NuSTAR and VERITAS observations of Galactic HAWC sources

Kaya Mori (Columbia University)
on behalf of VERITAS and HAWC collaboration
8/27/2018

HAWC-VERITAS-NuSTAR Legacy program

- After the HAWC catalog was released, we formed a large collaboration to follow up Galactic HAWC sources with VERITAS and NuSTAR.

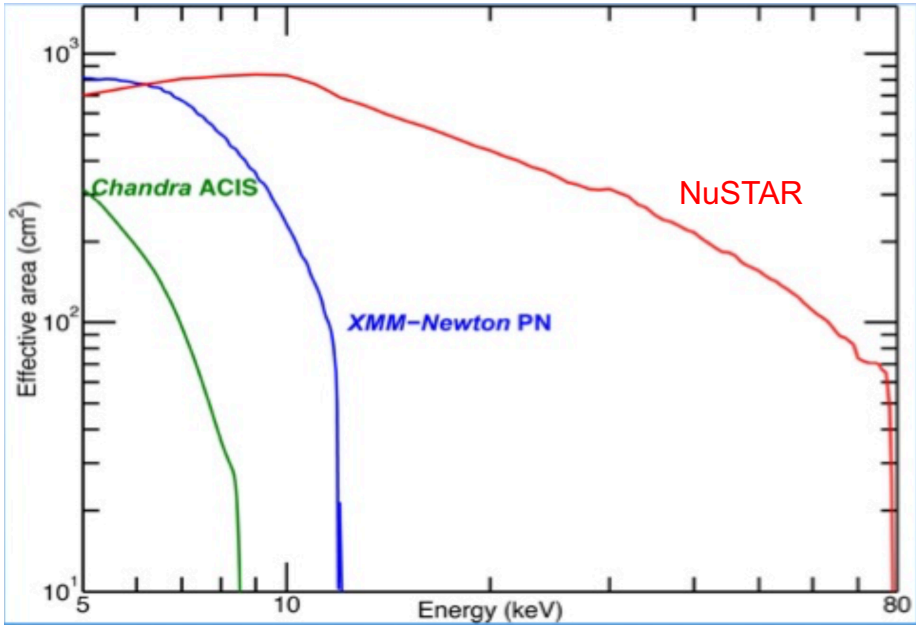
- NuSTAR Legacy program for large, risky but highly rewarding observations from community input (https://www.nustar.caltech.edu/page/legacy_surveys)

- Completed and future observations with VERITAS and NuSTAR
  - 2HWC J1953+294: Pulsar wind nebula DA495
  - 2HWC J1928+177: unidentified TeV source
  - HESS J0632+057: TeV gamma-ray binary
  - 2HWC J1825-134 (in fall 2018): Pulsar with very hard X-ray and gamma-ray spectra

- Our program has expanded to other X-ray and Infrared observation proposals (XMM-Newton, Chandra, Gemini …)

NuSTAR X-ray telescope and TeV gamma-ray sources

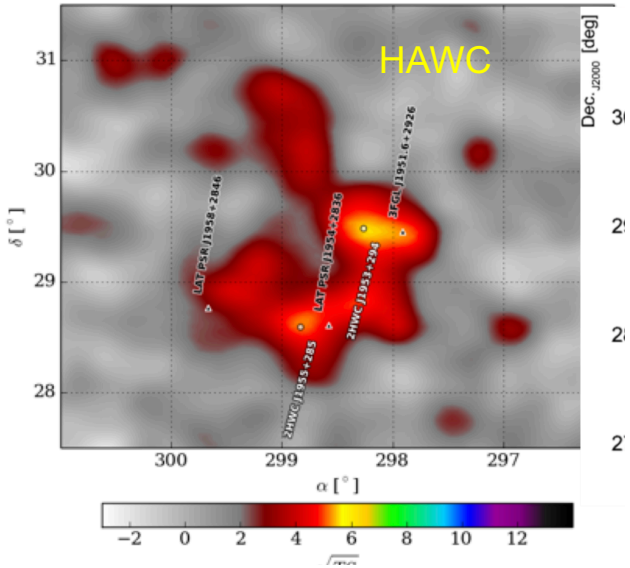
- The first and only focusing telescope operating above 10 keV.
  - 58” resolution (HPD) and 18” (FWHM) angular resolution
  - Broad-band energy band (3-79 keV) -> constraining non-thermal spectra
  - 2 micro-second timing resolution -> pulsation search
- 4 publications from NuSTAR observations of TeV sources and many more on SNRs and PWNe

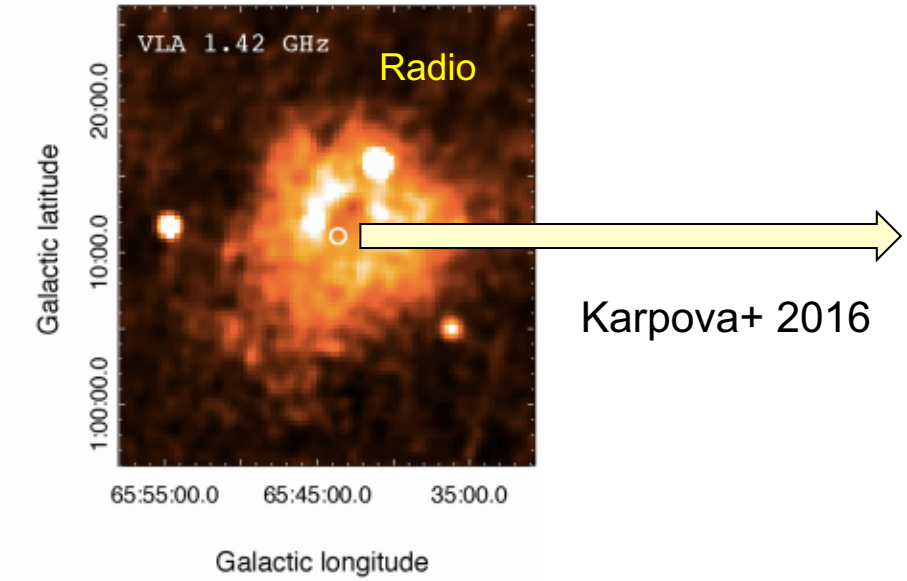


2HWC J1953+294 (DA495)

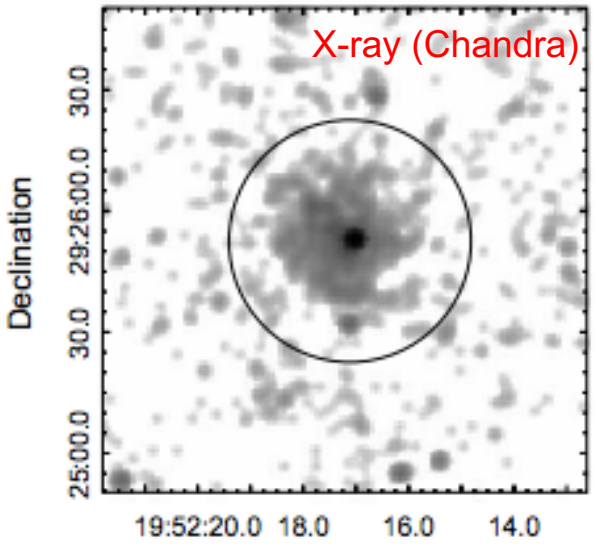
HAWC detection of pulsar wind nebula DA495

- First detection in TeV band by HAWC.
- No GeV detection by Fermi.
- Detection in radio and X-ray bands
- **Large radio nebula (r ~ 12' or 3.5 pc) vs compact X-ray nebula (r ~ 20" or 0.1 pc).**
- Follow-up VERITAS + NuSTAR observations to investigate its emission mechanism and constrain PWN parameters.





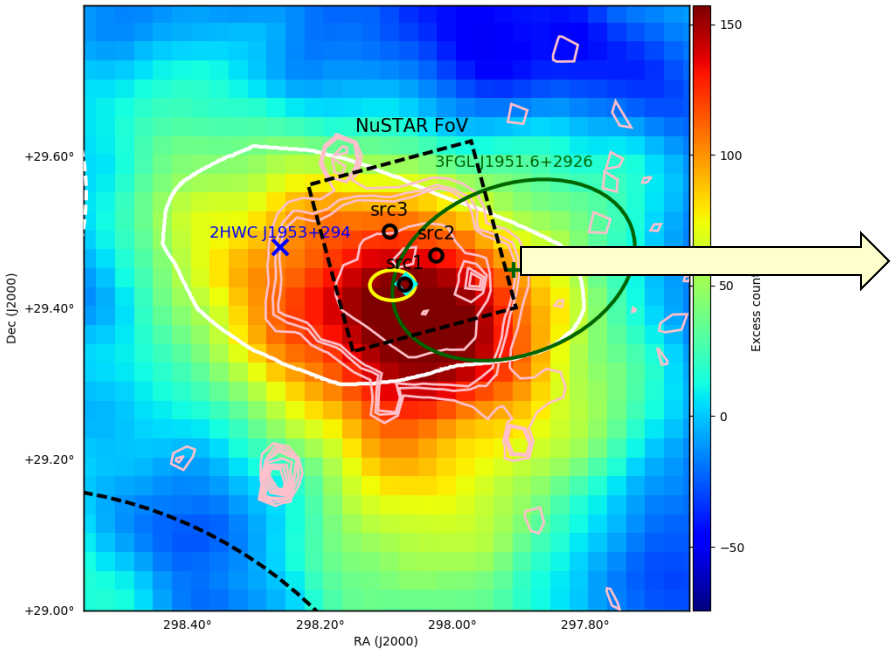
Karpova+ 2016



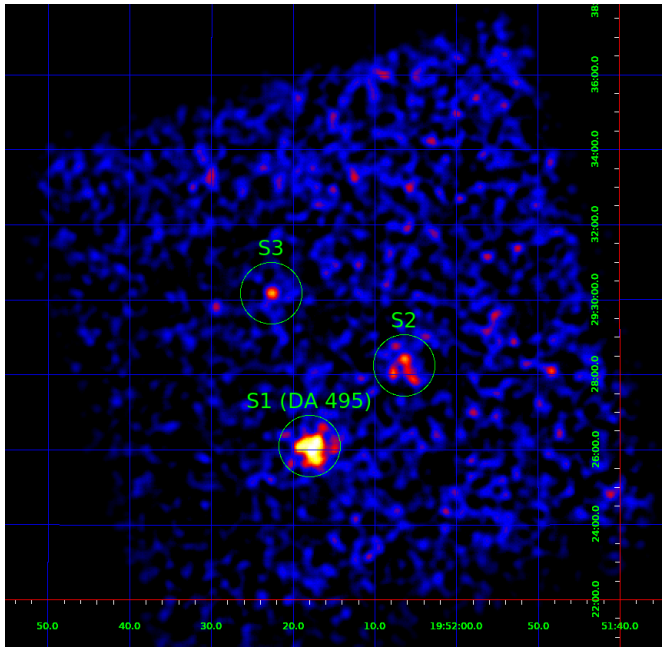
VERITAS and NuSTAR observations of DA 495

- VERITAS detected extended gamma-ray emission (**r = 8.4' +/- 1.2'**) comparable to the radio nebula size.
- NuSTAR detected 3 hard X-ray sources above 10 keV.
  - **DA 495 was detected up to ~20 keV**.
  - S2 and S3 are point sources with Lx < 10^{31} erg/s => likely active binaries or LMXBs => not related to TeV gamma-ray emission.

VERITAS (Nahee Park, ICRC 2017)



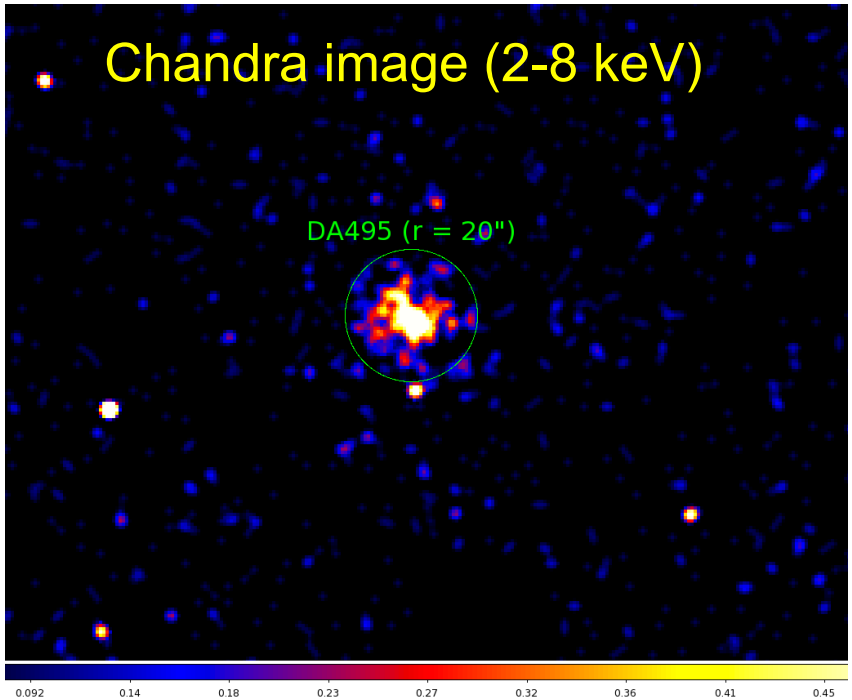
NuSTAR 3-20 keV image



White contours: HAWC 5-sigma standard deviations
Light pink contours: 1.4 GHz radio

DA495 X-ray nebula is compact throughout different energy bands

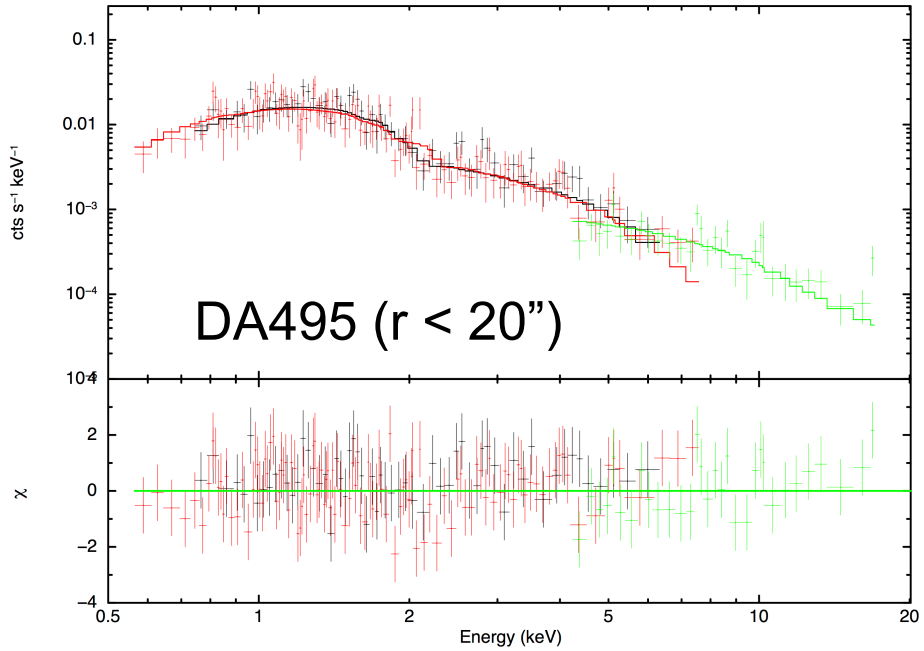
- X-ray nebula size of DA495 is compact (r < 20”).
- X-ray counts drop by a factor of ~8 outside r ~ 20”.
- We did not detect PWN size variation in different energy bands.



X-ray nebula size	**σ (arcsec)**
Chandra 2-5 keV	5.6 +/- 0.2
Chandra 5-8 keV	5.6 +/- 0.2
NuSTAR 8-20 keV	8.5 +/- 2.3

Broad-band X-ray spectra fit to a single power-law model

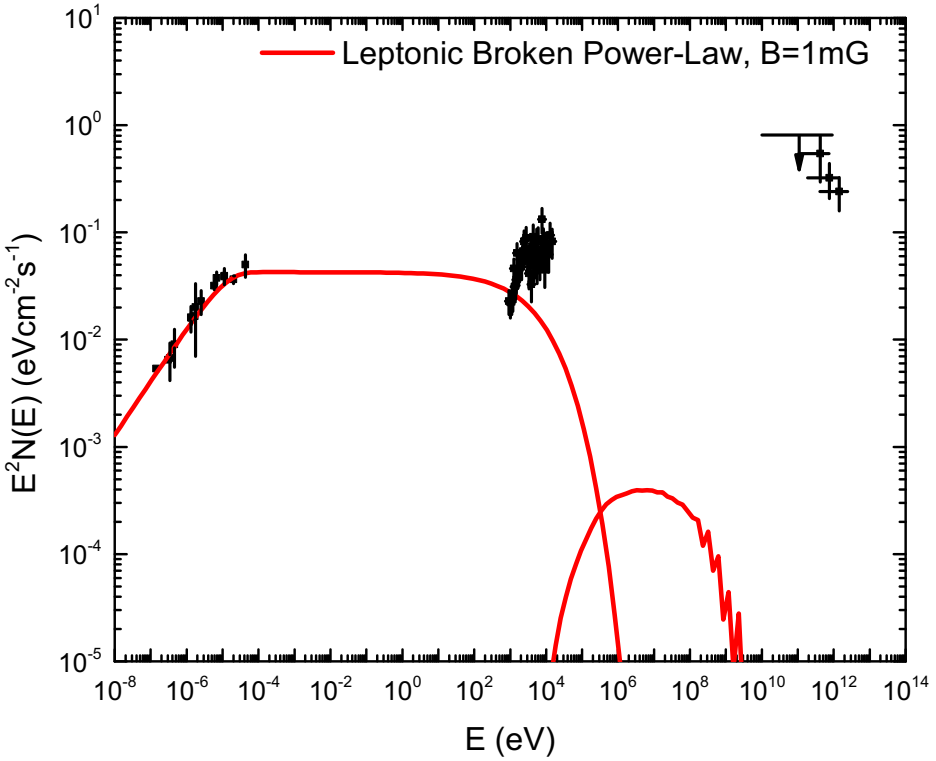
- An absorbed power-law model fits the spectra well (χ^2 = 0.9, 205 dof)
  - Neutral H column nH = 2.1 x 10^{21} cm^{-2} => consistent with 1-3 kpc distance
  - Photon index **Γ = 2.1 +/- 0.1**
  - X-ray luminosity (2-10 keV): 6 x 10^{31} erg/s



Green: NuSTAR
Black: Chandra
Red: XMM-Newton

Leptonic models with B ~ 1 mG do not fit the TeV gamma-ray data

- **B ~ 1.3 mG** estimated from a radio spectral break (Kothes+ 2007)
- Leptonic SED model with B ~ 1 mG **grossly underestimates** TeV gamma-ray fluxes.
- There is no extra IR/optical/UV emission in the region to enhance TeV emission.

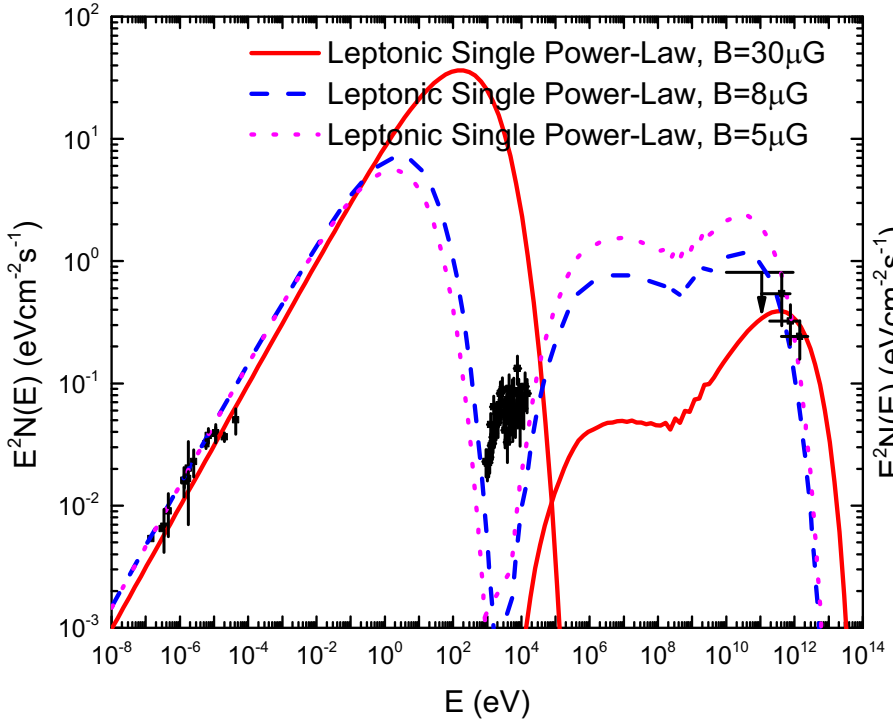


A leptonic model at B = 1 mG (by Haocheng Zhang) fit to radio, X-ray, VERITAS data and the upper limits from Fermi.

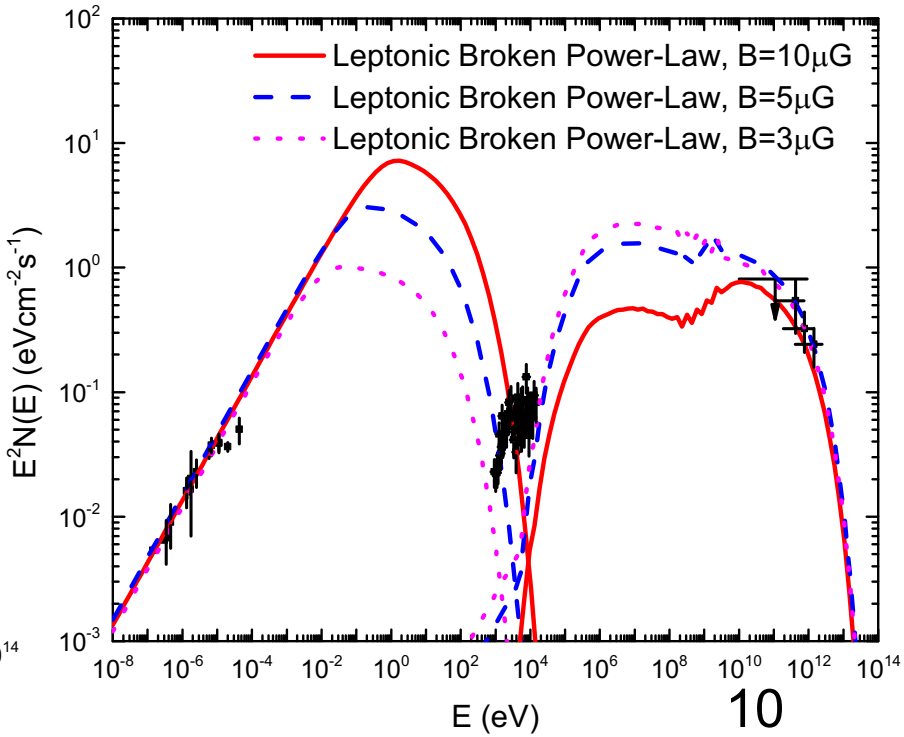
Leptonic SED models with lower B-field still do not fit the SED data

- Single PL models overshoot the X-ray flux or Fermi upper limits.
- Broken PL models predict a spectral index change in the X-ray band which is not observed.

Single power-law model with a cutoff

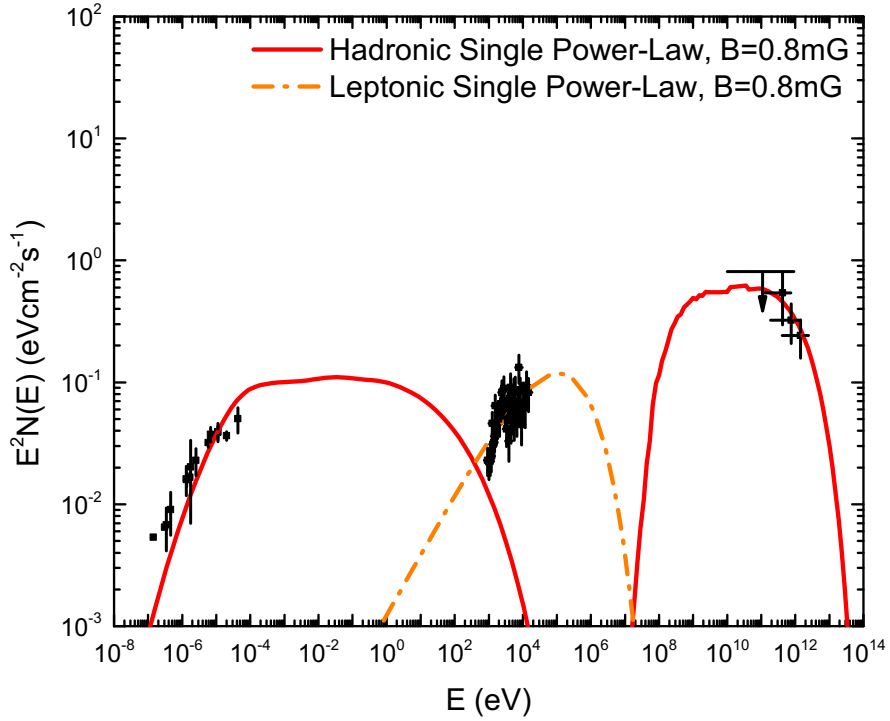


Broken power-law models with a cutoff



If a hadronic component is added, our model fits the data well…

- The compact X-ray emission is not co-spatial with the larger radio/TeV emission => can we treat radio/TeV and X-ray emission separately?
- X-ray data fit by a Leptonic component (dotted pink line), while a hadronic component fits radio and gamma-ray data (red lines).
- Although this hybrid model fits the SED data well, we are investigating whether the parameters make sense…

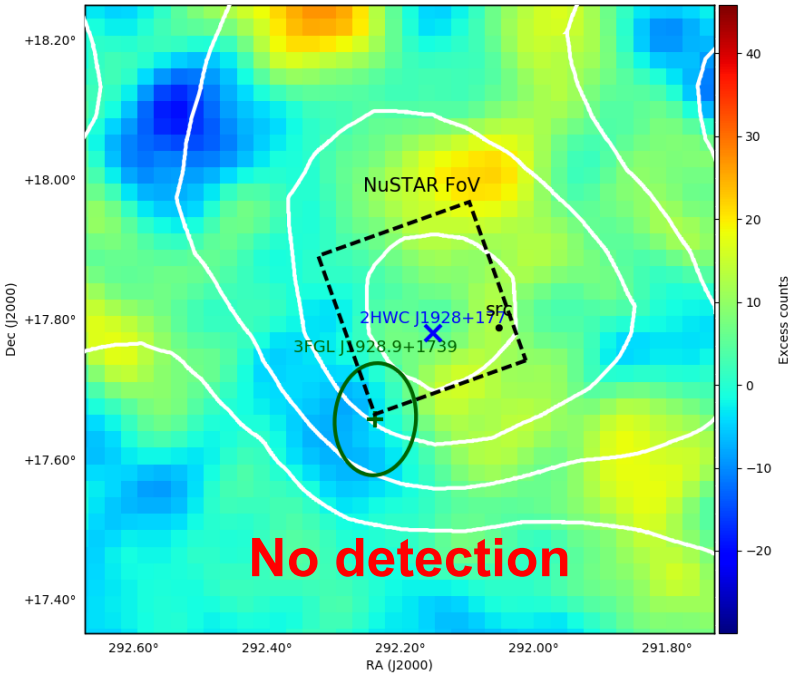


2HWC J1928+177

VERITAS and NuSTAR observations of 2HWC J1928+177

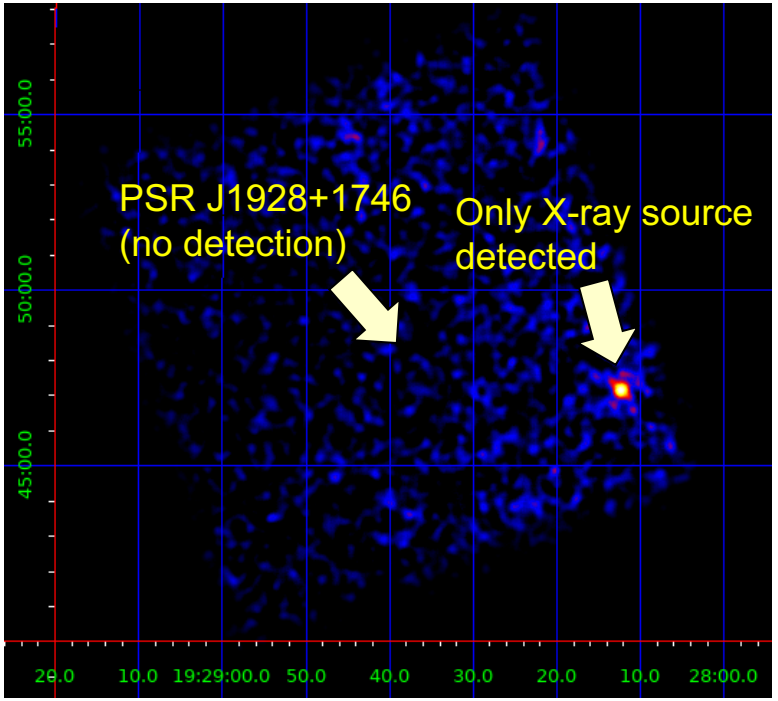
- No detection by VERITAS (N. Park, ICRC 2017) and HESS (Lopez-Coto, ICRC 2017). Fermi source 3FGL J1928.9+1739 nearby.
- NuSTAR 92 ks observation detected **only one X-ray source** at ~5' away from the HAWC centroid.

VERITAS image (Nahee Park, ICRC 2017)



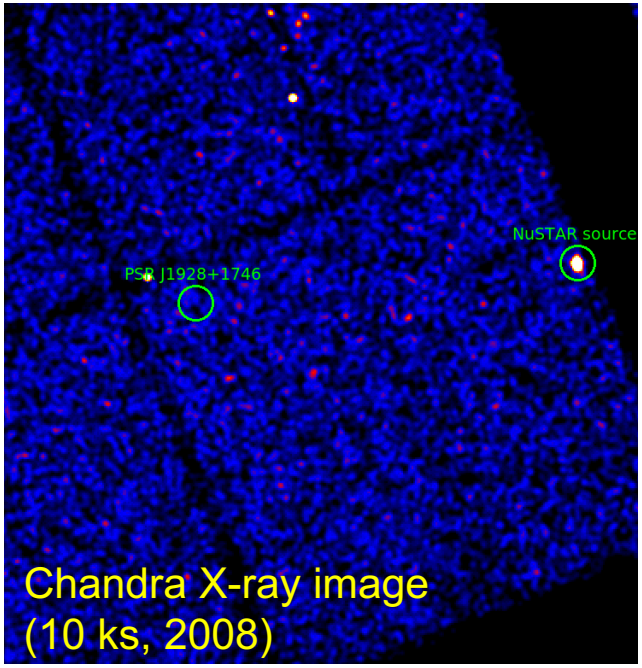
White contours: HAWC 5, 6, 7 standard deviations

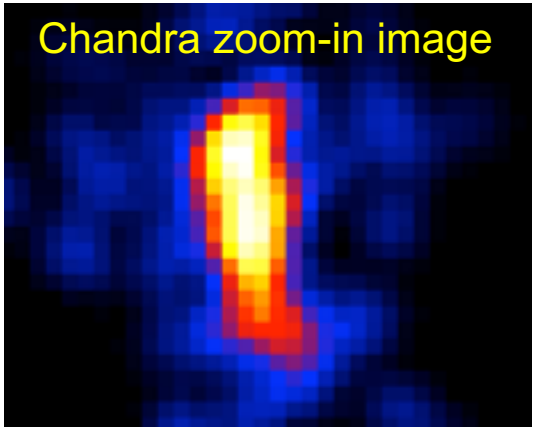
NuSTAR 3-20 keV image



The NuSTAR source is a point source with a bright IR counterpart (O star?)

- No detection of PSR J1928+1746 by Chandra and NuSTAR (Fx < 5.8×10^{-15} erg/cm^2/s => Lx < 2×10^{31} erg/s, Lopez-Coto 2017)
- There is a bright IR source at K-magnitude ~ 13 at the Chandra position (2MASS, NOMAD, GLIMPSE, UKIDSS catalogs)
- A crude IR color analysis suggests the IR source is an O-type star.



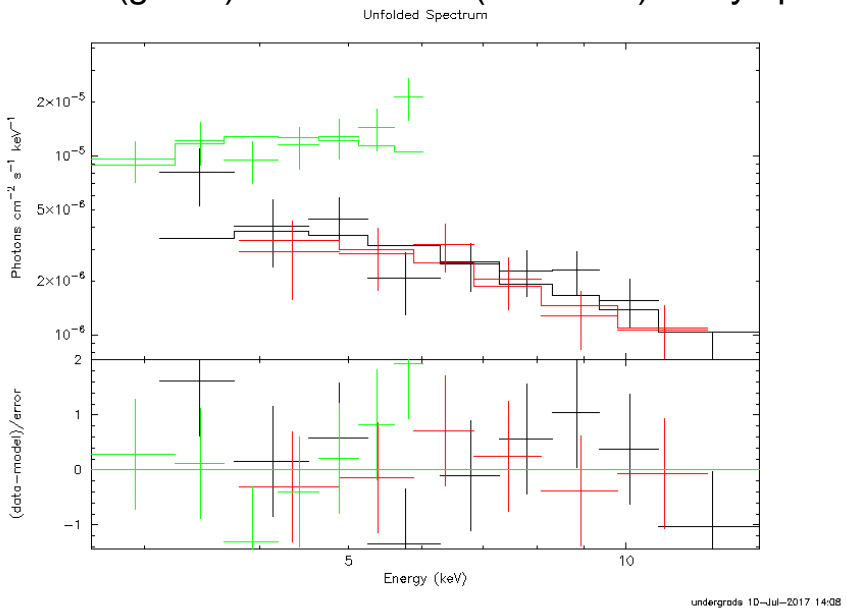


This X-ray source is actually a point source (size < 0.7”) It looks elongated due to off-axis Chandra PSF.

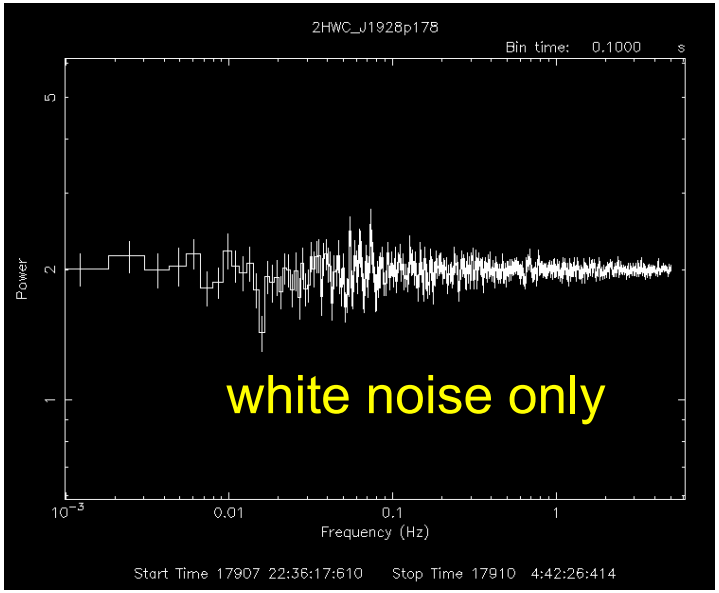
The NuSTAR source has variable, non-thermal X-ray spectra

- NuSTAR and Chandra spectra fit to an **absorbed power-law model**.
  - Power-law photon index = 1.6 +/- 0.4. nH = 1×10^{23} cm^{-2}
  - Lx = (0.9-5) x 10^{33} erg/s (assuming 6 kpc distance).
- Chandra flux (in 2008) is **~4 x higher** than NuSTAR flux (in 2016)
- NuSTAR power density spectrum shows **no red noise**, a signature of accretion usually seen in LMXBs.

Chandra (green) and NuSTAR (black/red) X-ray spectra

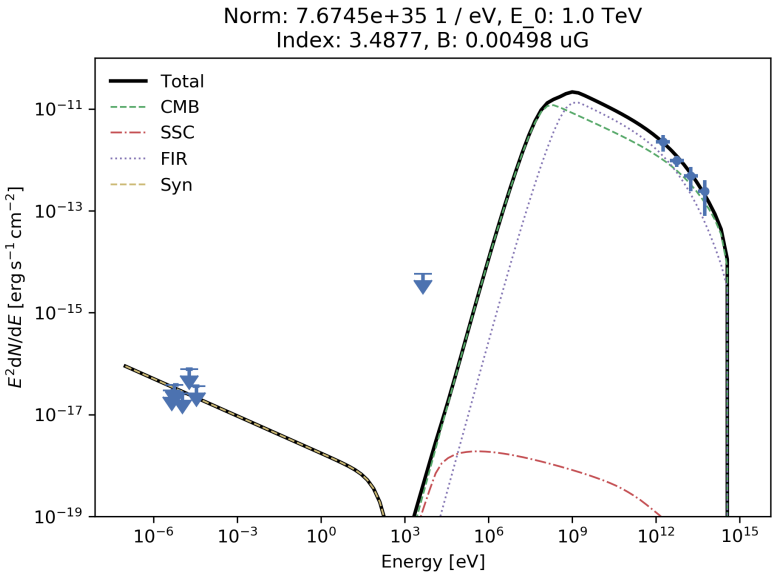


NuSTAR X-ray power density spectrum



Is the radio pulsar PSR J1928+1746 associated with the HAWC source?

- PSR J1928+1746: spin-down power = 1.6×10^{36} erg/s, age = 82 kyrs
- No radio nebula detected (Cordes+ 2006)
- No X-ray detection => **X-ray efficiency (Lx/Edot) < 10^{-5}** (typically, ~10^{-4} - 10^{-3} for X-ray PWNe).
- Leptonic SED model, fitting to the HAWC TeV data, requires very low B-field (~ 5 x 10^{-3} μG << ISM B-field) to be consistent with the radio/X-ray flux upper limits.



Naima SED model fit
(electron energy spectrum consistent with Lopez-Coto 2017)

Is the HAWC source a new TeV gamma-ray binary?

- If the NuSTAR source is an X-ray counterpart, its X-ray properties suggest a TeV gamma-ray binary.
  - A point source with variable X-ray flux
  - Non-thermal X-ray emission
  - No red noise in power density spectra
  - A high-mass (O-type) companion star?
- EGRET source 3EG J1928+1733 is variable (Torres+ 2001)
- The detection by HAWC and non-detection by VERITAS/HESS due to source variability?
- Next steps…
  - Searching for periodicity in X-ray band (Swift) and TeV gamma-ray band
  - Further X-ray survey (XMM) of the region to look for other X-ray sources
  - Companion star ID by IR spectroscopy with Gemini/Framingos2 (PI: Eikenberry)

Summary

- HAWC-VERITAS-NuSTAR program has formed a large collaboration between gamma-ray and X-ray community and resulted in student projects, several papers in prep and proposals.

- DA495 (A. Coerver et al. in prep)
  - With VERITAS and NuSTAR data, we can constrain PWN parameters well.
  - Does this PWN possess high ~1mG magnetic field?
  - Can Leptonic models account for the multi-wavelength SED data or do we need a hadronic component?

- 2HWC J1928+177 (K. Mori et al. in prep)
  - Can the radio pulsar PSR J1928+1746 account for the TeV emission?
  - Is this a new TeV gamma-ray binary?
  - Did we miss other X-ray counterparts to the HAWC source?
  - Hadronic origin? [Lopez-Coto 2017]