# Multiwavelength studies of Galactic PeVatron candidates with VERITAS

Presented by Nahee Park

for VERITAS Collaboration, Isaac Pope, Kaya Mori, Moaz Abdelmaguid, Joseph Gelfand


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# VERITAS

Very Energetic Radiation Imaging Telescope Array System

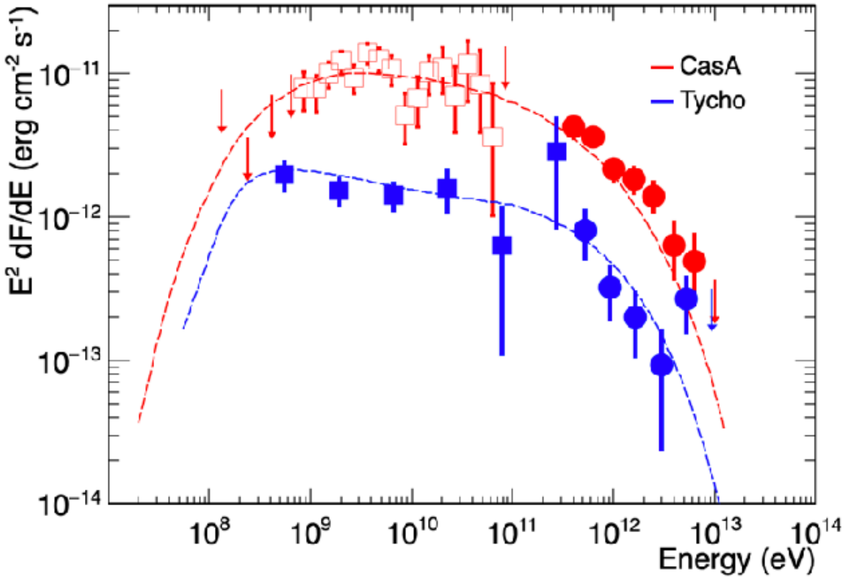
## Fully operational since 2007

- An array of imaging atmospheric Cherenkov telescopes
  - Sensitive in energy range from ~ 85GeV to > 30 TeV gamma-rays
  - Can detect 1% Crab Nebula signal in ~ 25 hours  w/ angular resolution of <0.1 degree at 1 TeV
- ~ 1000 hours/year in “dark time” observation,
  ~300 hours of bright moonlight data (moon illumination>30%)

# Galactic PeVatrons Searches with VERITAS

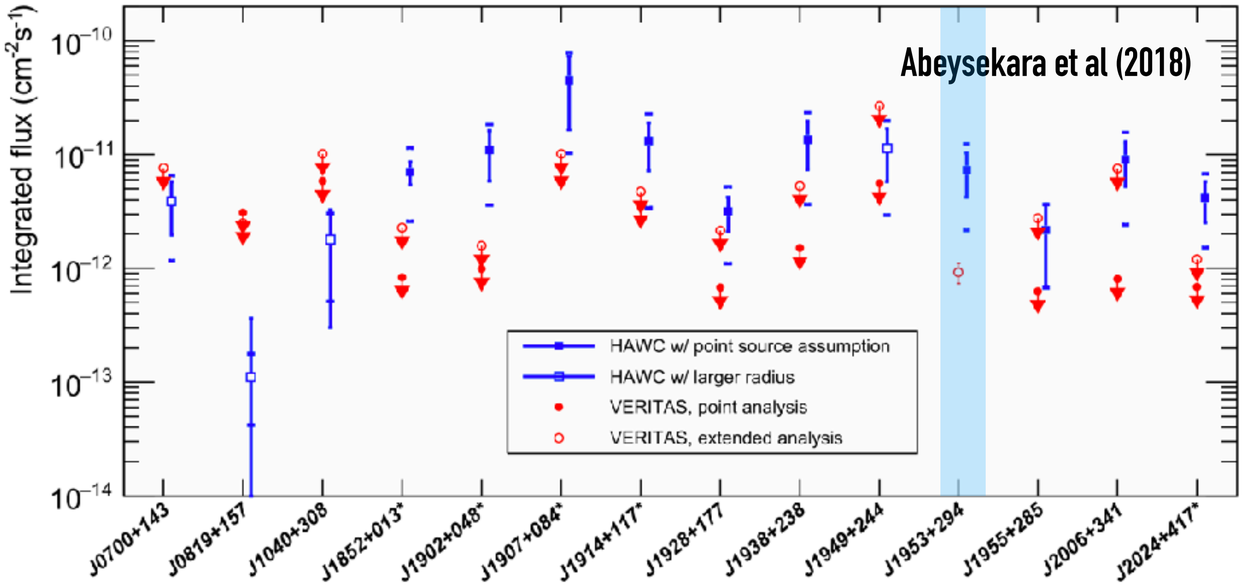
## Deep observations of the young Supernova Remnants

- Tycho's SNR: $E_{cut}$ (TeV) = 1.70 ± 1.23 (2σ) *(Archambault et al, 2017)*
- Cassiopeia A: $E_{cut}$ (TeV) = 2.31 ± 0.51 (4σ) *(Abeysekara et al, 2020)*




## Study the origin of unidentified, hard index sources

- MGRO J2019+37 *(Aliu et al, 2014; Abeysekara et al, 2018)*
- MGRO J1908+06 *(Aliu et al, 2014)*
- VER J2227+608 (SNR G106.4+2.7 region) *(Acciari et al, 2009)*
- Followup observation of HAWC sources *(2HWC follow-up: Abeysekara et al, 2018)*
- Followup observation of LHAASO sources: including LHAASO J2108+5157 & LHAASO J0341+5258



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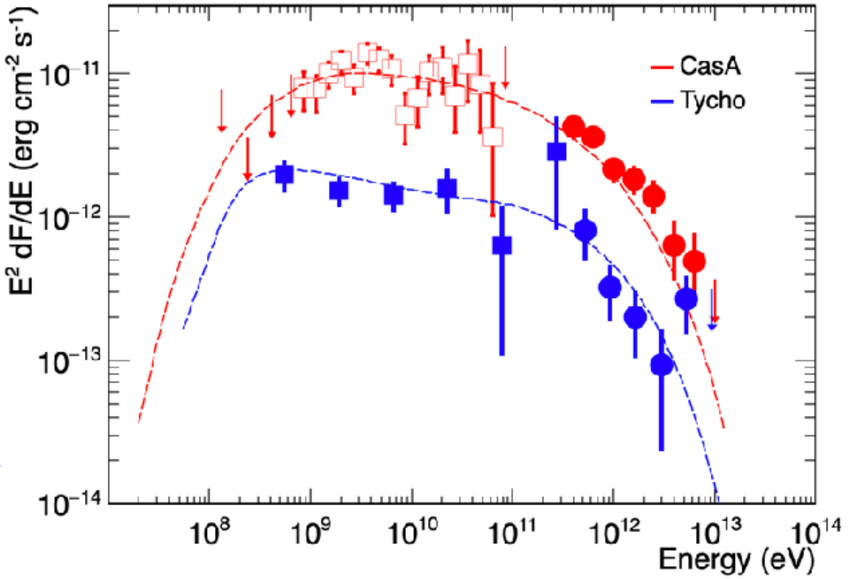


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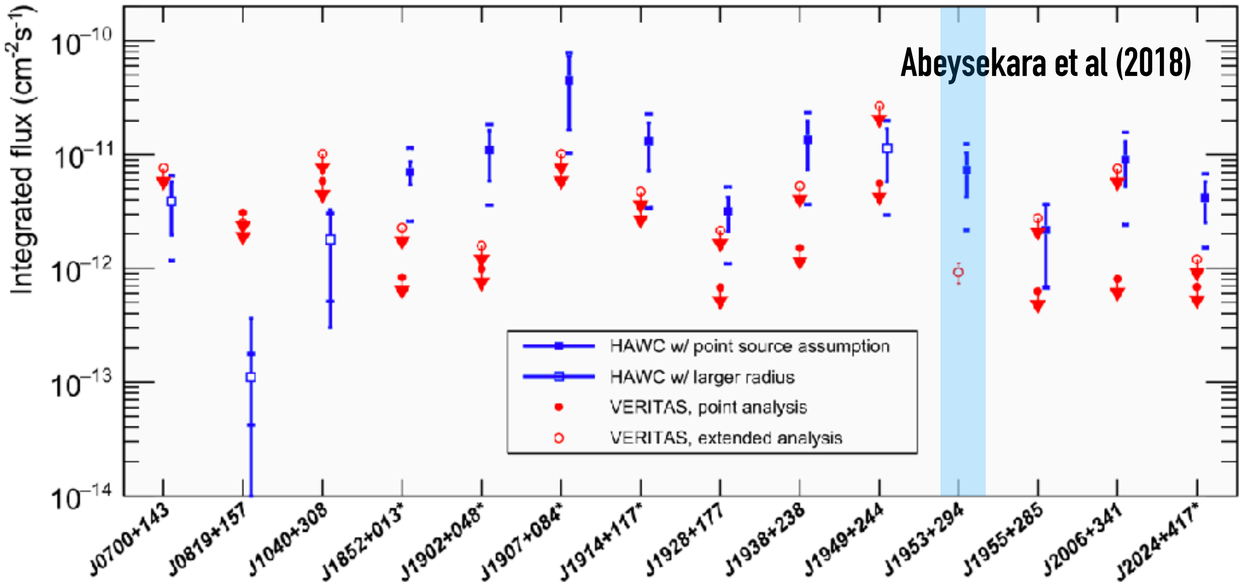

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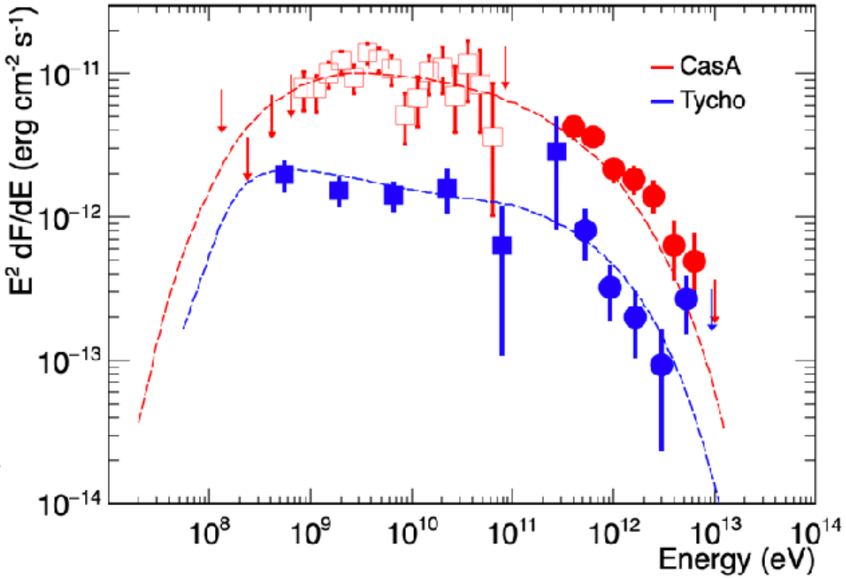


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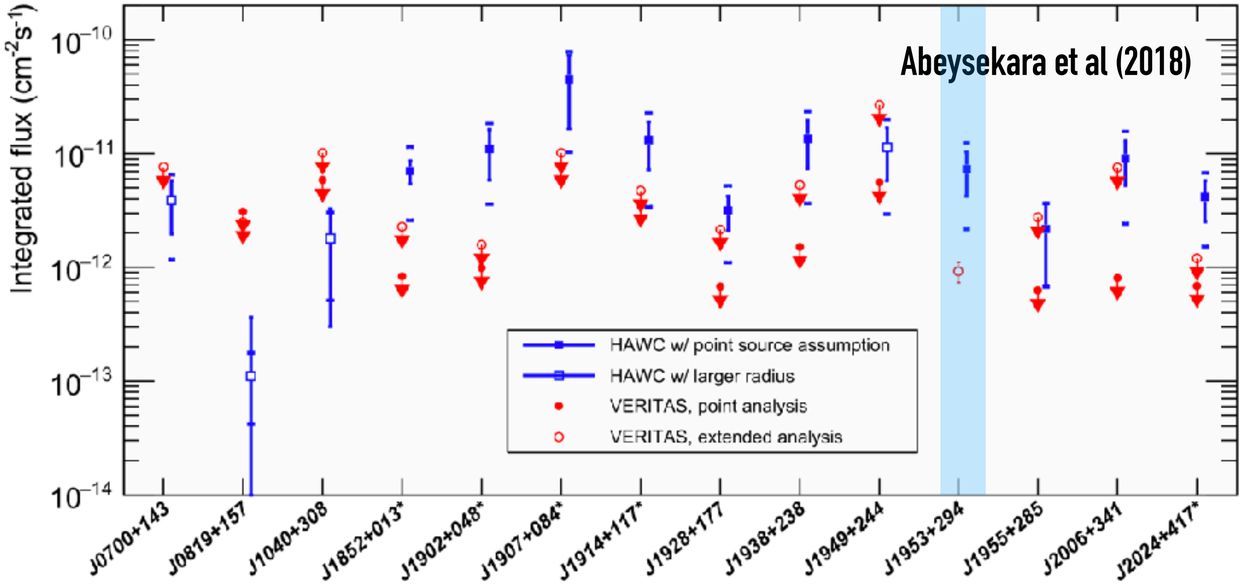

# LHAASO Sources (w/ ~300 days of exposure)

**12 sources w/ UHE photons up to 1.4 PeV**

- LHAASO J0534+2202
- LHAASO J1825-1326
- LHAASO J1839-0545
- LHAASO J1843-0338
- LHAASO J1849-0003
- LHAASO J1908+0621
- LHAASO J1929+1745
- LHAASO J1956+2845
- LHAASO J2018+3651
- LHAASO J2032+4102
- LHAASO J2108+5157
- LHAASO J2226+6057

**Other LHAASO sources**

- LHAASO J0341+5258
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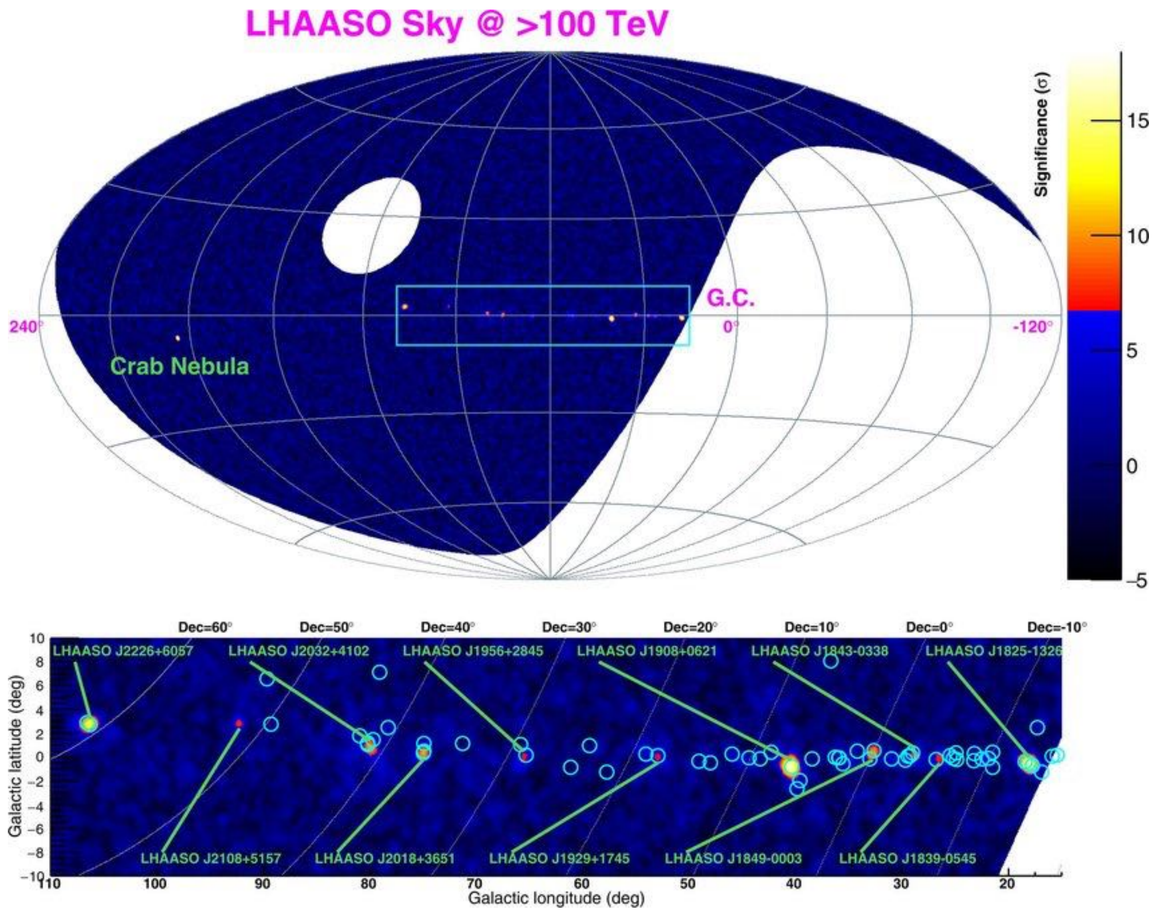


Cao et al (2021)

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- LHAASO J2108+5157
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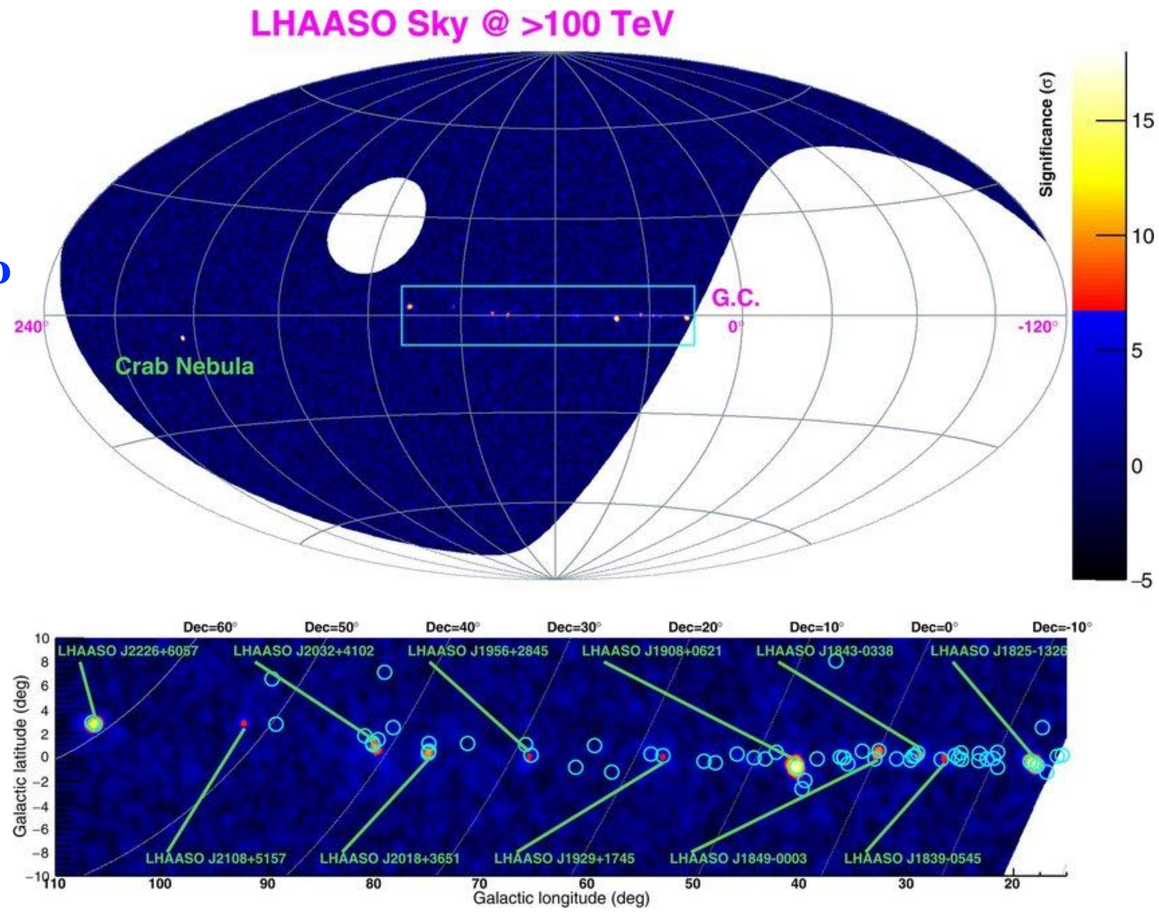


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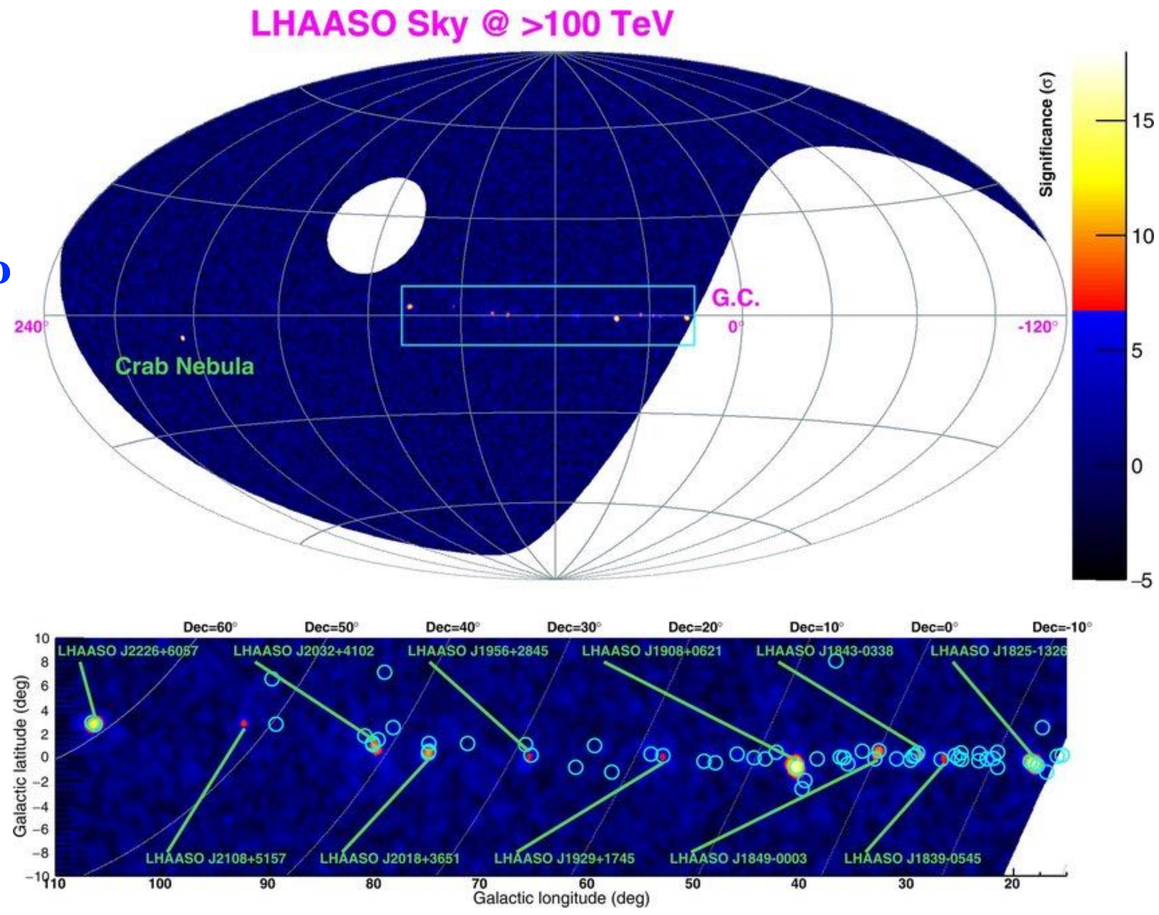


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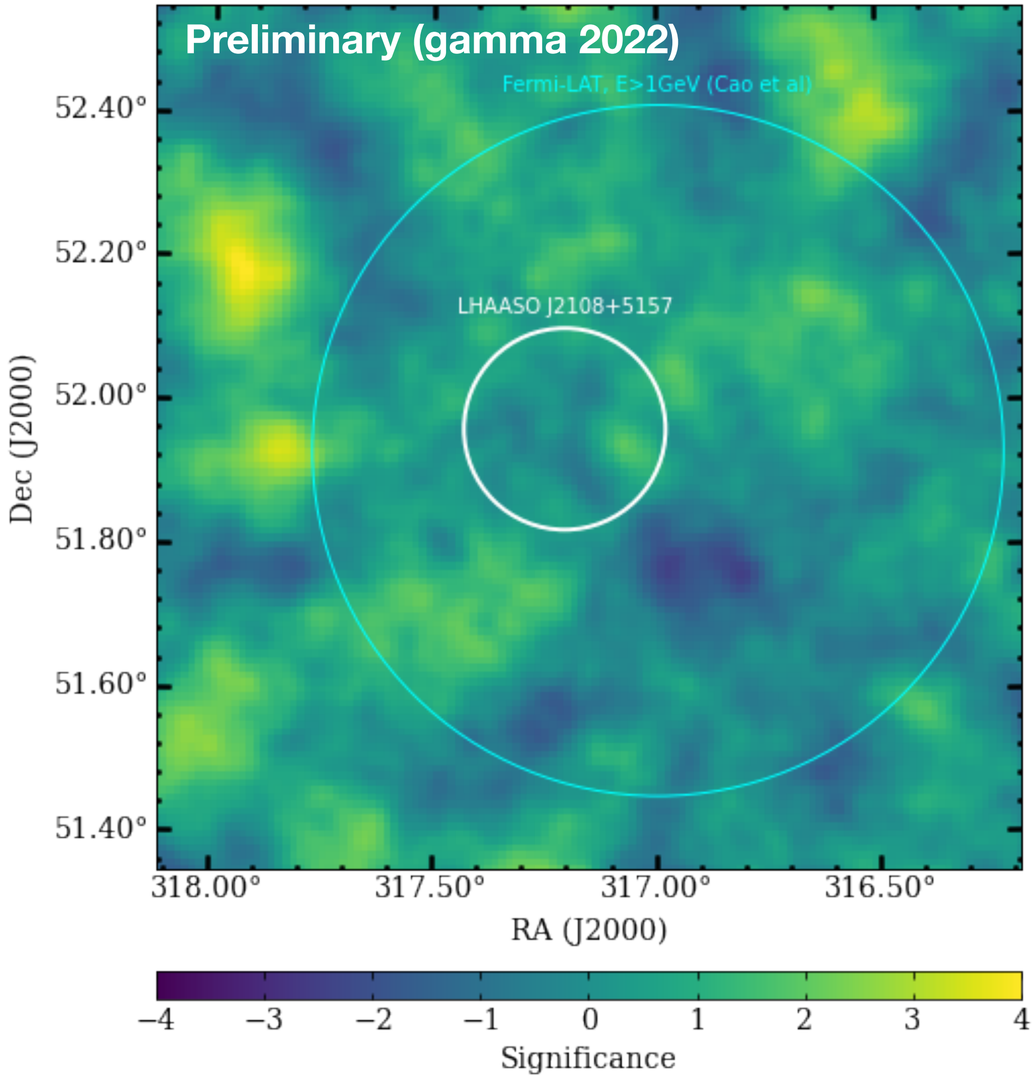
# Followup for LHAASO J2108+5157

## LHAASO J2108+5157

- No counterpart detected by IACTs
- Point-like to LHAASO (extension upper limit: 0.26°)
- Coincident w/ 4FGL J2018.0+5155 (UID)
  - For E> 1GeV, LHAASO team reports an extension of the source: 0.48±0.06°

## VERITAS followup observations

- 35 hours of exposure time
  - Both point source search & extended source search yielded no detection



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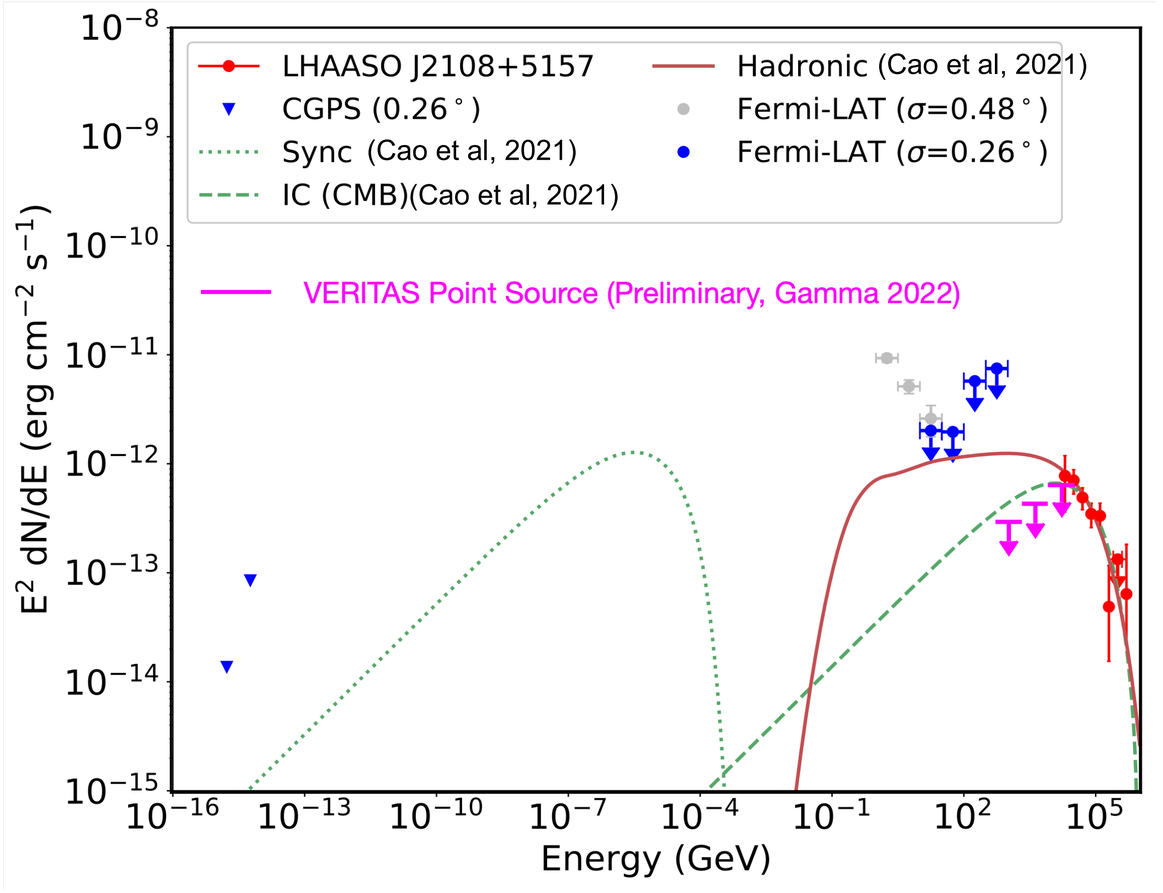
## VERITAS followup observations

- 35 hours of exposure time
  - Both point source search & extended source search yielded no detection
- VERITAS's measurements indicate the cut-off energy to be in multi-TeV range
  - Ruling out the hadronic model of Cao et al (2021)



# SNR G106.4+2.7 region

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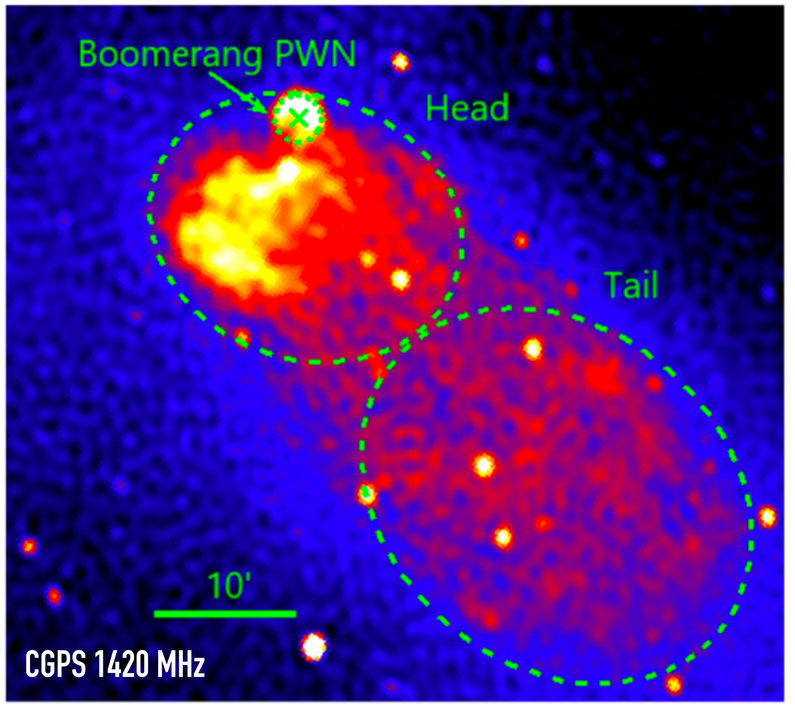
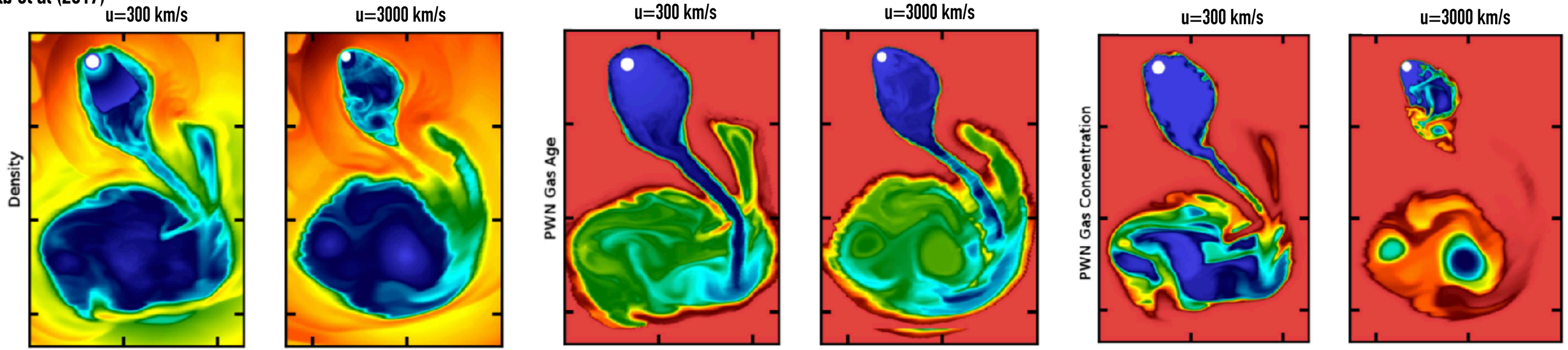
- Head region
  - Contains Boomerang PWN + PSR J2229+6114
- Tail region
  - Contains VER J2227+608, strong gamma-ray emission in the region up to 500 TeV
  - Faint and diffused in radio & X-ray
  - Nature of the gamma-ray is unclear
    - ✦ leptonic vs. hadronic (w/ molecular cloud)



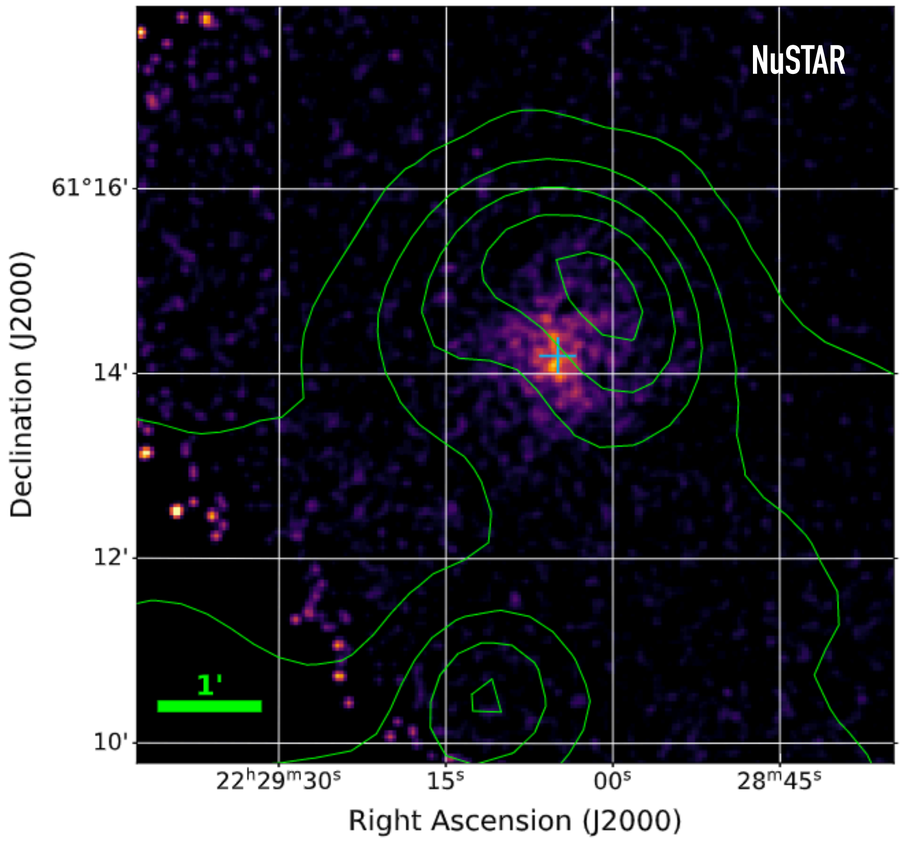

Kolb et al (2017)

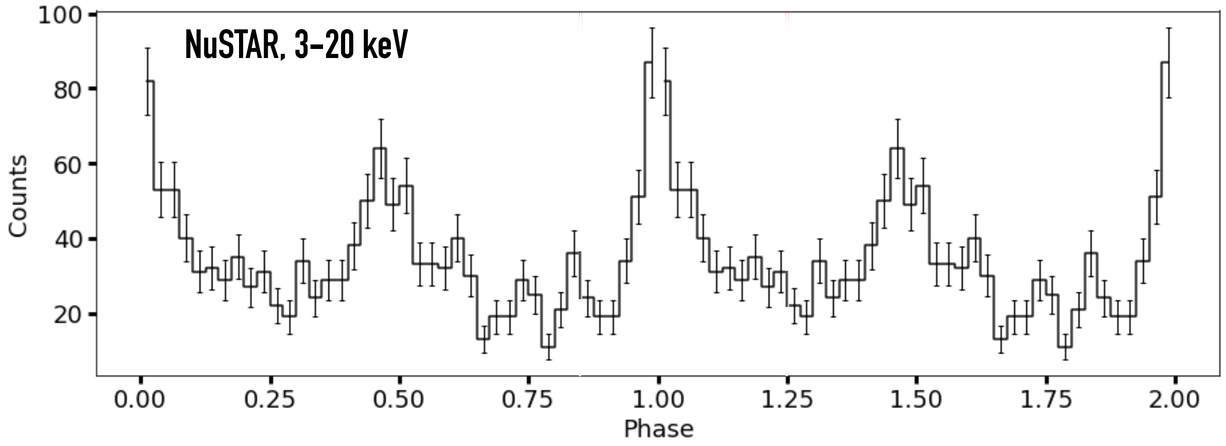


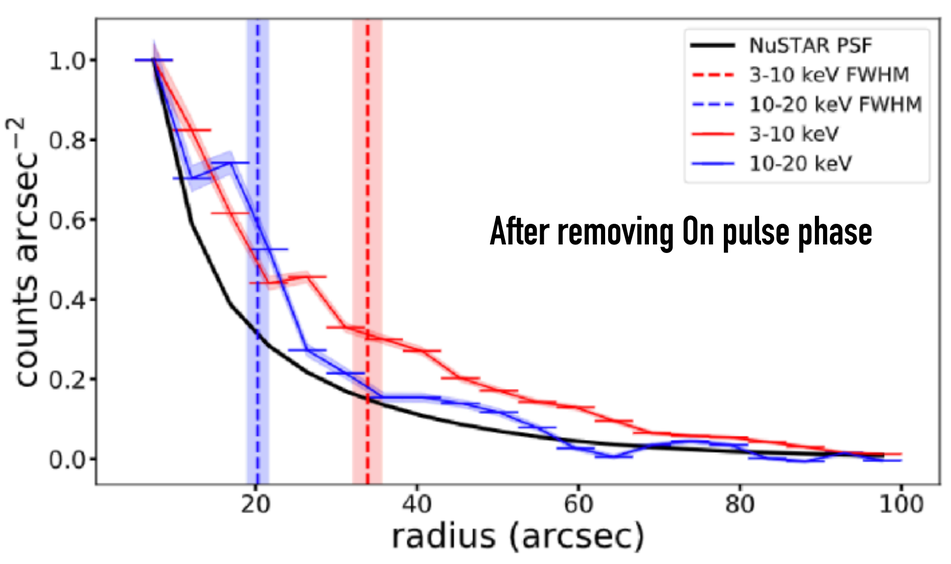
# NuSTAR Observations

## NuSTAR detects PSR J2229+6114 and the extended PWN

- X-ray emission is extended: ~ 100 ″
  - The lower energy band observes a larger extension compared to the higher energy band
  - Smaller extension compared to radio



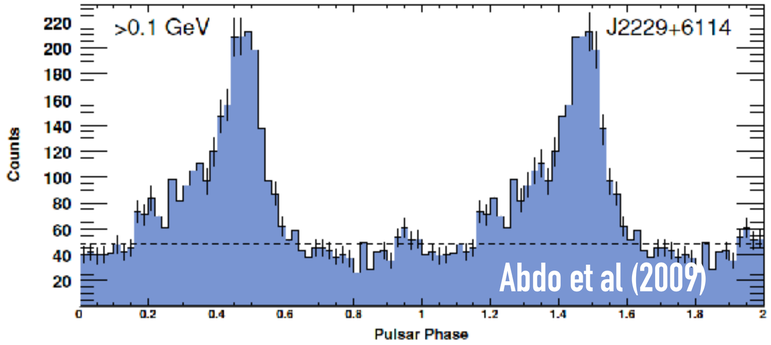



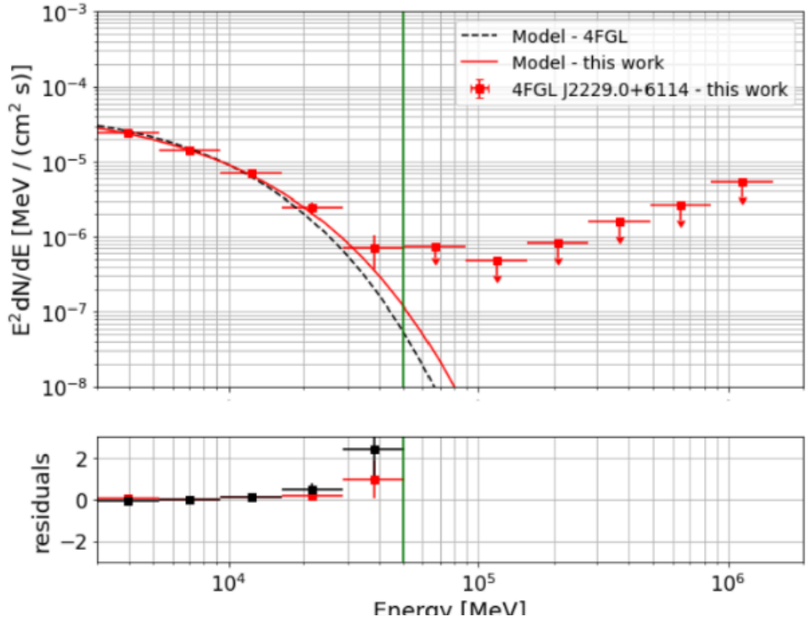



# Gamma-ray observations

## Fermi-LAT analysis

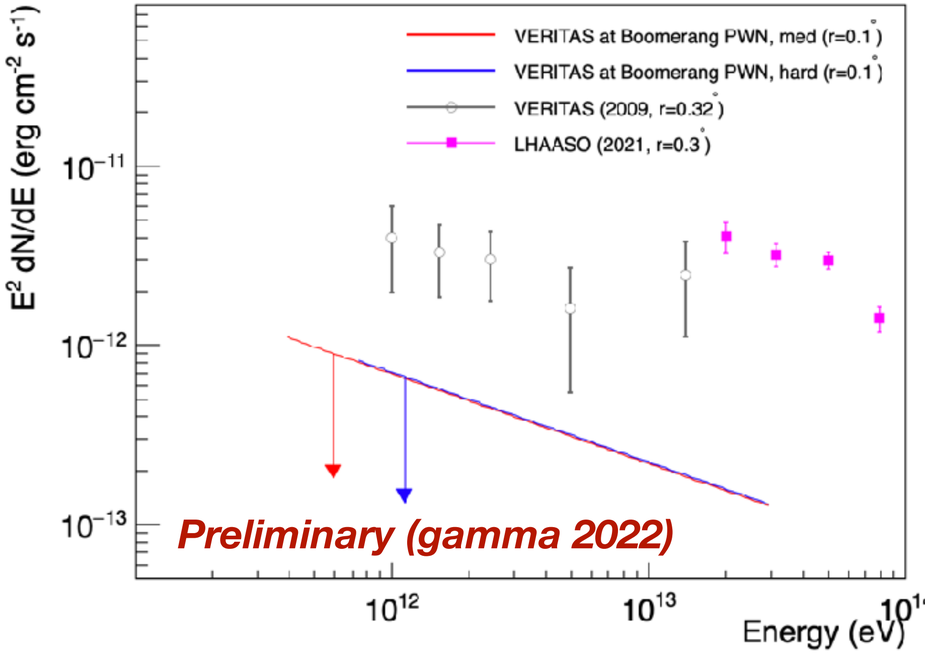
- 4FGL J2229.0+6114 is the counterpart of PSR J2229+6114
- Analyze for E>3 GeV: no detection




## VERITAS observations

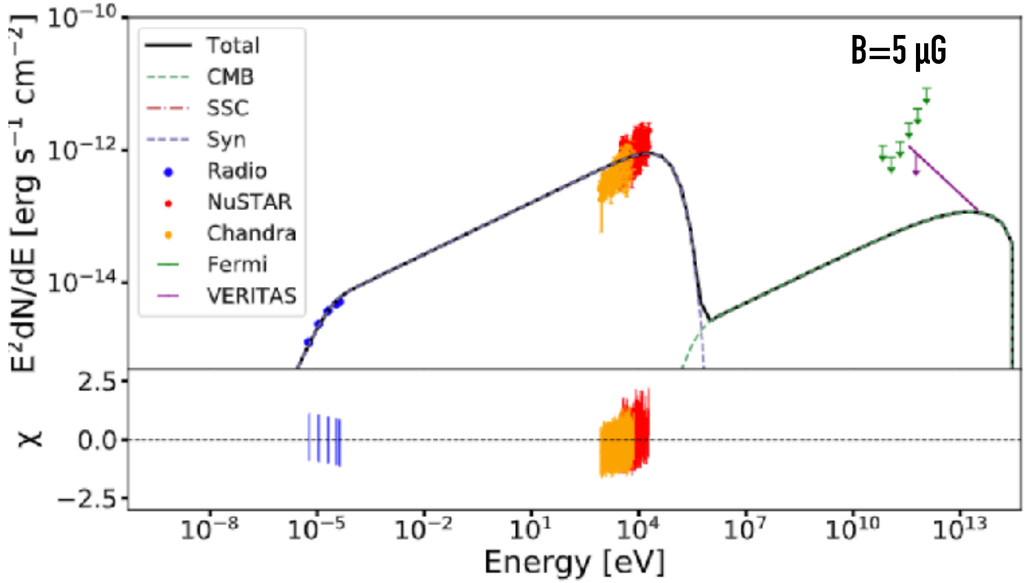
- V4+V5 data: total 57.7 hours
- Study with point-like source search as X-ray region is small (~ 100 ″)
  - No detection



# Modeling Studies

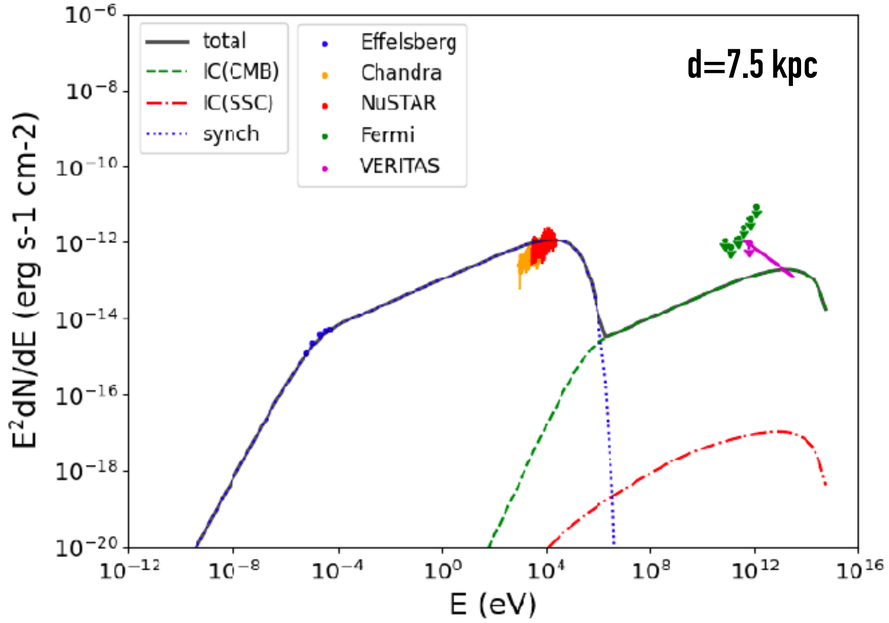
## NAIMA models

- Time-independent one-zone model
- Pointing toward a lower magnetic field (≲ 10 μG)
- Generally hard to fit X-ray data well




## GAMERA model

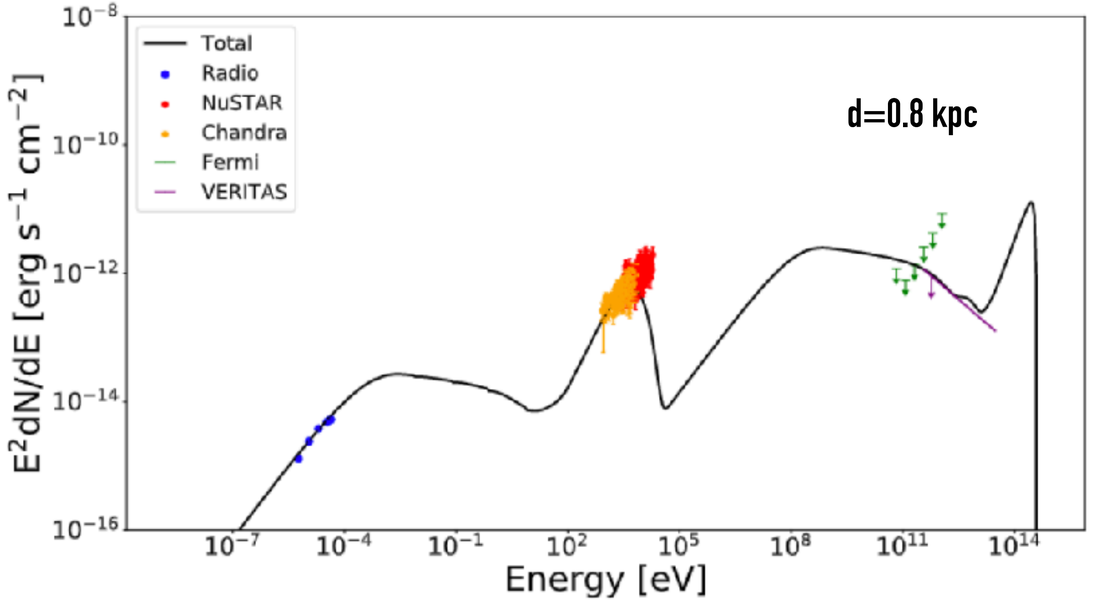
- Consider the recent evolution of the particle distribution
  - Assuming the expansion velocity of PWN to be constant in time
- Prefer d=7.5 kpc compared to 0.8 kpc
- The fitting to the X-ray flux is still not looking very good

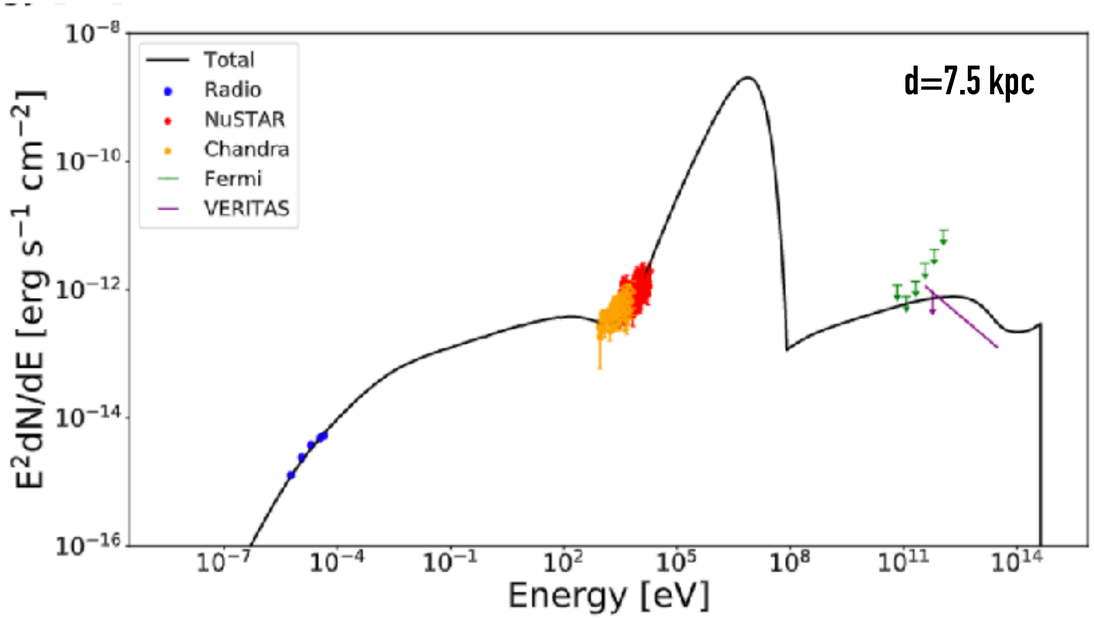


# Modeling Studies: PWN evolution model

**Dynamical PWN evolution model**

- Include PWN, SNR, and its environment, and time evolution of the environment and particle energy distribution
  - This was used by many PWN studies including CTA 1, Eel PWN, & PWN G21.5-0.9
- d=0.8 kpc is disfavored
  - hard to allocate the pulsar's expended rotational energy without overshooting the flux.
- At d=7.5 kpc, favoring a model with a re-expanding PWN after SNR crush



# Summary

**Galactic PeVatron search in gamma-ray observations is one of the key scientific objectives of VERITAS.**

- Deep observations of young SNRs revealed spectral cut-offs at ~ TeV energy range, motivating the program to search for the PeVatrons from the unidentified hard index sources.

**The recent discovery of LHAASO revealed 11 known TeV sources and one unknown source have SEDs extending up to 1.4 PeV.**

- We report non-detection of LHAASO J2108+5157 w/ 35 hours of VERITAS observation.

**Combined information from multi-wavelength/multi-messenger observation is essential to prove the nature of these PeVatron candidates.**

- We report the studies of Boomerang PWN with VERITAS, Fermi, and NuSTAR.