Studies of Supernova Remnants and Pulsar Wind Nebulae with VERITAS

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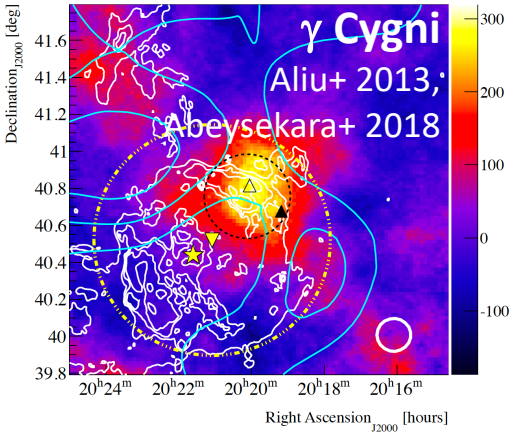
NASA Goddard Space Flight Center
University of Maryland – College Park

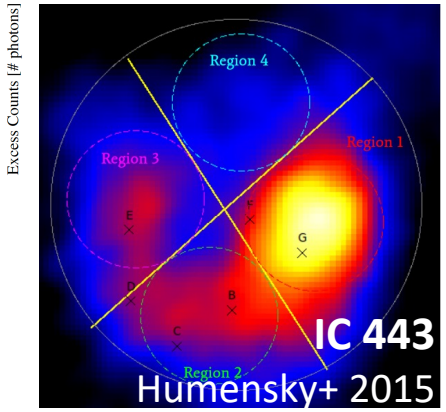
TeVPA – September 15, 2023

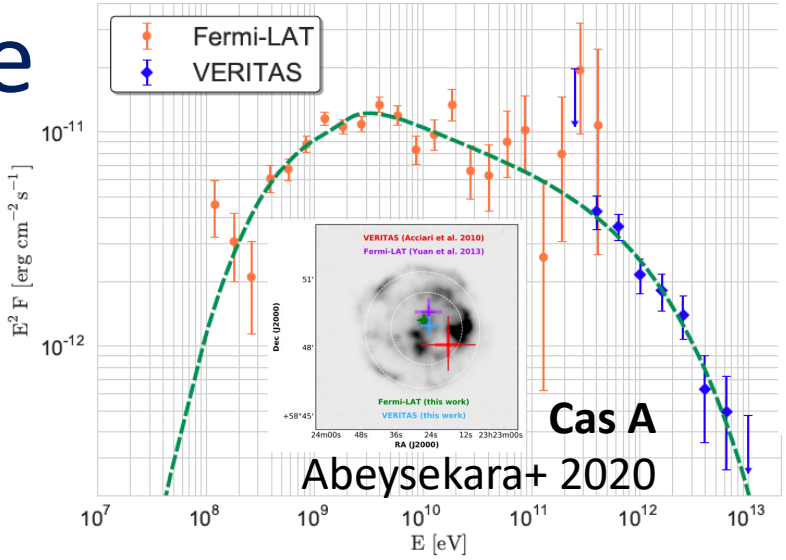
VERITAS

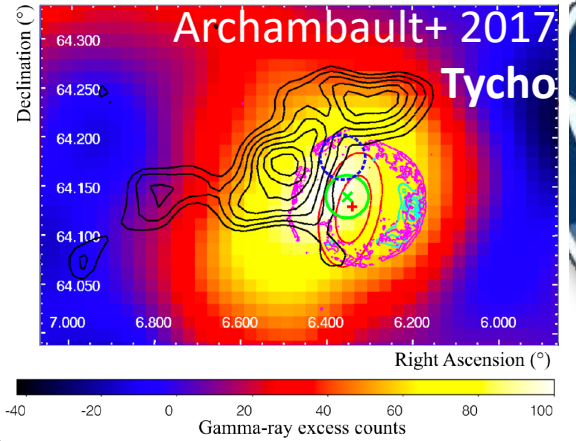
- Full-array operations begin: 2007 - 16 years of operation.
- Energy range: ~85 GeV to ~30 TeV.
- Sensitivity: 1% Crab in 25 hr, 10% in 25 min, Ang. resolution: 0.08° resolution @ 1 TeV.
- Prototype SCT telescope for CTA on site.
- Funded by National Science Foundation (USA), Smithsonian Astrophysical Observatory (USA), Natural Sciences and Engineering Research Council (Can), Helmholtz Association (Ger).

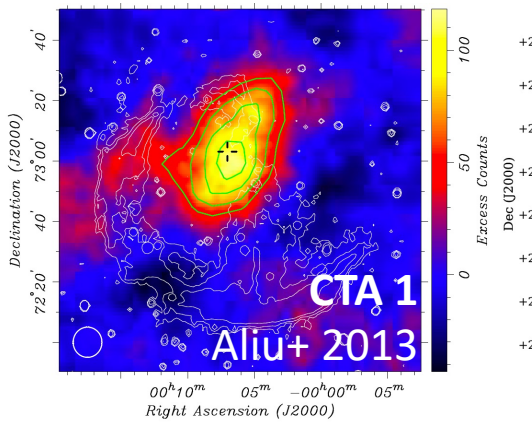
VERITAS SNRs & PWNe

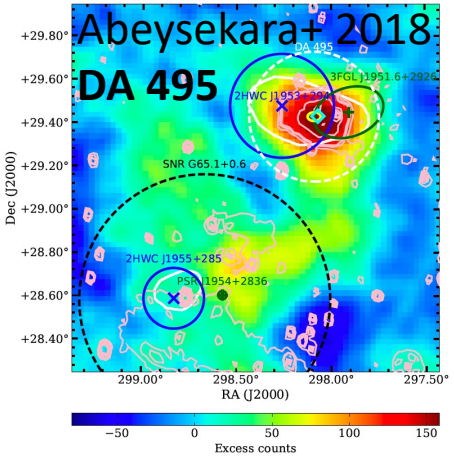


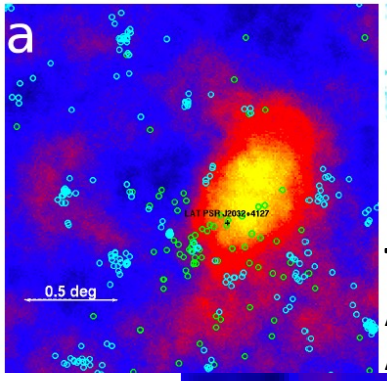


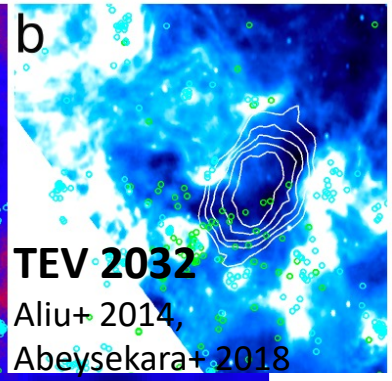


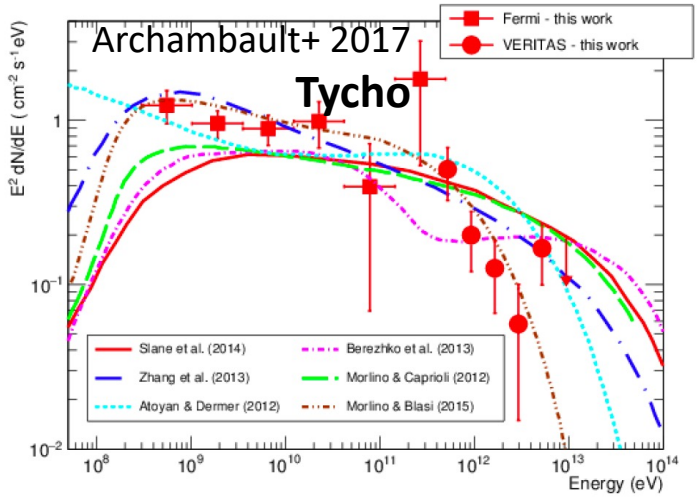


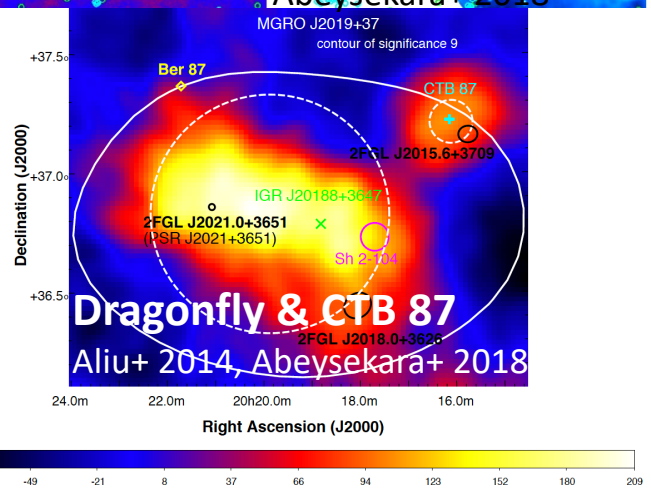


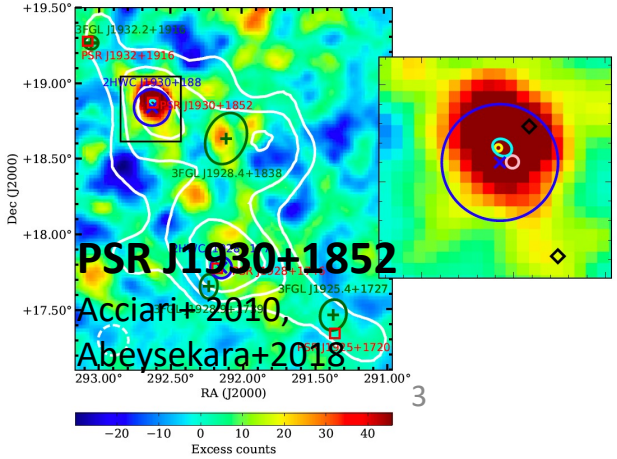












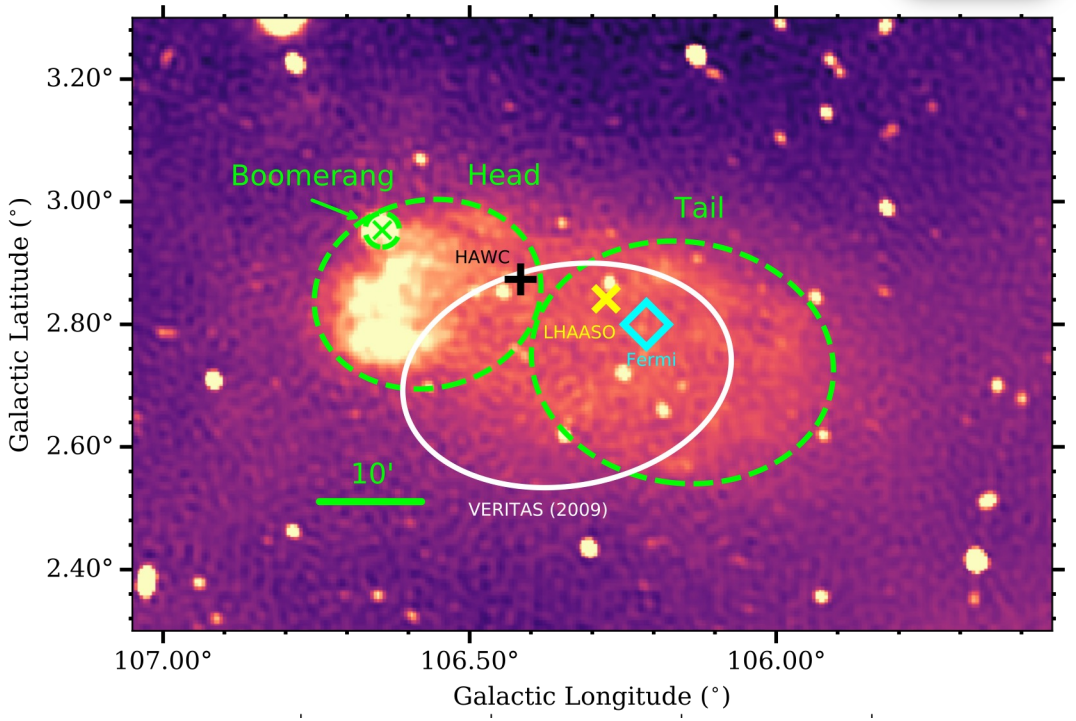
Today:

- Boomerang / SNR G106.3+2.7
- MGRO J1908+06

VER J2227+608 in SNR G106.3+2.7 region

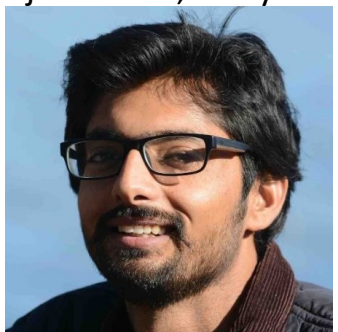
- Very faint & diffuse in radio & X-ray.
- Typically divided into two regions: Head & Tail.
- Head region:
  - Contains Boomerang PWN + PSR J2229+6114.
    - Pulsar characteristic age of 10 kyr.
    - Distance: 0.8 kpc - 12 kpc.
- Tail region:
  - Coincide with VER J2227+608 (VERITAS 2009), strong gamma-ray emitter.
  - Recent measurements show gamma-ray emission extends up to 500 TeV (Tibet, HAWC, LHAASO).
    - One of the promising PeVatron Candidates.

VERITAS+NuSTAR
(2023 ApJ submitted)



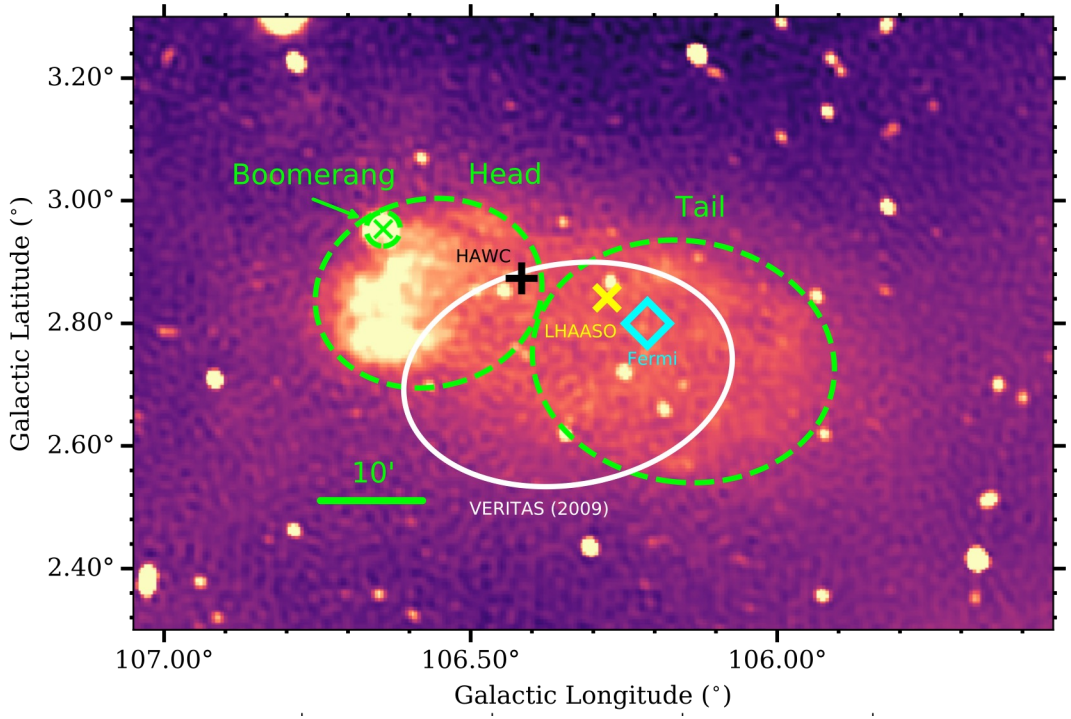
Nahee Park, Queens

Sajan Kumar, Maryland



SNR G106.3+2.7 region

- Origin of gamma ray emission in the SNR G106.3+2.7 region
  - Leptonic scenarios:
    - PWN of PSR J2229+6114?
      - No strong emission coincident with X-ray PWN.
      - Relic PWN?
    - Particle reaccelation due to PWN-SNR interaction?
    - Leptonic counterparts of X-ray diffuse non-thermal emission from SNR G106.3+2.7? (Ge 2021 Innov)
  - Hadronic scenarios:
    - Interaction of SNR G106.3+2.7 & MC?
      - No kinematic evidence of interaction (Liu 2022ApJ).



VERITAS+NuSTAR
(2023 ApJ submitted)

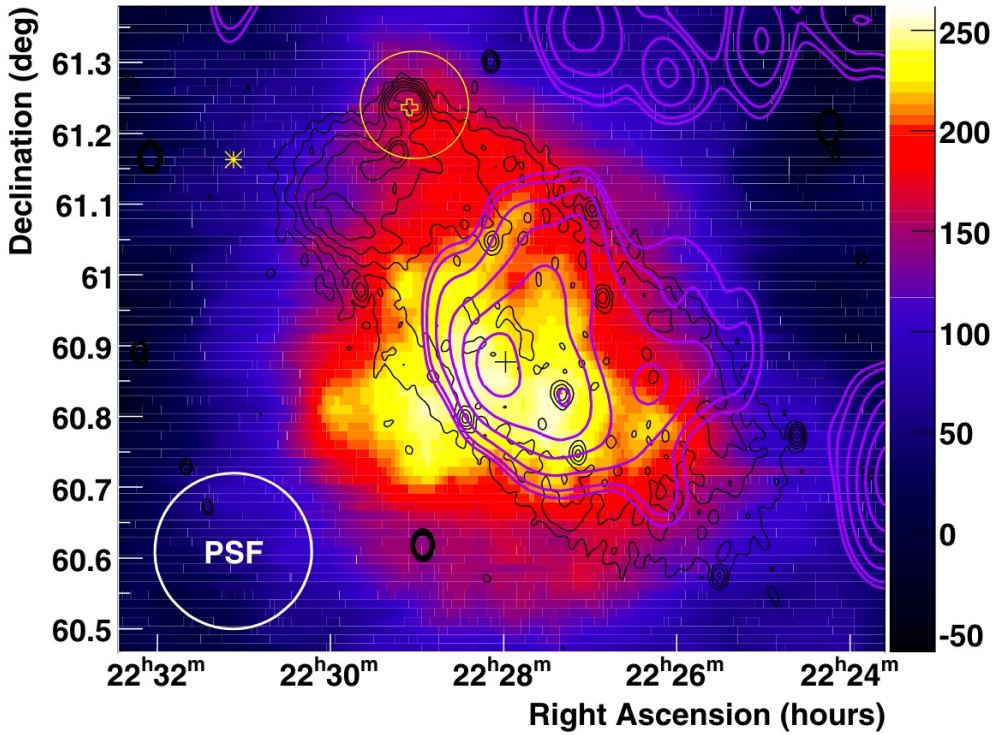
VERITAS Observations

- VERITAS accumulated > 150 hours of exposure in the SNR G106.3+2.7 region
  - Accumulated over 13 years (Two Major Updates in the telescope configuration):
    - V4: 45.8 hours

      Discovery paper w/ 33.4 hours (2009)
    - V5 (After T1 movement): 22.3 hours

      Boomerang PWN paper w/ NuSTAR team (2023 submitted)

Better sensitivity & angular resolution



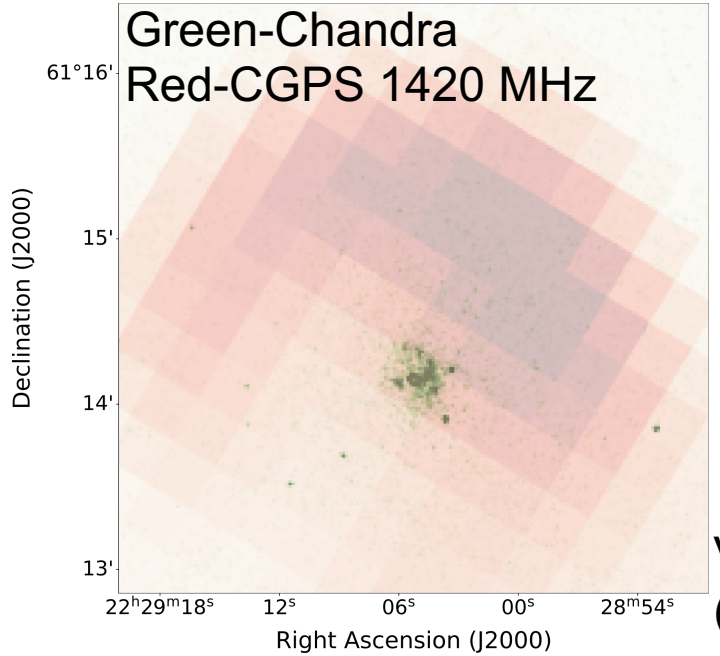
VERITAS (ApJ2009)

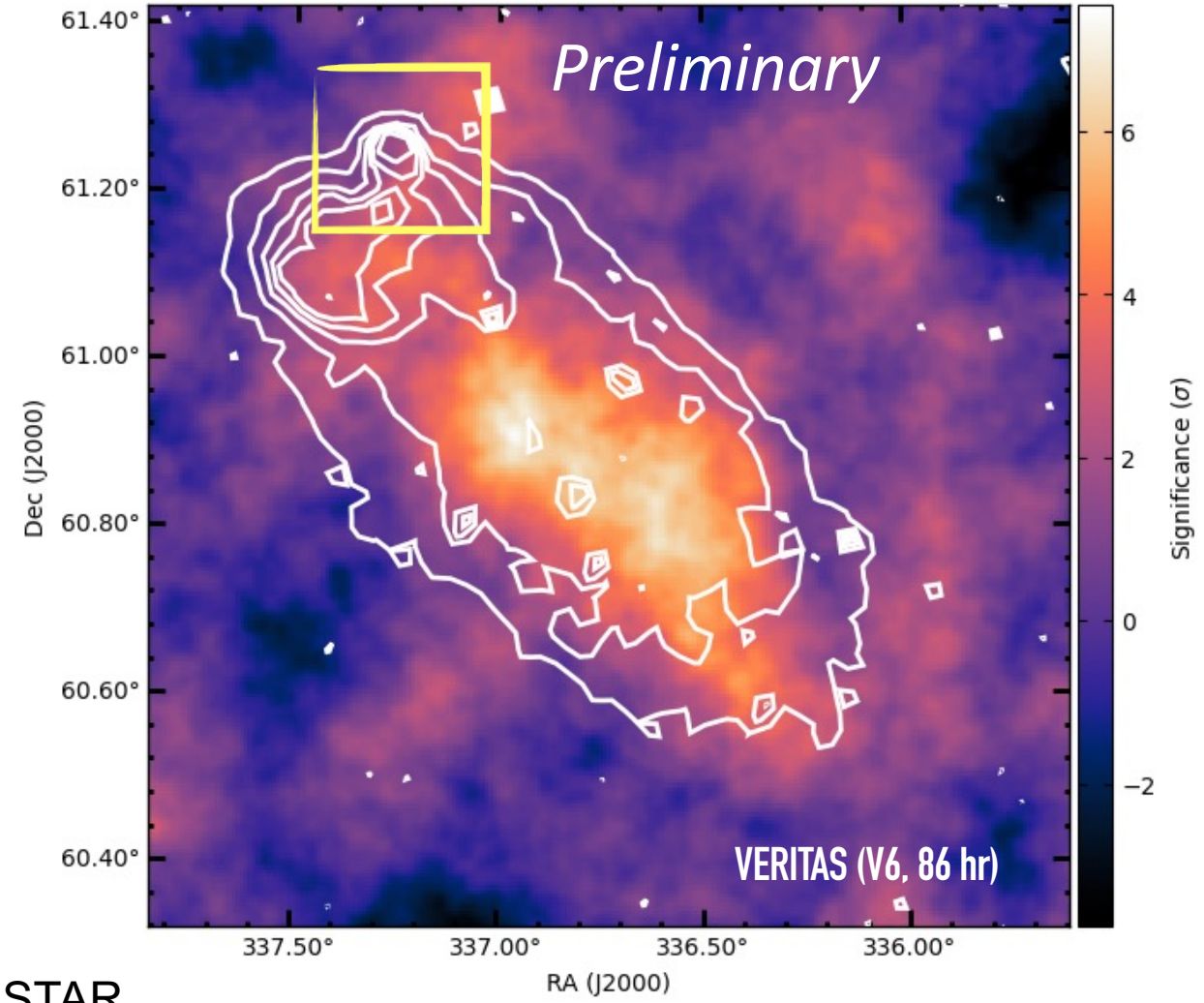
- V6 (After camera update): > 86 hours

Partial data set of 86 hours of observations will be shown today

VERITAS Observations of SNR G106.3+2.7

- Boomerang PWN:
  - Powered by PSR J2229+6114.
    - Characteristic age: 10 kyr.
    - Spin-down luminosity: 2.2×10^{37} erg/s.
  - X-ray emission is more confined and offset from radio PWN.
  - No strong TeV emission observed.

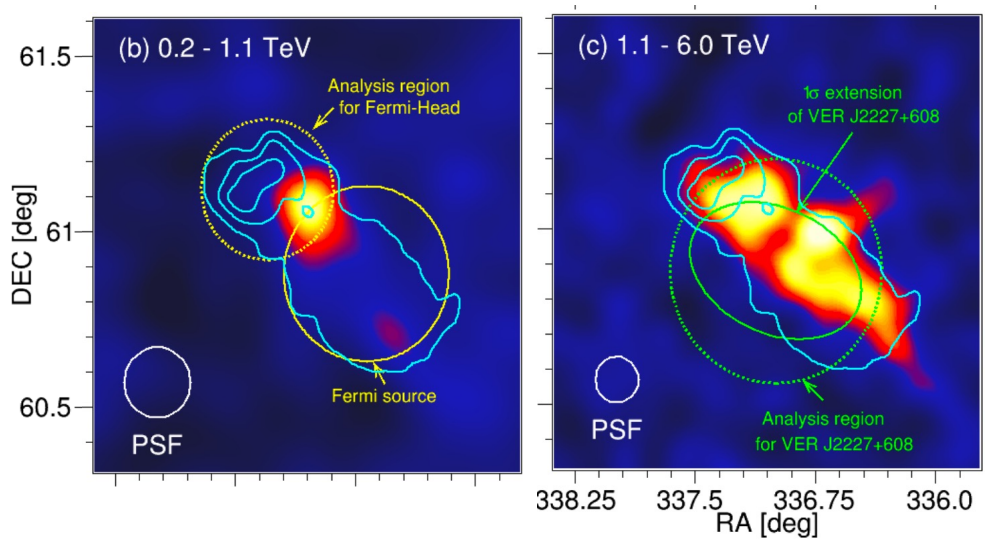




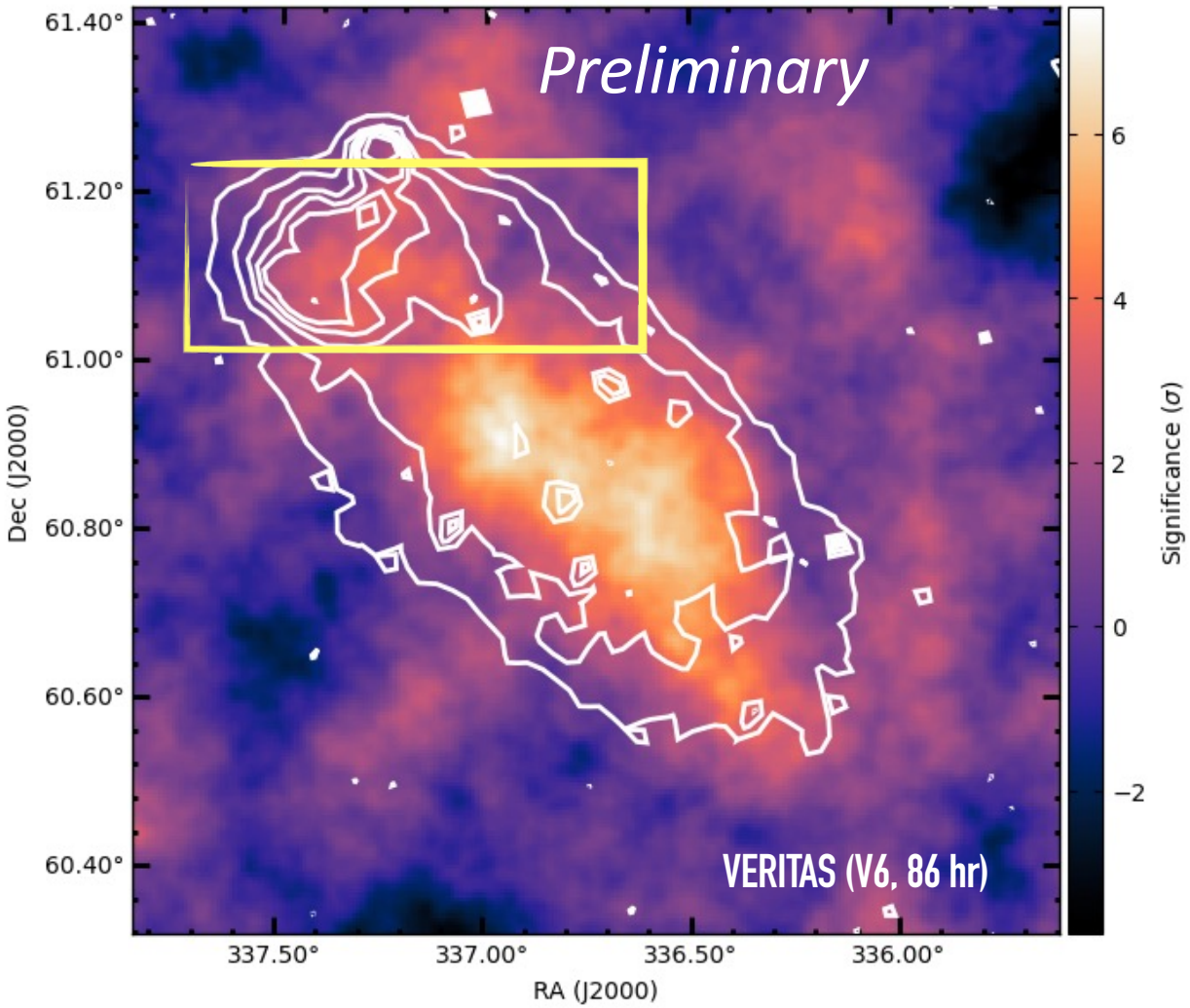
VERITAS+NuSTAR
(2023ApJ submitted)

VERITAS Observations of SNR G106.3+2.7

- SNR G106.3+2.7 compact region ("Head" region):
  - MAGIC reported significant emission.

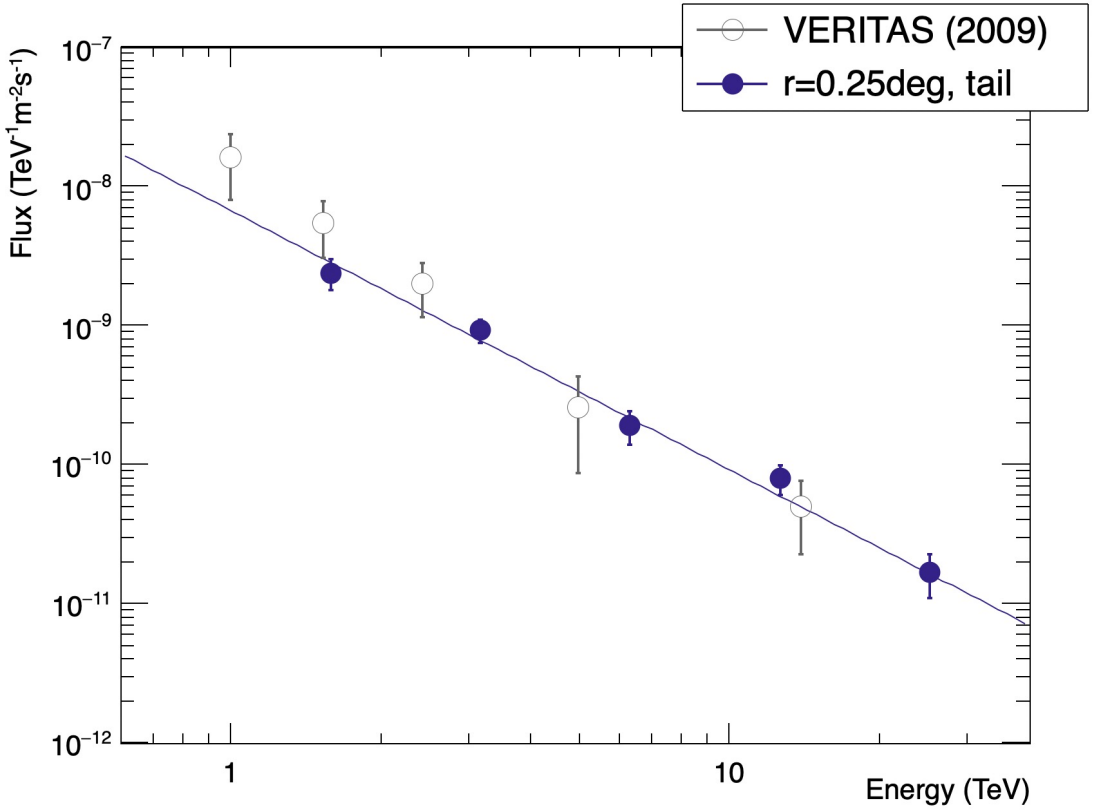


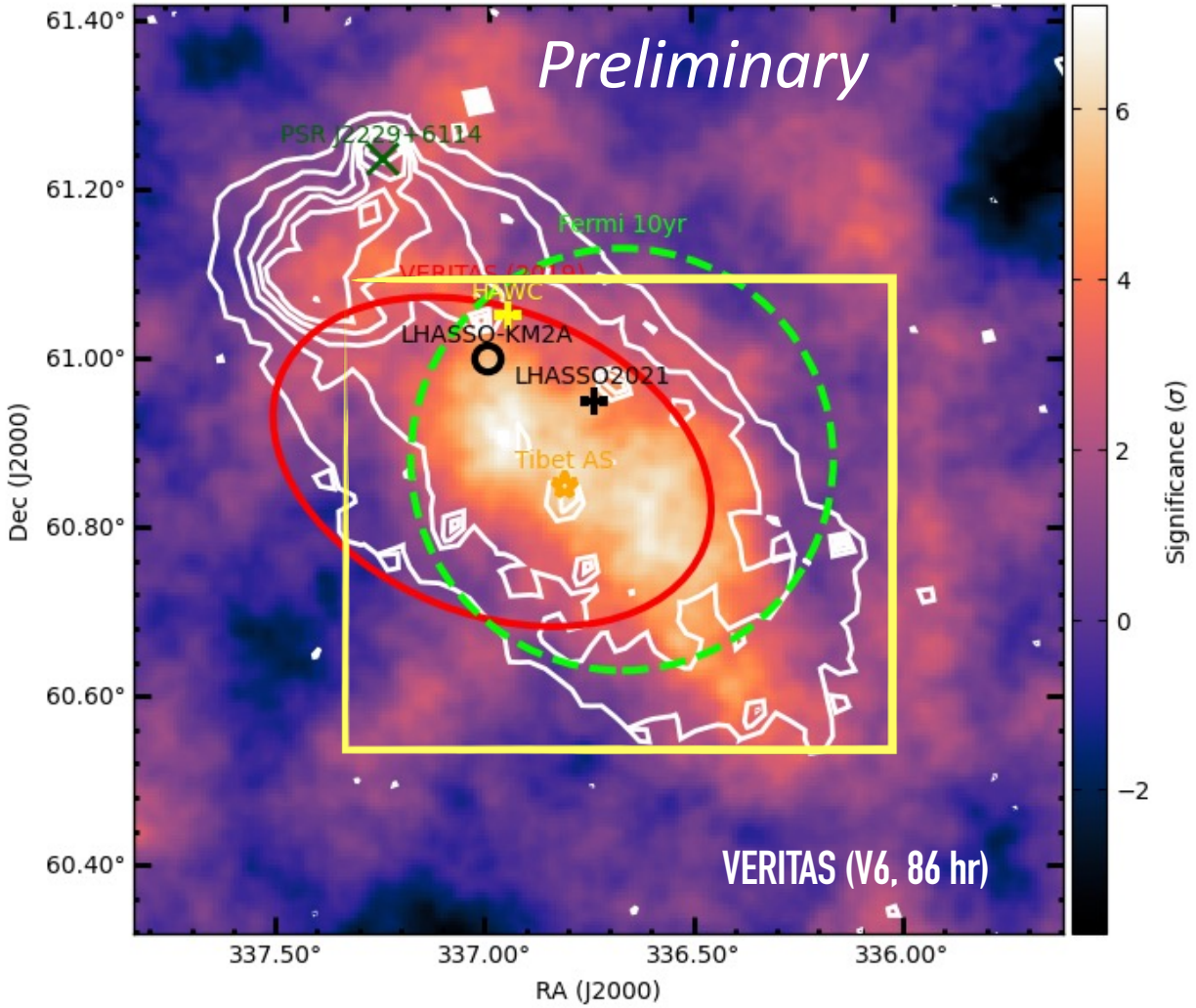
  - Diffuse emission observed by VERITAS.



VERITAS Observations of SNR G106.3+2.7

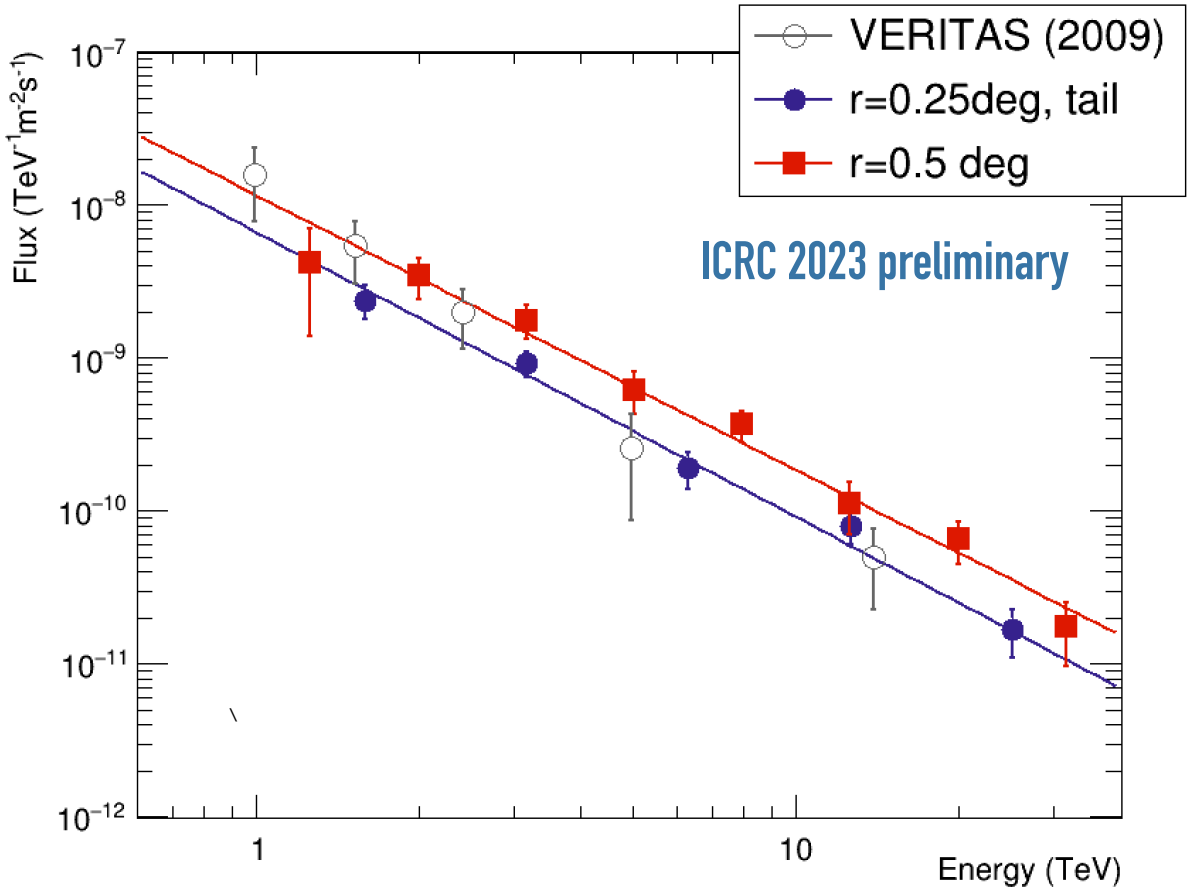
- SNR G106.3+2.7 diffuse region ("Tail" region)
  - Strong gamma-ray emission
  - VERITAS measurement of spectrum
    - Power-law index: 1.86 ± 0.10

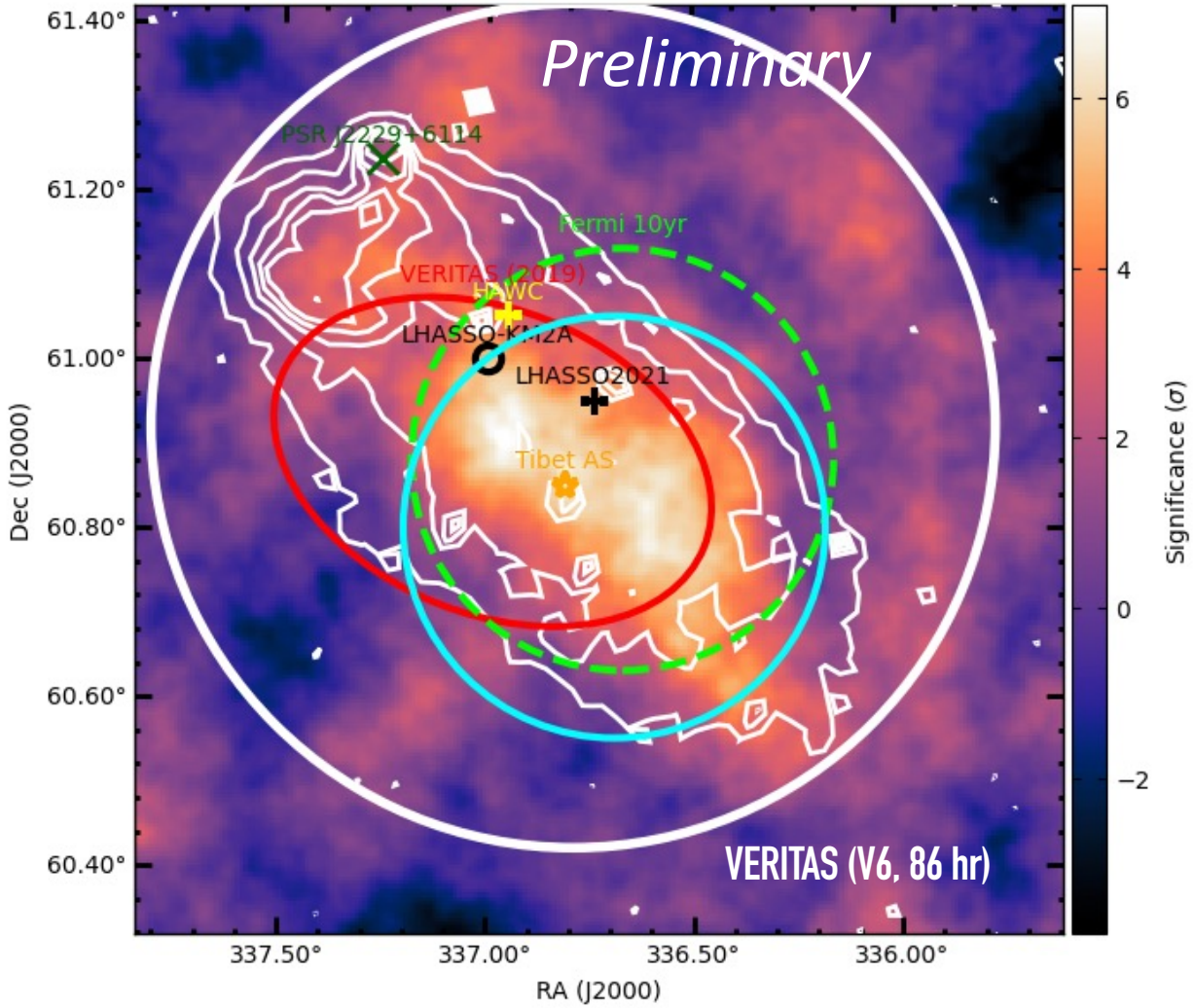




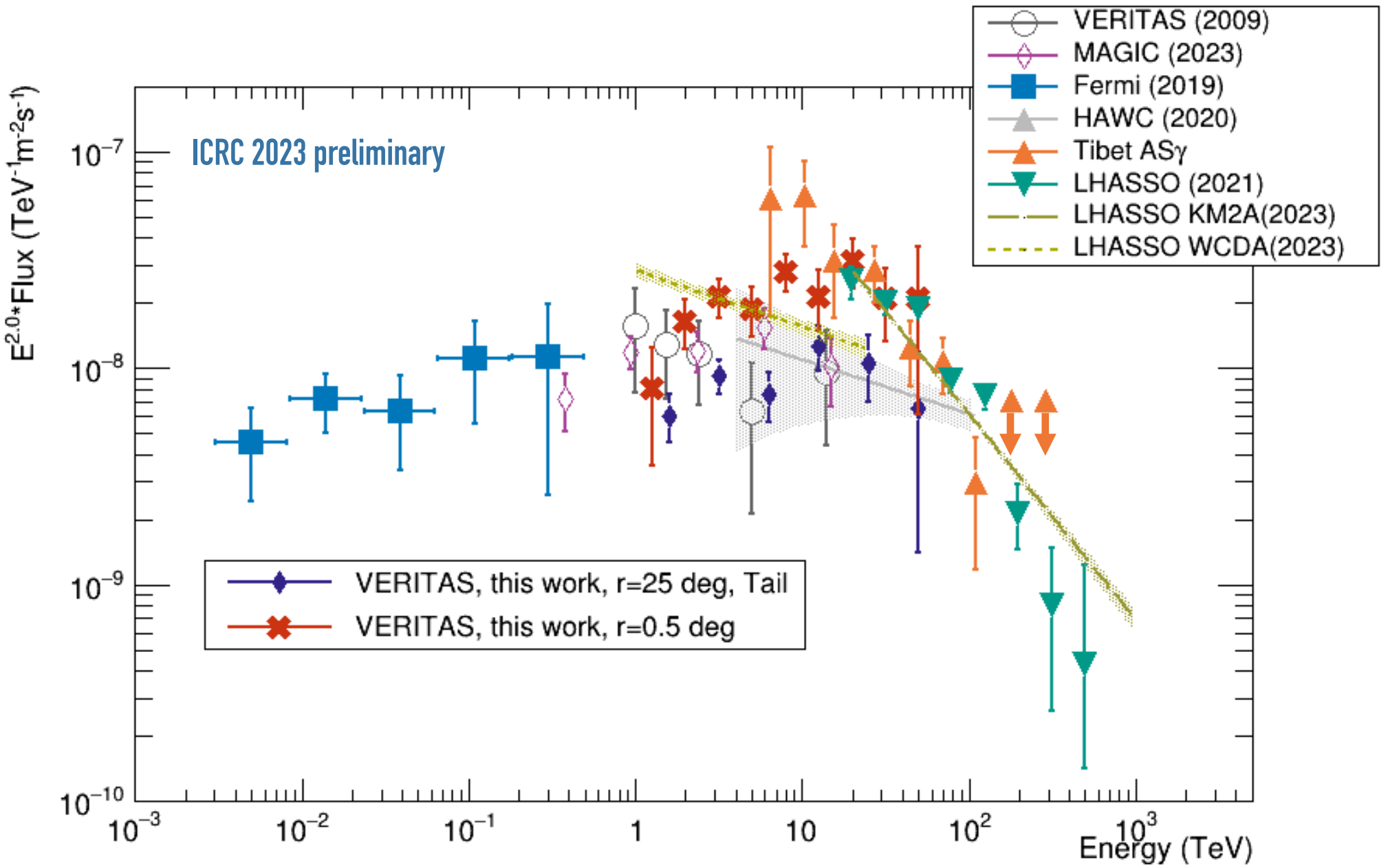
VERITAS Spectrum

- Overall SNR region (r=0.5°)
  - Spectral index: 1.80±0.09
  - Tail region account for ~50-60%





Broad-band Gamma-ray Spectrum

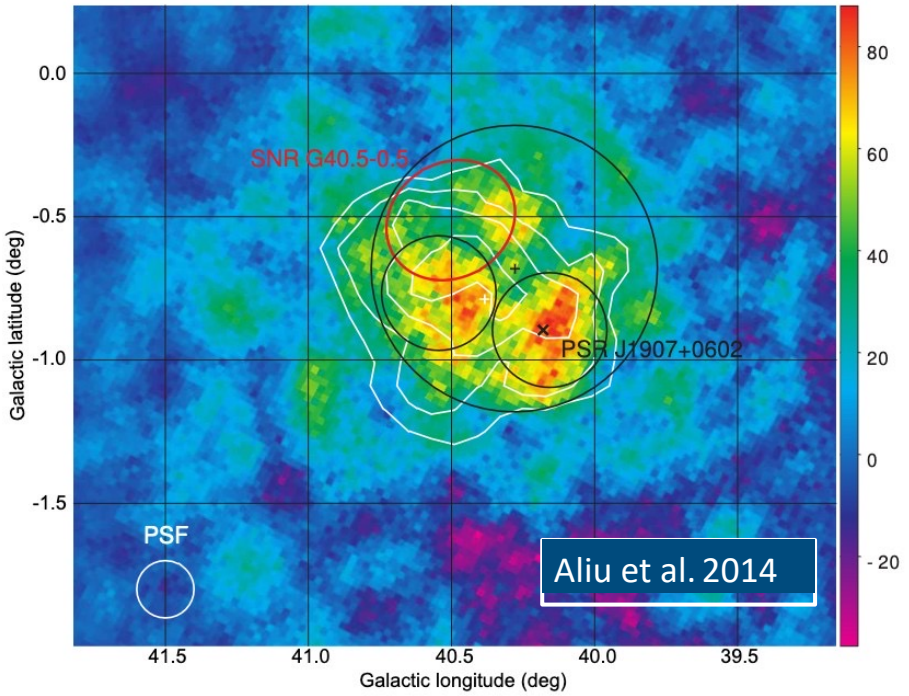


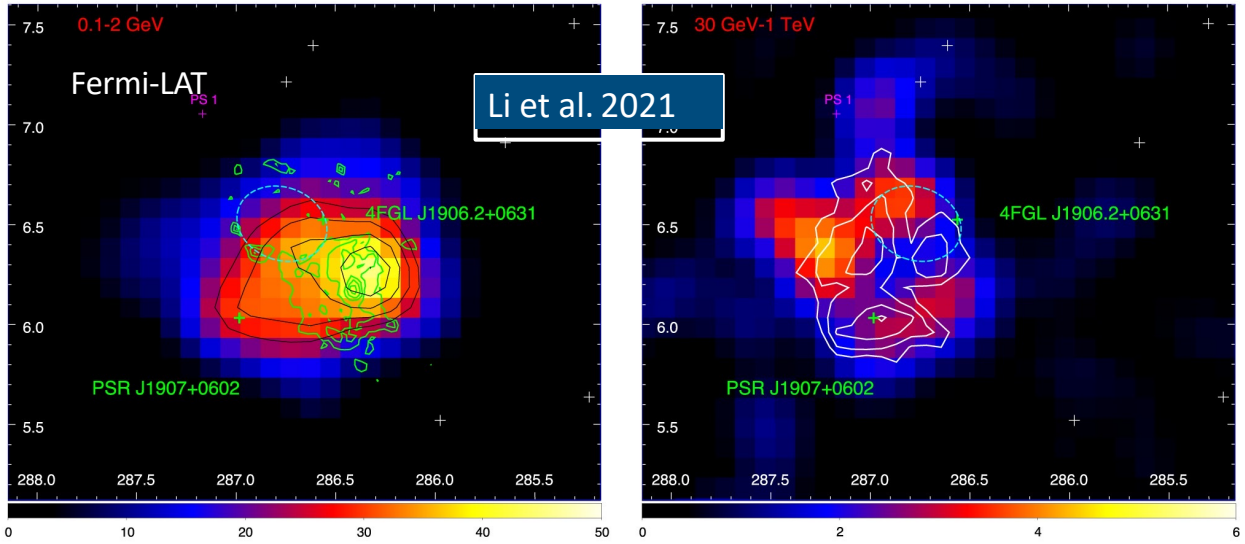
MGRO J1908+06

- Galactic unidentified source.
- Several potential counterparts; no identification in X-ray and radio yet. Two good candidates are the Pulsar PSR J1907+0602 and SNR G40.5-0.5.
- Distance estimate: ~ 3kpc (PSR, SNR).
- PeVatron candidate: Extended gamma-ray emission exceeding several hundred TeV. LHAASO: TeV detection of PWNe.
- Previous VERITAS analysis: 62h, 2007-2012 data.

Tobias Kleiner, DESY

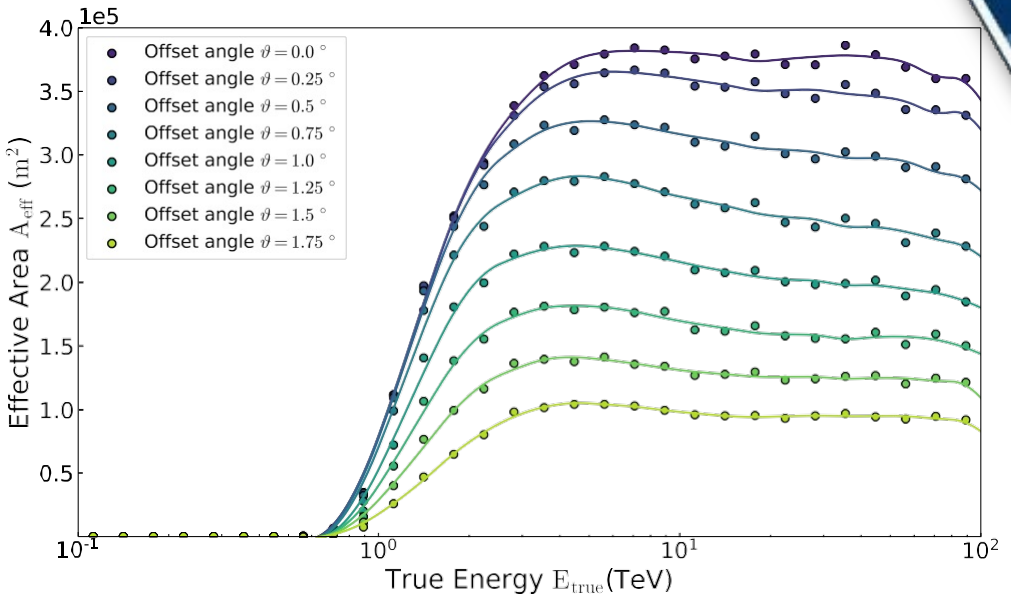
Ruo Shang, Barnard



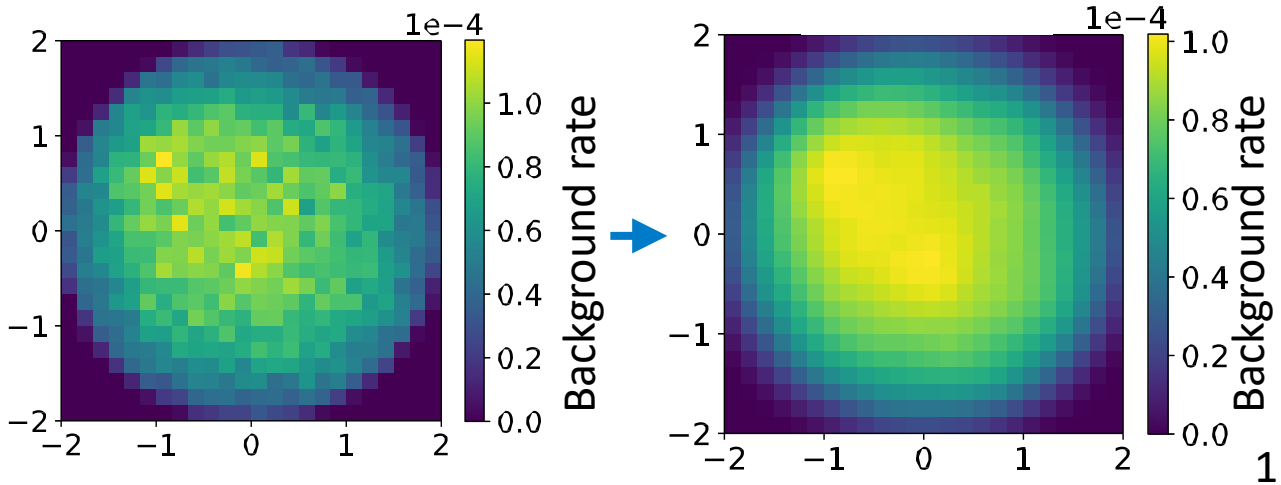


Extended Source Analysis of MGRO J1908+06

- 130 h of data between 2009 and 2022.
- Energy threshold 0.8 TeV.
- Adjusted exclusion regions to mask extended gamma ray emission: 1.5 deg radius around 3HWC centroid.
- Require extended-source analysis:
  - Accurate background modelling.
  - Offset-dependent instrument response.
  - Validation of background models and maximum likelihood analysis.
  - *gammapy* used for these stages.
    - https://www.gammapy.org



raw and smoothed background models



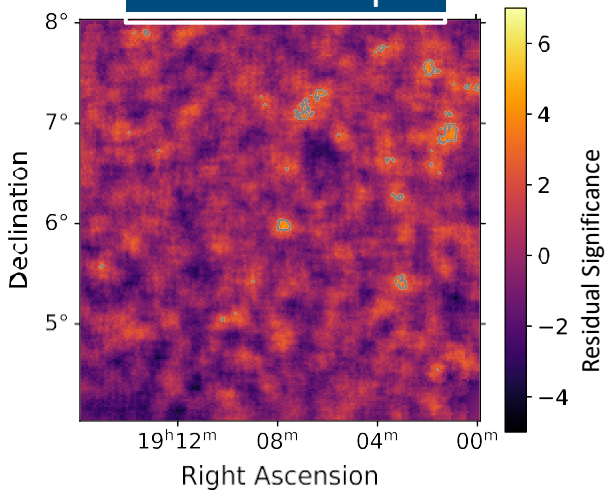
VERITAS MGRO J1908+06 Significance Map

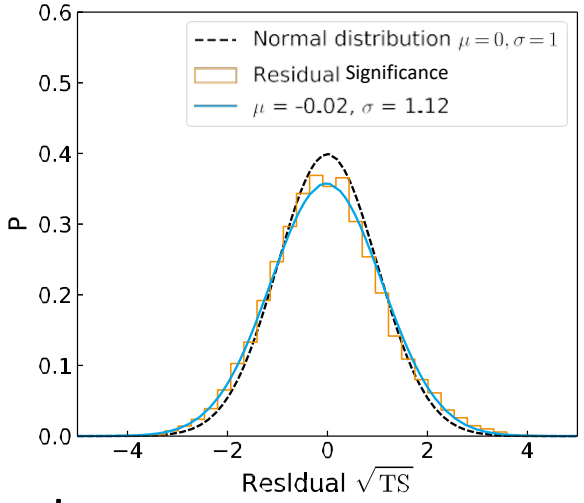
Emission best described by symmetric Gaussian model:

Best-Fit Parameters:

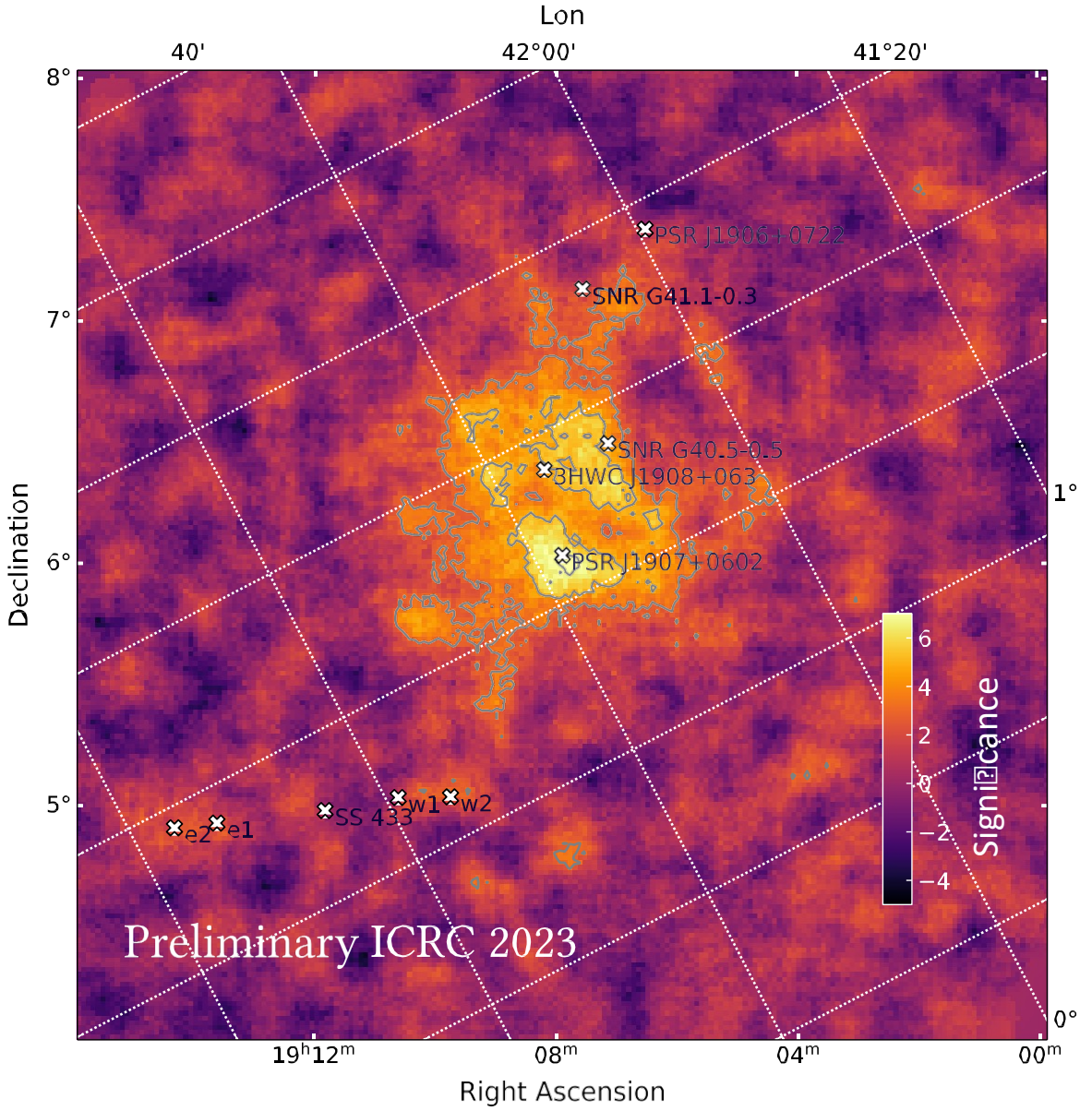
lon	286.96
lat	6.39
σ	0.46

Residual map





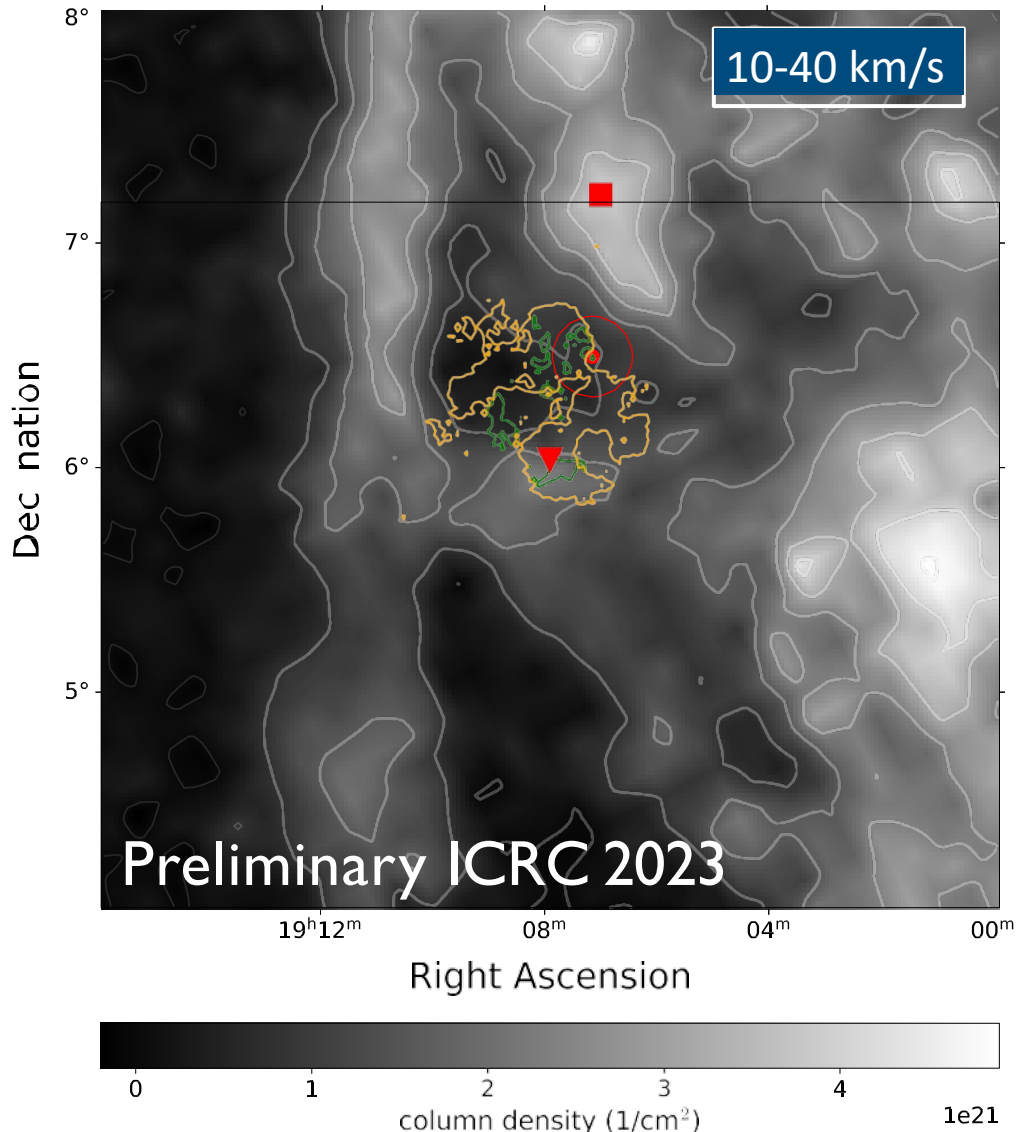
Energy dependent morphology:
In the lower energy range, the emission is closer to the MGRO J1908+06 position, in the high energy range the emission is closer to the PSR J1907+0602 position.



CO Molecular Cloud Analysis

- Estimate molecular cloud densities in the region to constrain origin of the gamma-ray emission.
- Molecular cloud data from 1.2m CO survey of the Smithsonian Astrophysical Observatory:
  - Velocity slice 1 (10-40 km/s): 0.7-2.5 kpc.
  - Velocity slice 2 (40-70 km/s): 2.5-4.7 kpc.
  - Bulk of the gamma-ray emission lies in a cavity.

5 sigma VERITAS contours:
0.8-3.05 TeV (green)
3.05-12.3 TeV (orange)



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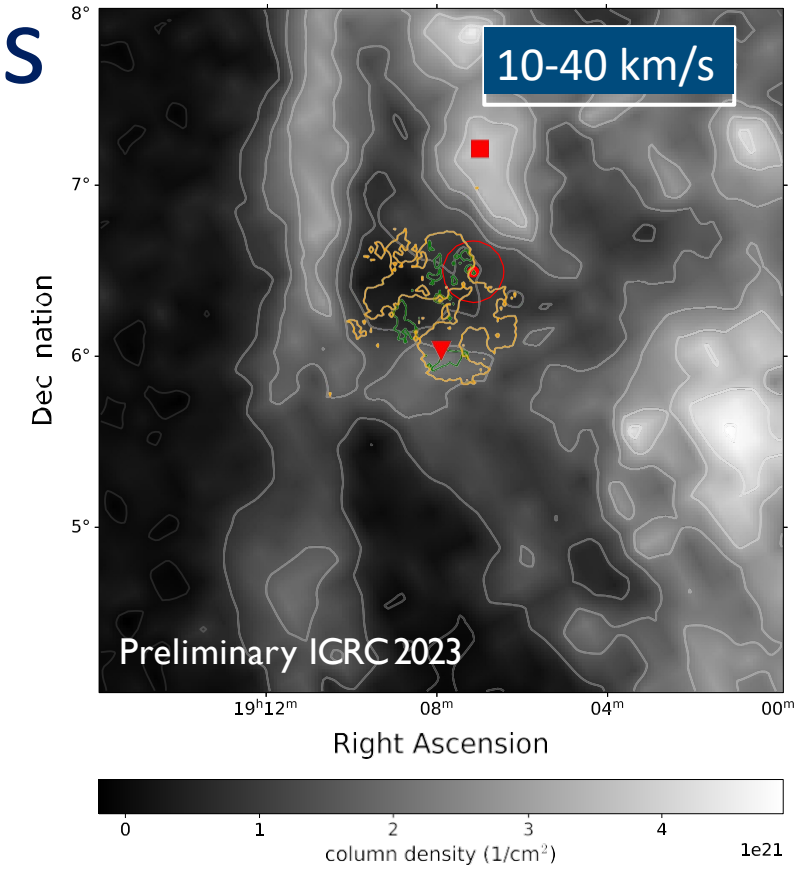

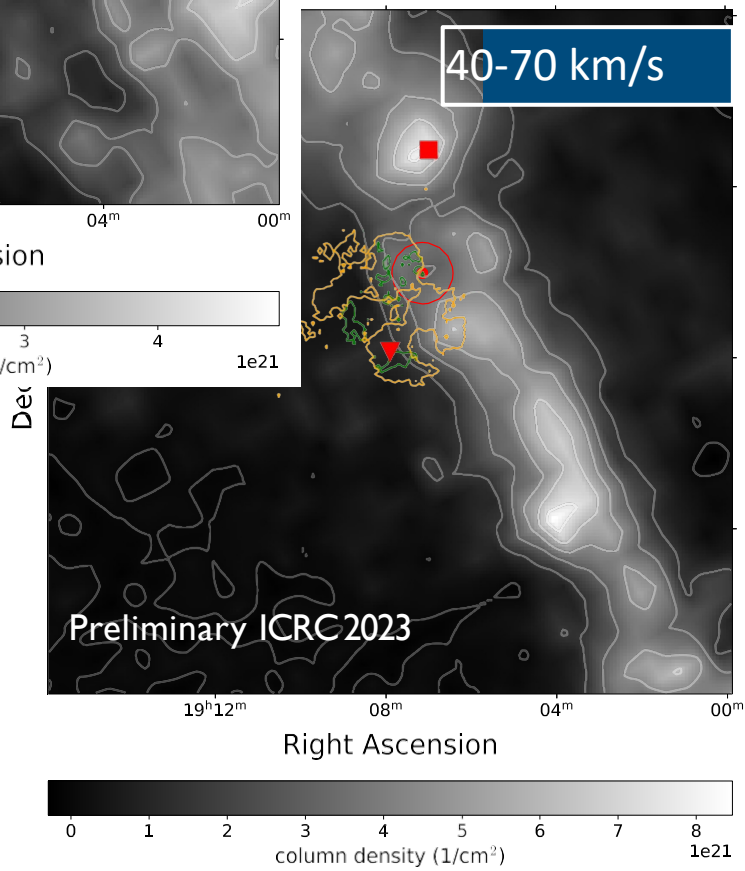

5 sigma VERITAS contours:
0.8-3.05 TeV (green)
3.05-12.3 TeV (orange)

Multiwavelength Spectral Modelling

- Based on the energy-dependent morphology and the cavity in molecular clouds, which we assume to be associated with the PWNe, we use a leptonic model.
- Simple model with synchrotron and inverse Compton components.
- Middle aged pulsar: only including CMB photon field.
- Electrons injected with a broken power law with exponential cut-off

$$f(E) = \exp(-(E/E_{\text{cutoff}})) \begin{cases} A(E/E_{\text{ref}})^{-\alpha_1} & : E < E_{\text{break}} \\ A(E_{\text{break}}/E_{\text{ref}})^{\alpha_2-\alpha_1}(E/E_{\text{ref}})^{-\alpha_2} & : E > E_{\text{break}} \end{cases}$$

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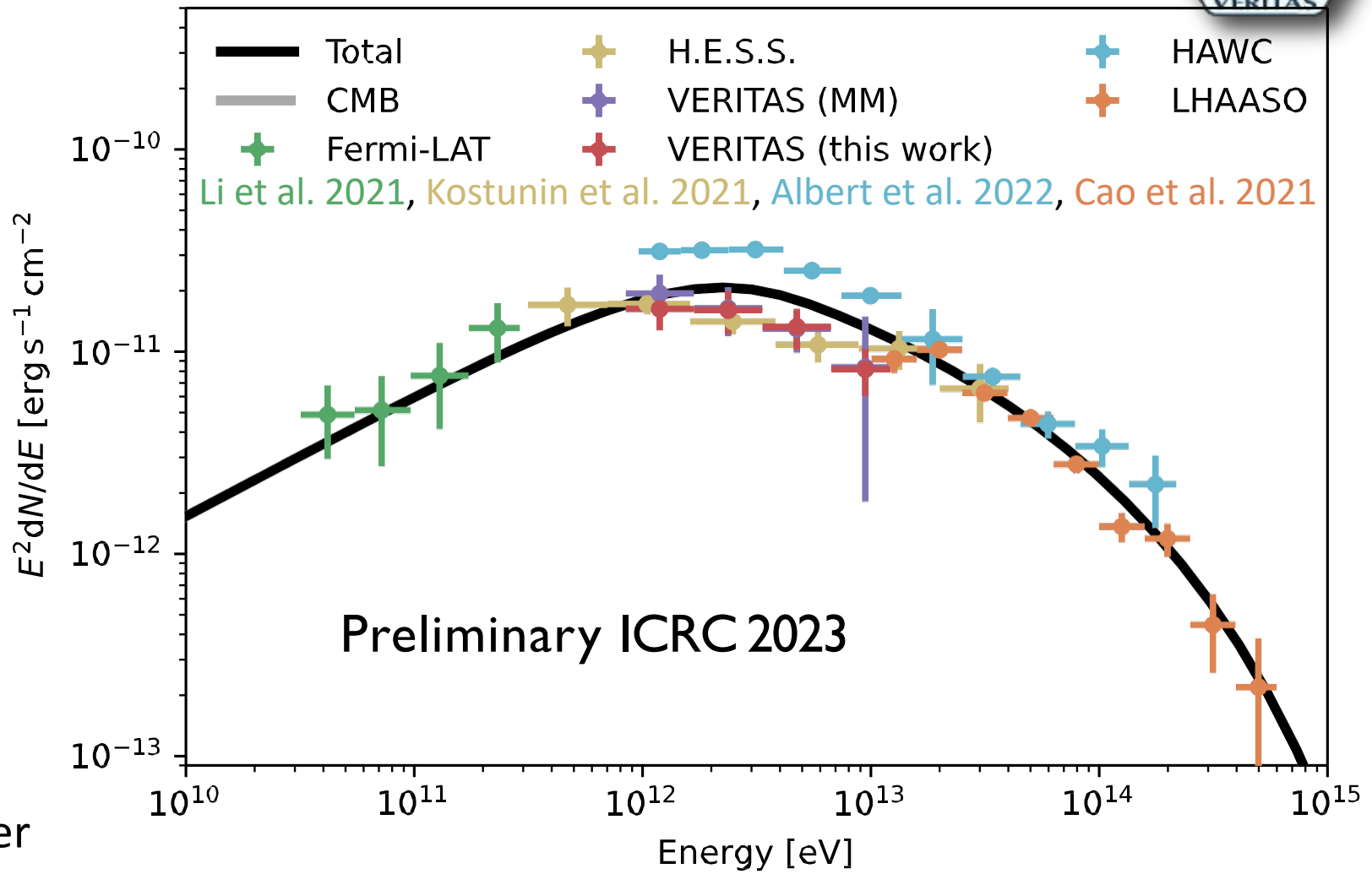
MGRO J1908+06 MWL SED, Leptonic Model

Best-fit parameters of the model:

Parameter	Value
A	$4^{+4}_{-2} \cdot 10^{34}\ 1/\mathrm{eV}$
E_{break}	$19 \pm 3\ \mathrm{TeV}$
α_1	$1.8^{+0.3}_{-0.5}$
α_2	$3.36^{+0.11}_{-0.15}$
E_{cutoff}	$800^{+4000}_{-400}\ \mathrm{TeV}$
B	$5^{+5}_{-4}\ \mu\mathrm{G}$

$W_e(>0.511\ \mathrm{MeV}) = 6 \cdot 10^{47}\ \mathrm{erg}$

- Consistent with Abdo et al. 2009 $2.84 \cdot 10^{36}$ erg/s spin-down power of PSR J1907+0602 for a pulsar age estimate of ~ 20 kyr.



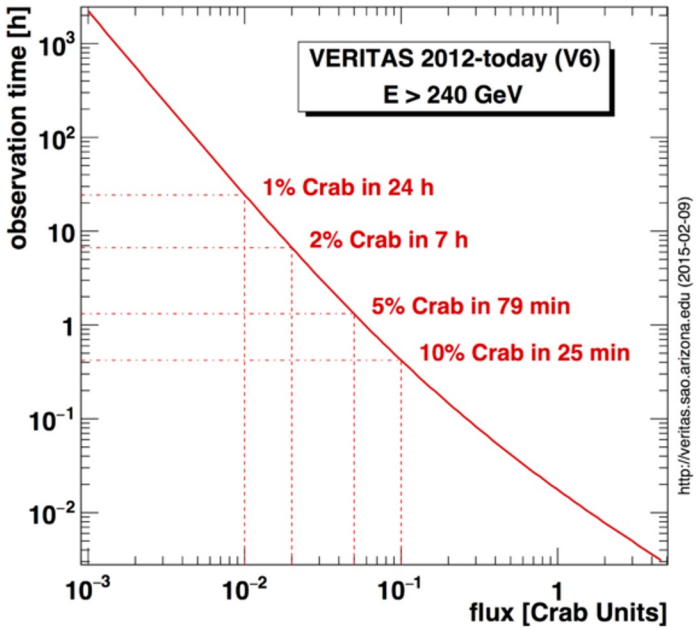
Summary

- VERITAS has a large archival data set and ongoing observations, and welcomes collaboration.
- SNR G106.3+2.7 region is a PeVatron candidate with spectrum extending to 500 TeV.
  - Updated VERITAS with 86 hours of observation shows
    - Lack of gamma-ray emission on the top of X-ray PWN & radio Boomerang PWN.
    - Diffuse emission in the “Head” region off from X-ray & Boomerang PWN.
    - Strong emission in the “Tail” region from 1TeV up to 30 TeV w/ a hard index of 1.8.
    - ~2x larger flux in the entire SNR region, consistent w/ results from other gamma-ray observations.
  - Systematic studies on-going within VERITAS to explore the full data set (> 150 hours).
  - Potential connection to a very extended source, 1LHAASO J2229+5927u.
- MGRO J1908+06:
  - Pulsar PSR J1907+0602 remnant of SN explosion, kicked to current location.
  - Consistent with electrons cooling as they are transported away from pulsar.
  - Emission from MGRO J1908+06 consistent with a Leptonic model of the SED.

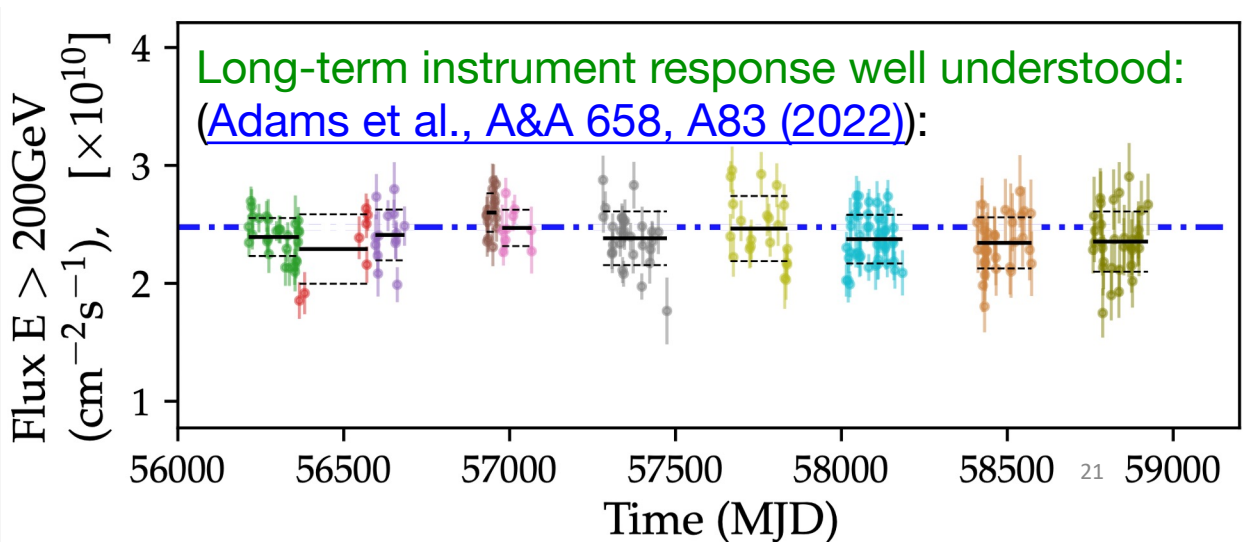
Backup

VERITAS Performance + Observations

- FoV 3.5 deg (diameter)
- Energy range: ~85 GeV to ~30 TeV
- Effective Area: 10^5 m^2 @ 1 TeV
- Ang. resolution: 0.08° resolution @ 1 TeV
- Sensitivity: 1% Crab in 25 hrs, 10% in 25 min
- Energy resolution: ~17%

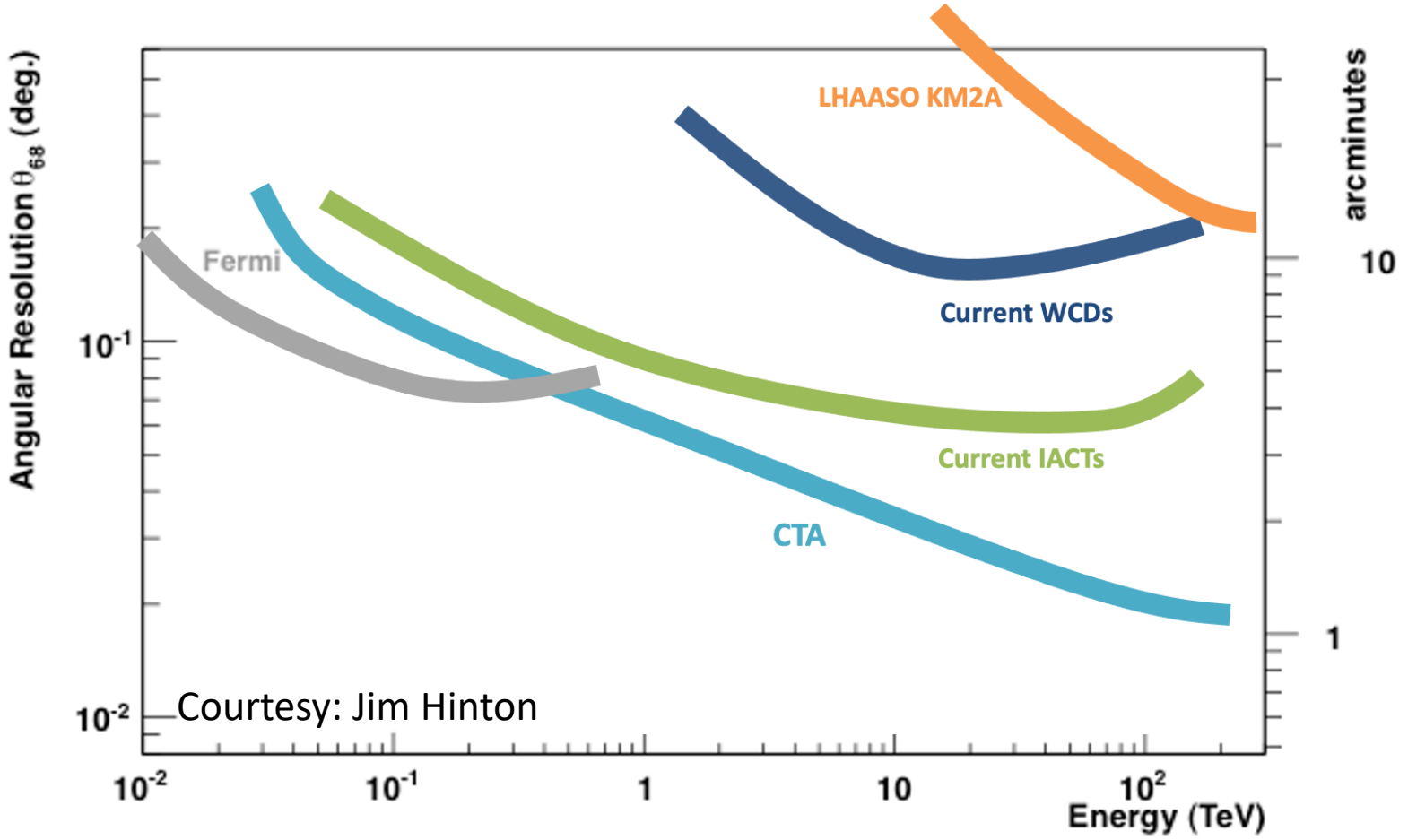


- Operates September – July (summer monsoon)
- ~950 hrs dark time, ~250 hrs bright moon (30-65% illum.).
- Optical stellar intensity interferometry during full moon (> 65%)
- Remote observing capabilities introduced during lockdowns - now a long-term option



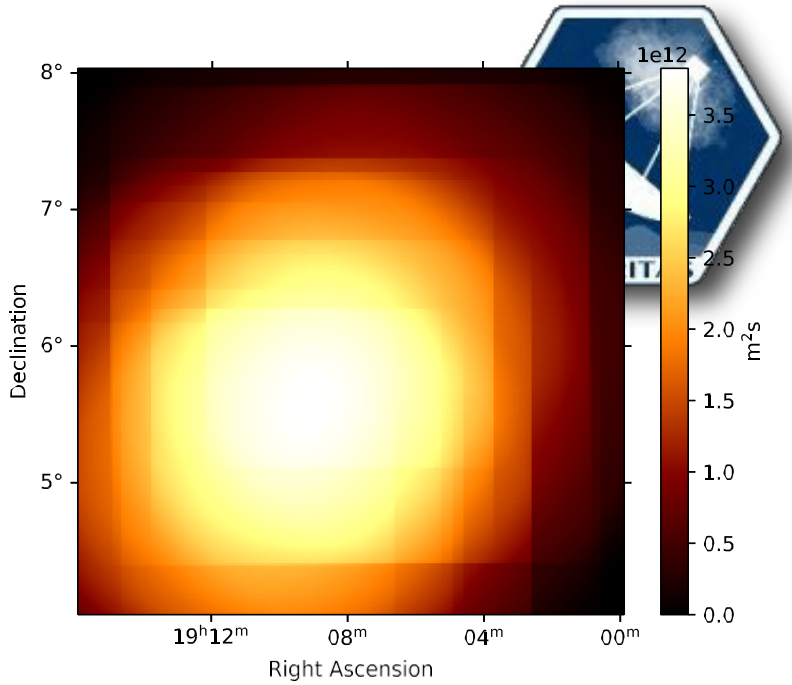
What Do IACTs Add to PeVatron Searches?

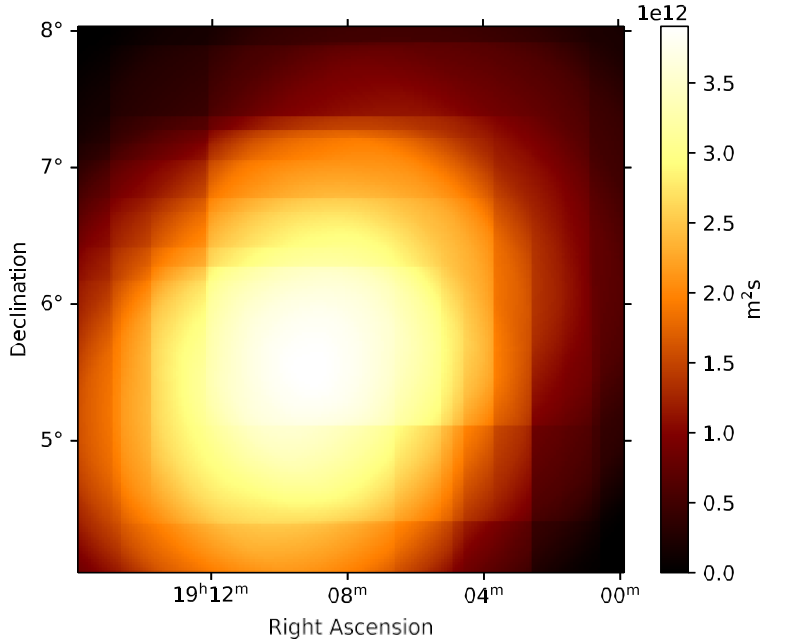
- Angular resolution
  - Identification of MWL counterparts
  - Disentangling of components/ confused sources
- Extension of spectra
  - Constrain evolution of particle population with energy
- High(er) statistics
  - Steeply falling power laws



VERITAS Mimic Data Method

- Objective:
  - Bias estimation, reduction and systematic error estimation from the analysis.
- Method:
  - Replicate observation conditions with independent mimic datasets.
  - Observations in mimic datasets are matched in zenith angle, elevation angle, night-sky background, instrument status (epoch).
  - Mimic datasets are analysed in the same way as the data for the analysed source.
  - Pointing of the observations in the mimic datasets are adjusted to achieve a match in observation conditions to the MGRO J1908+06 dataset.

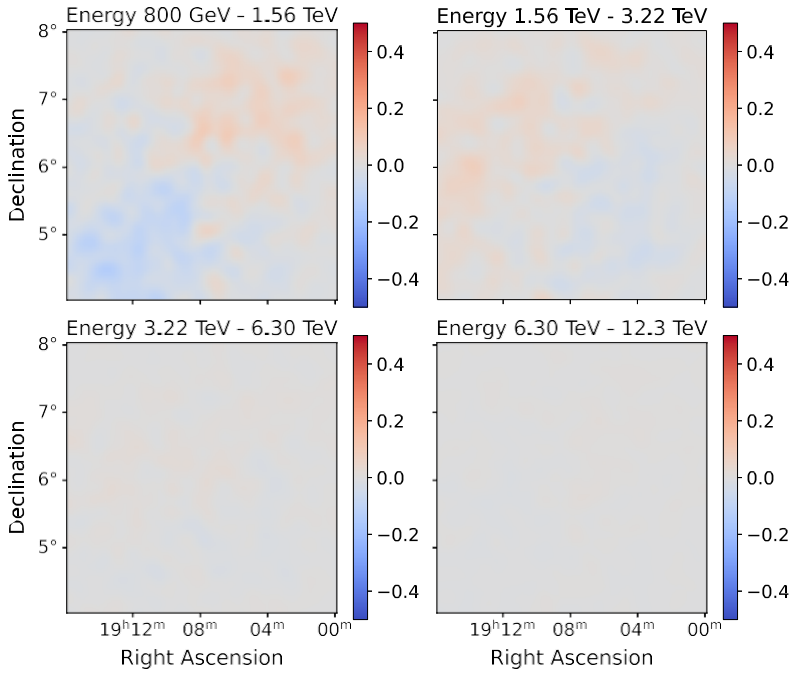




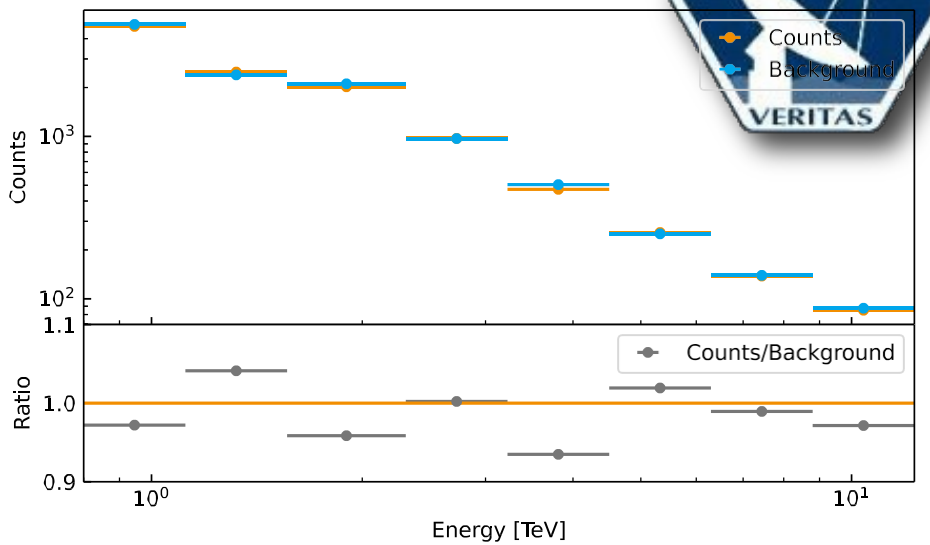
VERITAS Mimic Data Method

- We use the mimic data method to correct for biases from the analysis method.
- The energy dependent systematic error from the analysis method is estimated at 5-12% of the flux.

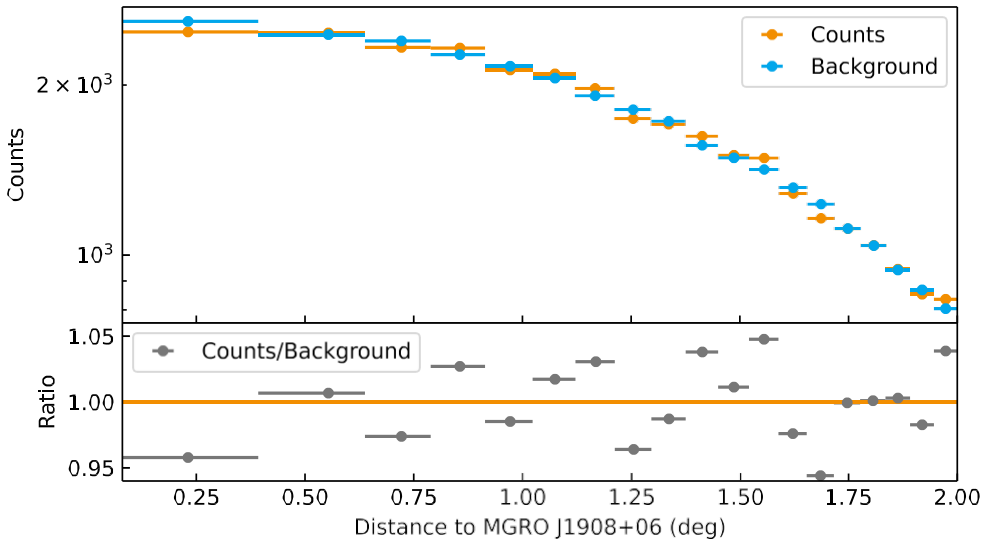
Mimic dataset excess map



Energy dependence of predicted counts and background counts.

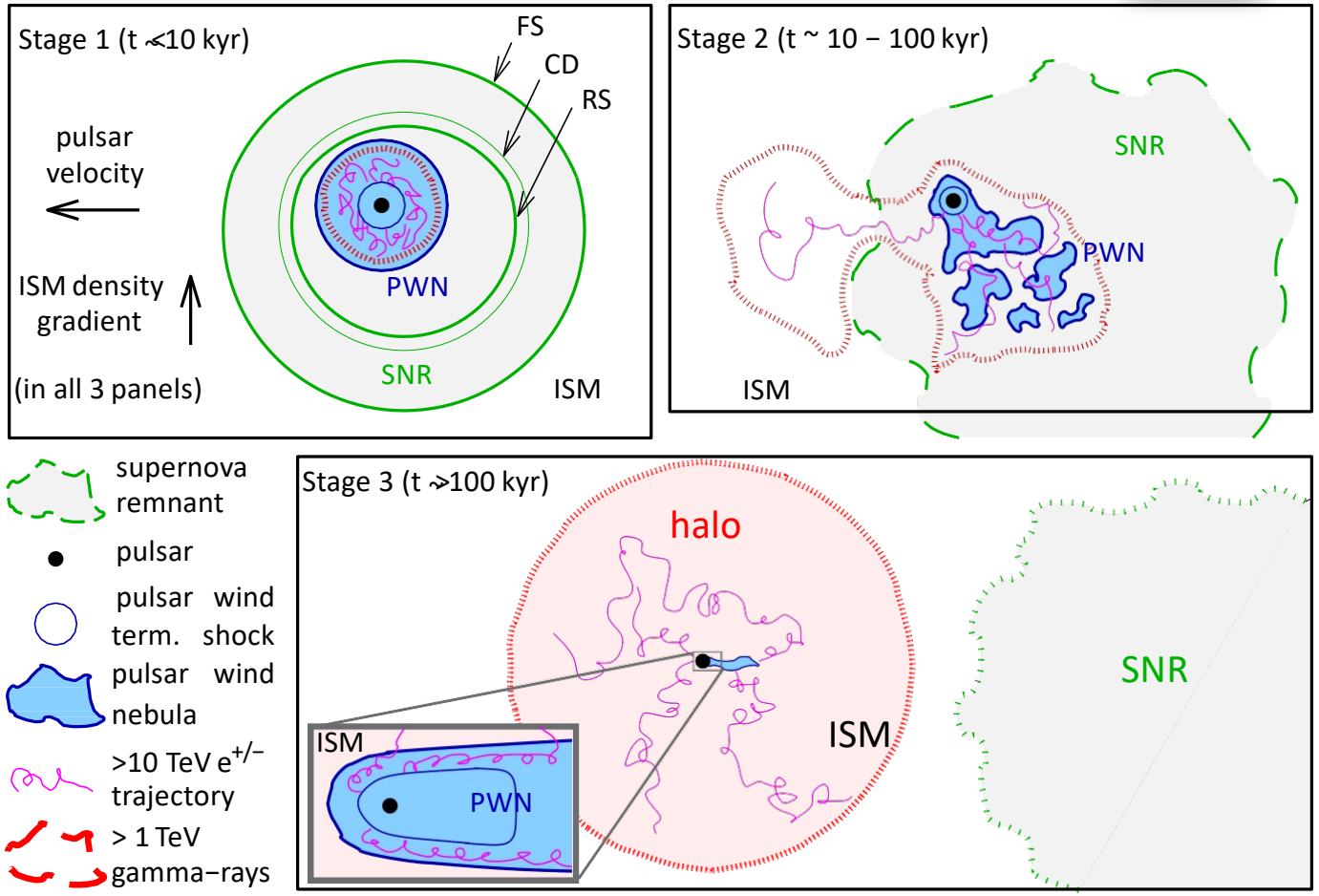


Radial dependence of predicted counts and background counts



PWNe in MGRO J1908+06

- Close-by middle aged PWNe are particularly suited to study at GeV to TeV.
- Allows investigation of morphology and particle acceleration/transport resulting from interactions from the host SNR and the PWNe.
- Evolutionary phases of PWNe:
  - I: Free expansion phase
  - II: Reverse shock of the SNR interacting with the PWN
  - III: PSR escaped SNR



Giacinti et al. 2020