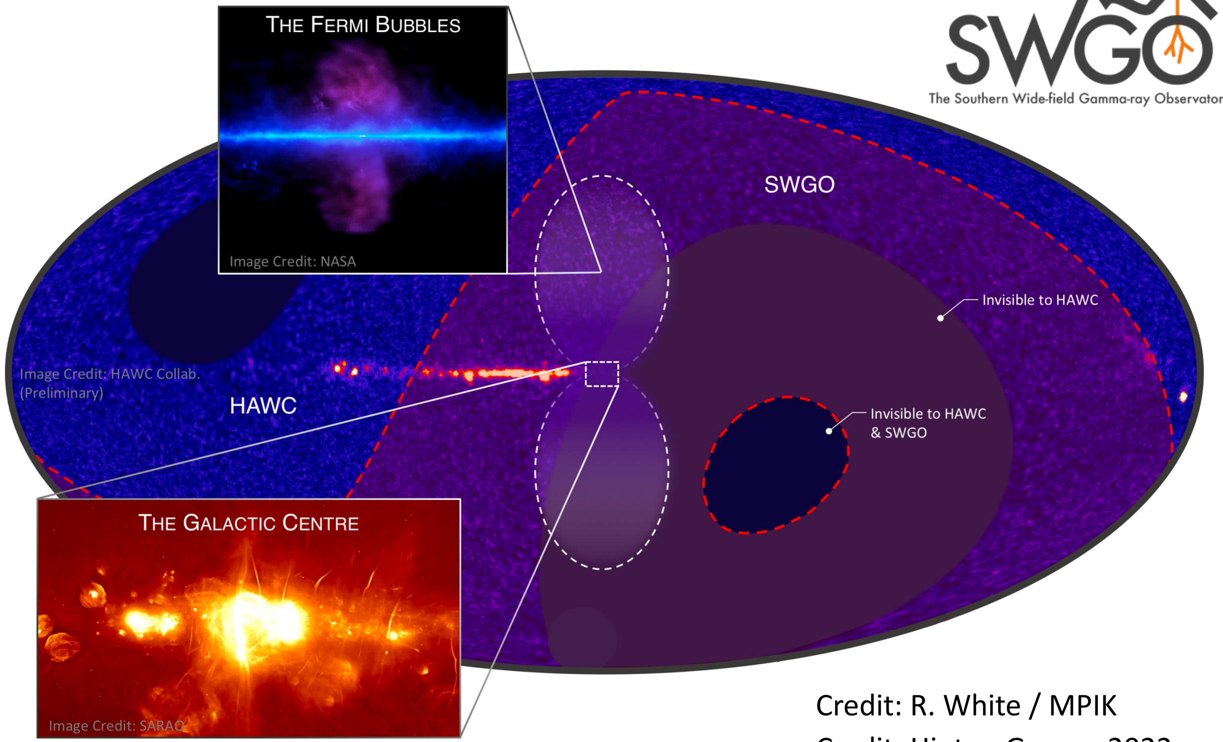
→ Good angular and energy resolution

→ Reaction and sensitivity to transient phenomena

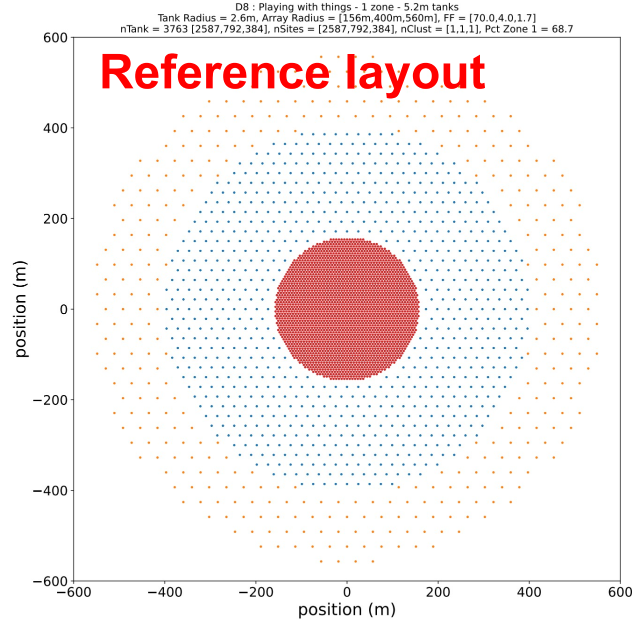
Southern Wide-field Gamma-ray Observatory

https://www.swgo.org/

- Ground-based water Cherenkov detectors are well suited to the highest energies and full sky surveys.
- Impressive results from current experiments (HAWC, LHAASO...)
- Future → observe the Southern sky
- (Galactic Science for SWGO → E.O. Angüner & AM)



Credit: R. White / MPIK
Credit: Hinton Gamma2022



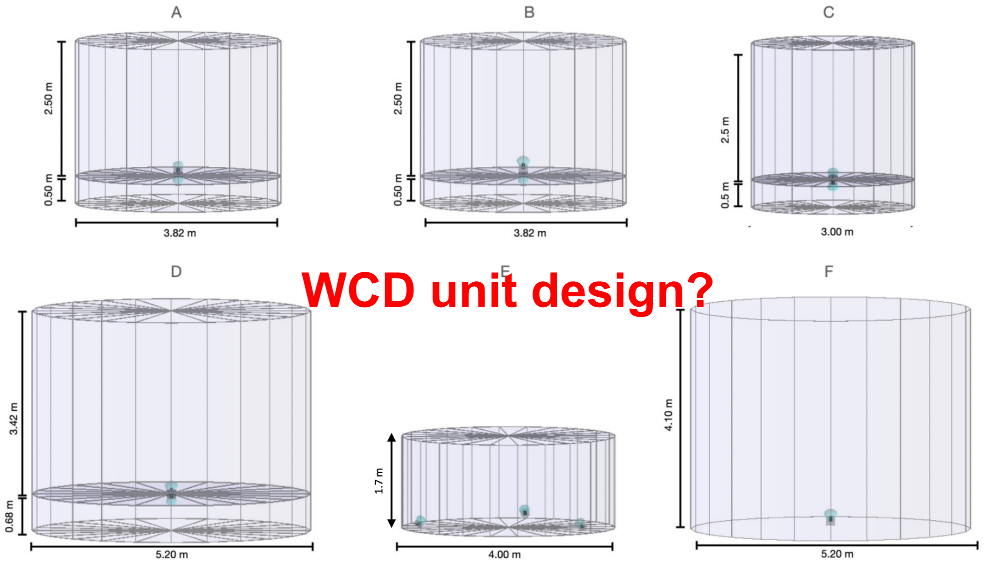
The Shortlisted sites are (in alphabetic order):

***Argentina*: Alto Tocomar** ; 24°12'16.22" S, 66°30'29.71" W (4800 m.a.s.l)

***Chile* : Pampa La Bola** ; 22°56'41.30" S, 67°40'39.09" W (4770 m.a.s.l)

***Peru* : Imata** ; 15°50'40.4" S, 71°03'56.7" W (4500 m.a.s.l)

Location shortlist



Outlook

- H.E.S.S. telescopes will continue until 2028
- Call for proposals this autumn for 2025 – 2028 period
- Ideal opportunity to strengthen ties with other multiwavelength facilities in Africa

- Gamma-ray view of the **Southern** sky will be enhanced soon by
  CTA-South (Chile)
  SWGO (Argentina / Chile / Peru → decision **this week**)

- Looking forward to a constructive week
  → new ideas, new collaborations

Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Thank you for your attention

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