A Brief Intro to the Chandra Mission

Jonathan McDowell

CHANDRA X-RAY OBSERVATORY

CIAO

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

The Chandra X-ray Observatory

Launched over 20 years ago 23 July 1999

A revolution in X-ray astronomy
and astronomy in general

What is Chandra?

NASA Chandra X-ray Observatory – operated by Chandra X-ray Center (CXC) at the Center for Astrophysics (Cambridge, MA) in collaboration with MIT

The greatest X-ray telescope ever built!

Orbits the Earth to be above the atmosphere

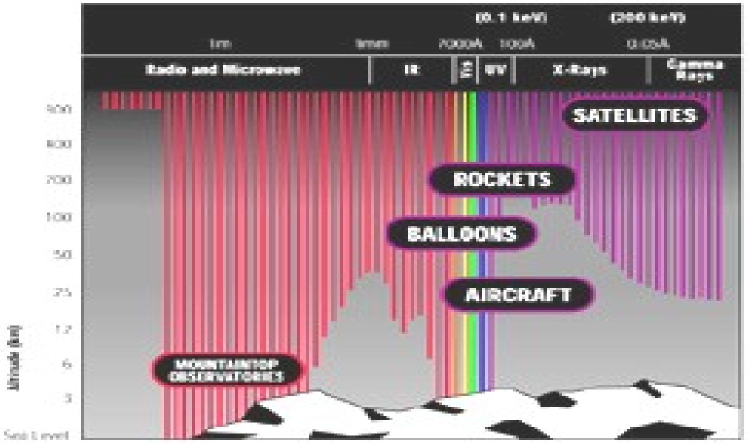
Goes 1/3 of the way to the Moon

every 64 hours (2 ½ days)

Observing only while outside radiation belts

Chandra takes superbly sharp images:

with good spectral resolution too!



X-ray Telescopes are different

Chandra’s mirrors are almost cylinders

X-rays don’t reflect off a normal mirror – they get absorbed.

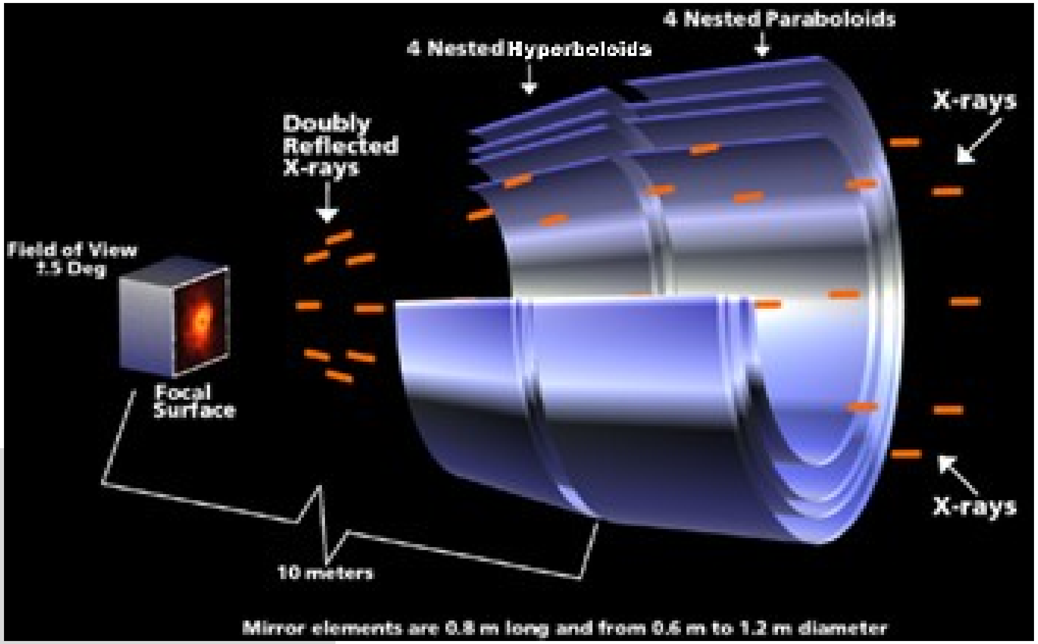
Only by striking a mirror at a glancing angle, about 1°,

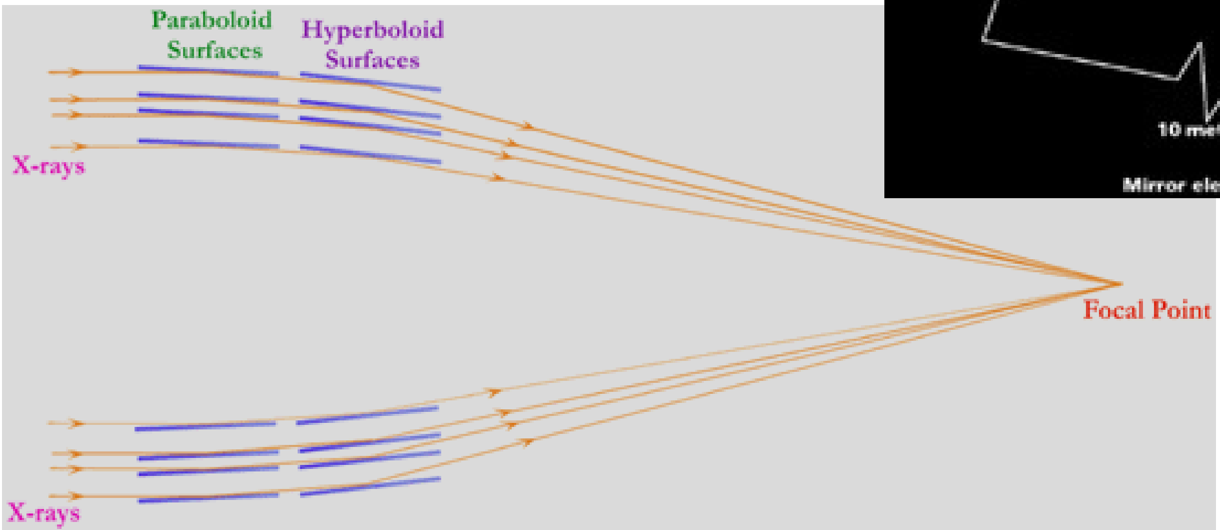
do X-rays reflect.

Focal length 10 m

4 mirror pairs -

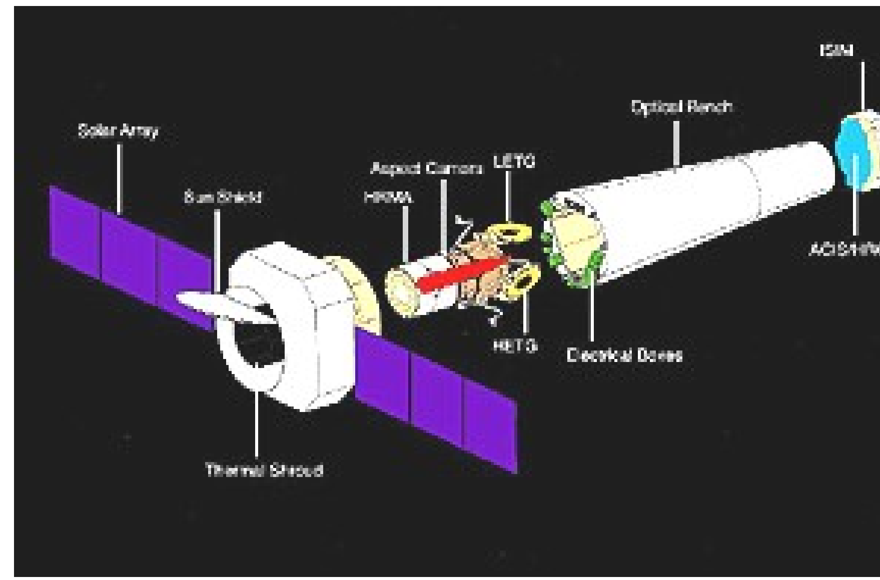
  perfectly aligned (not quite)





The Chandra spacecraft

10 meters (32 ½ ft) from mirror to detector, 1.2 meters (4ft) across mirror



…but focuses X-rays onto a spot only 25 microns across

Chandra Instruments and Gratings:

ACIS   Advanced CCD Imaging Spectrometer

- Most Chandra observations use ACIS
- 10 x 1 Mpix chips, use any 4 (caveats)
- Sub arcsecond imaging on axis
- Each chip is 8 x 8 arcmin
- Spectrum in each pixel, 0.5 (ish) to 7 (ish) keV

HRC-I and HRC-S   High Resolution Camera

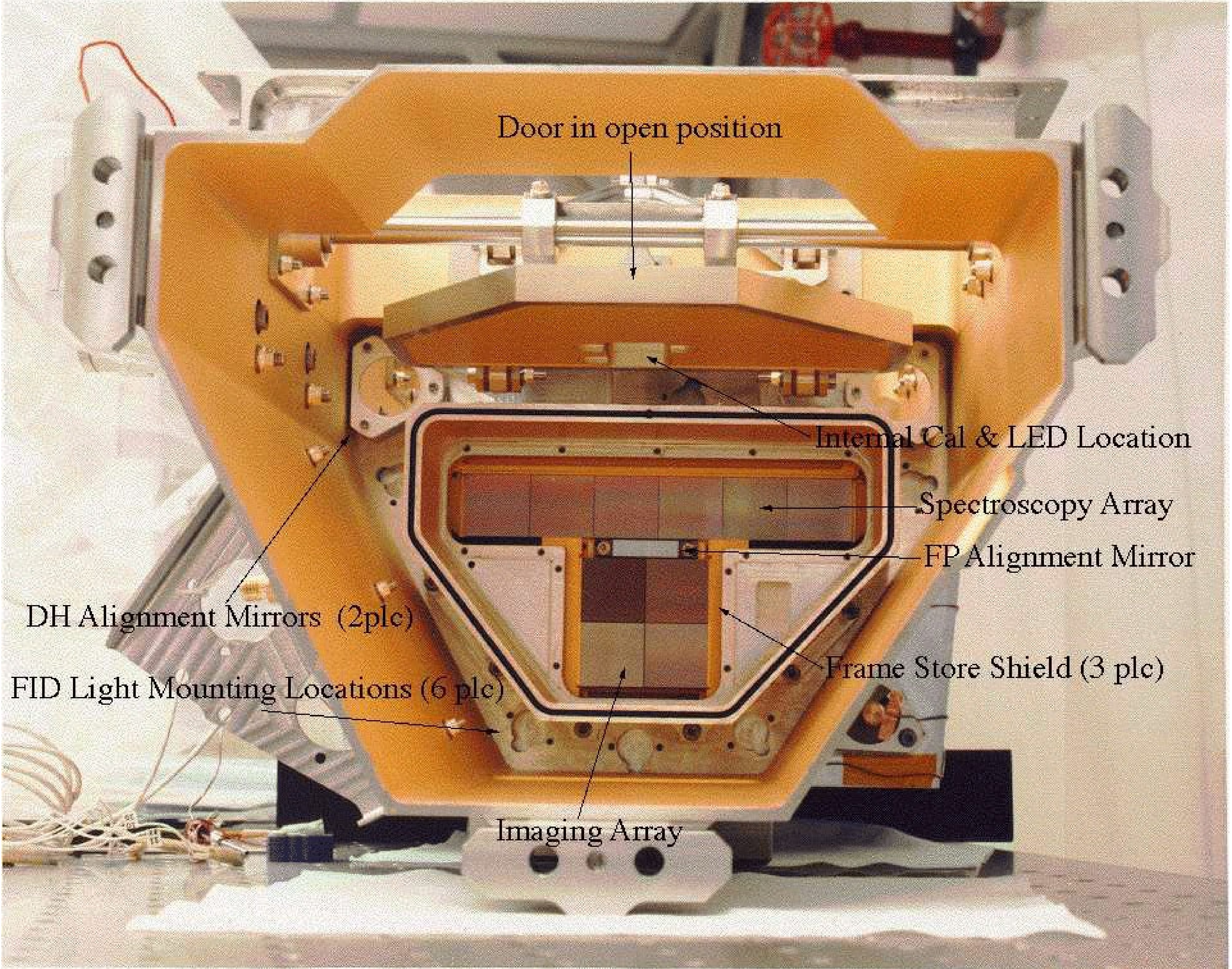
- Microchannel plate, highest spatial and timing res but no spectral res

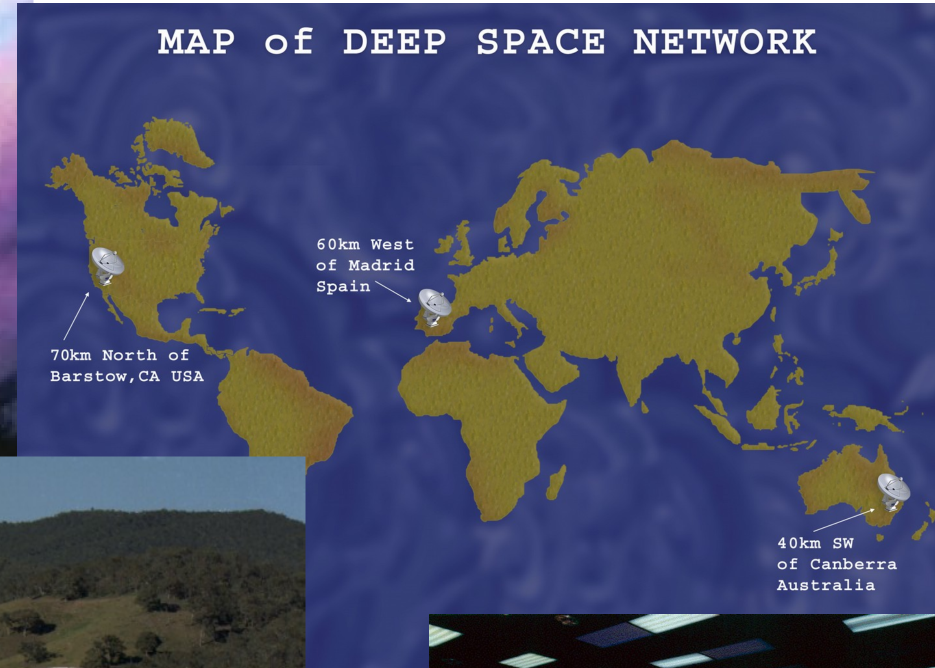
HETG   High Energy Transmission Grating

- Disperses spectrum onto ACIS
- Two gratings, HEG and MEG, at an angle to each other
- Order sorting possible via CCD energy discrimination

LETG   Low Energy Transmission Grating

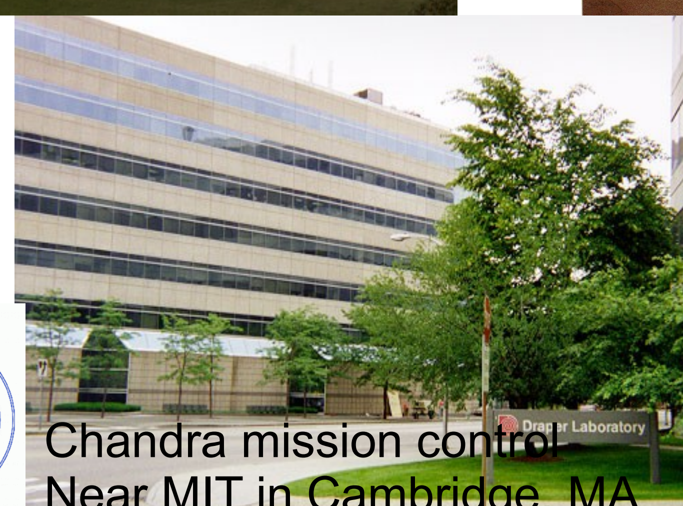
- Disperses spectrum onto HRC-S or ACIS
- Single dispersed spectrum
- Orders superimposed


Door in open position
Internal Cal & LED Location
Spectroscopy Array
FP Alignment Mirror
DH Alignment Mirrors (2plc)
Frame Store Shield (3 plc)
FID Light Mounting Locations (6 plc)
Imaging Array



DSN control
at Jet Propulsion Lab
Pasadena, CA

Chandra science center
Smithsonian Observatory, at
Harvard (Cambridge, MA)



Chandra mission control
Near MIT in Cambridge, MA

Main CIAO software release December each year (typically)

Proposals due in March each year

Archive available all year round!! cxc.harvard.edu

Introduction to X-ray Data Analysis

Jonathan McDowell

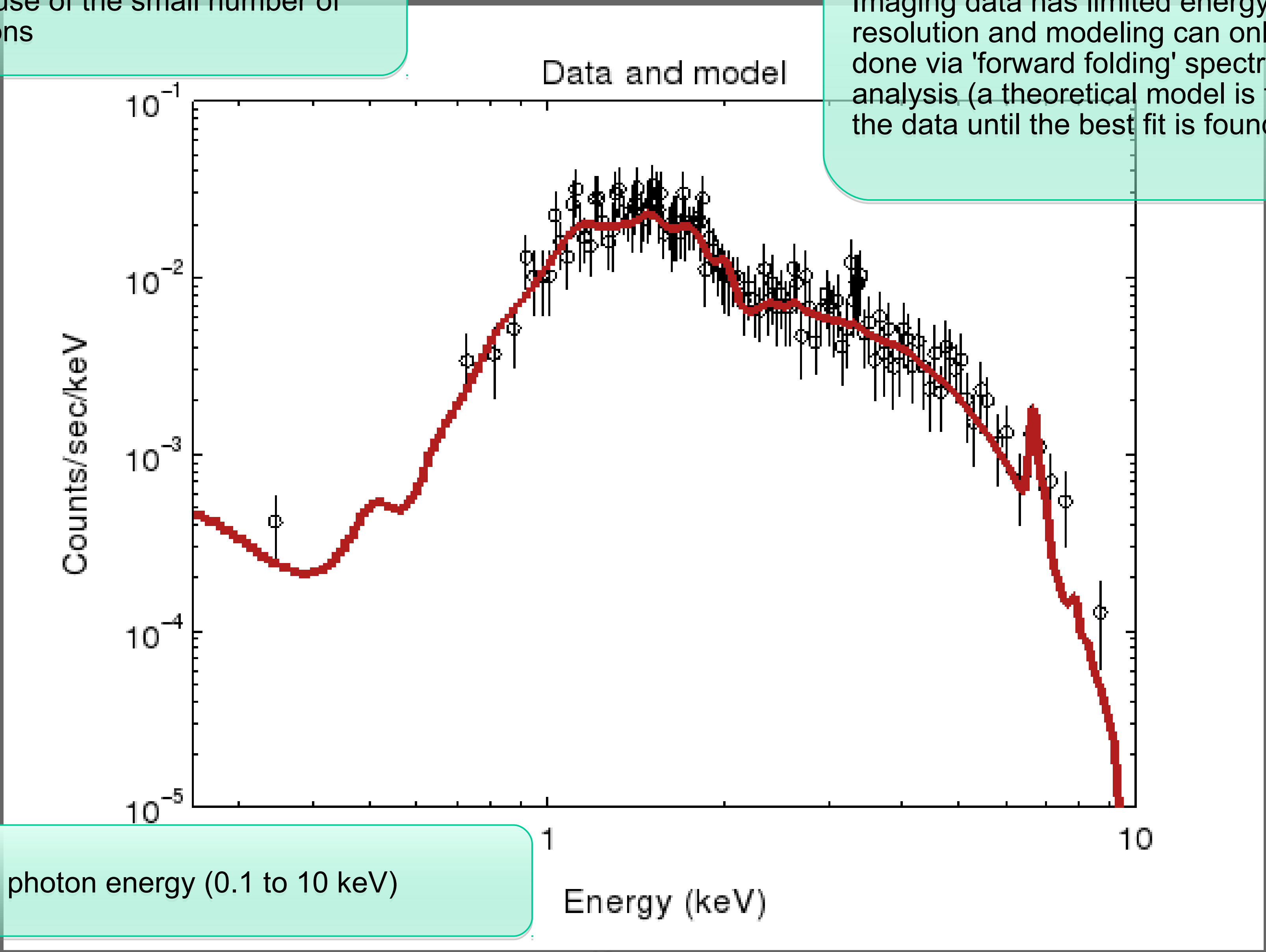
Introduction to X-ray Data Analysis

- X-ray astronomy is different .....
  - Problem 1: Photon counting with small number statistics
  - Problem 2: Spectral line spread function is often broad and messy - forced to foward-folding approach
  - Problem 3: Bands are very broad, so energy (wavelength) dependence more obvious (e.g. in PSF)
  - Problem 4: Different optics - PSF degrades rapidly off axis
  - Problem 5: The telescope is not pointing steadily like, say, HST - it's moving back and forth across the source.
  - But:
  - Advantage: We have more information on each photon (position, energy, arrival time)

Complexities in X-Ray and Chandra Data Analysis

In Poisson statistics regime because of the small number of photons

Imaging data has limited energy resolution and modeling can only be done via 'forward folding' spectral analysis (a theoretical model is fitted to the data until the best fit is found)



2 decades of photon energy (0.1 to 10 keV)

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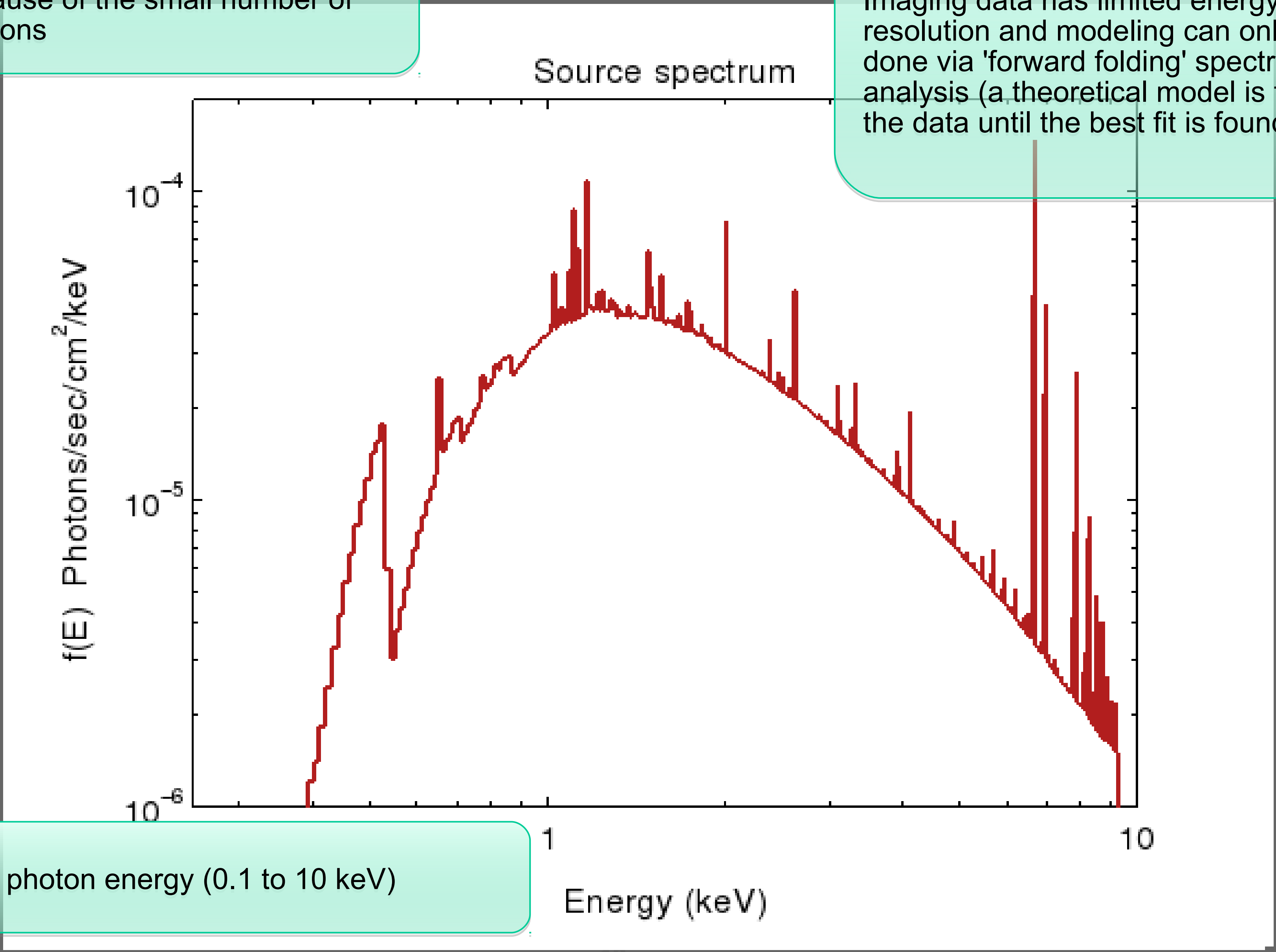


2 decades of photon energy (0.1 to 10 keV)

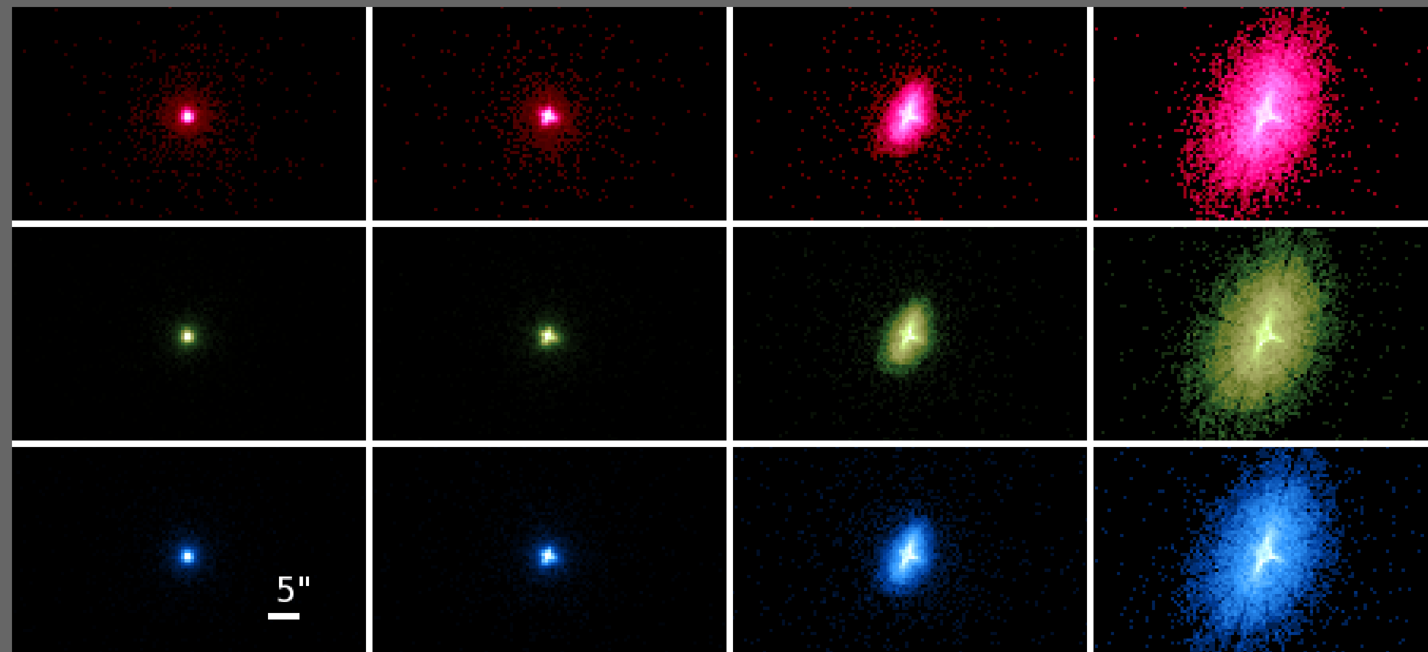
Complexities in X-Ray and Chandra Data Analysis

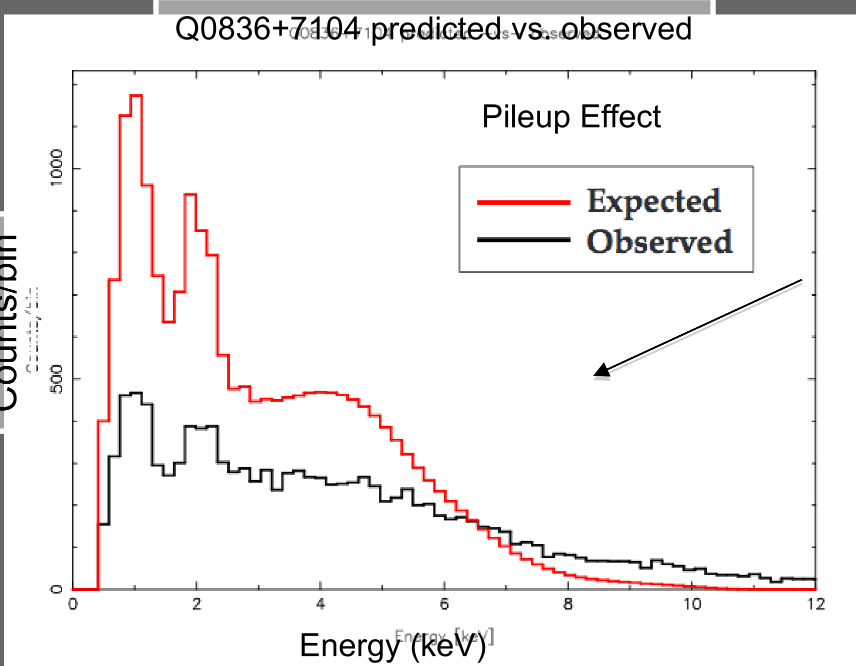
Every aspect of the observation varies with

- **energy**
- **position**
- **time**

(e.g. image sharpness, sensitivity, instrumental energy scale)

The Chandra PSF

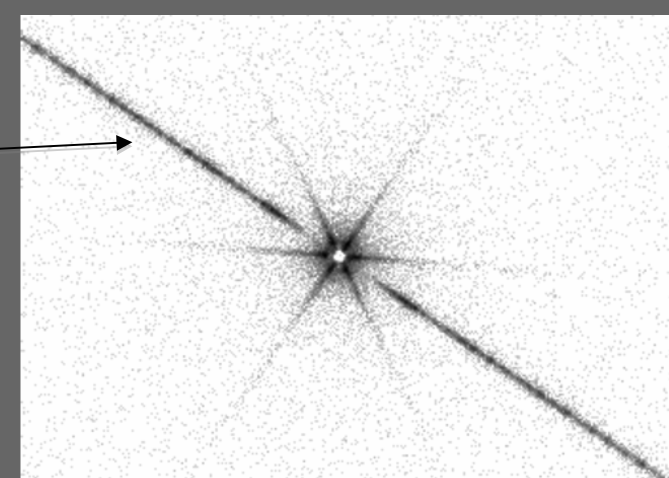




Specific instrumental effects eg.

readout streak

pileup - two or more photons detected as single event



Basics of CIAO

- Data files are in FITS format (usually binary tables, not just images)
  FITS: Flexible Image Transport System (1979-present)
- CIAO can also operate on ASCII files in many cases
- All (well, almost all) CIAO tools that want an input file can accept a CIAO Data Model “virtual file”
  e.g instead of evt.fits
  take “evt.fits[energy=300:1000,sky=circle(4096,4096,20)]”

Each file (dataset) is made up of sections called 'blocks' (HDUs for FITS fans)
Blocks can be tables or images

Key tools:
  dmcopy infile outfile
  dmlist infile opt=blocks,cols,data

  ahelp dmlist → help for tool dmlist
  plist dmlist → list parameters for dmlist

Key applications:
  Sherpa - fitting
  ds9 – imaging and analysis
    (also Prism, now within ds9: file explorer)

The Event File

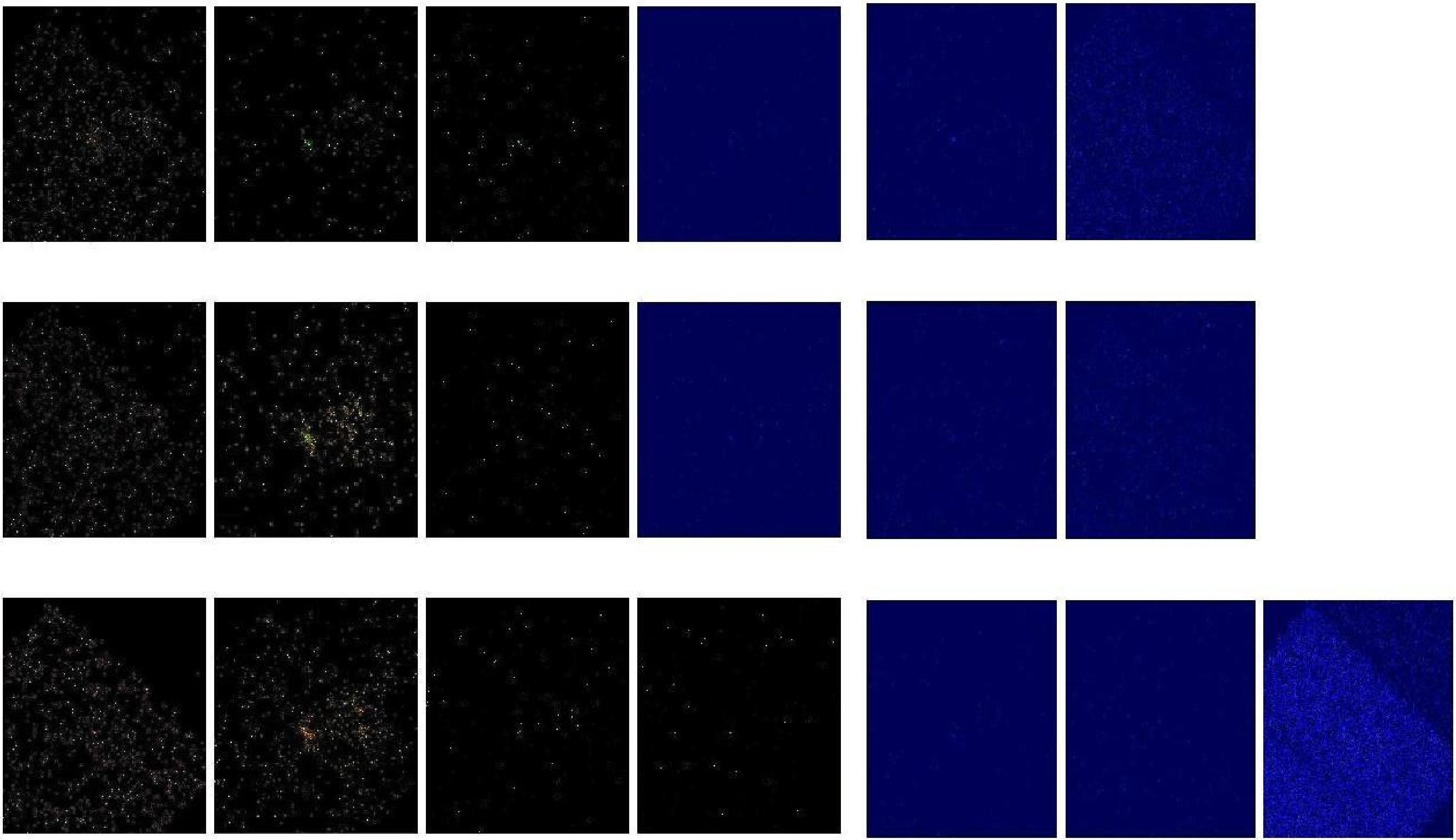
- In optical astronomy, the primary data set is an image. In radio interferometry, it's a visibility array.
- In X-ray astronomy, the primary data set is an event list - a table of (putative) photons
  - Our software makes it easy to generate an image from the event list, so it's easy to forget that's what you have. But making the image loses information.
  - First cut way of thinking about the event list: it's a 4-dimensional array of x, y, time, energy. But most pixels are empty (we don't have many photons!) so it's more compact to just list the non-empty ones.
  - Complication: we actually have many more parameters for each photon, not just 4.

Inside the event list

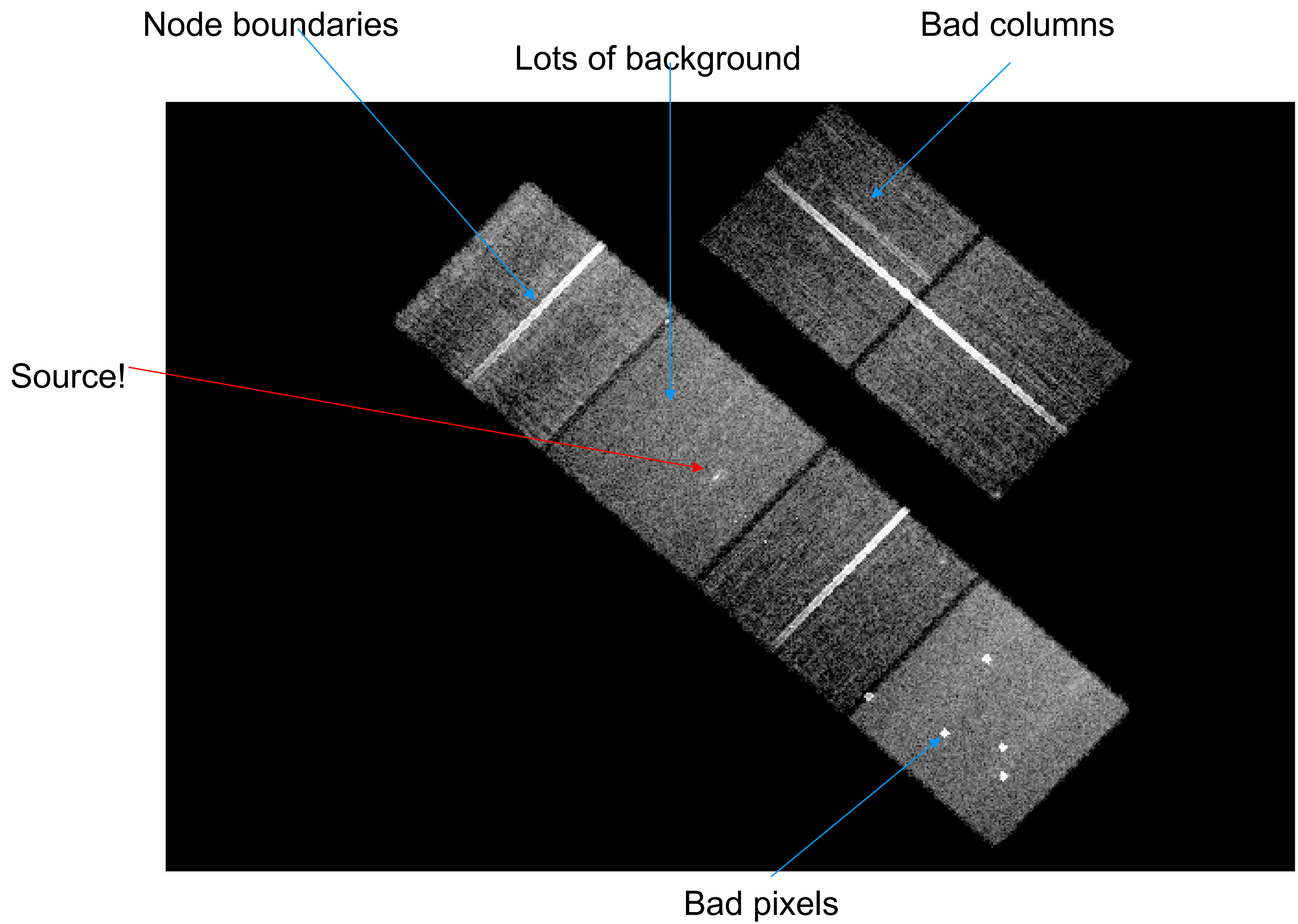
```
jupiter> dmlist acisf03041_001N001_evt3.fits cols

--------------------------------------------------------------------------------
Columns for Table Block EVENTS
--------------------------------------------------------------------------------

ColNo  Name                 Unit         Type             Range
   1   time                 s             Real8          154361559.6127299964:154436827.4158599973 S/C TT corresponding to mid-exposure
   2   ccd_id                             Int2           0:9                     CCD reporting event
   3   node_id                            Int2           0:3                     CCD serial readout amplifier node
   4   expno                              Int4           0:2147483647            Exposure number of CCD frame containing event
   5   chip(chipx,chipy)    pixel         Int2           1:1024                  Chip coords
   6   tdet(tdetx,tdety)    pixel         Int2           1:8192                  ACIS tiled detector coordinates
   7   det(detx,dety)       pixel         Real4          0.50:      8192.50      ACIS detector coordinates
   8   sky(x,y)             pixel         Real4          0.50:      8192.50      sky coordinates
   9   pha                  adu           Int4           0:36855                 total pulse height of event
  10   pha_ro               adu           Int4           0:36855                 total read-out pulse height of event
  11   energy               eV            Real4          0:  1000000.0           nominal energy of event (eV)
  12   pi                   chan          Int4           1:1024                  pulse invariant energy of event
  13   fltgrade                           Int2           0:255                   event grade, flight system
  14   grade                              Int2           0:7                     binned event grade
  15   status[4]                          Bit(4)                                 event status bits
```

```
jupiter> dmlist acisf03041_001N001_evt3.fits"[cols -status]" data,raw,clean rows=1:20
#  time               ccd_id node_id expno    chip(chipx,chipy) tdet(tdetx,tdety) det(detx,dety)                    sky(x,y)                          pha        pha_ro     energy                pi      fltgrade grade
 154362662.7665936351   0    1        107      369 513    3574 4763    3540.2504882812    1556.8157958984    1473.2664794922    4129.1977539062    3868    3680    15358.6318359375   1024    16    4
 154362662.7665936351   0    2        107      562 589    3650 4570    3615.2900390625    1748.9260253906    1676.4797363281    4093.9599609375    3977    3750    15254.2246093750   1024    64    2
 154362662.7665936351   0    0        107      247 876    3937 4885    3902.1516113281    1435.5321044922    1426.5589599609    3750.3830566406    3765    3514    14473.1611328125    992     0    0
 154362662.8076336384   7    0        107      189 301    4106 2003    4069.4038085938    4313.6518554688      4280.3339843750    4160.218750     3568    3503    15899.1279296875   1024    11    6
 154362662.8076336384   7    1        107      264 388    4181 2090    4144.4223632812    4225.7763671875    4209.175781250    4069.1887207031     128     109      632.9125366211     44    72    6
 154362662.8076336384   7    2        107      555 410    4472 2112    4435.0400390625    4204.0610351562    4245.8291015625    3780.0749511719    1717    1702     7969.5327148438    546     8    3
 154362662.8076336384   7    2        107      676 441    4593 2143    4556.0268554688    4172.6386718750    4239.1547851562    3655.2526855469    1908    1853        8829.906250     605    16    4
 154362662.8076336384   7    1        107      483 465    4400 2167    4363.3208007812    4149.5029296875    4178.0693359375    3839.4790039062    1011     994     4767.4877929688    327     2    2
 154362662.8076336384   7    3        107      881 613    4798 2315    4760.8256835938    4001.3994140625    4112.1772460938    3420.4289550781    1348    1310     6024.1176757812    413     0    0
 154362662.8076336384   7    2        107      690 834    4607 2536    4569.7802734375    3780.8713378906    3857.9919433594    3563.6794433594    2011    1942     9294.6806640625    637    72    6
 154362662.8076336384   7    1        107      348 925    4265 2627    4228.7290039062    3689.4941406250    3700.4628906250    3879.6706542969    1722    1664     8069.8139648438    553     2    2
 154362662.8076336384   7    1        107      502 954    4419 2656    4381.6430664062    3660.5825195312    3702.6135253906    3724.0622558594    3011    2957    14100.3310546875    966   208    6
 154362662.8486736417   6    3        107      803 548    3678 2250    3639.6469726562    4066.6665039062    3952.636718750    4532.1162109375    2258    2095     8640.0263671875    592     2    2
 154362662.8897136450   3    0        107       40 717    4415 3101    4376.0224609375    3215.3222656250    3265.1691894531    3640.8110351562    3146    2950       12326.56250      845     0    0
 154362662.8897136450   3    0        107       78 901    4231 3139    4192.5224609375    3177.2634277344    3191.2951660156    3813.0412597656    2252    2077       8826.3281250     605    64    2
 154362662.9307536483   2    0        107      208 240    3301 3878    3266.0554199219    2440.0964355469    2284.2392578125    4573.9658203125    3451    3423    13226.7988281250    906    16    4
 154362662.9307536483   2    2        107      517 719    3780 3569    3744.8583984375    2748.1215820312    2681.5275878906    4166.1748046875    3816    3544     14376.746093750    985    64    2
 154362662.9717936218   1    0        107      101 567    4565 4208    4527.886718750    2109.5788574219    2211.8908691406    3271.5732421875    1644    1543     6498.9438476562    446    64    2
 154362662.9717936218   1    3        107      996 952    4180 5103    4141.839843750    1216.6264648438    1259.9039306641    3471.8693847656    2406    2170        9509.4218750    652    16    4
 154362666.0075938106   0    2        108      683 156    3217 4449    3183.1049804688    1869.4627685547    1709.3774414062    4541.6933593750    3466    3429    13290.0634765625    911     0    0
```

Energy slices through an event list, 0.1 - 10 keV



Level 1 Event List - Calibrated but Dirty

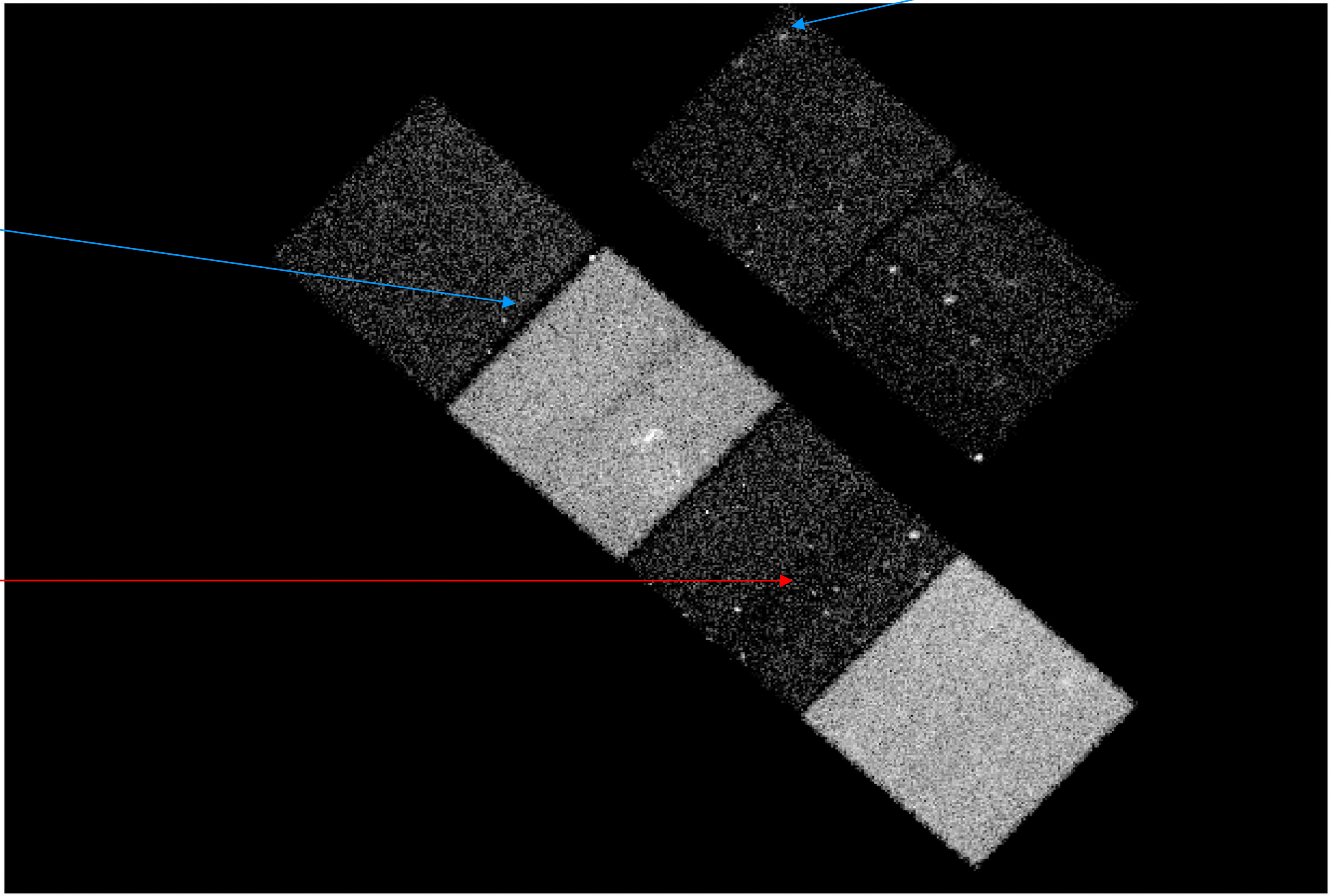


Level 2 event list - cleaned and filtered

Energy filter 300-7000 eV removes background but not signal
Grade filter removes cosmic ray events etc
Good time filter removes times of high background, poor data quality

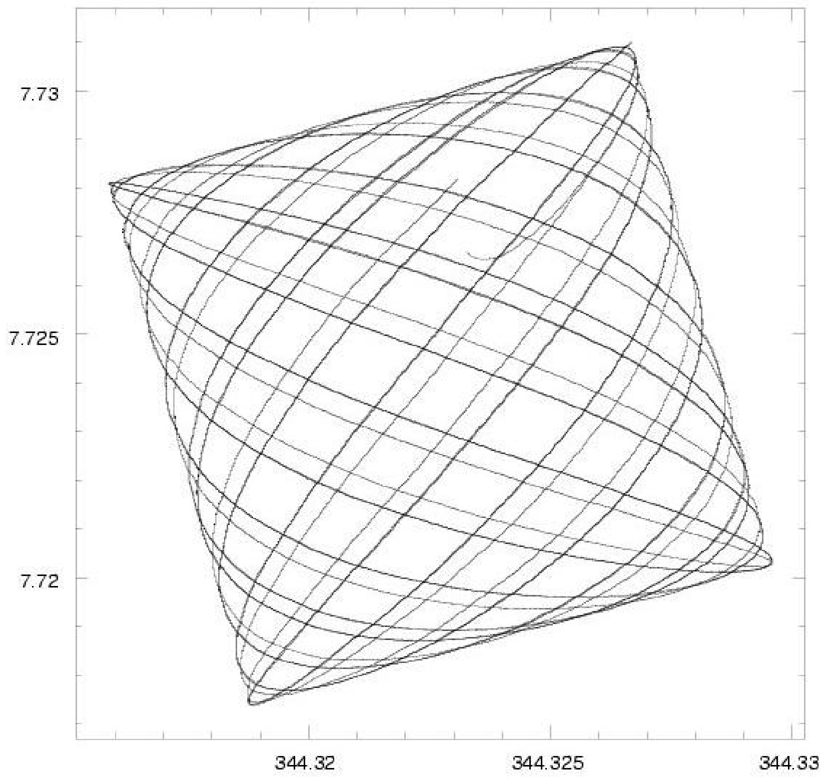
Sources fuzzy far off axis (PSF big)

Beware chip gaps!



More sources!

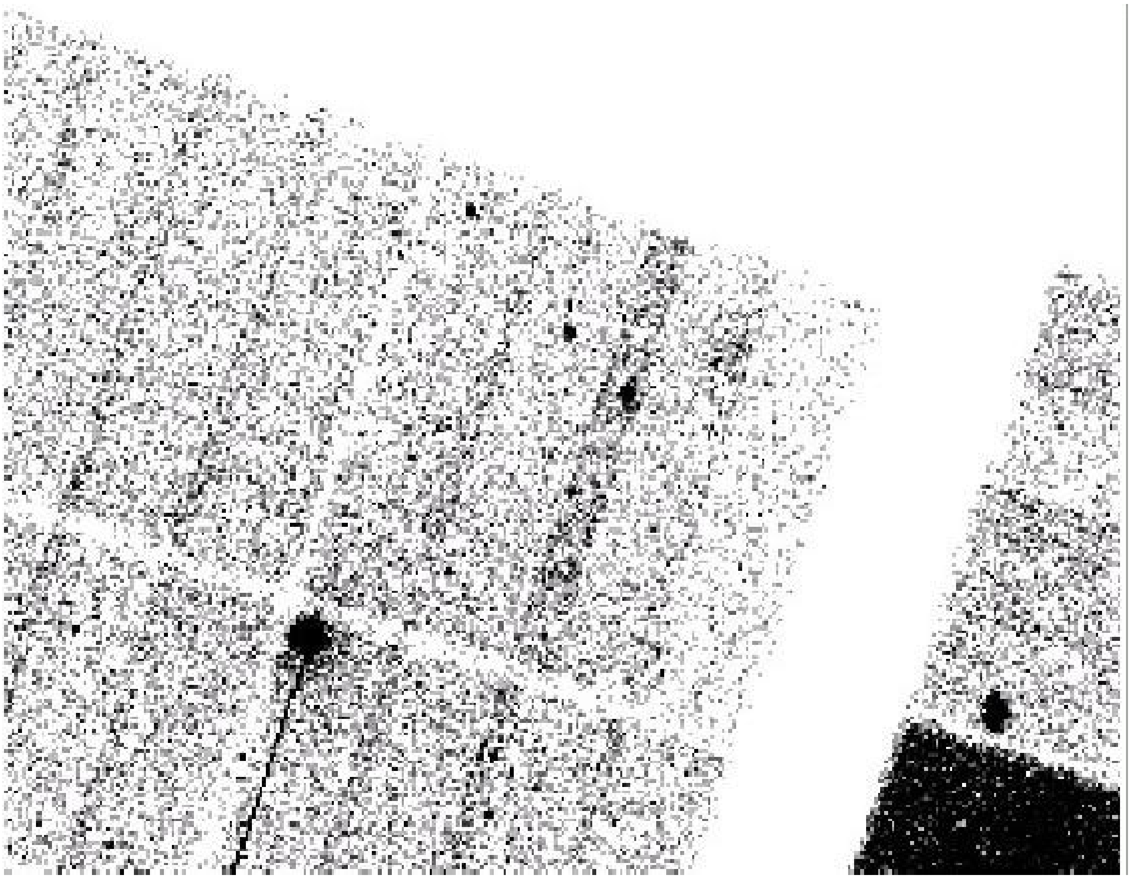
The aspect solution



During an observation, Chandra's optical axis describes this 'dither pattern' on the sky, (Problem 5), smearing the image of a point source. The RA, Dec, roll angle of the telescope versus time is called the 'aspect solution'; the asol1.fits file provides this for each observation.

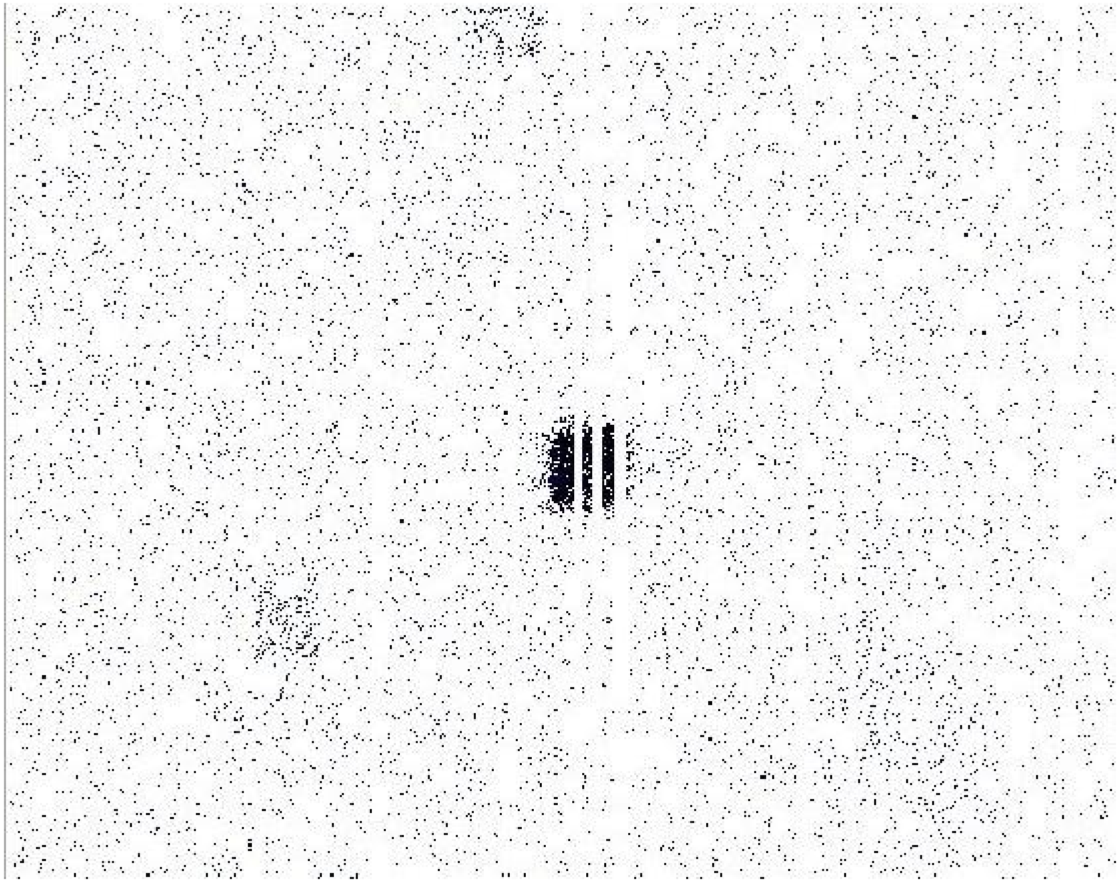
We record the motion of the guide stars in the star tracker so that we can calculate RA and Dec for EACH PHOTON and so reconstruct the image.

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

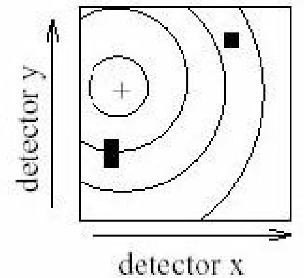
Spatial Response: EXPOSURE MAP

The *Exposure Map*, $E(\Delta h, \lambda, \hat{p})$ retains spatial information at the expense of spectral. It has units of [cm^2 counts photons^{-1}] .

$$\int d\lambda\, S(\lambda, \hat{p}) \approx \frac{C(\Delta h, \hat{p})}{E(\Delta h, \lambda, \hat{p})}$$

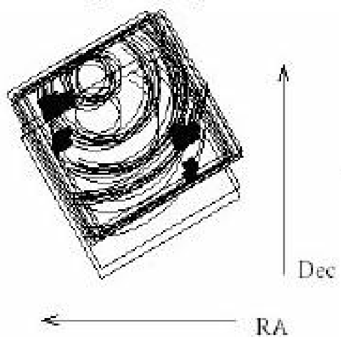
C is the observed counts per spatial bin in a pulse-height bin. *S* is the source flux, with units of [phot cm^{-2}s^{-1}Å^{-1}].

Instrument Map – efficiency calibration information, band integrated. (create with `mkinstmap`)



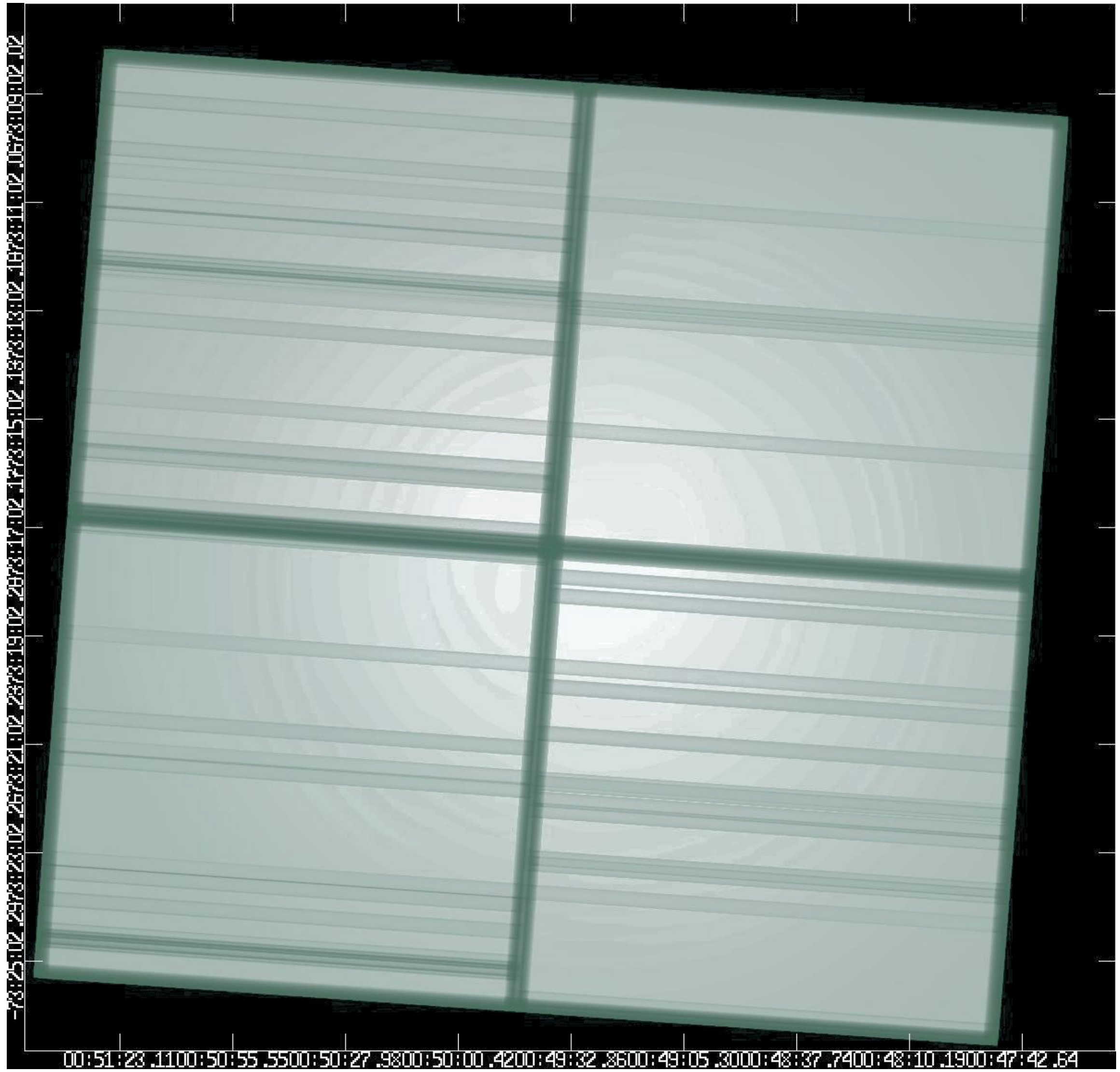
= mirror area x detector QE

Exposure Map – applies telescope aspect history and coordinate transformations (= area x time). (create with `mkexpmap`).



= Instmap $\otimes$ Aspect

Typical exposure map



Problem 3: Exposure map is energy dependent; must assume a spectrum if using a broad band

Event analysis or binned analysis?

- Don't make an image too quickly. If you can get an answer directly from the event list, that's better - binning the data loses information, and collapsing the axes loses information.
- Spatial analysis: make an image (using dmcopy)
  - lose energy and time information
- Spectral analysis: make a 'PHA file' using dmextract (or a grating spectrum using tgextract)
  - lose spatial and time information
- Temporal analysis: make a light curve using dmextract

The fundamental equation of astronomy

$$N(E) = A(E)F(E)\Delta T$$

Our instrument makes a spectrophotometric measurement; the sensitivity ("effective area") A(E) tells us how to convert from flux to instrumental counts for a given exposure time ΔT

But, a real instrument doesn't measure the true energy, it measures instrumental energy E'. The line spread function ("response matrix" in X-rays) R(E,E') describes how a monochromatic input spectrum is broadened by the instrument (Problem 2)

Let us further assume that the instrumental energy E' is measured in discrete channels (bins) E'i. Then

$$N(E_i') = \int A(E)R(E, E_i')F(E)dE\Delta T$$

Of course, you may not be measuring all of the light from the source. Even if it's a point source, there may be an aperture correction. We need the PSF P(x-x',y-y') and the spatial dependence of the QE, q(x,y). Then at a given instrument position x',y'

$$\boxed{N(E_i', x_i', y_i') = \int\int A(E)R(E, Ei)F(E, x, y)P(x-x_i', y-y_i')q(E, x_i', y_i')dEdxdy\Delta T}$$

The source may also be variable in time - we'll ignore this for the purposes of this talk.
The detector sensitivity is time-variable on long timescales, but for a single observation you just have to worry about times when the data is filtered - the Good Time Intervals (GTIs)

$$N(E_i', x_i', y_i') = \int\int\int A(E)R(E, Ei)F(E, x, y, t)P(x-x_i', y-y_i')q(E, x_i', y_i')dEdxdydt$$

Pulse height

When you plot an optical spectrum, the wavelength (or energy) axis is really an instrumental quantity. A spectral line is broadened by instrumental effects, so the energies plotted are not the true energies of the photon. However, the instrument is calibrated (i.e. the definition of instrumental energy is rescaled) such that the peak of a line is at the correct energy.

In X-ray astronomy, instead of using the instrumental energy E', we work with the energy bin number. For historical reasons to do with long-forgotten instruments, this bin number is know as the PI channel (for 'pulse invariant' channel) - we'll denote it by P. So, for fixed energy bin widths dE,

$$E' = P\, dE =[\text{on average}]\ E$$

The instrument actually measures a raw energy bin number p, called the PHA channel, or 'pulse height analyser channel'. The scaling of the instrumental energy to real energy depends on position and time:

$$E'(\text{raw}) = p\, dE = g(x,y,t) P\, dE$$

This function g (the gain) is usually assumed to obey

$$g(x,y,t) = g\_spatial(x,y)\ g\_t(t)$$

and we provide calibrations of both the spatial gain and the temporal gain.

Spectra in Poissonland

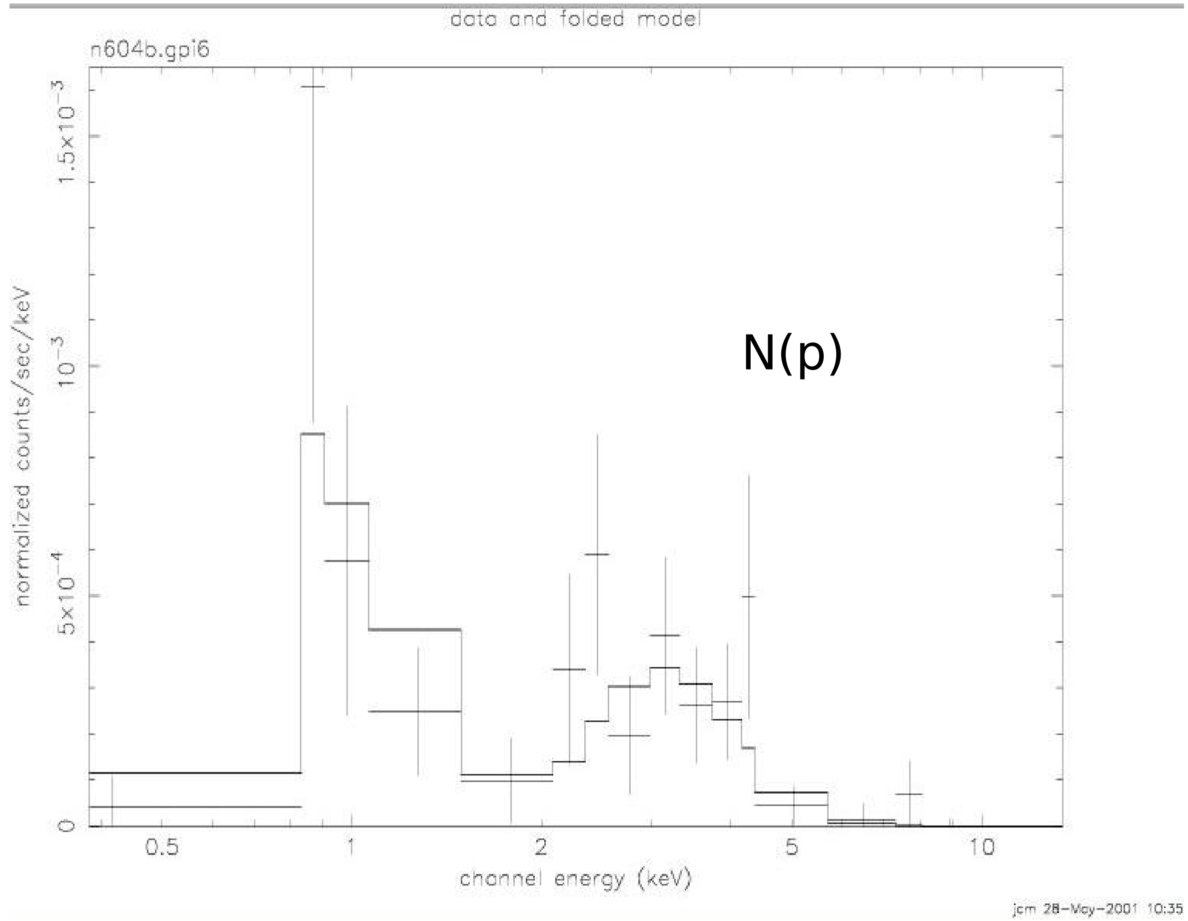
$$N(p) = \int R(E,p)A(E)F(E)dE$$

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.

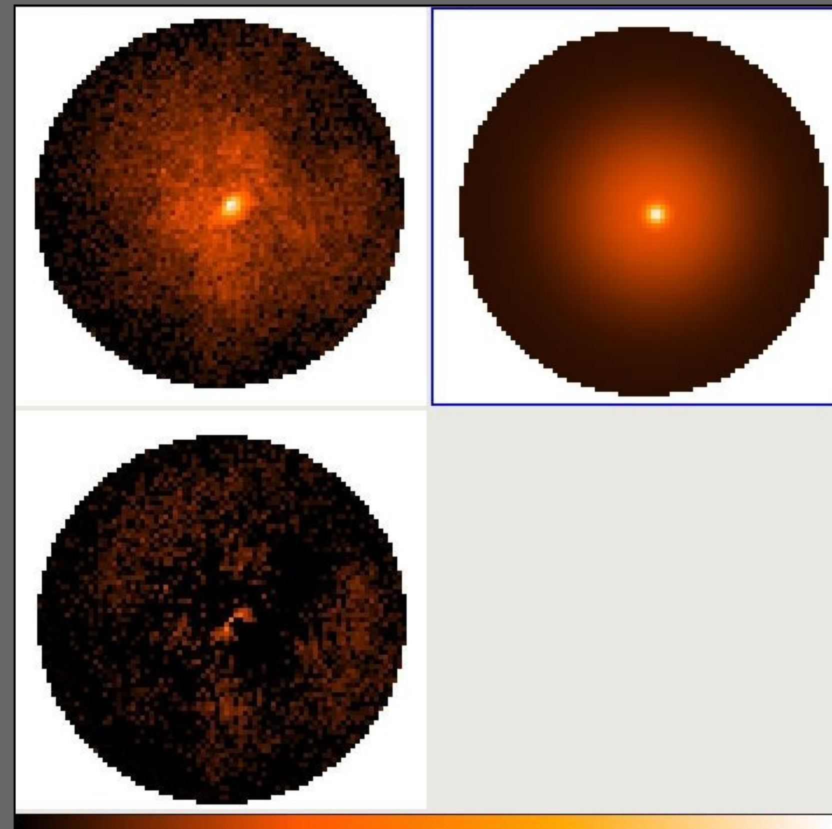
Does one model fit significantly better than another? Be careful that two physically different models may look quite similar in F(E) space.

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.



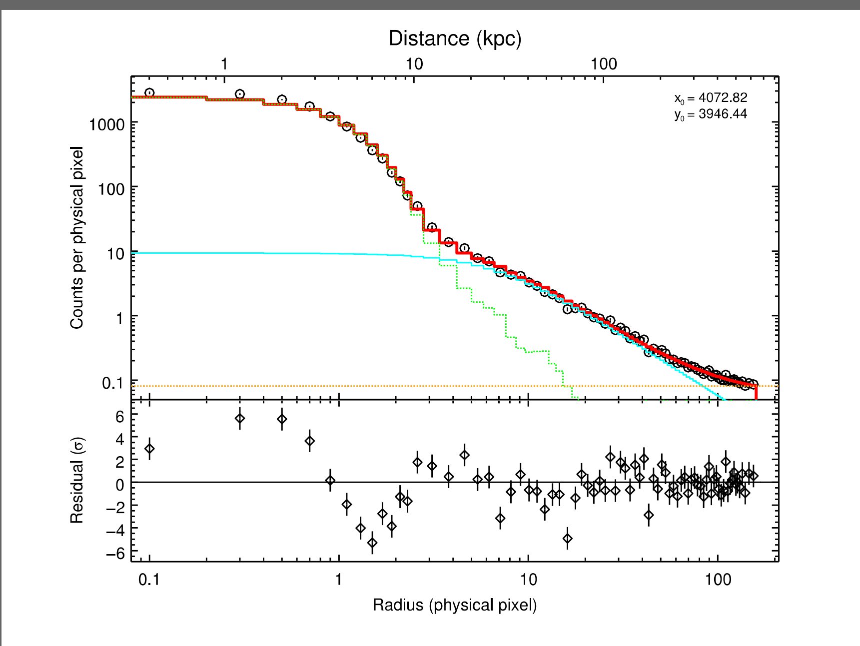
Sherpa: Modeling and Fitting in Python

Sherpa

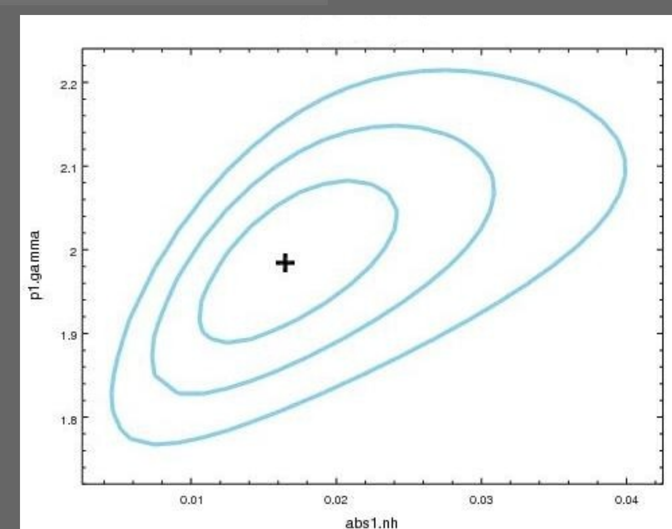


Coded in a Python environment – familiar to the new generation of astronomers and used in other missions

Modeling and fitting for 1-D and 2-D datasets **in any waveband** including: spectra, images, surface brightness profiles, light curves, general ASCII data.



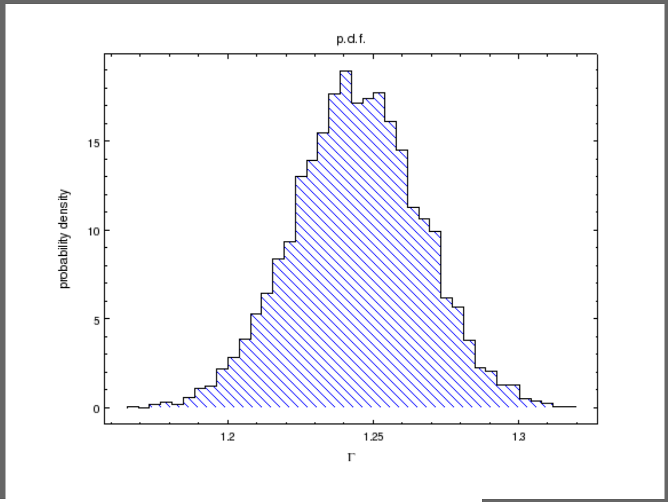
Model Poisson and Gaussian data



Calculate confidence levels on the best-fit model parameters

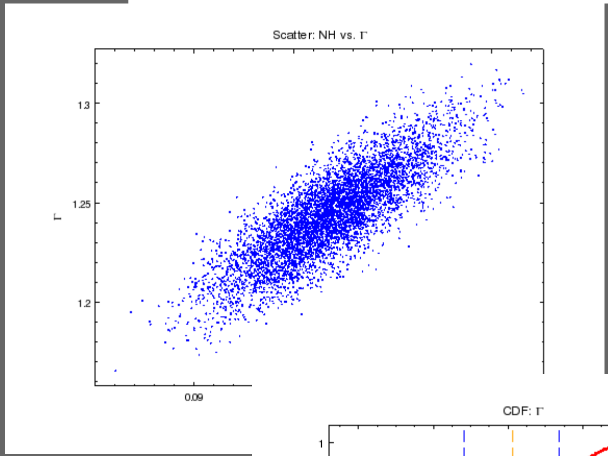
Sherpa: Modeling and Fitting in Python

Sherpa



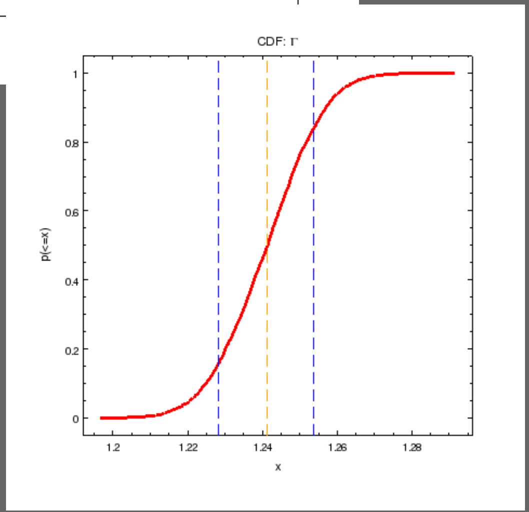
- comes with well-tested, robust optimization methods - e.g. Levenberg-Marquardt, Nelder-Mead Simplex or Monte Carlo/Differential Evolution

- comes with statistics for modeling Poisson or Gaussian data



- can perform Bayesian analysis with Poisson Likelihood and priors, using Metropolis or Metropolis-Hastings algorithm in the MCMC (Markov-Chain Monte Carlo); allows to include non-linear systematic errors (calibration uncertainties) in the analysis

- is extensible (with python and compiled code):
  - is used in CIAO tools and scripts
  - in the Xija Chandra thermal modeling code
  - is used in the TeV HESS data analysis software
  - is used in the IRIS spectral energy distribution program

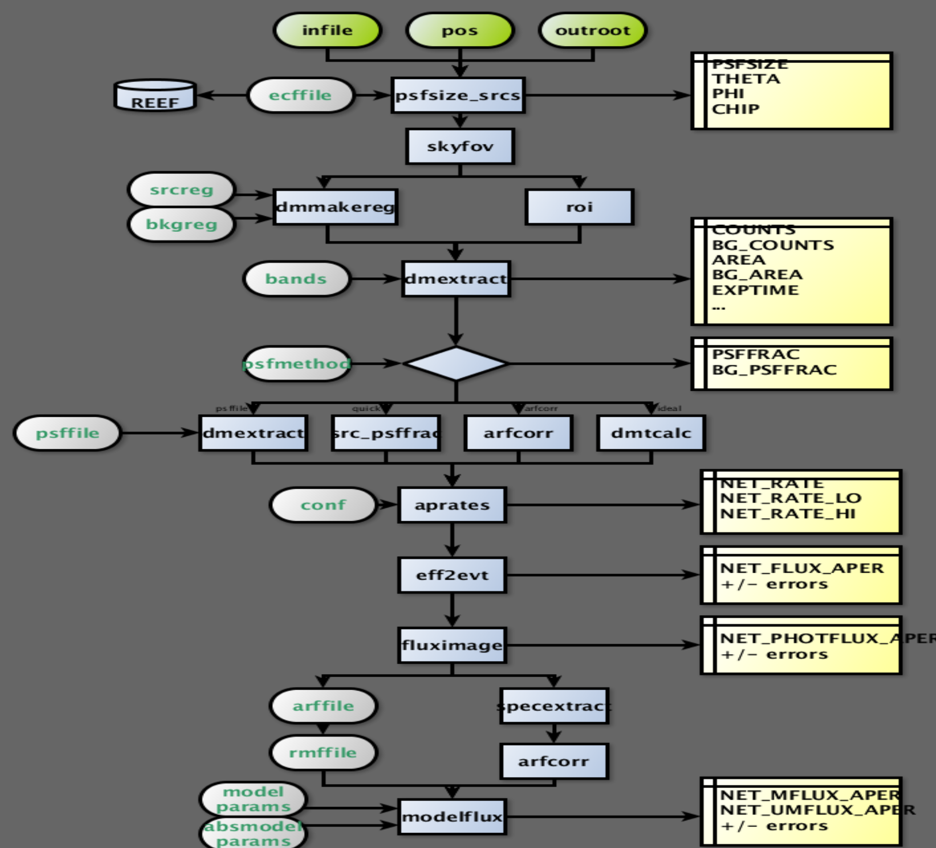


CALDB

- The CALDB (Calibration Database) contains everything you need that's not part of your specific observation.
- It's designed as a multimission directory structure. The Chandra files are in $CALDB/data/chandra
- Within that, they are arranged by instrument and kind of calibration. But, with luck, the software will find the CALDB files you need automatically.
- Just make sure that you keep the CALDB up to date! But, be careful - if you start off processing with a given version of the CALDB and CIAO, then upgrade to a new CALDB and CIAO, things are sometimes incompatible. Check the release notes.

Calculating Source Flux

$ **srcflux** myevt2.fits “03:29:29.250 +31:18:34.73” myflux



Encodes the logic described in six different CIAO threads.

Return count rates and fluxes and errors with all appropriate corrections.

Uses many tools written for the Chandra Source Catalog.

Complementary to it for special cases and fields not covered by the catalog.

Summary of source fluxes

Position 0.5 - 7.0 keV

Value 90% Conf Interval

3 29 29.25 +31 18 34.7 Rate 0.0398 c/s (0.0381,0.0415)

Flux 5.17E-13 erg/cm2/s (4.94E-13,5.39E-13)

Mod.Flux 4.38E-13 erg/cm2/s (4.2E-13,4.57E-13)

srcflux capabilities

- finds auxiliary files automatically, like specextract

- automatically determines PSF-appropriate extraction region size for source and background, or accepts user choice

- uses one of four methods to apply aperture correction

- runs on multiple energy bands including named CSC bands

- accepts one position or a list (catalog of sources)

- calculates count rates using aprates method

- calculates fluxes two different ways (specified spectral model and eff2evt method; however, no spectral fit is performed)

- generates spectral reponses for further analysis

Ongoing work: handling of warning flags for hard cases, e.g. chip edge