

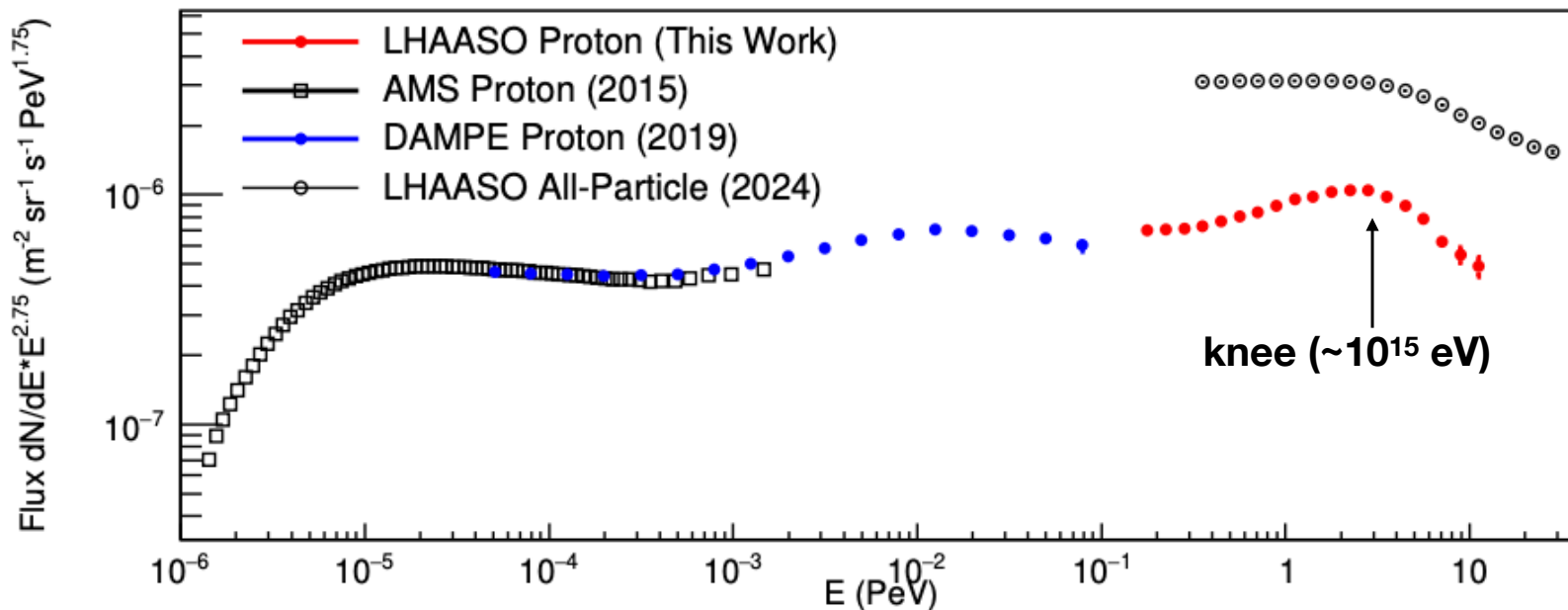
Recent X-ray Studies of Microquasars

PeVatron workshop @Nevis Labs, Columbia University, NY
8–10 Oct 2025

Naomi Tsuji (ICRR/University of Tokyo)

Cosmic ray energy spectrum

(LHAASO Collab. 2025; Zhen's talk)



- New features in the Galactic cosmic-ray energy spectrum
- Microquasars and stellar clusters emerged as new PeVatron candidates

Microquasars at VHE-UHE gamma rays

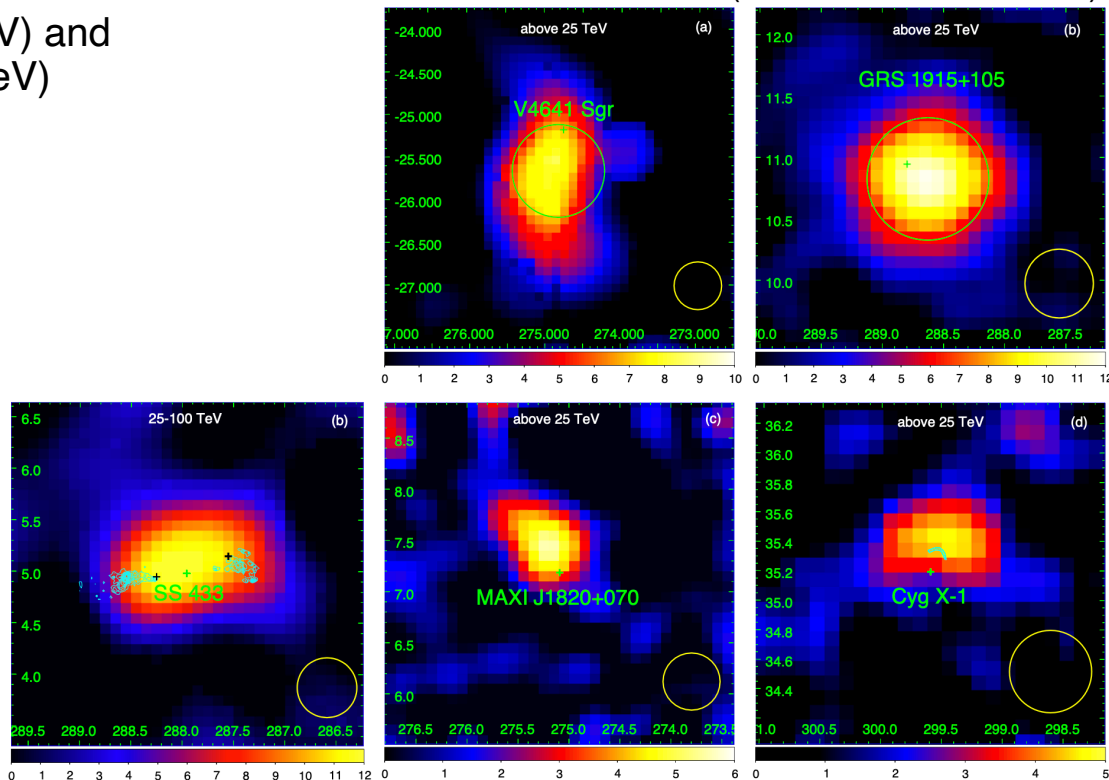
(LHAASO Collab. 2024)

- Very-high-energy (VHE; >0.1 TeV) and Ultra-high-energy (UHE; >100 TeV) gamma rays from microquasars:

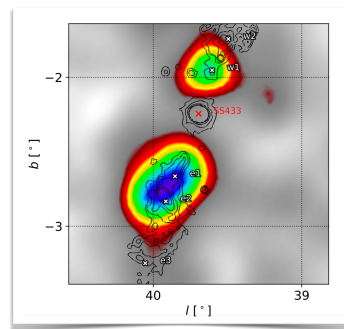
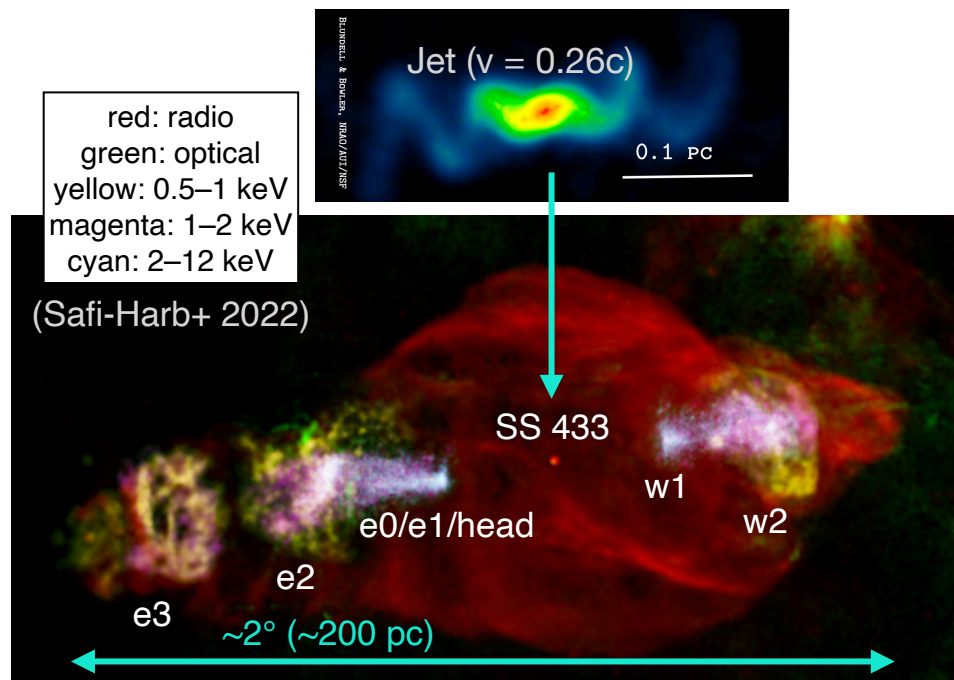
- SS 433
- V4641 Sgr
- GRS 1915+105
- MAXI J1820+070
- Cyg X-1

→ Particle accelerated up to $> \text{PeV}$

→ Microquasars (substantially) contribute to PeV cosmic rays?

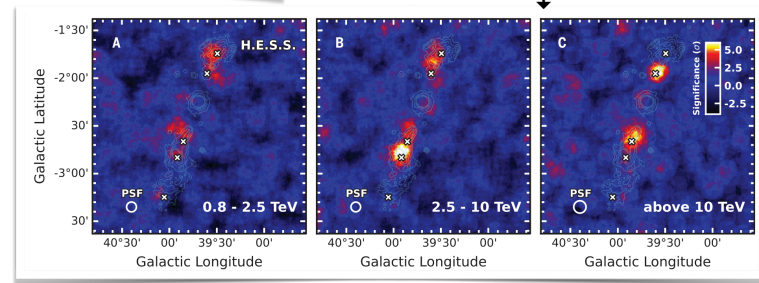


Microquasar SS 433/W50

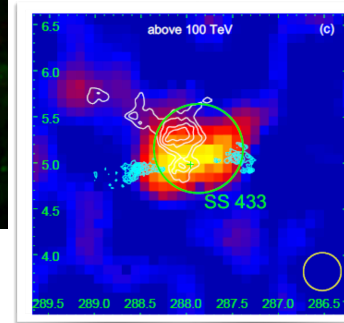


← Discovery of TeV gamma rays (HAWC Collab. 2018)

Identified acceleration sites (HESS Collab. 2024)

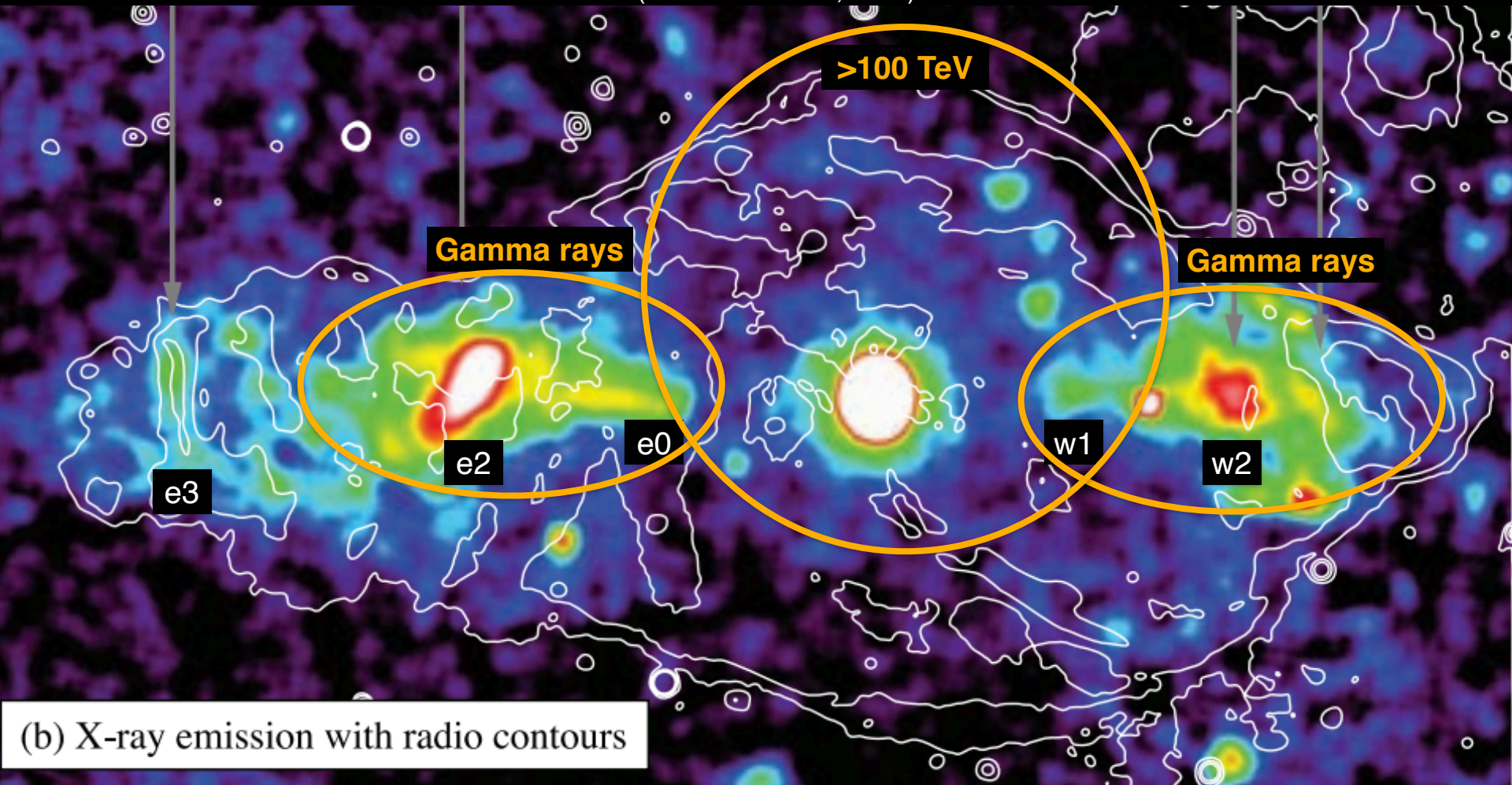


← Discovery of >100 TeV gamma rays (LHAASO Collab. 2025)



Observation by VERITAS (Tobias's talk at ICRC2025)

Initial survey by ROSAT, ASCA, and RTXE in 1990s
(Safi-Harb+ 1997; 1999)



(b) X-ray emission with radio contours

eROSITA in 0.5-6 keV

XMM in 2004

Chandra in 2003

e3

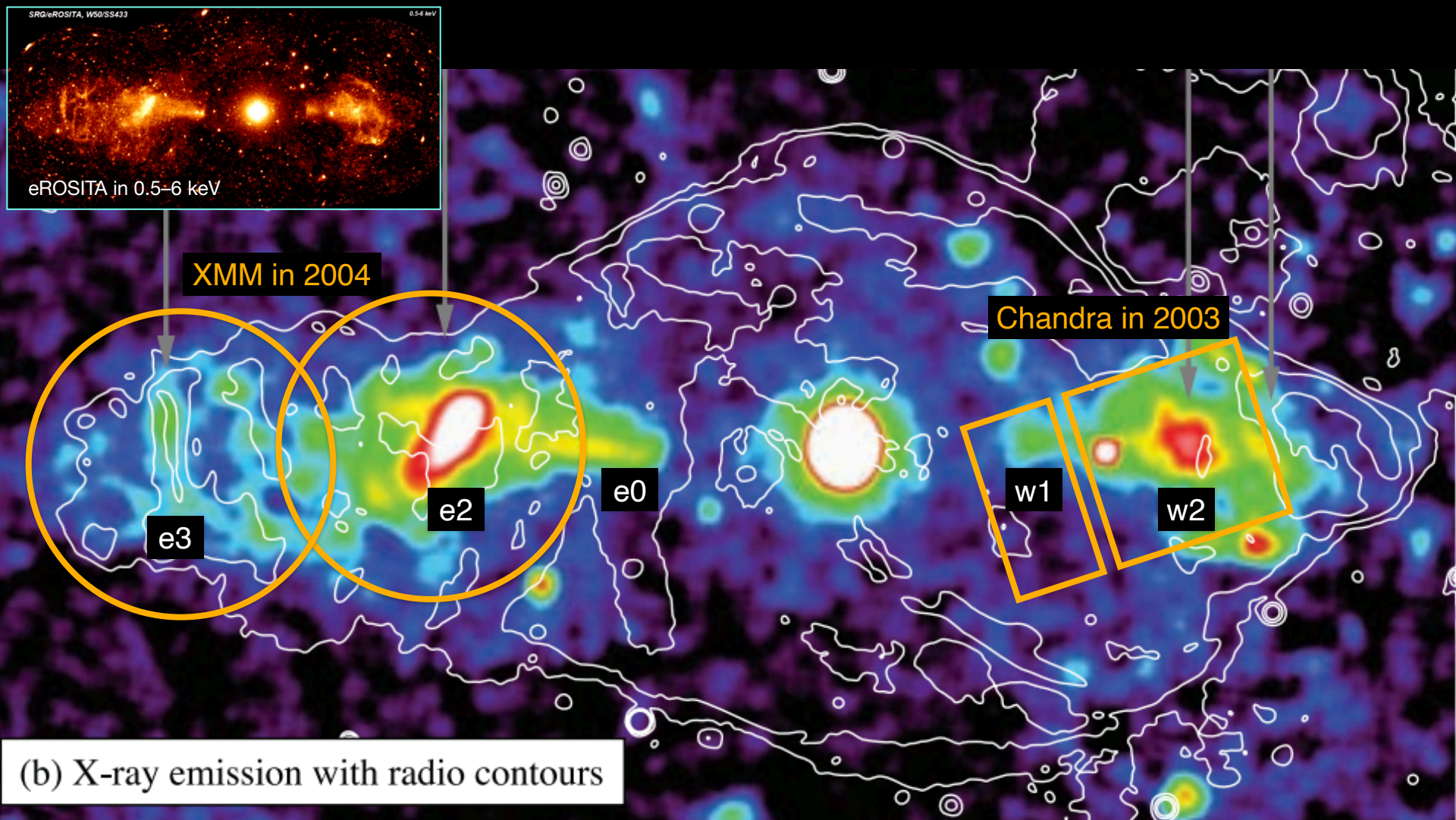
e2

e0

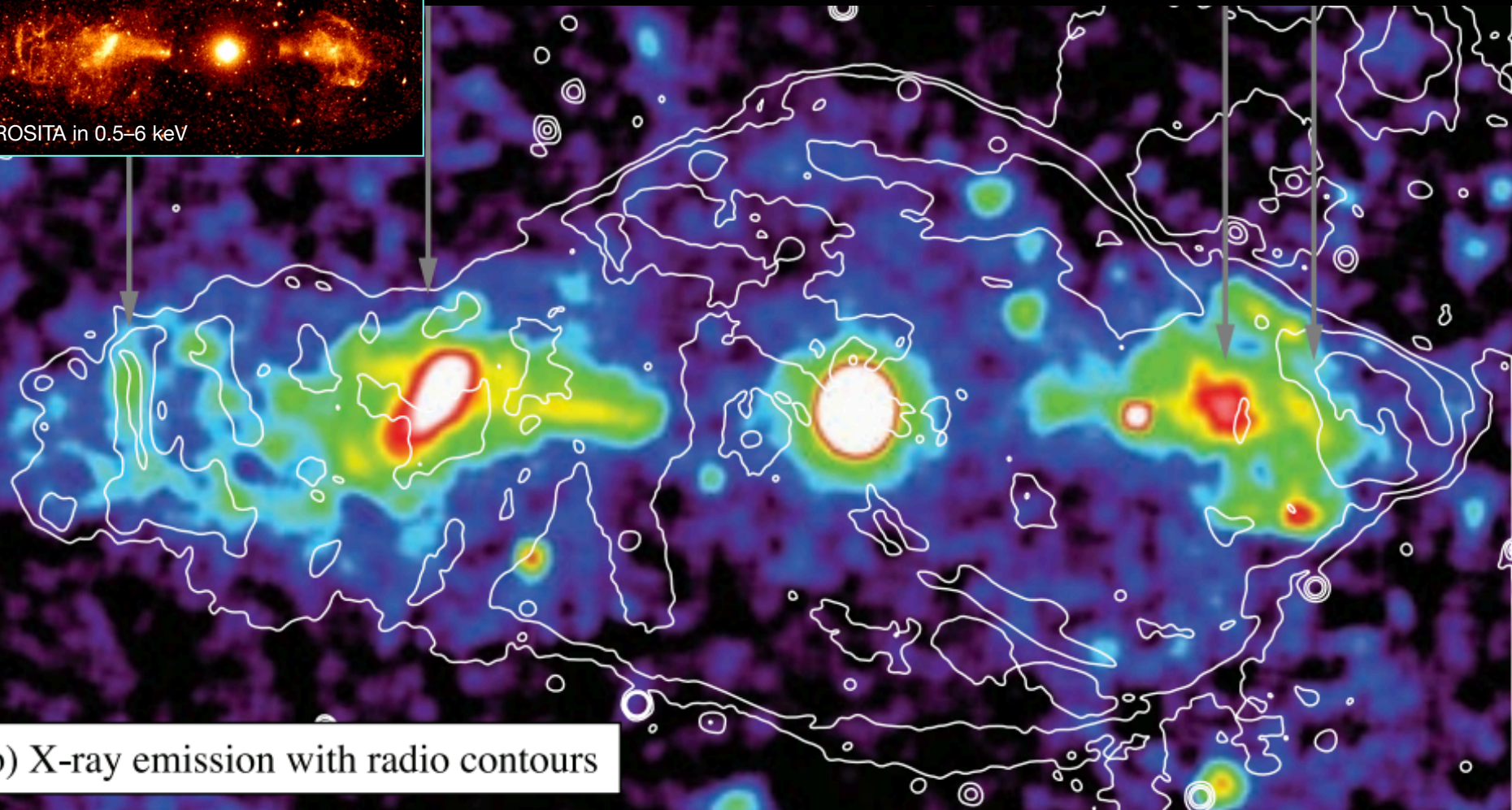
w1

w2

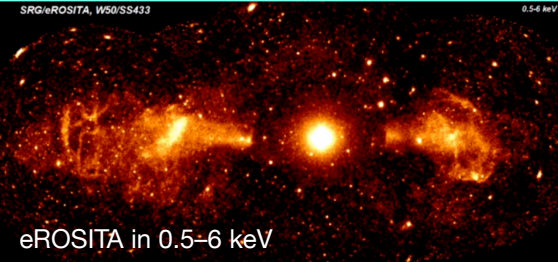
(b) X-ray emission with radio contours



eROSITA in 0.5-6 keV



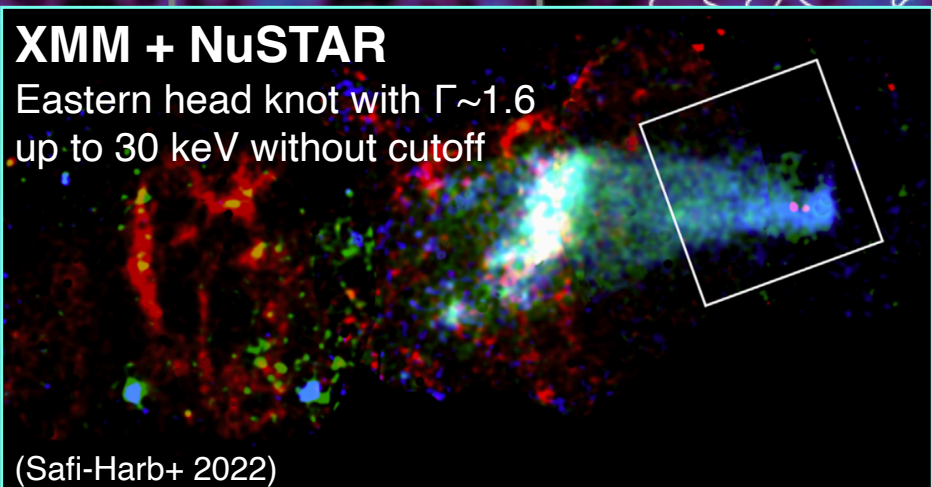
(b) X-ray emission with radio contours



eROSITA in 0.5-6 keV

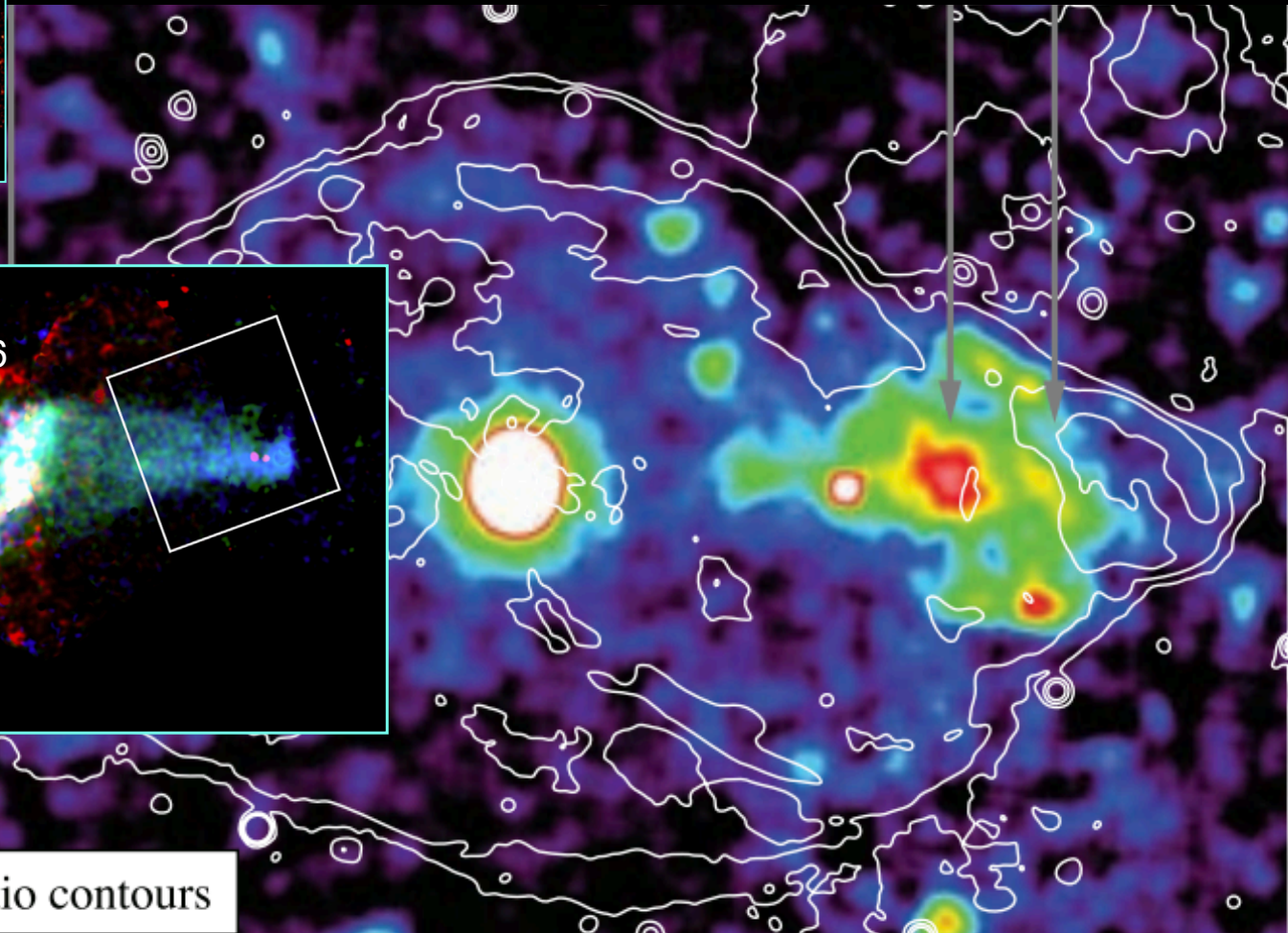
XMM + NuSTAR

Eastern head knot with $\Gamma \sim 1.6$
up to 30 keV without cutoff



(Safi-Harb+ 2022)

(b) X-ray emission with radio contours



eROSITA in 0.5–6 keV

XMM + NuSTAR

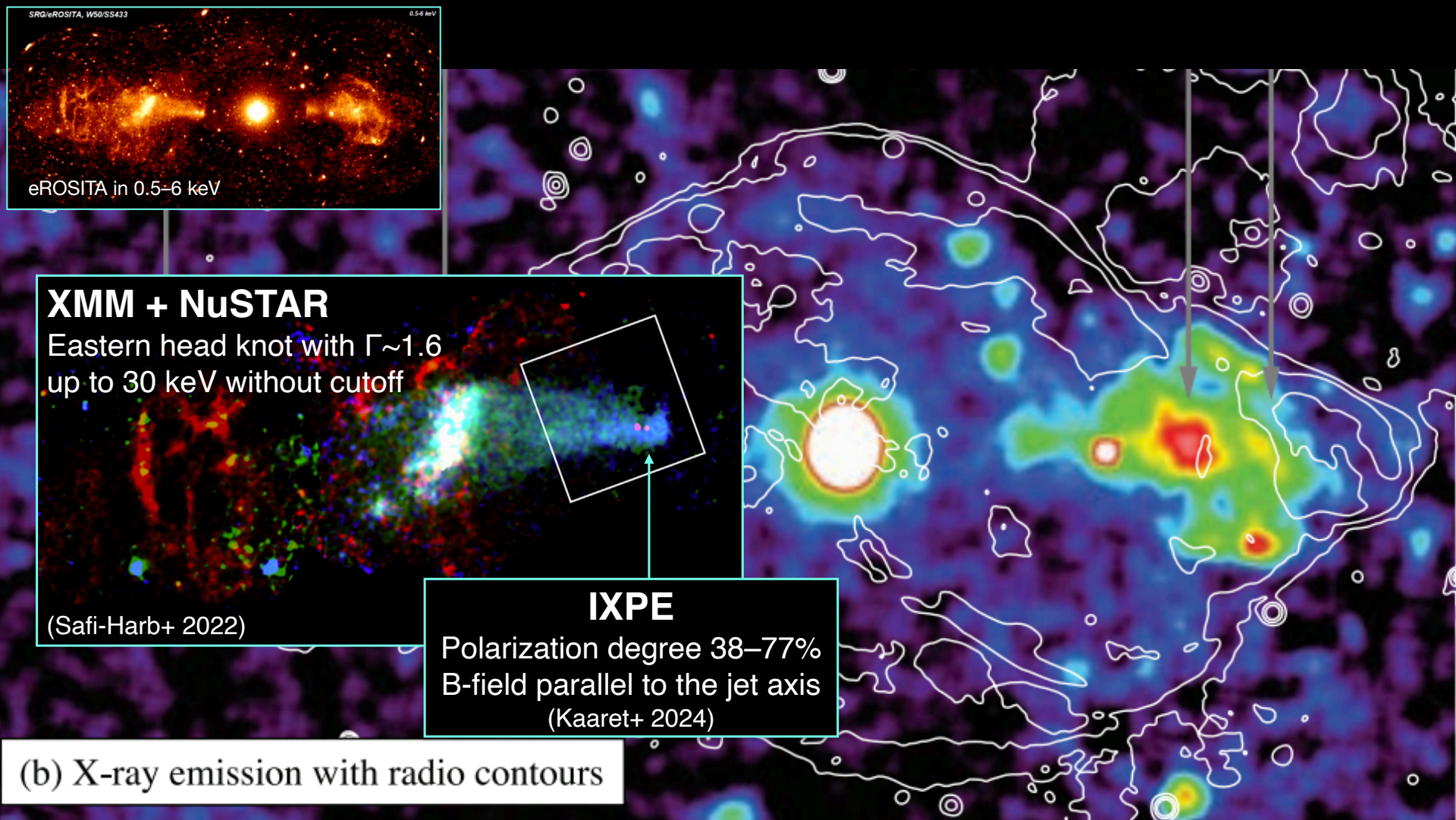
Eastern head knot with $\Gamma \sim 1.6$
up to 30 keV without cutoff

(Safi-Harb+ 2022)

IXPE

Polarization degree 38–77%
B-field parallel to the jet axis
(Kaaret+ 2024)

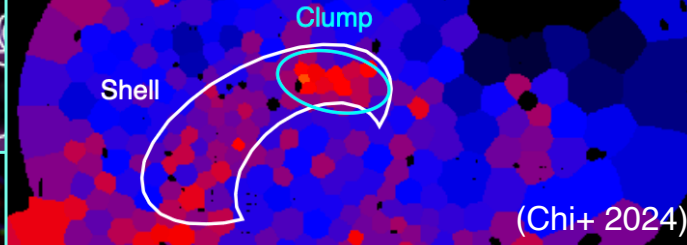
(b) X-ray emission with radio contours



eROSITA in 0.5–6 keV

XMM

Thermal ($kT \sim 1$ keV) emission (a)
SNR or jet/wind?

**XMM + NuSTAR**

Eastern head knot with $\Gamma \sim 1.6$
up to 30 keV without cutoff

(Safi-Harb+ 2022)

IXPE

Polarization degree 38–77%
B-field parallel to the jet axis
(Kaaret+ 2024)

(b) X-ray emission with radio contours

eROSITA in 0.5–6 keV

XMM + NuSTAR

Eastern head knot with $\Gamma \sim 1.6$
up to 30 keV without cutoff

(Safi-Harb+ 2022)

XMM

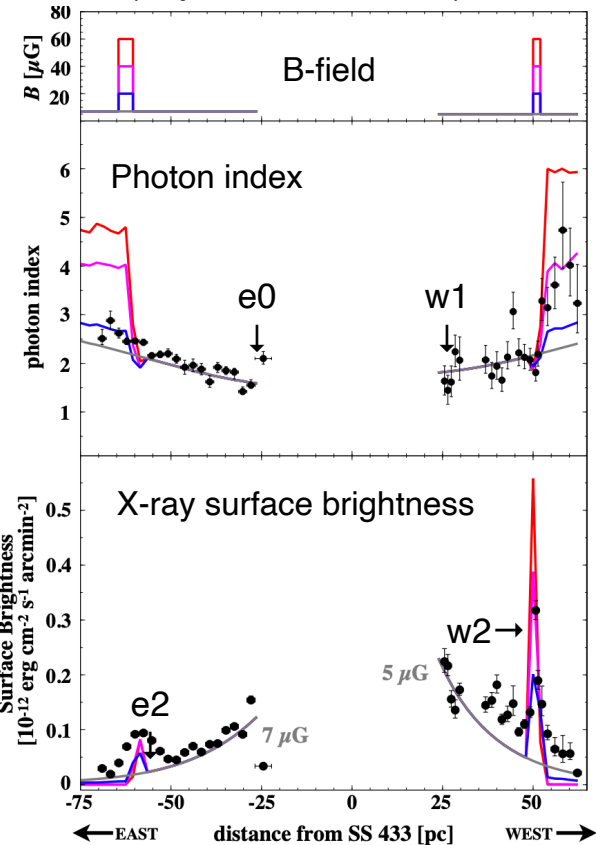
Thermal ($kT \sim 1$ keV) emission
SNR or jet/wind?

Shell
Clump

IXPE

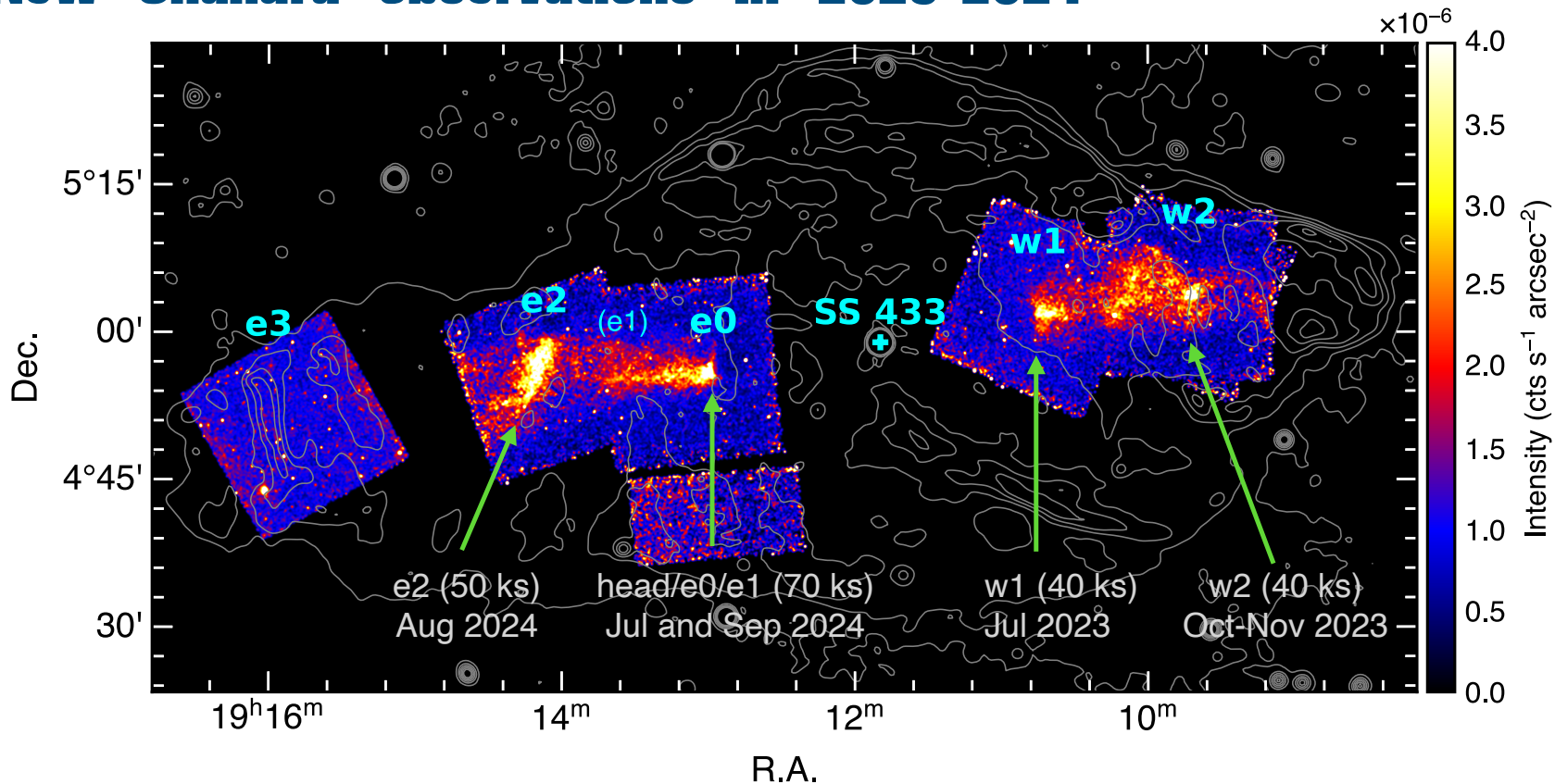
Polarization degree 38–77%
B-field parallel to the jet axis
(Kaaret+ 2024)

X-ray spectral profile along the lobes
(Kayama+ 2022; 2025)

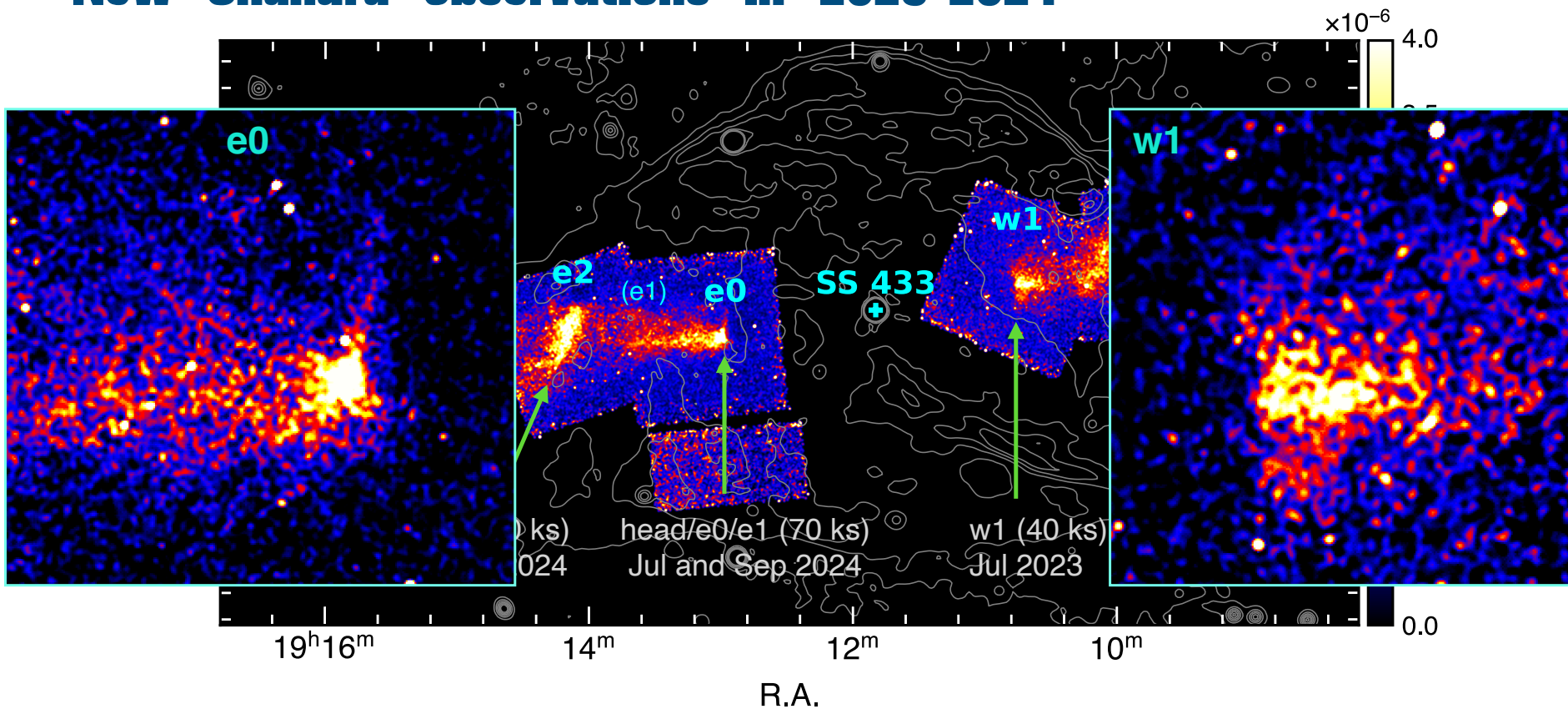


(b) X-ray emission with radio contours

0.5–7 keV
New Chandra observations in 2023-2024

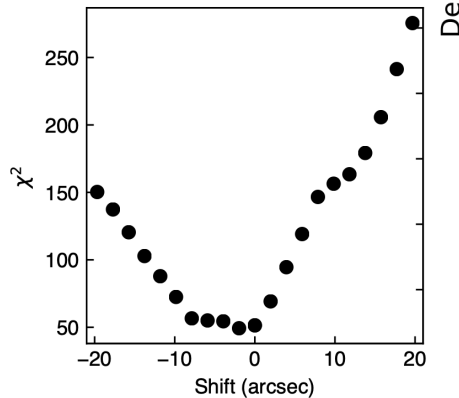
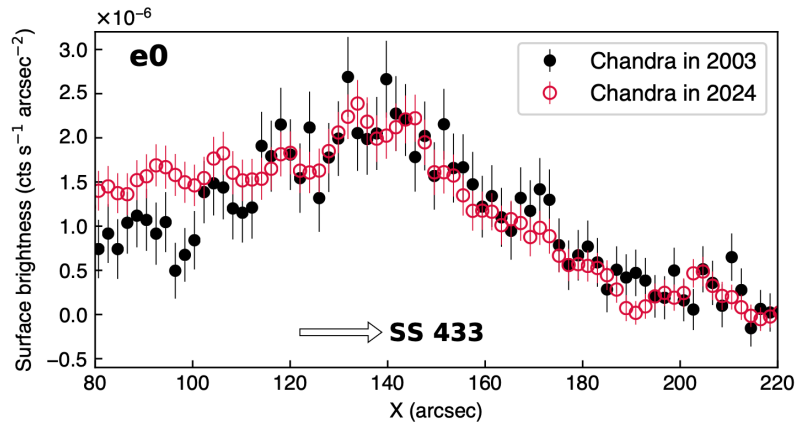


0.5–7 keV
New Chandra observations in 2023-2024

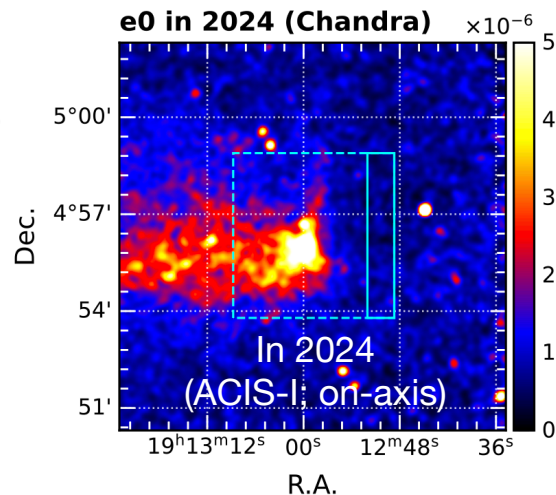
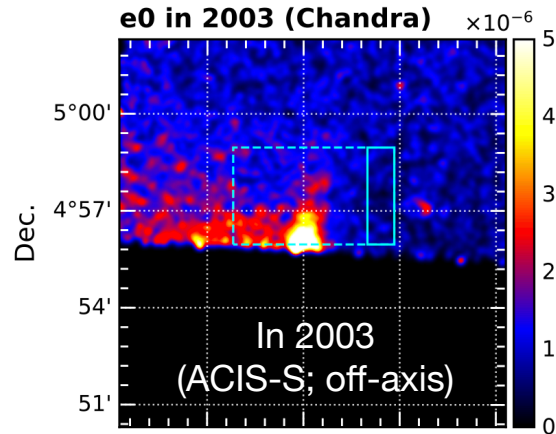


Proper motion measurement

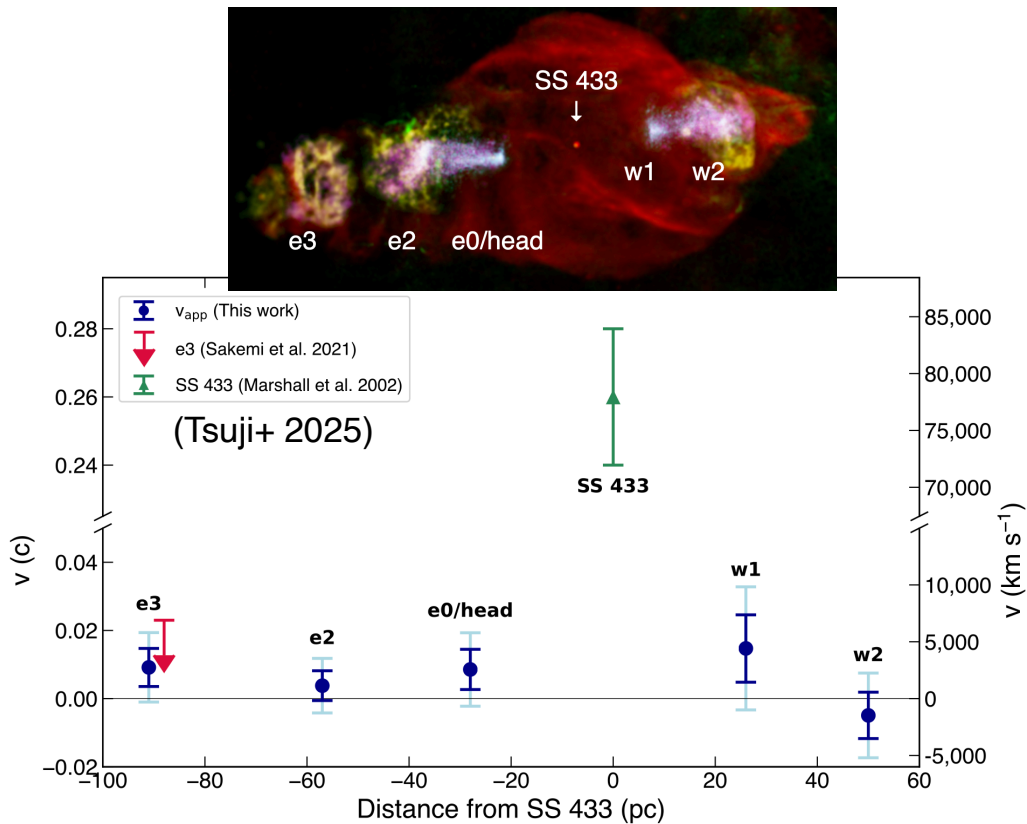
Eastern head region (e0/head)



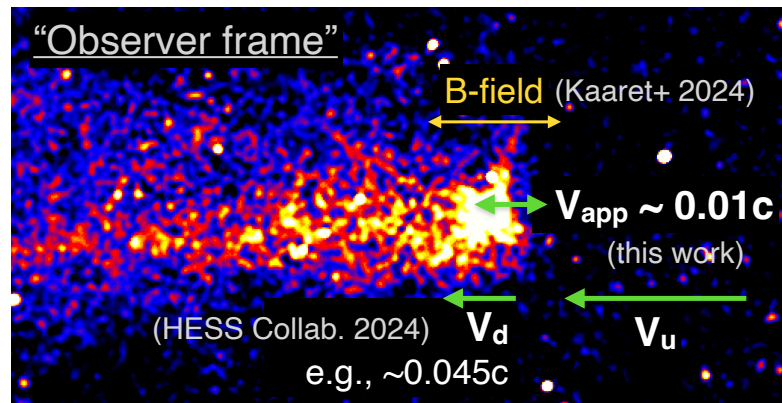
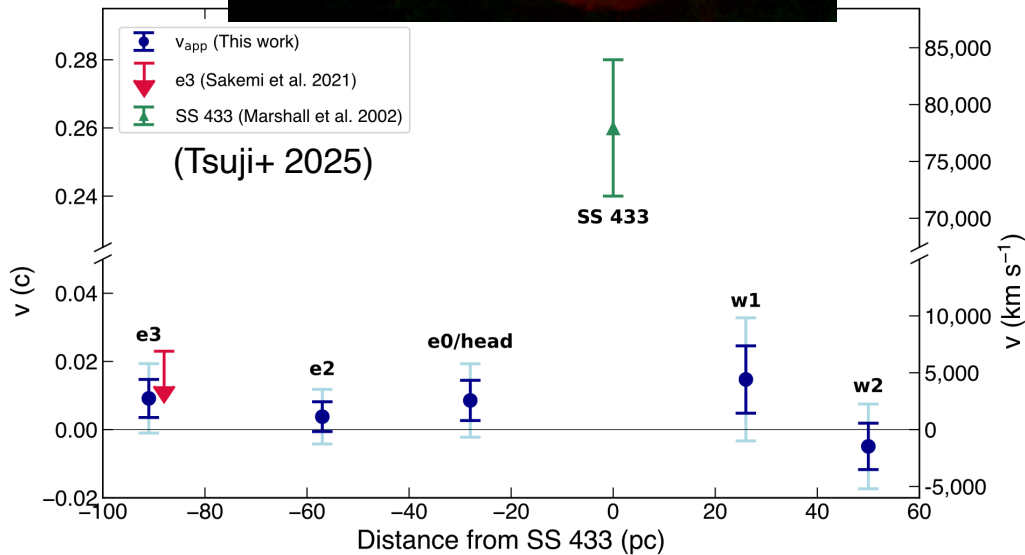
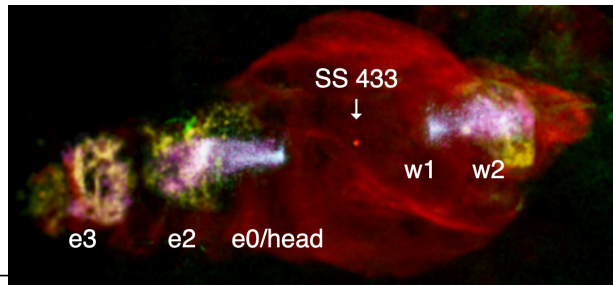
- Shift measured by χ^2 : 2.1 ± 1.4 arcsec (90% C.L.)
- Hint of motion, but not significant ($<3\sigma$)
- Proper motion ($d = 5.5$ kpc)
 - $V_{\text{app}} = (0.0086 \pm 0.0059)c$
 - $V_{\text{app}} = -0.002c$ to $0.019c$ in 3σ C.I.



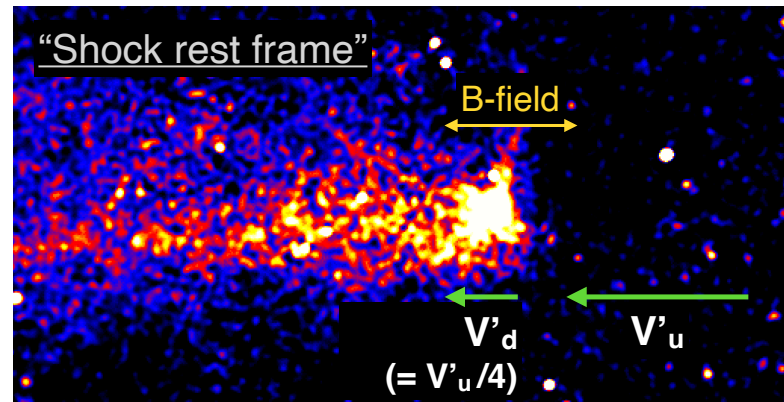
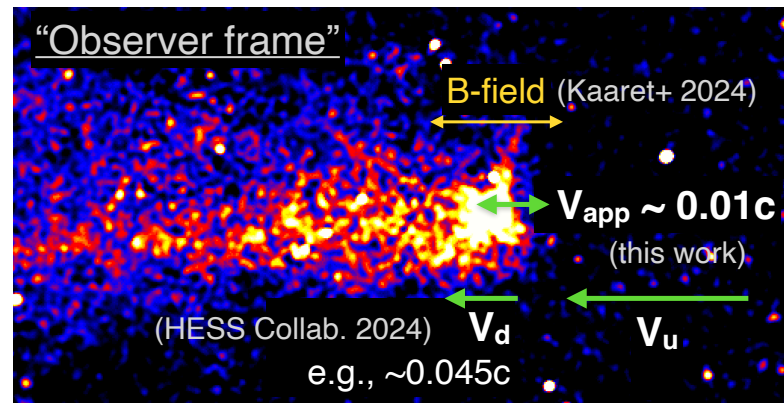
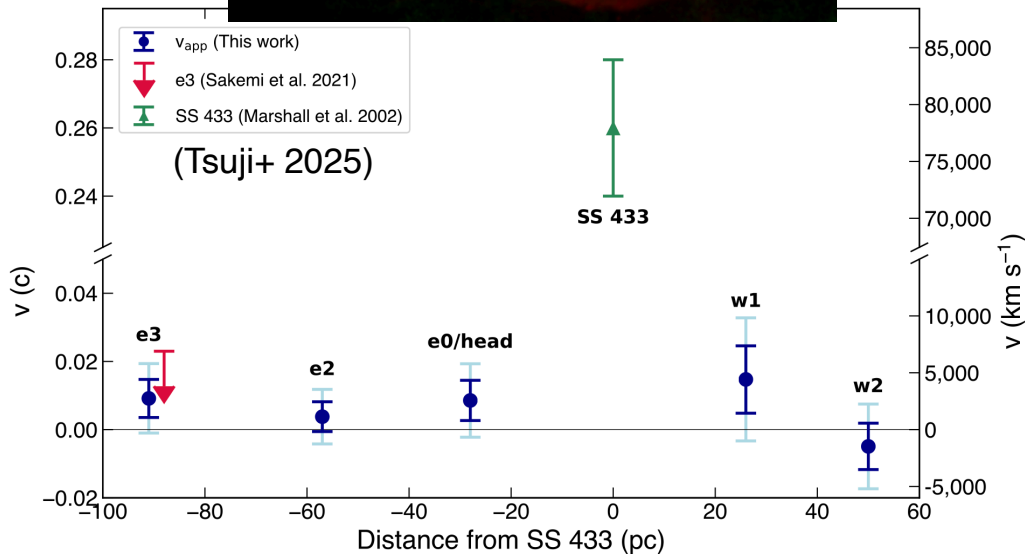
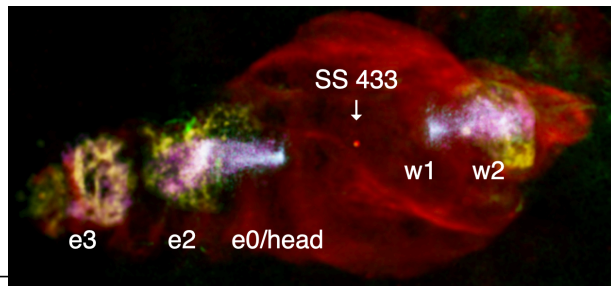
Proper motion measurement



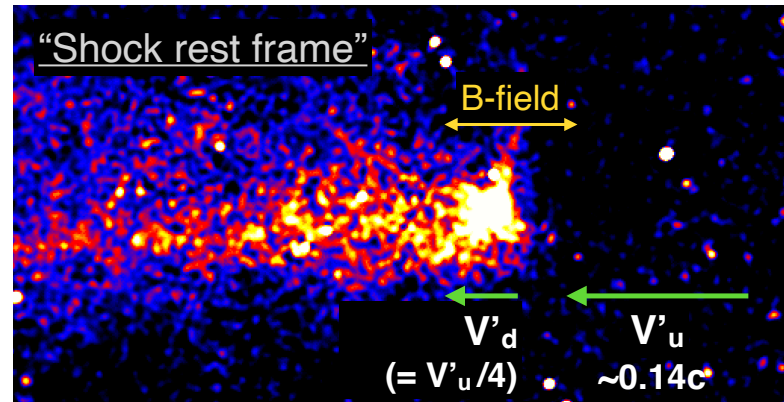
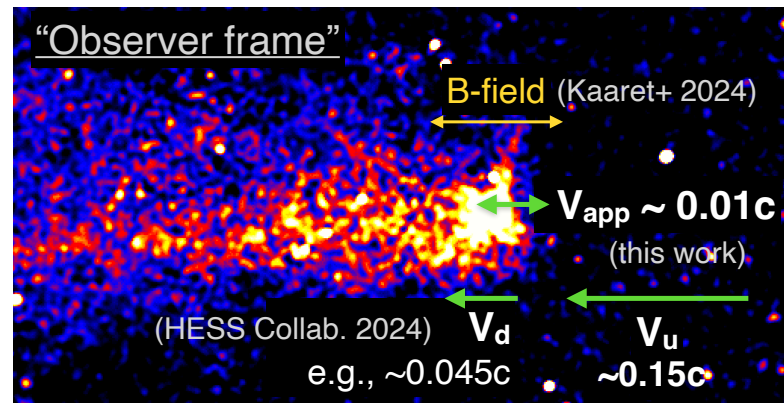
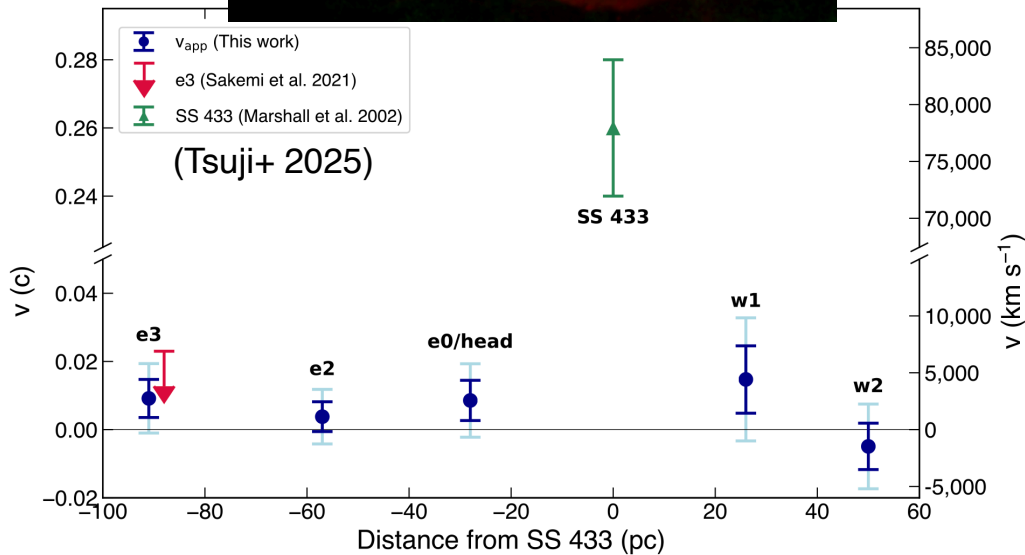
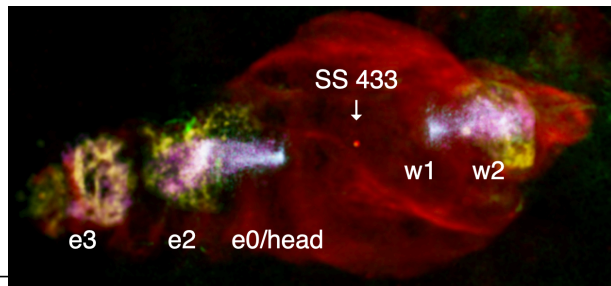
Proper motion measurement



Proper motion measurement



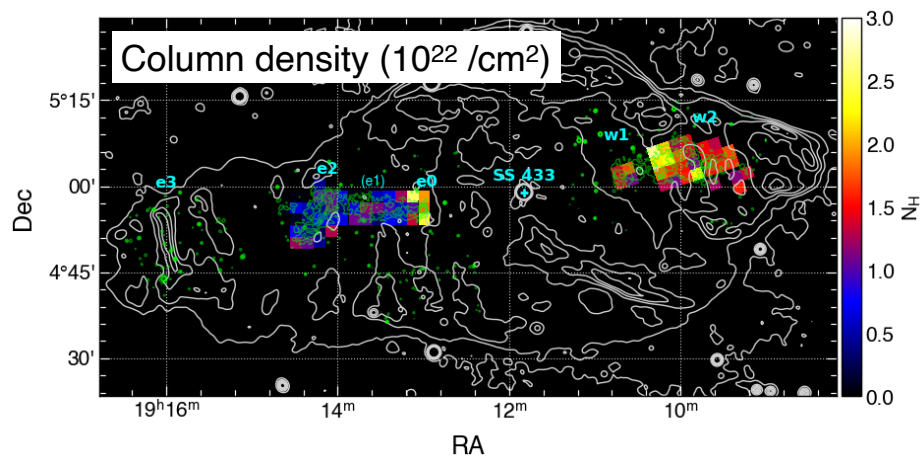
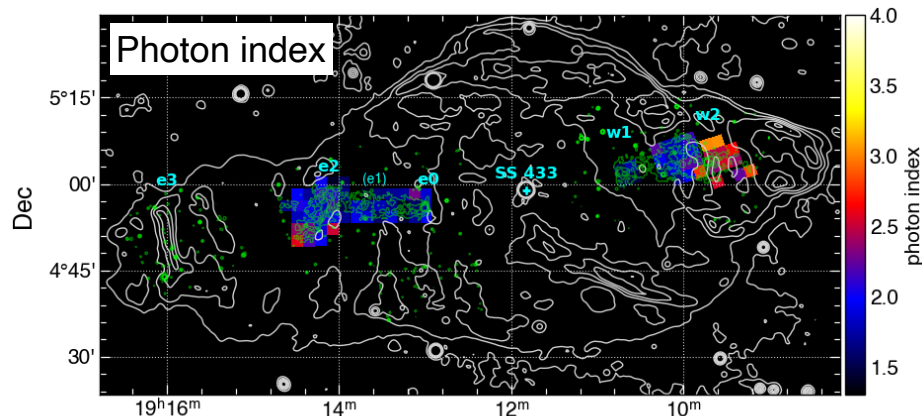
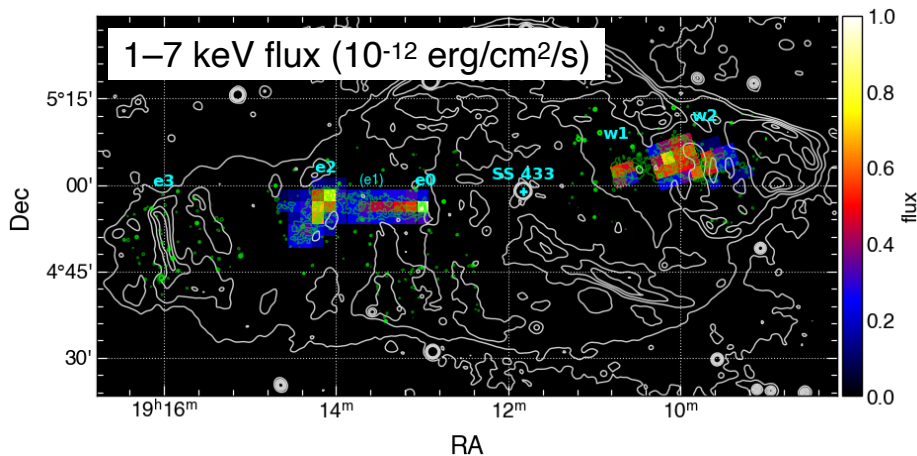
Proper motion measurement



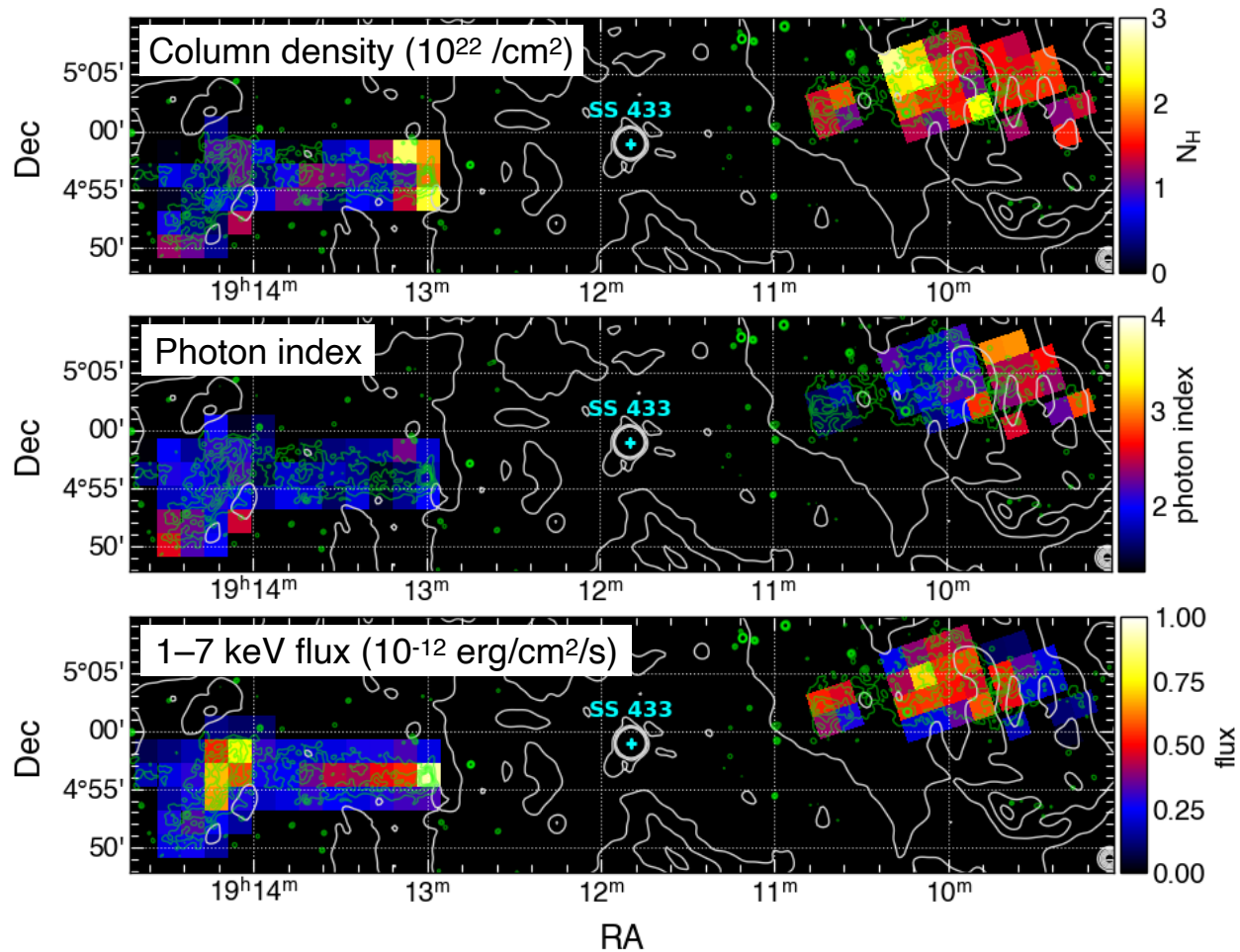
Shock speed (V'_u) $\sim 10^4$ km/s (depending on V_d of 0.045–0.08c) $\rightarrow$ efficient particle acceleration

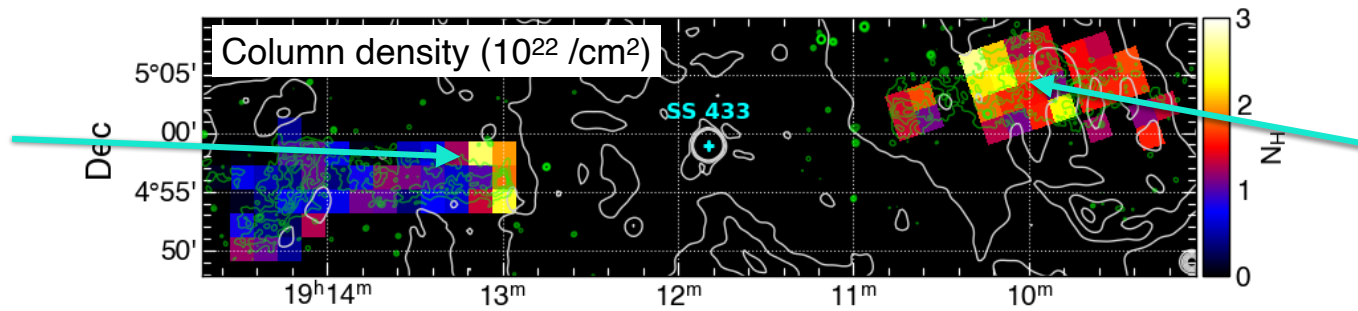
Spectral map in 2023-2024

- Fit each region (2x2 arcmin²; 3x3 pc² for d=5.5 kpc) with an absorbed power-law model and map the parameters
- Thermal emission not considered as these are non-thermal dominated regions
- Explore spectral map and 20-yr flux variation

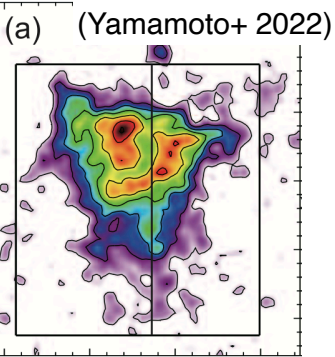
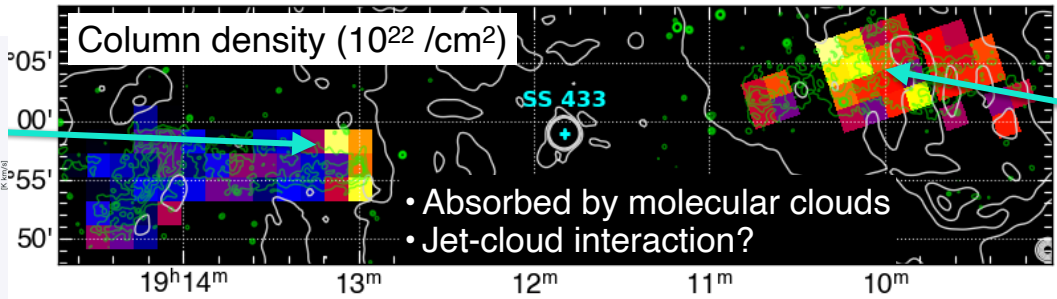
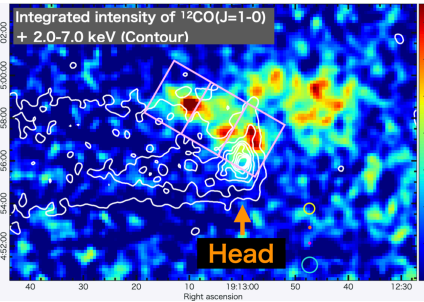


Zoom-in

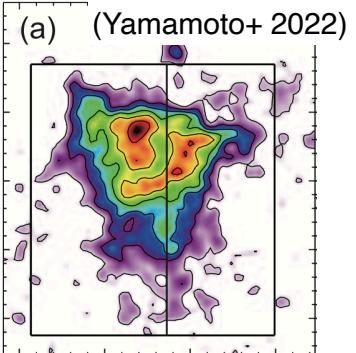
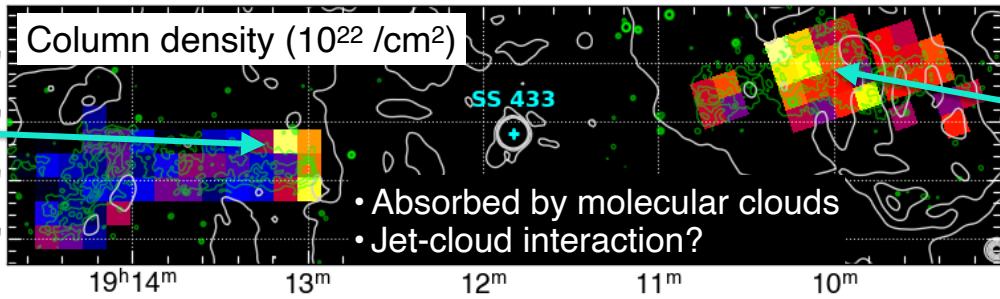
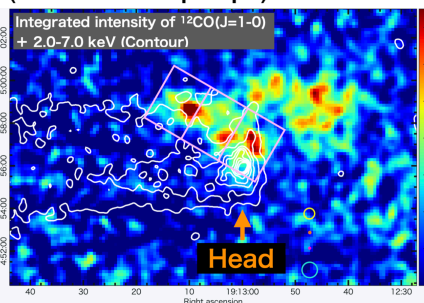




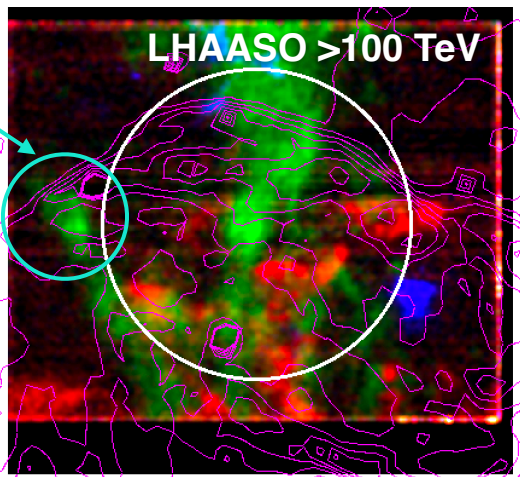
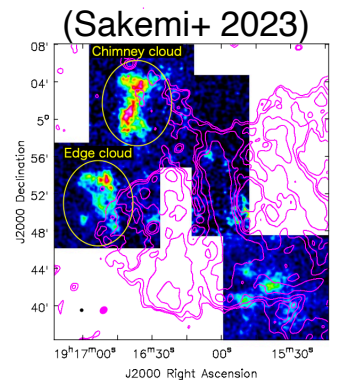
(Sakemi in prep.)



(Sakemi in prep.)



Fermi periodic emission
and Ariyama cloud at 35 km/s



**Survey by
Nobeyama 45-m radio telescope
(continue in 2025~)**

Red: 21–26 km/s
Green: 33–37 km/s
Blue: 48–52 km/s

d <3 kpc or >10 kpc
→ No apparent molecular cloud in
LHAASO >100 TeV spot

Time variability between 2003 and 2023 in west

Column density

Fixed to the values in Kayama+ 2022

Photon index

Almost stable

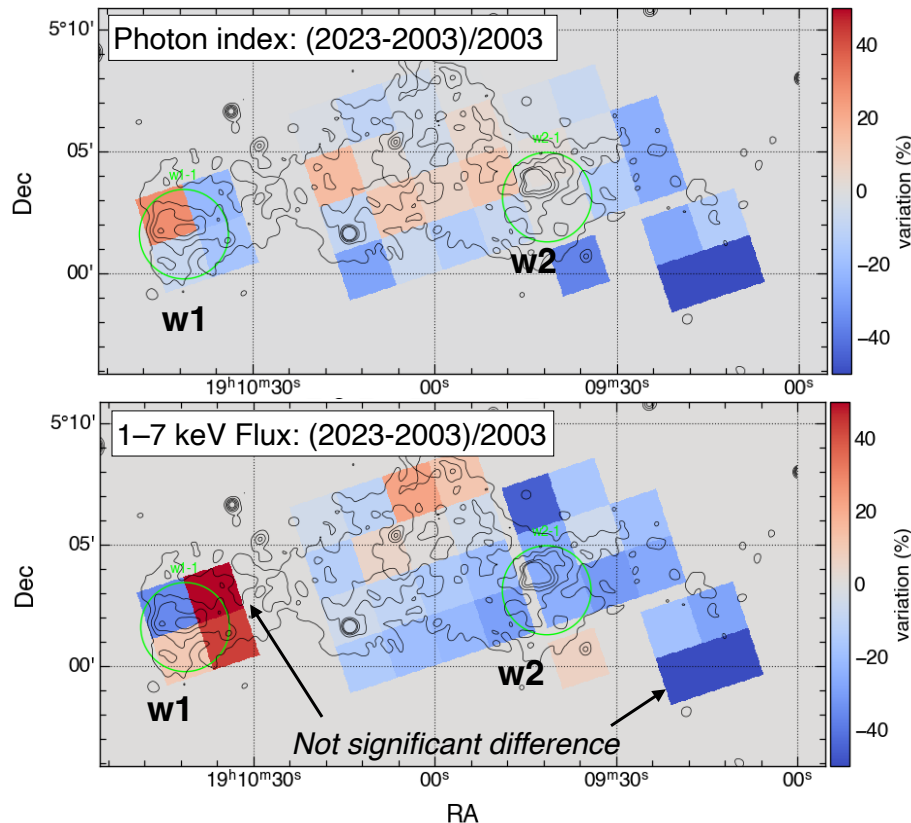
Not variable with $< 3\sigma$ in all regions

Flux

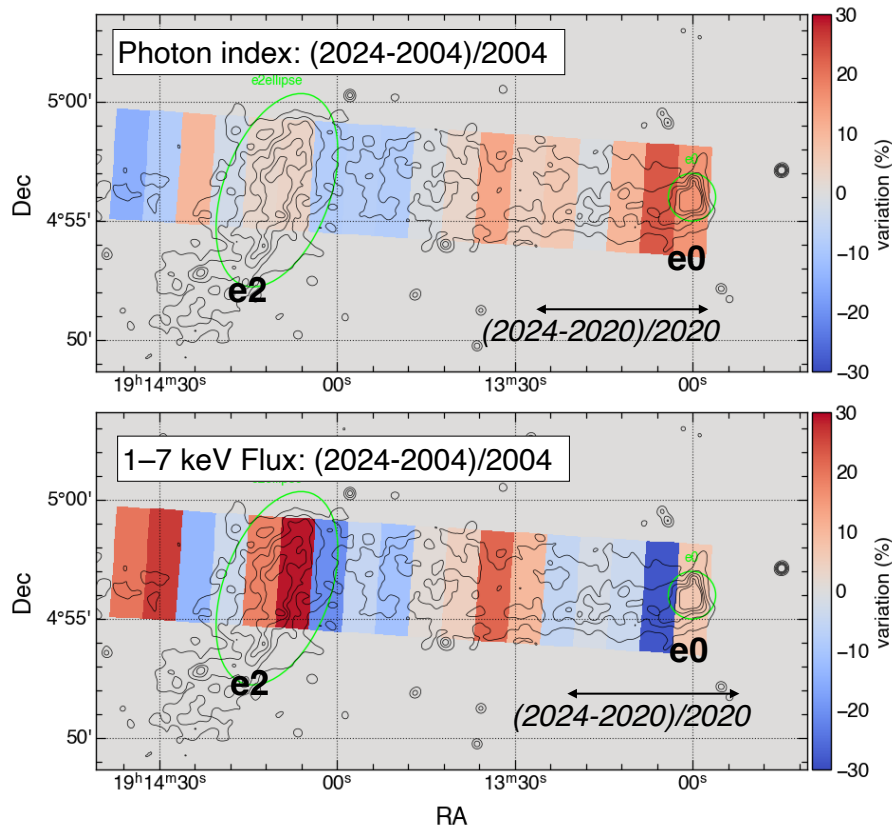
Variable with $\sim 4\sigma$ only around w1 and w2

$\sim 35\%$ decrease at w1

$\sim 25\text{--}30\%$ decrease at w2



Time variability between 2004 and 2024 in east



Column density

Fixed to the values in Kayama+ 2025

Photon index

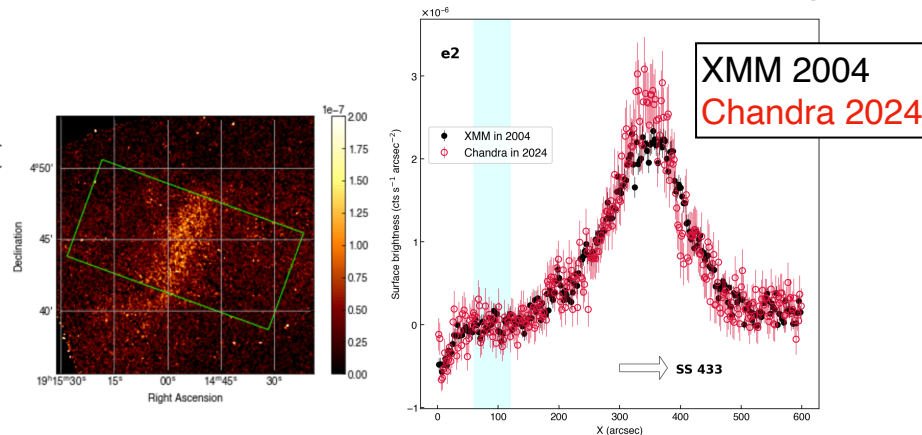
Almost stable

Not variable with $< 3\sigma$ in all regions

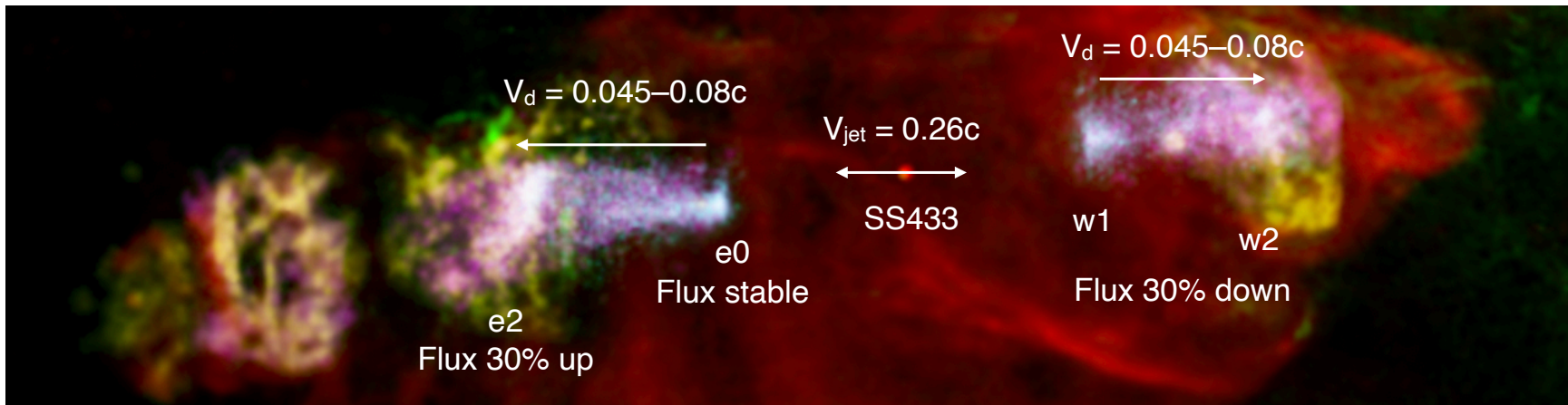
Flux

Stable at e0/head

30% increase at e2 ⚠ XMM-Chandra comparison



Time variability in knots



(assuming $d=5.5$ kpc)

The flux varying region of e2/w1/w2
1.5–3 pc

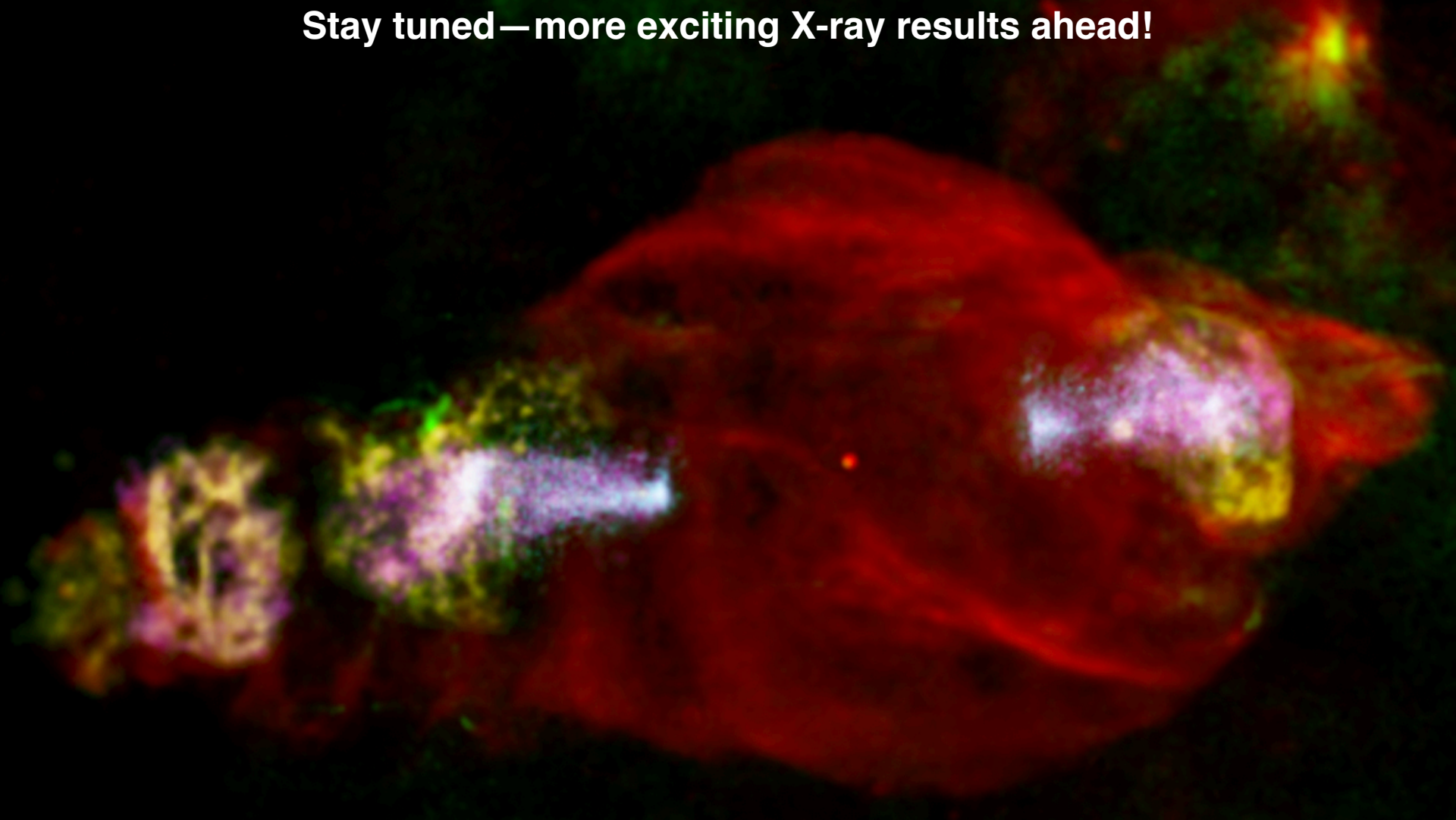
$\gtrsim$

Advection length for 20 yr and $0.26c$ (V_{jet})
1.6 pc

Advection length for 20 yr and $0.045-0.08c$ ($=V_d$)
0.3–0.5 pc

Flux increase/decrease due to re-acceleration/cooling, advection (unlikely?), escape, or ...?

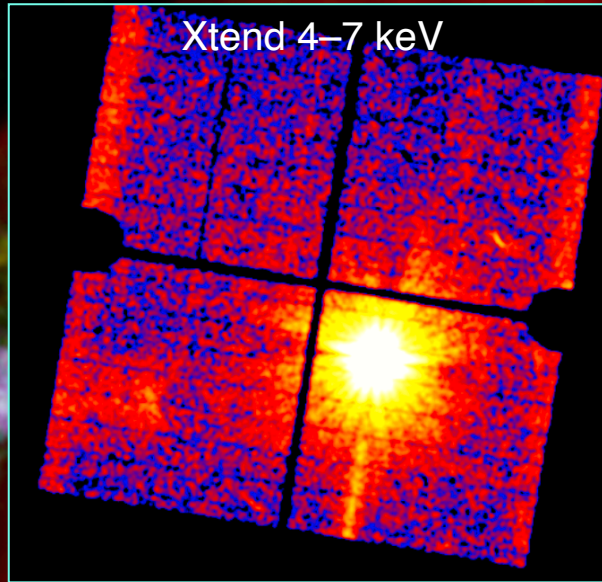
Stay tuned—more exciting X-ray results ahead!



Stay tuned—more exciting X-ray results ahead!

XRISM

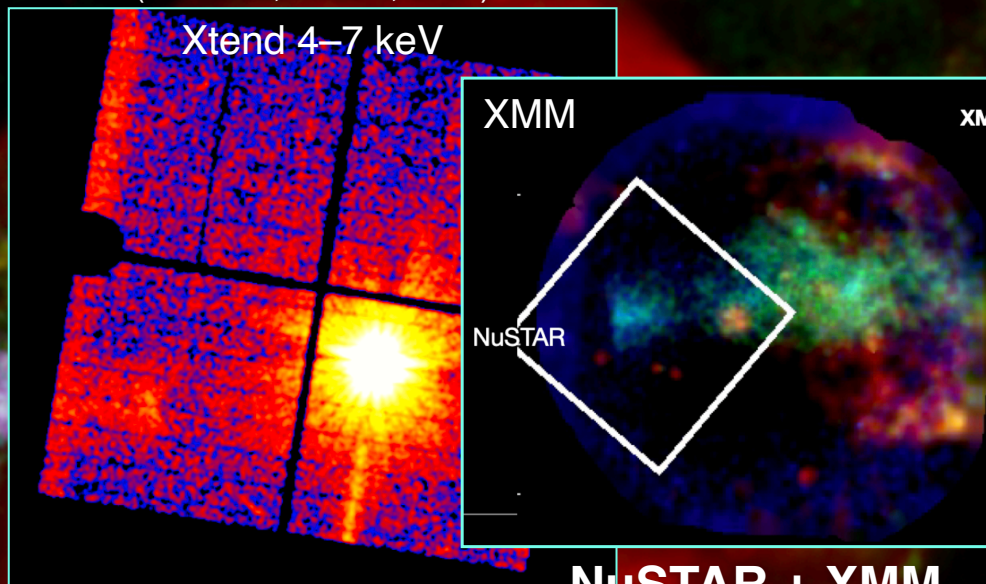
Resolve on SS 433 + Xtend on diffuse
184 ks (PV), 80 ks (AO-2) and 80 ks (AO-3)
(Shidatsu, Suzuki, et al.)



Stay tuned—more exciting X-ray results ahead!

XRISM

Resolve on SS 433 + Xtend on diffuse
184 ks (PV), 80 ks (AO-2) and 80 ks (AO-3)
(Shidatsu, Suzuki, et al.)



NuSTAR + XMM

New w3 or w2-north/w2-south?
($kT \sim 0.27$ keV; enhanced Mg and Si)
(Mac Intyre+ in prep.)

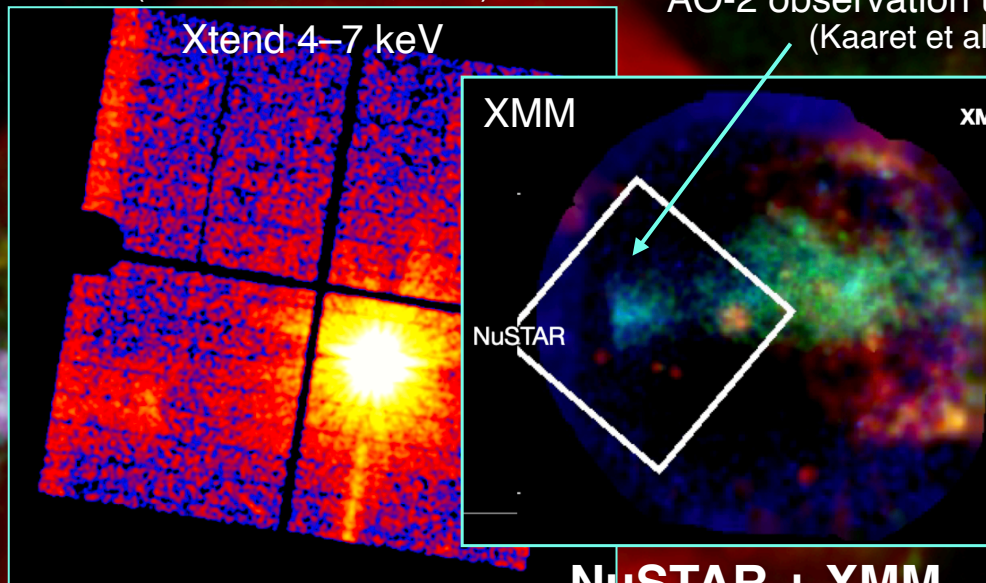
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XRISM

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184 ks (PV), 80 ks (AO-2) and 80 ks (AO-3)
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IXPE

Polarization at w1
AO-2 observation underway
(Kaaret et al.)



NuSTAR + XMM

New w3 or w2-north/w2-south?
(kT $\sim$ 0.27 keV; enhanced Mg and Si)
(Mac Intyre+ in prep.)

Stay tuned—more exciting X-ray results ahead!



AXIS

NASA's Probe mission
(Reynolds+2023; Safi-Harb+ 2023)

XRISM

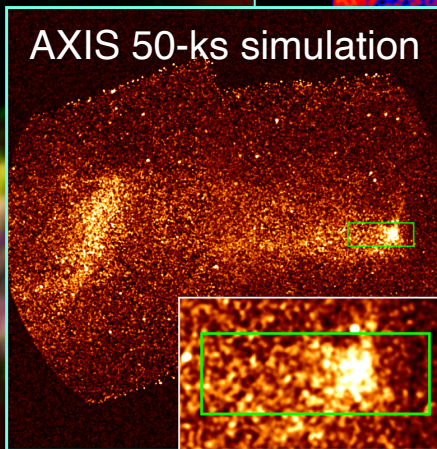
Resolve on SS 433 + Xtend on diffuse
184 ks (PV), 80 ks (AO-2) and 80 ks (AO-3)
(Shidatsu, Suzuki, et al.)

Xtend 4–7 keV

IXPE

Polarization at w1
AO-2 observation underway
(Kaaret et al.)

AXIS 50-ks simulation



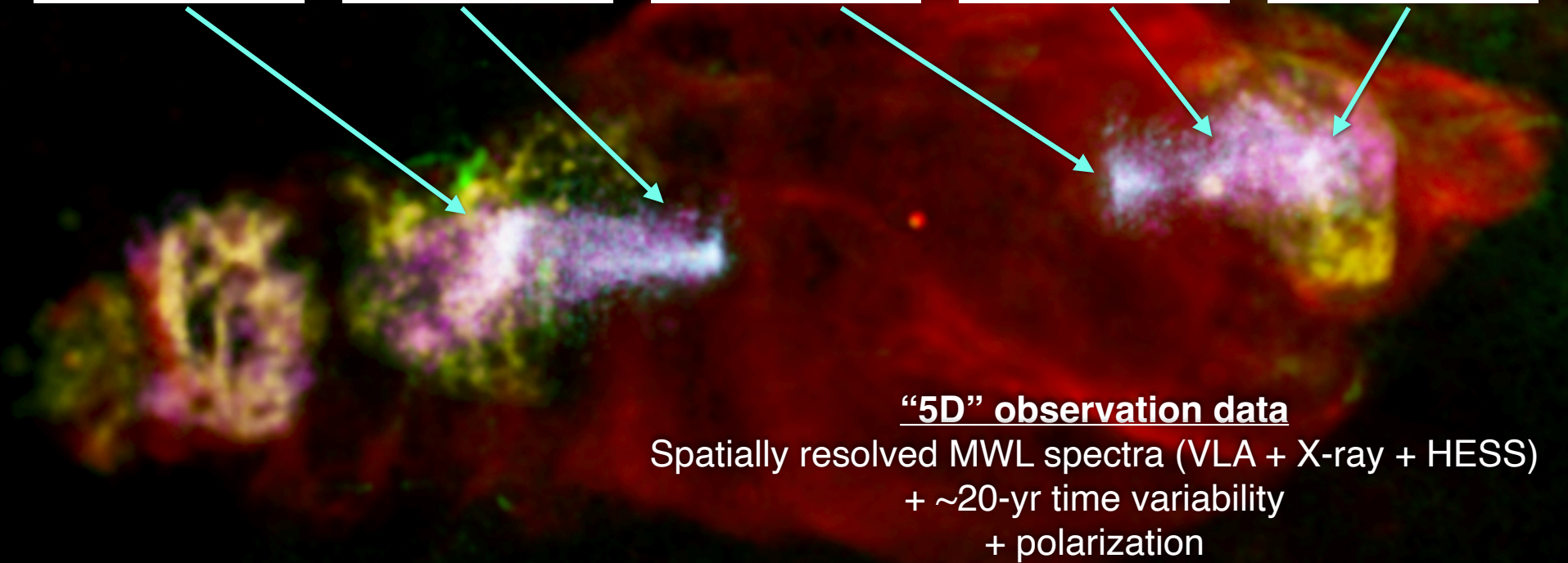
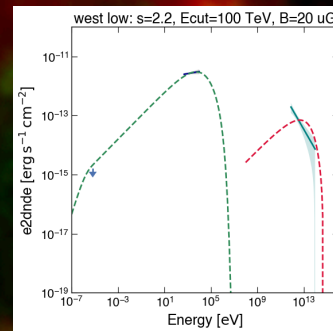
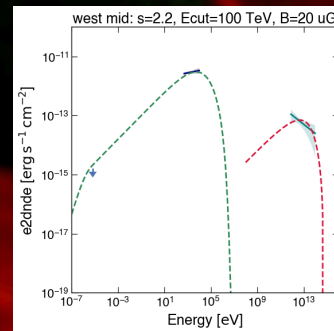
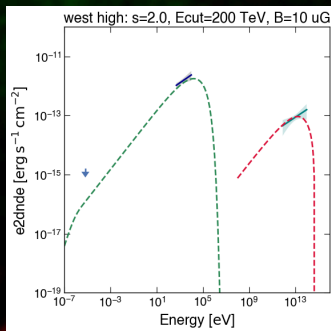
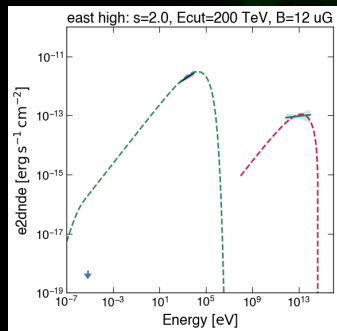
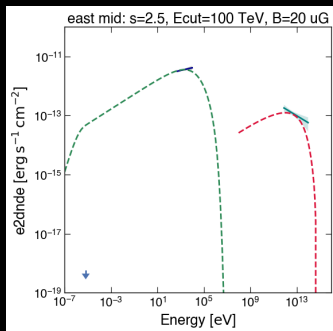
XMM

NuSTAR

XM

NuSTAR + XMM

New w3 or w2-north/w2-south?
(kT $\sim$ 0.27 keV; enhanced Mg and Si)
(Mac Intyre+ in prep.)



“5D” observation data

Spatially resolved MWL spectra (VLA + X-ray + HESS)
+ ~20-yr time variability
+ polarization

$S_{\text{(tephenson)}} S_{\text{(anduleak)}} 433$

$D \sim 5.5 \text{ kpc}$

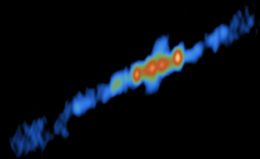


HMXB

$L_j \sim 10^{39-40} \text{ erg/s}$

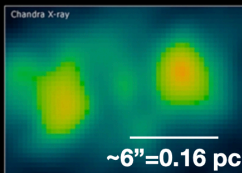
4-20 Suns
 $v = 0.26 \text{ c}$

VLA



$L_x \sim 10^{36} \text{ erg/s}$

hadronic jets

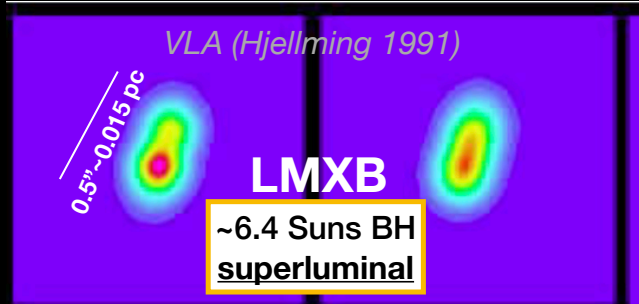


Migliari et al. 2022
Marshall et al. 2013

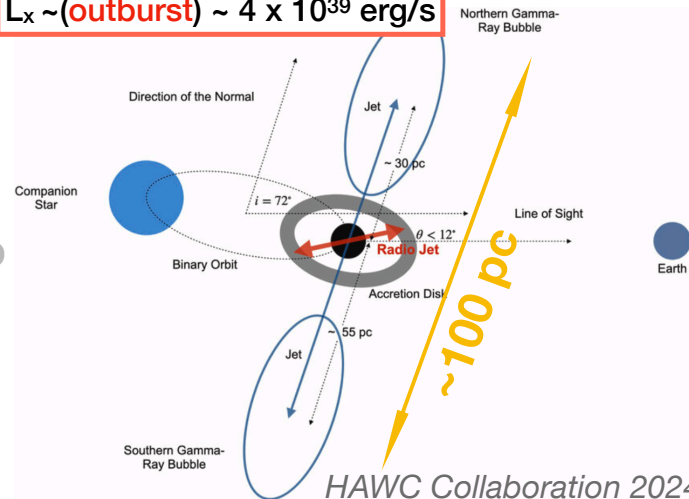
200 pc

V4641 Sgr

$D \sim 6.2 \text{ kpc}$



$L_x \sim (\text{outburst}) \sim 4 \times 10^{39} \text{ erg/s}$



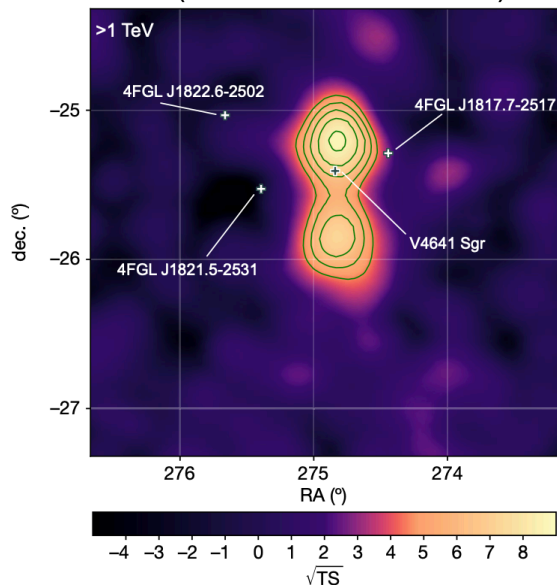
HAWC Collaboration 2024

Samar Safi-Harb

2nd example of VHE gamma-ray microquasar: V4641 Sgr

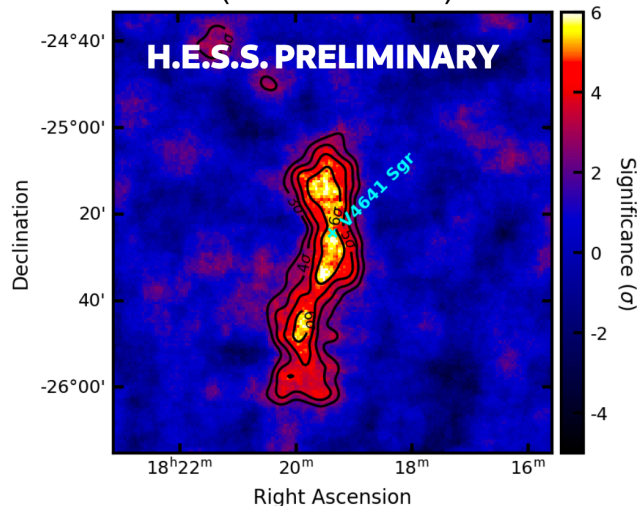
Xiaojie's talk

(HAWC Collab. 2024)



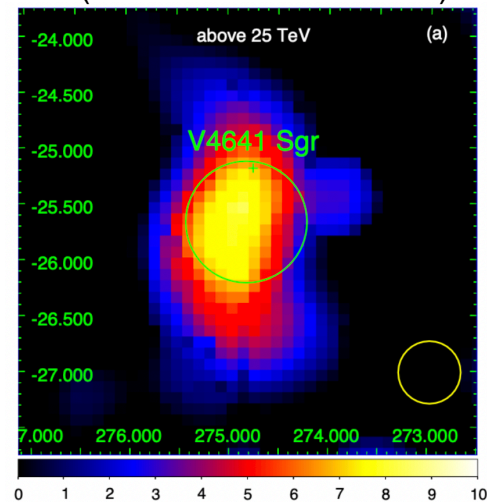
Laura's talk

(HESS Collab.)



Zhen's talk

(LHAASO Collab. 2024)



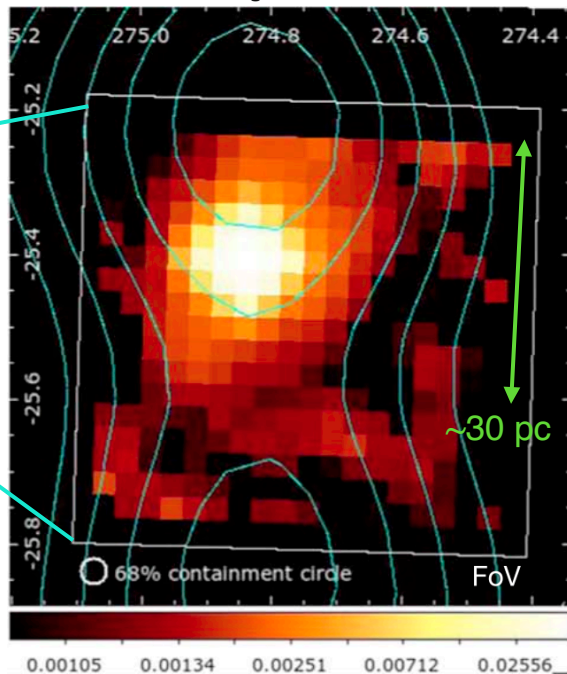
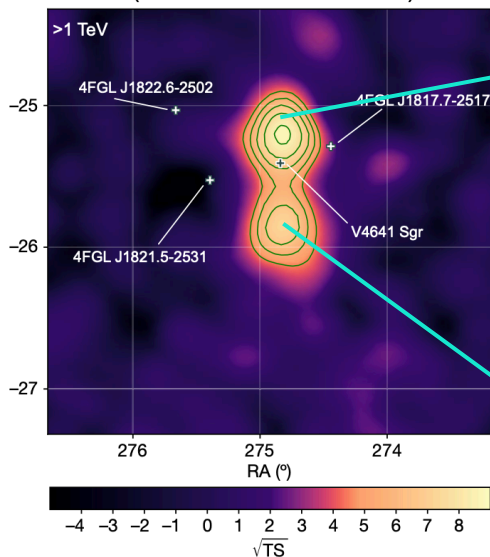
V4641 Sgr in X-ray

XRISM/Xtend image in 1.2-7 keV

(Suzuki+ 2025)

(c) NXB-subtracted, vignetting-corrected
1.2–7.0 keV image with HAWC contours

(HAWC Collab. 2024)



XRISM DDT observation

- 2024-09-30
- 12.1 ks
- Xtend → Suzuki+ 2025
- Resolve → Parra+ submitted

Image: detection of diffuse (~ 30 pc)
X-ray emission with $>4.5\sigma$

Spectrum: poorly constrained

- $\Gamma \sim 1.6-2.7$ if nonthermal
- $kT \sim 3$ keV and $n \sim 0.3$ cm $^{-3}$ if thermal

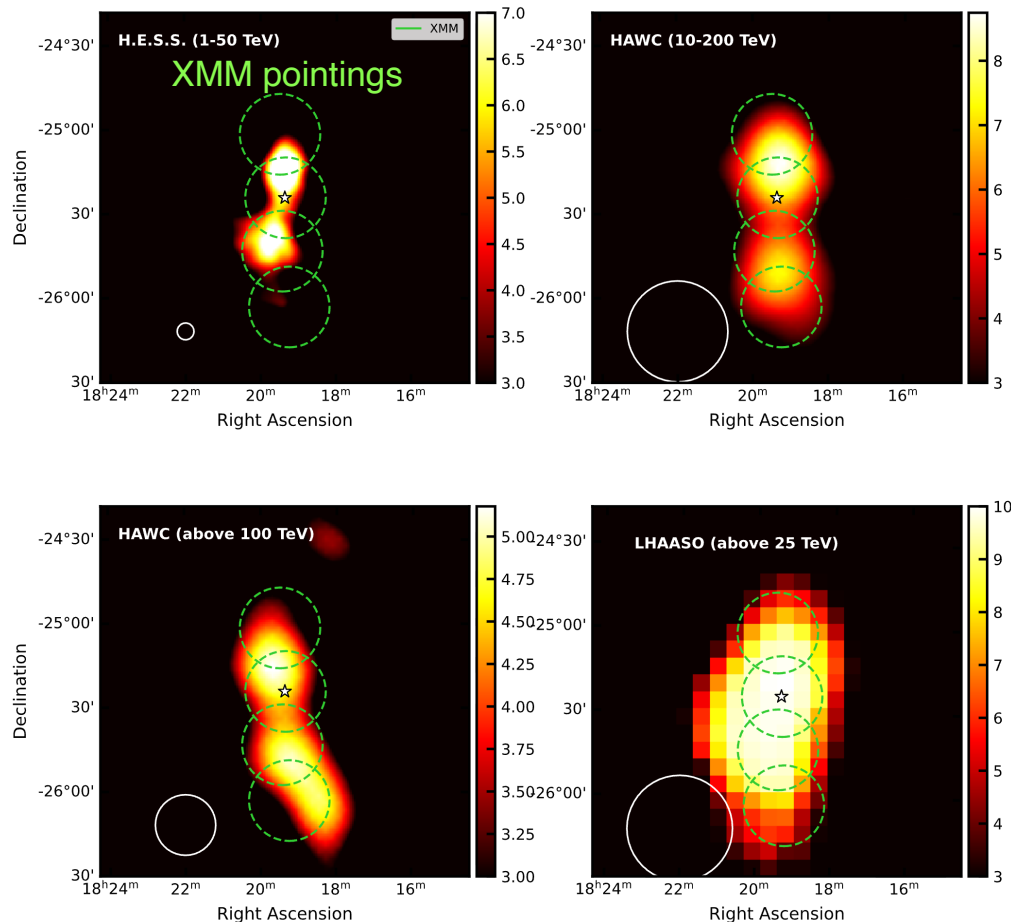
X-ray observation campaign

XMM 160 ks in 2025 Sep
40 ks x 4 pointings

NuSTAR 490 ks in 2026 spring
70 ks x 7 pointings

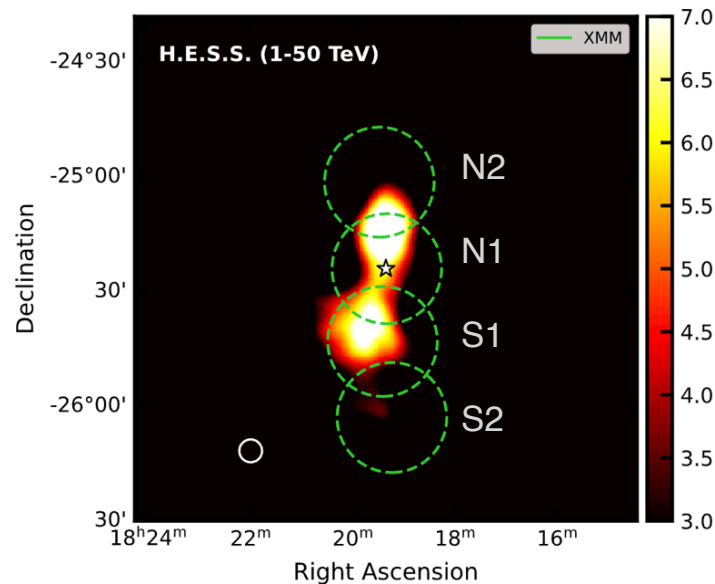
Chandra 180 ks in 2026–2027
60 ks x 3 pointings

(PI: Kaya Mori, co-PI: NT)



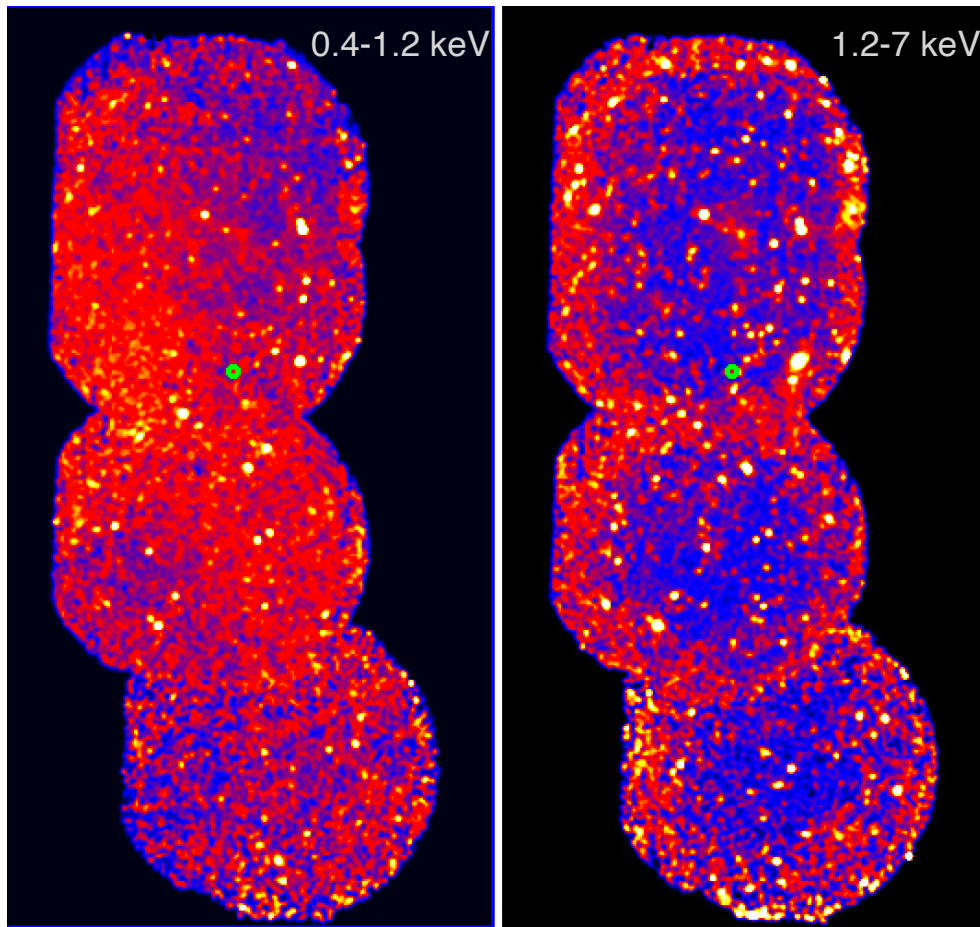
XMM-Newton observation

Effective exposure					
	ObsID	Date	MOS1 (ks)	MOS2 (ks)	PN (ks)
N2	971600101	2025-09-11	38	38	33
N1	971600201	2025-09-13	42	42	39
S1	971600301	2025-09-21	32	32	28
S2	971600401	2025-09-23	14	14	8



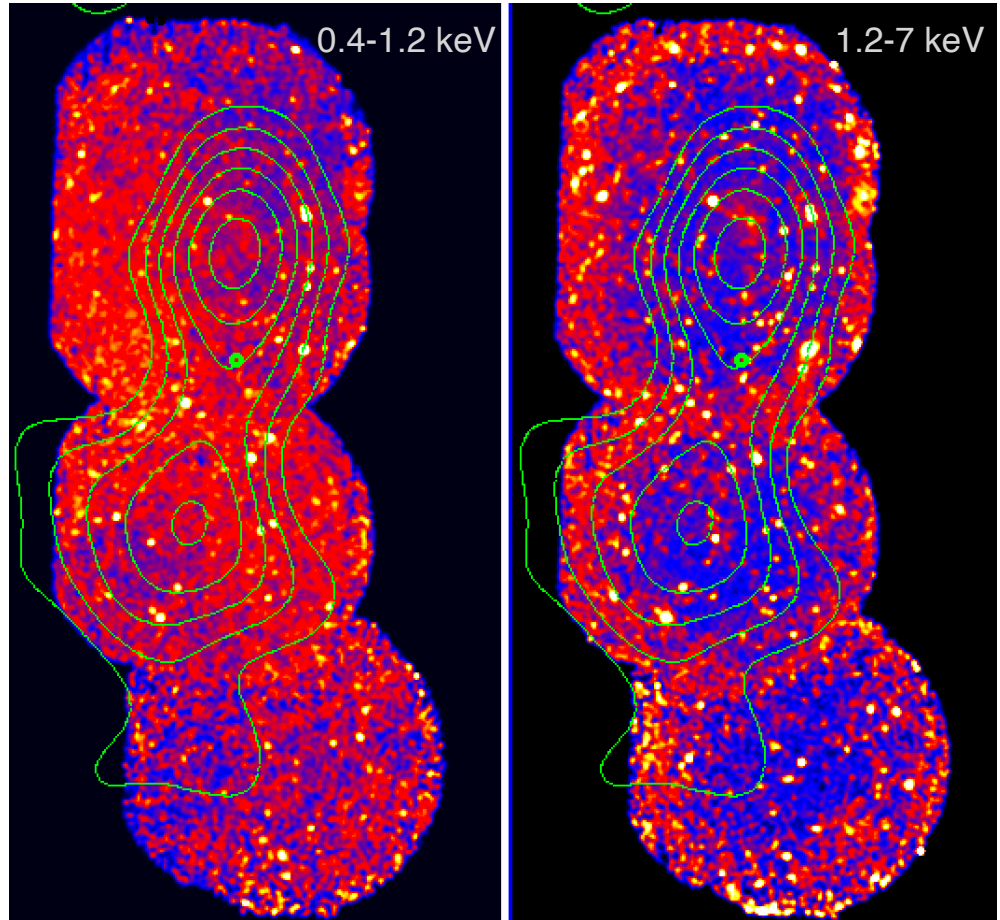
- ☑ V4641 Sgr in quiescent state
 - Monitored by MAXI and Swift
 - Swift-XRT DDT observation on September 5-6 (analyzed by Maxime Parra)
 - $NH = 0.15 \times 10^{22} \text{ cm}^{-2}$ and $\Gamma = 1.5$ (fixed)
 - 0.3–10keV absorbed flux upper limits of $2.5 \times 10^{-13} \text{ erg/s/cm}^2$ at 90% c.l.

XMM-Newton observation

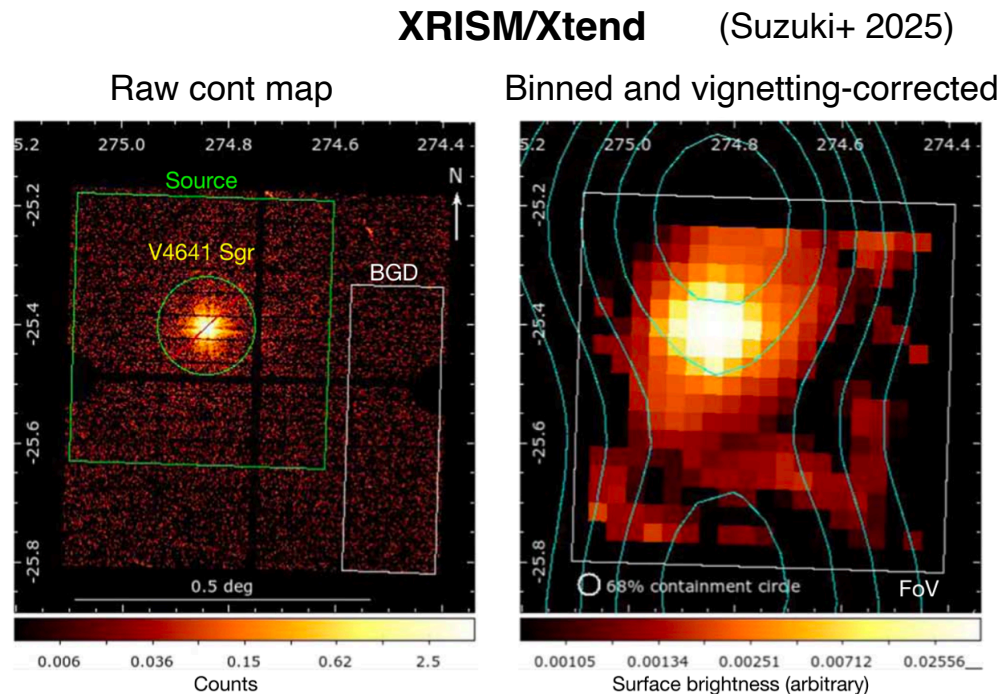
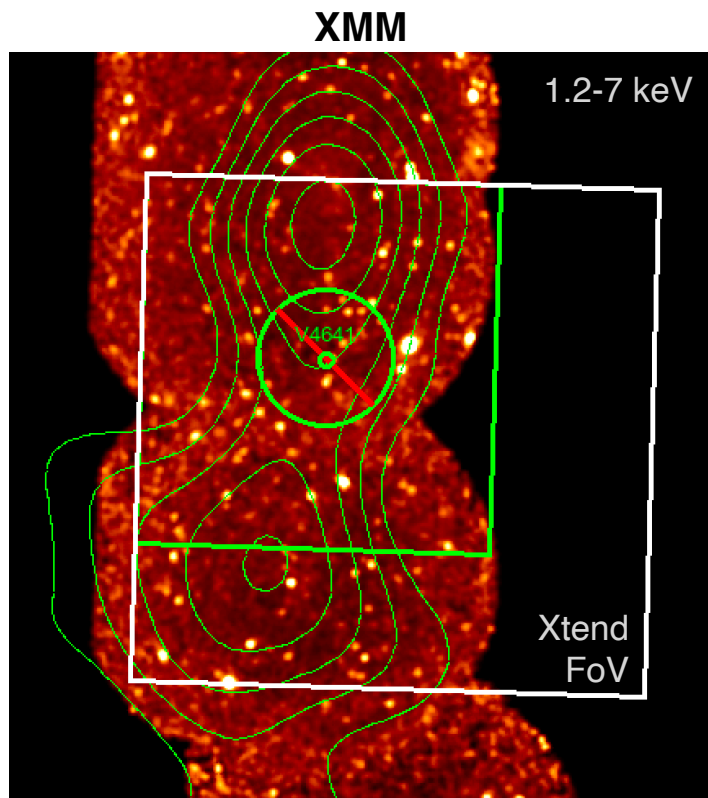


XMM-Newton observation

- Some structures in soft/thermal band
(Probably not related to V4641)
- No clear X-ray counterparts of the gamma-ray emission
- Faint diffuse emission around north gamma-ray peak?
- Many point-like sources
 - Too many at $b = -5$ degree?
 - XRISM/Xtend diffuse $\rightarrow$ unresolved point sources?
 - Some might be molecular cores?
- Future work: detailed analysis (spectra, diffuse, point-like sources)



XMM vs XRISM/Xtend



Point-like sources + no apparent diffuse emission
→ XRISM/Xtend's surface brightness would be upper limit
→ $B < 2\text{--}3 \text{ uG}$ (Laura's talk)

Summary

■ X-ray observations of SS 433/W50

- Proper motion measurement
 - $V_{\text{app}} < 0.019\text{--}0.033c$
 - Shock speed $\sim 10^4$ km/s at the innermost knots, indicating efficient particle acceleration
- Spectral time evolution over 20 years
 - Photon index is stable
 - No flux change at e0/head, $\sim 20\text{--}30\%$ flux decrease at w1/w2, and $\sim 30\%$ flux increase at e2 (preliminary)

■ X-ray observations of V4641 Sgr

- New XMM observations on September 2025
 - No clear diffuse emission
- NuSTAR and Chandra observations scheduled in 2026-2027