# Giant Radio lobes of Centaurus A studied with the Chandra


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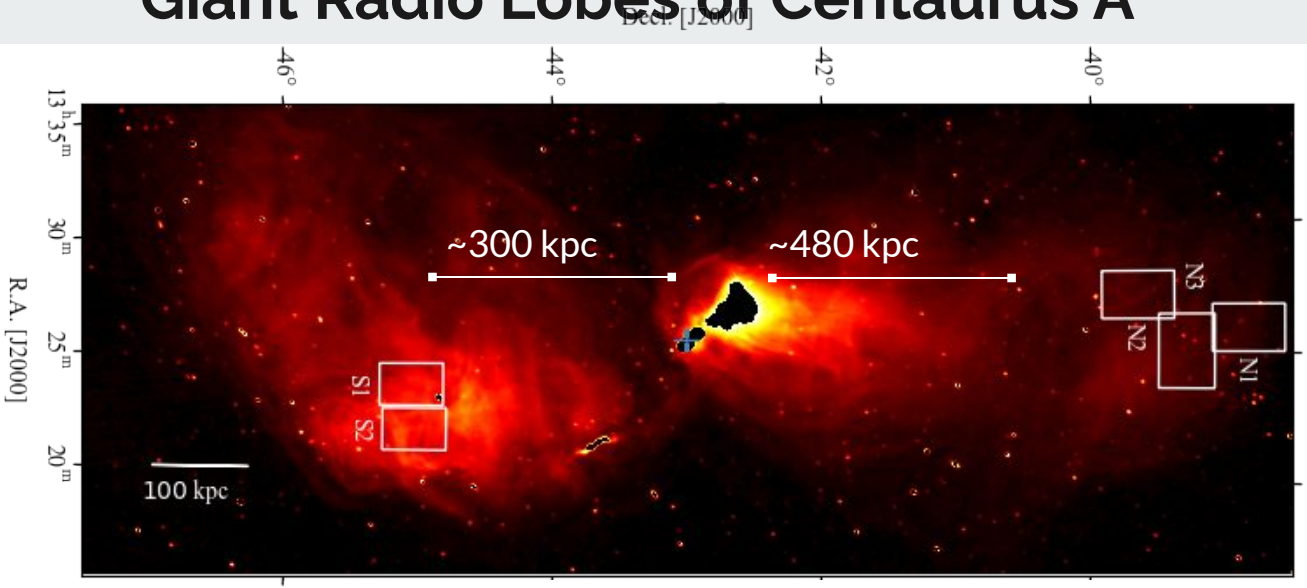
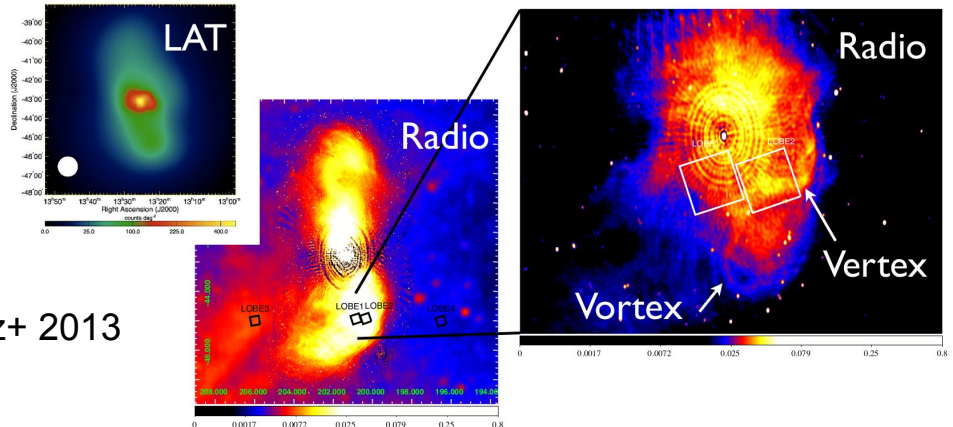
# Giant Radio Lobes of Centaurus A



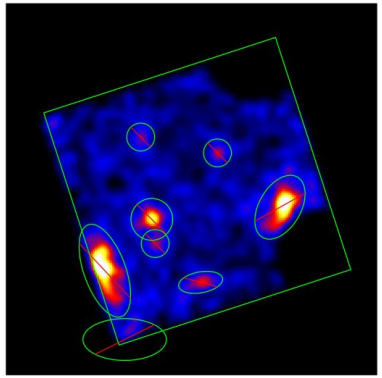

Adapted from McKinley+2022
MWA @ 185MHz

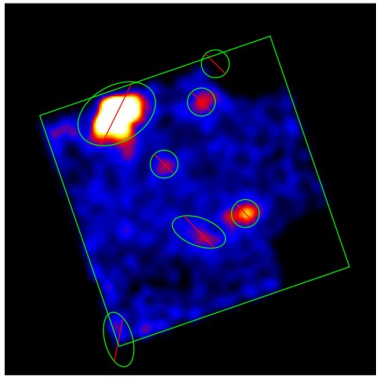


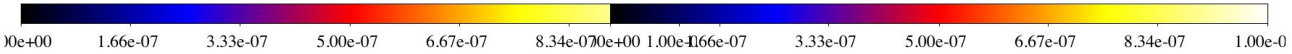

Stawarz+ 2013

- Flat Λ-CDM (Planck XIII 2016): H0=67.8, Ωm=0.308
- z=0.001830 (Spoon+2022)
- Distance = 3.8±0.1 Mpc (Harris+2010)
- Scale: 1◦ ≈ 0.1409Mpc
- $D_A$=8.068Mpc, $D_L$=8.1Mpc
- Age at z = 11.596 Gyr

| Region | Distance from center (kpc) |
|---|---|
| S1 | 306.042 |
| S2 | 314.197 |
| N1 | 575.449 |
| N2 | 461.210 |
| N3 | 523.541 |







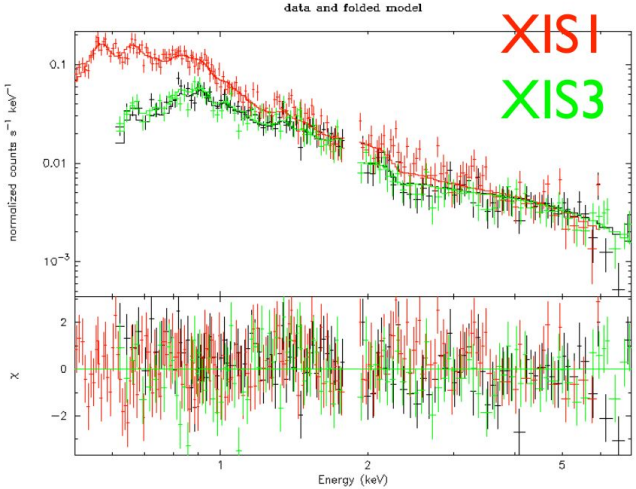

Stawarz+ 2013

Lobe 1

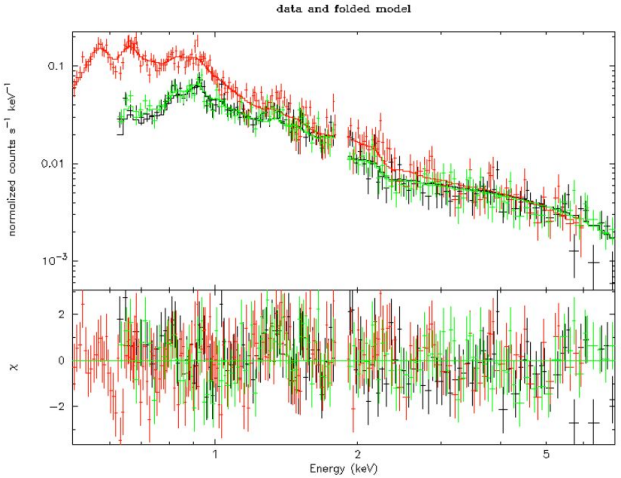
XIS0

XIS1

XIS3




Lobe 2




# Lobe spectrum

- mekal+wabs*(mekal+p)ow) ,
  which corresponds to Local hot bubble, Galactic halo, and cosmic X-ray background
- 1.8-1.9 keV were ignored due to calibration uncertainty of Si K-edge (1.84 keV)
- In the fit, 0.6-7.0 keV were utilized for XIS0 and 3, and 0.5-6.0 keV for XIS1

Modeling Results for the Diffuse Emission

| Region (1) | $kT_{LB}$ (2) | $Norm_{LB}$ (3) | $kT_{GH}$ (4) | $Norm_{GH}$ (5) | $Norm_{CXB}$ (6) | $F^{abs}_{0.5-2\,keV}$ (7) | $F^{abs}_{2-10\,keV}$ (8) | $Z/Z_\odot$ (9) | Red. $\chi^2$/dof (10) |
|---|---|---|---|---|---|---|---|---|---|
| Lobe 1 ("on") | $0.19 \pm 0.01$ | $3.53^{+0.20}_{-0.20}$ | $0.60^{+0.03}_{-0.03}$ | $7.42^{+0.79}_{-0.82}$ | $0.97^{+0.03}_{-0.02}$ | 7.88 | 6.32 | $1.0^f$ | 1.16/441 |
| Lobe 2 ("on") | $0.20 \pm 0.01$ | $3.22^{+0.18}_{-0.17}$ | $0.66^{+0.02}_{-0.03}$ | $7.38^{+0.68}_{-0.69}$ | $1.01^{+0.03}_{-0.02}$ | 7.67 | 6.59 | $1.0^f$ | 1.13/512 |
| Lobe 3 ("off") | $0.20 \pm 0.01$ | $3.30^{+0.33}_{-0.32}$ | $0.70^{+0.12}_{-0.09}$ | $3.79^{+1.28}_{-1.16}$ | $1.04^{+0.05}_{-0.05}$ | 7.19 | 6.73 | $1.0^f$ | 1.30/131 |
| Lobe 4 ("off") | $0.19 \pm 0.01$ | $2.34^{+0.33}_{-0.31}$ | $0.80^{+0.16}_{-0.13}$ | $3.45^{+0.88}_{-0.84}$ | $1.18^{+0.05}_{-0.06}$ | 5.87 | 7.63 | $1.0^f$ | 0.87/123 |

**Notes.** (1) Region fitted; (2) temperature of the LB component in keV units; (3) `MEKAL` normalization of the LB component $\times 10^{-3}$; (4) temperature of the GH component in keV units; (5) `MEKAL` normalization of the GH component $\times 10^{-4}$; (6) normalization of the CXB component $\times 10^{-3}$; (7) absorbed 0.5–2 keV flux in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$/0.35 deg$^2$; (8) absorbed 2–10 keV flux in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$/0.35 deg$^2$; (9) fixed ("*f*") abundance; (10) reduced $\chi^2$ value/degree of freedom.

Excess soft emissions seems present for both two "on" pointings, around 0.8 keV

| Region (1) | $Z_{GH}/Z_\odot$ (2) | $kT_{GH}$ (3) | $Norm_{GH}$ (4) | $Z_{ext}/Z_\odot$ (5) | $kT_{ext}$ (6) | $Norm_{ext}$ (7) | $\Gamma_{CXB}$ (8) | $Norm_{CXB}$ (9) |
|---|---|---|---|---|---|---|---|---|
| Lobe 1 ("on") | $1.0^f$ | $0.16^{+0.01}_{-0.02}$ | $7.34^{+3.48}_{-1.52}$ | $0.3^f$ | $0.59 \pm 0.02$ | $3.60 \pm 0.17$ | $1.41^f$ | $1.04 \pm 0.02$ |
| Lobe 2 ("on") | " | " | " | " | $0.73 \pm 0.02$ | $3.15 \pm 0.15$ | " | " |
| Lobe 3 ("off") | " | " | " | " | $0.71 \pm 0.11$ | $1.43 \pm 0.27$ | " | $1.30^{+0.04}_{-0.03}$ |
| Lobe 4 ("off") | " | " | " | " | $1.59 \pm 0.36$ | $1.31 \pm 0.30$ | " | " |

**Notes.** (1) Region fitted; (2) fixed ("*f*") abundance of the GH component; (3) temperature of the GH component in keV units; (4) `APEC` normalization of the GH component $\times 10^{-3}$; (5) fixed ("*f*") abundance of the extra thermal component; (6) temperature of the extra thermal component in keV units; (7) `APEC` normalization of the extra thermal component $\times 10^{-3}$; (6) fixed ("*f*") photon index of the CXB component; (9) normalization of the CXB component $\times 10^{-3}$.

Stawarz+ 2013

**Table 4**

Modeling Results for the X-Ray Spots Detected at $>5\sigma$ Level

| Source (1) | Red. $\chi^2$/dof (2) | $\Gamma$ (3) | $F_{x,abs}$ (4) | $F_x$ (5) | Red. $\chi^2$/dof (6) | $kT$ (7) | $F_{x,abs}$ (8) | $F_x$ (9) | $Z/Z_\odot$ (10) | Norm (11) | Red. $\chi^2$/dof (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| src 3 | 1.340/8 | $1.32^{+0.12}_{-0.12}$ | 29.2 | 30.4 | 0.671/51 | 32.8 | 28.3 | 29.5 | $0.3^f$ | $17.1^{+3.6}_{-2.2}$ | 0.639/52 |
| src 5 | 0.211/8 | $2.00^{+0.35}_{-0.32}$ | 6.6 | 7.3 | 1.192/30 | $4.6^{+4.7}_{-1.6}$ | 6.3 | 6.8 | $0.3^f$ | $4.77^{+0.81}_{-0.82}$ | 1.249/31 |
| src 6 | 0.395/8 | $1.89^{+0.24}_{-0.21}$ | 7.5 | 8.3 | 0.804/36 | $4.6^{+2.6}_{-1.3}$ | 6.9 | 7.4 | $0.3^f$ | $5.24^{+0.66}_{-0.67}$ | 0.788/37 |
| src 7 | 0.693/8 | $2.52^{+0.24}_{-0.23}$ | 7.1 | 8.3 | 1.020/38 | $2.1^{+0.7}_{-0.3}$ | 5.8 | 6.5 | $0.3^f$ | $6.55^{+0.69}_{-0.69}$ | 1.373/39 |
| src 8 | 0.598/8 | $1.68^{+0.14}_{-0.14}$ | 15.8 | 16.8 | 0.685/47 | $7.3^{+4.3}_{-2.1}$ | 14.9 | 15.8 | $0.3^f$ | $9.57^{+0.73}_{-0.71}$ | 0.770/48 |

**Notes.** (1) Source ID; (2) quality of a constant fit to the source light curve (reduced $\chi^2$ value/degree of freedom); (3) photon index in the PL model with 90% confidence level errors; (4) absorbed 0.5–10 keV flux of the source in the PL model, in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$; (5) unabsorbed 0.5–10 keV flux of the source in the PL model in the same units; (6) quality of the PL fit; (7) plasma temperature for the APEC model in units of keV with 90% confidence level errors (except for src 3, for which no meaningful errors could be calculated); (8) absorbed 0.5–10 keV flux of the source in the APEC model, in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$; (9) unabsorbed 0.5–10 keV flux of the source in the APEC model in the same units; (10) fixed ("$f$") abundance in the APEC fit; (11) APEC normalization $\times 10^{-5}$; (12) quality of the APEC fit.

- Due to bad statistics, it was not possible to distinguish between thermal and non-thermal
- Fit with Thermal plasma or non-thermal PL

**The FoV is filled with kT~0.5 keV thermal gas ($P_g$ ~8x10$^{-14}$)**

**Is Thermal emission has too high pressure? $n_g$ kT ~ 10$^{-10}$ $R_{1.5}^{-3/2}$**

## Materials and Methods

### Data Reduction

• Raw ACIS-I observations (Chandra proposal 14900703, cycle 14) for five regions (see Tab.1) were used for this study.

• Reduction using CIAO-4.15.1 with CALDB-4.10.4 (Fruscione+2006)

• Energy separation in Broad (0.5−7.0keV), Soft (0.5 −1.2keV), Medium (1.2 − 2.0keV), and Hard (2.0 − 7.0keV) bands.

• Identification of point sources using ***wavdetect*** (Freeman+2002) with **sigthresh = 1.23 × $10^{-8}$** corresponding to a false count rate of 1 per 81M pixels.

• Counts, flux, spectra, and light curve extraction in each energy band for individual sources using ***srcflux*** (Γ=2.0) and **%GAL** (Davis+2012) for adaptive galactic absorption) at 3σ confidence level.

## Characterization :

• Hardness Ratios: $HR_{HS}$, $HR_{HM}$, $HR_{MS}$ and X-ray colors $C_{HS}$, $C_{HM}$, $C_{MS}$ using ***BEHR*** (Park+2006).

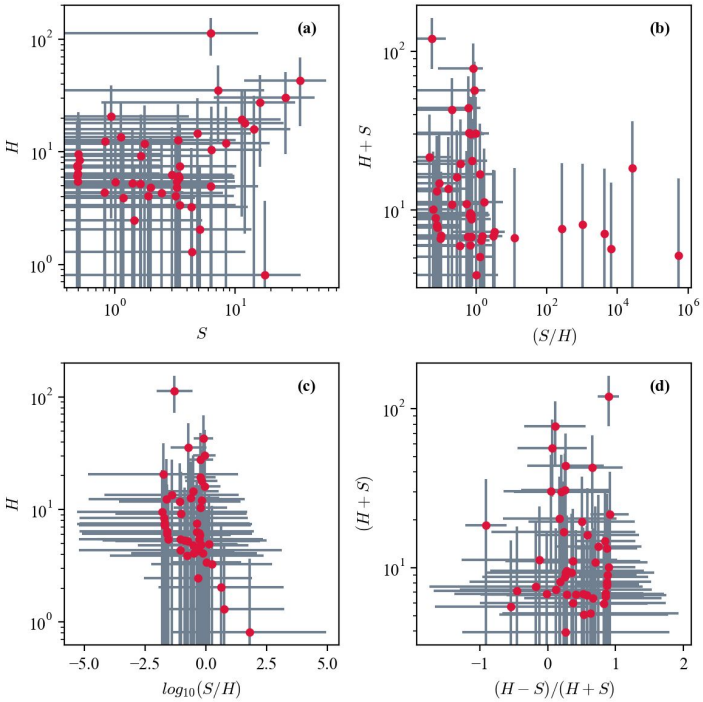
• Cross matching with *GAIA DR3*, *AllWISE*, *2MASS*, and *GALEX* for spectral energy distribution fitting to be done using CIGALE (Yang+2022)

| Region | Chandra ObsID | RA J2000 | DEC J2000 | Size W × H | Wavdetect | CSC v2.0.1 | GAIA DR3 | AllWISE |
|---|---|---|---|---|---|---|---|---|
| S1 | 15199 | 200.86 | −45.16 | 0.44° × 0.47° | 34 | 25 | 19 | 19 |
| S2 | 15200 | 200.39 | −45.14 | 0.44° × 0.47° | 41 | 31 | 17 | 25 |
| N1 | 15201 | 201.47 | −38.94 | 0.45° × 0.54° | 52 | 37 | 13 | 29 |
| N2 | 15202 | 201.78 | −39.76 | 0.46° × 0.54° | 40 | 24 | 11 | 21 |
| N3 | 15203 | 201.16 | −39.31 | 0.72° × 0.42° | 47 | 29 | 11 | 30 |
| Totals | | | | | 214 | 146 | 71 | 124 |

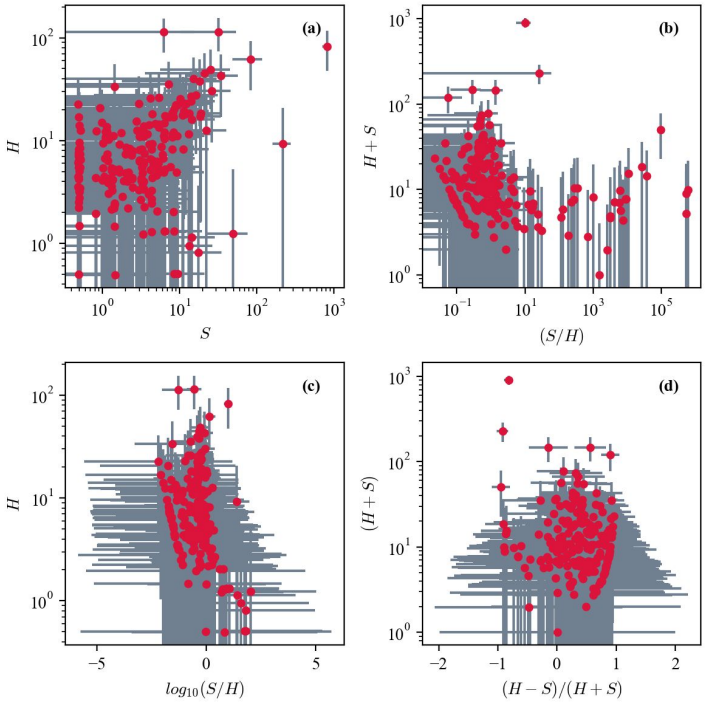
No counterparts in GALEX AIS 5+6

# Hardness Ratio

15203 N3




Combined



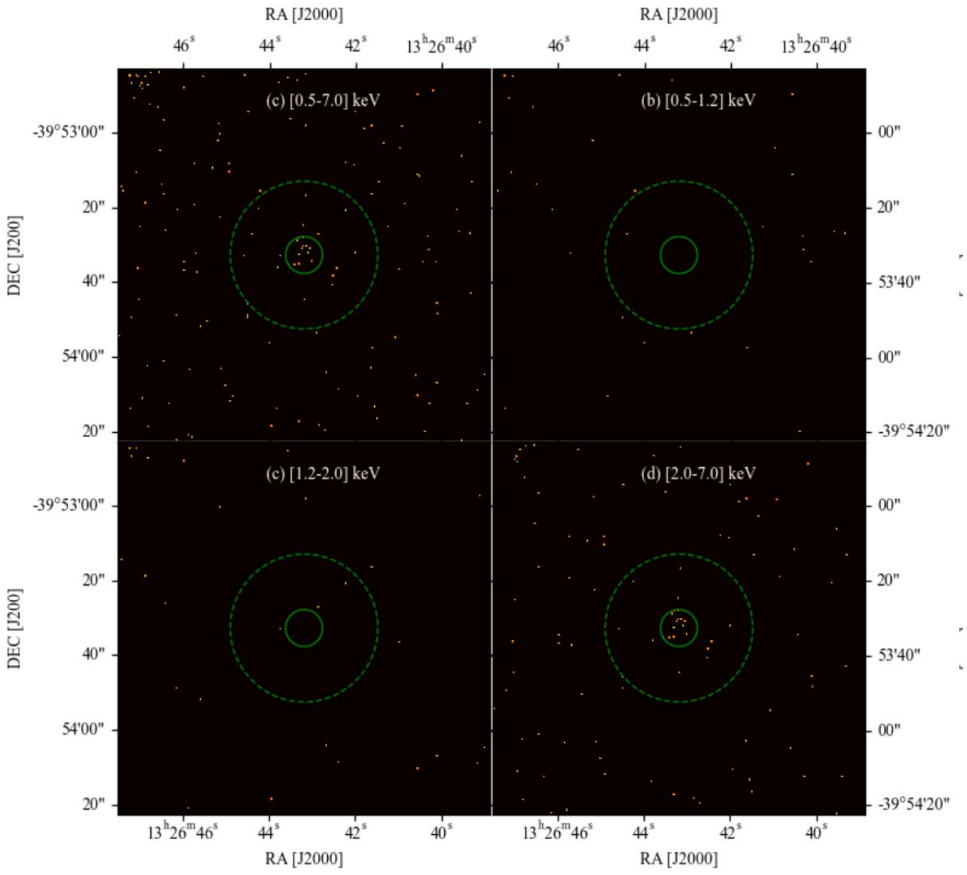
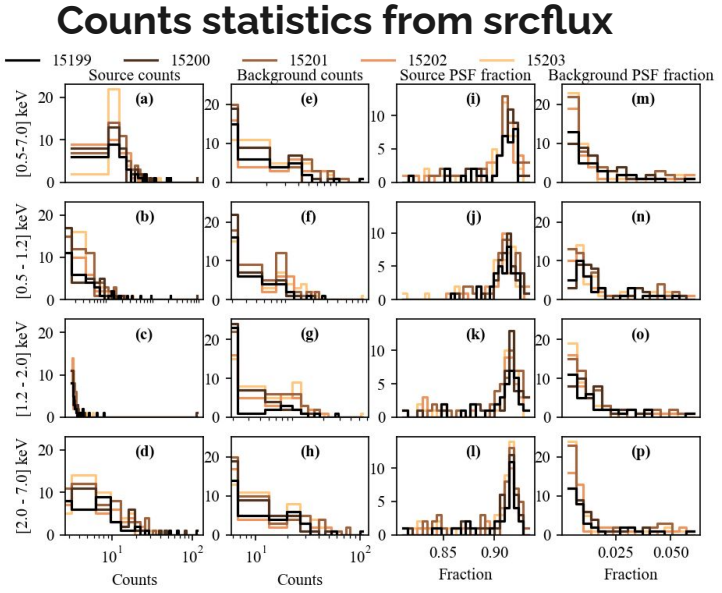



**Figure 2:** An example of a hard X-ray source at $13^h26^m43.19^s$, $-39°53^m m32.69^s$ identified in N2.

- A wide variation of low count and band-specific sources. See Fig.2 for a hard X-Ray source.
- The counts statistics for the five regions in the Broad, Soft, Medium and Hard bands $3\sigma{\sim}99.73\%$ confidence levels are shown in Fig.3. The GRL are a low X-ray count region, with a few notable exceptions appearing in the soft and hard bands.
- The hardness ratios for the region S1 are shown in Fig. 4. The significant population of purely hard sources contribute to the top left and bottom right of the panels (a) and (b).



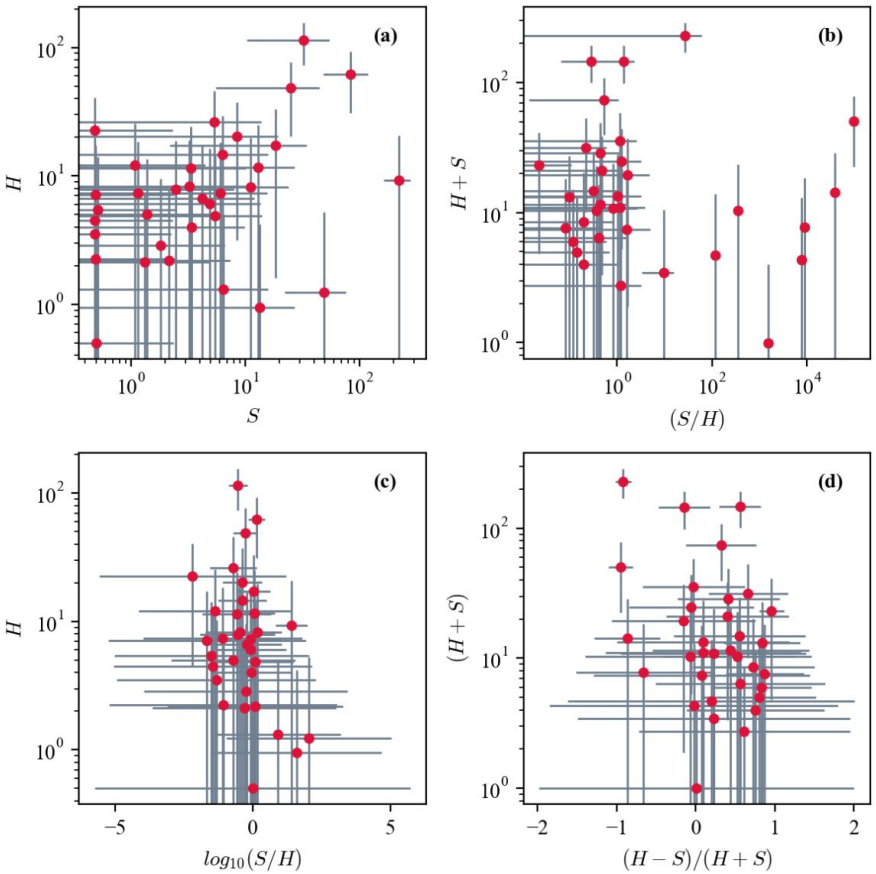



**Figure 4:** Hardness ratios and color diagrams for the sources in the S1 region at $3\sigma$ confidence level.

# SUMMARY

1. We present a consolidated **pipeline** to identify and ***characterise point like sources*** in arbitrarily large-scale studies of Chandra observations.

2. We find the GRL to be a ***low X-ray count region***, with slightly higher emissions in the sparse **northern lobes** for **soft X-rays**, with the **southern lobe** contributing more to the **hard X-rays**.

3. *Higher photon counts above 3 keV* could possibly be influenced by ionisation or non-thermal processes. (**L. Stawarz +13**)

4. Possible identification of previously undiscovered sources, characterisation in progress.

# Currently, looking for positions

## Research Experience

| | |
|---|---|
| Aug 2022 – July 2023 | **Postdoctoral Fellow**, *National Tsing Hua University, Taiwan*, with the supervision of Dr. Hsiang-Kuang Chang. |
| Dec 2021 – | **Associate**, *Astronomical Observatory of the Jagiellonian University, Kraków Poland.* |
| Oct 2016 – Nov 2021 | **Ph.D. in Exact and Natural Sciences of Astronomy**, *Astronomical Observatory of the Jagiellonian University, Kraków Poland.* <br>○ "***Fluorescent Iron Lines in Various Types of Radio-Loud Active Galactic Nuclei***" under the supervision of Dr hab. Łukasz Stawarz and co-advisor Dr. Volodymyr Marchenko. |
| Apr 2015 – Jun 2016 | , ***M.Sc. Project***, Indian Institute of Astrophysics, India. <br>under the supervision of Dr F.K. Sutaria and Dr Subinoy Das, Indian Institute of Astrophysics, India ***"Unidentified Emission line in Stacked X-ray spectra of Dwarf galaxies , looking for Dark matter candidates"***. |
| Jan 2014 – Sept 2014 | , ***Visiting Intern Student***, Indian Institute of Astrophysics, India. <br>***"Dynamic Loading Assembly for Performance Testing of Segmented Mirror Telescope Actuator"*** Worked under the supervision of Dr Padmakar Singh Parihar . |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1. K. Balasubramaniam et al in prep.( 2023) : ***Giant Radio Lobes of Centaurus A, Studied with the Chandra X-ray Observatory***

2. K. Balasubramaniam et al in prep.( 2023) : ***Black Hole Spins in AGNs: A Systematic Perspective***