faculty of SCIENCE
discover the unknown + invent the future

(Canada Day version)

A hard X-ray look at the Manatee (W50) nebula
powered by the Galactic microquasar SS 433

Samar Safi-Harb

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy,
(Gamma2022)
04 July 2022, Barcelona

NSERC CRSNG

Canada Research Chairs

CSA ASC

The team (W50-east)

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Shuhan Zhang

Nate Saffold

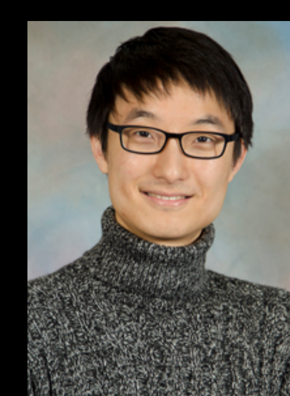
Chuck Hailey

Eric Gotthelf

Felix Aharonian (DIAS/MPIK)

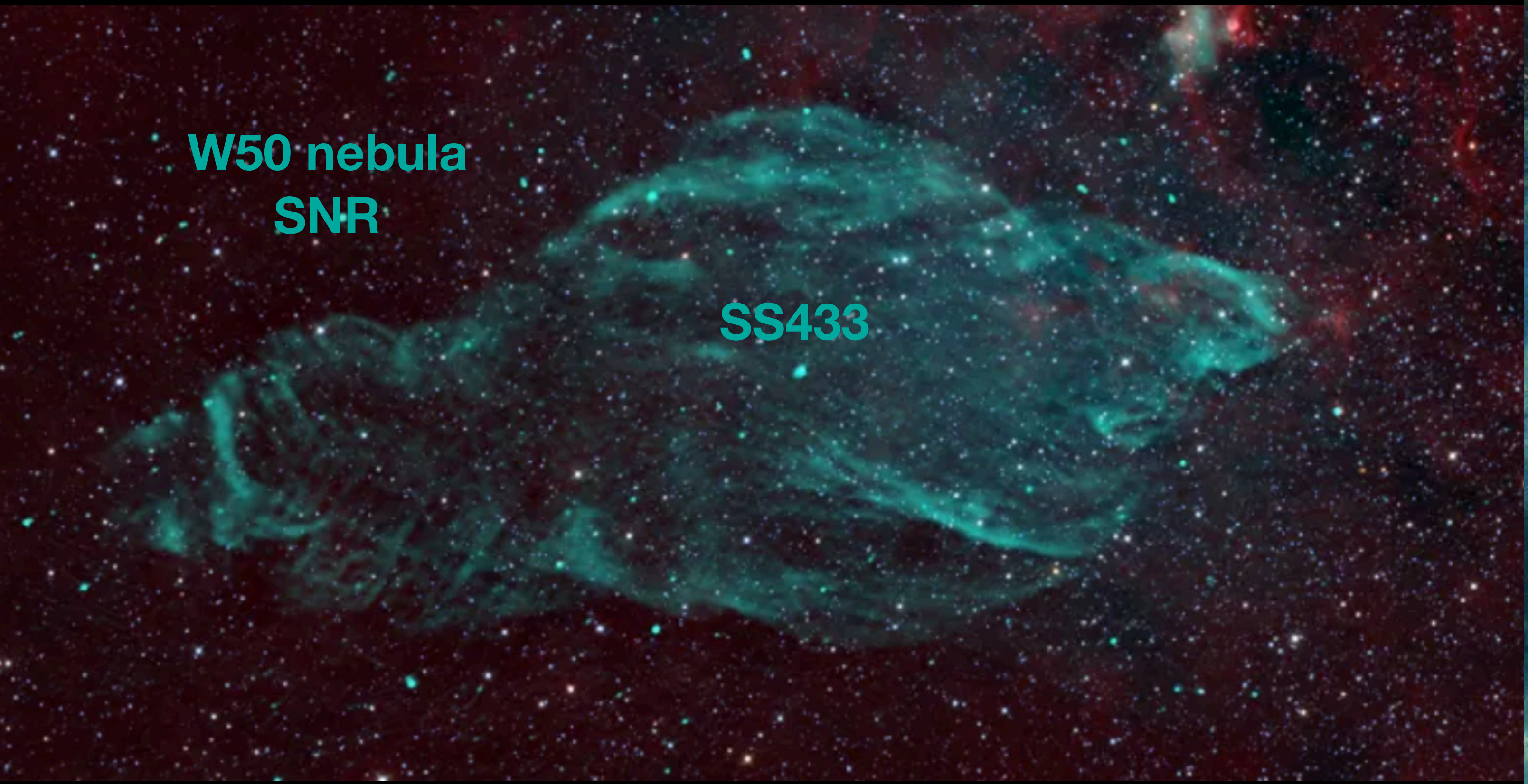
Mel Nynka (MIT)

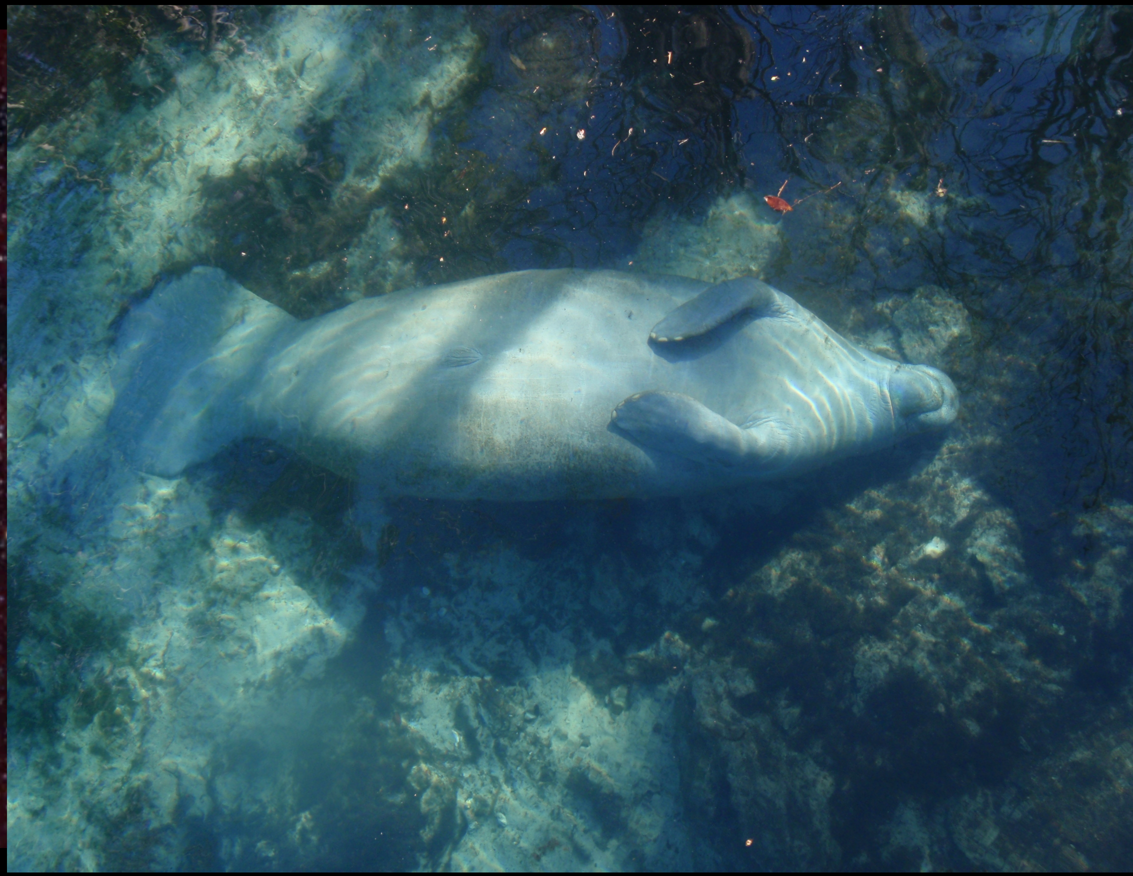
Ke Fang (U.Wisconsin)



Chang D Rho (Seoul)

A manatee in space!





Left: NSF's Karl G. Jansky VLA, NRAO/AUI/NSF (B. Saxton), K. Golap, M. Goss; NASA's WISE. Right: Tracy Colson

https://public.nrao.edu/gallery/w50-the-manatee-nebula/

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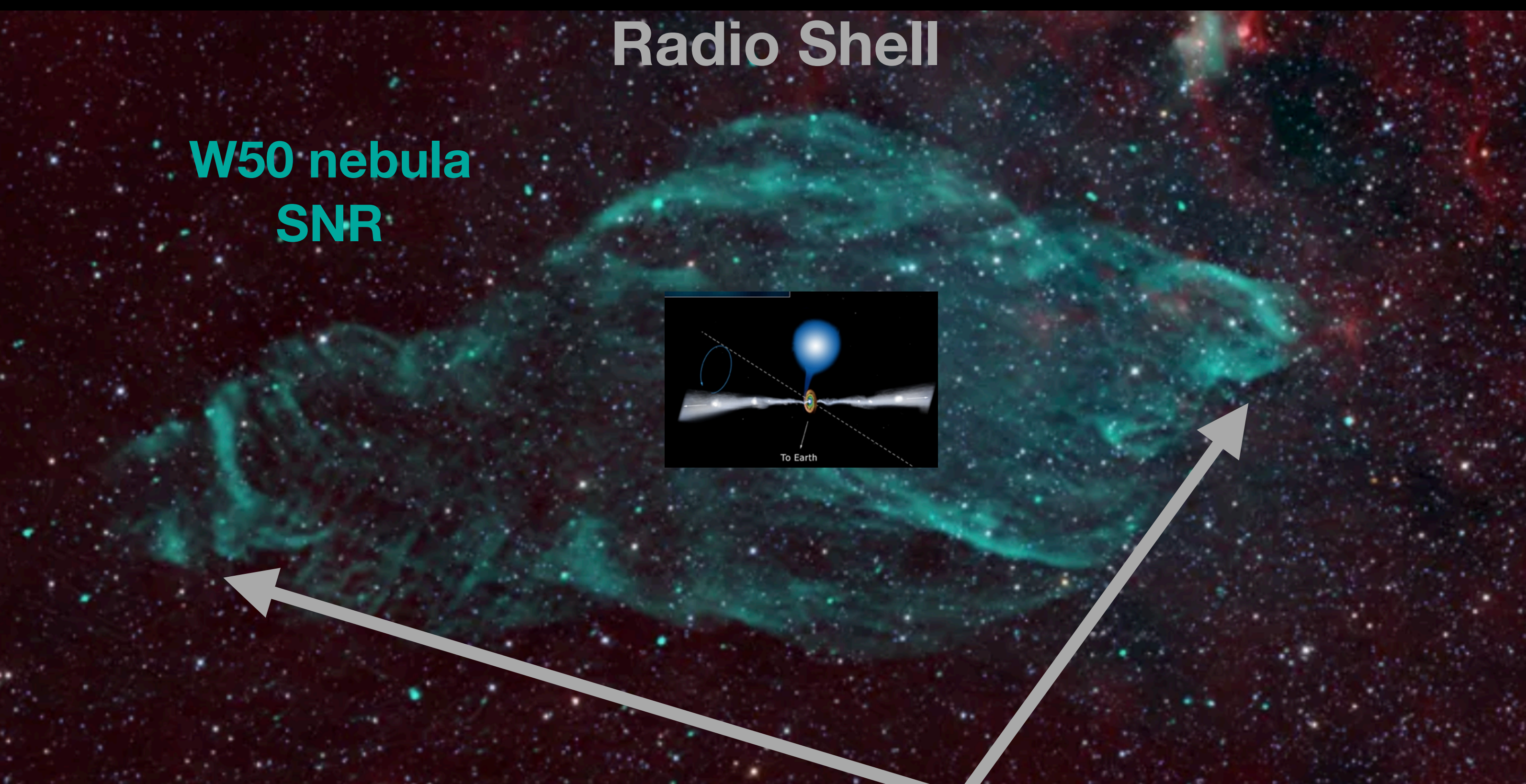

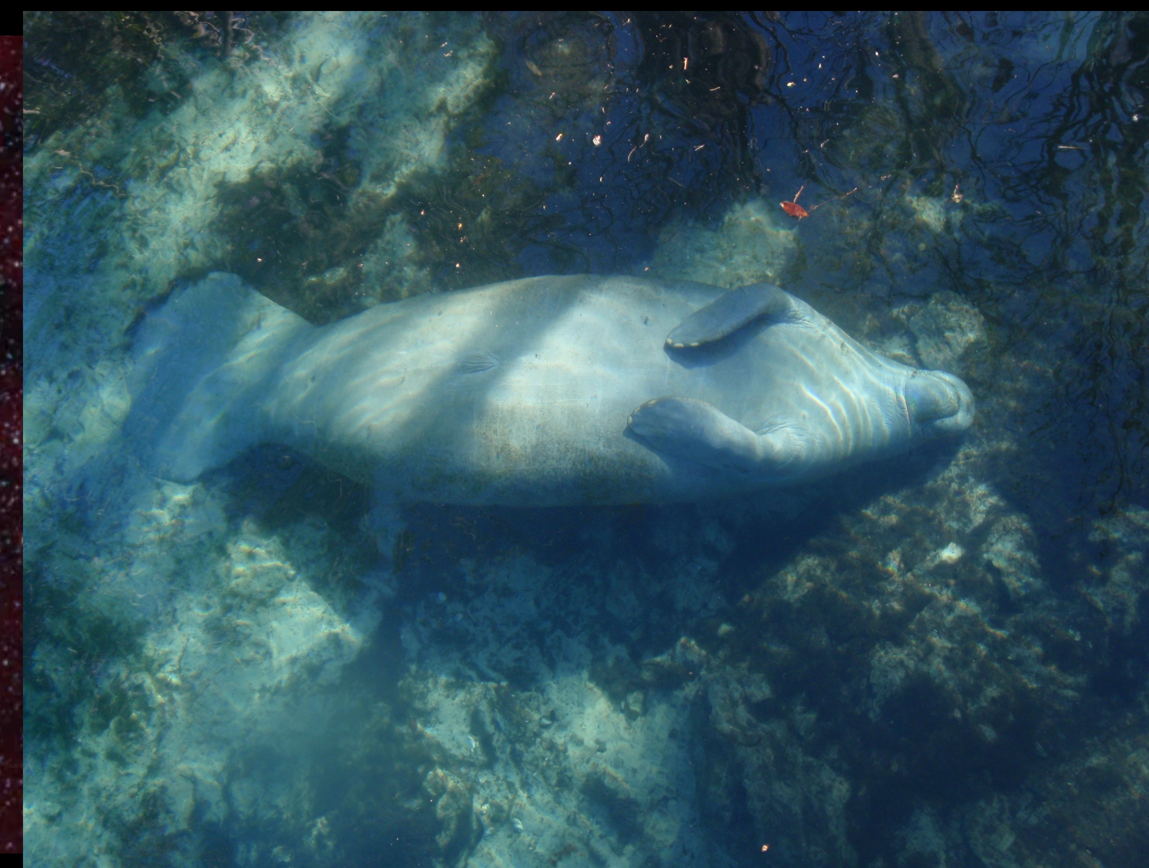

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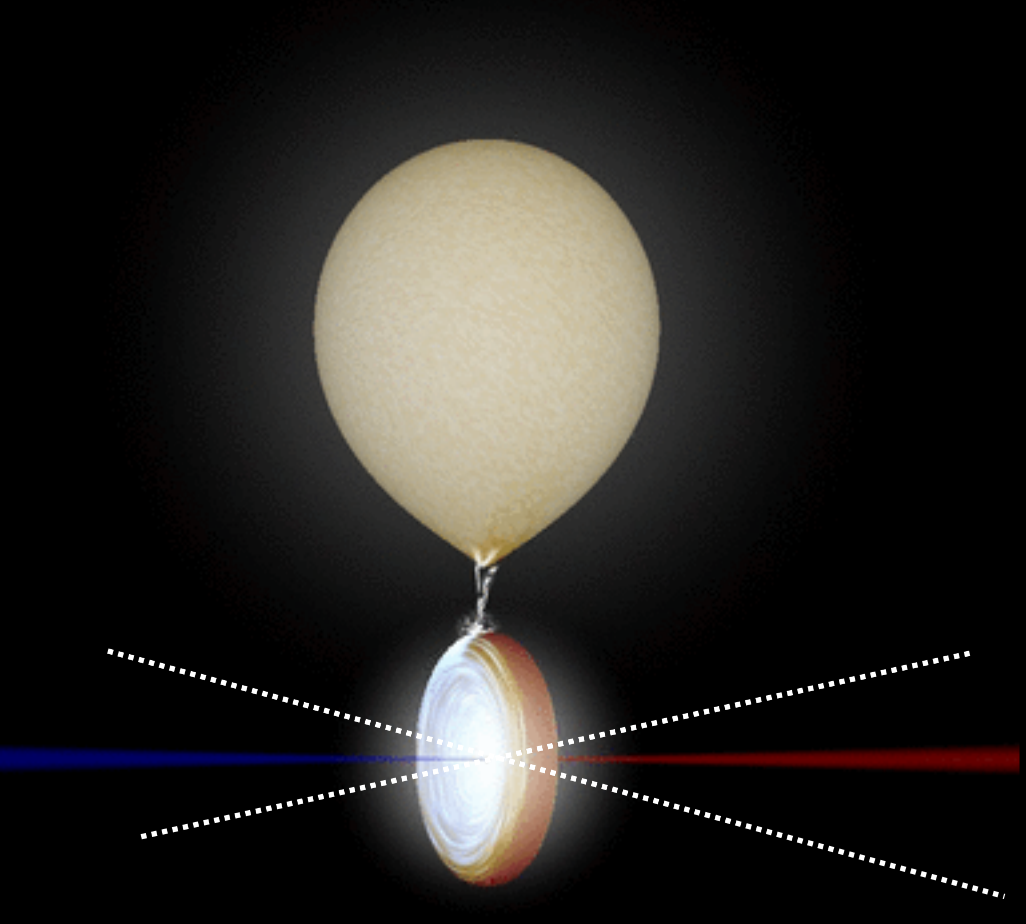
SS 433

>700 ADS records since 1978!!

- High-Mass X-ray Binary (P_{orb}~13 days)
- Microquasar
- **Stellar Mass Black Hole**
- **Super-Critical** Accretion
- **Two-sided baryonic jets**, v~0.26 c
- Precession Period ~162 days

Review by Fabrika 2004



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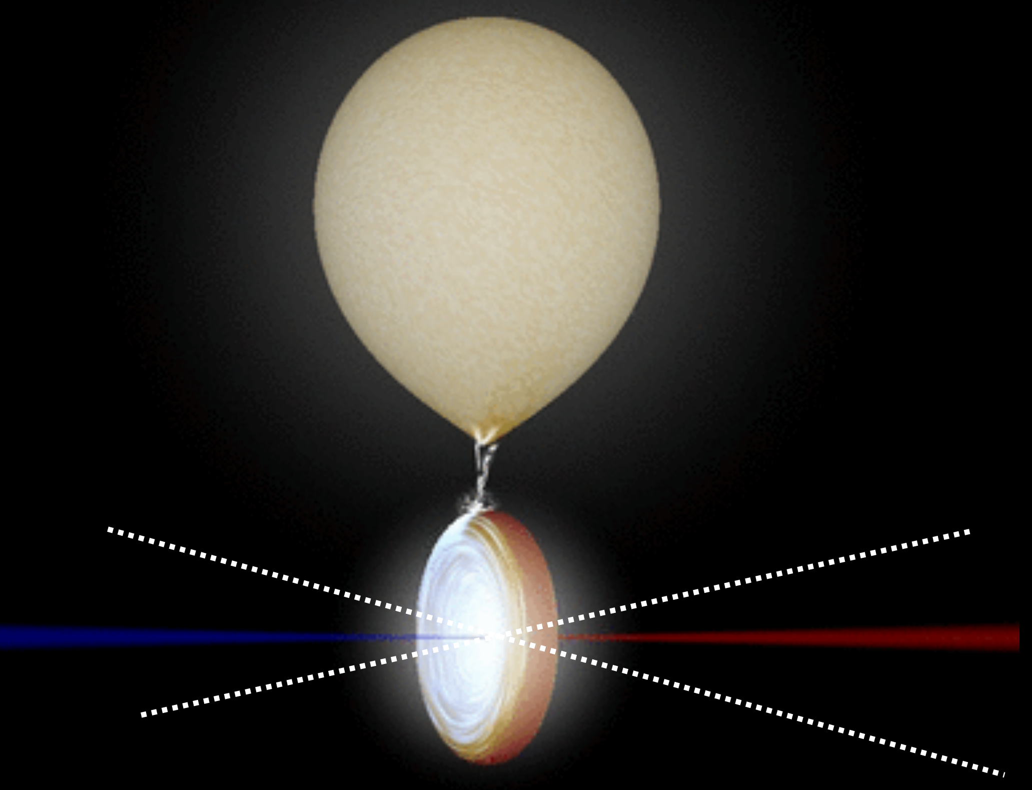

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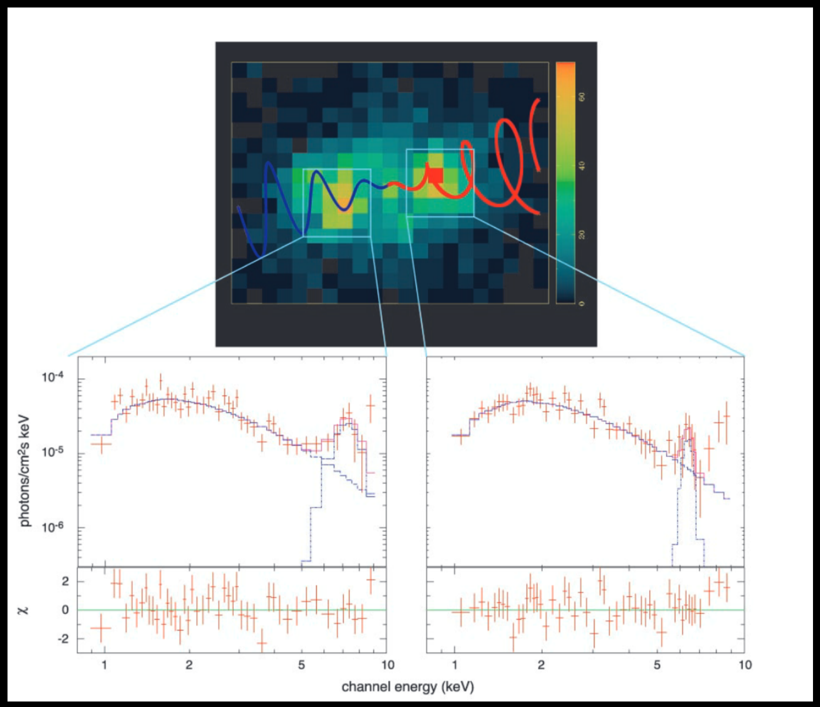
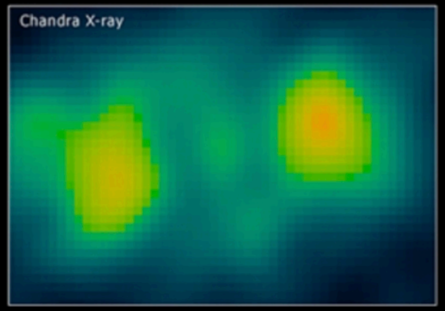
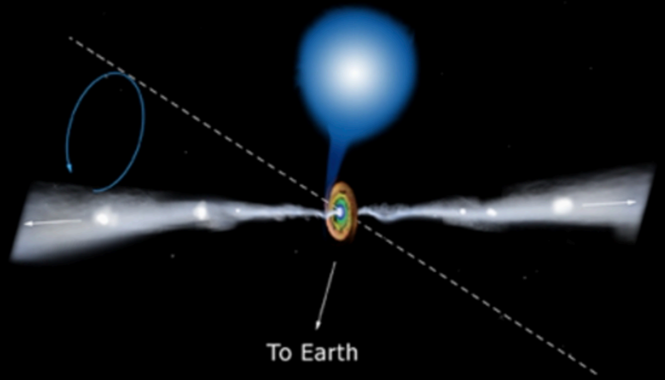


Migliari+2002

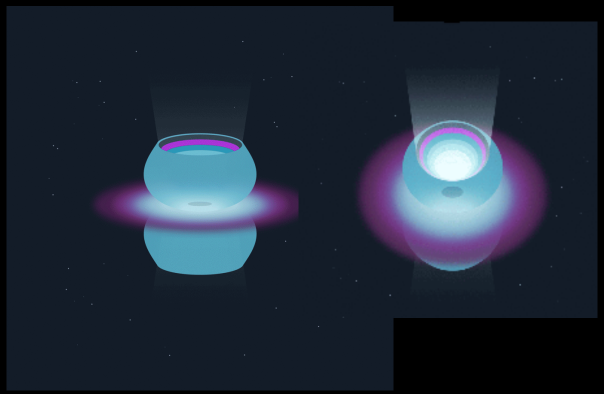
Chandra



Migliari et al. 2022
Marshall et al. 2013



Testbed for many astrophysical (high-energy) phenomena



- Black hole jets/microquasar
- Ultra-Luminous X-ray Sources
- Black Hole Remnants
- Active Galactic Nuclei
- (Pulsar) Wind Nebula
- Particle Acceleration to very high energies

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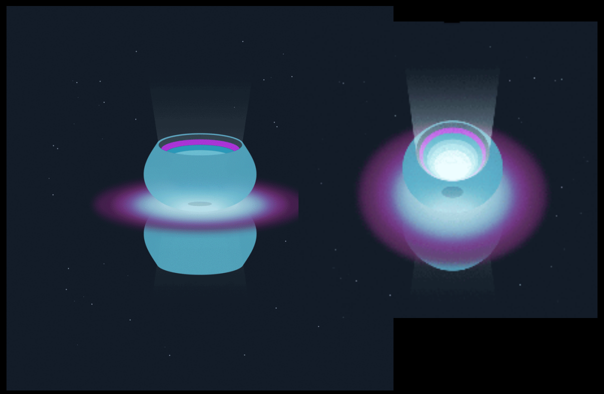

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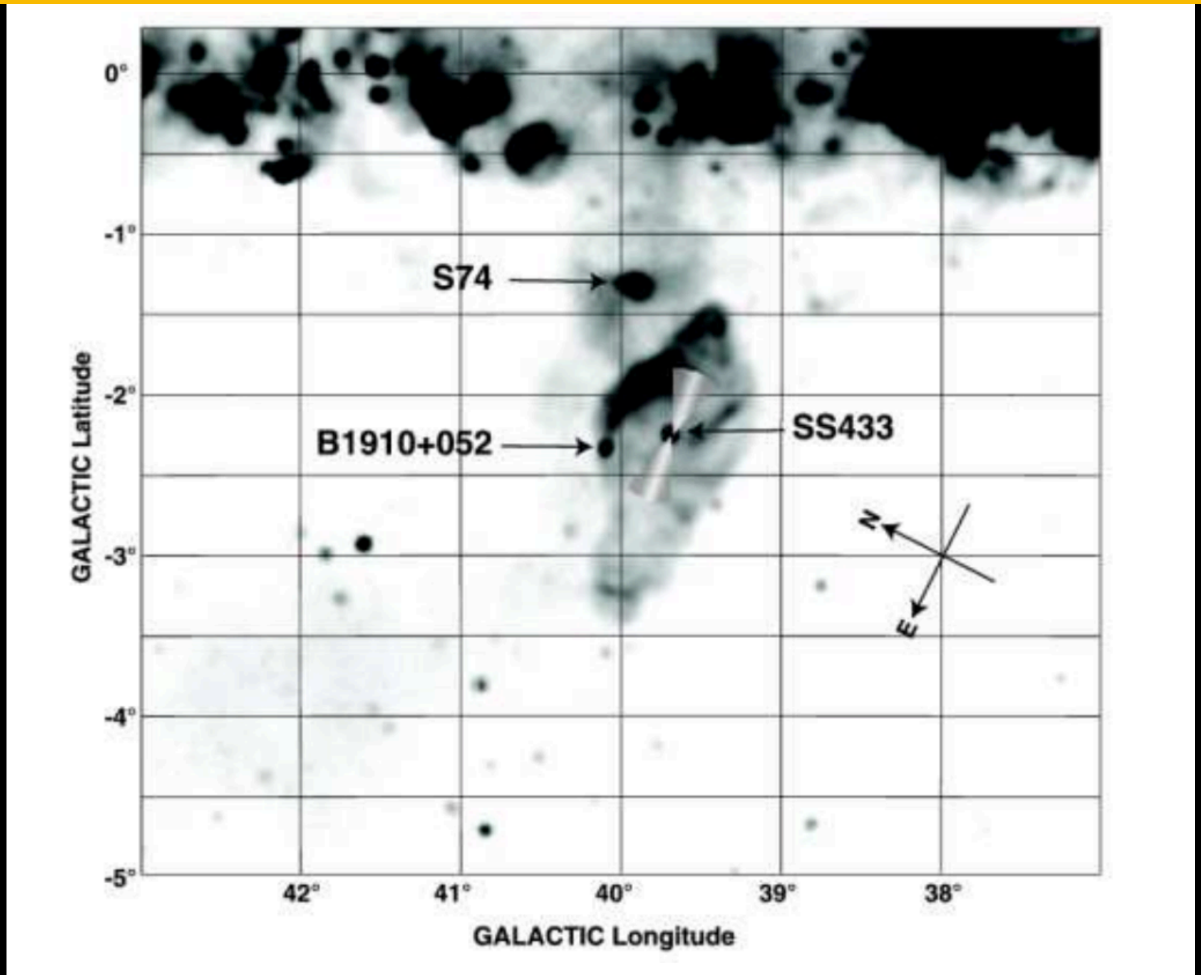
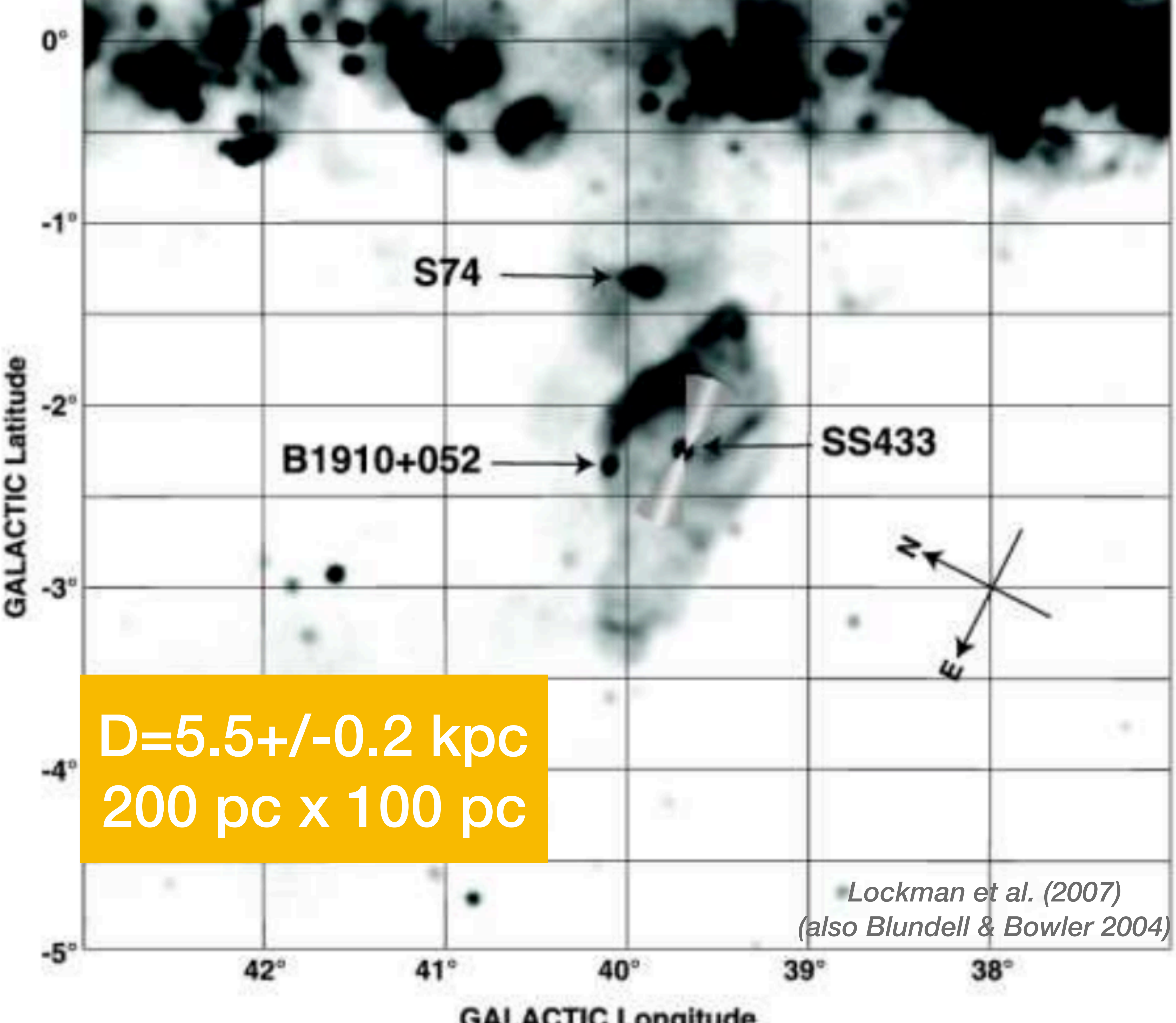
Among the largest known SNRs in our Galaxy and a rare case of a black-hole SNR





D=5.5+/-0.2 kpc
200 pc x 100 pc

Lockman et al. (2007)
(also Blundell & Bowler 2004)

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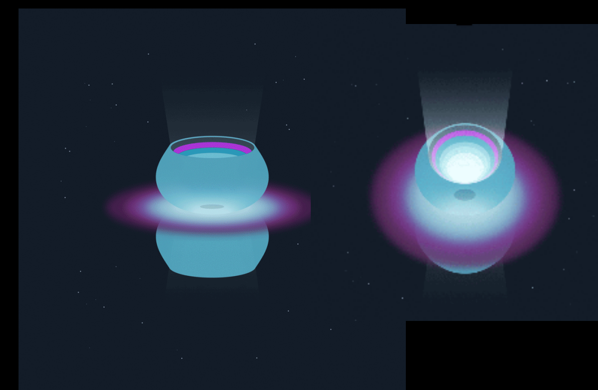

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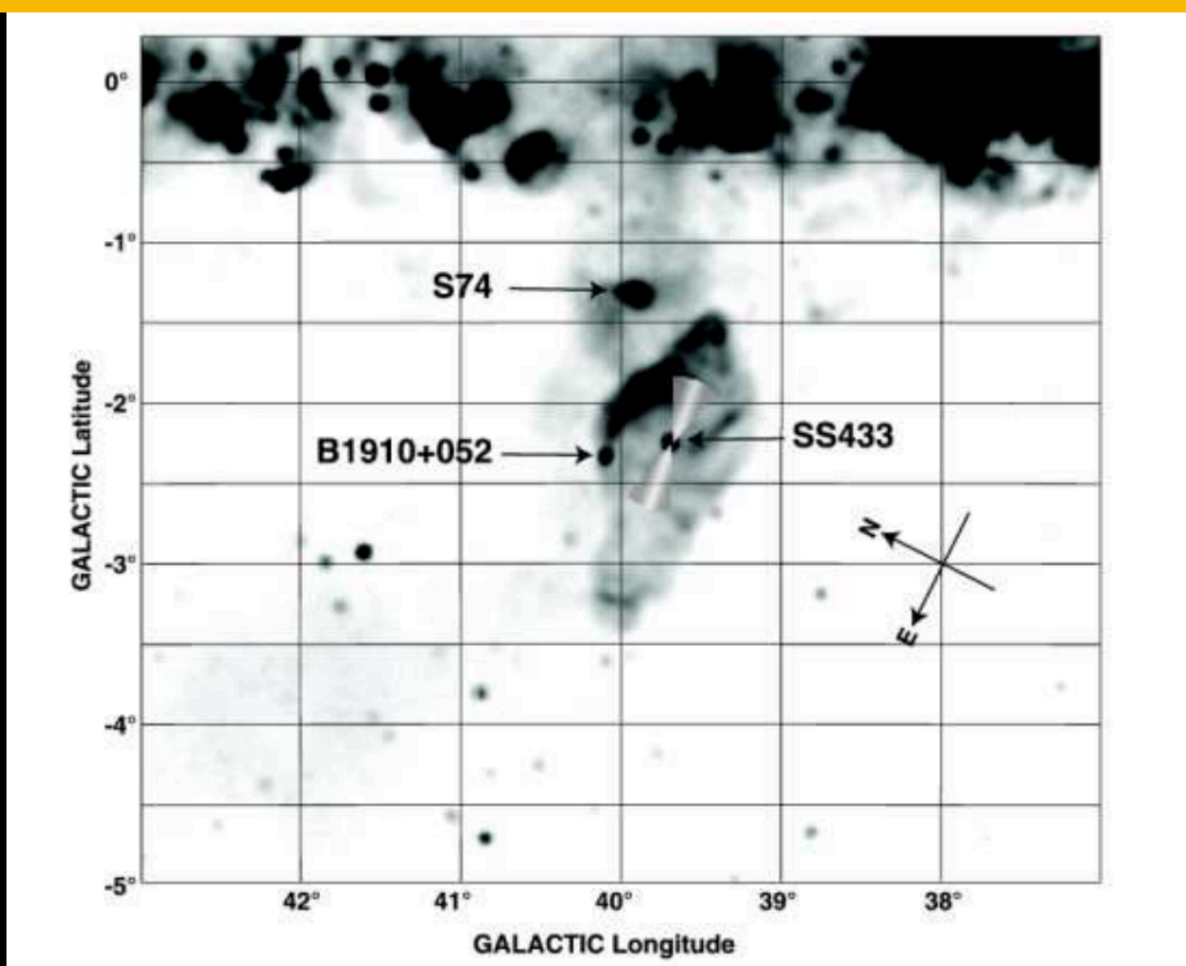
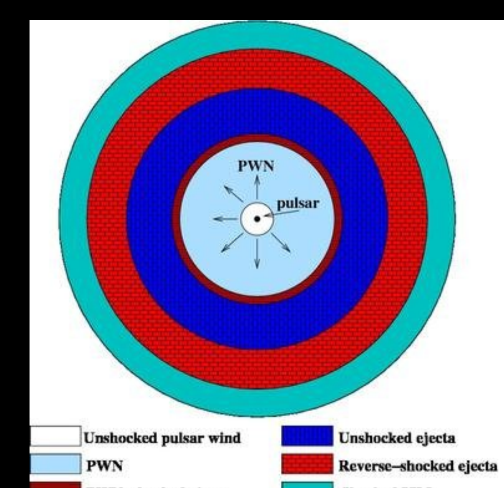
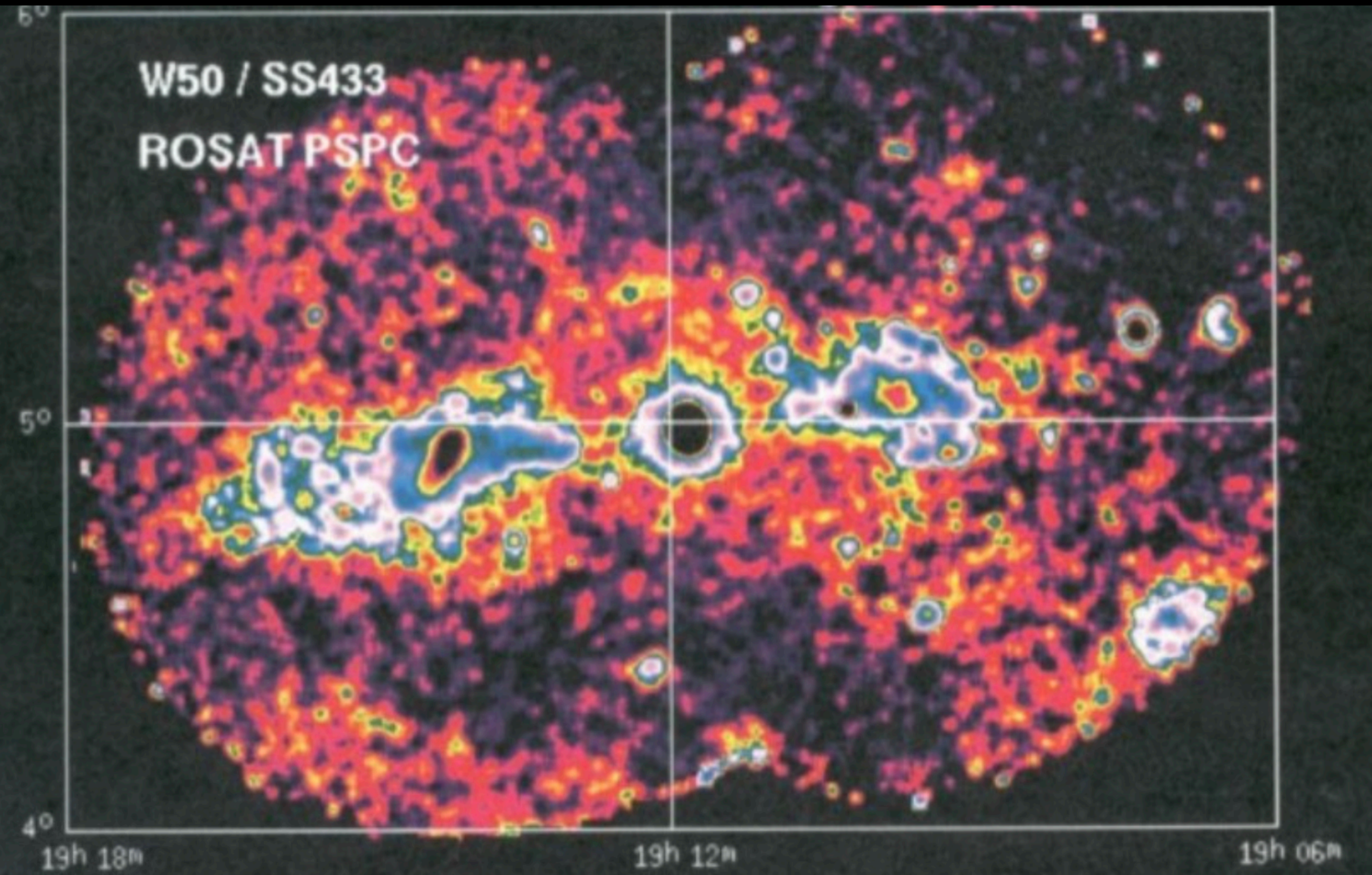




PWN

Early X-ray Observations



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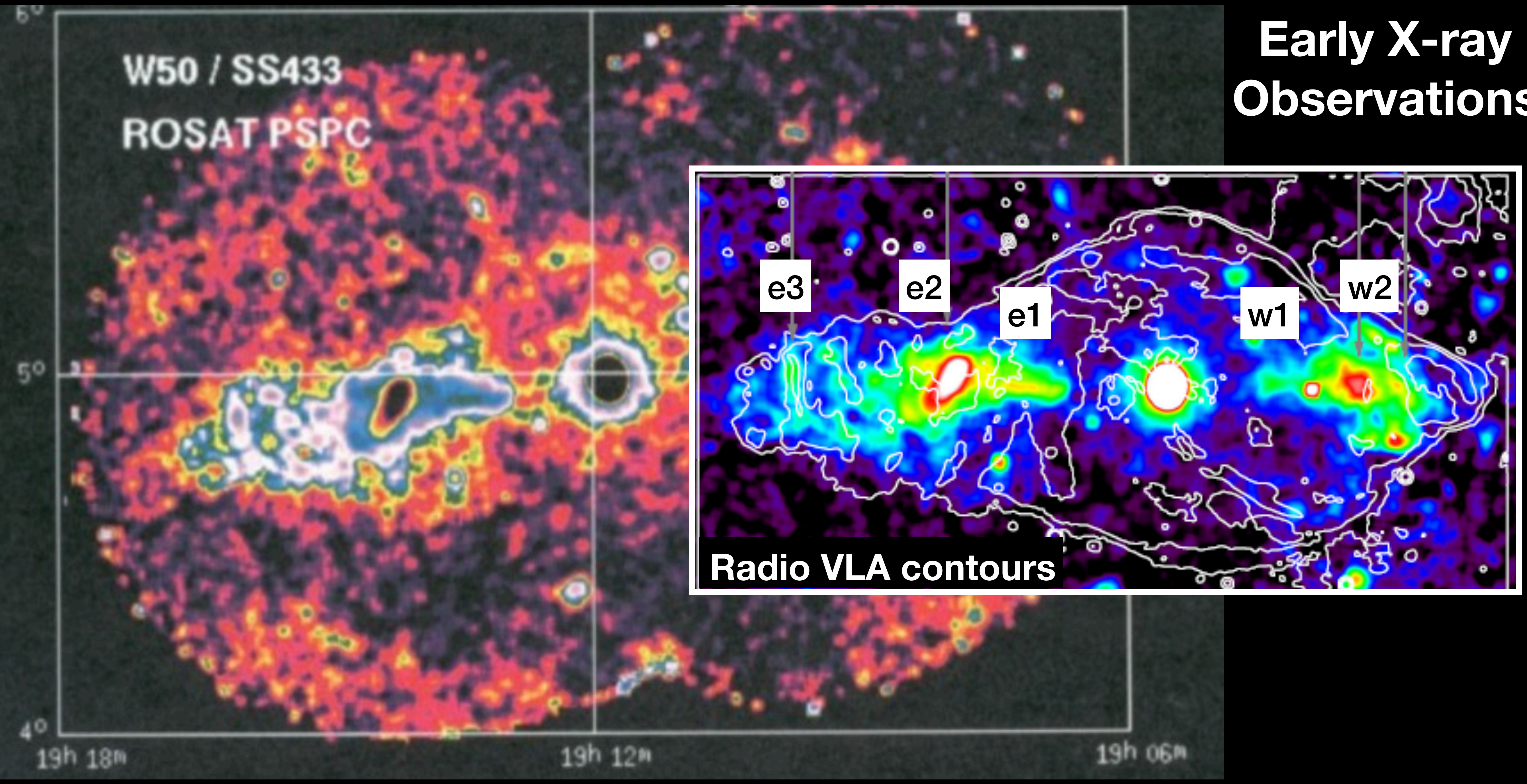

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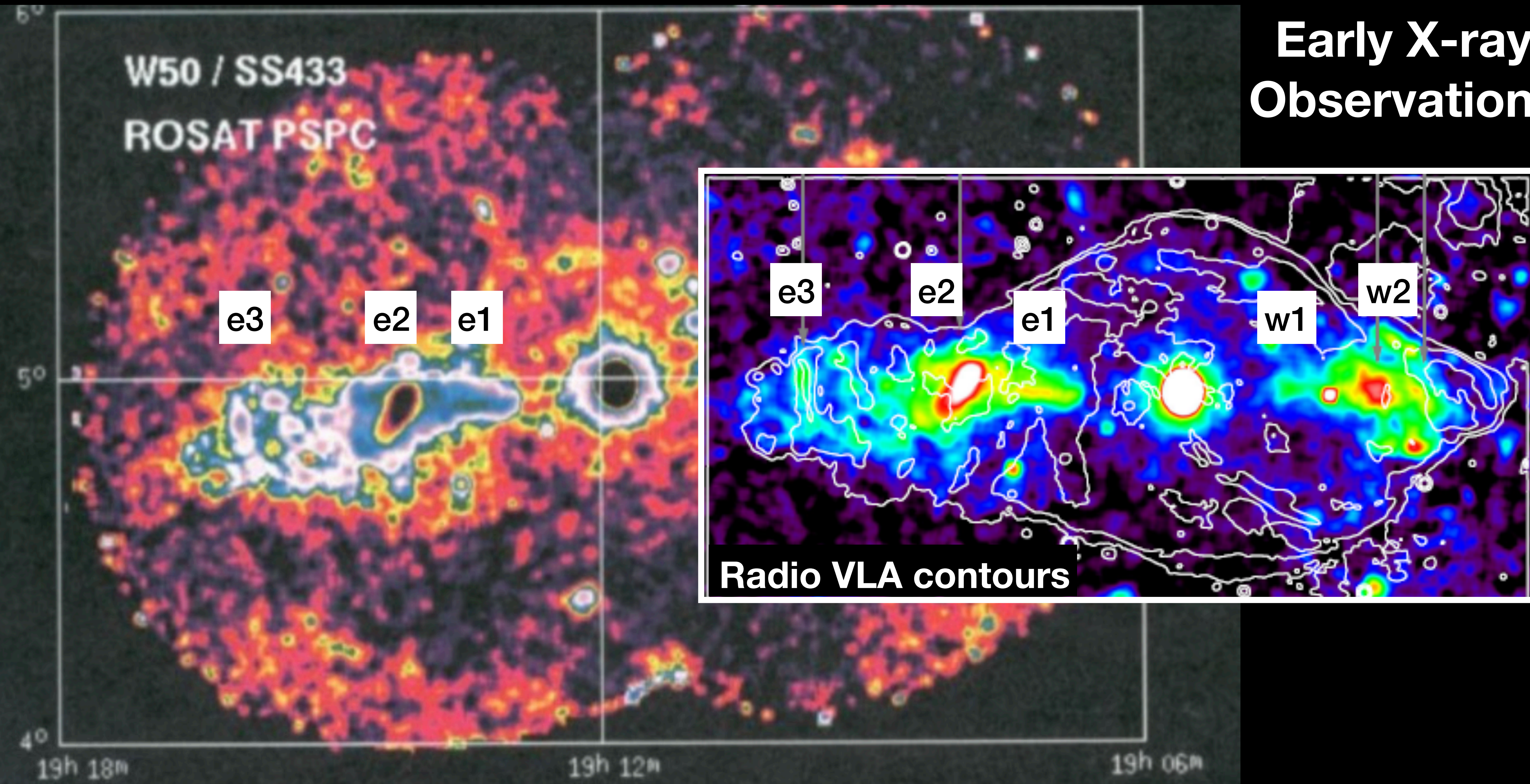
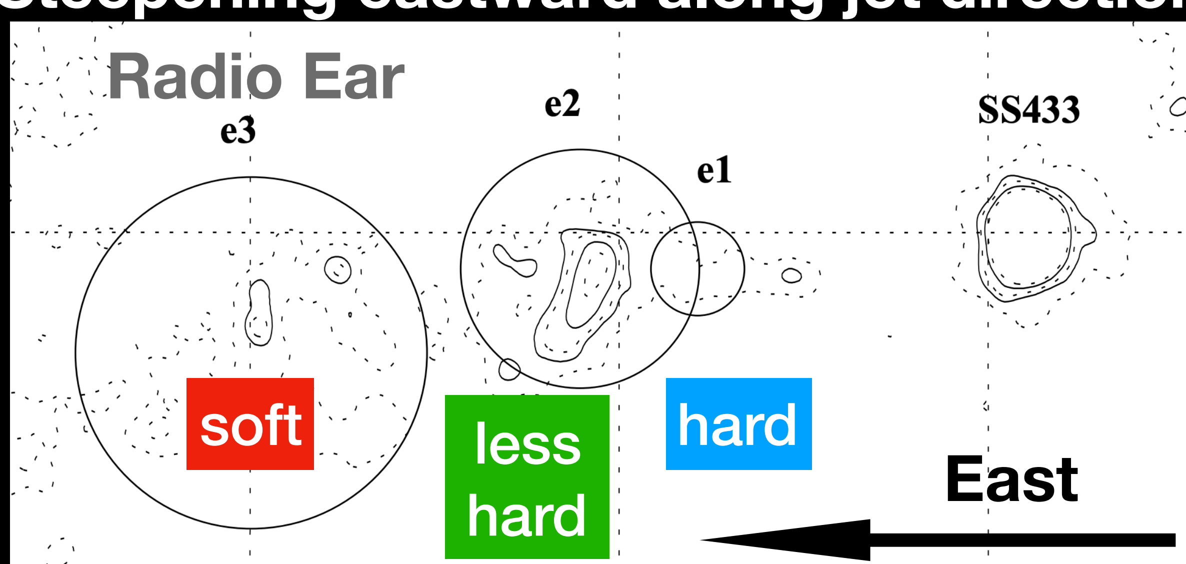


Steepening eastward along jet direction



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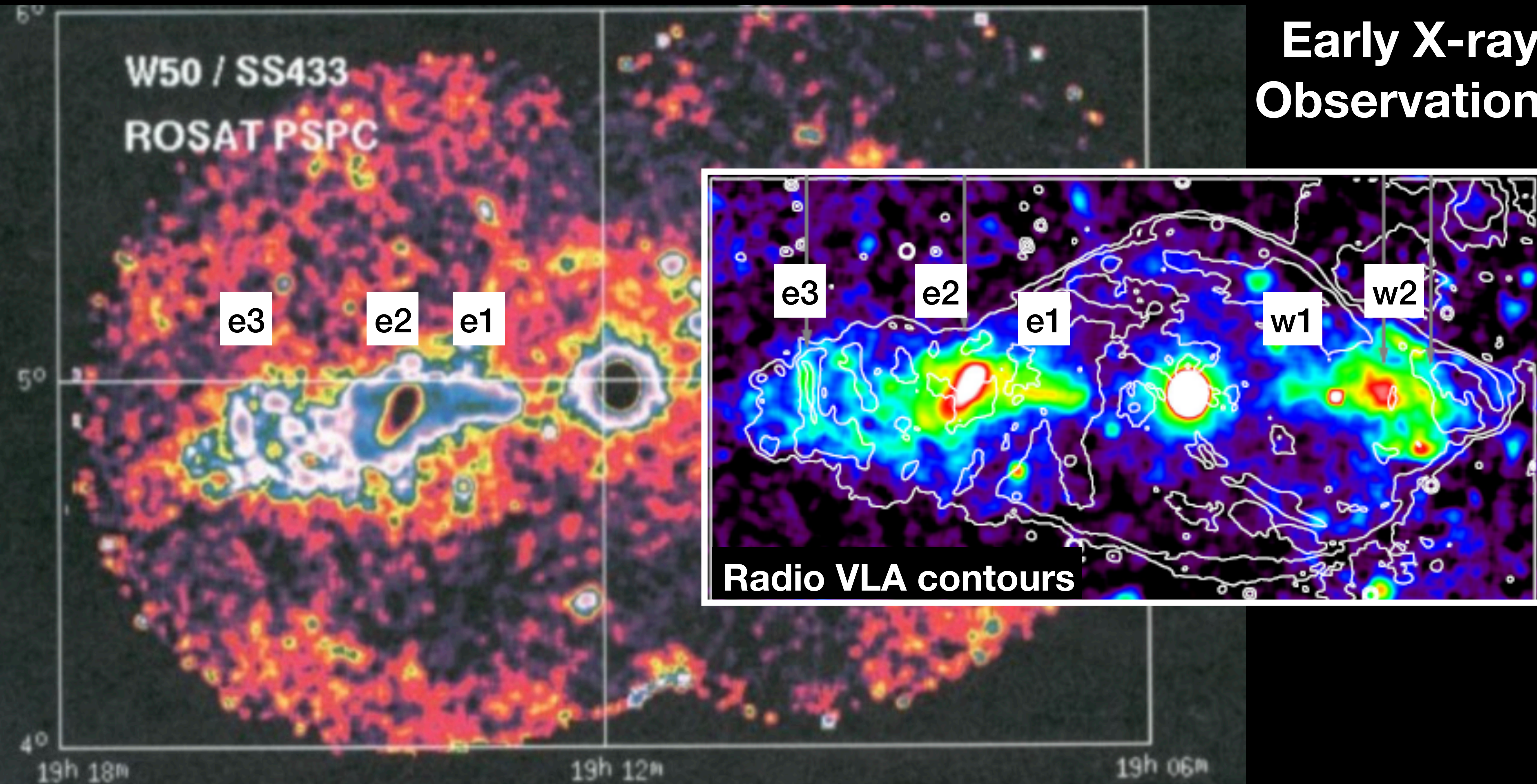

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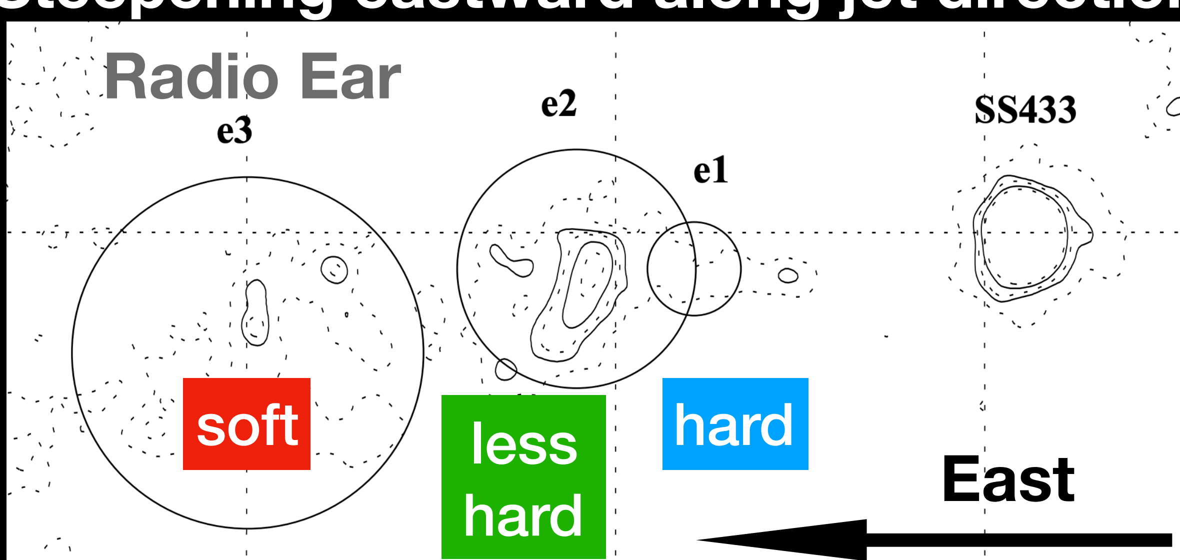


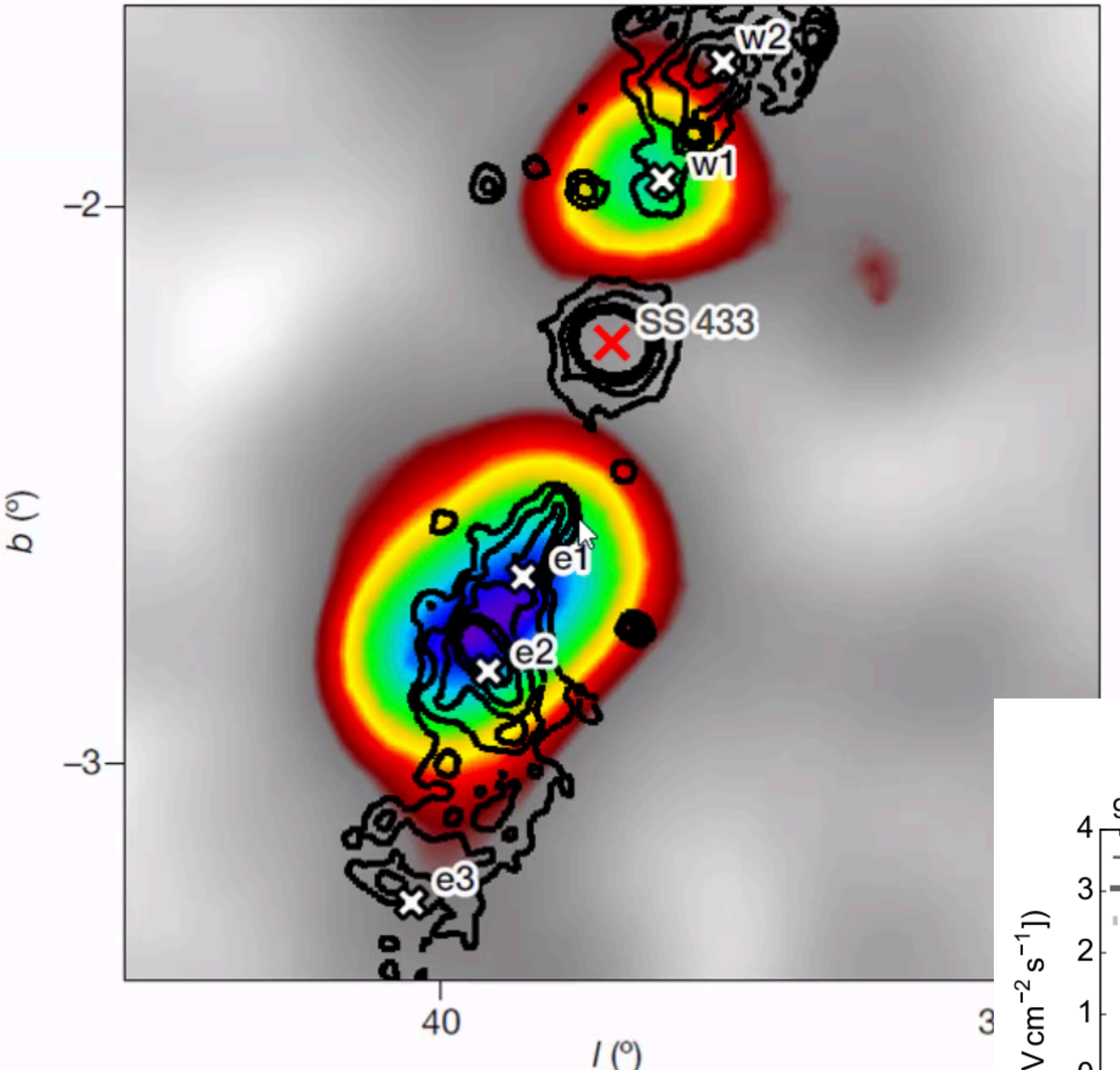
Galactic PeVatron Candidate

e1-e2: hard X-ray spectra
(same for w1-w2)
e1: Gamma~1.4-1.6
100's of TeV, 6-15 uG (e1-e2)

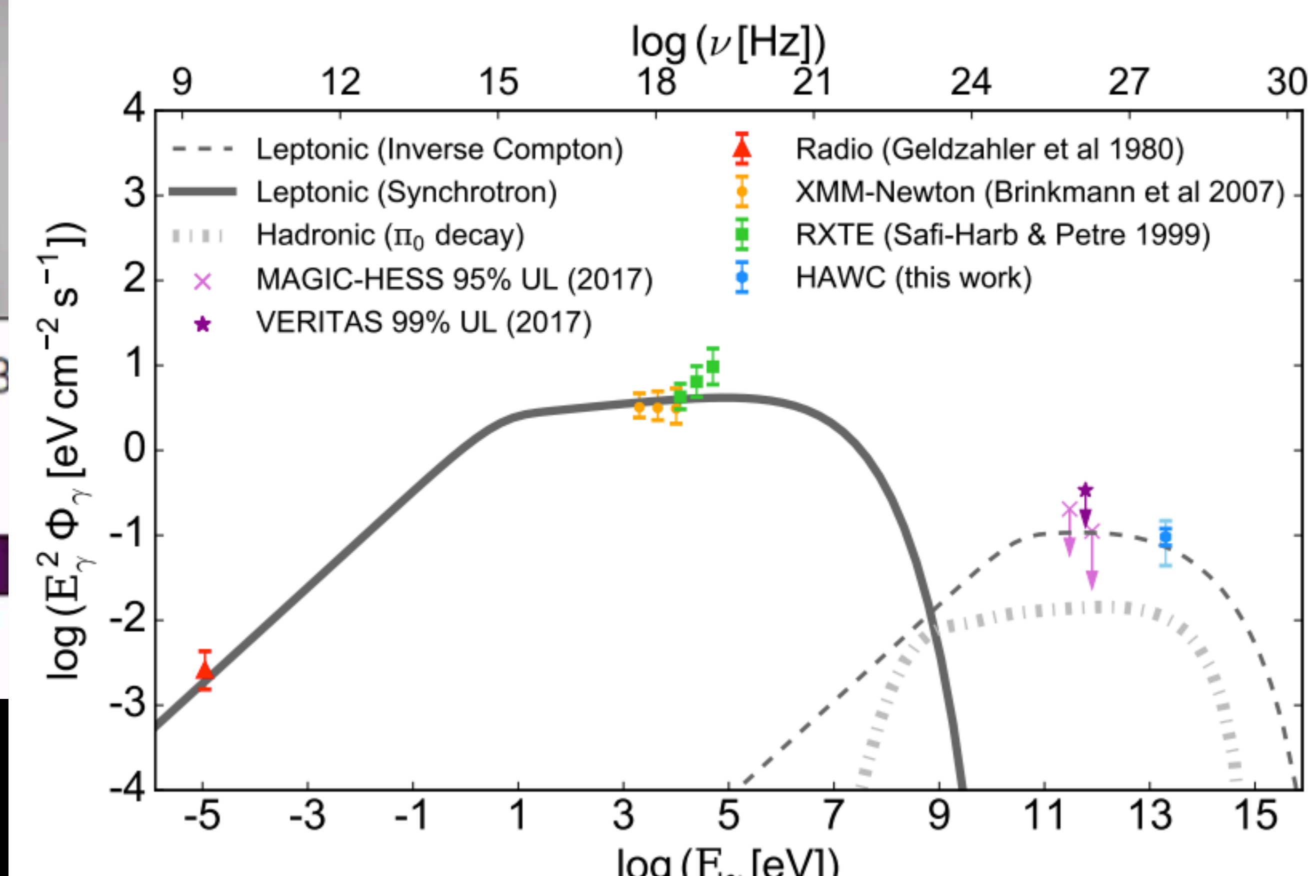
1990's

ROSAT, ASCA and RXTE (0.5-50 keV)

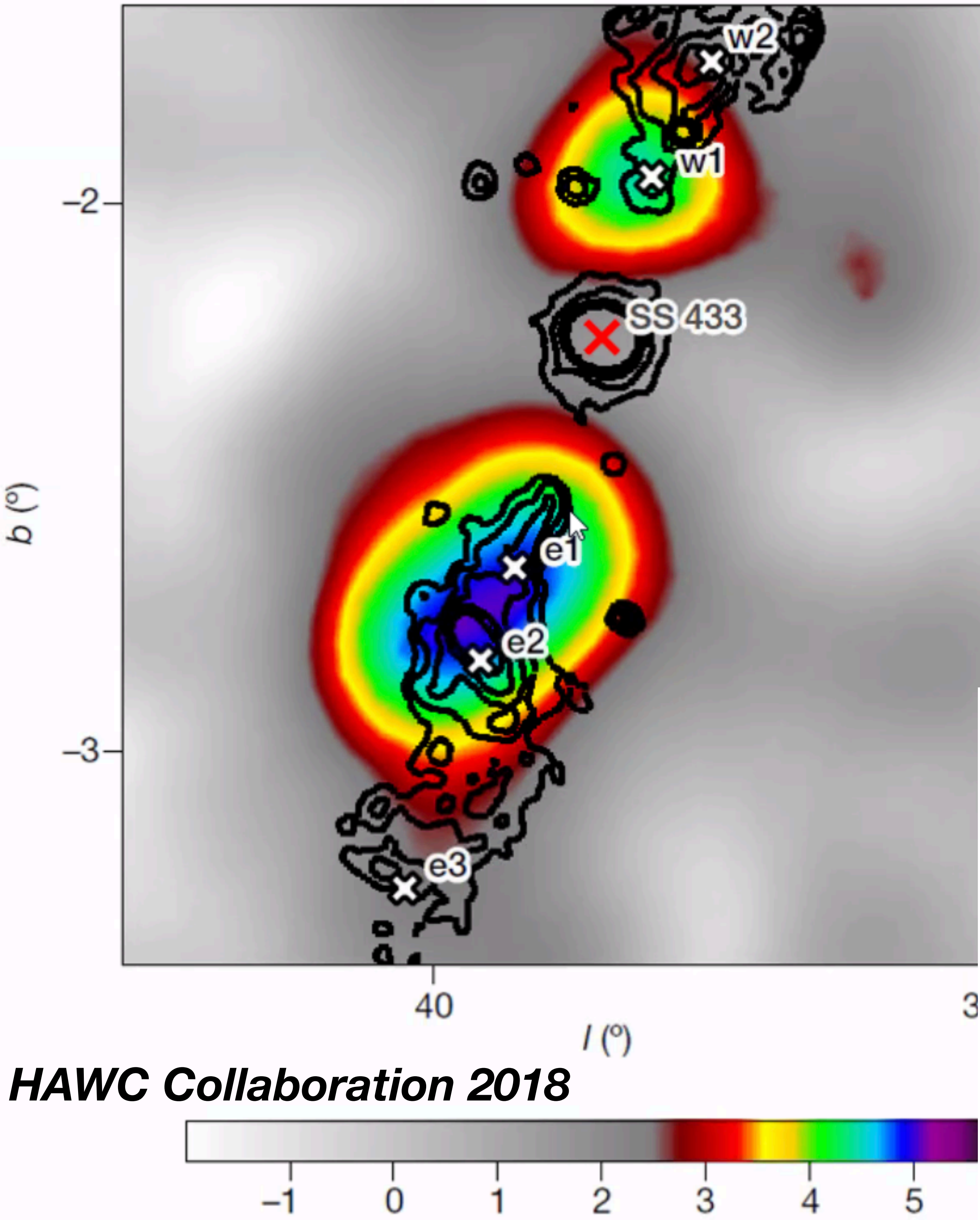
Safi-Harb & Ogelman 1997
Safi-Harb & Petre 1999

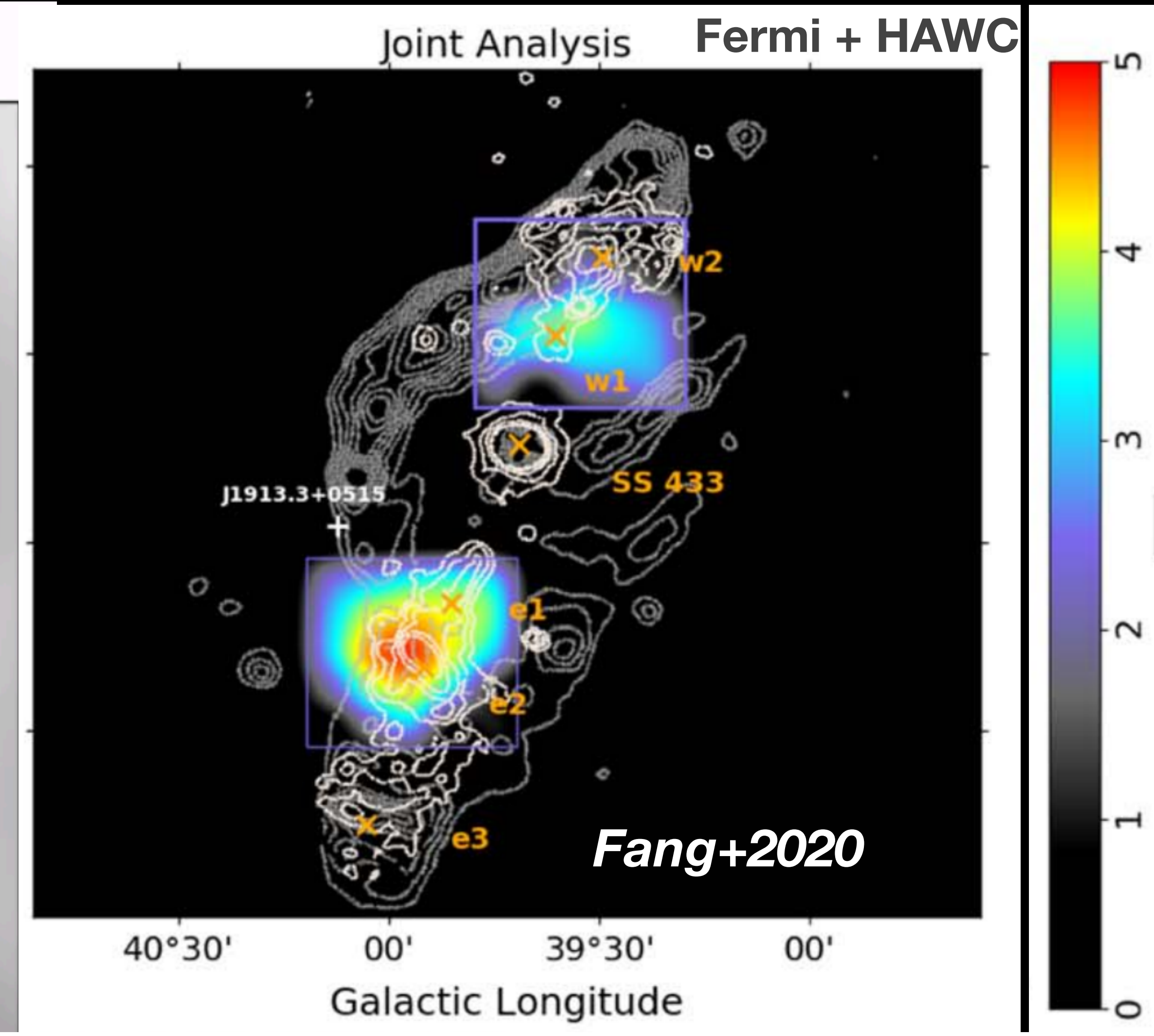


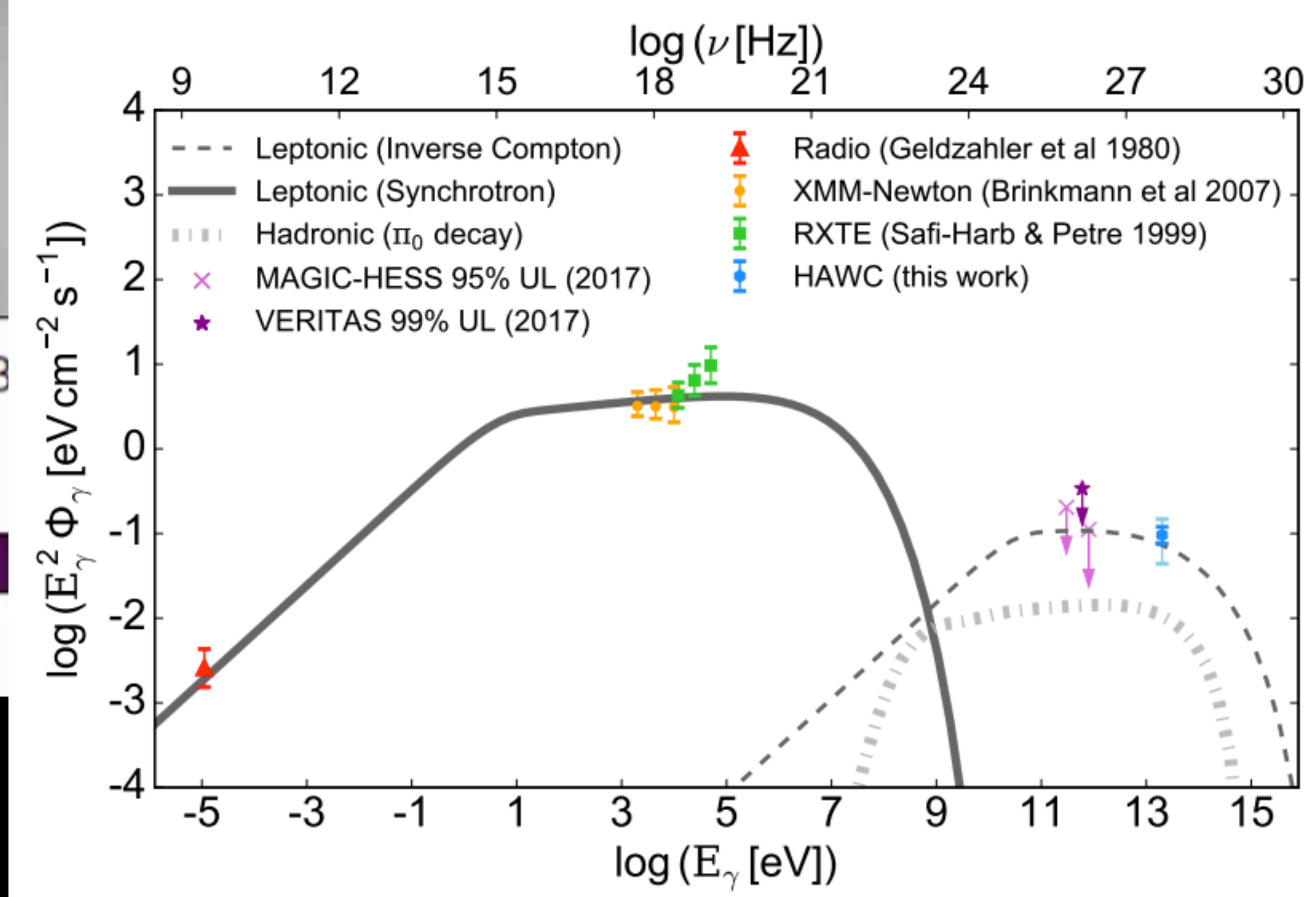
HAWC Collaboration 2018



hadronic? leptonic?
See also *Sudoh+2020 Kimura+2020*







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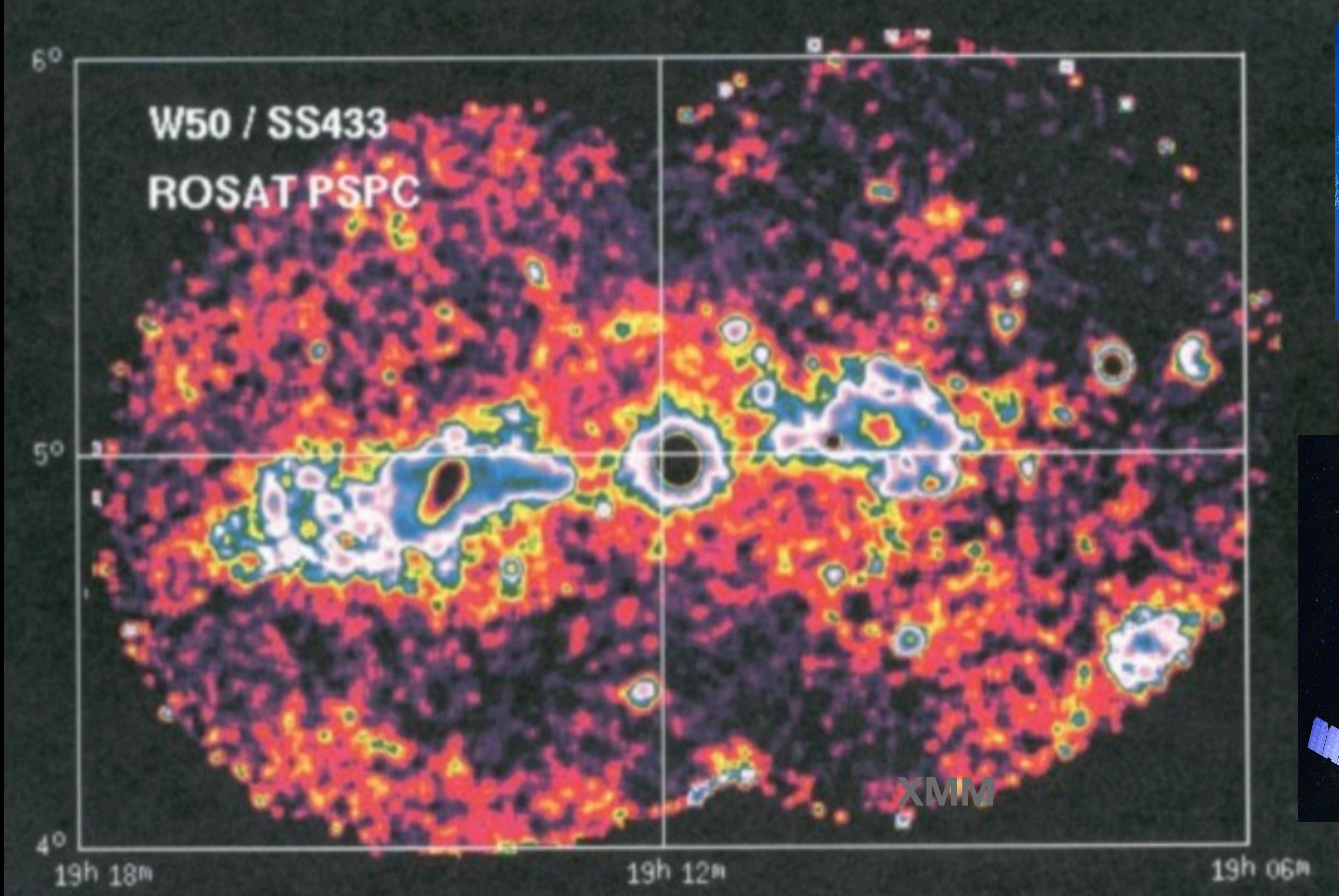
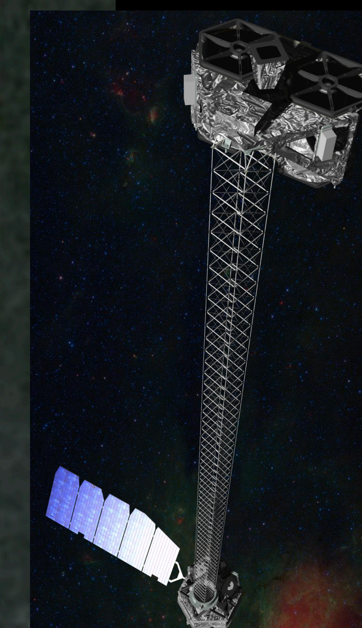
New X-ray Observations





NuSTAR 3-30 keV (12’x12’ FoV, 18” FWHM)
XMM 0.5-10 keV (30’ FoV, ~6” FWHM)
+archival XMM and Chandra (0.5-10 keV, 0.5”)

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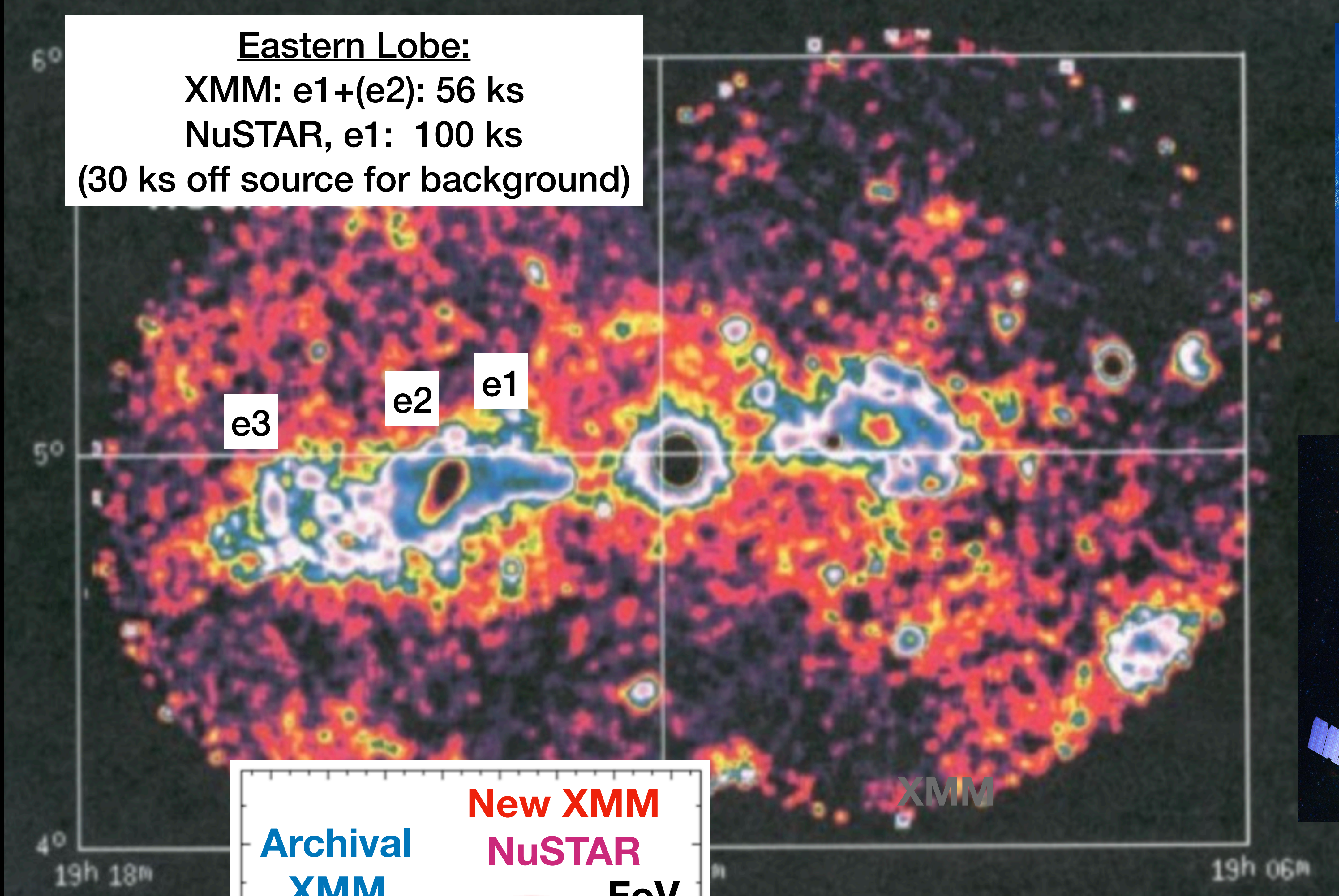

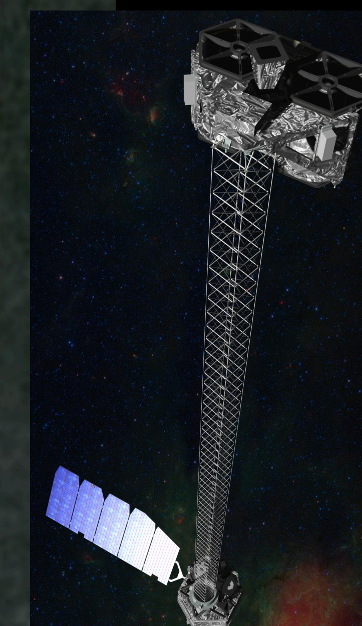

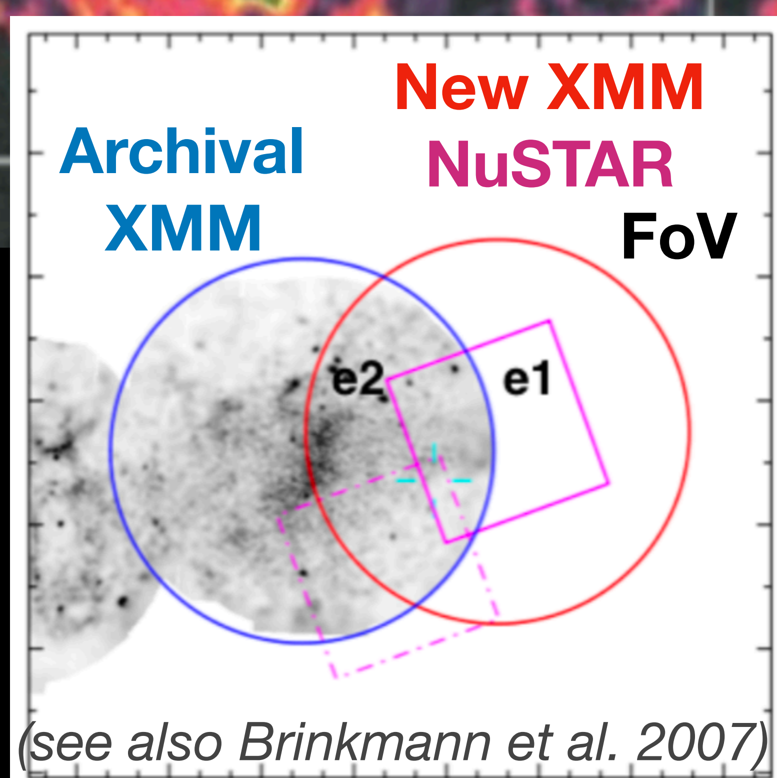

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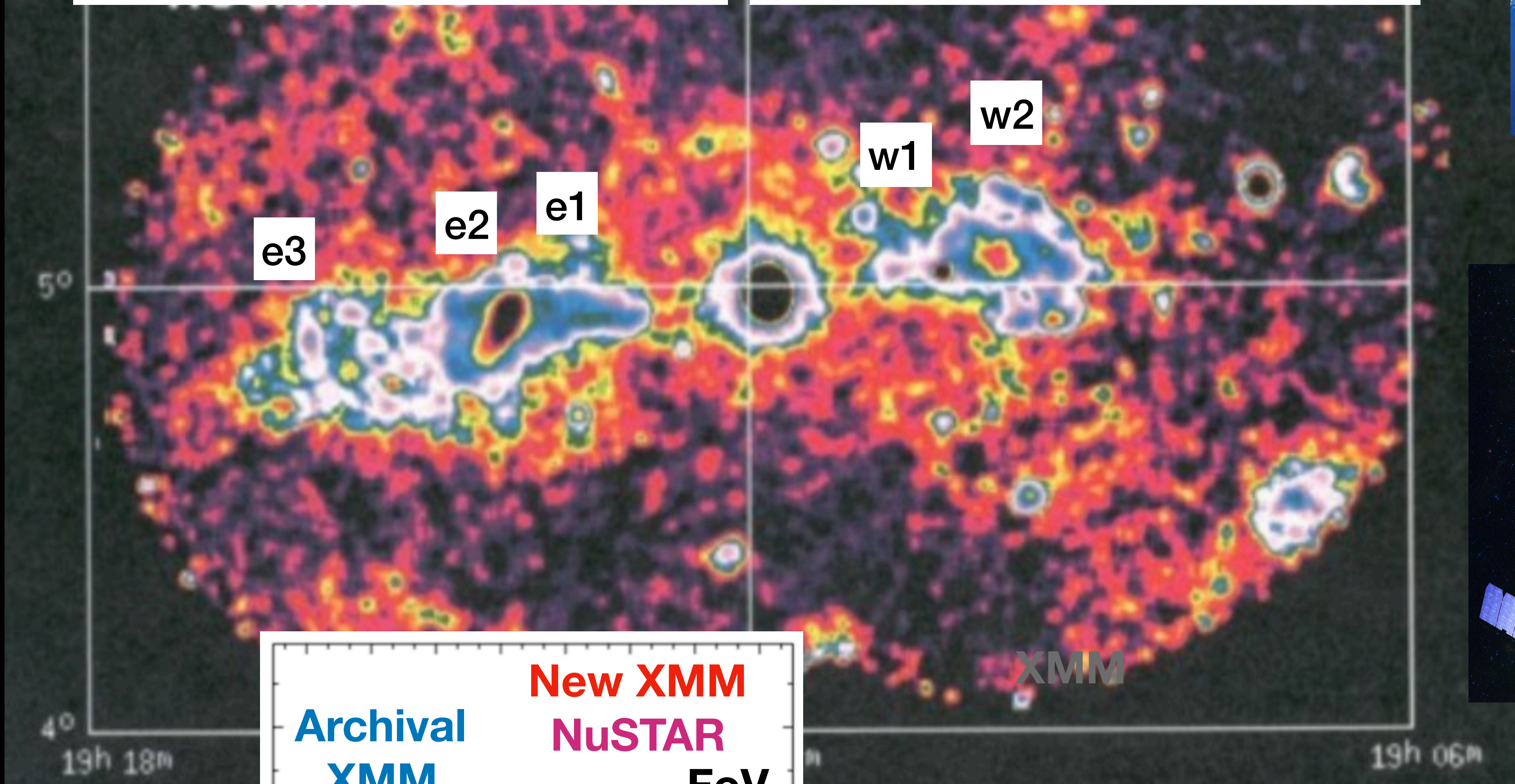
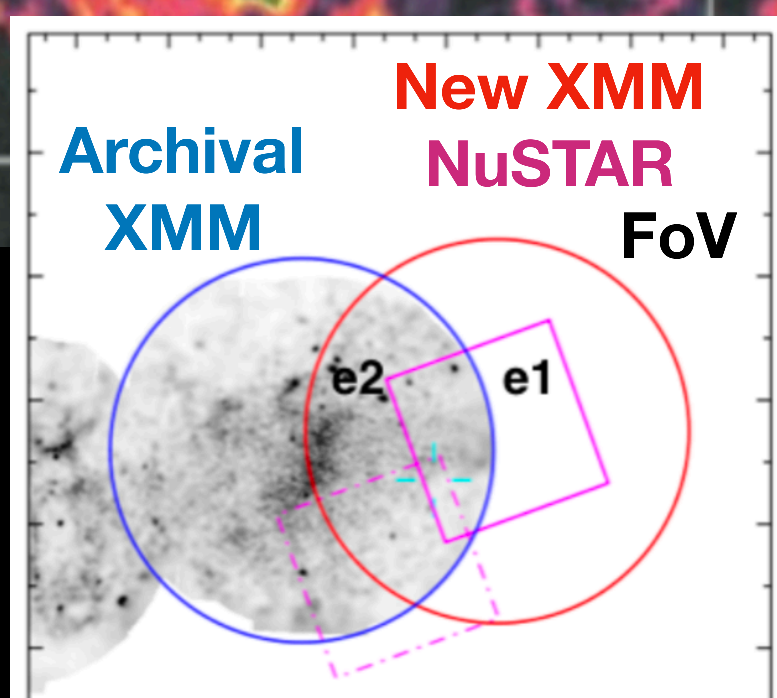
New X-ray Observations

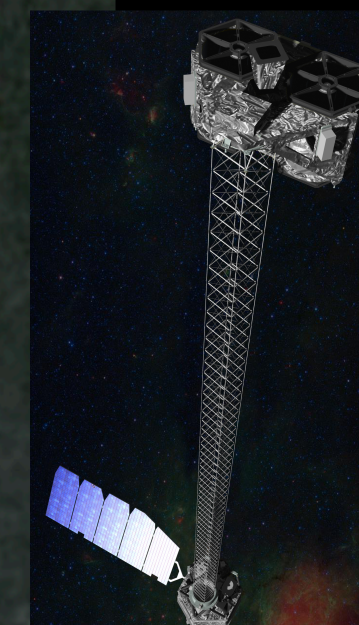
Eastern Lobe:
XMM: e1+(e2): 56 ks
NuSTAR, e1: 100 ks
(30 ks off source for background)

Western lobe:
most recently observed with
XMM: w1+w2: 50 ks
NuSTAR: w1: 100 ks





(see also Brinkmann et al. 2007)



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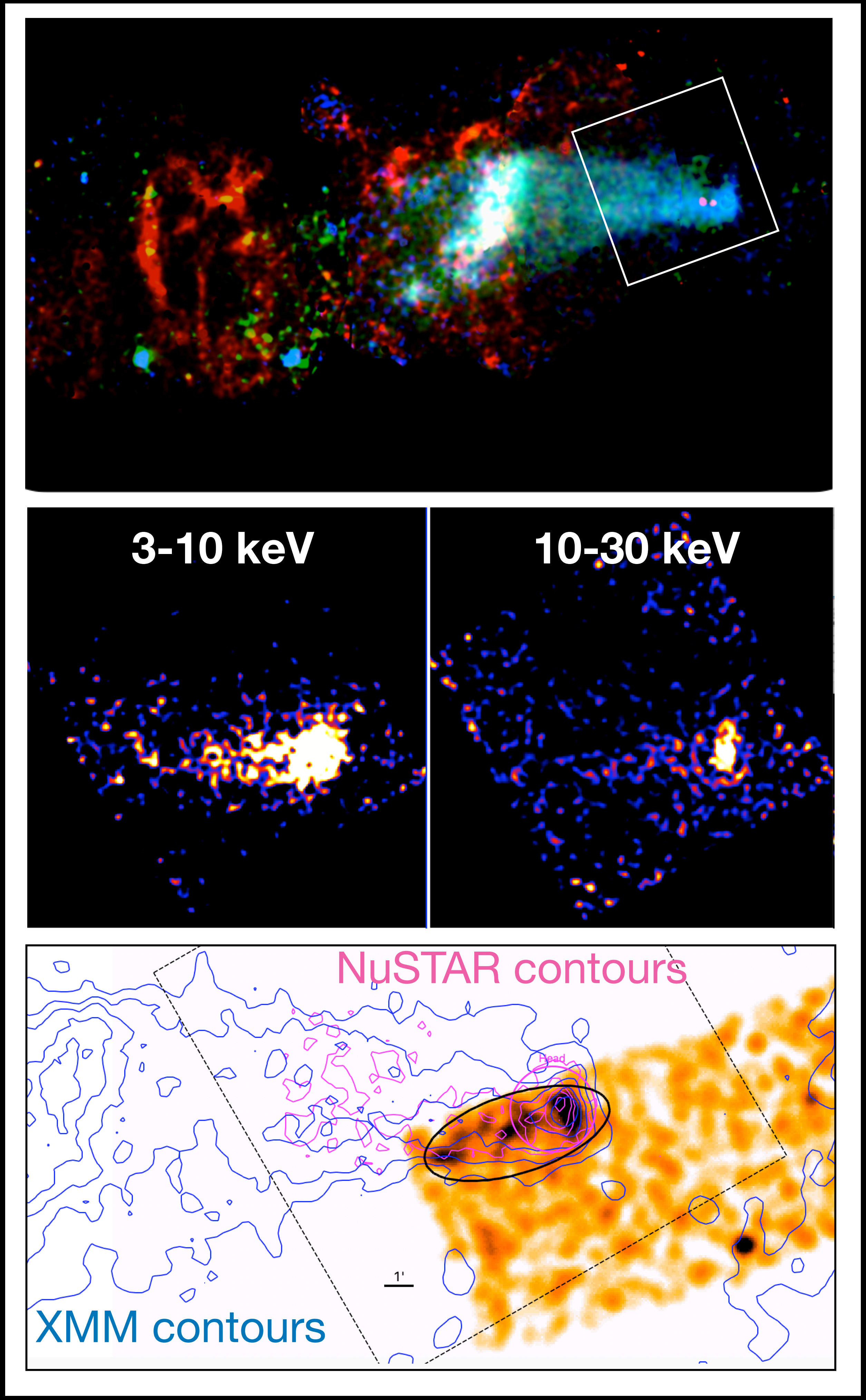
Eastern Lobe



XMM-Newton RGB image
0.5-1 keV
1-2 keV
2-10 keV

NuSTAR
FPMA and FPMB

serendipitous discovery of innermost 'head' region with Chandra

(0.5-8 keV)

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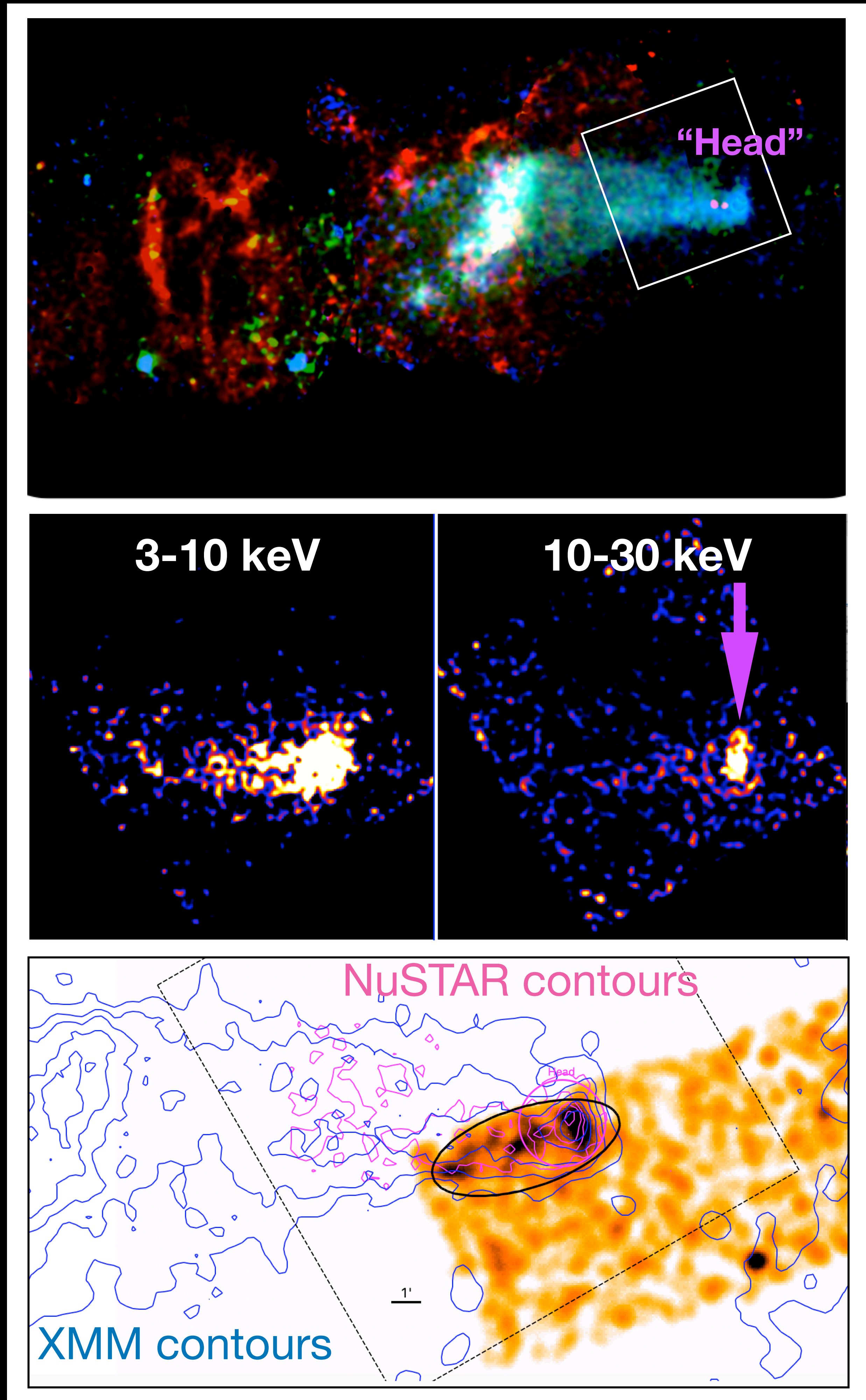

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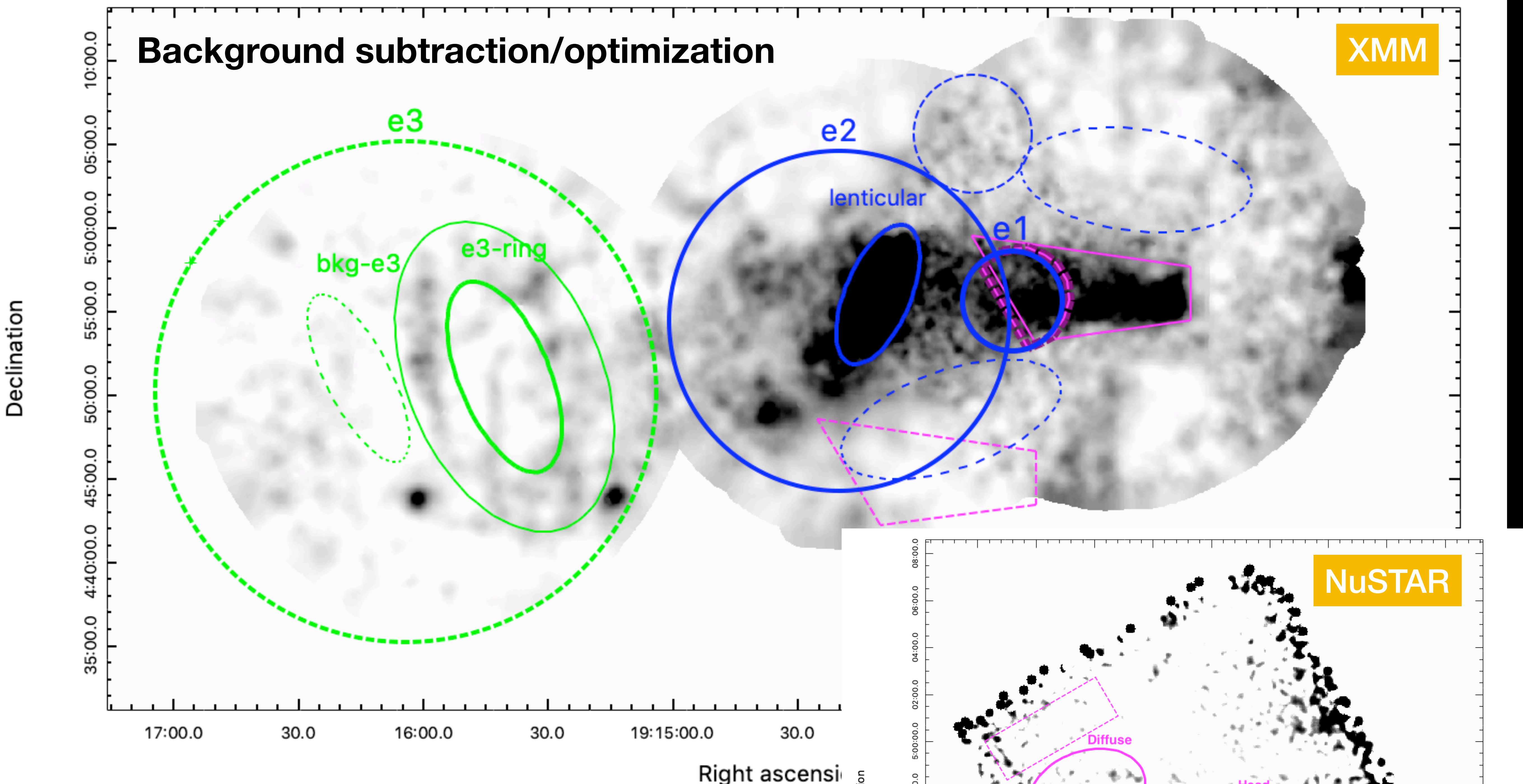
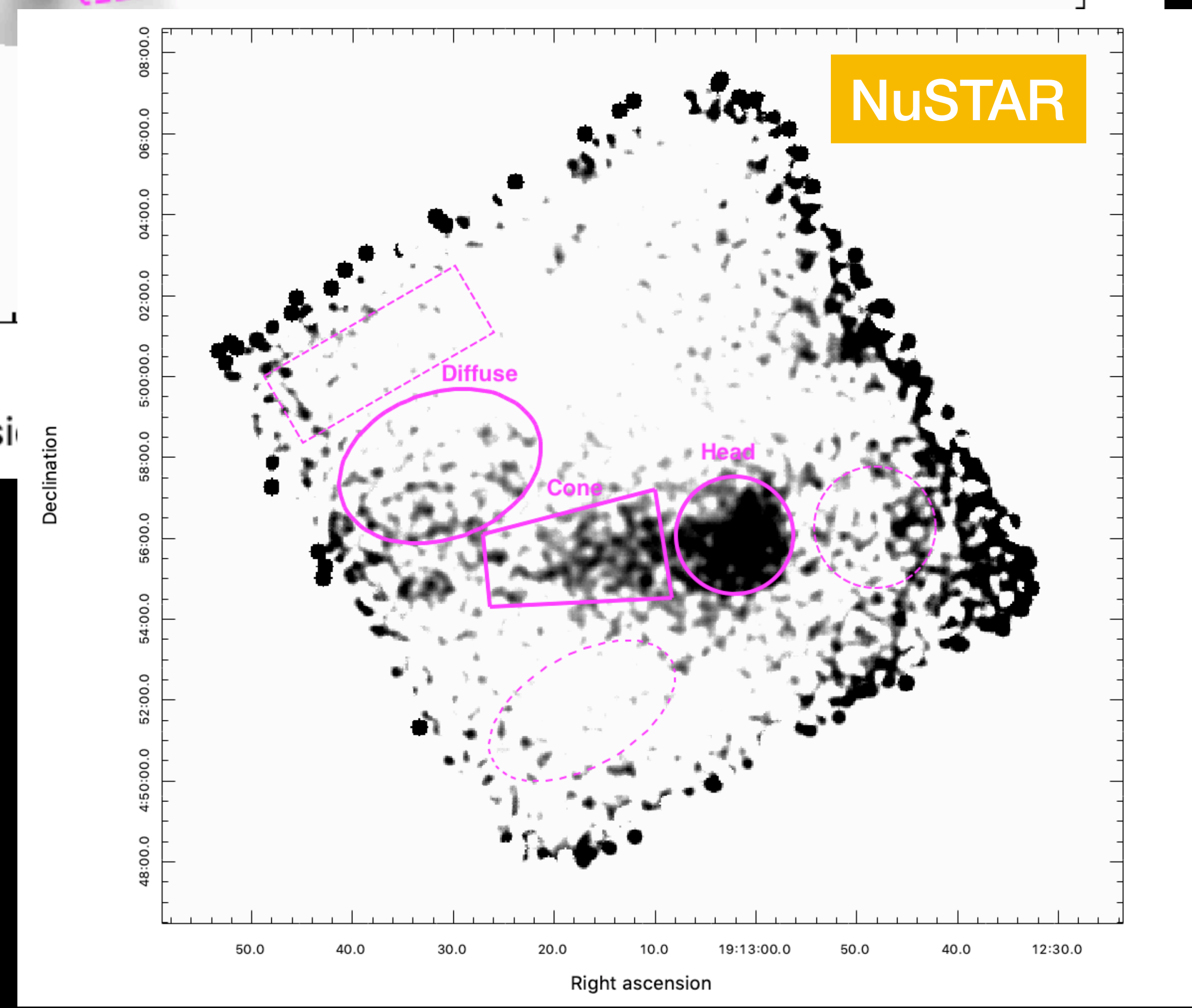


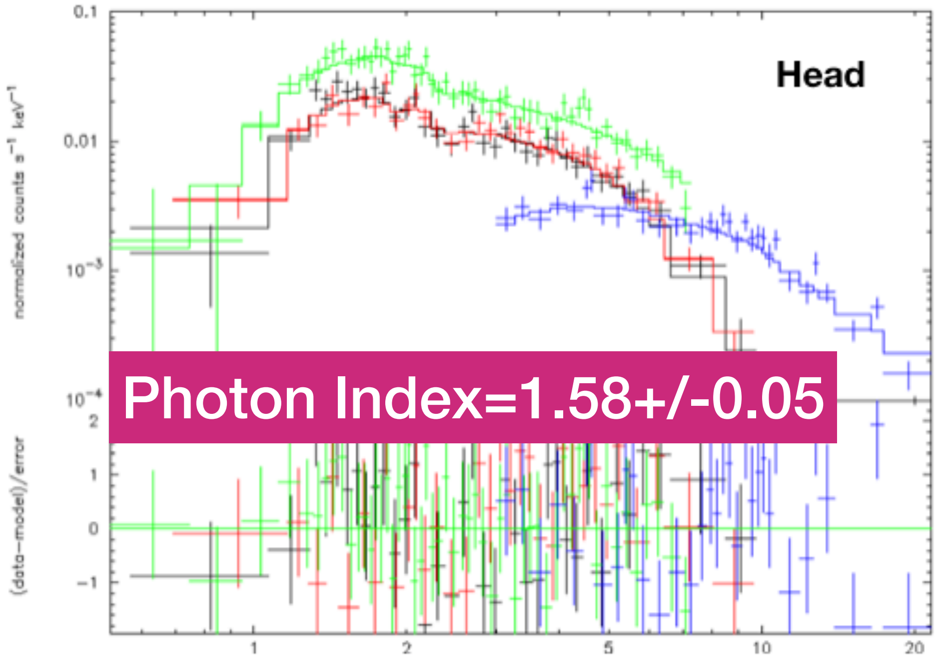


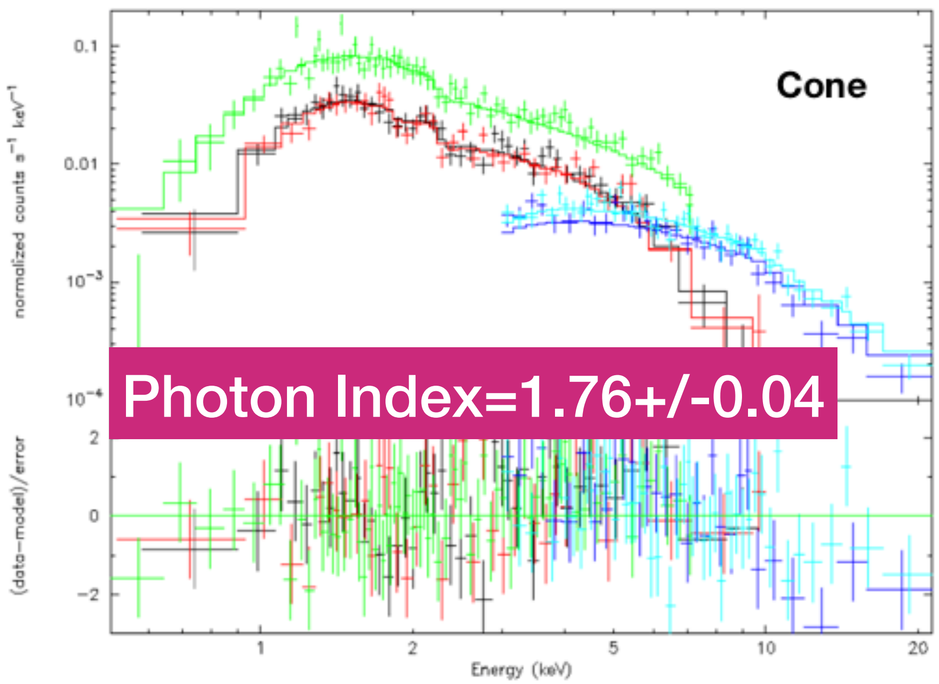
Source regions NuSTAR — XMM — —

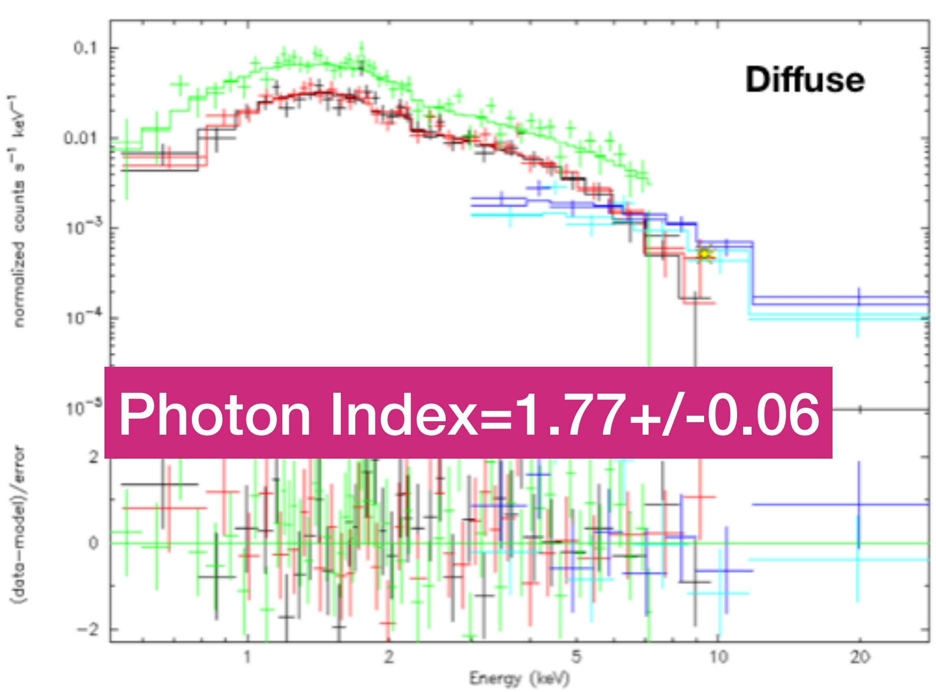
NuSTAR 3-30 keV (12’x12’ FoV, 18” FWHM)

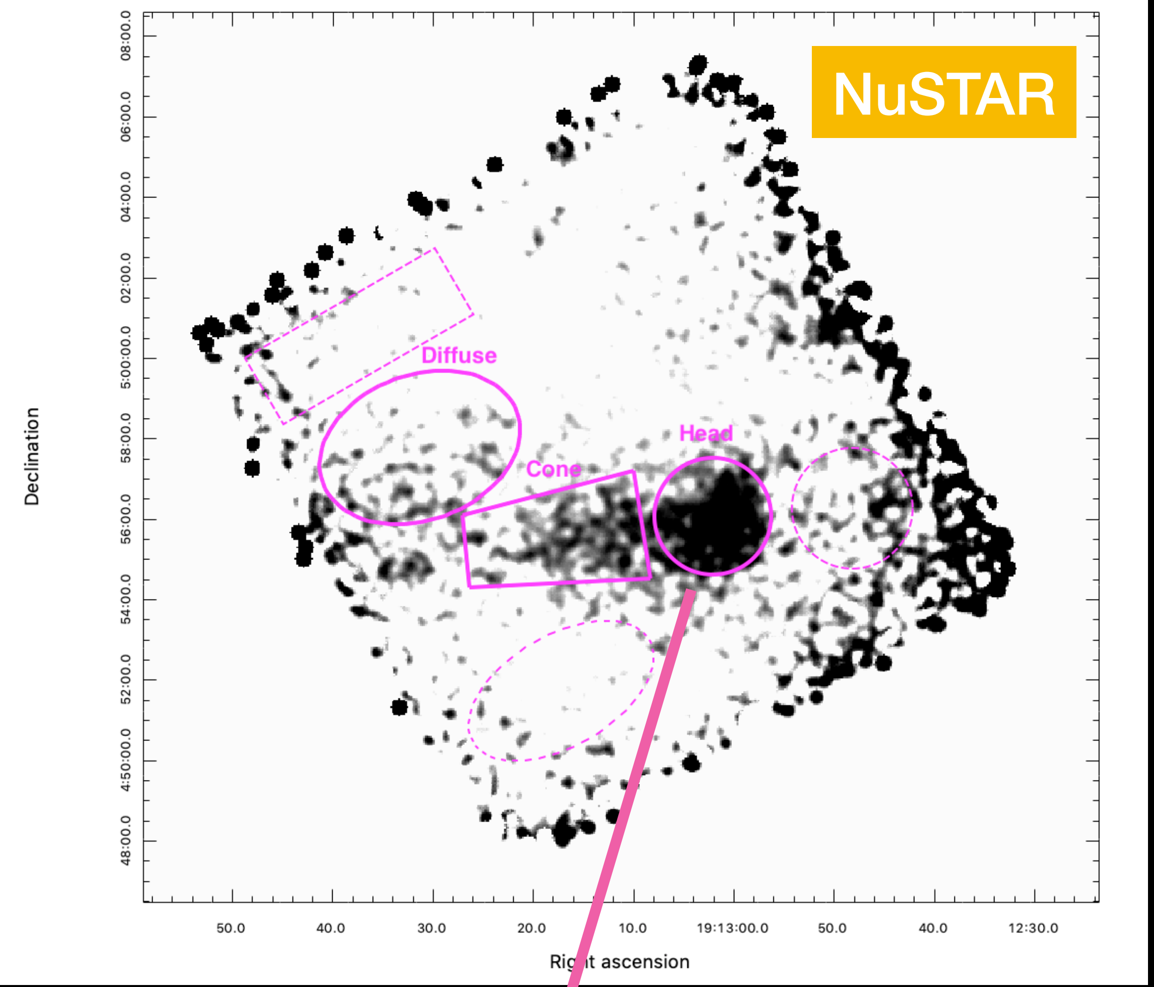
XMM 0.5-10 keV (30’ FoV, ~6” FWHM)

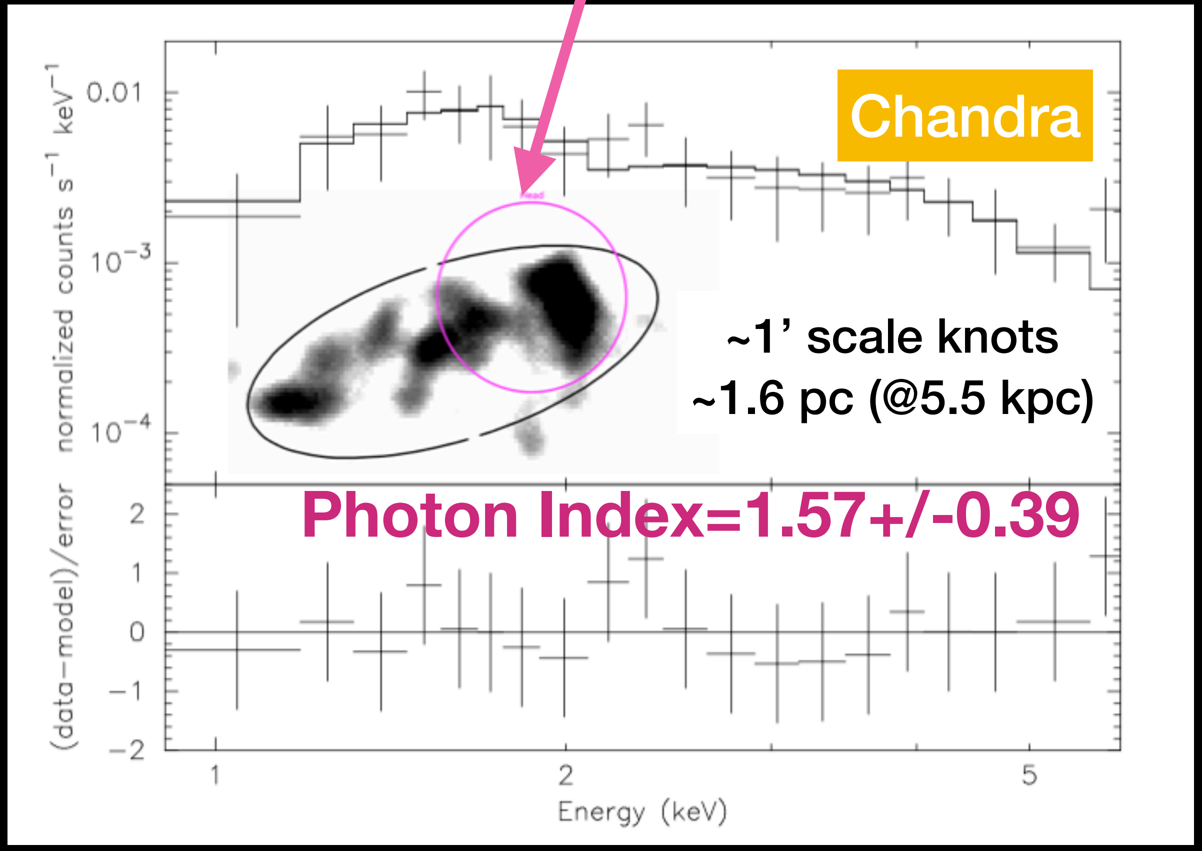
Background regions - - - dashed


Head
Photon Index=1.58+/-0.05
normalized counts s^{-1} keV^{-1}
(data−model)/error

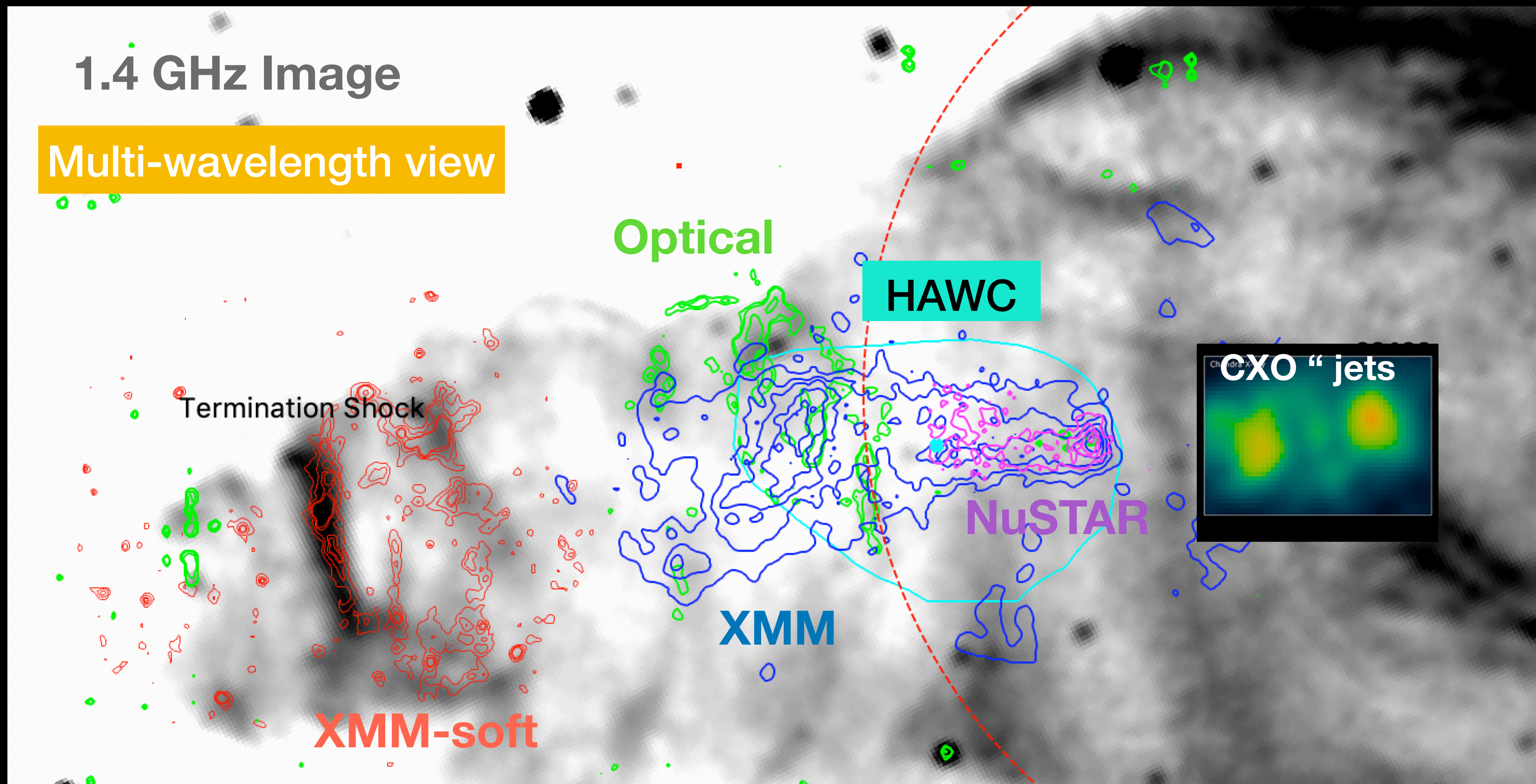

Cone
Photon Index=1.76+/-0.04
normalized counts s^{-1} keV^{-1}
(data−model)/error
Energy (keV)


Diffuse
Photon Index=1.77+/-0.06
normalized counts s^{-1} keV^{-1}
(data−model)/error
Energy (keV)


NuSTAR
Diffuse
Cone
Head
Declination
Right ascension


Chandra
~1' scale knots
~1.6 pc (@5.5 kpc)
Photon Index=1.57+/-0.39
normalized counts s^{-1} keV^{-1}
(data−model)/error
Energy (keV)

Implications

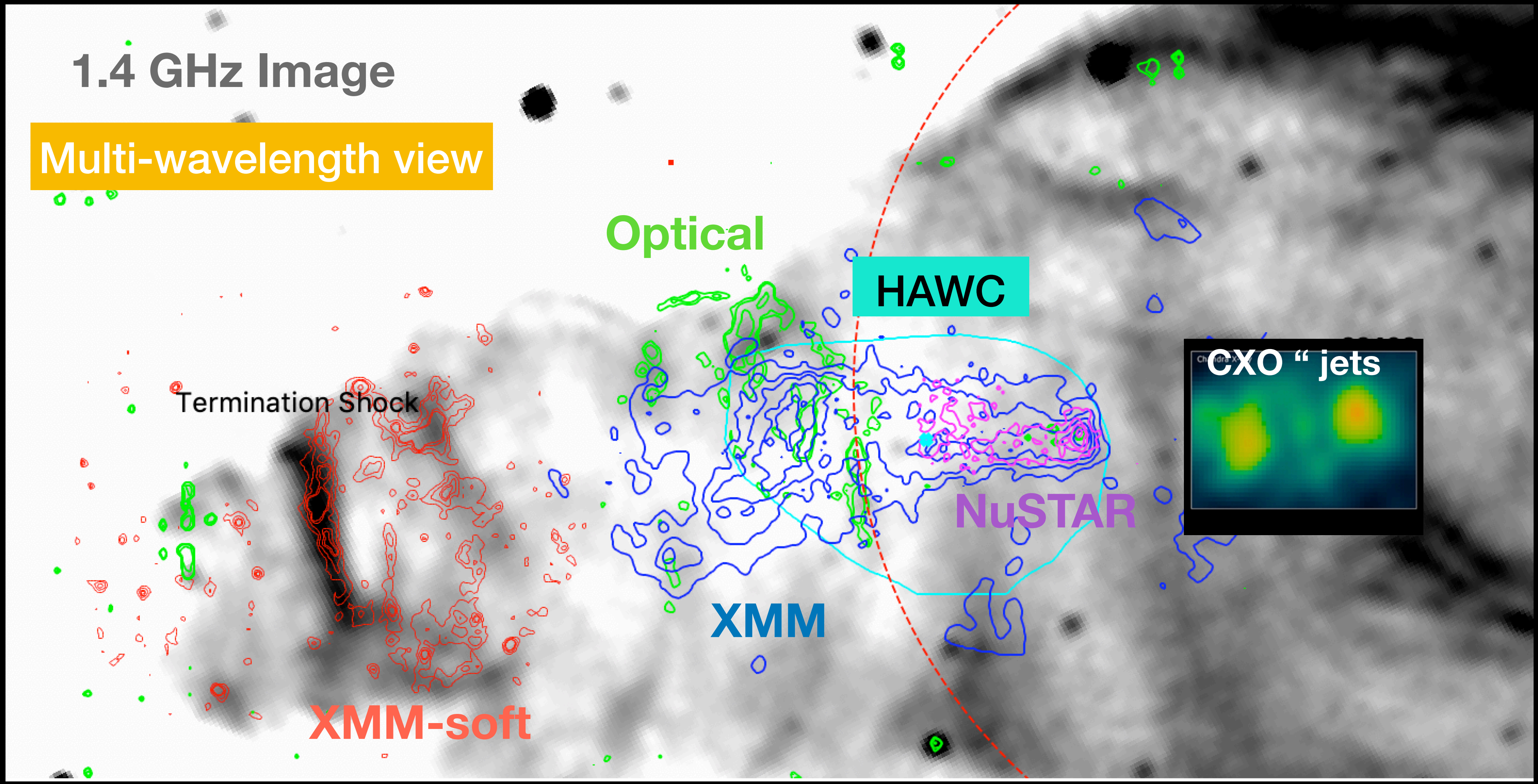


Eastern Lobe `HEAD’

- ⋆ Lx (Head)~ 1.1 10^{34} erg/s (0.3-30 keV); L_x (eastern lobe)/Power (jets)<~10^{-3}
- ⋆ Photon index~1.5=>particle index~2=> E^{-2} distribution of electrons.

  (similar to what is seen in some AGN jets and PWNe)
  - Column density varies along jet: mass entrainment, internal shocks?
- ⋆ Harder than typical DSA (Hard differential injection spectrum, harder than E^{-1}
- ⋆ **Challenges traditional particle accleration process**

Implications

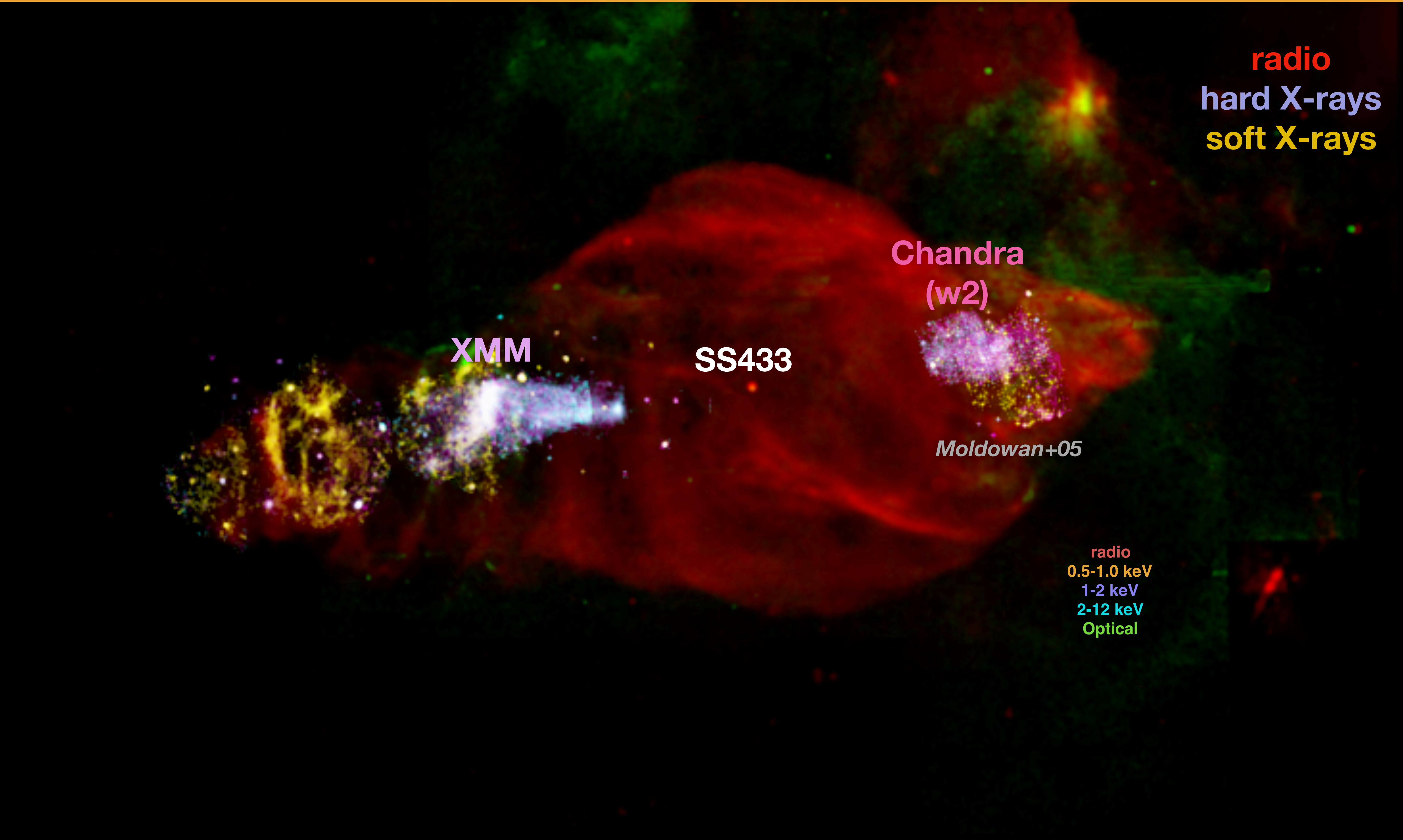


Eastern Lobe `HEAD'

- $B_{equipartition}$ (Head) >~ **12 micro-Gauss** (Volume~1.6 10^{58} cm^3 @5.5 kpc)
- Radiative Loss Timescale ~ 1 kyr << W50-age (<~30 kyr)
- Max Energy of Electrons: E_{max} (Head)~**250 TeV**

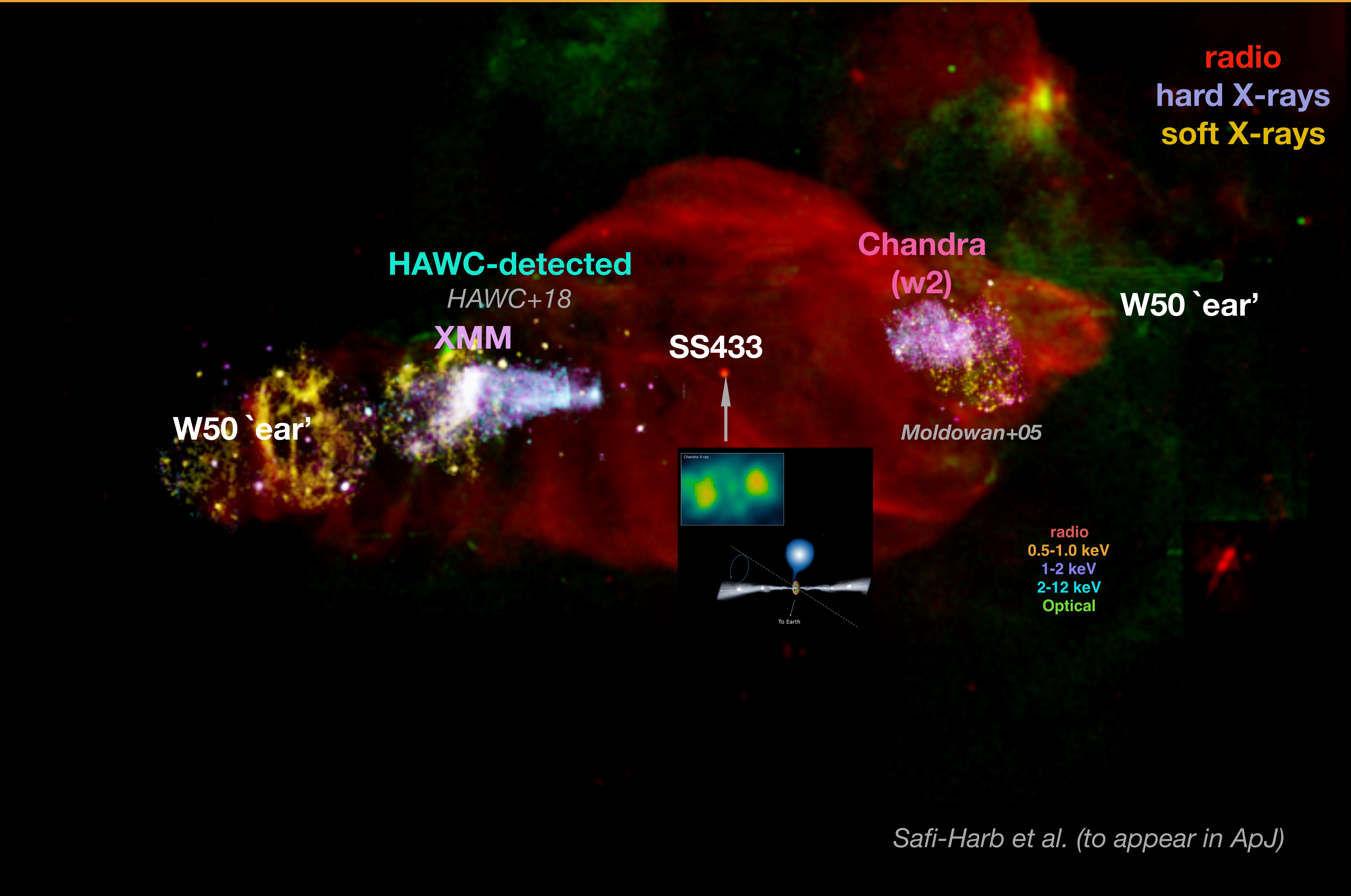
Injection and re-acceleration of SS 433 jets

Conclusions



Safi-Harb et al. (to appear in ApJ)

Conclusions



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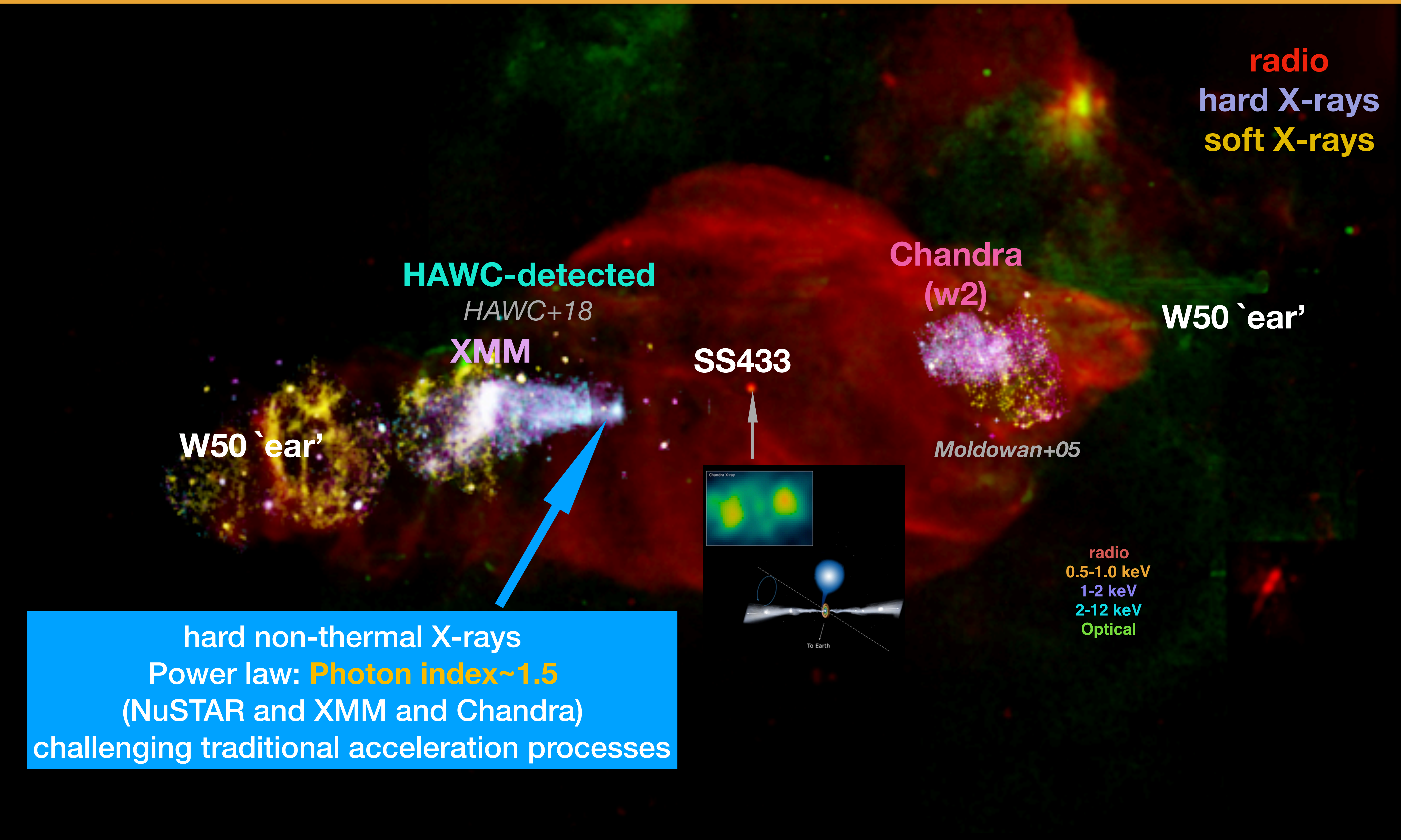

hard non-thermal X-rays
Power law: Photon index~1.5
(NuSTAR and XMM and Chandra)
challenging traditional acceleration processes

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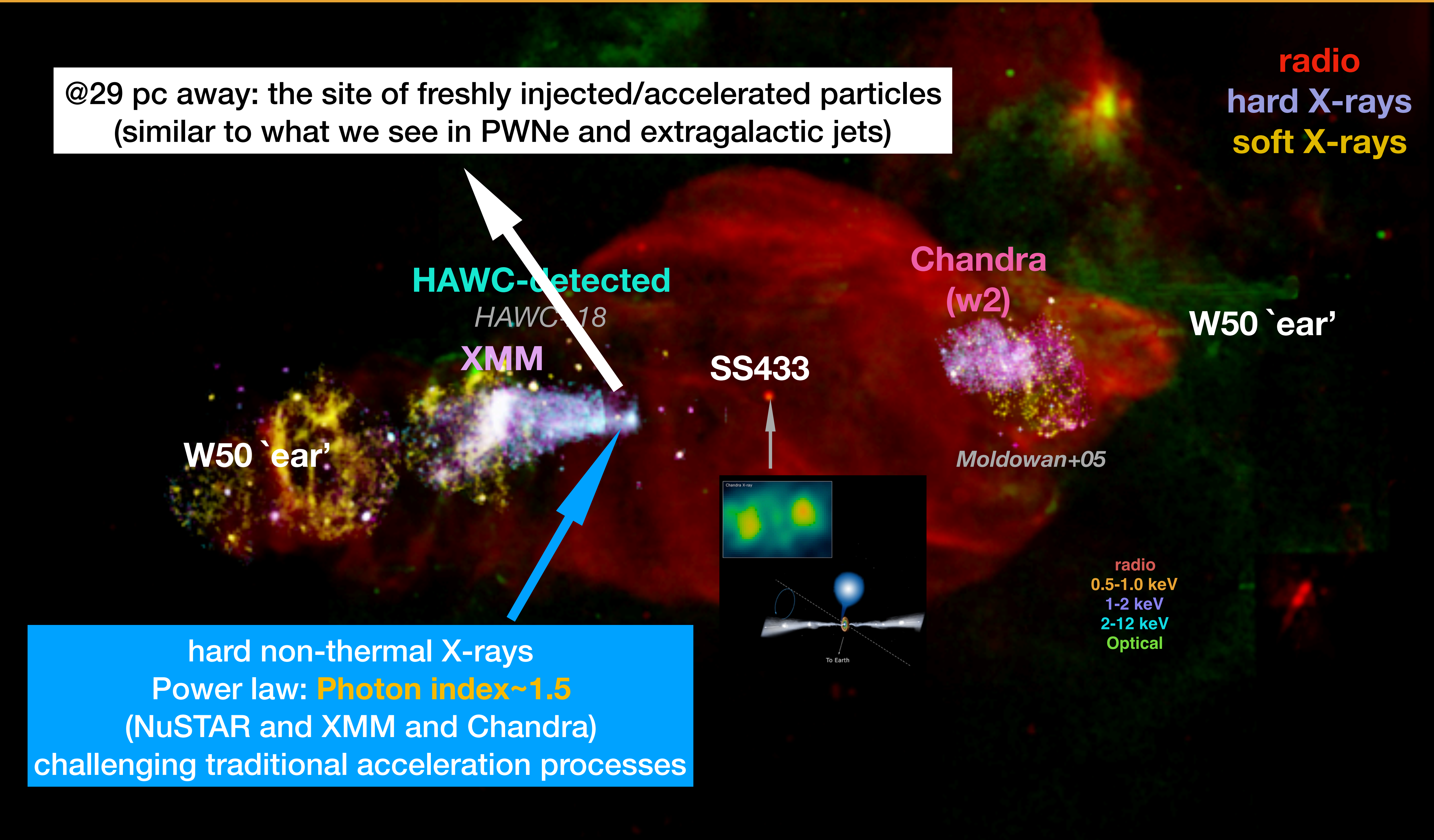

@29 pc away: the site of freshly injected/accelerated particles
(similar to what we see in PWNe and extragalactic jets)

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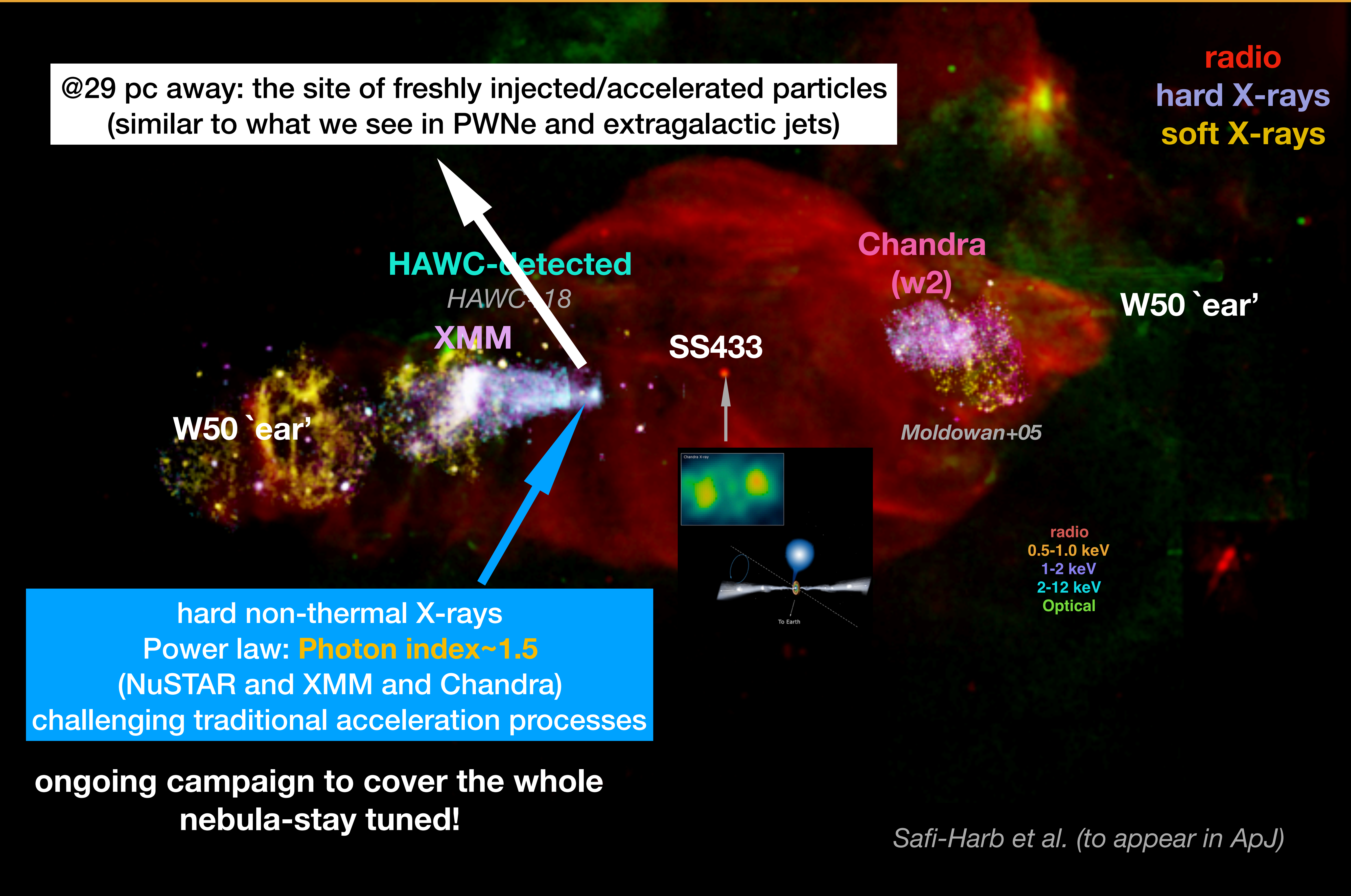

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Power law: Photon index~1.5
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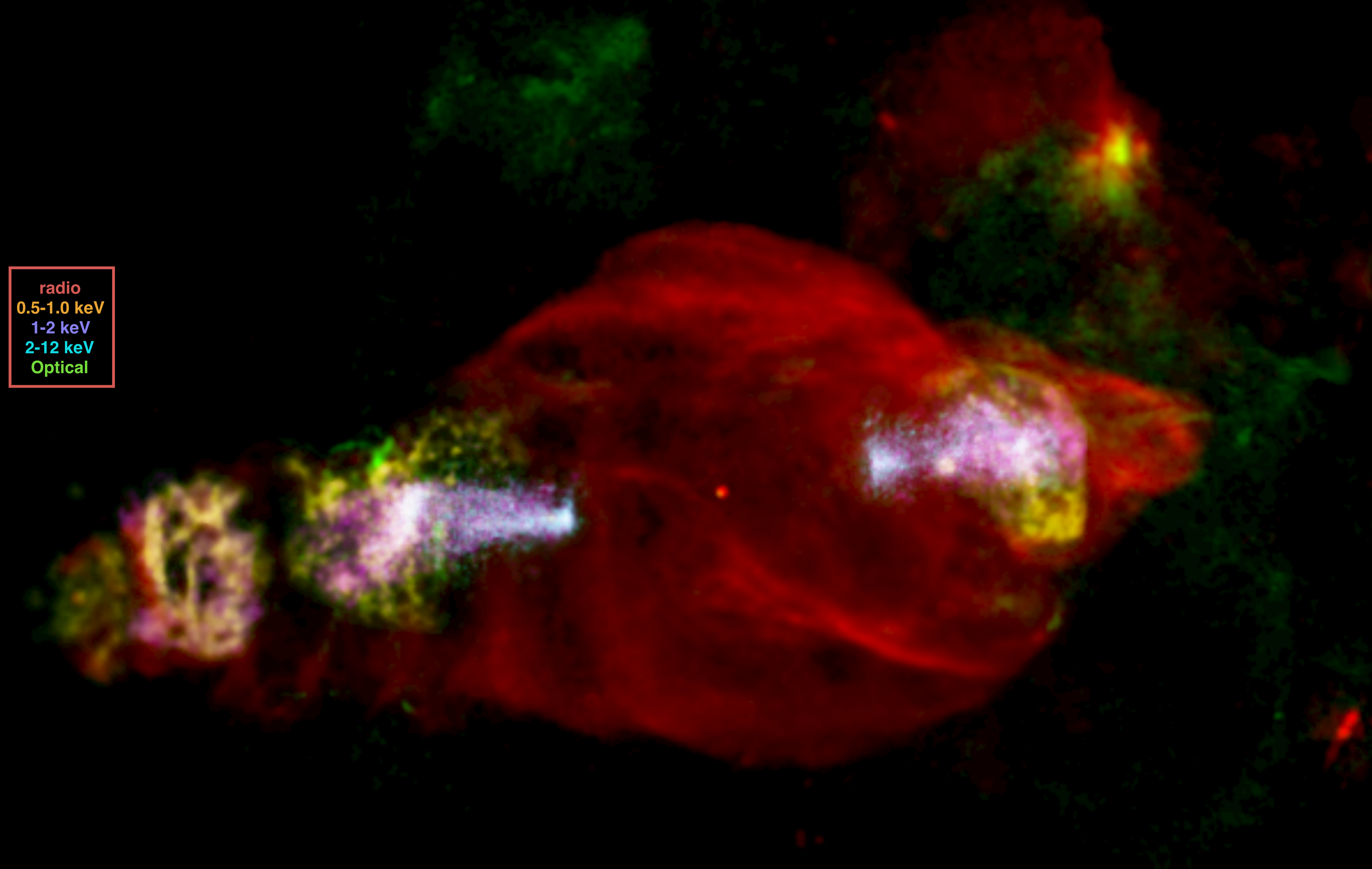
ongoing campaign to cover the whole nebula-stay tuned!

Safi-Harb et al. (to appear in ApJ)

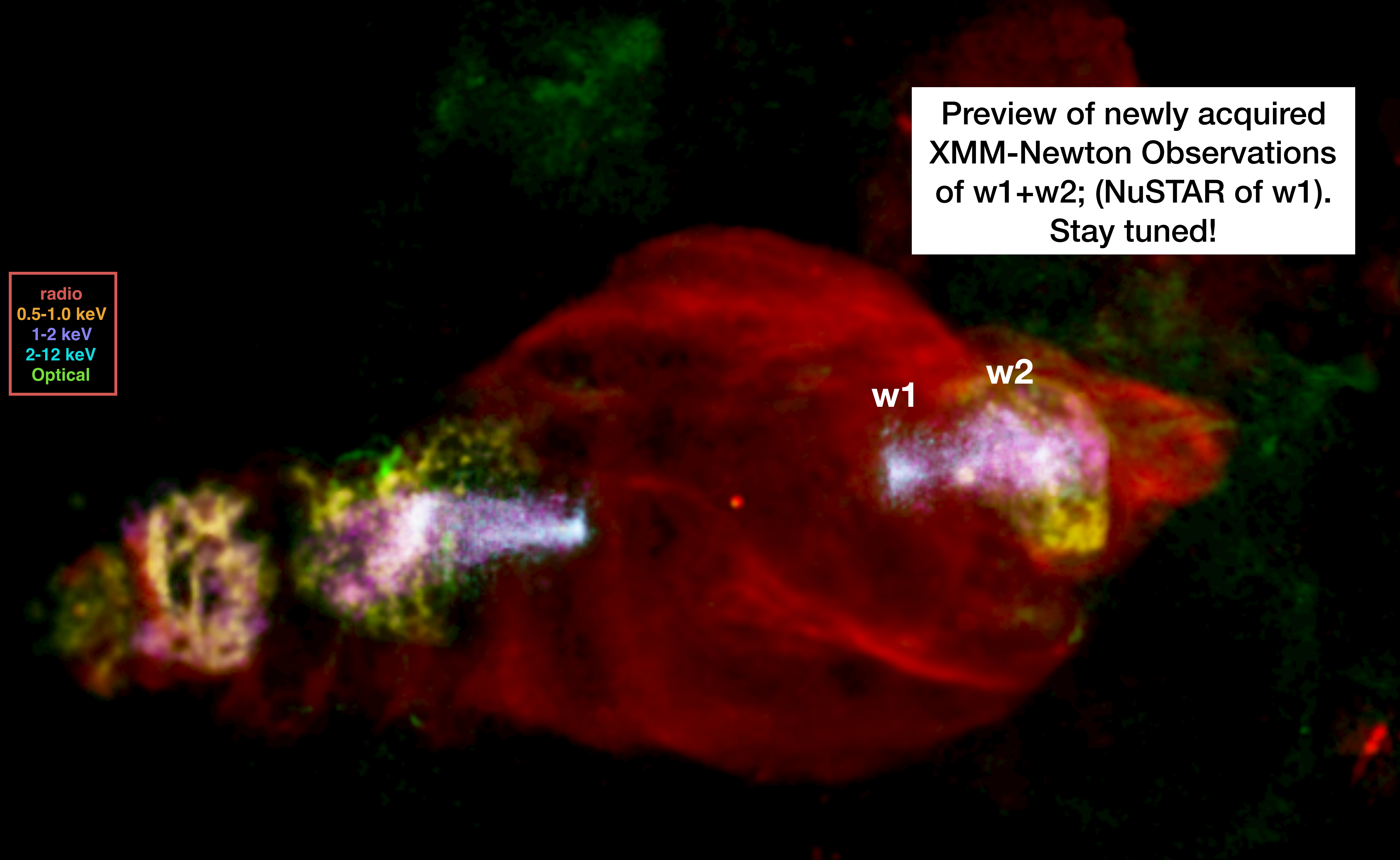
arXiv:2207.00573 , ESA release (2022/07/04)



NEXT: Ongoing/Upcoming X-ray, ALMA and multi-wavelength SED modelling

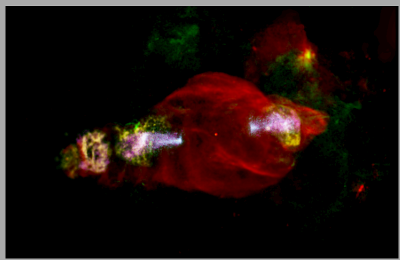
in collaboration with Naomi Tsuji, Dmitry Khangulyan and Takahiro Sudoh et al.

arXiv:2207.00573 , ESA release (2022/07/04)

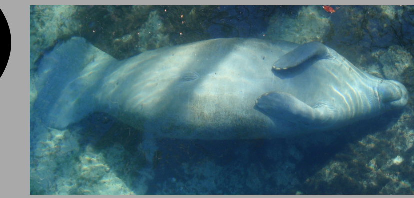


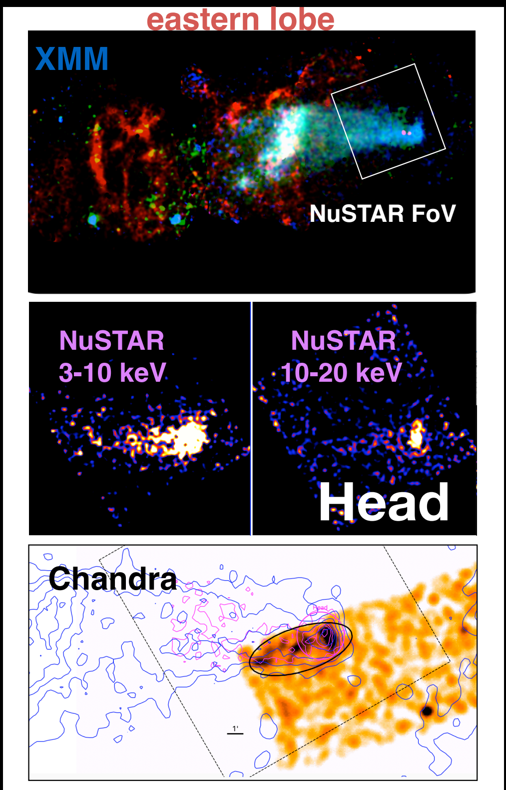
NEXT: Ongoing/Upcoming X-ray, ALMA and multi-wavelength SED modelling

in collaboration with Naomi Tsuji, Dmitry Khangulyan and Takahiro Sudoh et al.

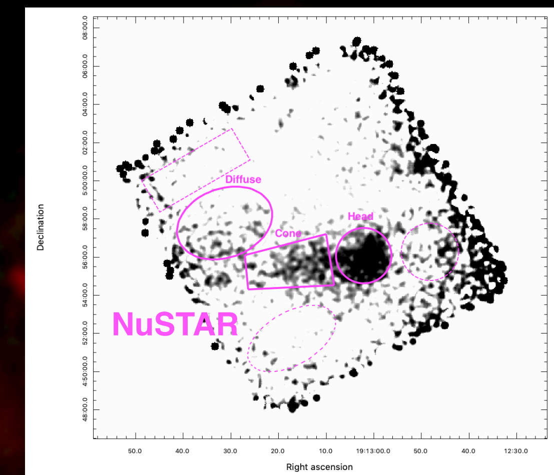


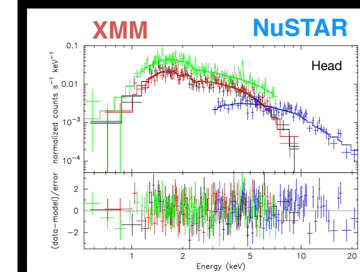
A hard X-ray look at the Manatee Nebula (W50) powered by the Galactic Microquasar SS 433

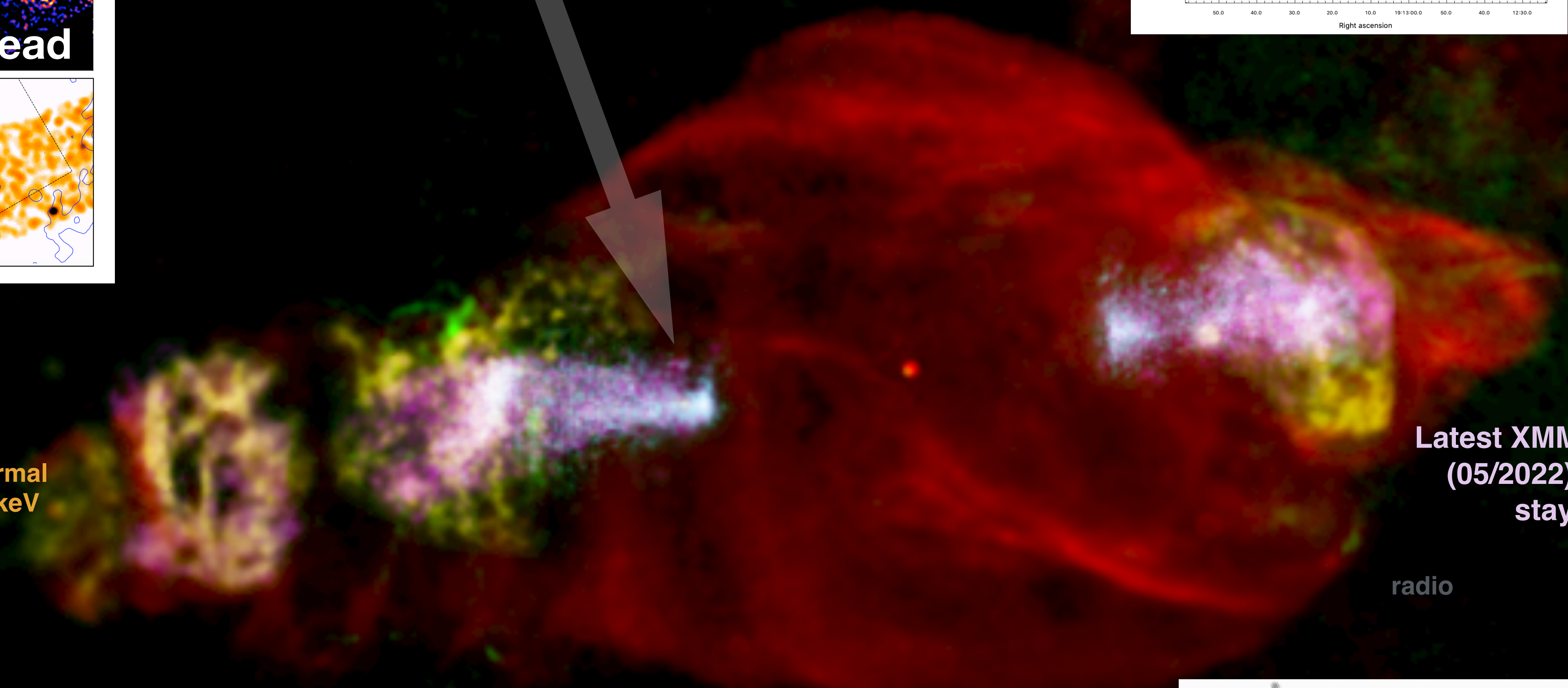




- Discovery with **NuSTAR (+XMM+Chandra)** of hard x-ray emission starting at **~18' (29 pc) east of SS433**
- Called **`Head': Photon index ~1.5-1.6, very hard!**
- This challenges traditional particle acceleration process
- Hard photon index similar to AGN jets and PWNe
- Particle injection and re-acceleration of SS 433 jet







radio (VLA)
0.5-1.0 keV
1-2 keV
2-12 keV
Optical (Skinakas)

soft x-rays dominated by thermal emission kT~0.2 keV

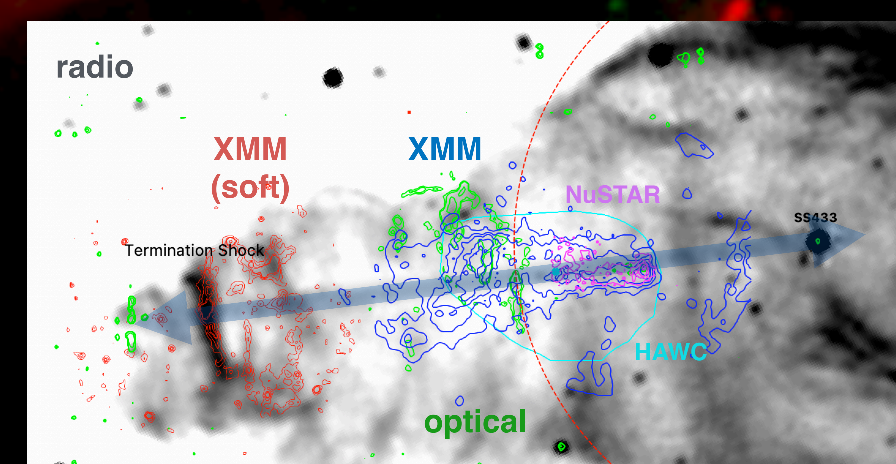
Latest XMM observations (05/2022)+NuSTAR— stay tuned!

Physical Properties (synchrotron)

Radiative loss timescale <~ 1 kyr
<< W50 age (~30 kyr)
B (Head) ~ 12 uG
E_{max} (Head)~250 TeV
L_x (eastern lobe)/Power (jets)<~10^{-3}

Outlook

- ⋆ multi-wavelength SED modelling, new observations upcoming!
- ⋆ Nearby Laboratory for ULX bubbles!
- ⋆ Fascinating source for upcoming missions including CTA, ATHENA, (AXIS, HEX-P)……



Safi-Harb et al. 2022, ApJ (in press)

Thank you gamma2022!

Extra Slides

Eastern Lobe XMM+NuSTAR

Region	Parameter	XMM 0.5 – 10 keV	NuSTAR 3 – 30 keV	Joint 0.5 – 30 keV[c]
	Photon Index Γ	1.58 ± 0.06	1.6 ± 0.1	1.58 ± 0.05
Head	$F\left[\times 10^{-12}\right]^{a,c}$ (abs.)	1.23 ± 0.06	2.0 ± 0.1	2.45 ± 0.07
$N_{\rm H} = 1.77\times10^{22}$ cm^{-2}	$F\left[\times 10^{-12}\right]^{b,c}$ (unabs.)	1.80 ± 0.06	2.0 ± 0.1	3.0 ± 0.1
	χ^2_ν (DoF)	0.96(295)	1.19(79)	1.00 (375)
	Photon Index Γ	1.65 ± 0.05	$2.00^{+0.08}_{-0.07}$	1.76 ± 0.04
Cone	$F\left[\times 10^{-12}\right]^{a}$ (abs.)	1.29 ± 0.05	1.55 ± 0.09	2.13 ± 0.06
$N_{\rm H} = 1.18\times10^{22}$ cm^{-2}	$F\left[\times 10^{-12}\right]^{b}$ (unabs.)	1.81 ± 0.06	$1.58^{+0.10}_{-0.09}$	2.71 ± 0.08
	χ^2_ν (DoF)	0.96 (440)	0.98 (197)	1.03 (638)
	Photon Index Γ	1.75 ± 0.06	2.0 ± 0.2	1.77 ± 0.06
Diffuse	$F\left[\times 10^{-12}\right]^{a}$ (abs.)	$1.02^{+0.06}_{-0.05}$	$1.00^{+0.05}_{-0.14}$	1.61 ± 0.08
$N_{\rm H} = 0.76\times10^{22}$ cm^{-2}	$F\left[\times 10^{-12}\right]^{b}$ (unabs.)	1.39 ± 0.06	$1.00^{+0.15}_{-0.14}$	1.99 ± 0.09
	χ^2_ν (DoF)	0.98 (467)	1.33 (59)	1.02 (527)
	Photon Index Γ	1.58 ± 0.03	1.99 ± 0.07	1.65 ± 0.03
Full	$F\left[\times 10^{-12}\right]^{a}$ (abs.)	5.60 ± 0.14	8.8 ± 0.4	11.4 ± 0.2
$N_{\rm H} = 1.03\times10^{22}$ cm^{-2}	$F\left[\times 10^{-12}\right]^{b}$ (unabs.)	7.5 ± 0.2	9.0 ± 0.4	13.4 ± 0.2
	χ^2_ν (DoF)	1.03 (1589)	0.97 (98)	1.07 (1688)
	Photon Index Γ	1.73 ± 0.05	2.2 ± 0.2	1.76 ± 0.05
Nue1	$F\left[\times 10^{-12}\right]^{a}$ (abs.)	1.62 ± 0.07	2.0 ± 0.2	2.89 ± 0.19
$N_{\rm H} = 0.78\times10^{22}$ cm^{-2}	$F\left[\times 10^{-12}\right]^{b}$ (unabs.)	2.20 ± 0.08	2.0 ± 0.2	3.48 ± 0.12
	χ^2_ν (DoF)	1.05 (652)	1.53 (35)	1.09 (688)
	Photon Index Γ	2.05 ± 0.02	–	–
Lenticular[d]	$F\left[\times 10^{-12}\right]^{a}$ (abs.)	3.74 ± 0.06	–	–
$N_{\rm H} = 0.71\times10^{22}$ cm^{-2}	$F\left[\times 10^{-12}\right]^{b}$ (unabs.)	5.68 ± 0.08	–	–
	χ^2_ν (DoF)	1.04 (1101)	–	–
	Photon Index Γ	$2.0^{+0.4}_{-0.5}$	–	–
e3-ring	kT (keV)	0.2 ± 0.1	–	–
$N_{\rm H} = 0.79\times10^{22}$ cm^{-2}	χ^2_ν (DoF)	1.14 (797)	–	–

Table A2. XSPEC fits using `const*tbabs*power` with the `cFlux` model added to acquire flux values. Column densities frozen to their best fit value using the XMM-Newton data. For the 'e3-ring' region, the additional component shown corresponds to a thermal (`mekal` in XSPEC) model with solar abundances. Quoted uncertainties for 90% C.L.

[a] Absorbed flux in erg cm^{-2} s^{-1}.

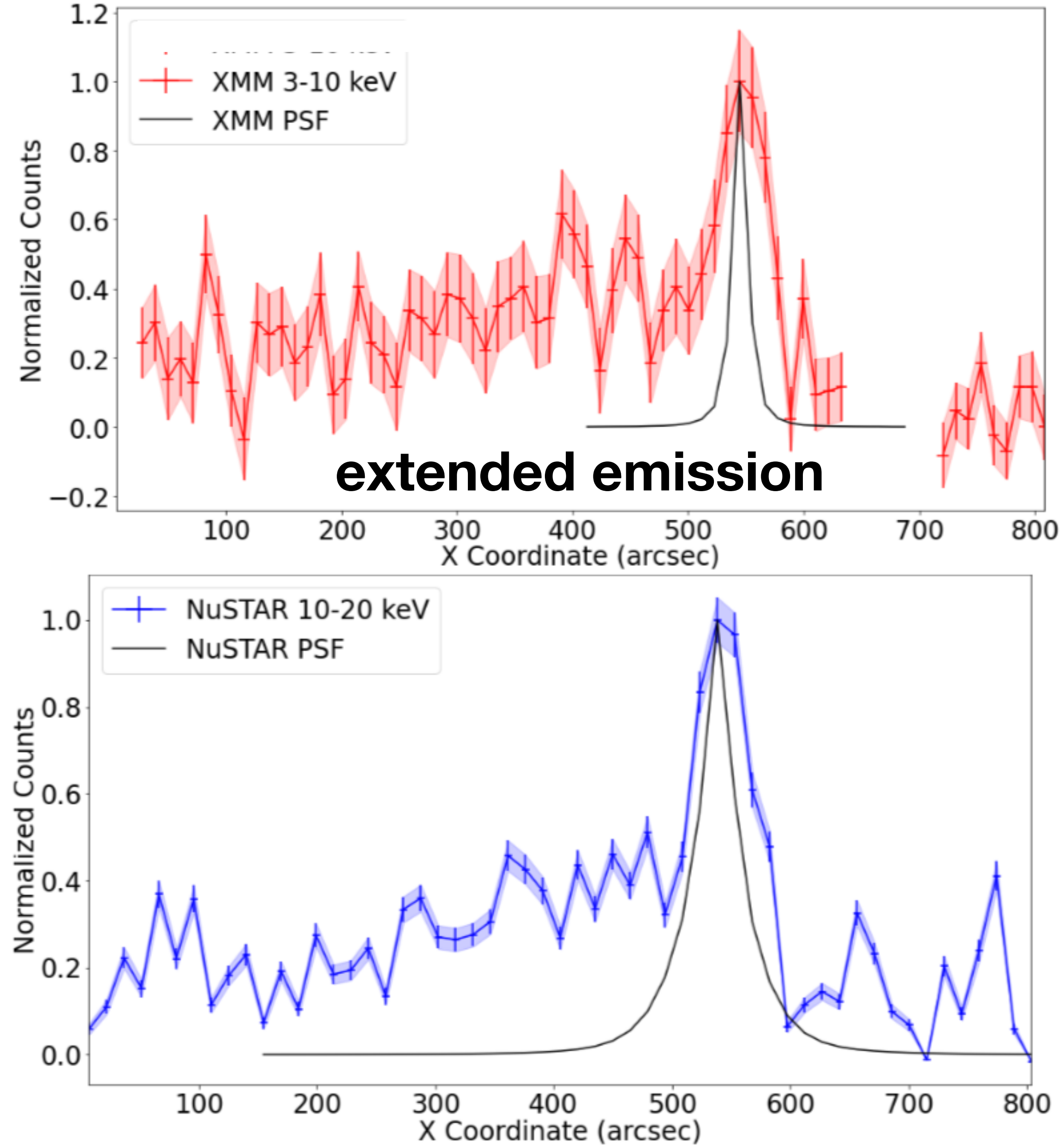
[b] Unabsorbed flux in erg cm^{-2} s^{-1}.

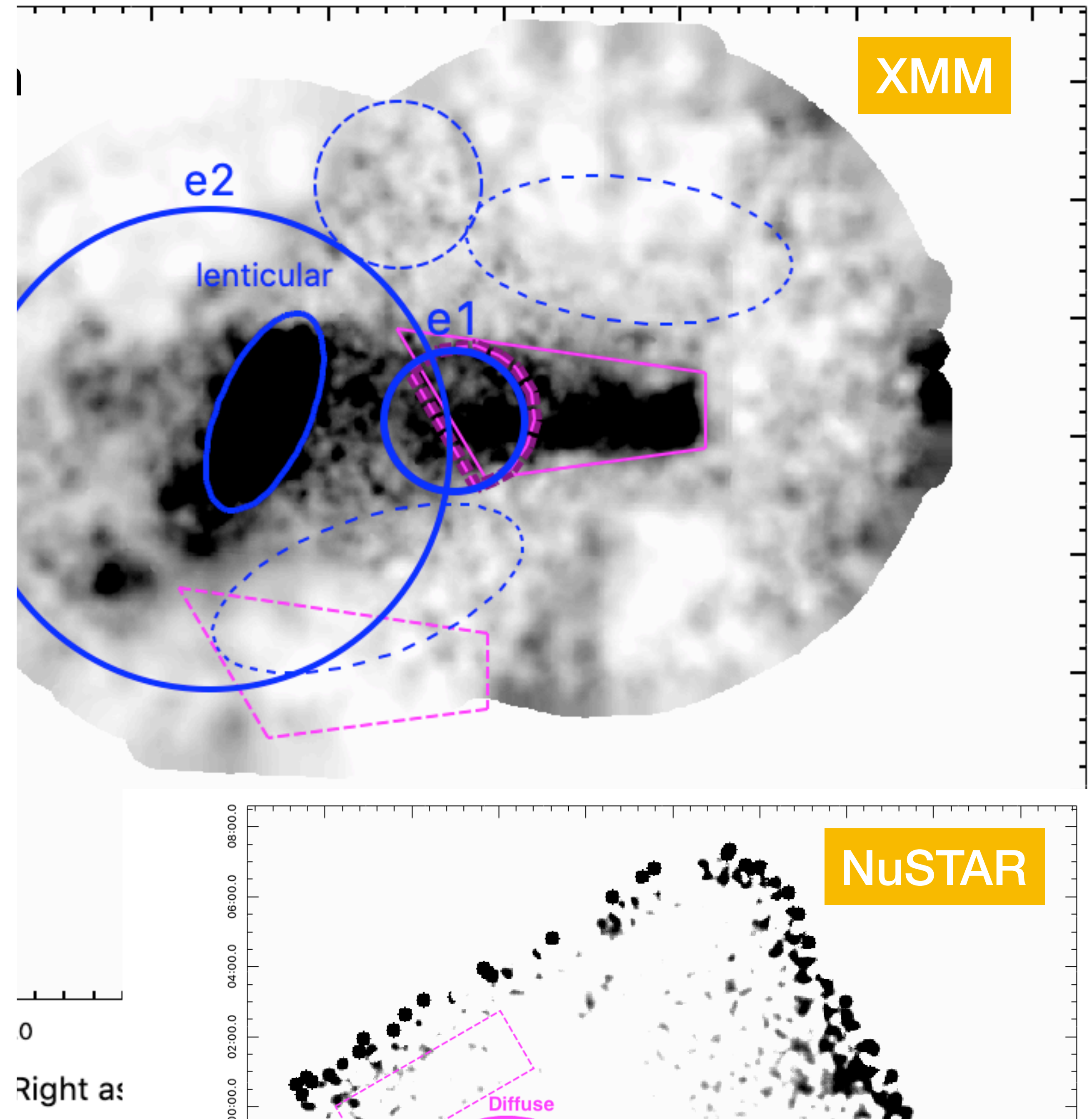
[c] For the joint 0.5–30 keV flux, we list the combined 0.5–10 keV (XMM) and 10-30 keV (NuSTAR) fluxes with the model parameters frozen to their best values from the joint fit.

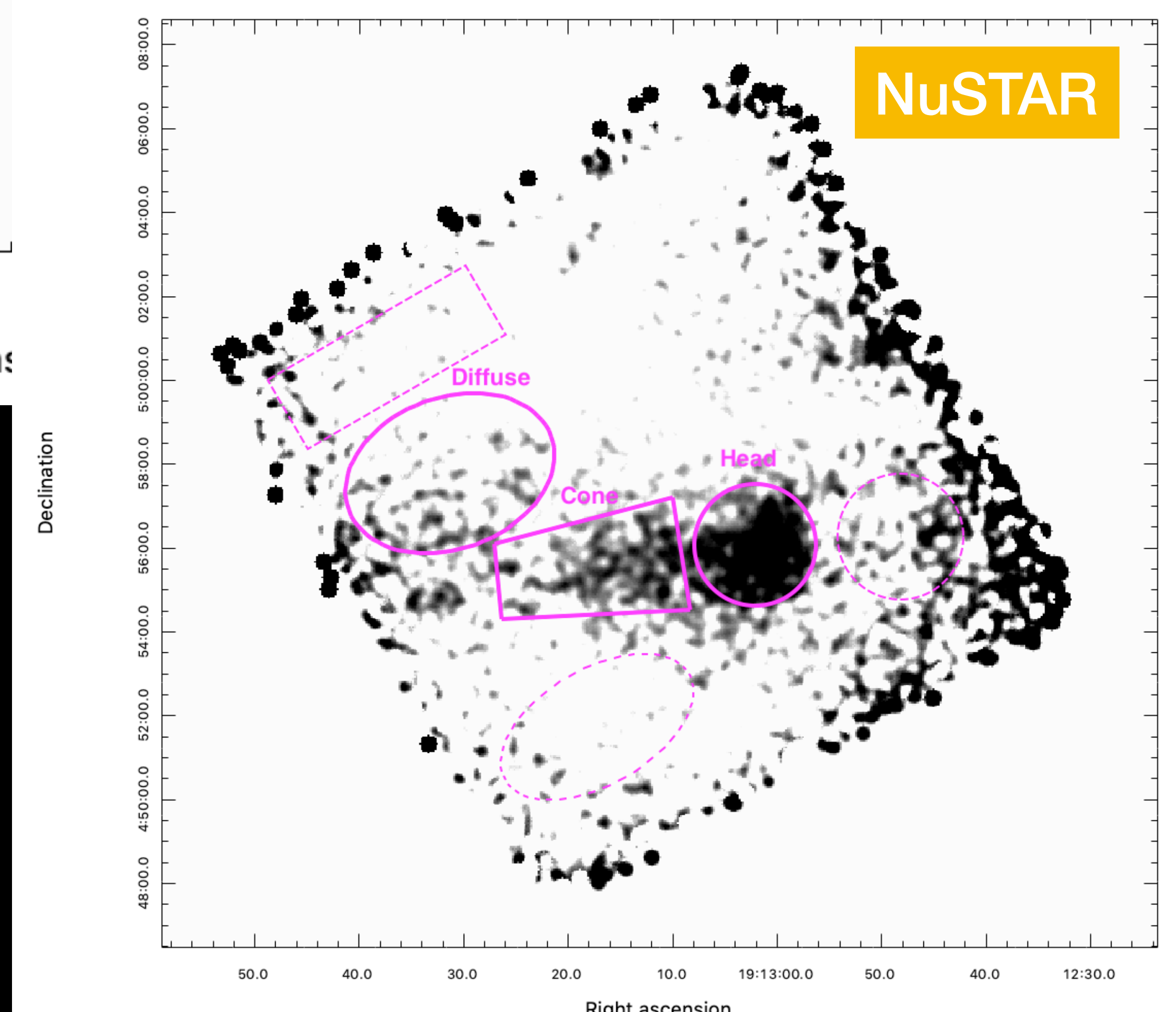
[d] The larger 'e2' region encompassing the 'lenticular' region (see Figure 2) shows evidence of soft thermal X-ray emission with $kT \lesssim 0.2$ keV, however with the thermal parameters poorly constrained.

SSH et al 2022 (ApJ in press)

spatial profile of head into e1







Source regions NuSTAR — XMM — —

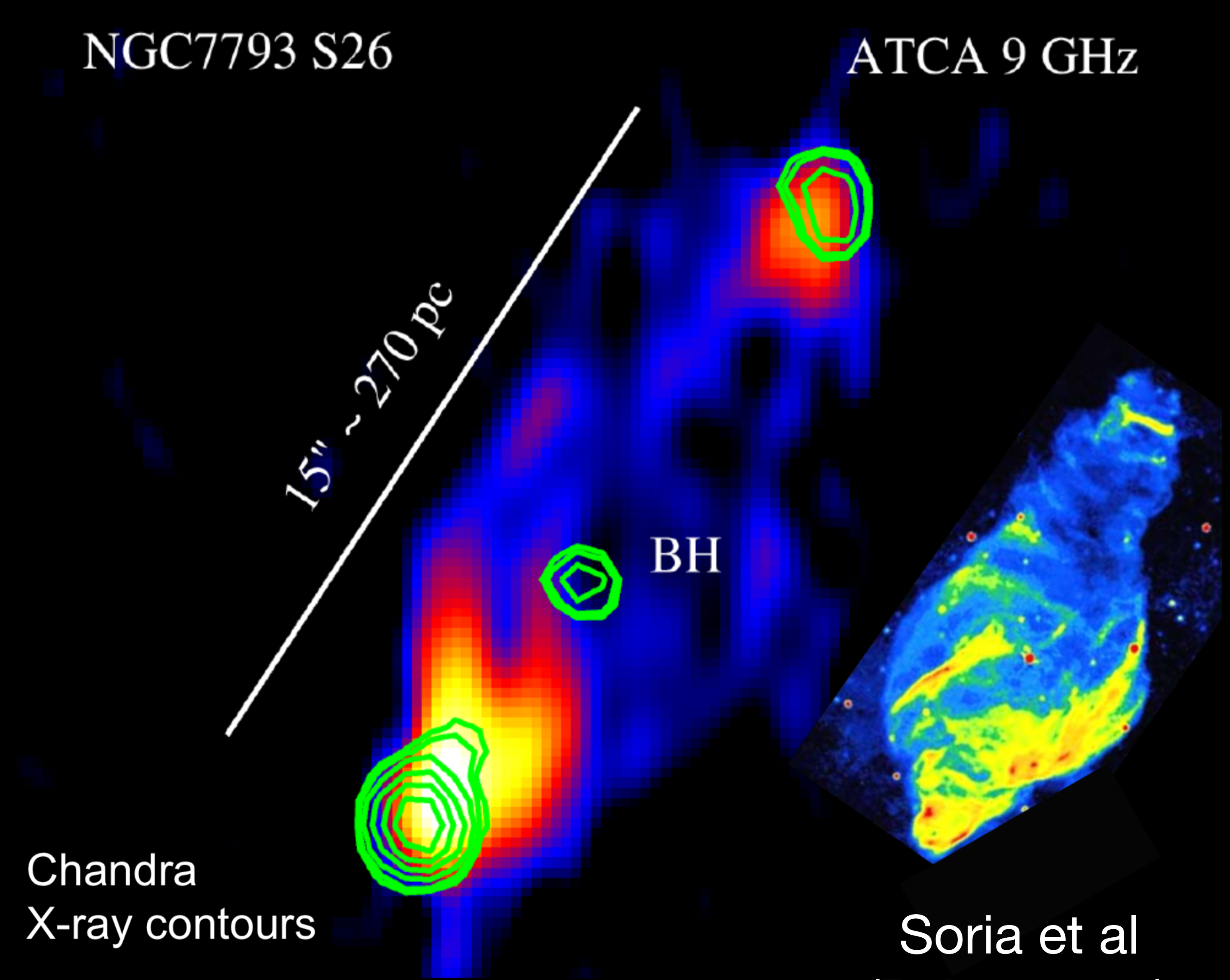
NuSTAR 3-30 keV (12’x12’ FoV, 18” FWHM)

XMM 0.5-10 keV (30’ FoV, ~6” FWHM)

Background regions - - - dashed

ULX bubbles

- SS 433: suggested as the nearest ULX catalog (*Fabrika & Mescheryakov 2001*)—BUT seen edge-on==> atypical ULX
- W50 nebula: **the most accessible ULX bubble analog**
- ULX bubbles: a few 100's parsecs: radio and optical nebulae; a few detected in X-rays but mostly thermal (likely termination hot spots)
- Many similarities between W50 and a few ULX bubbles, but to date, **no non-thermal X-ray emission has been reported from the diffuse emission in an ULX bubble** (resulting from jets/ISM interaction)



Soria et al
(Pakull et al.)

W50: Wind-blown bubble?

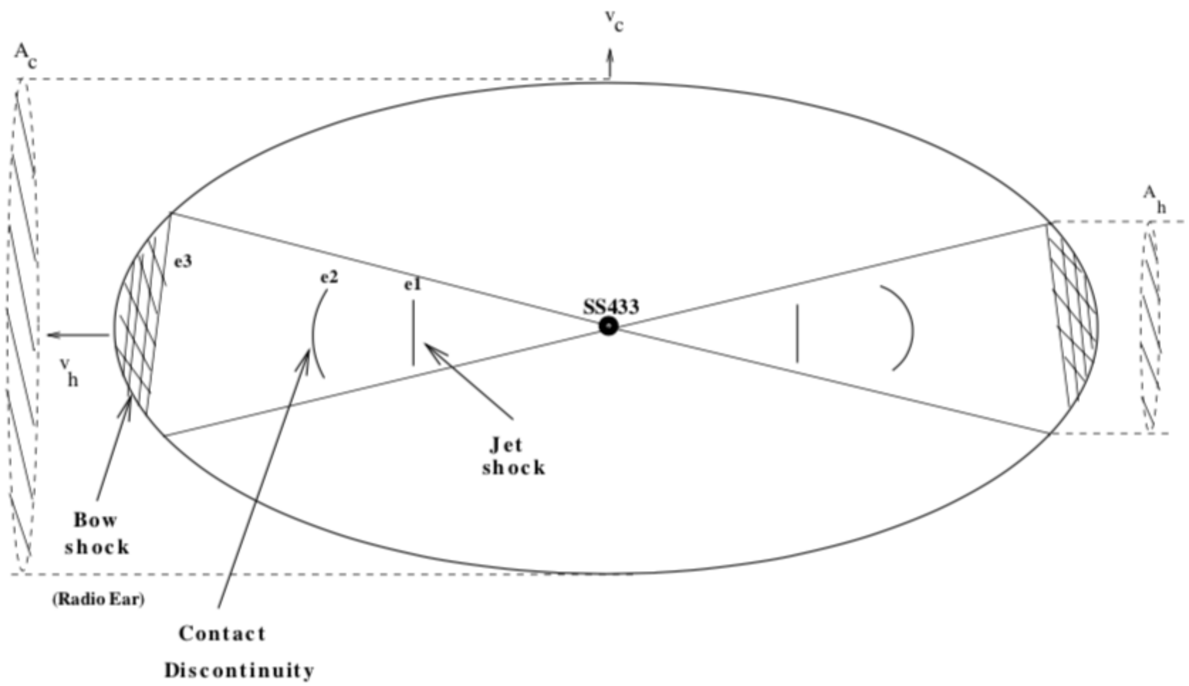


FIG. 12.—A sketch of the jet model adopted for the interpretation of the morphology of W50 and the derived jets parameters: v_h and v_c represent the head and the cocoon's speed, respectively, and A_h and A_c are the corresponding cross-sectional areas.

TABLE 8

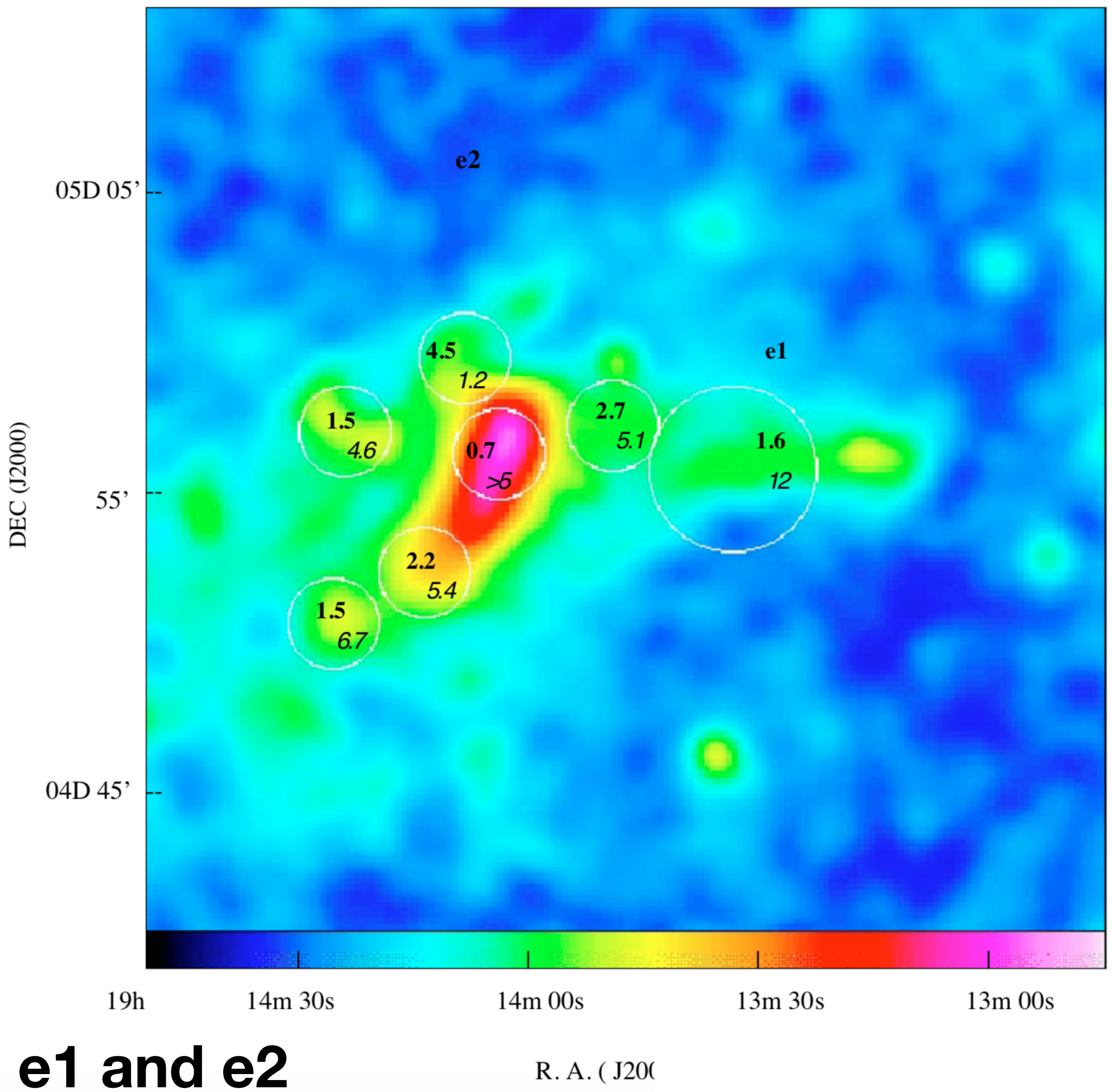
DERIVED JET PARAMETERS[a]

Parameter	Value
$\rho_j v_j$ (g cm^{-2} s^{-1})......	4×10^{11}
$\dot{M}_j$ ($M_\odot$ yr^{-1})..........	5×10^{-5}
L_j (ergs s^{-1})............	$\leq 10^{41}$
W (ergs)	$\leq 10^{53}$
ρ_j (g cm^{-3})............	$\sim 2.5 \times 10^{-28}$
R_j	$6'$

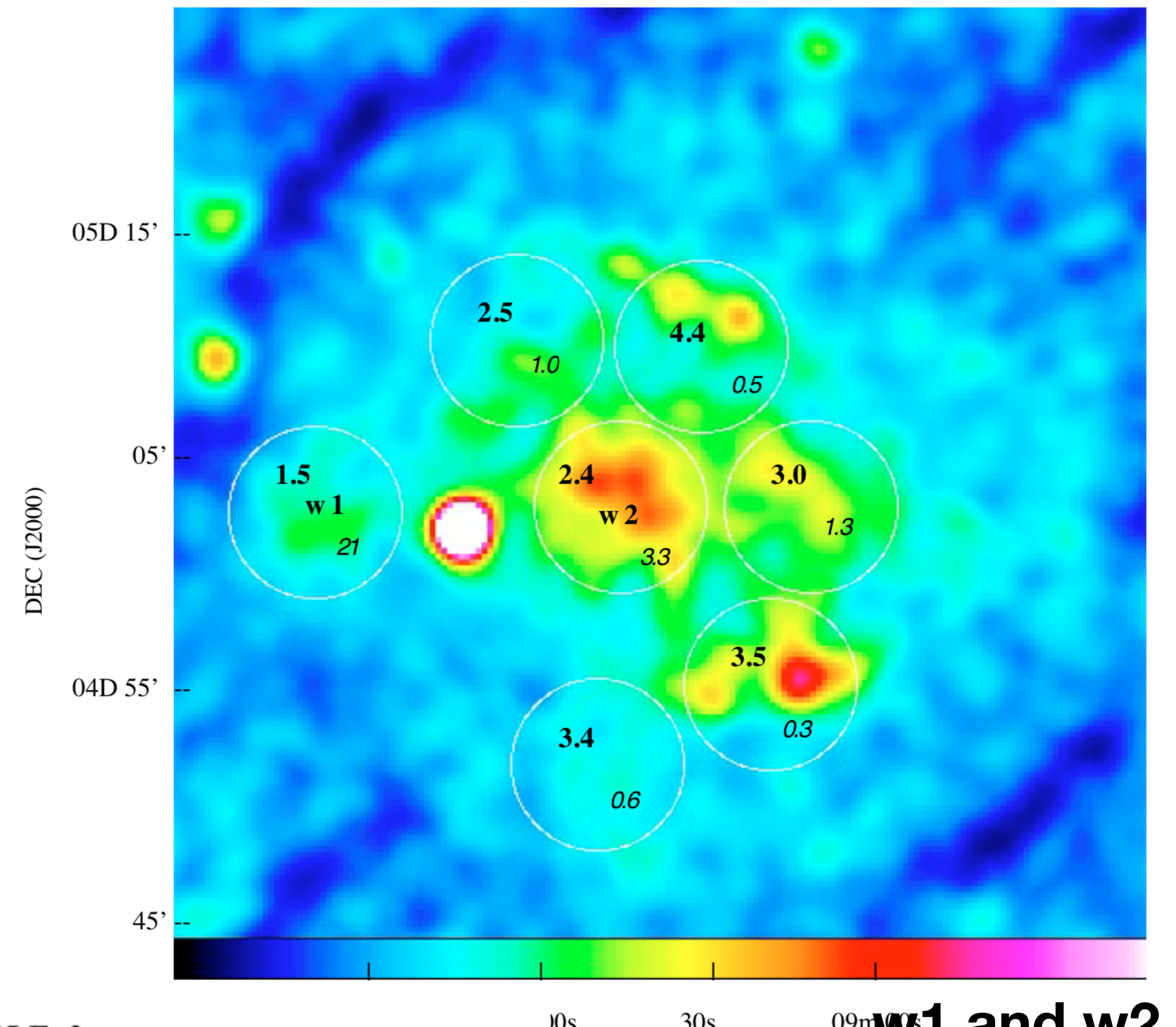
[a] Assuming a distance of 5.5 kpc, an ambient density of 3×10^{-26} g cm^{-3}, and an age of 3×10^4 yr. The average jet density, ρ_j, and effective radius, R_j, are estimated at 35′ from SS 433.

SSH & Ogelman 1997
(Begelman & Cioffi 1989)

EARLY ROSAT AND ASCA OBSERVATIONS



e1 and e2



w1 and w2

TABLE 3

POWER-LAW MODEL RESULTS[a]

Region	N_H (10^{21} cm^{-2})	Γ	L_x (10^{34} ergs s^{-1})	χ^2
e1	$2.7^{+1.5}_{-1.2}$	$1.6^{+0.18}_{-0.15}$	0.73	260/99 = 2.63
e2	$2.5^{+0.8}_{-0.7}$	2.0 ± 0.1	1.2	194/95 = 2.11
w1......	6^{+4}_{-3}	1.45 ± 0.35	0.65	118/94 = 1.26
w2......	$5.9^{+2.3}_{-1.9}$	$2.41^{+0.34}_{-0.26}$	1.83	134/95 = 1.41

[a] With both GIS detectors as well as the *ROSAT* spectra coincident with the circular regions e1 and e2 selected from the eastern lobe, and centered at 24′ and 35′ east of SS 433, respectively. We also show the power-law fits for the regions w1 and w2 selected from the western lobe, and centered at 19′ and 31′ west of SS 433, respectively. The errors are 3 σ.

e3: soft with some thermal X-rays

SSH & Ogelman 1997

ASCA+RXTE

A Galactic PeVatron candidate

TABLE 3

THERMAL BREMSSTRAHLUNG (TB) AND POWER-LAW (PL) MODEL RESULTS FOR REGION e1 WITH THE *ASCA*, PCA, AND HEXTE SPECTRA (OBSERVATION 02-05)[a]

Model	Model Parameter	Normalization (10^{-3} photons cm^{-2} s^{-1} keV^{-1})	χ^2 (dof)
TB......	$kT = 105$ (keV)[b]	1.92	1.54 (107)
PL......	$\Gamma = 1.43 \pm 0.1$	1.04 ± 0.1	1.36 (110)

[a] The parameters for e2 have been frozen to the values indicated in Table 1. The TB parameters are unconstrained, and the errors quoted on the PL parameters are at the 3 σ level.

[b] The TB temperature and the normalization are inconsistent with the *ASCA* fits (see Fig. 4).

TABLE 2

PL AND TB MODEL FITS TO THE PCA AND HEXTE SPECTRA OF W50 IN THE 10–50 keV RANGE (SEGMENT 02-05)[a]

Model	Region	Model Parameter	Normalization (10^{-3} photons cm^{-2} s^{-1} keV^{-1})	χ^2 (dof)
PL	e1	$\Gamma = 1.4$	1.04	1.38 (30)
Broken PL......	e2	$\Gamma_1 = 1.6$	1.33	...
		$\Gamma_2 = 2.6$		
		$E_b = 3$ keV		
TB	e1	$kT = 12$ keV	1.56	2.15 (29)
	e2	$kT = 5$ keV	1.71	...

[a] The fit parameters correspond to the values derived from fitting the combined *ROSAT* and *ASCA* spectra of the regions e1 and e2 of the eastern lobe (see Fig. 1).

"The detection of X-rays from W50 up to energies of ~ 50 keV implies electron energies, E_e~300-450 TeV, for an estimated B-field of 6-15 micro-Gauss (synchrotron interpretation) ==> an important site for CR acceleration!"

Safi-Harb & Petre 1999

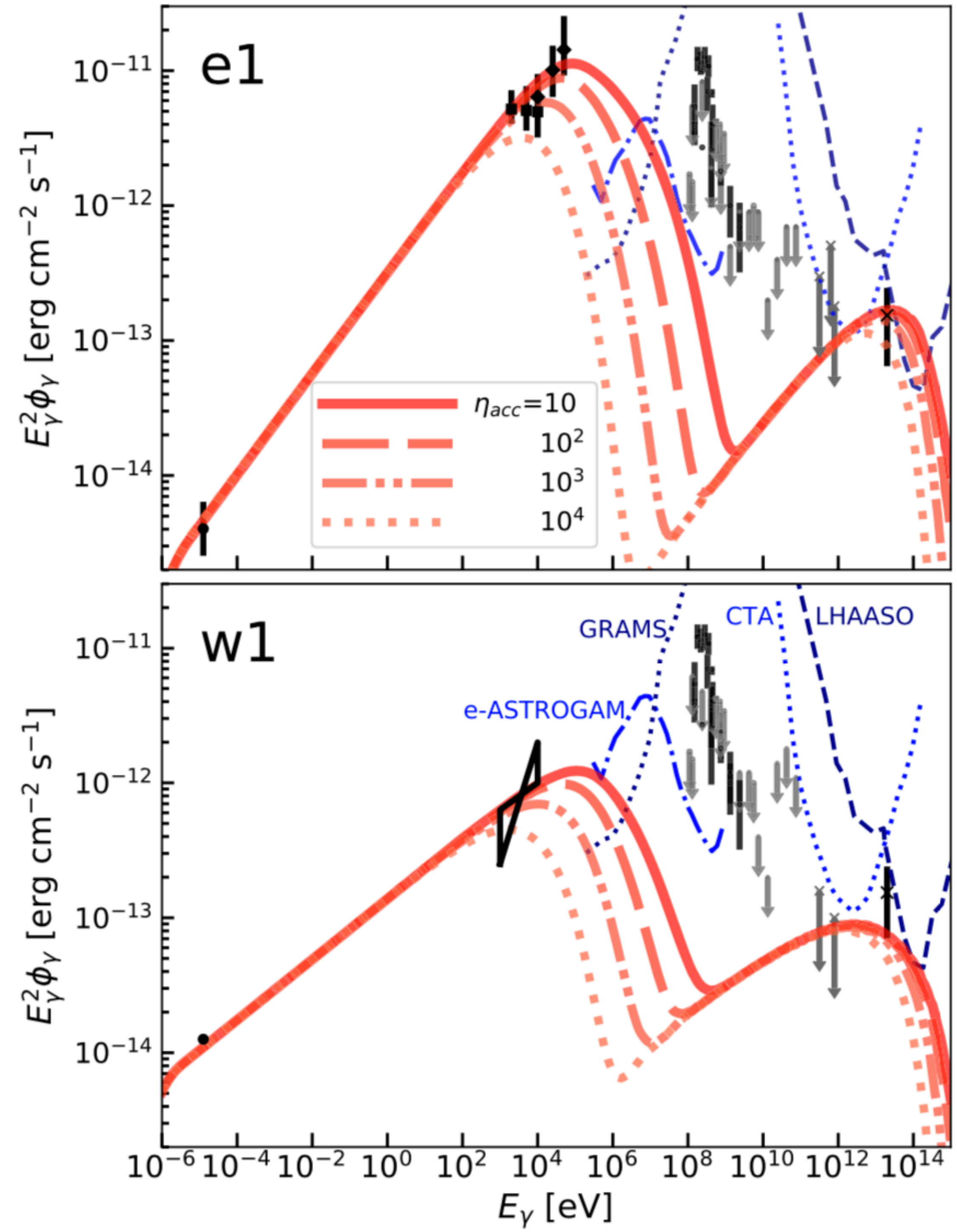


Figure 2. Broadband spectral energy distribution of the e1 (top) and w1 (bottom) region. Orange curves are model predictions for different choices of η_{acc}, as labeled. Black and gray points are observational data and upper limits, respectively, from Geldzahler et al. (1980) (radio), Brinkmann et al. (2007), Safi-Harb & Ögelman (1997), Safi-Harb & Petre (1999) (X-ray), Bordas et al. (2017), Xing et al. (2019), Rasul et al. (2019), Sun et al. (2019) (HE), Ahnen et al. (2018), Kar (2017), Abeysekara et al. (2018) (VHE). Expected sensitivities are also shown for CTA (North, 50 hours; Acharya et al. 2019), LHAASO (one year; Bai et al. 2019), *e-ASTROGAM* (three years; De Angelis et al. 2017), and *GRAMS* (three years; Aramaki et al. 2020).

Sudoh et al. 2020
(see Kimura+2020)