X-ray Astronomy and the Analysis of X-ray Data

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X-ray Astronomy's Age of Wonders

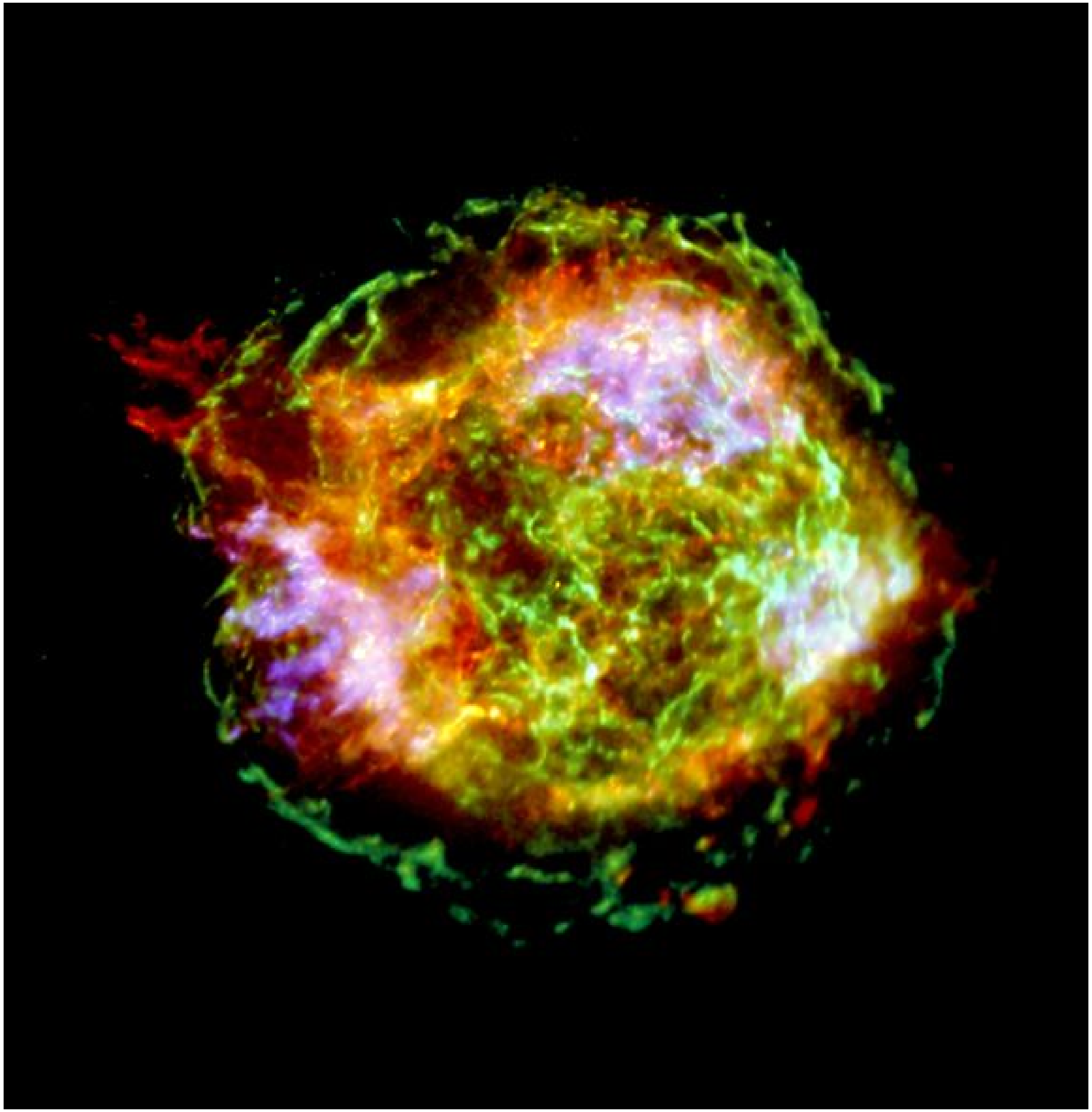
Major Observatories

- 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 will give good low background and broad band integrated spectra of extended objects, despite loss of XRS

Chandra

- 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

Cas A – fresh elements



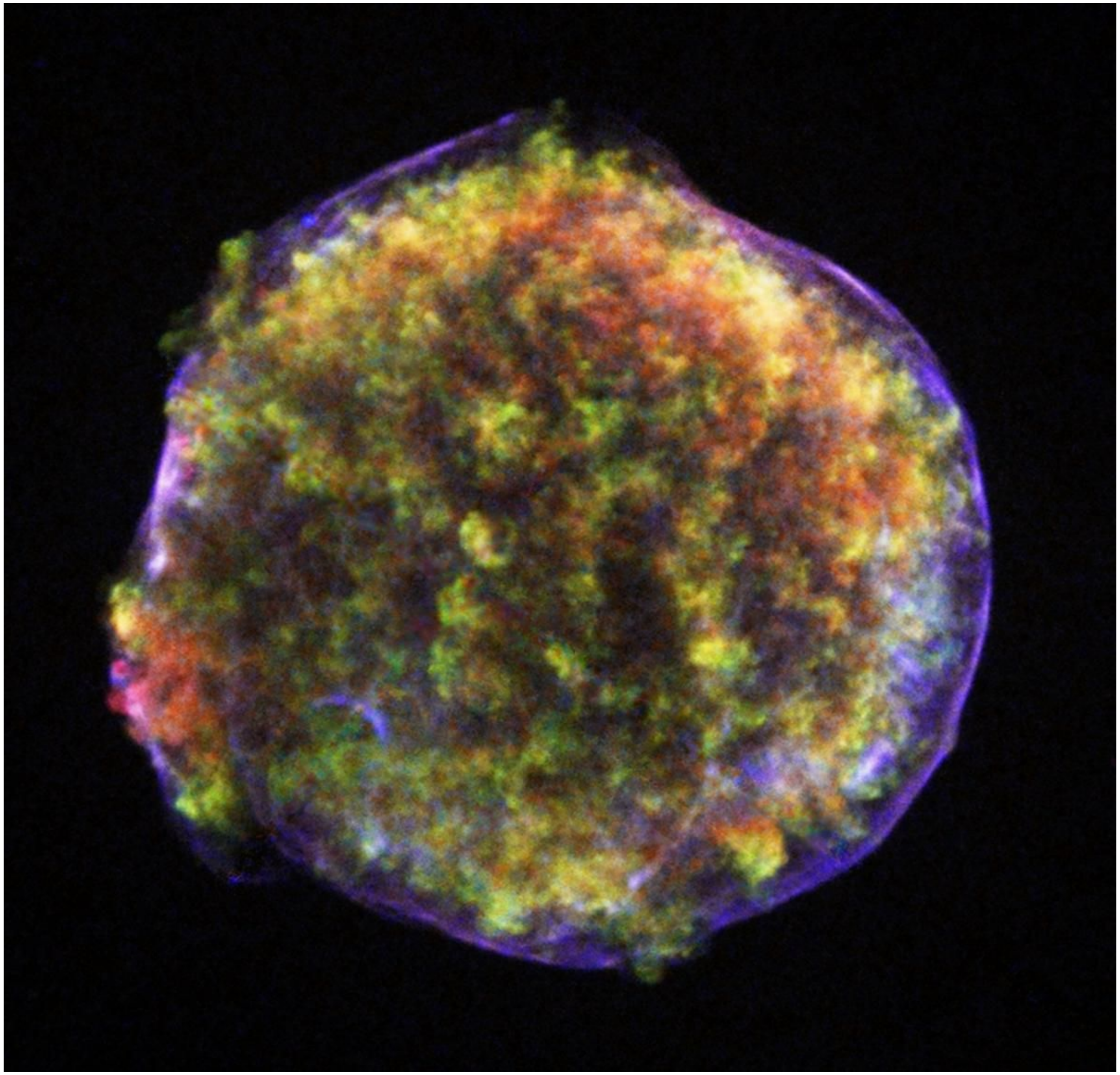
Green: continuum shock

Red: silicon line

Blue: iron line

Hwang et al 2004

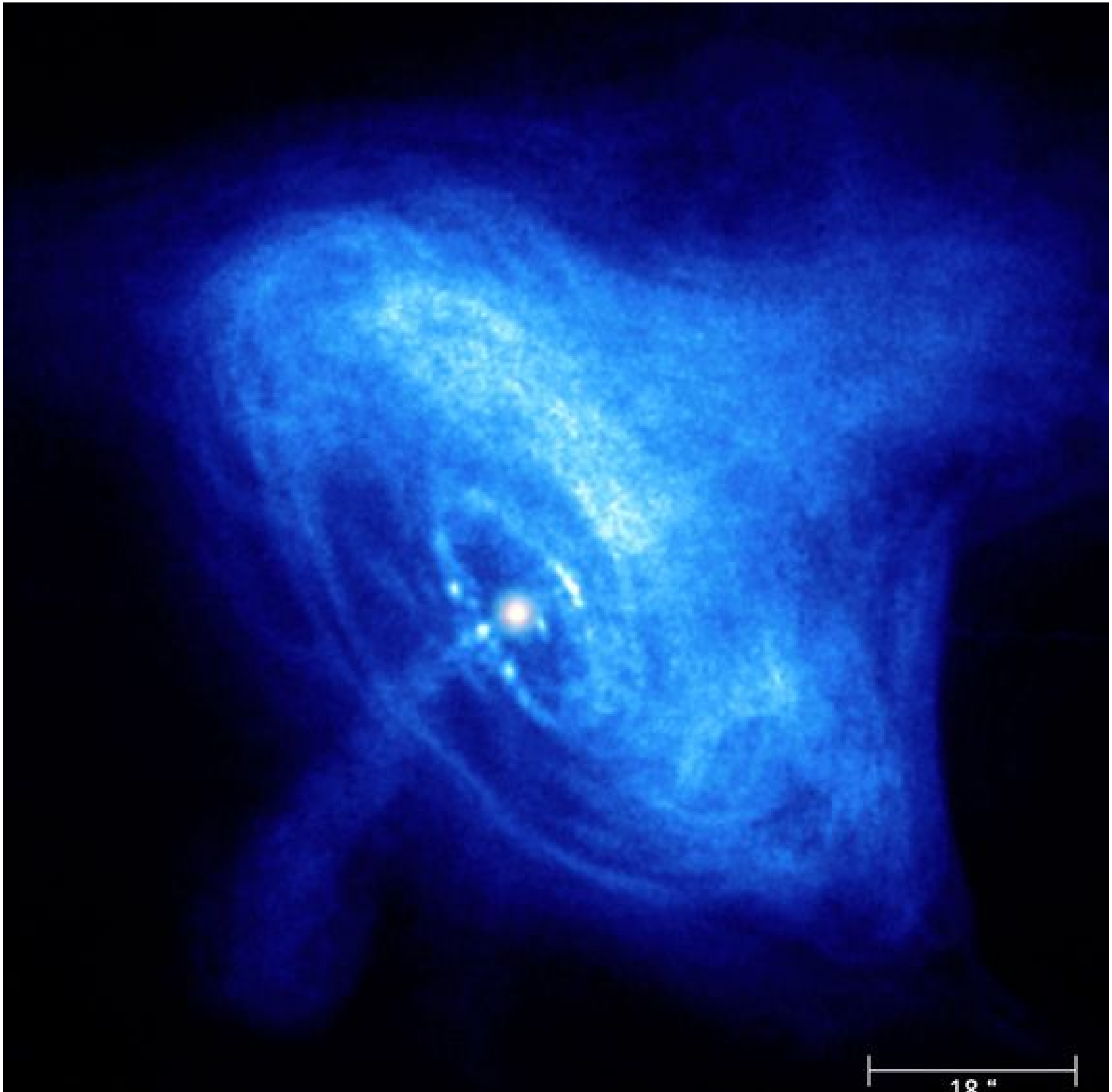
Tycho: ejecta and shock

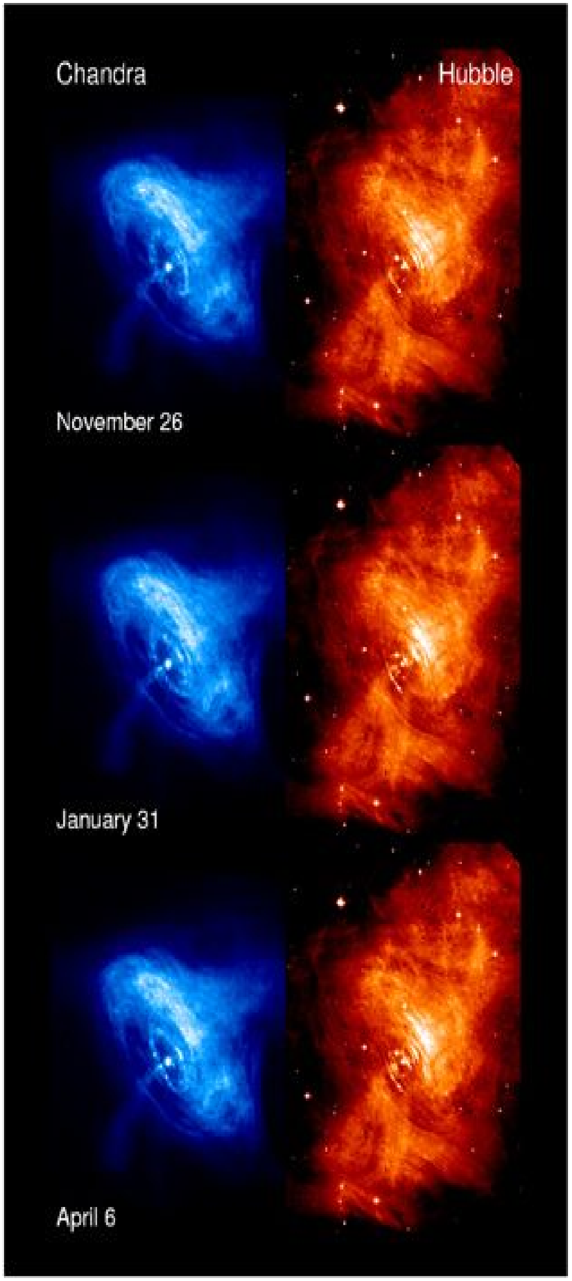


Warren and Hughes 2005

Crab Nebula

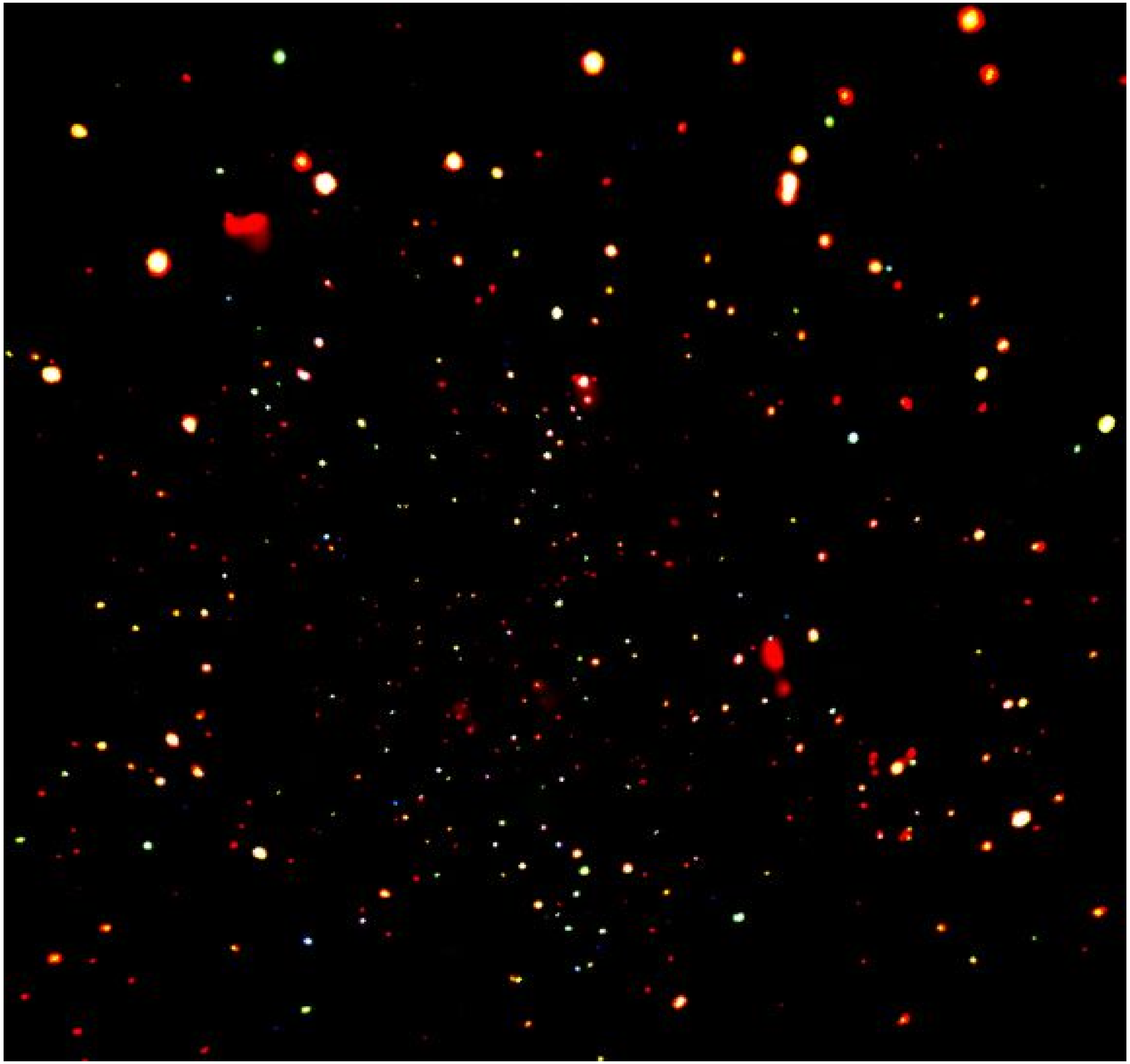
Chandra monitoring shows features moving in jet and torus at ~0.5 c





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.

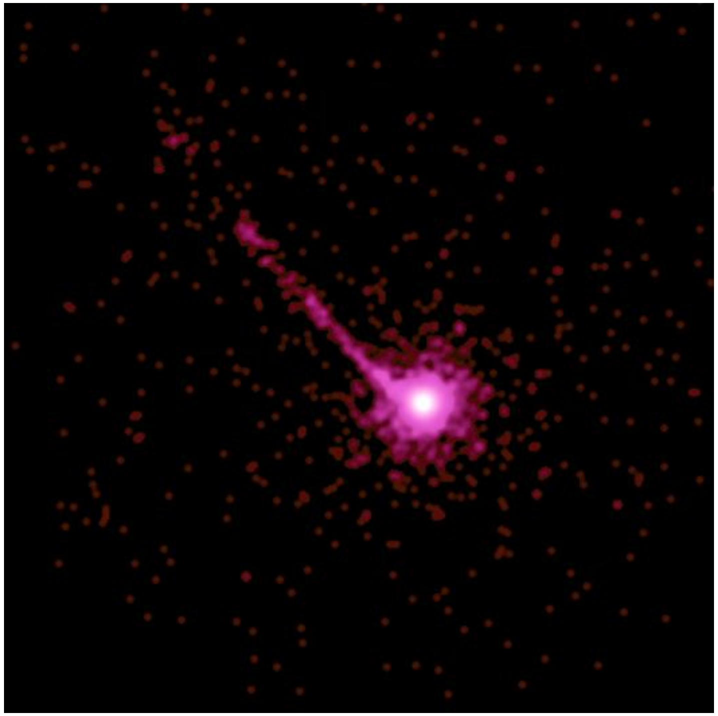
The change in the spectral resolution and sensitivity of the instrument over the period is significant.

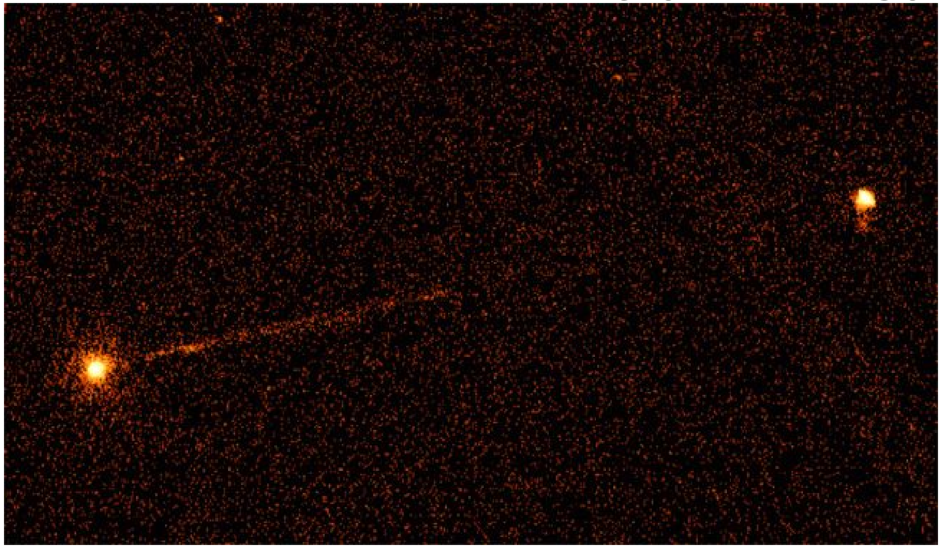
The exposure map (“flat field”) for each chip has significant energy dependence as well as discontinuous variations associated with chip and node boundaries.

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

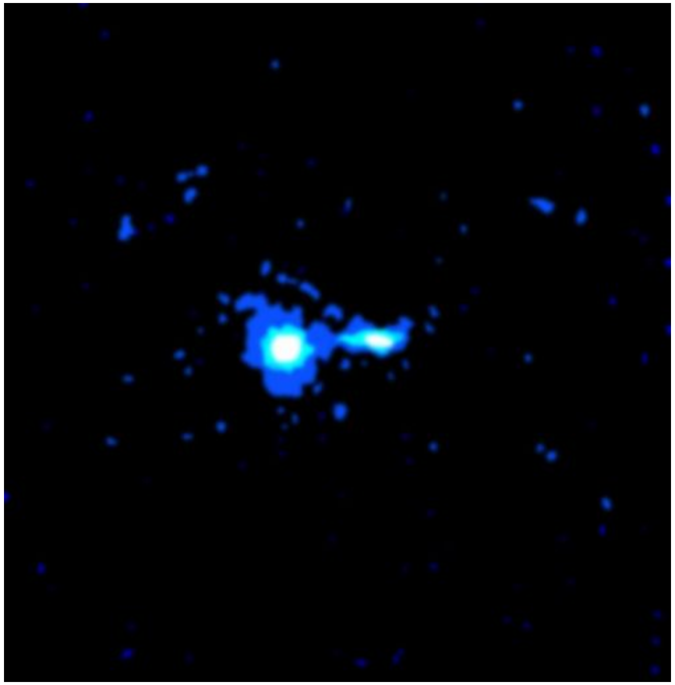
AGNs with Jets

Pictor A - Wilson



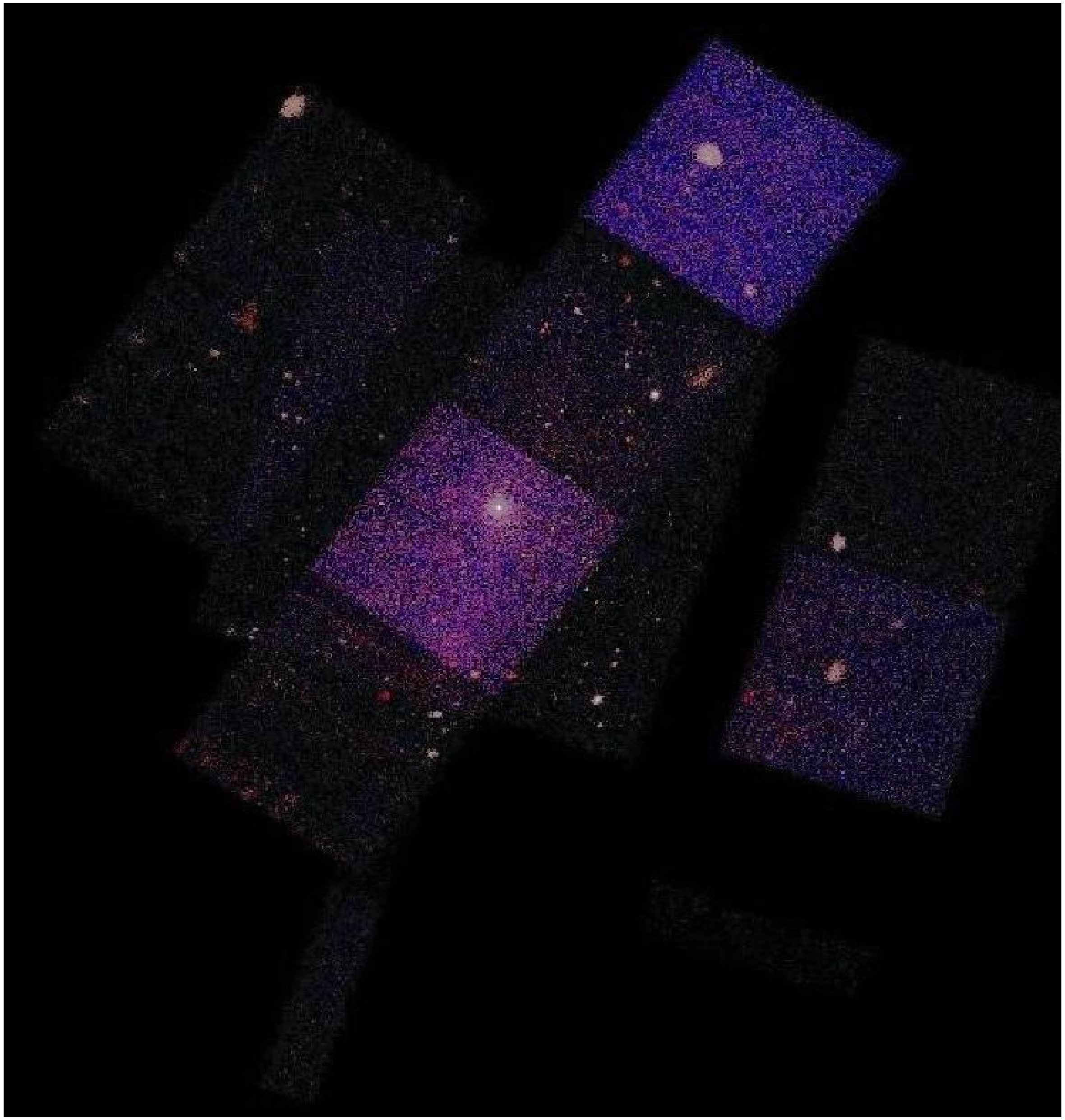


PKS 1127-145 - Siemiginowska, Bechtold



PKS 0637-75 - Chandra first focus image

M33 – compact populations



McDowell et al 2002
Grimm et al 2005

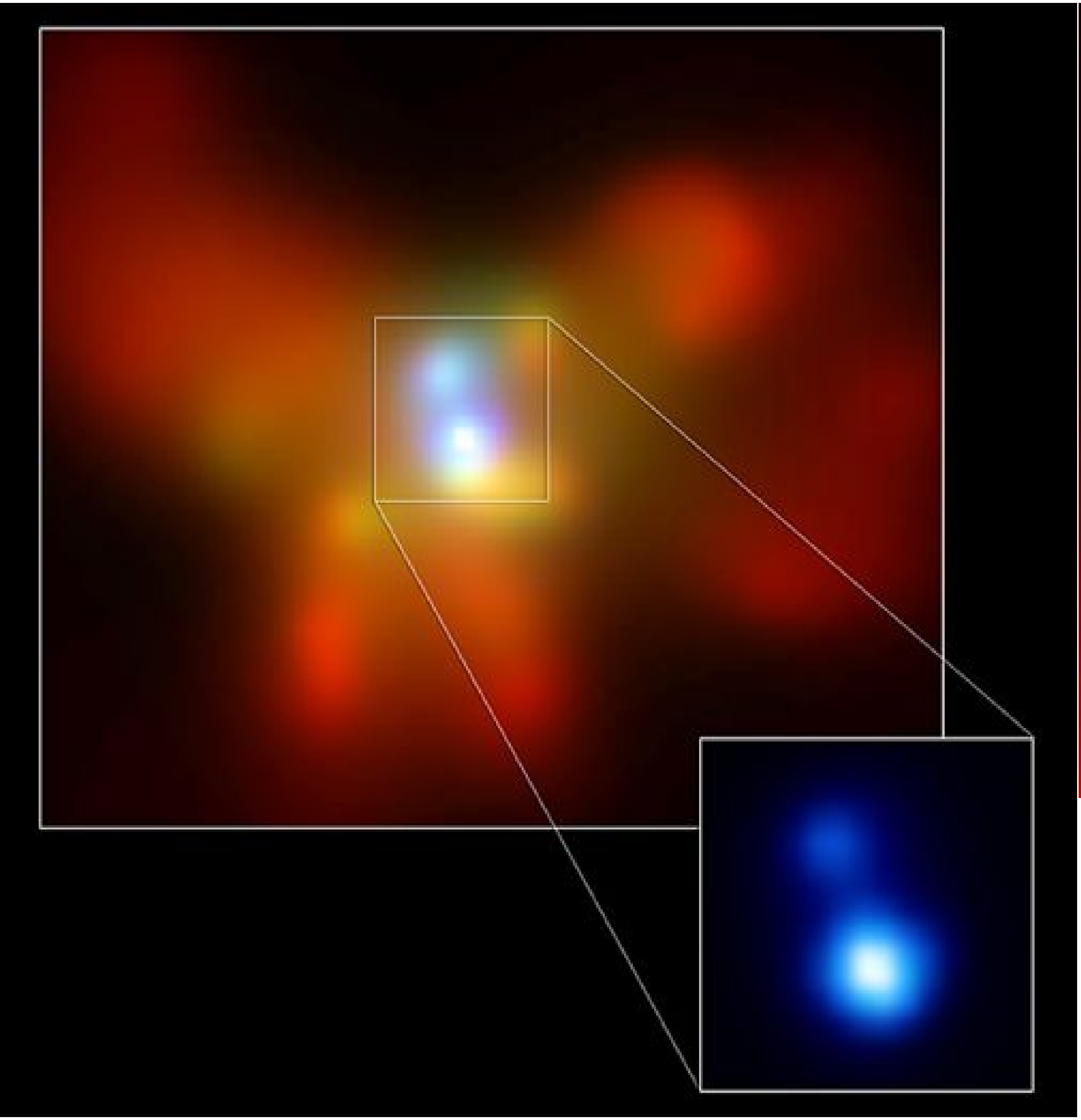
X-ray CCDs

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., astro-ph/0506353

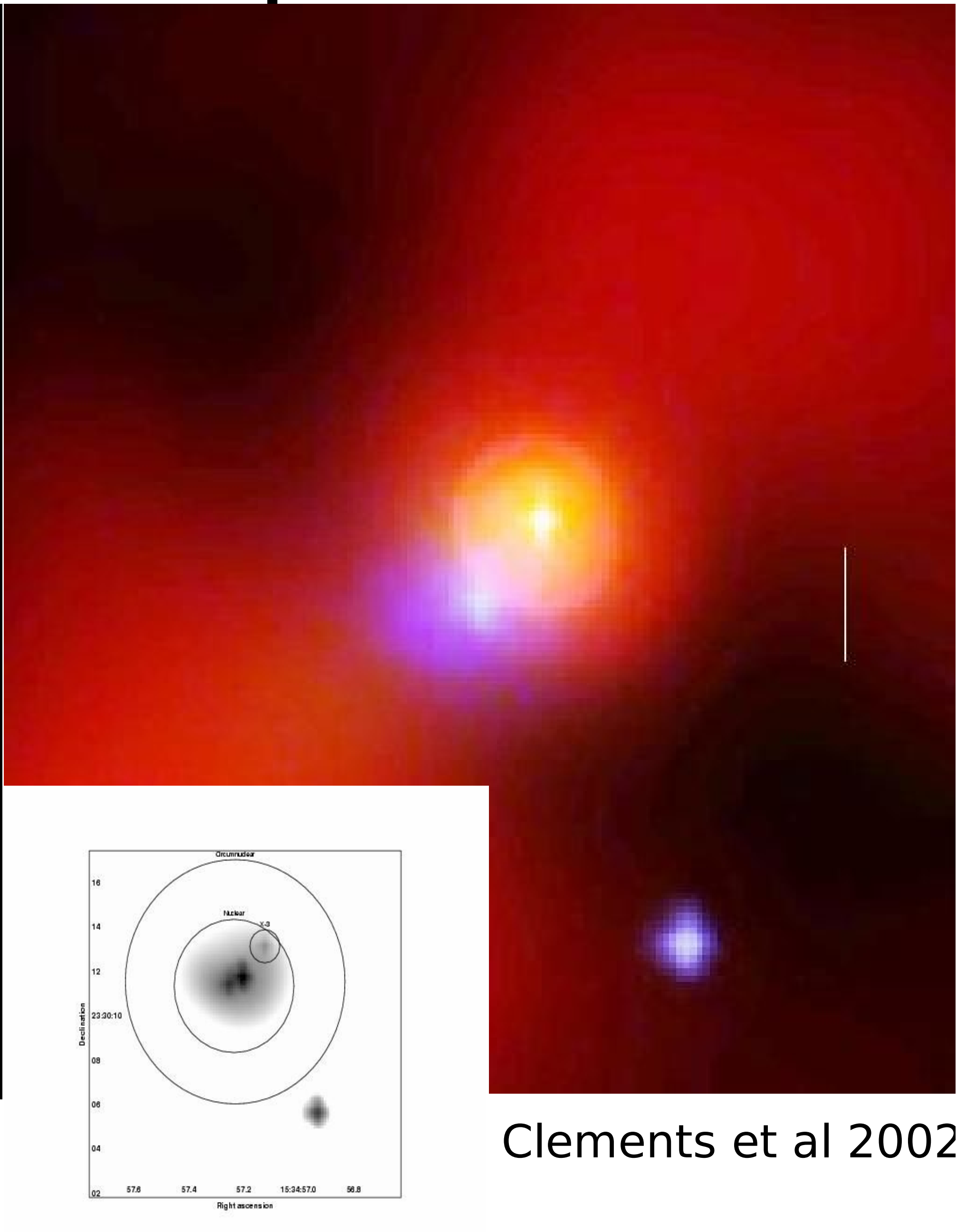
The luminosity function reaches 2 x 10**34 erg/s and includes neutron star binaries, supernova remnants, supersoft sources, etc.

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

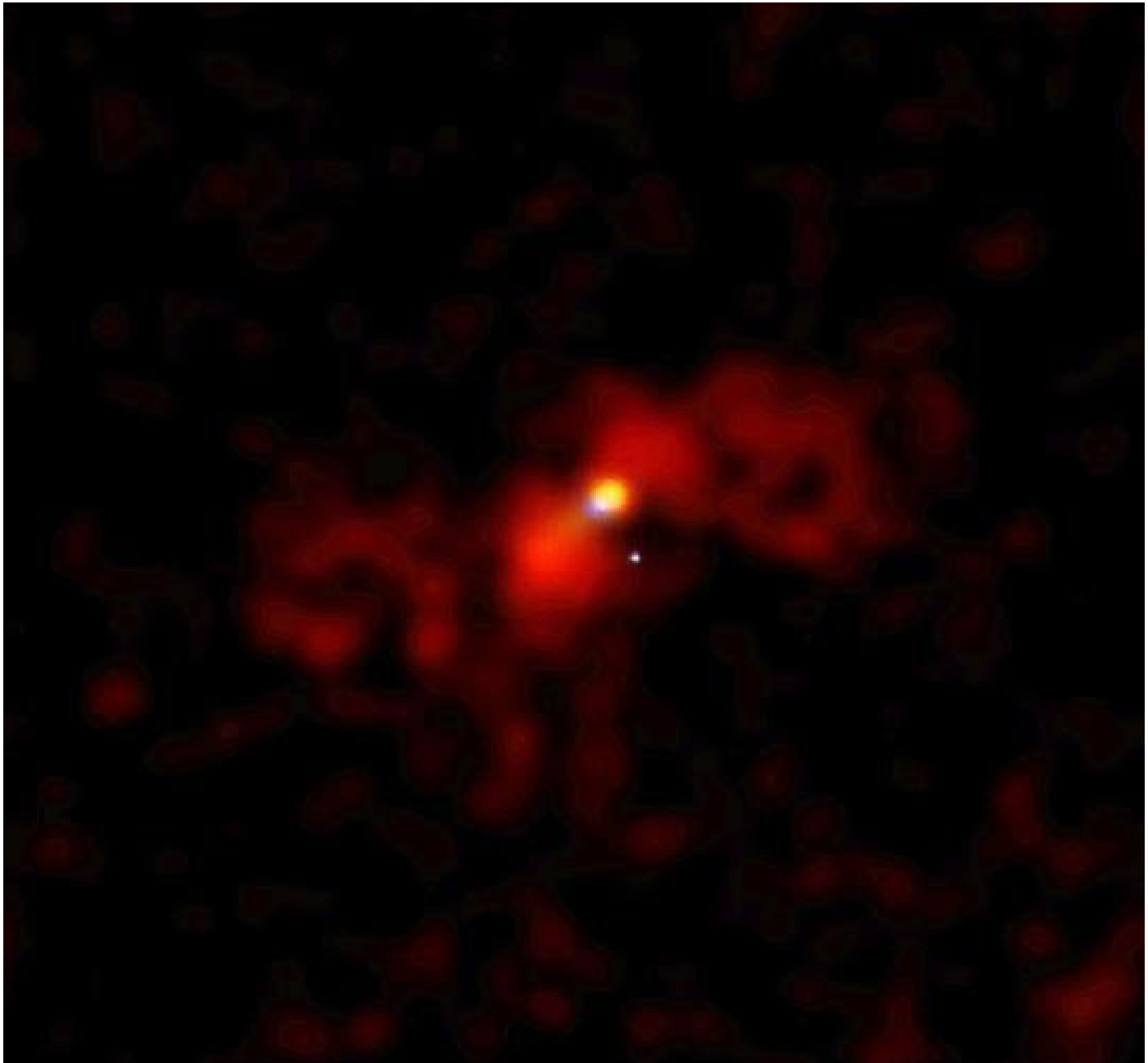
Marginal extent

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.

Arp 220



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).

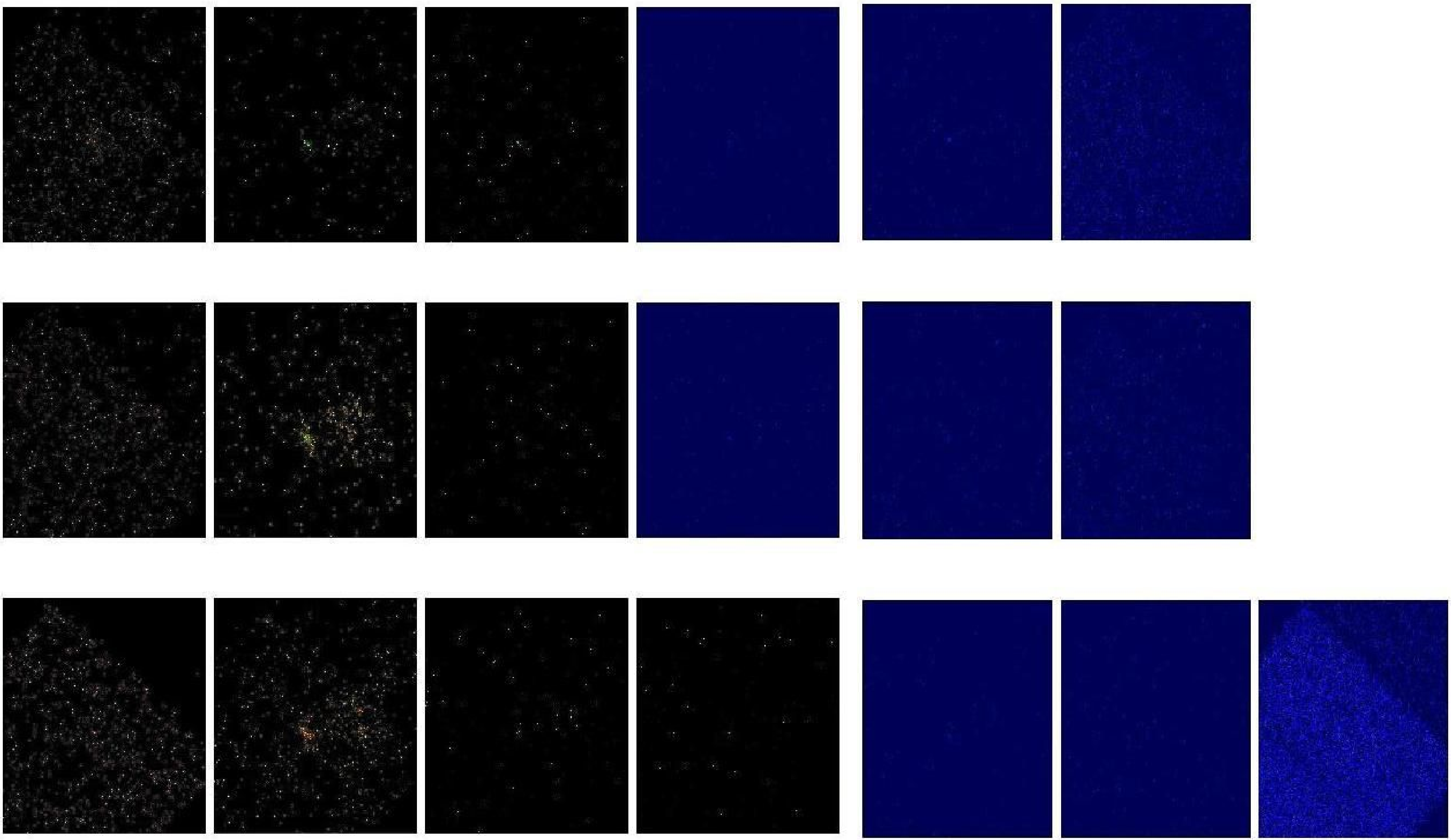
Always in the X-ray domain, we use fluxed, smoothed, deconvolved data to suggest a model, and then we take a forward-folding approach - convolve the model with a telescope simulator and compare in raw count space - to validate the model and measure numerical quantities.

X-ray Analysis Software

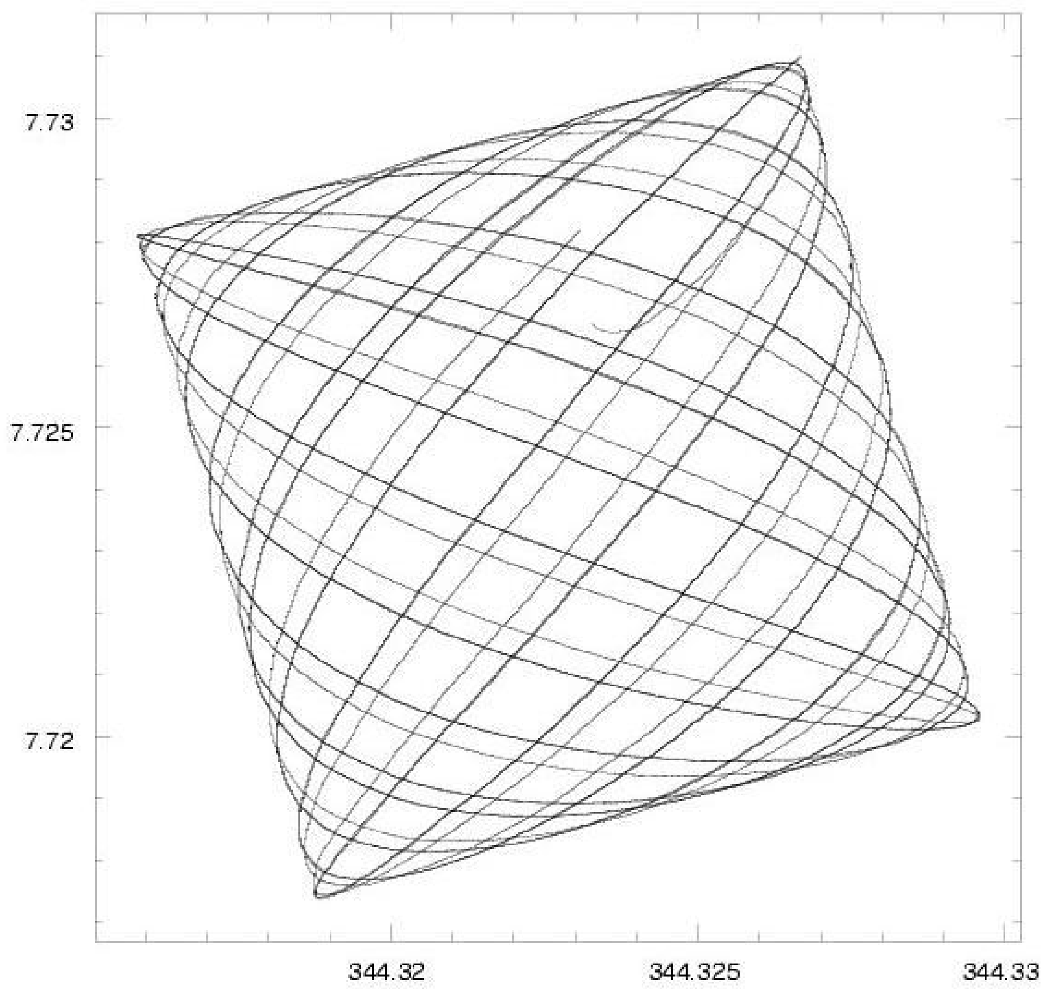
- CIAO (cxc.harvard.edu) – SAO/MIT general analysis package, optimized for Chandra, strong in spatial analysis
  - dmcopy, acis_process_events, sherpa
- HEASOFT (heasarc.gsfc.nasa.gov) - Goddard general purpose X-ray package
  - fdump, xselect, xspec
- SAS (xmm.vilspa.esa.es) - Specific to XMM-Newton
- 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

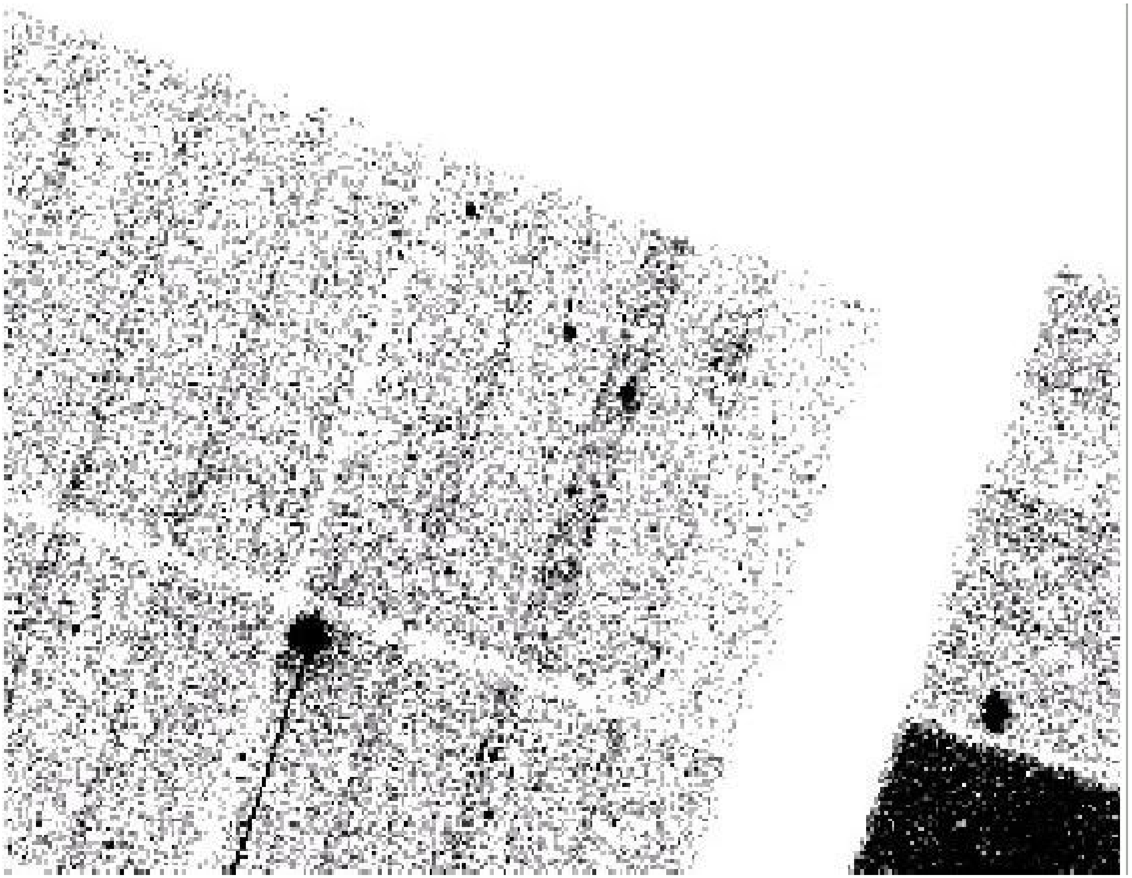


Aspect Solution



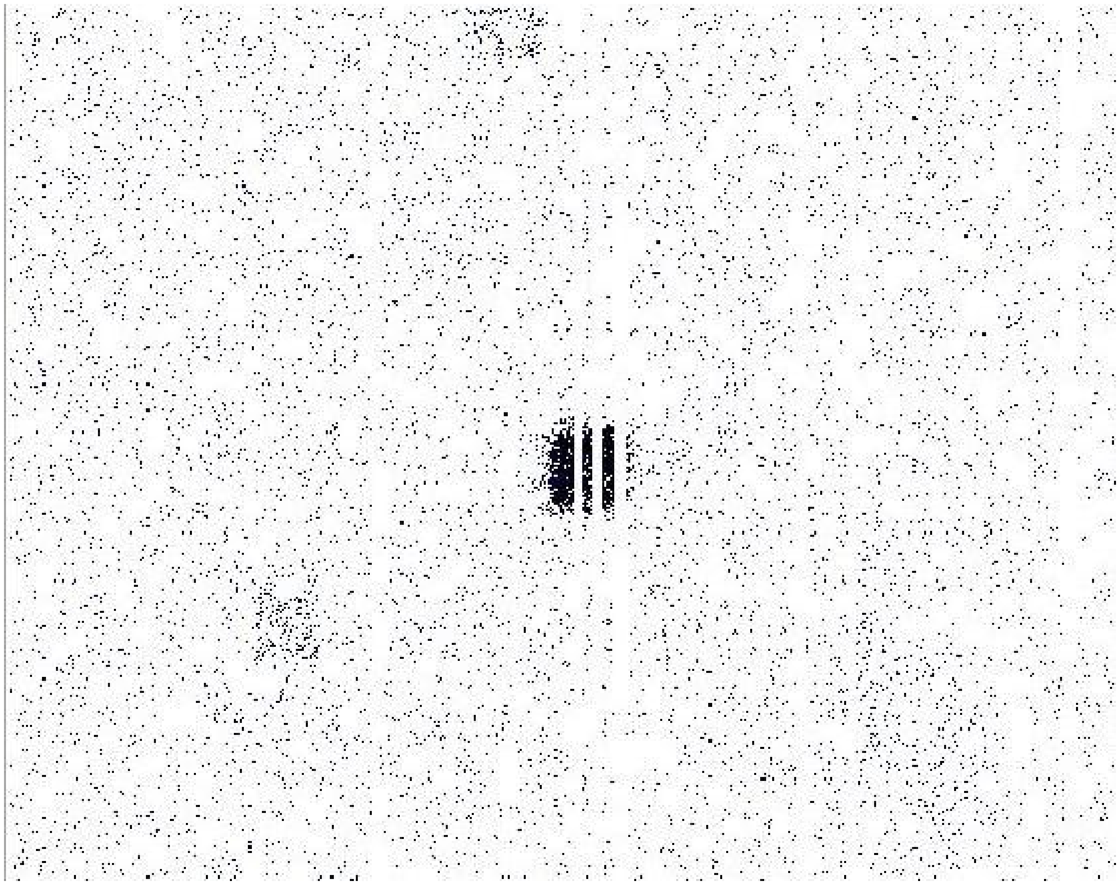
Chandra moves the telescope in this pattern, smearing a source on the detector.
We record the motion of guide stars so we can reconstruct RA and Dec for each photon.

Chandra aspect-corrected data



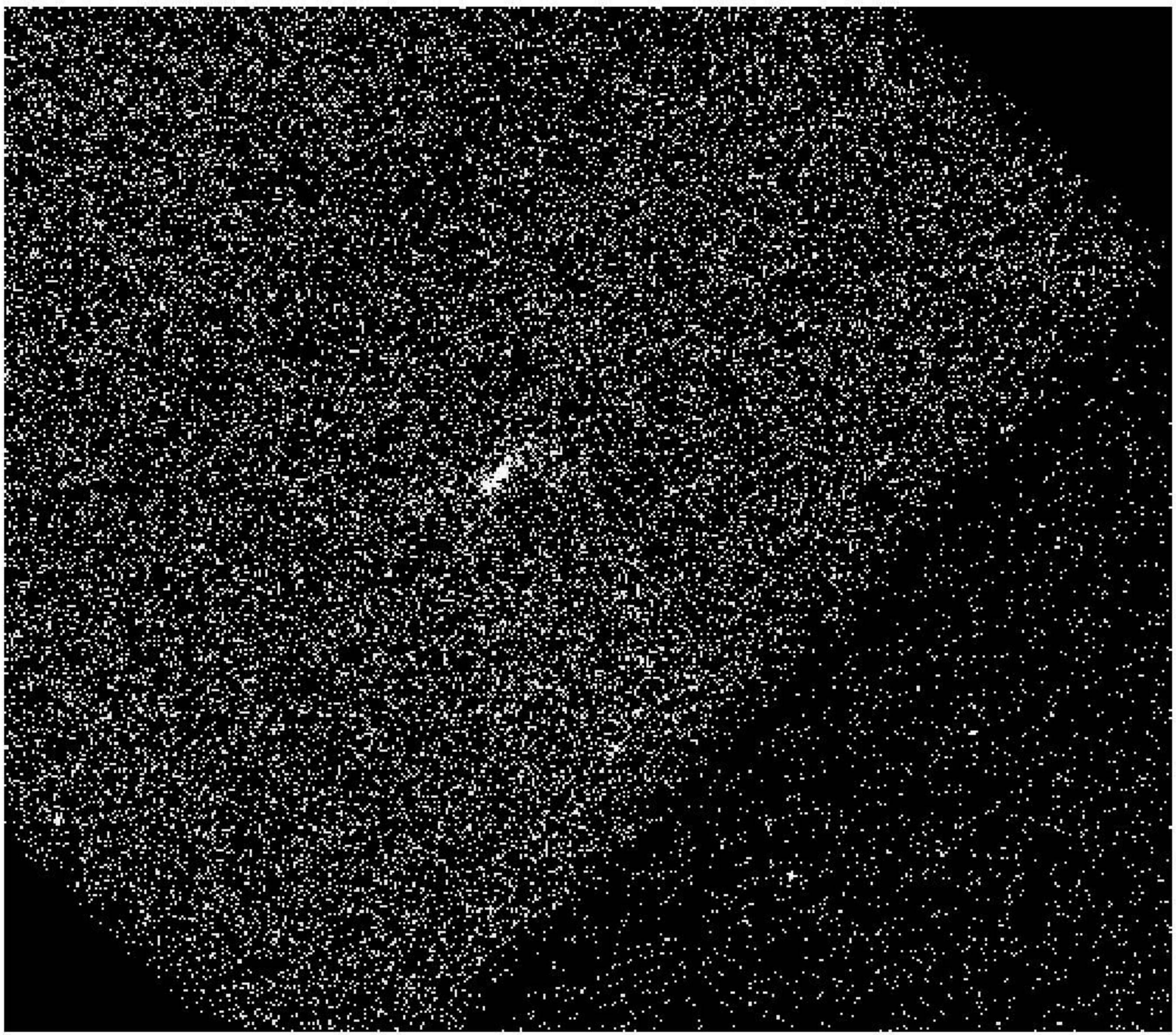
This is what you get after calibration but before cleaning the data. Note the sharp point sources near the center.

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

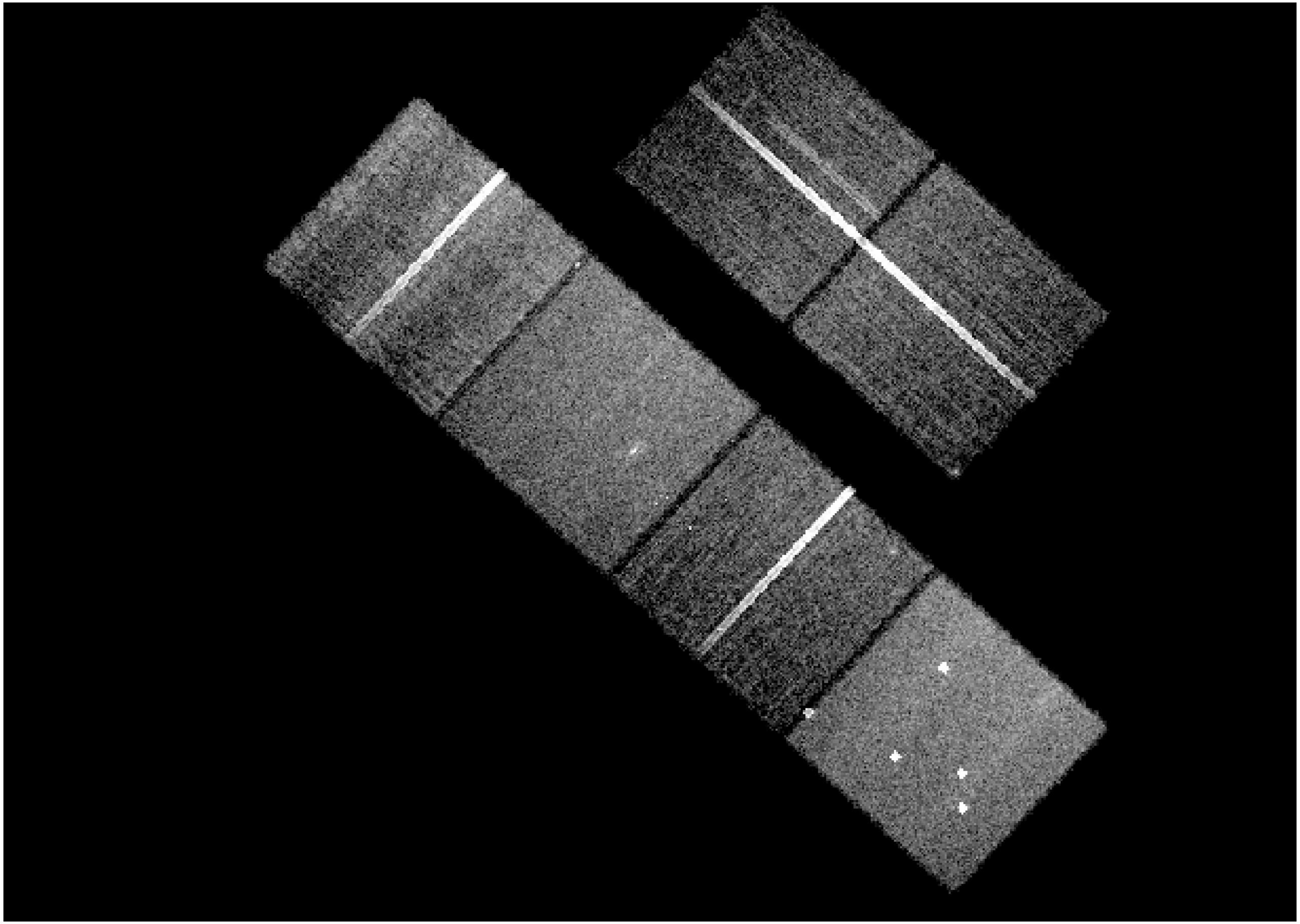
X-ray Event Lists



Arp 220 before background subtraction

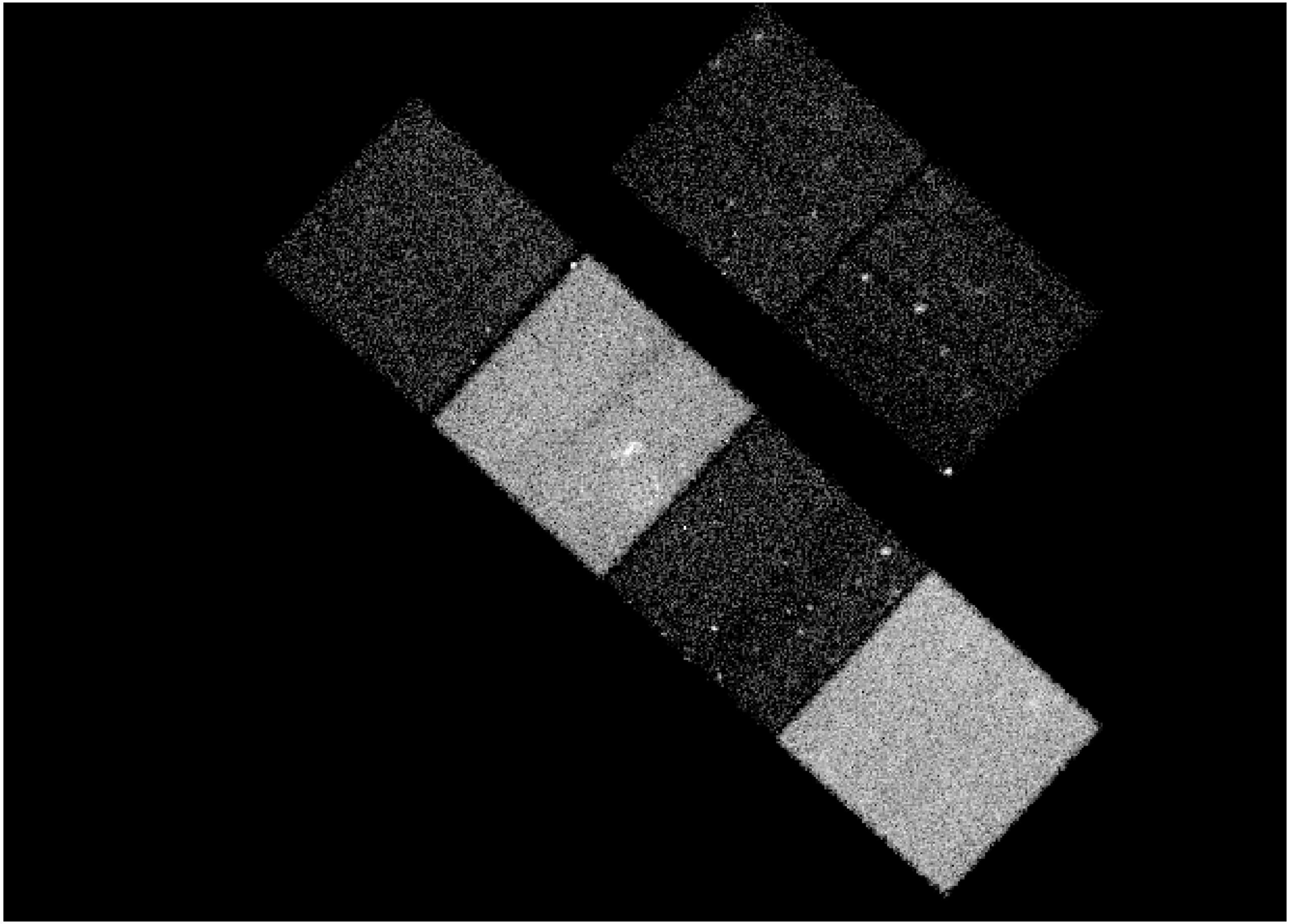
X-ray Event Lists

Level 1 data with bad columns, times of high background



X-ray Event Lists

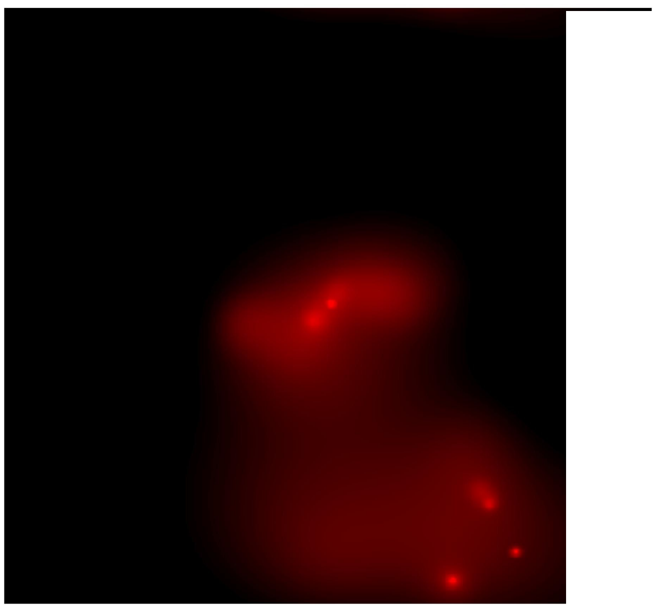
Level 2 event list, cleaned and energy filtered



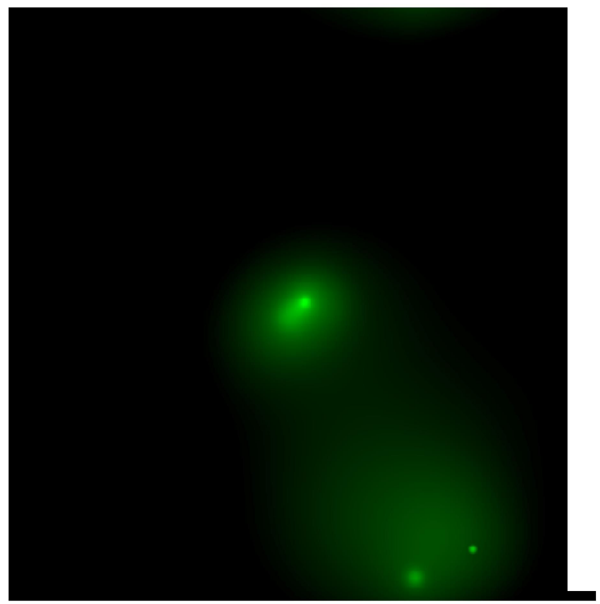
X-ray Event Lists

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

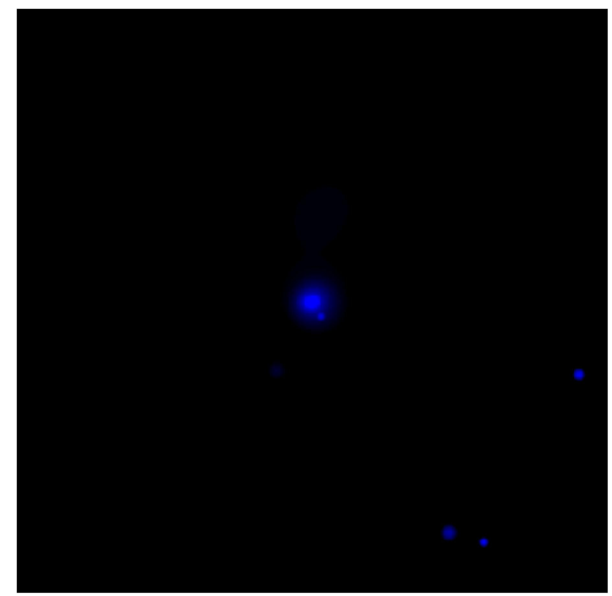
Note the hard AGN, and the soft emission from the gas being stripped from the background galaxy



0.1-1 keV

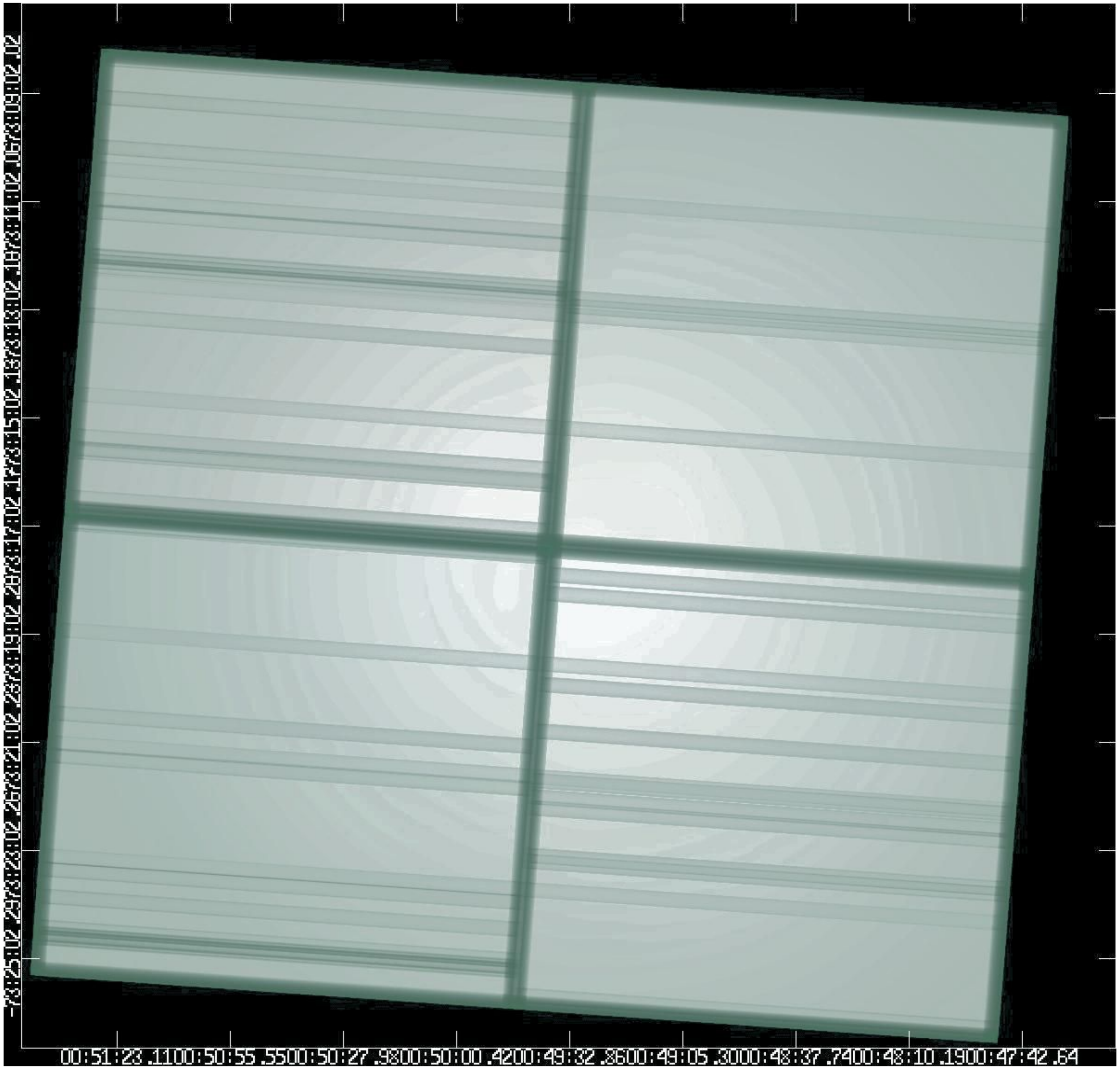


1 - 2 keV

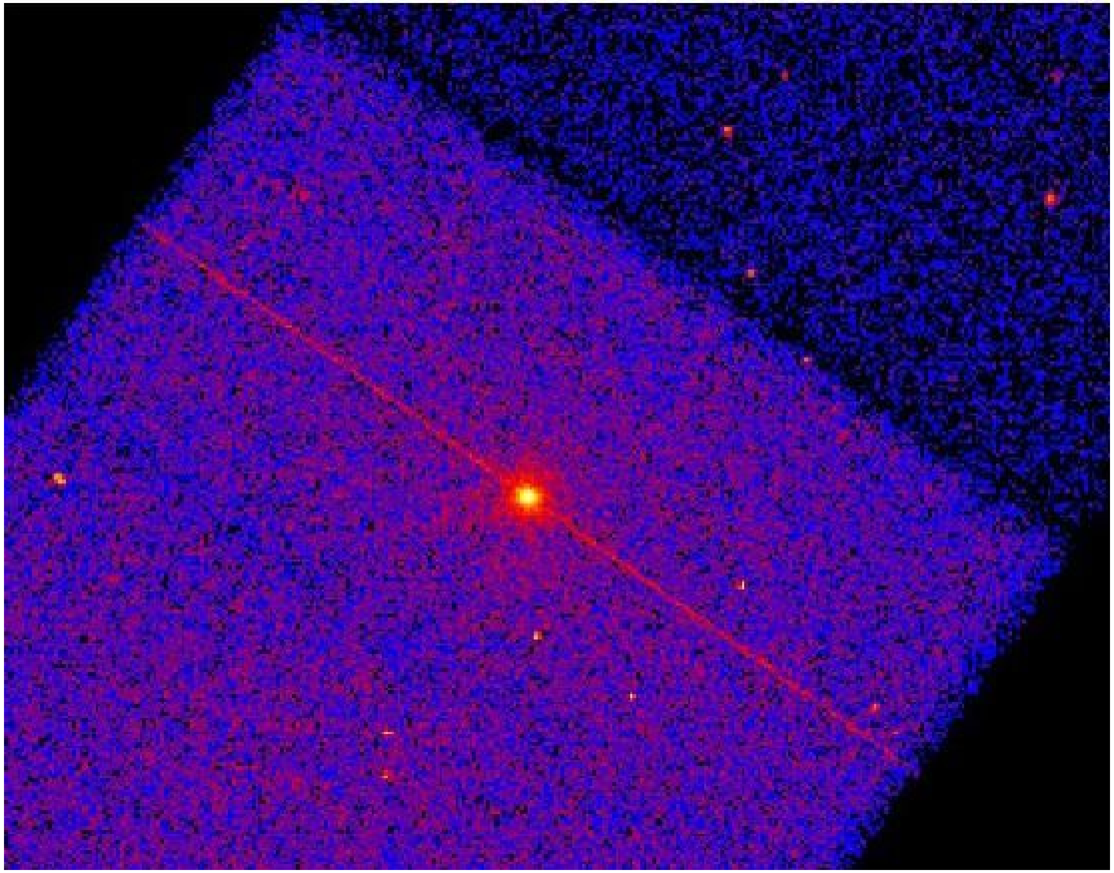


2-8 keV

Exposure Maps

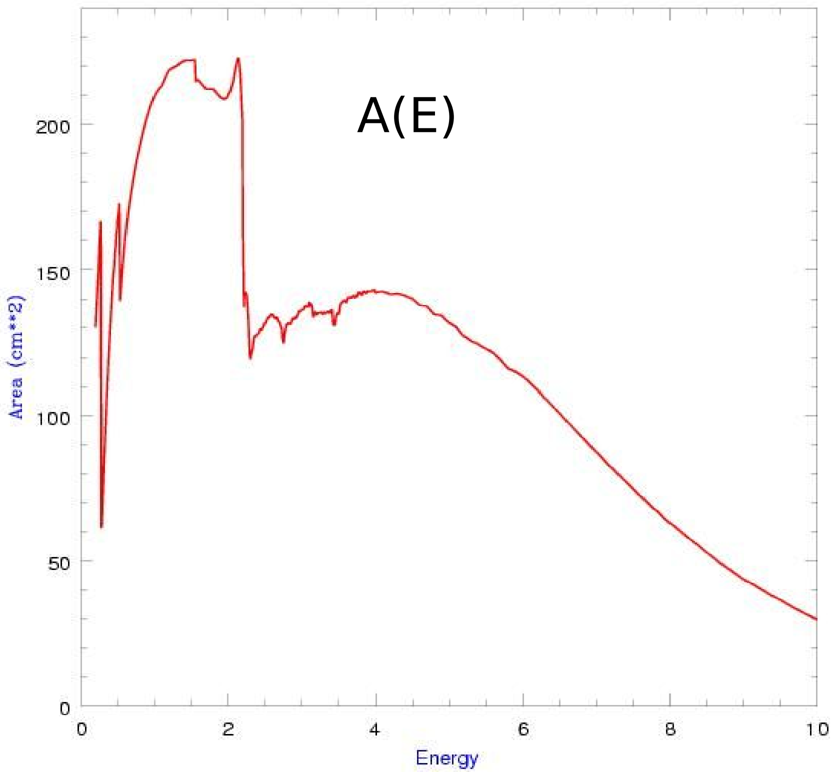


Out-of-time events

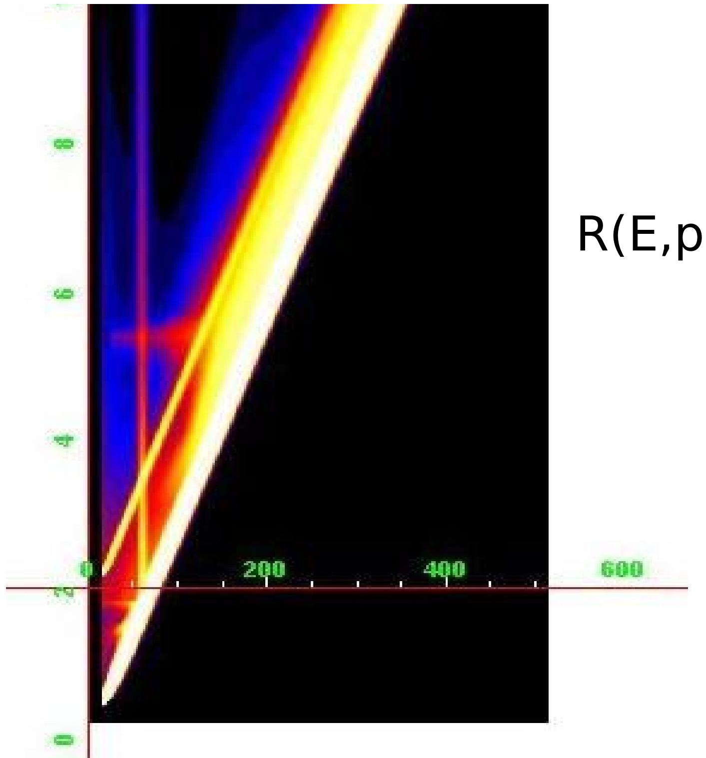


We don't have a shutter on the chip - so photons keep arriving as you clock the charge out. Software exists to clean this up for bright sources.

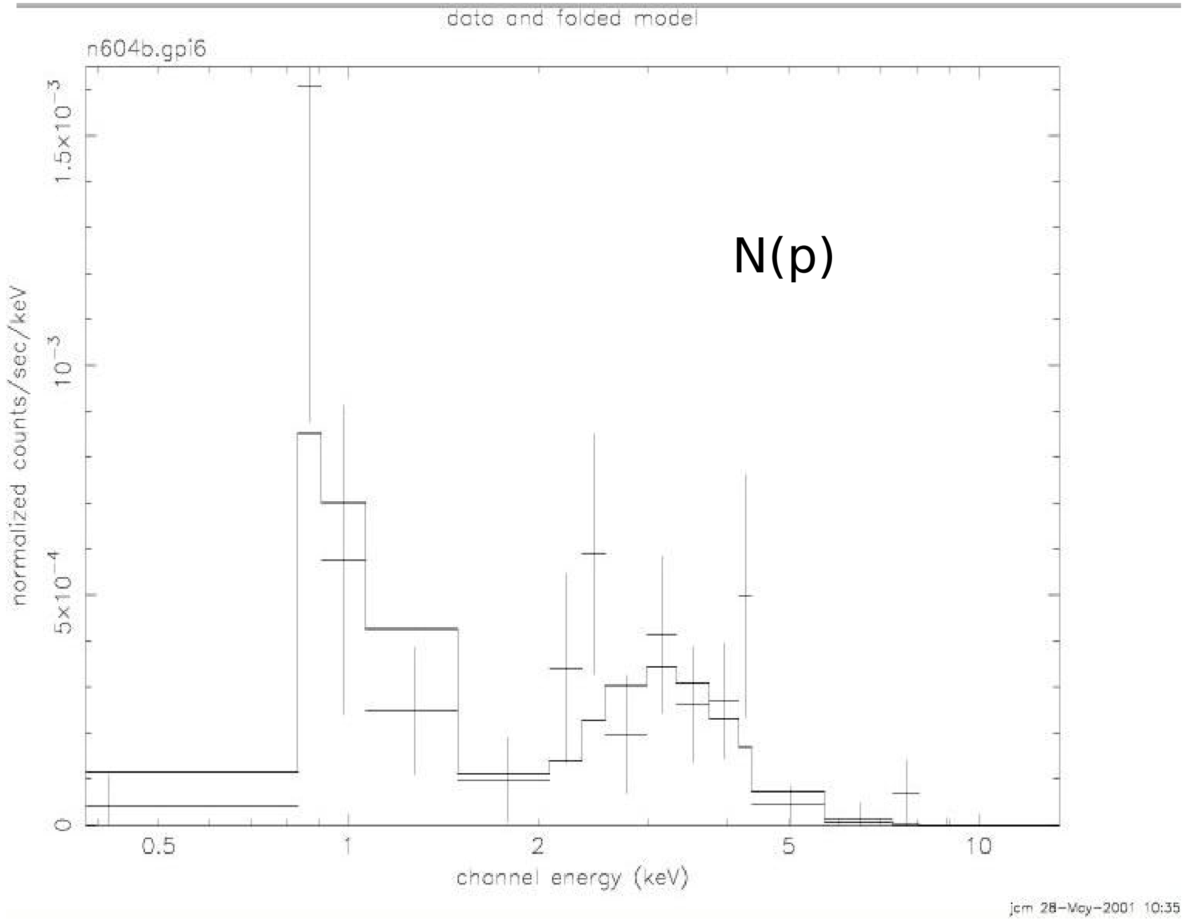
Spectra in Poissonland

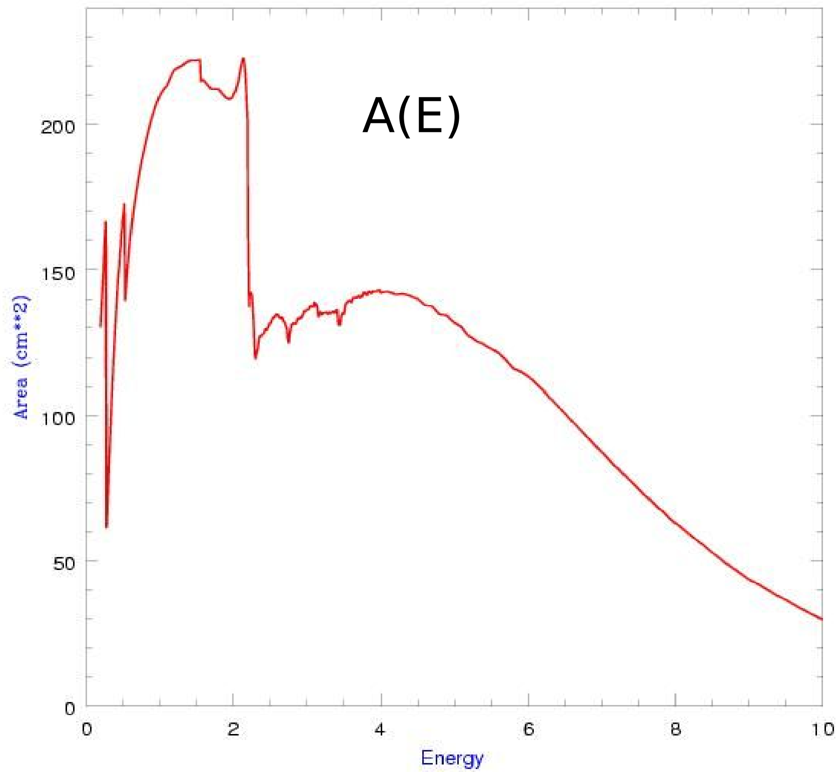


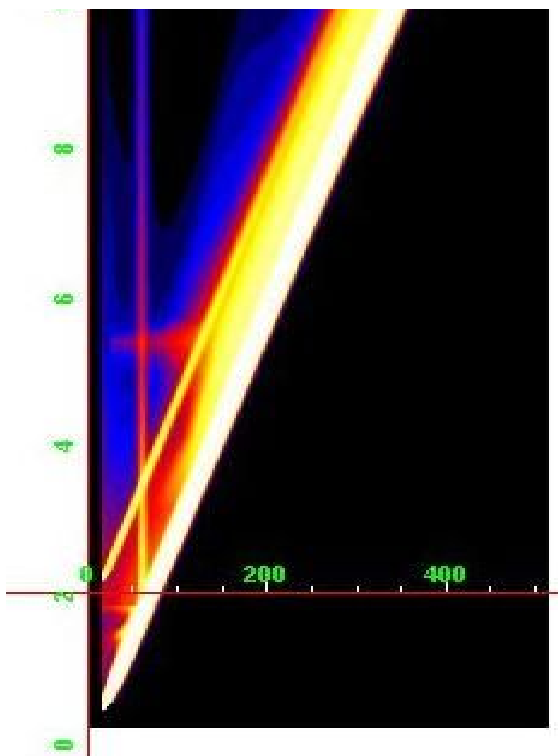
$$N(p) = \int R(E,p)A(E)F(E)dE$$



R(E,p)







R(E,p)

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

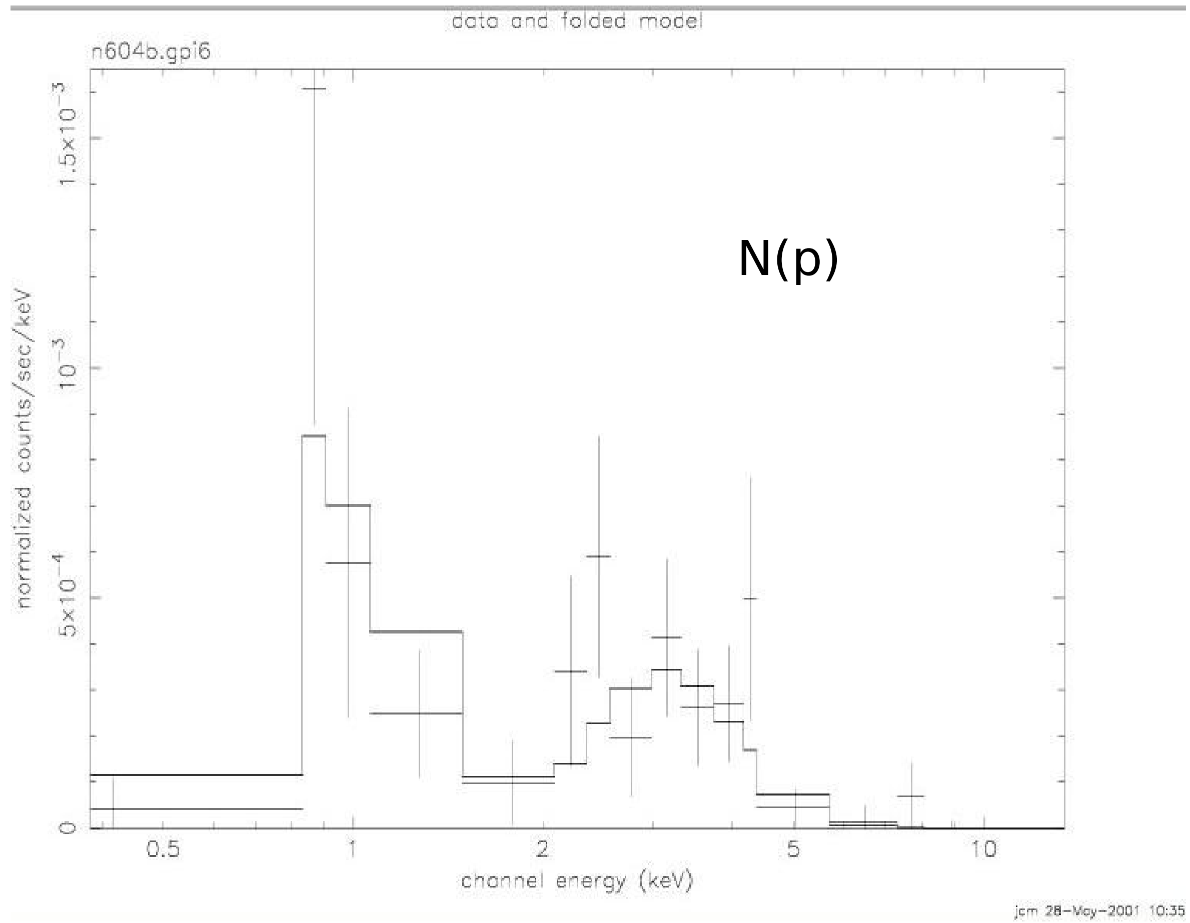
We pick a parameterized F(E) such as warm absorber models, lines, thermal plasma codes. Which F(E)? You must pick one based on expected physics, but match number of free parameters with quality of data.

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