

X-ray imaging of relativistic shock in Pictor A galaxy

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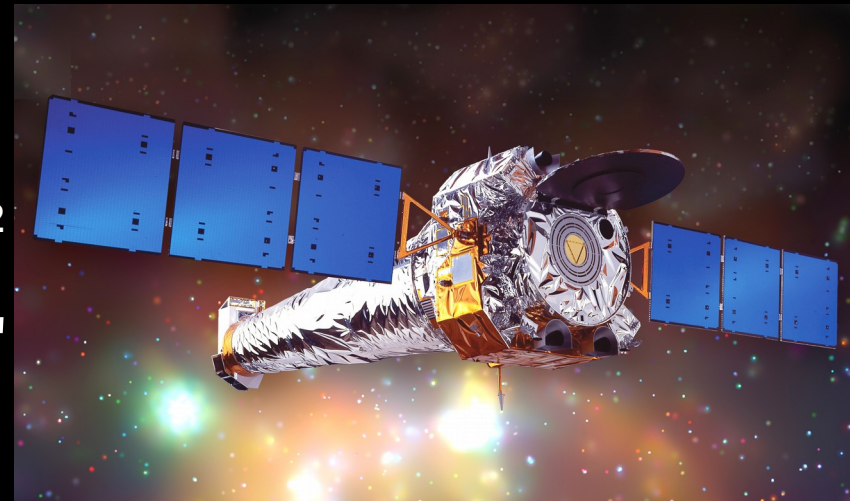
X-ray imaging of relativistic shock in PicA galaxy

- **Introduction**
- **Analysis**
- **Results**
- **Conclusion**

Introduction

Chandra X-ray Observatory (CXO)

- Launched in July 1999
- Energy Range: **0.1–10 keV**
- Effective Area:
ACIS-I ~500 cm²; HRC-I ~225 cm²
- FOV: **ACIS-I 16' X 16'** & **HRC-I 30'X30'**
- Energy Resolution:
 $E/\Delta E$ 20-50 at 1 keV
- Angular Resolution **< 1"**



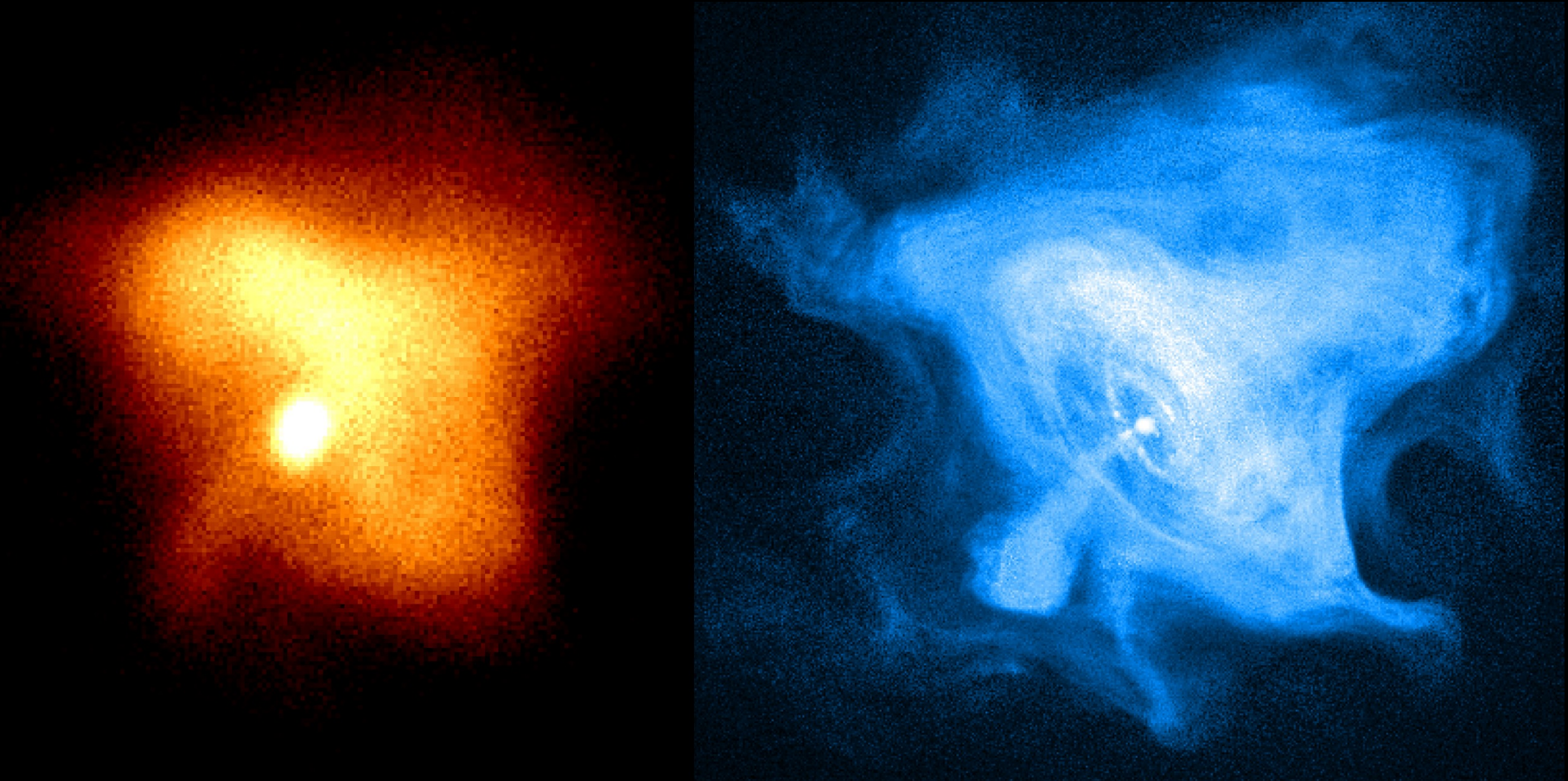
Credit: <https://svs.gsfc.nasa.gov/>

Introduction

Chandra X-ray Observatory (CXO)

- Very sensitive to observe X-ray sources in the extended regions of the galaxy
- Goes 1/3 of the way to the Moon
- every 64 hours (2 ½ days)
- CXO– operated by Chandra X-ray Center (CXC) at the Center for Astrophysics (Cambridge, MA) in collaboration with MIT

Introduction



Credit: Crab Nebula - ROSAT: S. L.Snowden USRA, NASA/GSFC &

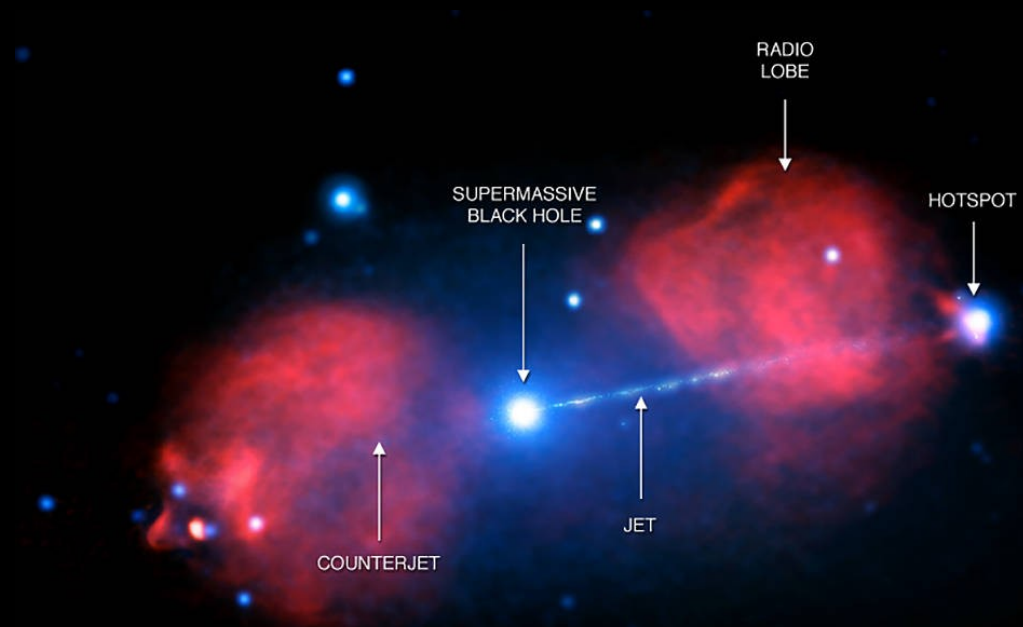
Crab Nebula - Chandra: NASA/CXC/SAO/F.Seward et al

- **Left: HR Image on the Rontgen satellite (Rosat); Right: ACIS on Chandra.**
- **Details-rings and jets in the region around the pulsar, valuable information for understanding how the pulsar transmits energy to the nebula.**

Introduction

Pictor A ($z=0.035$)

- One of the most prominent FR II type radio galaxy, located nearly 153 Mpc from the earth.
- Discovered & named by Stanley and Slee (1950).



Credit : X-ray: NASA/CXC & Radio:CSIRO/ATNF/ATCA

- Its total angular extension of $\sim 8'$ (Perley et al. 1997).

Introduction

- **The jet in Pic A is the continuous X-ray emission over a distance of 175 kpc.**
- **Pic A's relative proximity and Chandra's ability we can make detailed X-ray images.**
- **Detailed features of the jet, core, hotspots, lobes**

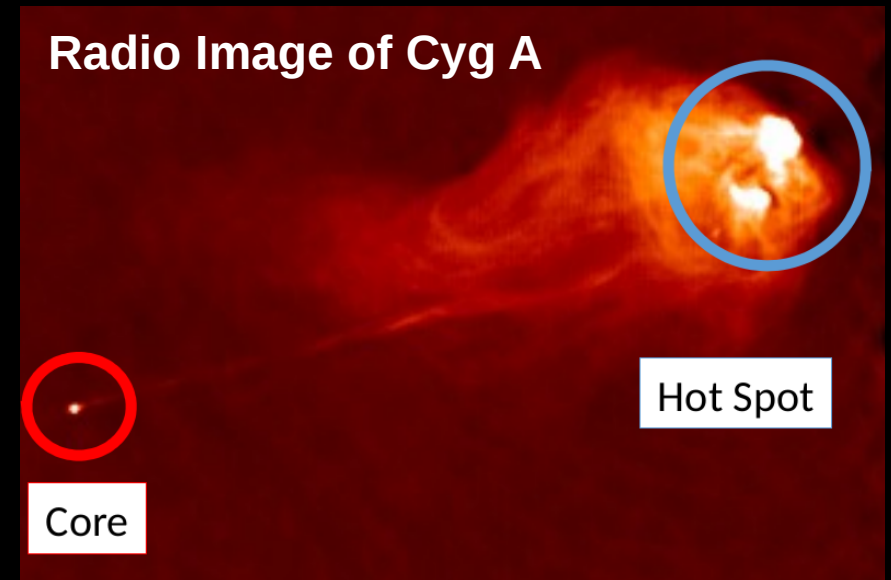
Structures of AGN Jet

- AGN jets have several structures.

Knot

Hotspot

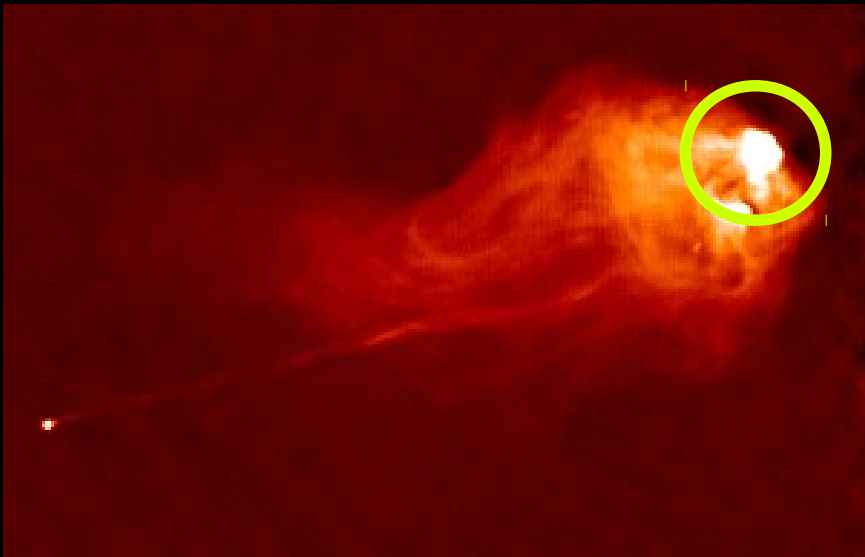
Radio lobe



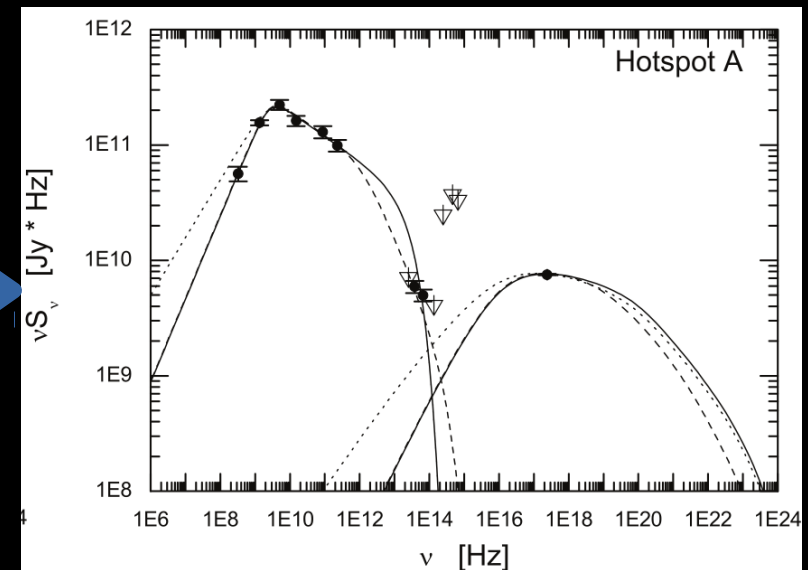
- In a hotspot, there are relativistic electrons accelerated in a shock region where the jet interacts with ICM.
- In the hot spot, there is not a simple point source but complex structures.

Radiation in Hotspot

- Hotspot has a broad-band radiation from radio to X-ray bands.



Multi-wavelength Spectrum



Stawarz+ 2007

- Low energy : Synchrotron radiation
- High energy: Inverse-Compton radiation

Analysis

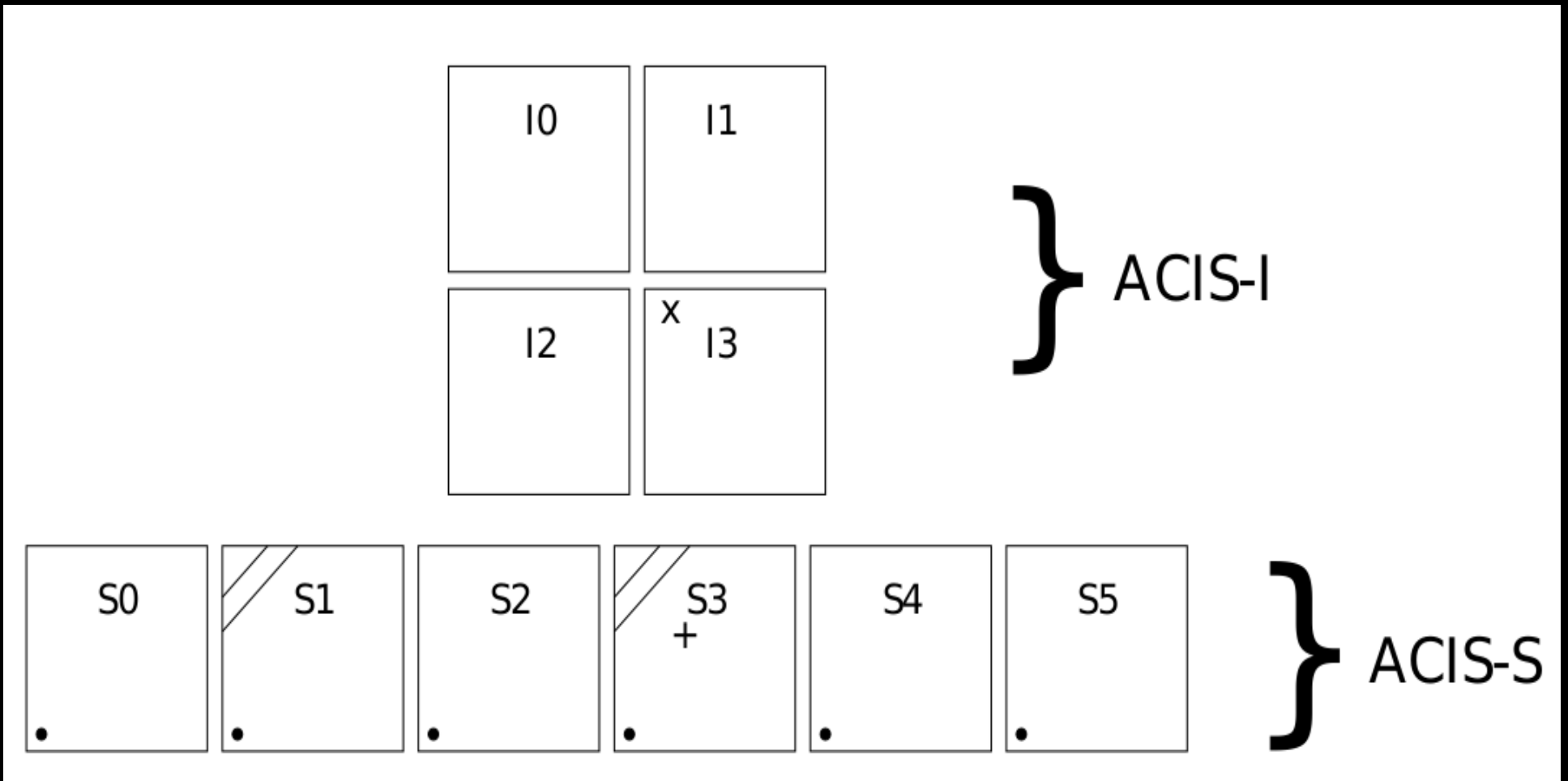
We focused on the W hotspots (WH) of Pictor A.

Obs. ID	Date	Exposure (ks)	Pointing	Satellite roll (deg)	Epoch
346	2000-01-18	25.8	Core	322.4	1
3090	2002-09-17	46.4	W hotspot	88.1	2
4369	2002-09-22	49.1	W hotspot	88.1	2
12039	2009-12-07	23.7	Jet	3.2	3
12040	2009-12-09	17.3	Jet	3.2	3
11586	2009-12-12	14.3	Jet	3.2	3
14357	2012-06-17	49.3	Jet	174.3	4
14221	2012-11-06	37.5	Jet	36.2	5
15580	2012-11-08	10.5	Jet	36.2	5
15593	2013-08-23	49.3	Jet	110.5	6
14222	2014-01-17	45.4	Jet	322.6	7
14223	2014-04-21	50.1	Jet	232.7	8
16478	2015-01-09	26.8	Jet	315.2	9
17574	2015-01-10	18.6	Jet	315.2	9

Data collected spanning over 15 years about 464 ks

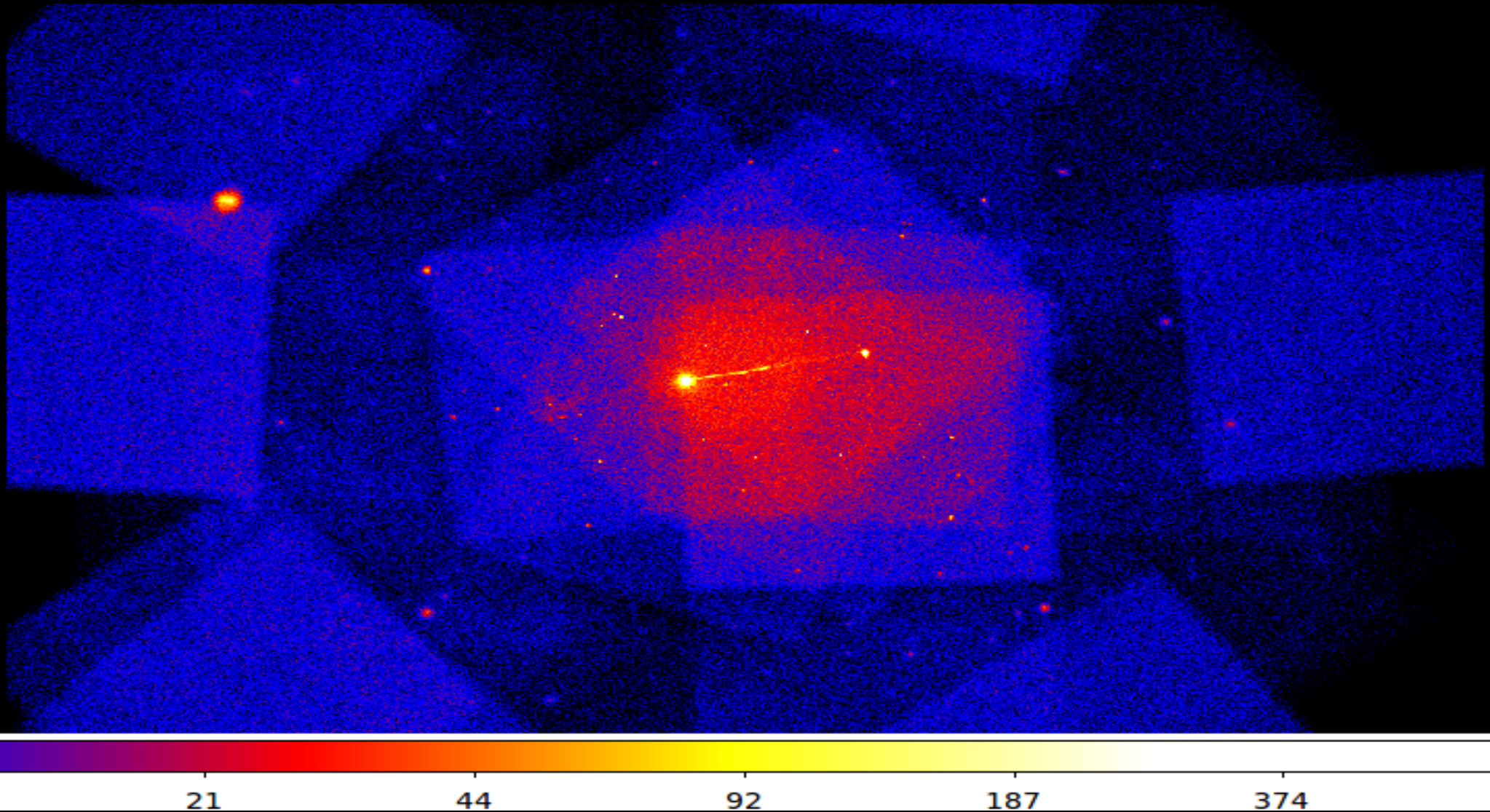
Analysis

ACIS Layout



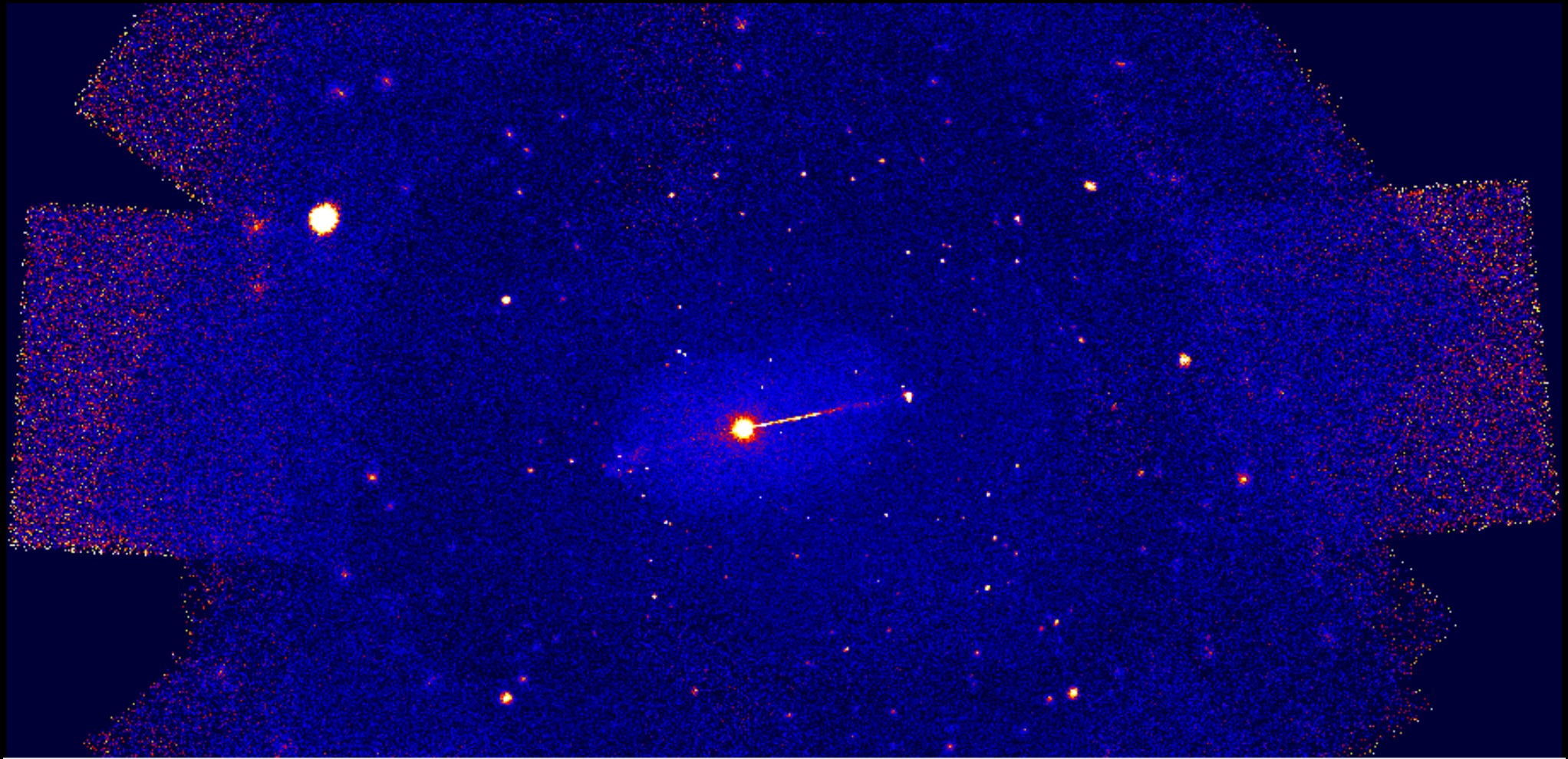
Analysis

Merged Chandra image of Pictor A



Analysis

Exposure-corrected image of Pictor A



5.93e-08

1.39e-07

2.97e-07

6.15e-07

1.24e-06

2.50e-06

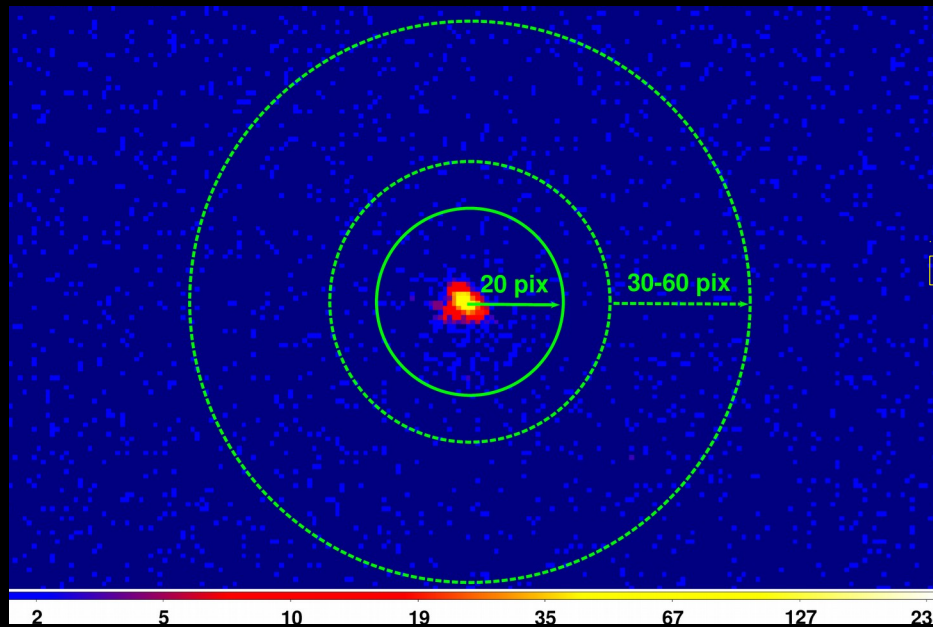
5.02e-06

Analysis

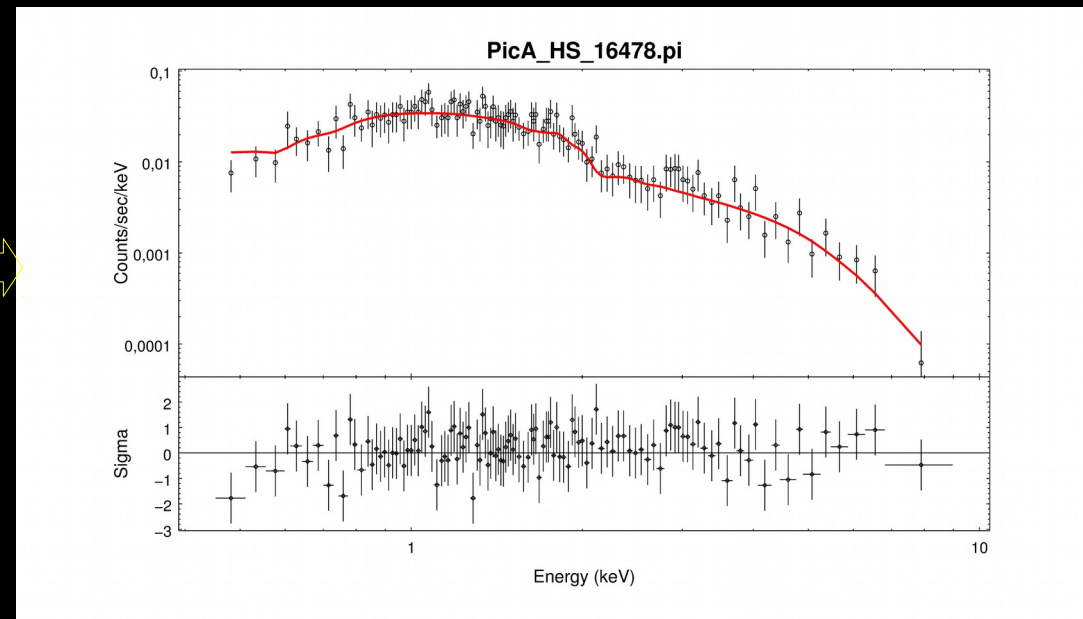
Chandra Interactive Analysis of Observations (CIAO)

Spectra extracted for the source (wh) region .

Source & background region



model - broken power law



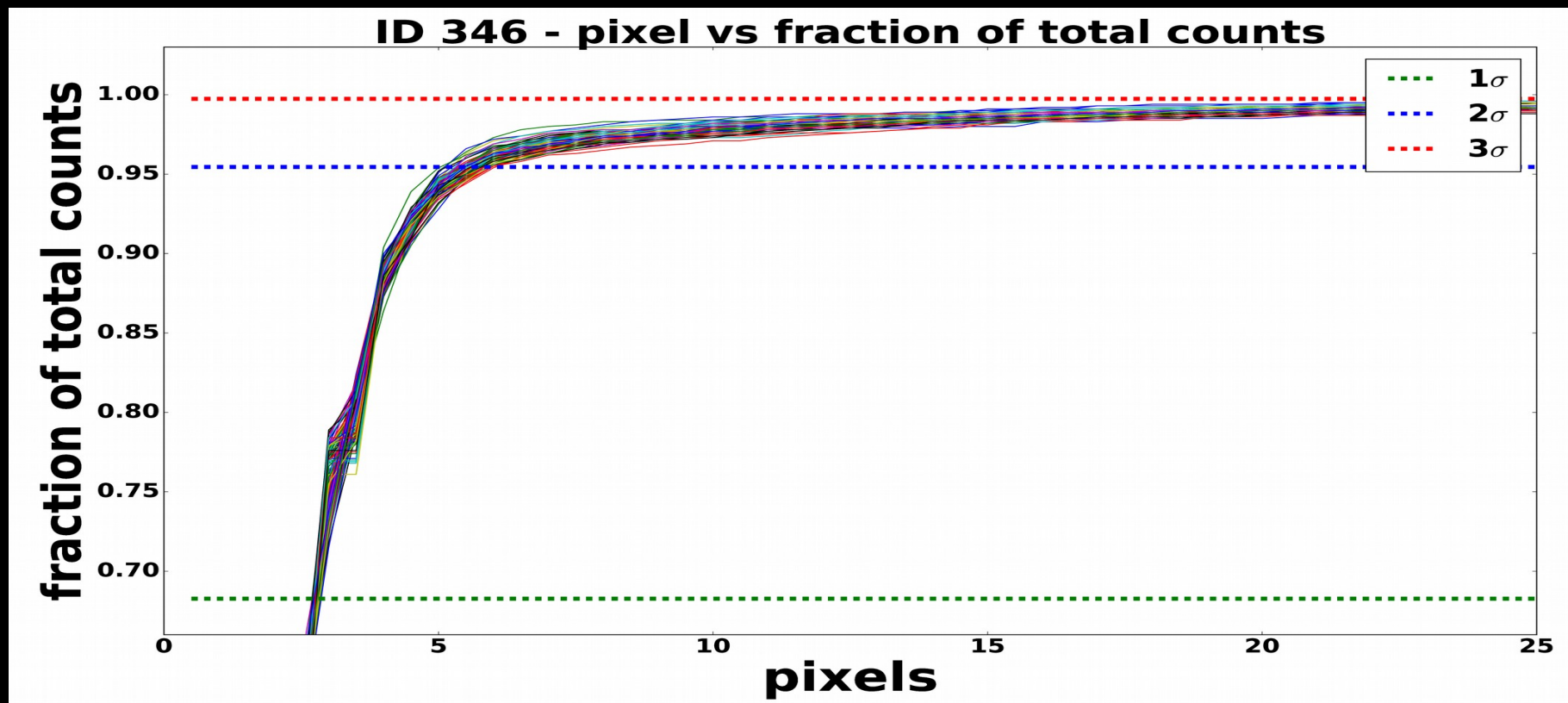
X-ray spectrum of the western hotspot of Pictor A for ID 16478 (scale : log-log)

Analysis - ChaRT

- **ChaRT** tool is the best available PSF for a point source at any off-axis angle and for any energy or spectrum.
- It needs the **coordinates, spectrum, and telescope aspect solution.**
- The Chandra PSF varies significantly across the field of view. It goes from sub-arcsec FWHM near the optical axis to over 100 arcsec at the extreme edges of the detectors.
- The location of the source can be entered in either celestial coordinates, RA and Dec or in Chandra off-axis angle, θ and ϕ .

Analysis

- **ChaRT + marx** simulations show the data at different aspects of the Chandra PSF.
- A different way to present the width of the PSF is the **encircled count fraction**.

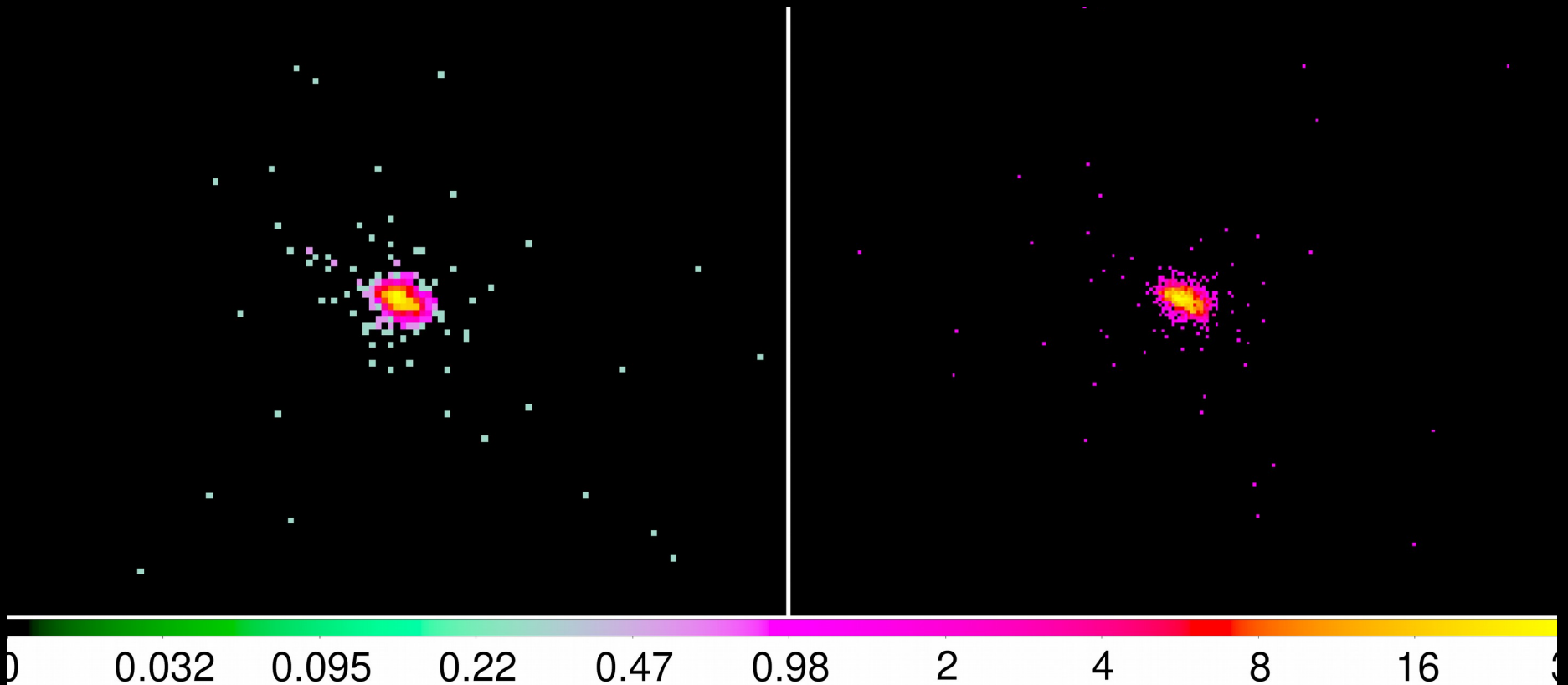


Analysis

ChaRT & MAR tools produced **PSF images**.

pixel

sub-pixel



Analysis

Image Deconvolution

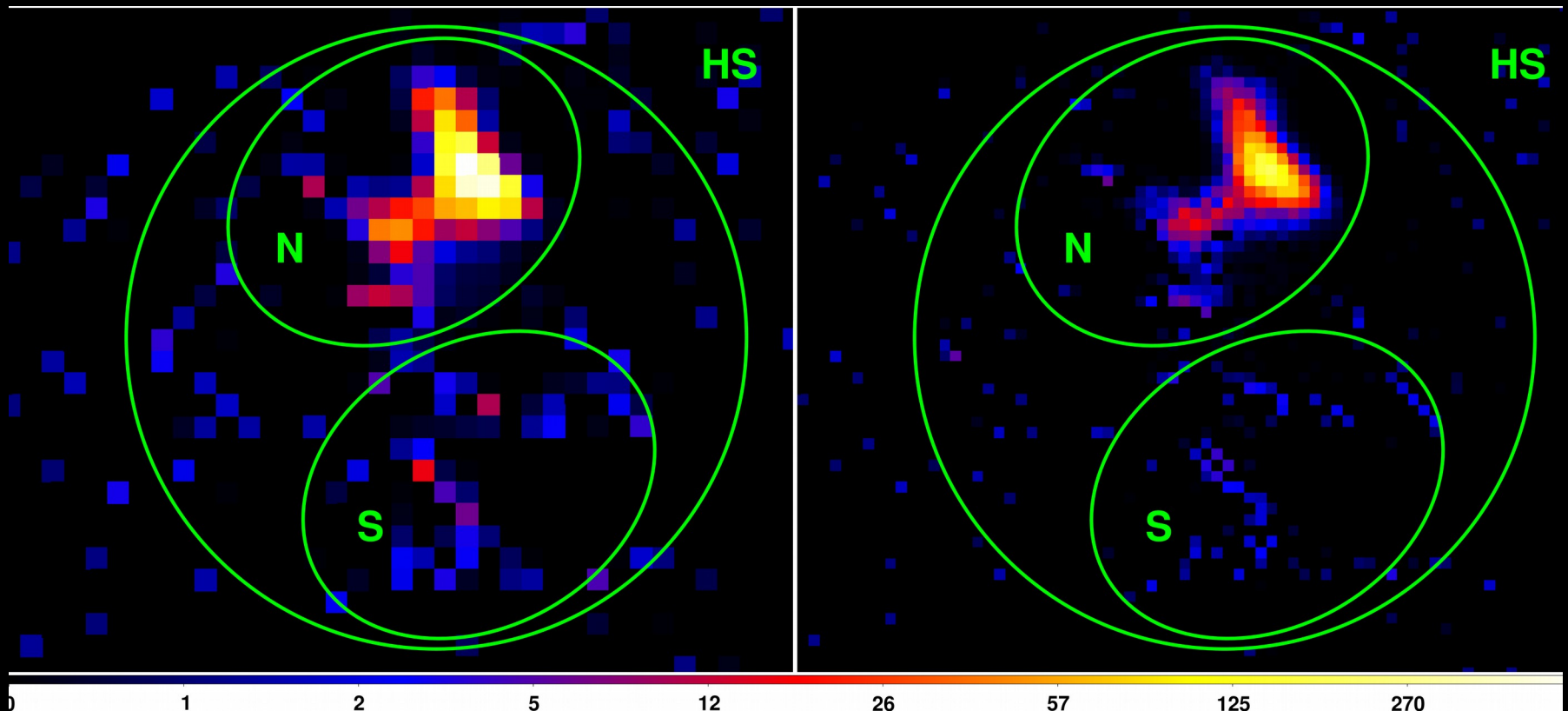
- CIAO provides Lucy-Richardson via **arestore**
- This deconvolution algorithm developed by the Richardson Lucy.
- The Lucy-Richardson method (**method=lucy**) performs well for bright point sources.

Results

Deconvolution image (HS, N & S): ObsID 346

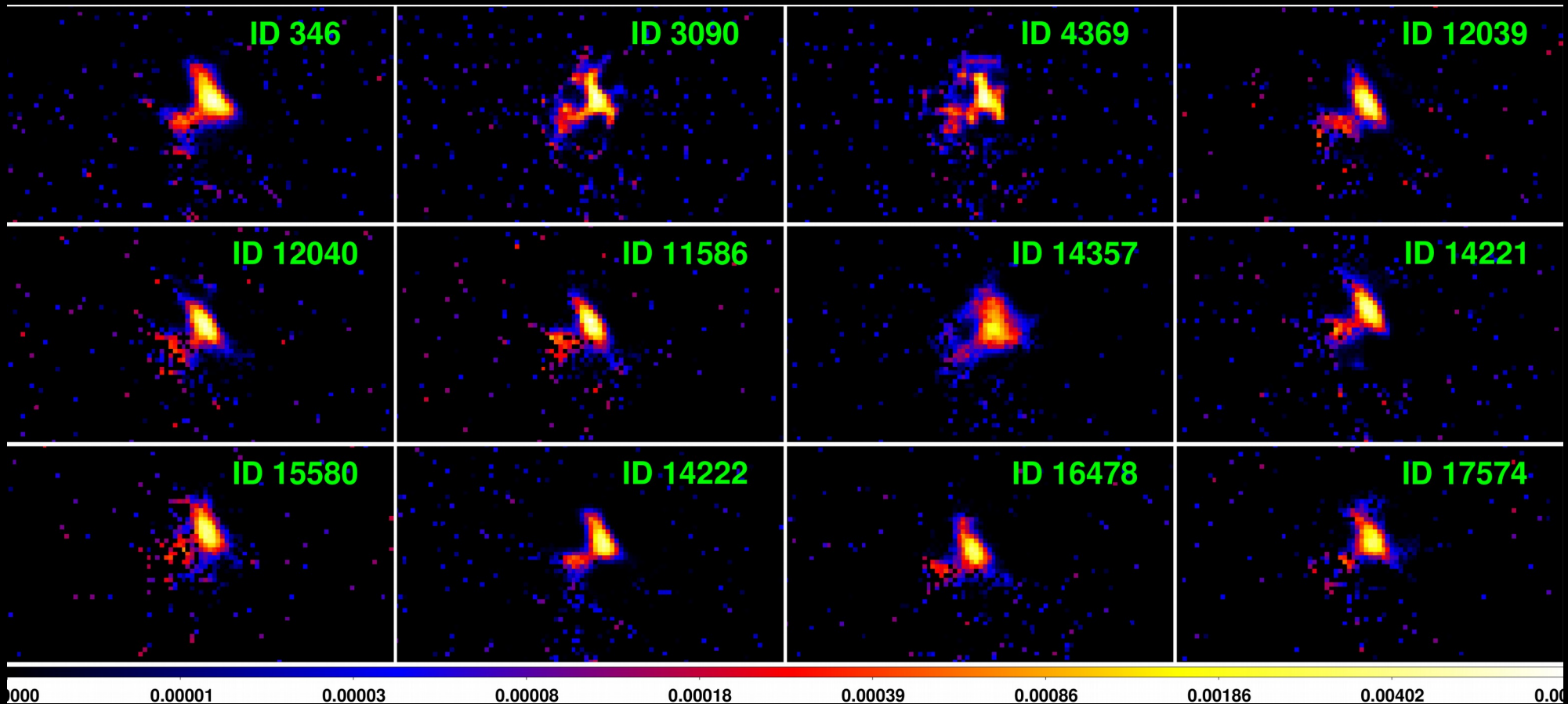
1 pix

0.5 pix



Results

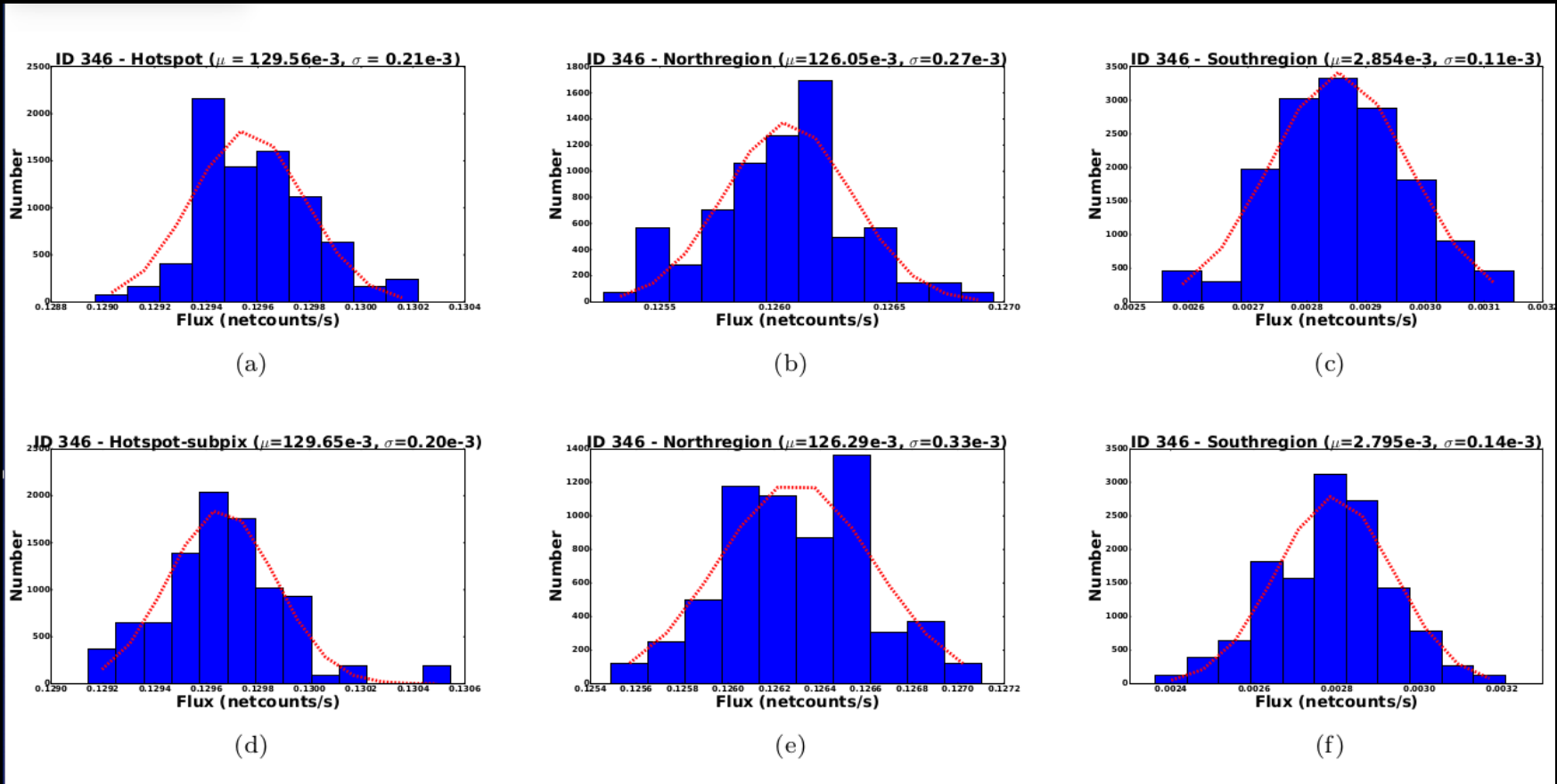
Deconvolution image : sub-pixel



Results

Histogram of HS, N & S region : ObsID 346

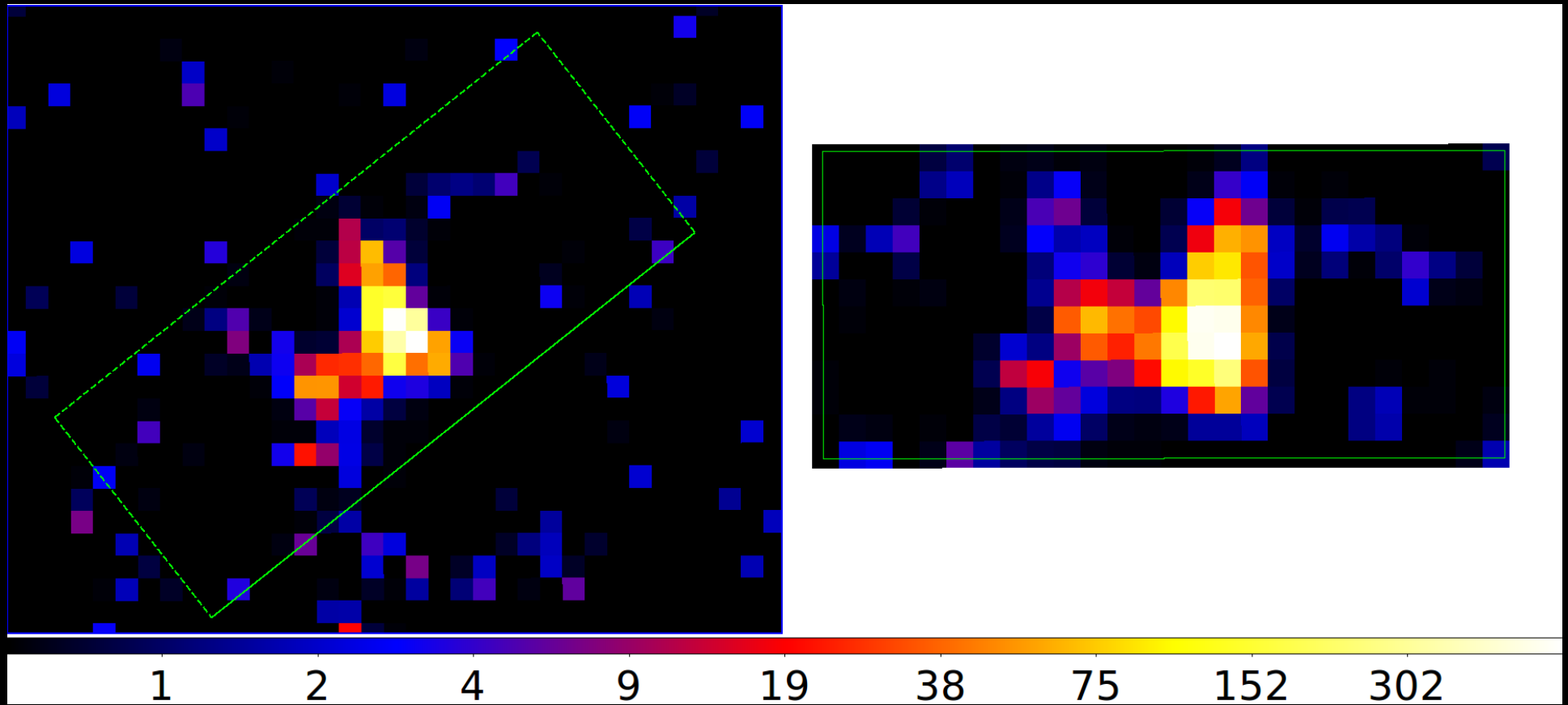
1 pix



0.5 pix

Results

Projection area of hotspot

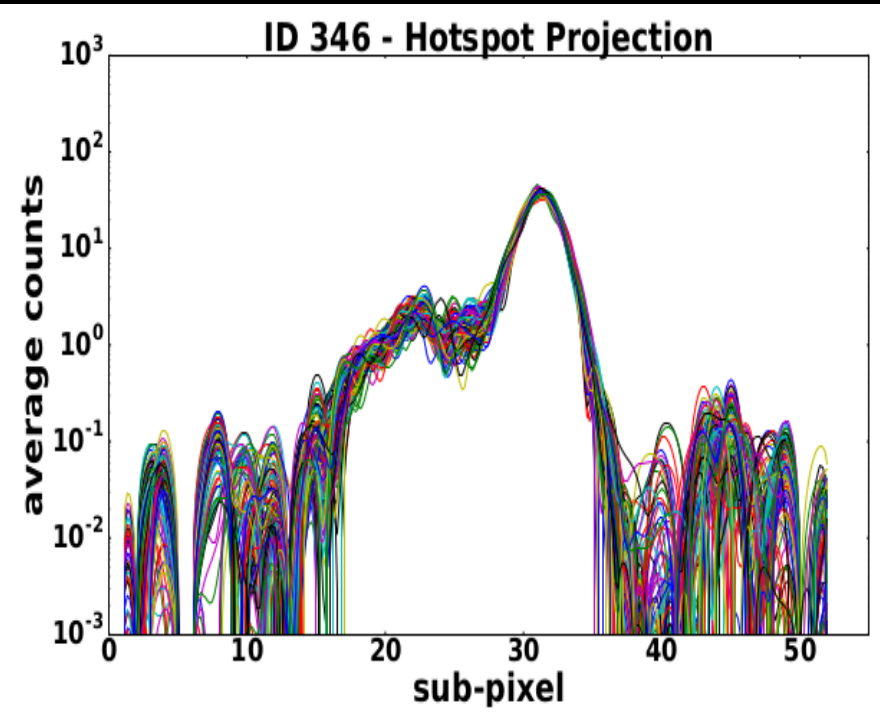
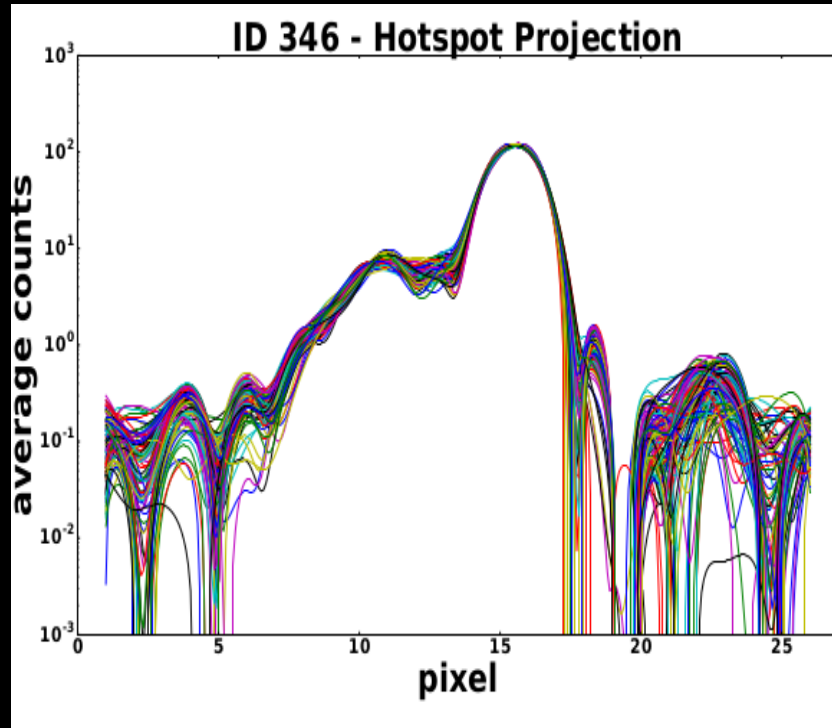


Results

Projection area of hotspot : ObsID 346

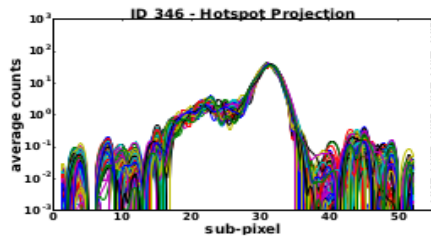
1 pix

0.5 pix

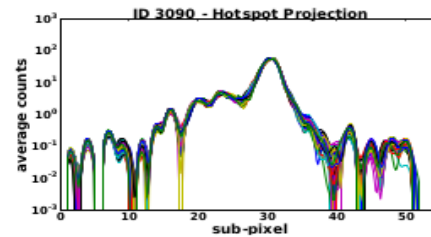


Results

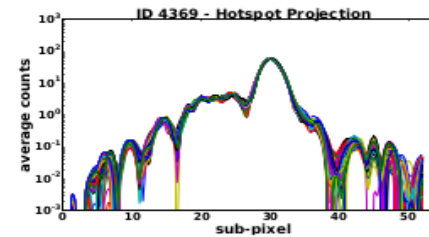
Projection area of hotspot : sub-pixel



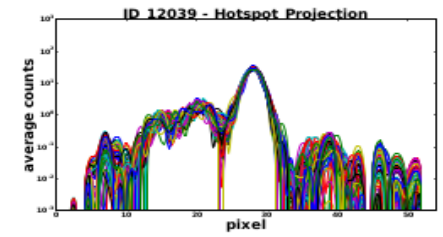
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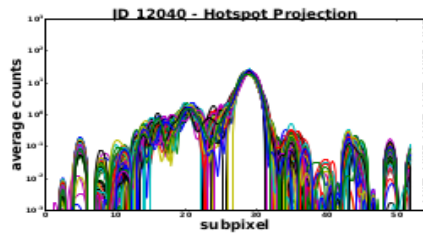
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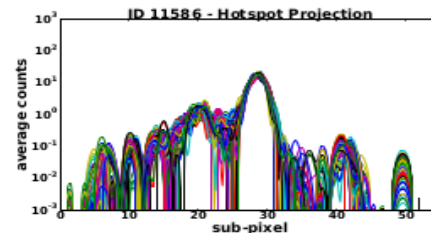
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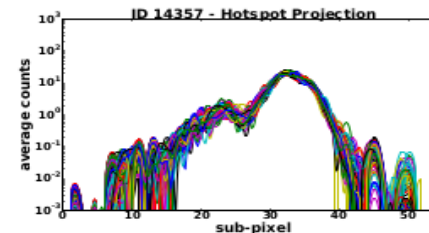
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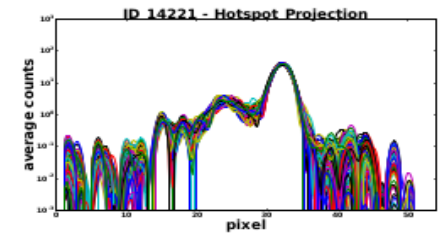
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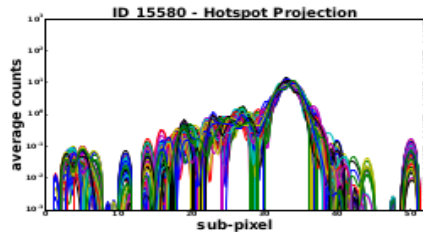
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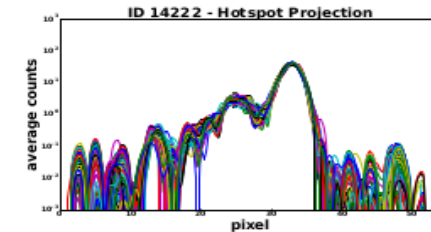
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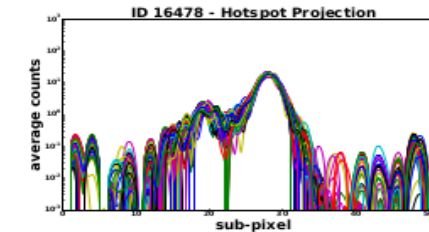
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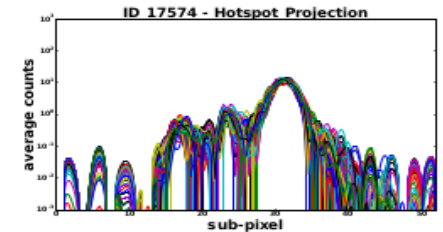
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ID 14222

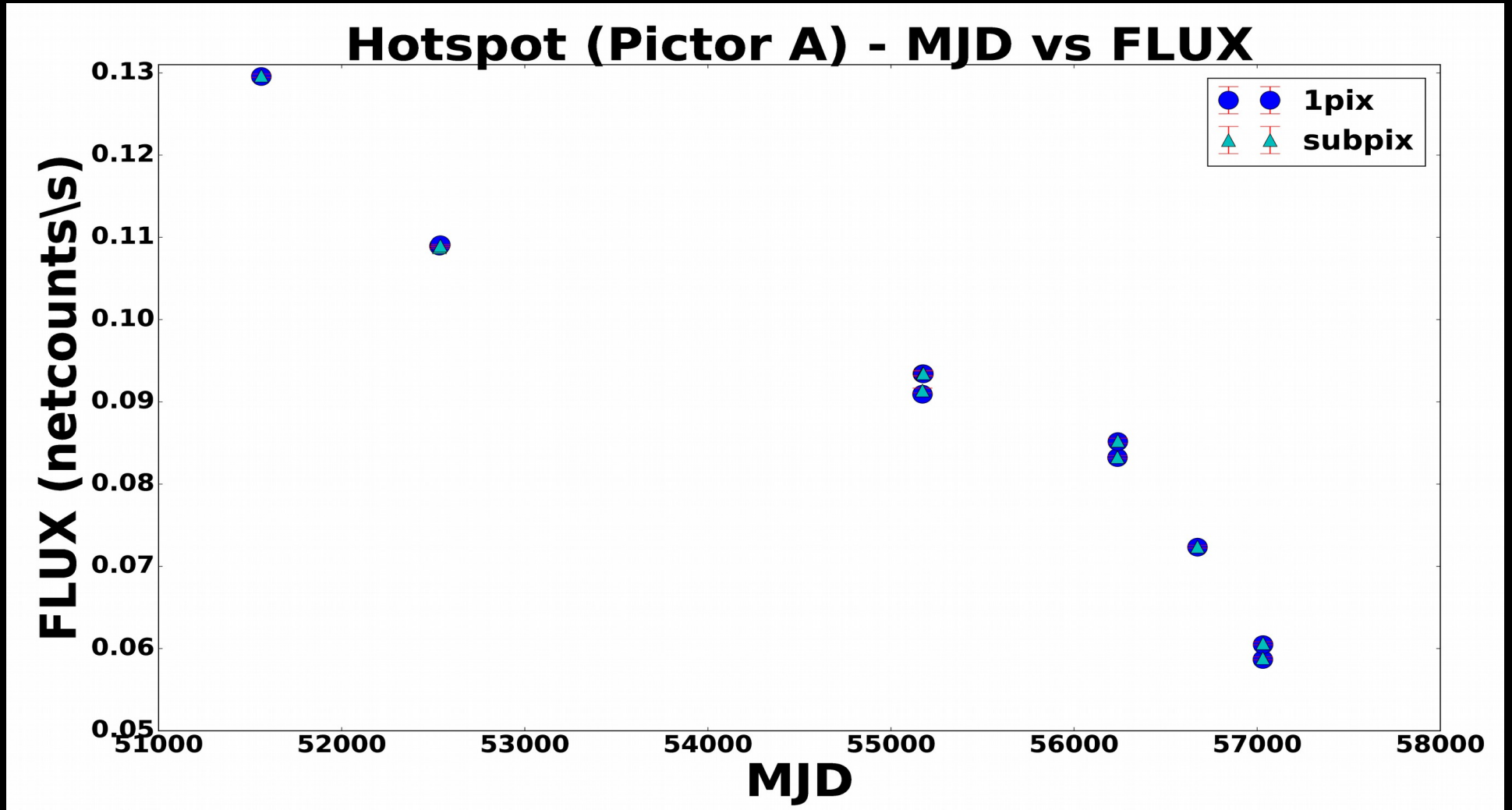


ID 16478



ID 17574

Results



Conclusion

- **We confirmed a variability of the X-ray emission of the Western hotspot in Pictor A on the timescale of several years.**
- **The observed flux changes are unexpected, since the spatial extension of the terminal shock, of the order of kpc, would imply the variability timescale of the order of thousands of years.**
- **Our finding suggests therefore relativistic shock, and this has profound consequences for understanding acceleration of high-energy particles in the astrophysical environment in general.**
- **Our next step is to perform a detailed spectral analysis of the X-ray emission in the hotspots.**
- **We also extend our analysis to extended lobes and AGN of Pic A.**

Resources

- **PSF Central**

http://cxc.harvard.edu/ciao/PSFs/psf_central.html

- **Calibration web site**

<http://cxc.harvard.edu/cal/>

- **Calibration Workshop Presentations**

<http://cxc.harvard.edu/ccr/>

- **CIAO Imaging Threads and Guides**

<http://cxc.harvard.edu/ciao/threads/imag.html>

- **CXC Help Desk**

<http://cxc.harvard.edu/helpdesk/>

- **WebChaser**

<http://cda.harvard.edu/chaser/>

- **Chandra Data Archive bibliography search**

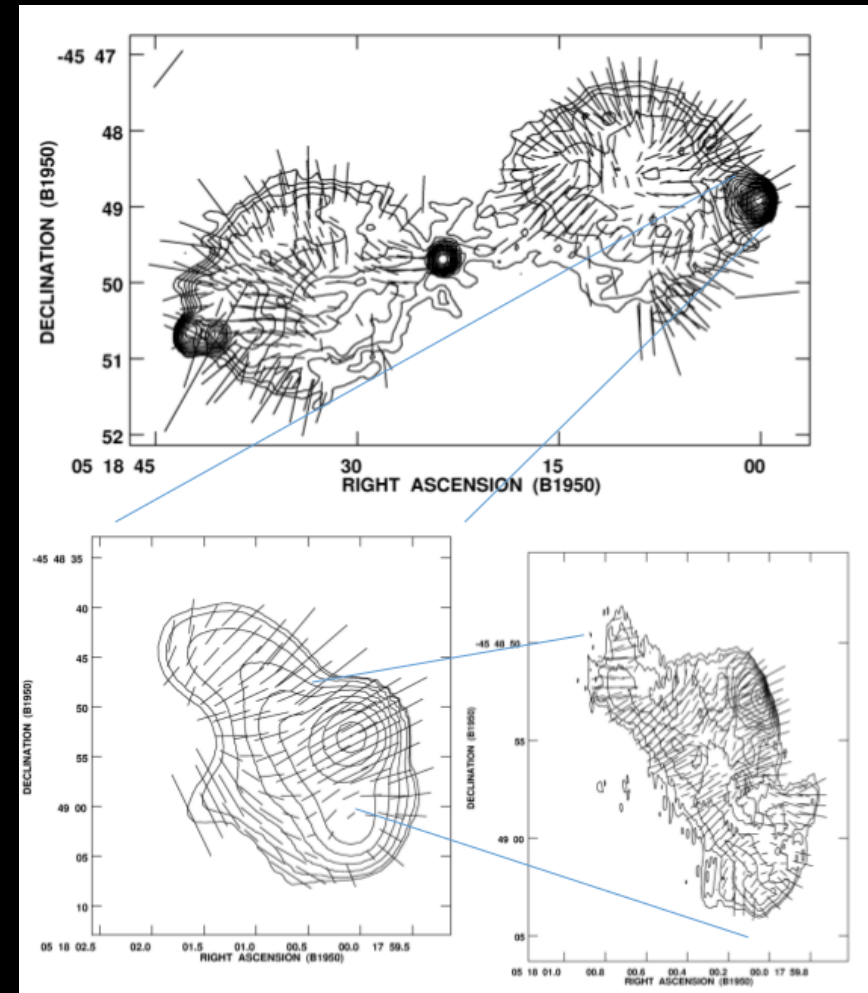
<http://cxc.harvard.edu/cgi-gen/cda/bibliography>

Thank You

Discussion

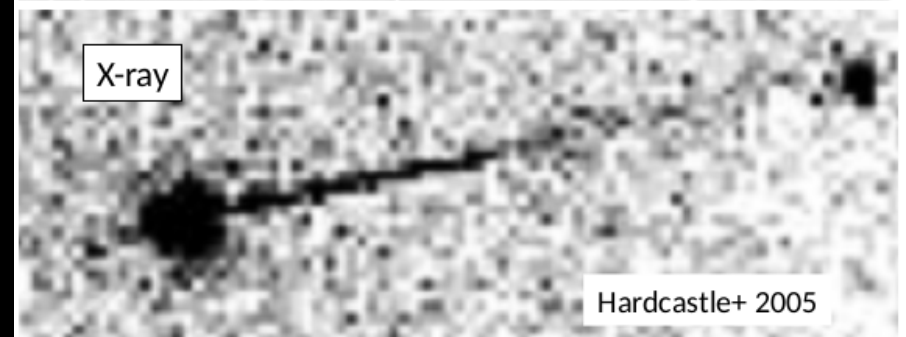
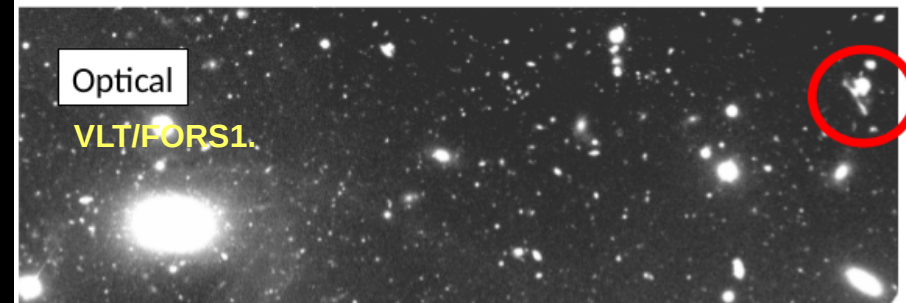
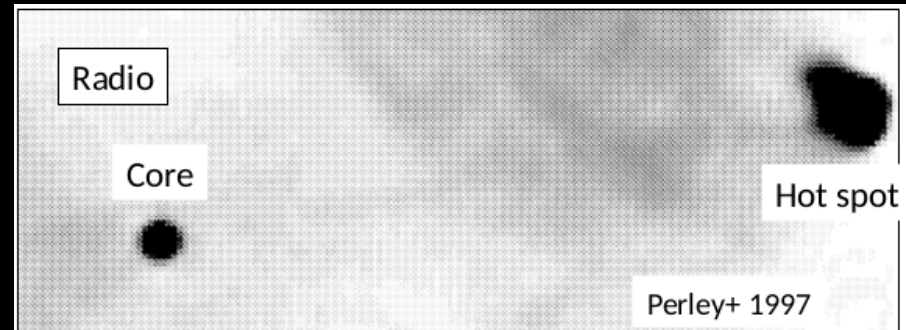
Polarization in Pictor A

- One of the most famous FR II type radio galaxies.
- There are two-side radio jets, hot spots in terminals of the jet, and radio lobes.
- There is a highly polarized emission in the western hot spot (WHS); 30%-60%.
- The emission is polarized parallel to the jet direction.
- Detected polarizations are distributed perpendicular to the radio lobe.



Multi-Wavelength Images

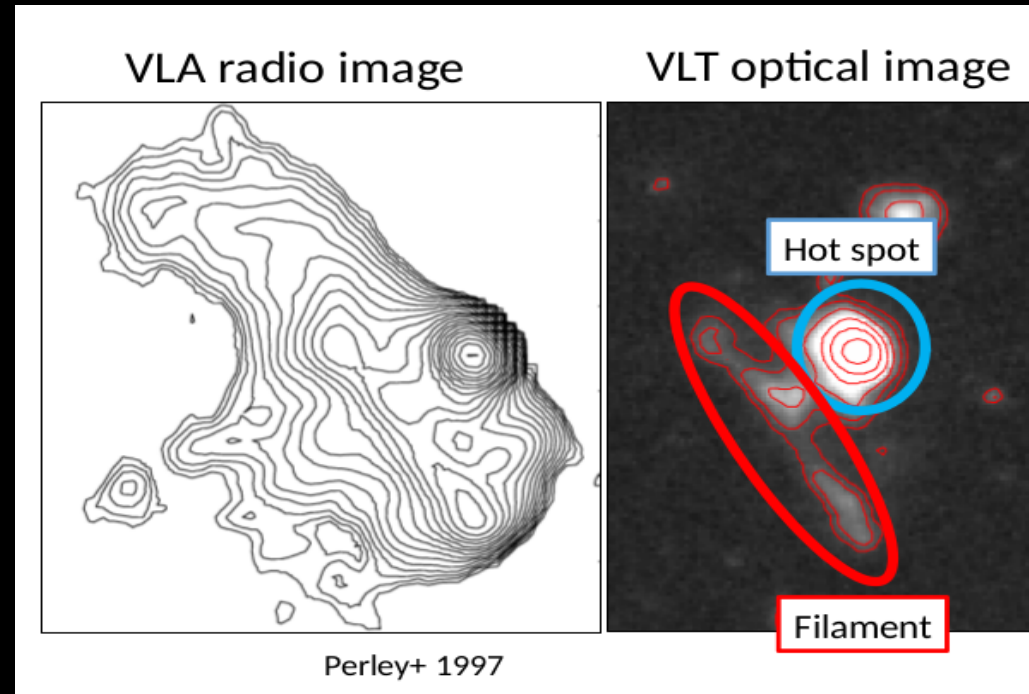
- Radio, optical and X-ray images of Pictor A.
- The WHS of Pictor A is bright in the radio, optical and X-ray bands.
- There is a distinct jet knot in the X-ray band.



Optical and Radio Images

- There are extended structure in the WHS of Pictor A in the radio and optical bands.

- Hot spot
- Filament



- The hotspot is 10 times Brighter than the filament.
- There is more effective particle-acceleration and cooling in the hotspot.