



Using Chandra and its Archive



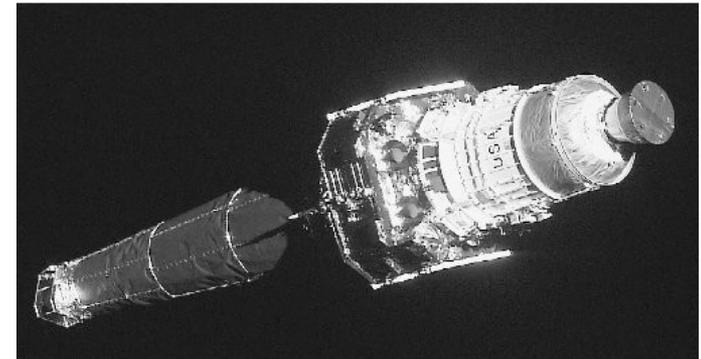
Jonathan McDowell
Smithsonian Astrophysical Observatory





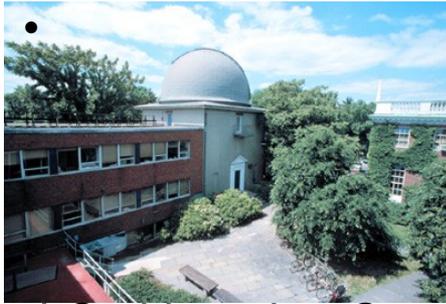
Chandra

- Launched July 1999 – now beginning second decade of operation.
- Science capabilities fully intact
- Operated by the Chandra X-ray Center – includes support for worldwide users.
 - Our goal is to make it easy for “non X-ray” astronomers to get science done with Chandra
- I will talk about
 - What Chandra can do
 - How to analyse Chandra data
 - The new Chandra Source Catalog





Who we are



Chandra X-ray Center (CXC)



MIT Kavli Institute
1 Hampshire St, Cambridge

Harvard-Smithsonian Center for
Astrophysics (CfA)
60 Garden St, Cambridge



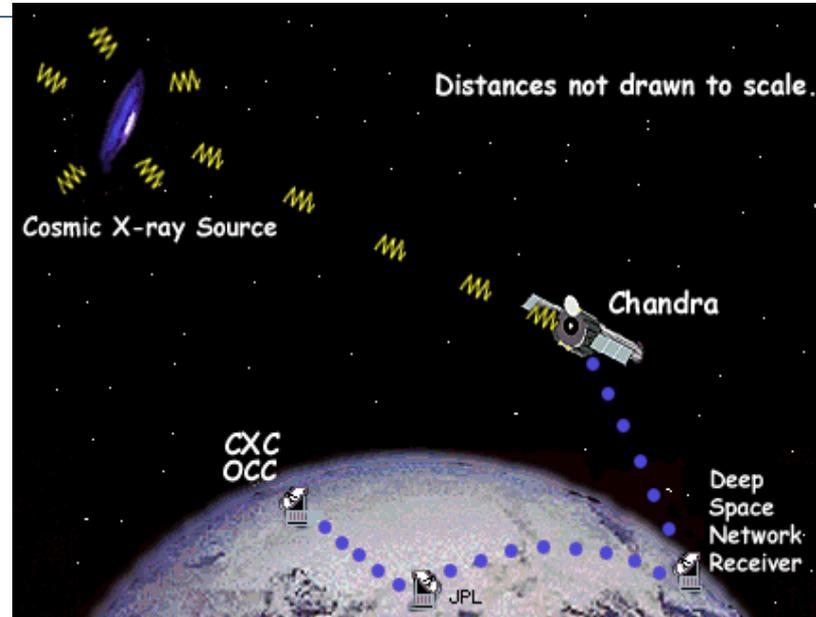
Smithsonian
Astrophysical
Observatory (SAO)



Chandra
Operations Control Center (OCC)
1 Hampshire St, Cambridge



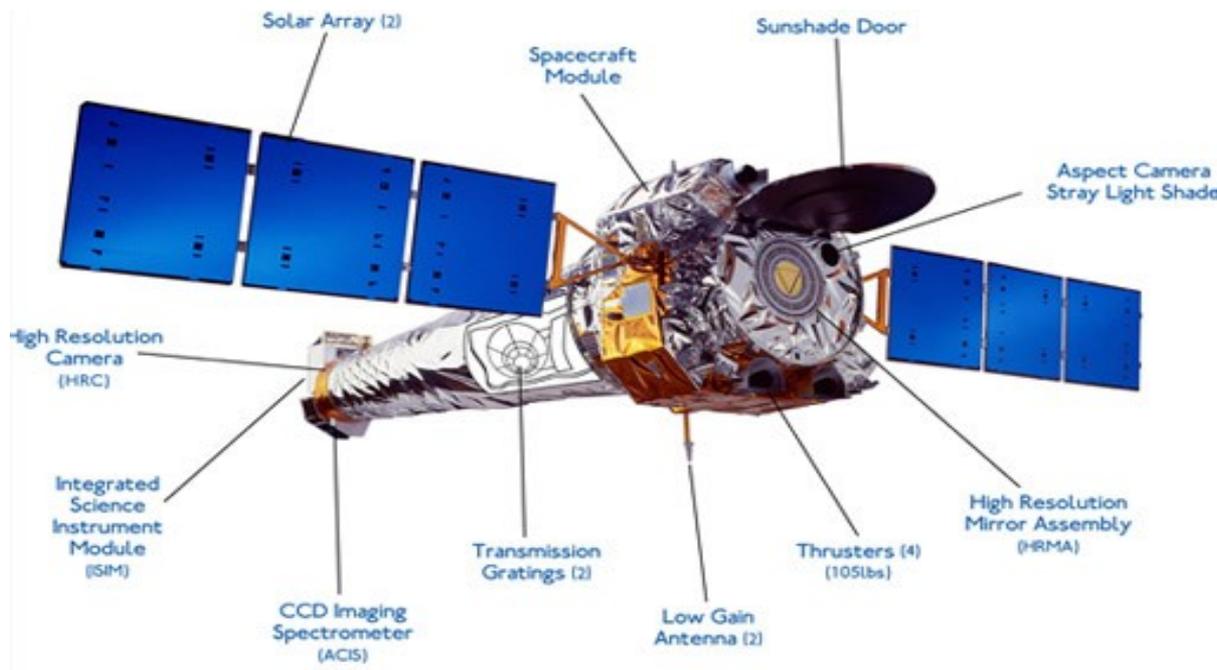
Harvard College
Observatory (HCO)



Chandra observes autonomously for days at a time
Occasional real-time commands for TOO (Target of Opportunity, e.g. gamma ray burst followup) or when radiation flares cause instrument safing. Observations stop for a few hours every 2.5 day orbit when we pass through the heavy radiation zones at perigee

We download data via the Deep Space Network, when it's not talking to Cassini or the Mars Rovers...

Processed, calibrated data products get to the user usually within 48 hours





What Chandra can do

- Deep searches for photometry and astrometry of faint point sources
 - ACIS Imaging Mode (ACIS-I or ACIS-S)
 - ACIS-S slightly superior in low energy response, but not much to choose from these days
 - ACIS-I has bigger field of view
- Integral field spectroscopy of bright extended sources
 - ACIS-I FOV is 16' x 16' (but spatial resn degrades off-axis)
 - Each pixel has spectral resolution R about 50-100
 - Background per pixel is low
- High resolution spectroscopy of bright point sources
 - HETG (High Energy Transmission Grating)
 - Resolution
 - Energy range
 - Measure equivalent widths, line centers



Major X-ray observatories



- CHANDRA launched Jul 99 – Highest spatial resolution, deepest look
 - XMM-NEWTON, launched Dec 99 – most collecting area, high S/N spectra
 - SUZAKU, launched Jul 05 – XIS+HXD give good low background and broad band integrated spectra of extended objects, despite loss of XRS
-



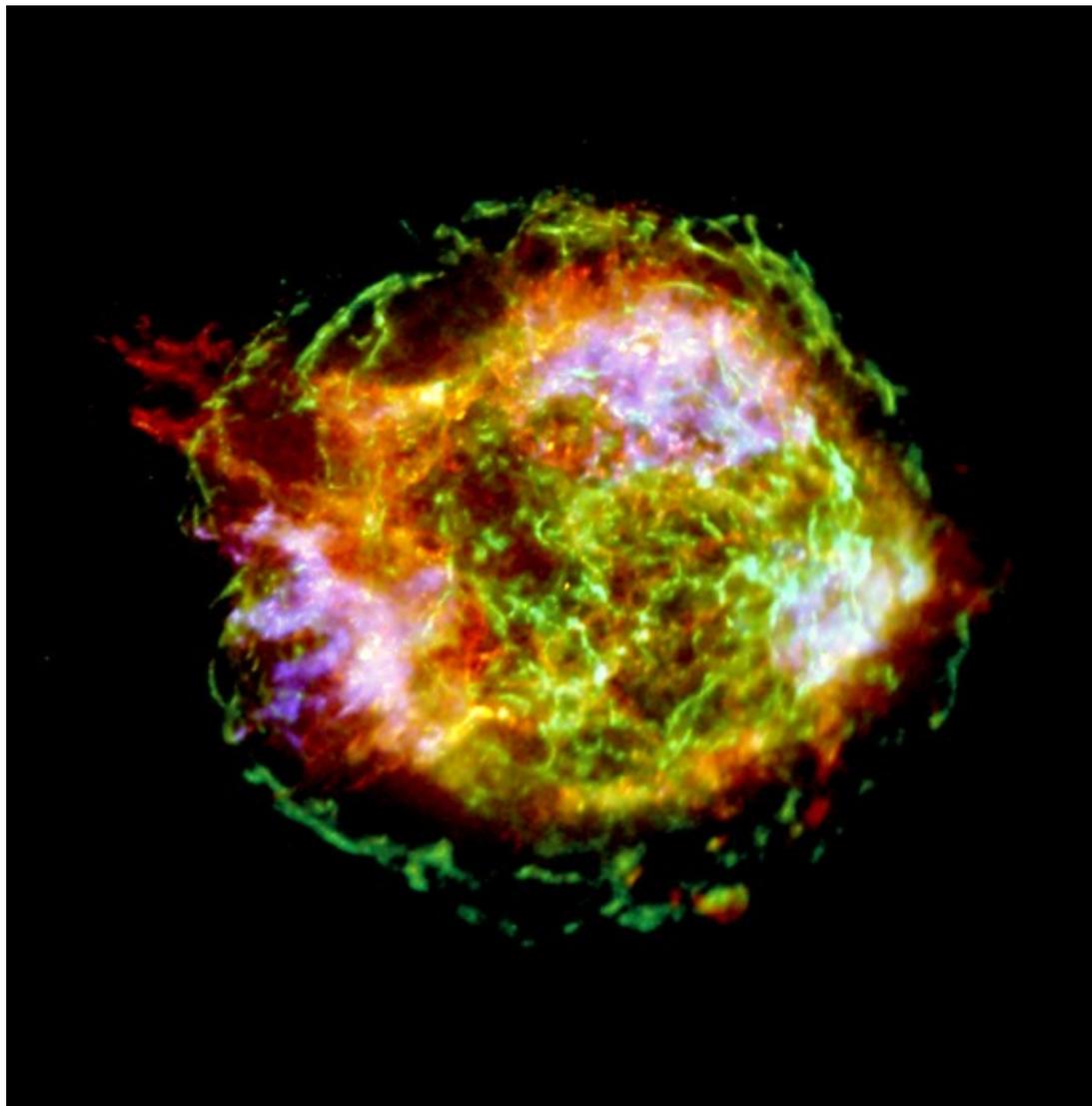
A sampling of Chandra science..



- I will concentrate on results from the ACIS X-ray CCD imager
 - Lots of great results from high resolution transmission gratings, but I don't have time (or expertise..)
-



Cas A - fresh elements



Green: continuum
shock

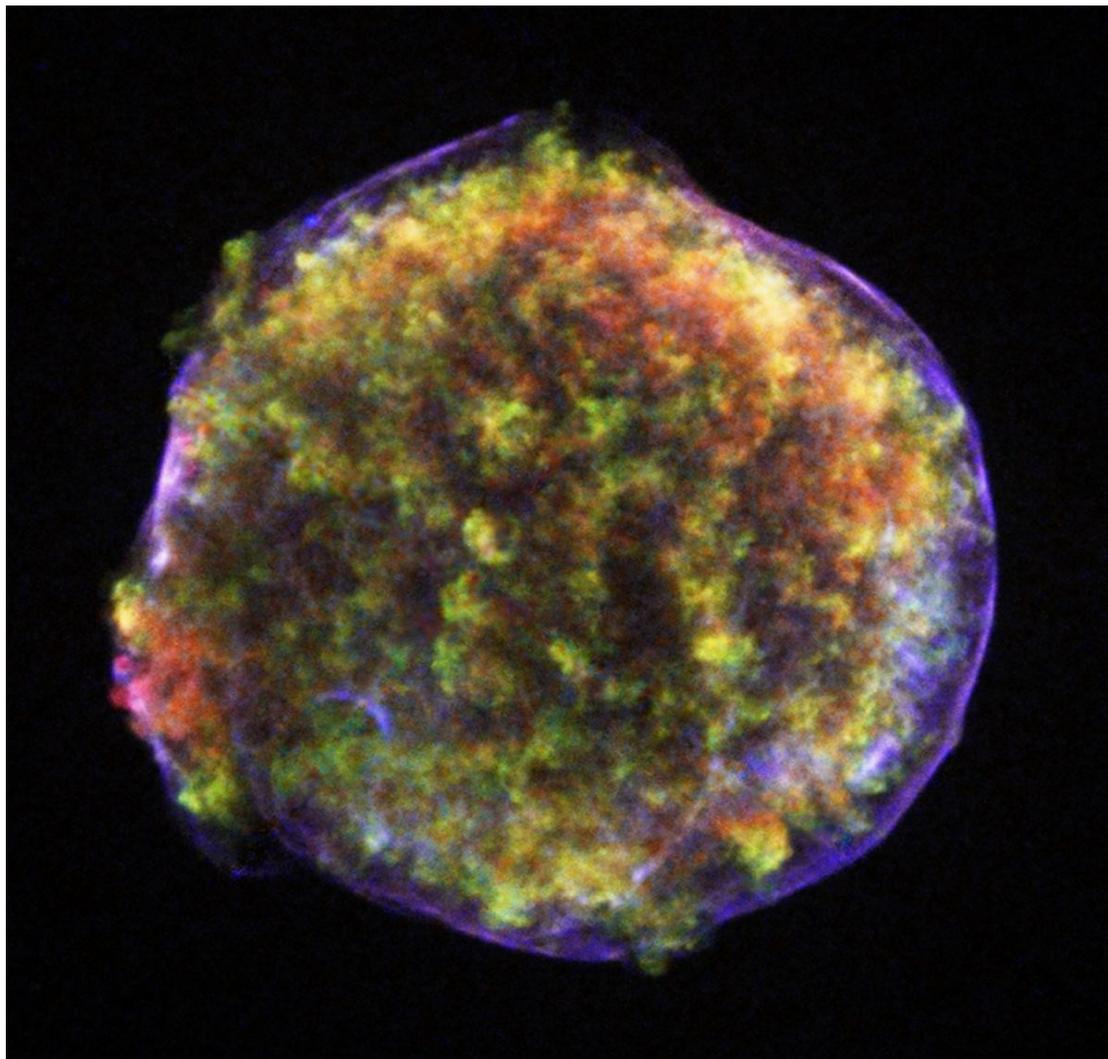
Red: silicon line

Blue: iron line

Hwang et al
2004



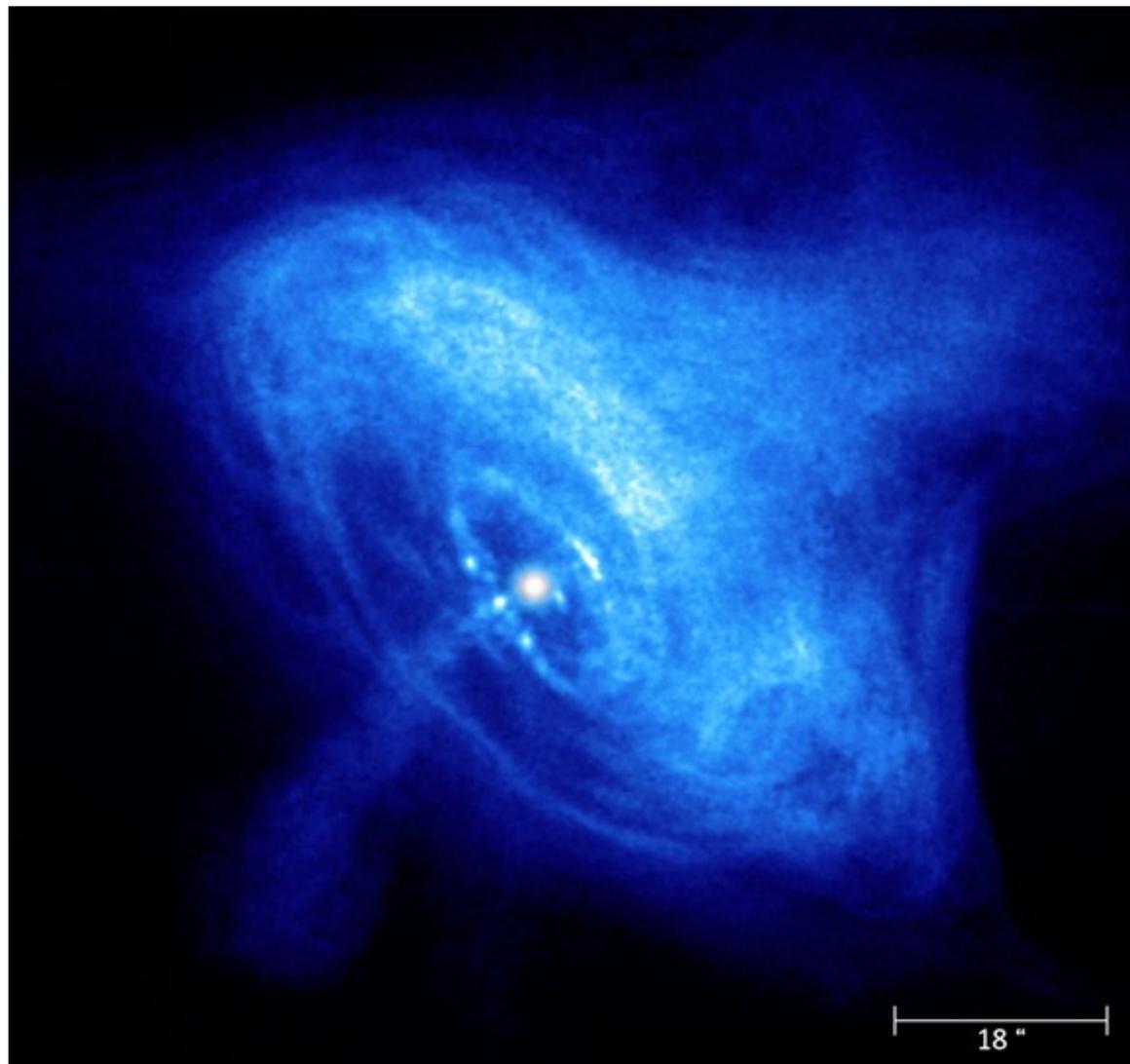
Tycho: ejecta and shock



Warren and
Hughes 2005



Crab Nebula



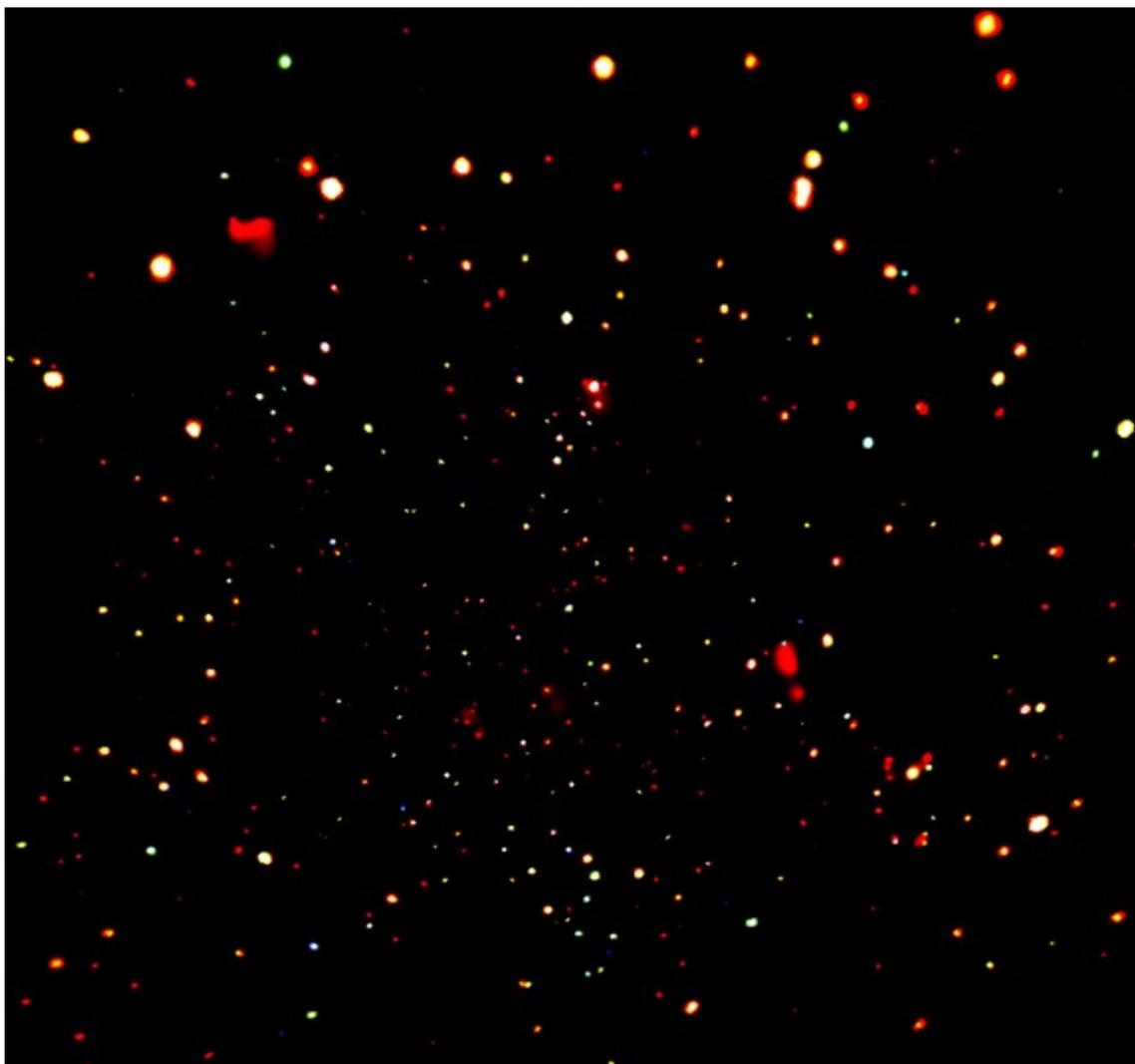
Chandra monitoring shows features moving in jet and torus at $\sim 0.5 c$



Hester et al 2002



Chandra Deep Field North



Bauer, Brandt,
Hornschemeier,
etc 2002-2005



Stacking the data

The CDFN accumulates 23 days of exposure time in 20 observations over a 3 year period. The observation reaches a limiting sensitivity of two photons a week (!) The result is a catalog of 500 AGN.

What are the data analysis challenges here?

The Chandra astrometric calibration is good to 1 arcsec across the field , so simply stacking the observations based on standard processing is not too bad - but manual adjustment of the WCS will give better registration.

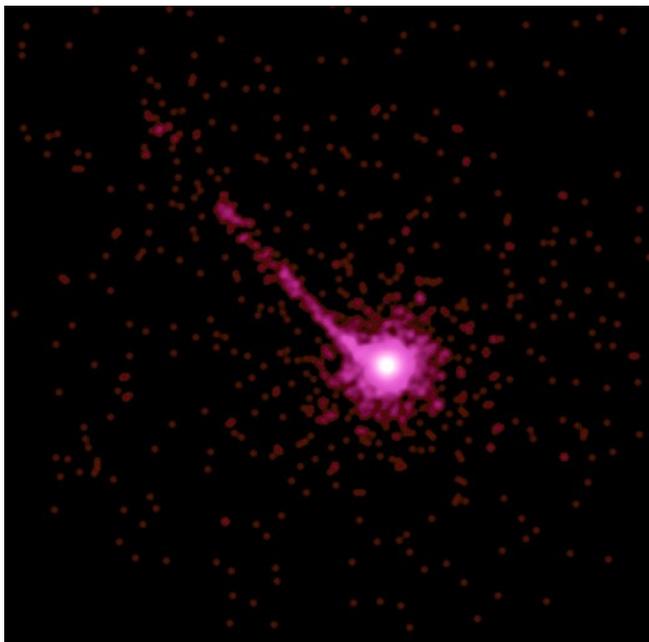
The change in the spectral resolution and sensitivity of the instrument over the period is significant.

The exposure map (“flat field”) for each chip has significant energy dependence as well as discontinuous variations associated with chip and node boundaries.

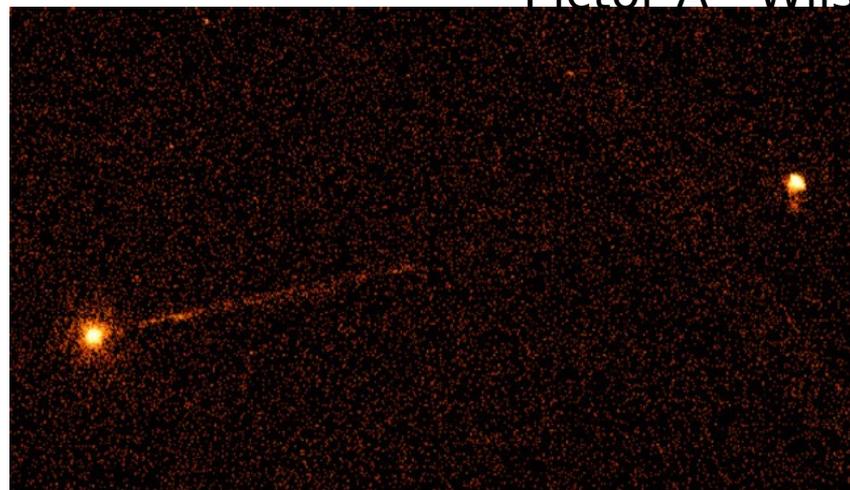
The PSF size is a strong function of distance from the field center, so the limiting sensitivity drops towards the edge of the field.



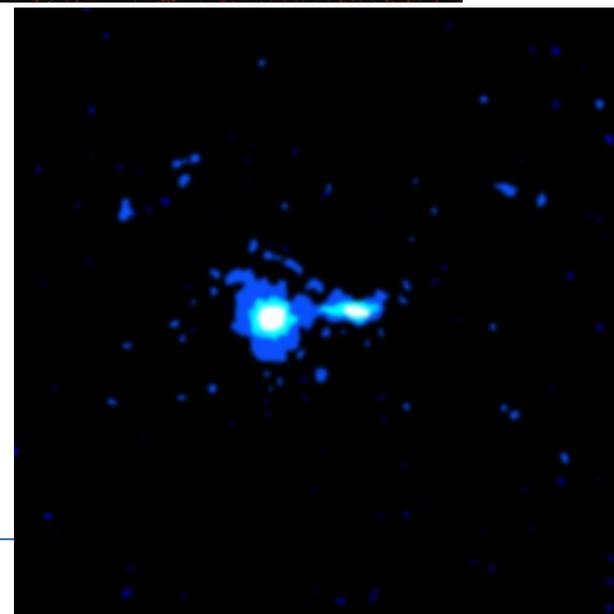
AGNs with Jets



PKS 1127-145 -
Siemiginowska,
Bechtold



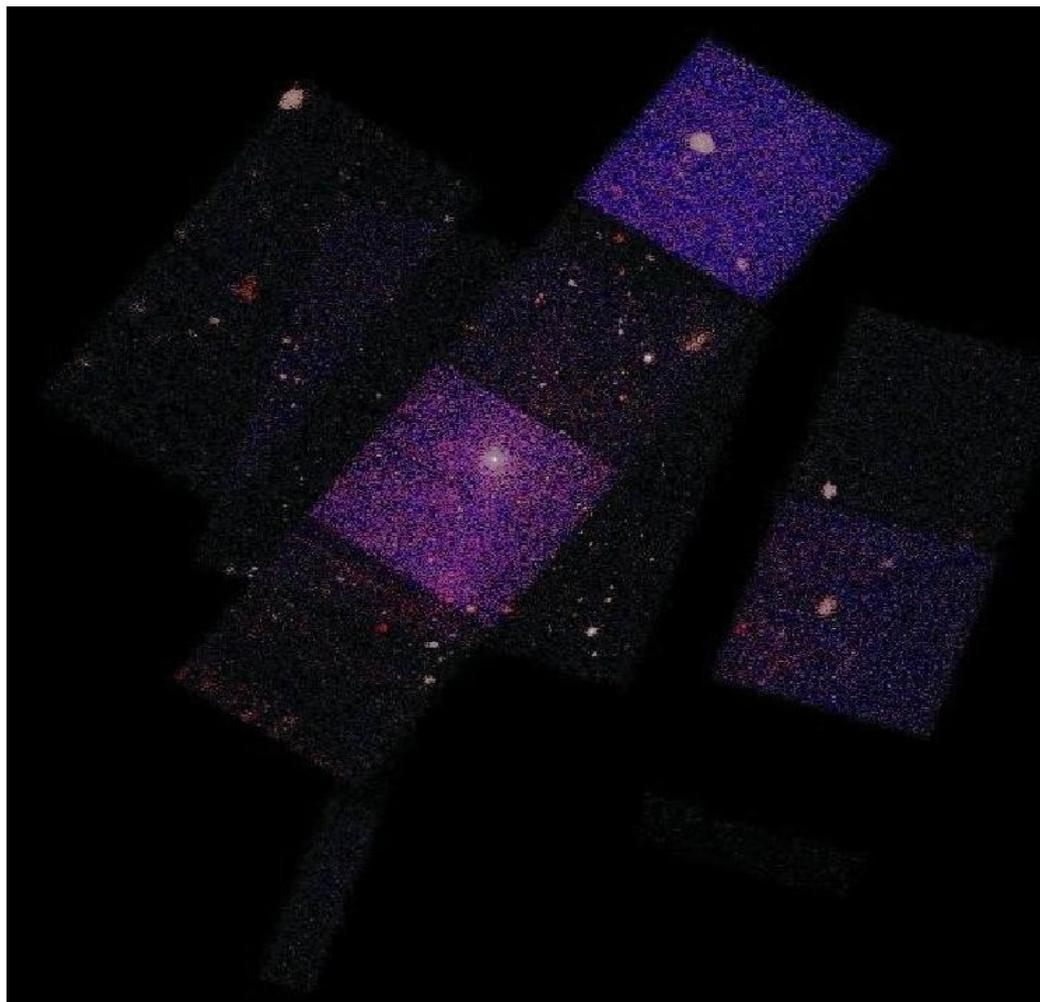
PKS 0637-75 -
Chandra first
focus image



Pictor A - Wilson



M33 – compact populations



McDowell et al 2002,
Grimm et al 2005



X-ray CCDs

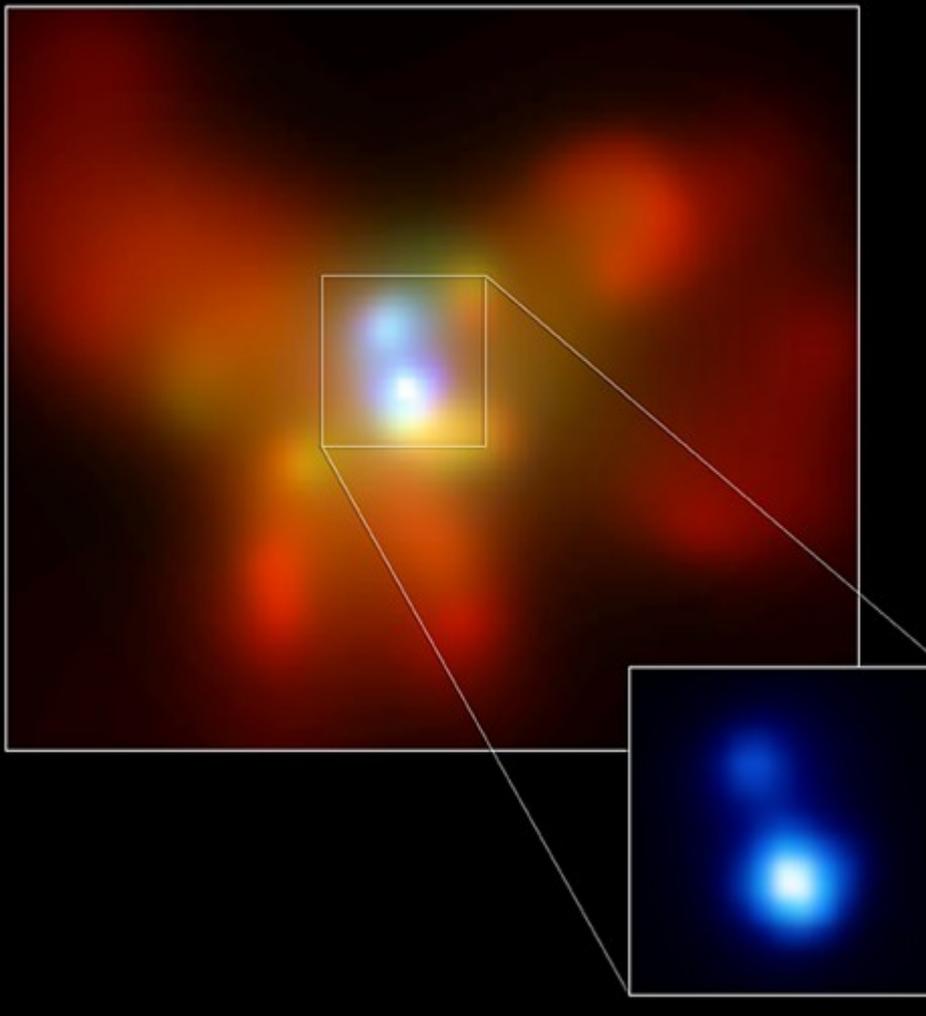
The image of M33 shows merged data from 2 Chandra observations; the source list resulting from this and a later observation has been published by H-J Grimm et al., 2005 (ApJS 161,271) and 2007(ApJS 173,70)

The luminosity function reaches 2×10^{34} erg/s and includes neutron star binaries, supernova remnants, supersoft sources, etc.

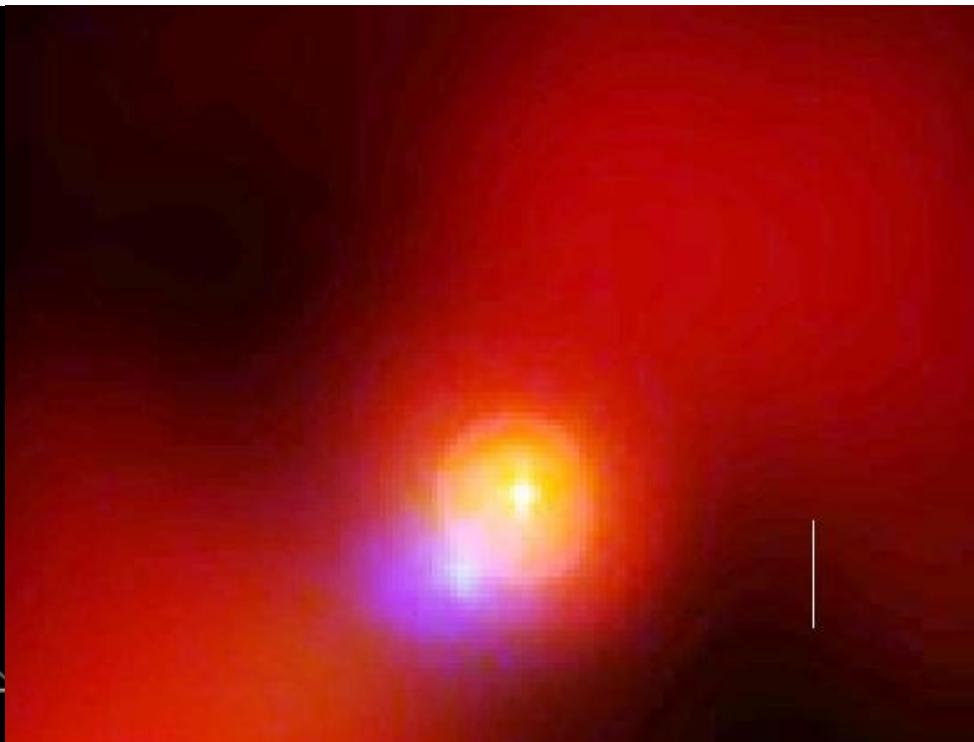
Note the two chips with obviously different background. The “back-illuminated” chips are less easily damaged by cosmic rays and have better low energy sensitivity. However, the low energy response has been lowered over time because of contamination buildup - this is accounted for in the software, but be careful when planning observation times and when comparing data taken at widely separated times.



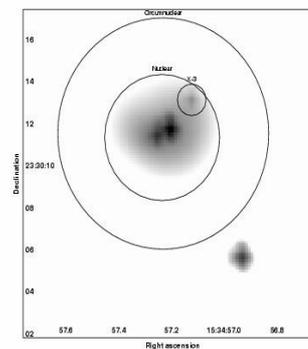
NGC 6240 and Arp 220



Komossa et al 2003



Clements et al 2002



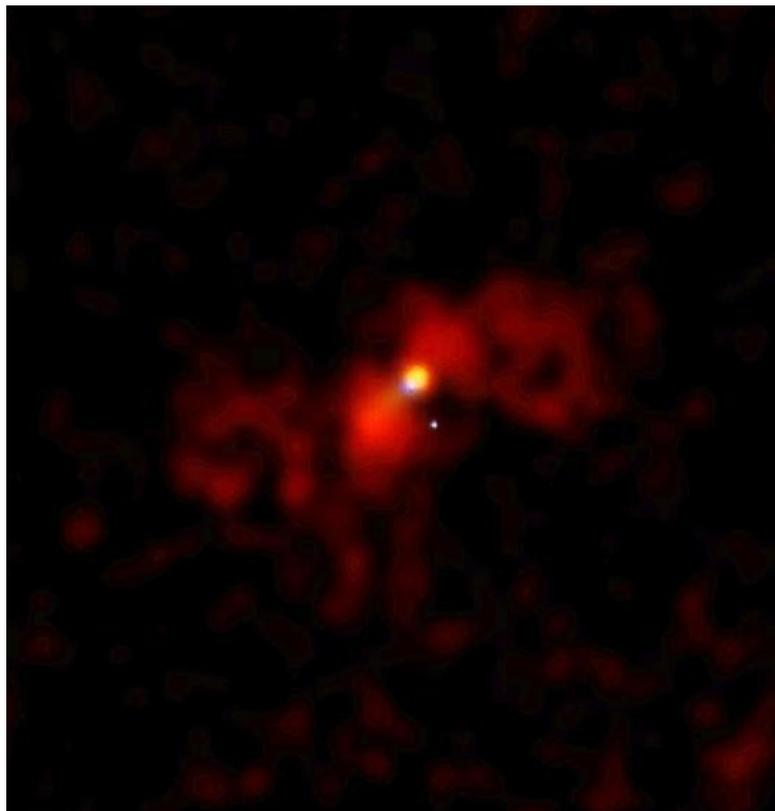


Marginal extent

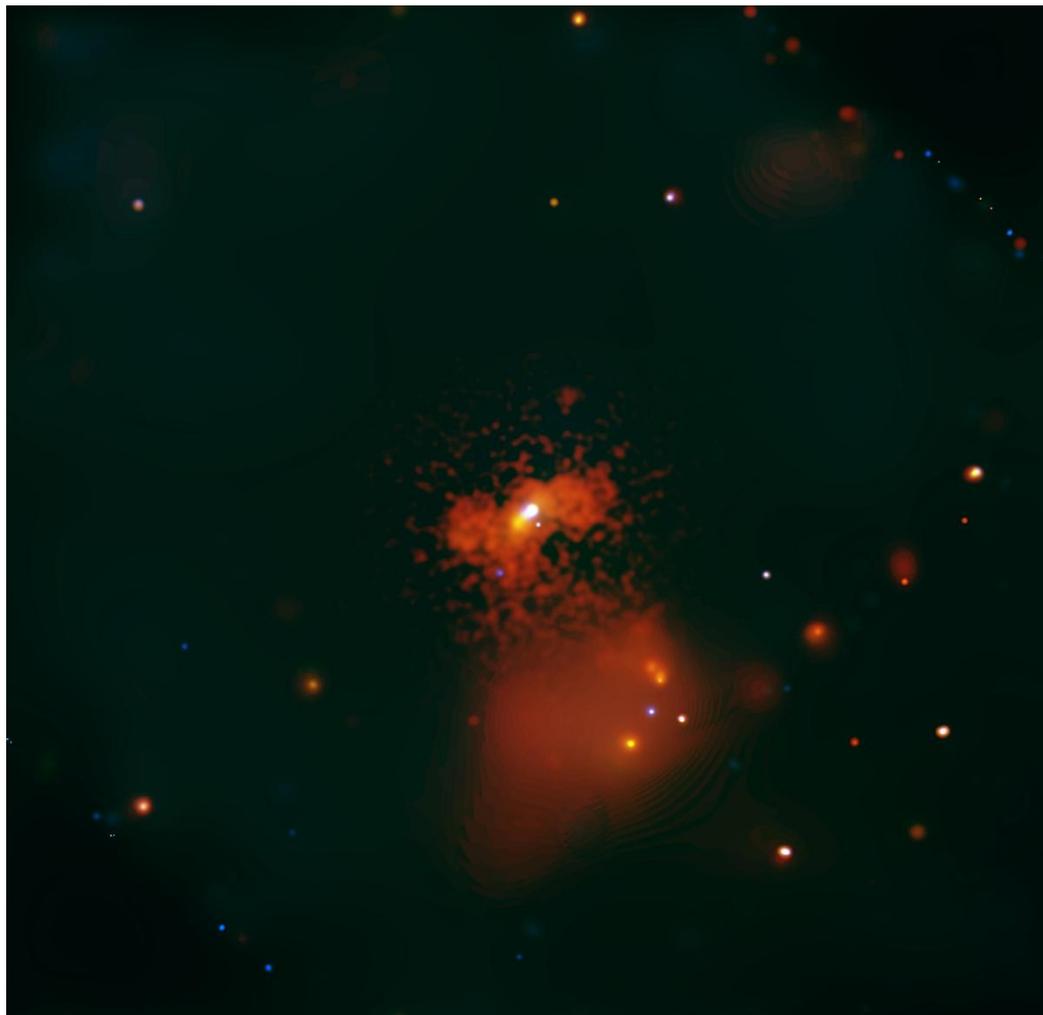
The super-mergers NGC 6240 and Arp 220 may have binary supermassive black holes in their nuclei. In the case of Stephanie Komossa's work on NGC 6240, the two X-ray nuclei are 1.5 arcsec apart and easily separated from each other by Chandra. Dave Clements and I foolishly chose the other obvious target, Arp 220, in which the two nuclei are only 0.5 arcsec apart, and this required more aggressive modelling with PSFs.

In both cases the sources are embedded in diffuse X-ray emission whose integrated luminosity is much brighter, so the highest possible spatial resolution was critical for this science. The analysis, however, is not particularly X-ray specific once the event lists have been reduced to multi-band images in the standard way. In particular, the aspect reconstruction errors add only a tiny (0.1 arcsec) contribution to the PSF.

For most X-ray missions though, the quality of the PSF calibration is not all that you'd want for finding faint extent (like X-ray jets). In Chandra things are pretty good on axis, but detector effects like CTI, out-of-time-events, bad pixels and columns, etc., make things hard. We're still working on modelling these effects properly.



McDowell et al 2003





Diffuse emission



The complex extended emission structures in Arp 220 are hard to pull out. In order to make the image seen here, we processed the data in three separate energy bands; carried out background subtraction; subtracted the brightest sources using a custom-generated PSF; applied adaptive smoothing to the remaining data; added the PSFs back in, and recombined the bands into this color image.

So obviously, you can't measure fluxes off this image.

BUT: you can use it to isolate regions of interest, and then go back to the raw data to extract counts and fit spectra.

For instance, the shape of individual blobs in the lower left lobe can't be trusted since each blob is around 20 photons. But the overall impression of an annular lobe is correct (flux in the center less than flux in the annulus, at the 4 sigma level).

Always in the X-ray domain, we use fluxed, smoothed, deconvolved data to suggest a model, and then we take a forward-folding approach - convolve the model with a telescope simulator and compare in raw count space - to validate the model and measure numerical quantities.



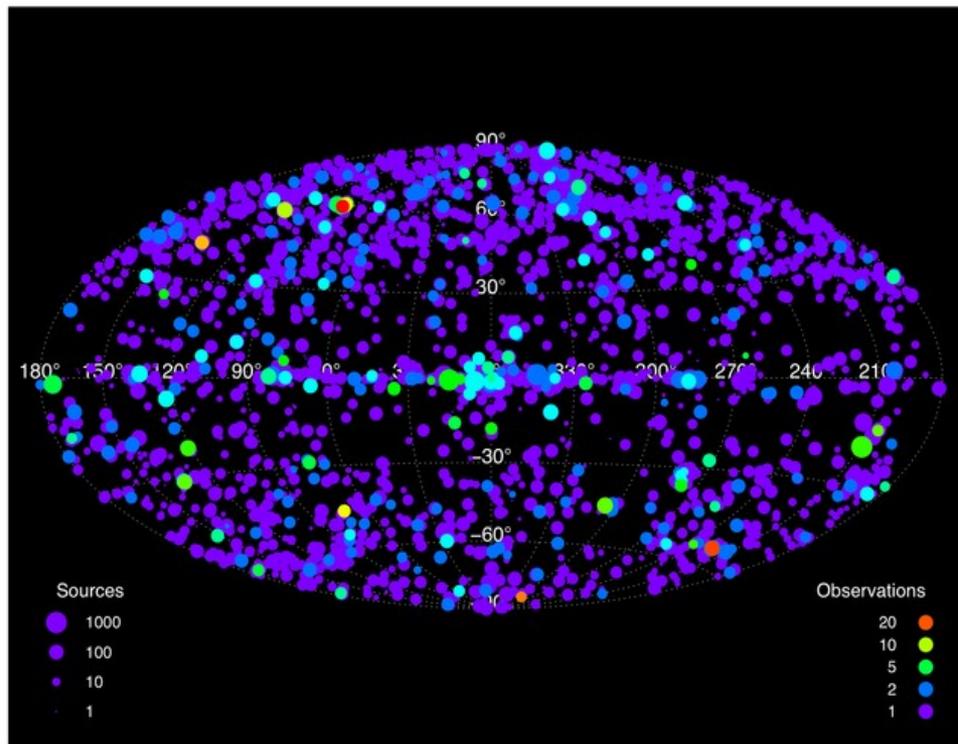
Chandra Source Catalog





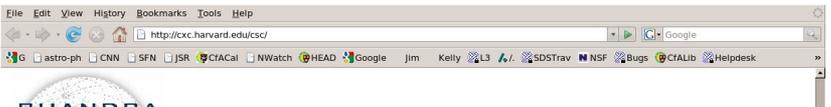
Chandra Source Catalog

- Release 1.0 contains 94700 X-ray sources
- 1 arcsecond absolute astrometry
- X-ray photometry in 3 bands (0.5-1.2, 1.2-2.0, 2.0-7.0 keV)
- Associated data products
- Public pointed observations, excluding chips with obvious extended sources

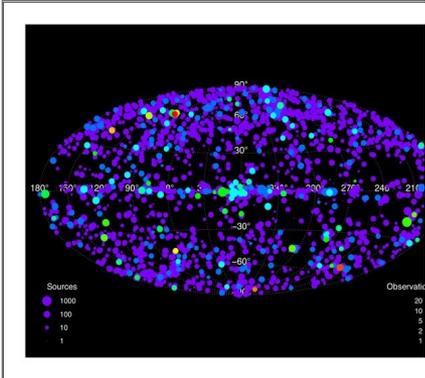




Catalog docs: cxc.harvard.edu/csc



The Chandra Source Catalog Release 1.0: Point and compact source catalog



The locations of observations included in the CSC. In Galactic coordinates (click the image for equatorial). The size of each symbol is proportional to the logarithm of the number of sources detected in the field while the color encodes the number of closely-floored observations.

CSC Data Access (CSCview)
CSCview Software Requirements
CSCview Help

CSC Homepage
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Catalog Release Views and Database Access Views
Catalog Statistical Characterization
Schedule and Status
Caveats and Limitations
Creating the Catalog
Observation Selection
Catalog Processing
Data Products
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Threads
Level-3 Files
CSCview GUI
Catalog Columns
Master Chandra Source Table
Table of Individual Source Observations
Column Descriptions
Position and Position Errors
Source Flags
Source Extent and Errors
Energy Bands
Source Fluxes
Source Significance
Spectral Properties
Source Variability

The Chandra Source Catalog (CSC) is ultimately intended to be the definitive catalog. To achieve that goal, the catalog will be released to the user community in a series of releases of the CSC. Includes information about sources detected in public ACI Chandra mission. Only point sources, and compact sources, with observed extended sources, and sources located in selected fields containing bright, high



Master Chandra Source Table

Each identified distinct X-ray source on the sky is represented in the catalog by a single "master source" entry, one for each observation in which the source has been detected. The master source entry records source, based on the data extracted from the set of observations in which the source has been detected.

Go to: [Catalog Columns Index](#) | [Alphabetical List](#)

Context	Column Name	Type	Units	source
Source Name	name	string		Jhmm use if RA is
Position and Position Errors	ra	double	deg	Source
	dec	double	deg	Source
	err_ellipse_r0	double	arcseconds	major ellips
	err_ellipse_r1	double	arcseconds	minor ellips
	err_ellipse_ang	double	deg	positi confi

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Level-3 Files
CSCview GUI
Catalog Columns
Master Chandra Source Table
Table of Individual Source Observations
Column Descriptions

Introduction

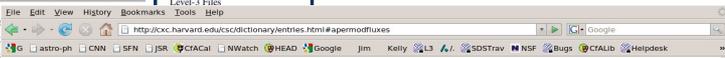


Threads

Conducting a Property Search
Conducting a Core Search
Retrieving Data Products
Using Source Property Associations

Main page
column descriptions
GUI usage
dictionary
special topics
etc...

Wien, Nov 2009



CSC Dictionary Entries

Alternating Exposure Mode

In alternating exposure mode, sometimes also referred to as interleaved mode, there is a long (primary) and a short (secondary) frame time, and the observation alternates between them. The long frames are joined into one event file and the short frames are joined into another event file. This mode is used to look for variability on different timescales or when observing a source that is expected to be piled. The observer gets the long-frame "piled" information, as well as the short-frame unpiled data.

Return to: [Dictionary index](#)

Aperture Model Energy Fluxes

The conversion from aperture source count rates in each science energy band to aperture model energy fluxes is performed by scaling from a model spectrum folded through the calibrated response, as follows:

For a source model $F(E)$ whose integral over the science band is $F(\text{band})$, calculate the corresponding band count rate $C(\text{band})$ in counts s^{-1} , given the effective area calibration $A(E)$ (and, if available, the RMF_i , $R(E)$, band) appropriate to the observation; this is the integral of $F(E)A(E)R(E)$, band over all energies, or if a diagonal RMF is assumed, the integral of $F(E)A(E)$ over the band.

Infer the aperture model energy flux from the measured aperture source count rate $C(\text{band})$ as $F(\text{band}) = F(\text{band})C(\text{band})/C(\text{band})$. The power law spectral model has a fixed photon index, α , defined as $F_{ph} = E^{-\alpha}$, equal to 1.7, and a fixed total neutral Hydrogen absorbing column $N_H = N_H(\text{Gal}) \text{ cm}^{-2}$. The black body spectral model has a fixed temperature $kT = 1.0 \text{ keV}$, and a fixed total neutral Hydrogen absorbing column $N_H = 3 \times 10^{20} \text{ cm}^{-2}$.

Return to: [Dictionary index](#)

Aperture Total Counts

"Aperture total counts" refer to the total number of source plus background counts measured in the modified source region; the modified background region; the modified elliptical aperture; and the modified elliptical background aperture, uncorrected by the PSF aperture fraction.

Return to: [Dictionary index](#)

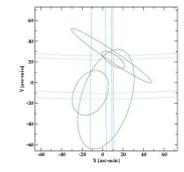
Source position, galactic latitude

Indicates an extended source. TRUE - deconvolved source extent is inconsistent with a point source at the 90% confidence level in any science energy band with a flux significance ≥ 3.0 in any contributing observation; otherwise, FALSE

Source Position Errors

Master Chandra Source Table

2-dimensional positional uncertainty of a source listed in the Master Chandra Source Table represents the best estimate of the source position based on several independent measurements. The merged result of multiple observations of the same source. To determine the best estimate of the position of a source from previous estimates of its position, we employ a 2-dimensional optimal weighting formalism to statistically average the source positions resulting from the set of individual observations of the source. This technique because it offers an improved estimate of source position where simple averaging fails, e.g. where the area defining the source position varies in measure to measure. We express the uncertainties of the estimates in the form of error ellipses centered upon the estimated source positions.



An example of input ellipses (green) and the combined ellipse (red). The x and y values represent input plane coordinates.

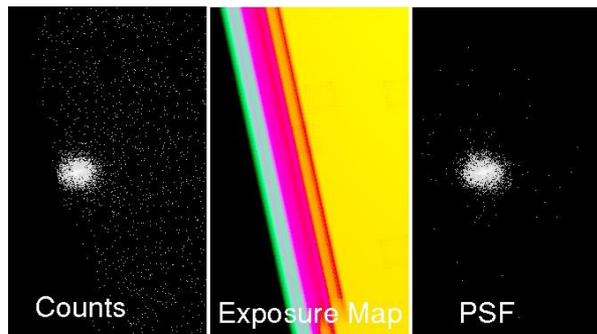
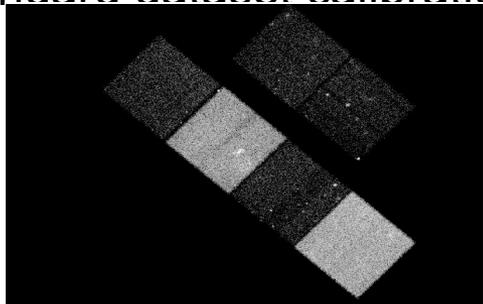
es that are combined to produce the "best estimate" error ellipse for the merged source entry result from the Chandra Multiwavelength Project (ChMP) positional uncertainty described in the page "Source Position Errors in the Table of Individual Source Observations."

multivariate optimal weighting formalism in the Chandra Source Catalog, described below, represents its first application to astrophysical data, as it is based on an analysis of Wien's thesis from the Naval Postgraduate School. For more information on this analysis and its use in the Chandra Source Catalog, see Joseph R. Orlovsky's "Single Source Error Ellipse Combination" and John Davis' CSC document "Combining Error Ellipses," respectively.



Catalog processing

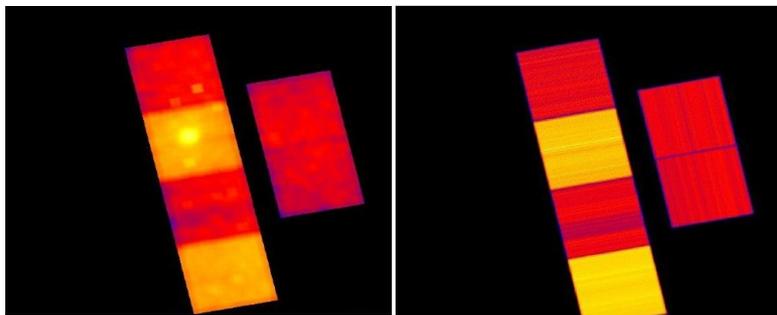
Standard dataset calibration



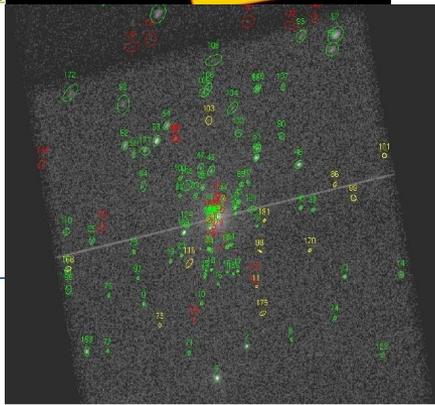
For each source region, we calculate the spatial exposure variation and run our ray trace code to get a model PSF.

Flare removal

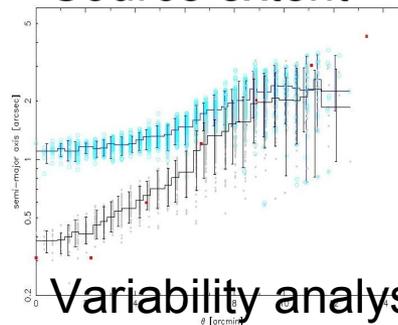
Background map



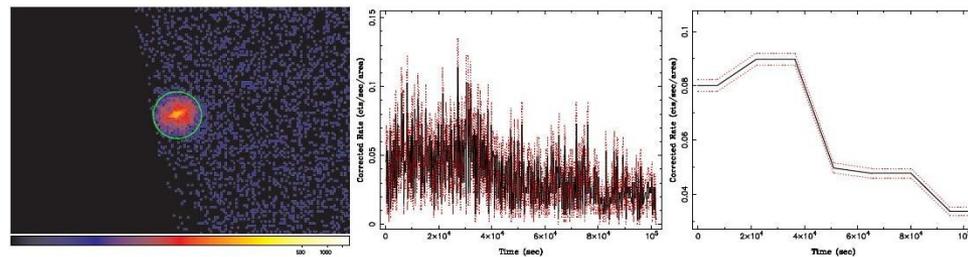
Wavelet detection



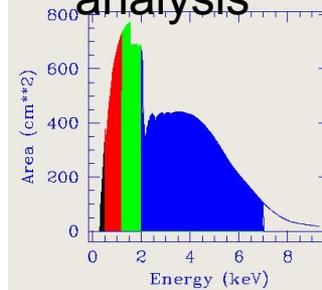
Source extent



Variability analysis

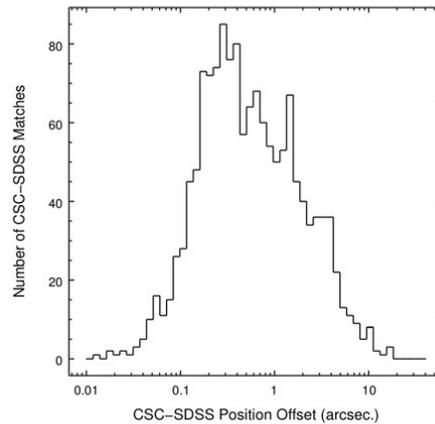
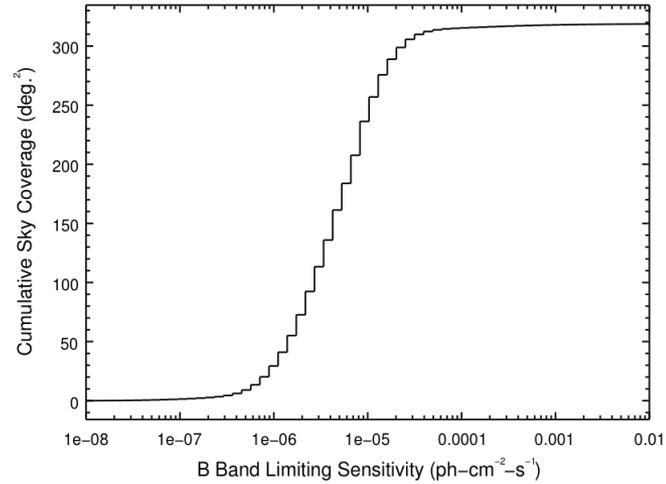
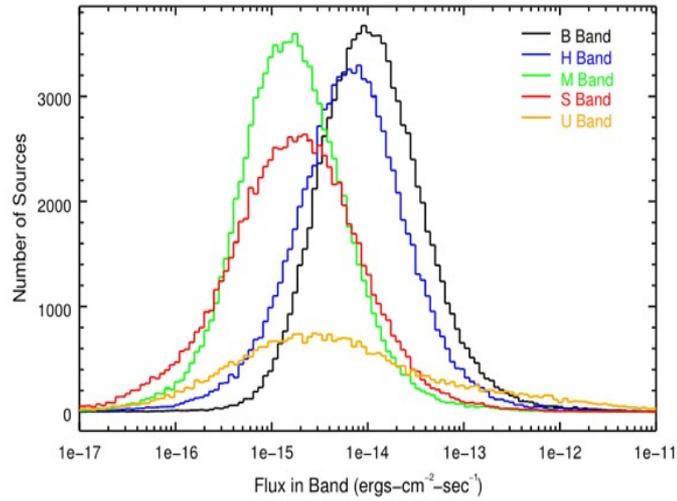


Spectral analysis





Catalog sensitivity and astrometry





TGCat

The gratings team at MIT has reprocessed all the HETG data into user-friendly form at

<http://tgcats.mit.edu>



RESULTS: Found 152 matching extractions

<input type="checkbox"/>	o	p	s	1673	2482	NGC 3516	ACIS	HETG	11:06:47.467	+72:34:7.176	2001-11-11 01:00:25	88011.4
<input type="checkbox"/>	o	p	s	1673	8451	NGC 3516	ACIS	HETG	11:06:47.484	+72:34:7.212	2006-10-11 09:49:34	47567
<input type="checkbox"/>	o	p	s	1673	7281	NGC 3516	ACIS	HETG	11:06:47.501	+72:34:7.284	2006-10-14 02:19:19	42509.5
<input type="checkbox"/>	o	p	s	1673	2080	NGC 3				+72:34:7.248	2001-04-10 17:55:54	73376.6
<input type="checkbox"/>	o	p	s	1673	8452	NGC 3				+72:34:7.176	2006-10-09 14:05:36	20754.8
<input type="checkbox"/>	o	p	s	1673	2431	NGC 3				+72:34:7.320	2001-04-09 14:12:05	35572
<input type="checkbox"/>	o	p	s	1673	7282	NGC 3				+72:34:7.212	2006-10-10 04:43:54	41454.5
<input type="checkbox"/>	o	p	s	1673	831	NGC 3				+72:34:7.104	2000-09-30 21:05:22	43893.8
<input type="checkbox"/>	o	p	s	1673	8450	NGC 3				+72:34:7.248	2006-10-12 07:00:26	38549.6
<input type="checkbox"/>	o	p	s	1666	2092	NGC 3783	ACIS	HETG	11:39:1.694	-37:44:18.960	2001-03-10 00:31:15	165454

Flux Spectrum (Click to preview all Images)

press "go" to operate on selections: limit download plot combined view sources

Go Change Columns New Search Help

TGCat - ObsID 2091 - ACIS/HETG - PREVIEW

ObsID 2091 :: NGC 3783 :: 169 ks :: 2001-02-27 09:17:51

Flux spectrum (1)

Flux spectrum (photons/cm²/s). The first panel shows a broad spectral range, while subsequent panels show detail in smaller wavelength ranges. HEG/MEG combined and positive and negative orders summed

HEG+MEG (rebinned to 0.01Å)

Customize Plots Spectral Props Help



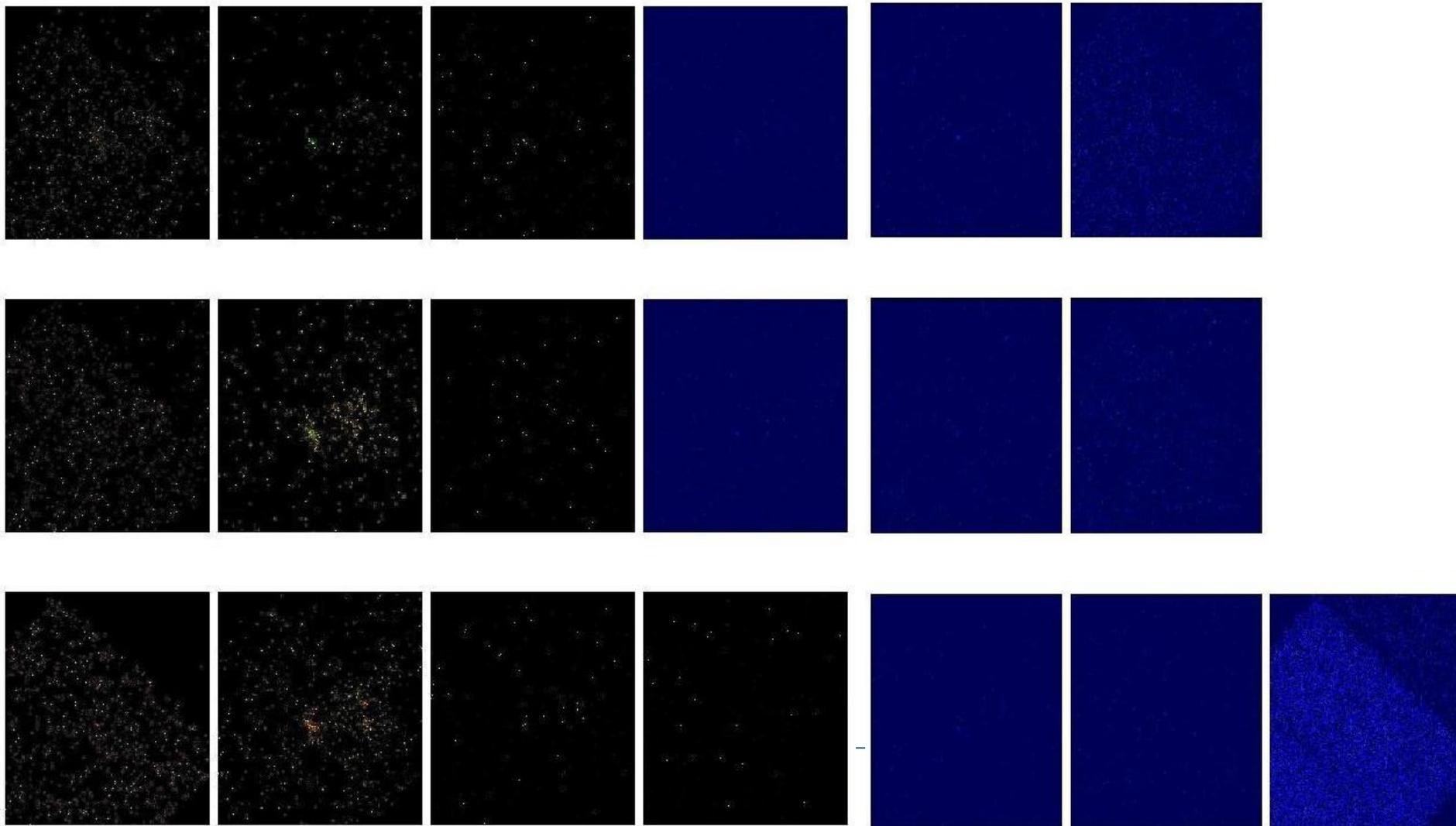
X-ray Analysis Software

- CIAO (cxc.harvard.edu) – SAO/MIT general analysis package, optimized for Chandra, strong in spatial analysis
 - dmcoppy, acis_process_events, sherpa
 - HEASOFT (heasarc.gsfc.nasa.gov) - Goddard general purpose X-ray package
 - fdump, xselect, xspec
 - SAS (xmm.vilspa.esa.es) - Specific to XMM-Newton
 - ROSAT era collaboration established common FITS standards for keywords and data file conventions
-



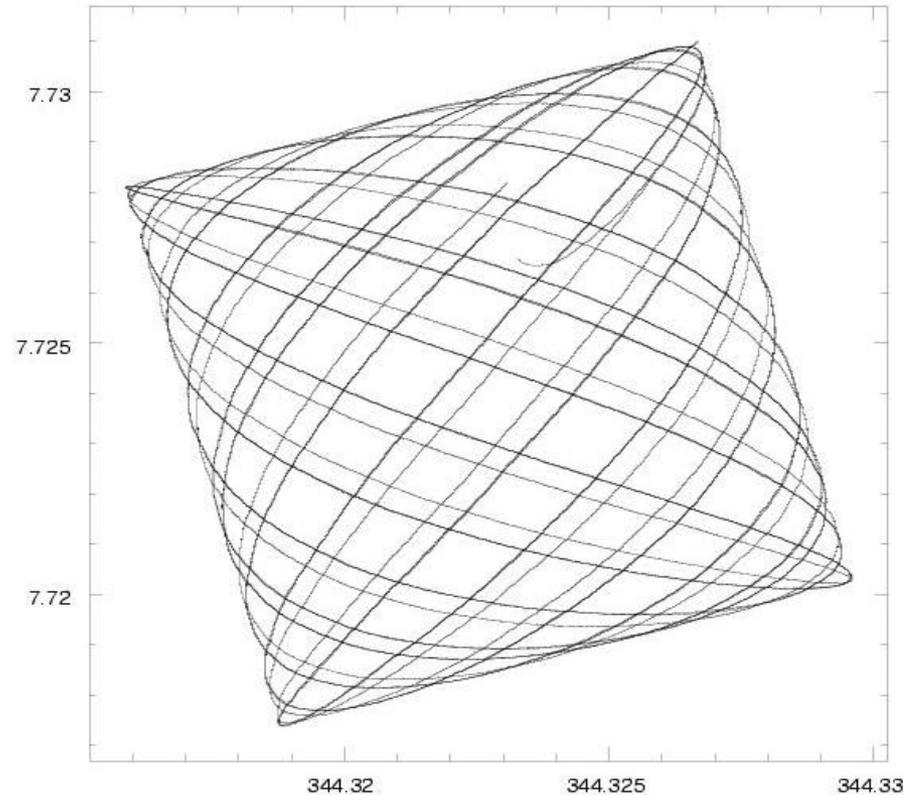
X-ray Event Lists

Energy slices through an event list from 0.1 to 10 keV





Aspect Solution

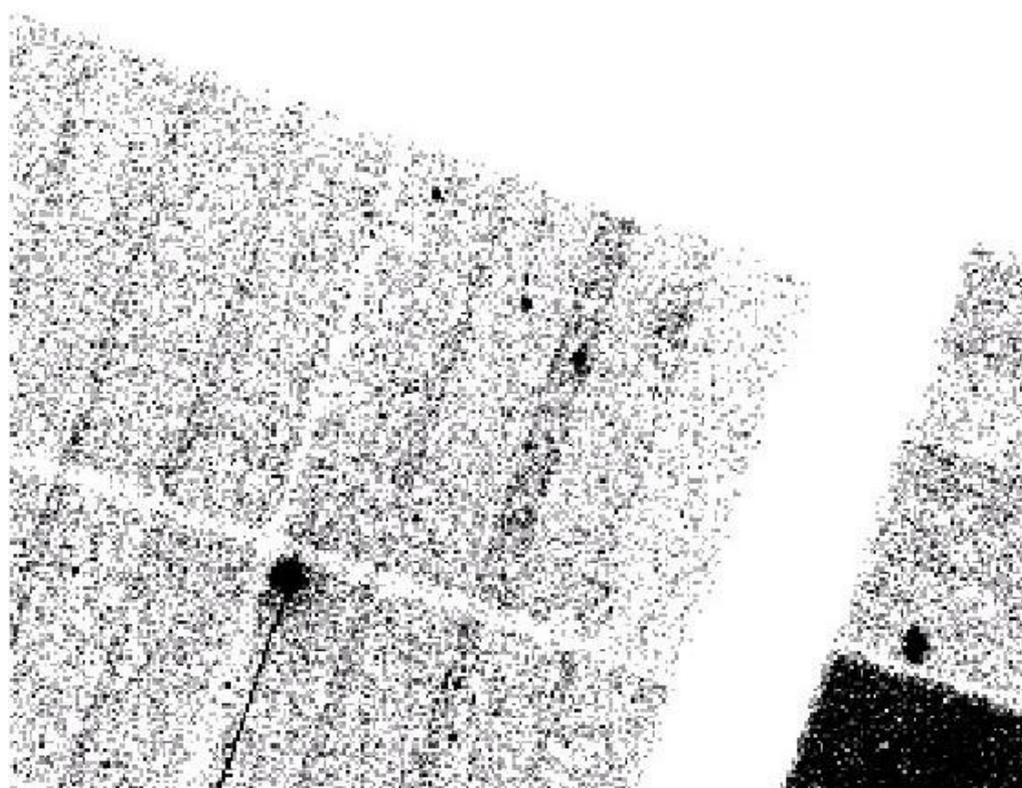


Chandra moves the telescope in this pattern, smearing a source on the detector.

We record the motion of guide stars so we can reconstruct RA and Dec for each photon.



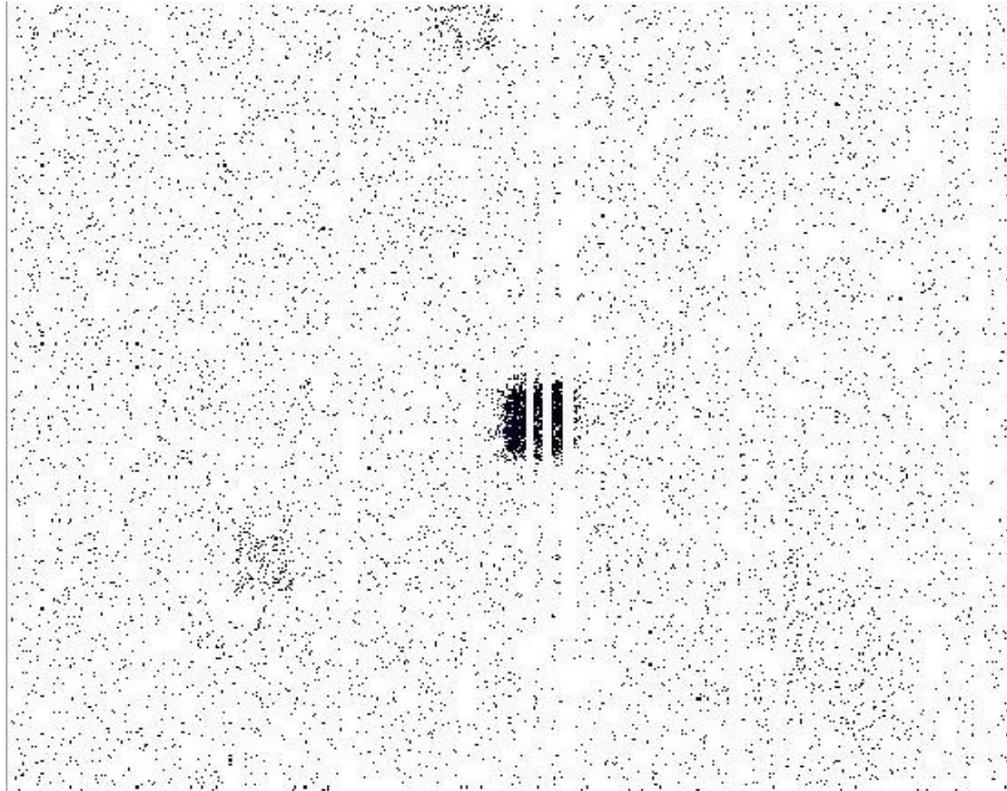
Chandra aspect-corrected data



This is what you get after calibration but before cleaning the data. Note the sharp point sources near the center.



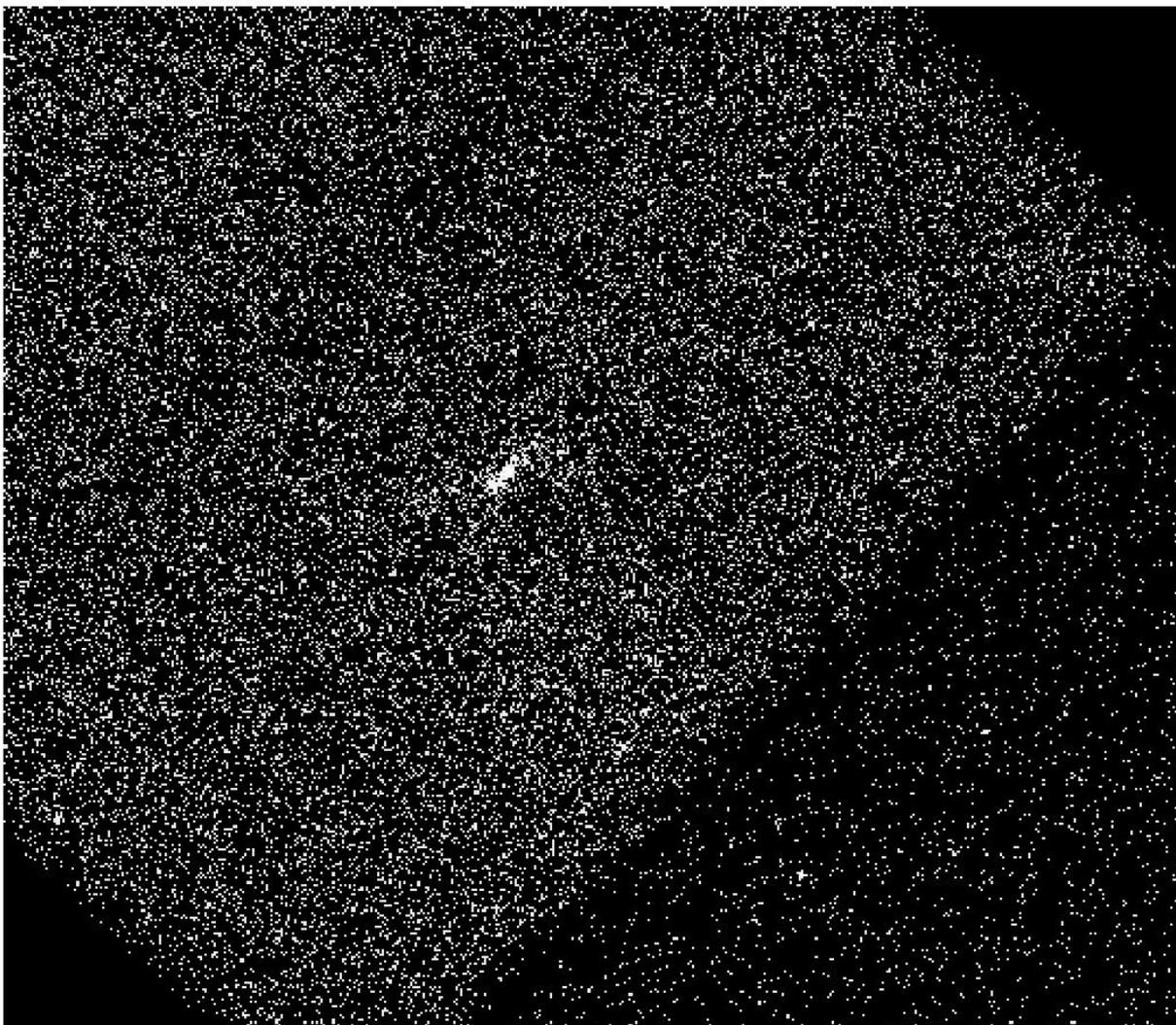
Chandra raw (chip) data



In instrument space, the photons are spread out over 20 arcsec and have bad columns going through them - so be careful of the effective exposure time. If you didn't dither, you could lose the source entirely if it landed on a bad pixel



X-ray Event Lists

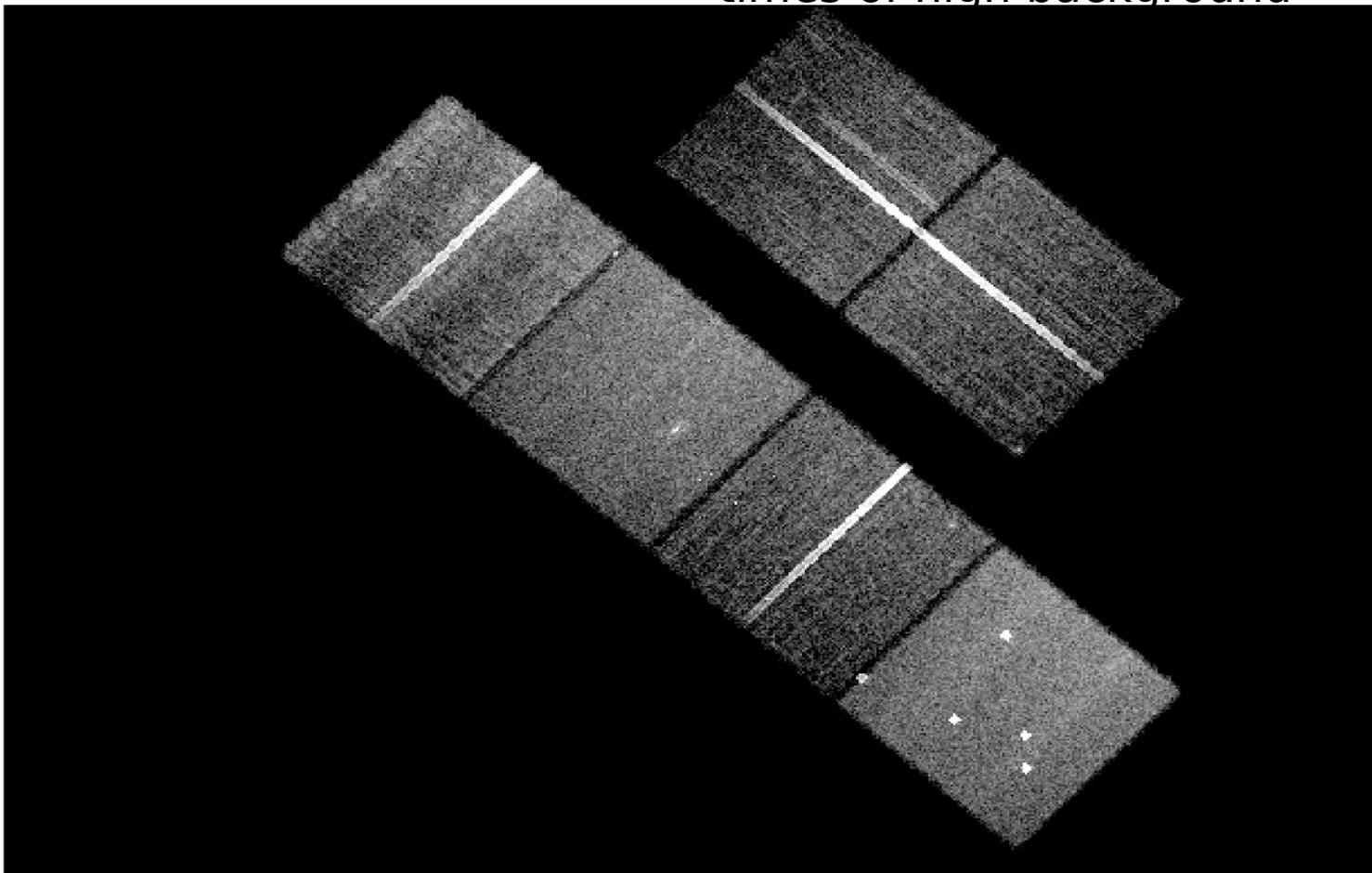


Arp 220 before
background
subtraction



X-ray Event Lists

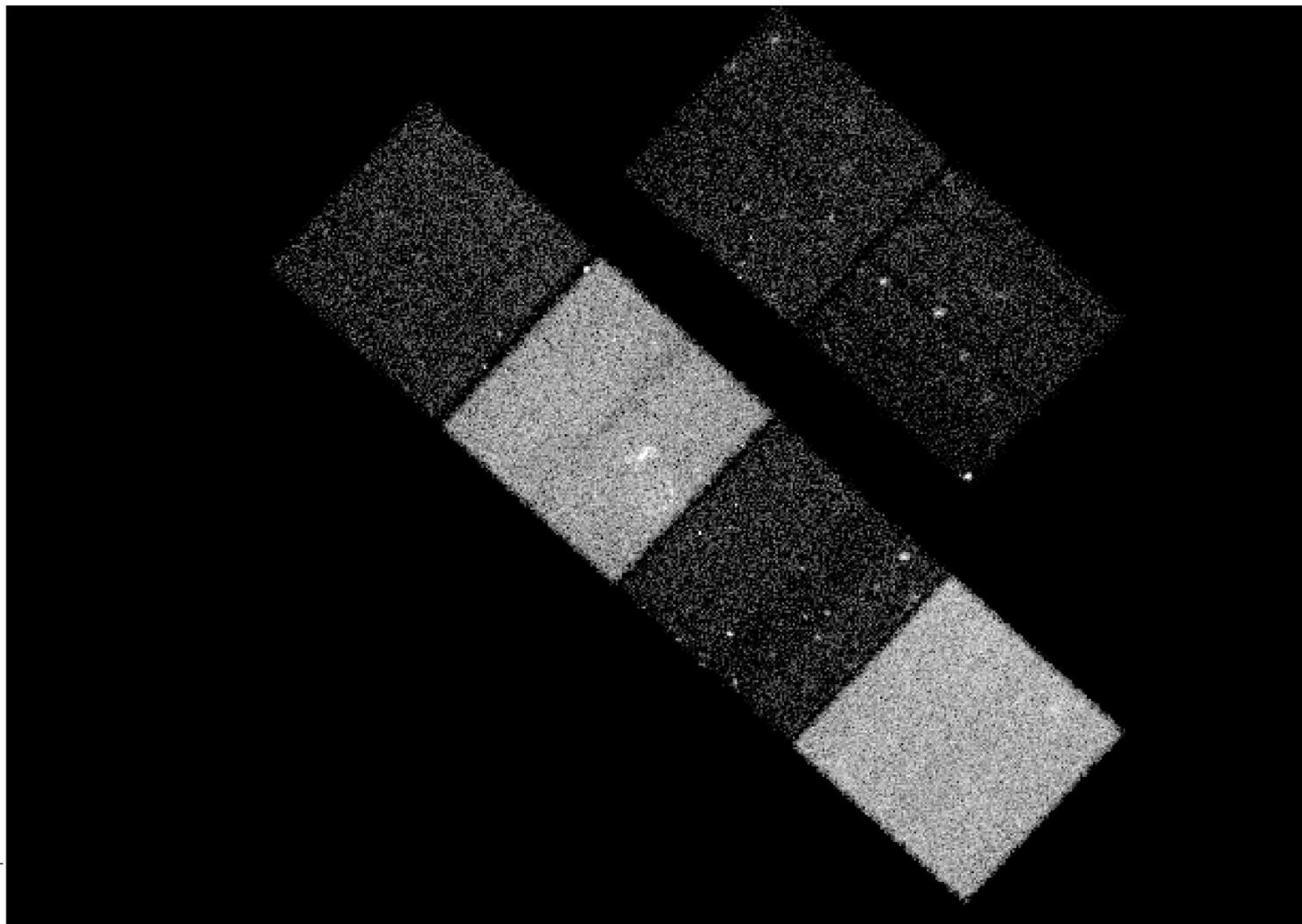
Level 1 data with bad columns,
times of high background





X-ray Event Lists

Level 2 event list, cleaned
and energy filtered

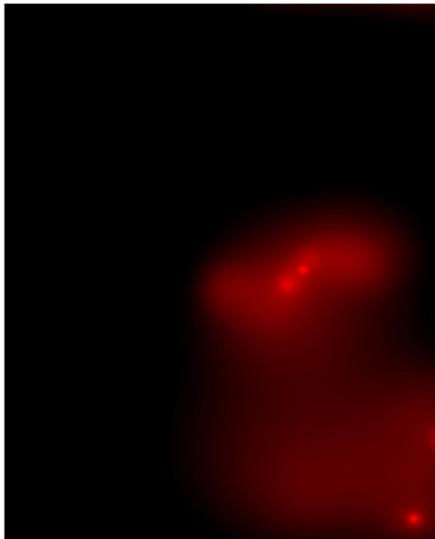




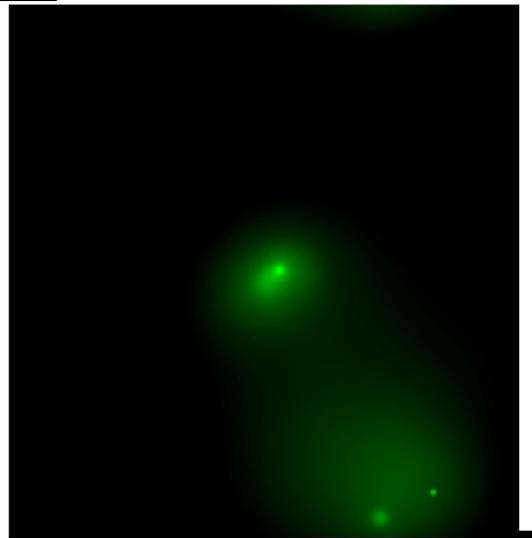
X-ray Event Lists

Arp 220 data smoothed in 3 bands - we are now dealing with images rather than events

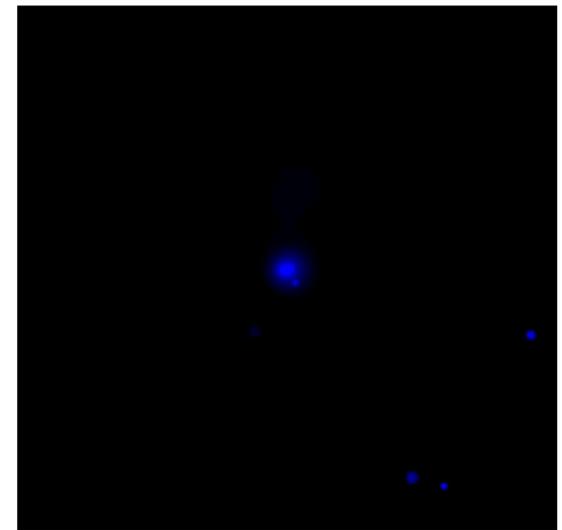
Note the hard AGN, and the soft emission from the gas being stripped from the background galaxy



0.1-1 keV



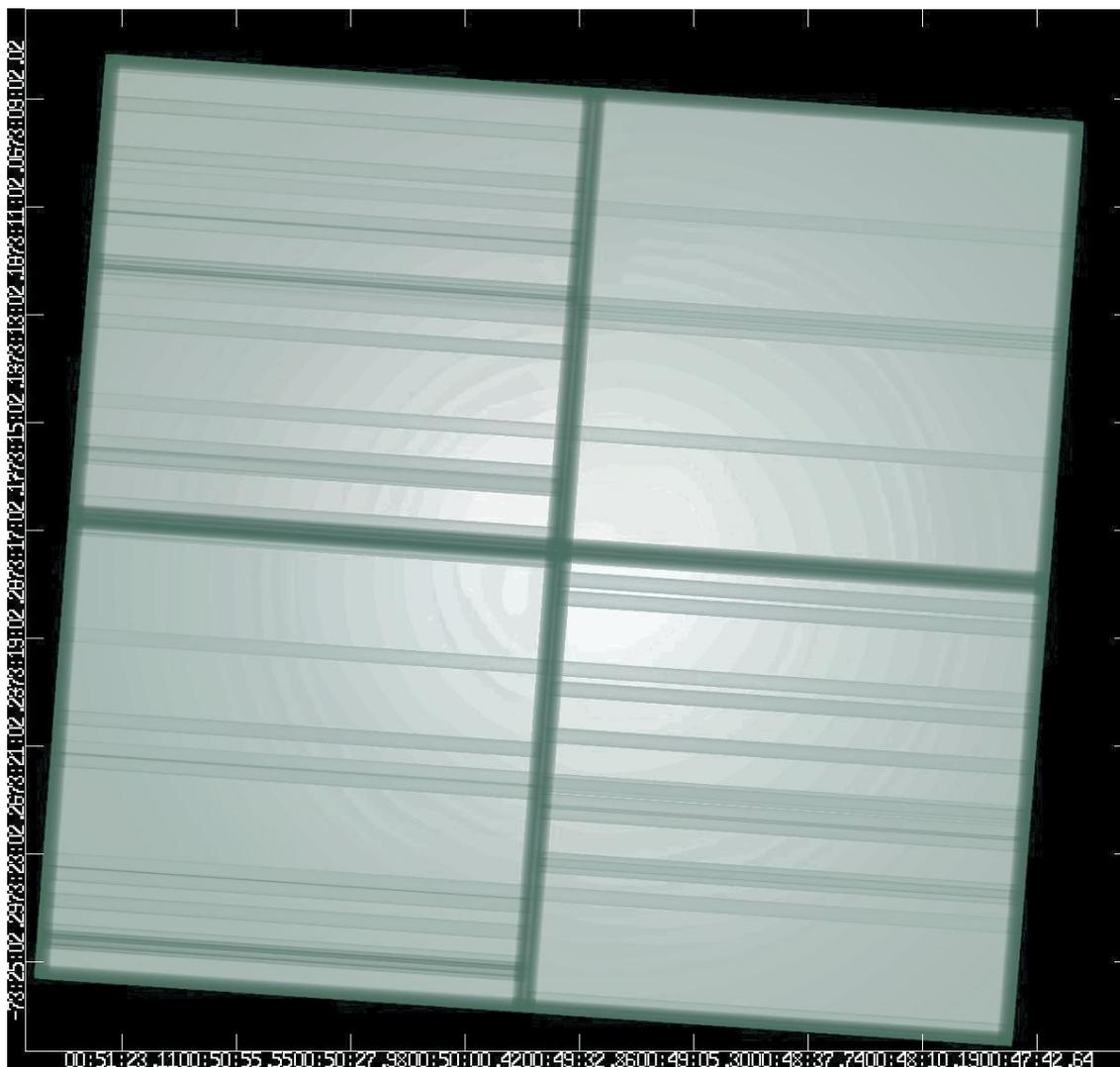
1 - 2 keV



2-8 keV

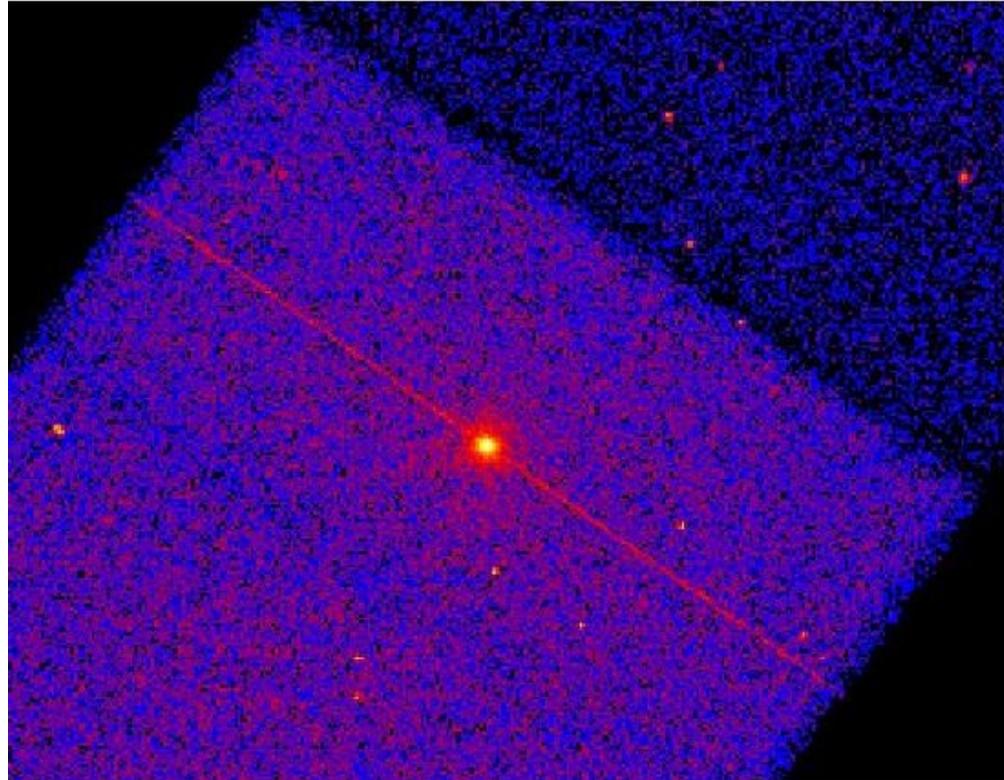


Exposure Maps



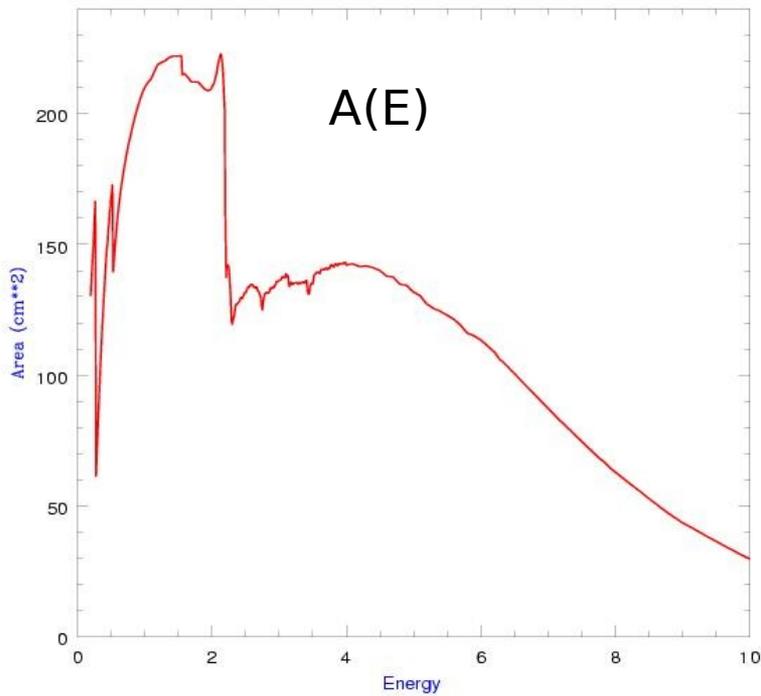


Out-of-time events

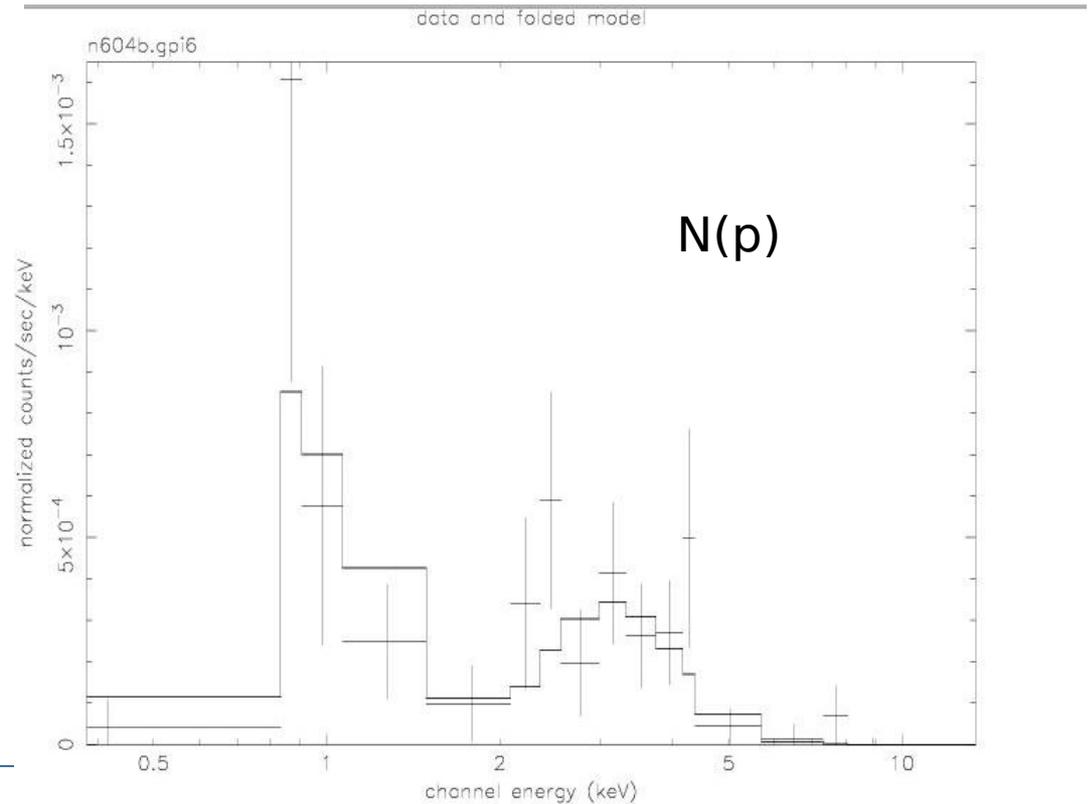
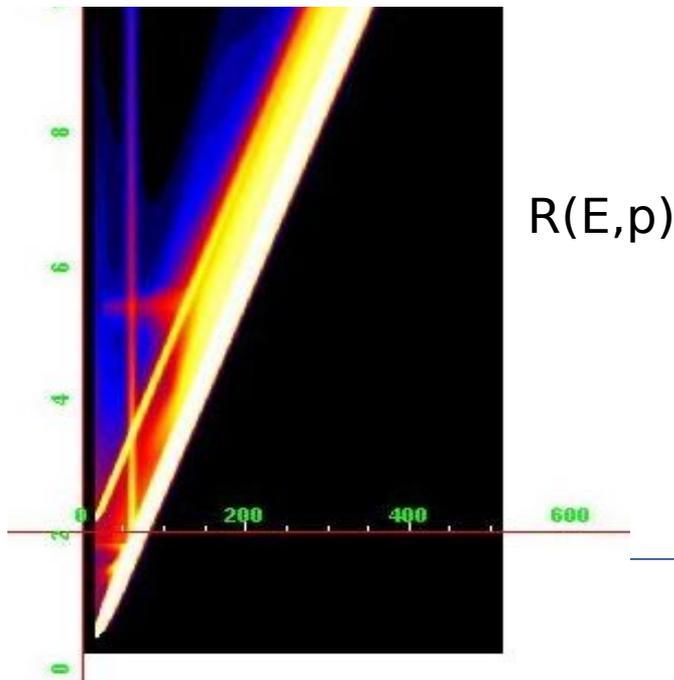


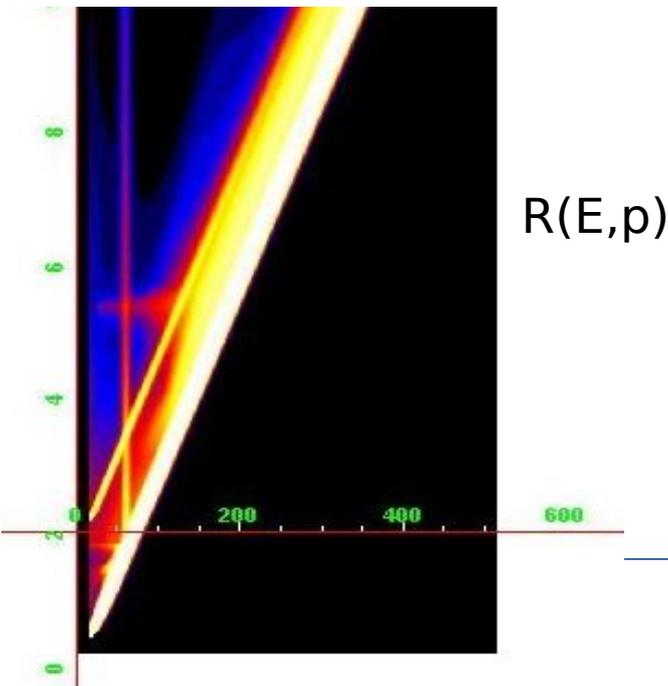
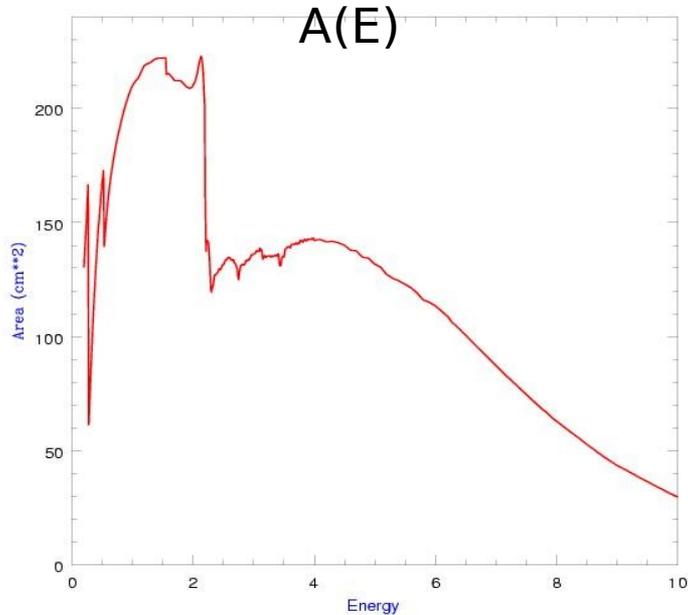
We don't have a shutter on the chip - so photons keep arriving as you clock the charge out. Software exists to clean this up for bright sources.

Spectra in Poissonland



$$N(p) = \int R(E, p) A(E) F(E) dE$$





$A(E)$ changes with time (contamination correction) and detector position (quantum efficiency uniformity map); so does the slope of $R(E,p)$, the “gain” mapping instrument channel to energy (TGAIN correction, gain map). The width of $R(E,p)$ changes due to CTI effects. The calibration also changes with CCD operating temperature.



Spectra in Poissonland

We pick a parameterized $F(E)$ such as warm absorber models, lines, thermal plasma codes. Which $F(E)$?

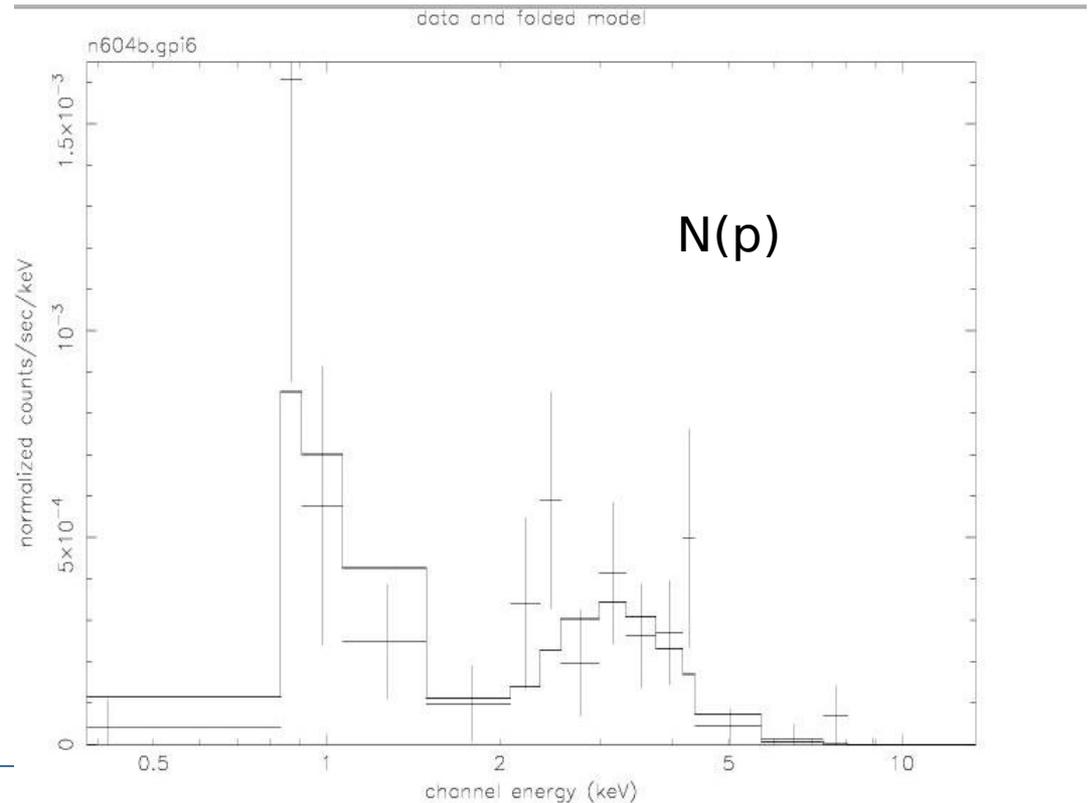
You must pick one based on expected physics, but match number of free parameters with quality of data.

With less than 100 counts, we usually just use count ratios (X-ray colors) for spectral analysis.

Does one model fit significantly better than another? Be careful that two physically different models may look quite similar in $F(E)$ space.

Incompletely calibrated instrumental features may show up in residuals, limiting factor in high S/N spectra - these features may include edges. Beware apparent science in regions where $A(E)$ is changing rapidly.

$$N(p) = \int R(E, p) A(E) F(E) dE$$





Summary 1 - Science

- Chandra's high resolution delivers unique science
 - X-ray background resolved into AGN
 - Spectral and spatial studies of SNR reveal the different histories of ejecta, shocks, jets
 - Galaxy and cluster studies giving census of compact objects, reveal ULX sources, galacto-ecological role of hot ISM
 - X-ray jets are common in AGN
 - I haven't talked about the grating results
-



Summary 2 - Analysis

- X-ray telescopes drift while observing, so the pixels in your image are not the instrumental pixels
 - When you publish a source with only 3 photons, make sure you understand the background.
 - Instrumental properties tend to vary with both off-axis angle and energy - and often with time
 - The X-ray way: forward folding
 - BUT: X-ray missions have high quality calibrated data in their archives and we all use the same data formats ---> the learning curve is not too bad, and great science to be done
 - The new catalog makes it even easier to use X-ray data and provides the first astrometric all-sky (but not complete) catalog at high energies.
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