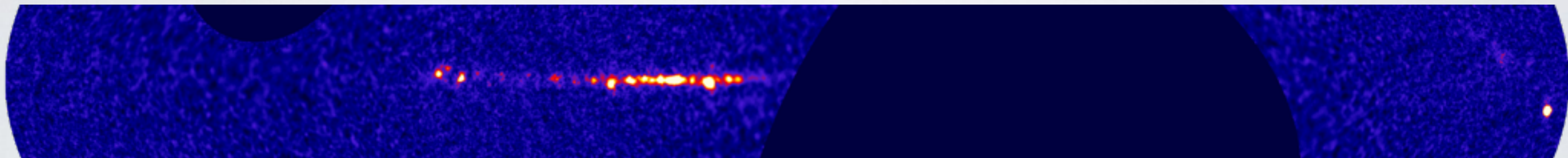


Follow-up *VERITAS* and *NuSTAR* observations of Galactic *HAWC* gamma-ray sources

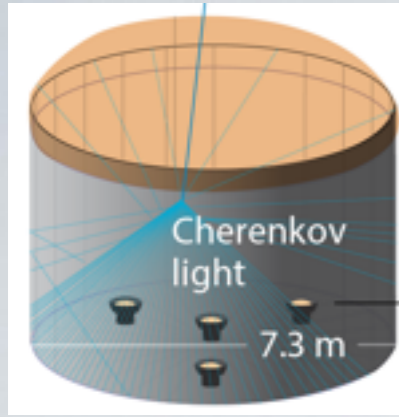


C. Michelle Hui (NASA/MSFC)
on behalf of the *HAWC* collaboration,
C. Hailey and K. Mori [*NuSTAR*],
B. Humensky, R. Mukherjee, and N. Park [*VERITAS*]

TeVPA, Aug 10 2017



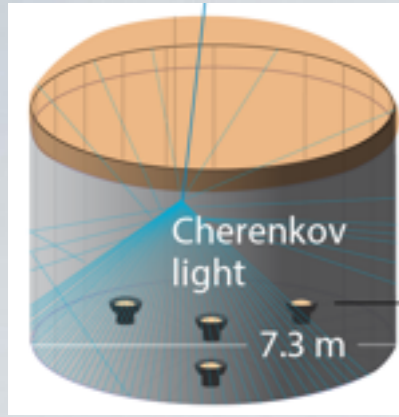
High Altitude Water Cherenkov Gamma-ray Observatory



HAWC observatory

- 300 water Cherenkov detectors at Sierra Negra, Mexico.
- Sensitive from 100 GeV to 100 TeV.
- Angular resolution (68% containment) 0.2-1.0 degrees.
- 2 sr instantaneous field of view, 2/3 of sky each day.
- >90% duty cycle.

High Altitude Water Cherenkov Gamma-ray Observatory



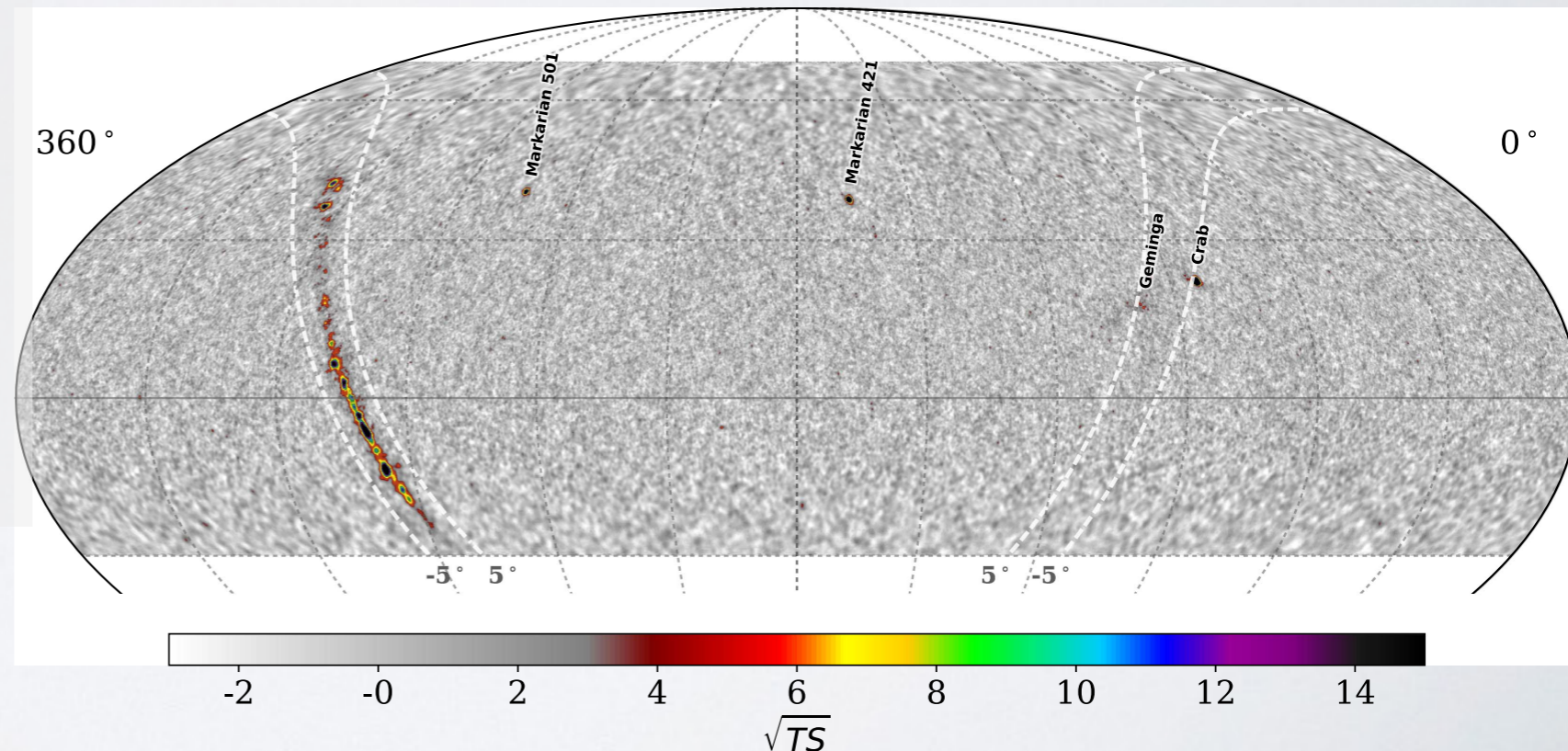
TeV Sky Survey

[Abeysekara et al., ApJ 843:40 \(2017\)](#)

- Most sensitive wide-field survey in TeV.
- Skymap from 507 days of data taken between Nov 2014 to Jun 2016.
- Point source analysis assuming power-law index of 2.7.
- 39 2HWC sources: 2 blazars, 10 PWN/SNR, 8 UIDs, **19 unassociated.**

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Very Energetic Radiation Imaging Telescope Array System (*VERITAS*)

- Four 12m atmospheric Cherenkov telescopes in Arizona.
 - Sensitive from 85 GeV to >30 TeV.
 - Angular resolution (68% containment) 0.08-0.13 degrees.
 - Field of view of 3.5 degrees.
 - 70-100 observation hours per month.
-

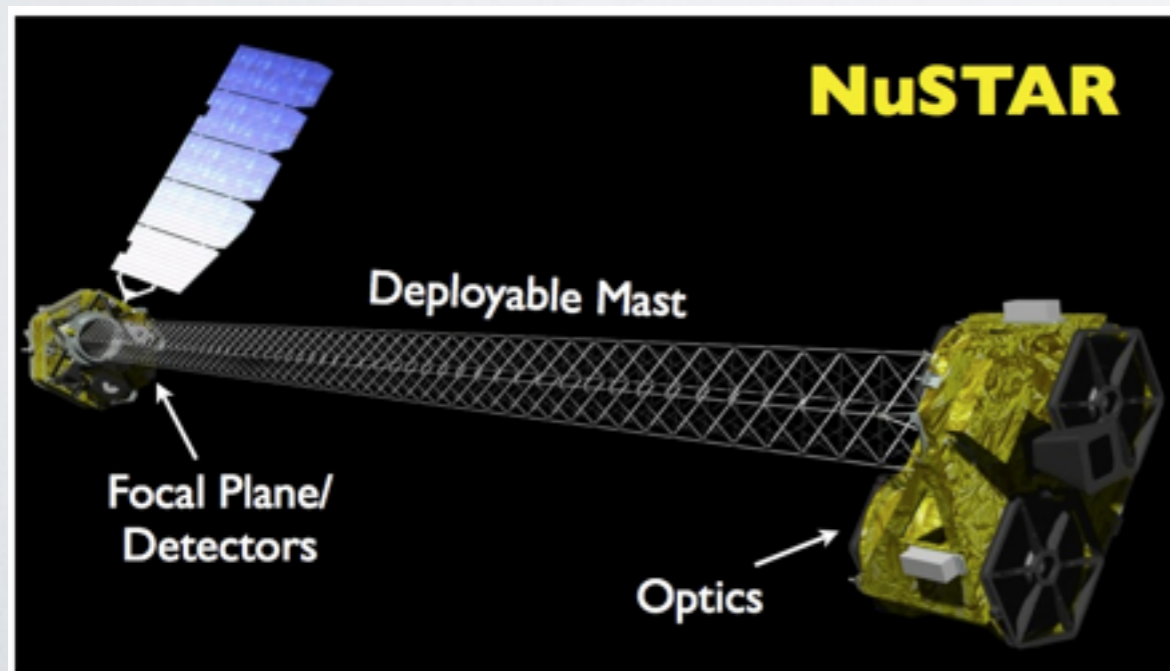


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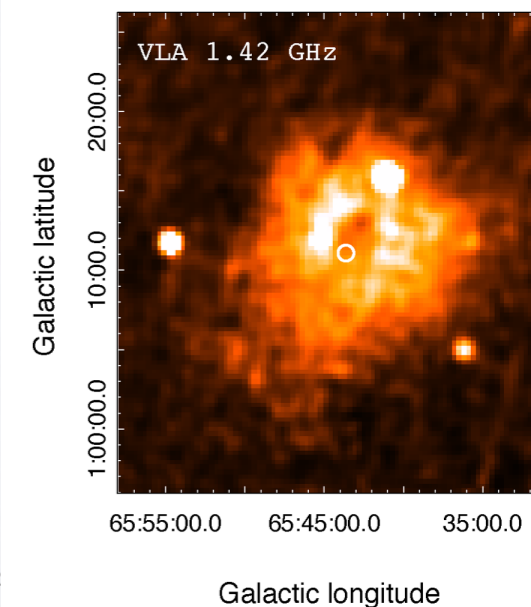
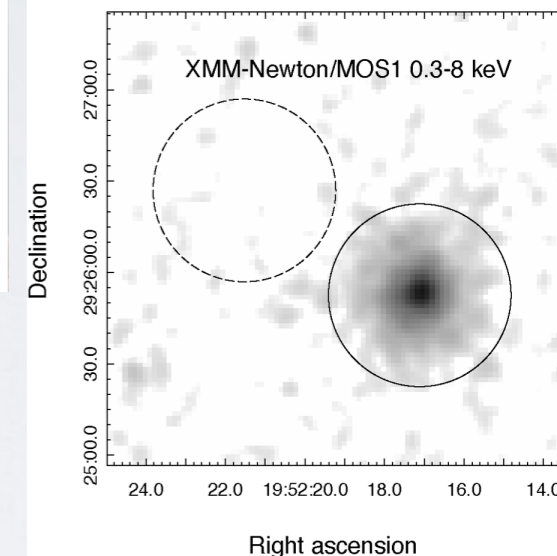
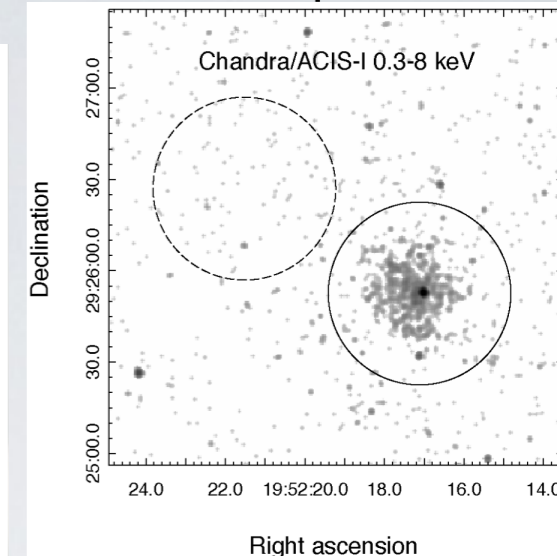
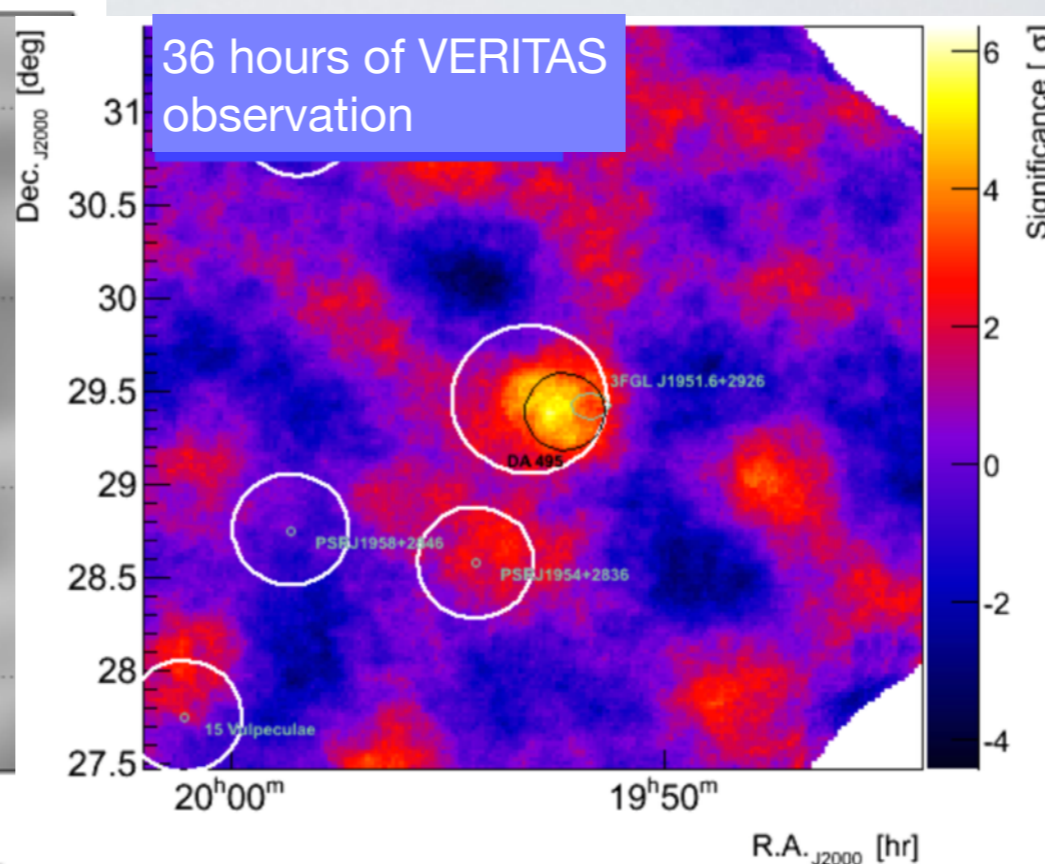
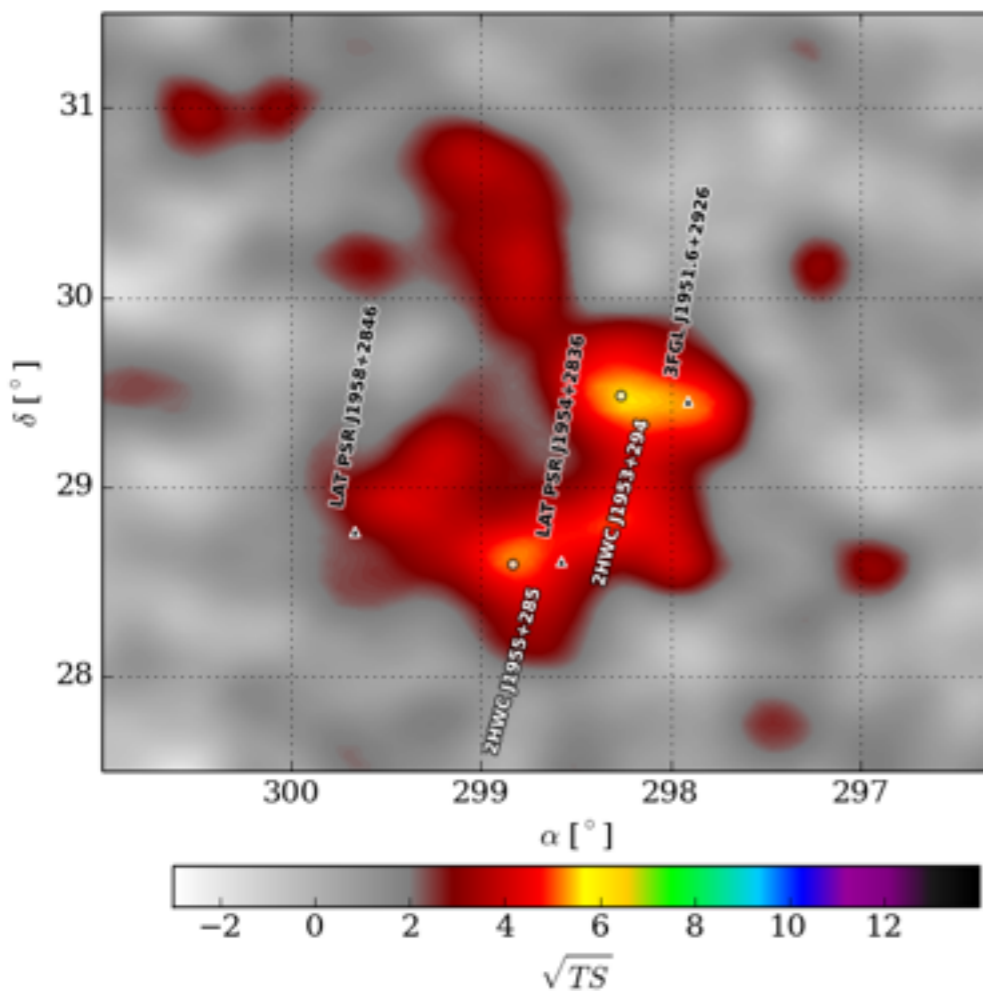
Nuclear Spectroscopic Telescope Array (*NuSTAR*)



- X-ray telescope launched in 2012.
- Sensitive from 3 - 79 keV.
- Angular resolution (FWHM) 18 arcsec (0.005 degrees).
- Field of view of 12 arcminute (0.2 degrees).
- Legacy surveys: Galactic and Extragalactic
 - ~30% of NuSTAR observation time

2HWC J1953+294 / DA 495

Karpova et al 2015

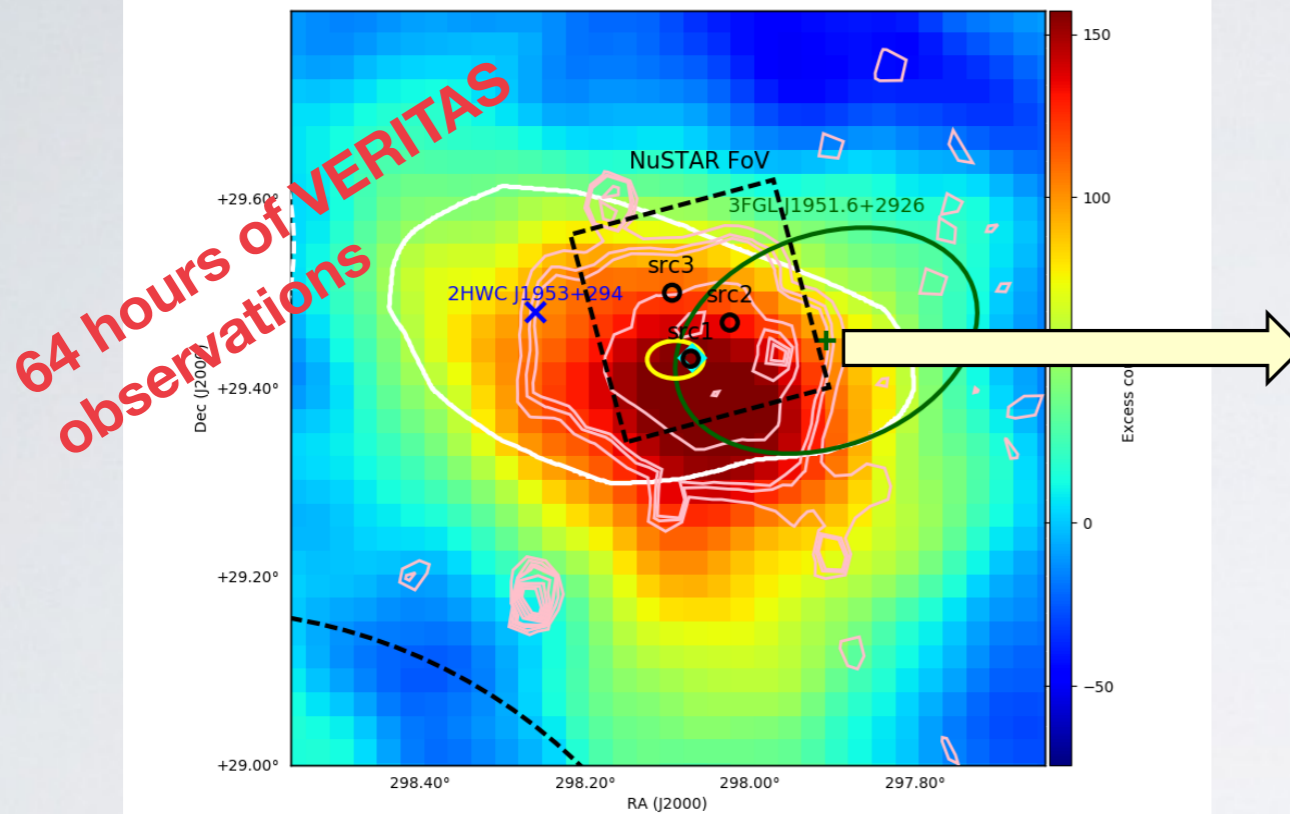


New TeV source 2HWC J1953+294

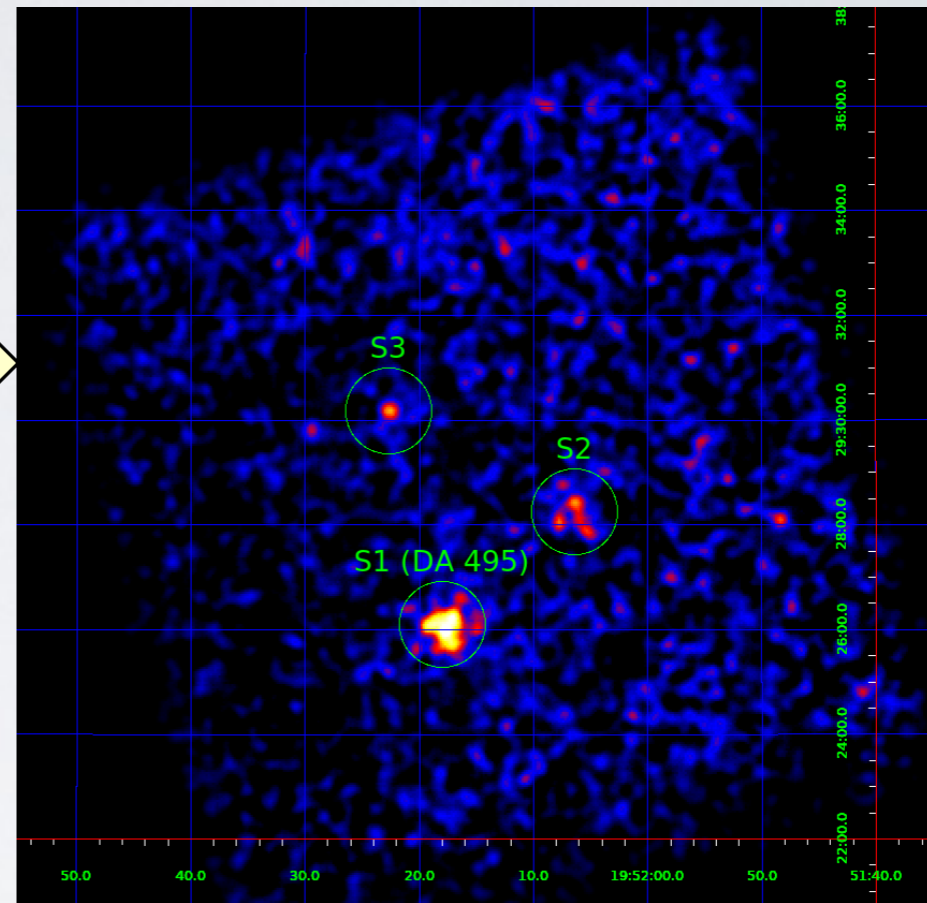
- TeV emission **confirmed by VERITAS**.
- Potential association:
 - PWN DA 495 seen in X-rays by *XMM* and *Chandra*.
 - *Chandra* X-ray nebula size ~ 40 arcsec.
 - Radio “hole” morphology with 25 arcmin size.
 - PWN age ~ 20 kyr, located at 1 kpc.
 - Pulsation not detected in any wavelength.
 - 3FGL J1951.6+2926 (potential SNR/PWN)

NuSTAR observation of DA 495

VERITAS image (Nahee Park, ICRC 2017)



NuSTAR 3-20 keV image (BKG-subtracted)

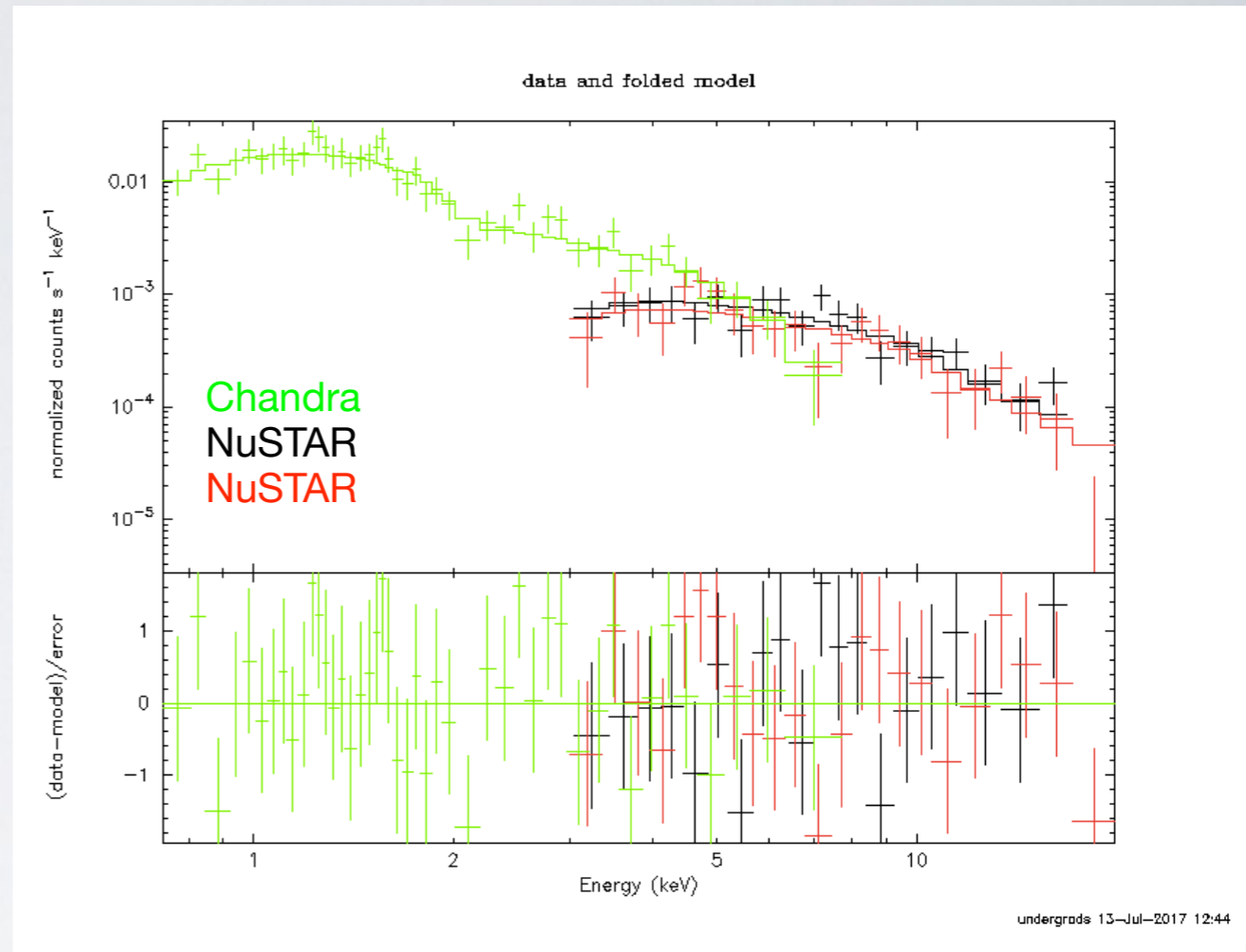


White contours: HAWC 5, 6, 7 standard deviations
Light pink contours: 1.4 GHz radio

- 60 ksec of observations on June 8 2017.
- 3 sources detected:
 - S1 is PWN DA 495
 - S2 and S3 are point sources, likely active binaries or faint LMXBs
-> unrelated to TeV emission.
- DA 495 is only likely X-ray counterpart to TeV source.
 - high B-field 1.3 mG estimated from radio data (Kothes et al. 2008), consistent with small X-ray PWN size due to faster synchrotron cooling.

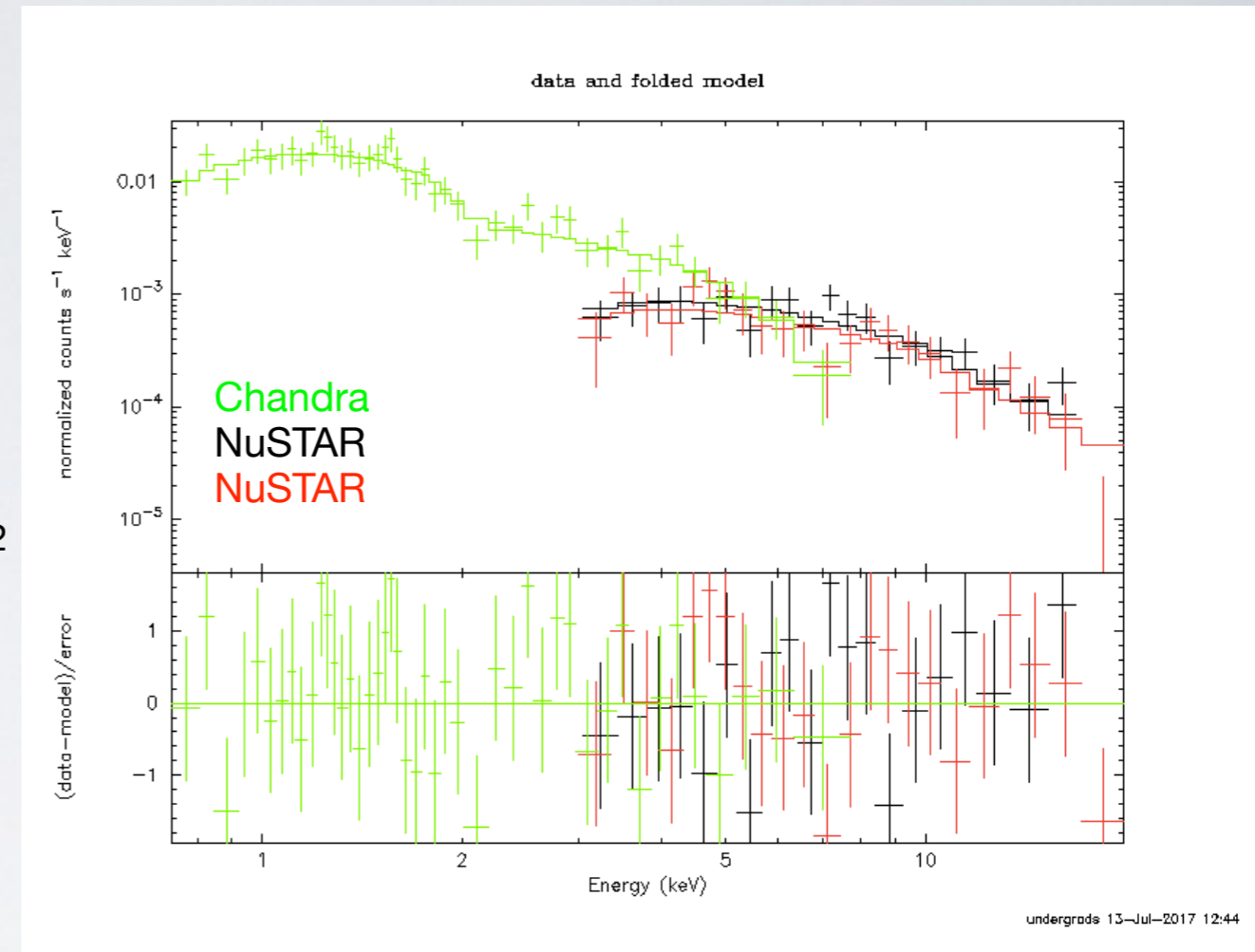
NuSTAR observation of DA 495

- Detected up to 20 keV.
-> electron energy ~ 20 TeV if X-rays are via synchrotron radiation.
- Absorbed power-law model fit to *Chandra* and *NuSTAR* spectra.
 - Neutral hydrogen column $nH = 1.3 \times 10^{21} \text{ cm}^{-2}$
-> consistent with 2 kpc distance.
 - Photon index of 1.8 ± 0.1 .
 - X-ray luminosity (2-10 keV) = $6 \times 10^{31} \text{ erg/s}$.

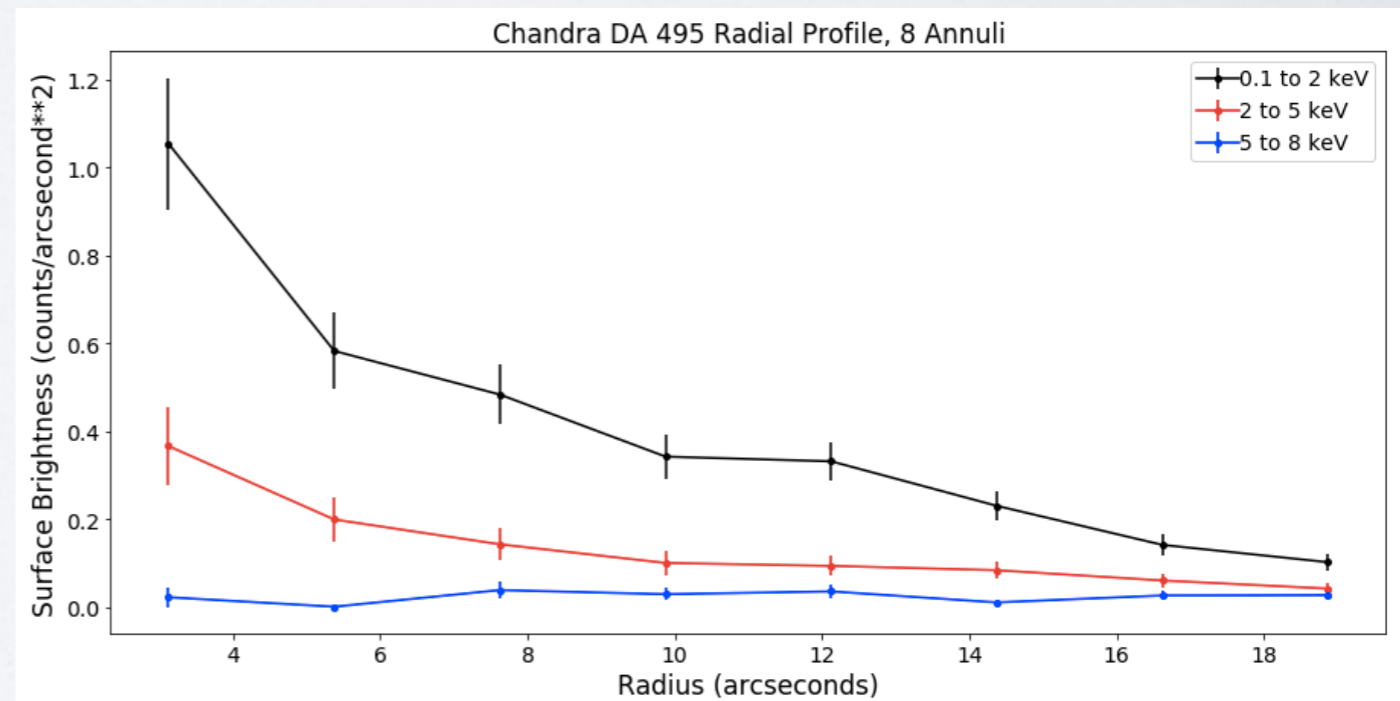


NuSTAR observation of DA 495

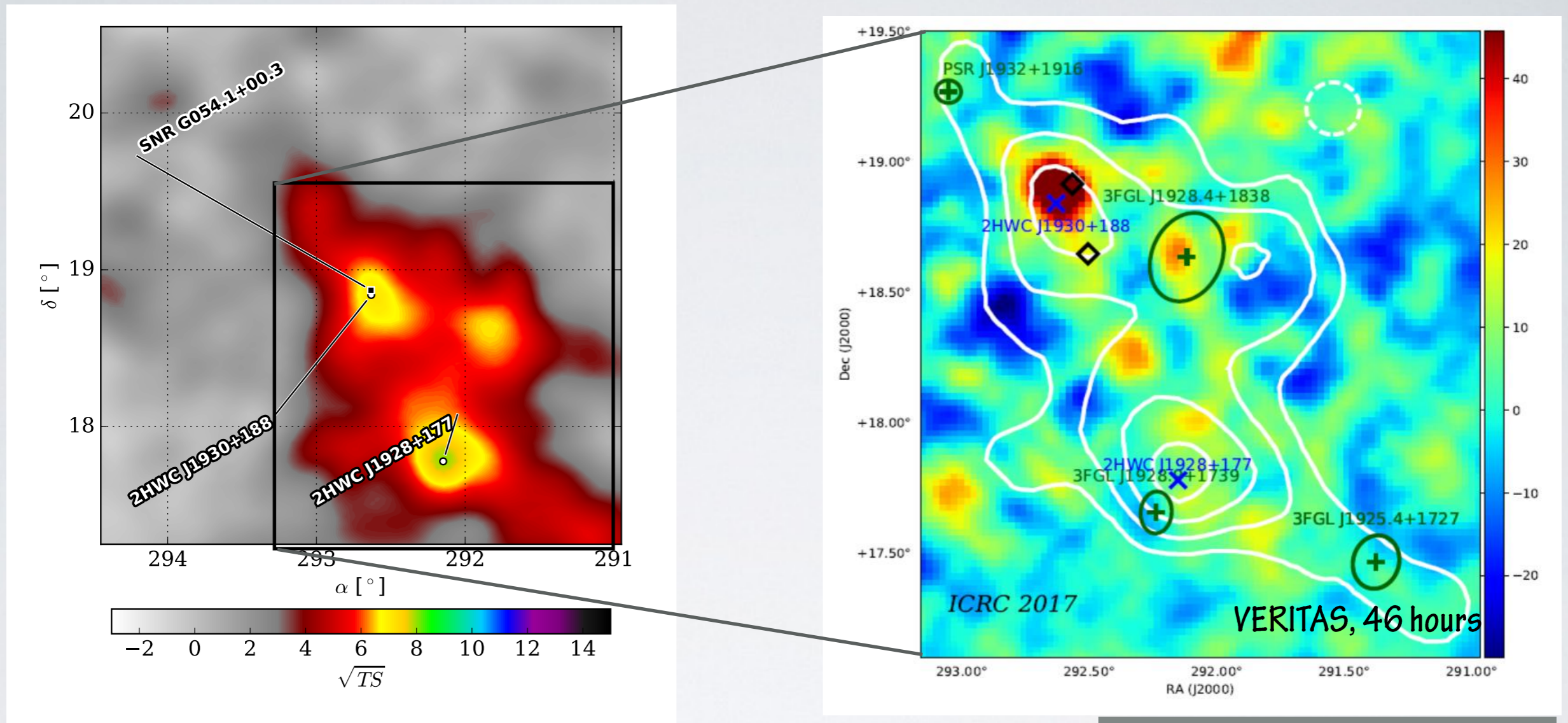
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- Analysis using *Chandra* archival data:
 - No spectral shape variation between different annuli regions around the pulsar.
 - No radial profile steepening as function of photon energy.



2HWC J1928+177



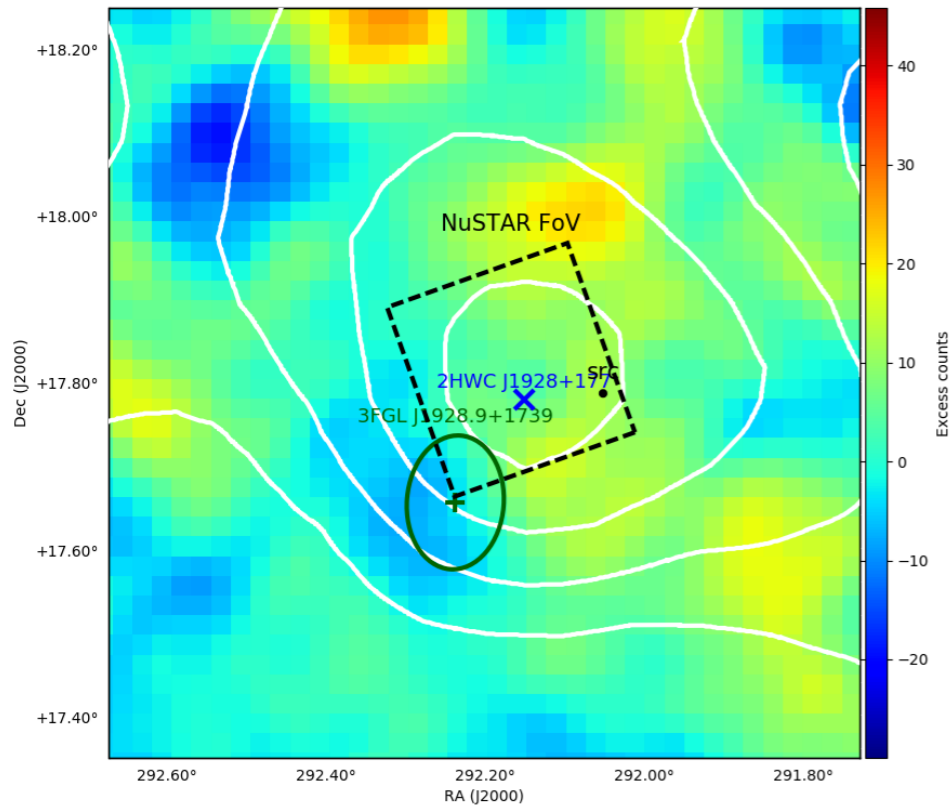
HAWC 5, 6, 7, 8 σ contour

New TeV source 2HWC J1928+177

- Stronger than SNR G54.1+0.3.
- Coincident with PSR J1928+1746 (83kyr old, 4.3kpc away, $\dot{E}=1e36$ erg/s).
- VERITAS and HESS detect G54.1+0.3 but not 2HWC J1928+177.
- Chandra 10 ksec observation in March 2008, no detection of PSR J1928+1746.

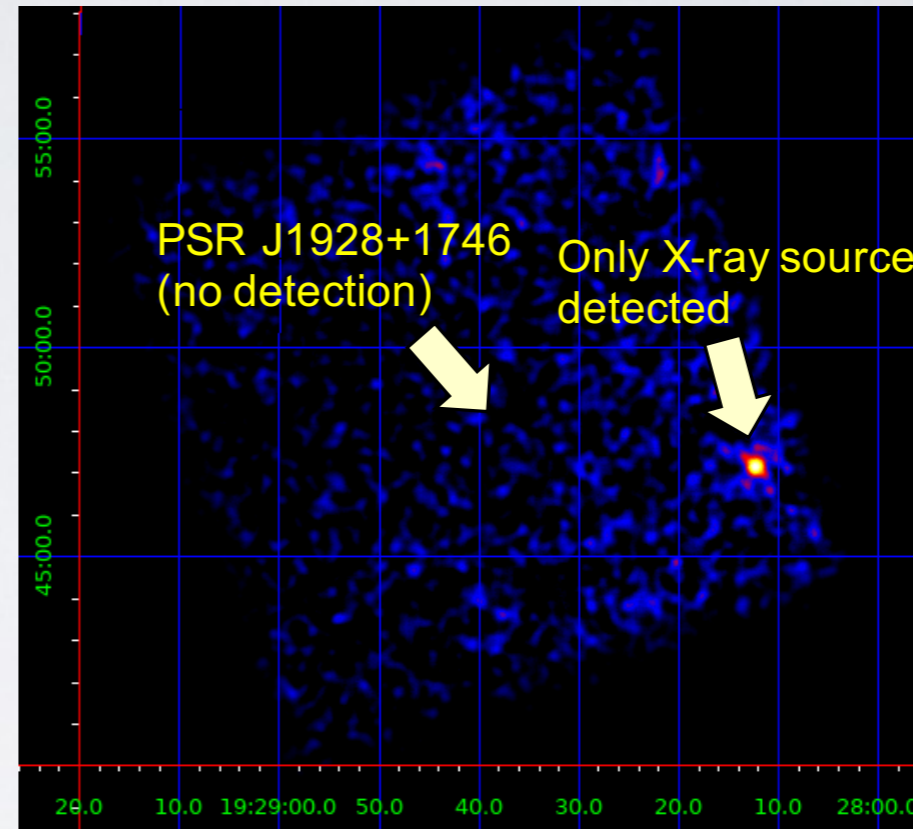
NuSTAR observation of 2HWC J1928+177

VERITAS image (Nahee Park, ICRC 2017)



White contours: HAWC 5, 6, 7 standard deviations

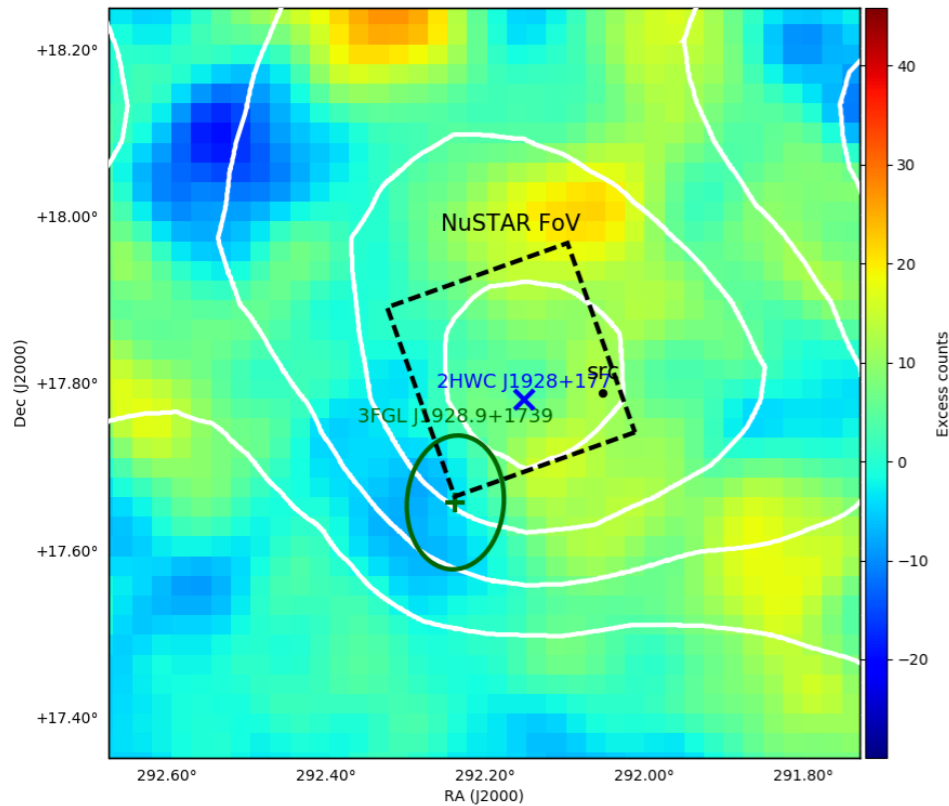
NuSTAR 3-20 keV image (BKG-subtracted)



- 92 ksec of observations on June 3 2017.
- 1 sources detected at 5 arcmin away from *HAWC* centroid.
 - also seen in *Chandra* near edge of view.
- **PSR J1928+1746 not detected by *NuSTAR* and *Chandra*.**

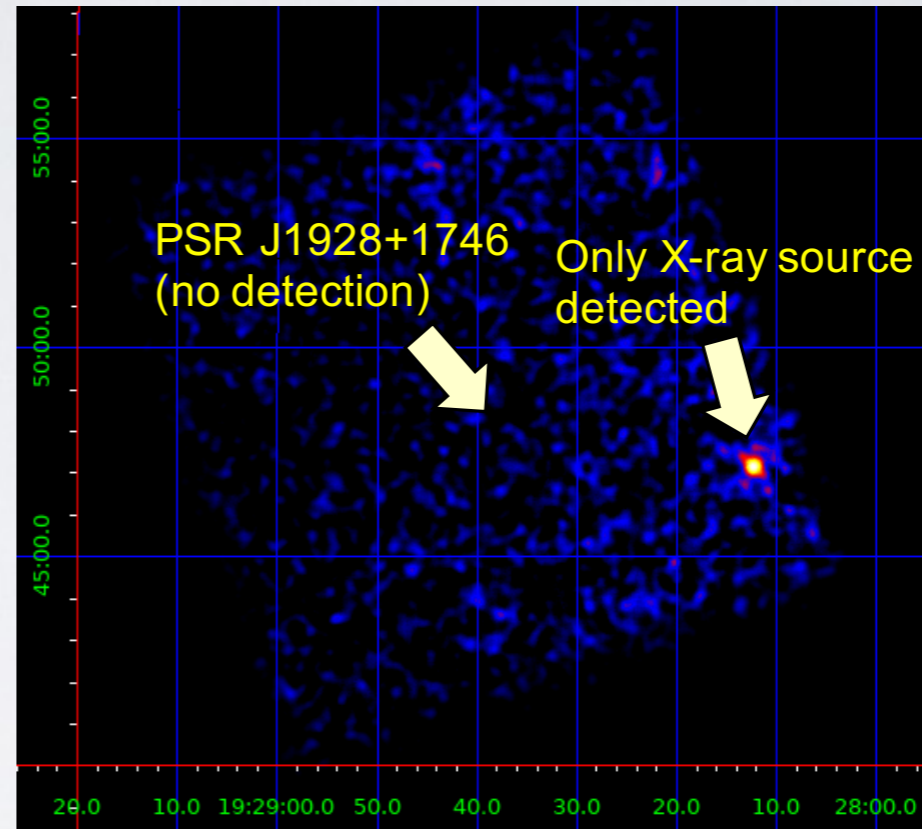
NuSTAR observation of 2HWC J1928+177

VERITAS image (Nahee Park, ICRC 2017)

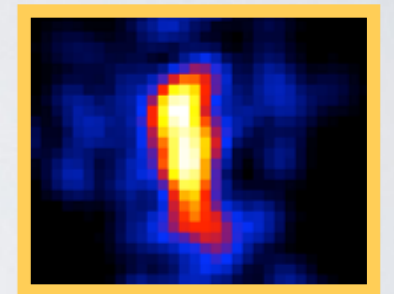


White contours: HAWC 5, 6, 7 standard deviations

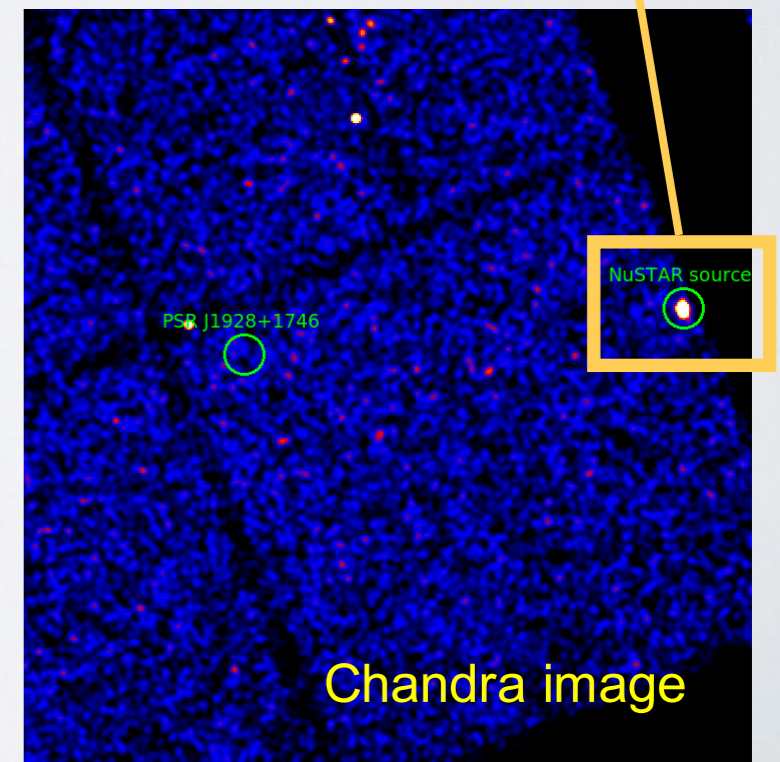
NuSTAR 3-20 keV image (BKG-subtracted)



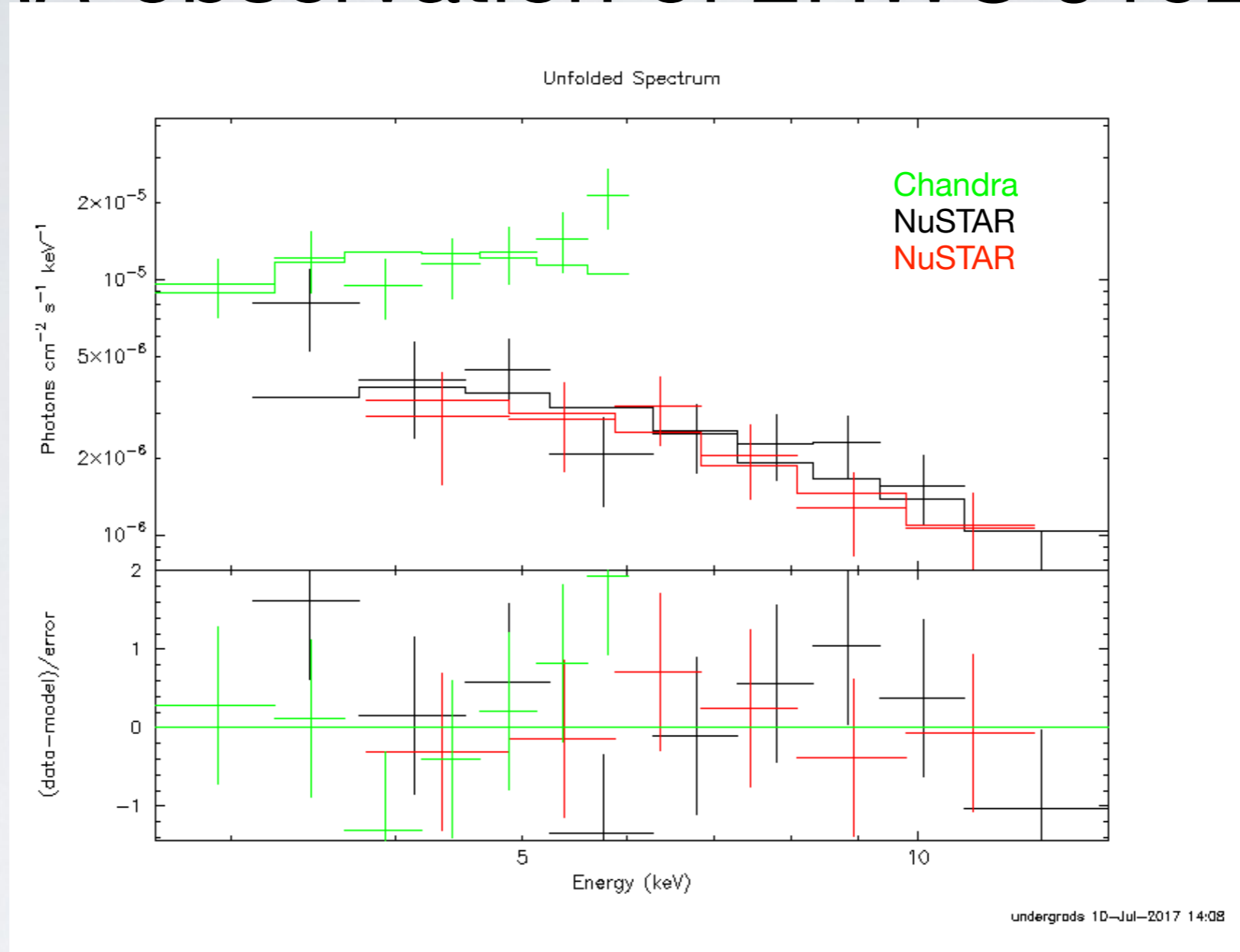
Chandra zoom-in image of NuSTAR source. Appeared elongated due to off-axis Chandra PSF, it is a point source ($<0.7''$)



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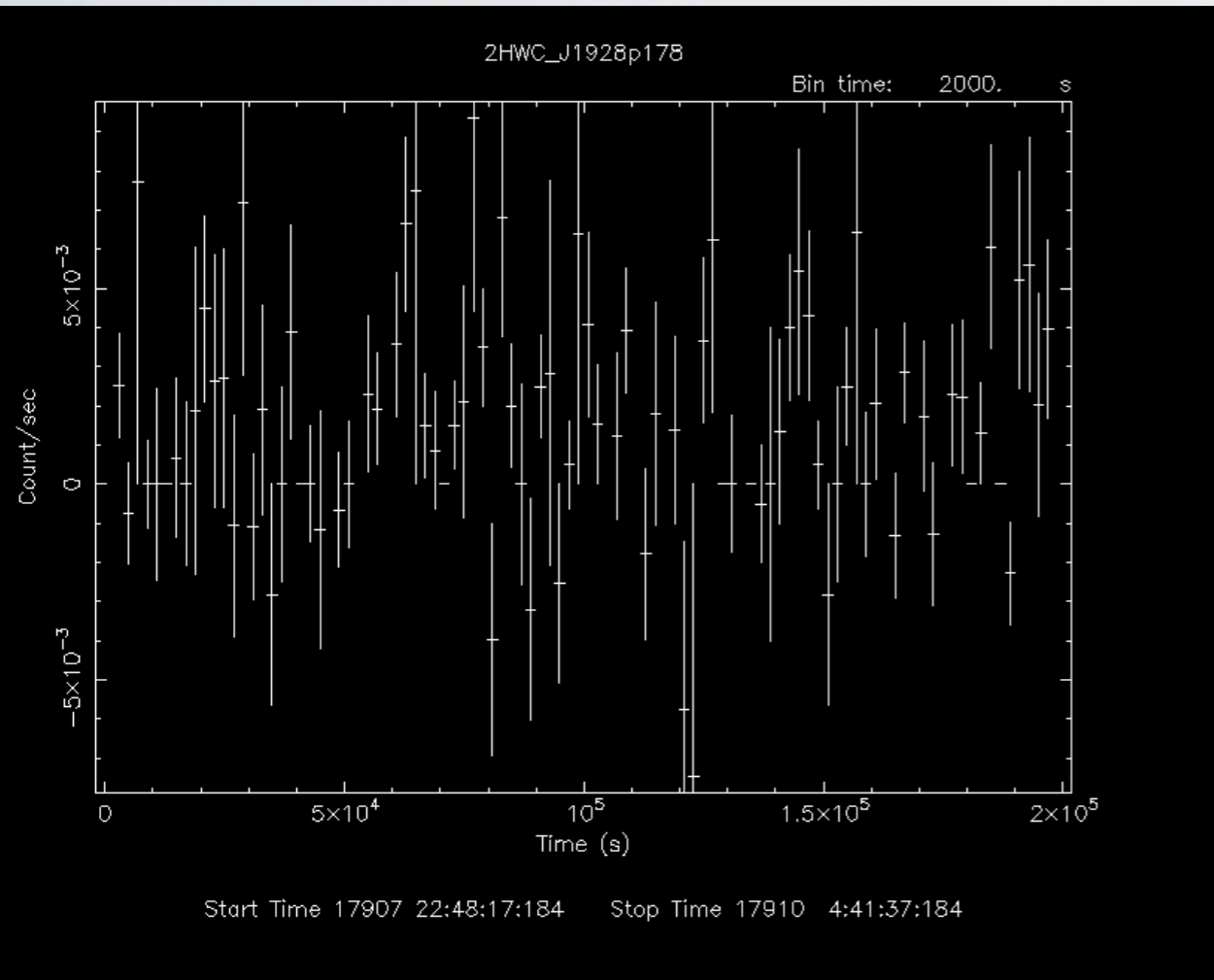
NuSTAR observation of 2HWC J1928+177



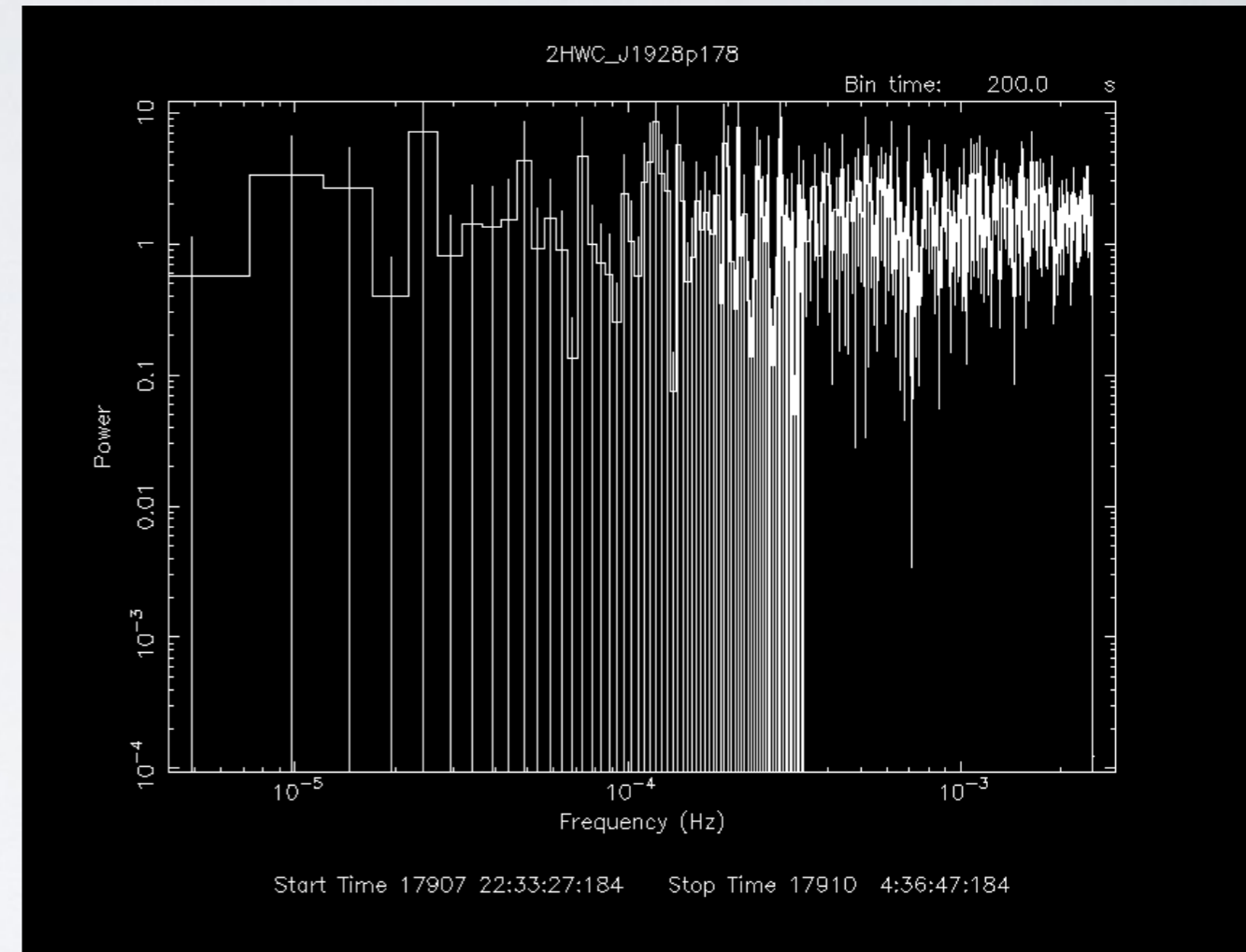
- *Chandra* flux is ~ 4 times higher than *NuSTAR* flux \rightarrow **time variable?**
- Absorbed power-law model fit to *Chandra* and *NuSTAR* spectra
 - Neutral hydrogen column $n\text{H} = 1 \times 10^{23} \text{ cm}^{-2}$
 \rightarrow higher than Galactic $n\text{H} 2 \times 10^{22} \text{ cm}^{-2}$ (local absorption?).
 - Photon index of 1.6 ± 0.4 .
 - X-ray luminosity (2-10 keV) = $(0.9-5) \times 10^{33} \text{ erg/s}$ assuming 6 kpc distance.

NuSTAR observation of 2HWC J1928+177

NuSTAR lightcurve



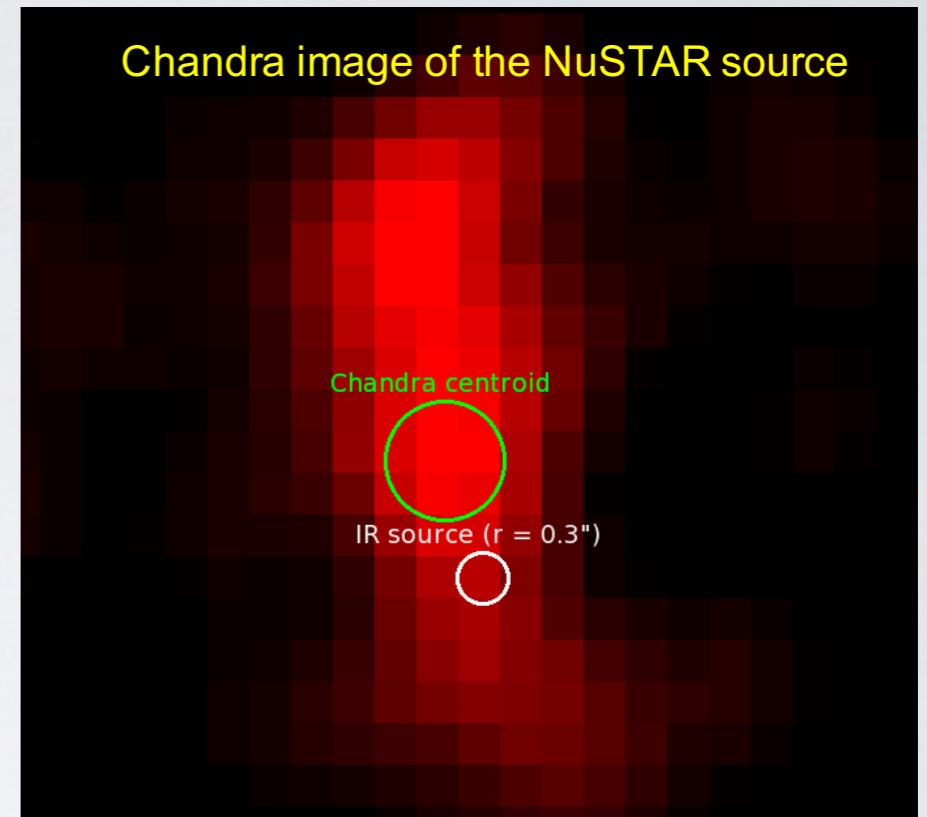
NuSTAR power density spectrum



- *NuSTAR* lightcurve over 1 day shows no variability.
- Power density spectrum is flat, no pulse-like signals. Indicating X-ray emission is NOT powered by accretion.

IR counterpart to *NuSTAR* source

- Bright IR source (K-magnitude ~ 13) at *Chandra* position (2MASS, NOMAD, GLIMPSE, UKIDSS catalogs).
- Estimate to be an O star after crude IR extinction correction.



- *NuSTAR* X-ray source could be a TeV binary.
 - Point-like source (based on *Chandra* imaging analysis)
 - Variable \rightarrow X-ray binary or AGN?
 - Power-law \rightarrow non-thermal
- Follow-up work on TeV/X-ray variability and better localization.

NuSTAR + *VERITAS* + *HAWC* Observation Summary

- *NuSTAR* follow-up of two *HAWC* sources were highly successful.
 - Detection of interesting X-ray sources above 10 keV
 - Broadband spectroscopy using *NuSTAR* and *Chandra* data
- Follow-up work on SED modeling with *NuSTAR* + *VERITAS* + *HAWC* for DA 495, TeV/X-ray variability study for 2HWC J1928+177.

