Studying PeVatron candidates with VERITAS and PANOSETI

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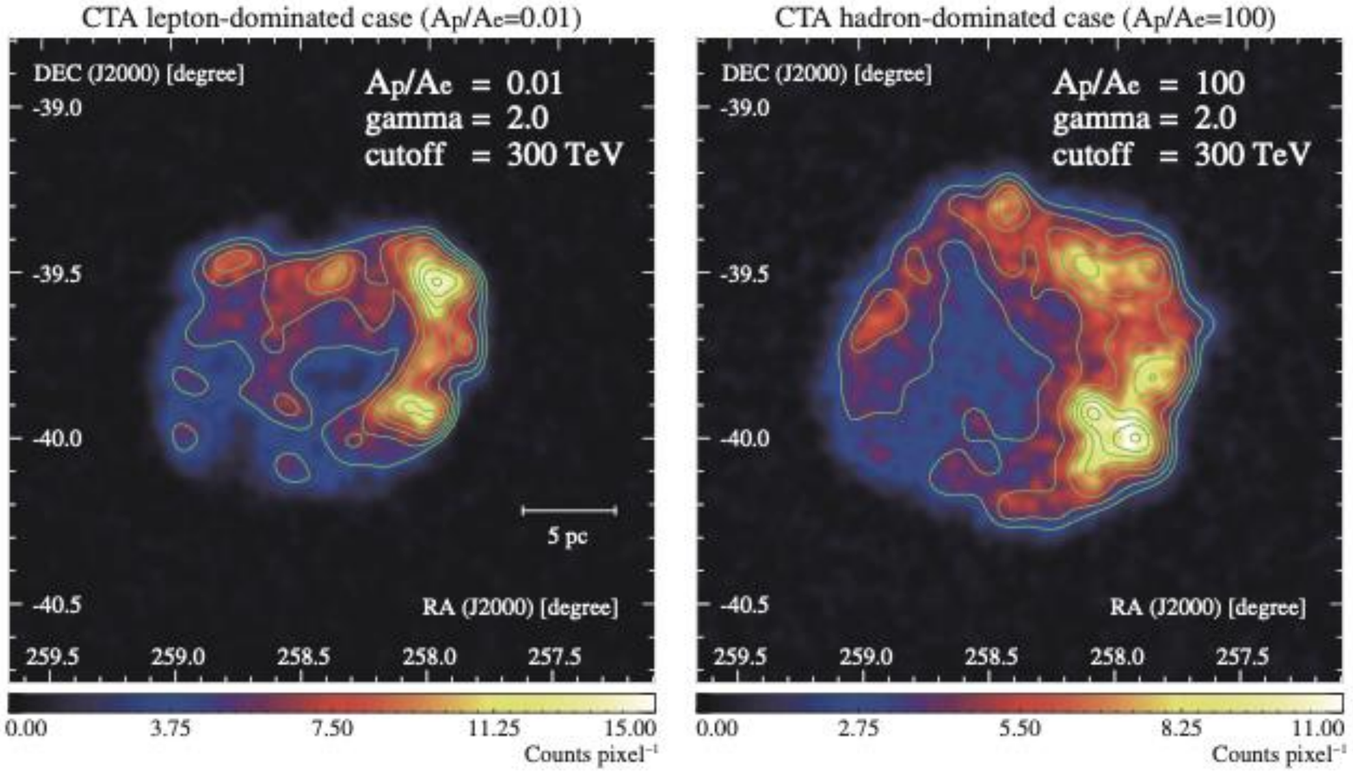
CDHY PeVatron Workshop
Oct 8 – 10, 2025
Nevis Labs, Columbia University

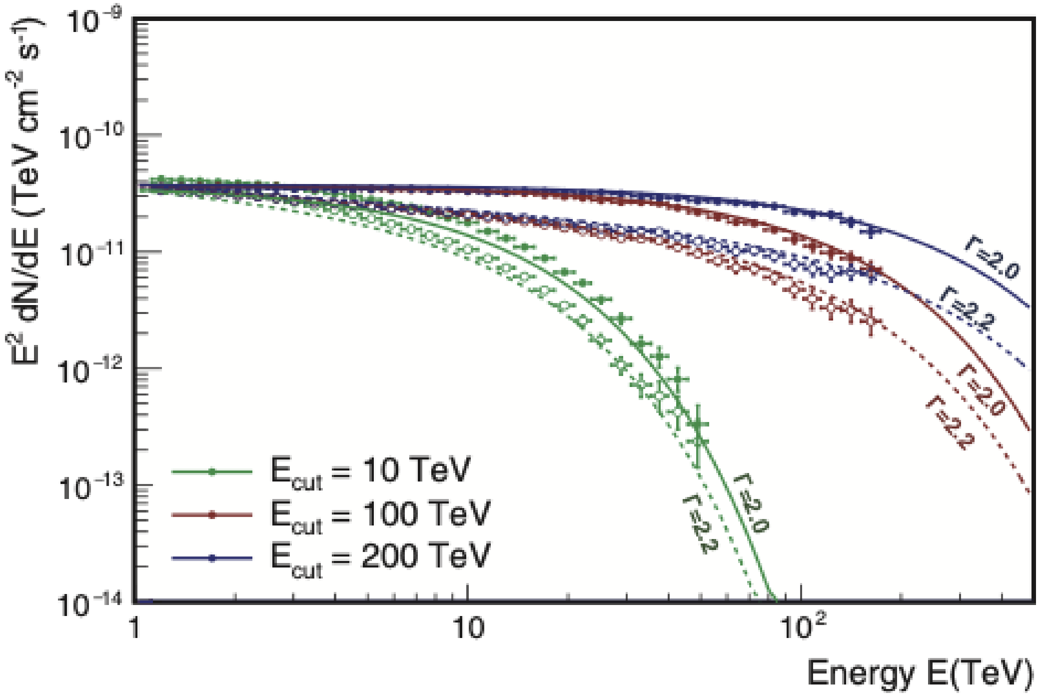
Motivations: Why look for PeVatrons with IACTs?

- What are the sources of the Galactic cosmic rays?
- What are the “PeVatrons” accelerating protons and nuclei up to 10^{15} eV and beyond?
- Current imaging atmospheric Cherenkov telescope arrays can only study gamma-ray sources up to typically 10’s of TeV.
- But 100 TeV gamma-ray emission results from PeV protons.
- Hadronic PeVatron signatures can be both spectral **and** morphological. IACTs provide excellent spectral and angular resolution.

Simulated CTAO gamma-ray sky maps for RXJ 1713.7-3946



Simulated CTAO spectra for a PeVatron source, using different indices and cut-off values

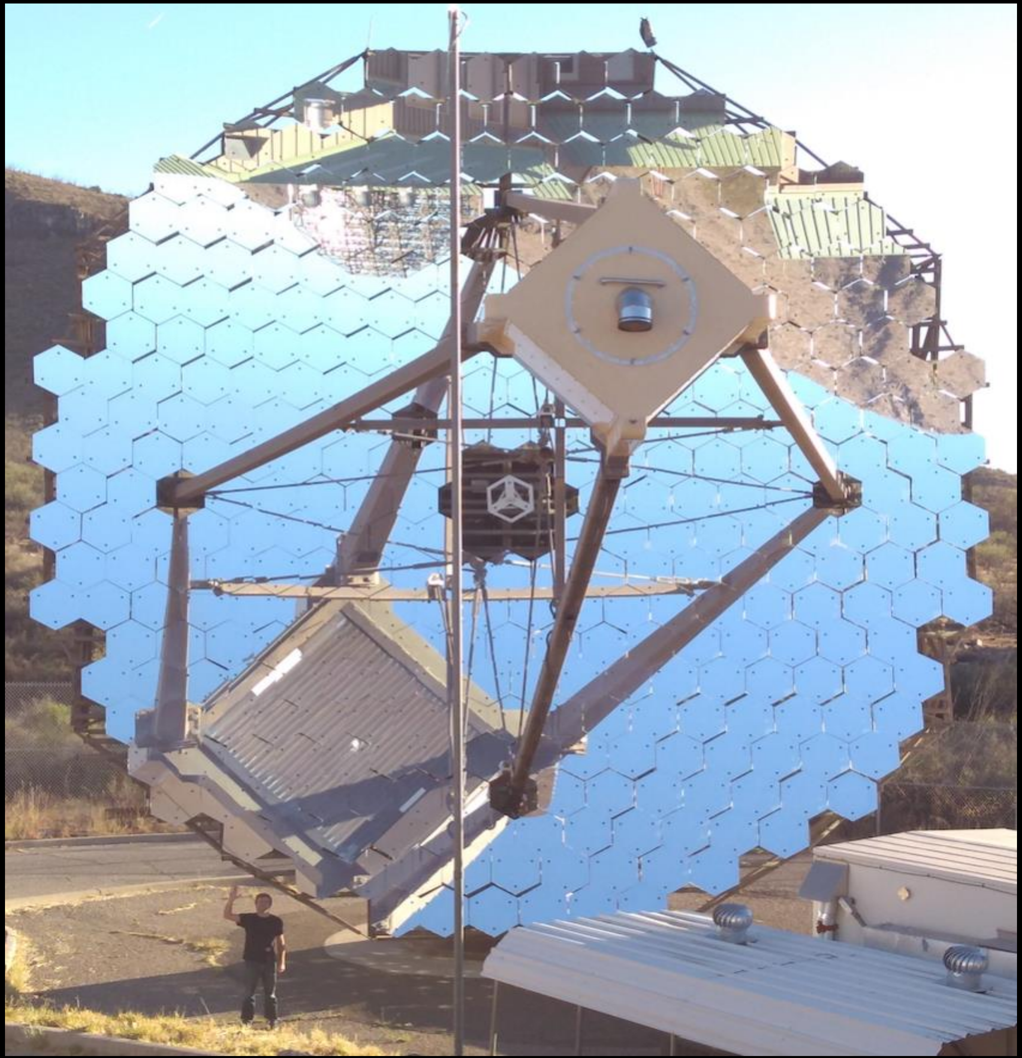


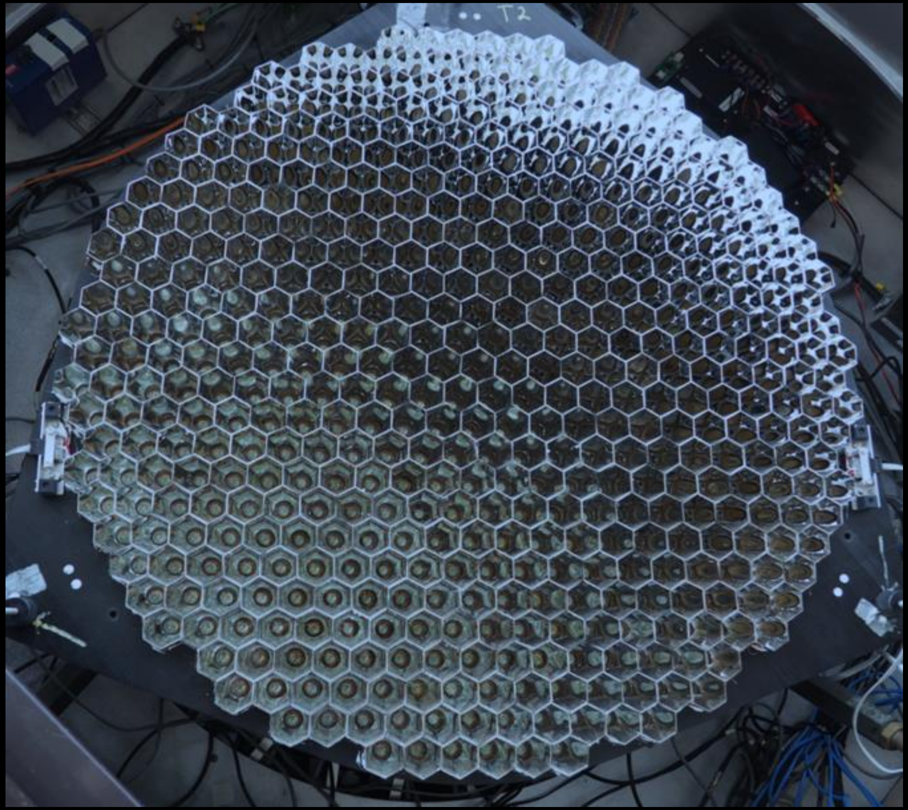
From “Science with CTA”

VERITAS

VERITAS

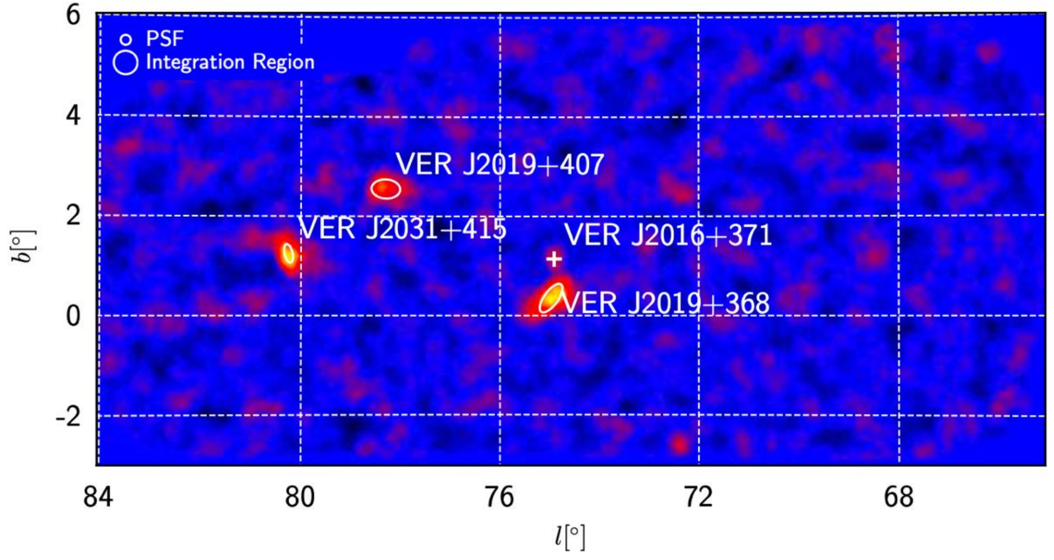
- Each telescope has an aperture of 12 meters (~110 m^2).
- Each has a 499-pixel photomultiplier tube camera, with a 3.5 degree diameter field of view.
- A trigger requires a coincidence between at least 2 of the 4 telescopes within 50 ns.
- The signal from each pixel is recorded with 2ns sampling flash-ADCs

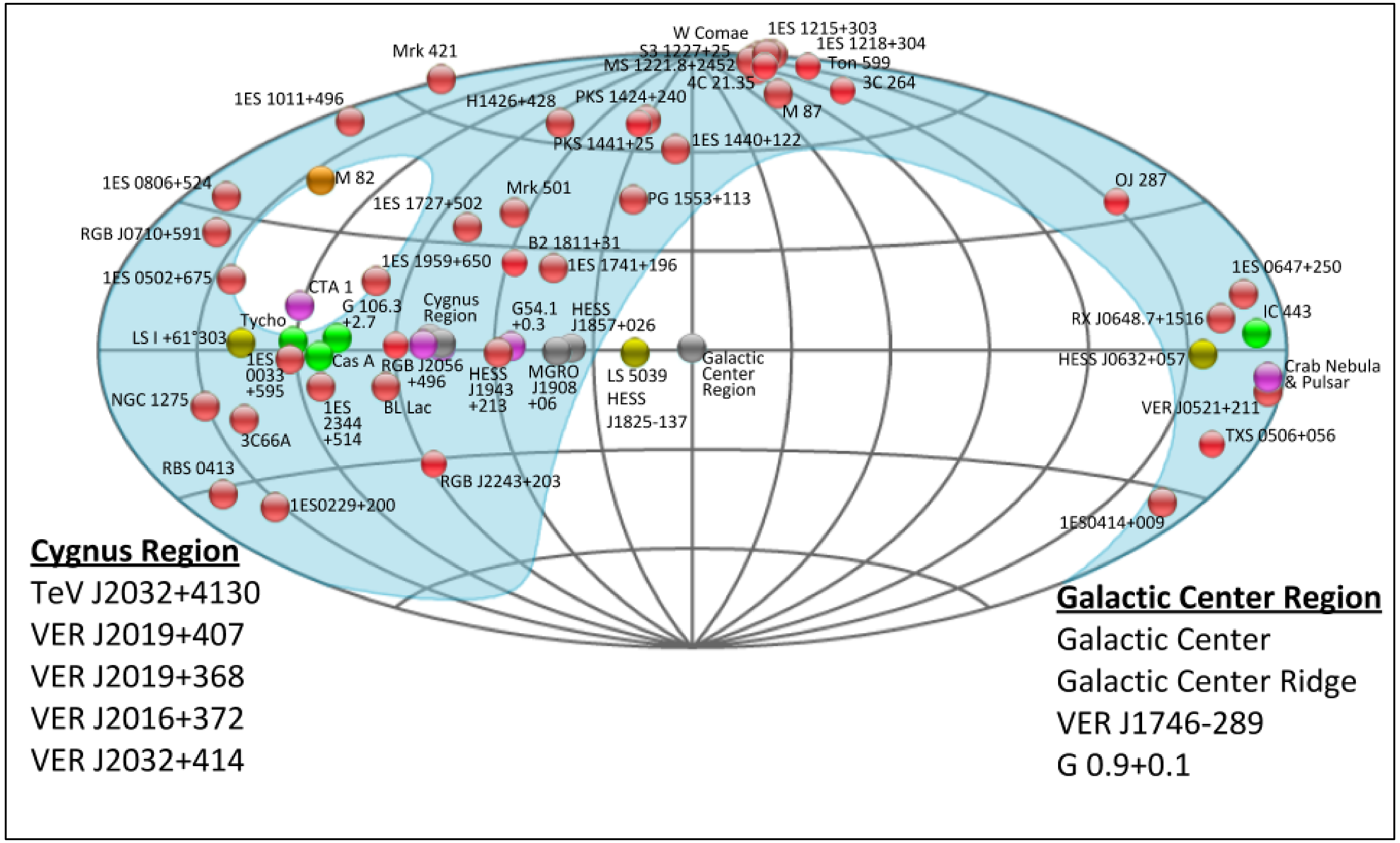




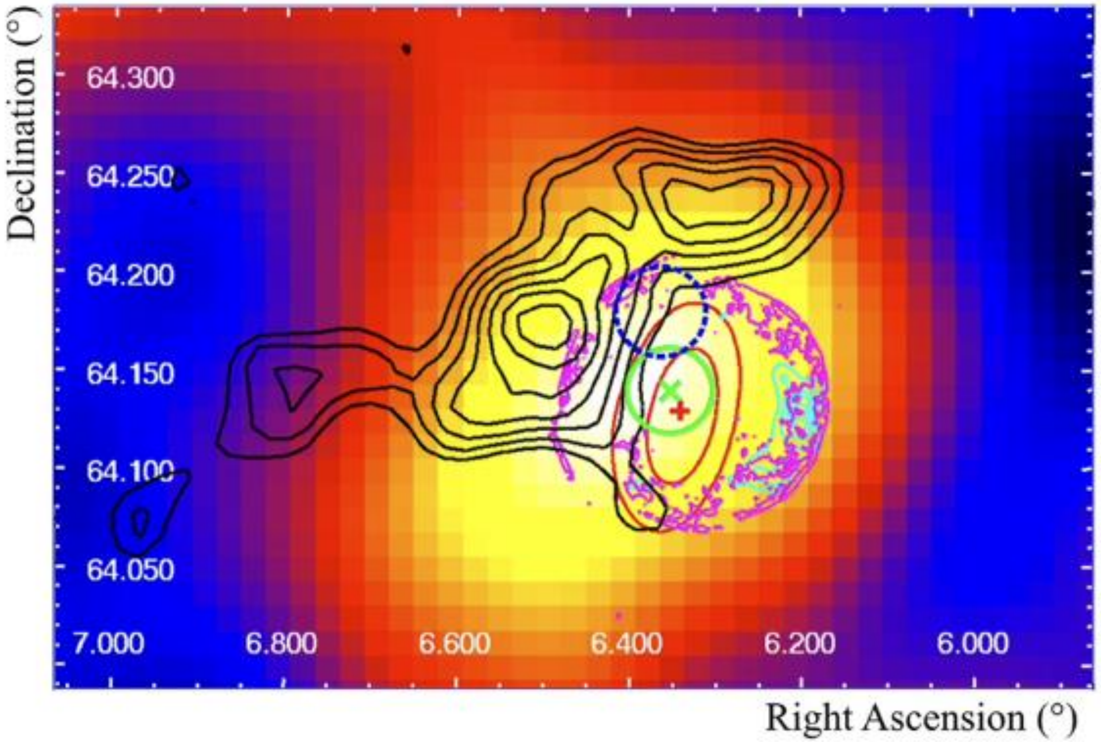
- VERITAS now has a rich catalog of ~70 sources.
- We have also surveyed the Cygnus region of the Galactic Plane.
- A third of VERITAS sources are Galactic, including SNR, PWN, binaries and sources whose nature is not yet established.

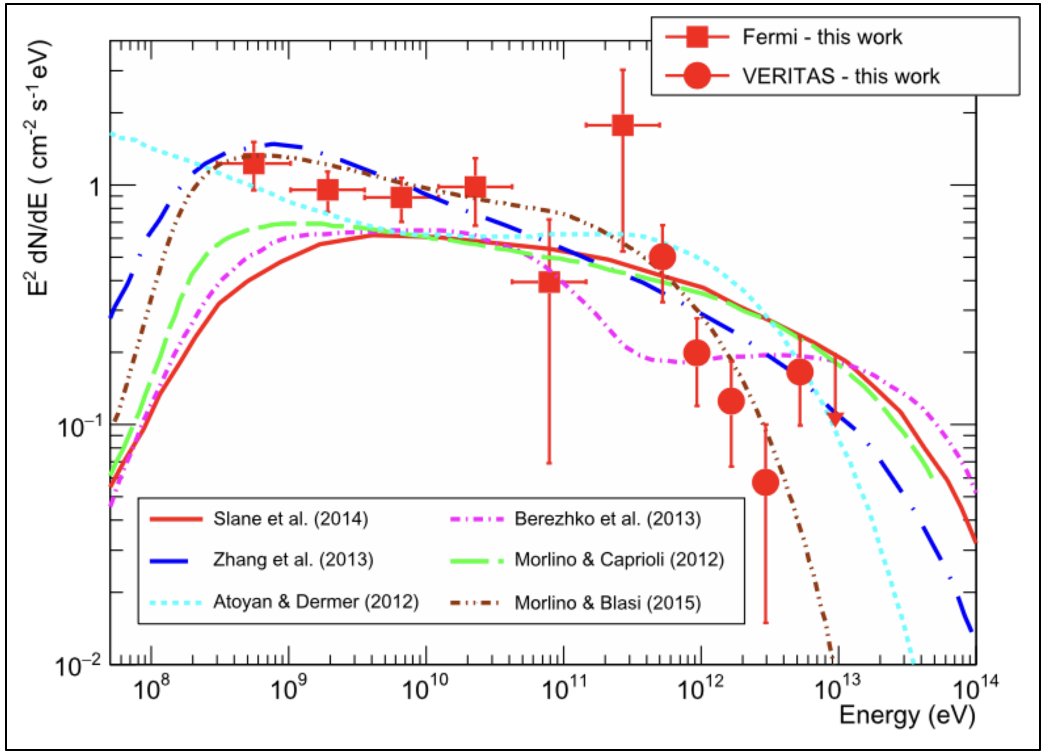
Cygnus region survey



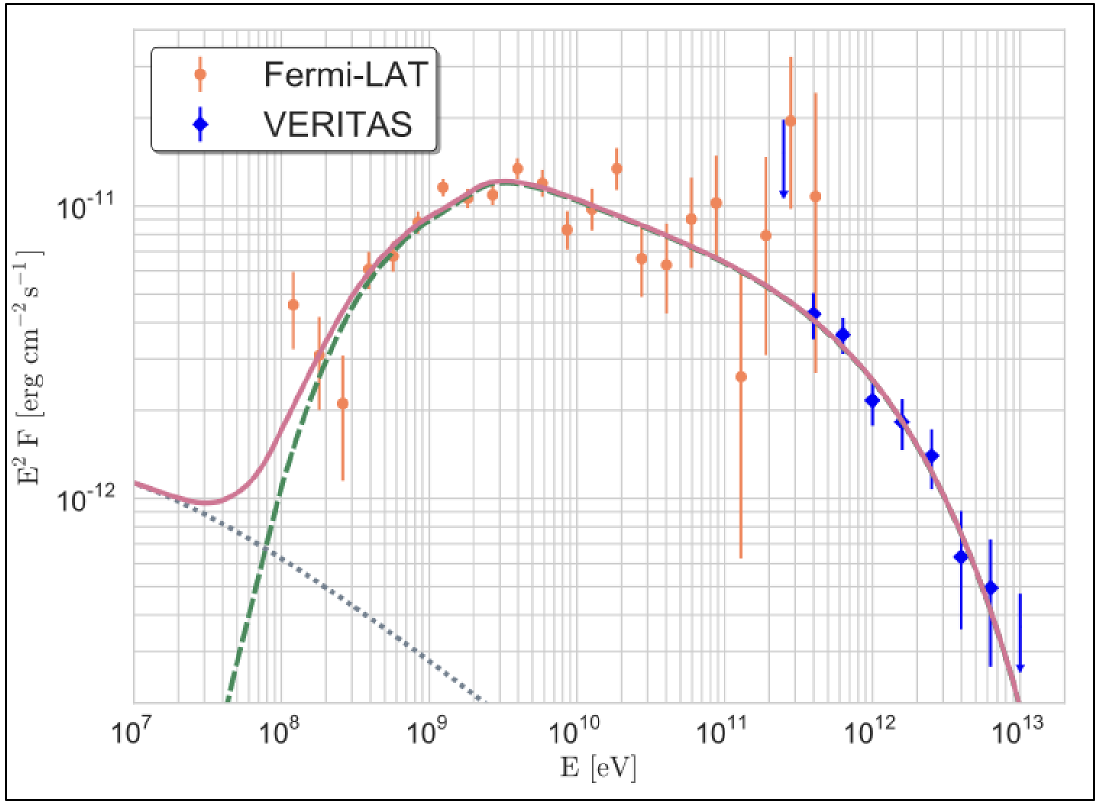


- Among these, supernova remnants provide compelling PeVatron targets.
- Young (i.e. historical) remnants may be the most efficient.
- VERITAS discovered TeV emission from **Tycho's SNR** in 2011 (<1% Crab)
- 150 hours of VERITAS observations, combined with Fermi-LAT results, now show spectral softening in the VHE range, suggesting a low maximum particle energy. Tycho is not a PeVatron.





- **Cas A** is the remnant of a Type IIb supernova
- It is also much brighter at TeV (>3% Crab)
- VERITAS (and MAGIC) results again show a cut-off above ~ 2 TeV.
- The maximum energies obtained for protons are 21 TeV and 6 TeV for purely hadronic and lepto-hadronic models, respectively.

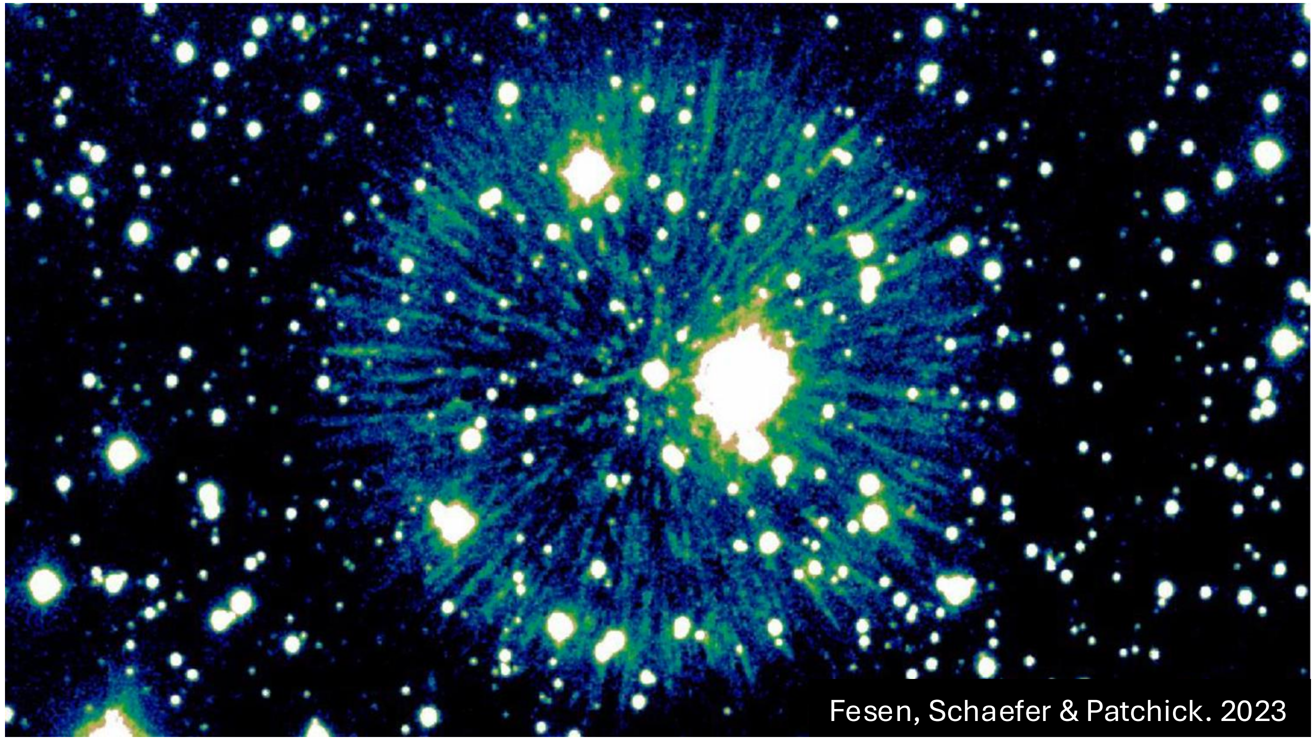


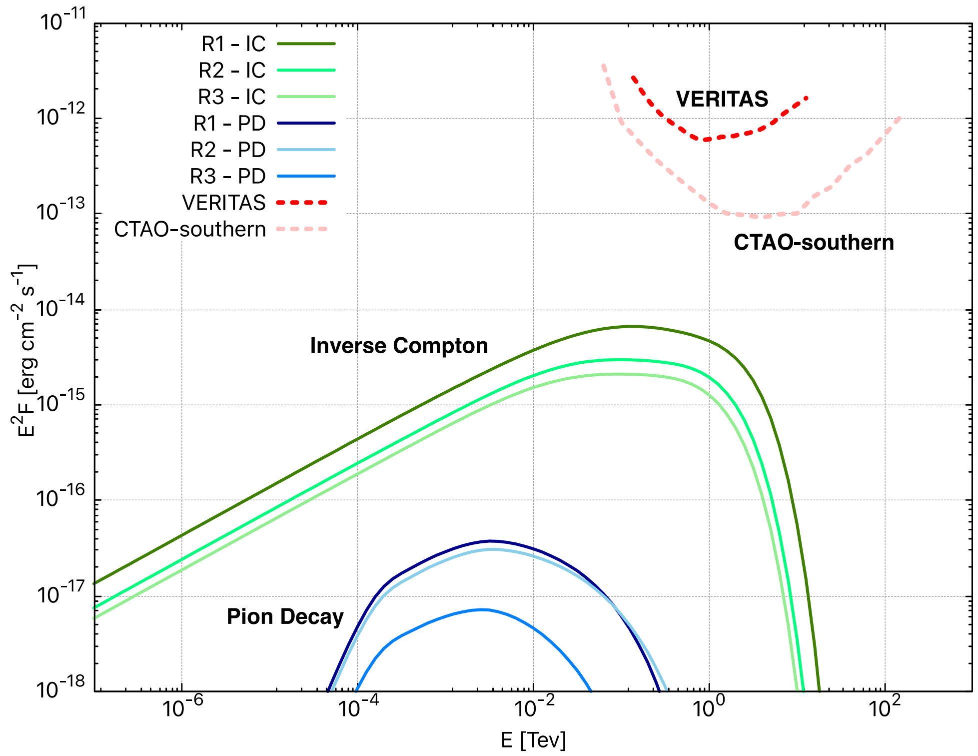
This shows the purely hadronic model, with TeV emission due to pion-decay.

In the lepto-hadronic model the highest-energy TeV emission is generated by the highest-energy inverse Compton contribution.

A pure leptonic model is ruled out by the broadband spectral shape (it predicts a peak at 100 GeV)

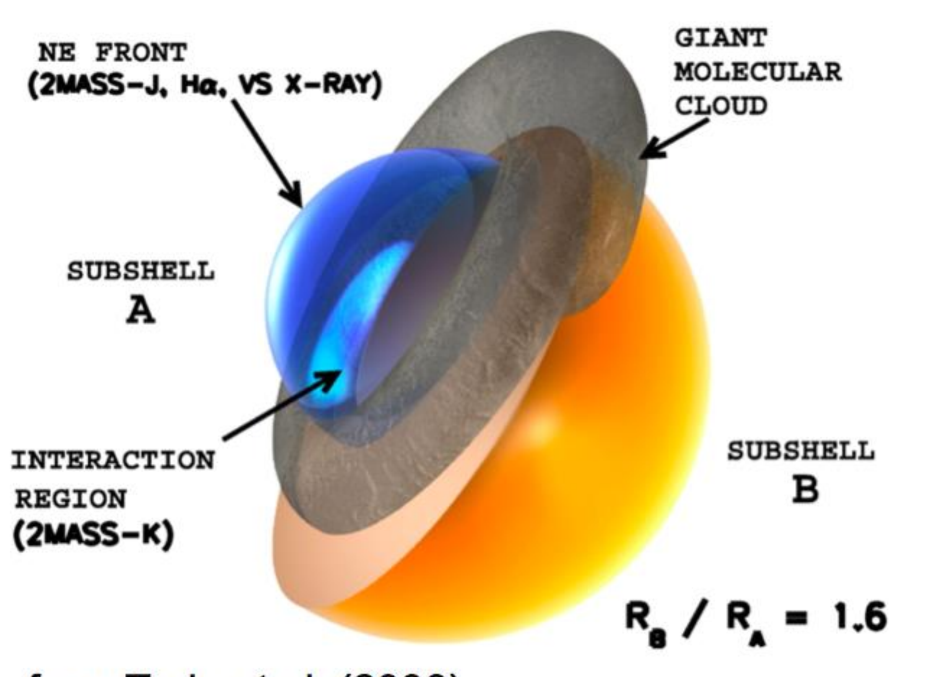
- We have also recently searched for emission from the newly identified remnant of **SN 1181**.
- This was likely a Type Iax supernova (WD-WD merger).
- Low energy explosion, expanding into a low density medium.
- No evidence for a signal – but unsurprising: modelling suggests any gamma-ray flux would be far below VERITAS and CTAO sensitivities


Fesen, Schaefer & Patchick. 2023

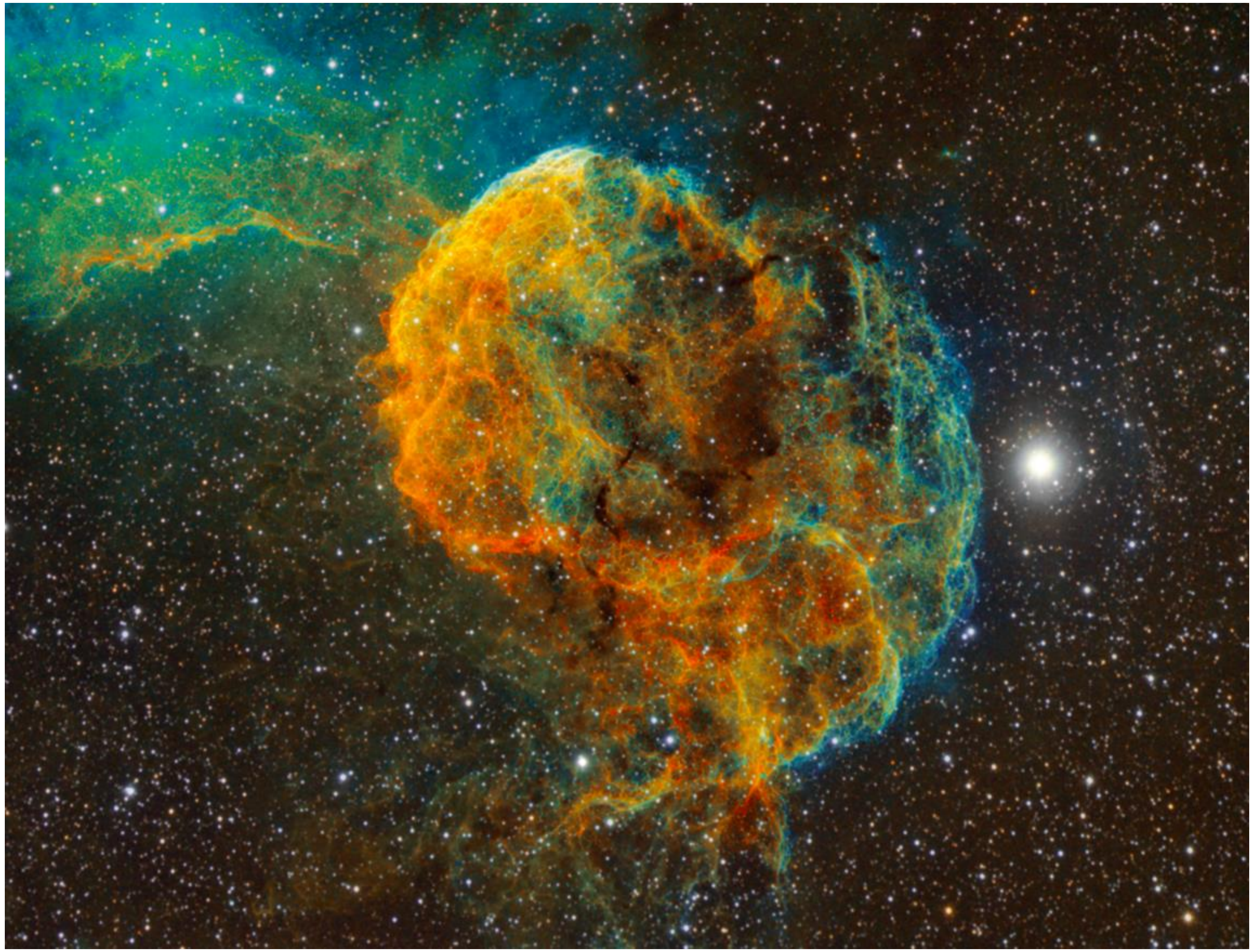


- Historical SNR do not appear to be cosmic ray PeVatrons.
- What about interacting, middle-aged SNR?

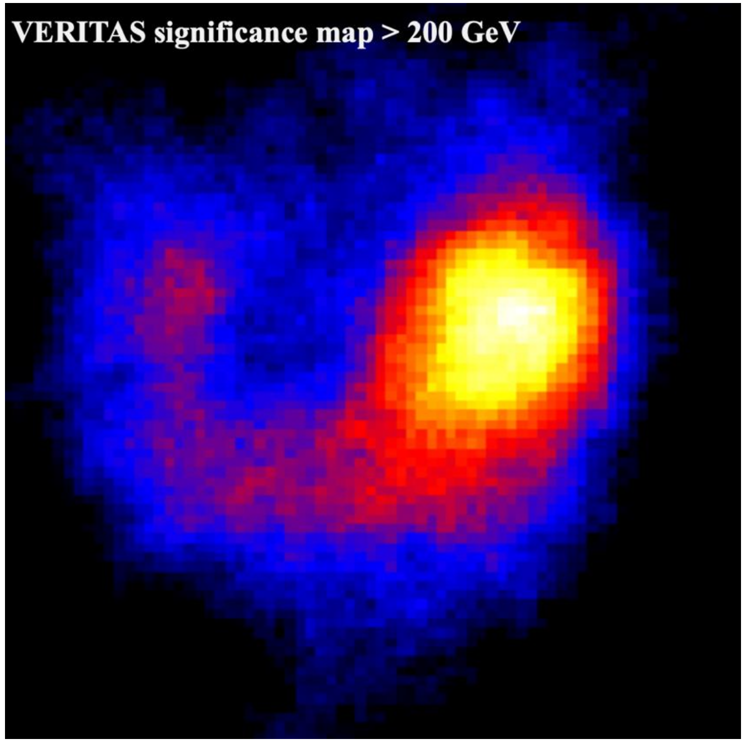
IC 443: A middle-aged (3-30kyr) supernova remnant in a complex environment.

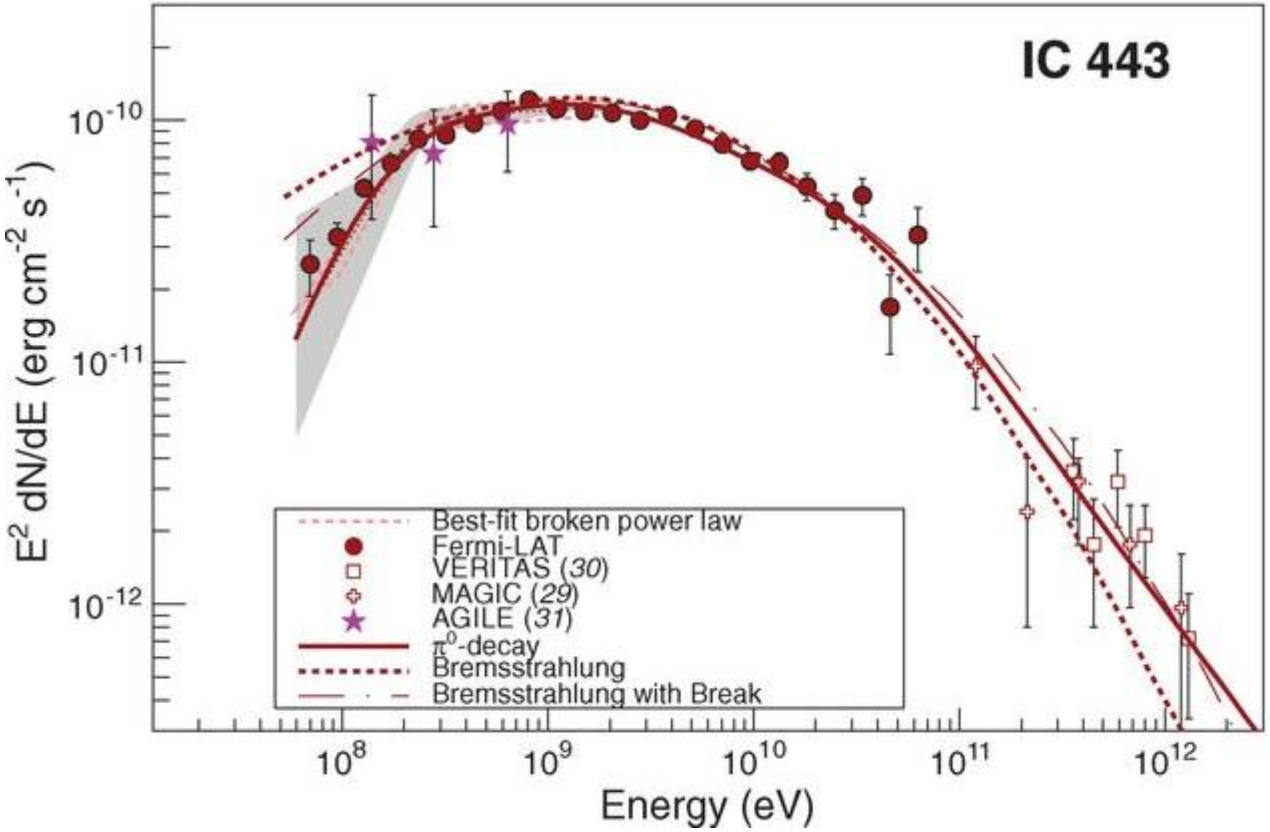


from Troja et al. (2006)



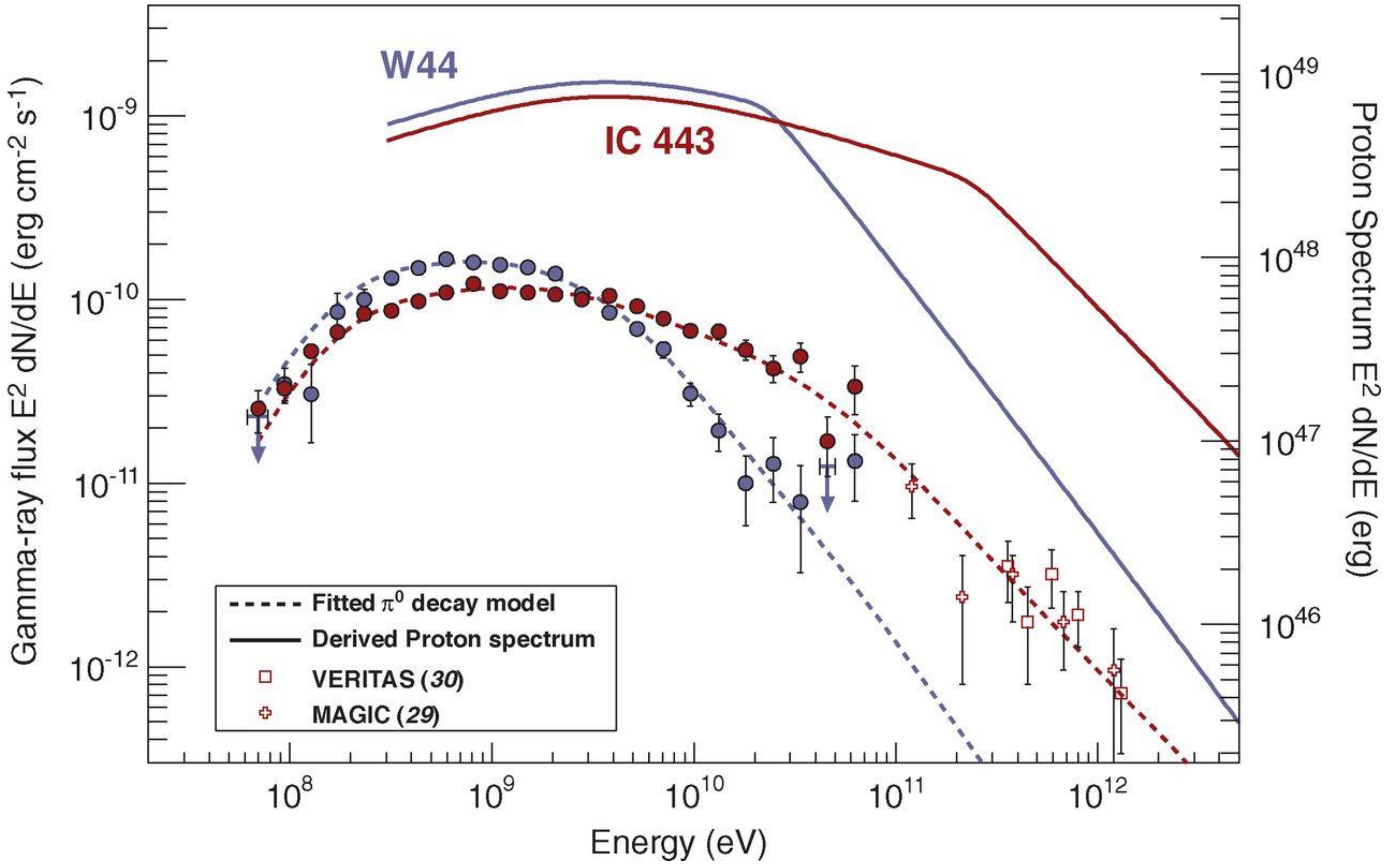
- VERITAS detects bright, extended TeV emission from the remnant.
- Fermi-LAT clearly measures a low energy break, consistent with the pion bump due to cosmic ray proton interactions.





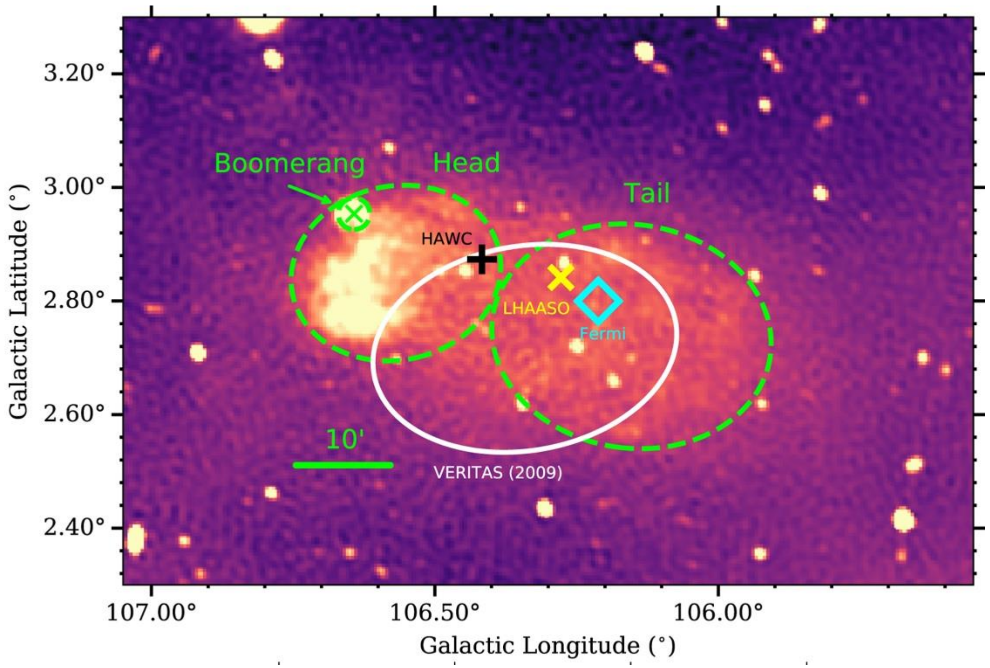
Ackermann et al, Science, 339, 807 (2013)

- But the underlying proton spectrum does not extend to PeV energies.

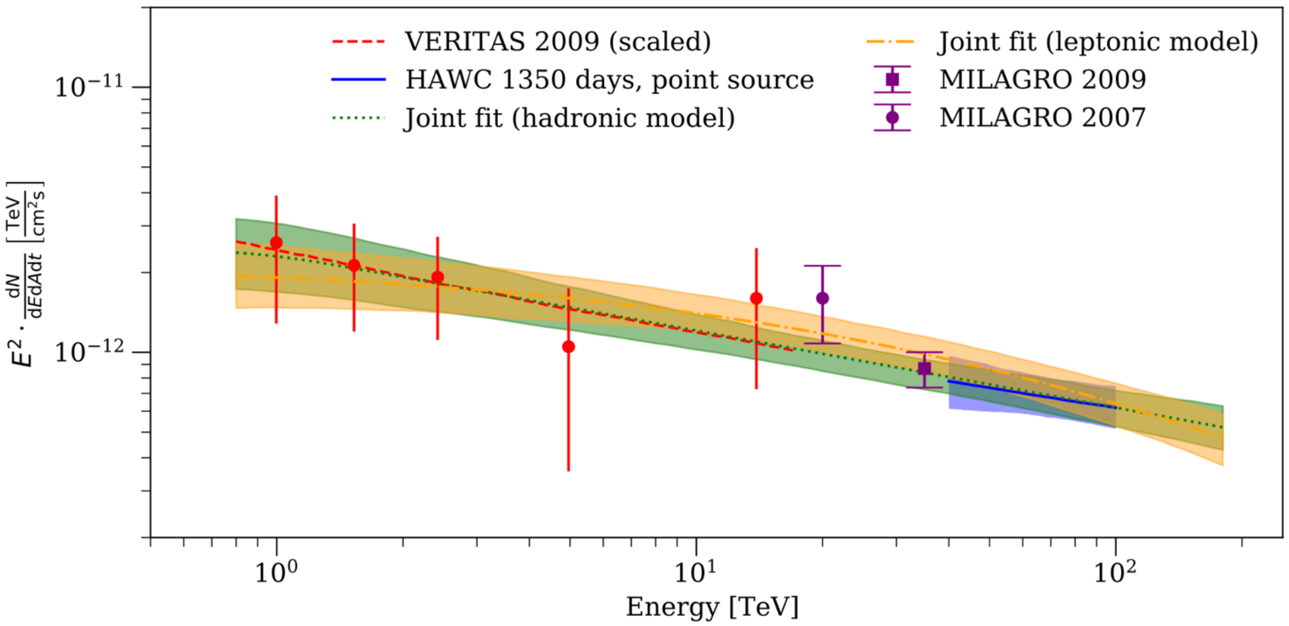


Ackermann et al, Science, 339, 807 (2013)

- One of the best PeVatron candidates in the northern sky was first firmly identified as a gamma-ray source by VERITAS in 2009.
- **SNR G106.3+2.7** is a complex composite SNR, comprising a pulsar, a boomerang-shaped PWN and distinct 'head' and 'tail' regions.
- HAWC see >100 TeV emission from the head region (HAWC J2227+610), implying protons above 800 TeV.

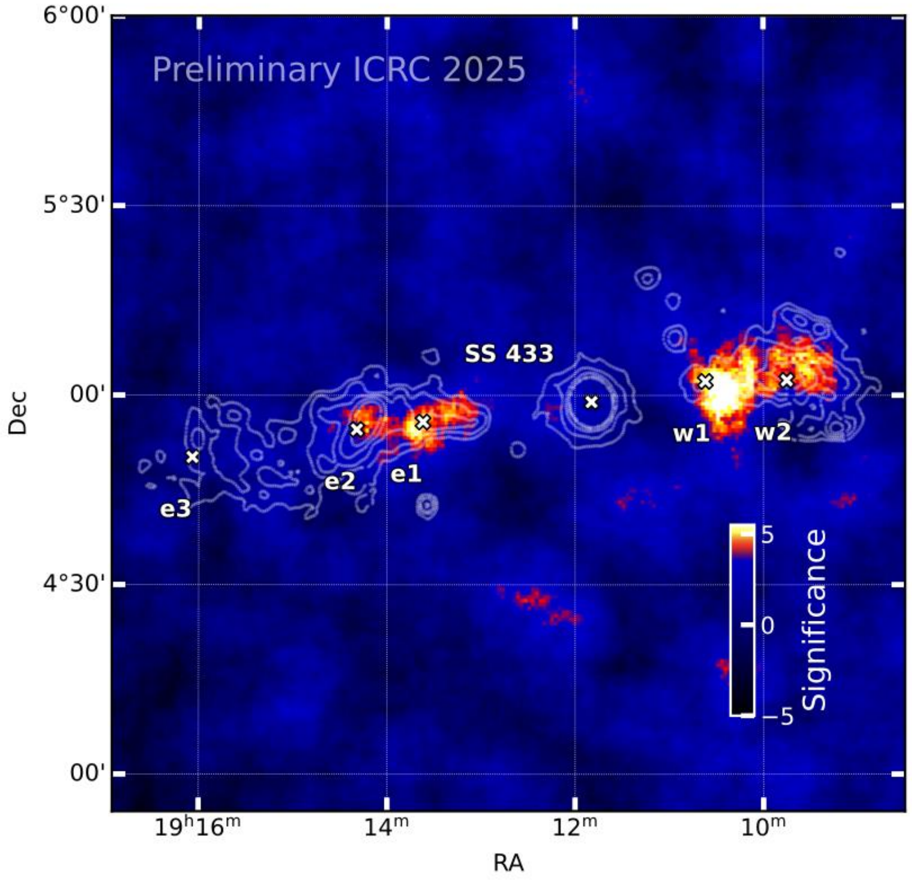


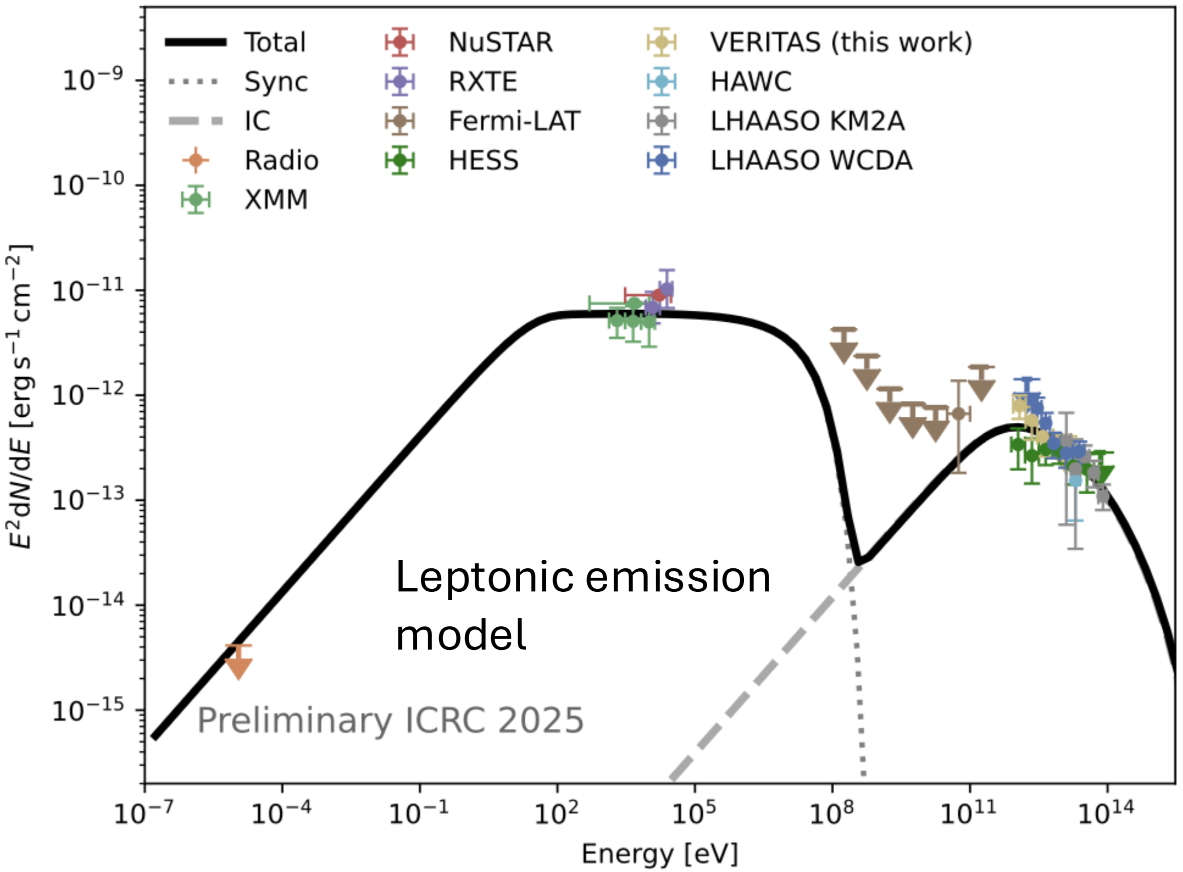
Pope et al., ApJ, 960, 75 (2024)



Albert et al., ApJL, 896, L29 (2020)

- VERITAS is also contributing to the exciting new topic of gamma-ray emitting microquasar outflows.
- Results on **SS 433** from this year's ICRC.



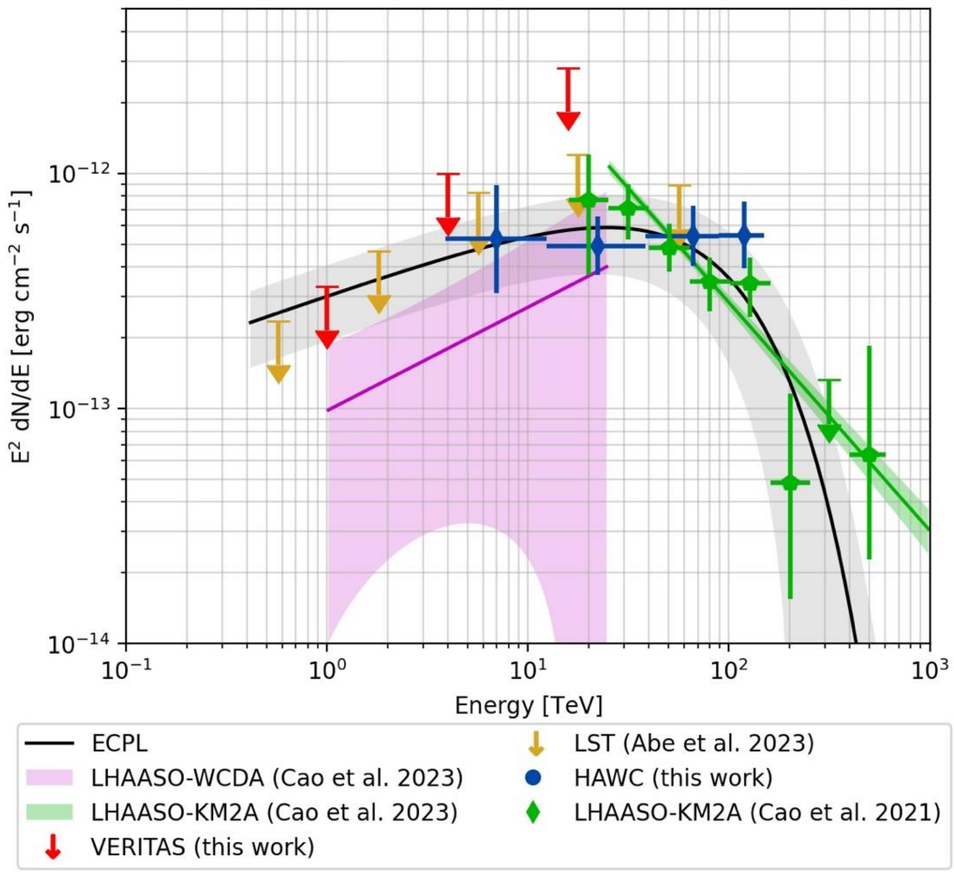


https://arxiv.org/abs/2509.21063

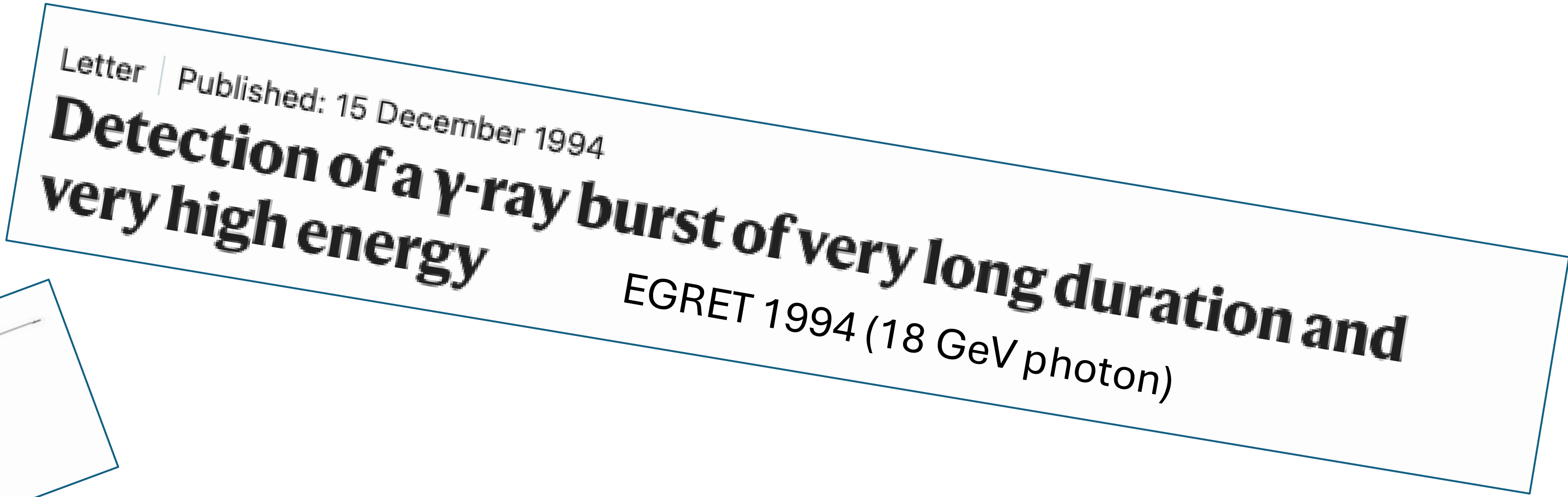
- LHAASO results provide a wealth of new potential PeVatron targets for VERITAS.
- Matthew will report on these in more detail later today. But a common feature of many is a *low* energy (<10 TeV) spectral hardening, which places them below the sensitivity of VERITAS and other IACTs.

LHAASO J2108+5157 is a bright LHAASO source with no clearly identified counterpart at other wavelengths.

VERITAS and LST-1 limits confirm the <10 TeV spectral hardening measured by WCDA.



- The most exciting gamma-ray science during the design phase of VERITAS in the late 1990’s was extragalactic.
- The Crab was the only convincing Galactic source.
- All known TeV sources were point-like.


Letter | Published: 15 December 1994

Detection of a γ-ray burst of very long duration and very high energy

EGRET 1994 (18 GeV photon)


GAMMA-RAY ASTRONOMY

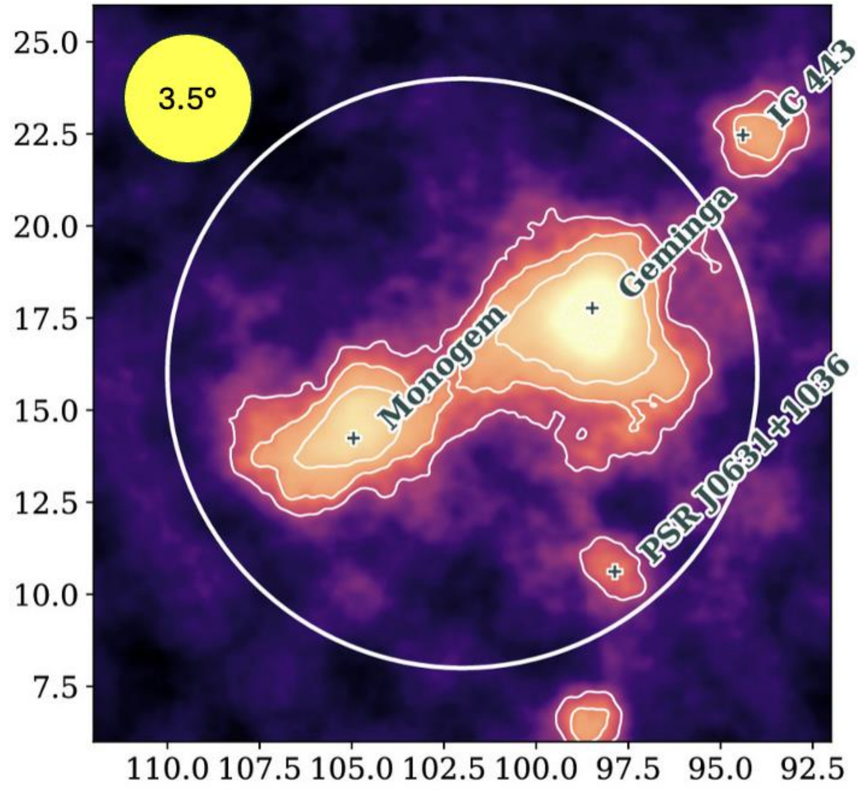
Catching photons from hell

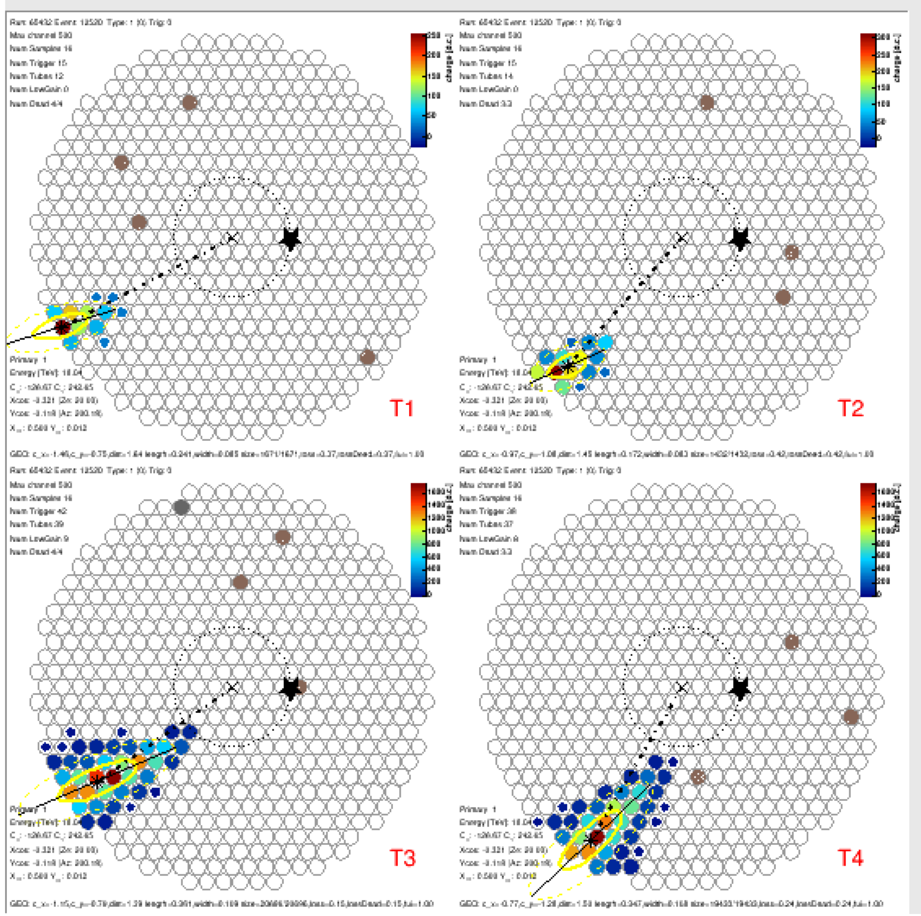
Francis Halzen

Mrk 421, 1992

The VERITAS design is optimized for maximum sensitivity to point sources in the energy range 100 GeV - 10 TeV (Weekes, 2001)

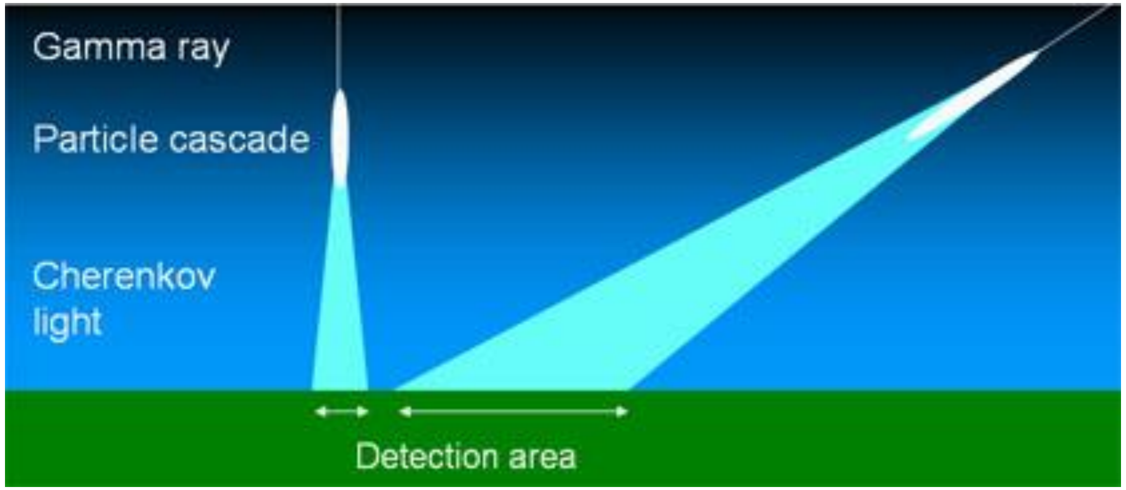
- This likely influenced design decisions – such as small cameras.
- Difficult to reconstruct high energy events with large core distances.
- Also adds challenges to modelling the background and analysing very extended sources.



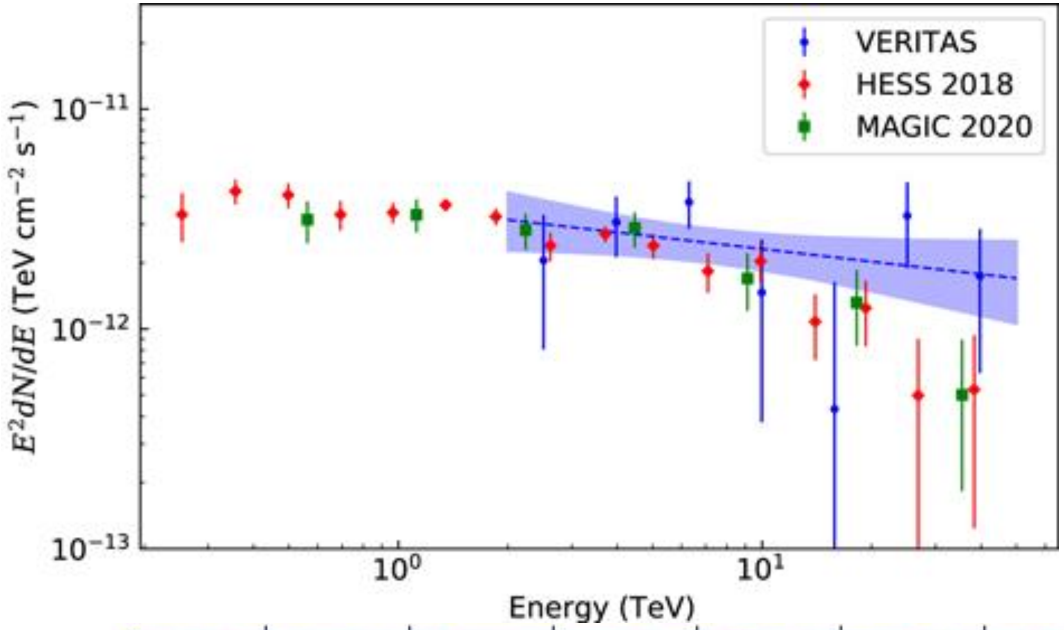


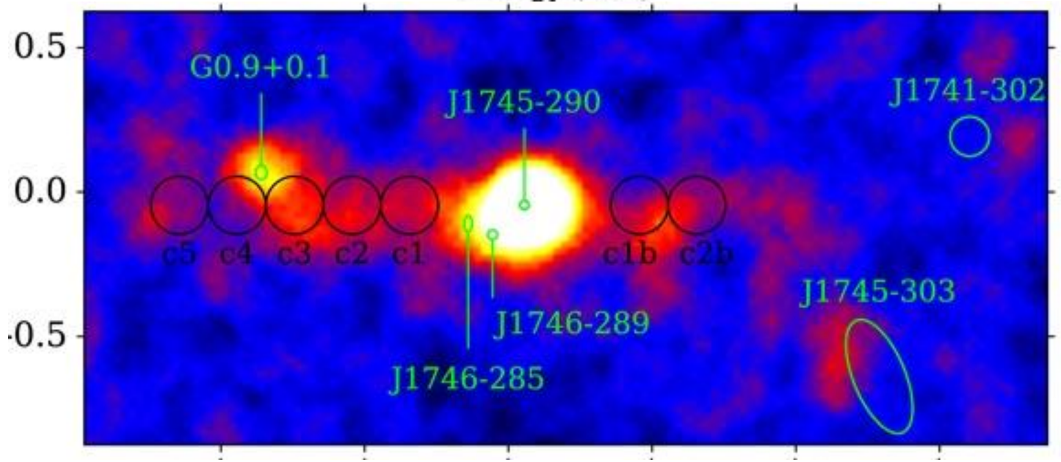
Simulated 18 TeV gamma.
274m core distance

- A 4-telescope array with 100m-spacing has an effective collection area largely defined by the size of the Cherenkov lightpool at ~1 TeV (~0.1 km^2).
- Large zenith angle observations can help. But this is only practical for a limited number of targets and adds systematic errors and other analysis challenges.



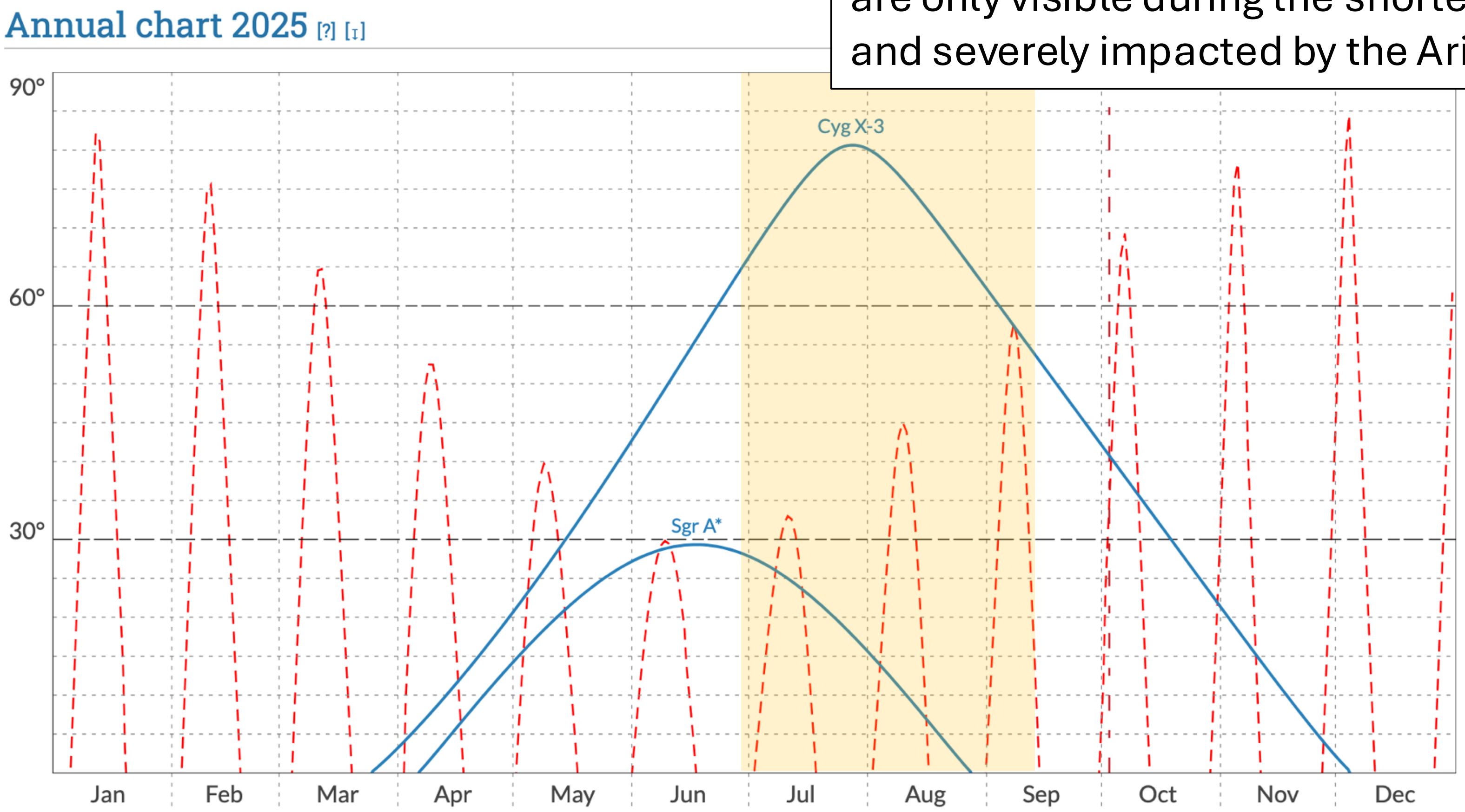
LZA observations of the Galactic Center region with VERITAS allowed us to measure emission from the GC ridge up to 40 TeV





- The location of VERITAS also presents challenges for Galactic PeVatron searches.

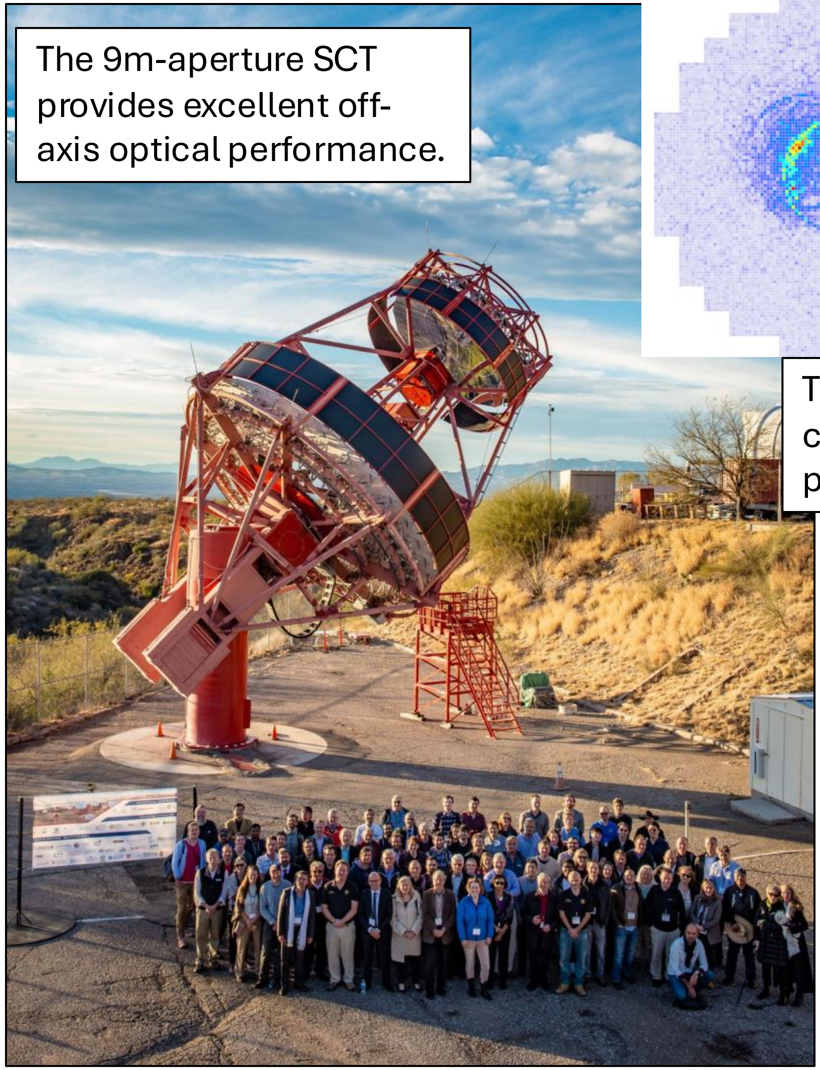
The most interesting regions of the plane in the north are only visible during the shortest (summer) nights, and severely impacted by the Arizona monsoon season



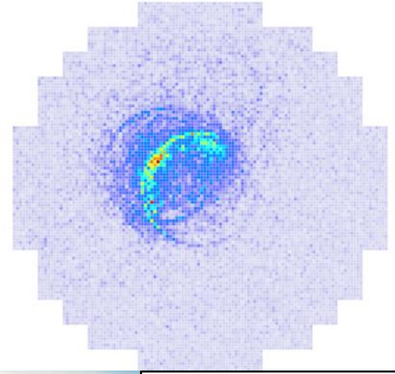
The inner galaxy is far to the south

- CTAO, LACT and ASTRI will be much better for PeVatrons.
- The US is heavily involved in aspects of CTAO which will contribute strongly to PeVatron studies.

37 4.3m-aperture SSTs provide 3km^2 effective area in the south

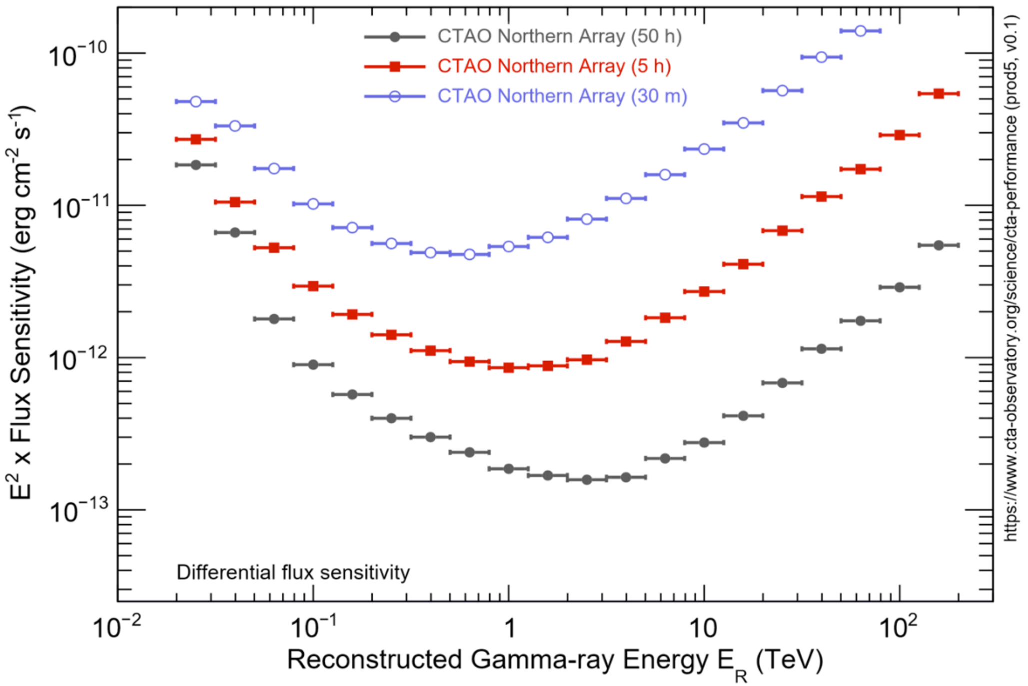


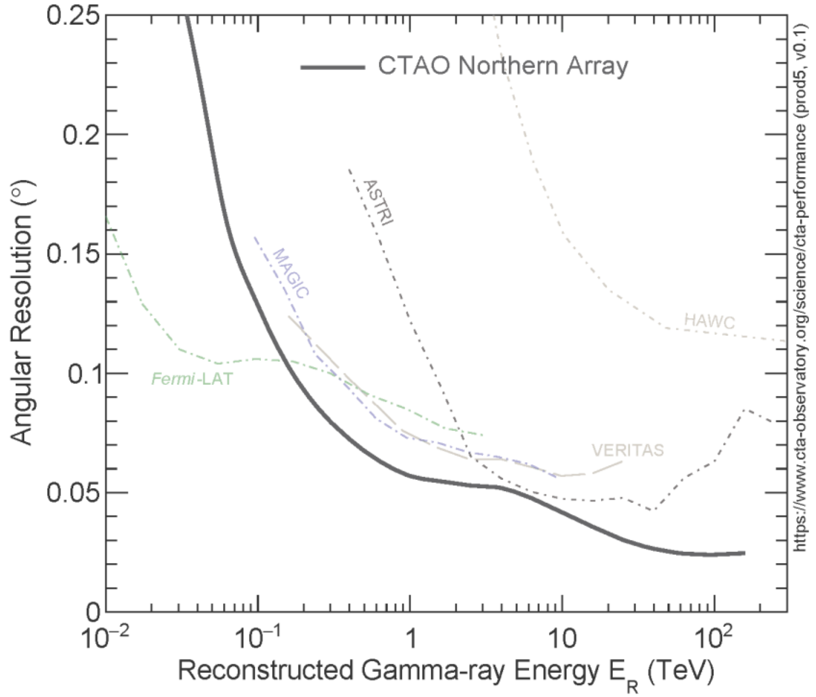
The 9m-aperture SCT provides excellent off-axis optical performance.



The high-resolution camera has 11,000 pixels over 8 degrees.

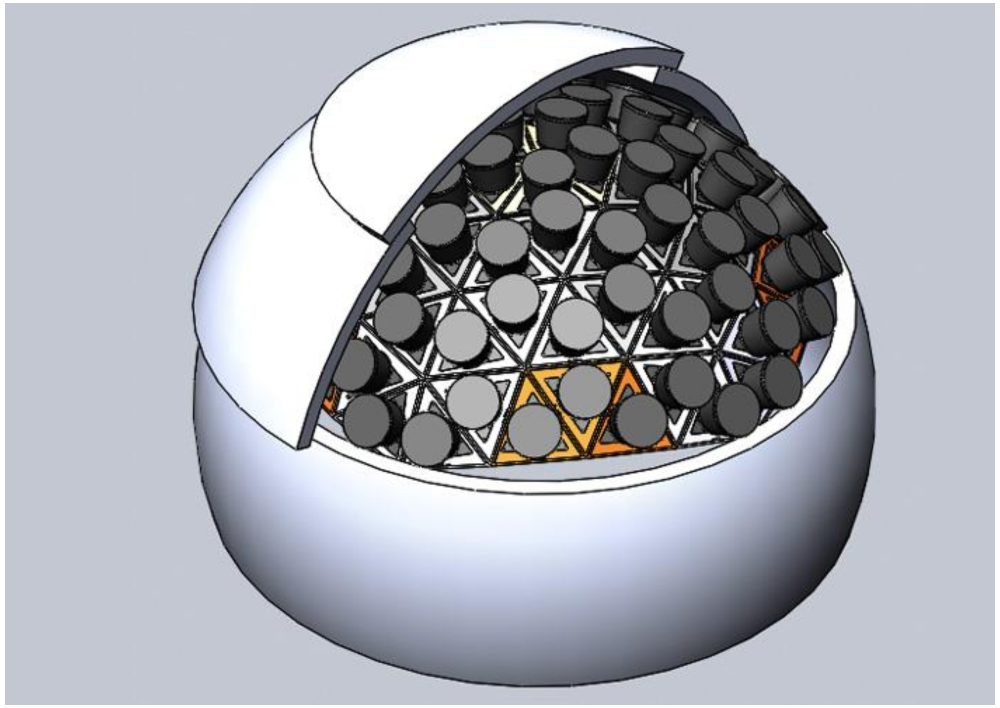
- But CTAO is a rather expensive “Swiss army knife”: Designed to do everything, extremely well. Covers 4 orders of magnitude in gamma-ray energy with excellent angular and spectral resolution.
- What if the design goal is *only* the highest energies, above 10s of TeV?
- Requires lots of small, cheap telescopes with a wide field -of-view.

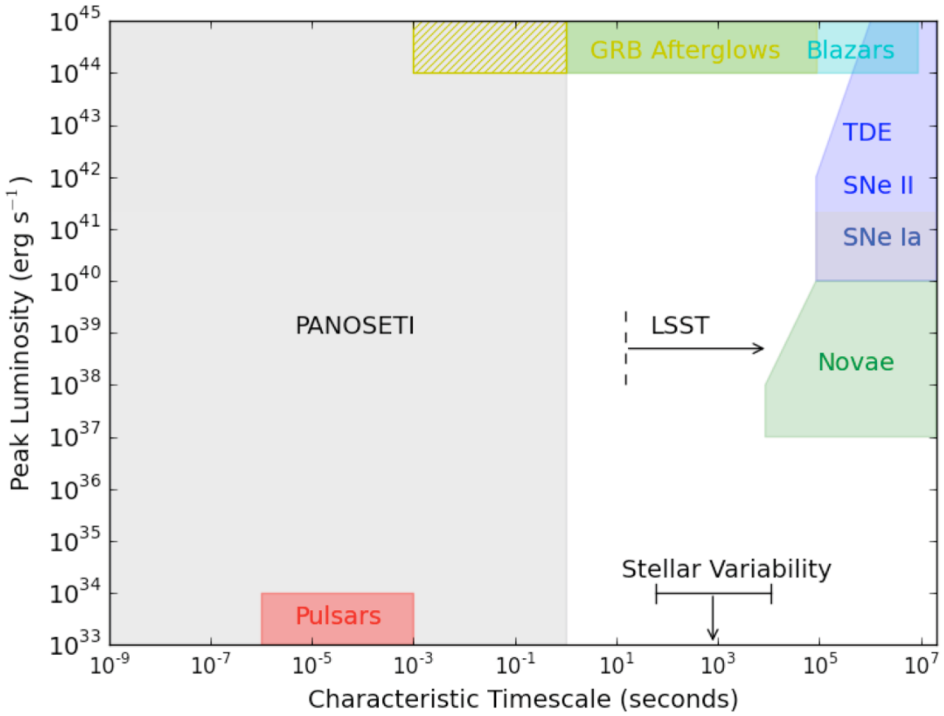




PANOSETI

- Originally designed as an all-sky optical transient monitor, with two widely separated domes housing many telescopes.
- Led by Shelley Wright at UC San Diego, Dan Werthimer (Berkeley), Paul Horowitz (Harvard), Andrew Howard (Caltech).



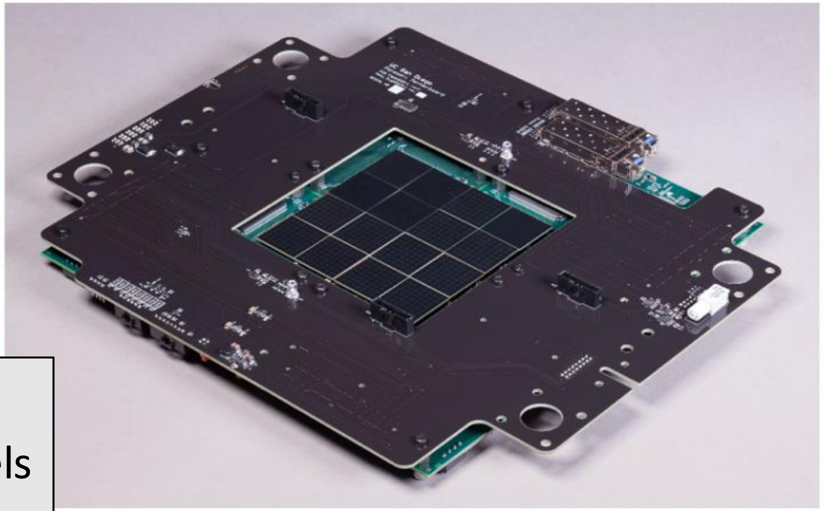


0.46m **Fresnel lens**
f/1.32

Custom-built lightweight aluminium shell.

Off-the-shelf iOptron mount with ZWO guide camera

Camera module

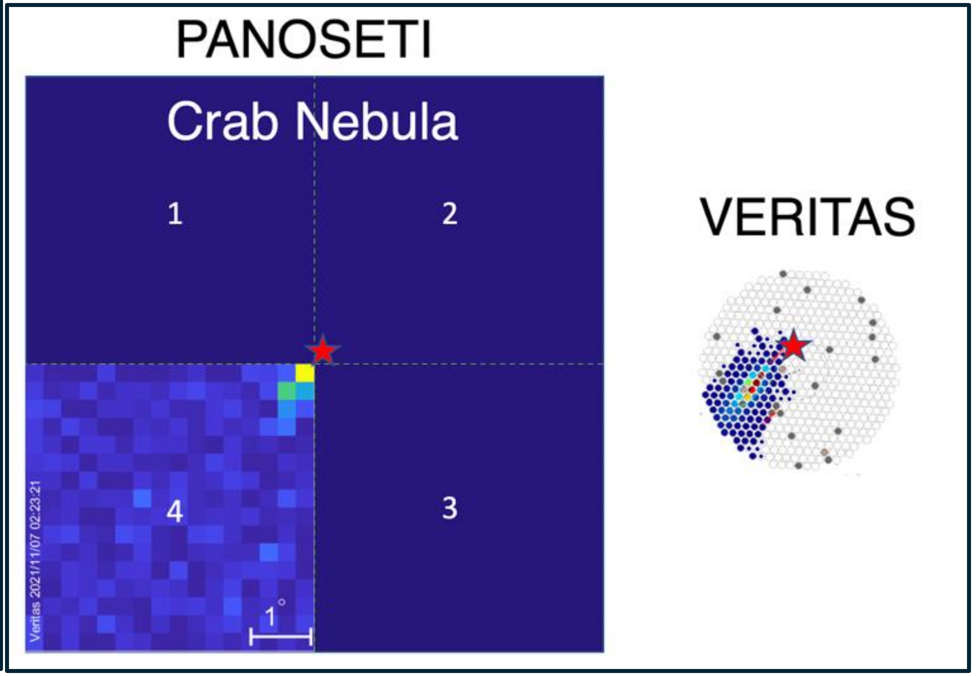


- 16, 8x8 SiPM arrays
- 1024 3mm, 0.3º pixels
- 9.6ºx9.6º field of view

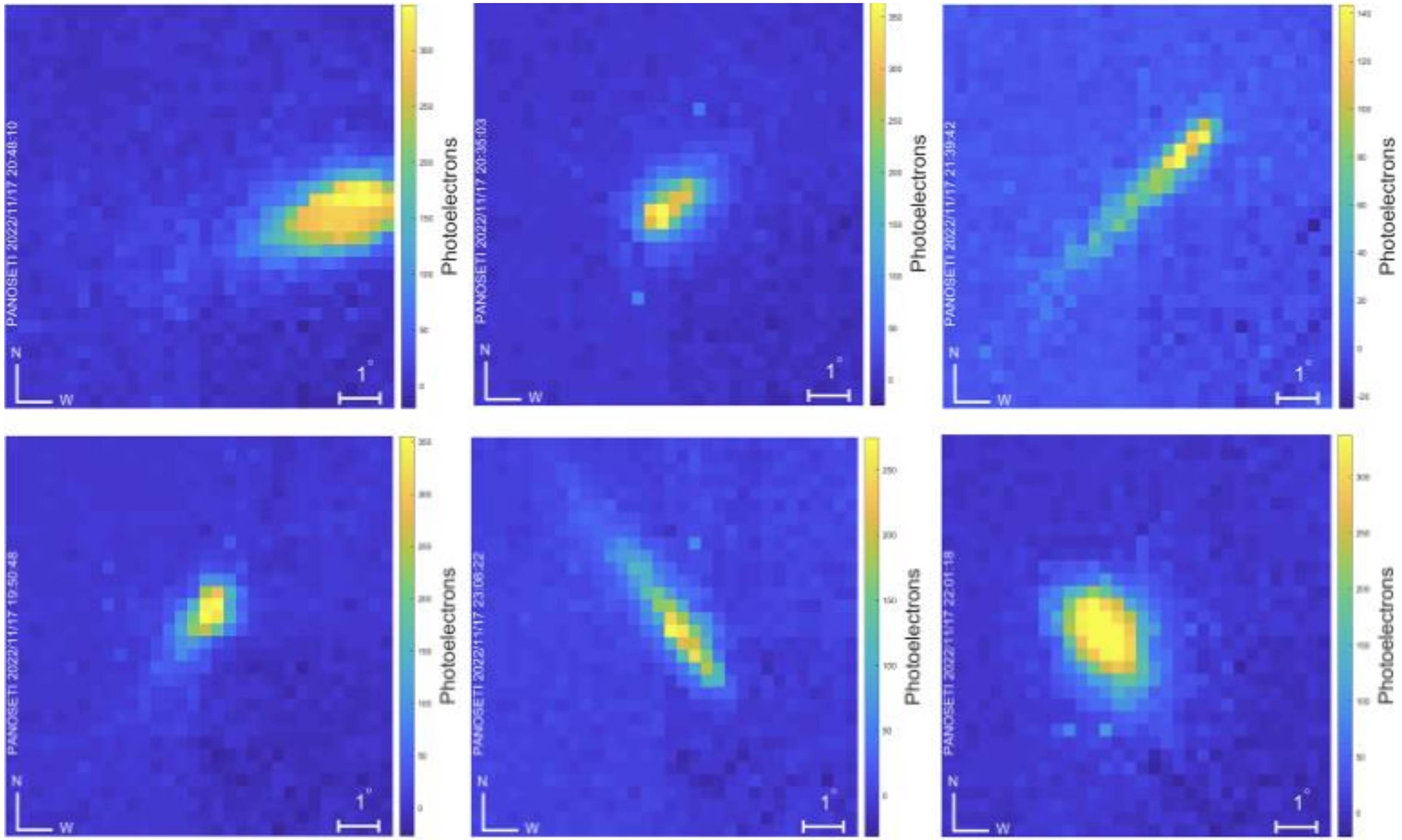
CITIROC-based ASIC readout

- PANOSETI’s background is our signal: Cherenkov emission from cosmic ray and gamma-ray air showers.
- As an initial test, we deployed two PANOSETI telescopes at VERITAS, and observed >10 TeV gamma-rays in coincidence.
- This led to further collaboration, funding through Elisa Pueschel’s group in Germany, and a revision of the PANOSETI deployment plans.

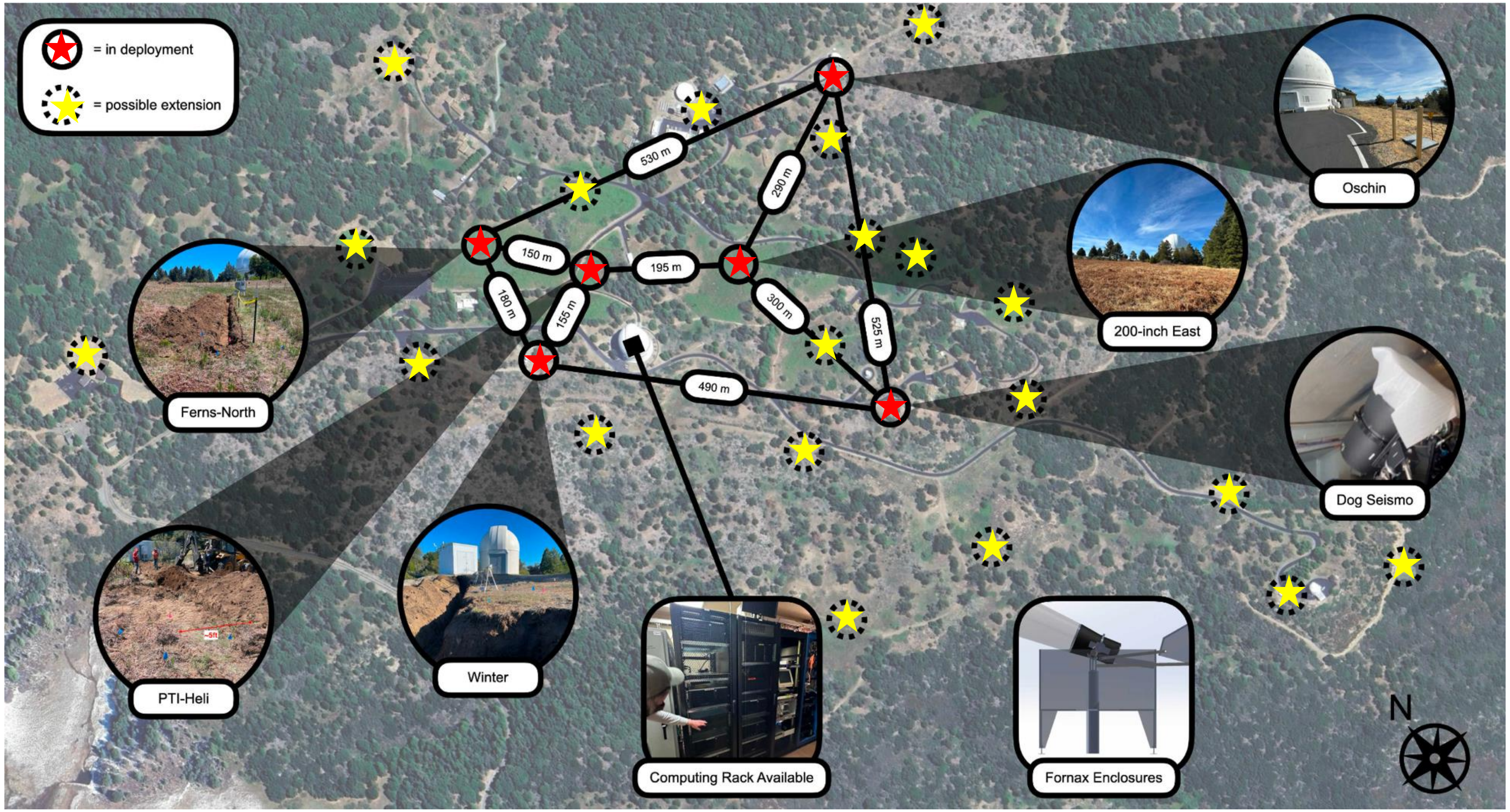
A 15 TeV gamma-ray from the Crab



- Two small modifications implemented for Cherenkov work
  - Add a multiplicity trigger (n-pixels from a quadrant)
  - Read out all four quadrants for every triggered event.
- Tested with cosmic ray observations at Lick Observatory.



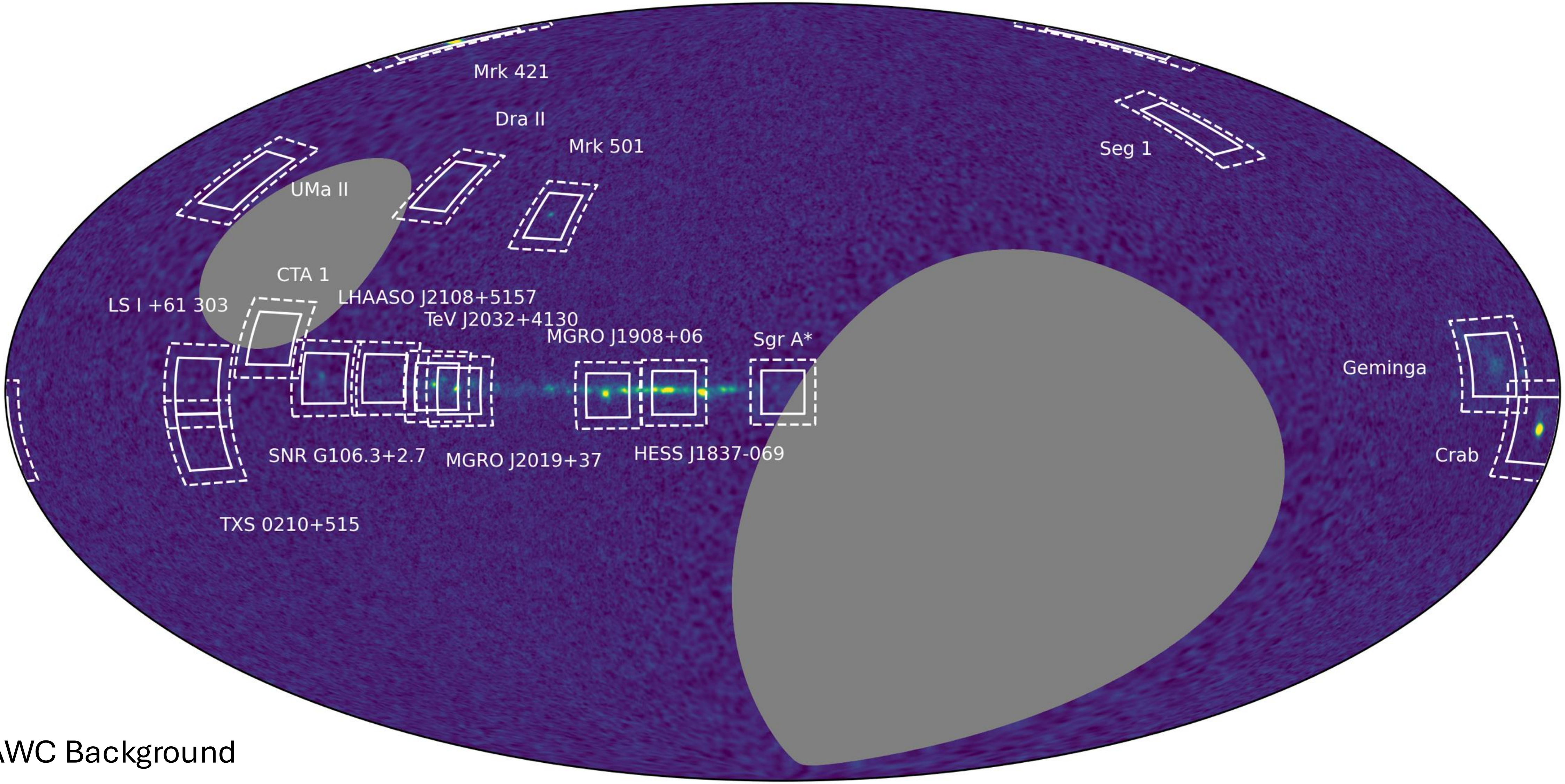
- Caltech recently provided enthusiastic access to Palomar Observatory.
- 2 telescopes operating. 2 more under deployment. 2 more in assembly.
- Aiming for 3-4 telescope operations this Fall (2025).
- Space for at least 25 telescopes on this site.



PANOSETI priorities for 2025/2026

- Deploy and operate the first few telescopes reliably and remotely.
- Calibrate tracking, optics and camera.
- Update the telescope model and simulate the response.
  - Demonstrate that the simulations match reality.
  - Calculate the energy threshold and effective area.
- Optimize tools to clean and parameterize images.
- Optimize tools to distinguish gamma-rays from the cosmic ray background efficiently.
- Detect the Crab Nebula and reconstruct its energy spectrum.

• An example annual observing program (still under development)

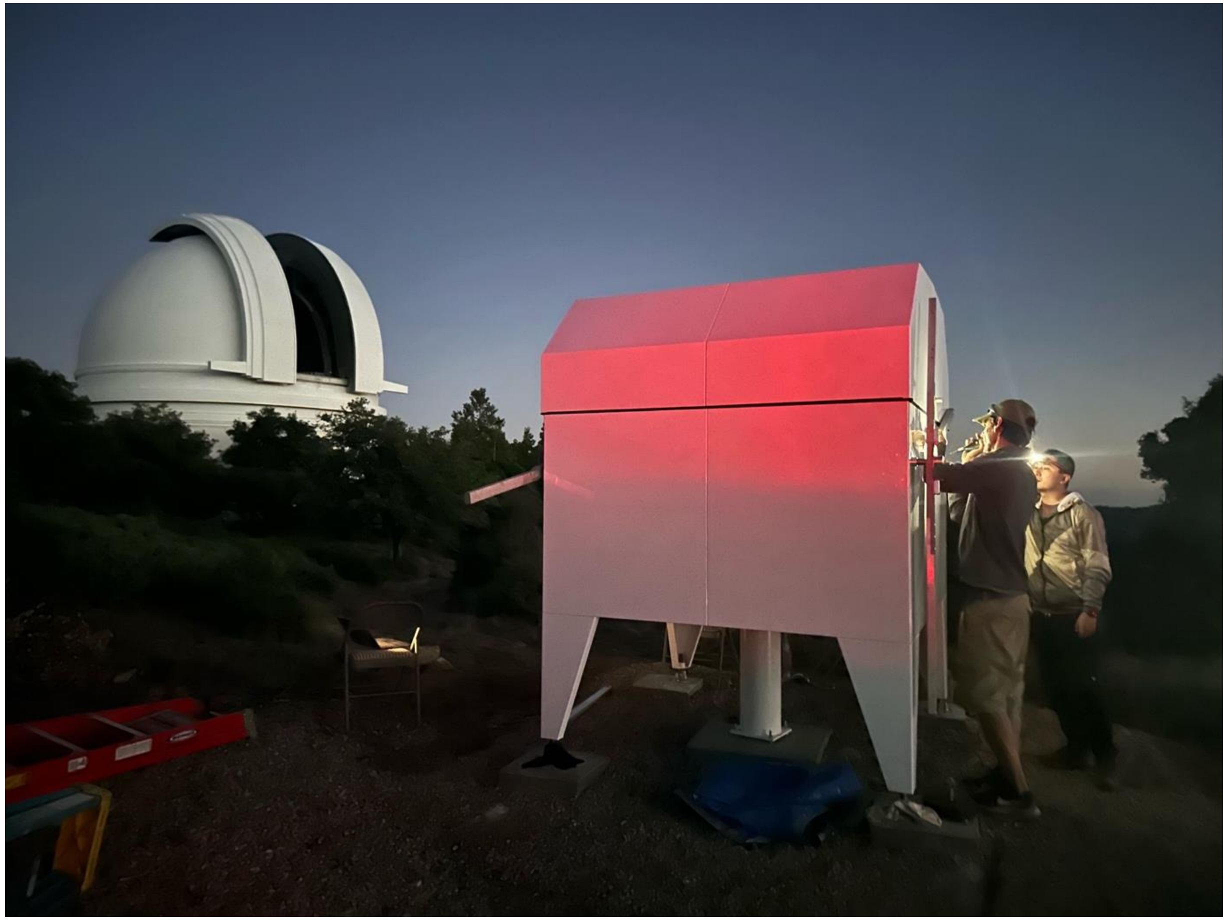


HAWC Background

shelley 11:31 AM

Two enclosures will be on a flight from London to San Diego tomorrow. Arriving tomorrow evening (Oct 9th in SD)

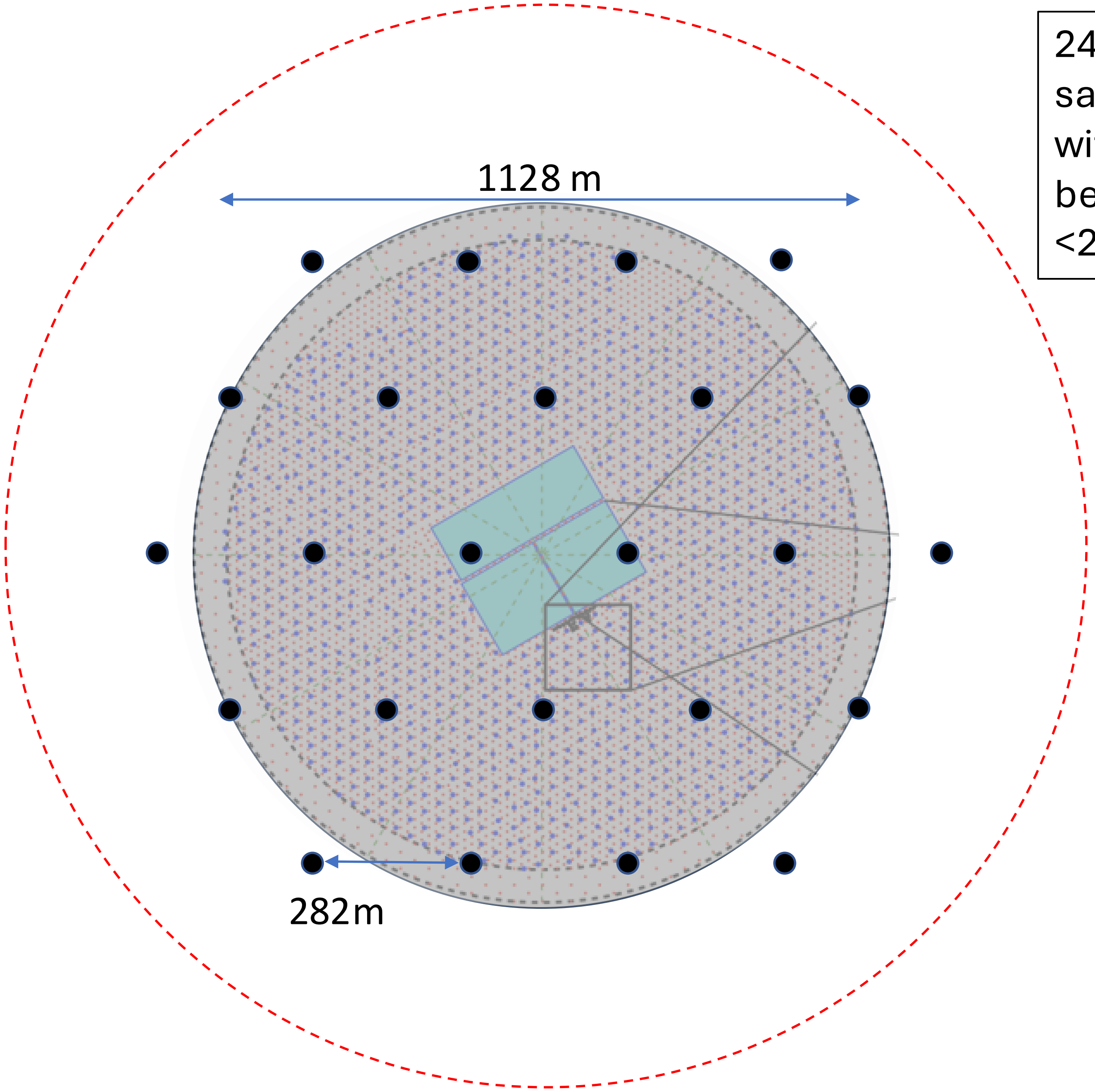
The first PANOSETI telescope at Palomar, installed inside an existing dome.



A custom enclosure for the second telescope. Based upon the HATs design (by Fornax).

PANOSETI Prospects

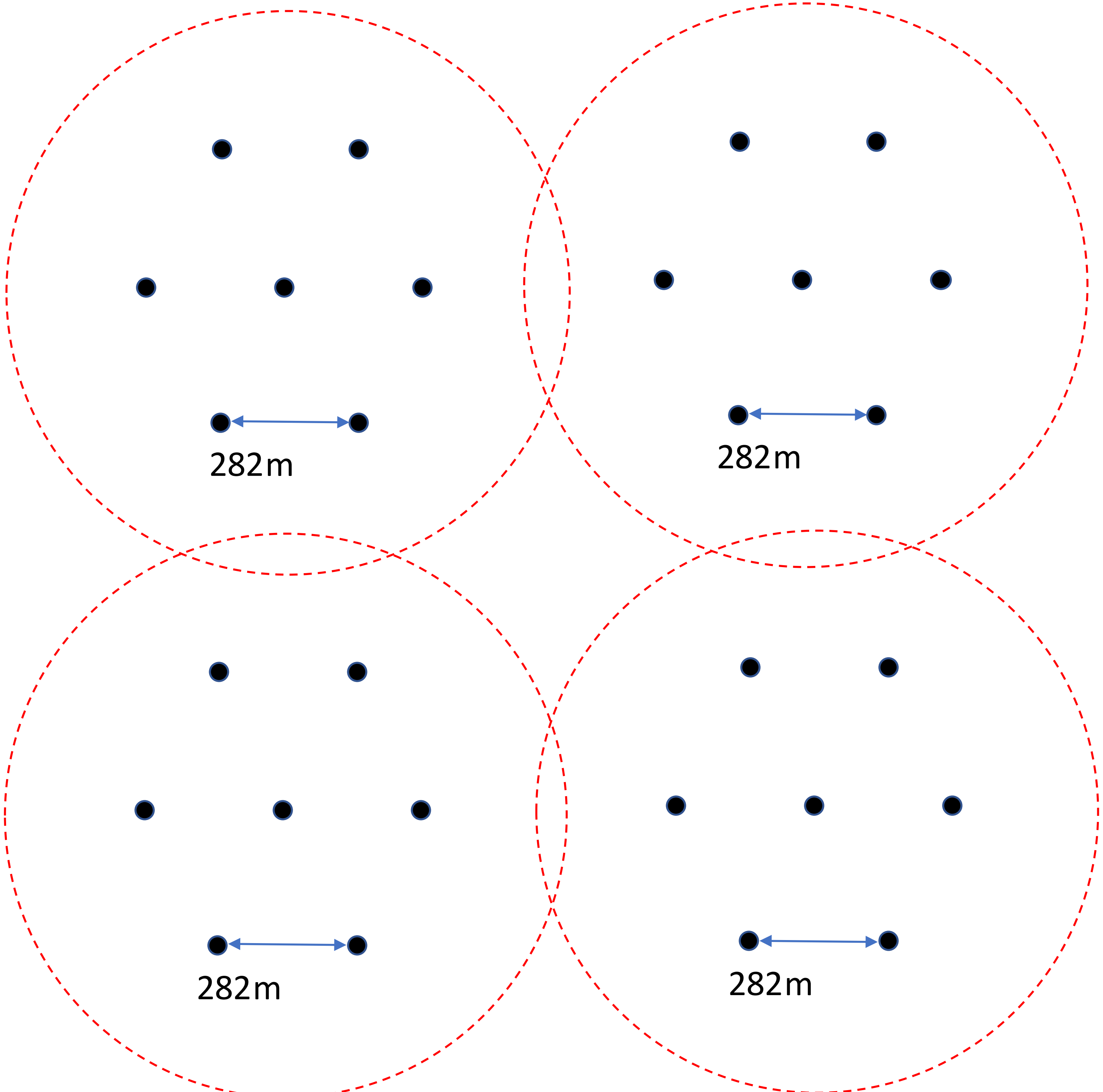
- PANOSETI telescopes are inexpensive, low environmental impact, and quick to construct and deploy.
- ***If*** we can demonstrate good performance there are lots of potential applications:
  - Standalone arrays.
    - One or a few large arrays
    - Many small arrays (combining data *e.g.* with gammapy)
  - Enhancements to particle detector arrays.
  - Outriggers for Cherenkov telescope arrays.
- Provides one potential path to >10 km^2 (100km^2 ?!) effective area.
- This is required to study the “super-PeVatron” sky.

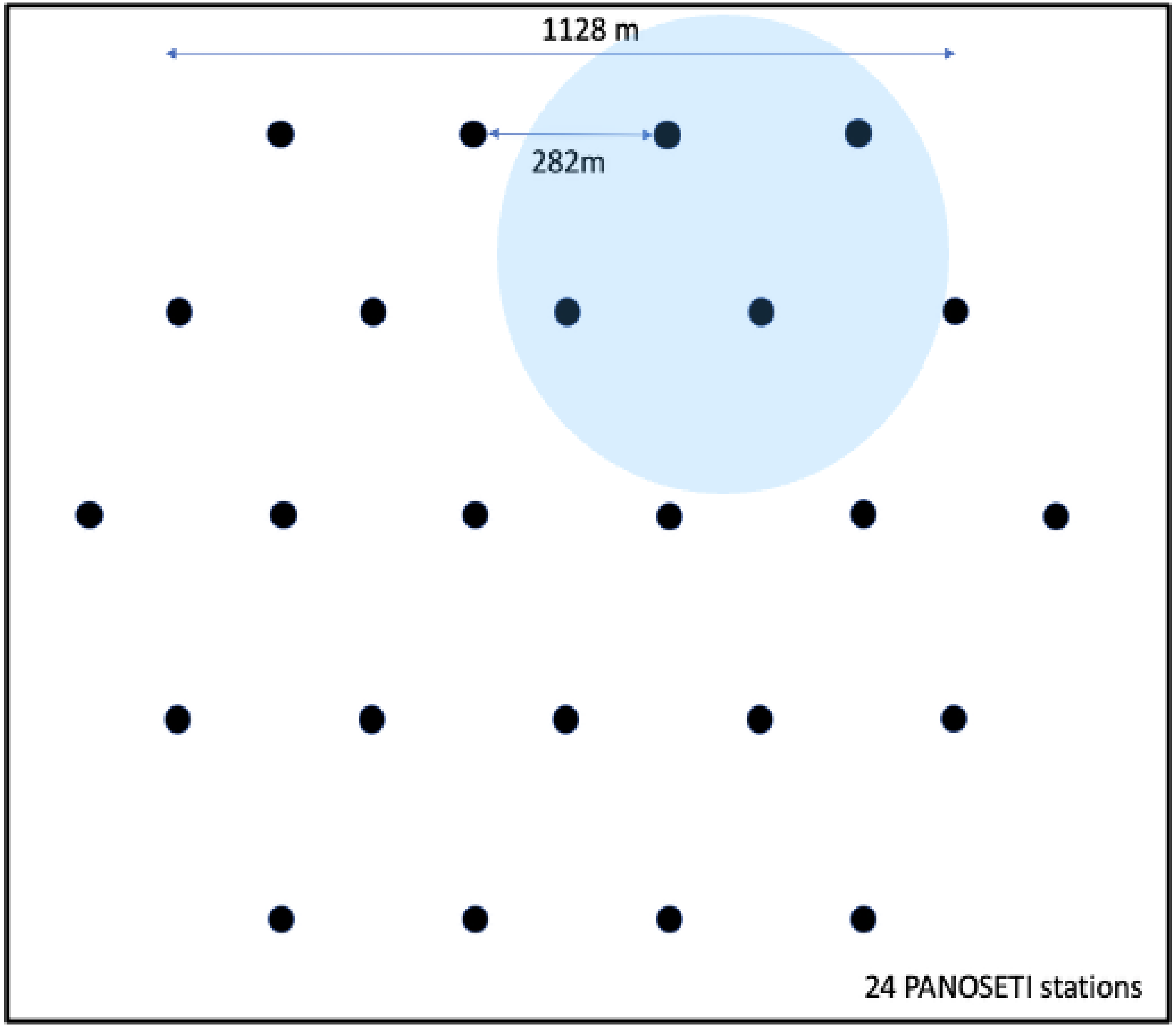


24 telescopes could cover the same physical area of LHAASO, with effective area extending well beyond this.
<2M$ hardware cost.

BACKUP

Multiple smaller arrays provide even larger effective area (at the cost of angular resolution), **and do not need to be co-located.**





1128 m
282m
24 PANOSETI stations

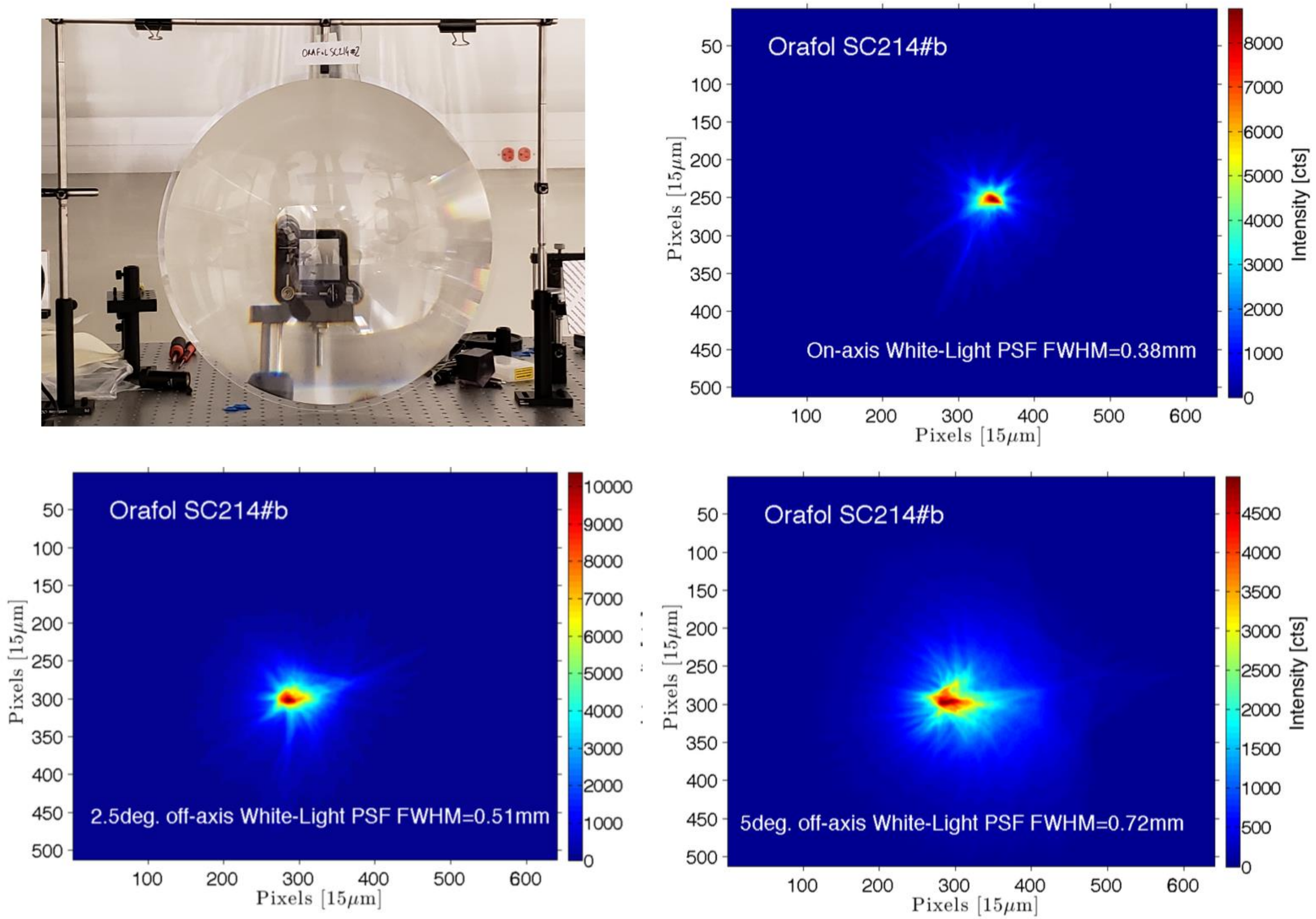
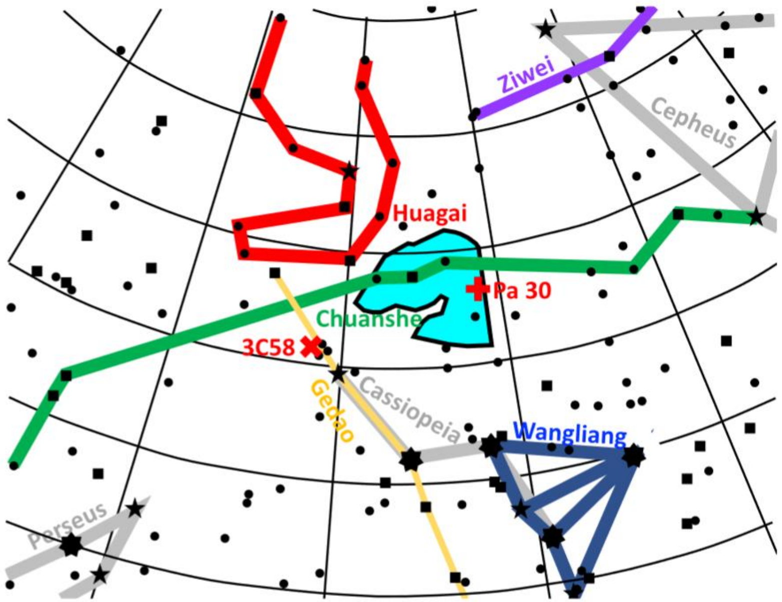


Figure 3: Top-left: Refractive Fresnel lens Orafol SC214 mounted on the optical table for spot size measurements. Top-right: On-axis spot obtained by imaging a white-light point-source (white LED with a 1mm pinhole located 7m from the lens). The green color represents pixels containing half of the maximal intensity. Bottom-left: white-light spot from 2.5° off-axis point-source. Bottom-right: white-light spot from 5° off-axis point-source.

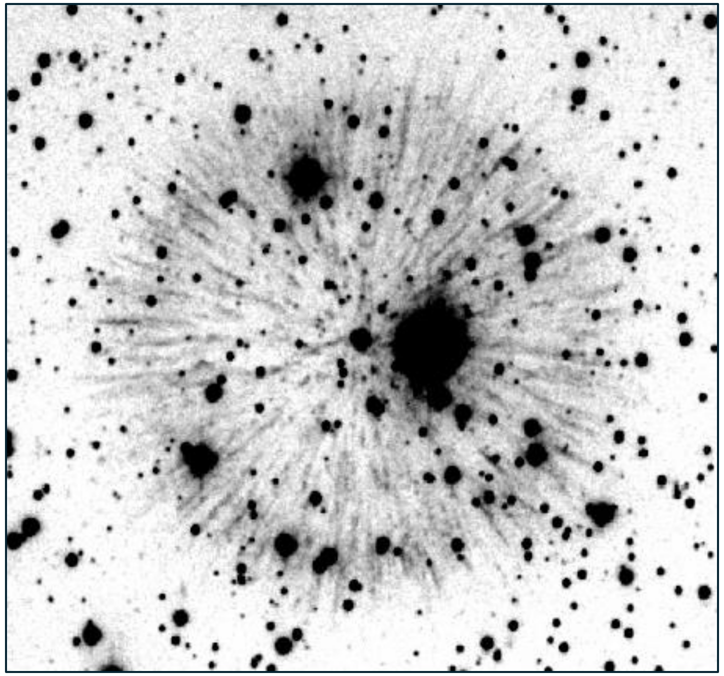
The missing historical supernova remnant: SN 1181

- First observed between August 4 and August 6, 1181 AD.
- Recorded in multiple texts by Chinese and Japanese astronomers. At peak, as bright as Vela (m=0).
- Appeared in the constellation Cassiopeia and was visible and motionless against the fixed stars for 185 days.
- Previously associated with PWN 3C 58 / PSR J0205+06449
  - 3C 58 was studied by VERITAS (22 hours, no detection, pulsar limits published)
  - Detected by MAGIC: 81 hours, 5.7 sigma, 0.65% Crab
- Re-assessment places 3C58 outside of the region given by historical constraints and suggests an age of ~5kyr:
- **3C58 is not the remnant of SN 1181.**



Pa 30: the remnant of SN 1181

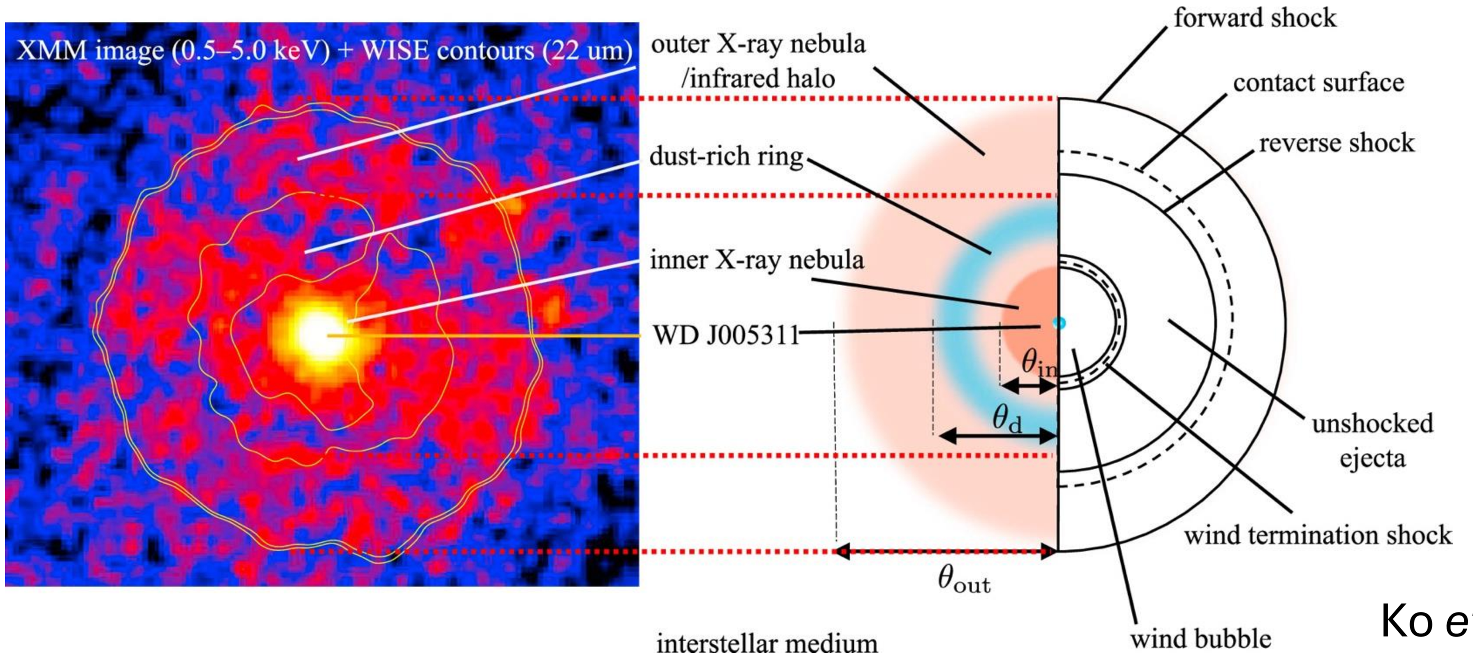
- Discovered in 2013 by Dana Patchick, an amateur astronomer searching for planetary nebulae in WISE data.
- Highly structured nebula 3 arcminutes in diameter, with long filaments extending radially from a very hot central star driving a high-velocity wind.
- The nebula's angular size, estimated 2.3 kpc distance, and 1100 km s^{-1} expansion velocity are consistent with an explosion date around 1181 AD.
- Association first proposed by Ritter *et al.* in 2021.

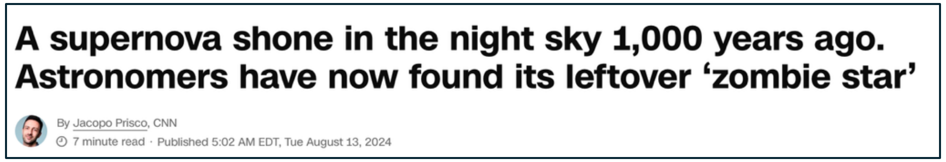


Fesen, Schaefer & Patchick. 2023

Pa 30: the remnant of SN 1181

- Properties of the remnant and its central star are best-explained by an unusual progenitor – a merger between CO and ONe white dwarfs, leading to a low-luminosity **Type Iax** supernova explosion.
- Rare sub-type of Type Ia supernovae in which the merging white dwarfs are not fully destroyed by the supernova explosion, leading to a double-degenerate merger product described (colourfully!) as a “zombie star”.




A supernova shone in the night sky 1,000 years ago. Astronomers have now found its leftover ‘zombie star’

By Jacopo Prisco, CNN
7 minute read · Published 5:02 AM EDT, Tue August 13, 2024

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- Caltech recently provided enthusiastic access to Palomar Observatory.
- 2 telescopes operating. 2 more under deployment. 2 more in assembly.
- Aiming for 3-4 telescope operations this Fall (2025).
- Space for at least 25 telescopes on this site.