

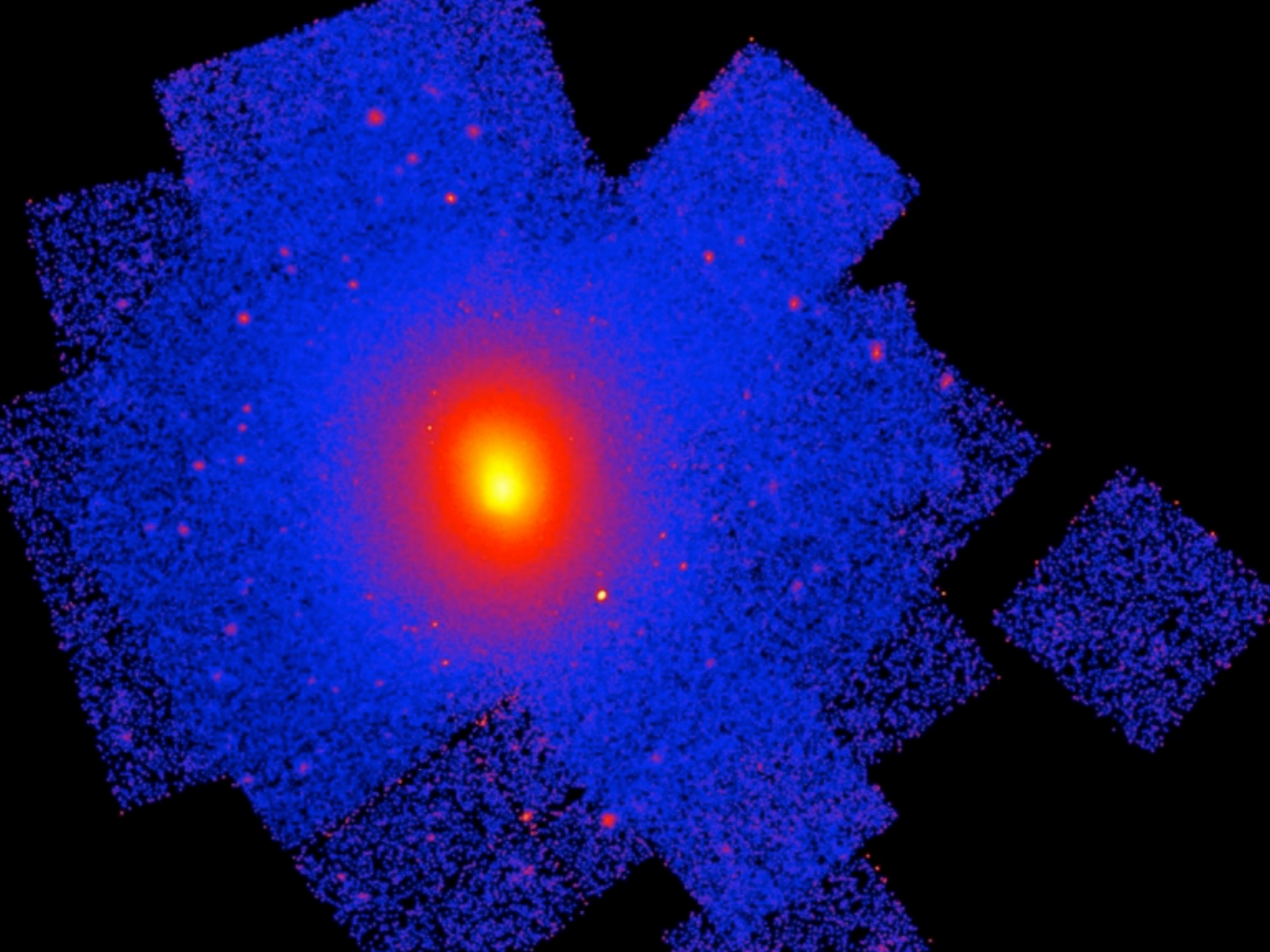
X-ray Imaging

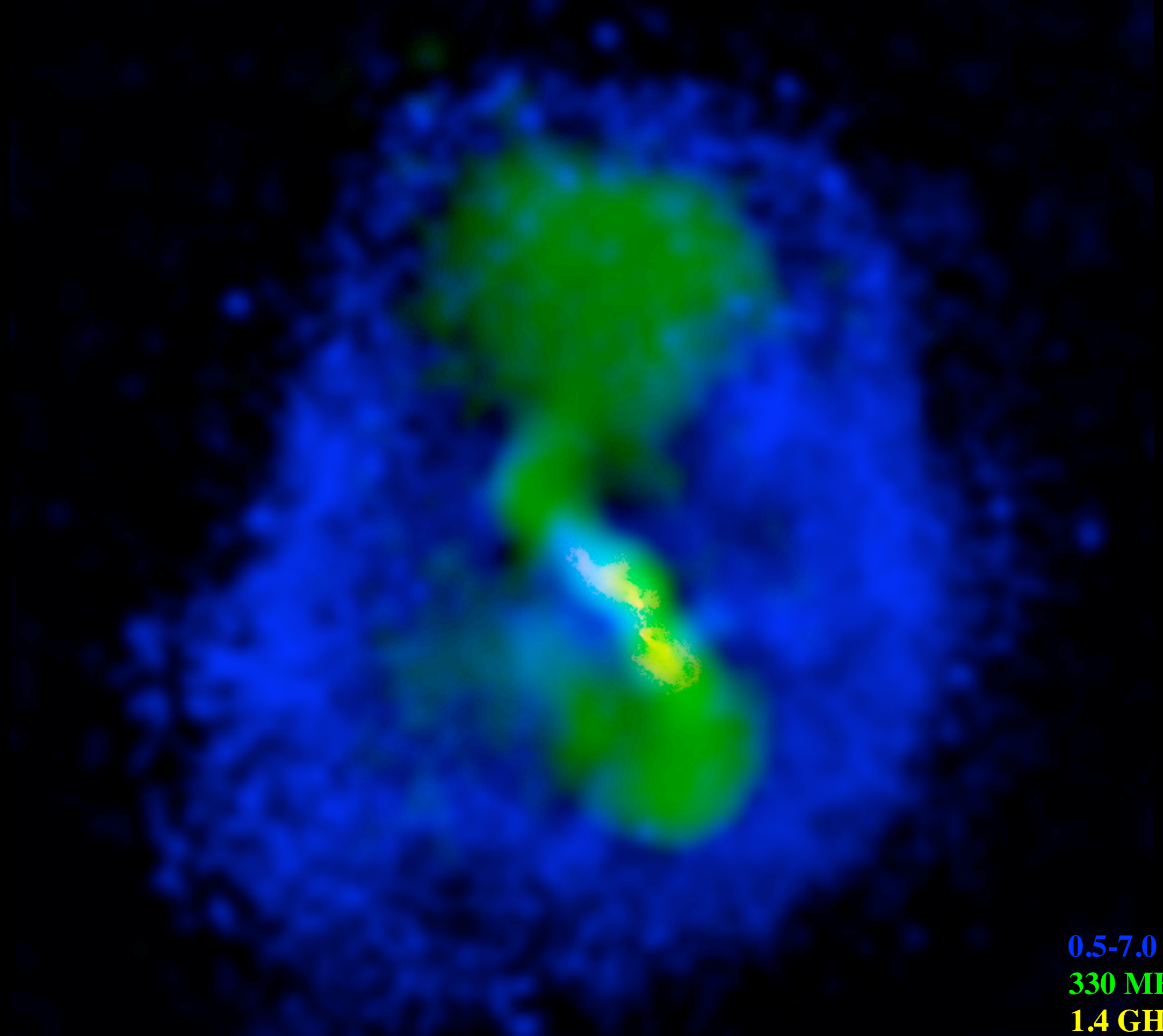
2nd School on Multi-wavelength Astronomy

06 July 2010

Michael Wise

ASTRON / LOFAR / UvA





0.5-7.0 keV
330 MHz
1.4 GHz



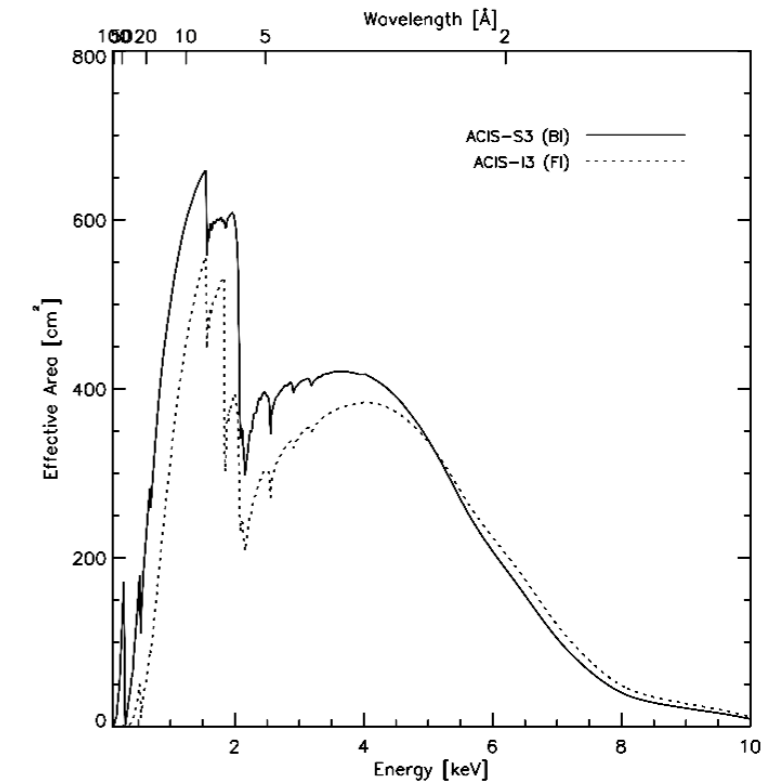
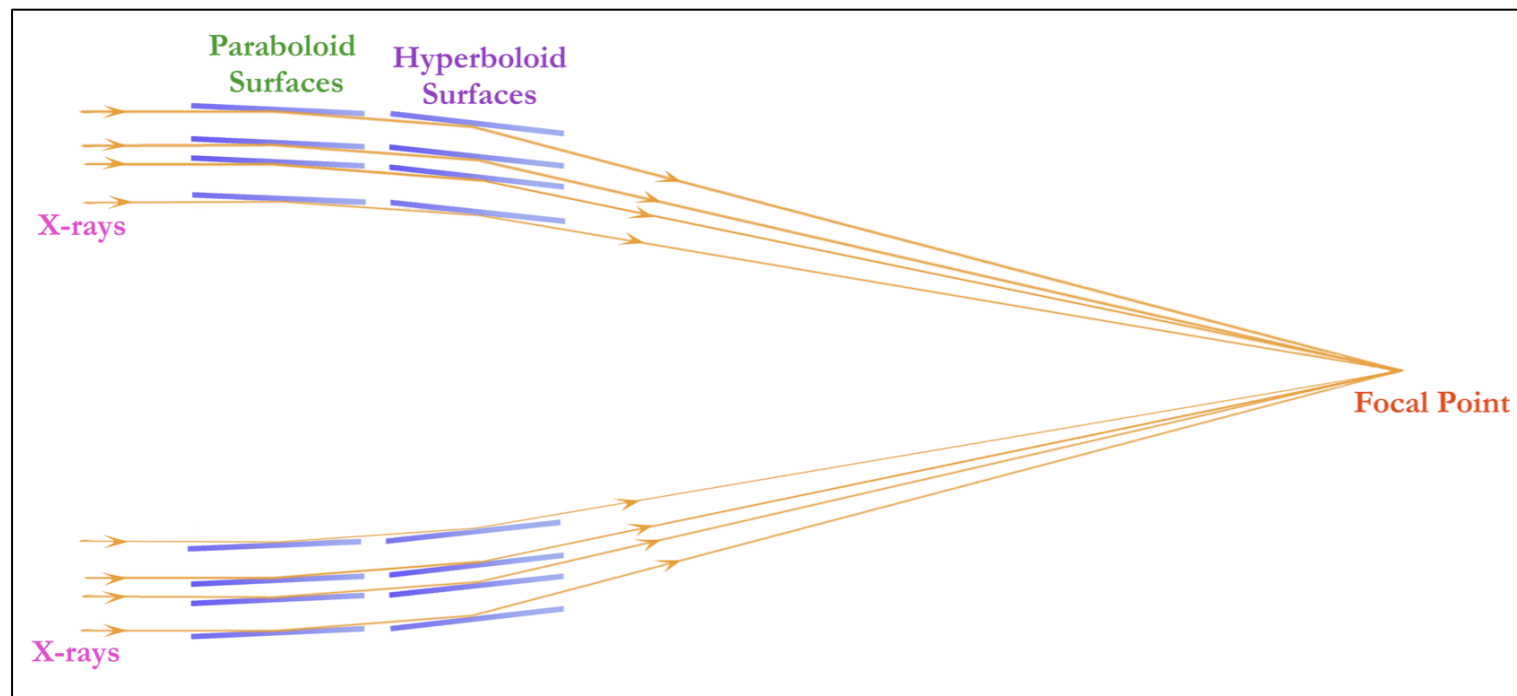
Overview

- X-ray data (*event files, filtering, and binning*)
- Standard re-processing (*bad aspect, flares, CTI correction, etc.*)
- Imaging point sources (*counts images, flux images, backgrounds*)
- Image analysis (*PSFs, region files, detection, spectral analysis*)
- Imaging diffuse emission (*Exposure maps, profile fitting, etc.*)

Caveats \Rightarrow *Chandra data (XMM, Suzaku, etc..)*
CIAO and HEASoft
ACIS (HRC, EPIC, etc.)



X-ray Data and Instruments



- Instruments are photon counting (*small number statistics*)
- Instruments are broad-band (*strong energy dependent response*)
- Grazing incidence optics (*PSF degrades rapidly off axis*)
- Operate in space (*Flares, radiation damage, aspect, etc.*)

Advantage ⇒ More information on each photon (x, y, E, t)



X-ray Event Files

The screenshot shows the fv software interface. The top window displays a summary of the file 'acisf06934N002_evt2.fits'. The table below shows the structure of the file:

Index	Extension	Type	Dimension	View
<input type="checkbox"/> 0	Primary	Image	0	Header Image Table
<input checked="" type="checkbox"/> 1	EVENTS	Binary	20 cols X 663365 rows	Header Hist Plot All Select
<input type="checkbox"/> 2	GTI	Binary	2 cols X 1 rows	Header Hist Plot All Select
<input type="checkbox"/> 3	GTI	Binary	2 cols X 1 rows	Header Hist Plot All Select
<input type="checkbox"/> 4	GTI	Binary	2 cols X 4 rows	Header Hist Plot All Select
<input type="checkbox"/> 5	GTI	Binary	2 cols X 5 rows	Header Hist Plot All Select
<input type="checkbox"/> 6	GTI	Binary	2 cols X 3 rows	Header Hist Plot All Select

The bottom window shows the 'Table Info' for the selected 'EVENTS' extension. It displays the total number of columns (20) and rows (663365). A list of columns is shown, with a blue arrow pointing to the 'time' column:

- time
- ccd_id
- node_id
- expno
- chipx
- chipy
- tdetx
- tdety
- detx
- dety
- x
- y
- phas
- pha
- pha_ro
- energy
- pi
- fltgrade
- grade
- status

- Fundamental data product
- Equivalent to optical images, radio visibilities, etc.
- Table of event properties
- Each “event” is a possible detected photon
- Will also contains spurious events that must be filtered

⇒ *X-ray images are binned event lists*



Standard Reprocessing

- Apply time dependent gain correction (*PHA to ENERGY/PI*)
- Correct for CTI in your data (*especially for FI chips*)
- Apply the L2 filters (*cosmic rays, bad pixels, etc.*)
- Filter out time intervals containing strong flares, bad aspect
- Apply energy filter from 0.3-7.0 eV (*reduce background*)

```
acis_process_events infile="../../../primary/acisf00922_000N003_evt1.fits" \
                    outfile="acisf00922_000N004_evt1.fits" \
                    acaofffile="@pcad_files.txt" \
                    apply_cti=yes \
                    apply_tgain=yes \
                    badpixfile="acisf00922_000N004_bpix1.fits" \
                    doevtgrade=yes \
                    check_vf_pha=no \
                    calculate_pi=yes \
                    stop=sky

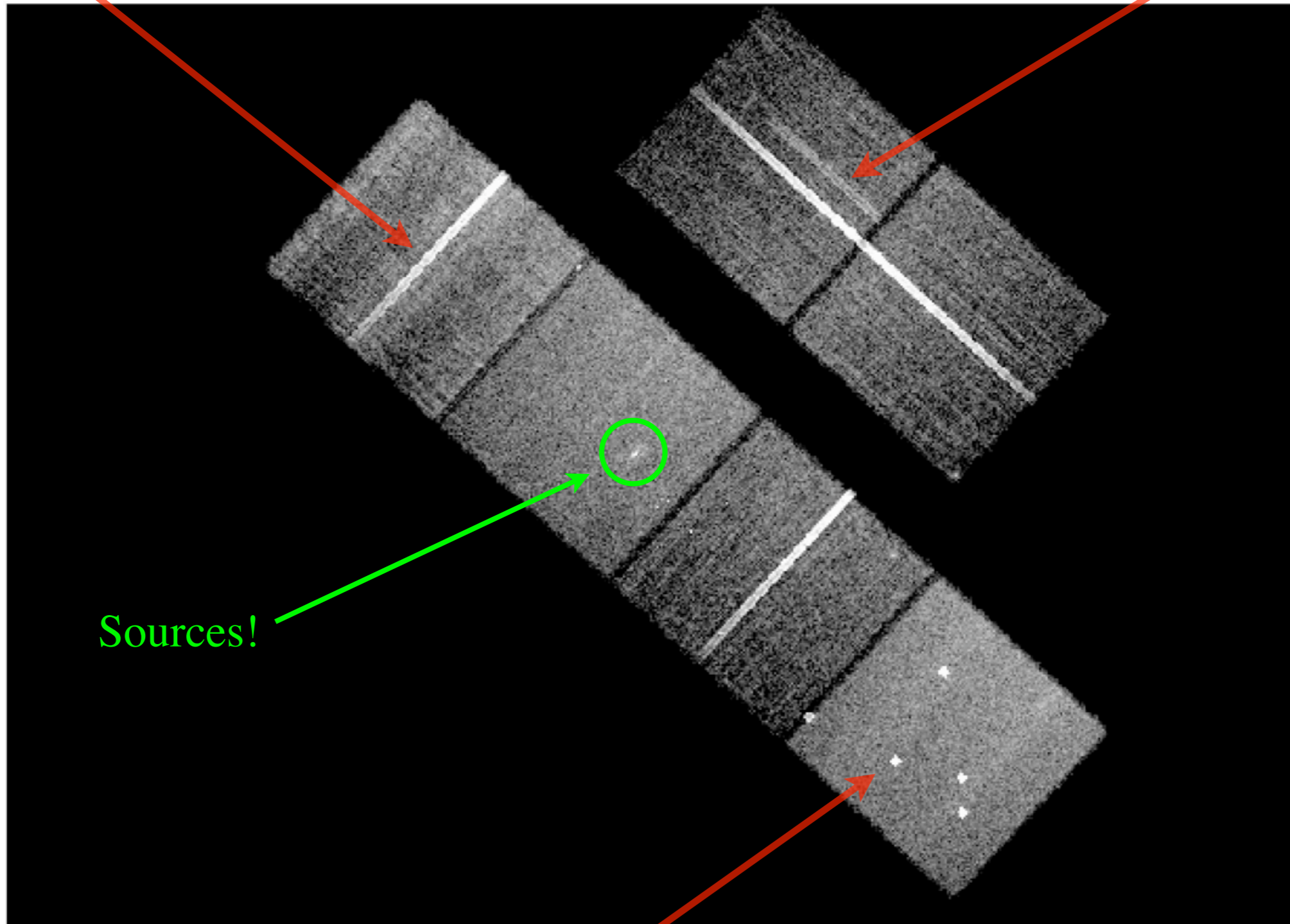
dmcopy "acisf00922_000N004_evt1.fits[status=0,grade=0,2,3,4,6]" \
       acisf00922N004_evt2.fits
```



Level 1 Event Files

Node boundaries

Bad columns



Sources!

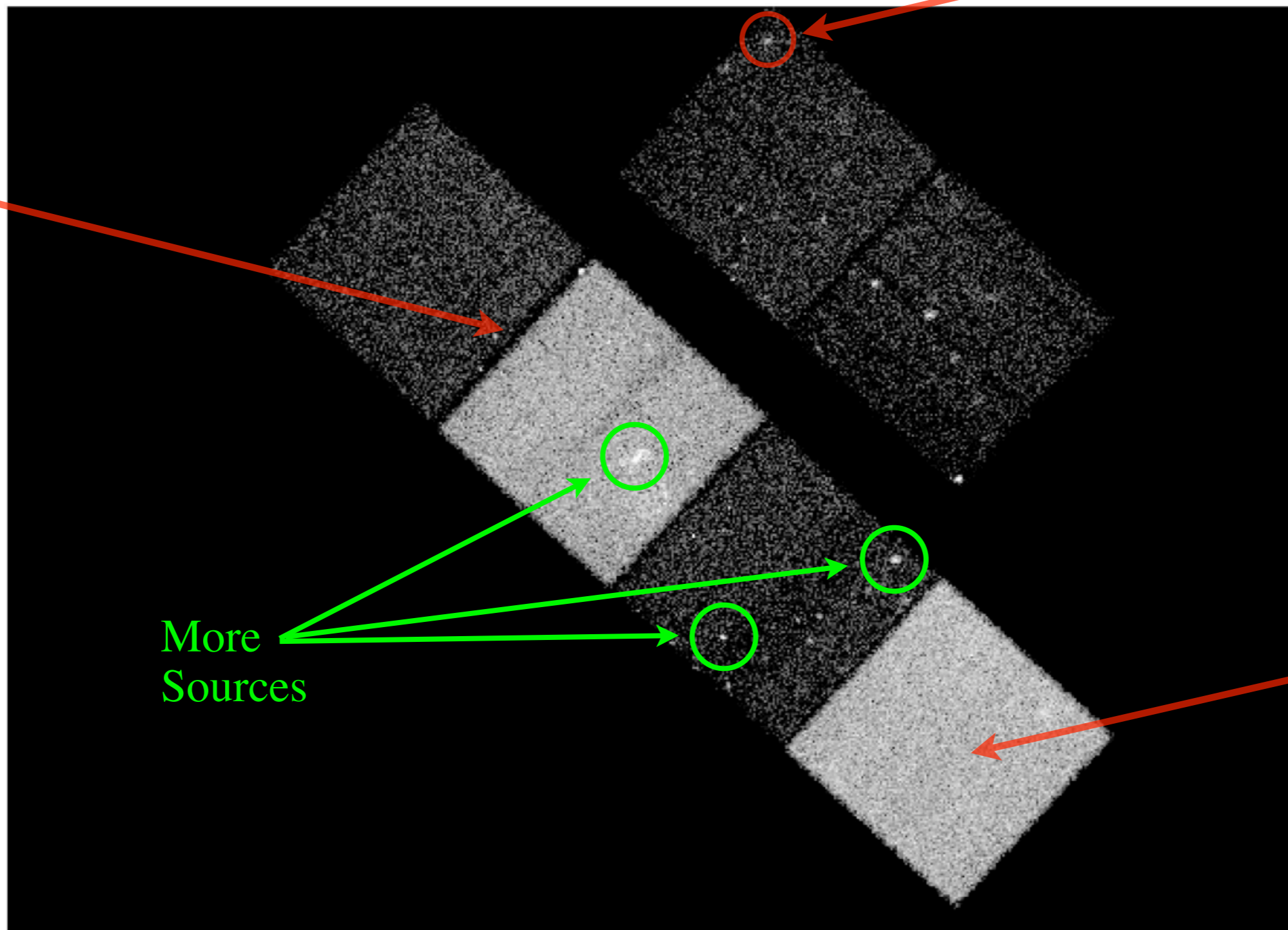
Bad pixels



Level 2 Event Files

PSF degraded for off-axis sources

Chip gaps

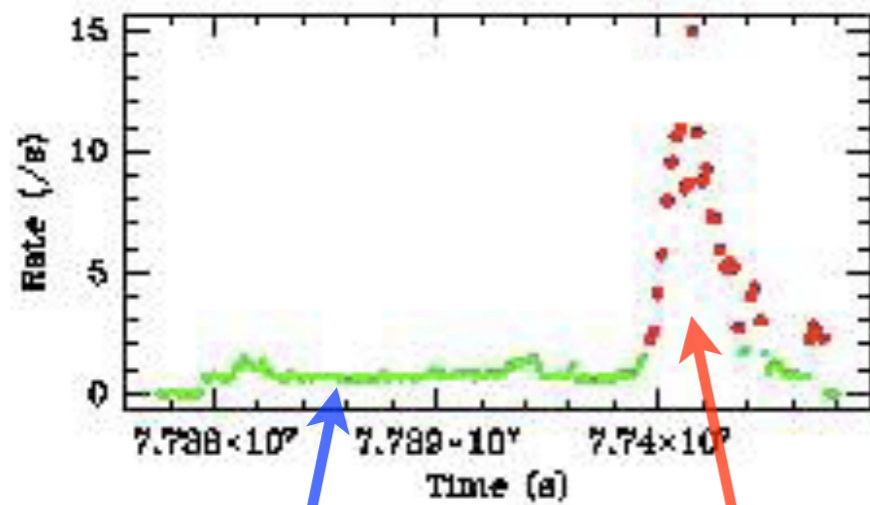


More Sources

Higher background on BI CCD



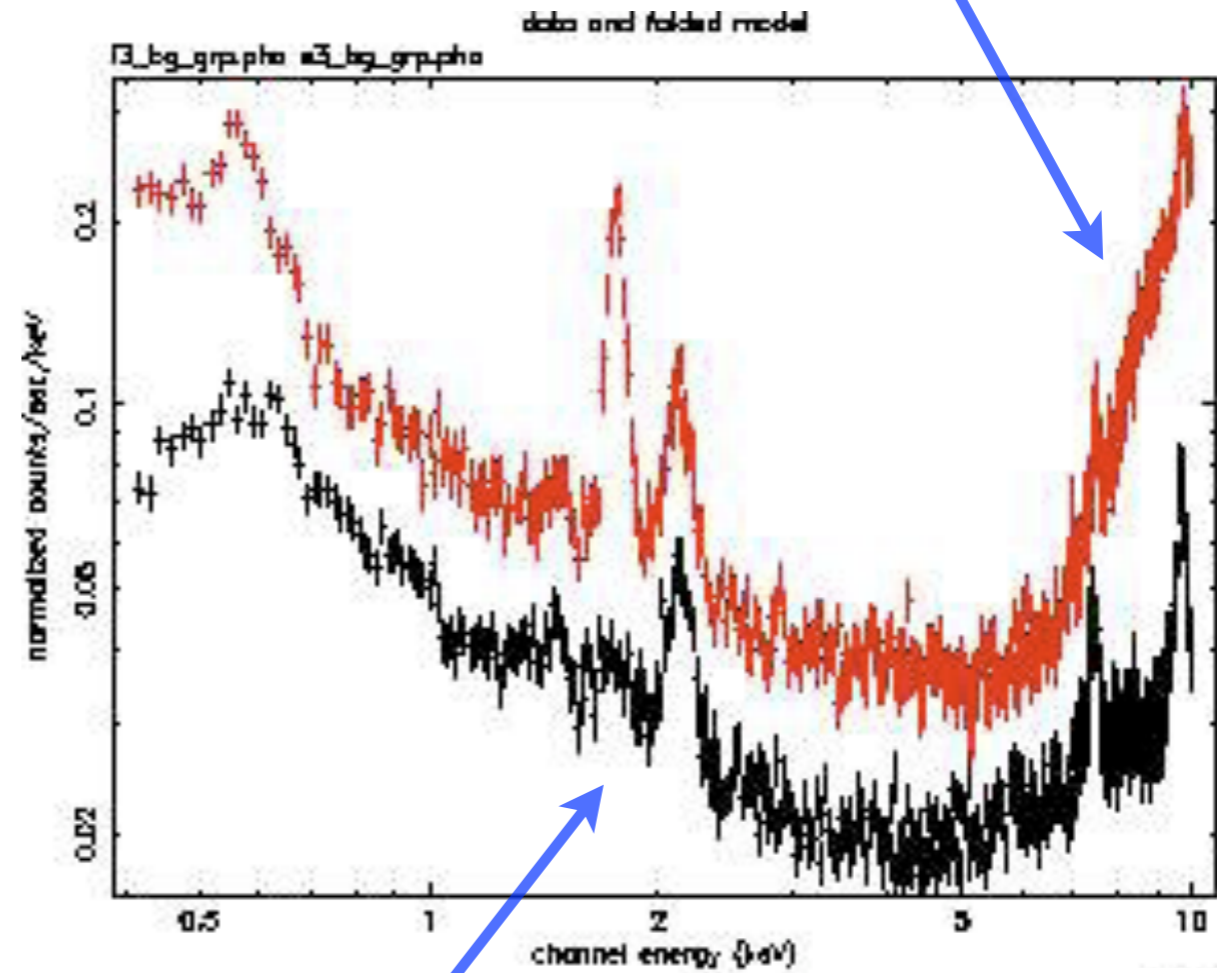
Background Flares



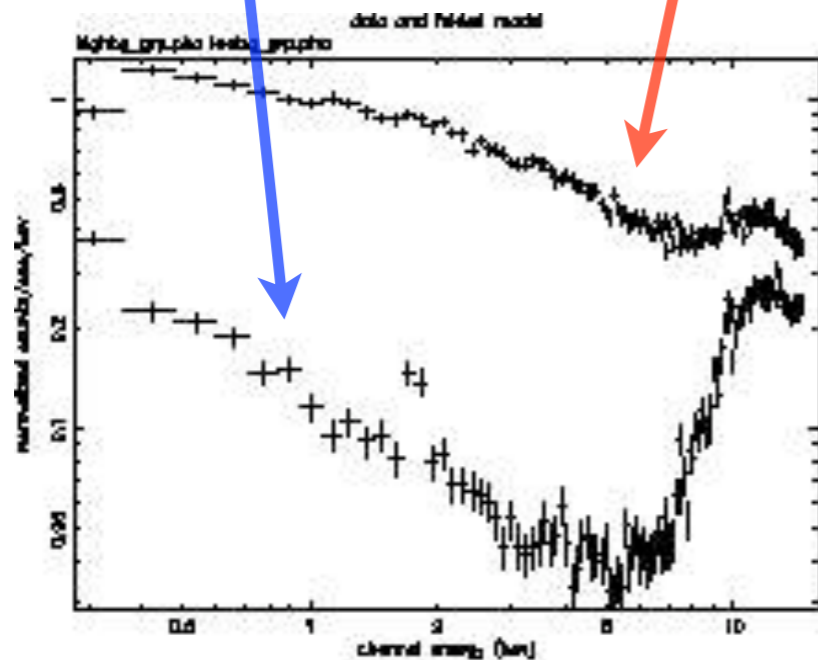
Quiescent

Flare

BI Quiescent



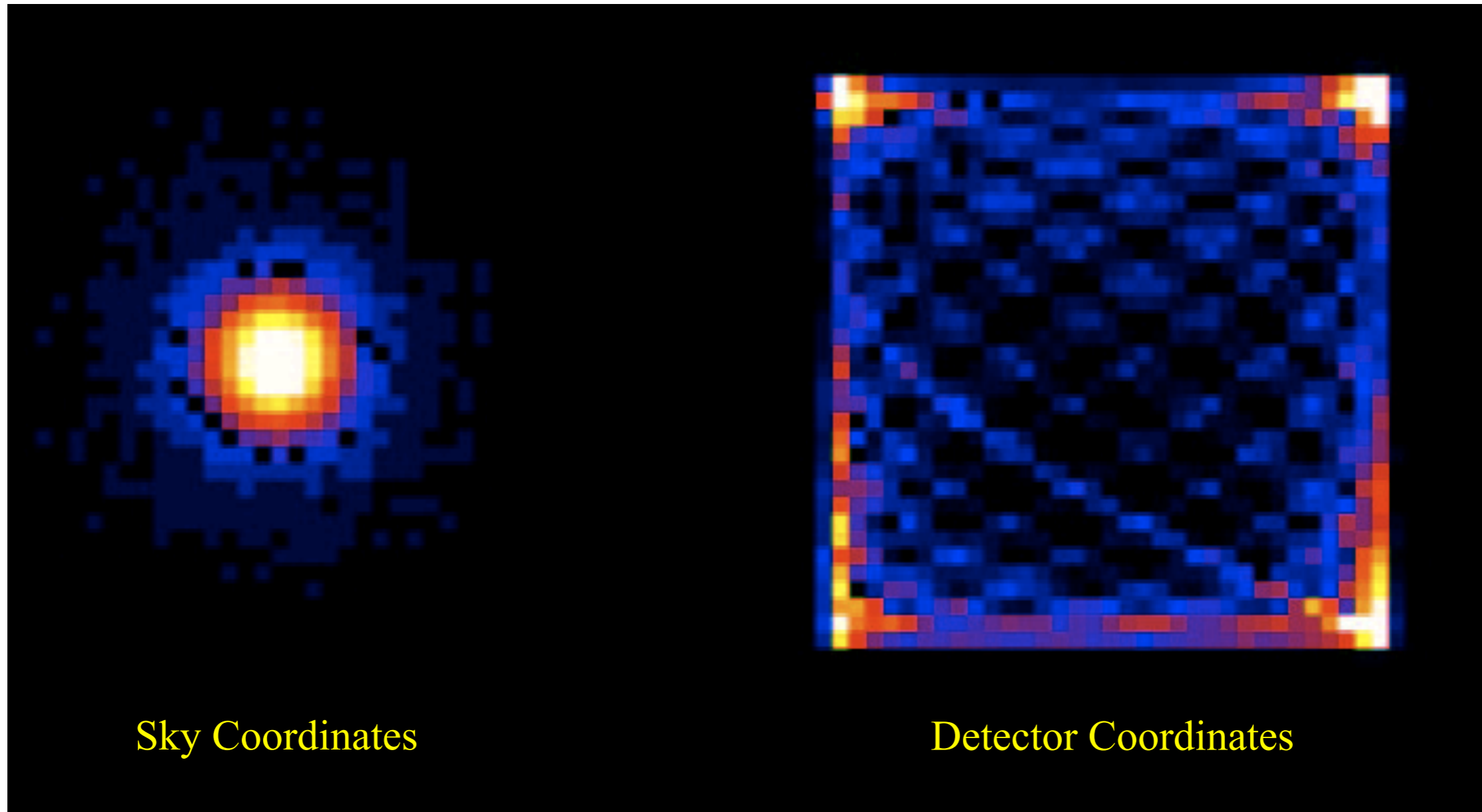
FI Quiescent

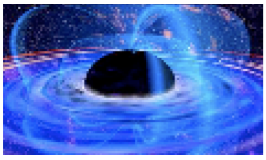


⇒ Filter out using *dmcopy*

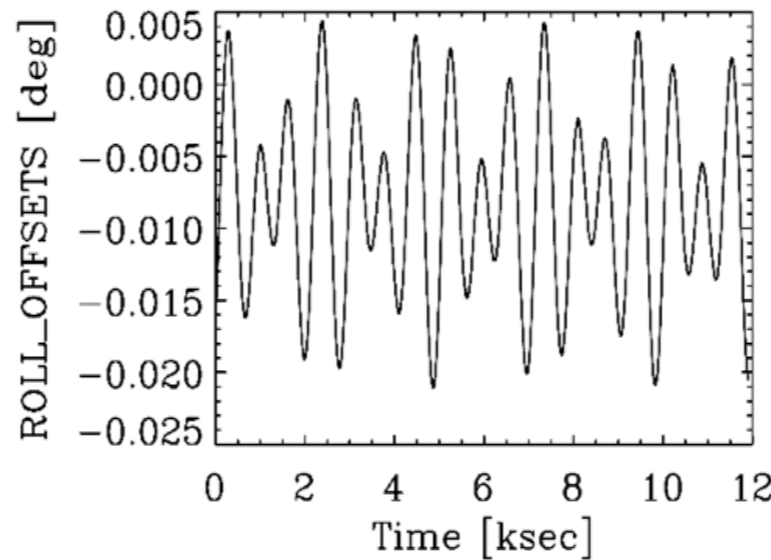
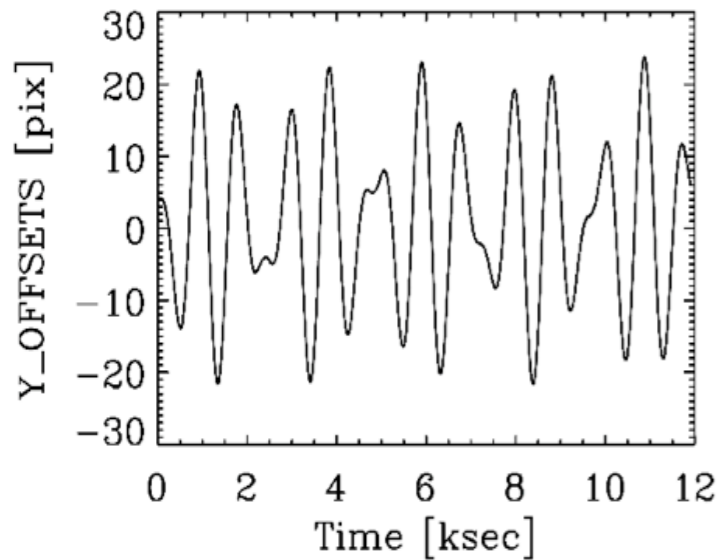
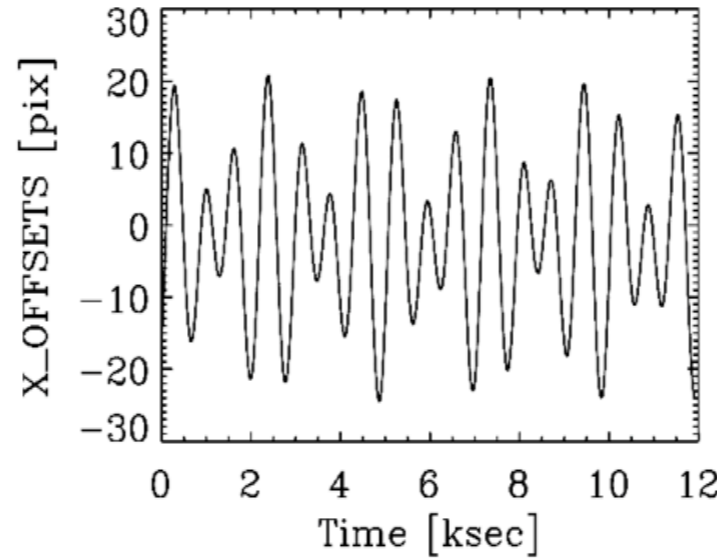
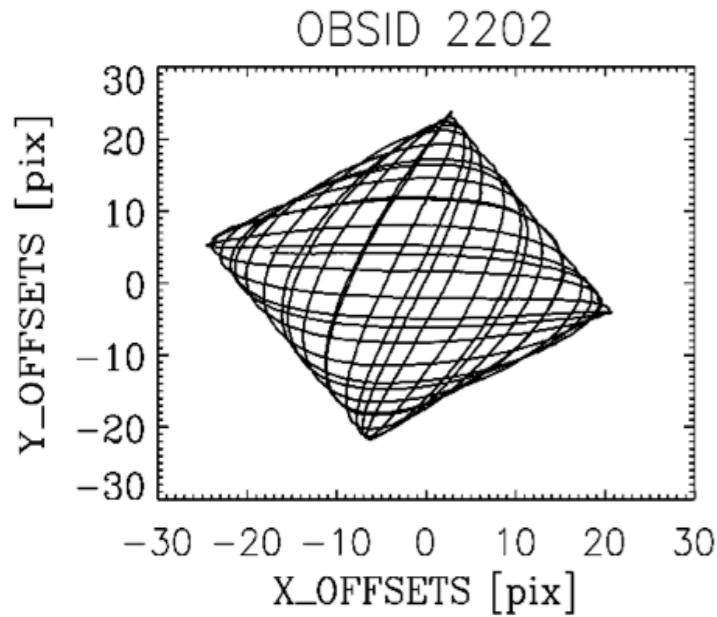
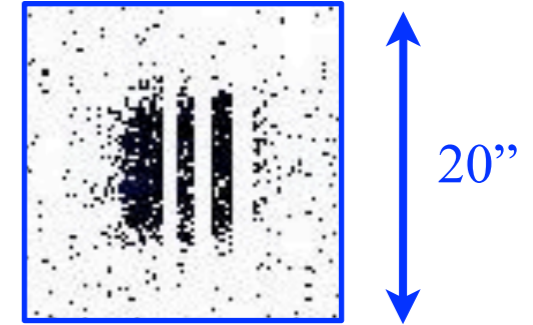


The Aspect Solution





The Aspect Solution

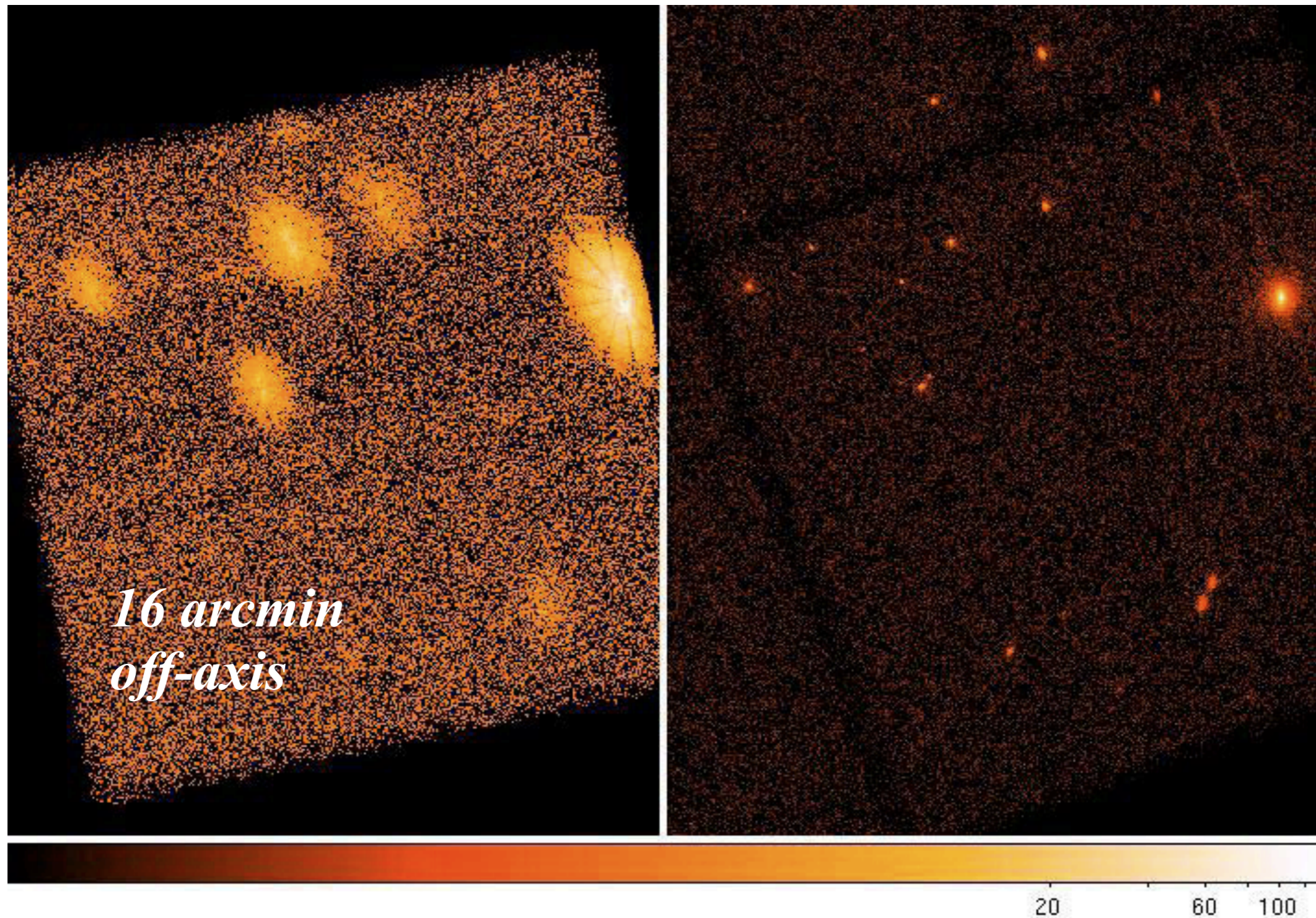


- During an observation, Chandra's optical axis describes a “dither pattern” on the sky
- The RA, Dec, and roll angle of the telescope versus time is called the “aspect solution”
- The aspect solution is used to reconstruct the image

Bad aspect ⇒ Blurry image!

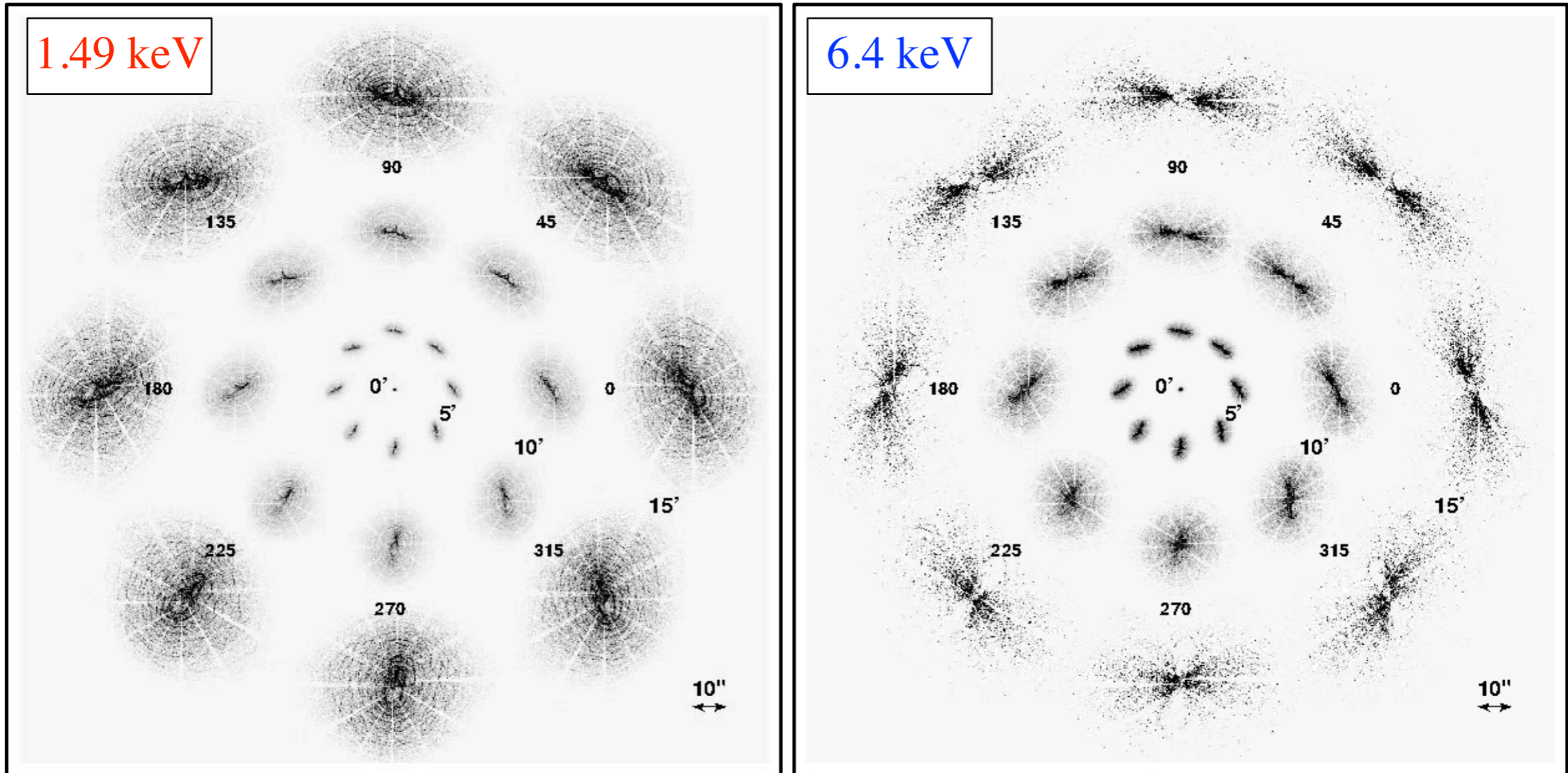


PSF Variations





Off-Axis Angle PSF Variations

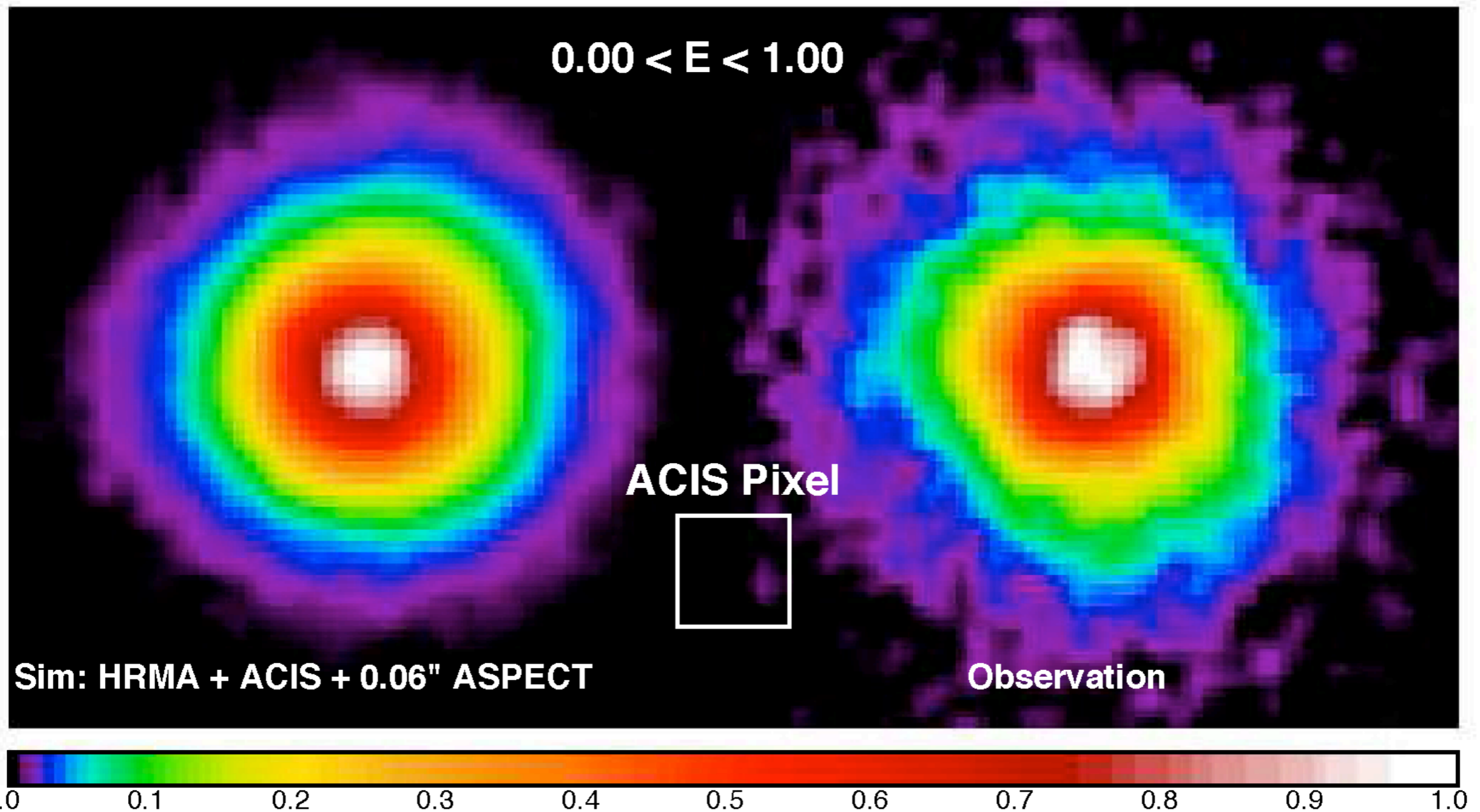


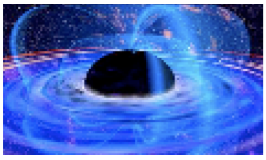
Chandra Ray Tracer (ChaRT): <http://cxc.harvard.edu/chart>



PSF Variations with Energy

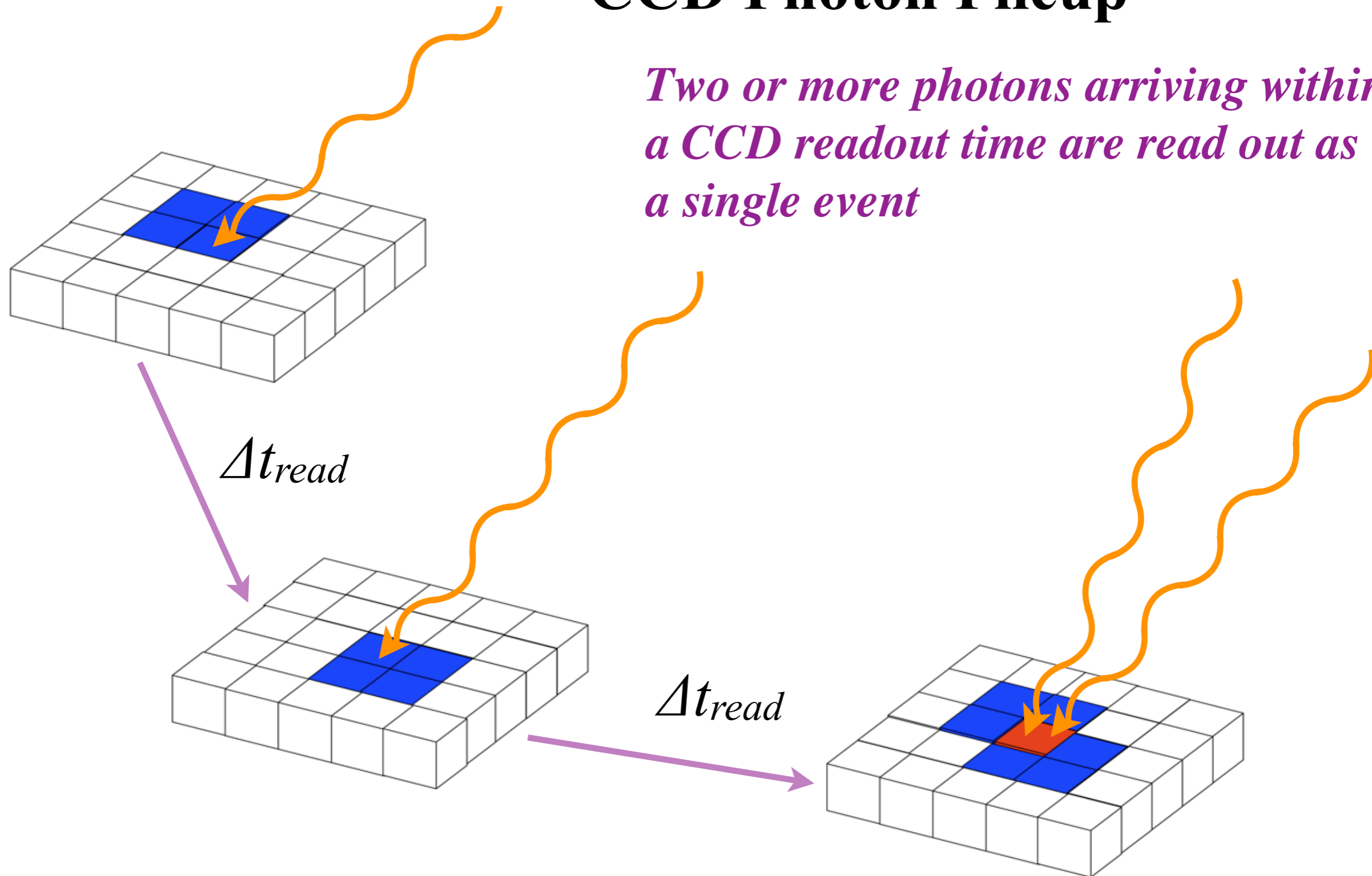
Merged off-axis ACIS Data: 7.7", 132deg az





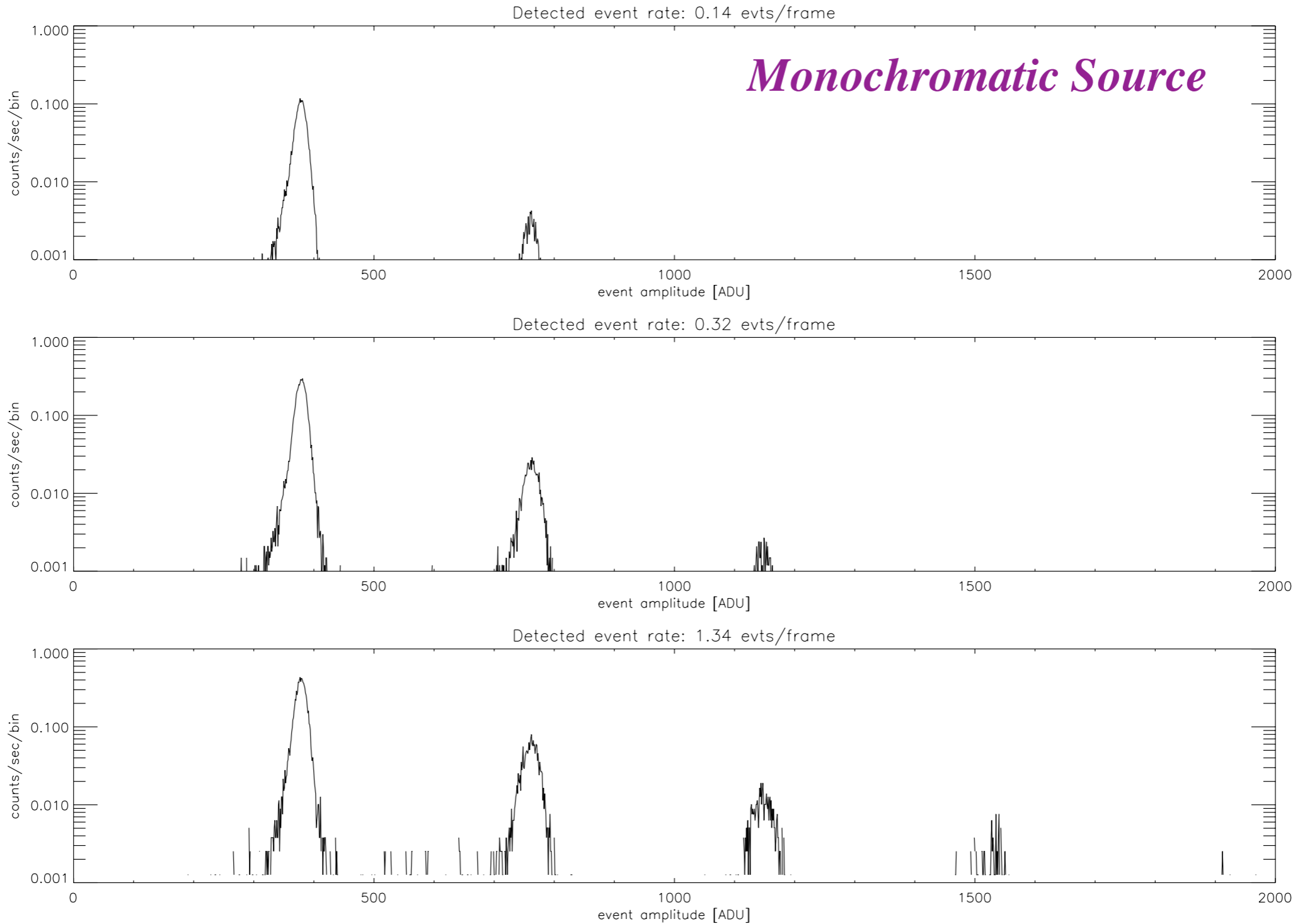
CCD Photon Pileup

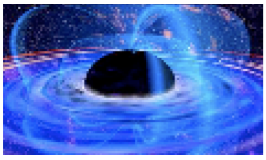
Two or more photons arriving within a CCD readout time are read out as a single event





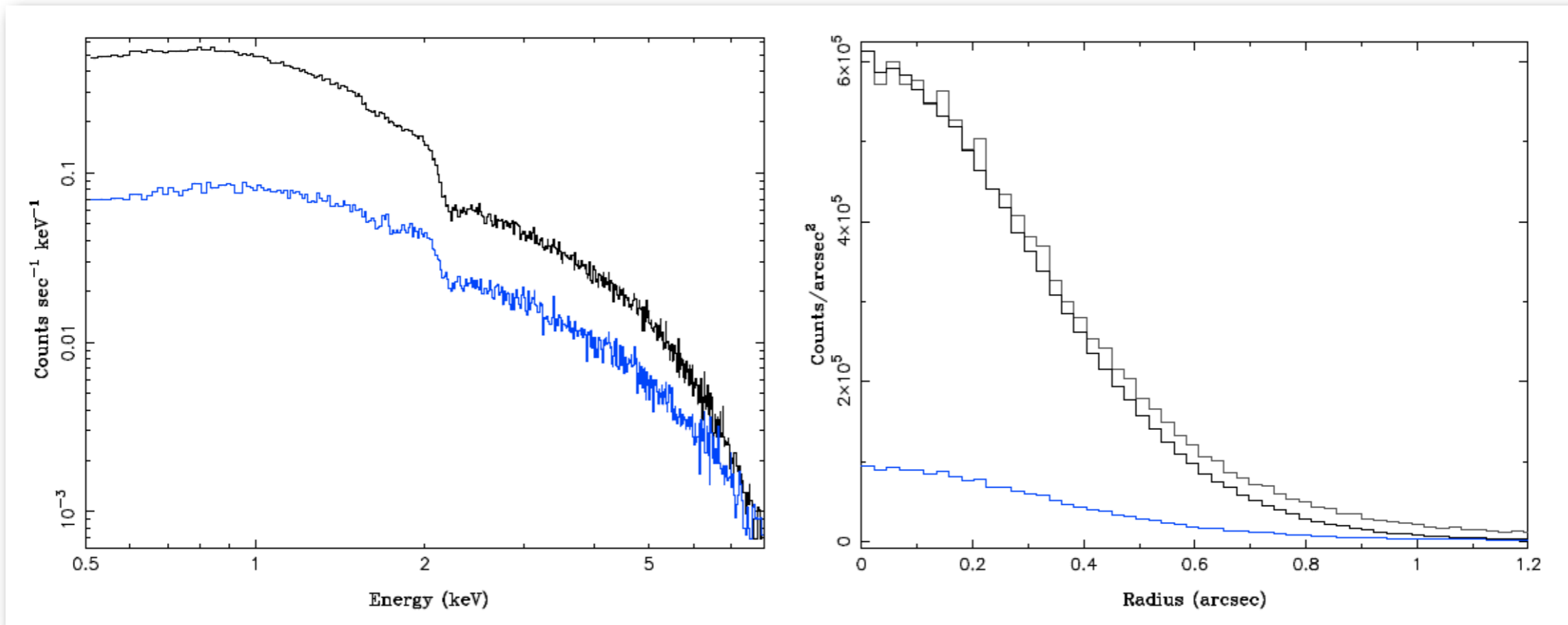
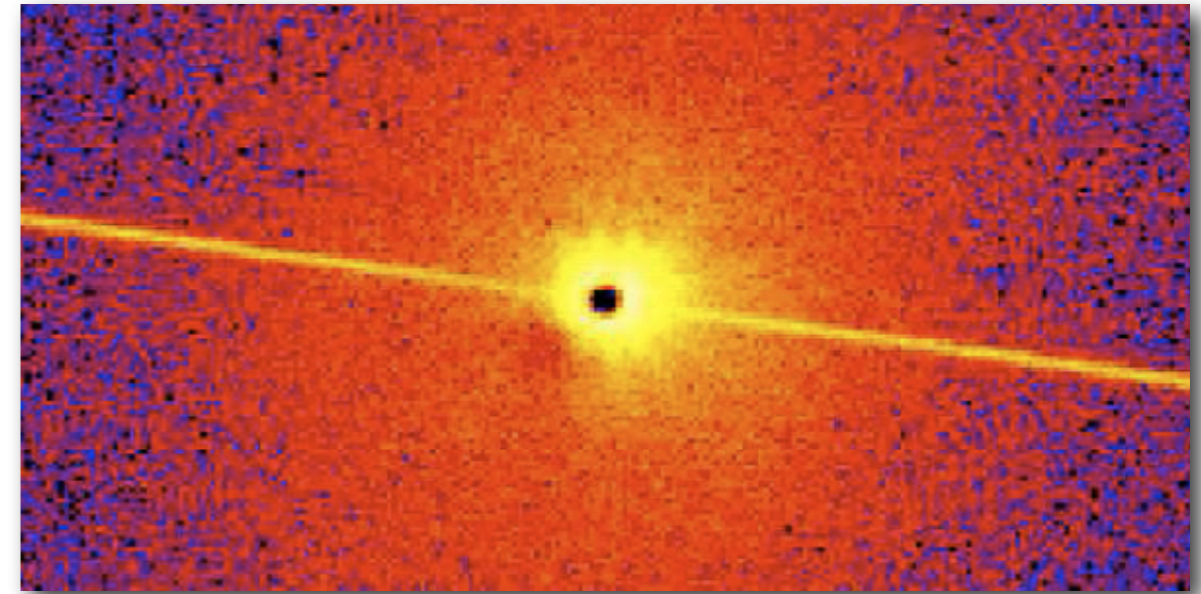
The Spectral Effects of Pileup





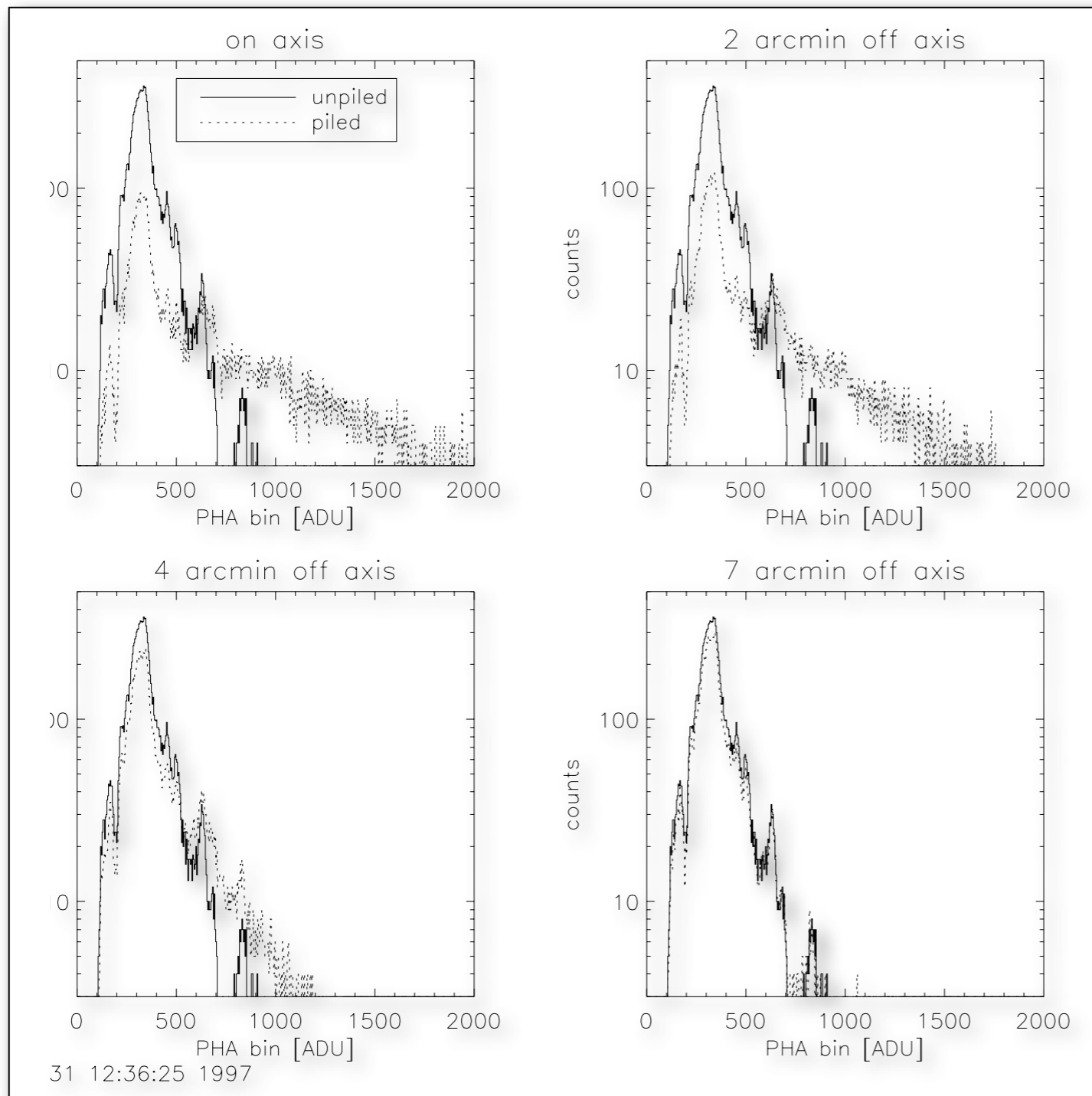
Spatial Effects of Pileup

- Spectrum becomes harder
- Surface brightness is suppressed
- PSF becomes broader





Mitigating the Effects of Pileup



- Offset pointing
- Shorter readout time
- CCD sub-arrays
- Turn off some CCDs
- Insert the gratings!

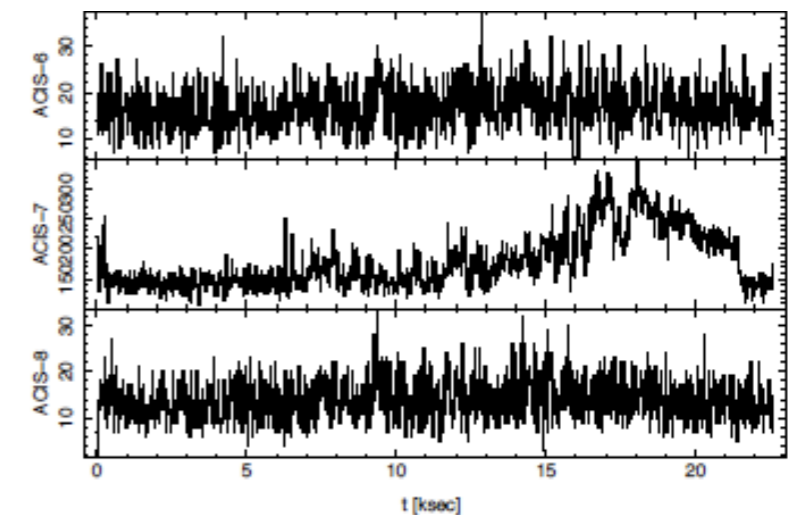
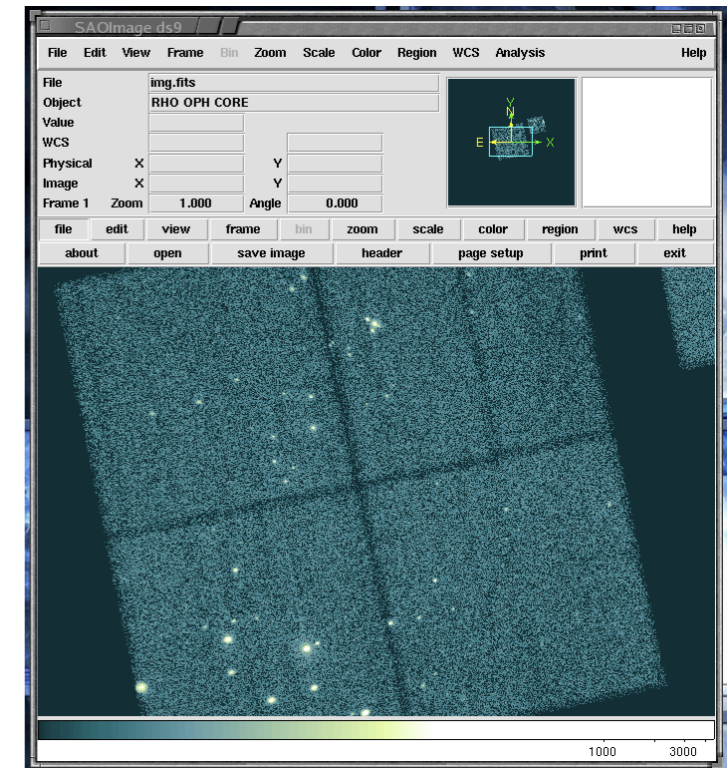
*If you can't avoid it,
include it in your fit!*



Spatial and Spectral Analysis

- Spatial analysis (*lose time and energy information*)
 - Create and display images: dmcopy, ds9
 - Create instrument maps: mkinstmap
 - Create exposure maps: mkexpmap
- Spectral analysis (*lose time and spatial information*)
 - Extract spectra using: dmextract
 - Create instrument responses: mkacismf
 - Create effective area: mkwarf
- Temporal analysis (*lose energy and spatial information*)
 - Extract light curves using: dmextract

Counts image



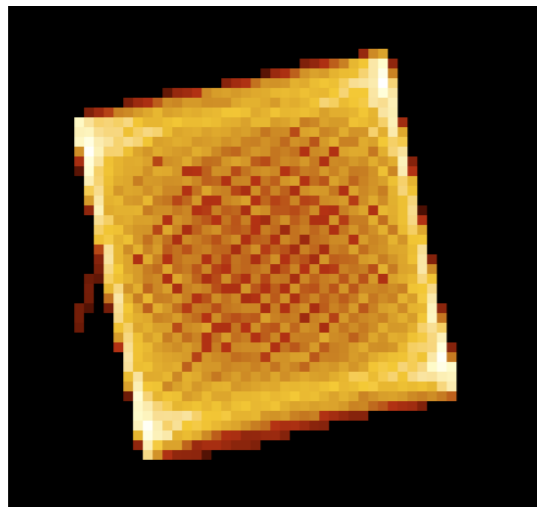
CCD light curves

Advice \Rightarrow ***Don't make an image too quickly.
Binning the data loses information.***

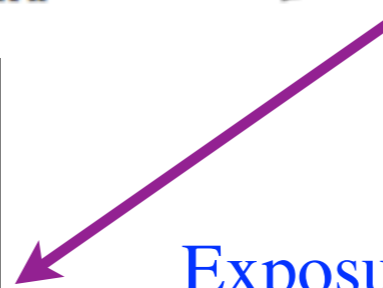
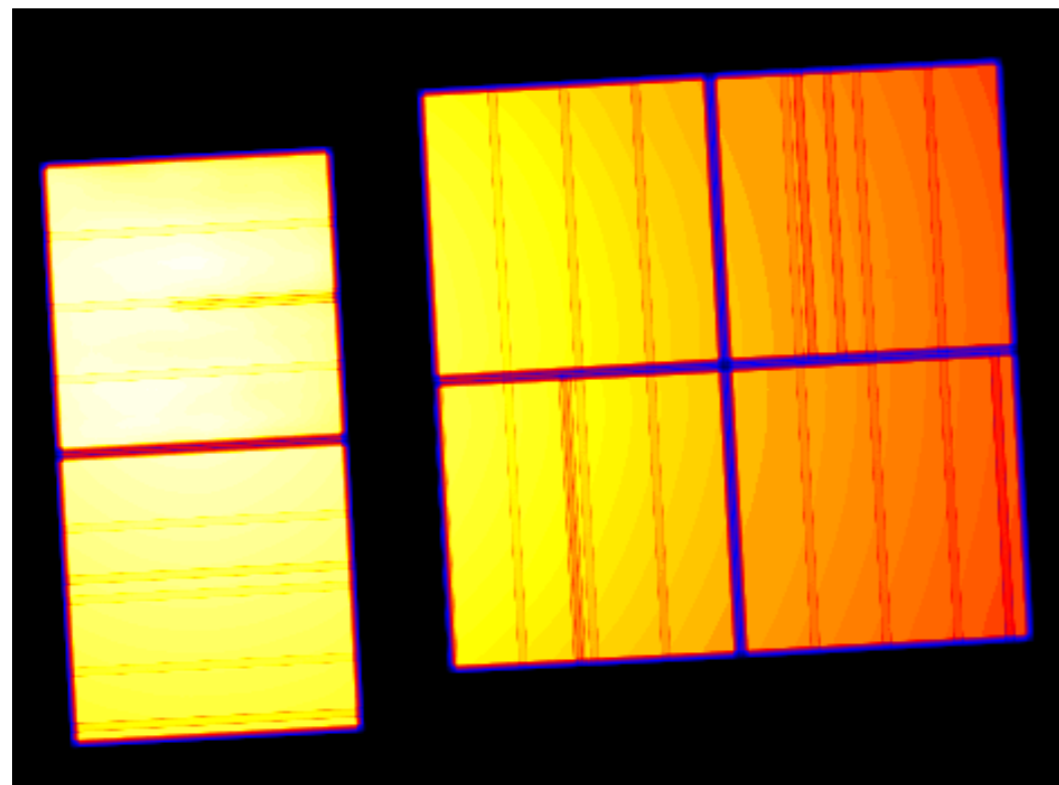
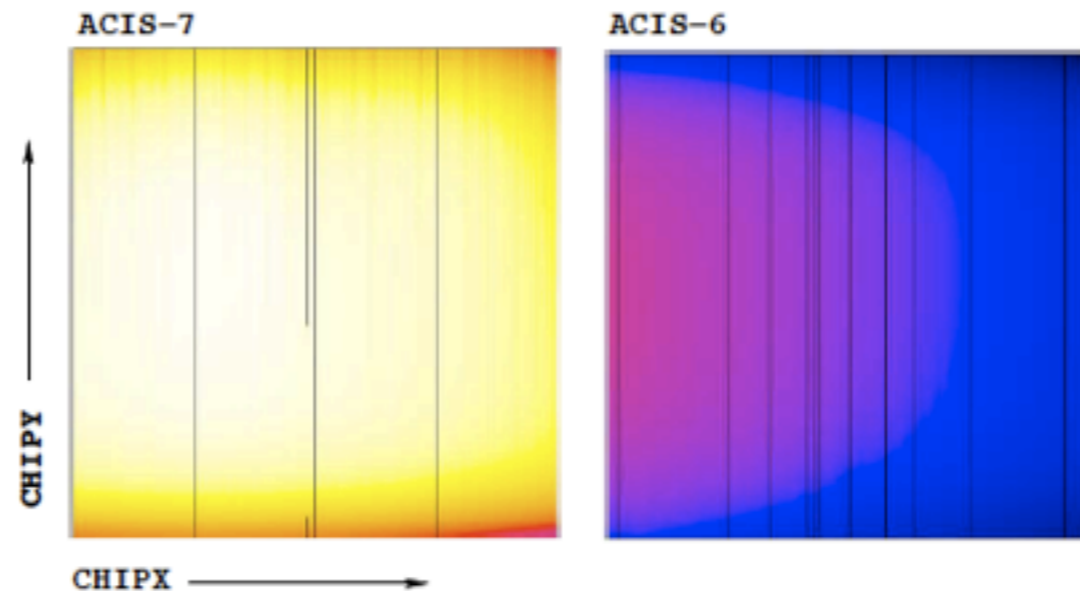


Instrument and Exposure Maps

Aspect solution



Instrument maps = mirror area x detector QE



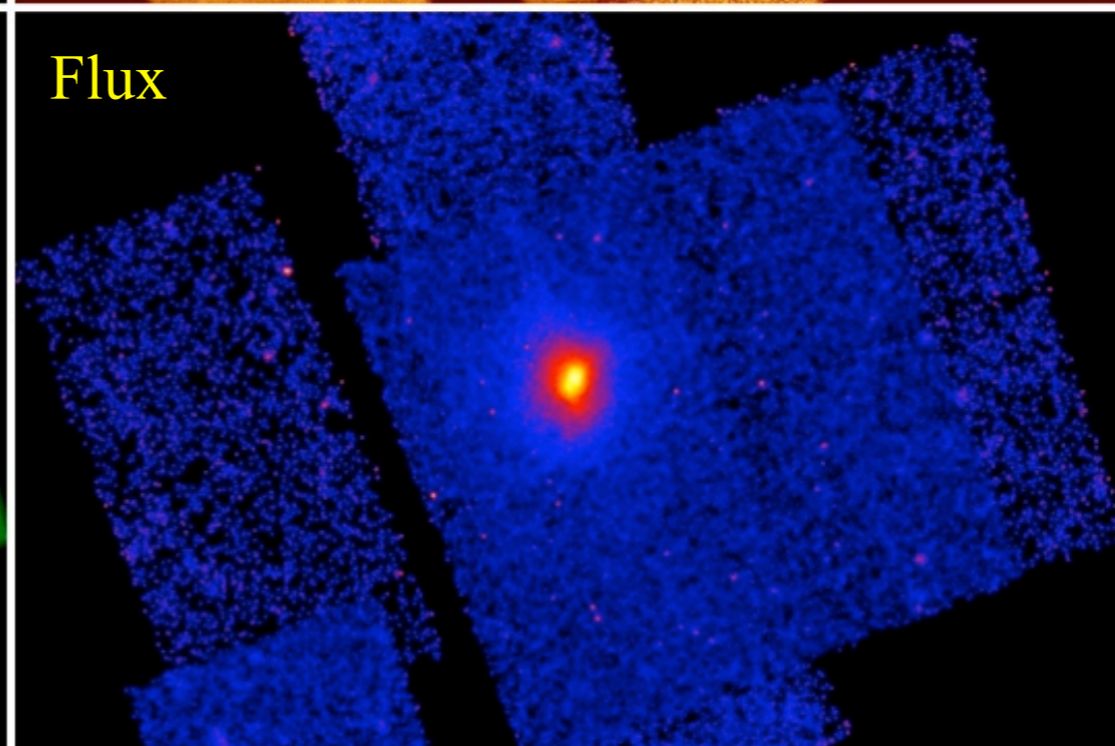
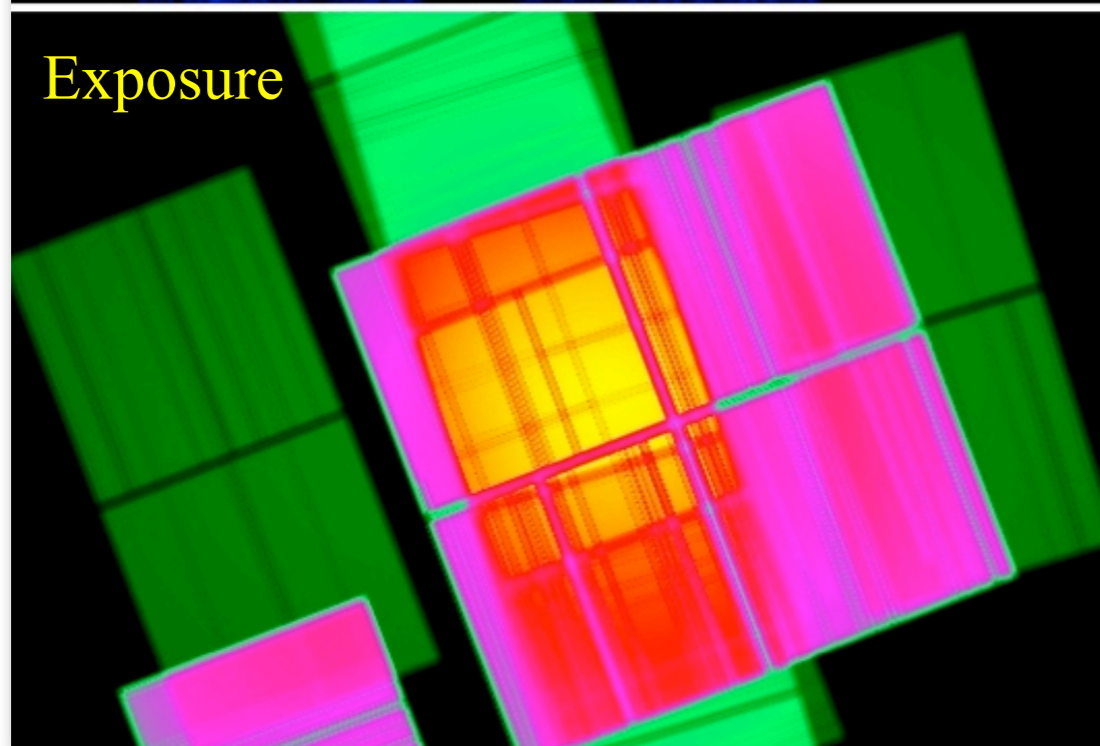
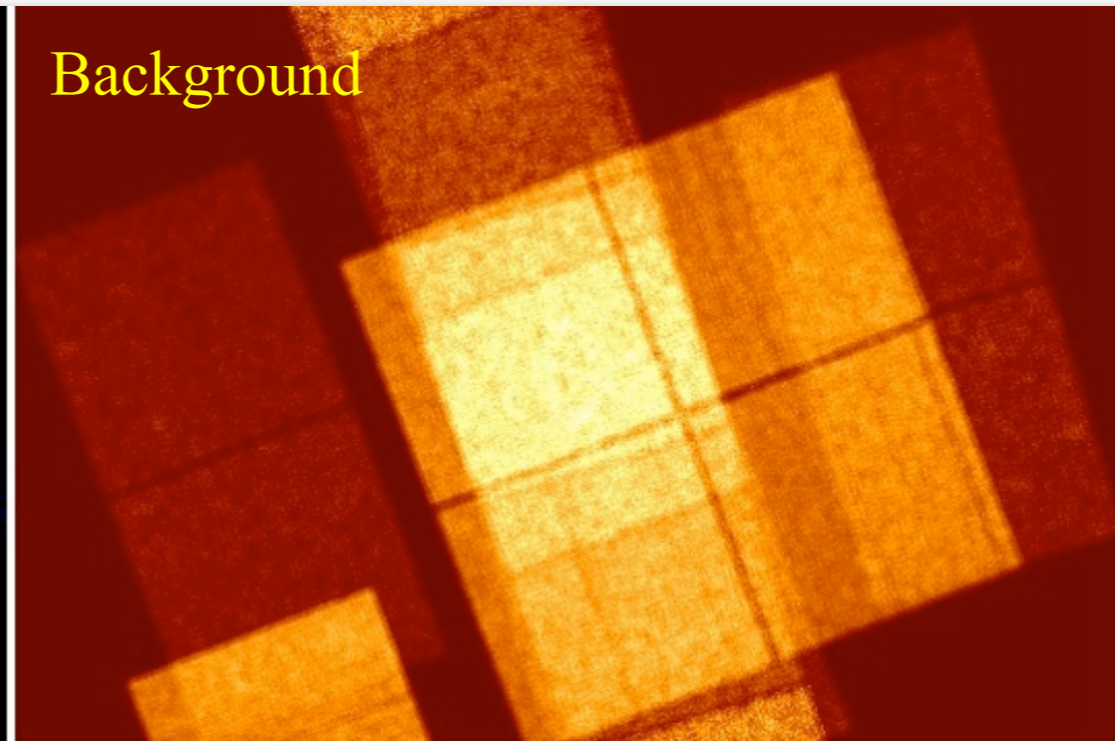
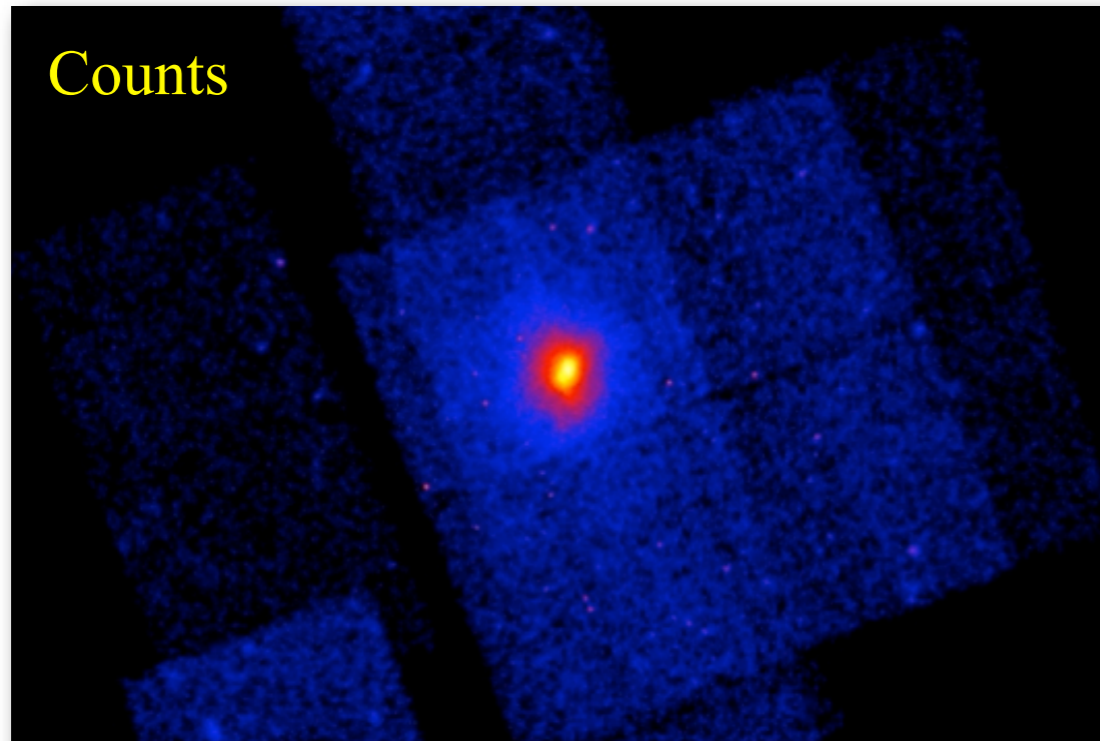
Exposure maps gives total effective area over the observation [cm² x sec]

$$\int_{\Delta E} dE \mathcal{S}_{\text{PSF}}(E, \hat{\mathbf{p}}) \approx \frac{1}{\tau_{\text{eff}}} \frac{C(\Delta h, \hat{\mathbf{p}})}{\mathcal{A}(\Delta h, E, \hat{\mathbf{p}})}$$

(see Davis 2001, ApJ, 548, 1010)

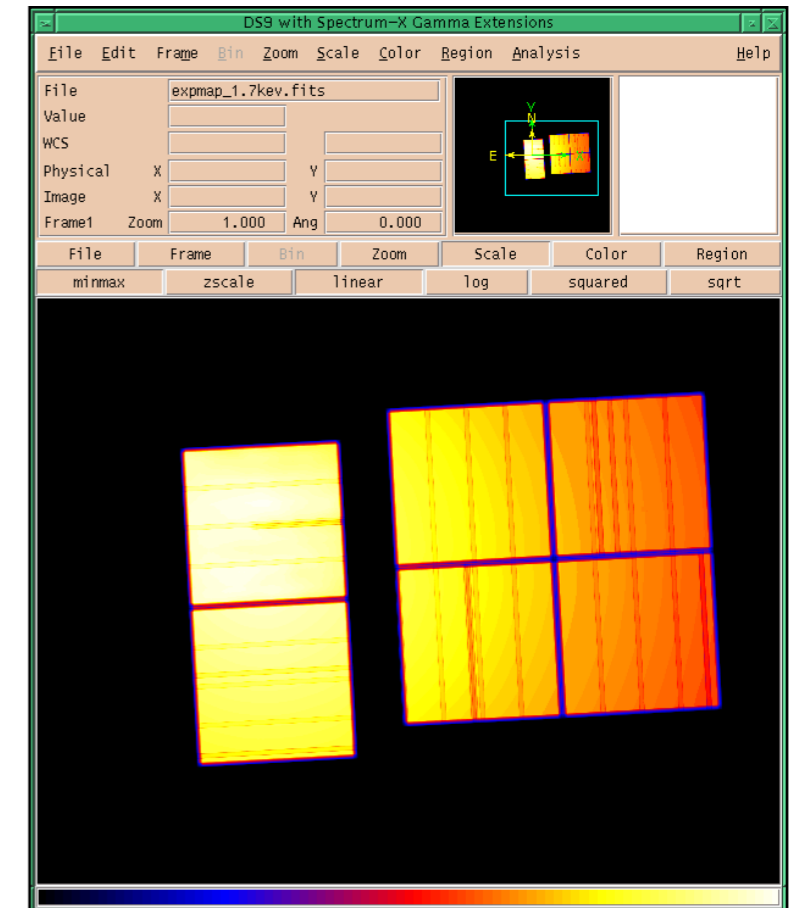
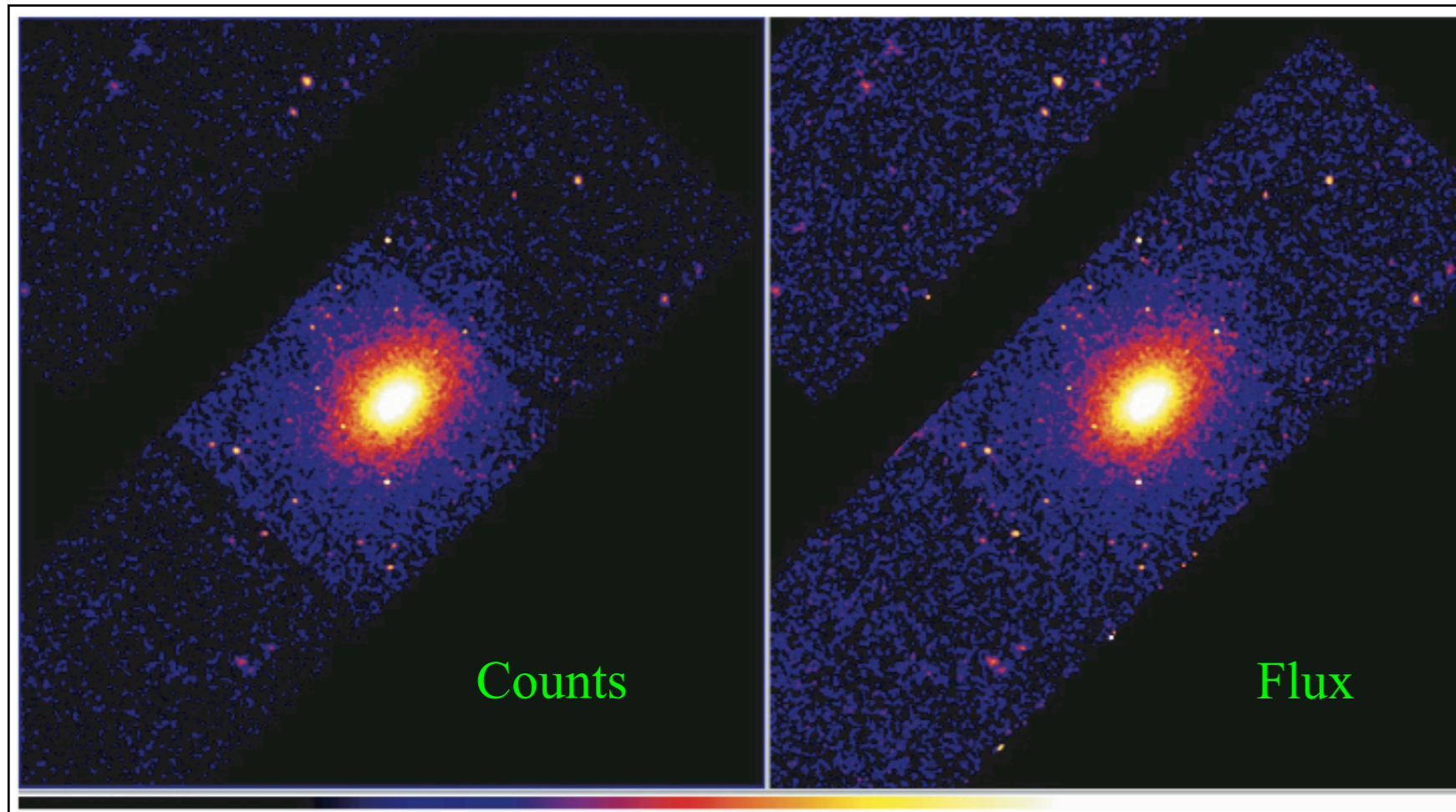


Exposure Corrected Images





Exposure Corrected Images

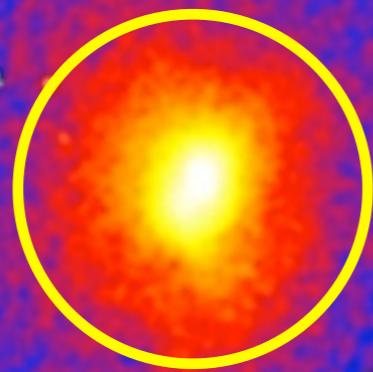


Exposure Map

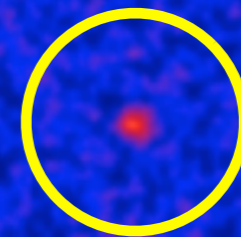
- Create counts image of field [dmcopy]
- Create instrument map for each chip [mkinstmap]
- Create exposure map for each chip [mkexpmap]
- Combine single exposure maps [dmregrid]
- Divide counts image by exposure map [dmimgcalc]

Defining the Background

Confused source
Non-local background

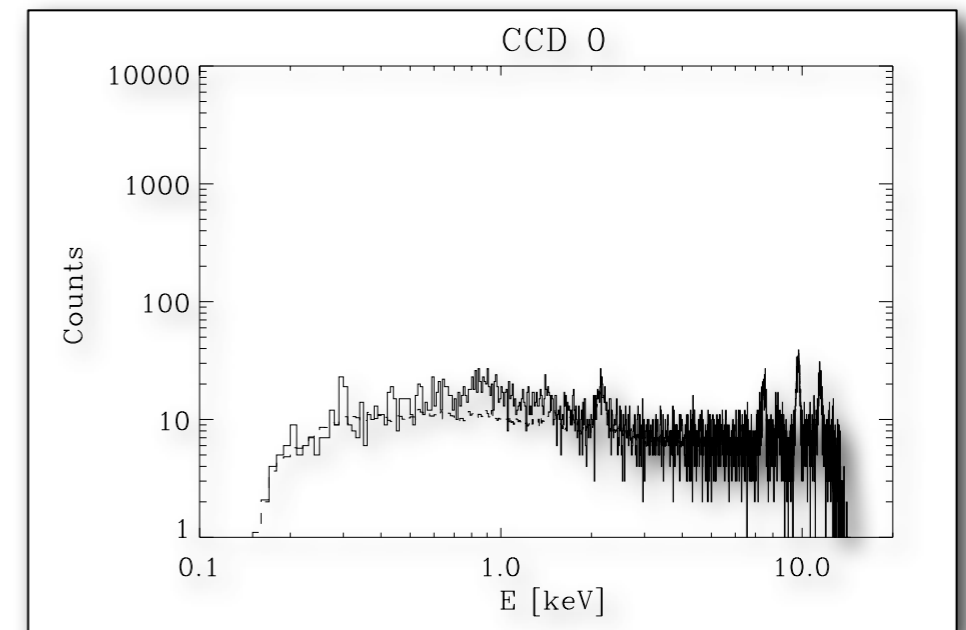
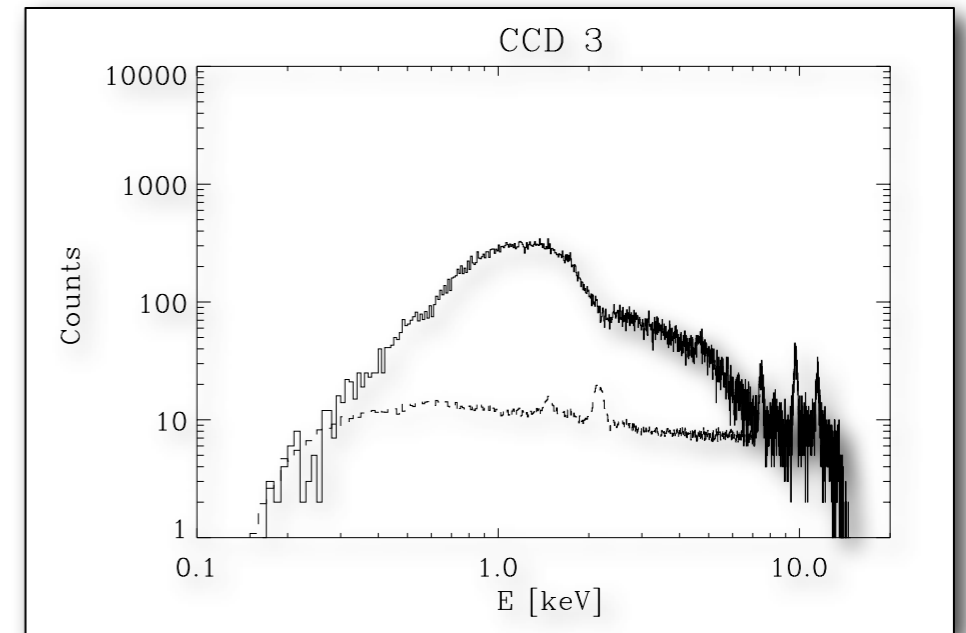
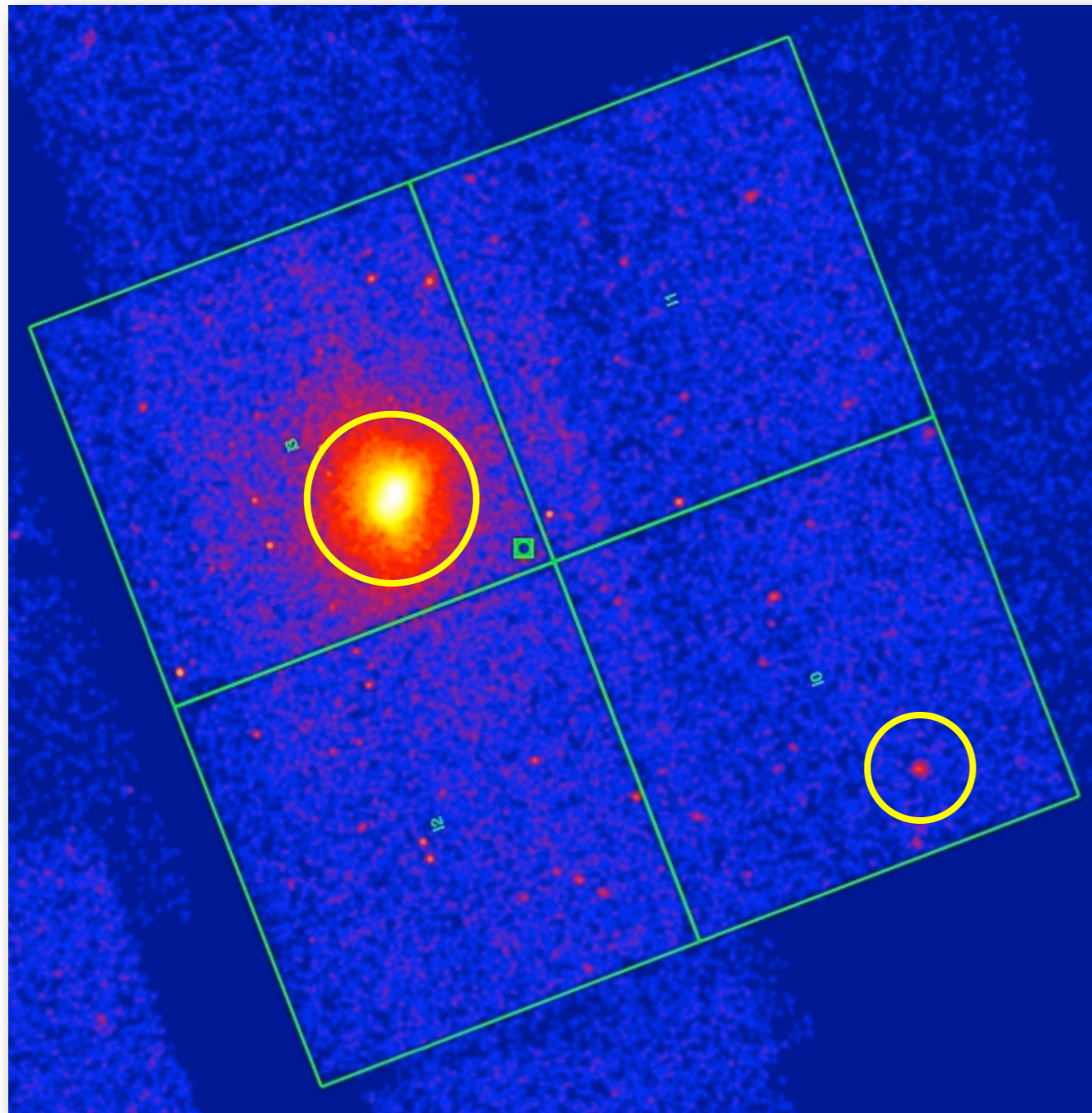


Isolated source
Local background



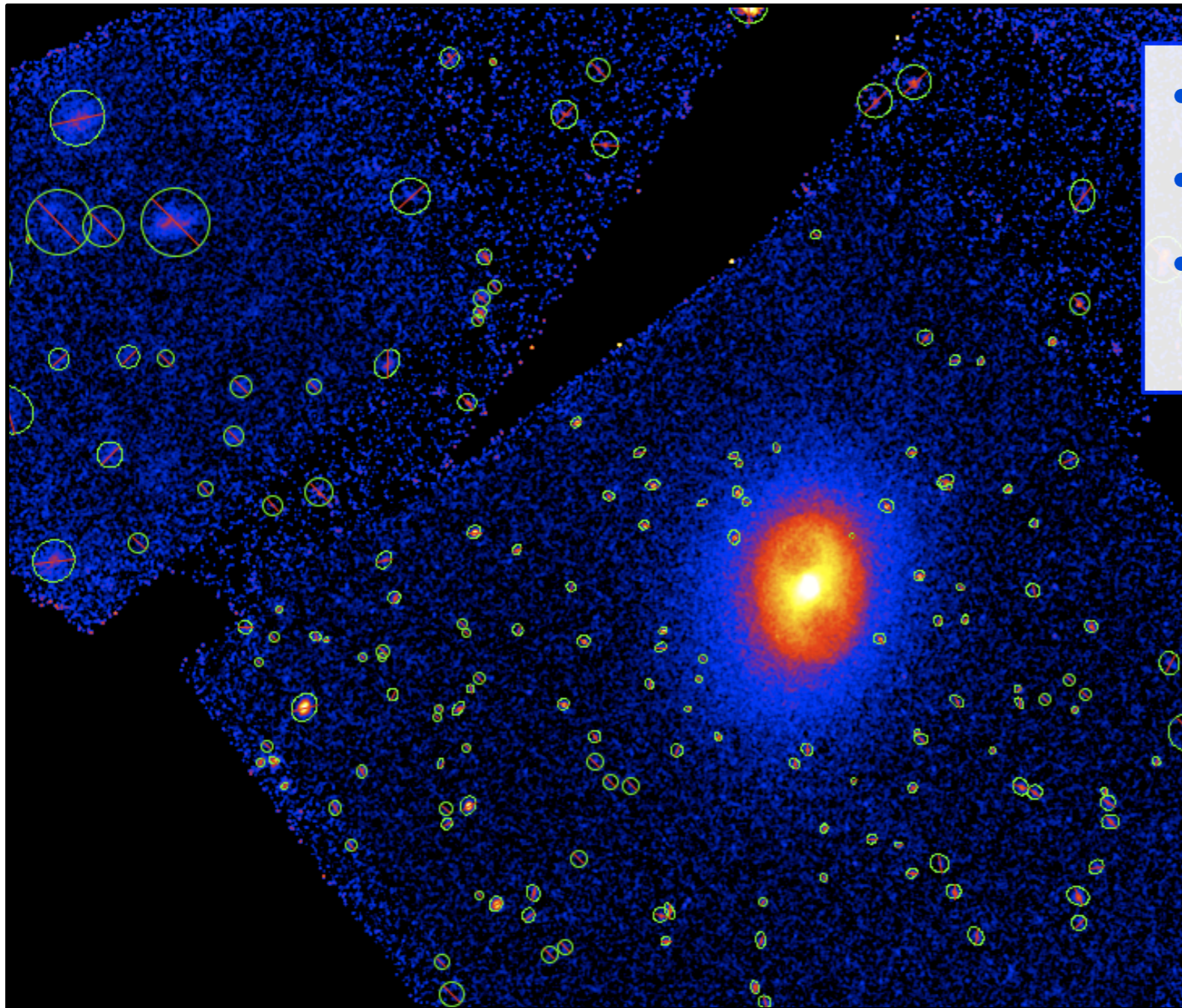


“Blank-sky” Background Files





Region Files

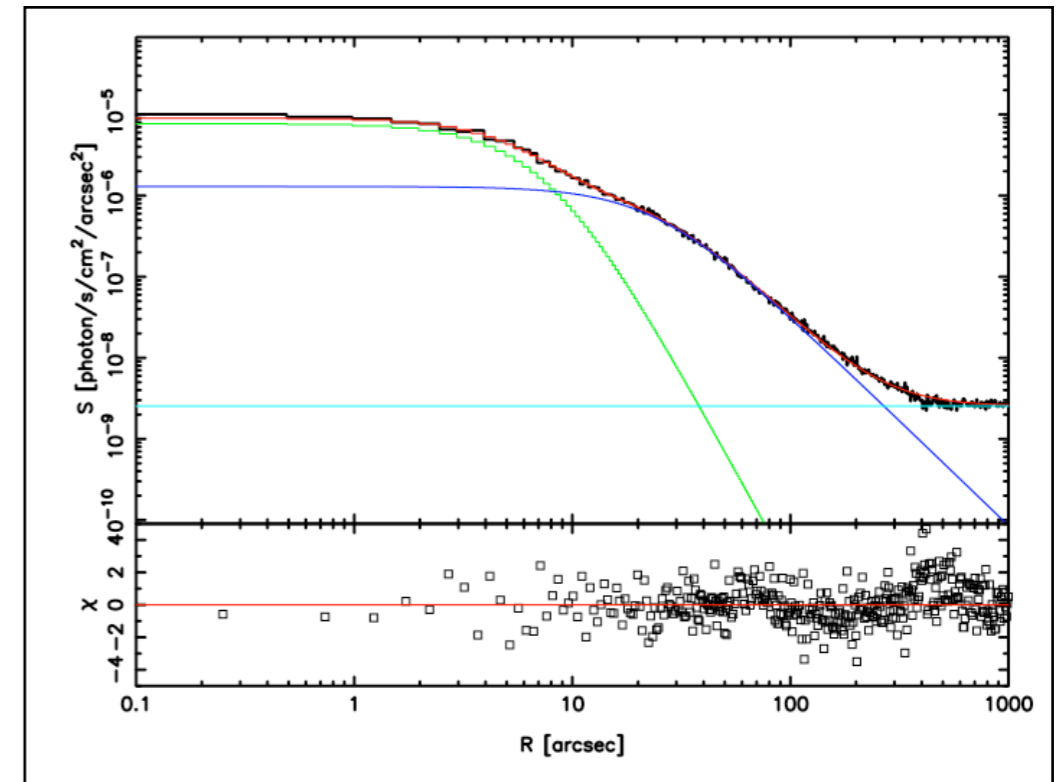
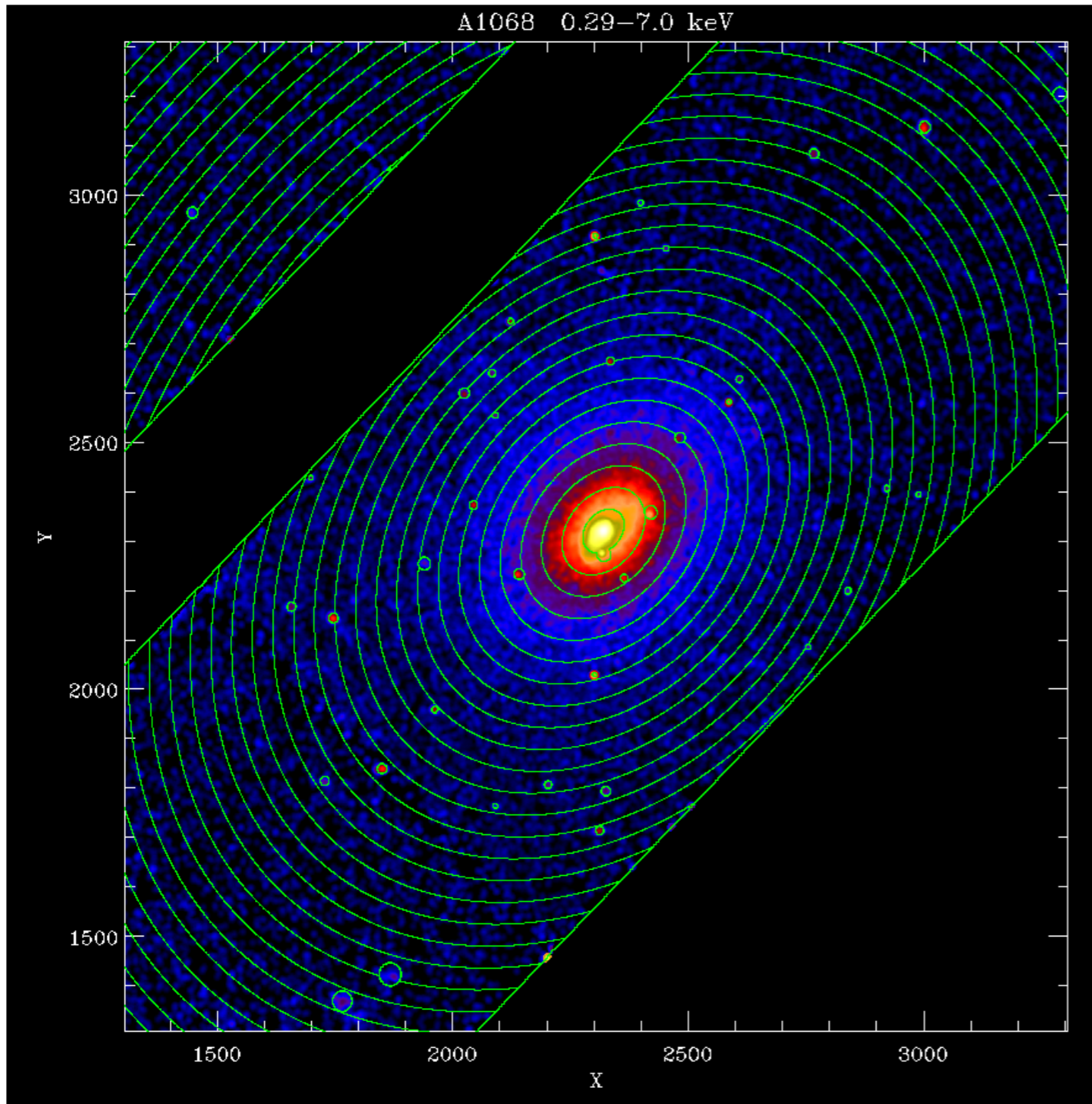


- Create with **wavdetect**, **vtpdetect**
- Create by hand: **ds9**
- Use with CIAO tools: **dmcopy**, **dmextract**, **dmstat**, etc.

```
Region
# Region file format: DS9 version 4.1
# Filename: /Users/wise/Work/Data/ms0735/ms0735_tot_flux_g03.fits
global color=green dashlist=8 3 width=1 font="helvetica 10 normal" size
fk5
-ellipse(115.85666,74.169261,11.521132",8.7877793",66.466424)
-ellipse(115.54798,74.192775,5.2482634",3.8145331",115.01658)
-ellipse(115.70051,74.192759,7.4630784",7.130289",168.58317)
-ellipse(115.86935,74.202022,9.8006405",5.3928701",53.150771)
-ellipse(116.06057,74.201865,17.724563",14.437109",54.44027)
-ellipse(115.73959,74.203653,7.1607874",6.4699004",32.341623)
-ellipse(115.63301,74.21059,6.0972182",4.7962207",123.8469)
-ellipse(115.71483,74.224904,7.653891",6.9387872",8.427741)
-ellipse(115.34744,74.225929,7.5254849",6.423767",163.87581)
-ellipse(115.61648,74.228517,5.2689608",4.2646309",12.197418)
-ellipse(115.2983,74.24723,6.6442194",5.8828317",42.751478)
-ellipse(115.5283,74.260198,8.5911042",6.6275952",95.045639)
-ellipse(115.64006,74.264205,6.1102188",5.1937946",22.618624)
-ellipse(115.33882,74.270766,9.1743516",7.4238426",162.33381)
-ellipse(115.52439,74.275398,6.745782",6.1505663",103.36217)
-ellipse(115.62975,74.277748,8.1634411",5.8237405",14.113738)
-ellipse(115.72536,74.298732,6.9847488",5.0978344",50.10555)
-ellipse(116.4136,74.35876,2.1304225",4.92",180)
-ellipse(115.30344,74.413691,20.643484",20.664",90)
-ellipse(115.54641,74.092938,13.084039",13.384256",80.384664)
-ellipse(115.5017,74.108266,7.9320191",4.4975811",105.75704)
-ellipse(115.61167,74.123869,5.7081589",5.0888756",43.823352)
-ellipse(115.49452,74.124265,9.8522582",5.6819102",94.032921)
-ellipse(115.61796,74.132751,9.3171383",8.6010193",28.985467)
-ellipse(115.60731,74.134021,10.248824",5.0767158",115.48979)
-ellipse(115.82133,74.136085,9.2608023",7.347712",69.467211)
-ellipse(115.25652,74.140649,8.8637285",8.5880412",136.35244)
-ellipse(115.41715,74.145363,4.7077581",4.5025469",170.78253)
-ellipse(115.35756,74.158379,6.1869905",5.5291216",45.622682)
-ellipse(115.41625,74.161927,5.5696486",4.3015501",74.566595)
-ellipse(115.1558,74.173997,8.7467807",8.6249944",7.534244)
-ellipse(115.30685,74.175676,6.0084073",5.1534766",68.303002)
```




Surface Brightness Profiles

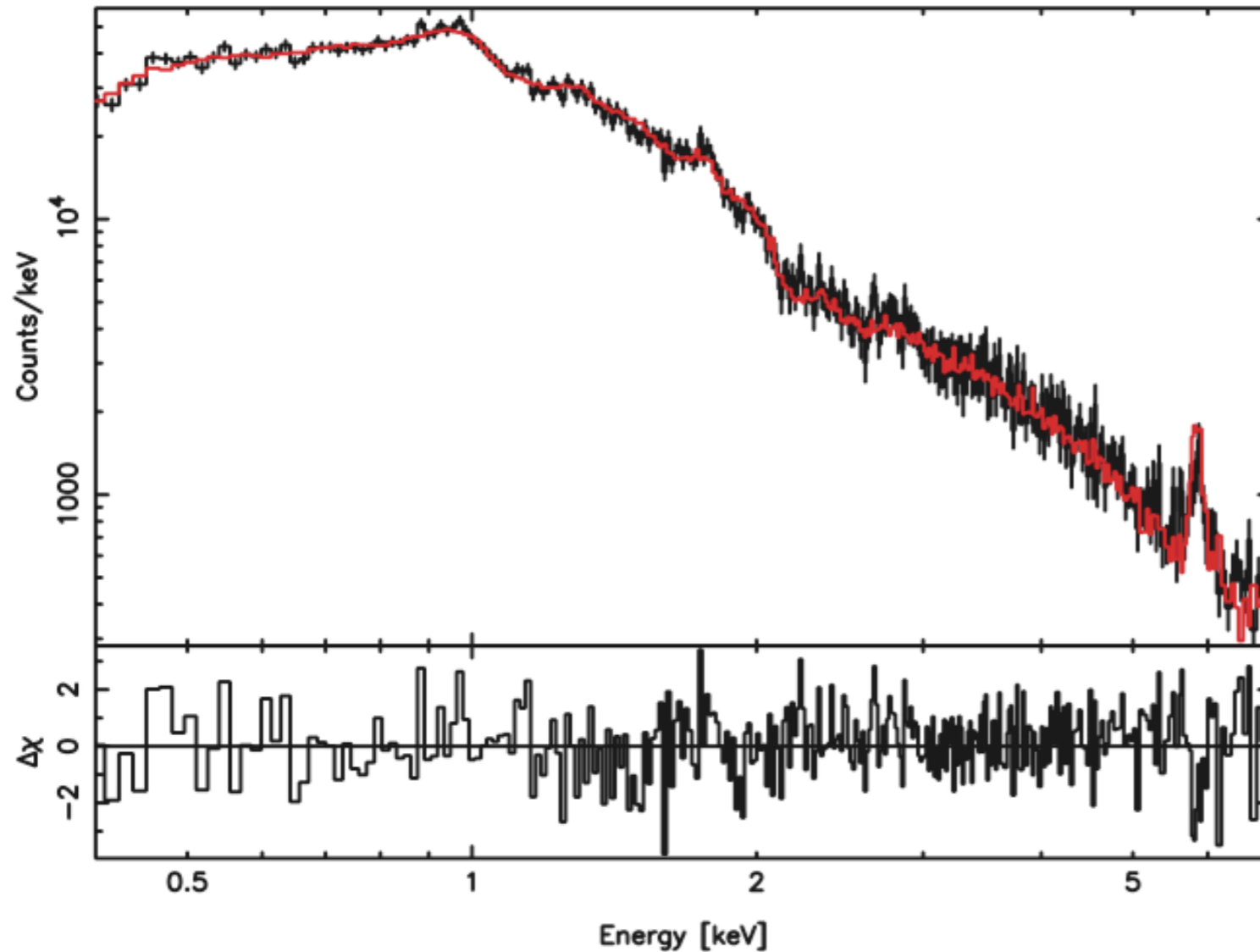


- Find and remove point sources
- Define annular regions
- Extract counts in each annulus
- Cut point source regions from exp. map
- Extract exposure in each annulus
- Divide counts by exposure
- Fit β model to profile

Tools: `dmcopy`, `ds9`, `dmextract`,
`dmtcalc`, `sherpa`



Spectral Analysis



Procedure

- Find and remove point sources
- Extract spectrum (and background)
- Create weighted ARF
- Create weighted RMF
- Correct ARF for contamination
- Define model and fit
- Save fitted spectrum

Tools

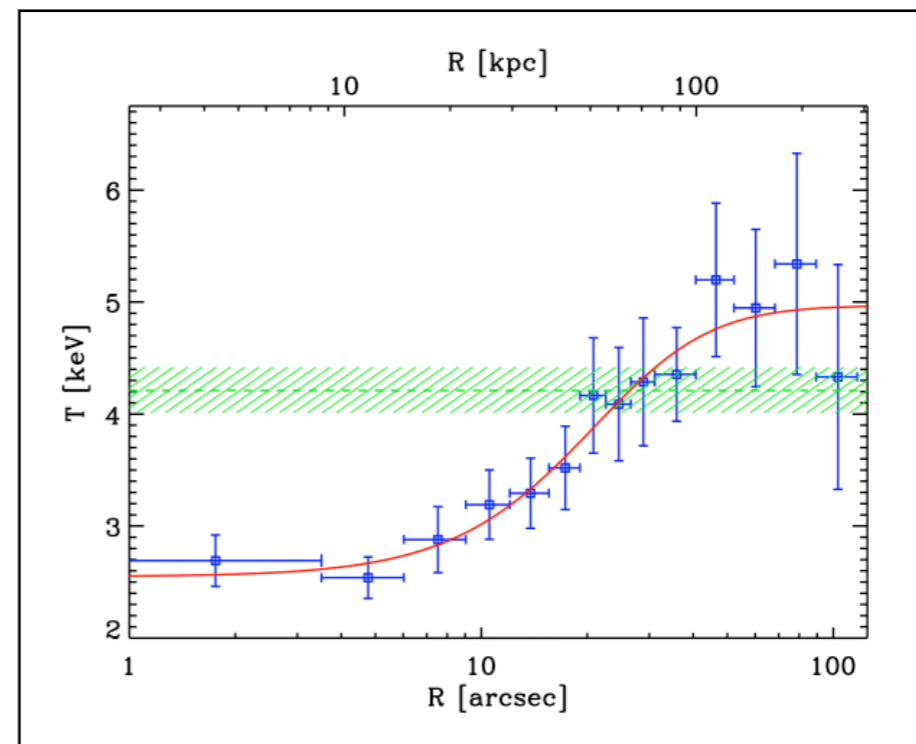
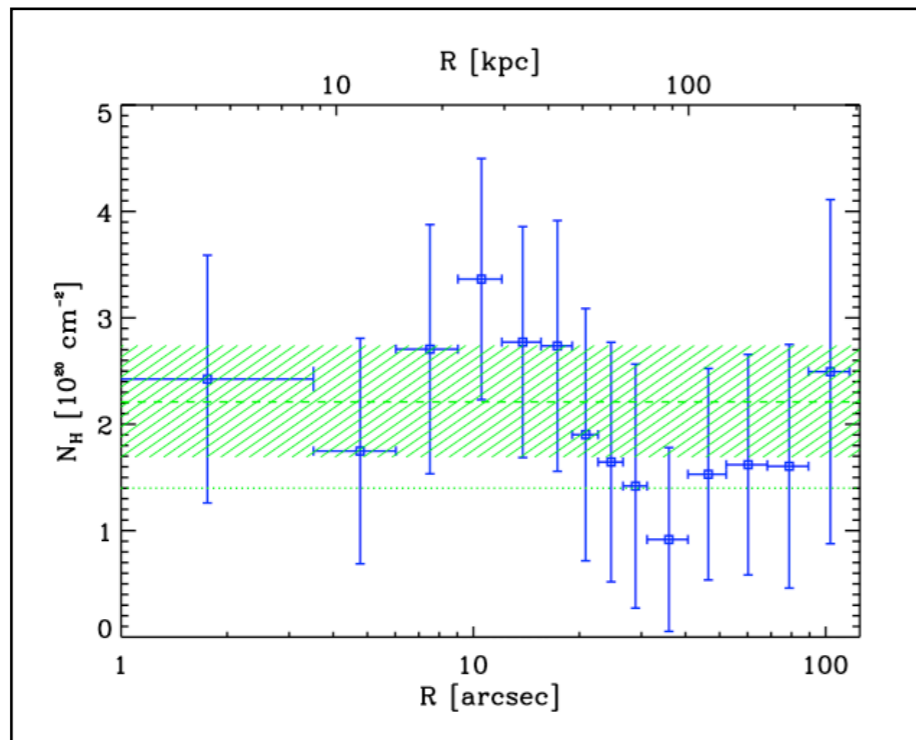
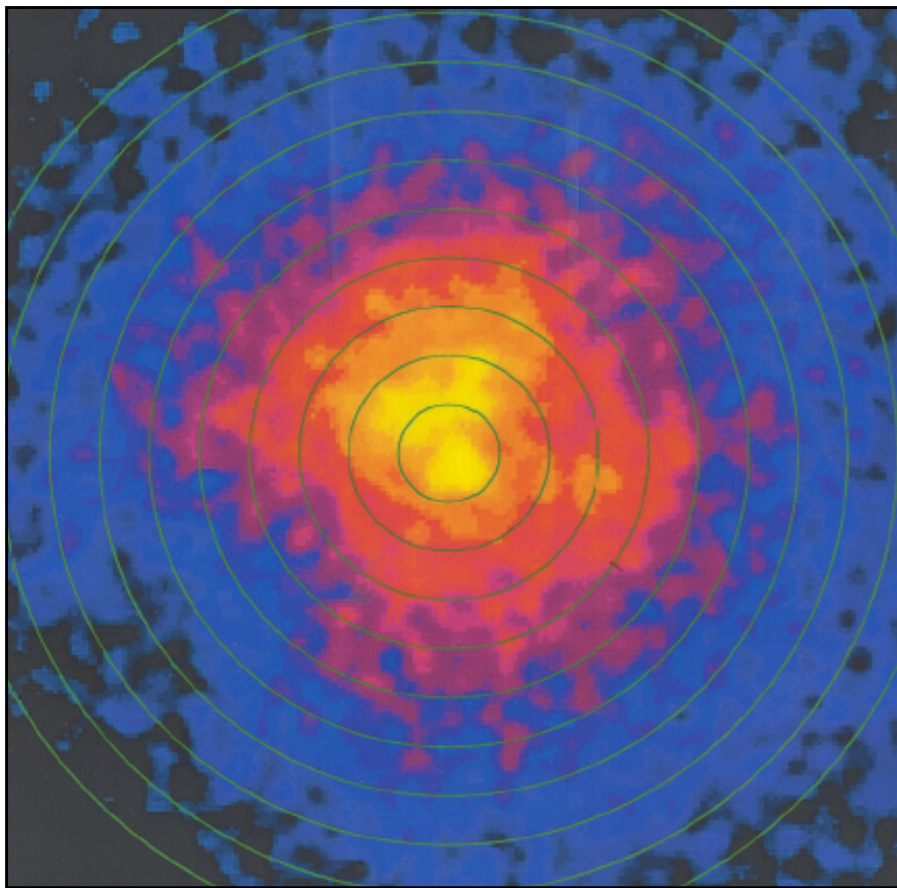
- `wavdetect`, `dmcopy`
- `dmextract`
- `mkwarf`
- `mkacisrmf`
- `sherpa`

```
dmextract infile="evt2.fits[sky=circle(4024.0,4240.0,300.0)][bin pi]" \  
          outfile="spect.pi" wmap="det=8"
```



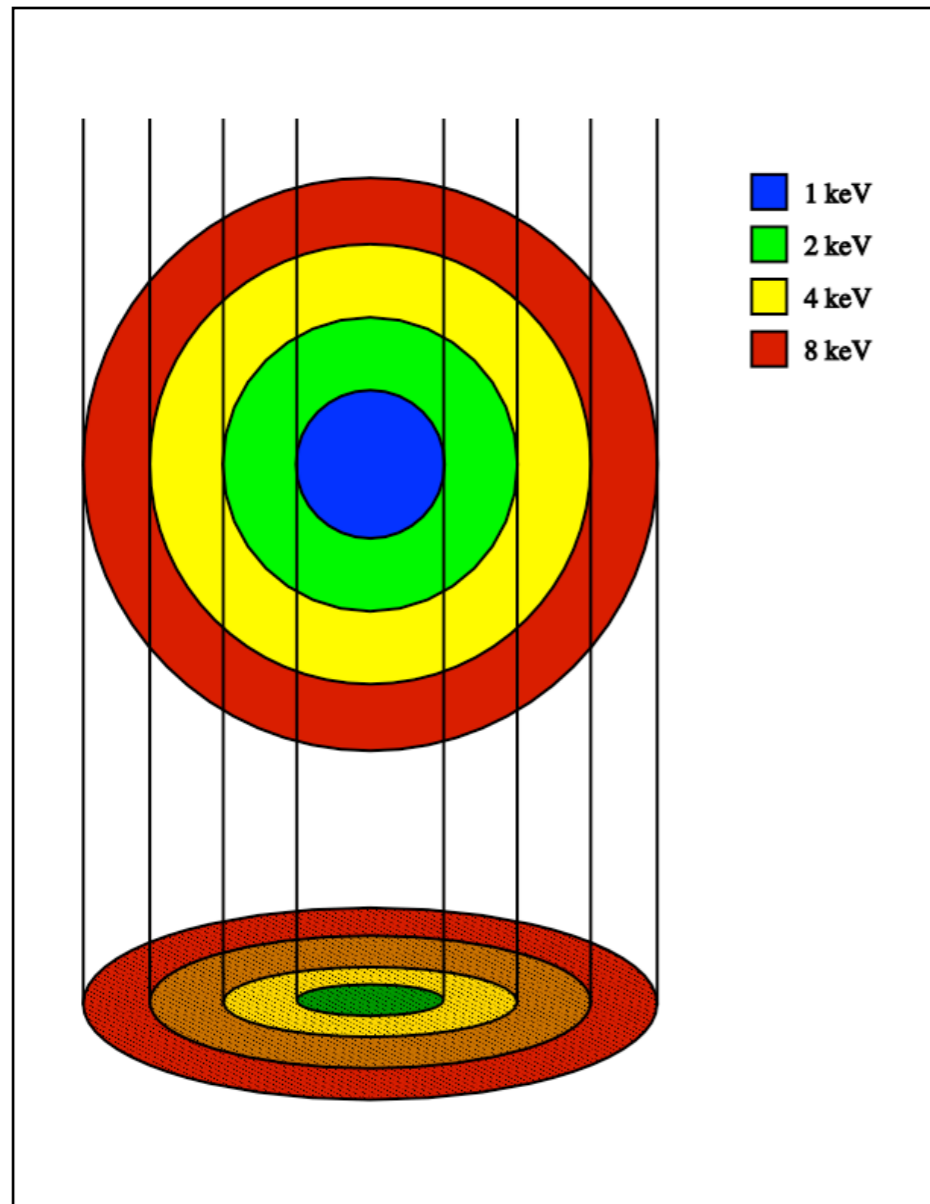

Imaging Spectroscopy

- Cut out point sources [`dmcopy`]
- Define annuli (equal counts?) [`ds9`, `sherpa`]
- Create spectrum and weighted RMF/ARF for each annulus [`dmextract`, `mkacirmf`, `mkwarf`]
- Define spectral model [`sherpa`]
- Repeat spectral fit for each annulus





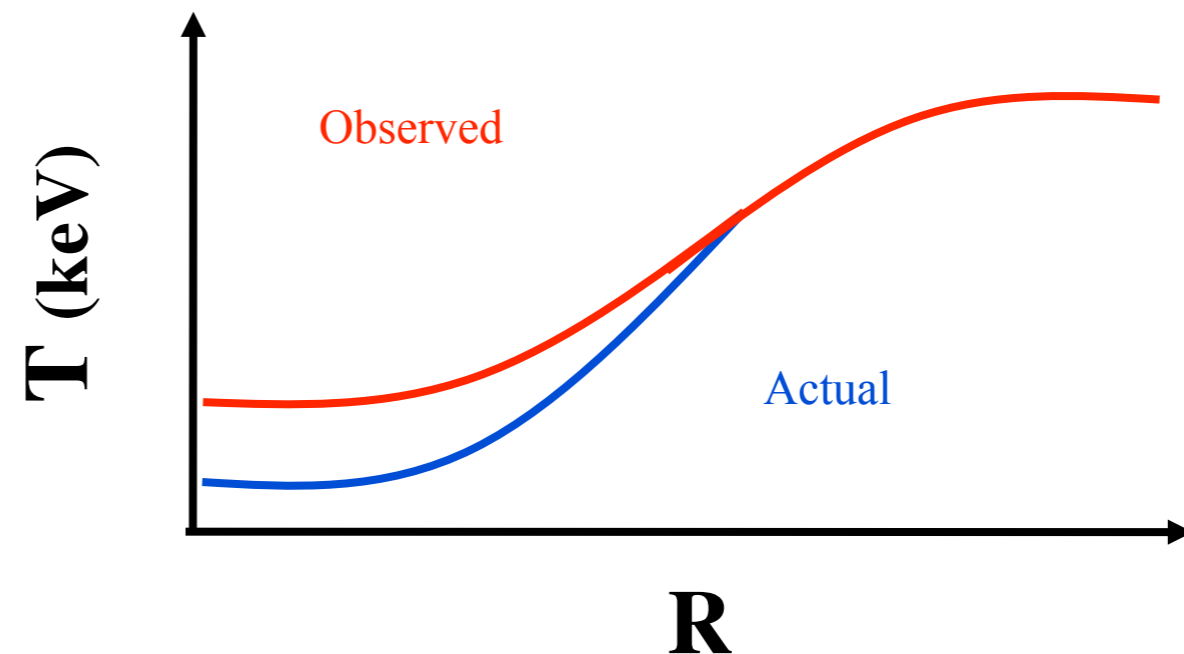
Deprojected spectral analysis



For an assumed geometry, one can calculate the partial volumes, V_{ij} , which contribute to any projected annulus

Problem: Projected spectra contain contributions for all annuli along line of sight

Effect: Measured $\langle T \rangle$ higher than true value



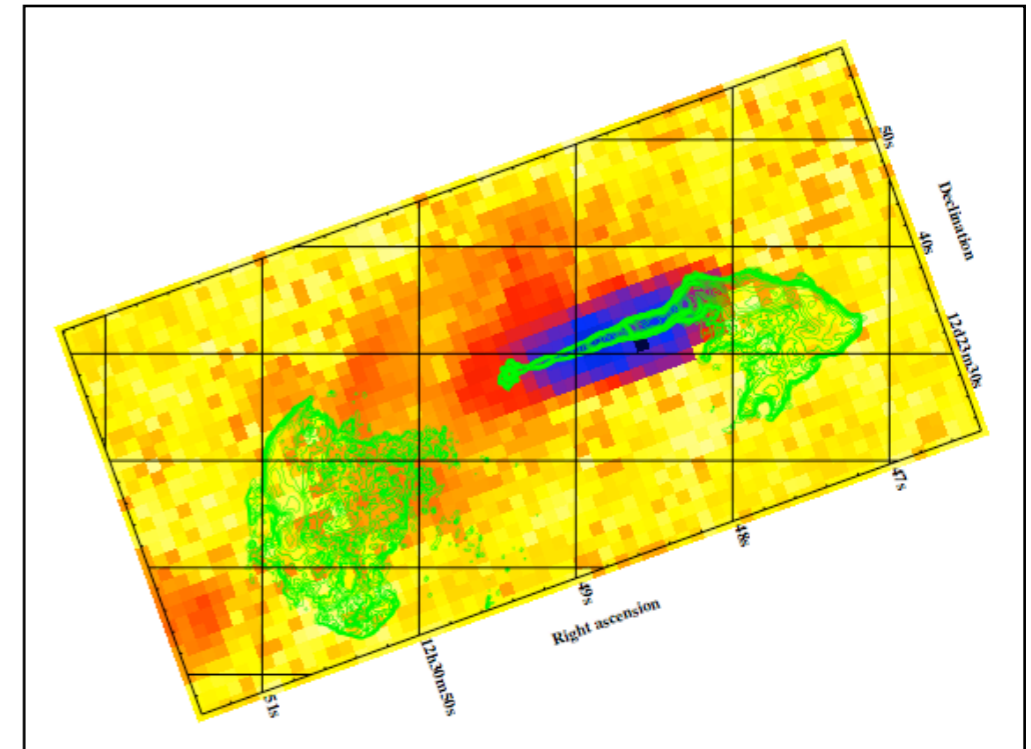
Solution:

- Calculate volume fractions
- Define custom spectral model
- Fit data from all shells simultaneously
- Coming soon to a thread near you



2D Spectral Mapping

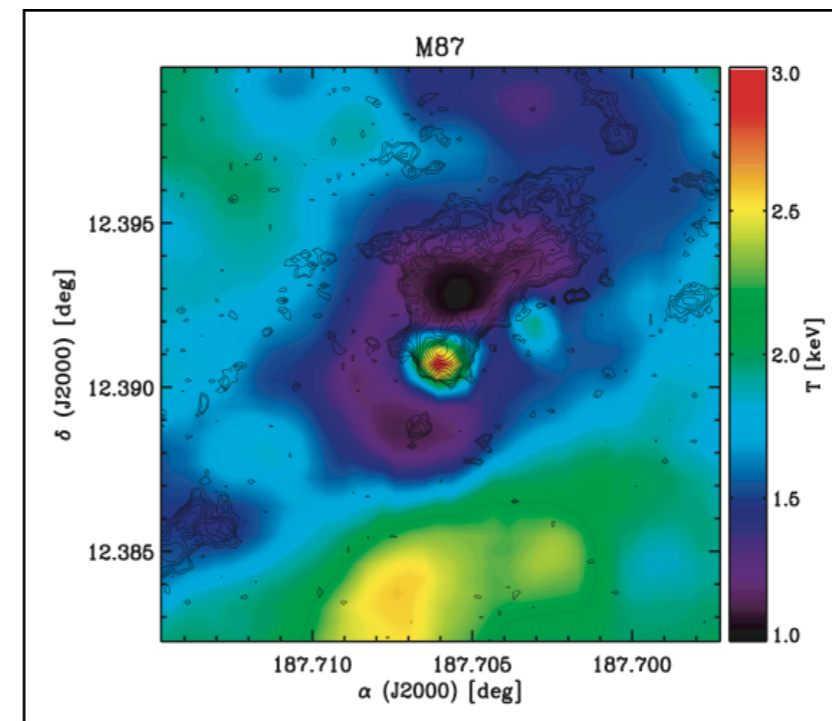
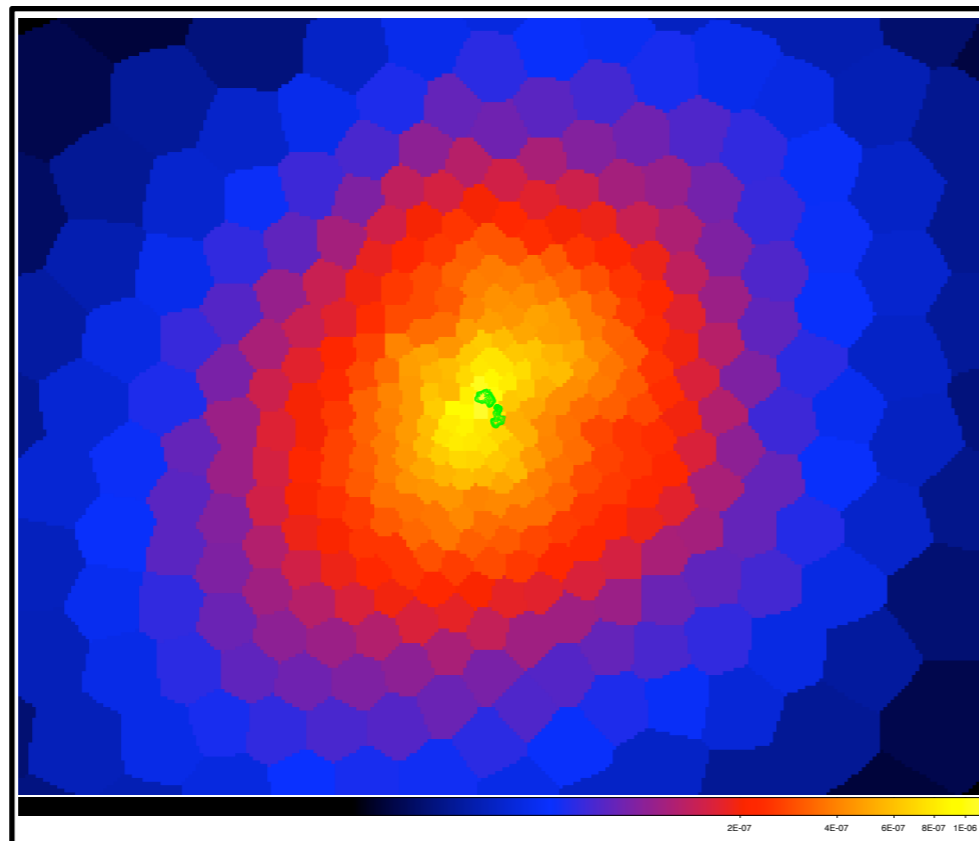
- Map is just **many** spectral fits
- Define grid of boxes containing counts
- Extract spectrum, calculate RMF/ARF for each box
- Fit model at each grid point
- Write out fit parameters as a function of position
- Can map any fit parameter



10^3 - 10^4 fits

CPU intensive

Distributed processing





Online Documentation

Threads - CIAO 4.1

http://cxc.harvard.edu/ciao/threads/index.html

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Last modified: 16 June 2009

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All threads
A list of all the threads on one page.

Introduction NEW UPDATED
Beginners should start here. The Introductory threads provide an overview of the main components (GUI applications, parameter files) and concepts (the Data Model, filtering) in the CIAO data analysis software.

Data Preparation UPDATED
When Chandra data goes through **Standard Data Processing (SDP)**, the most recently available calibration is applied to it. Since this calibration is continuously being improved, one should check whether there are newer files available. Similarly, some science decisions are made during SDP; every user has the option to reprocess the data with different parameters.

- CIAO documentation online:
<http://cxc.harvard.edu/ciao/threads>
<http://cxc.harvard.edu/ciao/guides>
<http://cxc.harvard.edu/ciao/why>
- Tutorials
- Guides
- Step-by-step instructions

The End