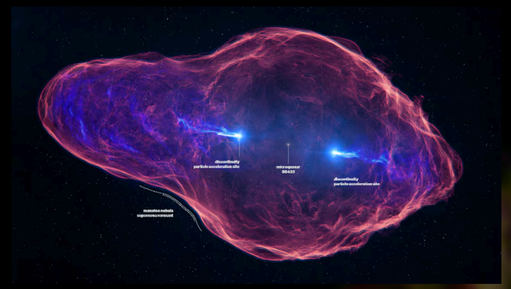
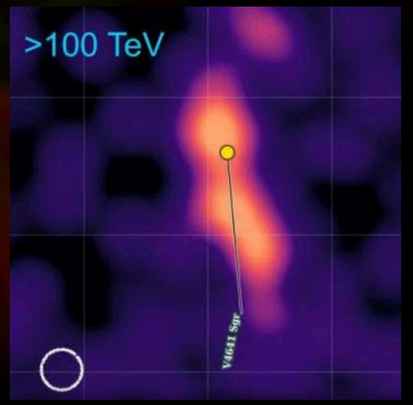
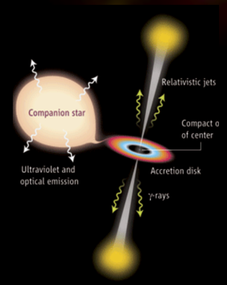
An X-ray Eye on microquasar jets and their impact on the surrounding medium

- Microquasars: Background/Motivation
- W50-SS 433 and V4641 Sgr in X-rays (campaign)
- Next generation X-ray mission: AXIS





Samar Safi-Harb
Brydyn Mac Intyre, Naomi Tsuji, Kaya Mori
Phil Kaaret, Ping Zhou, Hiromasa Suzuki,
Dmitry Khangulyan, Felix Aharonian
for the (many) W50 and V4641 Sgr collaborators

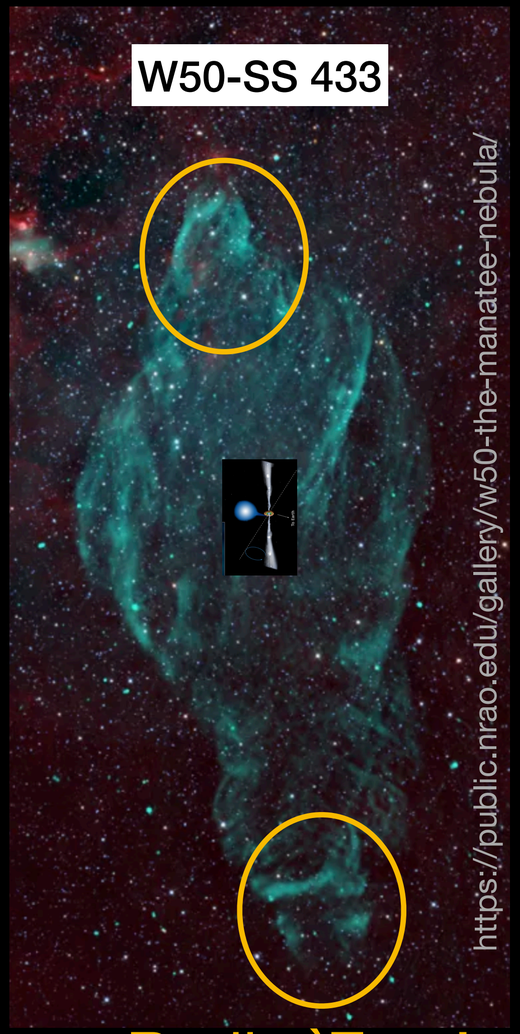


Variable Galactic Gamma-Ray Sources VII

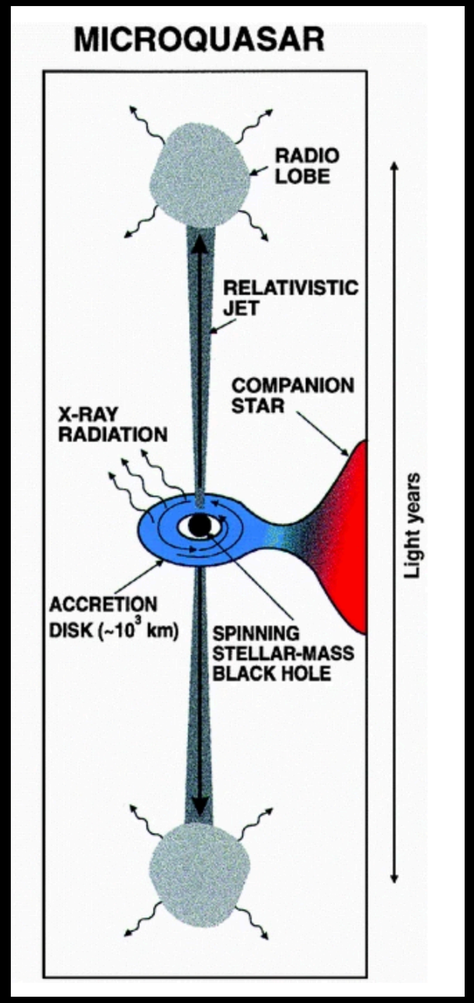
Barcelona, May 7, 2025

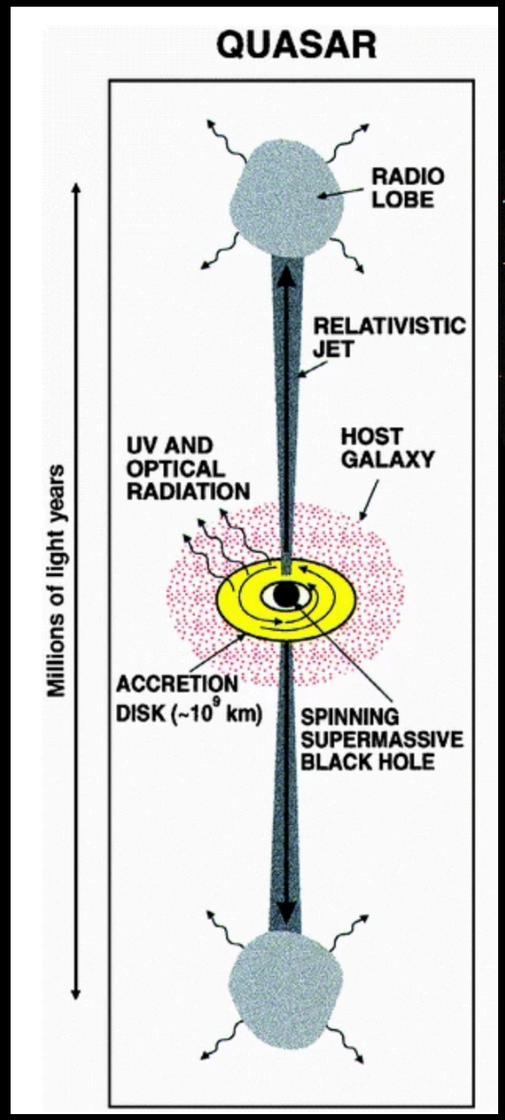
The UofM campuses are located on original lands of Anishinaabeg, Ininiwak, Anisininewuk, Dokata Oyate and Dene, and on the National Homeland of the Red River Métis

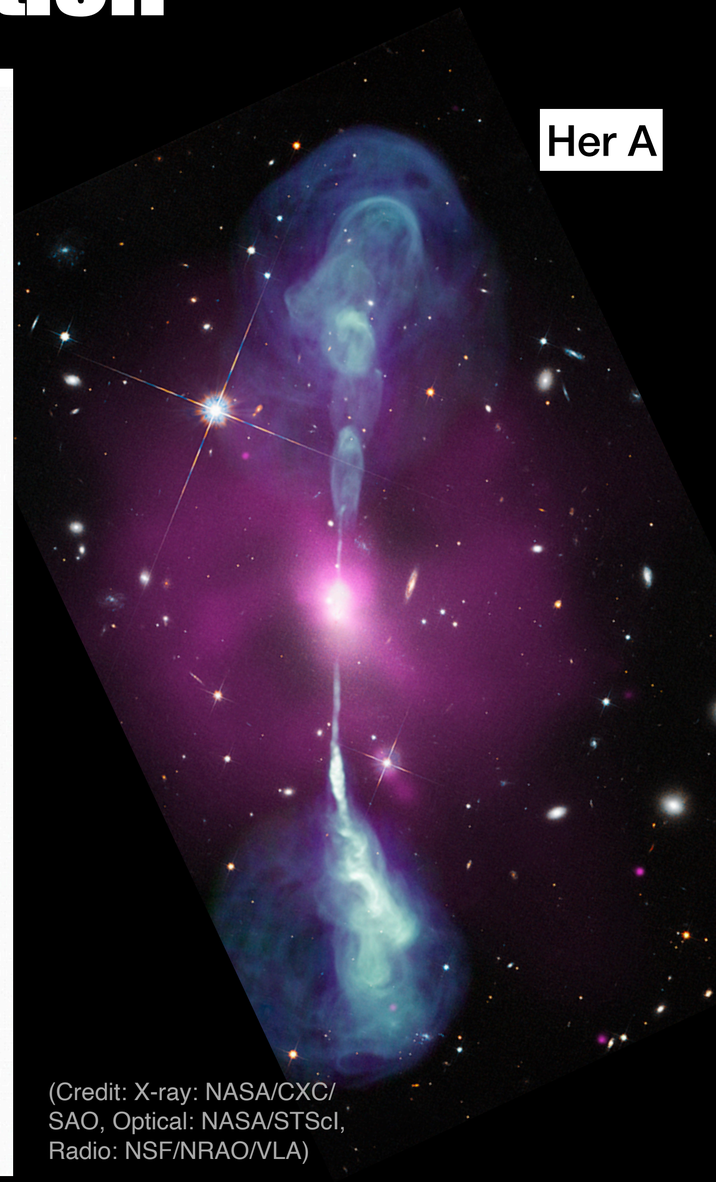
Large scale jets-ISM interaction



Radio `Ears'



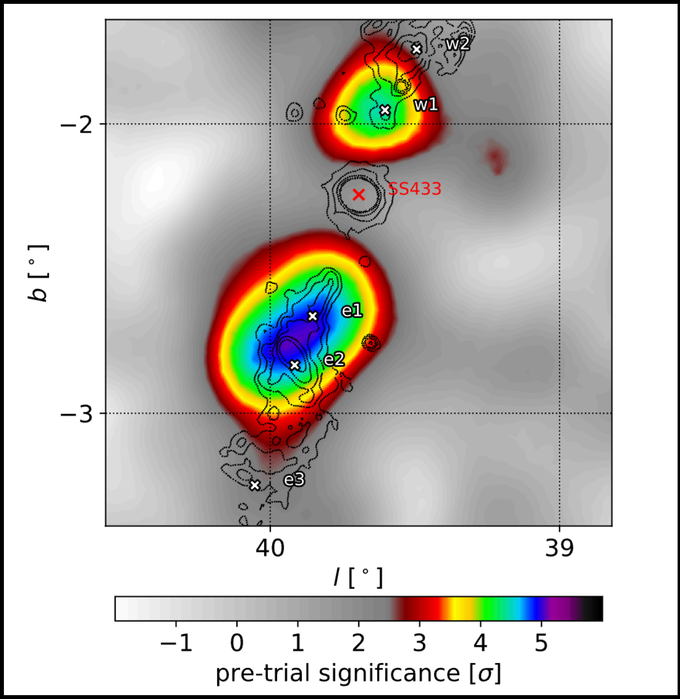




Two sources of interest

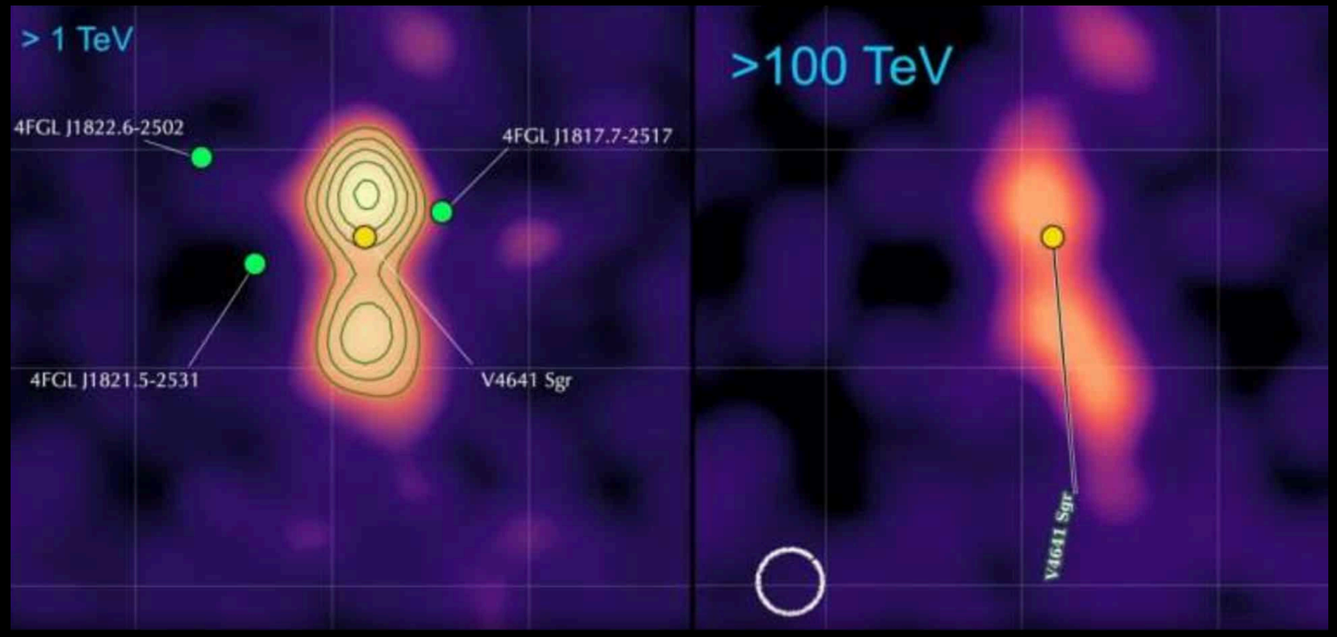
PeVatron Microquasars

SS 433-W50



HAWC collaboration 2018

V4641 Sgr lobes?



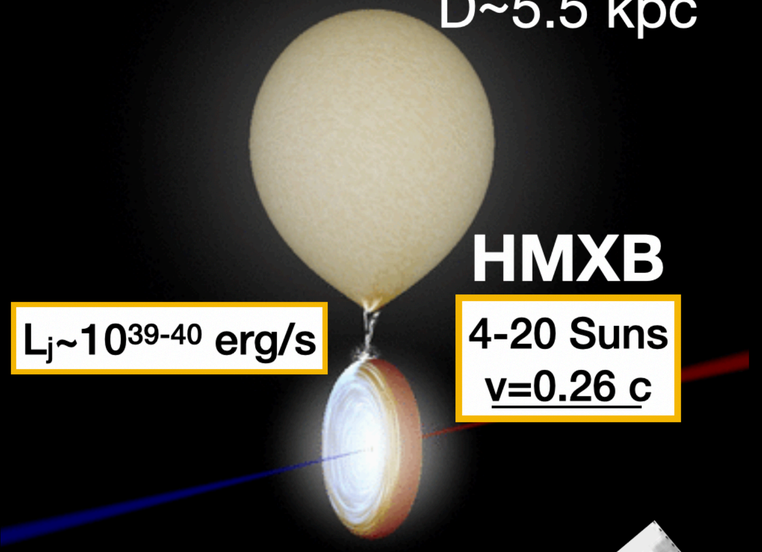
Near-Earth Microquasar V4641 Sgr Emits Unprecedented Gamma Radiation, Reshaping Cosmic Ray Research | The Daily Galaxy --Great Discoveries Channel

HAWC collaboration 2024

Recently detected with HESS (spatially resolved) and LHAASO: super-PeVatrons?

S(tephenson)S(anduleak) 433

D~5.5 kpc



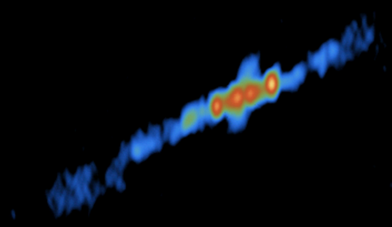
HMXB

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

4-20 Suns

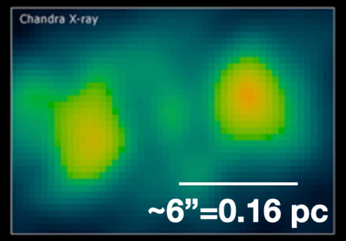
v=0.26 c

VLA

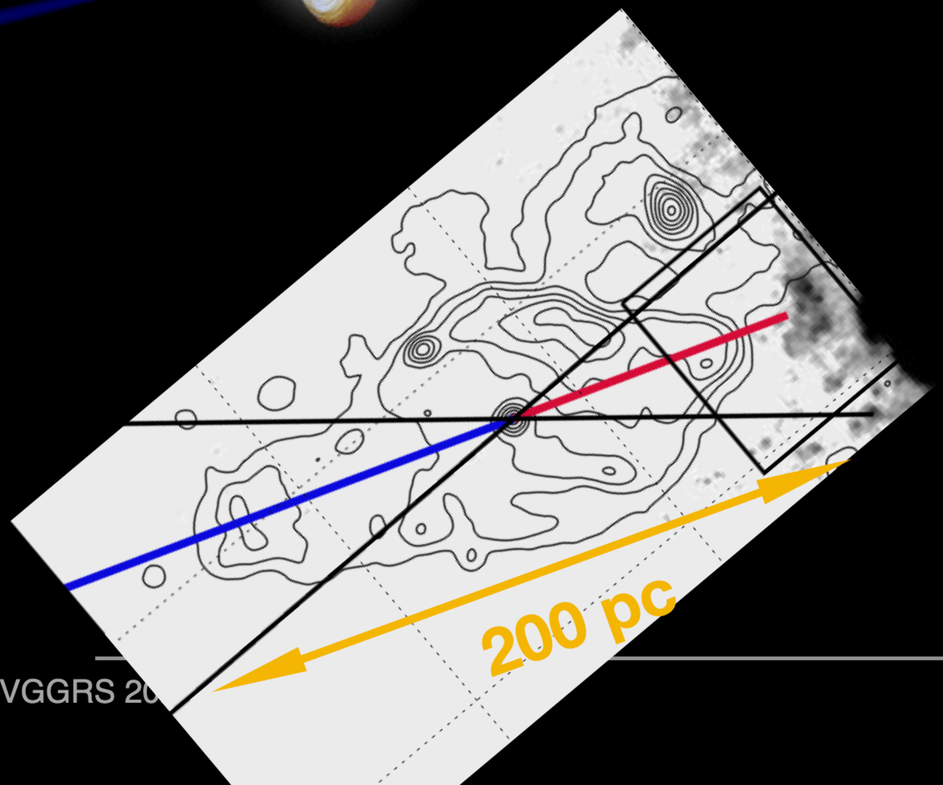


L_x~10^{36} erg/s

hadronic jets

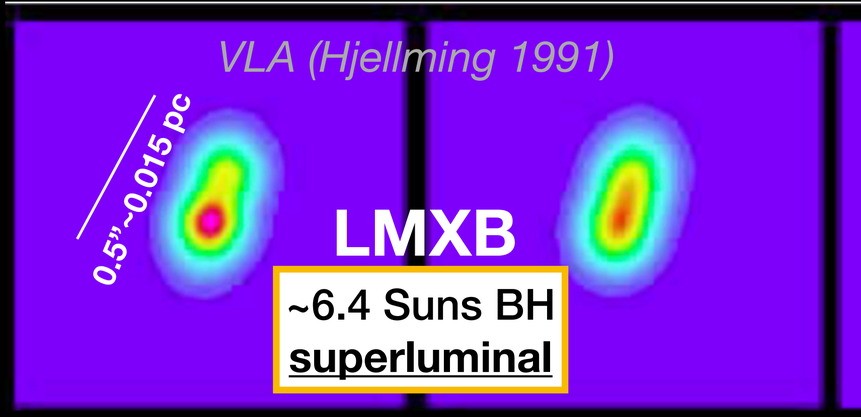


Migliari et al. 2022
Marshall et al. 2013



V4641 Sgr

D~6.2 kpc

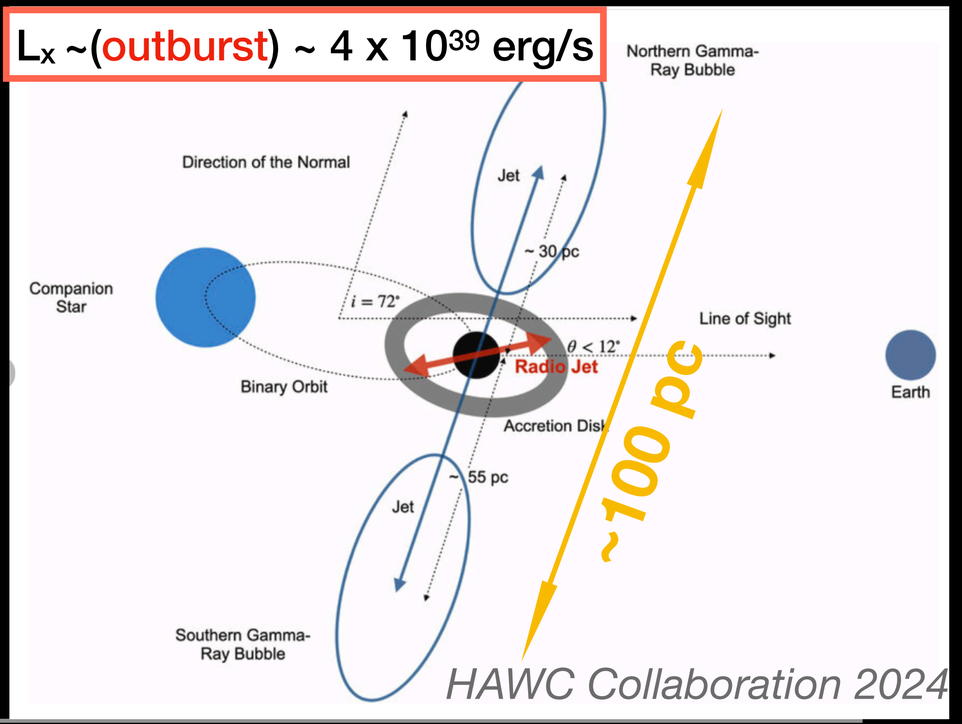


LMXB

~6.4 Suns BH

superluminal

L_x ~(outburst) ~ 4 x 10^{39} erg/s



HAWC Collaboration 2024

Tuesday talks (L. Fisher, S. Casanova, R-Y Liu, J. Li, others…)

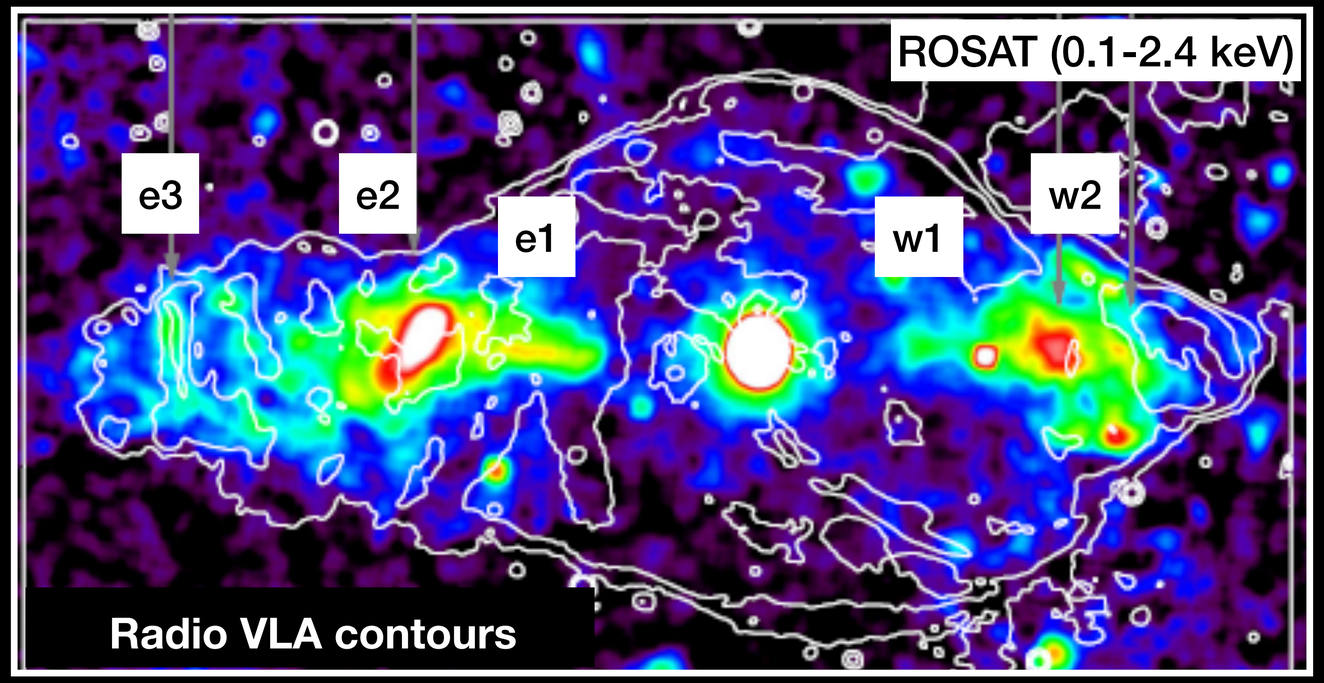
(very) high-energy gamma rays: leptonic vs hadronic, PeVatron nature

Focus of this talk

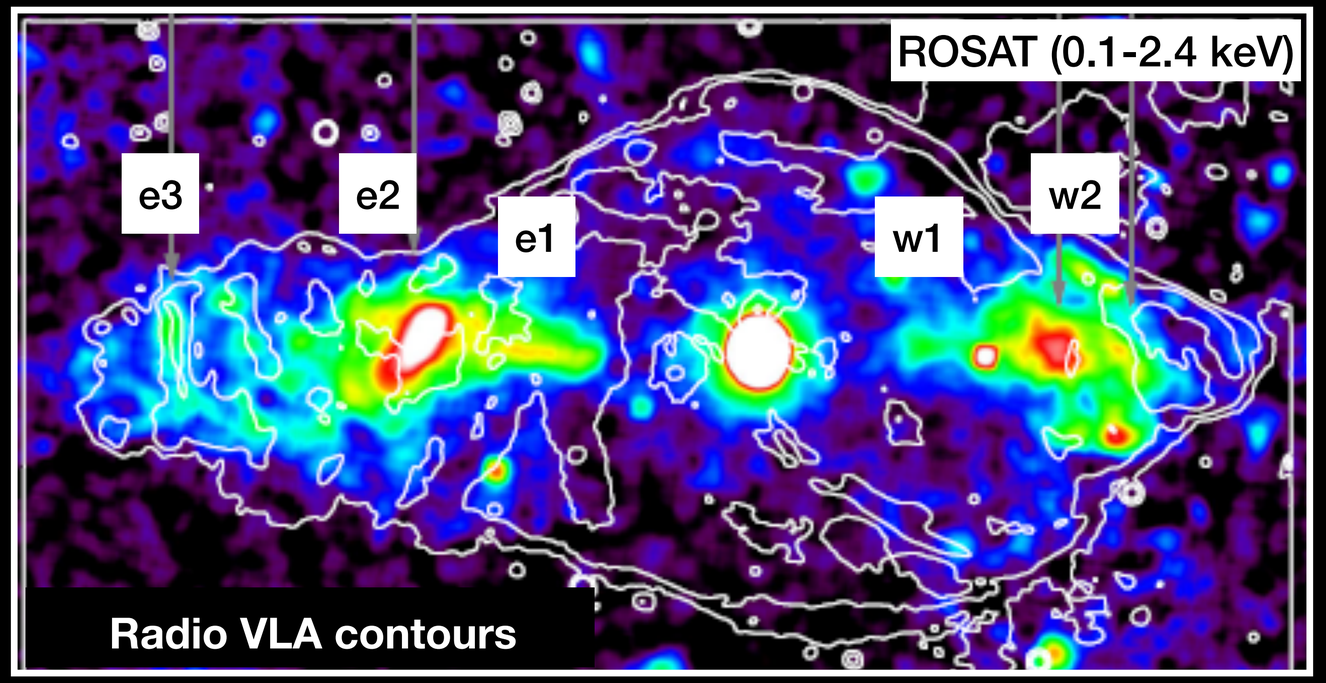
Where & how are particles **accelerated**?

X-rays to the rescue!

Early X-ray Observations of W50



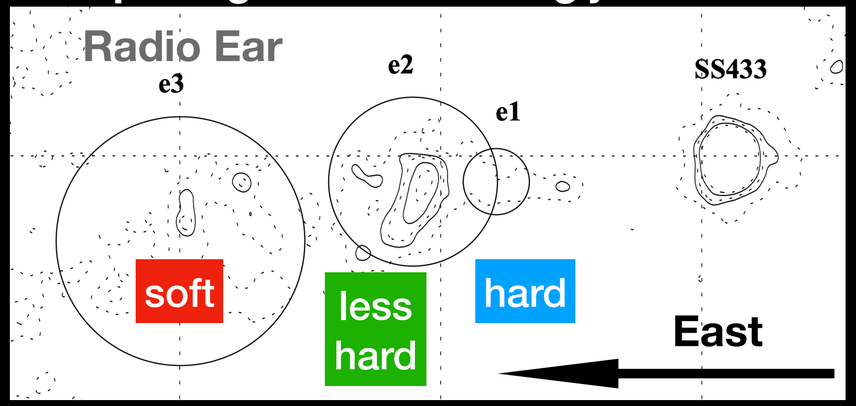
Early X-ray Observations of W50



1990's

ROSAT, ASCA and RXTE (0.1-50 keV)

Steepening eastward along jet direction



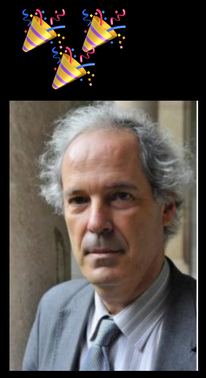
Galactic PeVatron Candidate?

e1-e2: hard X-ray spectra
(same for w1-w2)
Synchrotron emission
E >~300 TeV, B~6-15 uG

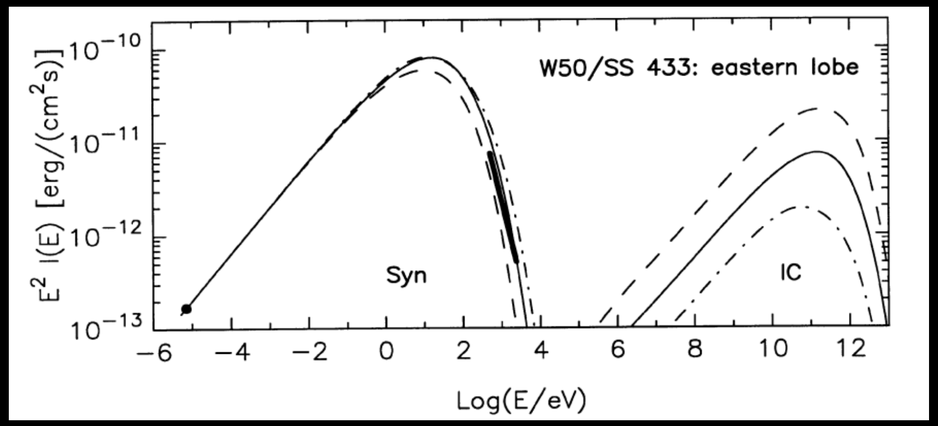
$\sim 15\ \mu$G. The detection of X-rays from W50 up to energies $E_\gamma \geq 50$ keV implies electron energies, E_e, given by $(E_e/10$ TeV$) \sim 0.5(B/1$ mG$)^{-1/2}(E_\gamma/1$ keV$)^{1/2}$. For an estimated field of 6–15 μG, the corresponding electron energies are ~300–450 TeV. This would imply that W50 is an important site for acceleration of cosmic rays. This can be tested for by looking for TeV γ-rays. At the EGRET energies (30

Safi-Harb & Ogelman (1997) *Safi-Harb & Petre (1999)*

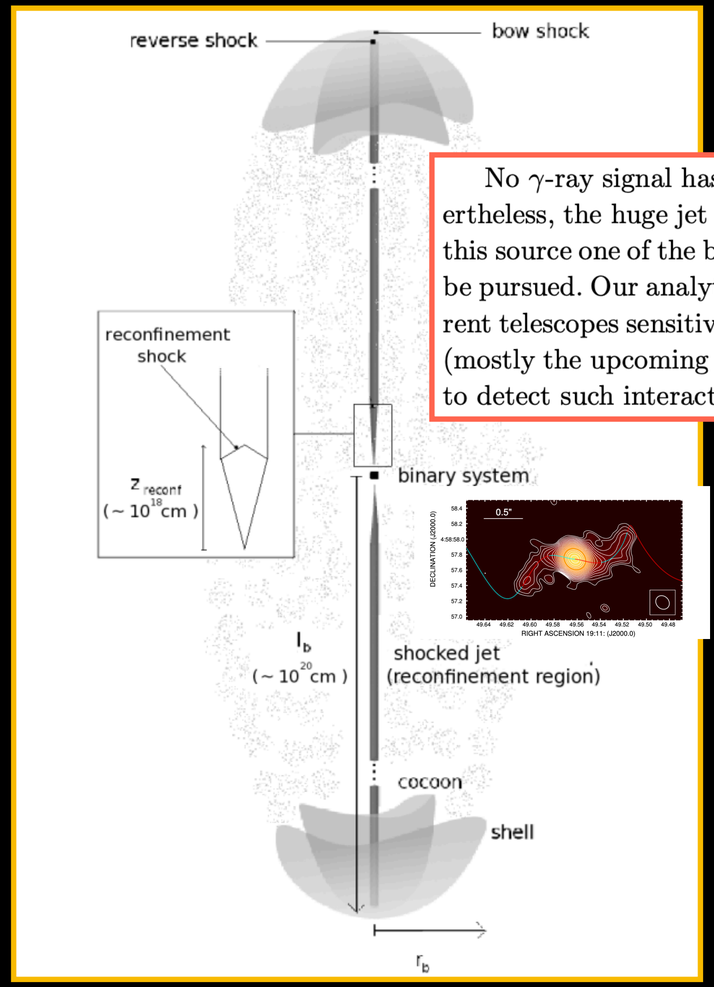
Motivated by non-thermal X-rays and modelling efforts, the hunt for TeV gamma-rays with IACTs started some 25 yrs ago!



Josep Maria Paredes+ & SS 433



Aharonian & Atoyan, New Astronomy Reviews (1998)
γ-rays from galactic sources with relativistic jets



No γ-ray signal has been found from the SS 433/W50 interaction regions. Nevertheless, the huge jet kinetic power and the high density of the W50 nebula, make this source one of the best microquasar/ISM interaction TeV-emitting candidates to be pursued. Our analytical treatment predicts fluxes that are slightly below the current telescopes sensitivity. Nevertheless, the improvement of the Cherenkov facilities (mostly the upcoming MAGIC and H.E.S.S. upgrades) could bring the opportunity to detect such interaction structures in the TeV regime for the first time.

*Marti+**Paredes**, 2015, ALMA*

Gamma-rays from SS 433 and its interaction with the W50 nebula

arXiv: 1011.2130

Pol Bordas

Departament d'Astronomia i Meteorologia and Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (UB/IEEC), Martí i Franquès 1, E08028 Barcelona, Spain
pbordas@am.ub.es

Valentí Bosch-Ramon

Max Planck Institut für Kernphysik, Saupfercheckweg 1, D69117 Heidelberg, Germany
vbosch@mpi-hd.mpg.de

Josep Maria Paredes

Departament d'Astronomia i Meteorologia and Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (UB/IEEC), Martí i Franquès 1, E08028 Barcelona, Spain
jmparedes@ub.edu

Non-thermal emission from microquasar/ISM interaction

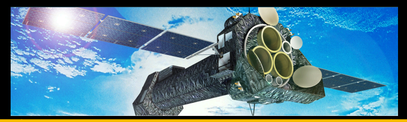
P. Bordas[1], V. Bosch-Ramon[2], J. M. Paredes[1], and M. Perucho[3]

[1] Departament d'Astronomia i Meteorologia and Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (UB/IEEC), Martí i Franquès 1, 08028 Barcelona, Spain
e-mail: pbordas@am.ub.es
[2] Max Planck Institut für Kernphysik, Saupfercheckweg 1, Heidelberg 69117, Germany
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Received 11 August 2008 / Accepted 11 December 2008

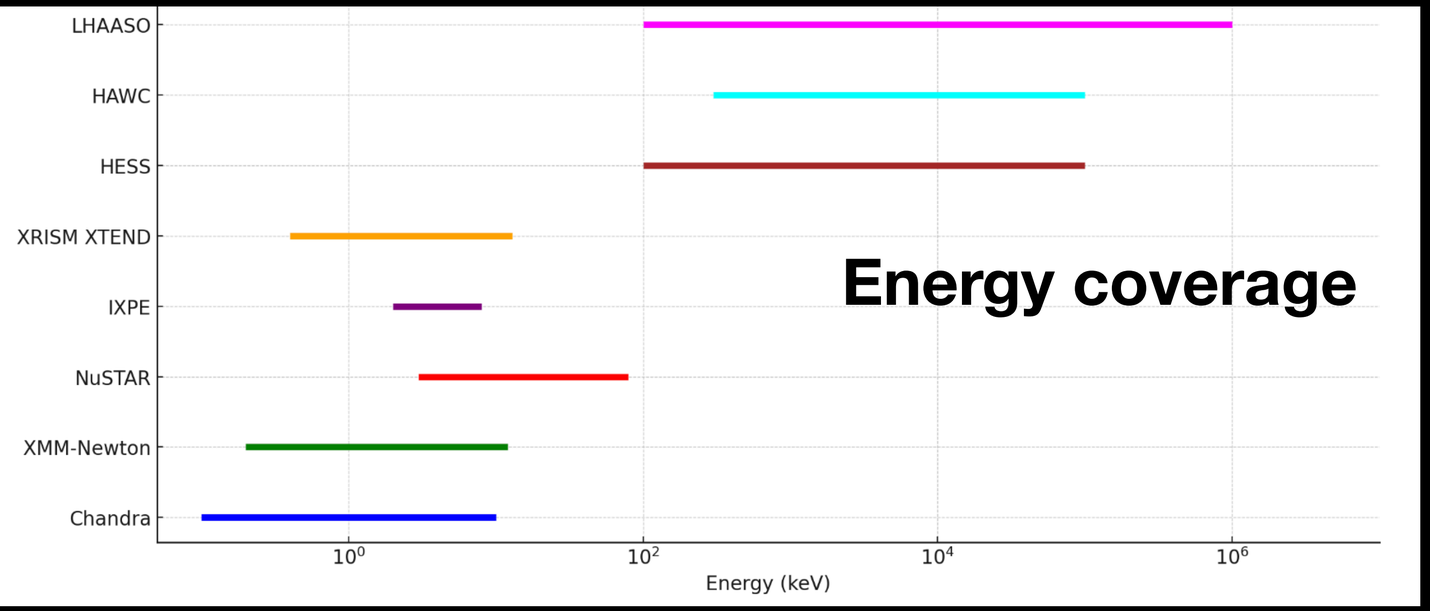
*Bordas, Bosch-Ramon, **Paredes**, Perucho+2009*

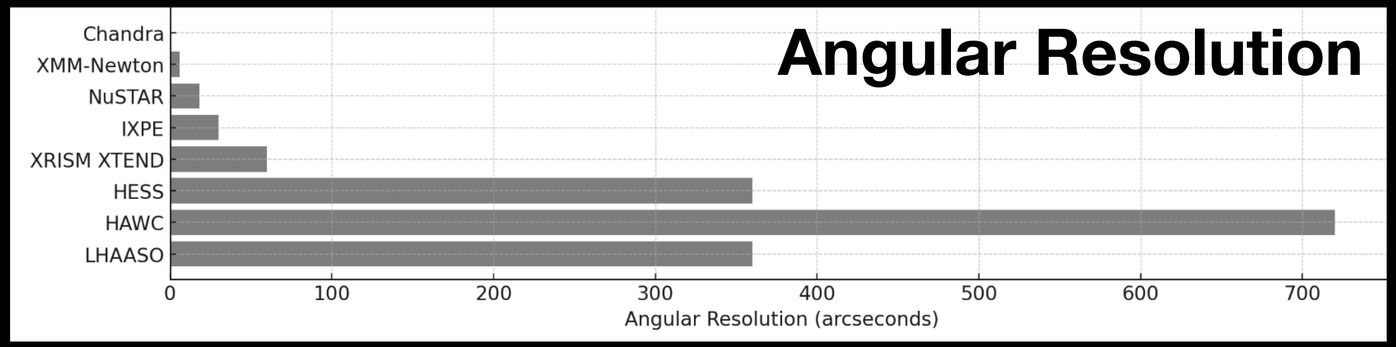
Current X-ray Missions

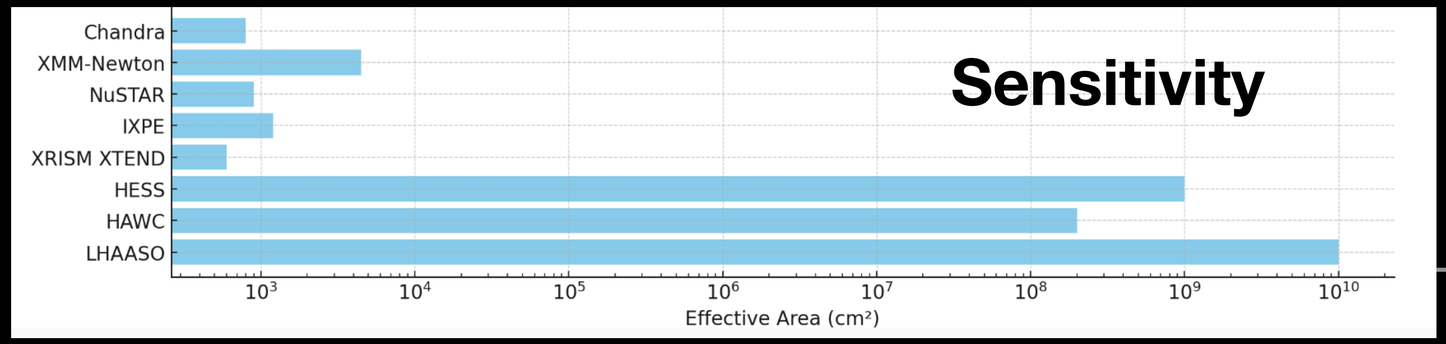


	Chandra	XMM-Newton	NuSTAR	IXPE *Polarimetry*	XRISM Xtend
Launch Date	July 1999	Dec 1999	June 2012	Dec 2021	Sep 2023
Energy Range	0.1-10 (keV)	0.2-12 (keV)	3-79 (keV)	2-8 (keV)	0.4-12 (keV)
Angular Resolution	~1” (ACIS)	6” (FWHM)	18" (FWHM)	6.4” (FWHM)	<1.3’
Field of View	17’ x 17’	sensitive to low surface brightness 30’	12’	12.9’	38’ x 38’ low background

X-ray and gamma-ray missions







X-rays are crucial

- ★ **Imaging**: site of particle acceleration
- ★ **Spectroscopy**: acceleration process
  - synchroton (X), ICS => leptonic
  - secondary electrons (X), pion decay=>hadronic
- **Polarization**: Magnetic Field (B)

X-ray campaign

(re-)ignited by HAWC

- **SS 433-W50 Interaction**
  - Safi-Harb+22 (East, e1-e3, XMM and NuSTAR)
  - Kayama+22 (West, w1-w2, Chandra)
  - Kaaret+23 (head-e1, IXPE)
  - Chi+25 (North-shell, XMM)
  - Mac Intyre+ *in prep* (West, XMM+NuSTAR, E-W comparison; modelling+SED)
  - Tsuji+ *in prep* (proper motion, West+East, Chandra)
- V4641 Sgr and its enviromnent
  - Suzuki+25, XRISM (Xtend)
  - Proposal to survey (XMM, NuSTAR, Chandra): Kaya Mori, NaomiTsuji+

The Astrophysical Journal, 935:163 (14pp), 2022 August 20 https://doi.org/10.3847/1538-4357/ac7c05

Hard X-Ray Emission from the Eastern Jet of SS 433 Powering the W50 "Manatee" Nebula: Evidence for Particle Reacceleration

Samar Safi-Harb[1], Brydyn Mac Intyre[1], Shuo Zhang[2], Isaac Pope[3], Shuhan Zhang[3], Nathan Saffold[4], Kaya Mori[3], Eric V. Gotthelf[3], Felix Aharonian[5,6], Matthew Band[1,7], Chelsea Braun[1], Ke Fang[8], Charles Hailey[3], Melania Nynka[9], and Chang D. Rho[10]

The Astrophysical Journal Letters, 961:L12 (8pp), 2024 January 20 https://doi.org/10.3847/2041-8213/ad103b

X-Ray Polarization of the Eastern Lobe of SS 433

Philip Kaaret[1], Riccardo Ferrazzoli[2], Stefano Silvestri[3], Michela Negro[4], Alberto Manfreda[5], Kinwah Wu[6], Enrico Costa[2], Paolo Soffitta[2], Samar Safi-Harb[7], Juri Poutanen[8], Alexandra Veledina[8,9], Alessandro Di Marco[2], Patrick Slane[10], Stefano Bianchi[11], Adam Ingram[12], Roger W. Romani[13], Nicolò Cibrario[14,15], Brydyn Mac Intyre[7],

(et al.)

The Astrophysical Journal Letters, 975:L28 (16pp), 2024 November 10 https://doi.org/10.3847/2041-8213/ad84ed

An X-Ray Shell Reveals the Supernova Explosion for Galactic Microquasar SS 433

Yi-Heng Chi (池奕恒)[1], Jiahui Huang (黄佳辉)[2,3], Ping Zhou (周平)[1,4], Hua Feng (冯骅)[5], Xiang-Dong Li (李向东)[1,4], Sera B. Markoff[6,7], Samar Safi-Harb[8], and Laura Olivera-Nieto[9]

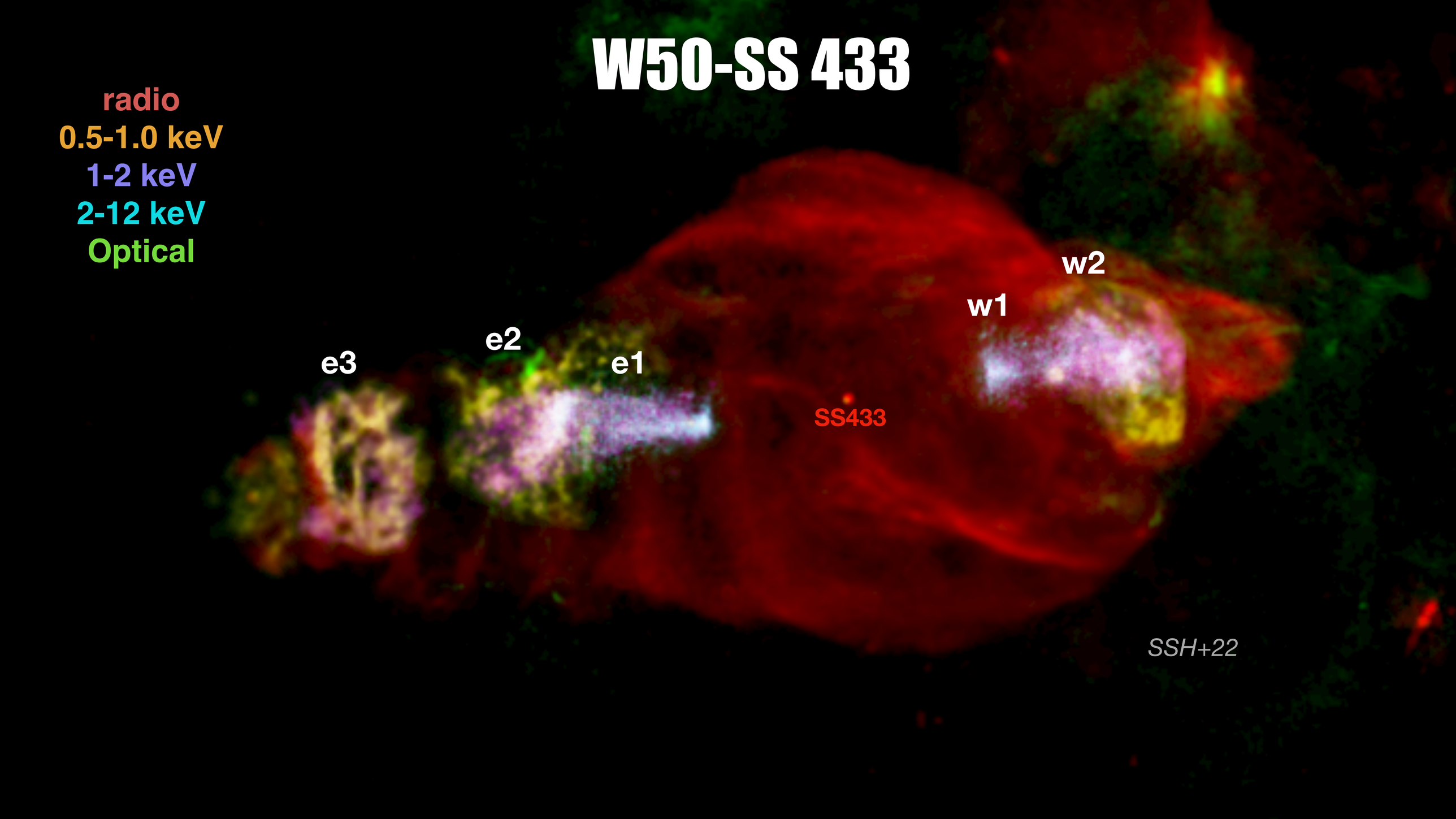
The Astrophysical Journal Letters, 978:L20 (7pp), 2025 January 10 https://doi.org/10.3847/2041-8213/ad9d11

Detection of Extended X-Ray Emission around the PeVatron Microquasar V4641 Sgr with XRISM

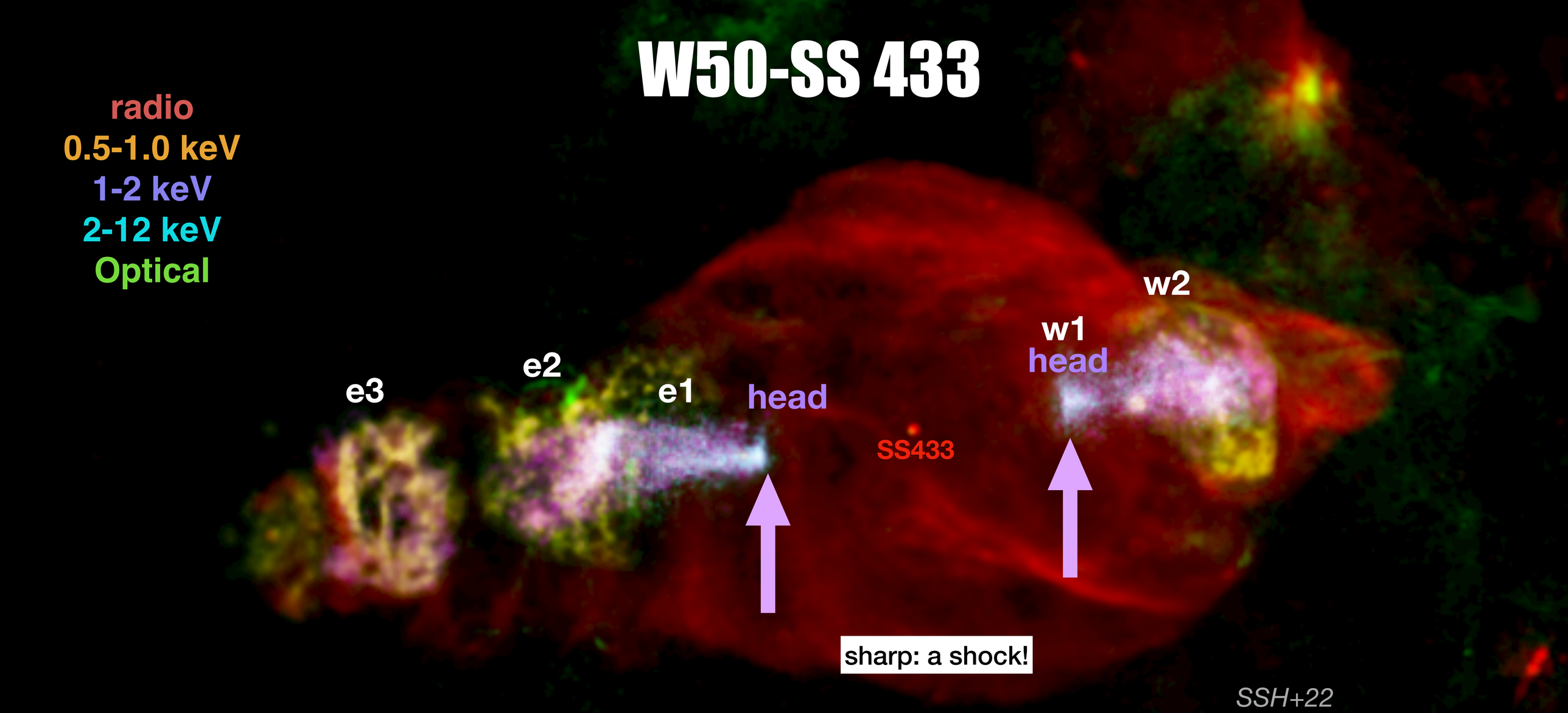
Hiromasa Suzuki[1], Naomi Tsuji[2,3], Yoshiaki Kanemaru[1], Megumi Shidatsu[4], Laura Olivera-Nieto[5], Samar Safi-Harb[6], Shigeo S. Kimura[7,8], Eduardo de la Fuente[9], Sabrina Casanova[10], Kaya Mori[11], Xiaojie Wang[12], Sei Kato[13,29], Dai Tateishi[14], Hideki Uchiyama[15], Takaaki Tanaka[16], Hiroyuki Uchida[17], Shun Inoue[17], Dezhi Huang[18], Marianne Lemoine-Goumard[19], Daiki Miura[1,14], Shoji Ogawa[1], Shogo B. Kobayashi[20], Chris Done[21], Maxime Parra[22,23], Maria Díaz Trigo[24], Teo Muñoz-Darias[25,26], Montserrat Armas Padilla[25,26], Ryota Tomaru[27], and Yoshihiro Ueda[28]

Radio/molecular cloud observations ongoing

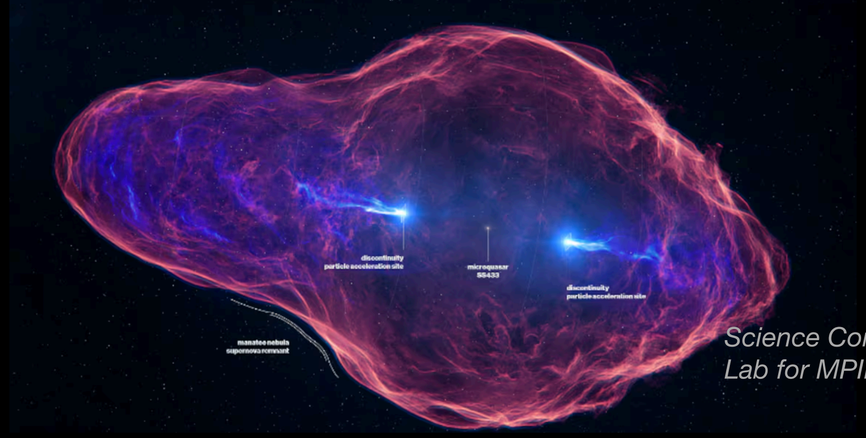
W50-SS 433


radio
0.5-1.0 keV
1-2 keV
2-12 keV
Optical
e3
e2
e1
SS433
w1
w2
SSH+22

W50-SS 433

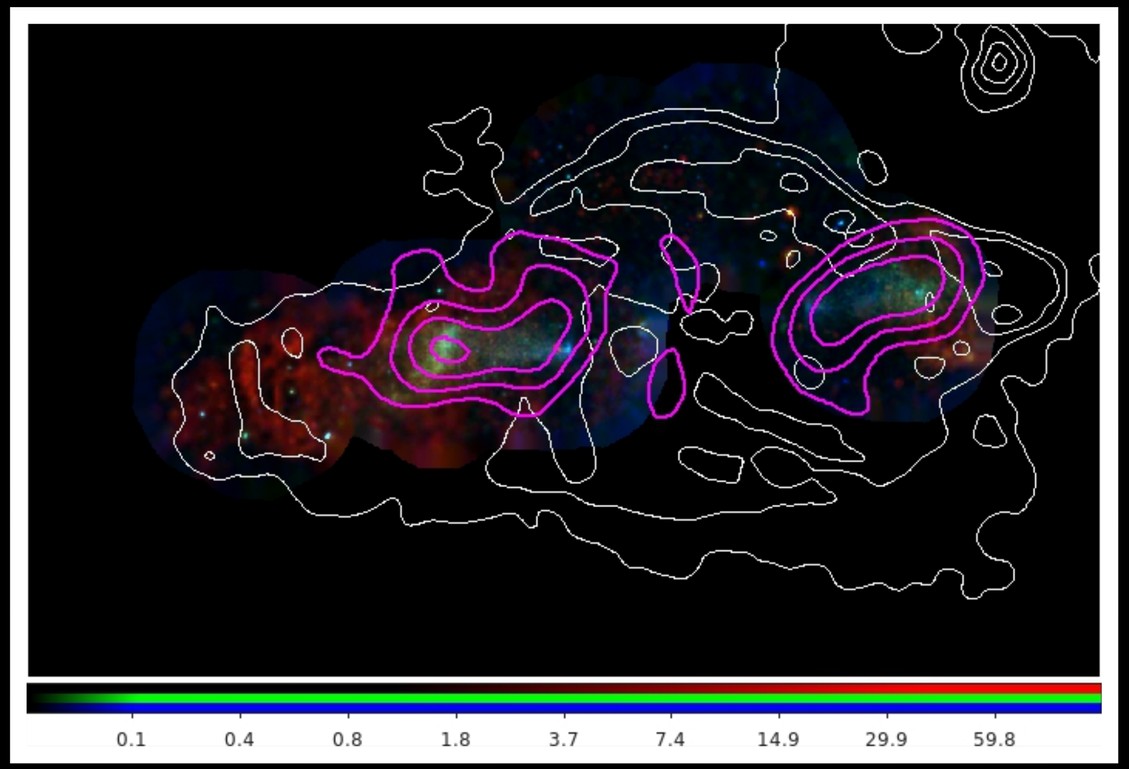


The ‘head’ where the jet reappears —
particle acceleration regions resolved!
~29 (east)/27 pc (west) from SS433

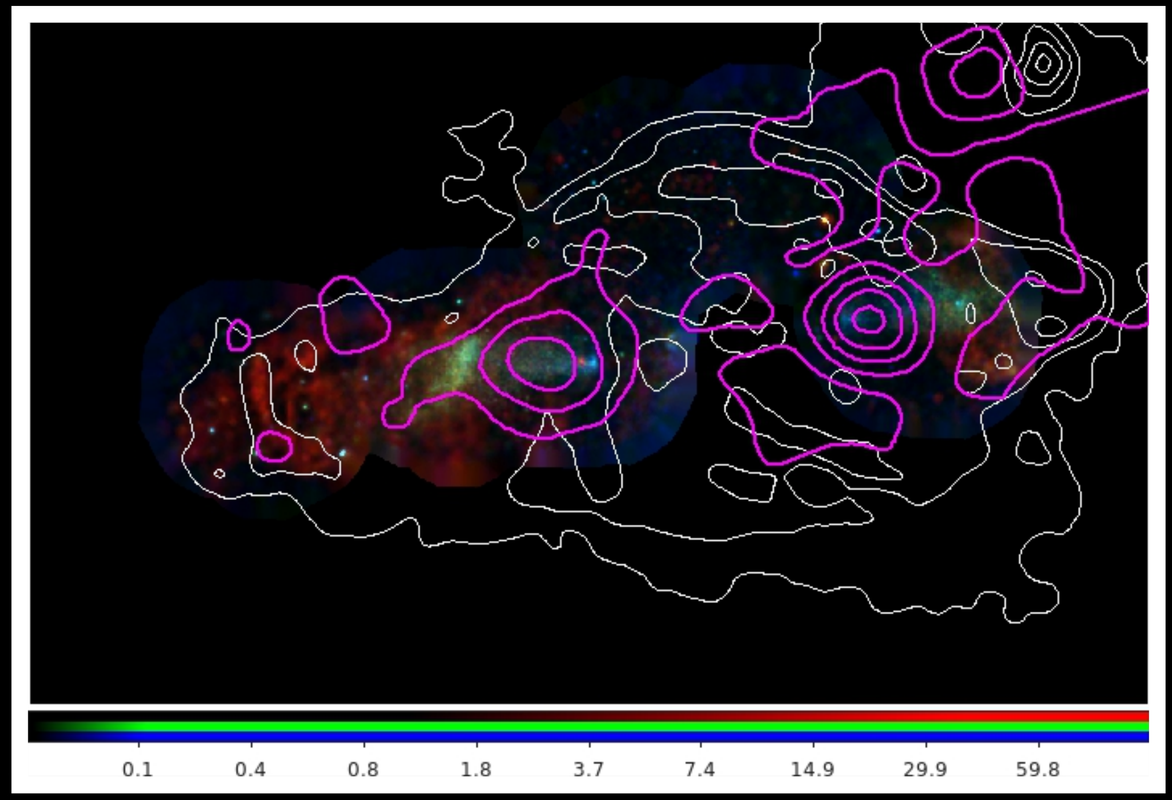


Science Communication
Lab for MPIK/H.E.S.S.

broadband HESS contours

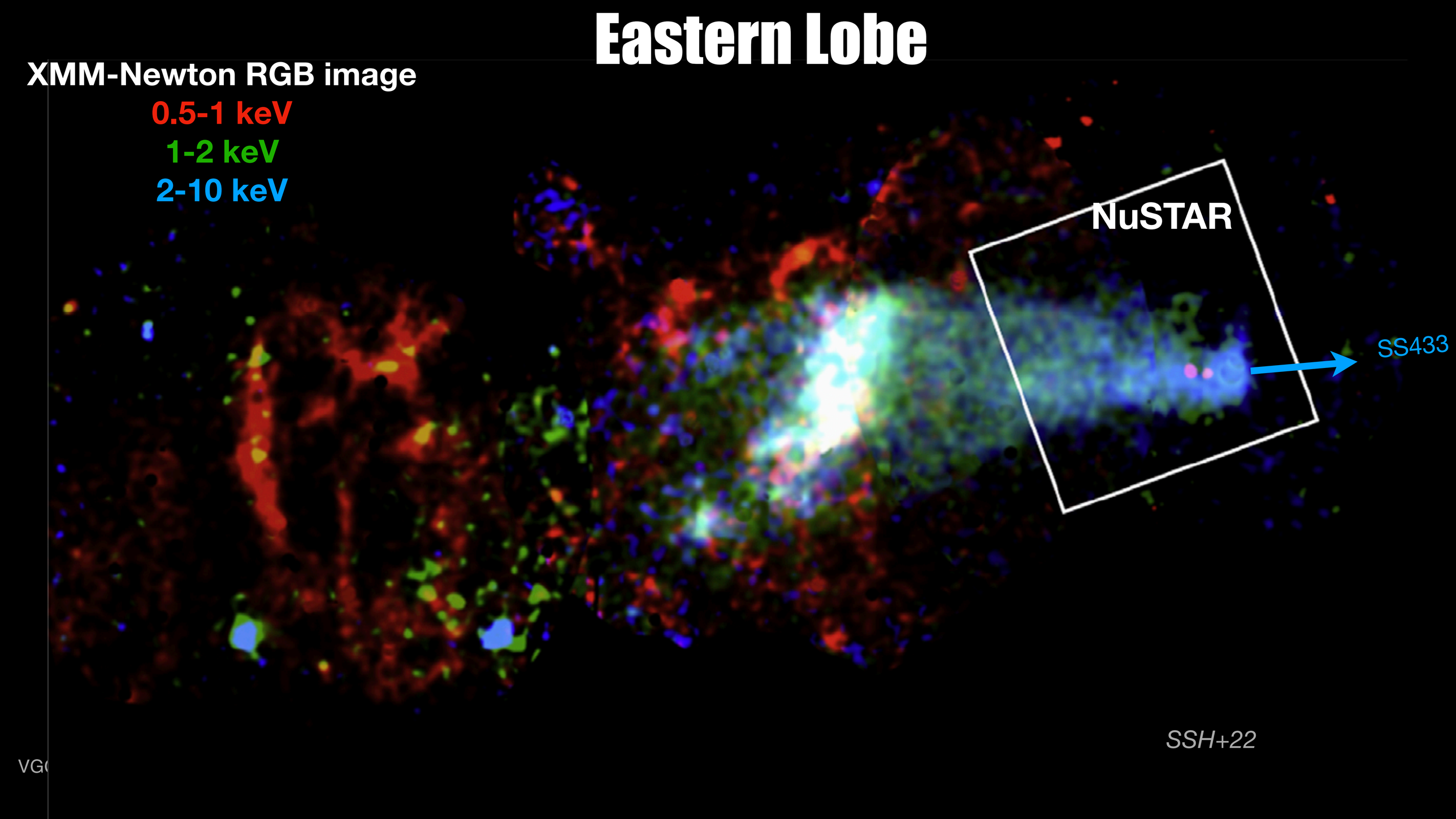


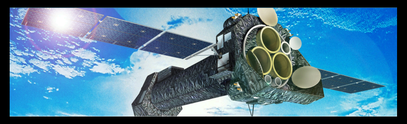
>10 TeV HESS contours

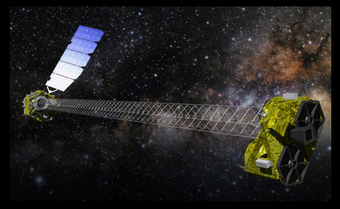


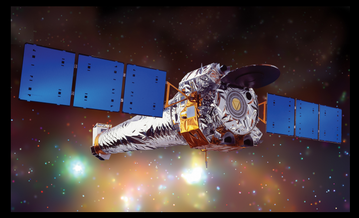
XMM-Newton RGB image with HESS Contours

Eastern Lobe



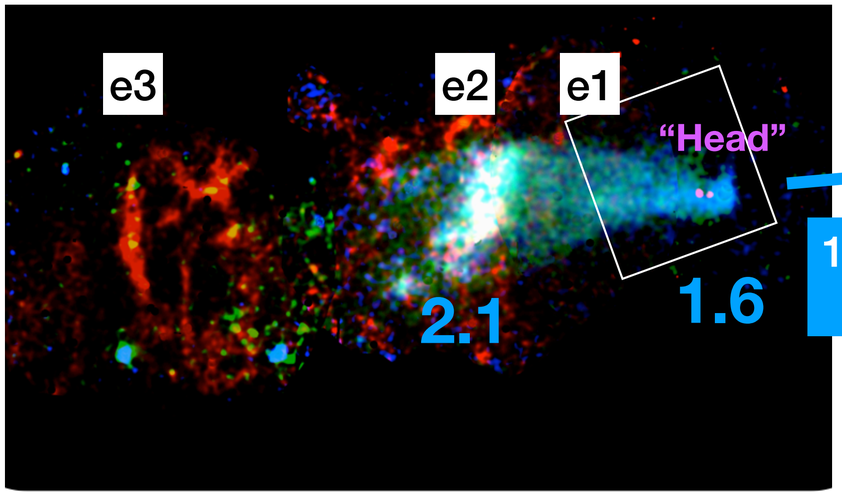






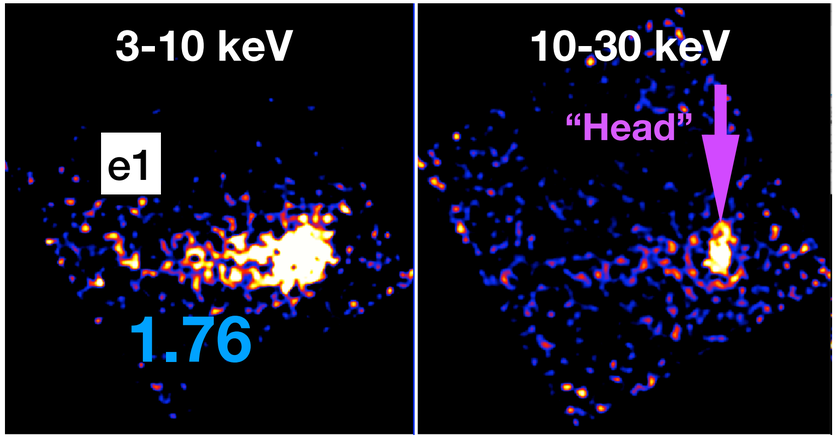
Eastern Lobe

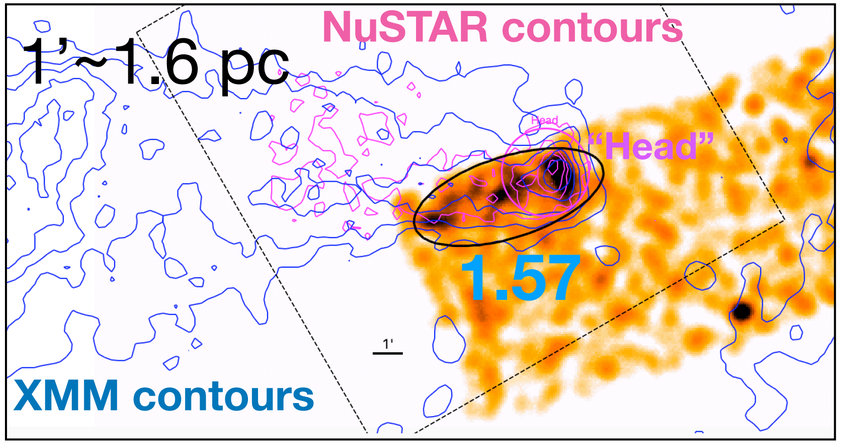
e2



SS433

18' (29 pc) east of SS 433





XMM-Newton RGB image

0.5-1 keV

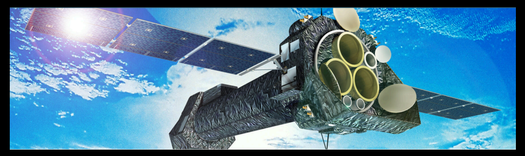
1-2 keV

2-10 keV

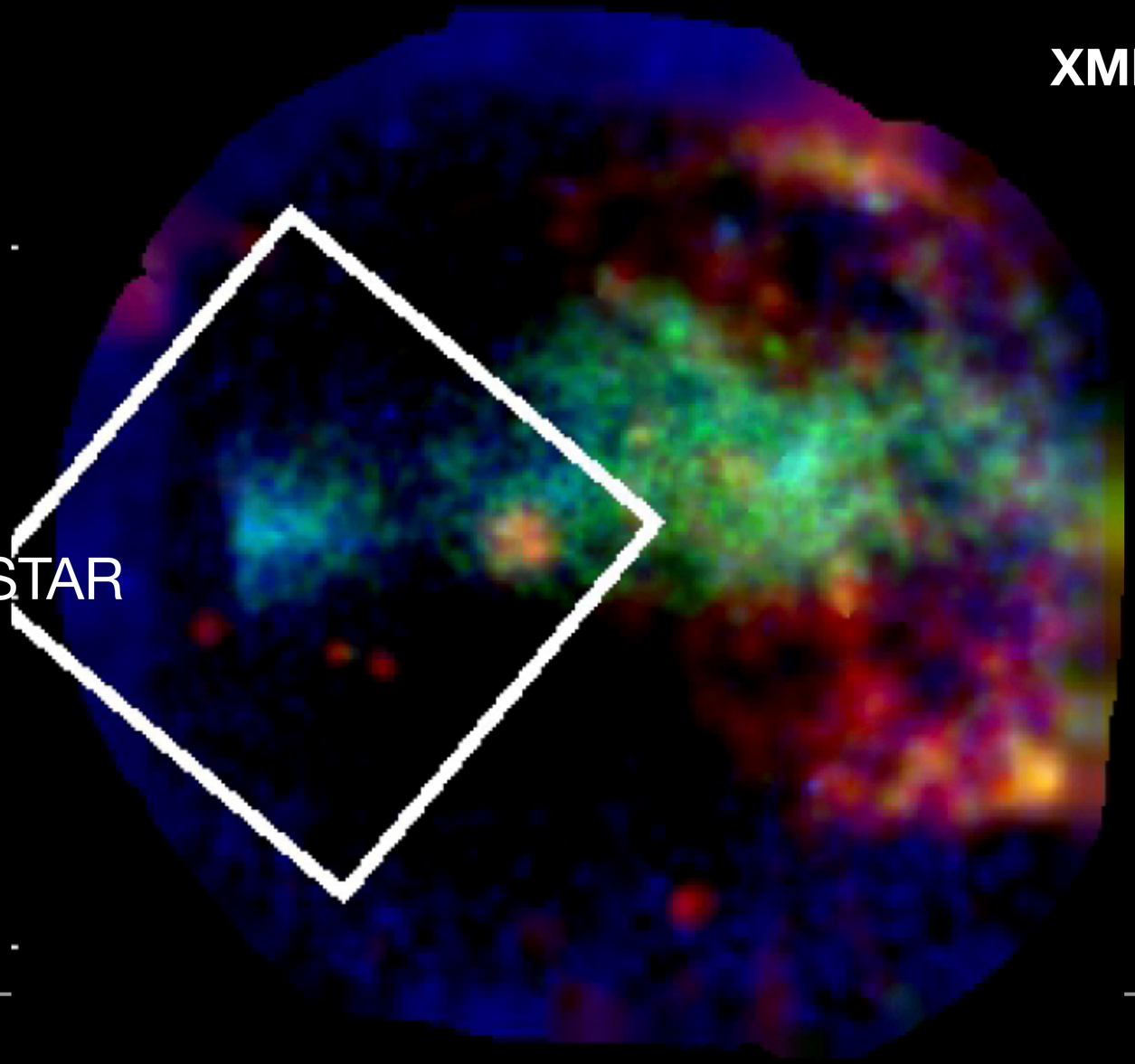
Head Photon Index=1.58+/-0.05
(XMM+NuSTAR, 0.5-30 keV)

Photon Index (Chandra)=1.57+/-0.39
(0.5-8 keV)

similar to what is seen in PWNe and some AGN jets



Western Lobe

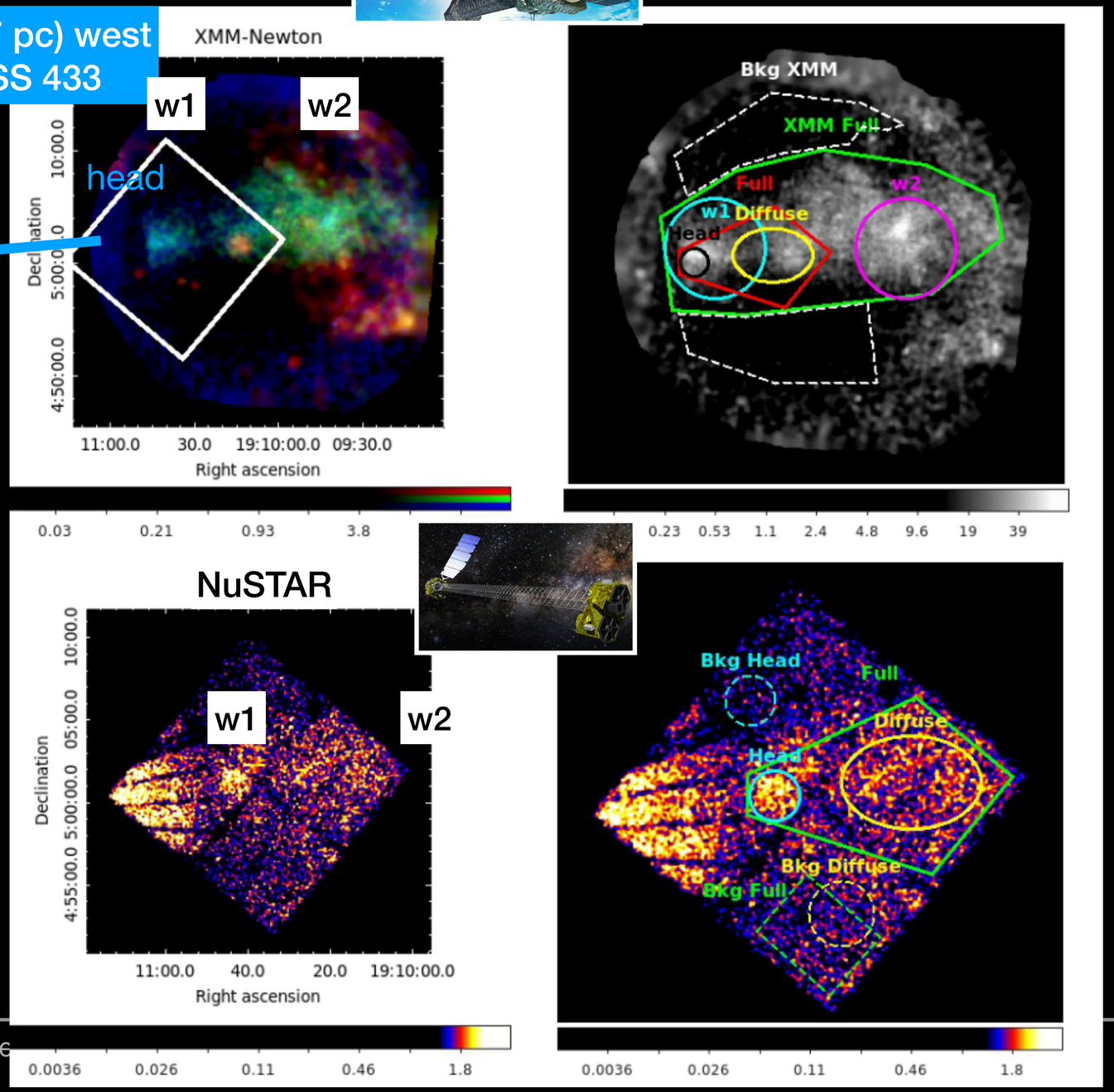


Mac Intyre+, in prep

Western Lobe

17’ (27 pc) west of SS 433

SS433



XMM-Newton RGB image

0.5-1 keV

1-2 keV

2-10 keV

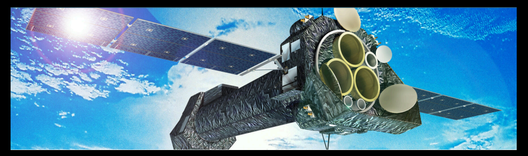
Region	Photon Index
Head	1.55+/-0.07
Diffuse	1.67+/-0.04
Full	1.72+/-0.03
w1	1.71+/-0.07
w2	2.10+/-0.05

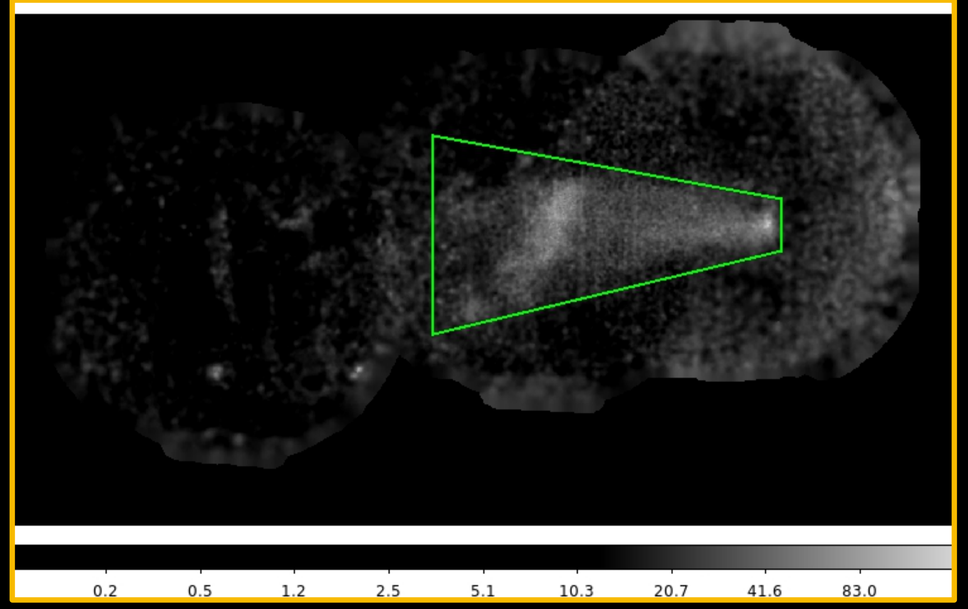
Mac Intyre+, in prep

Implications (non thermal X-rays)

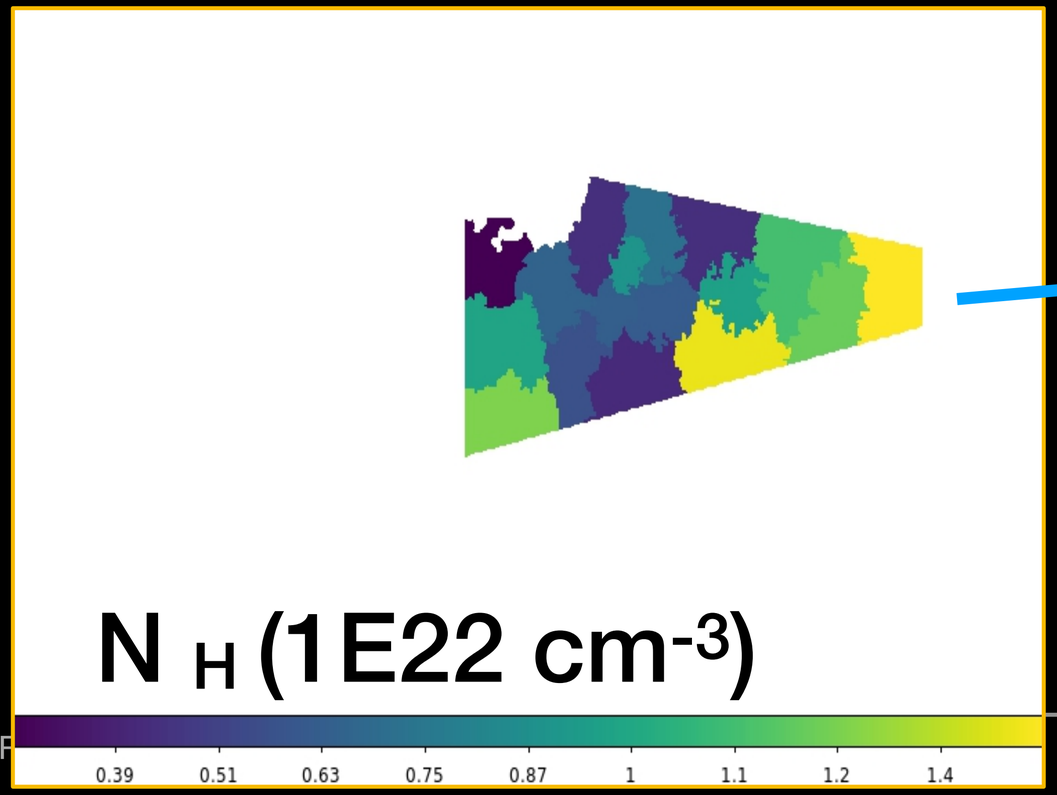
Lobe	D (pc) Accleration site	Photon Index (0.5-30 keV)	Lx (1E34 erg/s)	E_e (TeV)	B (eq) (uG)
Eastern Head	29	1.58±0.05	1.1	**250**	**12**
Western head	27	1.55±0.07	0.5	**180**	**15**

N_H and Spectral Index Maps

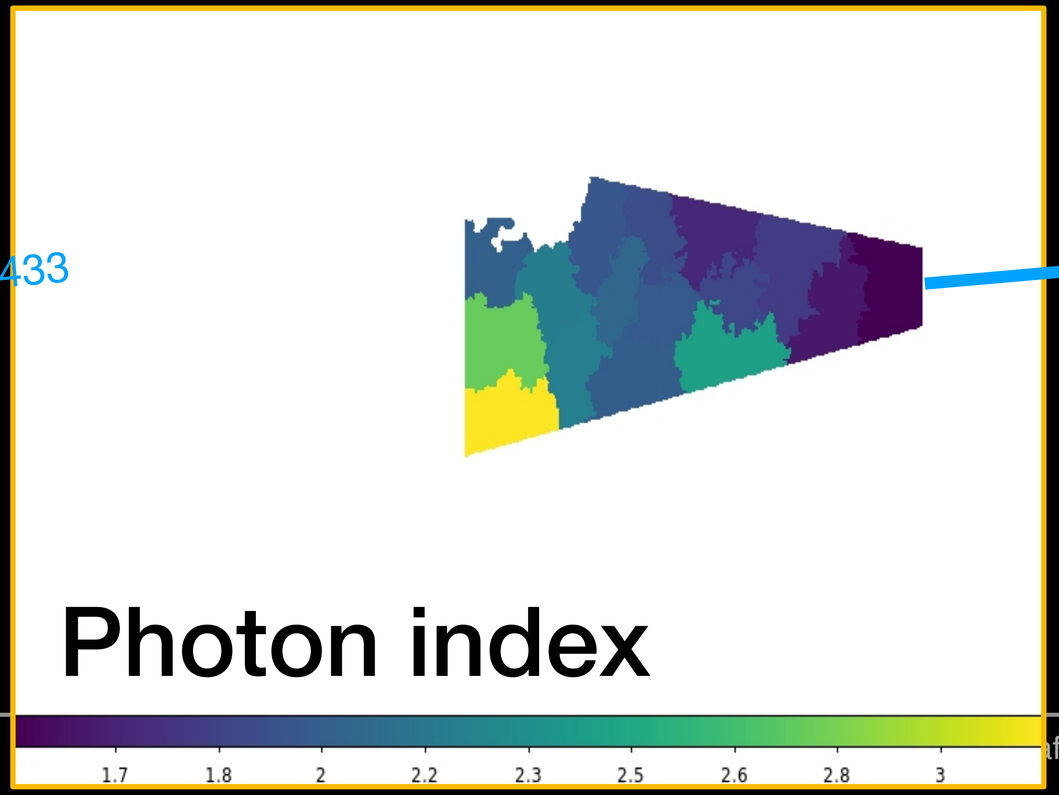




East (head-e1-e2)

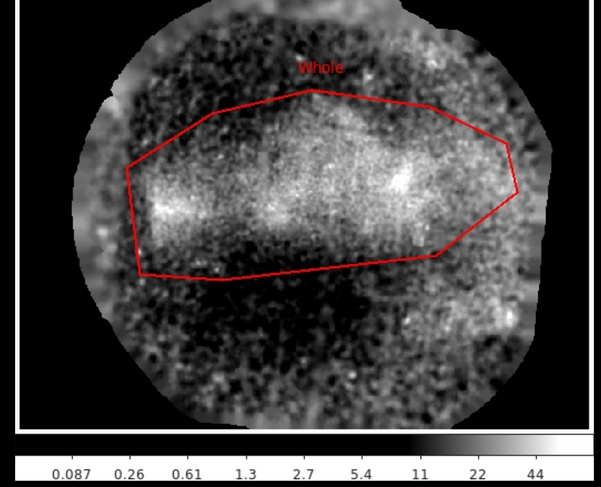


SS433



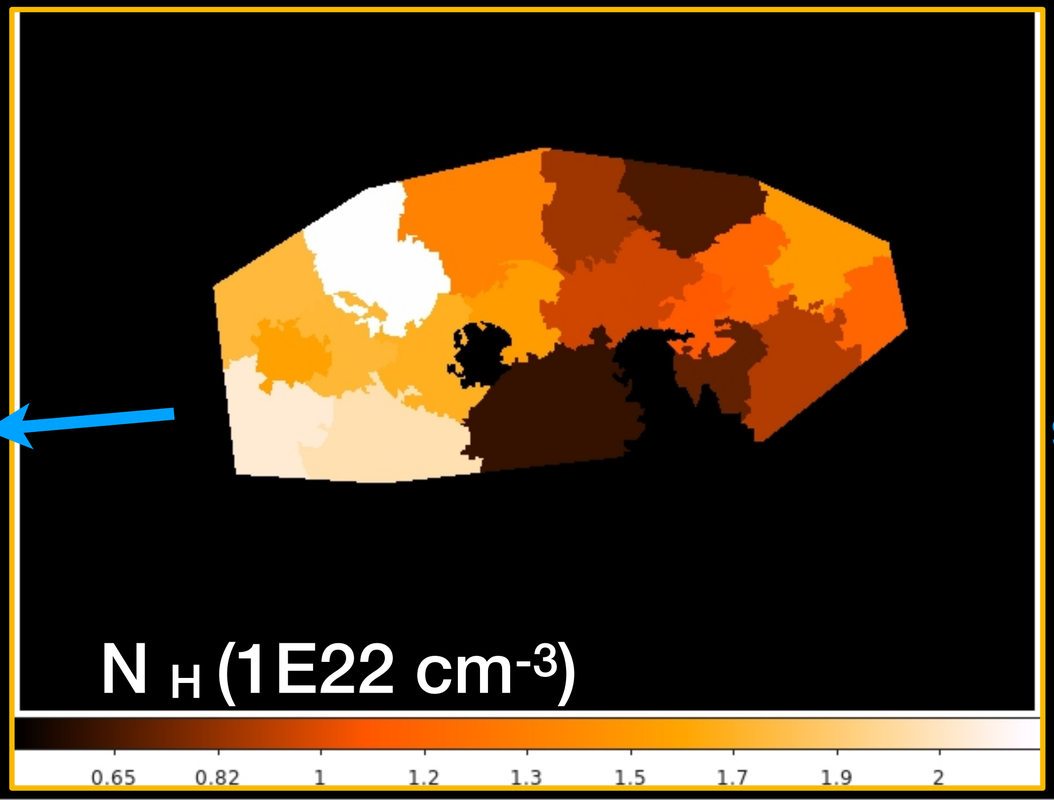
SS433

N_H and Spectral Index Maps

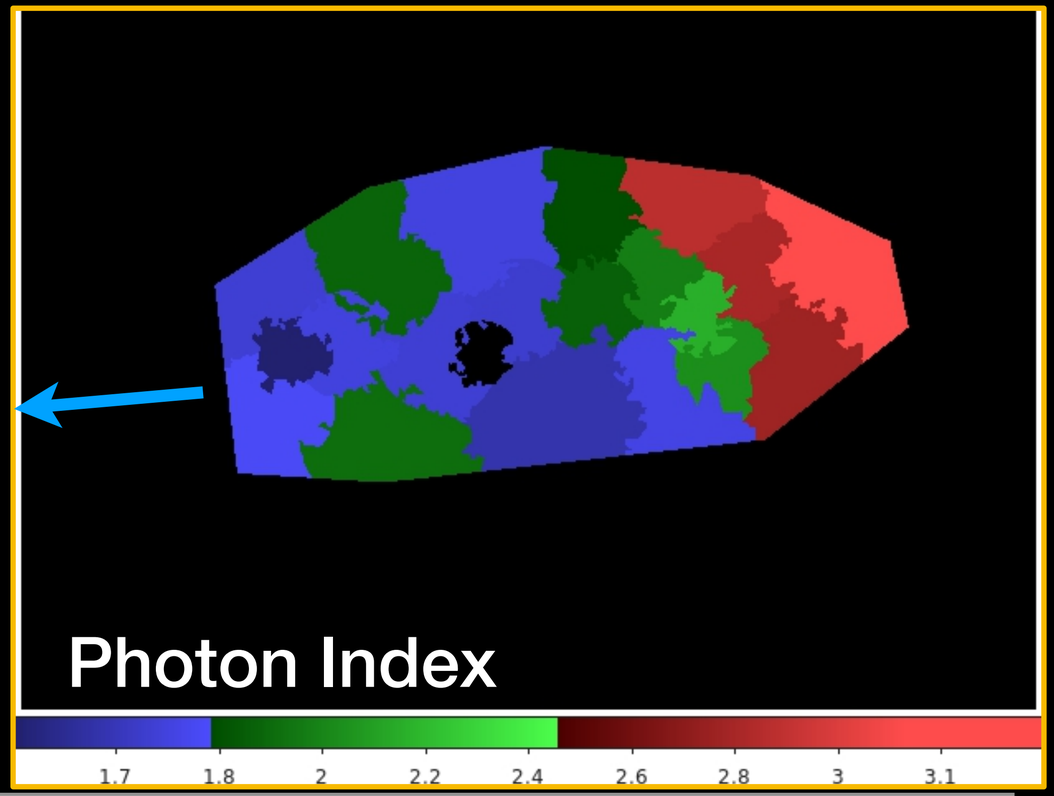


West-e1-e2

SS433

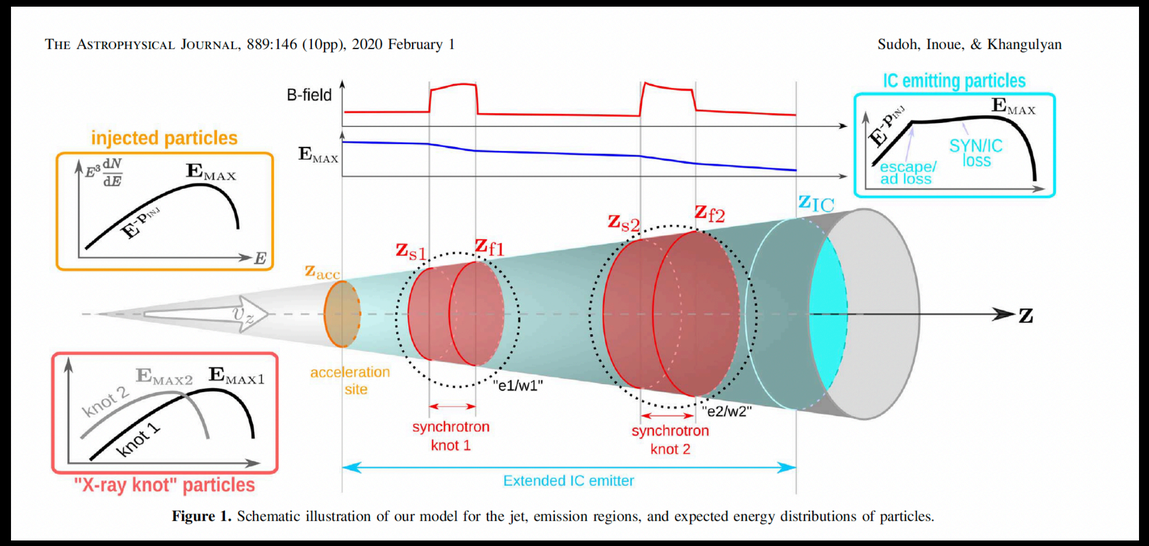


SS433



Modelling (in progress) with Dmitry Khangulyan

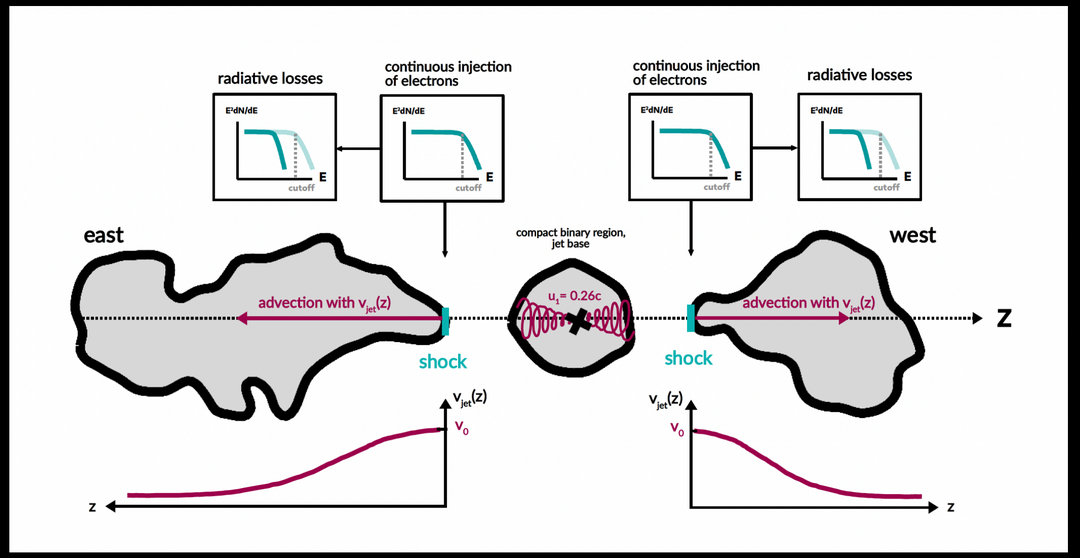
Sudoh+2020: 16 μG (e1), 9 μG (w1)



v_d~0.065-0.1c

Kayama+ (2022)

B~20 uG (e2)

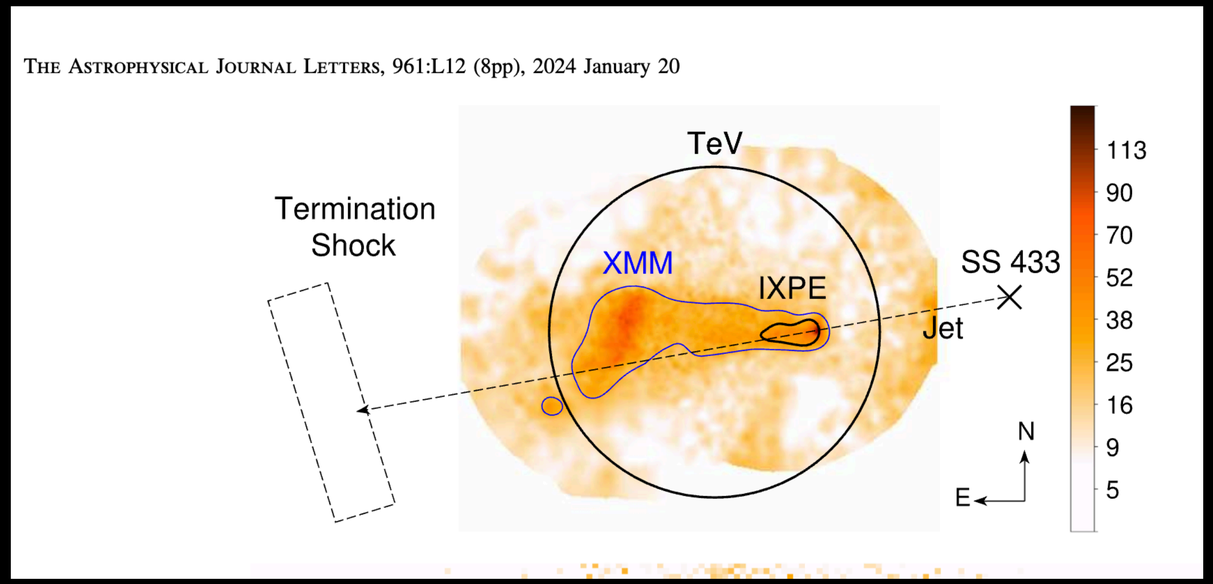


v_d~0.025-0.12c

HESS collaboration (2024)

X-ray polarization

- IXPE observed the inner eastern lobe
- Photon index (head): $\Gamma = 1.57 \pm 0.14$
- Luminosity = 1.3×10^{34} erg s^{-1} (0.3–30 keV)



➢ **Magnetic field is parallel to flow**

- Maximum PD = 70% for synchrotron with $\Gamma = 1.57$

➢ **Magnetic field is well ordered**

Similarities to (Vela) PWN and FRII jets!

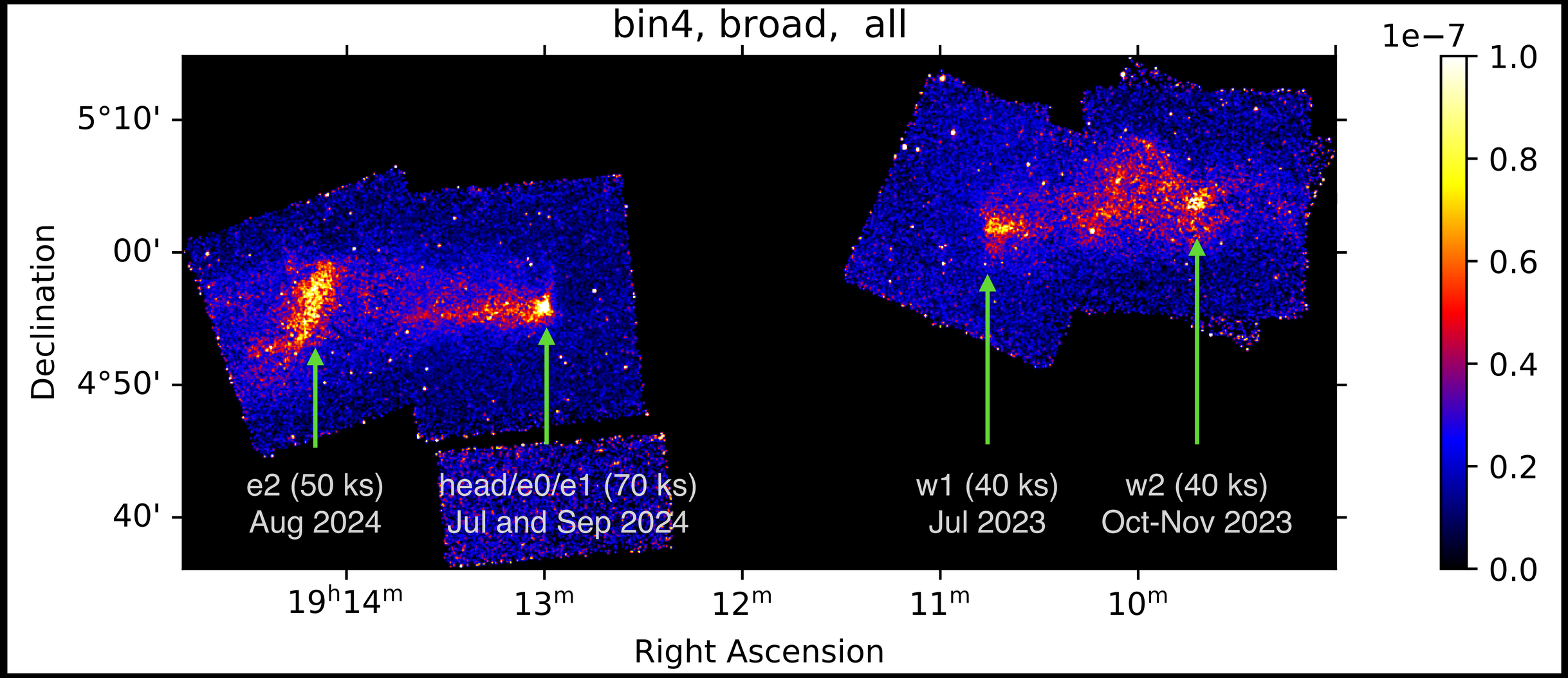
Shock acceleration at shear interfaces or at leading edge of head?

🎉 **IXPE observation of the western lobe is under way!**

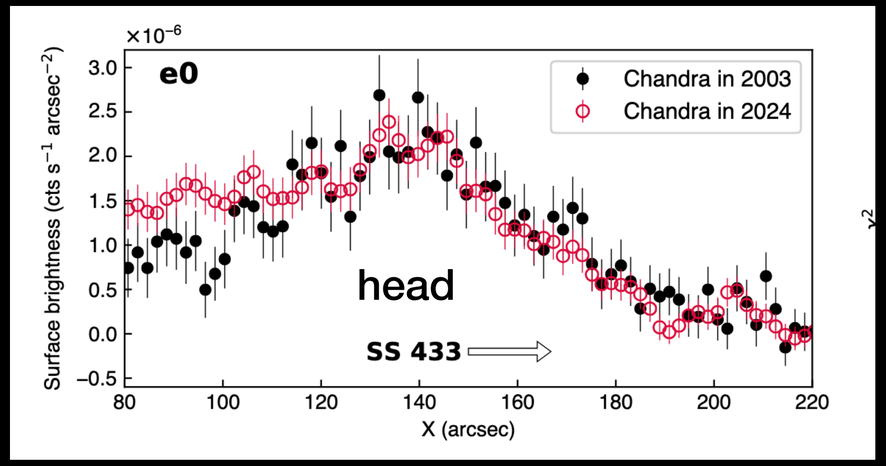
Kaaret (SSH) et al. 2023

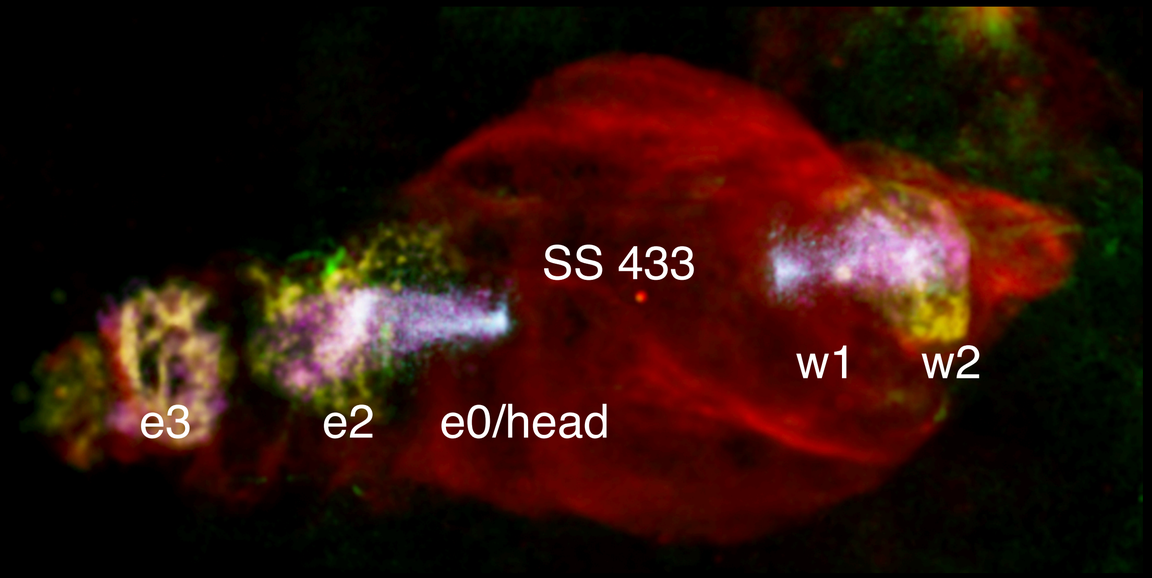
Mosaic Chandra coverage

N. Tsuji (PI), K. Mori, SSH, Y. Inoue, K. Kayama, D. Khangulyan,
L. Olivera-Nieto, T. Sudoh, T. Tanaka, T. Tsuru, H. Uchida, T. Michiyama..

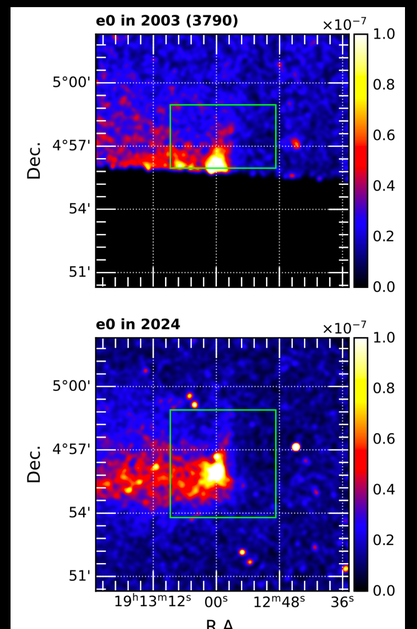


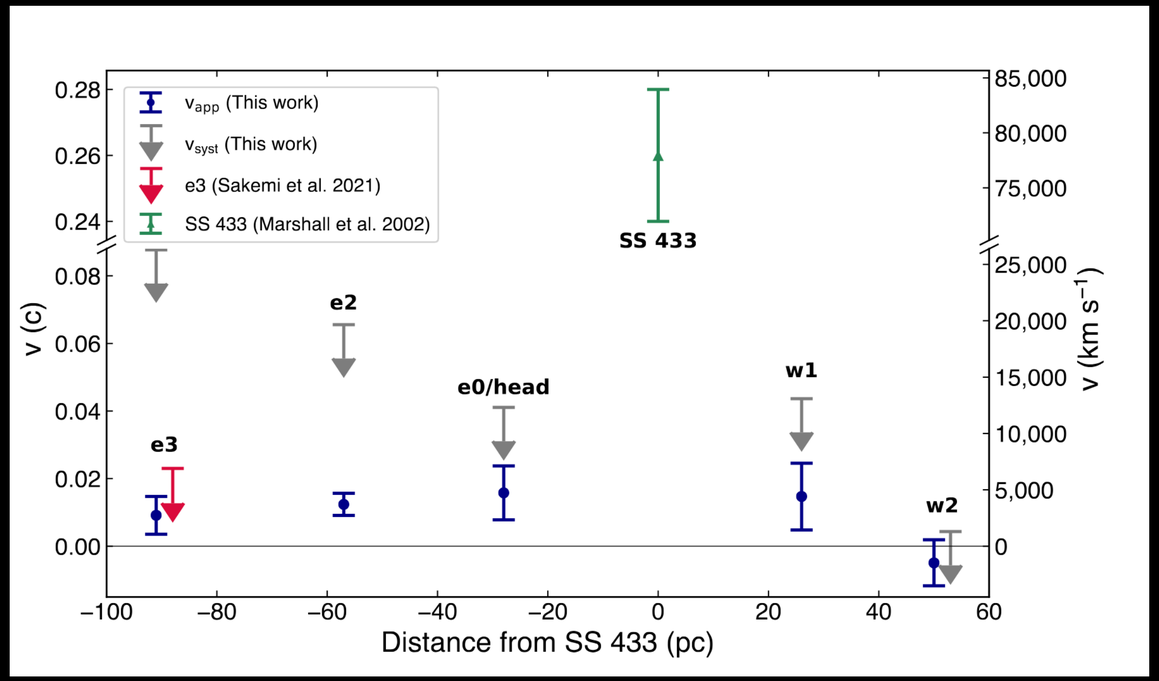
Proper Motion Measurement



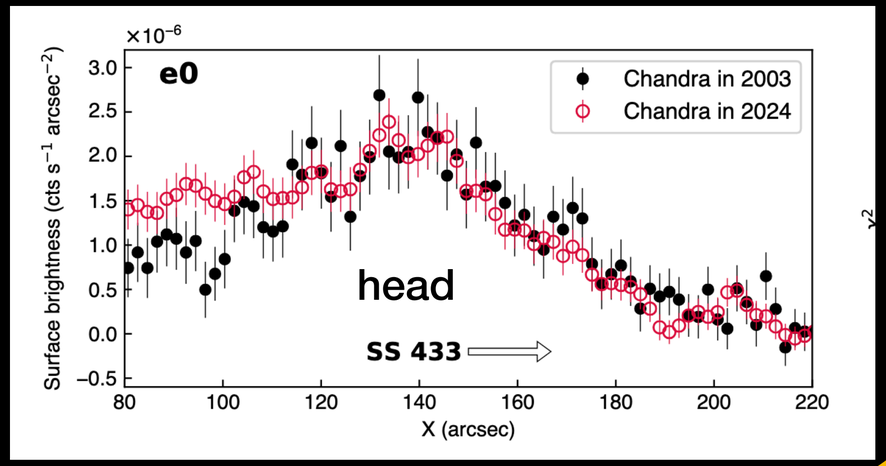


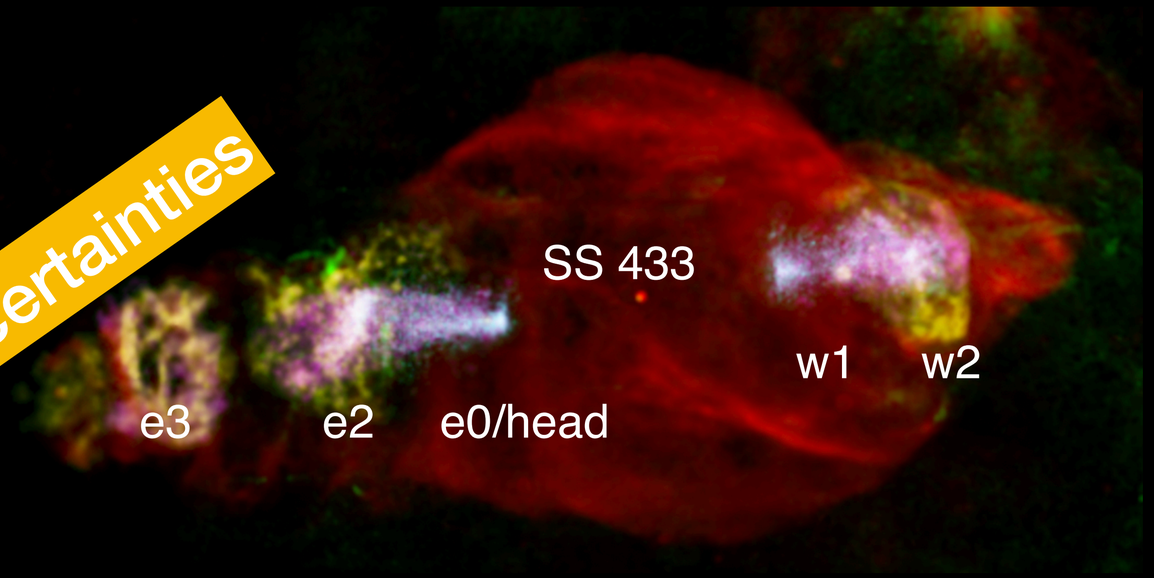
apparent motion outward





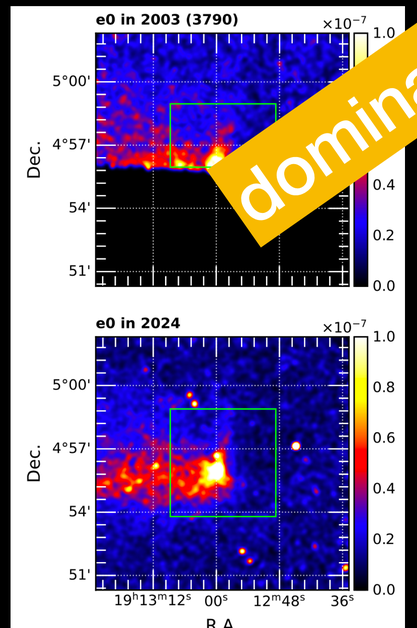
Proper Motion Measurement

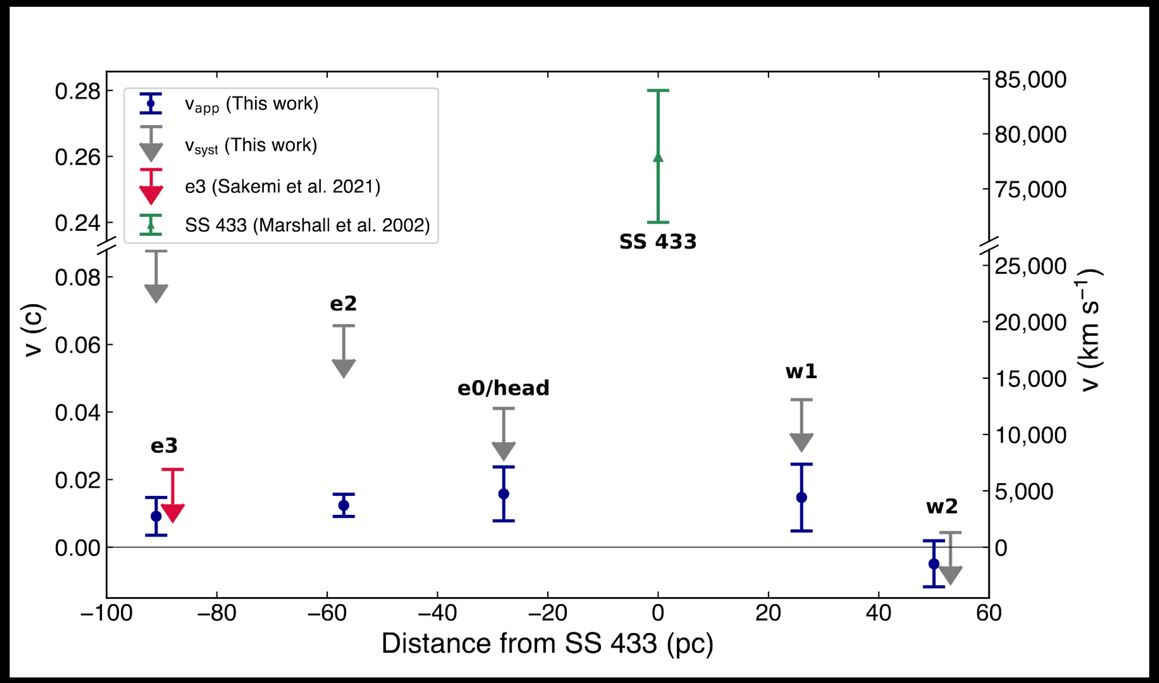




apparent motion outward

dominated by systematic uncertainties





AXIS is a huge leap forward

AXIS vs Chandra

- 5-10x larger effective area
- 6x better FoV-ave PSF

AXIS vs Swift

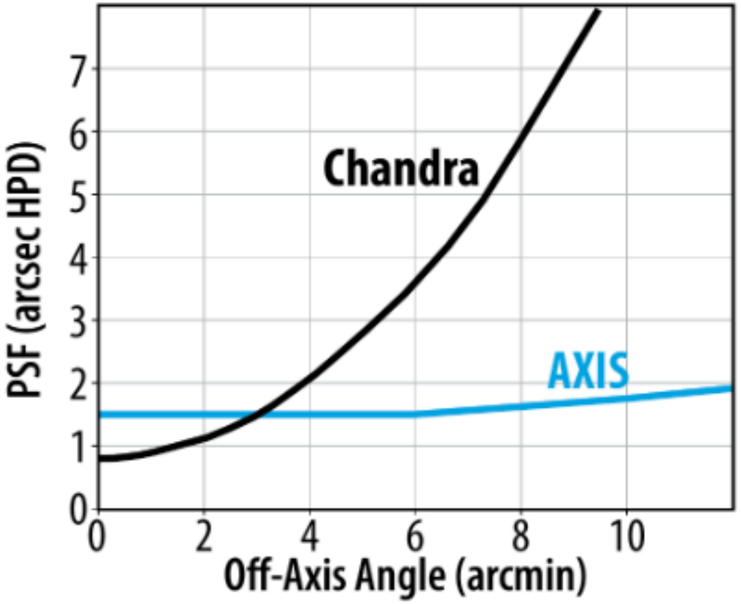
- Same fast ToO Response Time
- 60x better sensitivity

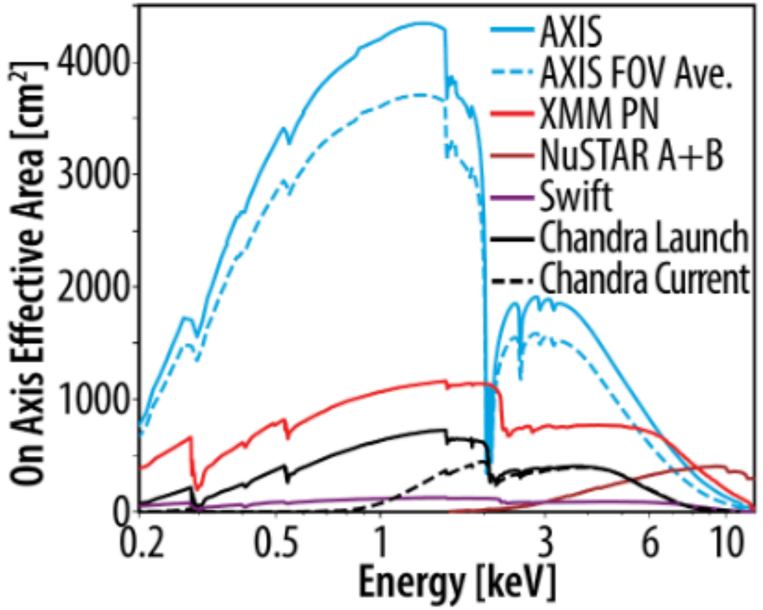
AXIS vs XMM-Newton

- 4x larger area below 2 keV
- 10x better PSF

AXIS vs NuSTAR

- Superior area below 8 keV
- 40x better PSF





AXIS has 70x the survey grasp (FoV x area) at 1.6″ than Chandra

enabling surveys that probe *further*, *wider*, and *faster*

- Phase A
- decision 2026
- Launch 2032

Zooming in on PeVatrons & uQ

Super Chandra +Super Swift!

Reynolds et al. 2023

Probing the acceleration process through proper motion studies

Zooming in on Micoquasars in the 2030's with AXIS

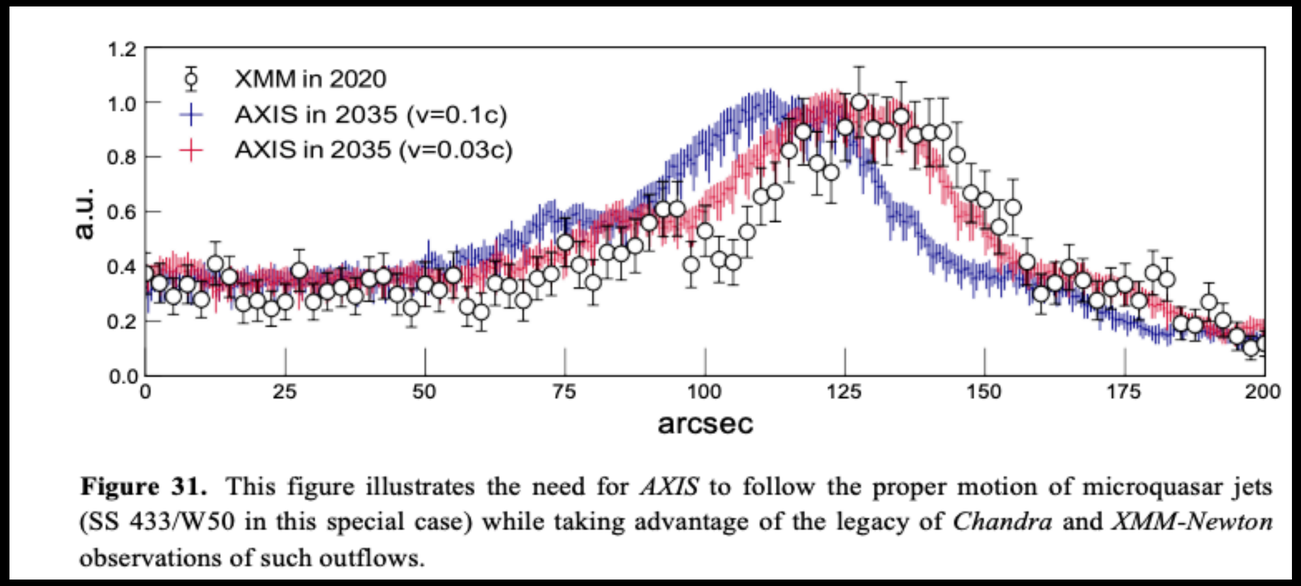
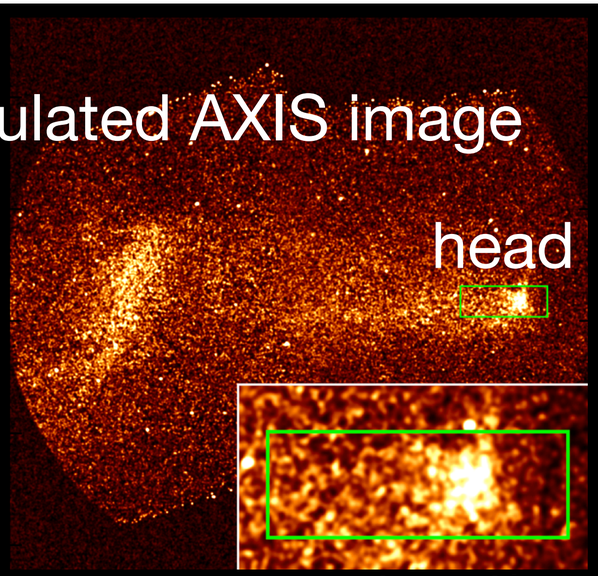
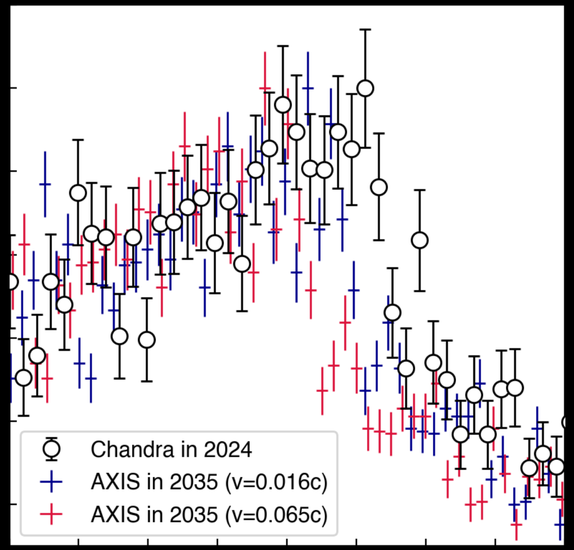


Figure 31. This figure illustrates the need for *AXIS* to follow the proper motion of microquasar jets (SS 433/W50 in this special case) while taking advantage of the legacy of *Chandra* and *XMM-Newton* observations of such outflows.

*SSH, Burdge+2023, **AXIS** White Paper*

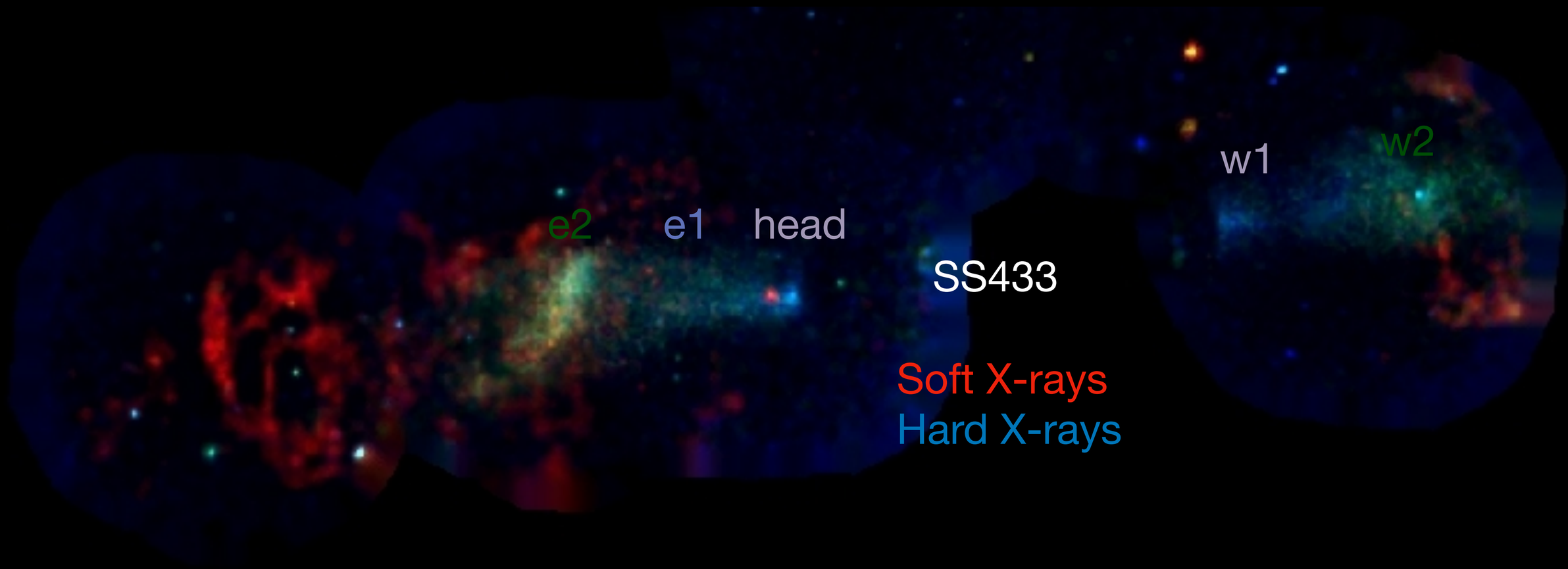




head/e0 simulation by Naomi Tsuji

W50 — Thermal X-ray emission

Thermal X-ray emission from W50



Thermal X-ray emission from W50

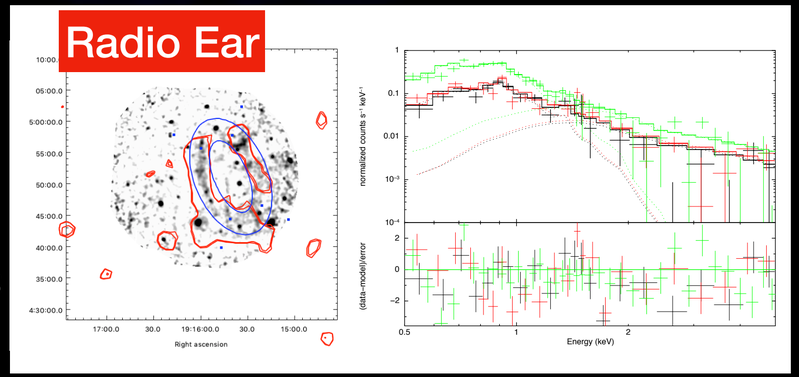
kT~0.2keV
'e3'

e2 e1 head

SS433

w1 w2

Soft X-rays
Hard X-rays



Thermal X-ray emission from W50

kT~0.2keV
'e3'

e2 e1 head

SS433

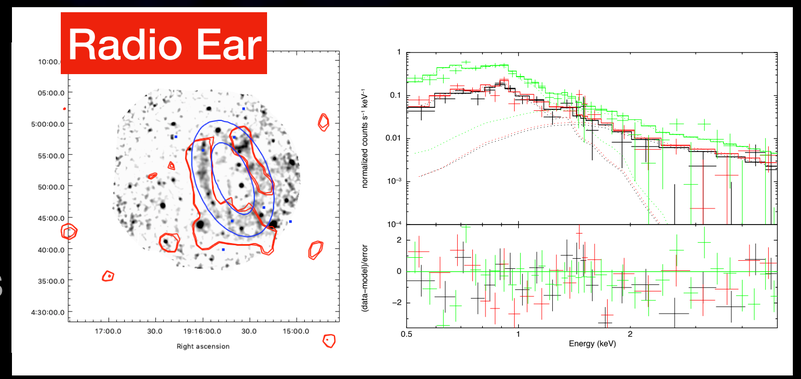
w1

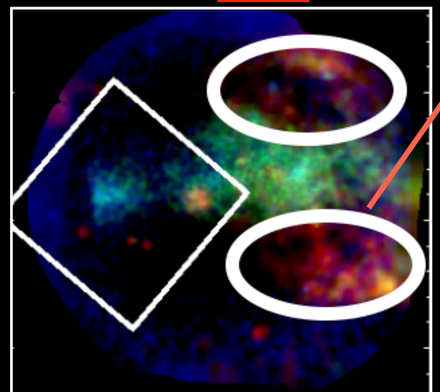
w2

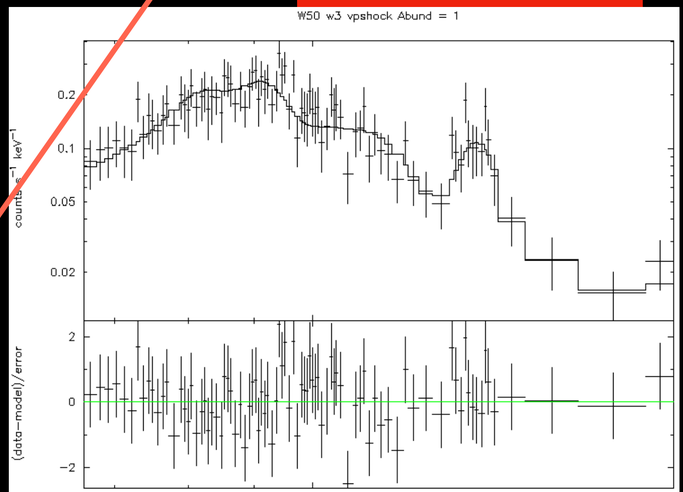
Soft X-rays
Hard X-rays

kT~0.27 keV
enhanced Mg, Si
'w3'

`w3'

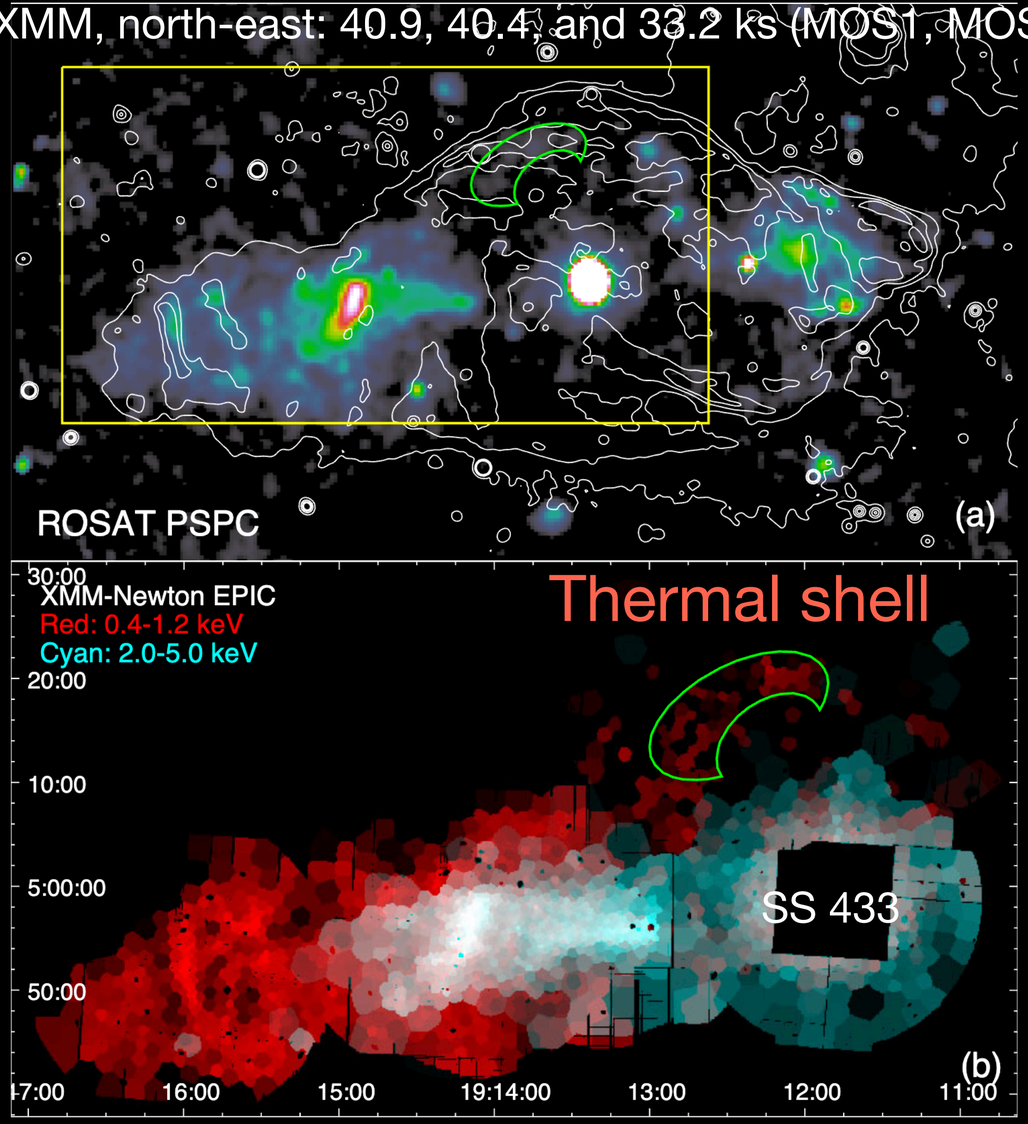


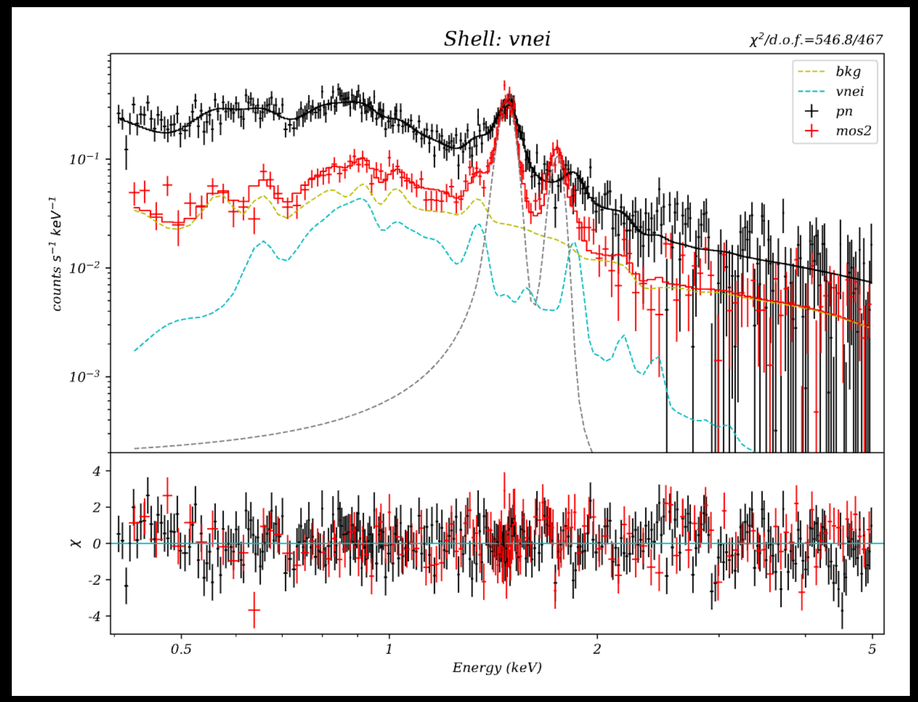




A black hole-SNR shell?

XMM, north-east: 40.9, 40.4, and 33.2 ks (MOS1, MOS2, pn)

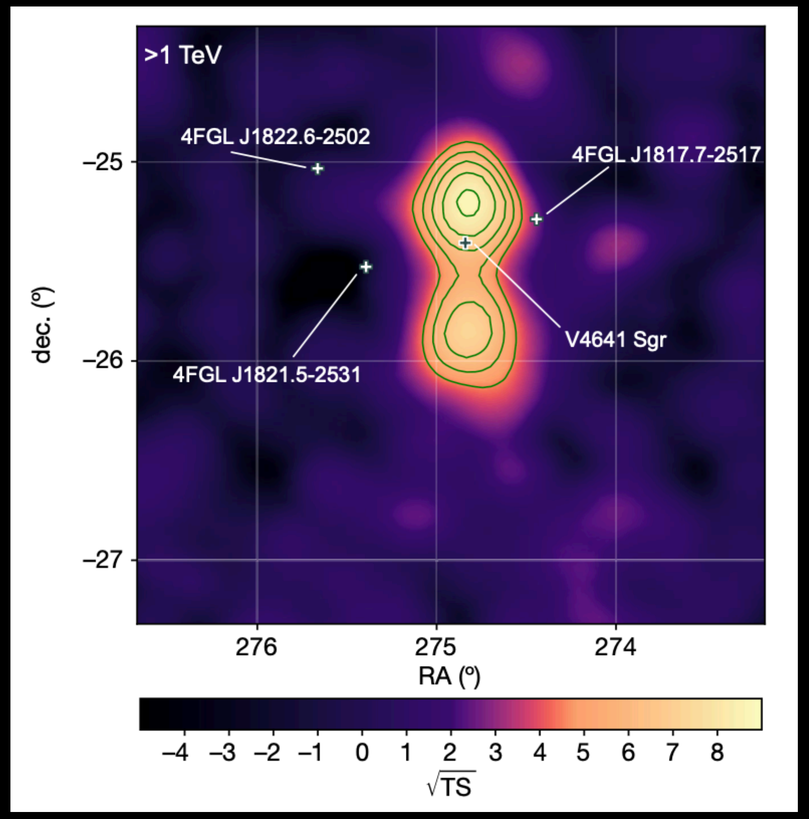




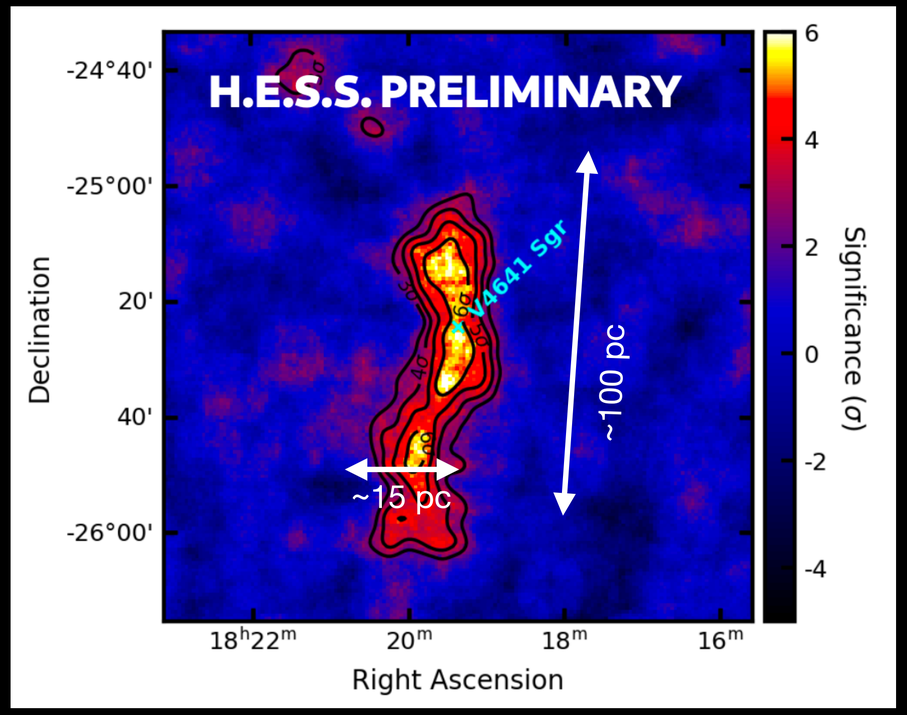
Chi, Zhou+2024

kT~ 1 keV
enhanced Si
under-ionized plasma
n~ 0.3 cm^{-3}
E<~1E51 ergs
t~20-30 kyr

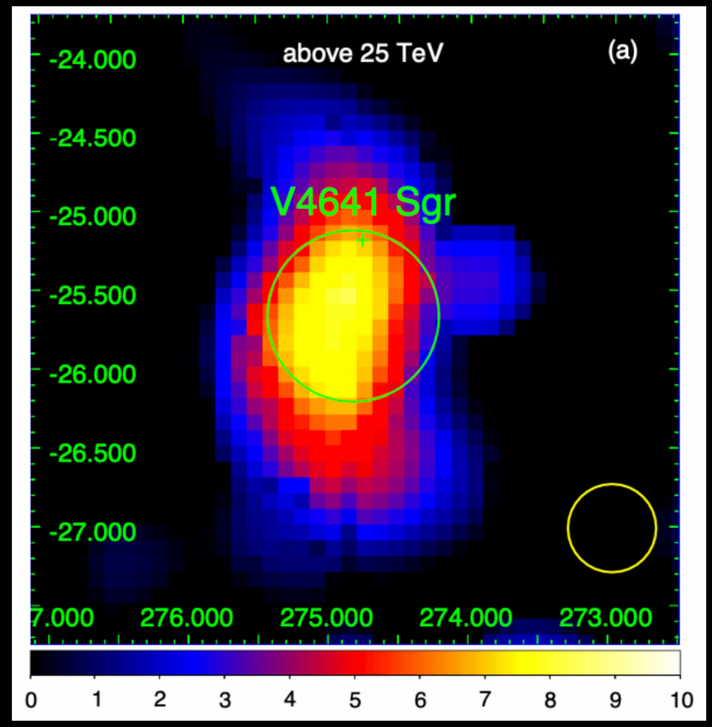
V4641 Sgr in TeV



HAWC Collaboration 2024



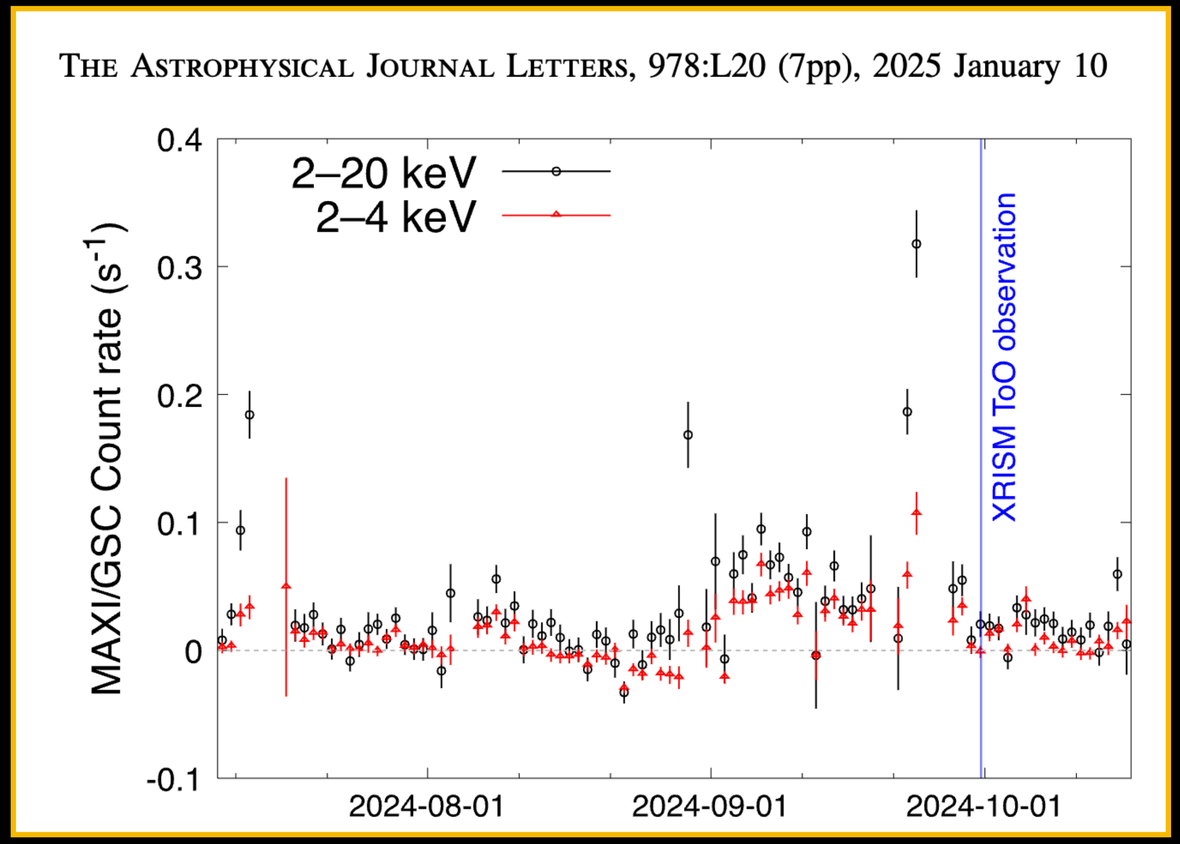
HESS Collaboration 2024

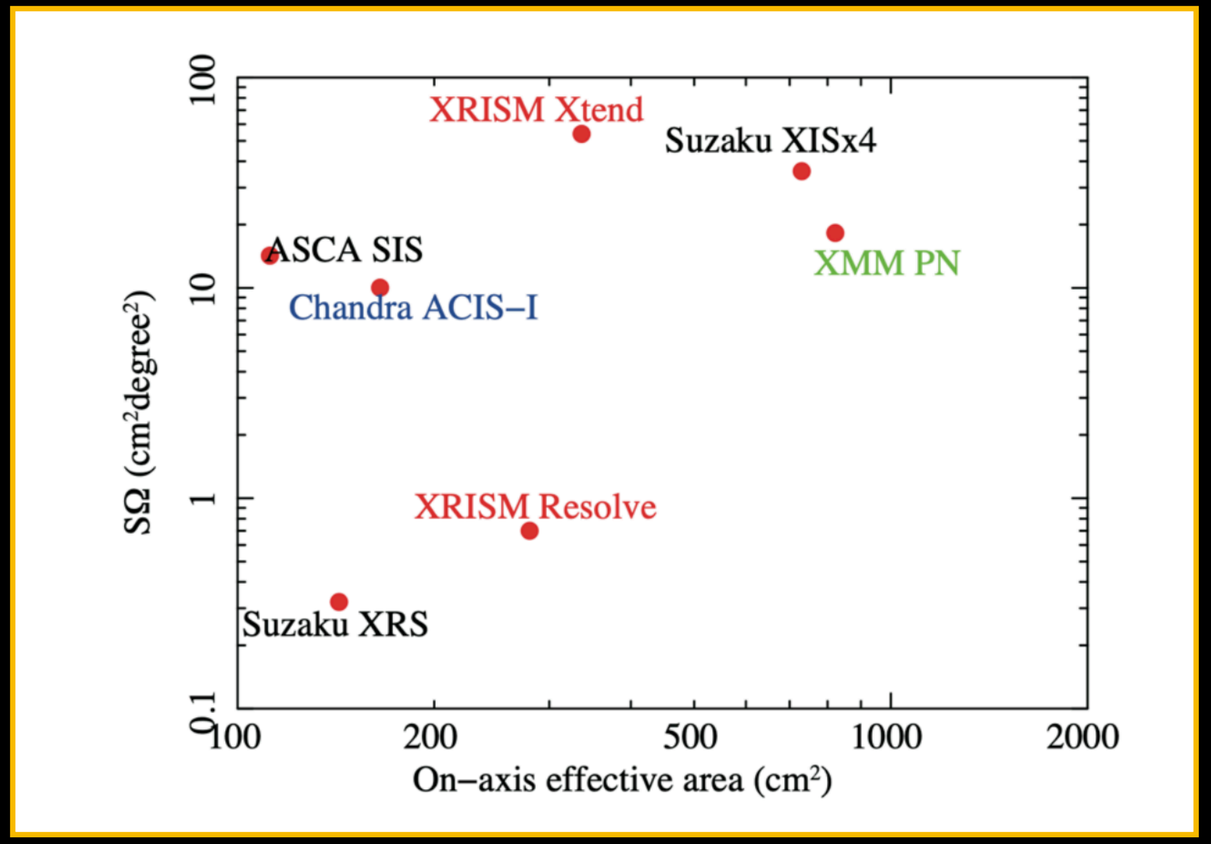


LHAASO Collaboration 2024

V4641 Sgr with XRISM

(ToO, 20 ks, 2024.09.30)

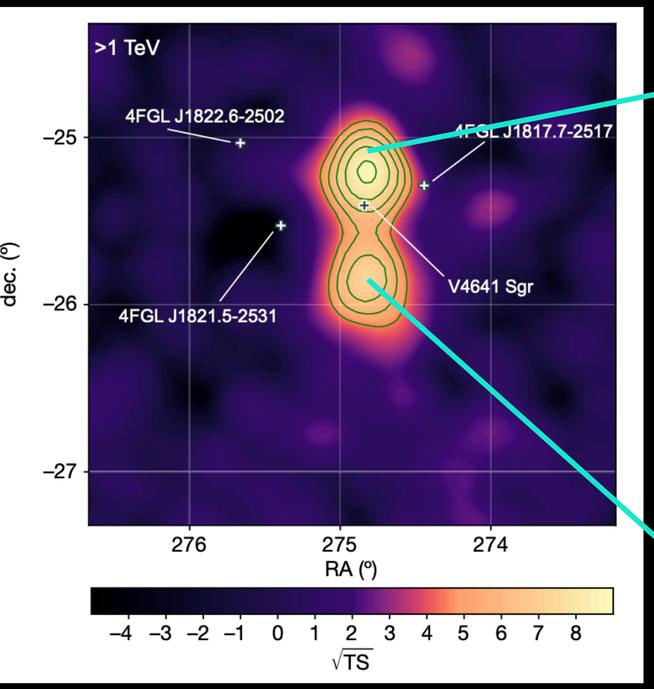




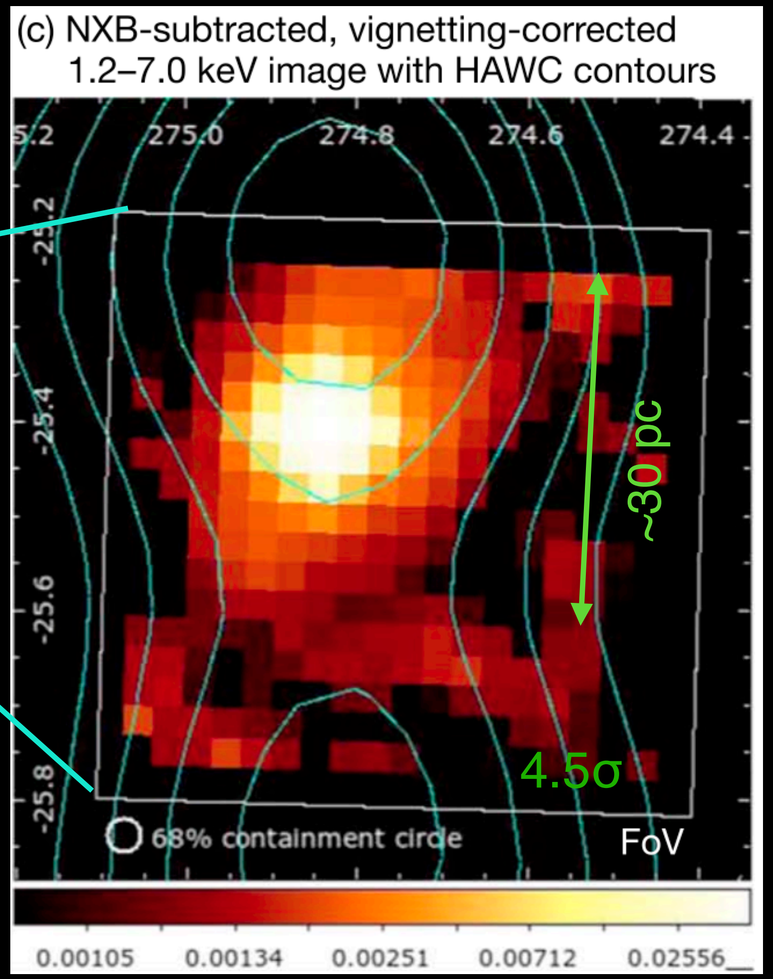
V4641 Sgr with XRISM

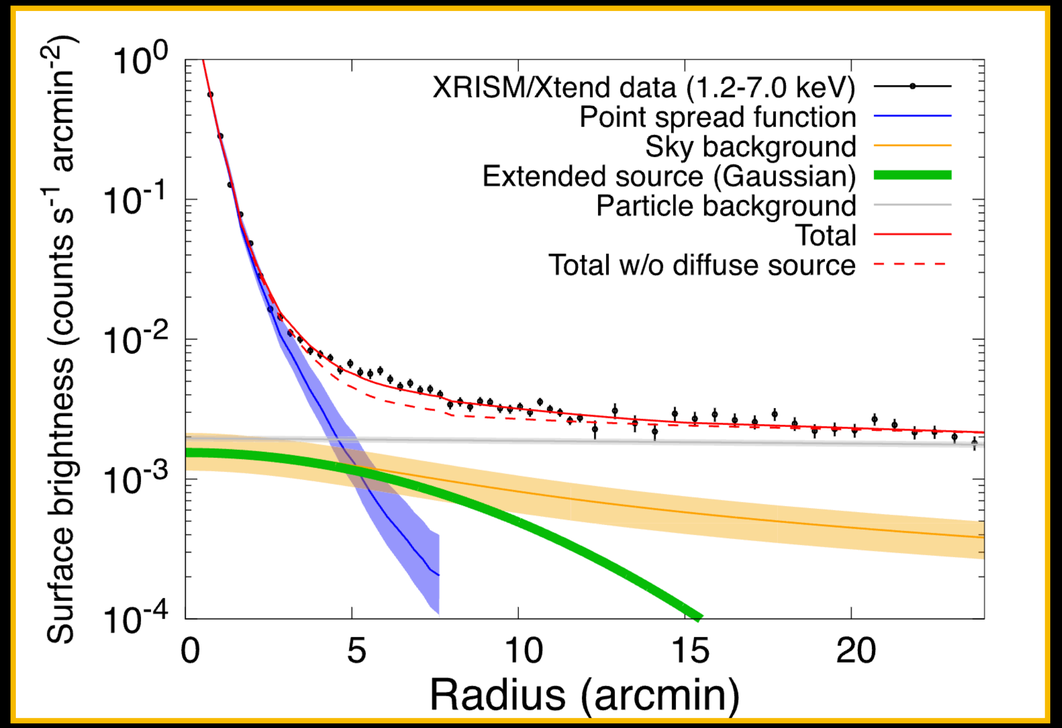
Suzuki+25

XRISM/Xtend image in 1.2-7 keV



Contours: > 1 TeV HAWC



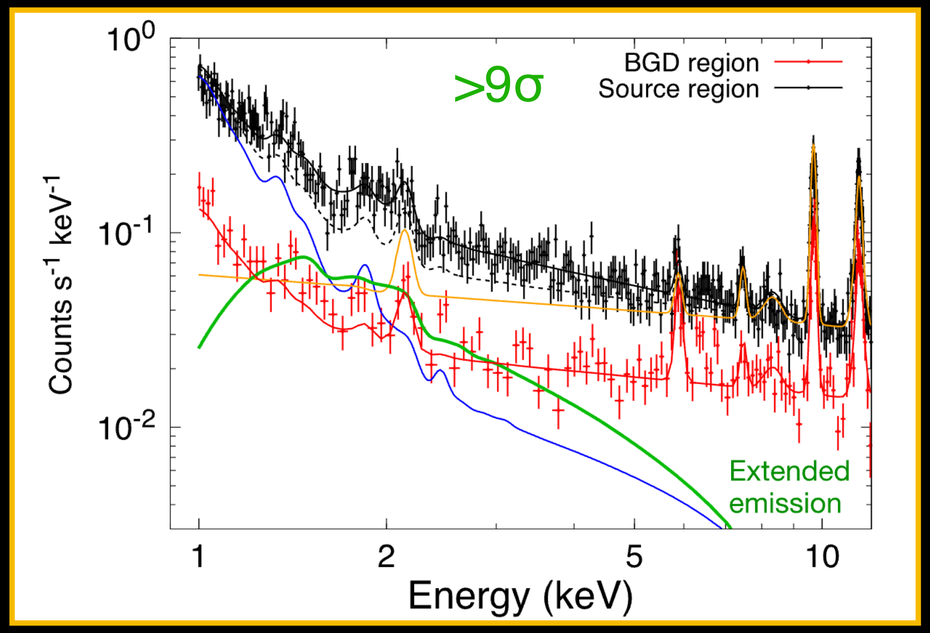


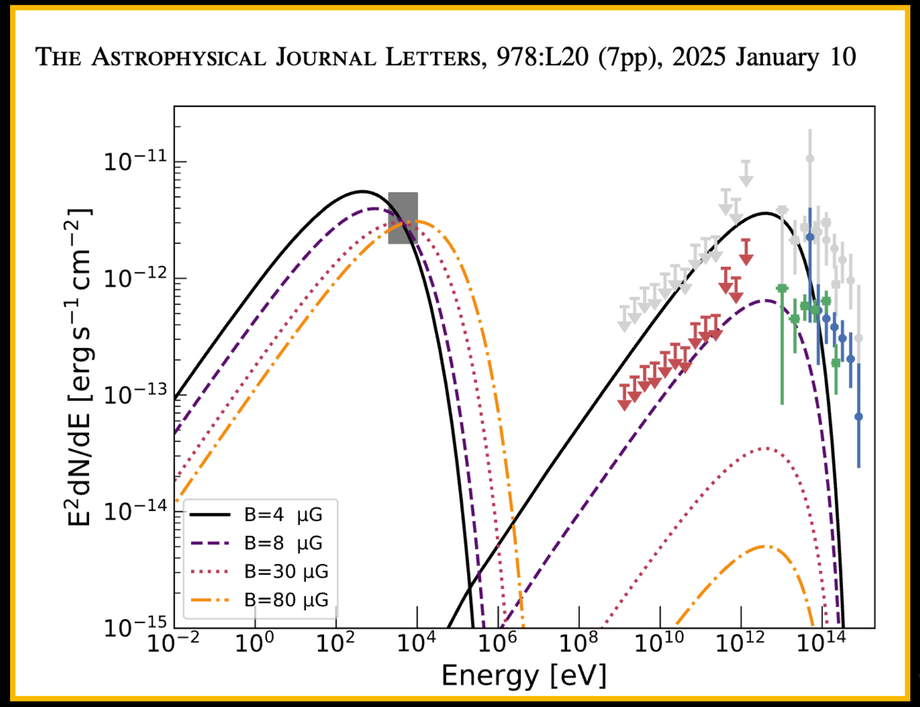
- ★ **Scale ~ 30 pc << TeV size**
- ★ particle acceleration site is within ~10 pc of uQ
- ★ comparable scale to SS433

V4641 Sgr with XRISM

Table 1
Best-fit Spectral Parameters of the Extended Emission

Case (a)	N_H (10^{22} cm^{-2})	1.8 ± 0.5
10% source contribution in BGD	Power-law index	2.4 ± 0.3
	Power-law flux (2–10 keV) (10^{-15} erg s^{-1} cm^{-2} arcmin^{-2})	7.8 ± 0.9
	Integrated power-law flux (2–10 keV)[a] (10^{-12} erg s^{-1} cm^{-2})	4.3 ± 0.5
	C-stat./d.o.f.	4190.1/3658
Case (b)	N_H (10^{22} cm^{-2})	0.6 ± 0.4
	Power-law index	1.8 ± 0.2
	Power-law flux (2–10 keV) (10^{-15} erg s^{-1} cm^{-2} arcmin^{-2})	9.2 ± 1.1
No source contribution in BGD	Integrated power-law flux (2–10 keV)[a] (10^{-12} erg s^{-1} cm^{-2})	5.1 ± 0.6
	C-stat./d.o.f.	4147.6/3658
Case (c)	N_H (10^{22} cm^{-2})	1.5 ± 0.4
	kT_e (keV)	3.2 ± 0.7
	$n_e n_p V$ (10^{58} cm^{-3})	1.3 ± 0.2
	C-stat./d.o.f.	4192.3/3658





- ★ Non-thermal: Γ ~ 1.6–2.7
- ★ L~$10^{37\text{-}38}$ erg/s << L_{edd}
- ★ B~80 uG or D~1E27 cm^2 s^{-1} at 100TeV

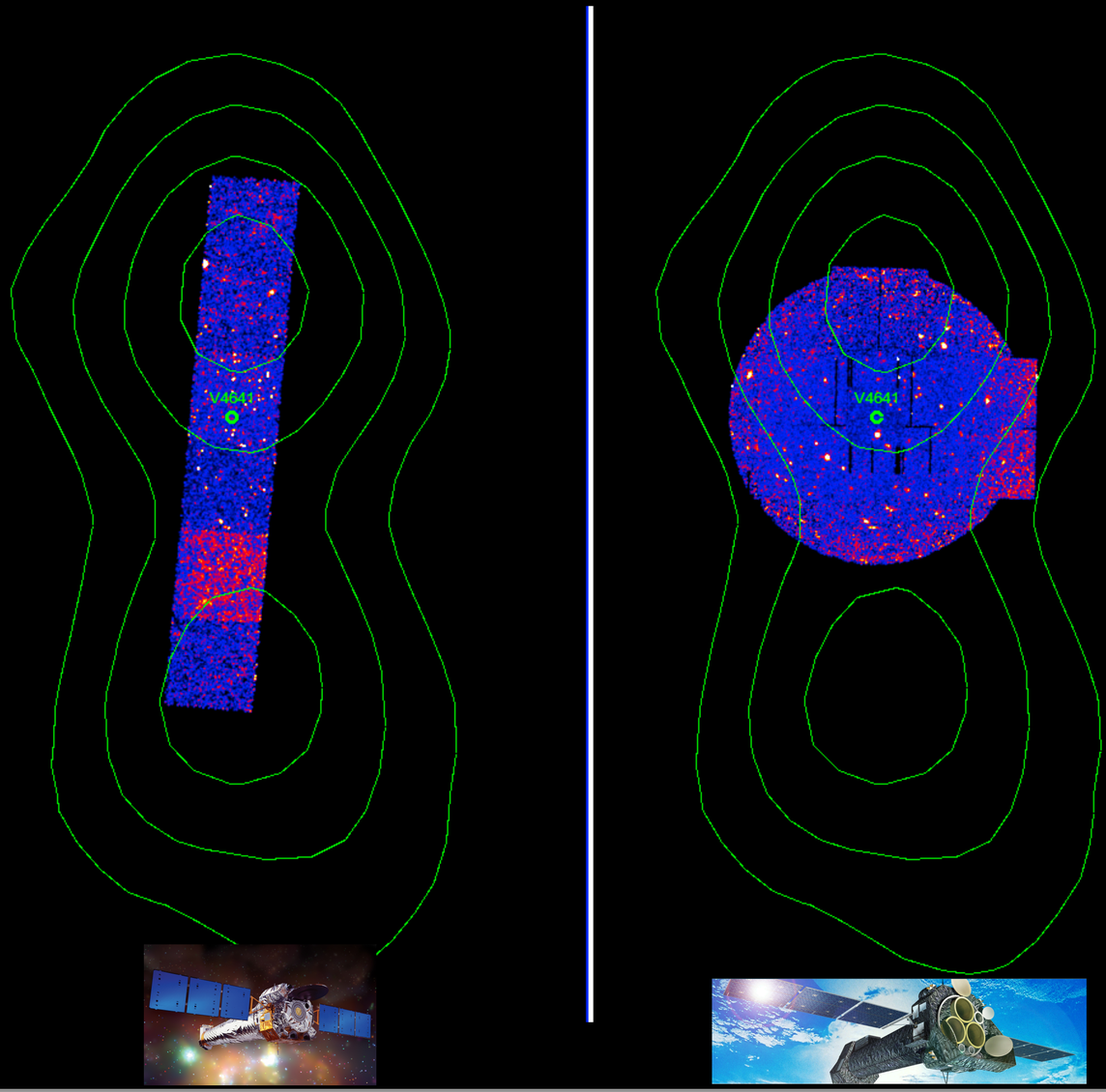
- ★ Thermal: kT~2.5-3.9 keV
  - n~0.3 cm^{-3}
  - L~2E39erg/s ~L_{edd}

Suzuki+25

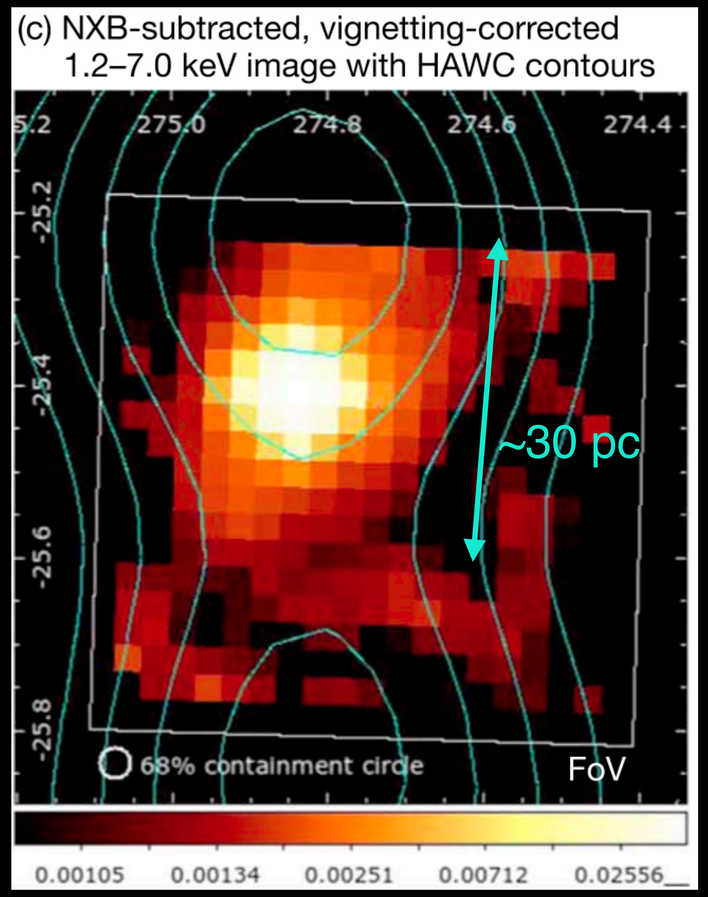
Archival

Chandra
(0.5-7 keV; 25 ks)

XMM
(0.3-10 keV; 30 ks)



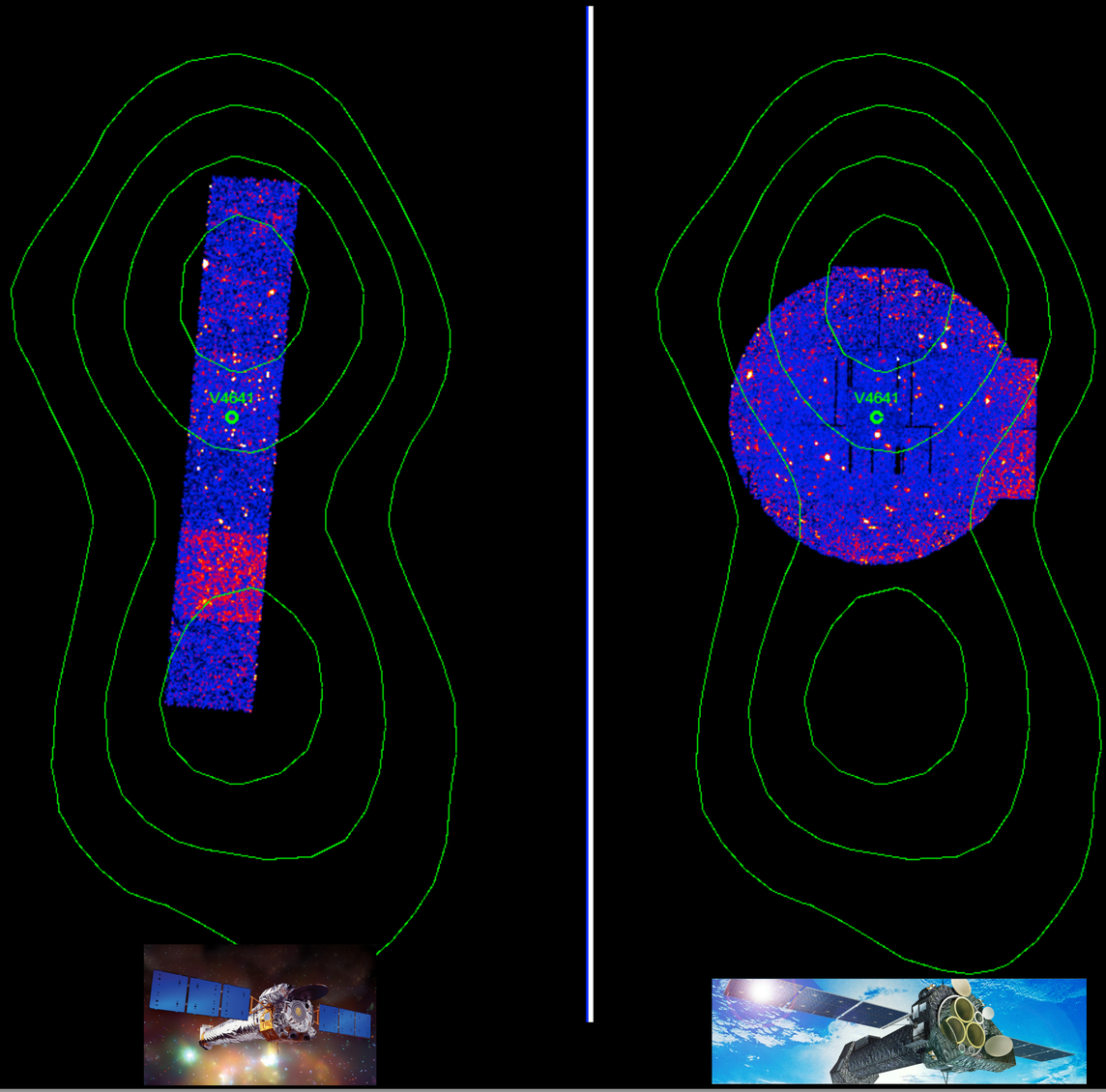
XRISM



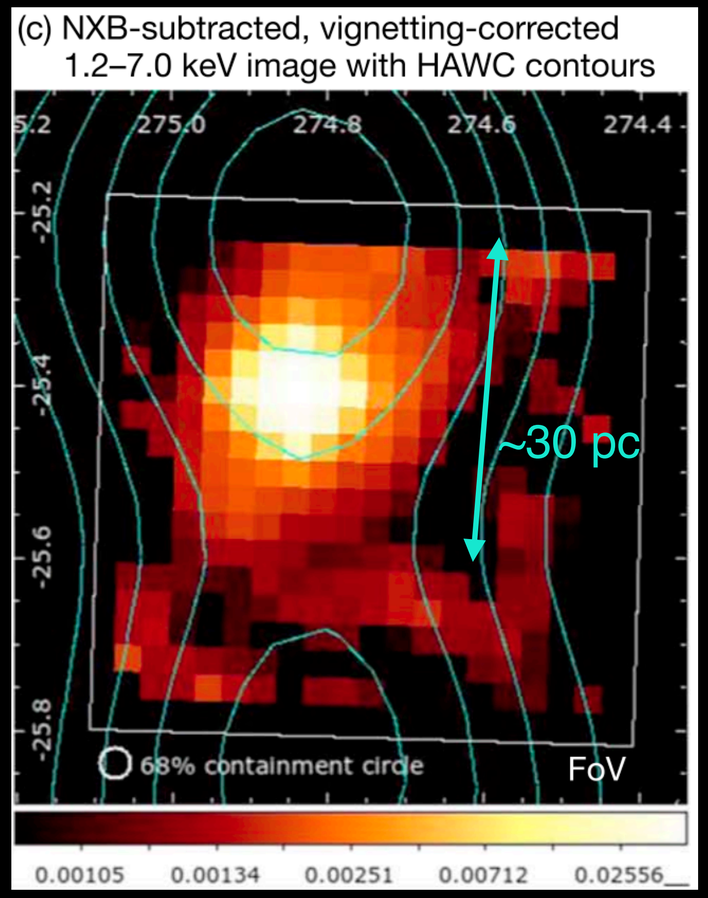
Archival

Chandra
(0.5-7 keV; 25 ks)

XMM
(0.3-10 keV; 30 ks)



XRISM



LP proposal ***just*** announced to be approved!
(PI Kaya Mori - 490 ks NuSTAR, 160 ks XMM)

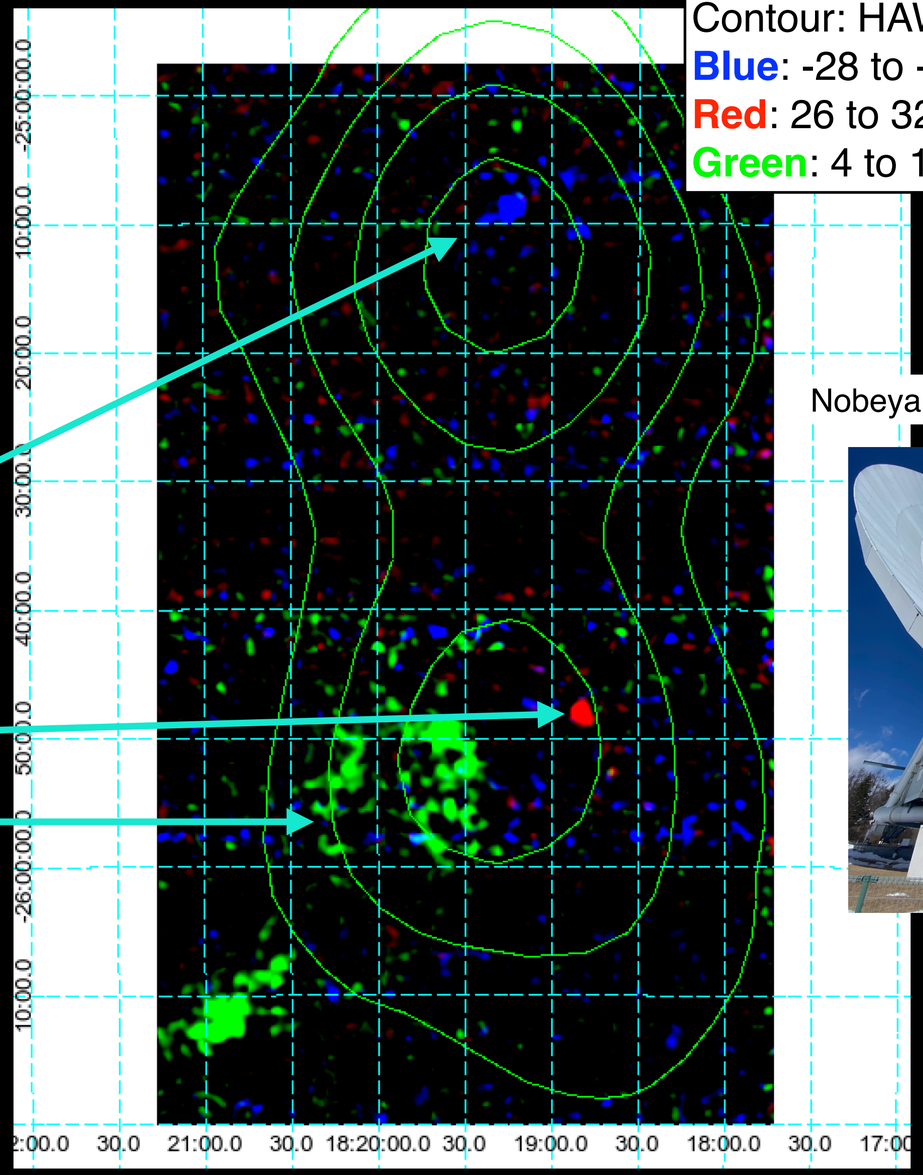
Molecular cloud in V4641 Sgr?

- ★ **Nobeyama** Observations (12CO): *Naomi Tsuji+*

- ★ **No emission at d=6.2 kpc (V4641)**
  - Challenging for hadronic scenario?

Three molecular clouds
- MC1 at V= -28 to -24 km/s
- MC2 at V= 26 to 32 km/s
- MC3 at V= 4 to 10 km/s
- Distance <4 kpc or >12 kpc

- ★ CO(J=3-2) observations by **APEX** ongoing: *E. de la Fuente, D. Tafoya+*

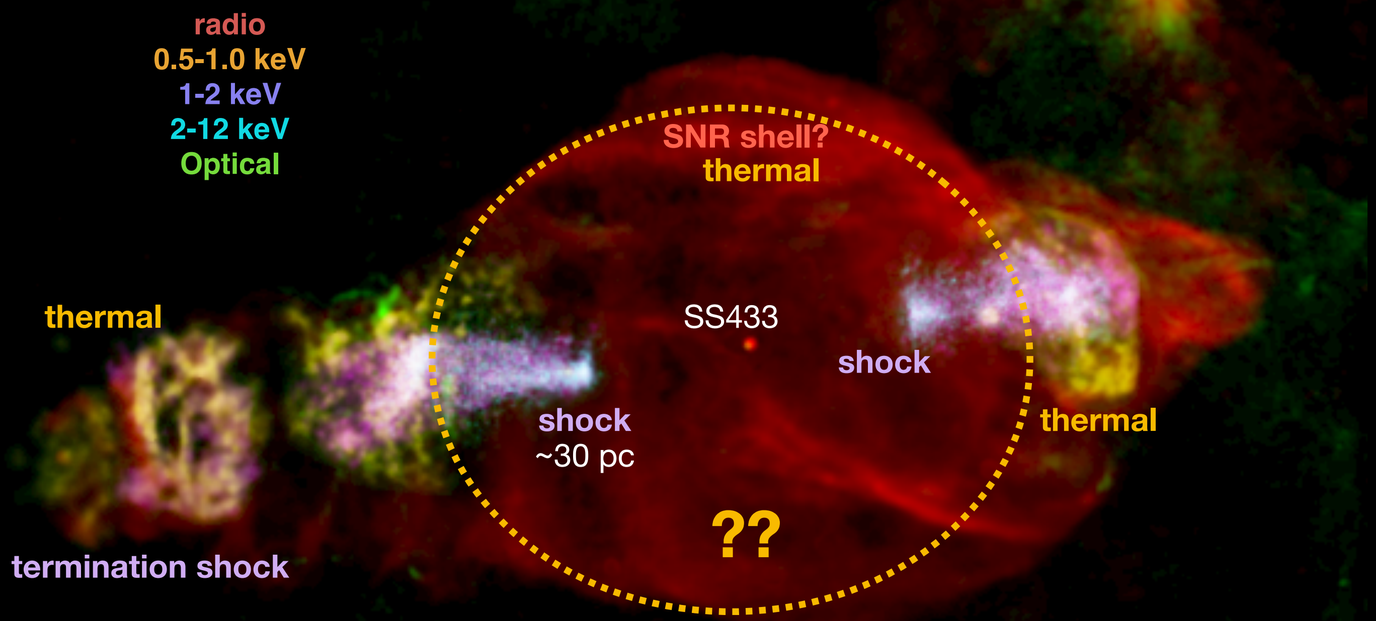


Nobeyama 45-m radio telescope

Summary

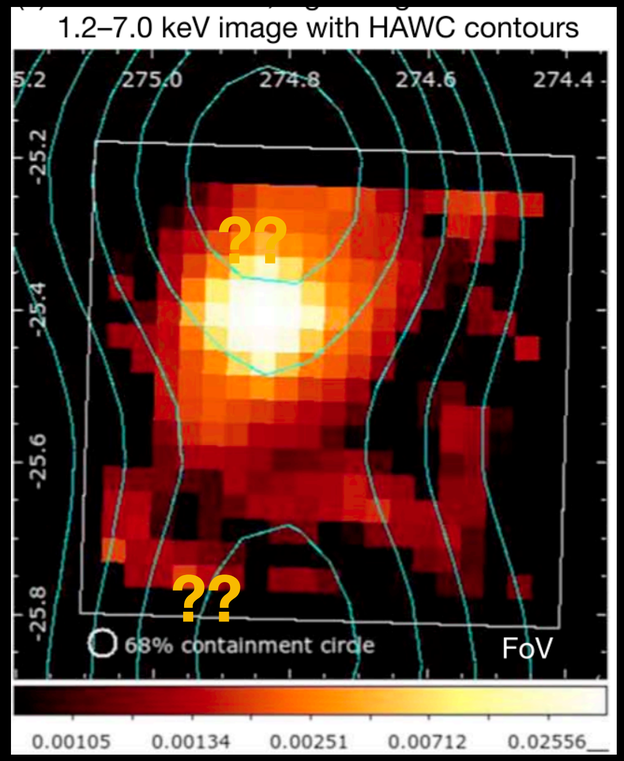
Where & how are particles **accelerated**?

W50-SS 433



- ★ X-rays=>resolve the site for efficient particle acceleration in a uQ jet, ~30 pc away!
- ★ E~ a few x100 TeV, B~12-15 uG at head, B along the jet flow in east
- ★ Knots moving out?
- ★ Termination shock at the eastern ear (e3), thermalizes with ISM
- ★ X-ray shell in the north==> Black hole remnant?
  - ★ shell-jet interaction at e2/w2?

V4641 Sgr



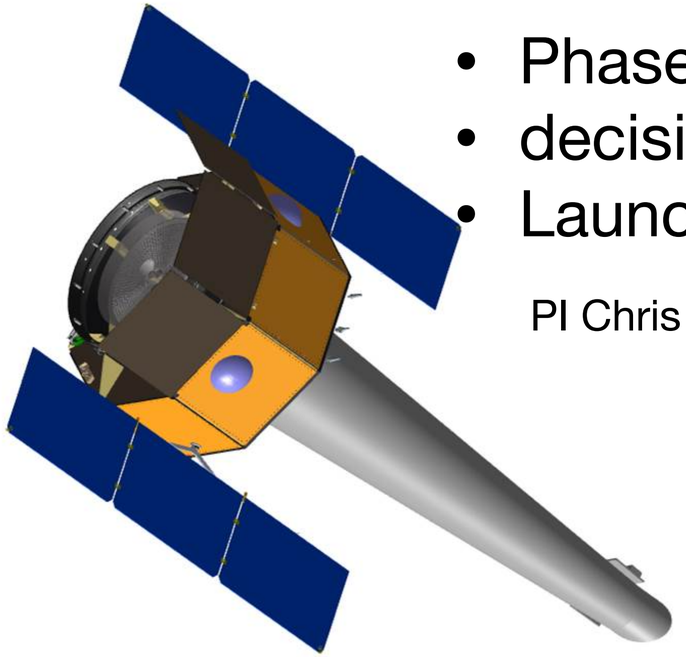
- ★ V4641 Sgr: Extended X-ray emission ~30 pc Comparable scale and acceleration site as for SS 433, but lots still unknown!

- ★ Modelling efforts & multi-wavelength sensitive surveys in X/radio (on going or being planned)
- ★ Future: more **sensitive** instruments with **large FoV, good angular resolution**, synergy with gamma

AXIS for the 2030's and beyond

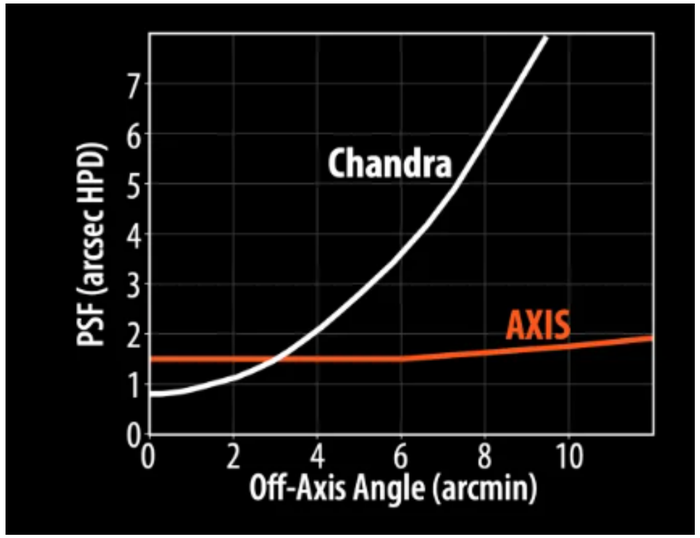
Advanced X-ray Imaging Satellite

Parameter	Value
PSF	1.5" on-axis, 1.75" FoV-ave (HPD)
Effective Area (incl. detector)	4200 cm^2 at 1 keV; 830 cm^2 at 6 keV
FoV	24 arcmin diameter
Bandpass	0.3-10 keV
Readout rate	>5 fps
Slew rate	120 deg. / 7 min.
Orbit	L2 Halo Orbit



- Phase A
- decision 2026
- Launch 2032

PI Chris Reynolds



- Simple, single instrument design
- 5 year prime mission; design for 10 year goal
- Combination of PSF, effective area, exquisite point source sensitivity ($F_{0.5\text{-}2.0keV}$=3x10^{-18}erg/s/cm^2 FOV-ave in 5Ms)
- Capable facility for transient science; <2 hour response time to alerts + onboard rapid transient detection.
- **True community facility; >70% time for Guest Observers**
- **Needed facility that would be synergistic with gamma-ray facilities**