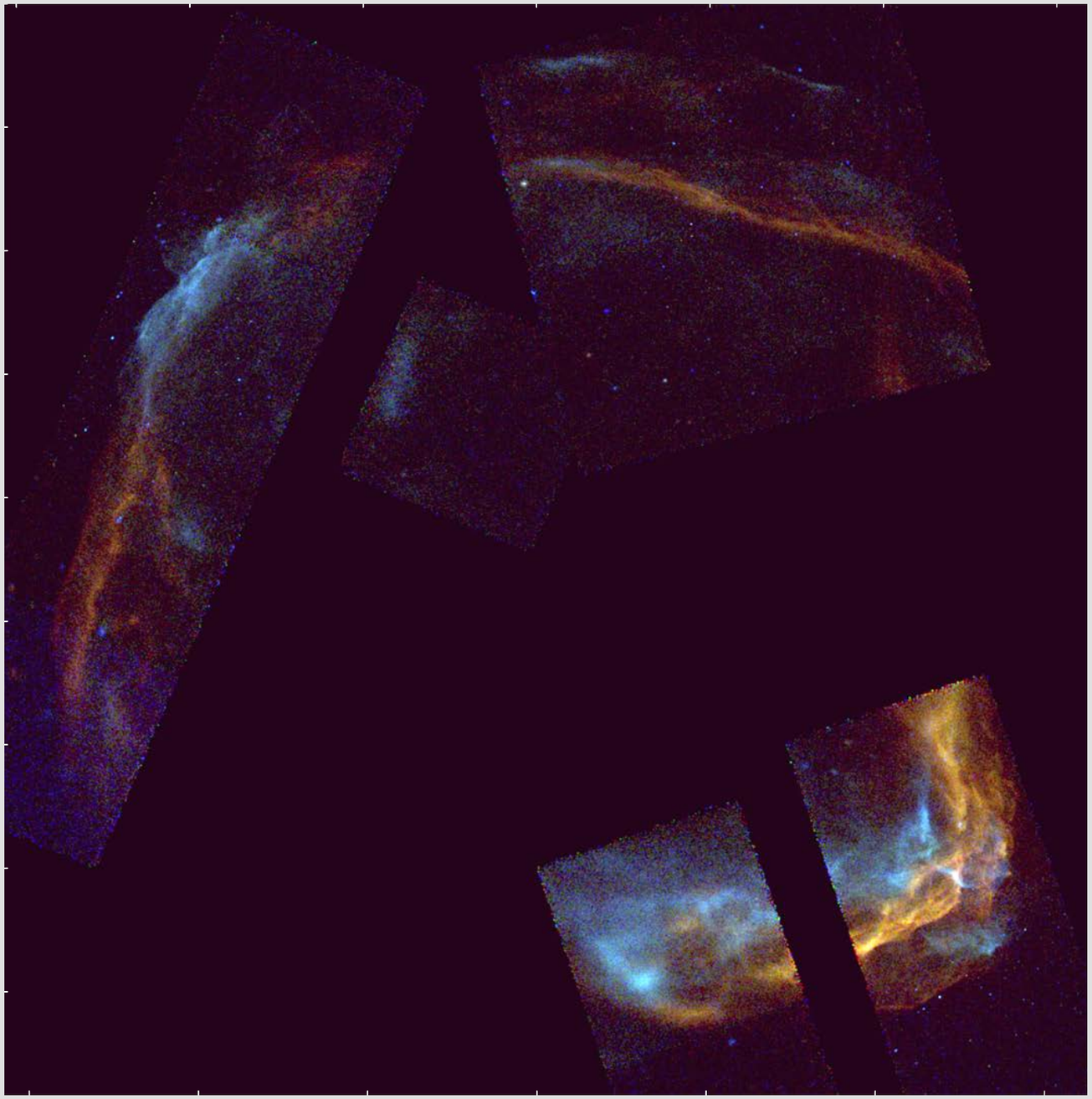
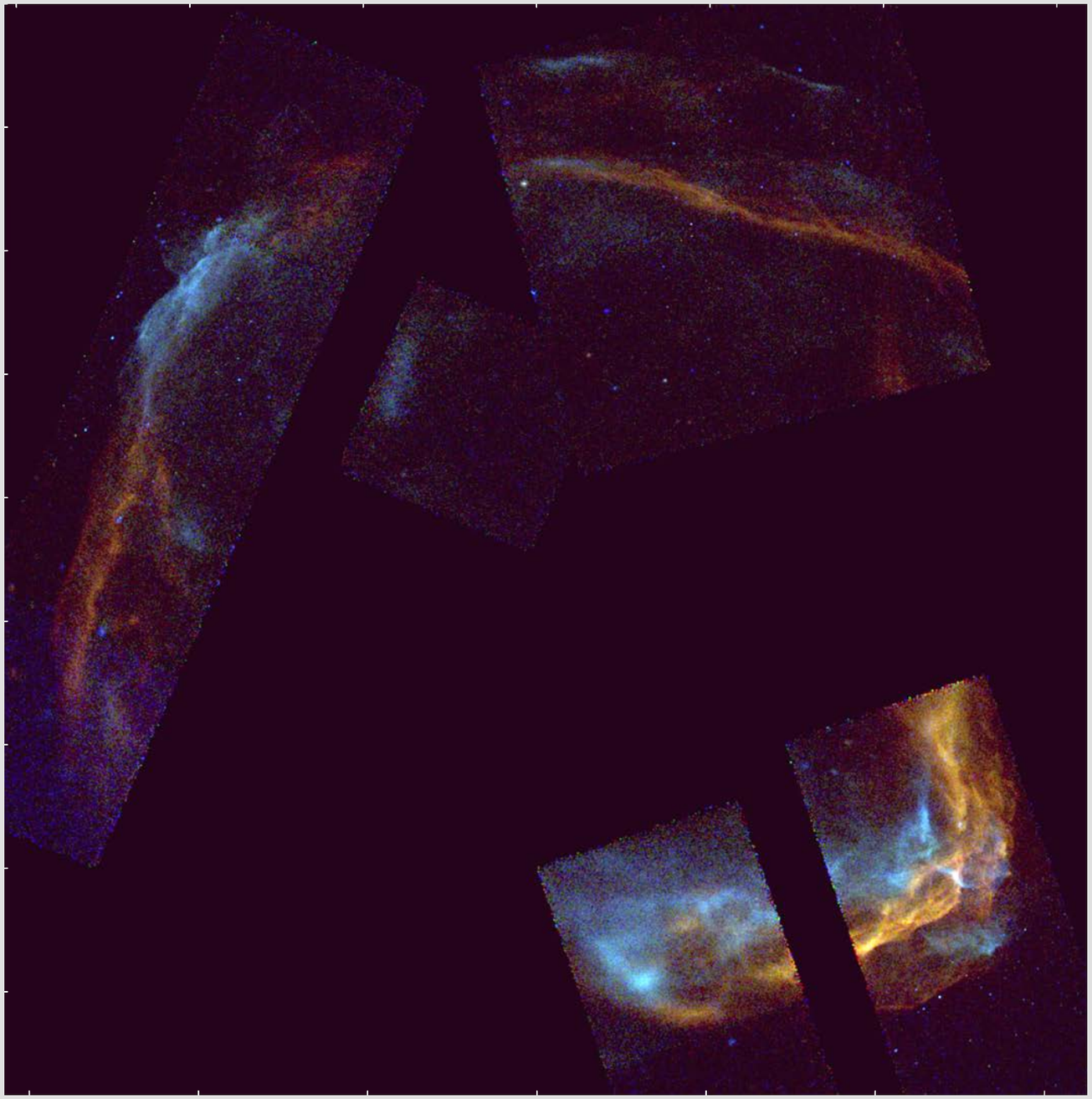
the northern rims of rcw 86:
chandra's recent observations and their implications for particle acceleration



supernova remnants – an odyssey
in space after stellar death
chania, crete 2016

daniel castro – gsfc + gmu

the northern rims of rcw 86:
chandra's recent observations and their implications for particle acceleration



collaborators

pat slane – cfa
hiroya yamaguchi – gsfc
brian williams – gsfc
laura lopez – osu
enrico ramirez-ruiz – ucsc

outline

what evidence is there that SNRs accelerate cosmic rays?

how does the magnetic field get amplified? and how do we know it does?

what have we learnt studying rcw 86 with chandra?

i. evidence

what evidence is there that SNRs accelerate cosmic rays?

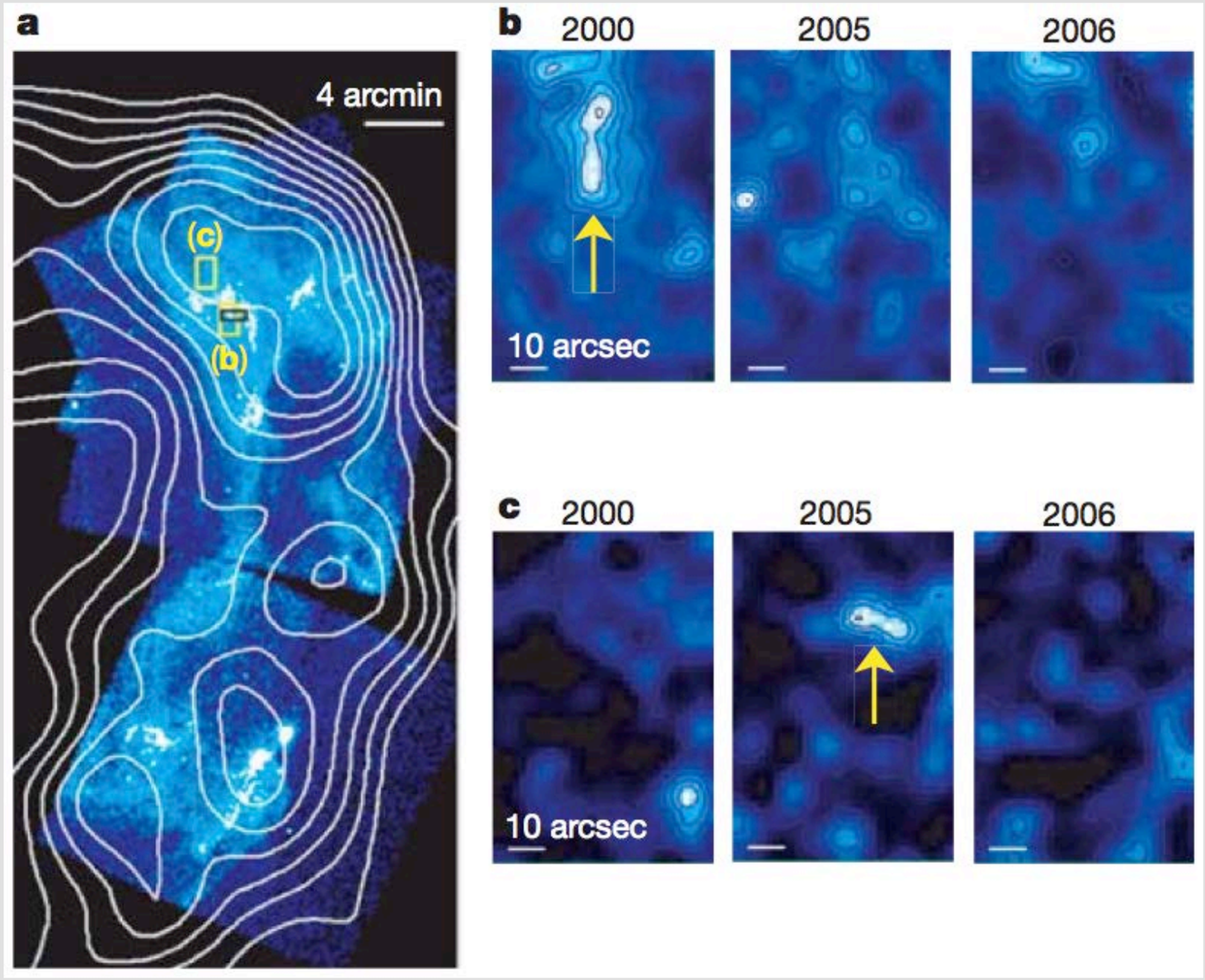
i. evidence

- dynamical properties
- structure

- γ-ray emission
- non-thermal X-rays
  - synchrotron spectra
  - magnetic field

heliosphere - Chevalier (1977)

$$t_{\rm synch} \approx 1.5\,(B/{\rm mG})^{-1.5}\,(\varepsilon/{\rm keV})^{-0.5}\ \text{years}$$



uchiyama+ 2007

ii. magnetic field amplification

how does the magnetic field get amplified? and how do we know it does?

ii. magnetic field amplification

how

.resonant cosmic ray streaming instability e.g. zirakashvili 2000
.bell's non-resonant instability bell 2004
.non-resonant long-wavelength instability bykov & toptygin 2005
.others…

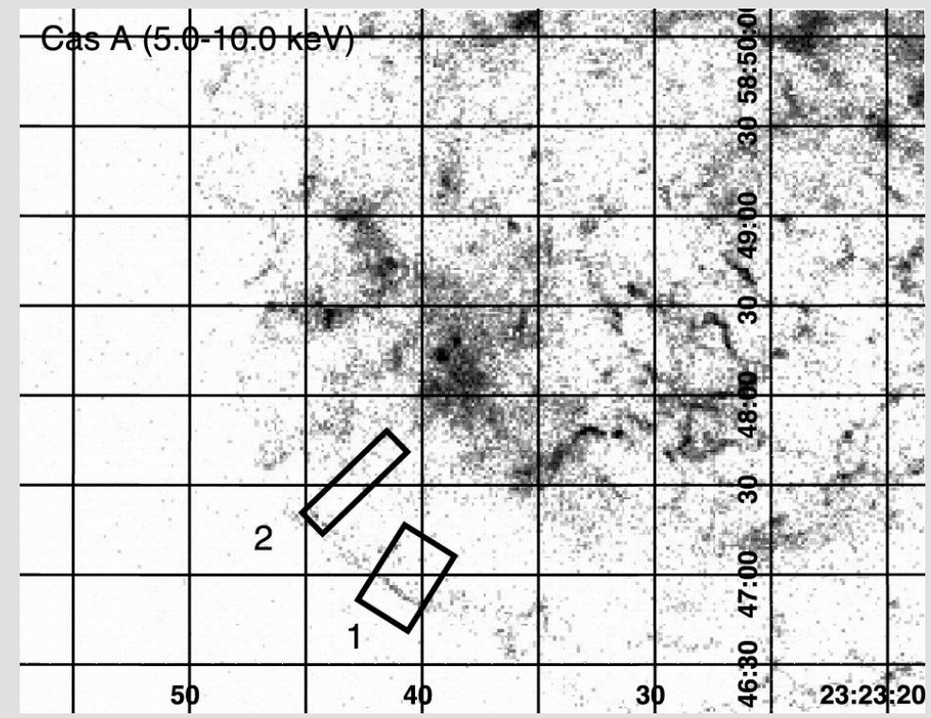
ii. magnetic field amplification

evidence

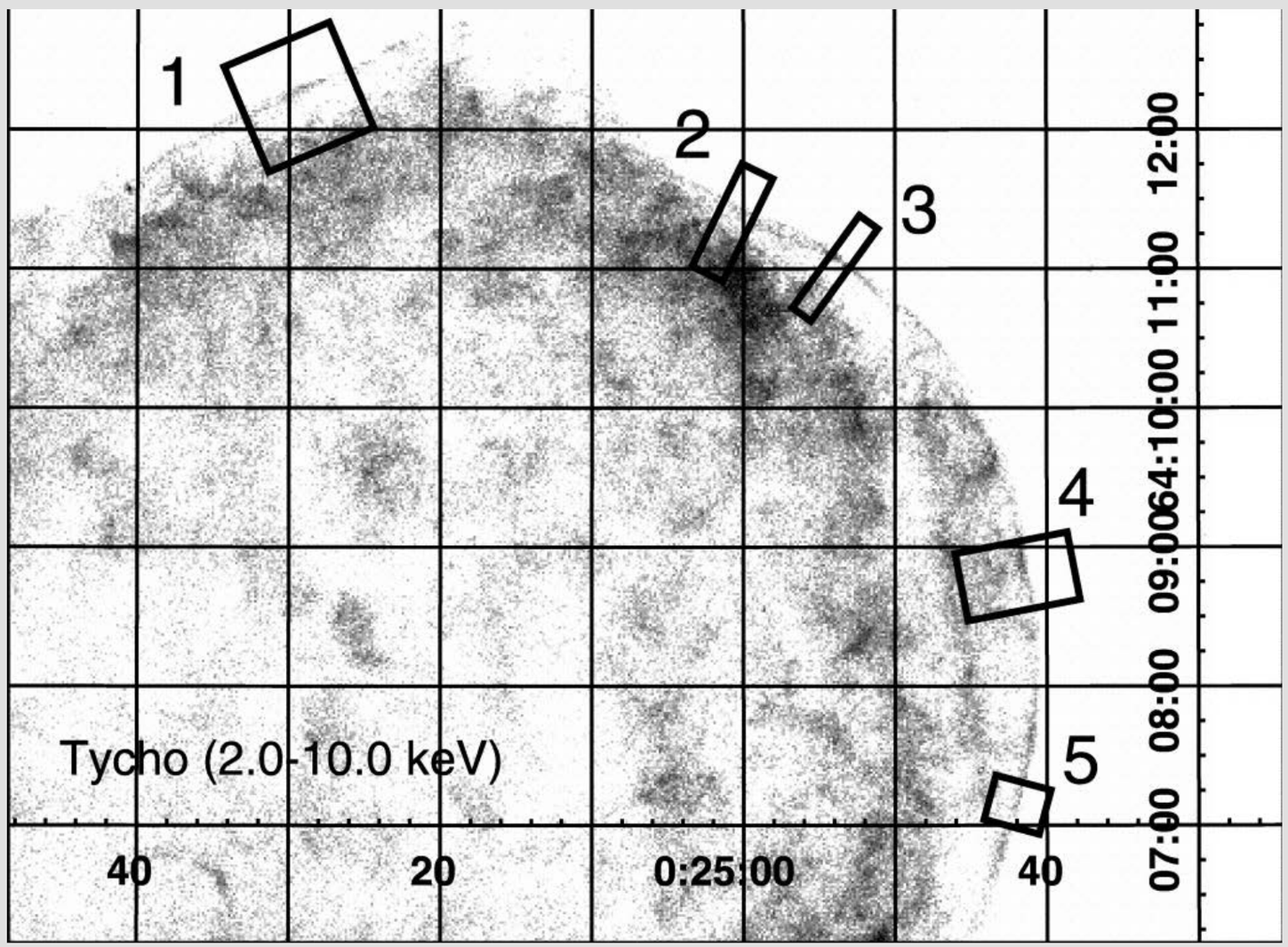
.broad-band fits of leptonic emission
.rapid variability of nonthermal X-ray emission
from bright filaments in SNRs
.sharp x-ray edges

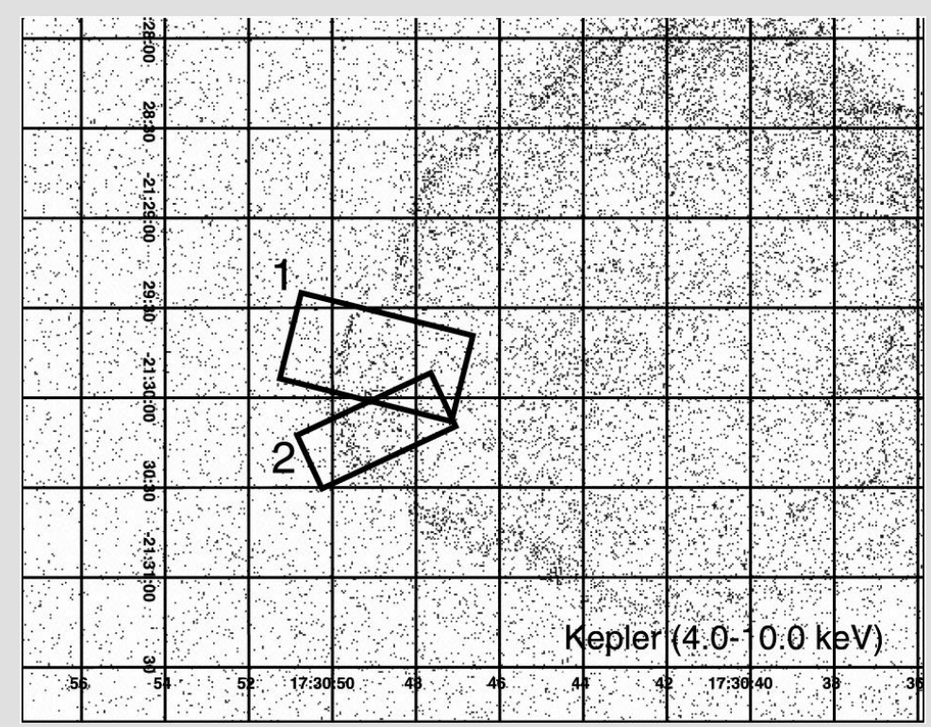
ii. magnetic field amplification

bamba et al. 2005



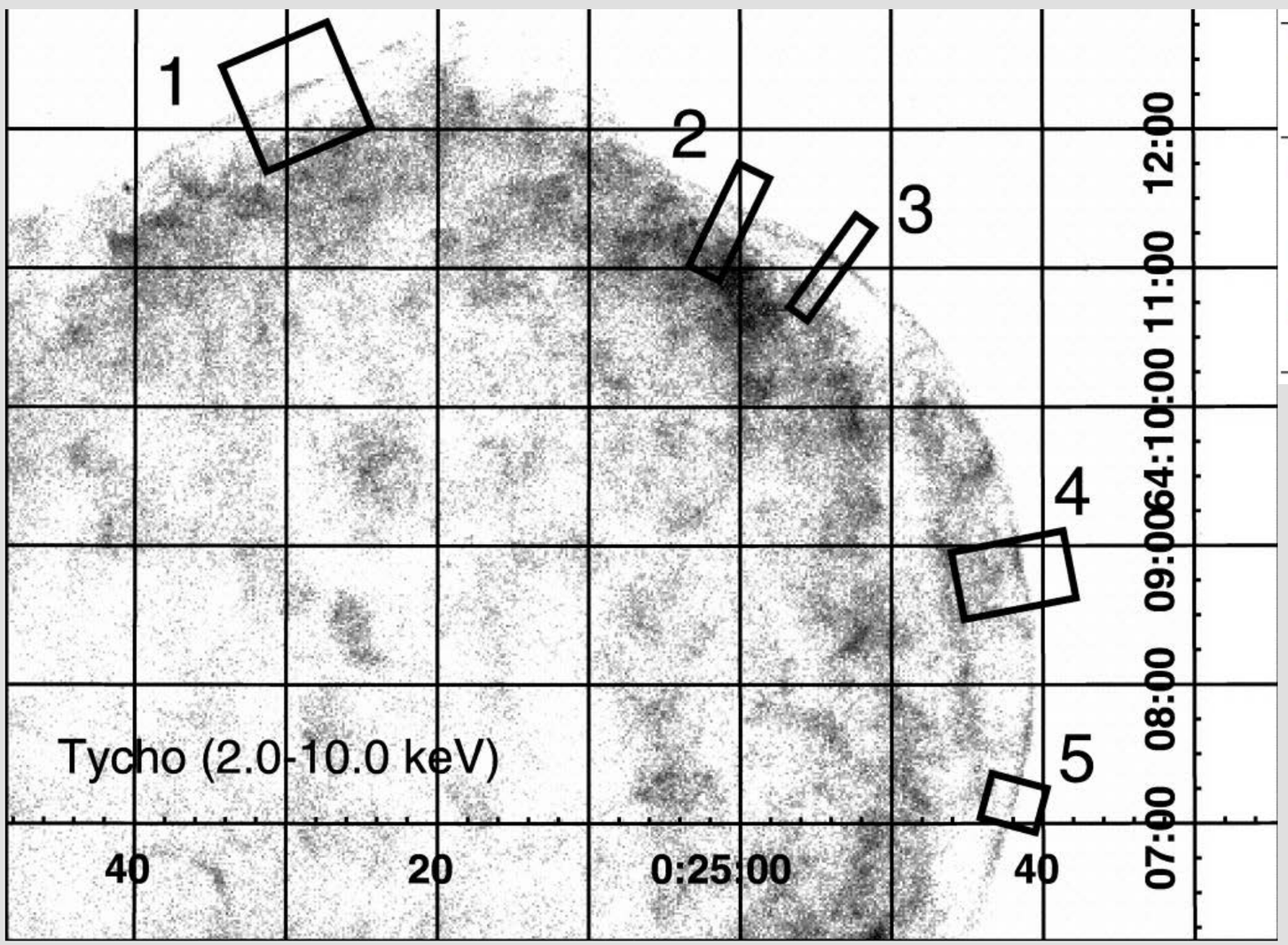
.sharp x-ray edges





ii. magnetic field amplification

.sharp x-ray edges



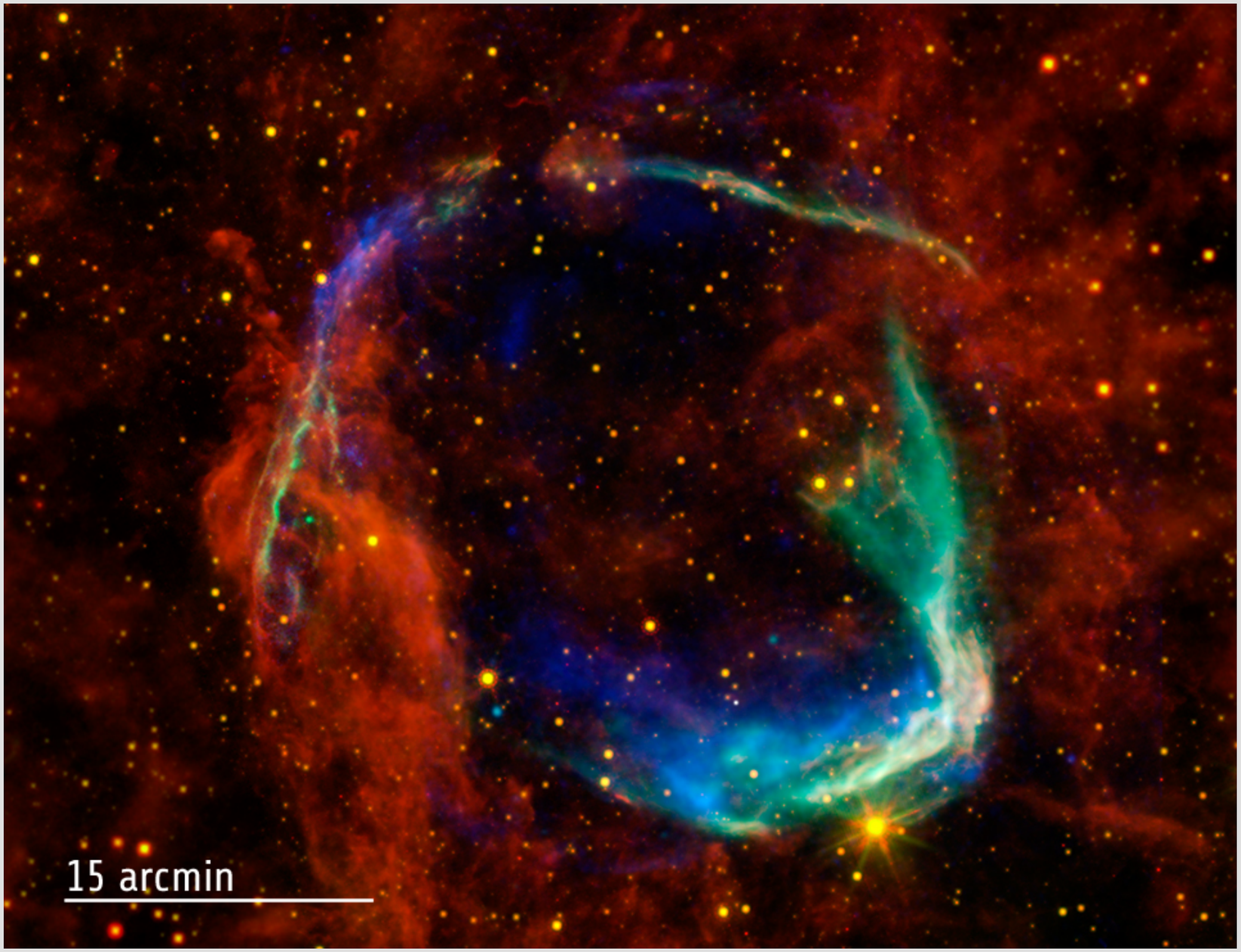
SNR	Dist kpc	V_s km s^{-1}	n_0 cm^{-3}	width $''$	B_{loss} μG	B_{diff} μG
Cas A	3.4	5200	3	0.5	249	299
Kepler	4.8	5300	0.35	1.5	97	113
Tycho	2.4	4500	0.3	2	113	165
SN1006	2.2	4300	0.1	20	30	39
RCW86	2.5	3500	0.1	45	24	14

vink 2006

iii. rcw 86

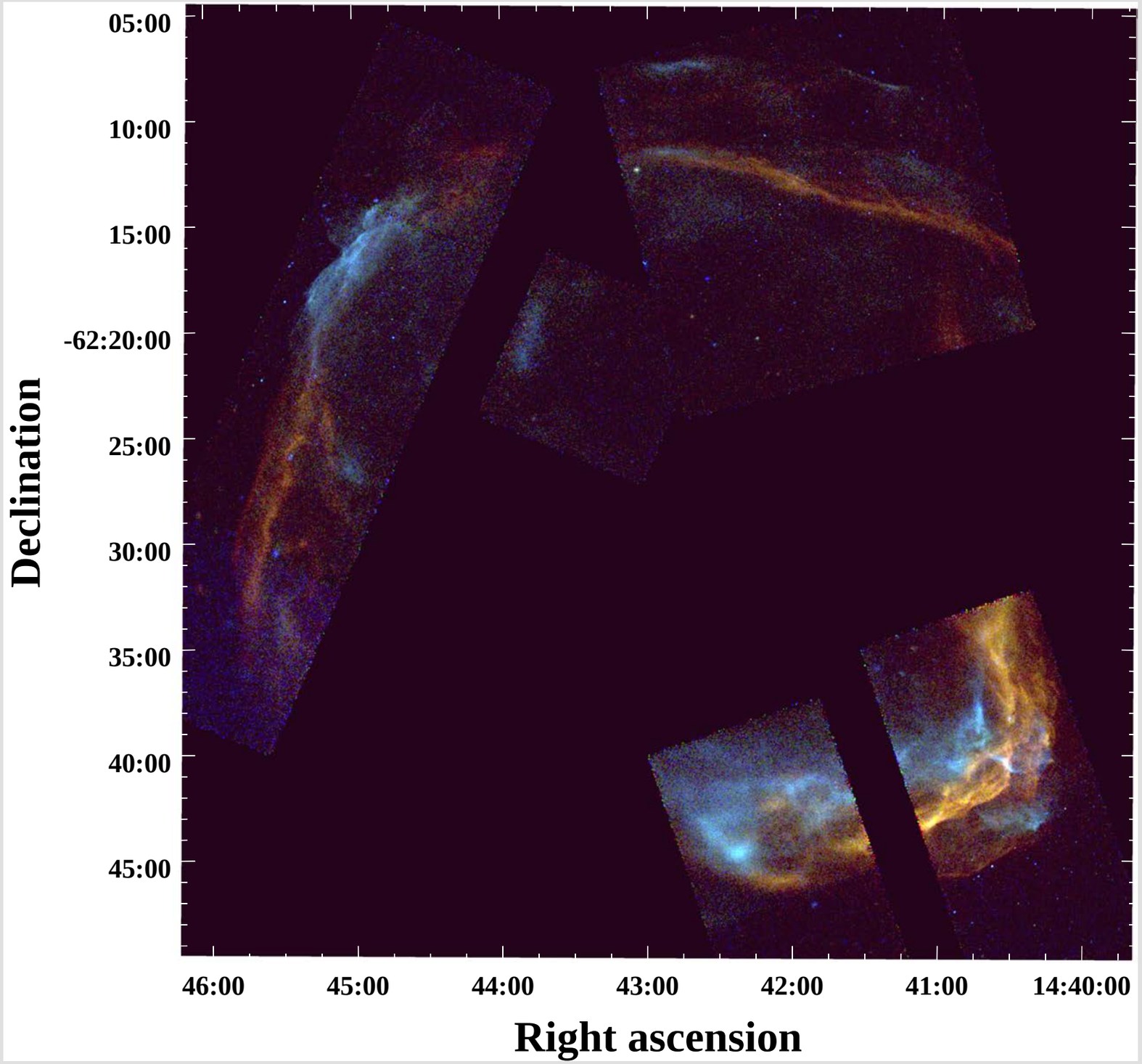
what have we learnt studying rcw 86 with chandra?

iii. rcw 86



williams+ 2011

iii. rcw 86



chandra
red: 0.5 - 1 keV
green: 1.5 - 2 keV
blue: 2 - 8 keV

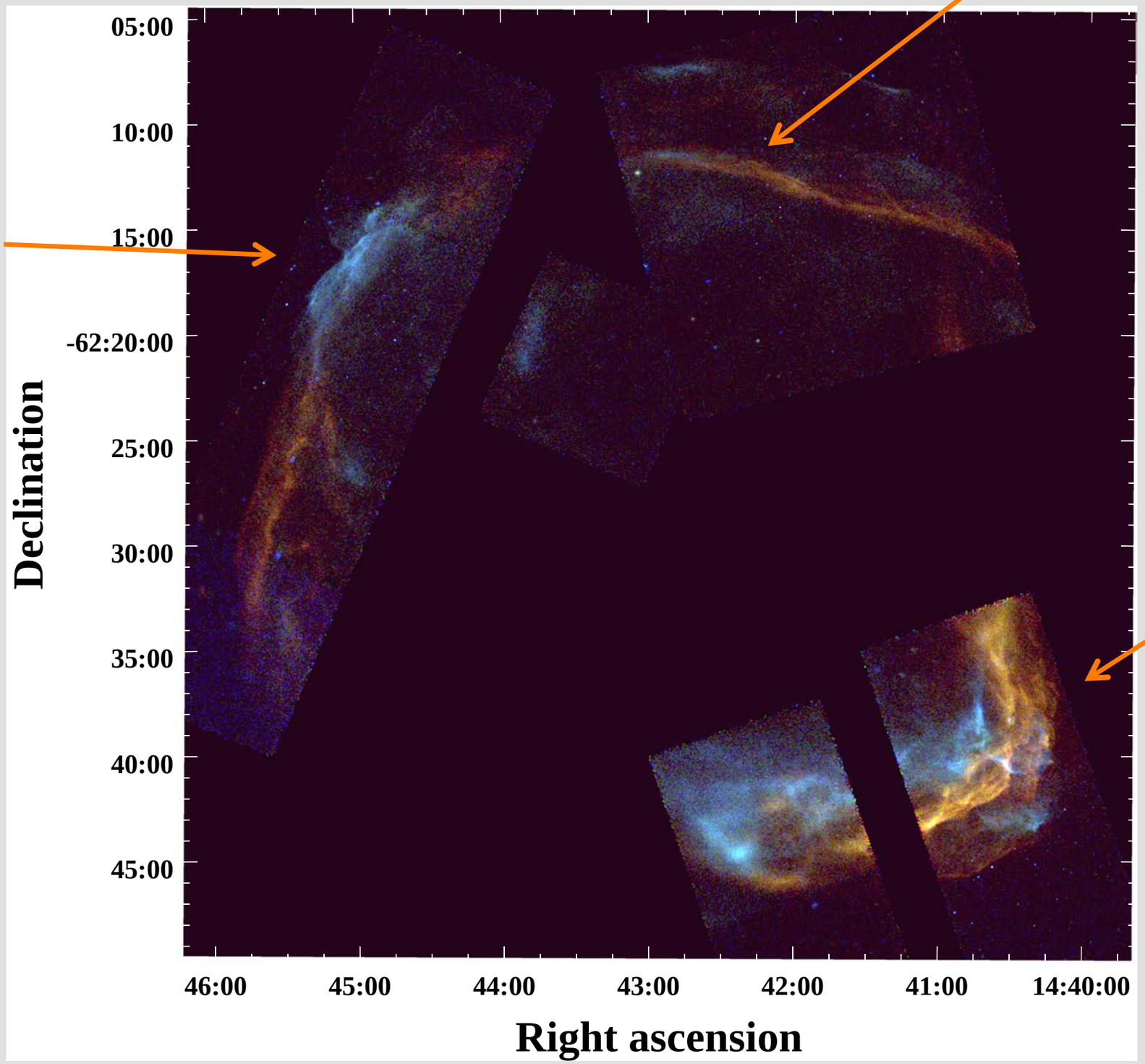
iii. rcw 86

shock velocity 650 km/s
from H-alpha studies

ghavamian 1999

shock velocity 3000 km/s
from X-ray proper
motion studies of the
non-thermal rim

yamaguchi+ 2016

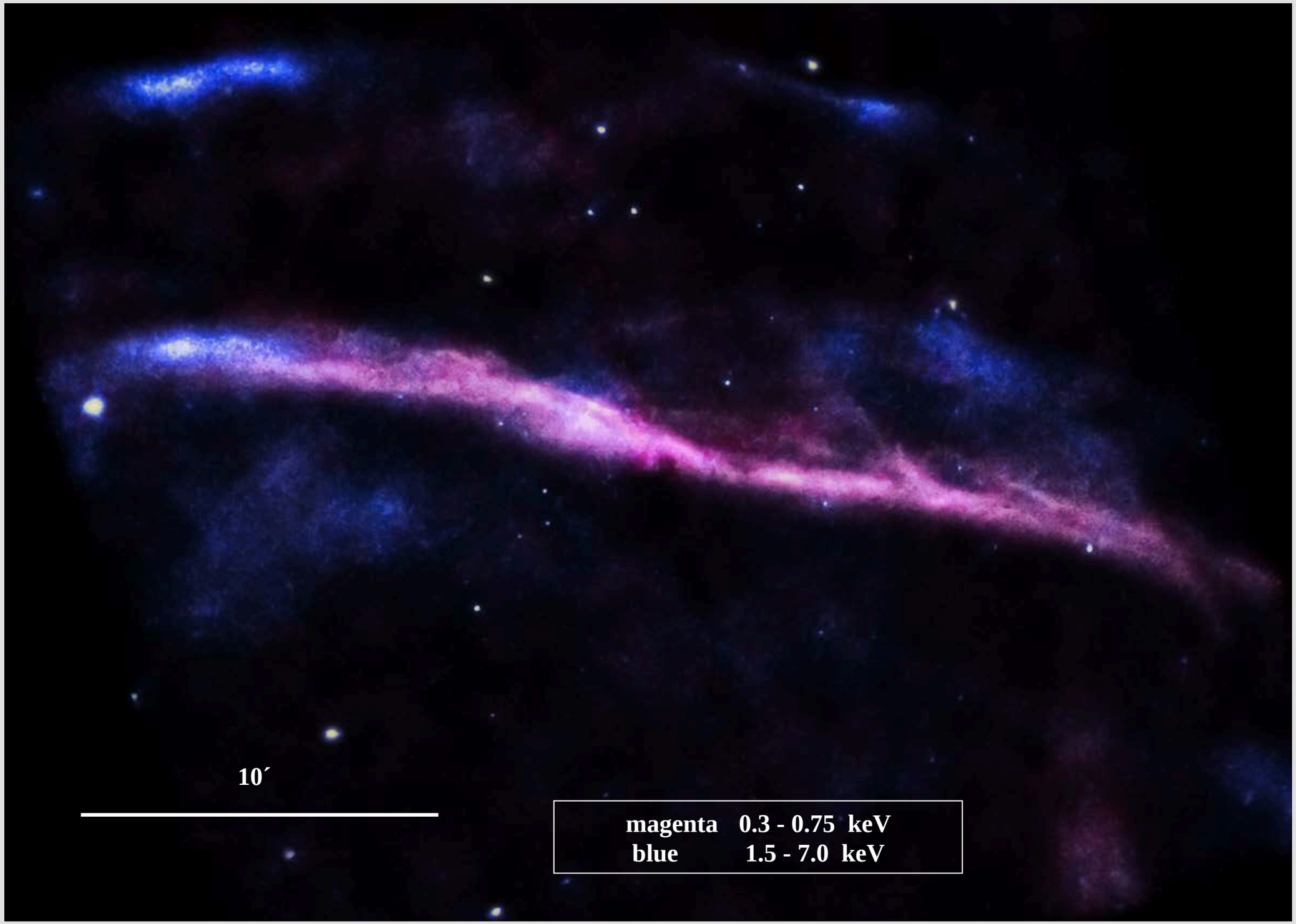


Satoru Katsuda is
currently working on
X-ray proper motion
studies here

chandra
red: 0.5 - 1 keV
green: 1.5 - 2 keV
blue: 2 - 8 keV

iii. rcw 86

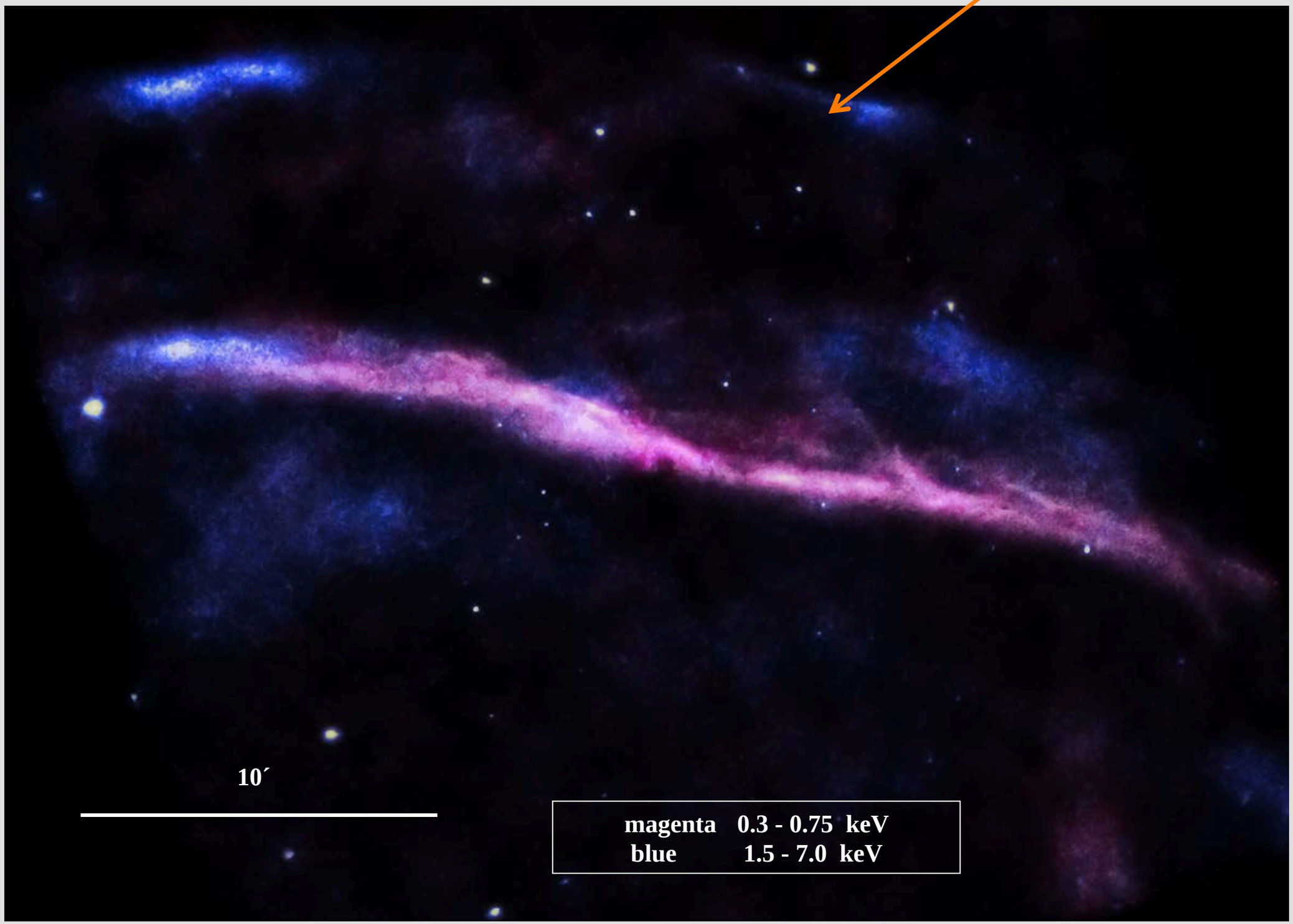
castro+ 2013



iii. rcw 86

credit to Joe DePasquale at CXC

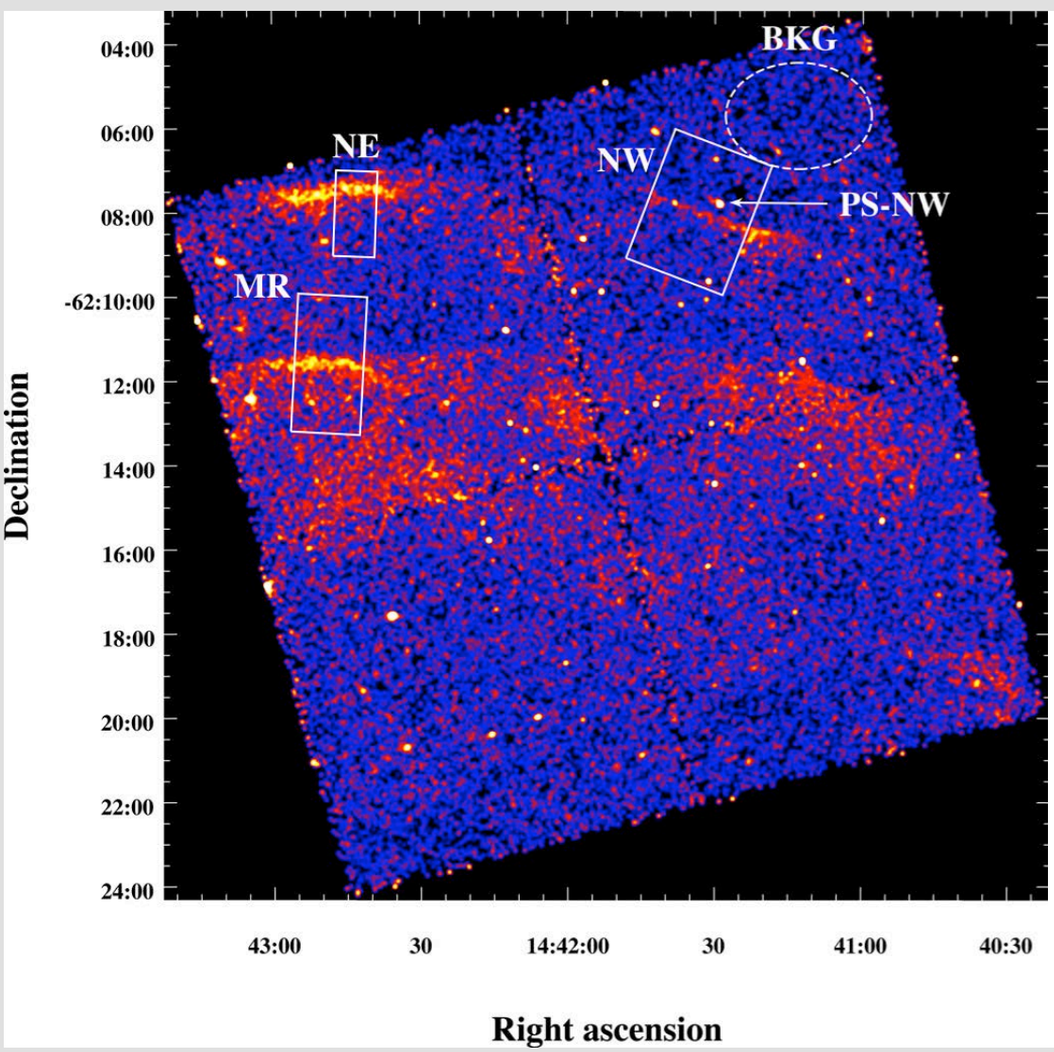
castro+ 2013

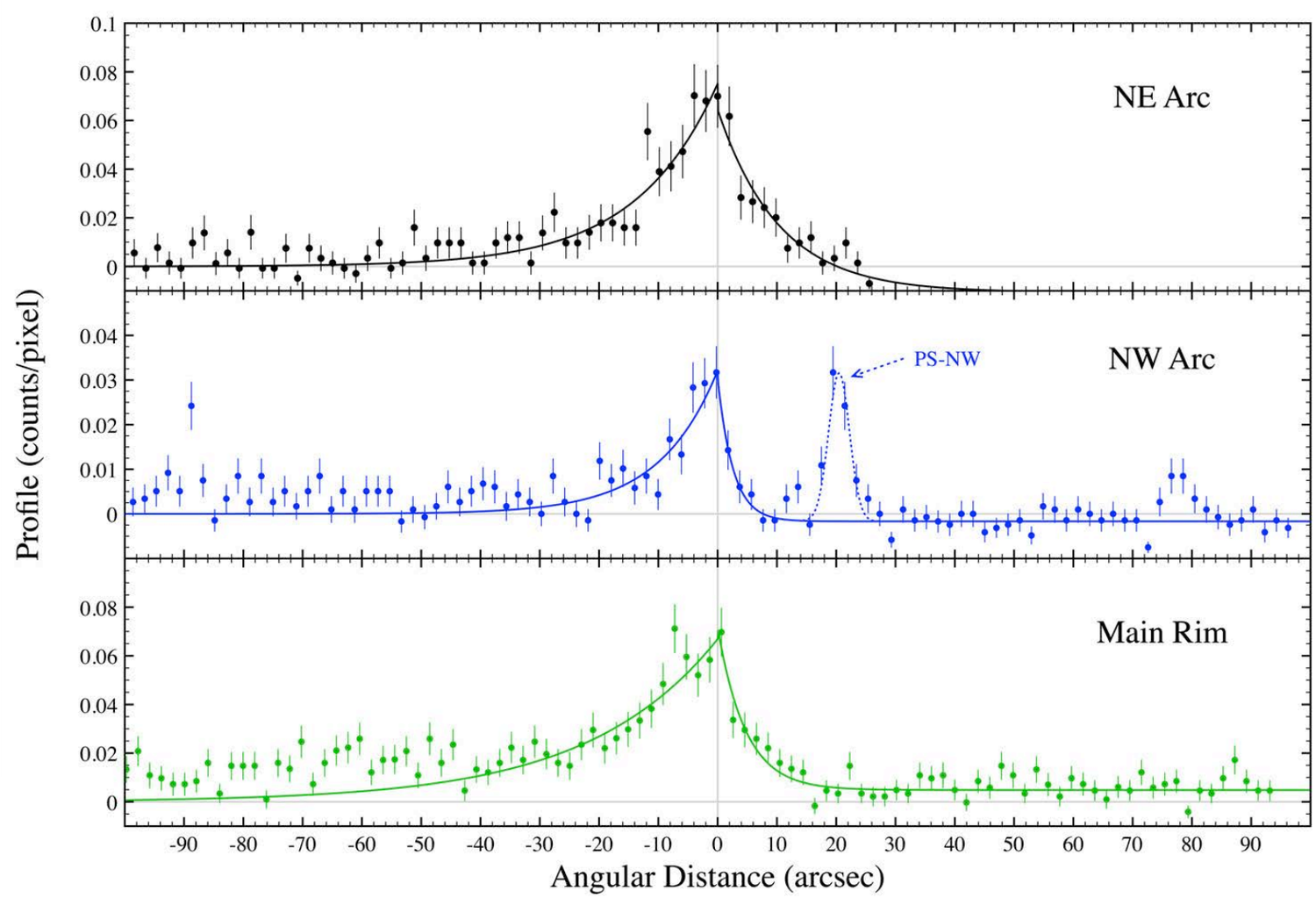


iii. rcw 86

from Bamba+ 2003

$$f(x) = \begin{cases} A \exp\left(-\left|\frac{x_0 - x}{l_{\mathrm{up}}}\right|\right) & x > x_0 \\ A \exp\left(-\left|\frac{x_0 - x}{l_{\mathrm{down}}}\right|\right) & x < x_0 \end{cases}$$





castro+ 2013

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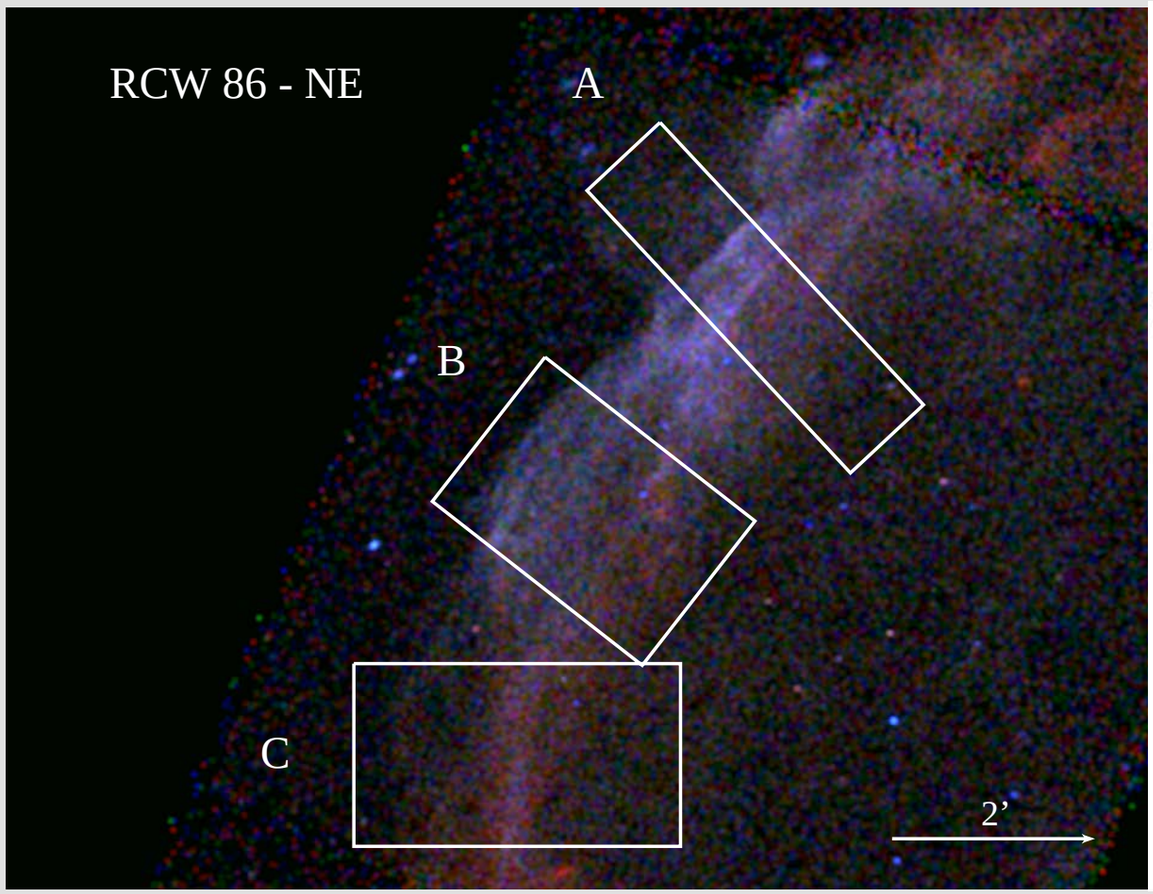
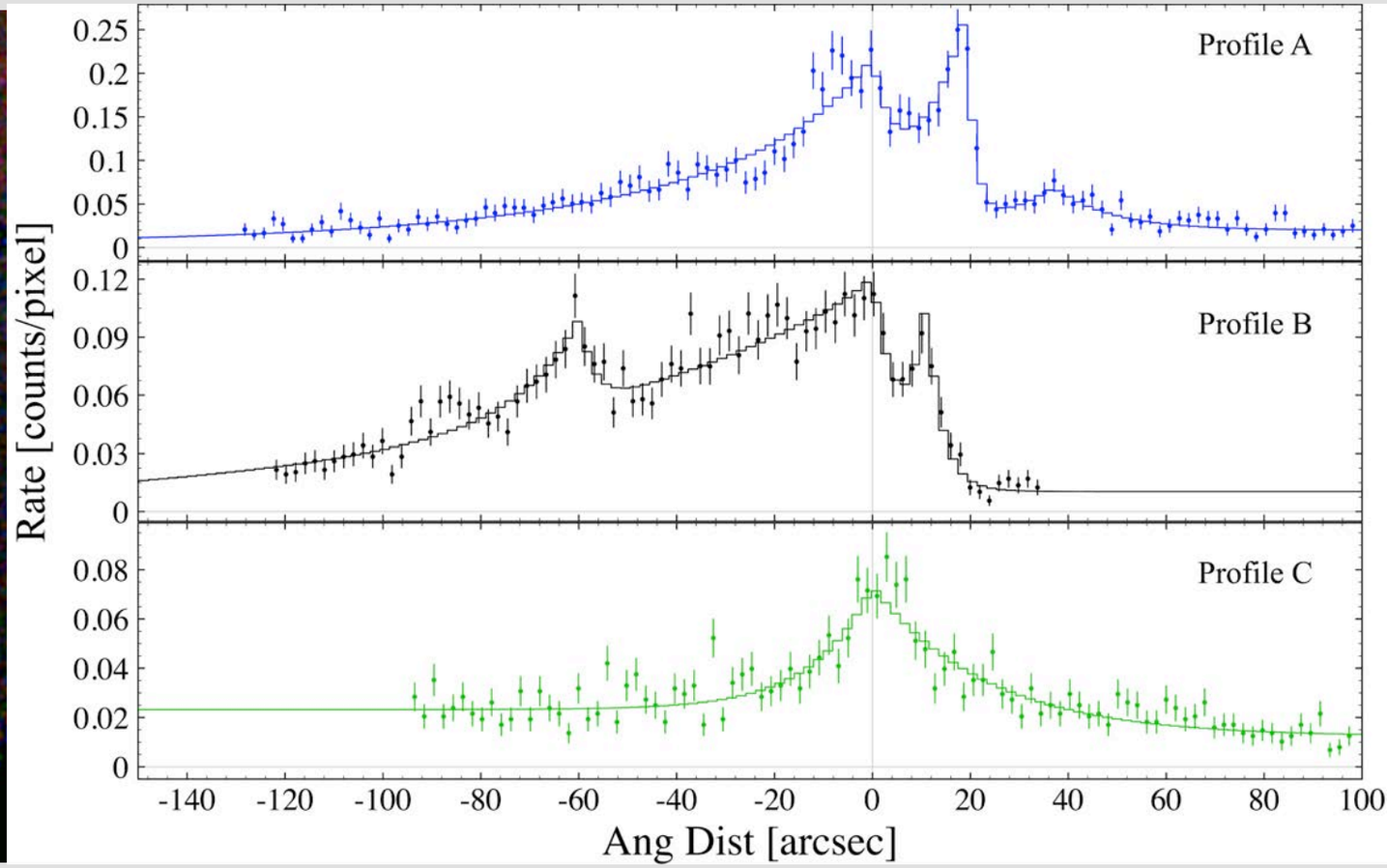
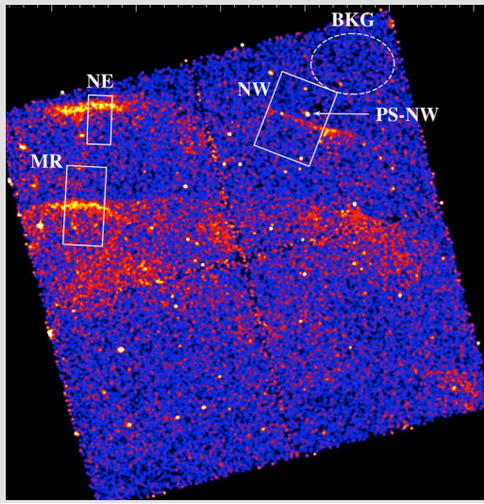




castro+ in prep (previously studied by vink+ 2006)

iii. rcw 86



NW

PROFILE FIT PARAMETERS AND MAGNETIC FIELD ESTIMATES

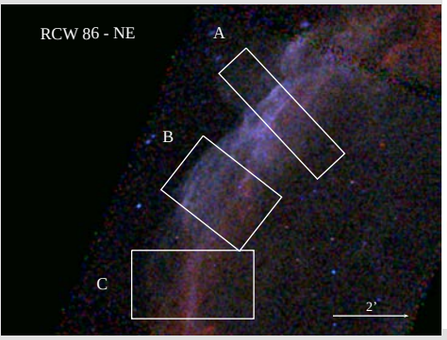
Region	l_{down} (arcsec)	l_{up} (arcsec)	$\chi^2/(dof)$	l_{down} (pc)	l_{up} (pc)	V_s[a] (km s^{-1})	B_{adv}[b] (μG)	$B_{diff,d}$[c] (μG)	$B_{diff,u}$[c] (μG)	B_{joint}[d] (μG)
NE Arc	14 ± 2	10 ± 3	60 / (59)	0.17 ± 0.03	0.13 ± 0.04	810 ± 150	27	300	140	110
NW Arc	10 ± 2	3 ± 1	94 / (74)	0.12 ± 0.02	0.03 ± 0.02	810 ± 150	33	370	360	140
Main Rim	22 ± 2	5 ± 1	75 / (65)	0.27 ± 0.03	0.06 ± 0.01	650 ± 120	17	250	280	80

NE

Profile Fit Parameters and Magnetic Field Estimates

Region	l_{down} (arcsec)	l_{up} (arcsec)	χ^2/dof	B_{adv} (μG)	$B_{diff,d}$ (μG)	$B_{diff,u}$ (μG)	B_{joint} (μG)
A	46 ± 8	5 ± 3	60/59	28 ± 5	50 ± 10	100 ± 50	39 ± 4
B	76 ± 6	5 ± 1	94/74	20 ± 2	40 ± 5	100 ± 20	28 ± 2
C	12 ± 3	23 ± 4	75/65	70 ± 20	130 ± 30	35 ± 6	90 ± 10

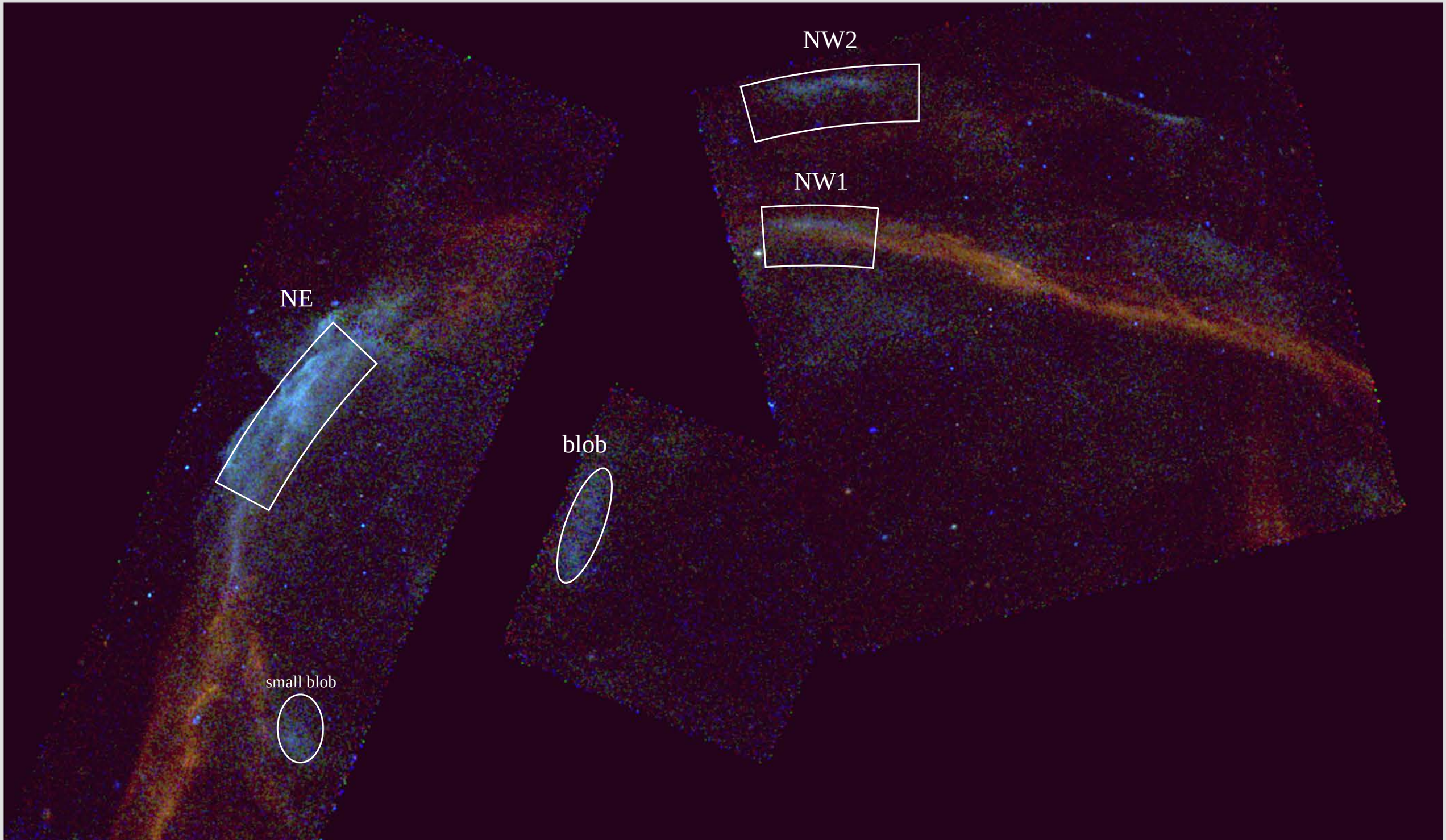
Note. — Both angular lengths, l_{down} and l_{up}, are converted to physical length using the estimated distance, $d = 2.5$ keV. The shock velocity used to calculate the magnetic field strengths is presumed to be 3000 ± 300 km/s, from Yamaguchi et al. (2016).



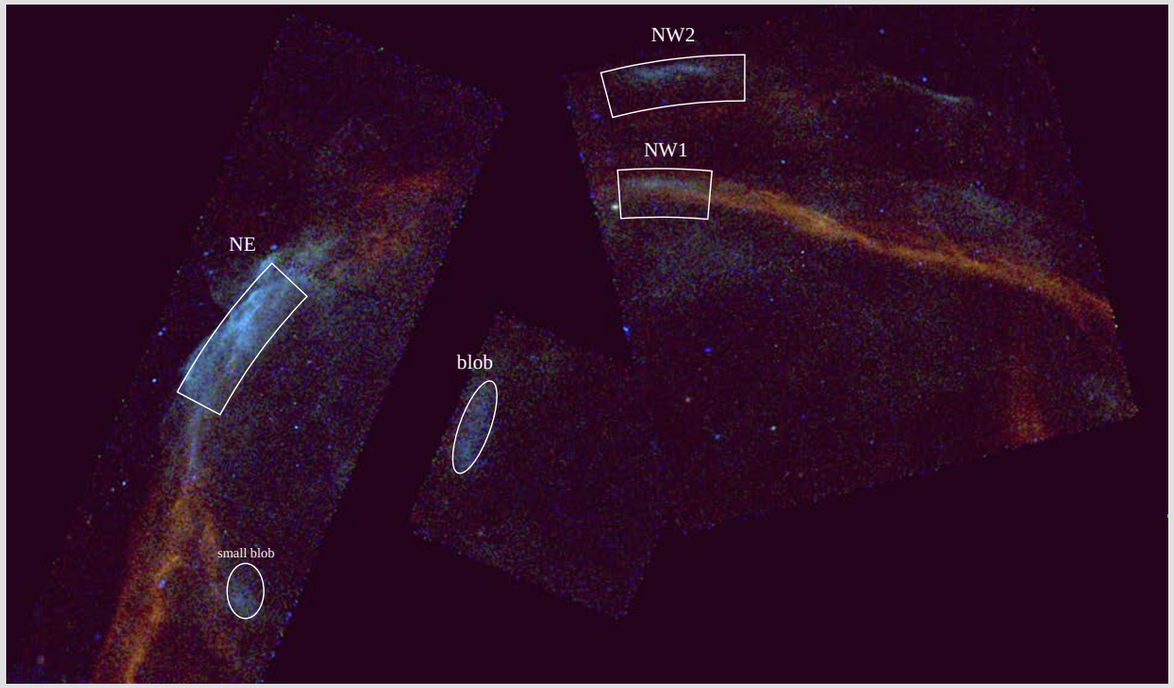
iii. rcw 86

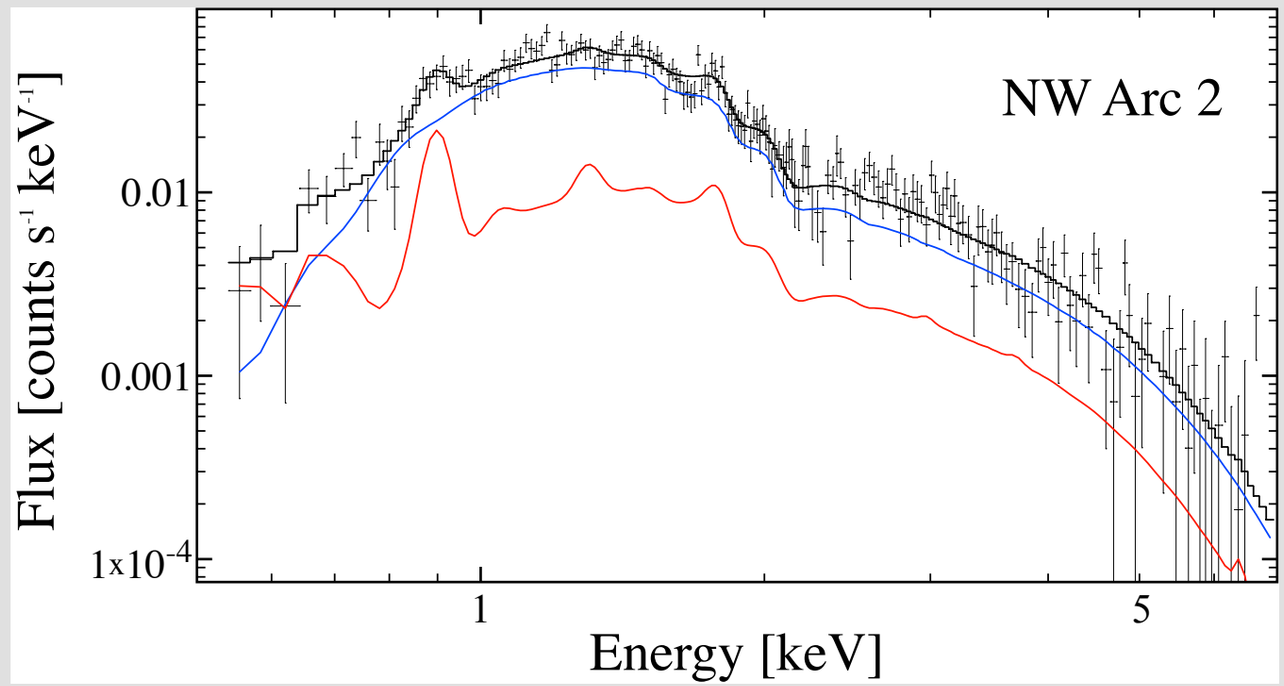
chandra

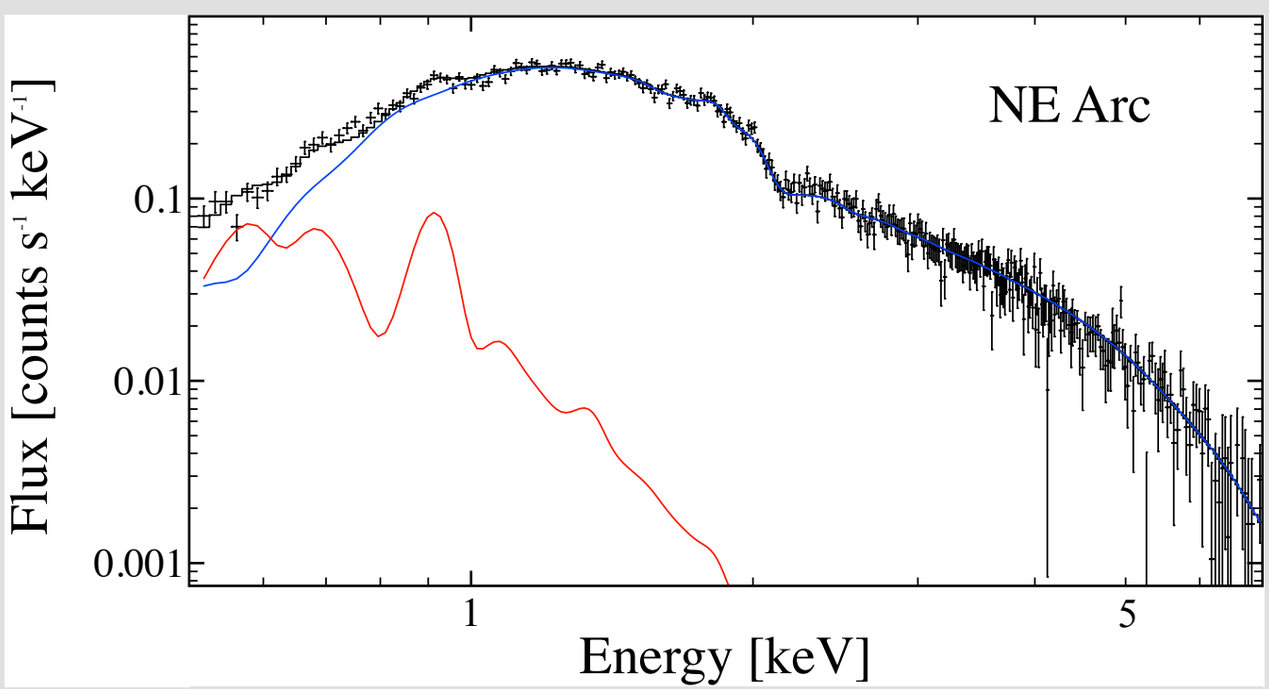
red: 0.5 - 1 keV
green: 1.5 - 2 keV
blue: 2 - 8 keV

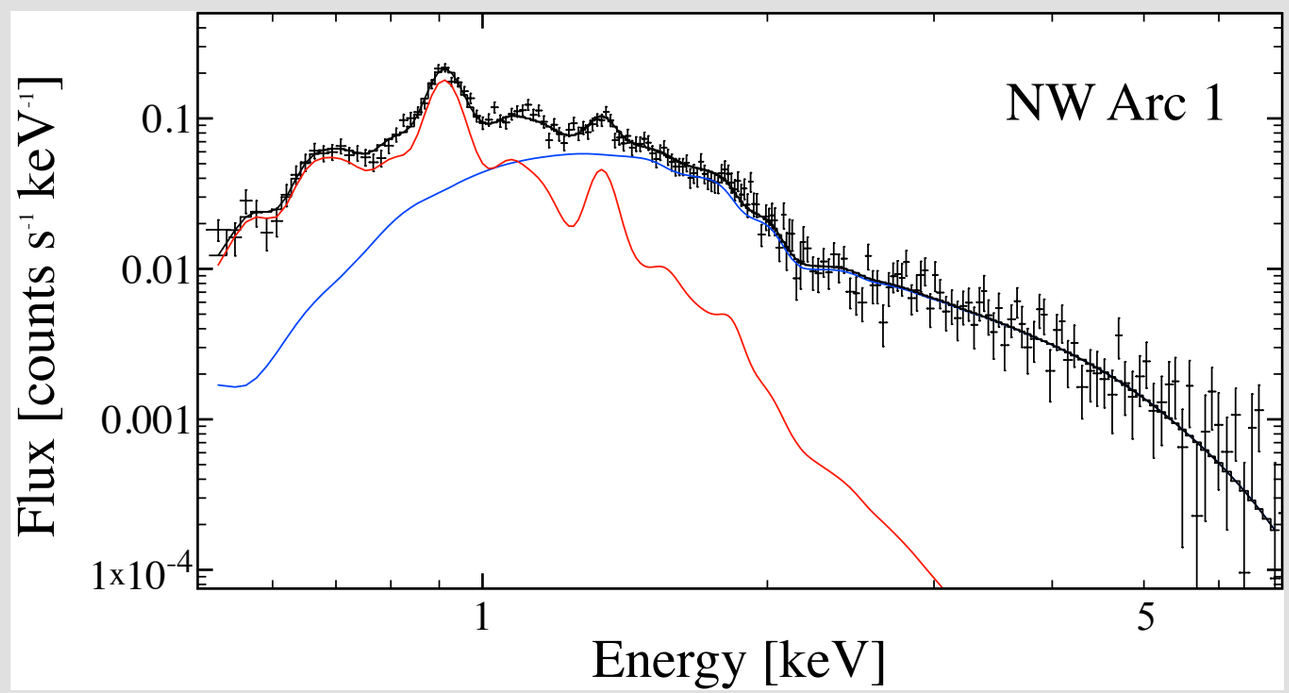


iii. rcw 86


NW2
NW1
NE
blob
small blob


NW Arc 2
Flux [counts s^{-1} keV^{-1}]
0.01
0.001
1x10^{-4}
1
5
Energy [keV]

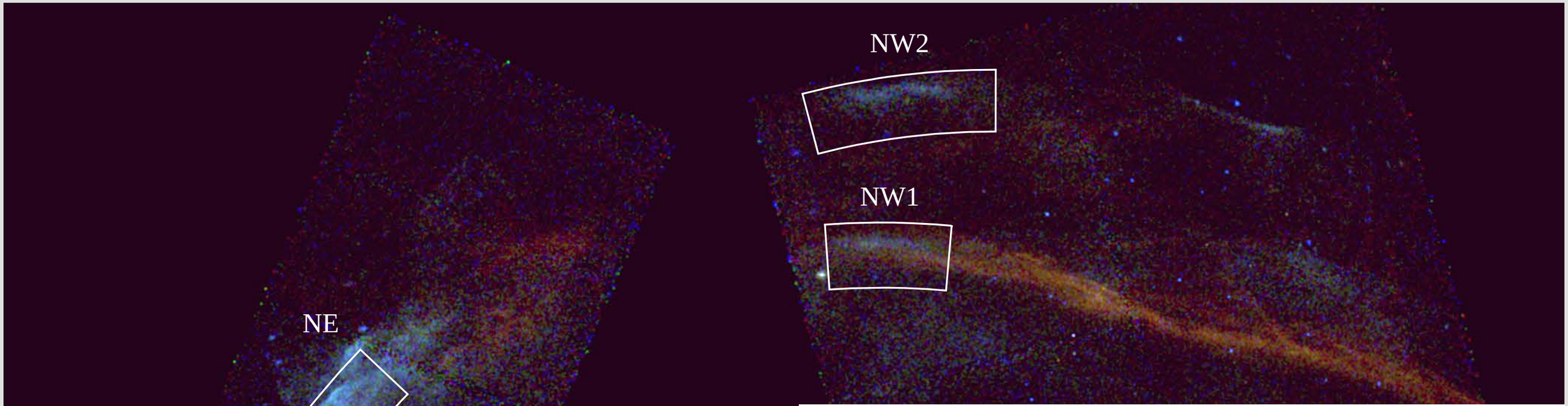

NE Arc
Flux [counts s^{-1} keV^{-1}]
0.1
0.01
0.001
1
5
Energy [keV]

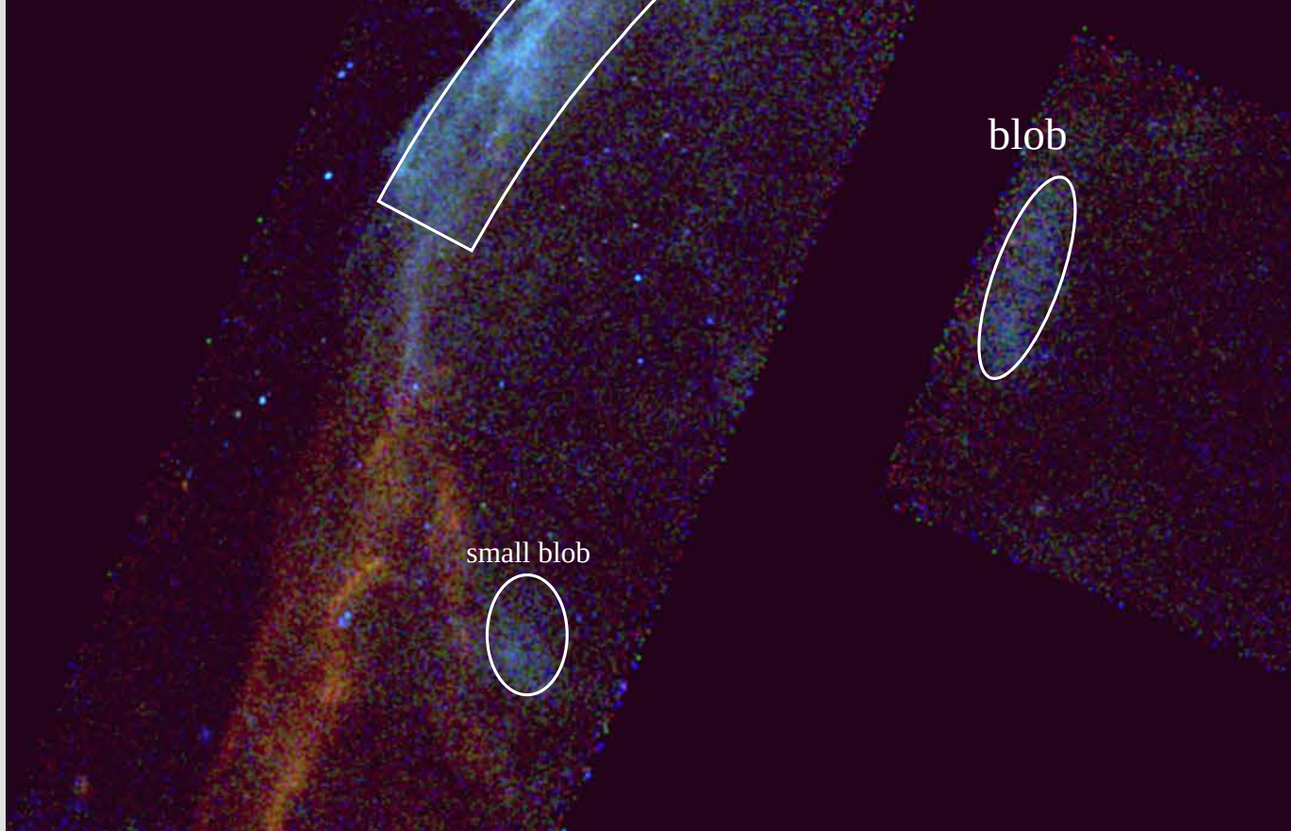

NW Arc 1
Flux [counts s^{-1} keV^{-1}]
0.1
0.01
0.001
1x10^{-4}
1
5
Energy [keV]

iii. rcw 86

chandra

red: 0.5 - 1 keV
green: 1.5 - 2 keV
blue: 2 - 8 keV





Results of Spectral Fitting of RCW 86 Northern Synchrotron Rims

			NE	NW1	NW2
Absorbing Column	N_H	10^{22} cm^{-2}	$0.85^{+0.04}_{-0.05}$	$0.88^{+0.05}_{-0.04}$	$0.5^{+0.1}_{-0.1}$
Temperature	kT_e	keV	0.1	0.1	1.4
Ionization Timescale	$n_e t$	10^{11} s cm^{-3}	350	450	0.03
Ambient Density	n_0	cm^{-3}	< 1.4	< 1.5	< 0.1
Roll-off Energy	$h\nu$	keV	$6.4^{+0.9}_{-0.7}$	$1.9^{+0.3}_{-0.4}$	4^{+1}_{-1}
Flux Density at 1 GHz	$F_{1\,\mathrm{GHz}}$	Jy	$1.5^{+0.2}_{-0.2}$	$1.1^{+0.4}_{-0.2}$	$0.4^{+0.2}_{-0.1}$
Fit Statistic	χ^2/dof		306.3/323	212.6/183	204.0/187
Spectral Index	Γ		$2.70^{+0.04}_{-0.04}$	$3.2^{+0.2}_{-0.1}$	$3.0^{+0.8}_{-0.2}$
Flux Density at 1 keV	$F_{1\,\mathrm{keV}}$	10^{-4} keV^{-1}cm^{-2}s^{-1}	36^{+1}_{-2}	$8.4^{+0.9}_{-0.7}$	5^{+1}_{-1}
Fit Statistic	χ^2/dof		321.9/323	200.7/183	205.1/187

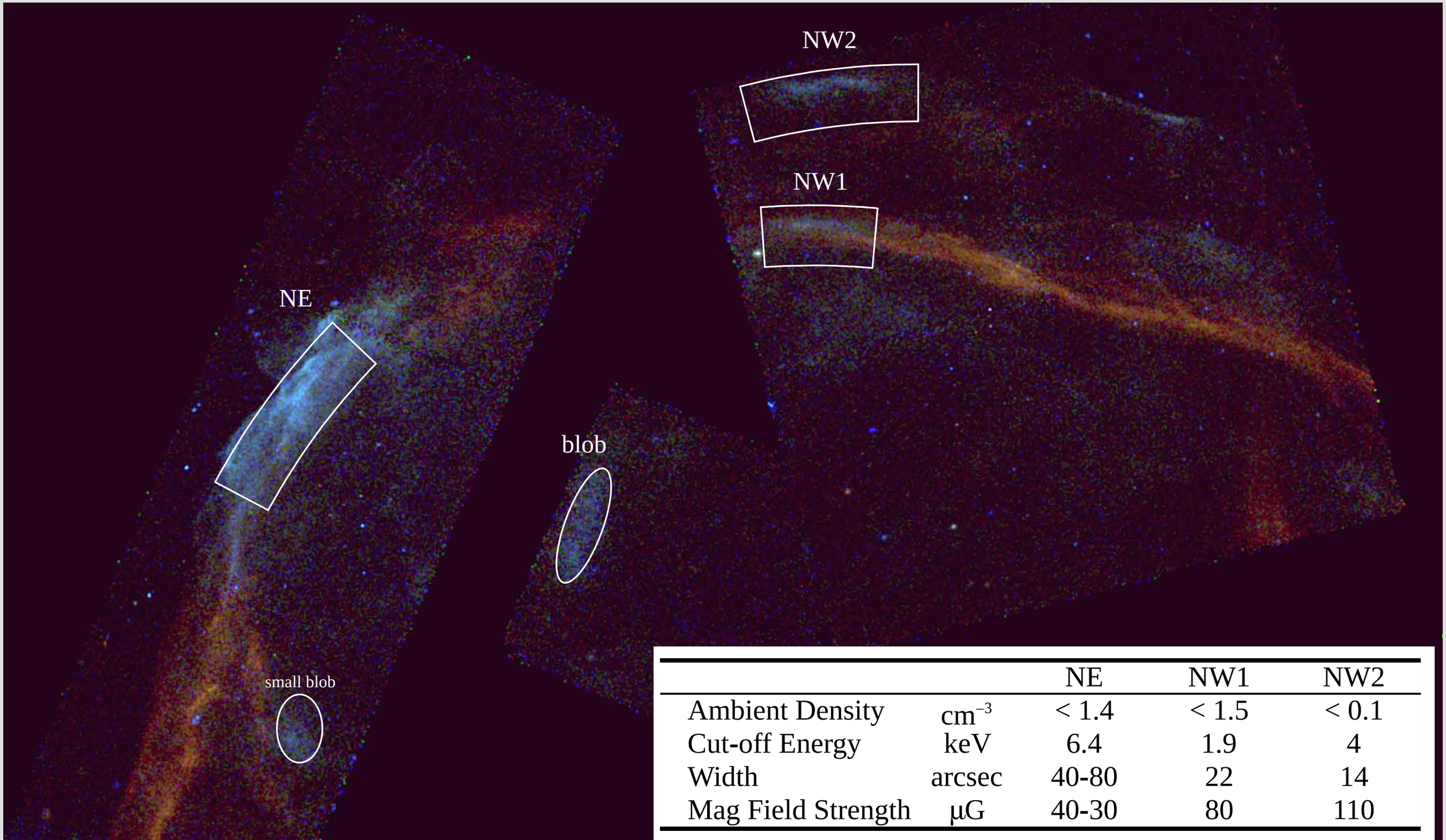
Note. — Absorption model and solar abundance values obtained from Wilms et al. (2000).

[a] Ambient density, n_0, derived from the normalization of the NEI thermal plasma component, using a distance of $d = 2.5$ kpc. a ratio of electron to hydrogen number density $n_e/n_H = 1.23$, and emitting volume as discussed in the text.

iii. rcw 86

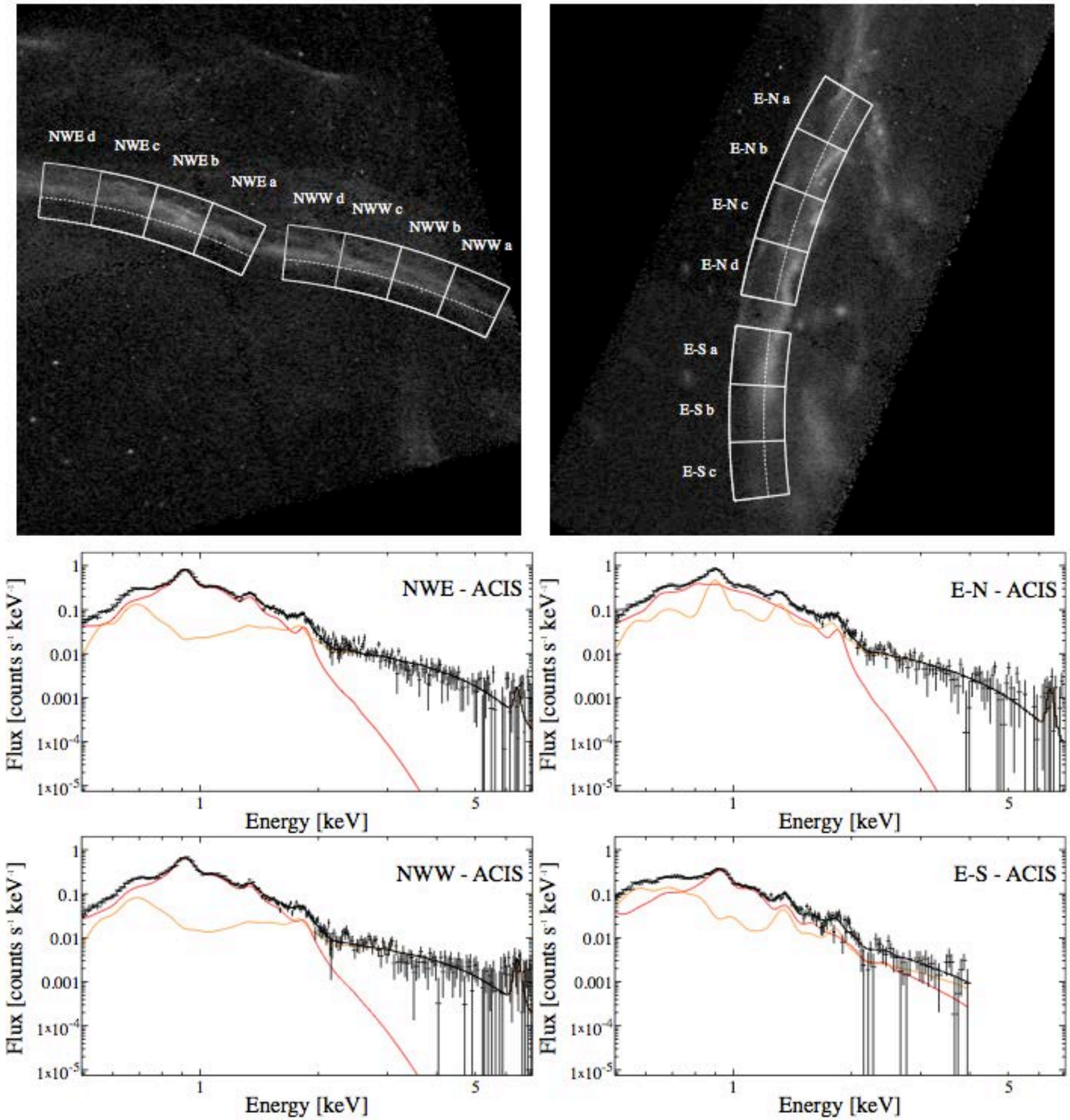
chandra

red: 0.5 - 1 keV
green: 1.5 - 2 keV
blue: 2 - 8 keV



		NE	NW1	NW2
Ambient Density	cm^{-3}	< 1.4	< 1.5	< 0.1
Cut-off Energy	keV	6.4	1.9	4
Width	arcsec	40-80	22	14
Mag Field Strength	μG	40-30	80	110

iii. rcw 86


NWE d
NWE c
NWE b
NWE a
NWW d
NWW c
NWW b
NWW a
E-N a
E-N b
E-N c
E-N d
E-S a
E-S b
E-S c
NWE - ACIS
E-N - ACIS
NWW - ACIS
E-S - ACIS
Flux [counts s⁻¹ keV⁻¹]
Energy [keV]
1
0.1
0.01
0.001
1×10⁻⁴
1×10⁻⁵
1
5

the end

.thin nonthermal x-ray rims observed in the nw and ne of rcw 86

.high magnetic fields derived using filament widths

.densities connected to filament width?