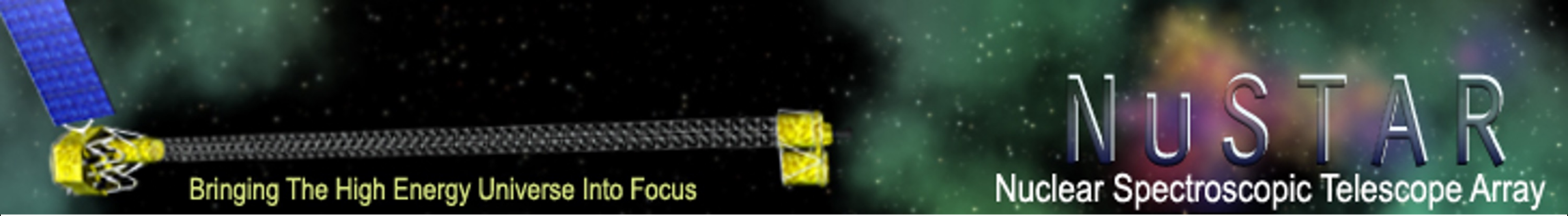


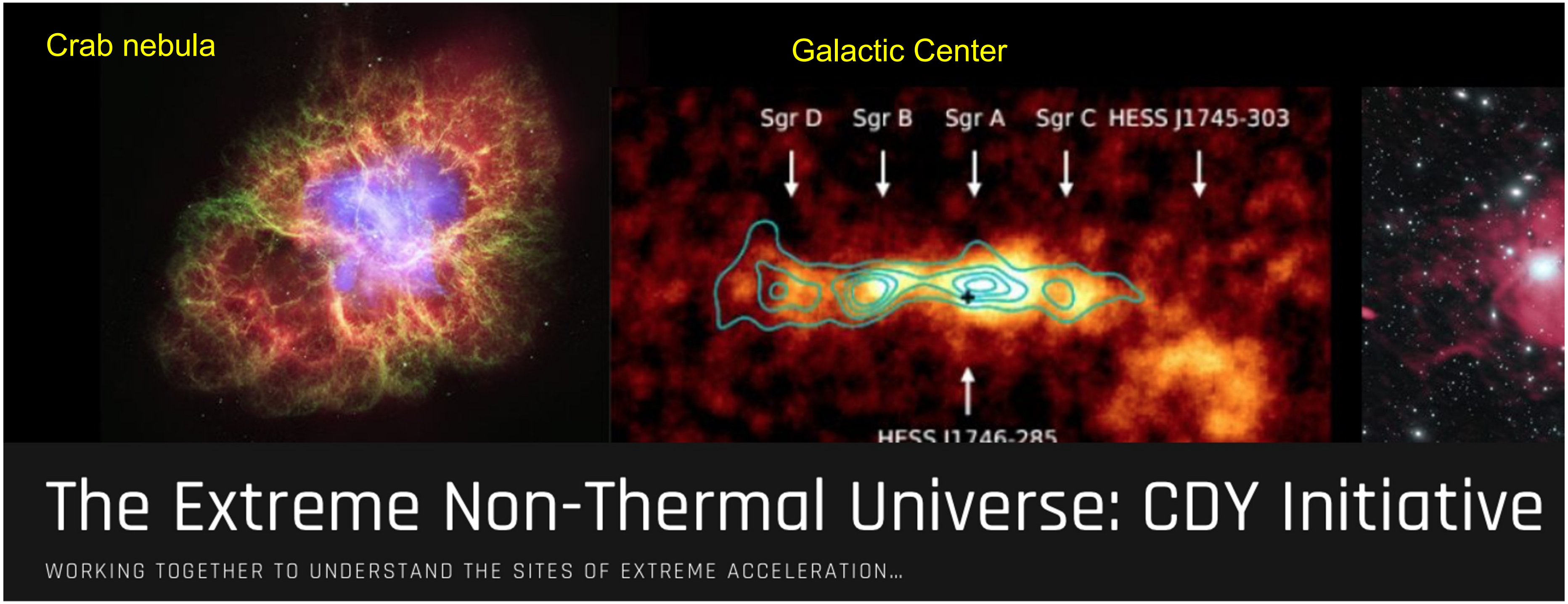

# *Highlights from NuSTAR observations of Galactic high-energy (TeV) sources*

Kaya Mori
(Columbia Astrophysics Laboratory)

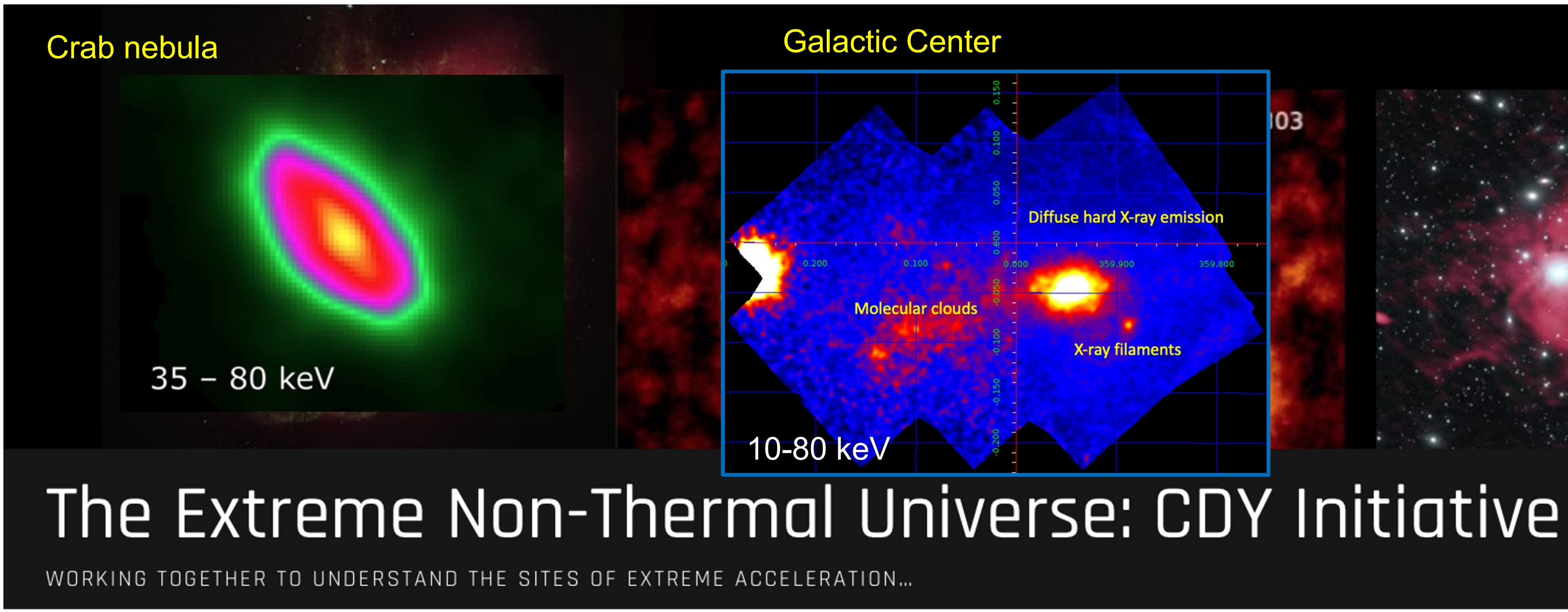
CDY lecture talk

May 3, 2023

## *CDY initiative: Non-thermal Universe and extreme particle acceleration*



# NuSTAR images hacking CDY website



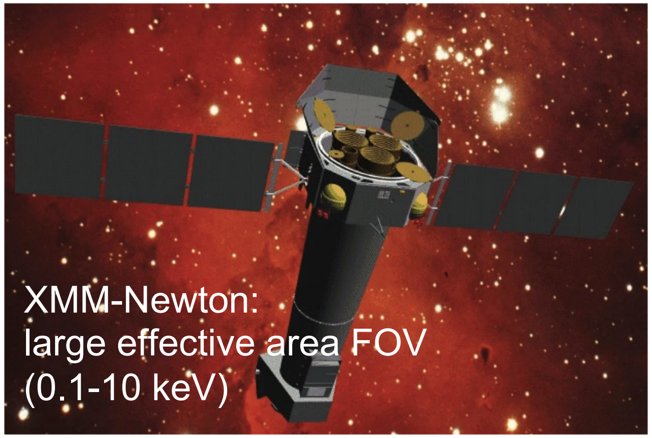
## *Outline of the talk*

- I will talk mostly about non-thermal, diffuse X-ray sources associated with Galactic TeV sources.
- I will NOT talk about (1) accreting objects, (2) transients, (3) extragalactic sources, or (4) thermal X-ray emission.
- Overview of NuSTAR telescope and observations (10 min)
- NuSTAR observations of Galactic TeV sources (30 min)
  - Supernova remnants
  - Pulsar wind nebulae
  - Other TeV sources
  - Galactic Center
- Future X-ray probe mission in the 2030s (5 min)

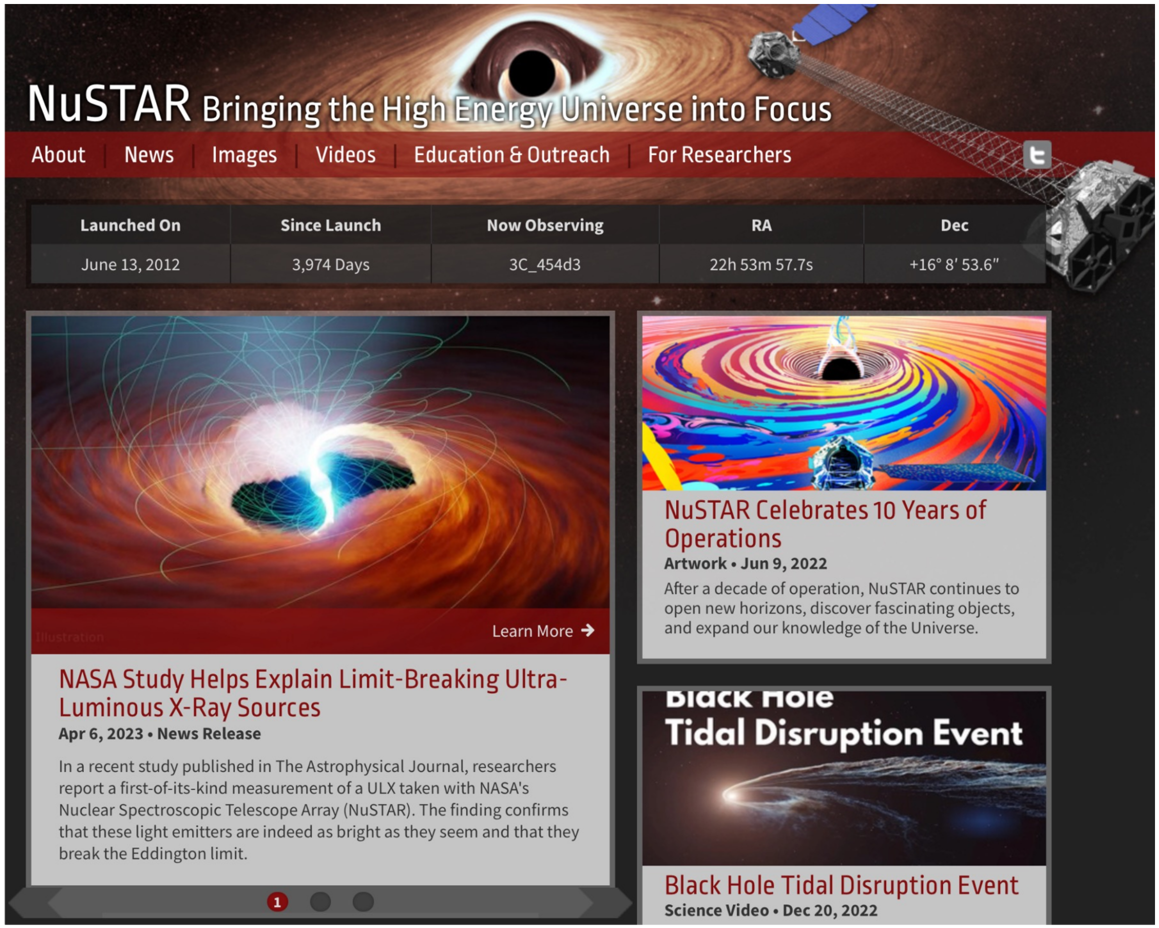
# *NuSTAR X-ray telescope*

# X-ray telescopes in the 2020s

- **Chandra, XMM, NuSTAR most utilized for observing diffuse X-ray emission**
- Swift, NICER and MAXI: X-ray transients
- IXPE: X-ray polarization (launched in December 2021)
- eROSITA: all-sky survey (currently suspending science operation)
- XRISM: high-resolution X-ray spectroscopy (FY 2023 launch)

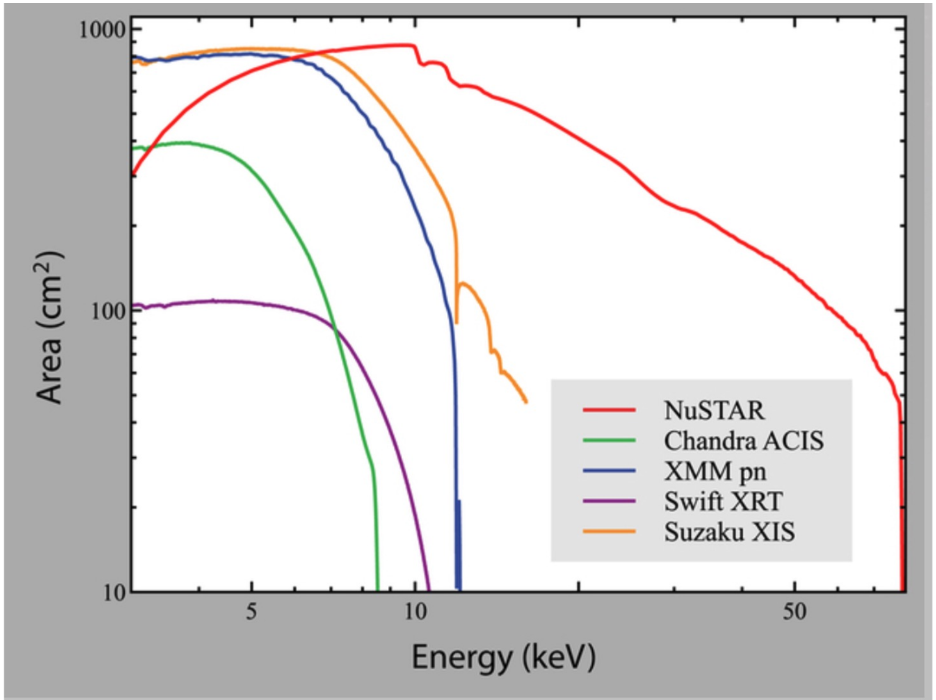

# NuSTAR: bringing the high energy Universe into focus




- www.nasa.gov/mission_pages/nustar/main/index.html
- www.nustar.caltech.edu

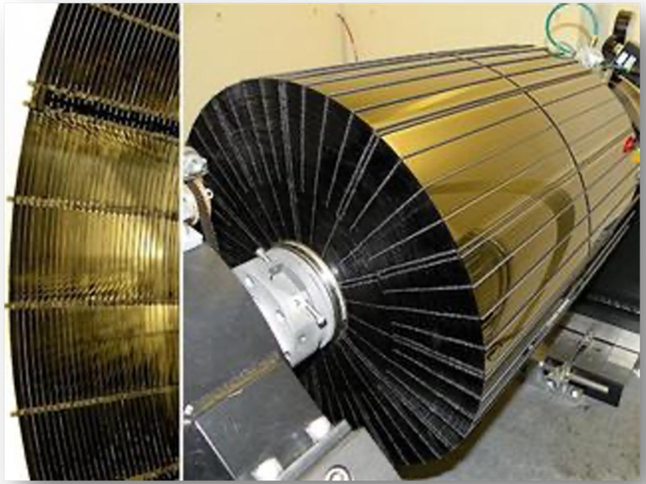
# NuSTAR: the first focusing X-ray telescope operating above 10 keV

- PI: Fiona Harrison
- Optics built at Columbia U (Lead: Chuck Hailey)
- Detectors developed at CalTech




*NuSTAR's effective area compared to other x-ray satellites.*

| | |
|---|---|
| **Energy Band** | 3 - 79 keV |
| **Angular Resolution** | 58" (HPD), 18" (FWHM) |
| **Focal Plane Size** | 12' x 12' |
| **Energy Resolution** | 0.4 keV at 6 keV, 0.9 keV at 60 keV (FWHM) |
| **Temporal Resolution** | 0.1 msec |
| **Maximum Flux Measurement Rate** | 10,000 cts/s |
| **ToO response** | < 24 hours |



# 11 years of NuSTAR operation

- NASA SMEX mission launched in June 2012

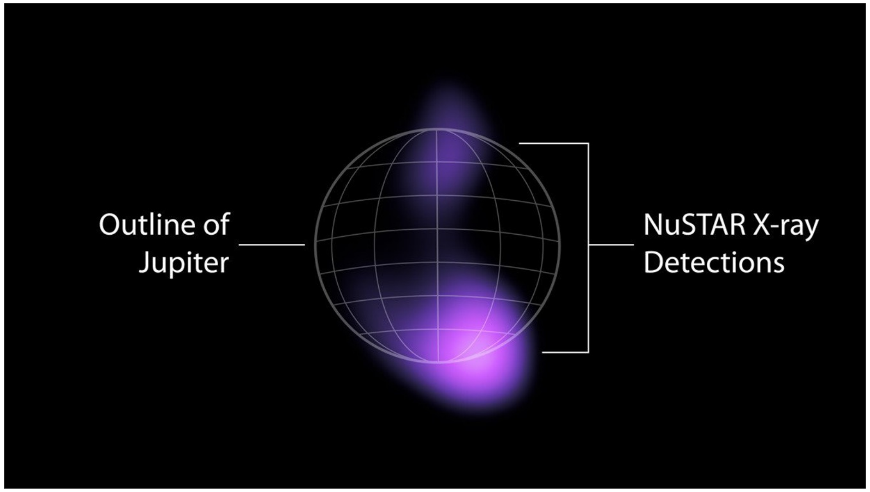
- Year 1-2: PI-led primary mission including the Galactic Center survey and young SNRs
- Year 3-5: Legacy program including Galactic TeV sources
- Year 3 and later: GO program

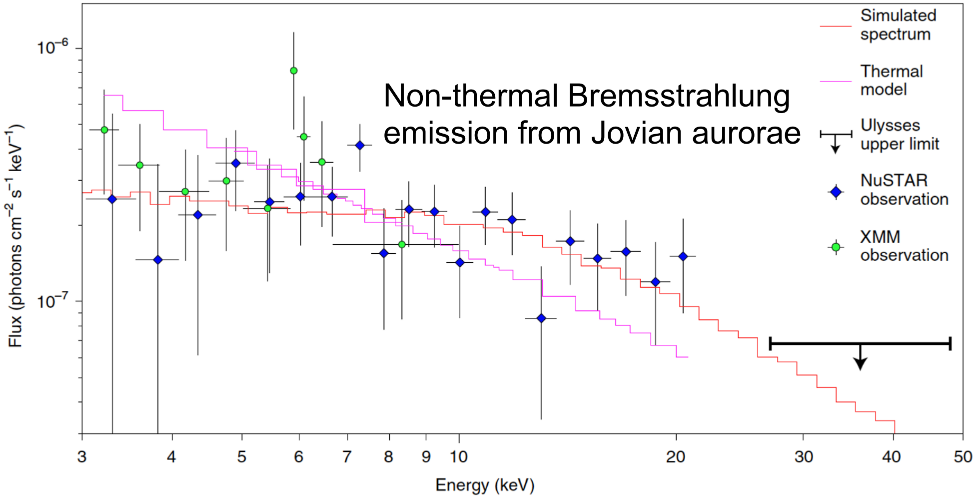
- More ToOs => time-domain astrophysics
- More Joint observations with other telescopes => multi-messenger astrophysics
- More Large GO programs (> 500 ks) => high-risk, high-return science

# *NuSTAR is an excellent non-thermal X-ray emission detector*

- Many X-ray sources show thermal emission (kT ~ 0.1 to few keV)
  - X-ray binaries
  - Neutron stars
  - Cataclysmic variables
  - SNRs
  - Star clusters
  - Diffuse X-ray emission
  - Jupiter (!)

- E > 10 keV (unique to NuSTAR) for detecting and characterizing non-thermal X-ray emission *cleanly*.

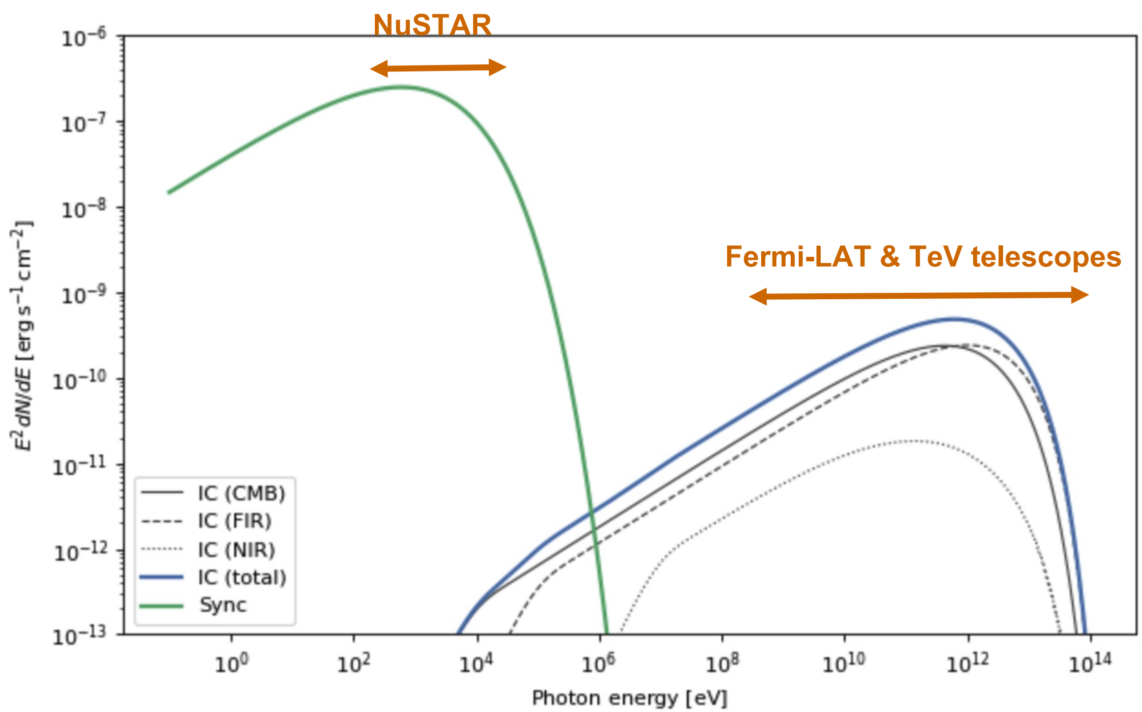



Mori+ 22 Nature Astronomy

# *NuSTAR uniquely explores synchrotron radiation from TeV-PeV electrons*

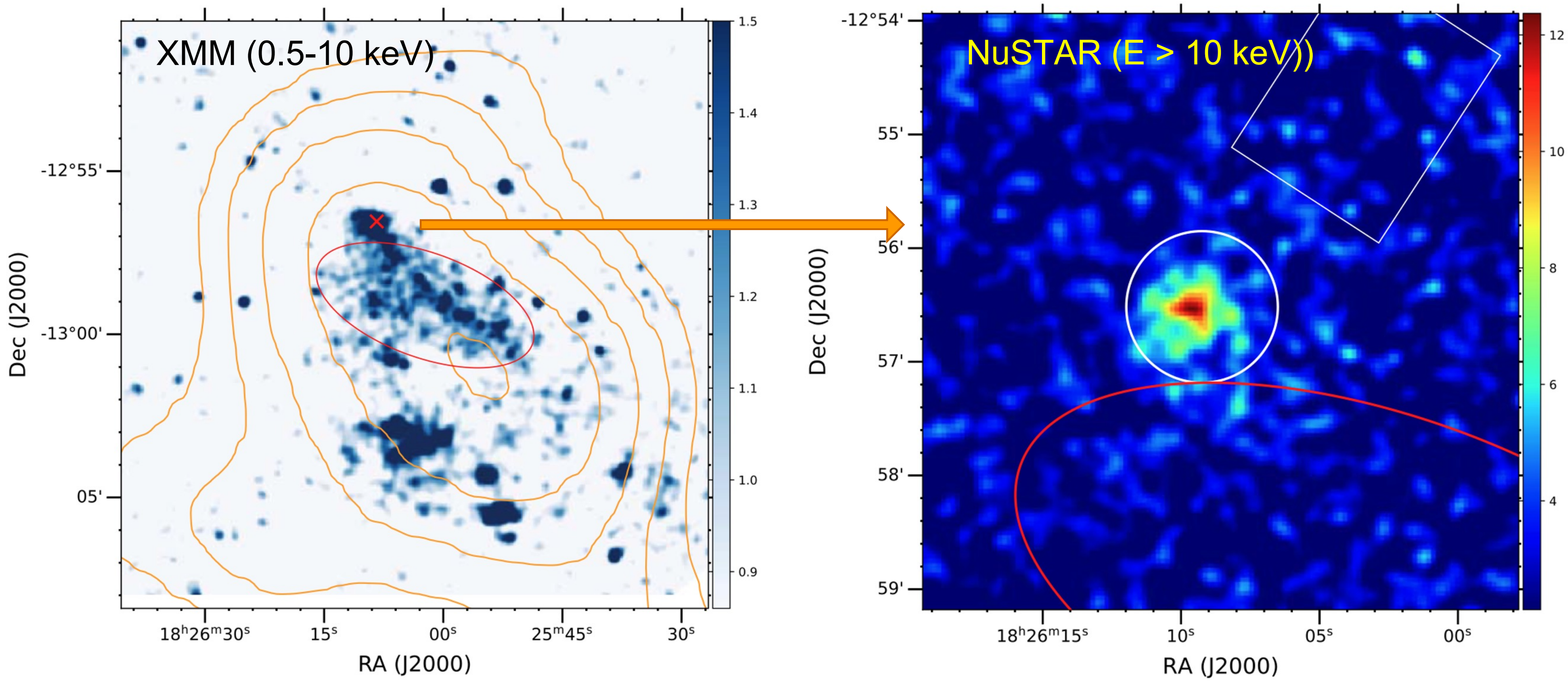
- Energetic particle accelerators produce TeV-PeV electrons
  - Primary electrons (leptonic accelerators like PWNe)
  - Secondary electrons from p-p collisions (hadronic accelerators)
- Hard X-ray band (> 10 keV)
  - $E_{syn}$ = 40 keV ($E_e$/100 TeV)$^2$(B/0.1 mG) => Sensitive to $E_{max,e}$
  - $t_{syn}$ = 1.2 yr (B/0.1 mG)$^{-3/2}$($E_{syn}$/10 keV)$^{-1/2}$ => Faster cooling/variability




Example SED model from NAIMA website

# *A conventional strategy to explore Galactic TeV sources in the X-ray band*

- Many Galactic TeV sources are extended, not well localized or have multiple counterpart candidates
- XMM survey with large FOV (or eROSITA) in the soft X-ray band
- NuSTAR follow-up, pinpoint observations for non-thermal X-ray spectroscopy and morphology




HESS J1826-130 = Eel PWN (Burgess+ 22)

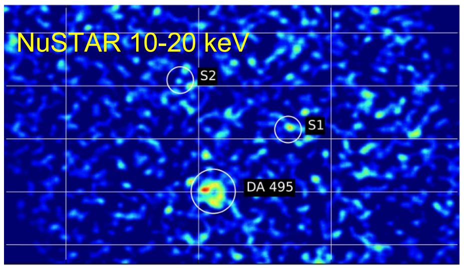
# NuSTAR legacy program in 2017-18: 3 Galactic TeV sources

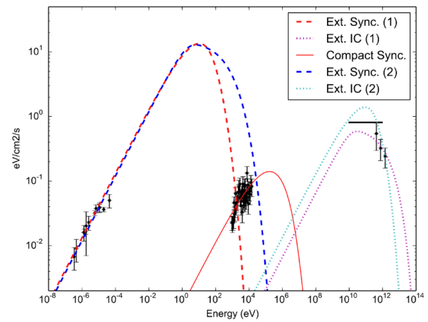
- NuSTAR legacy program => high-risk, long-exposure observations
  - Started with NuSTAR-VERITAS-HAWC collaboration
  - Our collaboration evolved into a large group of 40 members from NuSTAR, XMM, Chandra, XRISM, VERITAS, HAWC, Fermi, ICECUBE.
  - More X-ray observations proposed, approved and performed until now

- We observed 3 Galactic TeV sources
  1) PWN DA 495 (Coerver+ 2019)
  2) TeV gamma-ray binary HESS J0632+057 with VERITAS (Archer+ 2020)
  3) Unidentified HAWC source 2HWC J1928+178 (Mori+ 2020)

# NuSTAR legacy TeV source program as a bridge to GO observations

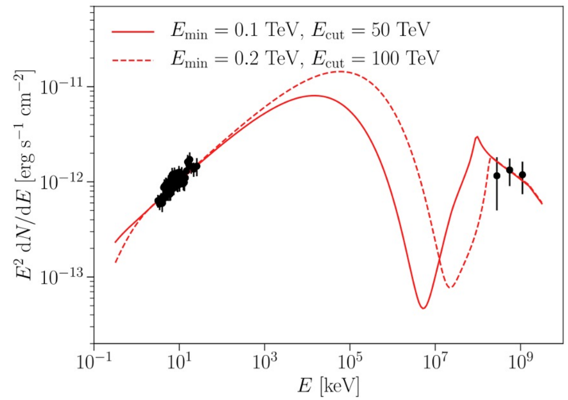
(1) DA 495 => NuSTAR large program of observing 8 middle-aged PWNe



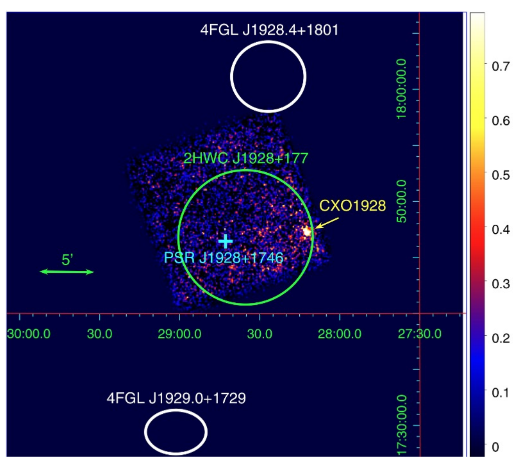

NuSTAR image (left) and SED (right) of DA 495

(2) HESS J0632+057 => NuSTAR + VERITAS observations of other orbital




NuSTAR + VERITAS SED data in pre-flare phase

(3) 2HWC J1928+178 => XMM-Newton survey of LHAASO/HAWC PeVatron sources (this year!)



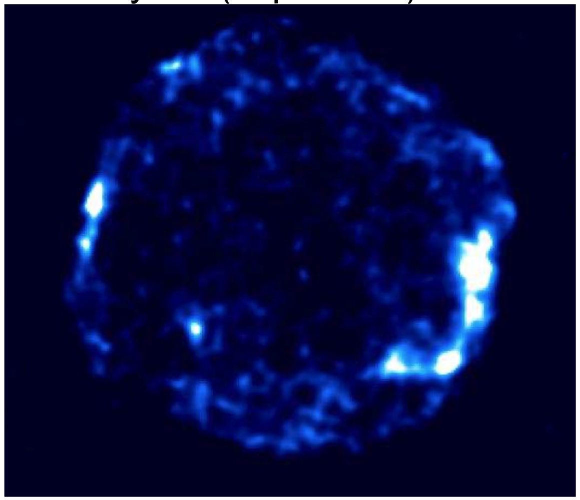

NuSTAR image:
No diffuse X-ray emission was detected

# ***Supernova remnants***

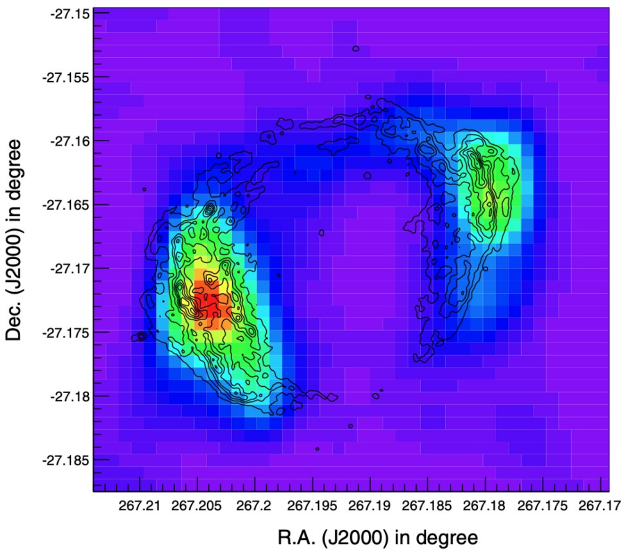
# *NuSTAR hard X-ray views of young SNRs*

- NuSTAR observed young SNRs (Cas A, SN1987A, Tycho, Kepler, G1.9+0.3) for Ti44 line science => SN explosion mechanism
- Ti44 mapping from Cas A (Grefenstette+ 13) and detection from SN1987A (Boggs+ 15)
- Dissecting non-thermal X-ray emission from thermal emission above E ~ 10-15 keV
- See a systematic study of young SNRs using NuSTAR, XMM and Suzaku (Tsuji+ 21)

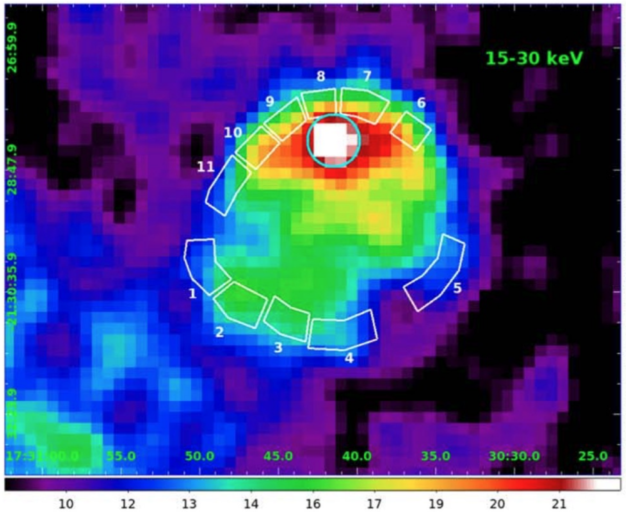
Tycho (Lopez+ 15)



G1.9+0.3 (Zoglauer+ 15)

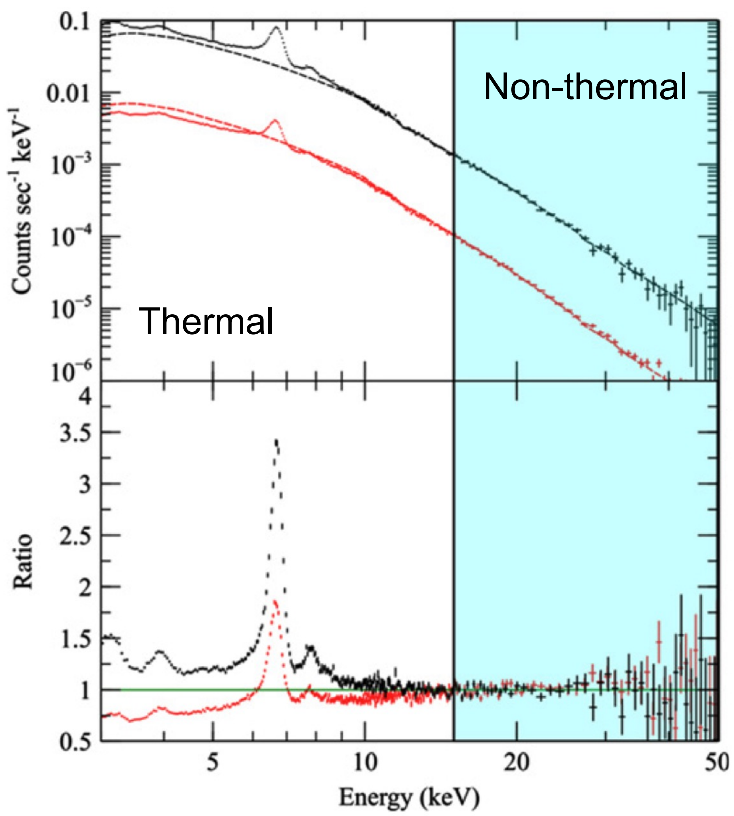


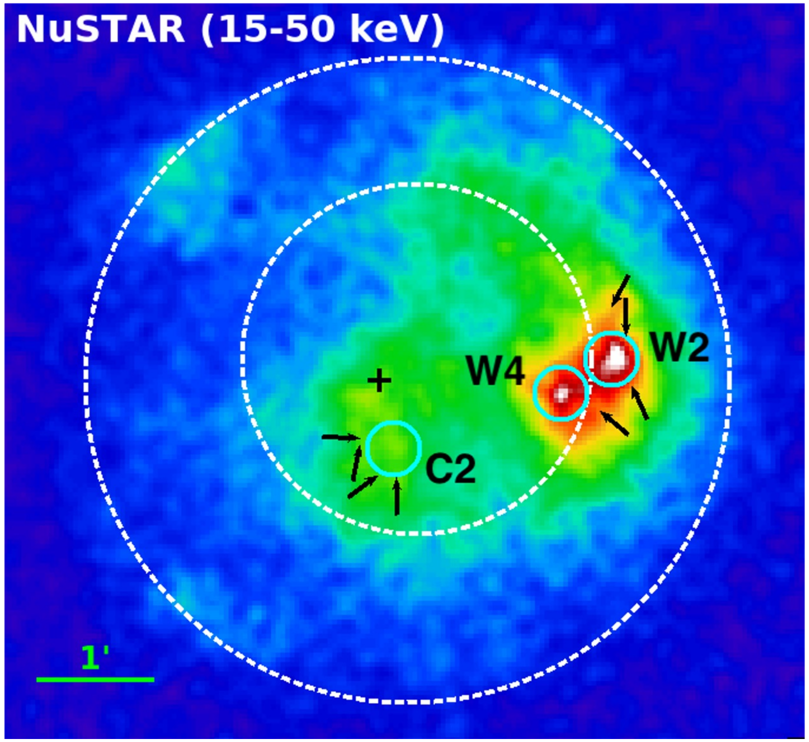

Kepler (Sapienza+ 22)



# Cas A: NuSTAR hard X-ray view of non-thermal X-ray emission

- NuSTAR observations in 2012-13 (2.4 Ms)
- NuSTAR paper “Locating the most energetic electrons in Cas A” (Grefenstette+15)
- Some local hard X-ray knots are detected => soft photon index ($\Gamma$ ~ 3)
- Different morphology from radio and thermal X-ray emissions

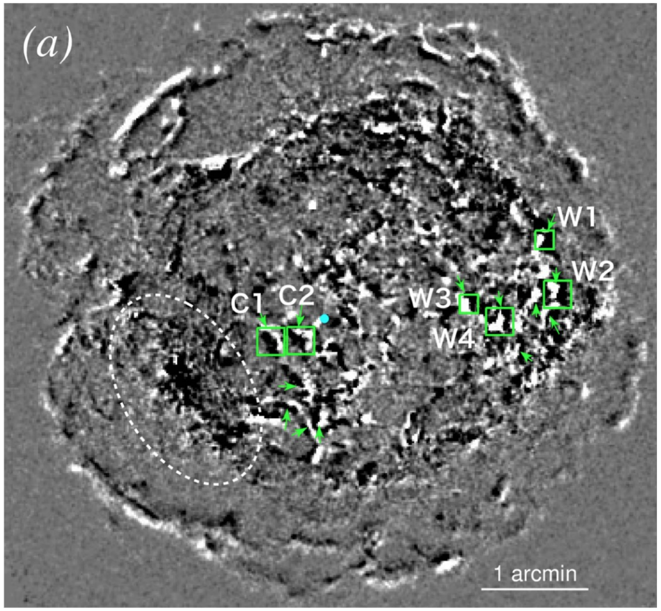


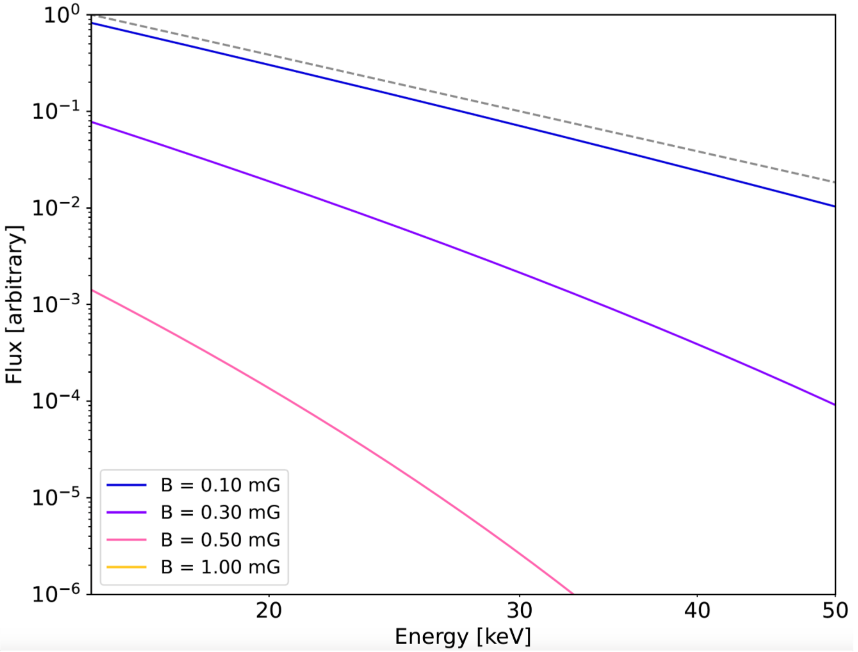
# *Cas A: Multi-epoch Chandra observations revealed the dynamics of X-ray filaments*

- Multi-epoch Chandra observations => proper motions and variabilities => $V_{shock}$ and B ~ 0.1-1 mG (Sato+ 18, 23)
- However, Chandra 4-6 keV “continuum” band (where atomic lines are absent) may be still contaminated by thermal emission.
- At higher B-fields, synchrotron X-ray spectrum should get softer and fainter more quickly (possibly with a few year time-scale).

Chandra 4-6 keV “difference” image between 2000 and 2014



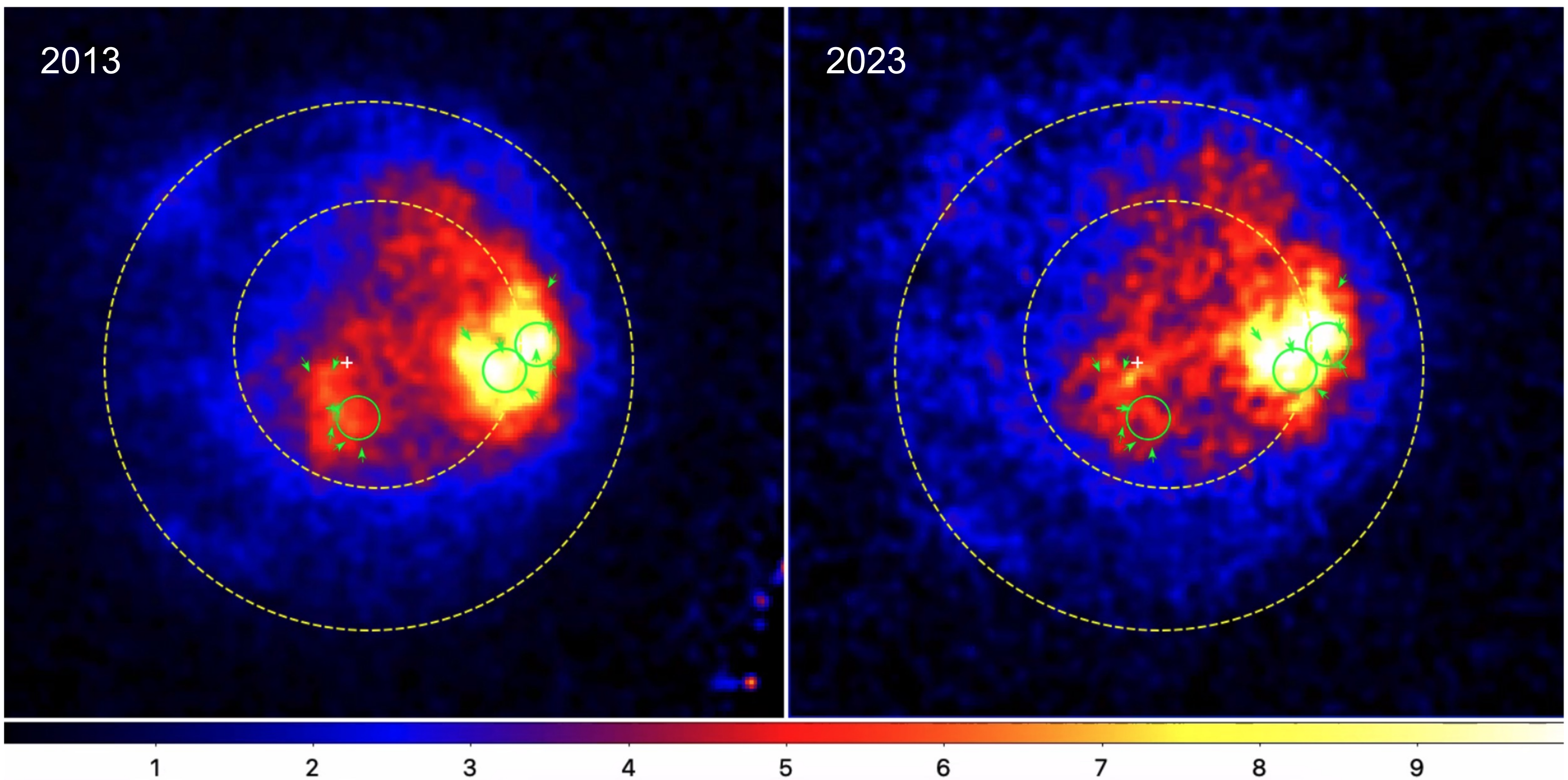

Synchrotron X-ray spectral evolution after 5 years (toy model)



# Cas A: hard X-ray knots varied over 10 yr?

- A new 200 ks NuSTAR observation in Apr 2023 (ongoing analysis by J. Woo)
- There could be some morphology changes but nothing dramatic: B ~ 0.1 mG?
- We are working on careful image comparison analysis for each hard X-ray knots

NuSTAR 15-50 keV flux maps (preliminary!)

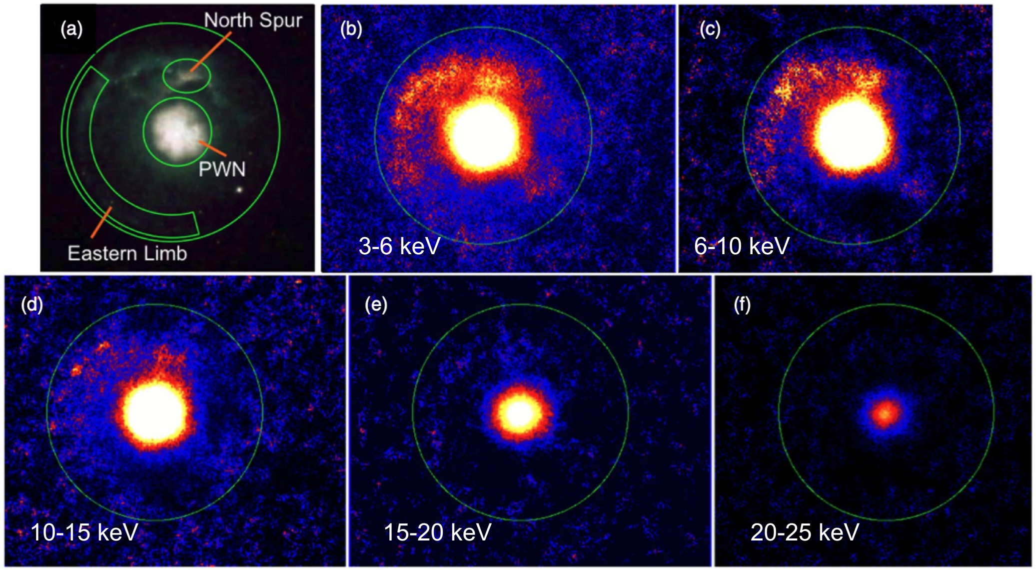


# *Pulsar wind nebulae*

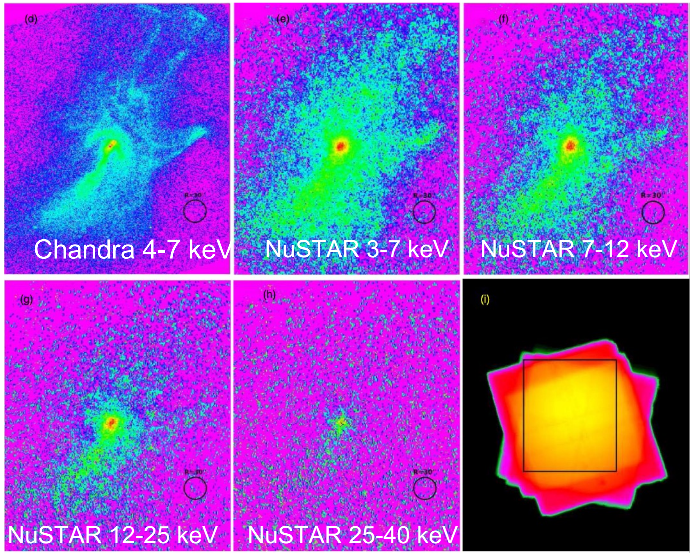
# NuSTAR hard X-ray views of young PWNe

- NuSTAR's timing => excise pulsar emission by phase-resolved analysis
- NuSTAR's broadband data => (1) energy-resolved morphology and (2) spatially-resolved spectroscopy
- NuSTAR detected synchrotron burnoff effects

G21.5 (NuSTAR; Nynka+ 15)

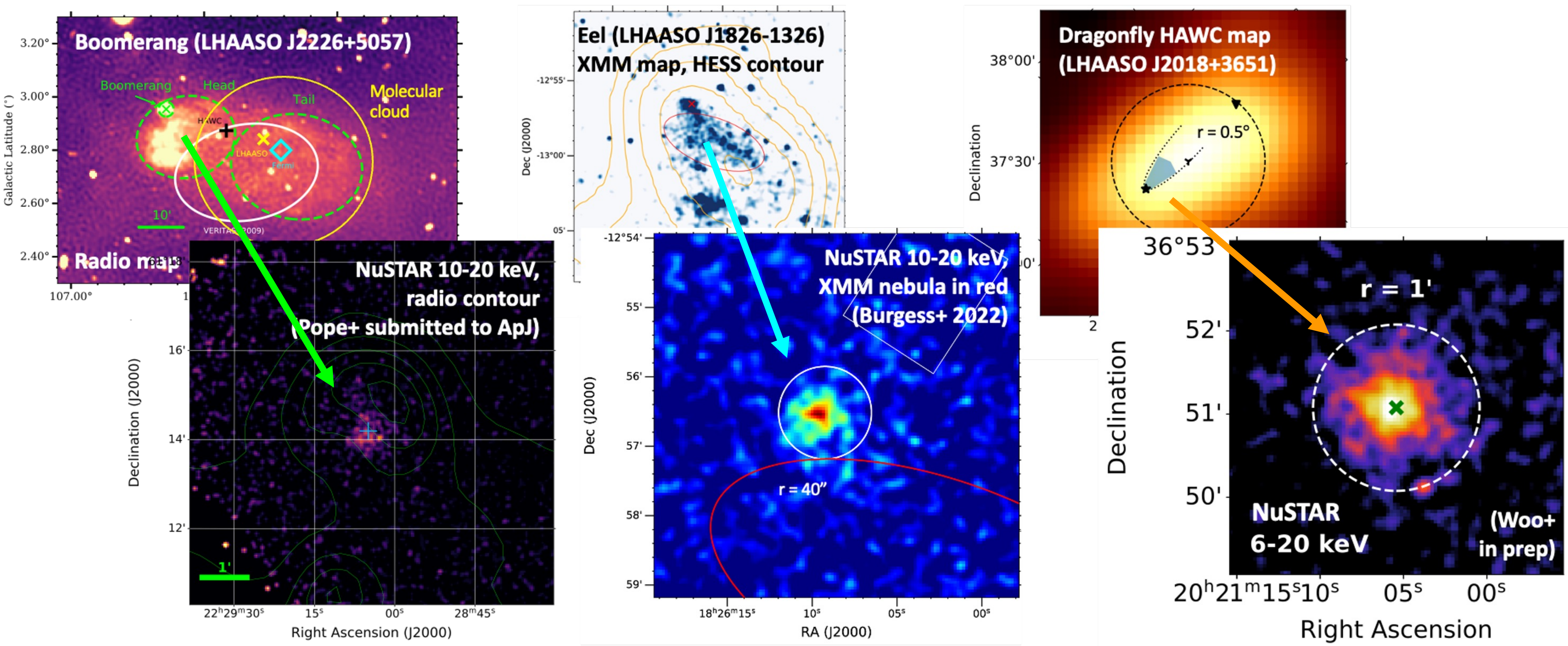



"Hand of God" MSH 15-52 (An+ 14)



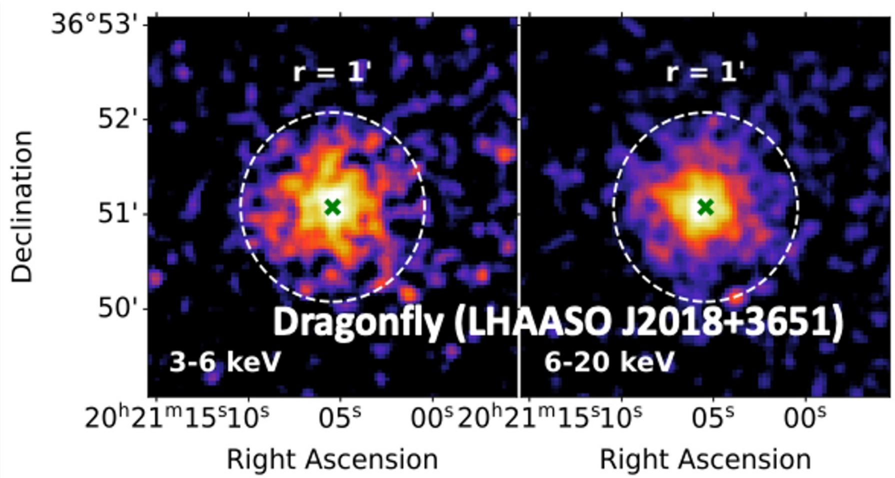
# *Hard X-ray views for middle-aged PWNe*

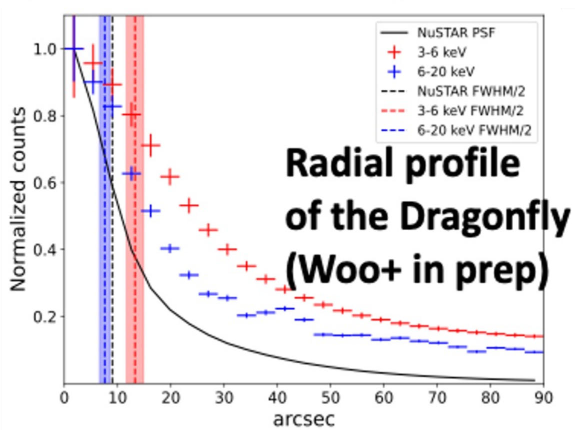
- Some middle-aged PWNe (> $10^3$ yr old) may be associated with LHAASO sources => Leptonic PeVatrons?
- NuSTAR detected compact hard X-ray nebulae around the pulsars

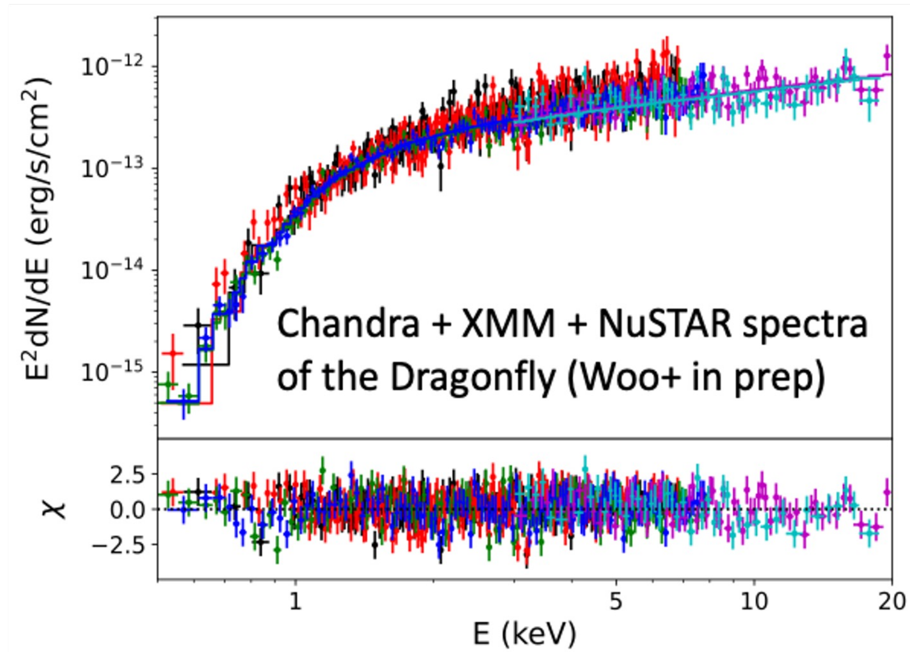


# *Synchrotron burnoff detected from middle-aged PWNe*

- PWN size shrinking at higher energies due to faster synchrotron cooling

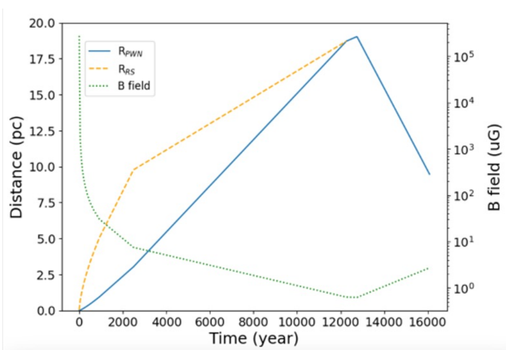


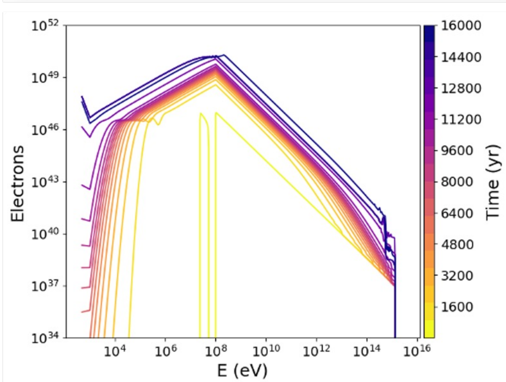



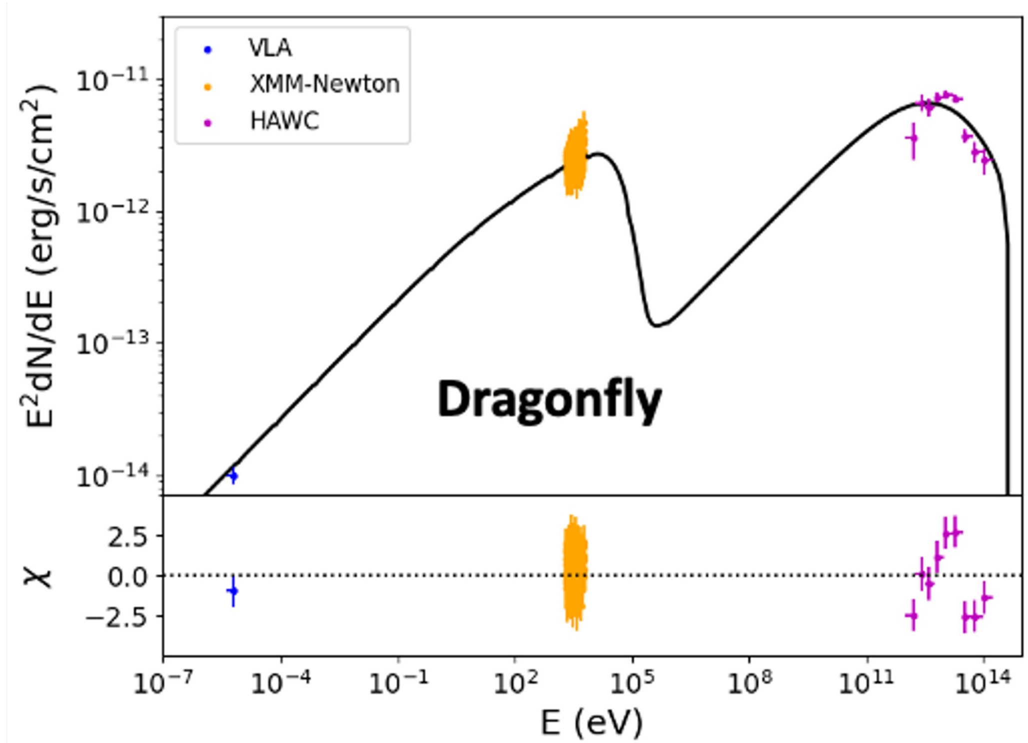



# *What do our results indicate about middle-aged PWN PeVatron candidates?*

- Compact hard X-ray PWN with synchrotron burnoff => B > 10 uG in the inner PWN
- Applying one-zone PWN time-evolution model (Gelfand+ 2008)
  - Overall B-field is low: B ~ few uG
  - Emax ~ 1 PeV
  - PWN compression by SNR reverse shock took place
  - See another multi-zone phenomenological model approach (Park+ 22)



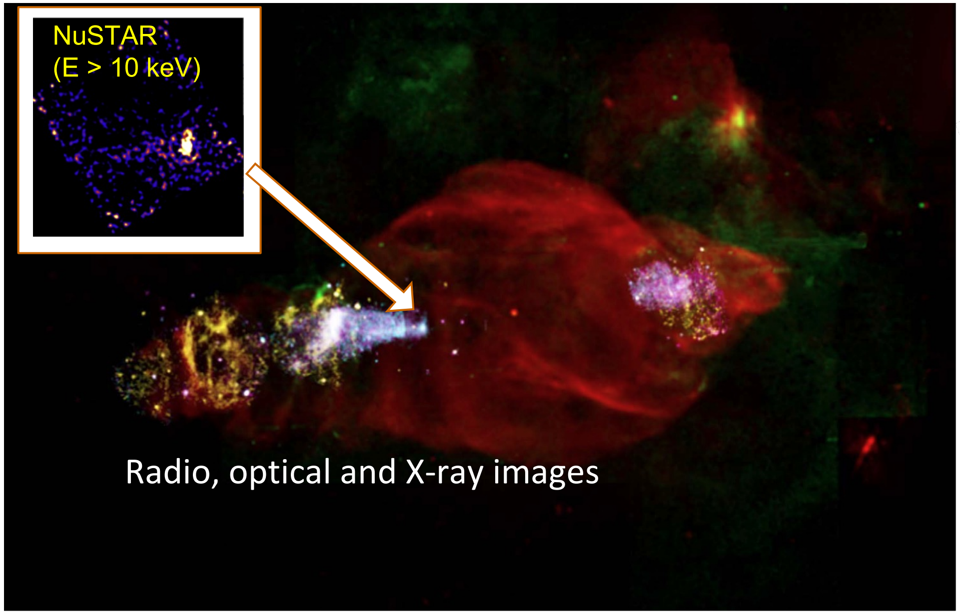



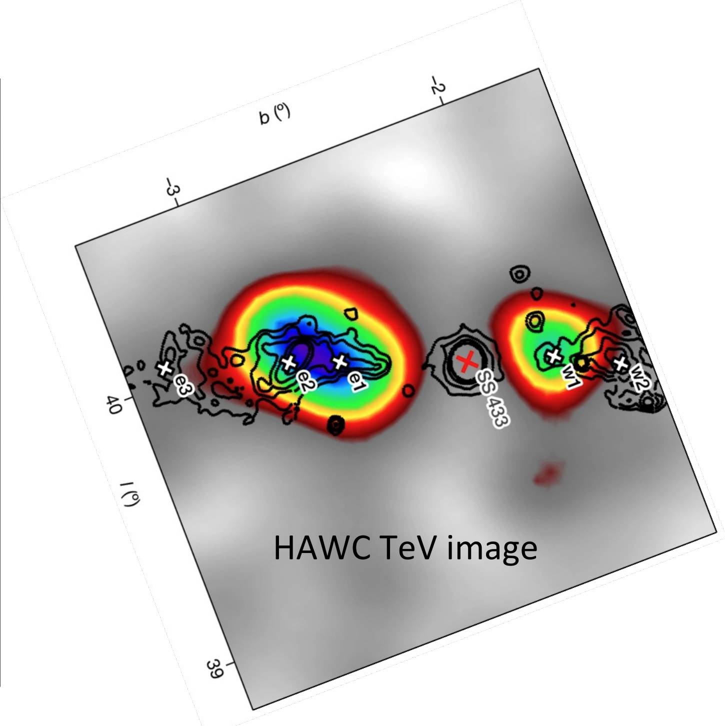



# *Other Galactic TeV sources*

# *W50 lobes: A unique PeVatron powered by microquasar jets*

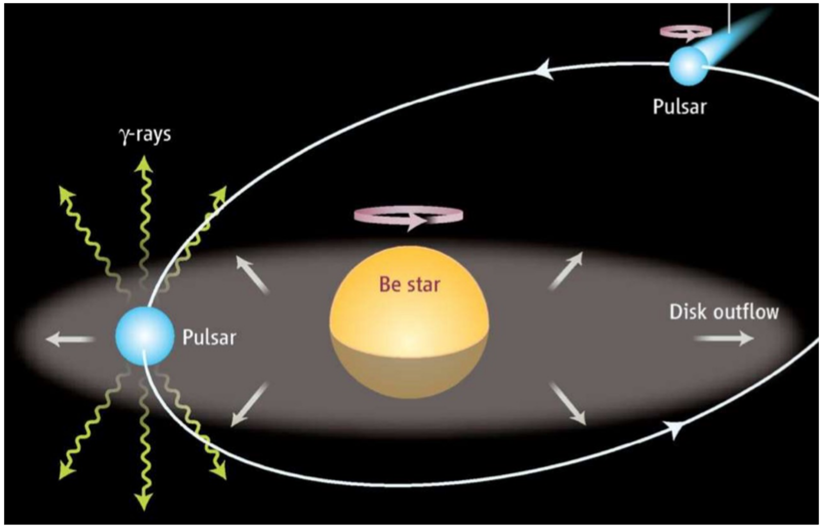
- Bipolar radio jets from microquasar SS433
- HAWC discovery of TeV emission from W50 lobes (Abeysekara+ 18)
- A large X-ray survey with XMM (Safi-harb), Chandra (Tsuji) and NuSTAR (Mori)
  - XMM+NuSTAR paper on the eastern lobe (Safi-Harb+ 22)
  - XMM+NuSTAR paper on the western lobe (Mac Intyre+ in prep)
  - **NuSTAR detected hard X-ray knots ($\Gamma$ ~ 1.6) in the eastern and western lobes.**



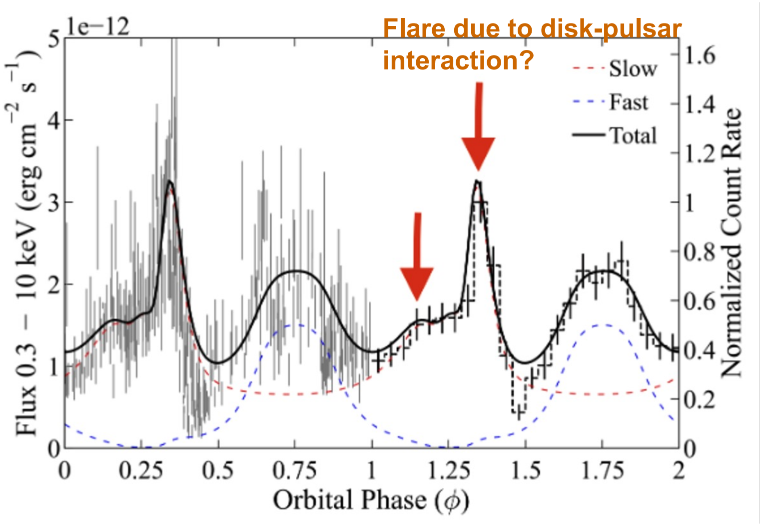



# *TeV gamma-ray binaries: Rare binaries not powered by accretion*

- Pulsar vs stellar wind collisions => intrabinary shock (IBS)
- NuSTAR observed all 8 known TeV binaries.
- HESS J0632+057 (317-day orbital period with Be companion)
  - First observed in the NuSTAR legacy program
  - 4 joint NuSTAR and VERITAS observations performed so far
  - IBS model applied to multi-wavelength SED and lightcurve data (Kim+ 22)
  - Swift, NICER, NuSTAR and VERITAS will target the next flare in Feb'24

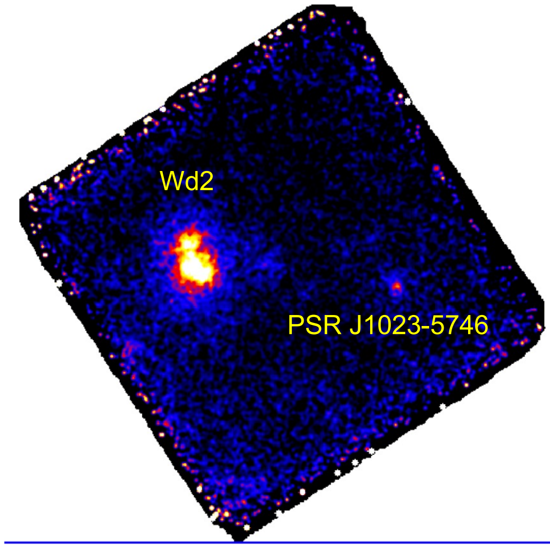


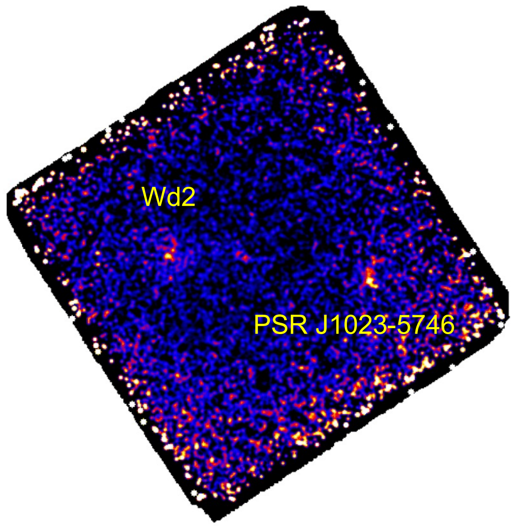

Mirabel 16

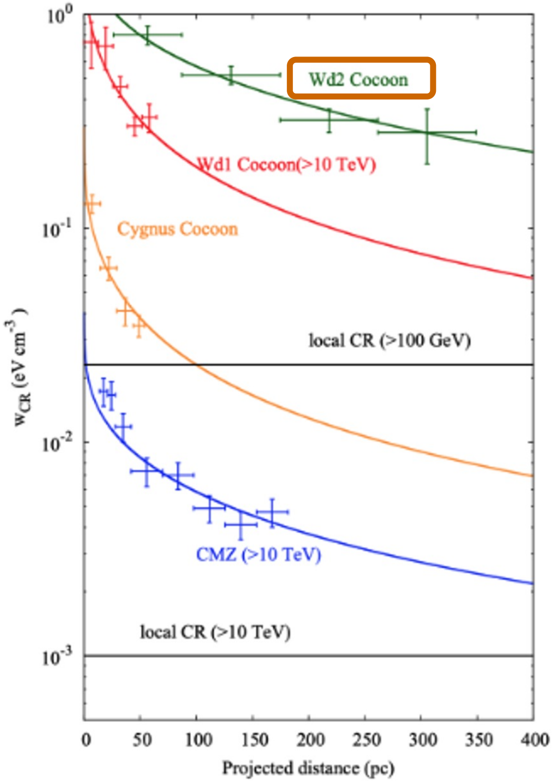


# Young star cluster: Westerlund 2

- Young star clusters (YSCs) are recognized as one of the primary hadronic PeVatrons.
- Some YSCs generate large-scale gamma-ray cocoons and superbubbles.
- NuSTAR observation of Westerlund 2 or HESS J1023-575 (ongoing analysis by J. Woo)
  - Non-thermal X-ray emission from colliding winds?
  - YSC detected up to 20 keV but looks faint…



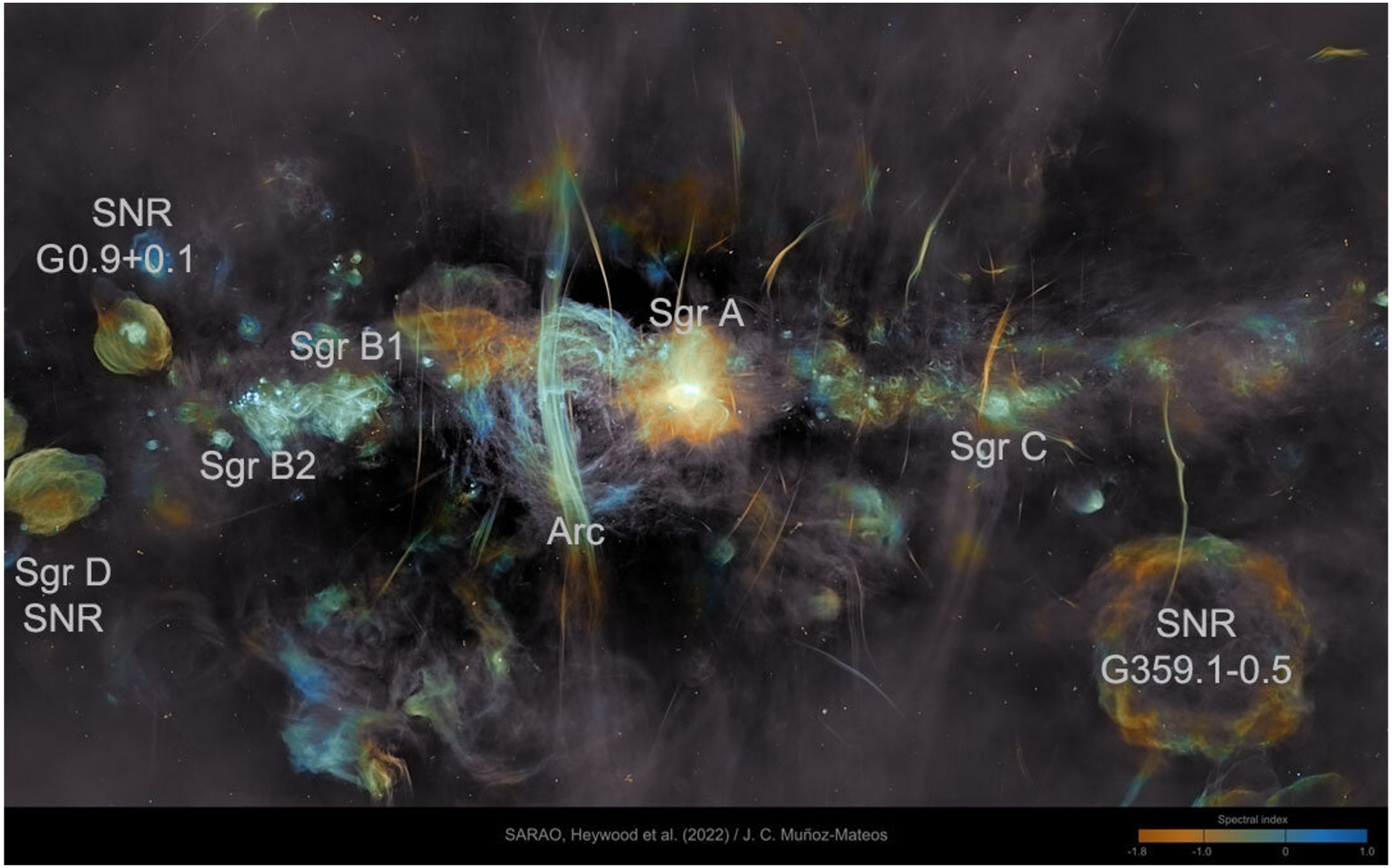




Cosmic-ray profiles for the gamma-ray cocoons (Yang+ 19)

# *Galactic Center*

# Radio view of the GC (MeerKAT)

- Many radio filaments => Complex magnetic field structures



# *Soft X-ray view of the GC (Chandra 2-8 keV)*

- ~10,000 X-ray point sources and diffuse X-ray emission
- Higher concentration of X-ray sources near Sgr A*

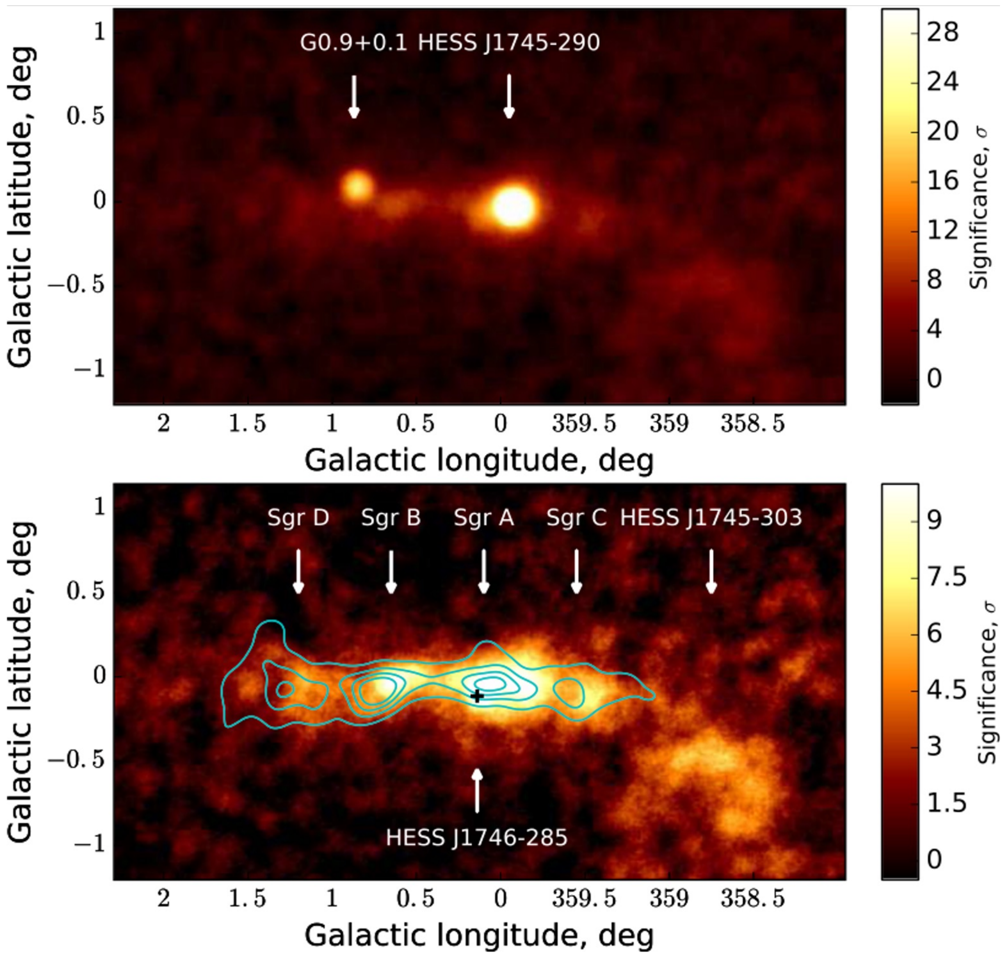
2 deg (280 pc)

0.8 deg (110 pc)

Chandra image of the GC region (Muno+ 09)

# TeV gamma-ray view of the GC

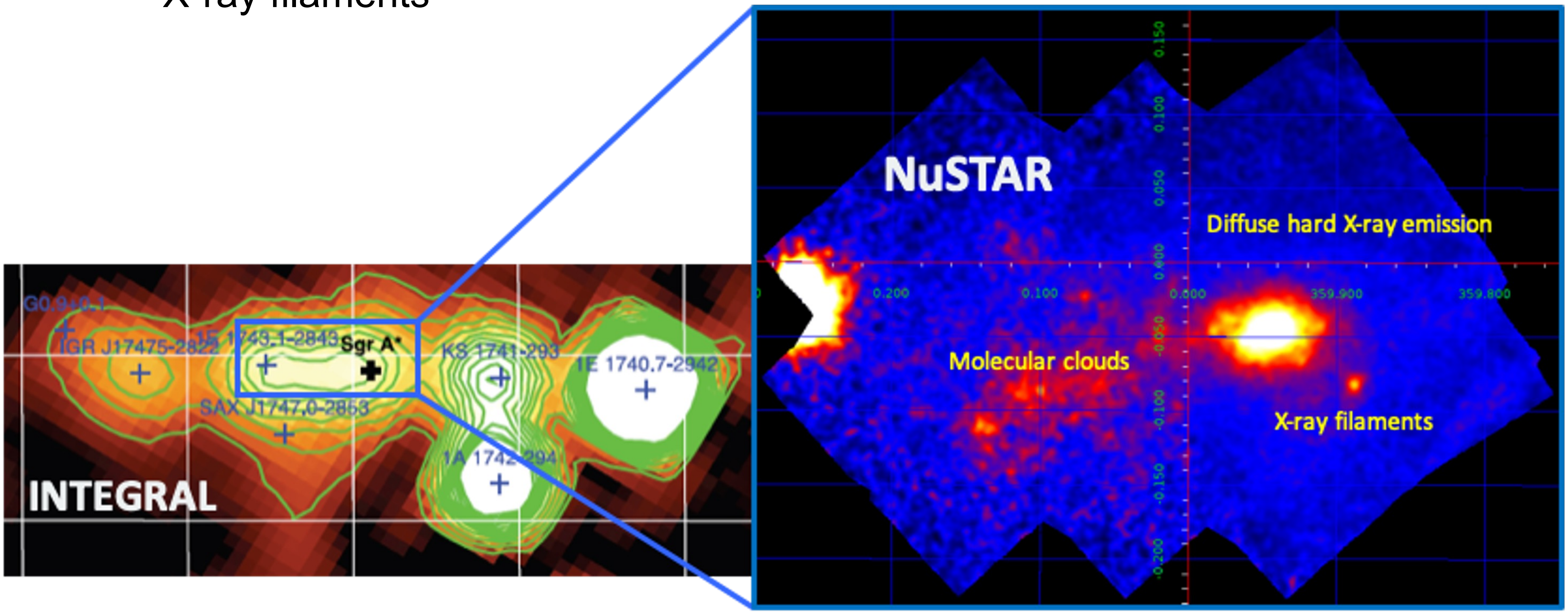
- Two bright TeV sources
  - HESS J1745-290
  - SNR/PWN G0.9+0.1
- Extended TeV sources are correlated with molecular clouds




HESS collaboration 2018

# NuSTAR: a new hard X-ray window of the Galactic Center

- New distinct hard X-ray sources (> 10 keV) revealed by NuSTAR
  - X-ray point sources (X-ray binaries, magnetic CVs)
  - Diffuse hard X-ray emission in the central 10 pc
  - Molecular clouds
  - X-ray filaments

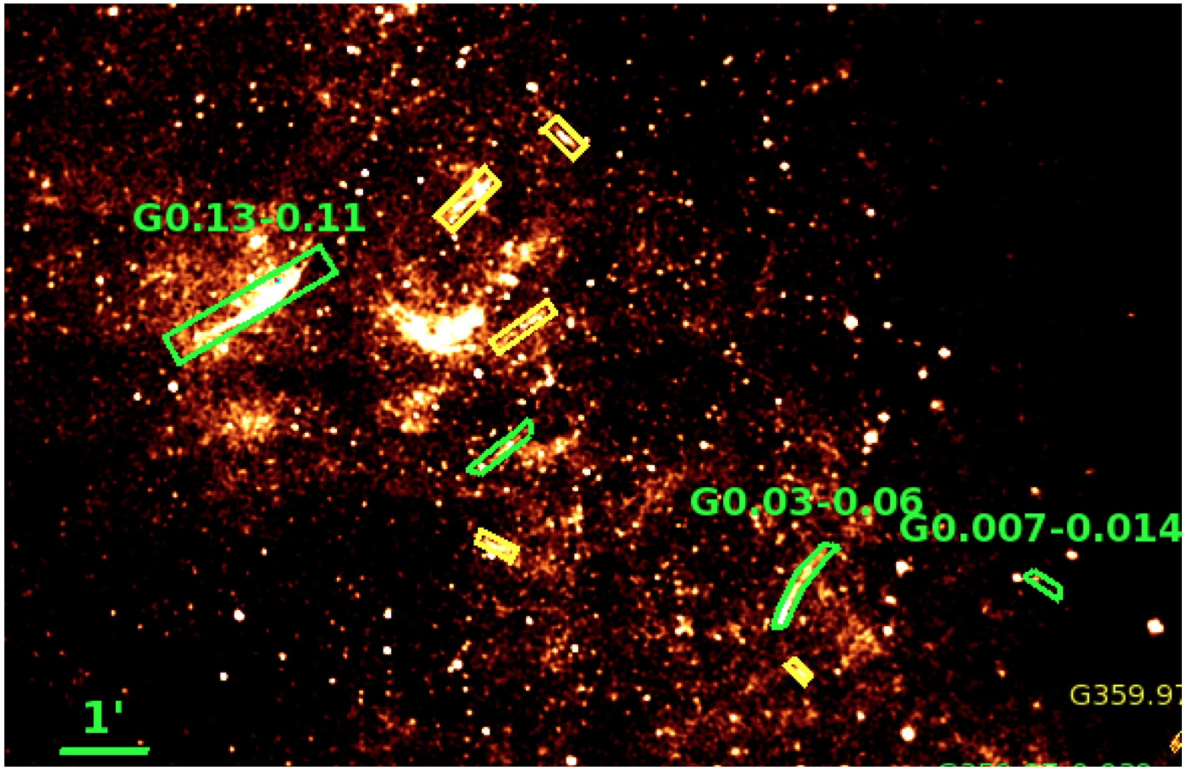



Belanger+ 06 (20-40 keV)
12' angular resolution (FWHM)

Mori+ 15 (10-79 keV)

# X-ray filaments as a tracer of TeV-PeV electrons in the GC

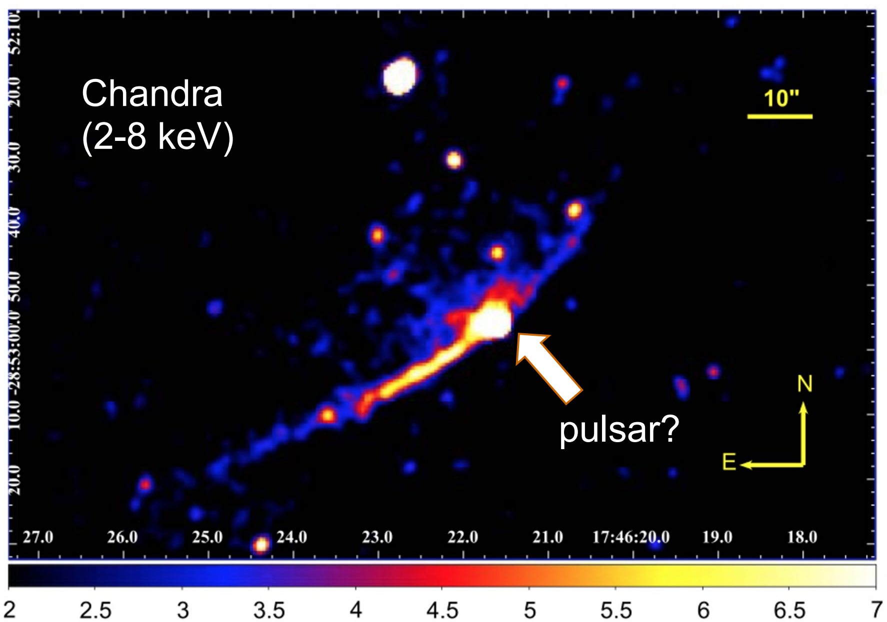
- ~25 X-ray filaments (Chandra) vs ~100 radio filaments (MeerKAT)
- A few of them are likely PWNe with point sources (= pulsars)
- B-field + TeV-PeV electrons => synchrotron hard X-rays
- NuSTAR detected 4 X-ray filaments above 10 keV

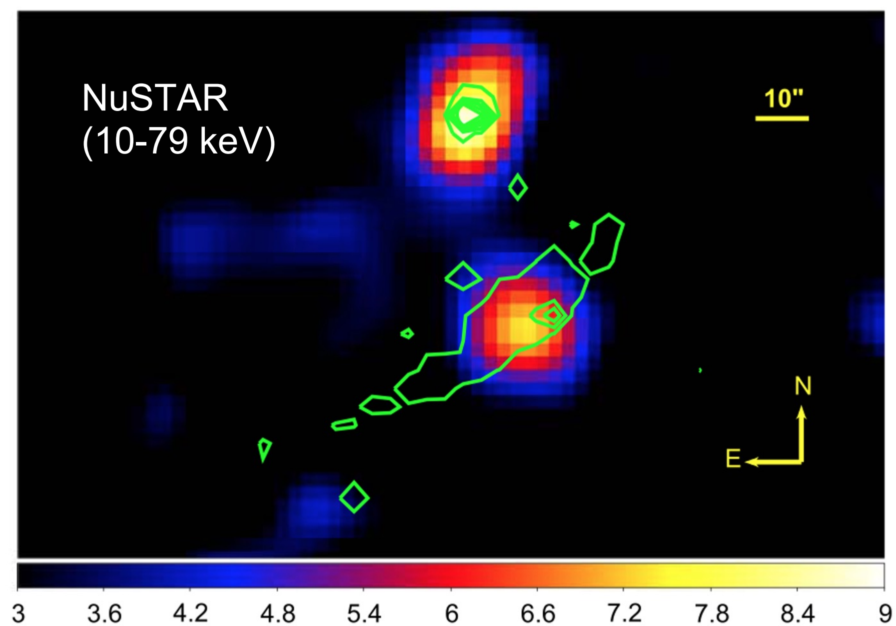



Chandra image of X-ray filaments (provided by Shuo Zhang)

# *G0.13-0.11: PWN detected in TeV band*

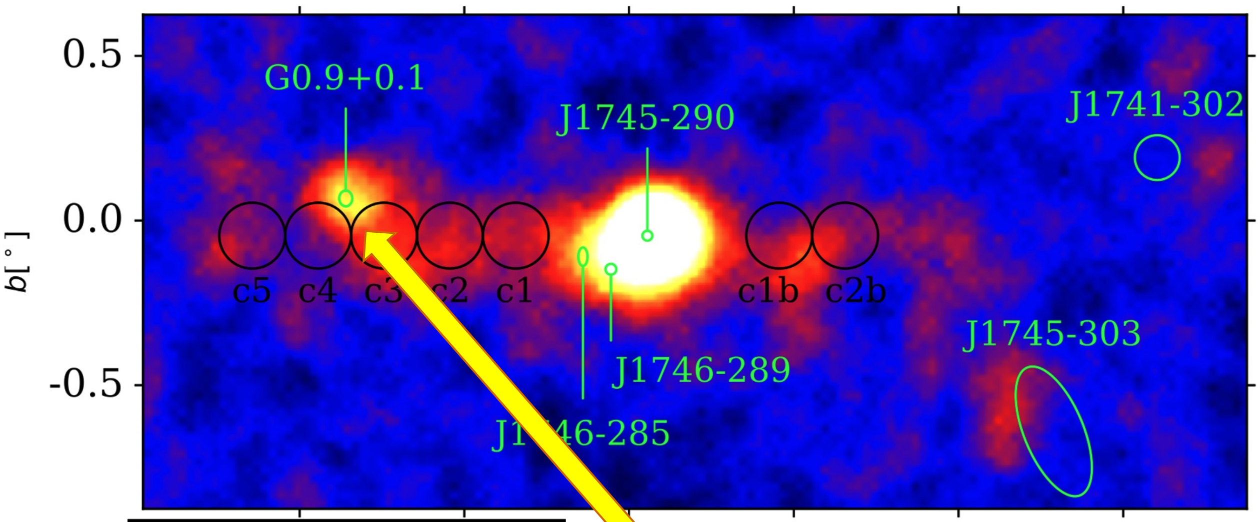
- Chandra revealed point source + filament morphology (Wang+ 02)
- NuSTAR detection above 10 keV (Zhang+ 20)
- Counterpart of TeV source HESS J1746-285 (HESS collab. 18)



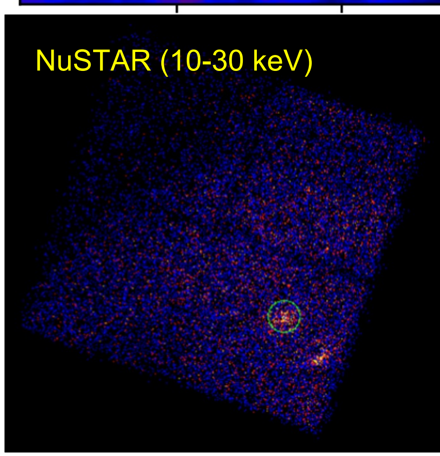



# PWN G0.9+0.1: the 2nd brightest TeV source in the GC

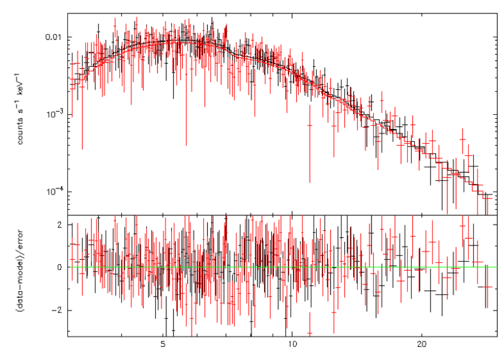
- One of the NuSTAR large program PWN targets
- NuSTAR detection up to 30 keV => power-law with $\Gamma$ ~ 2.3
- Working on PWN SED modeling




VERITAS TeV image
(Adams+ 21)

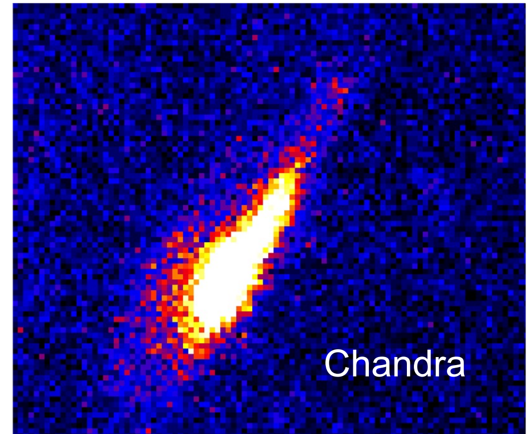


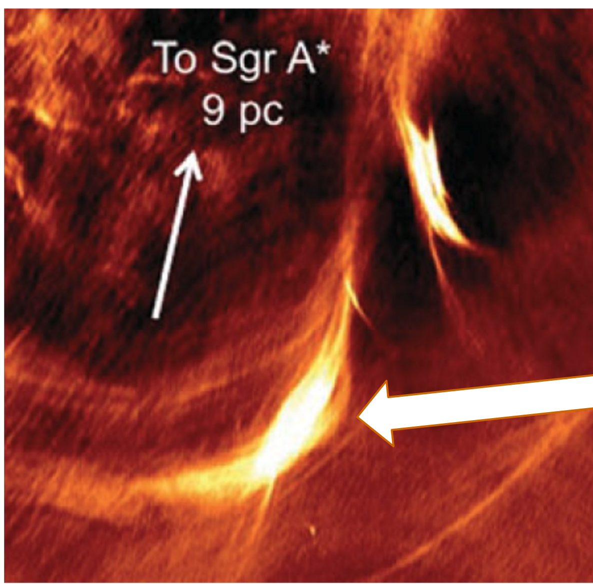

NuSTAR image and spectra of G0.9+0.1 (Nynka+ in prep)



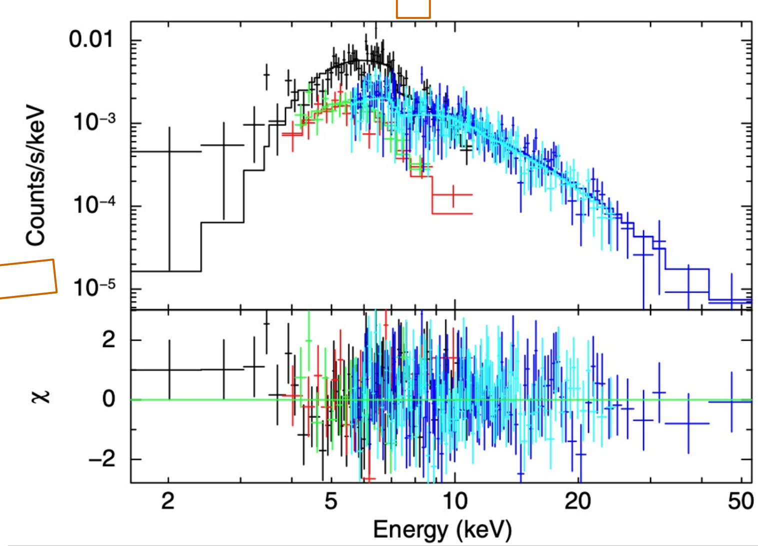
# *Sgr A-E knot: the brightest X-ray filament*

- Not a PWN. Radio image shows magnetic field bundles.
- NuSTAR detected non-thermal emission up to 50 keV ($\Gamma$ = 2.3)



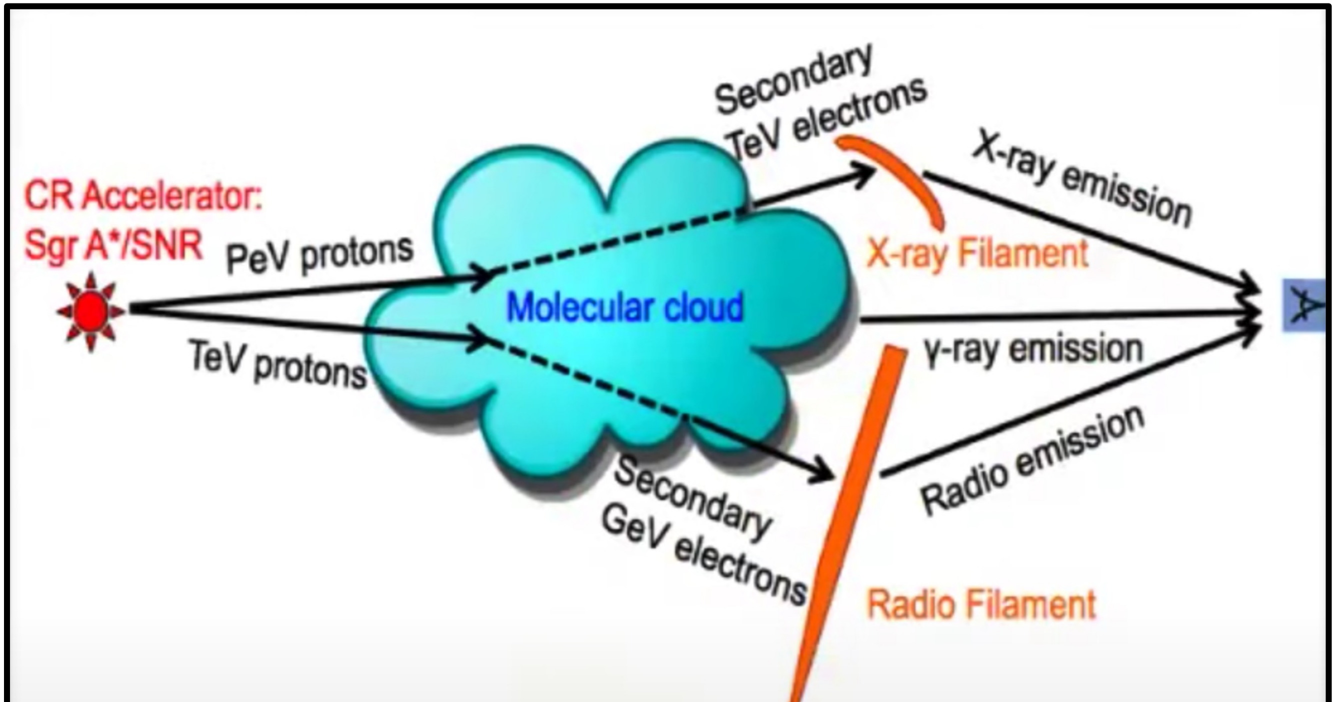

Radio image of Sgr A-E knot (Morris+ 14)




NuSTAR + Chandra spectra (Zhang+ 2014)

# X-ray filaments will allow us to probe CR distribution in the GC

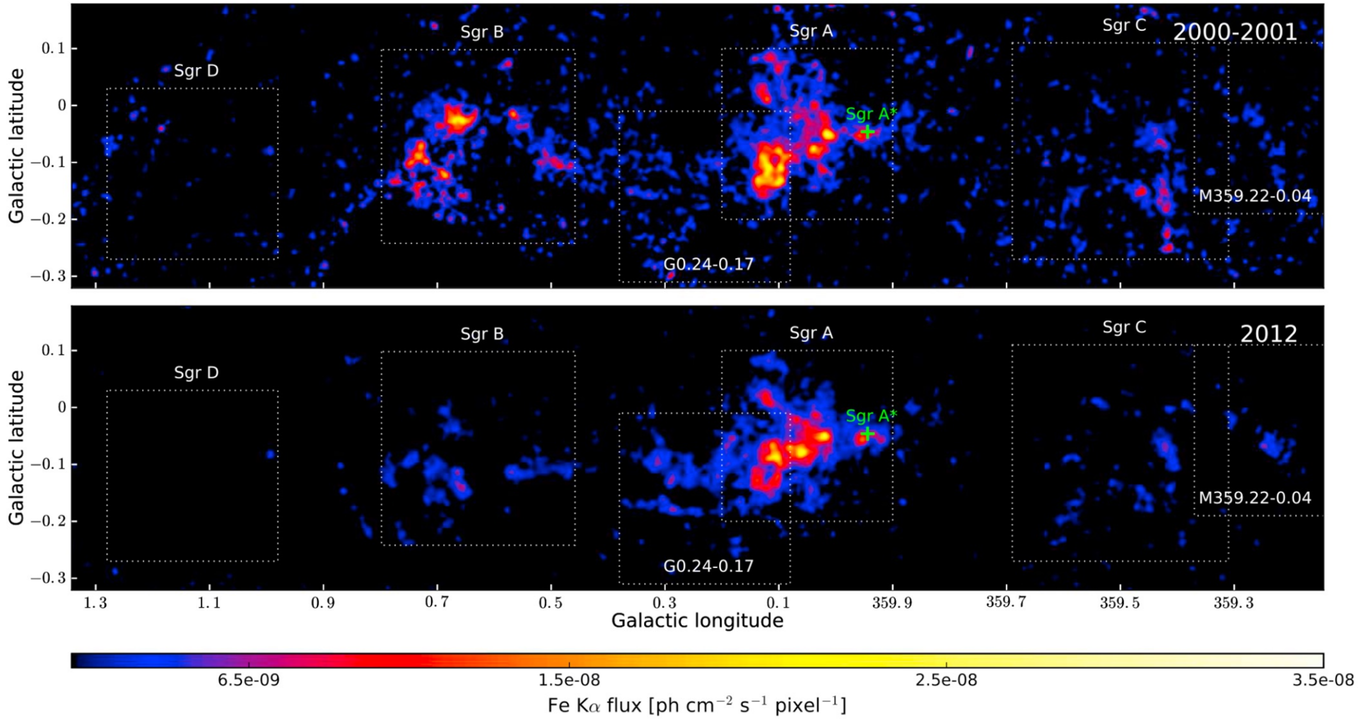
- Where do you get TeV electrons in situ when there is no particle accelerator (e.g., PWN)?
- TeV-PeV protons travel from accelerator sites to 20 km/s cloud next to Sgr A-E knot => producing secondary electrons




S. Zhang's AAS presentation

# GC molecular clouds emit X-rays in two different ways

- Some of the GC molecular clouds exhibit neutral Fe Ka line at 6.4 keV and non-thermal X-ray continuum emission
- Two X-ray components
  - Reflection of X-ray outbursts from Sgr A* (variable)
  - Cosmic-ray bombardment (steady) => relevant to TeV emission

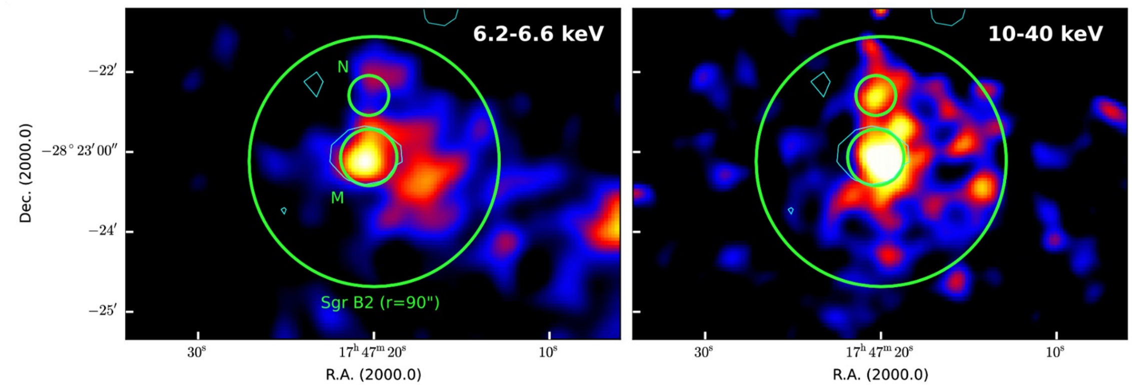



XMM 6.4 keV Fe Ka line maps (Terrier+ 18)

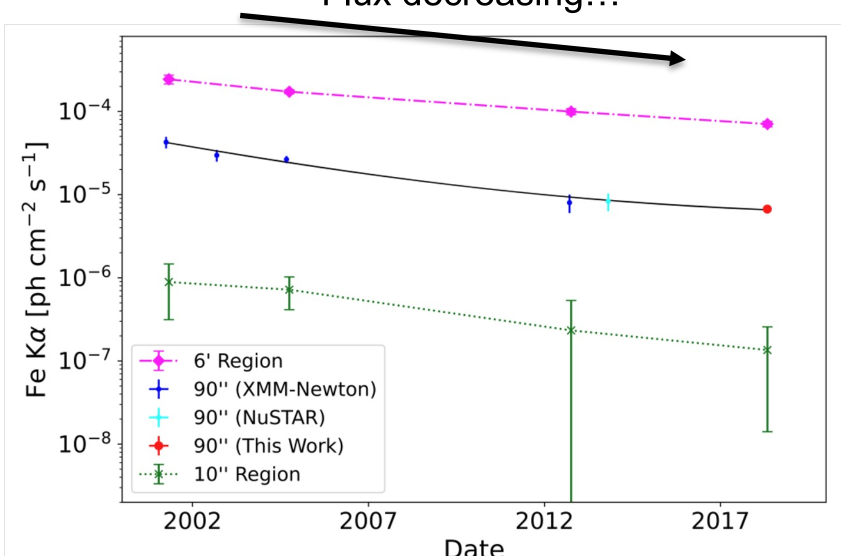
# *Sgr B2: the most massive GC cloud*

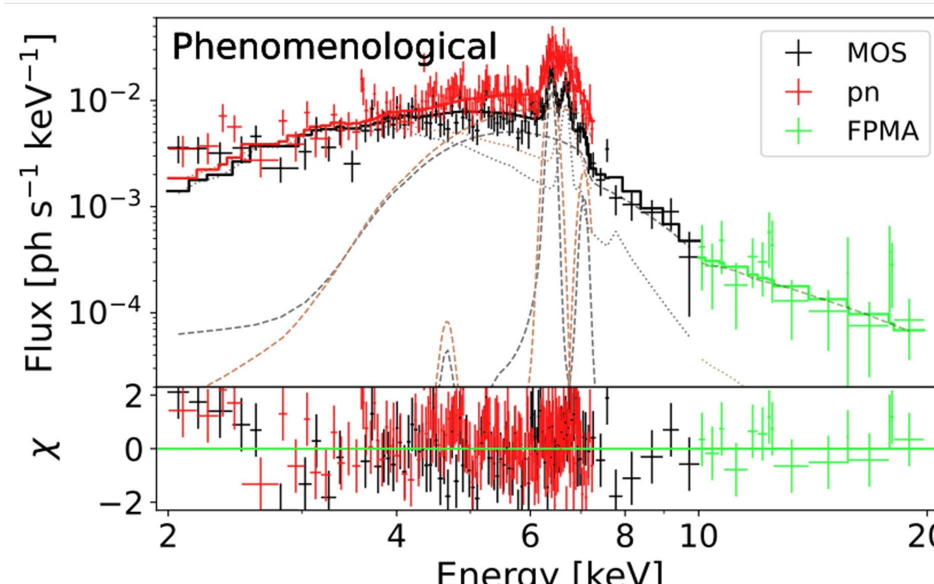
- Fe Ka line and X-ray continuum decreased over ~20 yr (Kuznetsova+ 22, Rogers+ 22)
- Finally hit a floor of the CR-induced X-ray emission? Time to compare with TeV data?

NuSTAR images (Zhang+ 15)



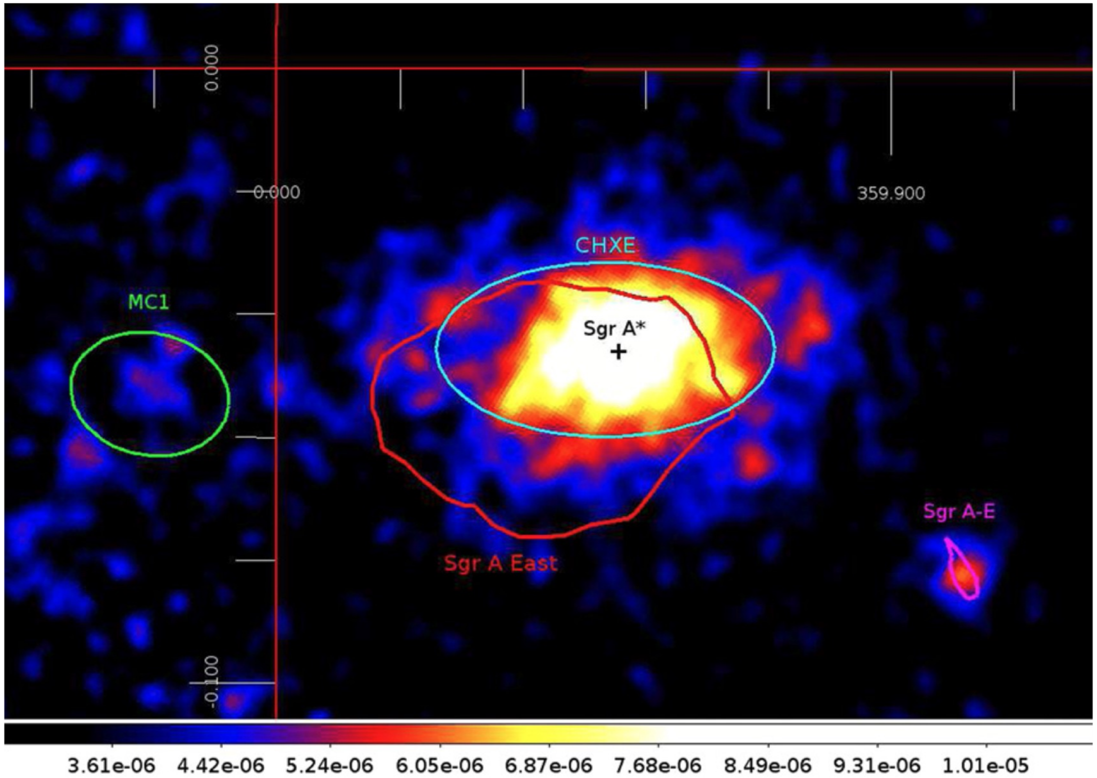

Flux decreasing…



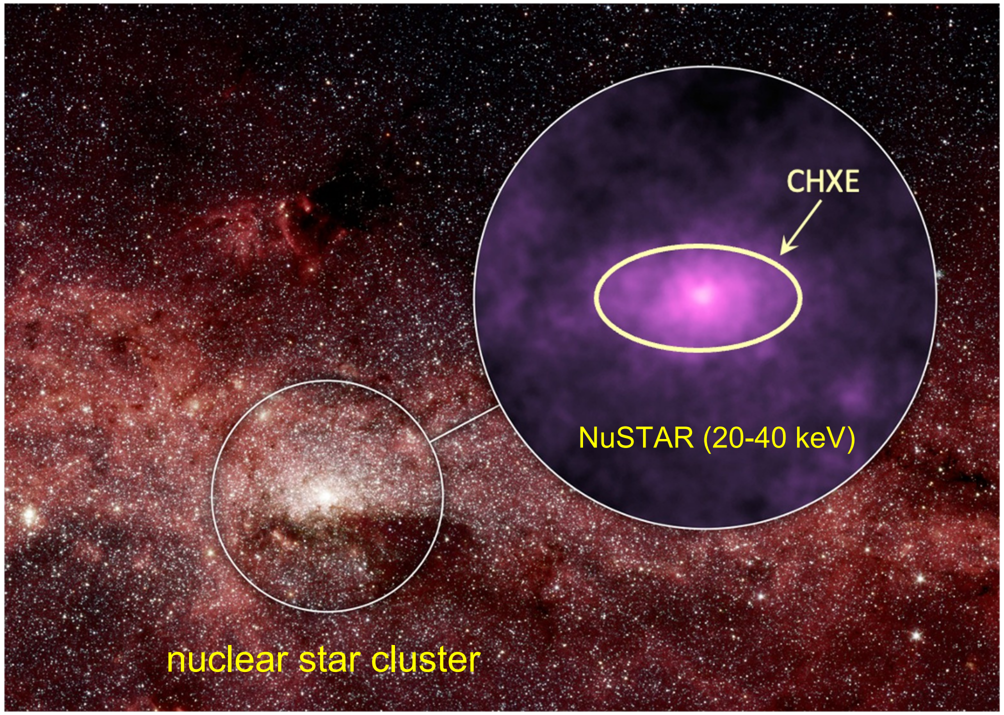
# NuSTAR 20-40 keV image: the central 10 parsec

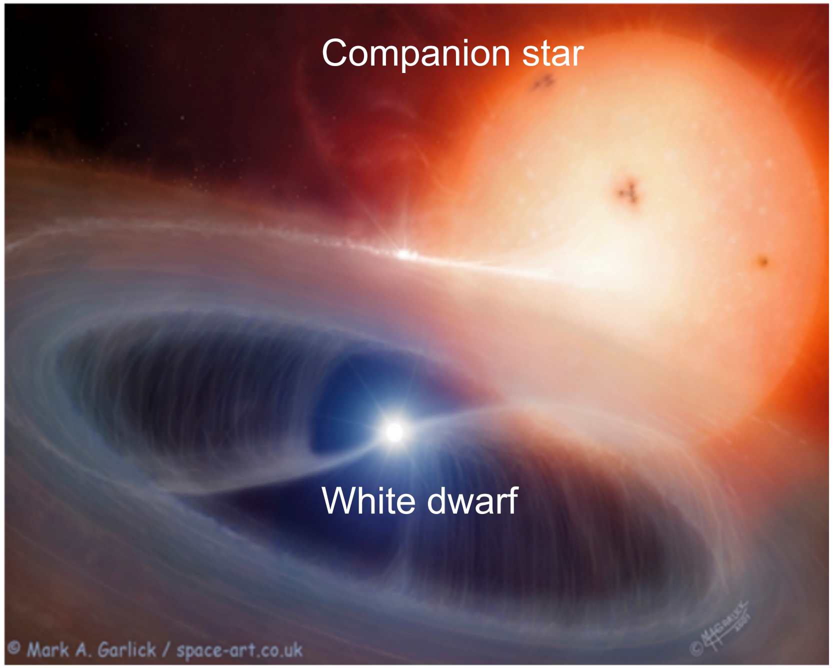
- Central hard X-ray emission (CHXE; Perez+ 15)
- Sgr A-E: X-ray filament
- MC1: molecular cloud
- SNR Sgr A East emits thermal X-rays (kT < 5 keV)



# *What is the central hard X-ray emission (a.k.a CHXE)?*

- The shape and size are consistent with the nuclear star cluster
- XMM + NuSTAR spectral analysis => thermal emission (kT ~ 35 keV)
- Hundreds of Chandra X-ray point sources in the region (Zhu+ 18)
- Unresolved population of magnetic CVs with mean $M_{WD}$~ 0.9 Ms (Hailey+ 16) => not relevant to GC TeV emission



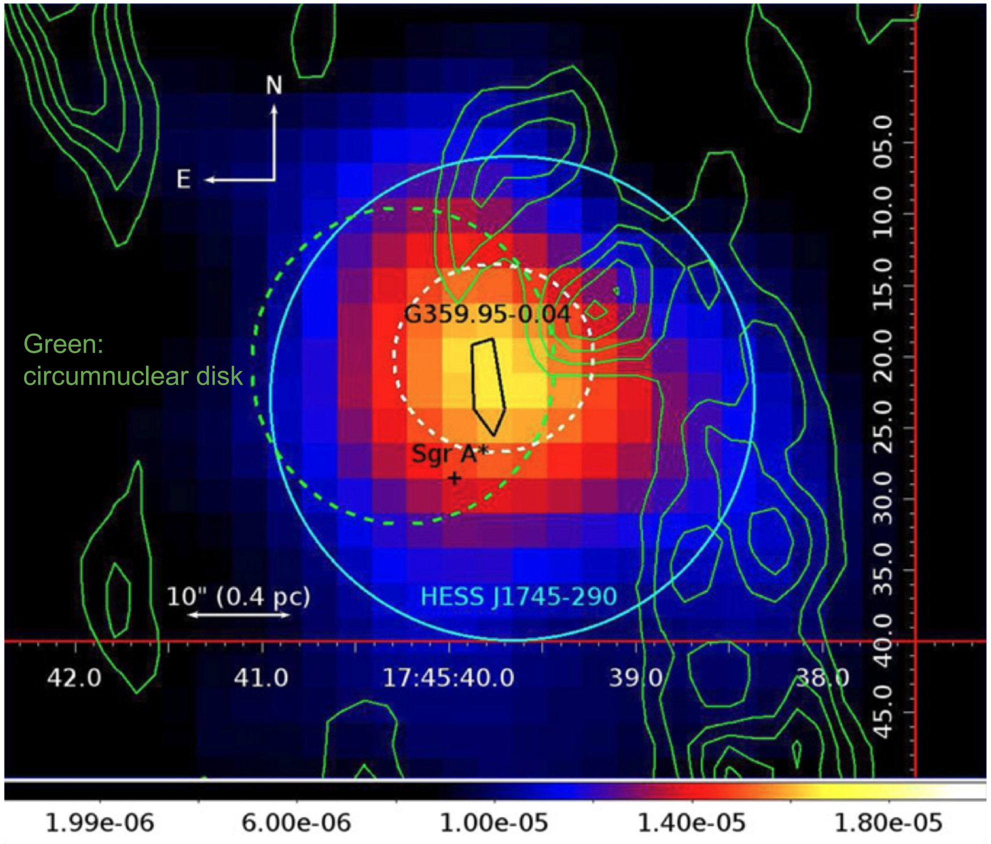

Background: Spitzer image. NuSTAR data shown in inset. Credit: JPL

Spitzer IR image with NuSTAR image in inset. Credit: JPL

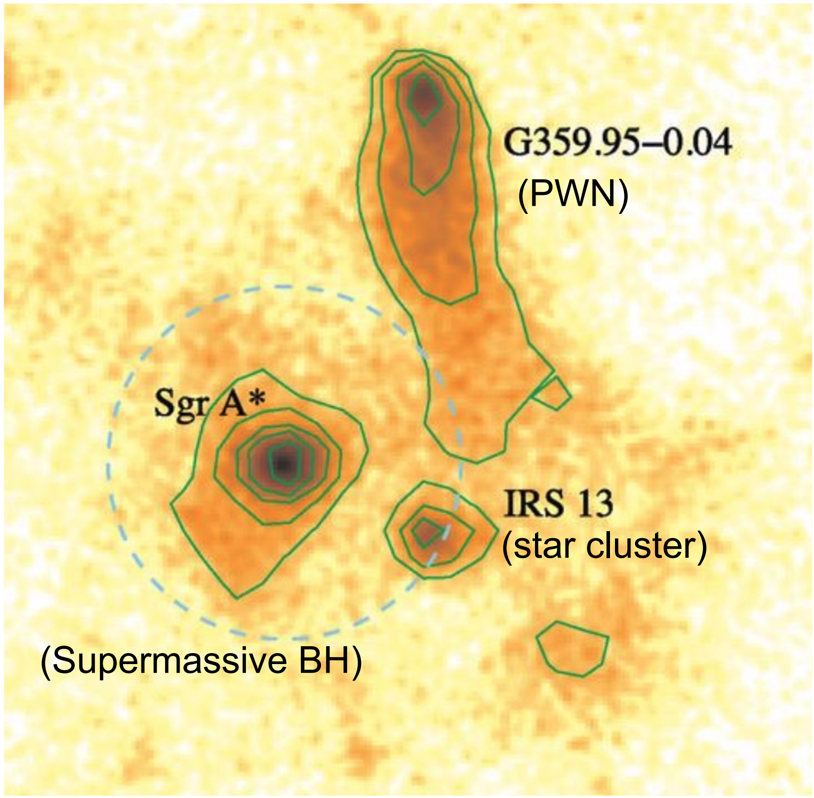
# *NuSTAR 20-40 keV image: the central few parsec*

- 20-40 keV emission is centered around PWN G359.95-0.04

NuSTAR 20-40 keV (Mori+ 15)

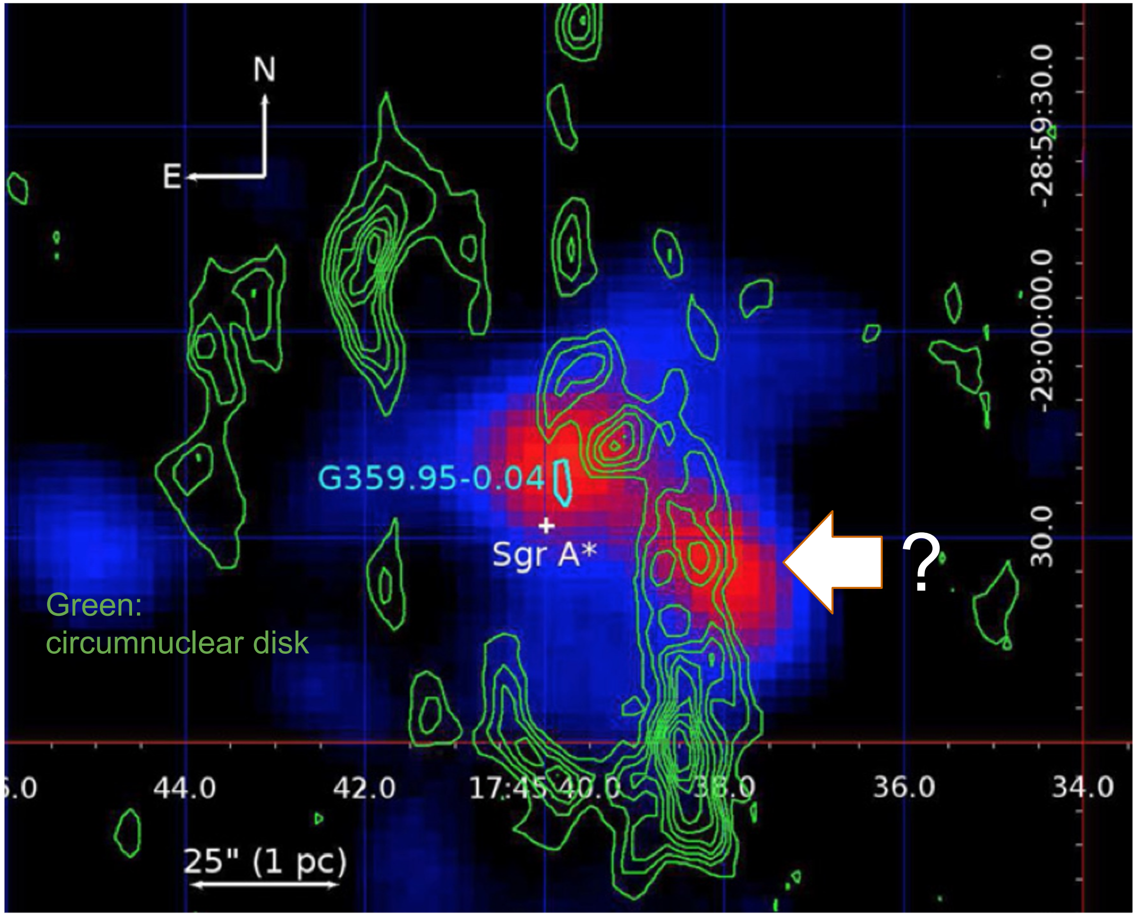



Chandra 2-8 keV (Wang+ 16)



# NuSTAR 40-79 keV image: the central few parsec

1) PWN G359.95-0.04
2) Unidentified hard X-ray source with no particular counterparts



# *PWN G359.95-0.04 = HESS J1745-290?*

- G359.95-0.04 is the prominent hard X-ray source in the central pc.
- Sgr A* emit X-ray flares otherwise its quiescent X-ray emission is faint.
- Consistent PWN parameters (age ~ $10^4$ yr) with Hinton & Aharonian 07

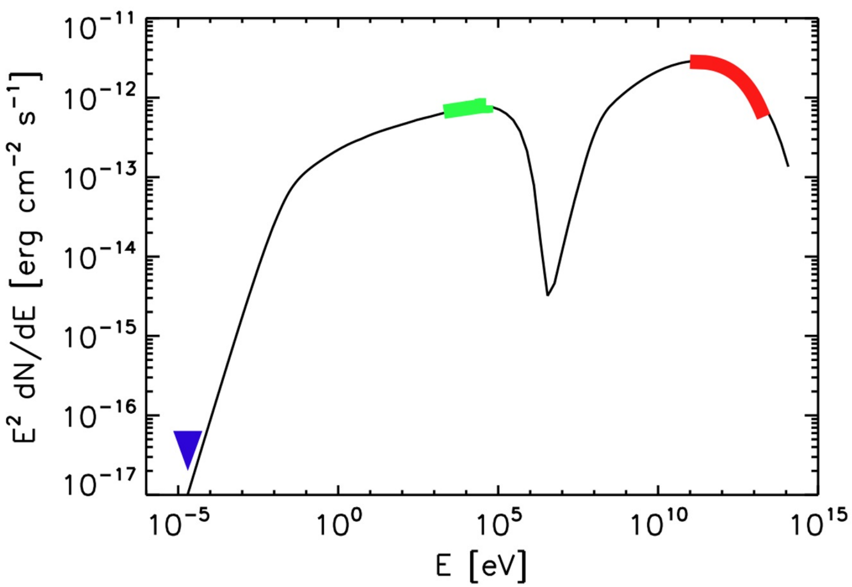



**Figure 12.** One-zone PWN model fit to the broad-band SED data including the 6 cm radio flux upper limit (blue arrow), G359.95–0.04 X-ray spectrum (green) and 0.1–10 TeV HESS spectrum of HESS J1745–290 (red).

Multi-wavelength SED fit with one-zone PWN evolution model (Mori+ 15)

Broken power-law model: p1 = 1.8, p2 = 2.0, Ebreak = 50 TeV, Emin = 0.5 TeV, Emax = 200 TeV

# *HEX-P: future X-ray probe mission in the 2030s*

# X-ray astrophysics landscape in the 2030s

- NASA's decadal survey => X-ray probe mission ($1B budget)
- Project timeline
  - Proposal submission for phase A study: October 2023
  - Selection for phase A study: early 2024
  - Final selection in 2025
  - Launch in early 2030s

0.1-80 keV — HEX-P (High Energy X-ray Probe)

STROBE-X — 0.2-30 keV (non-focusing)

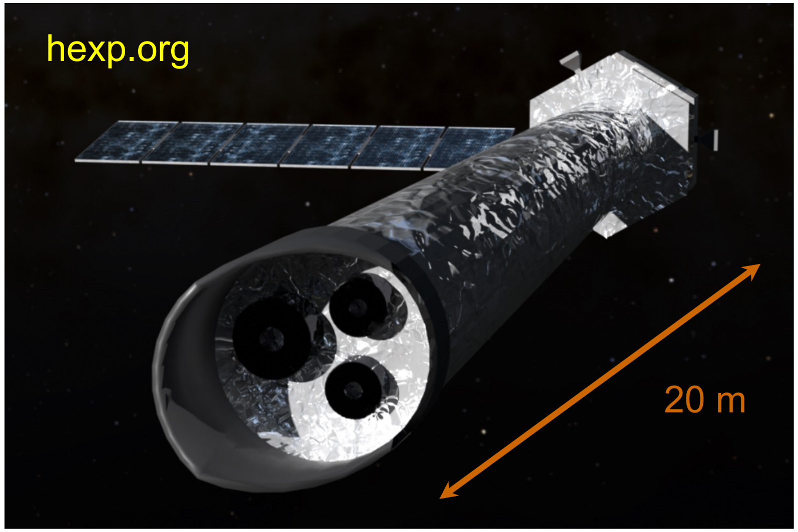
0.2-2 keV — LEM

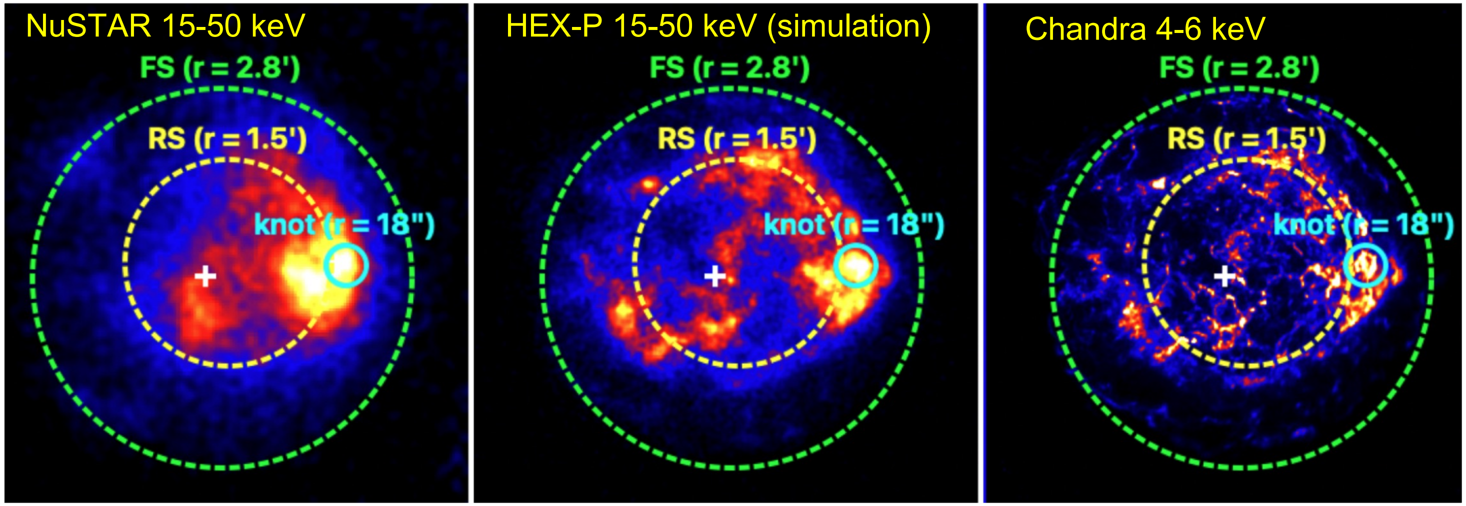
< 1.5 keV — ARCUS

0.2-10 keV — AXIS (Advanced X-ray Imaging Satellite)

# *HEX-P: next-generation all-purpose X-ray telescope*

- Super XMM + NuSTAR telescope
- Energy range: 0.1 - 80 keV
- One LET (0.1-20 keV): 4” angular resolution (HPD)
- Two HET telescopes (2-80 keV): 15-25” angular resolution (HPD)
- 25 HEX-P posters at the HEAD meeting.
- **HEX-P will be uniquely suited for studying non-thermal X-ray sources and extreme particle accelerators.**




Cas A

# Summary

- Many thanks to collaborators from NuSTAR, VERITAS, HAWC etc.
- NuSTAR detected non-thermal emission from numerous X-ray sources, including Galactic TeV sources
- NuSTAR measured photon indices varying between…
  - different source types: $\Gamma$ ~ 0 (Jupiter, magnetars), $\Gamma$ ~ 1.5 (pulsars), $\Gamma$ ~ 2-2.5 (PWNe, filaments, and many), $\Gamma$ ~ 3 (Cas A)
  - different regions: synchrotron burnoff
  - different times: Cas A hard X-ray knots
- Multi-wavelength SED and morphology studies are very important.
- Multi-messenger astrophysics for extreme accelerators in the 2030s
  - Synergy with other telescopes: COSI, CTA, ICECUBE, LHAASO, HAWC…
  - Particle acceleration, propagation + cooling => Morphology (x, y), time evolution (t) and photon energy (E).
  - Multi-zone, time-dependent SED modeling etc.
- Comments, suggestions, collaboration? Email: kaya@astro.columbia.edu