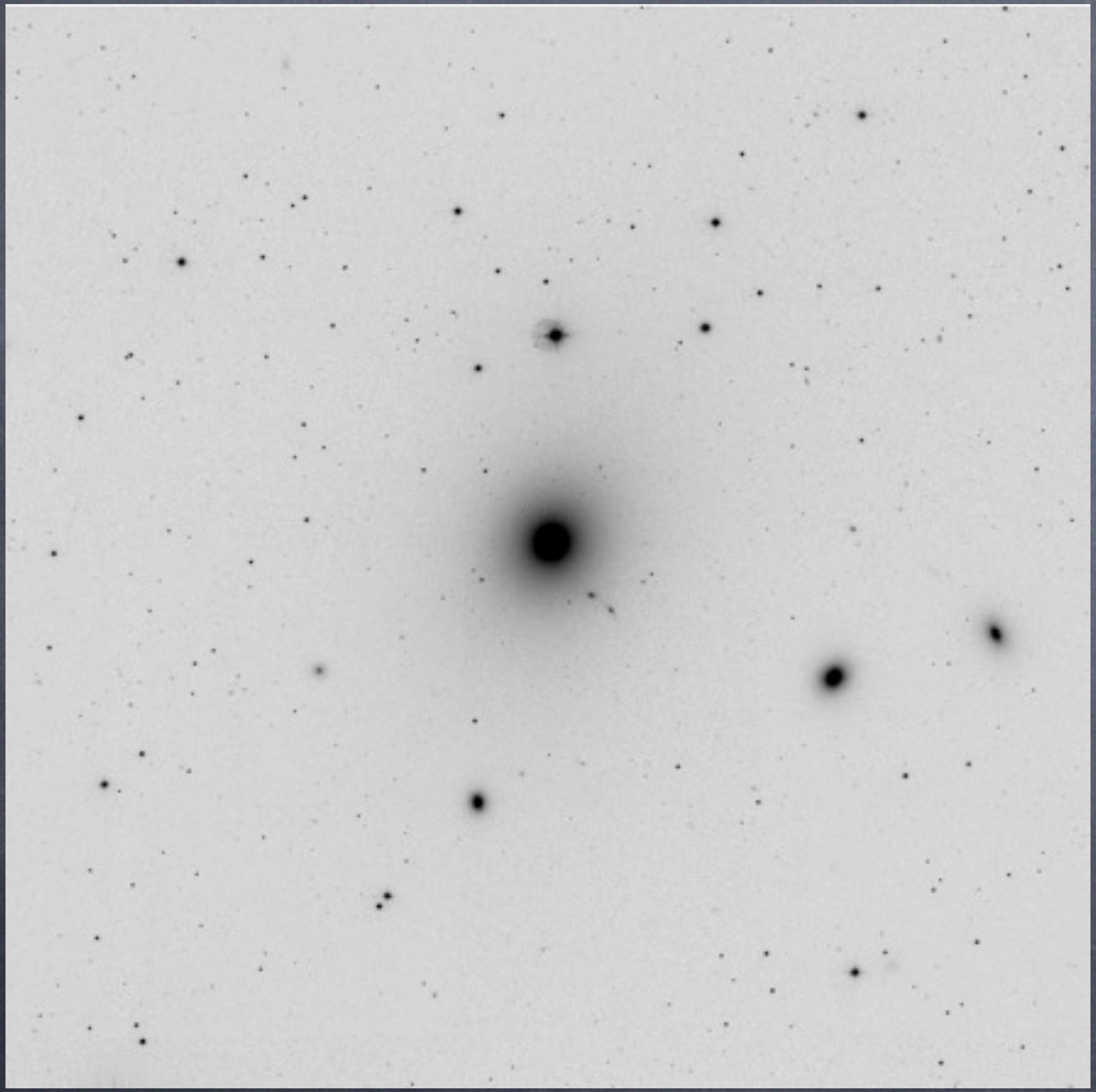
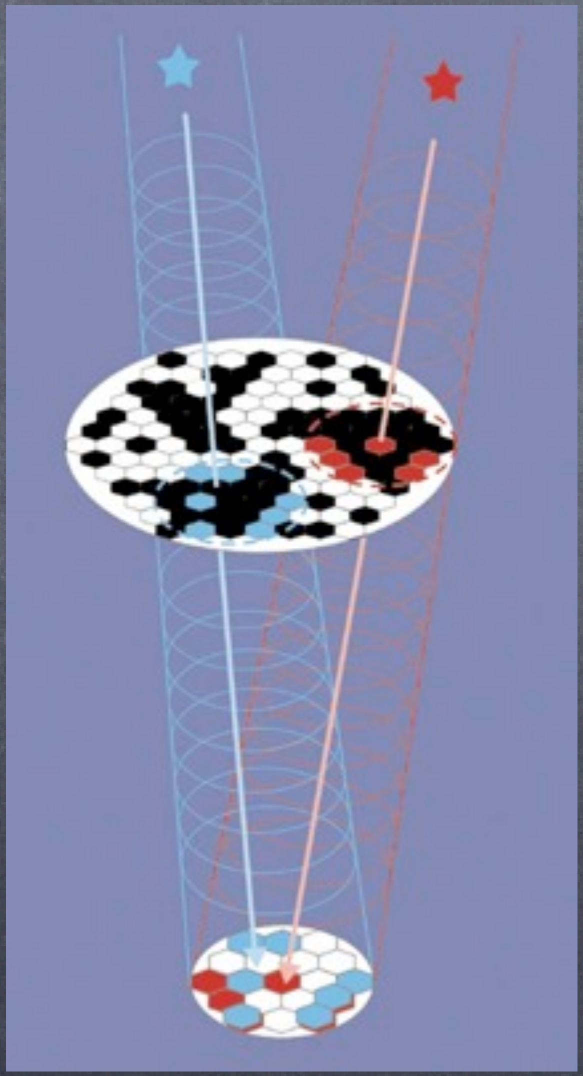
SDSS Mosaic of Virgo Cluster
Central galaxy M87 hosts a bright AGN



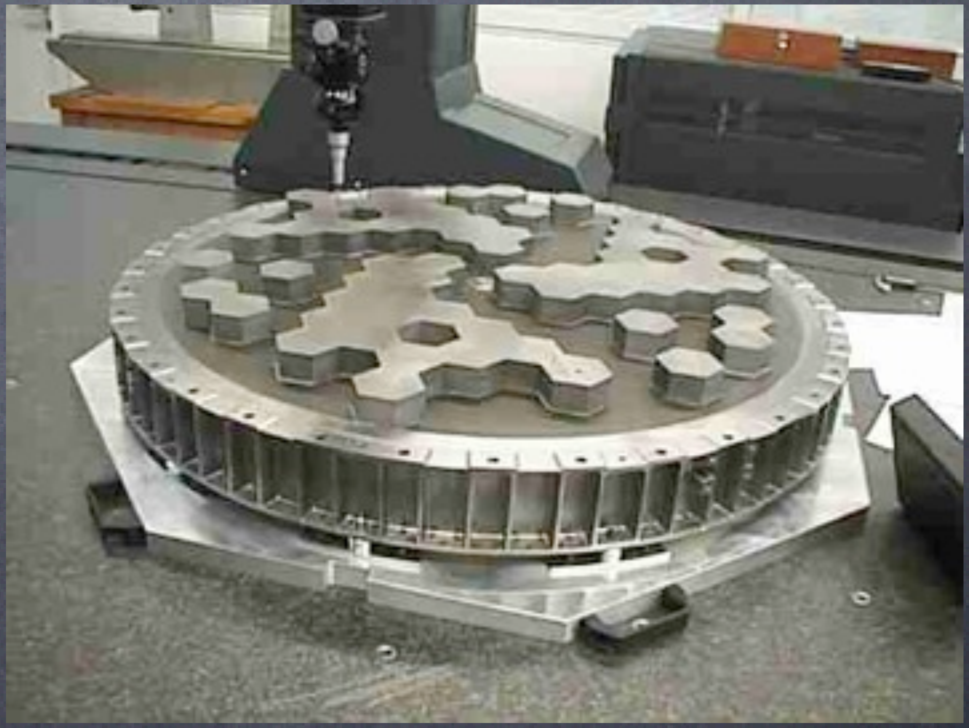
Focusing Hard X-rays

Higher energy X-rays and gamma-rays can not be focused by mirrors and other techniques must be used to provide some measure of directionality. Integral and Swift use the coded-mask technique.

Also provides good background subtraction using areas where the source is blocked.



Integral mask



Hard X-ray Detectors

Cadmium zinc telluride detectors (CdZnTe or CZT): used above 10 keV, semiconductor with better sensitivity to high-energy photons than Si (inner shell binding energies of 10-30 keV and higher atomic number).

- Bandgap of ~1.5 keV means they can operate at room temperature without a lot of dark current.

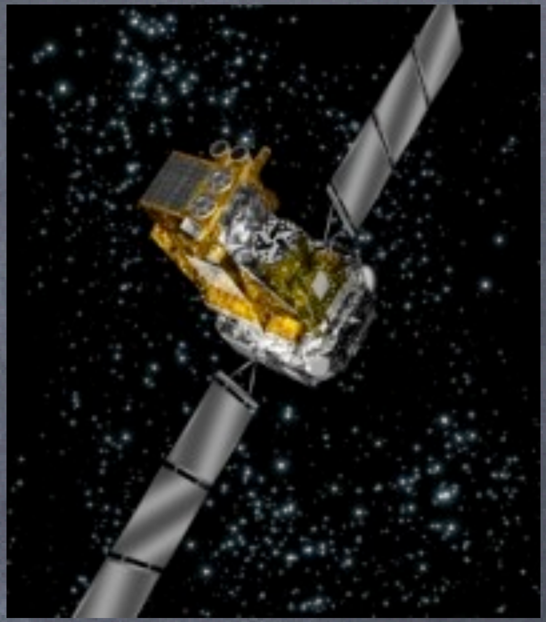
- Each pixel is readout independently like IR arrays.

Scintillators: use crystals like NaI and CsI which emit optical light when struck by X-rays. Good for higher energy X-rays and soft gamma-rays. The optical light is then detected with photomultipliers.

Hard X-ray Telescopes

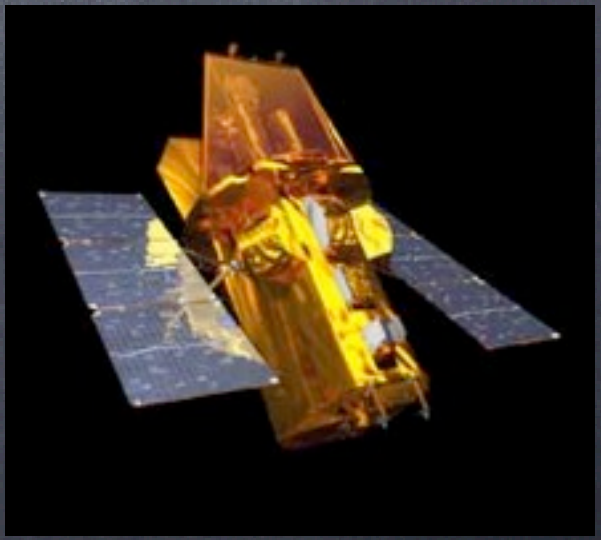
Integral:

- launched in 2002
- Instruments (coded mask):
  - JEM-X: X-ray monitor (3-35 keV), gas scintillators
  - IBIS: hard X, soft gamma imager (15 keV-10 MeV), CdTe and CsI tiles
  - SPI: spectrometer (20 keV-8 MeV)
- IBIS has an 8 deg FOV with 12′ resolution



Swift:

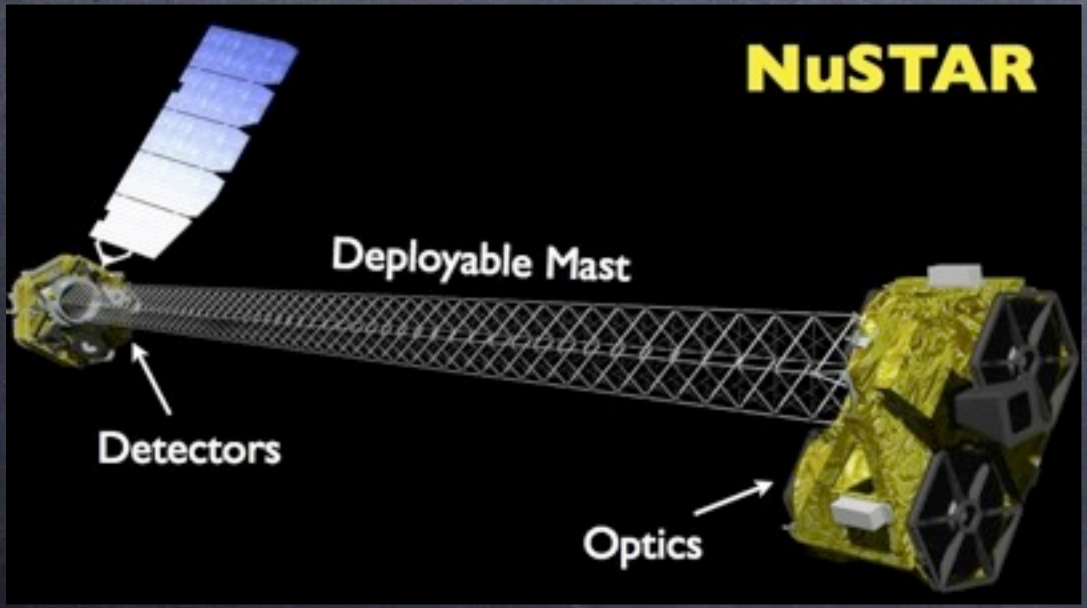
- gamma-ray burst monitor also carrying X-ray and optical telescopes, launched in 2004
- Instruments:
  - BAT: 15-150 keV, coded mask, CdZnTe detector, 1.4 steradian FOV, 17′ PSF
  - XRT: 0.2-10 keV, Wolter 1, 18″ PSF HPD

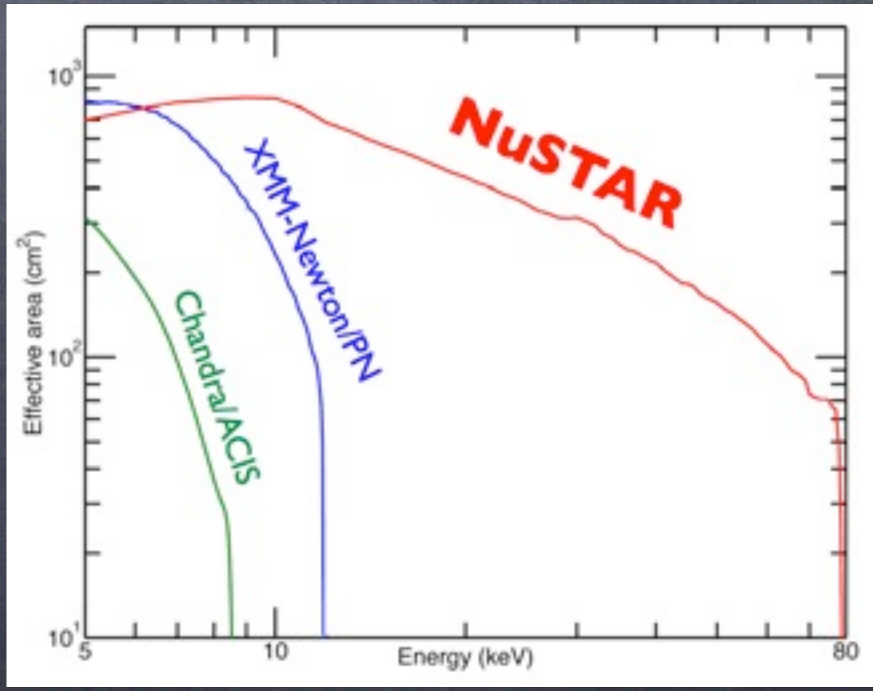


Hard X-ray Telescopes

NuSTAR:

- imaging hard X-ray telescope launched in June 2012
- 5-80 keV, 10″ resolution, 13′ FOV
- Wolter Type 1, 10m focal length achieved with extendable mast
- multilayer coatings including tungsten and platinum. The multilayer stack acts as a crystal lattice and constructive interference creates enhanced reflectivity
- CdZnTe detectors





X-ray Data and Data Reduction

"Handbook of X-ray Astronomy" - Arnaud, Smith, and Siemiginowska

Chandra Proposer's Observatory Guide: http://cxc.harvard.edu/proposer/POG/

Chandra Data Analysis threads: http://cxc.harvard.edu/ciao/threads/all.html

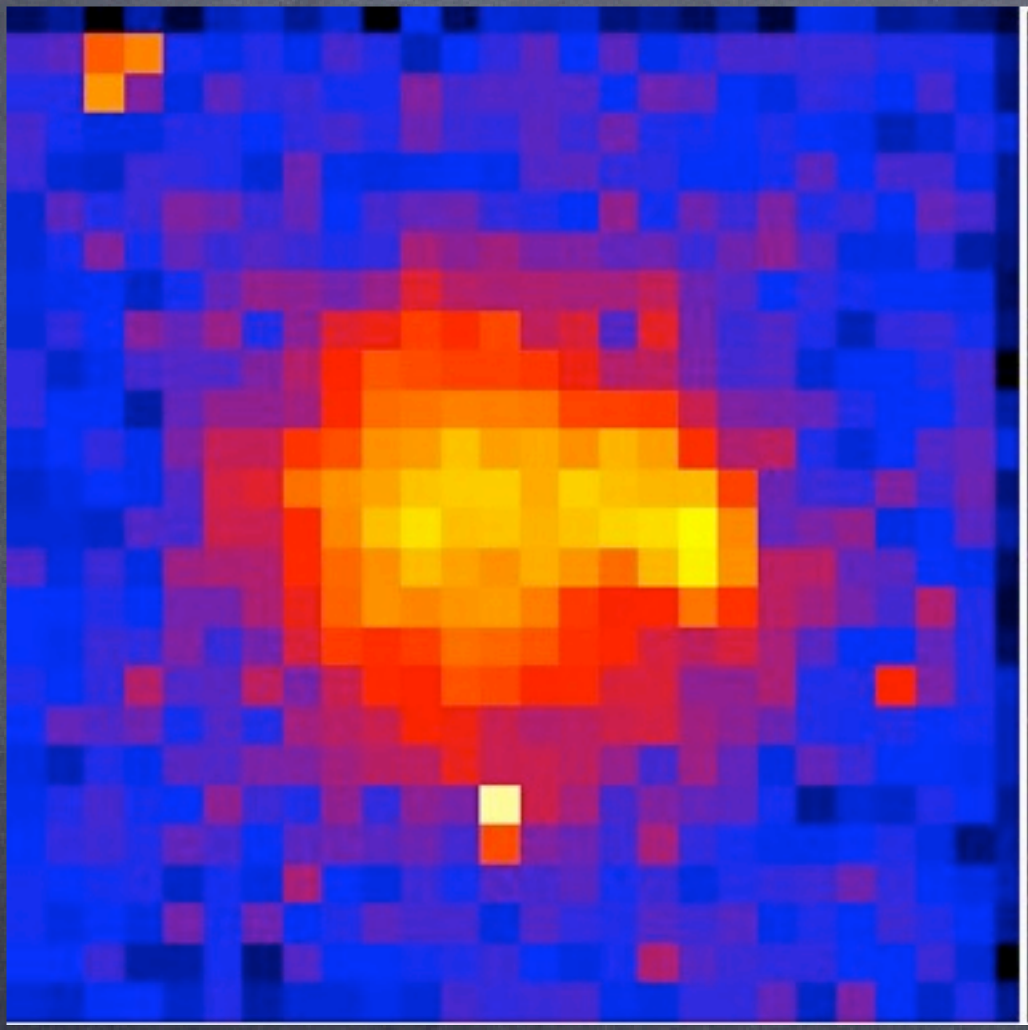
Photon Counting Data

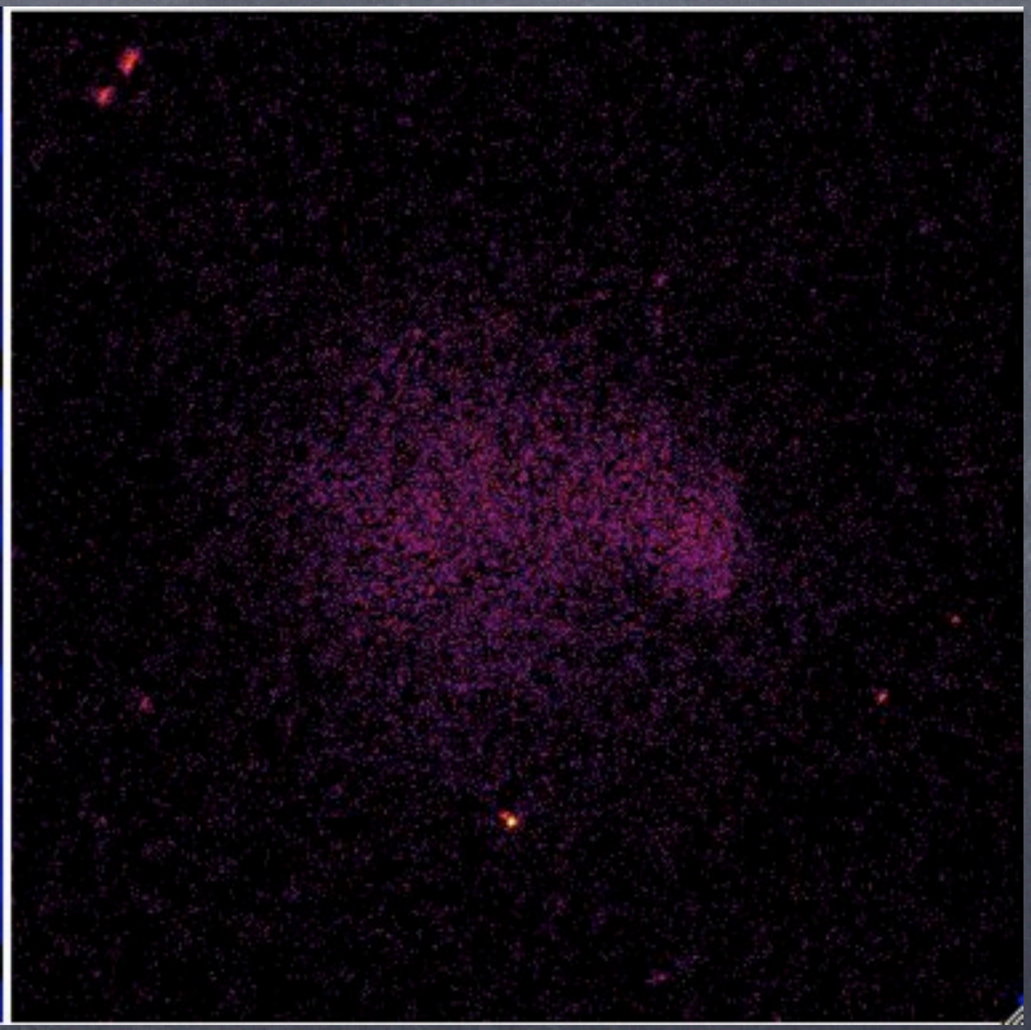
- X-ray data essentially consists of a large table (in FITS format) listing the properties of every photon (or particle) detected. This gives you a lot of options in how you can select and manipulate the data.

- For example you can:
  - Analyze individual events for likelihood that they are source signal (reduce particle background) and adjust them for instrumental problems (like CTI)
  - Create images of any portion of the field with any binning, sub-select on energy to maximize signal to noise, make your own colors/filters, isolate spectral features.
  - Do low-resolution spectroscopy directly from CCD data (or use gratings for higher resolution)
  - Bin in time (e.g. create light curves to look for variability) and crop out bad time intervals (high background, bad aspect solution)

Create Images

dmcopy “eventfile.fits[bin x=10:100:4,y=1:100:4]” image.fits





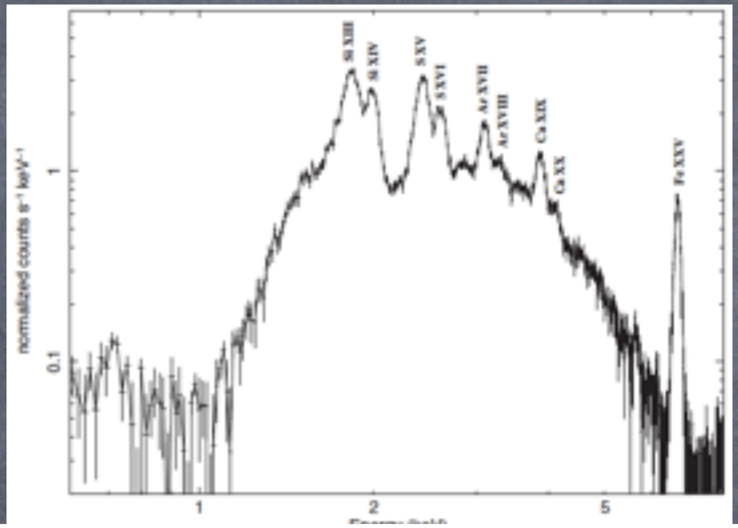
Chandra ACIS pixel scale is 0.492”, about the resolution
XMM sky pixel system is 0.05”/pixel, much much smaller than resolution

Low Resolution Spectroscopy

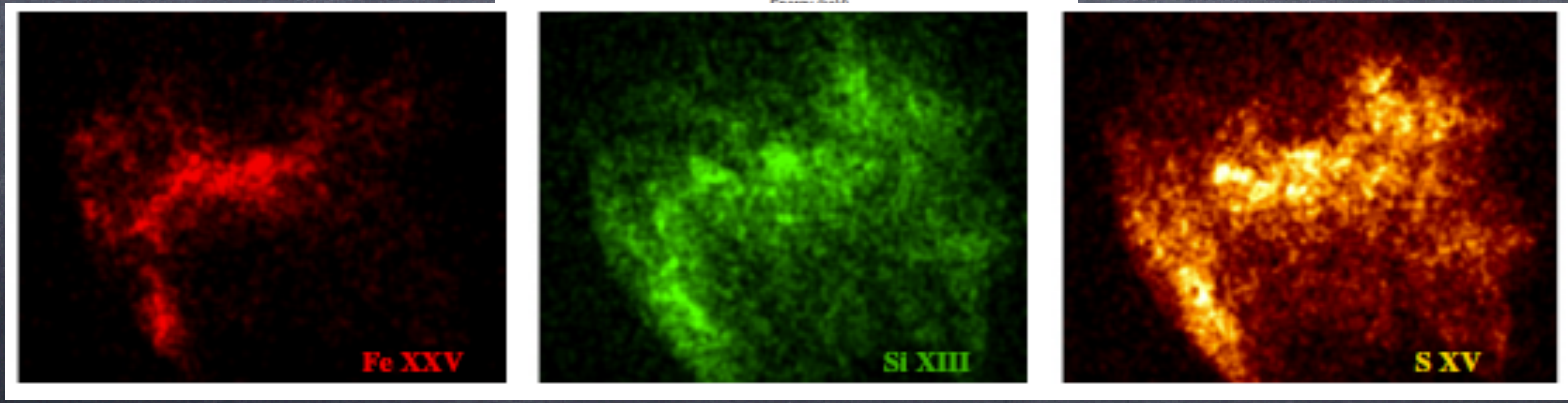
(and custom image filters)

dmcopy “eventfile.fits[energy=500:2000]” only_0.5-2keV.fits

dmextract “eventfile.fits[sky=region(ds9.reg)][bin pi]”



ACIS energy resolution is 100-300 eV

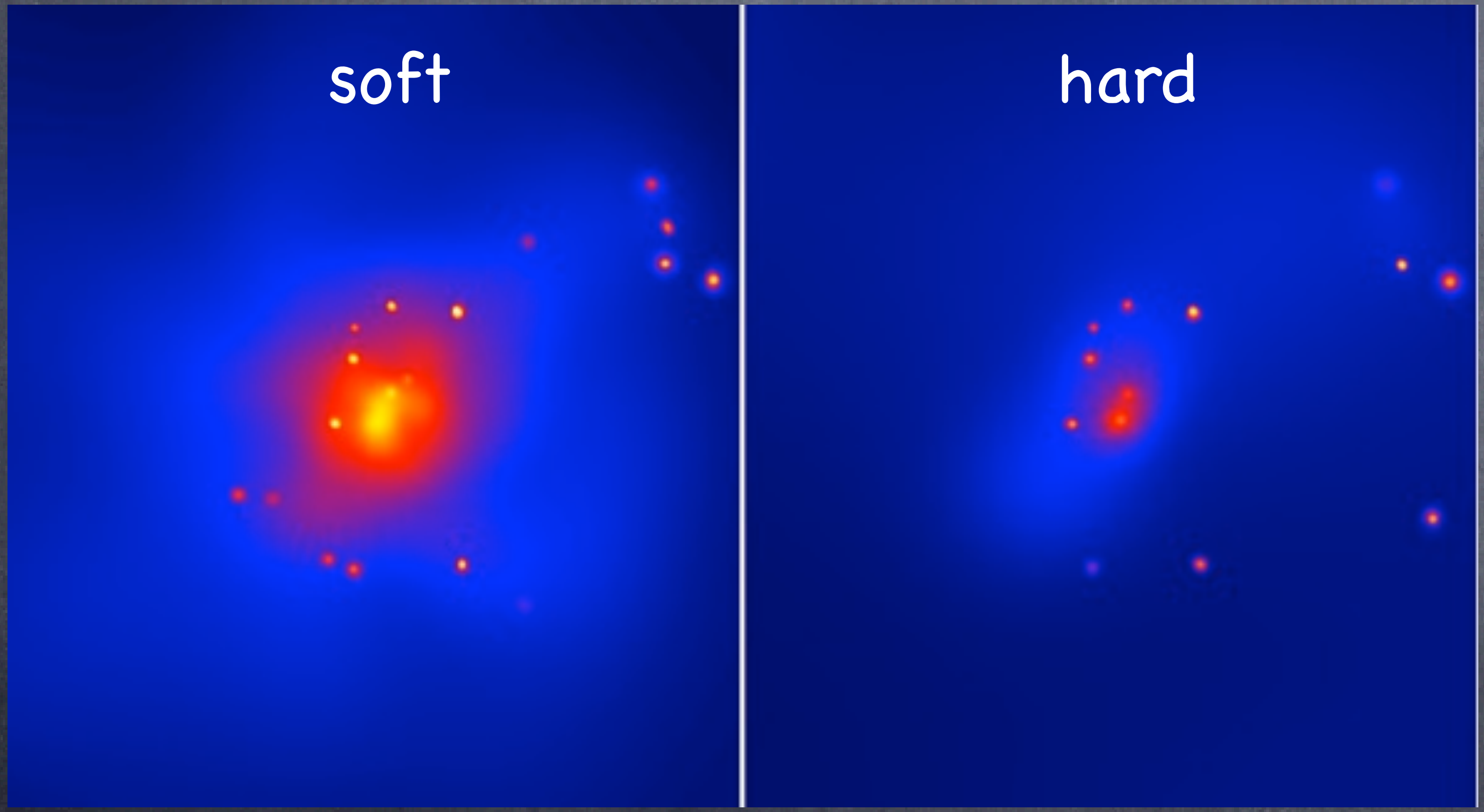


Lopez et al. 2009

Hardness Ratio
(a poor man's spectrum)

Take two energy bands and look at the ratio.
S: 0.5-2 keV, H: 2-10 keV   HR = (H-S)/(H+S)

Elliptical Galaxy



Examples:

AGN, binaries: power law spectra with range of slopes, but typically "hard"

hot gas: bremss. cuts off exponentially above kT, so often "soft" (galaxy ~1 keV, cluster ~5-10 keV)

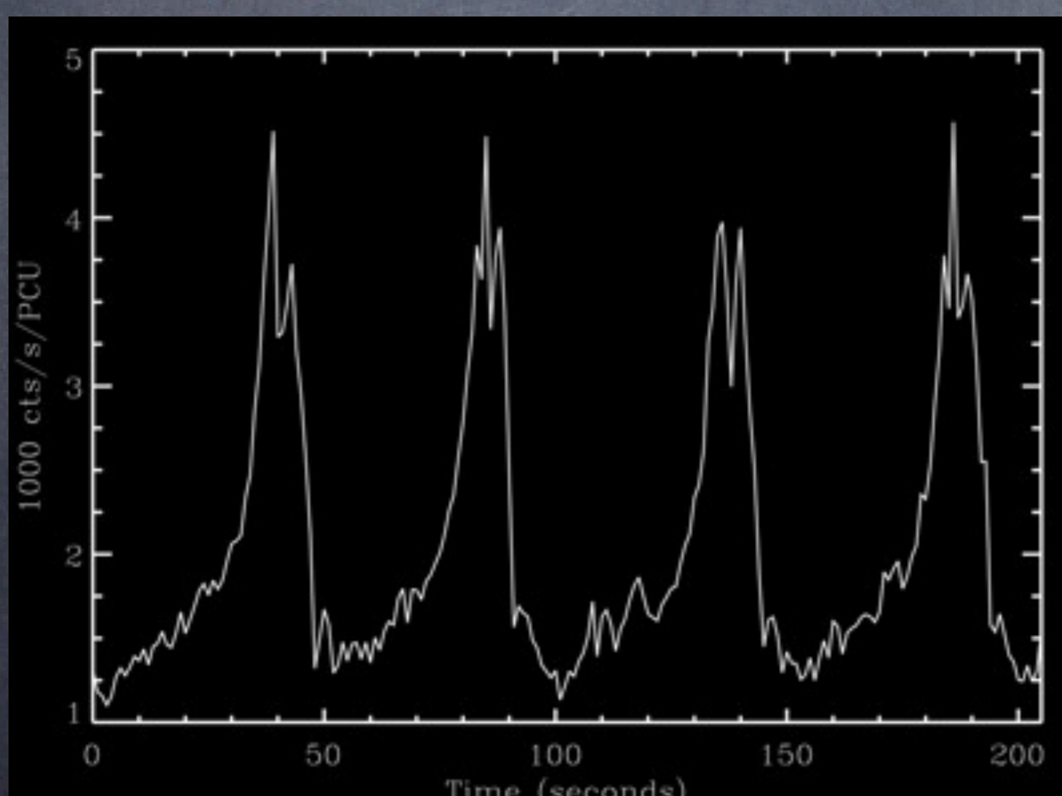
For a known source type, the HR probes absorption, i.e. obscured AGN appear in hard but not soft bands.

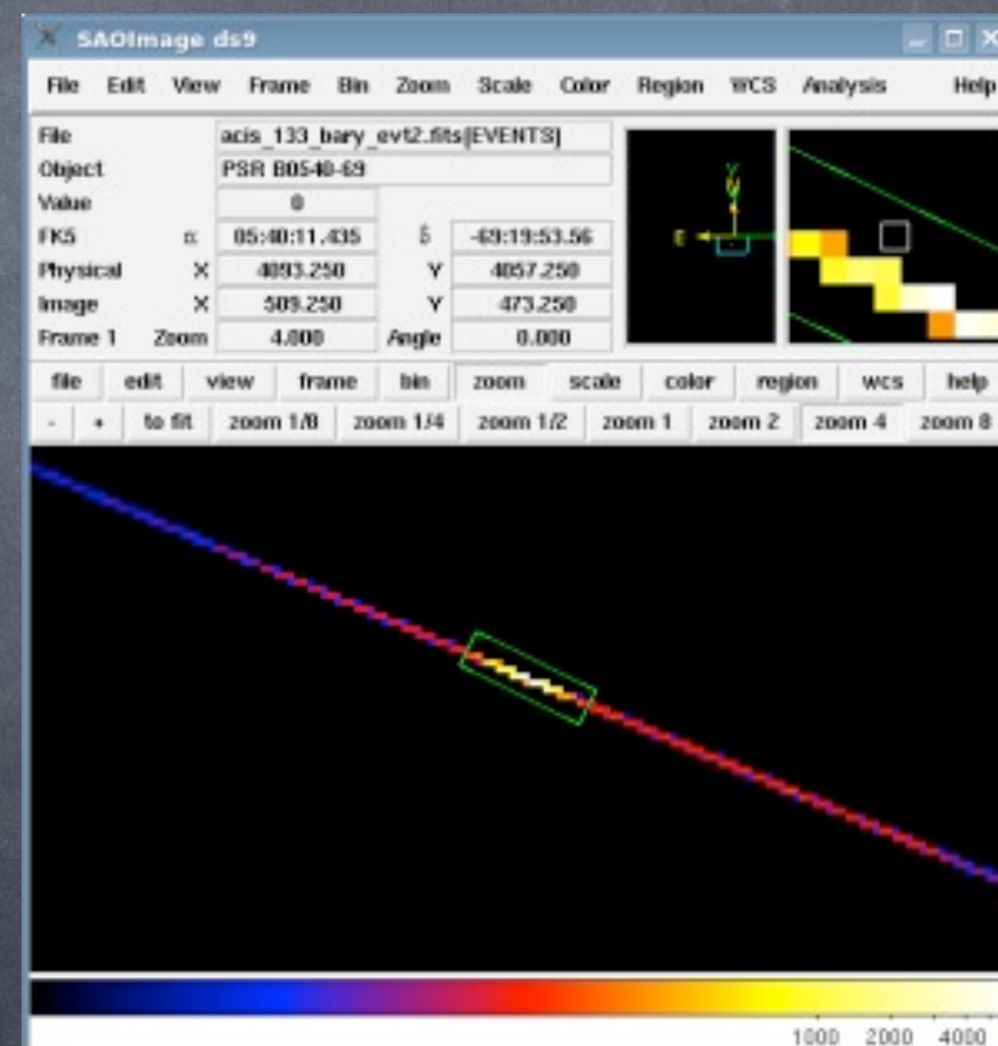
Light Curves - low resolution timing

dmextract “eventfile.fits[bin time=::200]” lightcurve.fits opt=ltc1

ACIS nominal frame time is 3.2 sec, but by running in “continuous clocking mode” one can get 2.85 msec timing.

GRS 1915+105 black hole binary



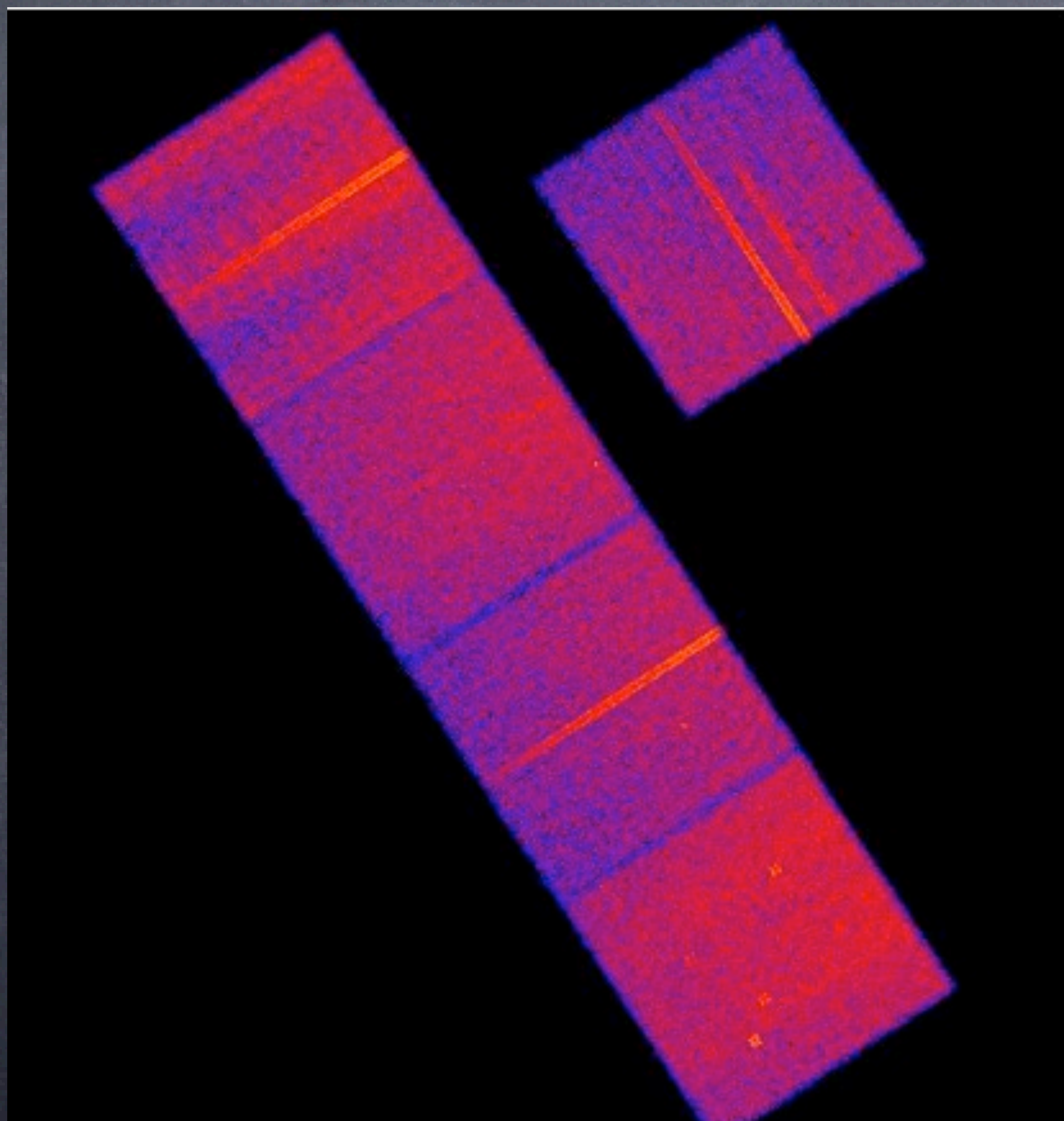


Continuous clocking mode

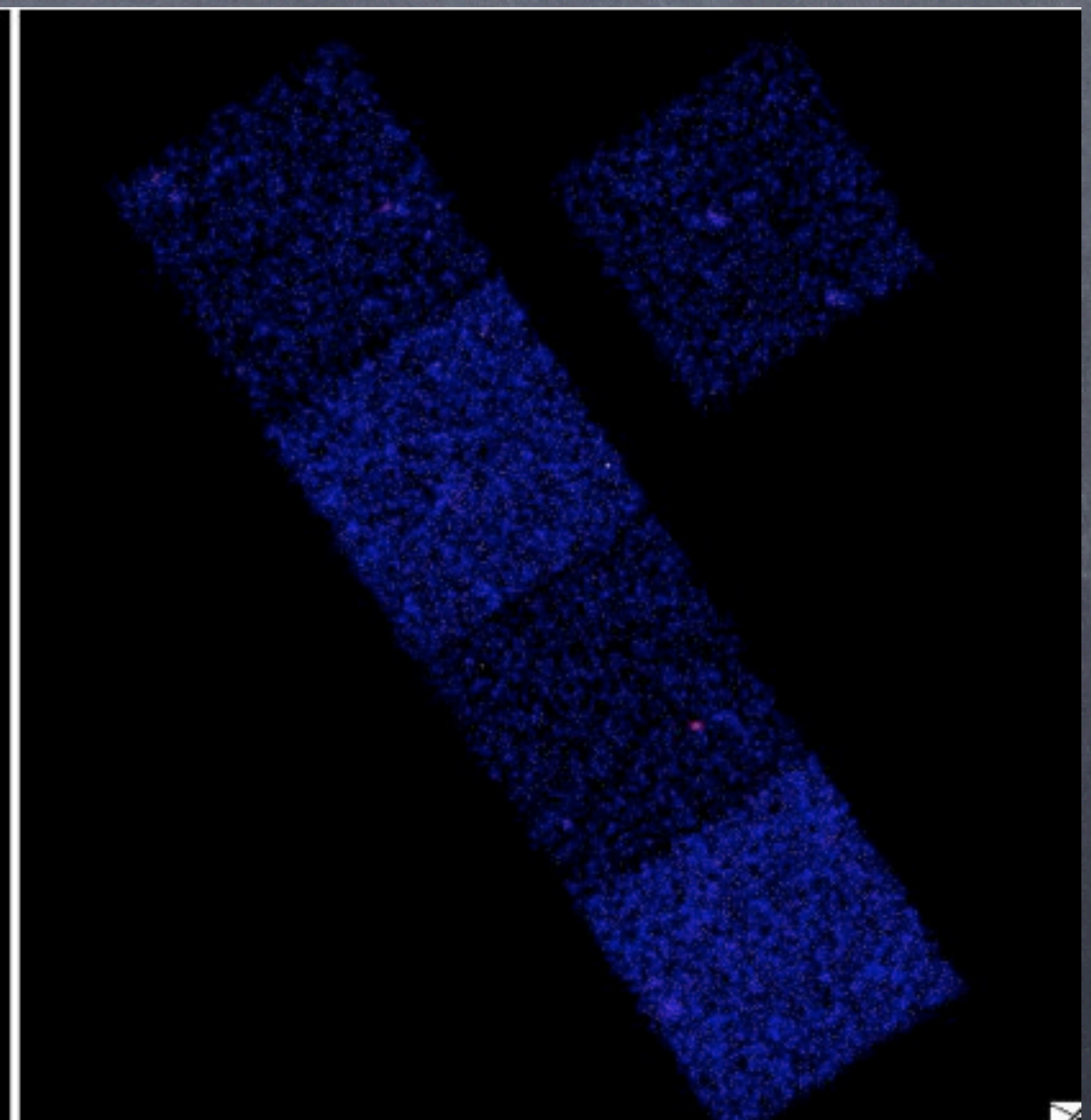
Before and After: Raw vs. Reduced Data

(actually telescope does some filtering before sending data down)

level 1 file (evt1)



level 2 file (evt2), with energy filtering



Basic Calibration Steps for CCD Data

1. Filter data to reduce particle background, remove cosmic rays and bad pixels, and apply gain and CTI corrections, filter on GTI (level 1 file --> level 2 file). Done by pipeline, but sometimes should be rerun.

2. Remove background flares.

3. Filter on desired energy range.

4. Imaging: create exposure map, background map, create PSF model, detect and filter background sources (if needed).

5. Spectroscopy: extract spectrum, extract background, create Redistribution Matrix File and Auxiliary Response File

Event Grades

The signal in a 3x3 region (or 5x5 region depending on mode) surrounding each event is analyzed and the signal pattern is used to maximize the signal-to-background.

32	64	128
8	0	16
1	2	4

Table 6.7: ACIS and ASCA Grades

ACIS Grades	*ASCA* Grade	Description
0	0	Single pixel events
64 65 68 69	2	Vertical Split Up
2 34 130 162	2	Vertical Split Down
16 17 48 49	4	Horizontal Split Right
8 12 136 140	3	Horizontal Split Left
72 76 104 108	6	"L" & Quad, upper left
10 11 138 139	6	"L" & Quad, down left
18 22 50 54	6	"L" & Quad, down right
80 81 208 209	6	"L" & Quad, up right
1 4 5 32 128	1	Diagonal Split
33 36 37 129	1	
132 133 160 161	1	
164 165	1	
3 6 9 20 40	5	"L"-shaped split with corners
96 144 192 13 21	5	
35 38 44 52 53	5	
97 100 101 131	5	
134 137 141 145	5	
163 166 168 172	5	
176 177 193 196	5	
197	5	
24	7	3-pixel horizontal split
66	7	3-pixel vertical split
255	7	All pixels
All other grades	7	

good

Chandra Proposer's Observatory Guide

Gain, CTI, and Afterglows

Gain: A gain file takes detected pulse height and converts to energy.

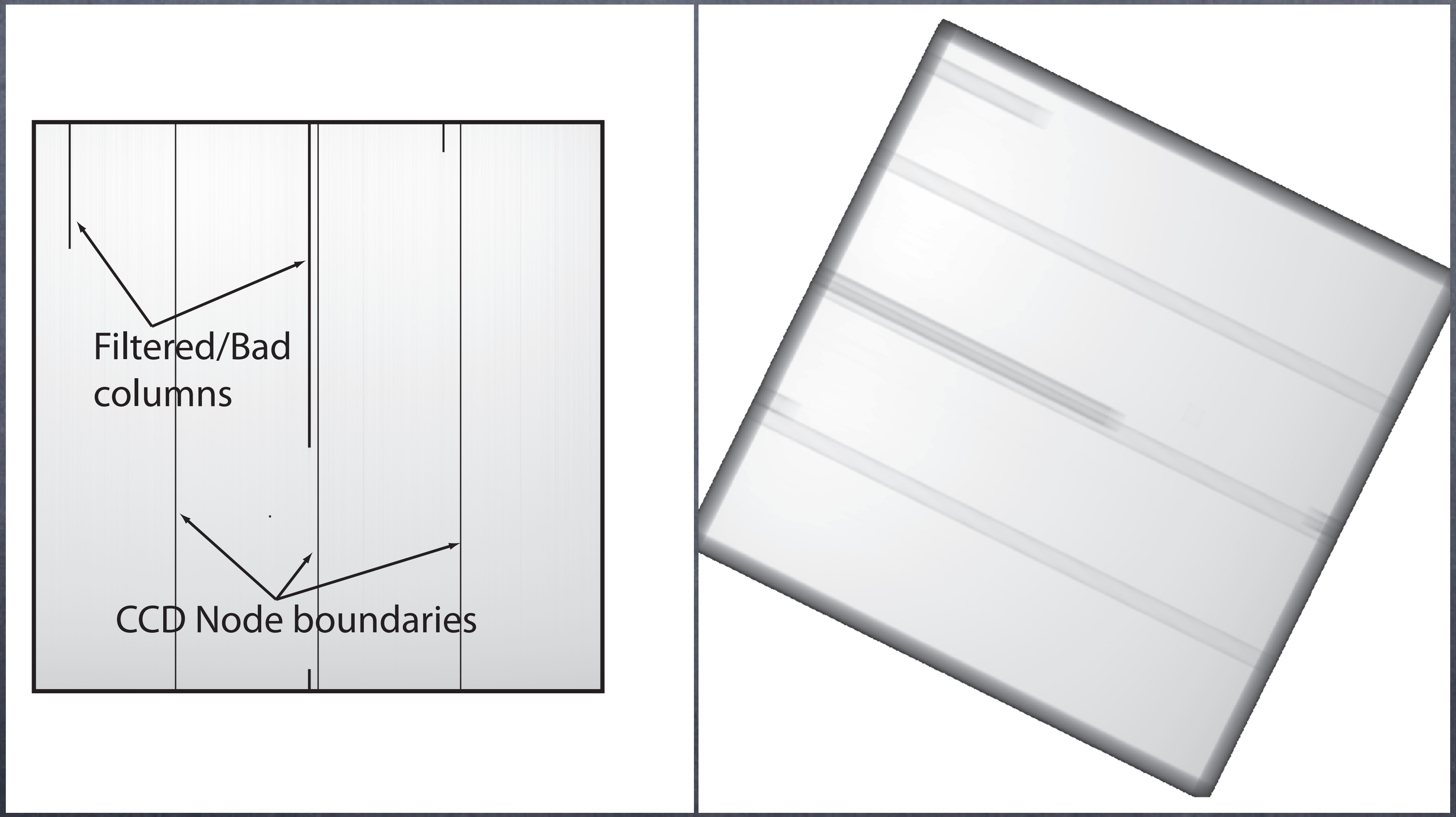
Charge Transfer Inefficiency: a problem for the ACIS FI chips which suffered radiation damage early in the mission. CTI can change the grades of events causing some good events to be lost. A CTI correction which adjusts the pulse height based on position and charge detected is part of the standard data processing.

Afterglows: cosmic rays can deposit a large amount of charge which is not all read out in a single frame. This may lead to a signal in the same pixel in several consecutive frames. Software algorithms are used to detect and remove these events.

** bias files are created and applied to determine PHA before you get the data. These can be used to flag bad pixels.

Bad Pixels

CCDs have bad pixels and columns (either dead or hot). In addition to known bad pixels/columns, bad pixels are searched for in a particular observation. Events in bad pixels/columns are removed along with adjacent pixels (because grading cannot be done properly).



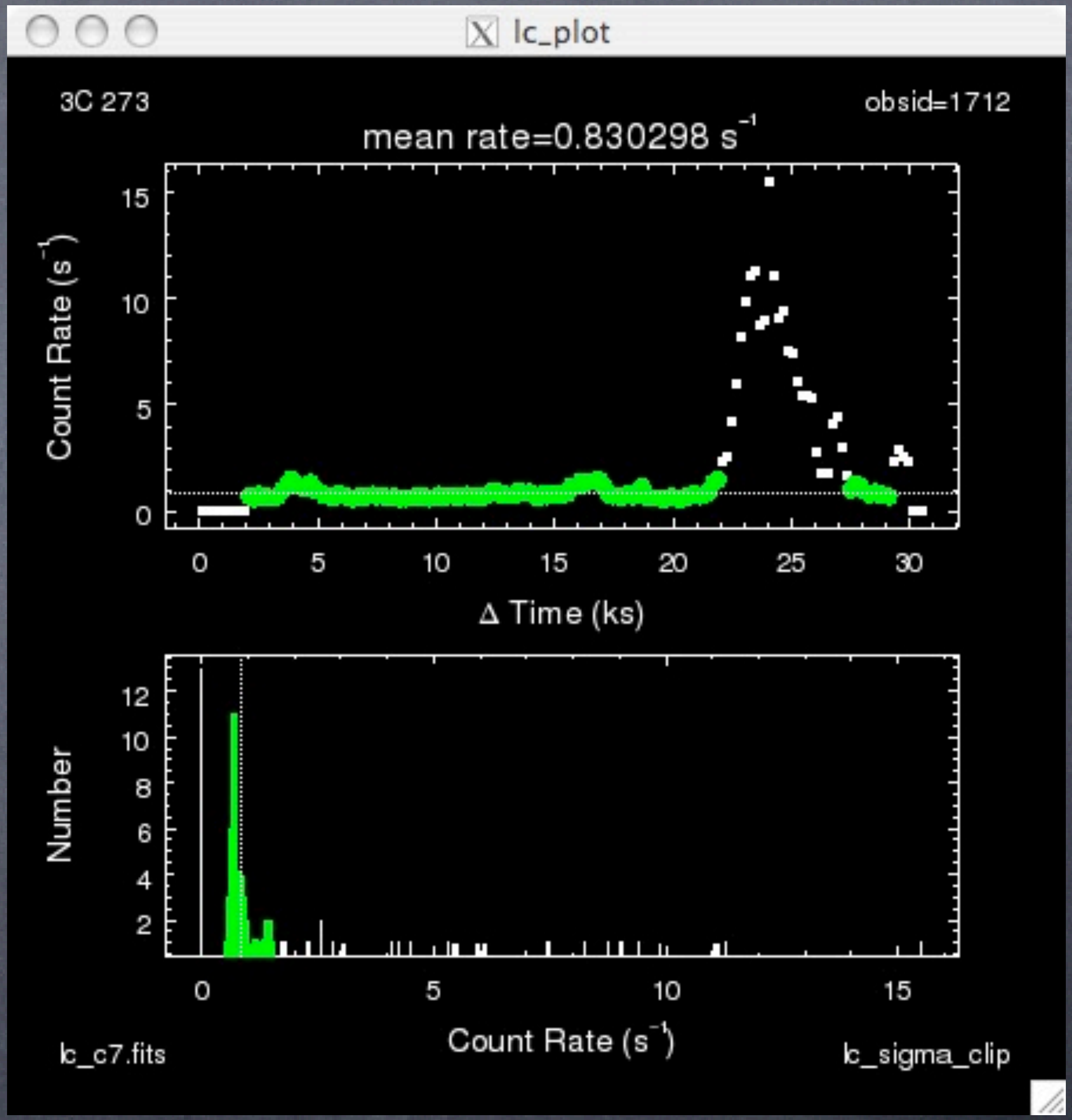
"Handbook of X-ray Astronomy"

Background Flares

In addition to a relatively quiescent particle background, there are flares lasting minutes to hours, which can increase the background by factors of several.

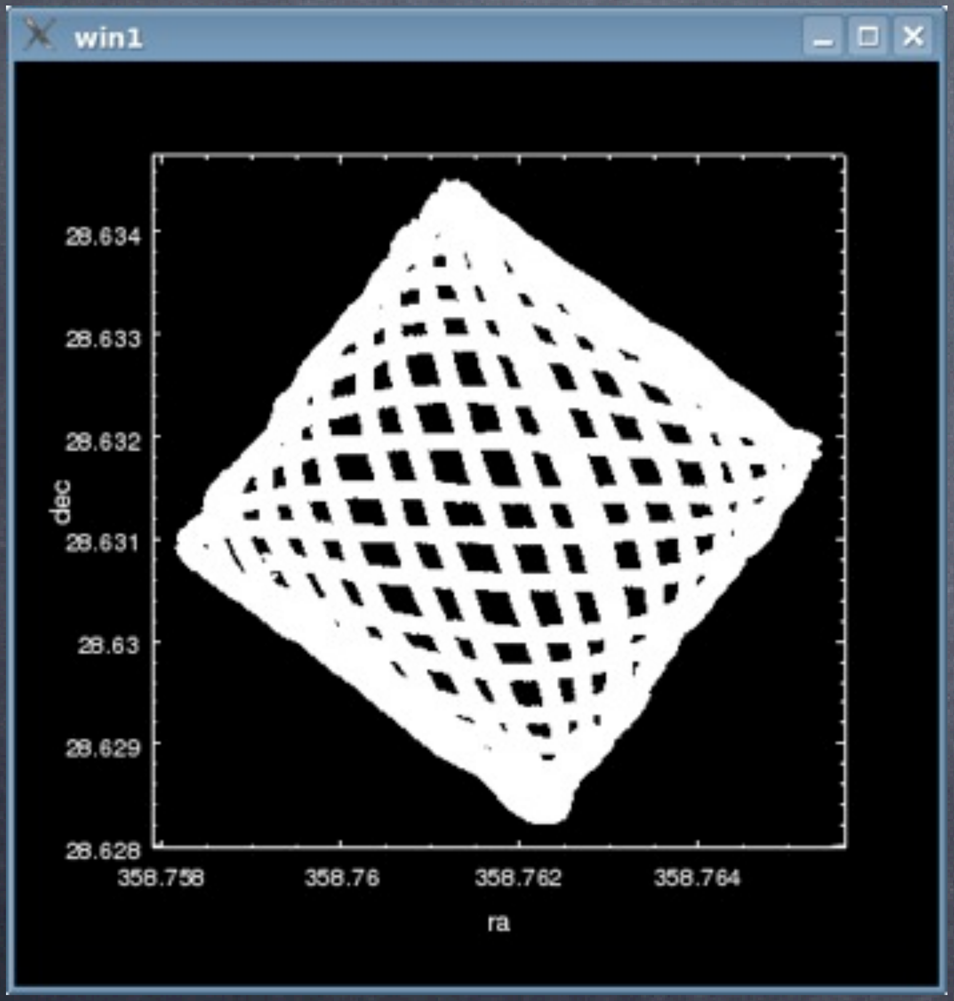
These are thought to be primarily due to geomagnetic protons when Chandra and XMM are outside the Earth's radiation belts.

These can be removed by filtering on time. Iteratively crop time bins above the mean rate.

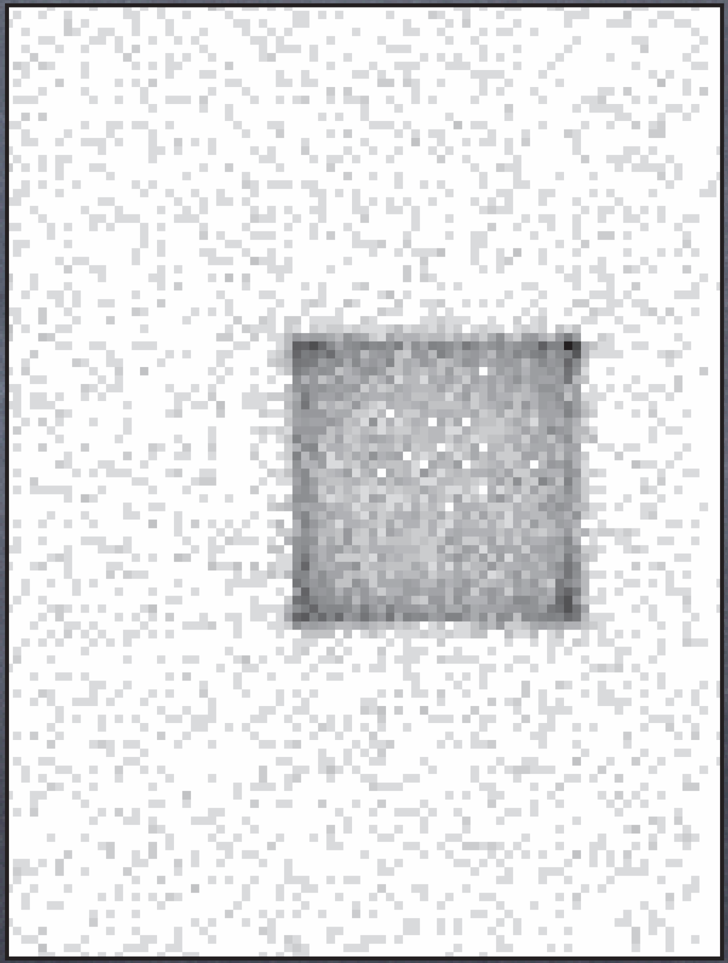


Chandra Dither

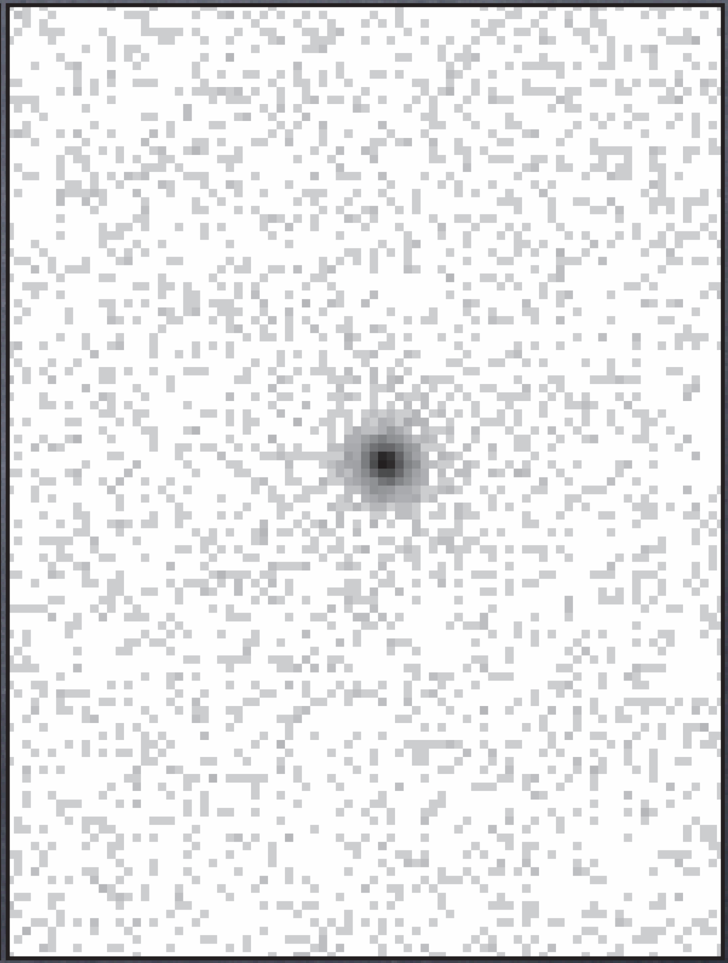
Chandra actually dithers throughout an observation, spreading the source signal over several pixels. This helps to even out the exposure filling in chip gaps and bad pixel regions.



chip coordinates



sky coordinates



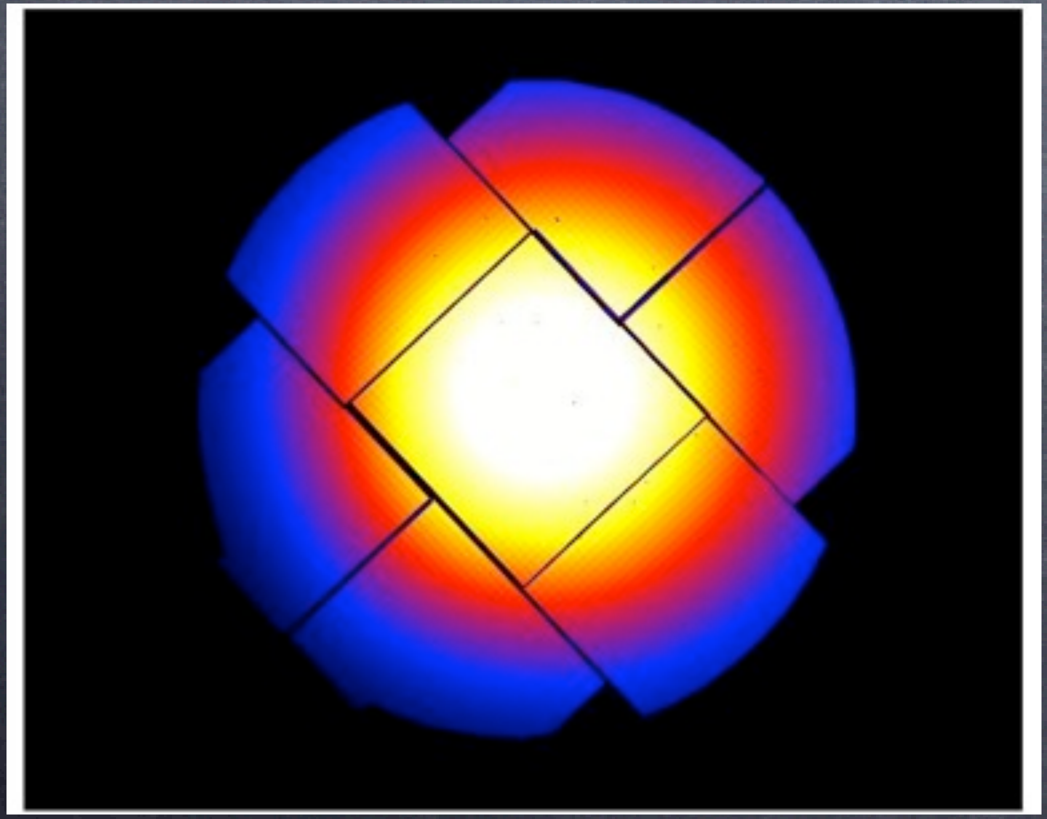
"Handbook of X-ray Astronomy"

Exposure Map

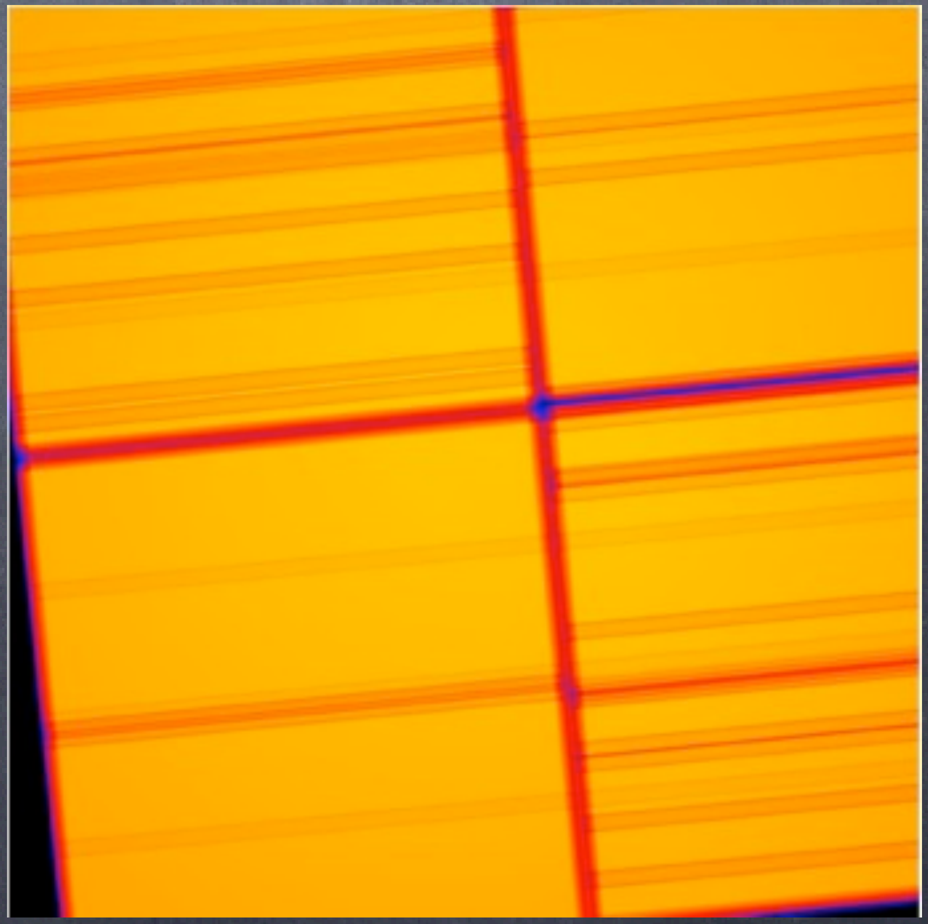
An exposure map is an X-ray astronomers version of a flat-field. It combines the effective area across the detector (QE, vignetting) with the aspect (amount of time pointing in a given direction). The units are cm^2 s and this converts counts from a source to flux.

Effective area is energy dependent, so you must specify an energy or weight by spectrum.

XMM MOS

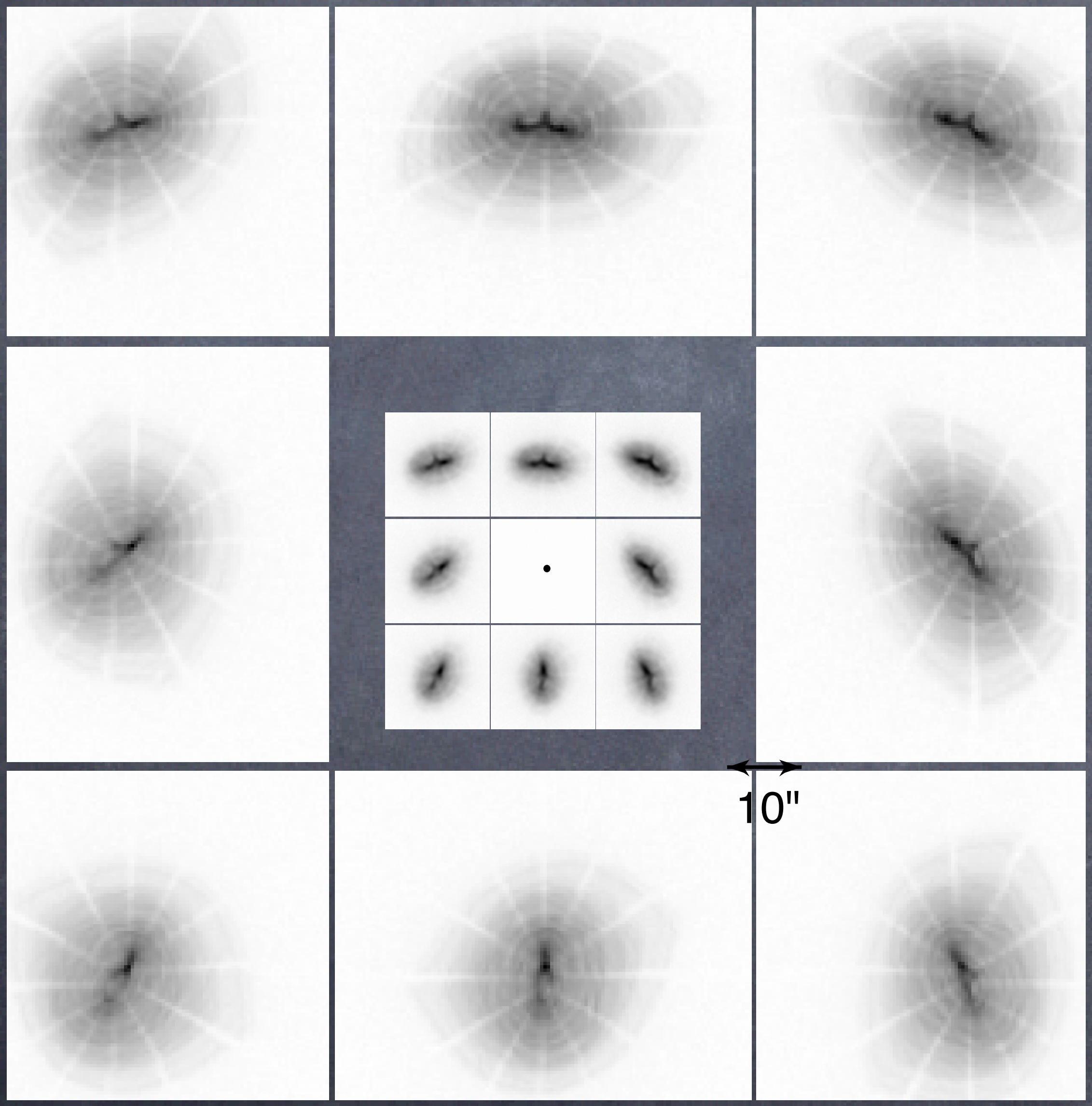


Chandra ACIS-I



Point Spread Function

"Handbook of X-ray Astronomy"

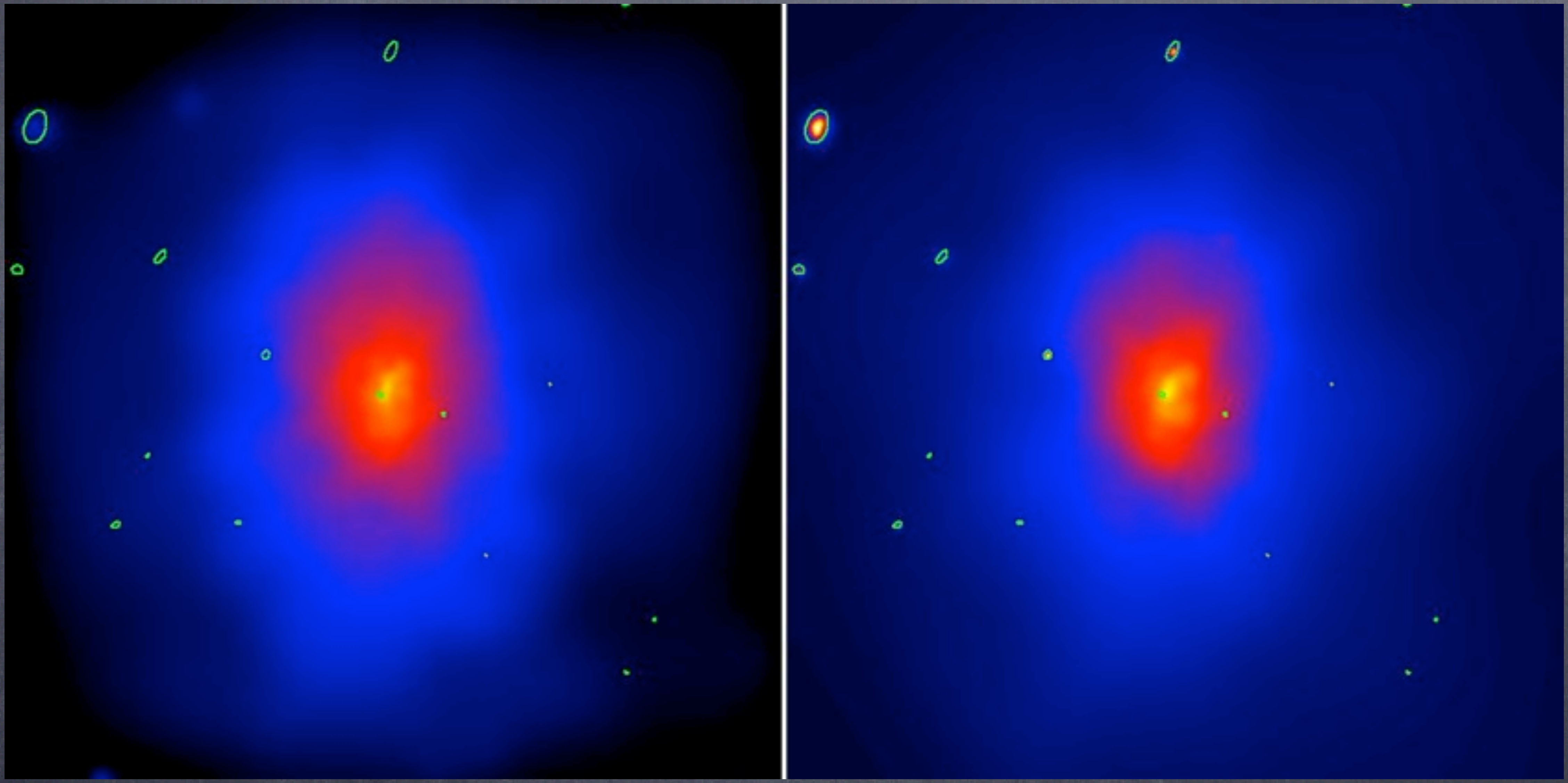


Chandra PSF 5′ and 10′ off-axis

The Chandra PSF is a strong function of off-axis angle (this is less true for XMM). It also depends on energy.

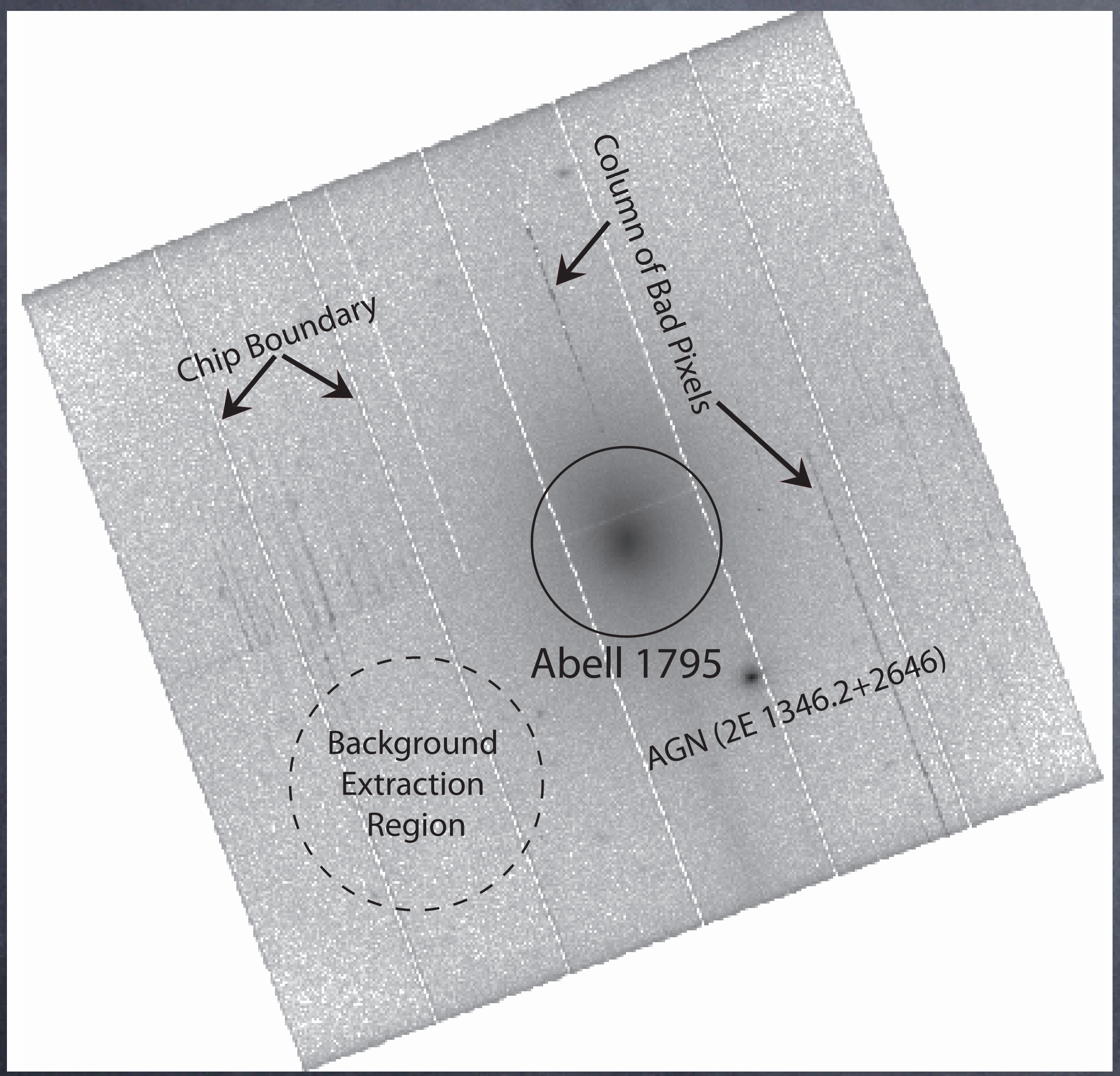
A model PSF image can be created for a given source position and energy. This is then convolved with the source model in spatial fitting.

Source Detection and Removal



CIAO includes several source detection algorithms and dmfilth a routine for removing and filling in source regions

Background Subtraction



"Handbook of X-ray Astronomy"

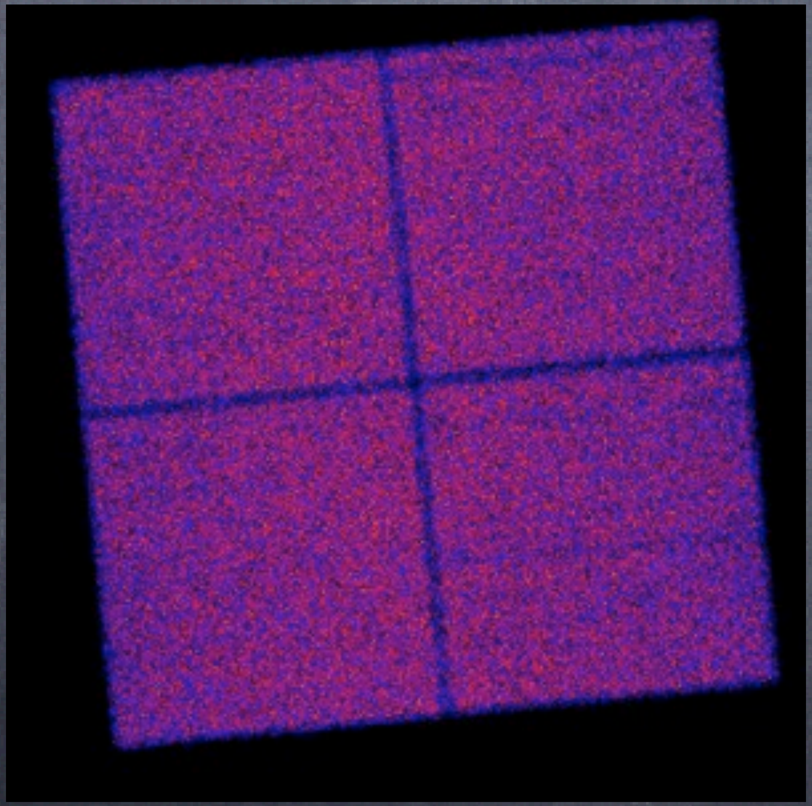
The X-ray background is a combination of particle, Galactic, cosmic, and instrumental backgrounds. The hard X-ray background is fairly constant across the sky, but the soft background is non-uniform.

In many cases, using a local background is preferred (similar to aperture photometry). This is used to estimate the average background for imaging, and for spectroscopy a background spectrum is extracted and subtracted from the source spectrum.

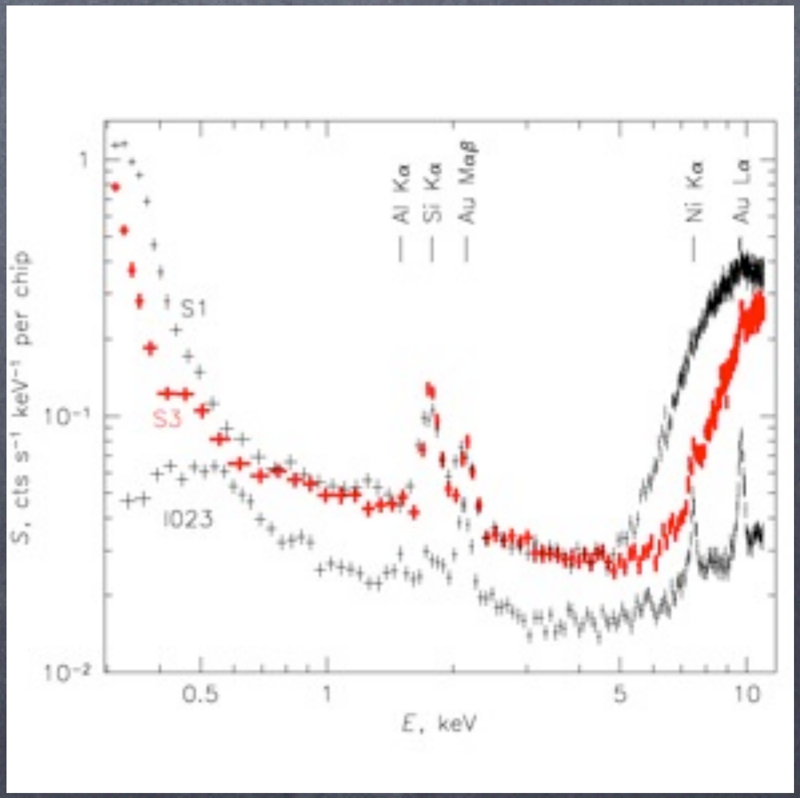
Blank-field and Stowed Backgrounds

In some cases your source fills the detector or one wants to match well the detector features in the source region. There are also "blank-field" backgrounds created from a sum of relatively source-free regions. In this case, you want to match time period and soft background.

ACIS-I blank-field background



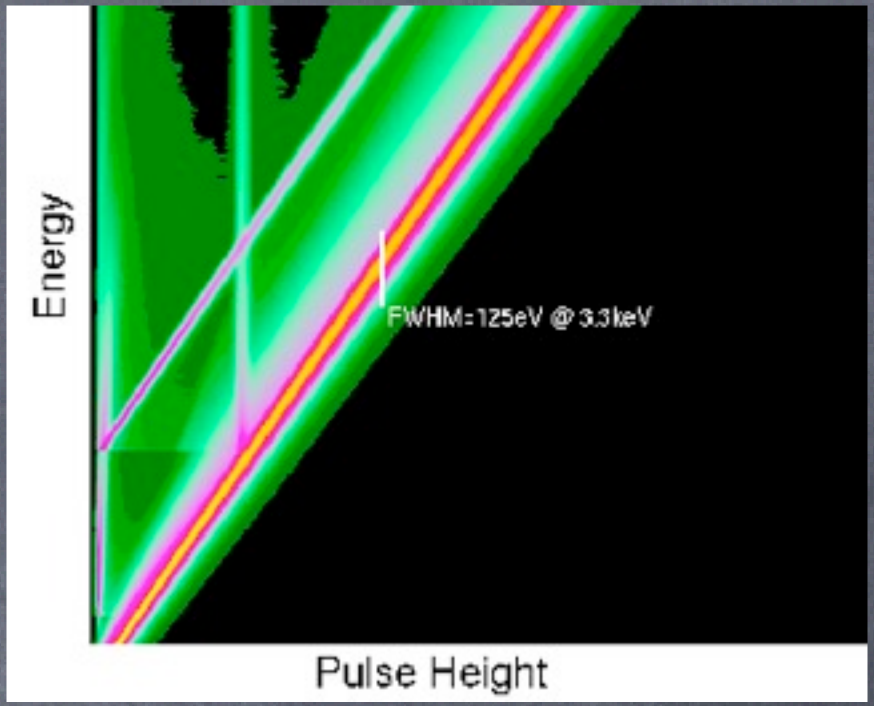
Spectrum of stowed background



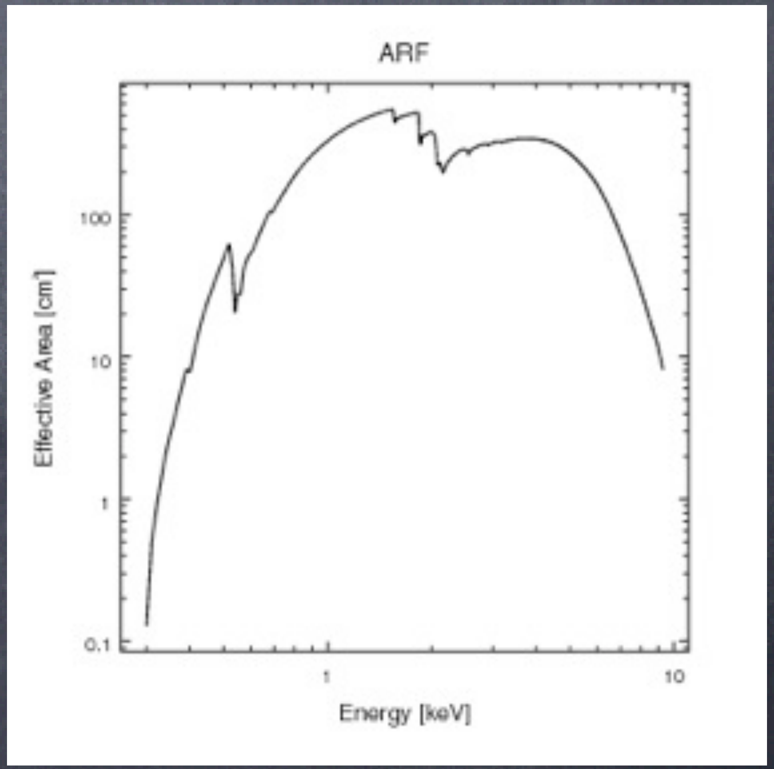
Line features are due to fluorescence of material in the telescope and focal plane.

Spectral Calibrations

RMF (Redistribution Matrix File): This file maps detector pulse height to energy including the dispersion as a function of energy (energy resolution). The RMF depends on position on the detector, and is created for the source position or weighted by position for extended sources.



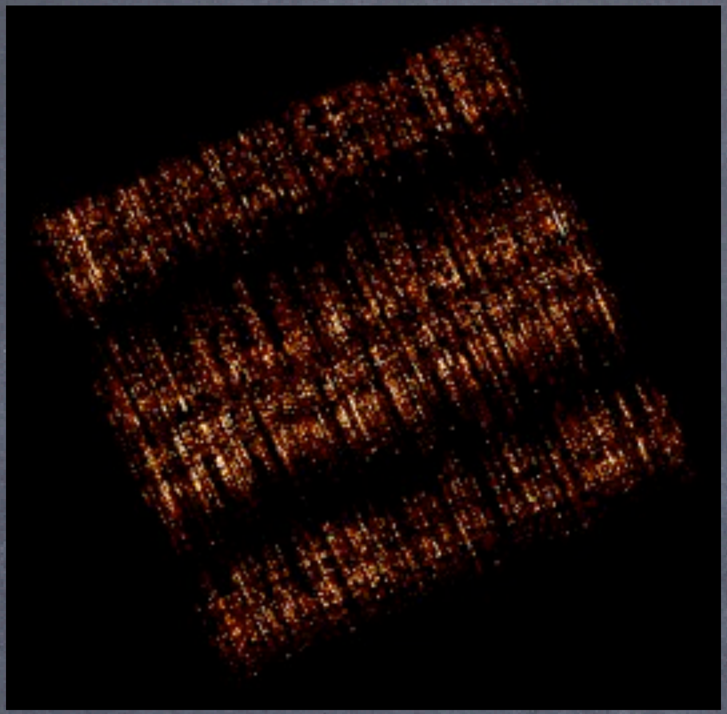
ARF (Auxiliary Response File): The ARF essentially maps the detector sensitivity as a function of energy. It is a combination of the telescope effective area and detector QE averaged over the aspect (time). Also depends on position.



The RMF and ARF are convolved with the assumed spectral model when fitting the data.

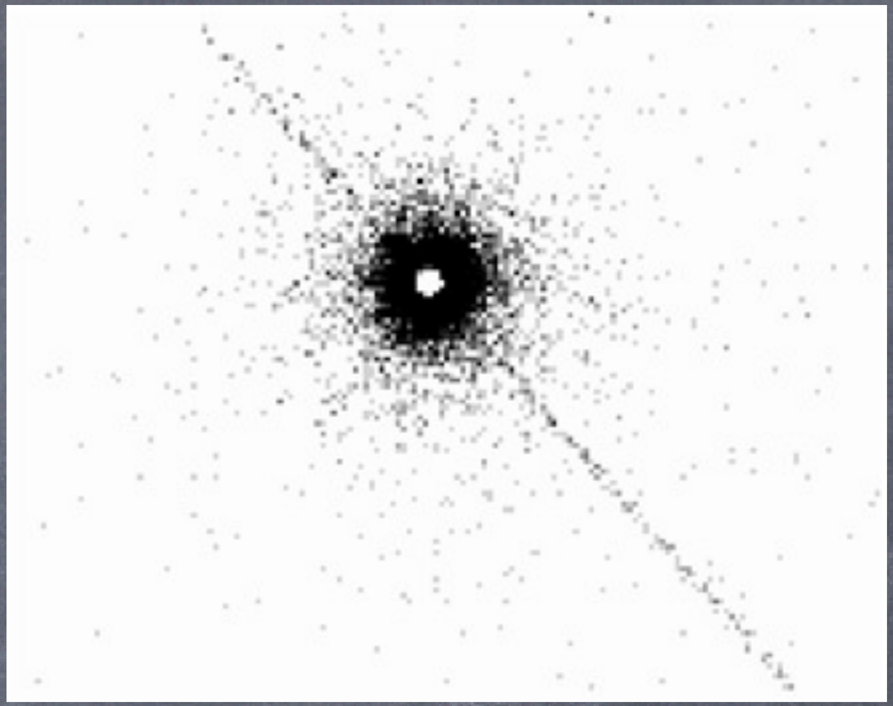
Additional Instrumental Features

Streaks on ACIS-S4



Caused by an error in the serial readout which randomly adds charge to columns as they are read out. Effects a small fraction of frames for any given column, and a software routine exists to remove them. Image shows only events identified as streaks.

Pileup and readout streak



For bright sources both pileup and a readout streak appear. The CCD takes data while it is being readout, so if events occur during readout they appear in the wrong place. Chandra POG: "Trailed image of a strong X-ray source. The core of the image is faint due to pileup. Most events here are rejected because of bad grades."

Basic Calibration Steps for CCD Data

1. Filter data to reduce particle background, remove cosmic rays and bad pixels, and apply gain and CTI corrections, filter on GTI (level 1 file --> level 2 file). Done by pipeline, but sometimes should be rerun.

2. Remove background flares.

3. Filter on desired energy range.

4. Imaging: create exposure map, background map, create PSF model, detect and filter background sources (if needed).

5. Spectroscopy: extract spectrum, extract background, create Redistribution Matrix File and Auxiliary Response File

Chandra Science Web Page:

http://cxc.harvard.edu/