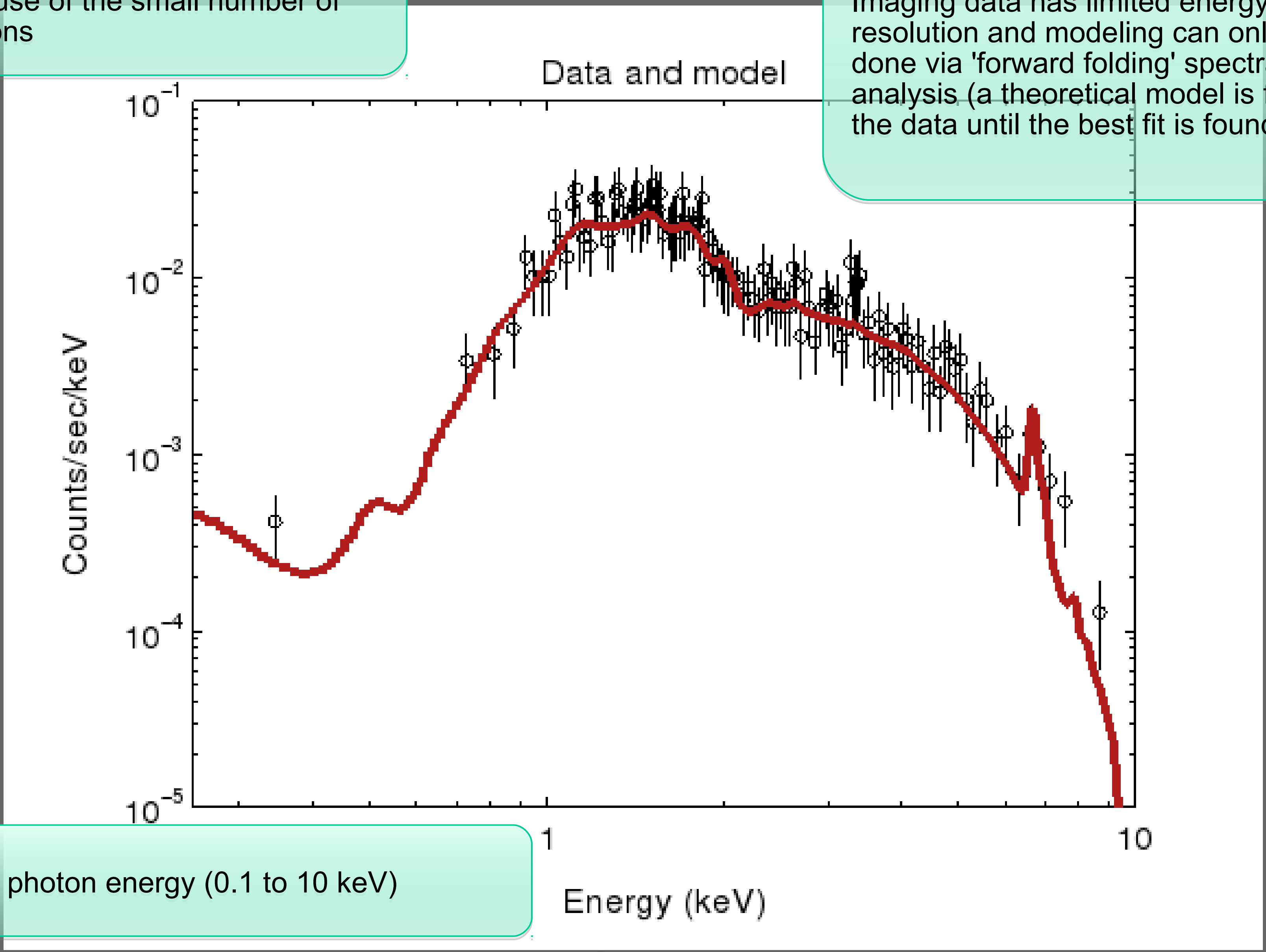
Introduction to X-ray Data Analysis

- 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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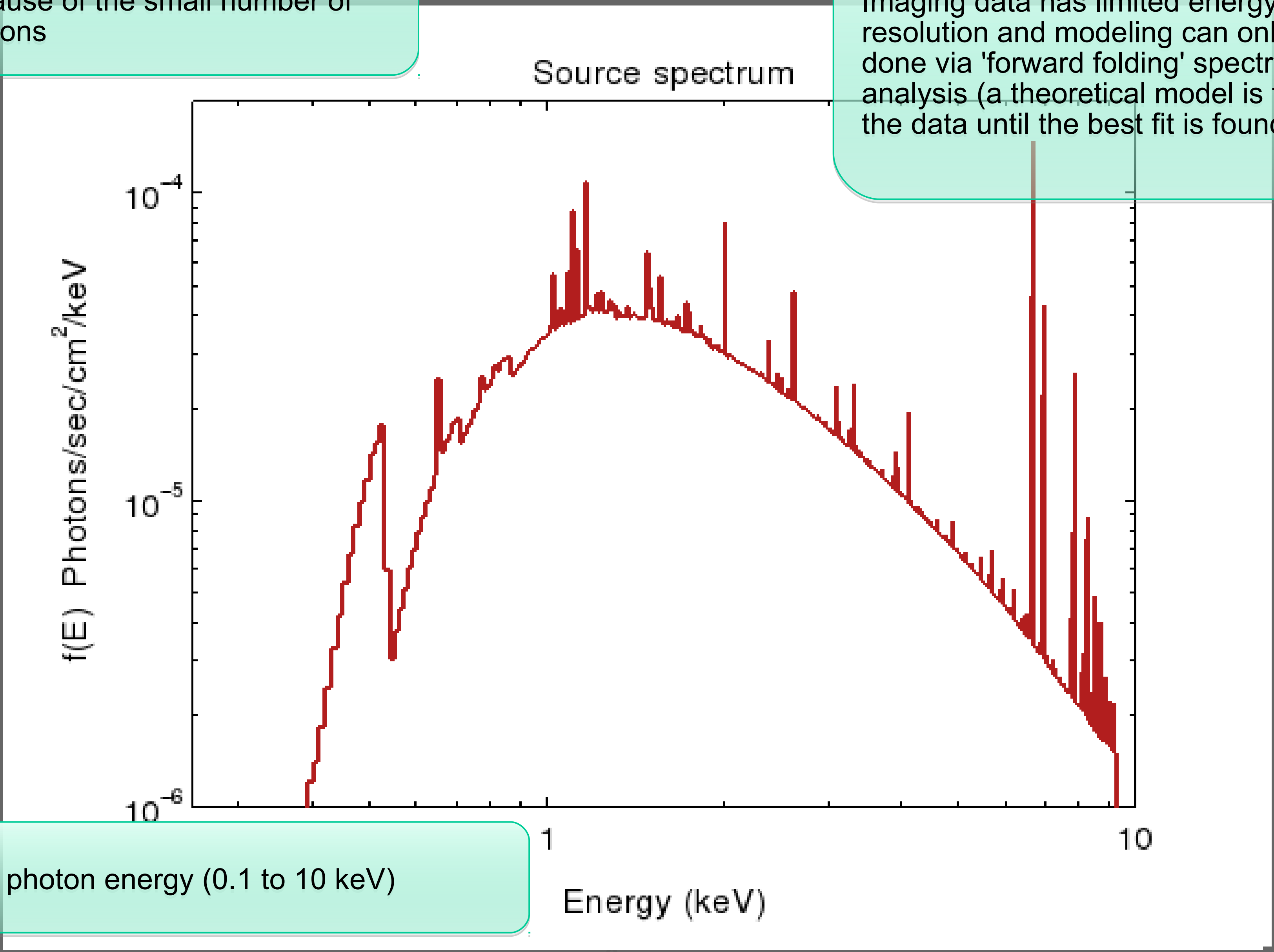


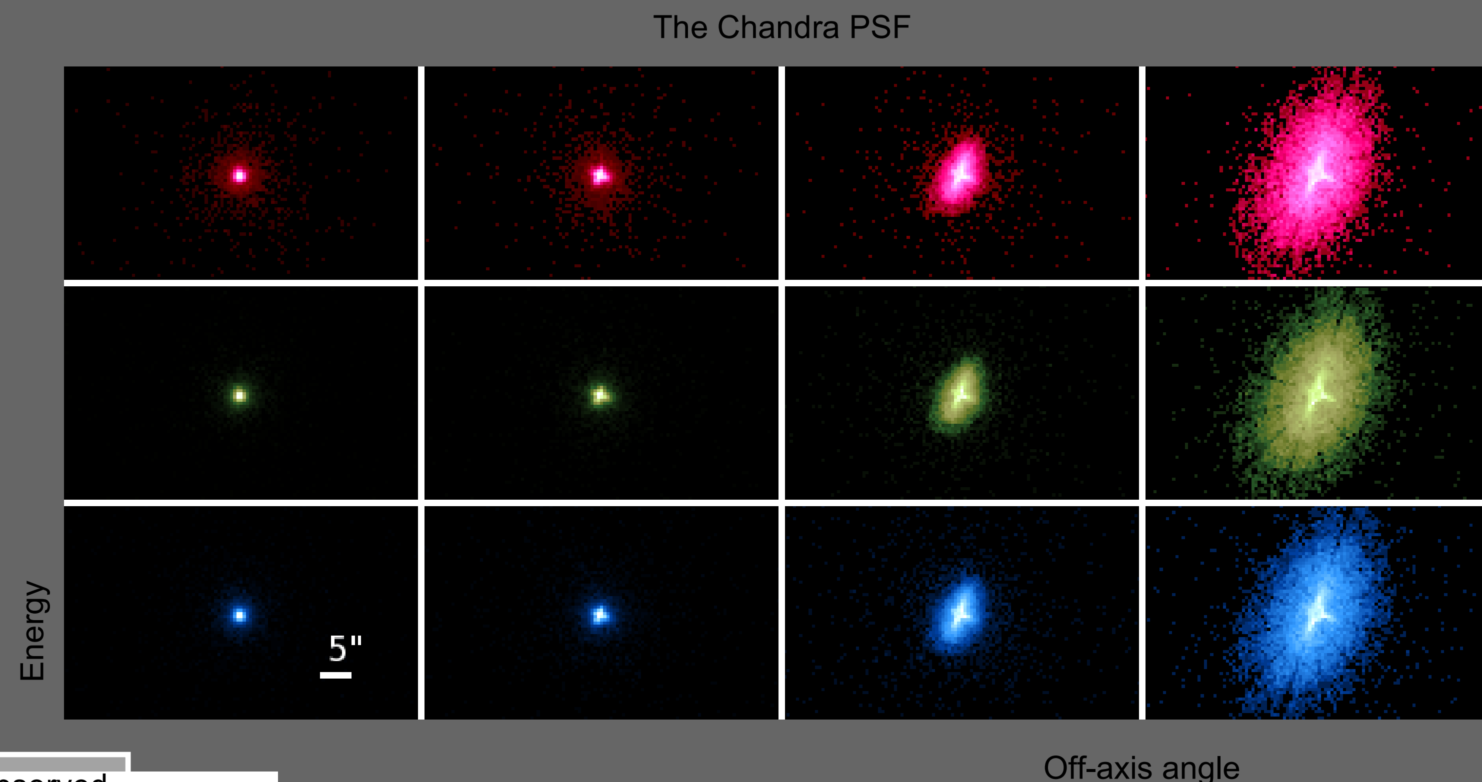
2 decades of photon energy (0.1 to 10 keV)

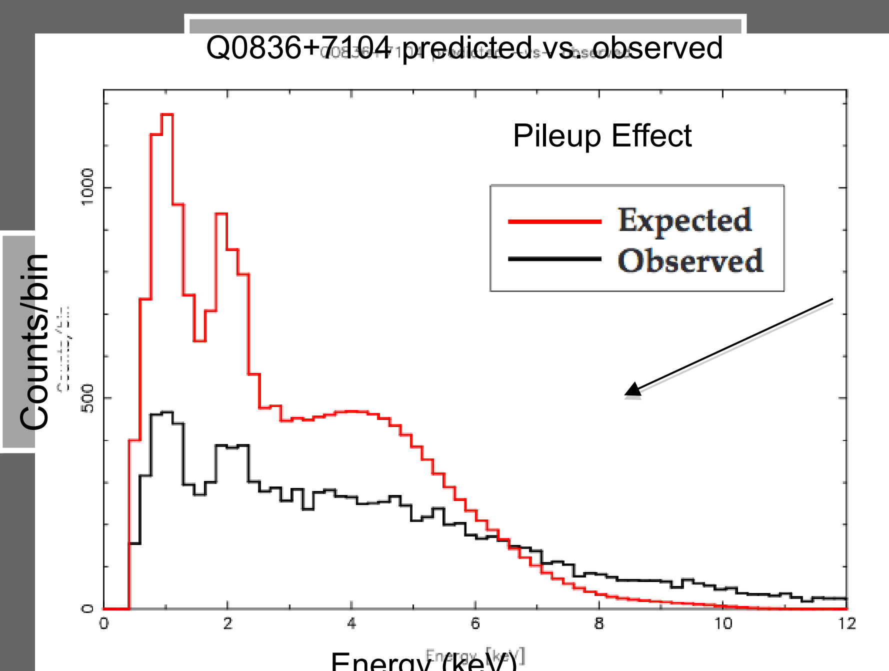
Complexities in X-Ray and Chandra Data Analysis

Every aspect of the observation varies with

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

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

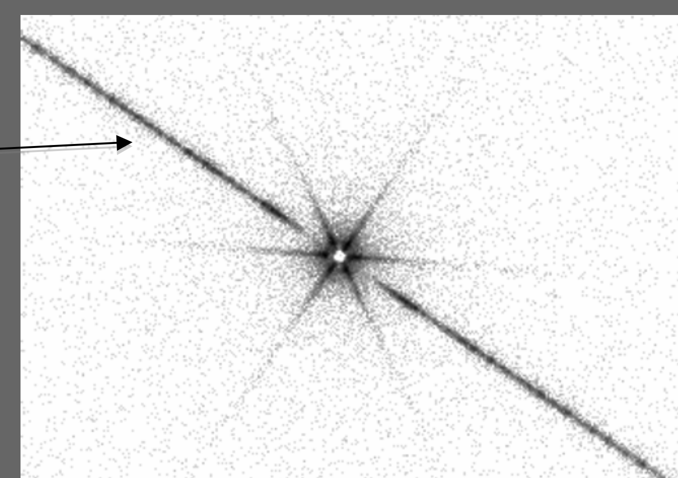




Specific instrumental effects eg.

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)
- CIAO can also operate on ASCII file in many cases
- All (well, almost all) CIAO tool 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

  ChIPS – plotting

  ds9 – imaging and analysis

The Event File

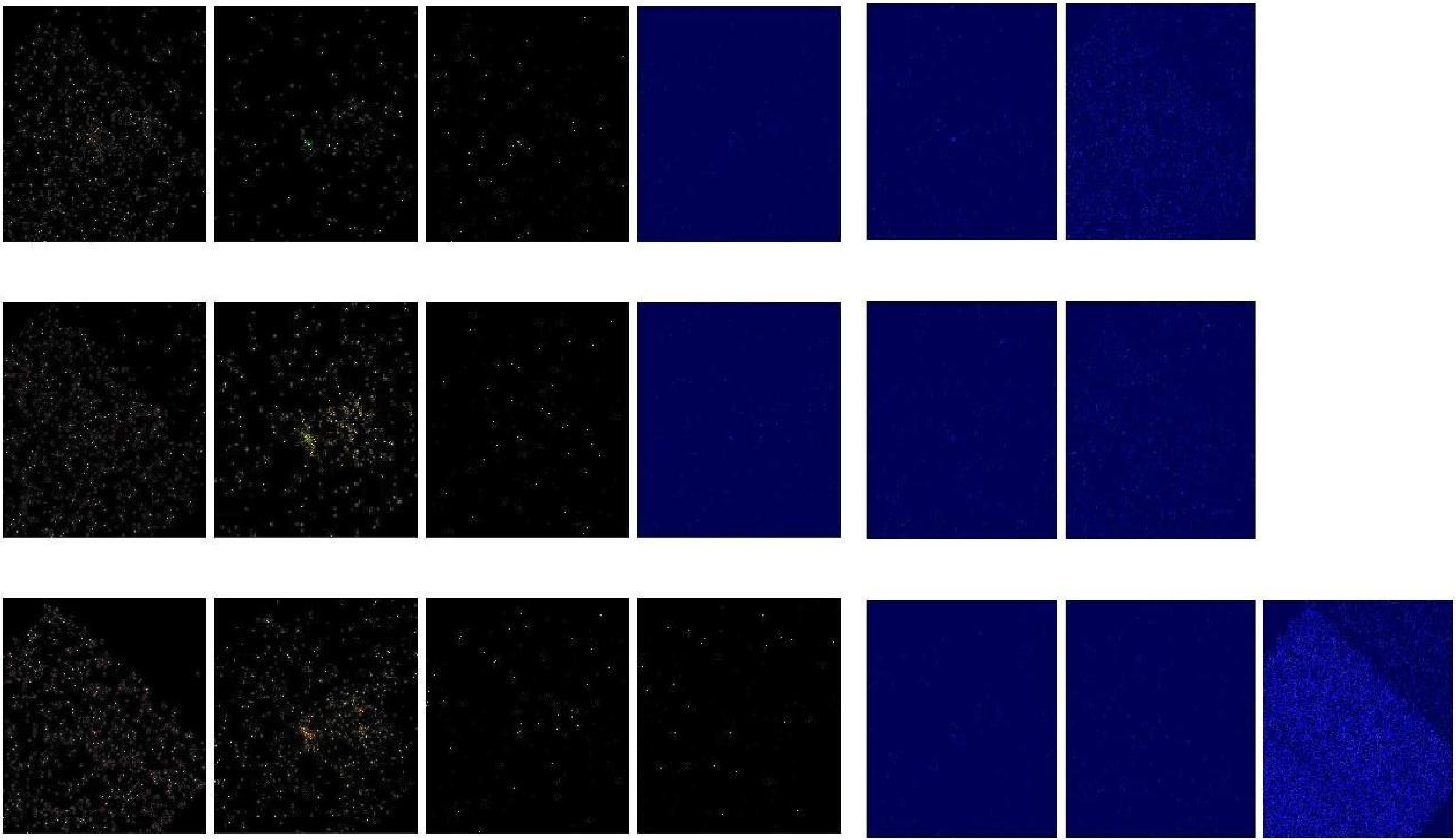
- In optical astronomy, the primary data set is an image. In radio interferometry, it's a visibility array.
- In X-ray astronomy, the primary data set is an event list - a table of (putative) photons
  - Our software makes it easy to generate an image from the event list, so it's easy to forget that's 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

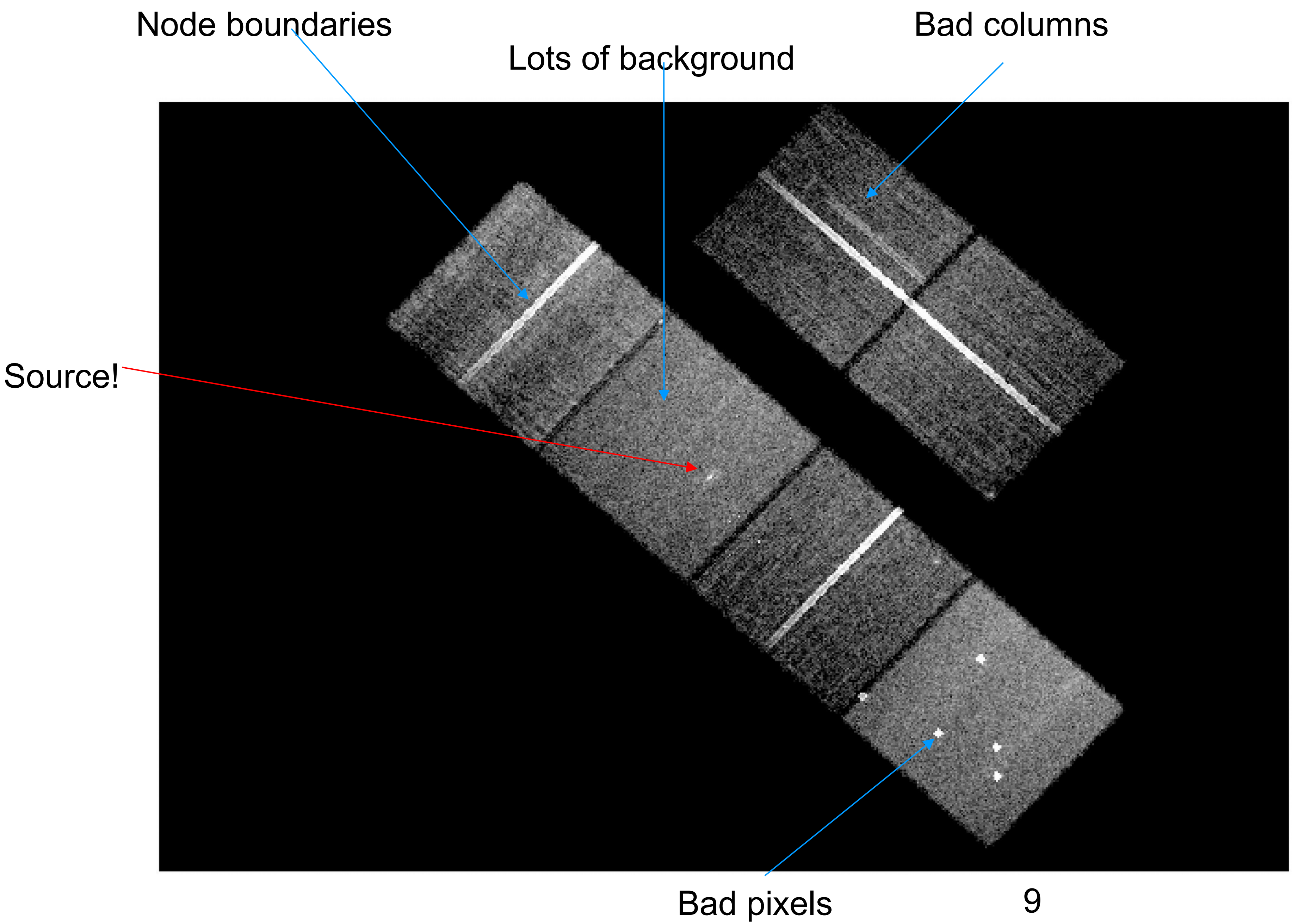
```
jupiter> dmlist acisf03041_001N001_evt3.fits cols

--------------------------------------------------------------------------------
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



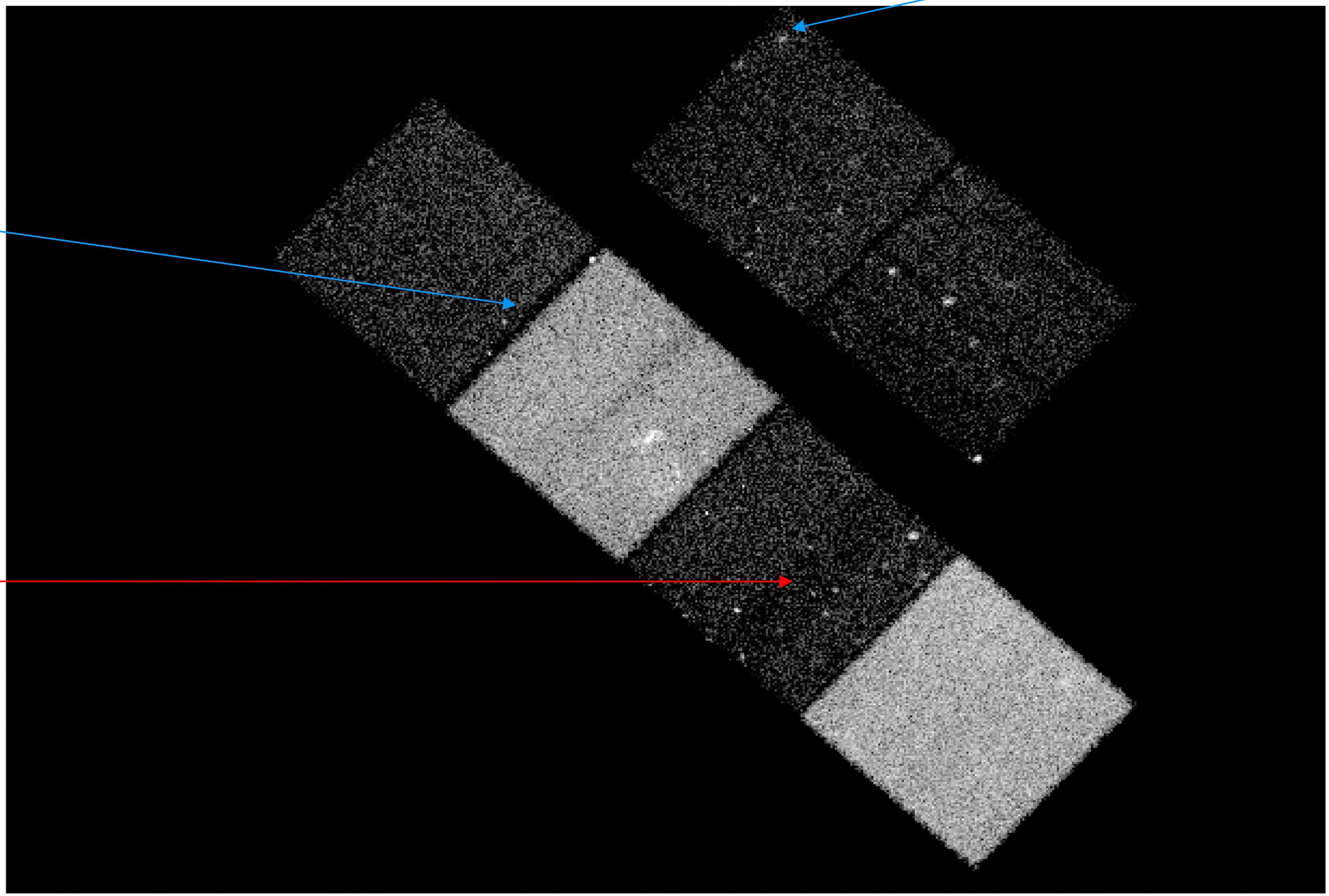
Level 2 event list - cleaned and filtered

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

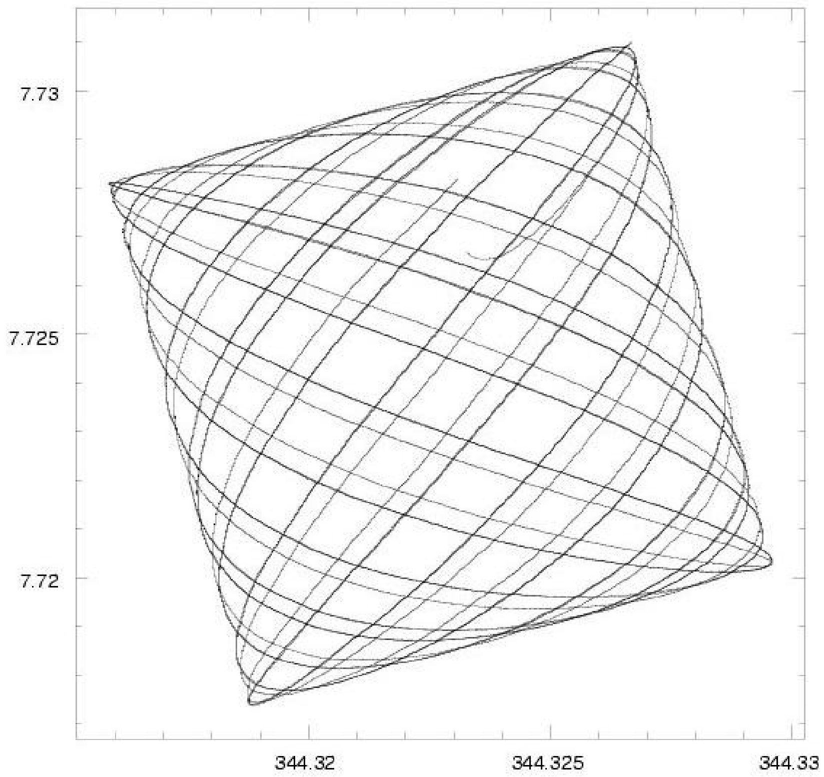
Sources fuzzy far off axis (PSF big)

Beware chip gaps!

More sources!



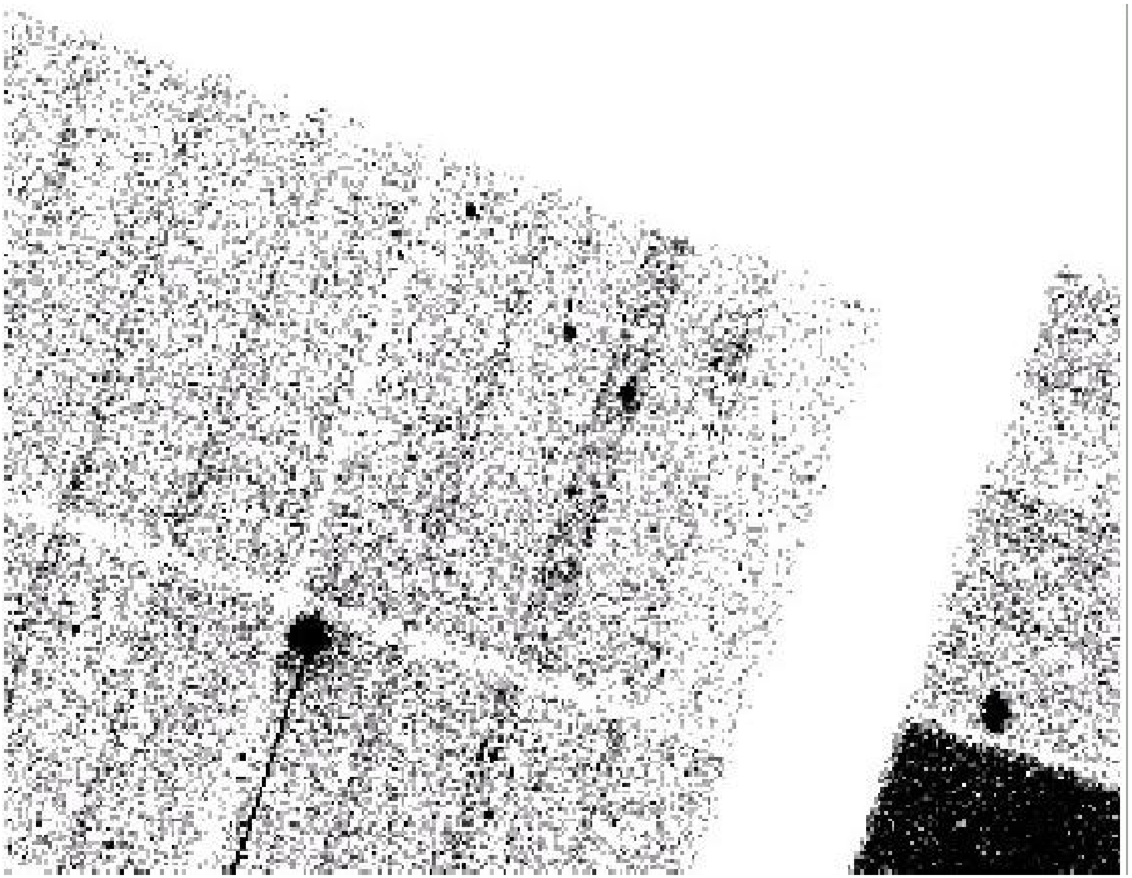
The aspect solution



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.

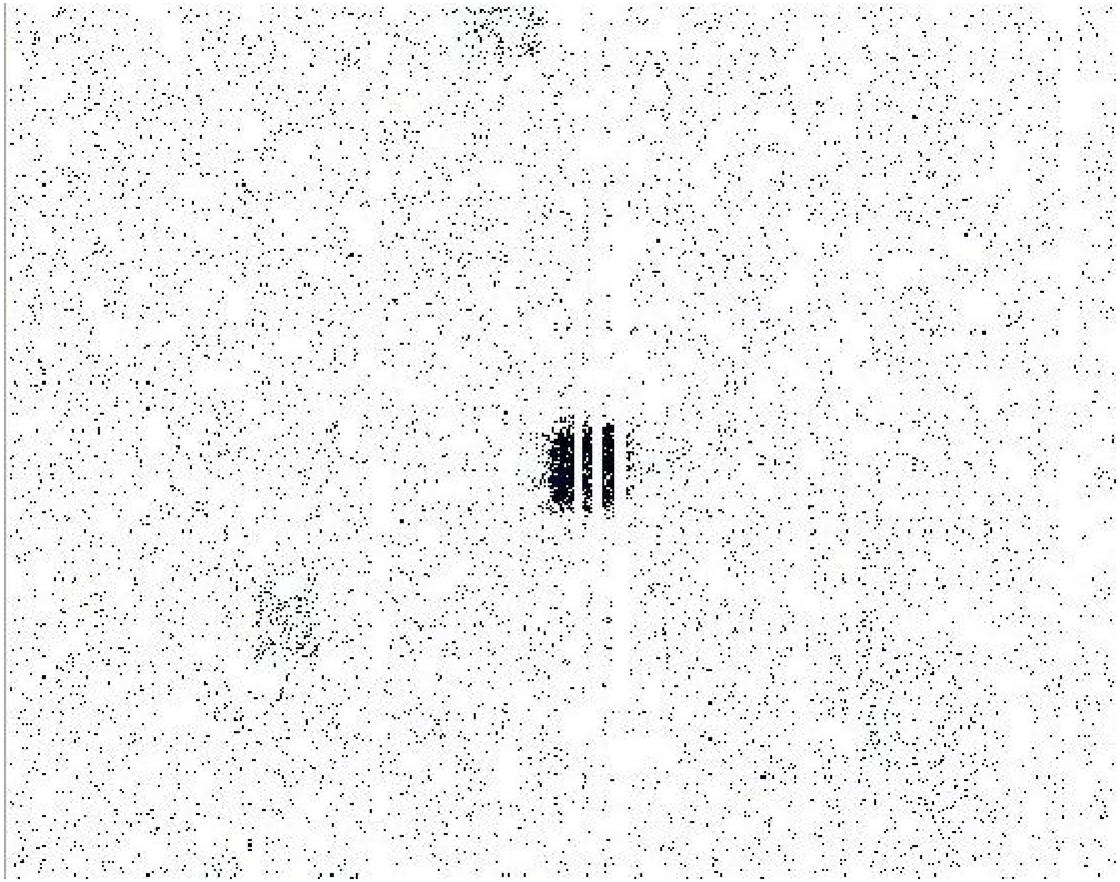
We record the motion of the guide stars in the star tracker so that we can calculate RA and Dec for EACH PHOTON and so reconstruct the image.

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

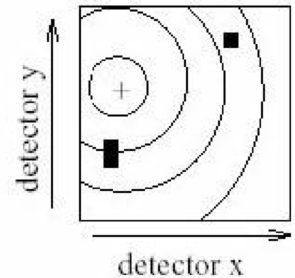
Spatial Response: EXPOSURE MAP

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

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

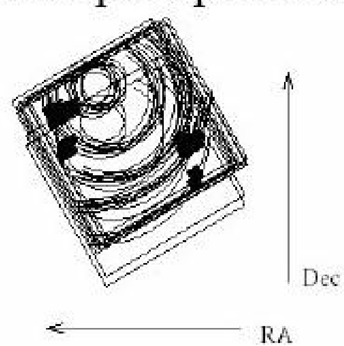
C is the observed counts per spatial bin in a pulse-height bin. S is the source flux, with units of [phot $cm^{-2}s^{-1}$Å^{-1}].

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



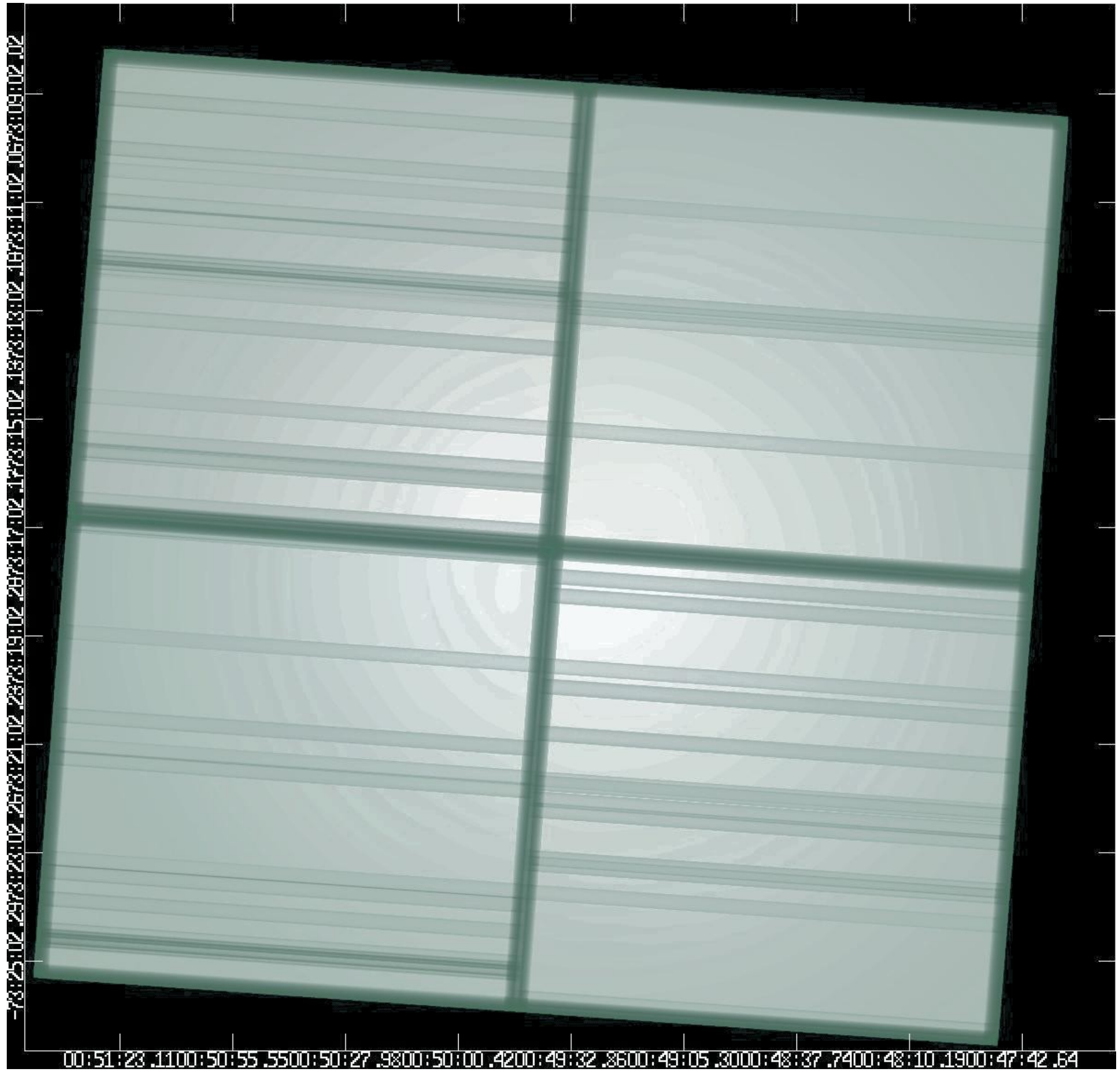
= mirror area x detector QE

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



= Instmap ⊗ 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'

$$N(E'_i, x'_i, y'_i) = \int\int A(E)R(E, Ei)F(E, x, y)P(x-x'_i, y-y'_i)q(E, x'_i, y'_i)dEdxdy\Delta T$$

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

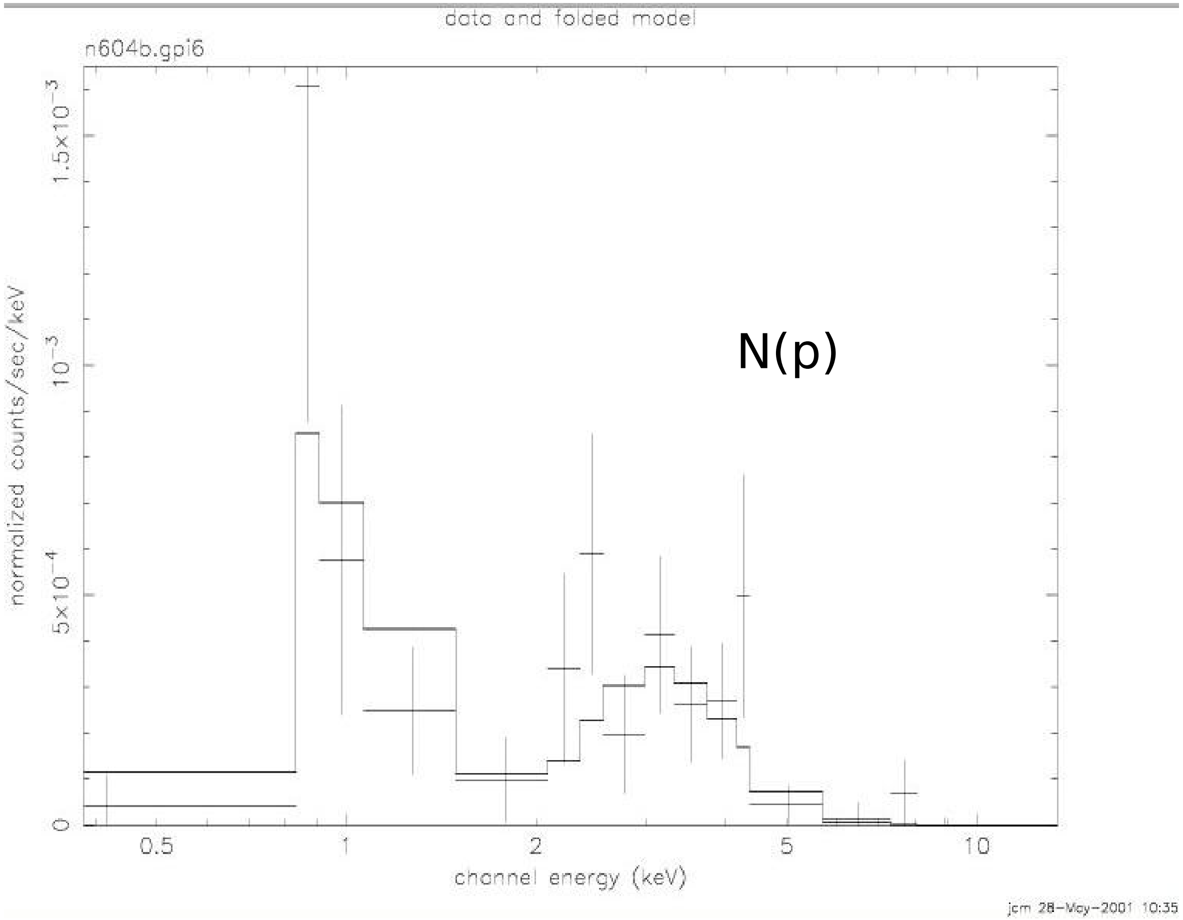
$$N(p) = \int R(E,p)A(E)F(E)dE$$

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.

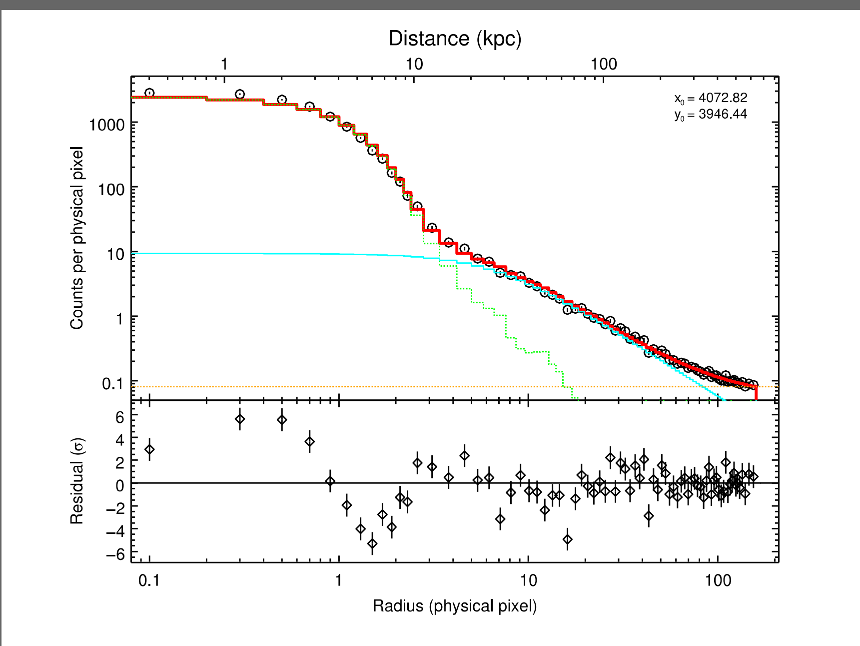
Incompletely calibrated instrumental features may show up in residuals, limiting factor in high S/N spectra – these features may include edges. Beware apparent science in regions where A(E) is changing rapidly.

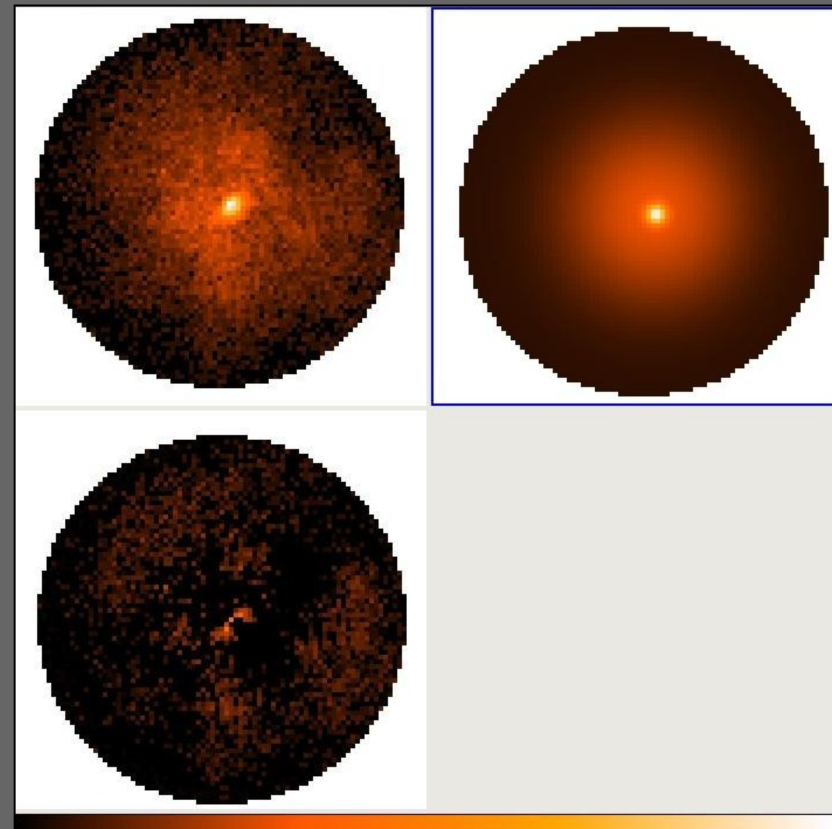


Sherpa: Modeling and Fitting in Python

Sherpa

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

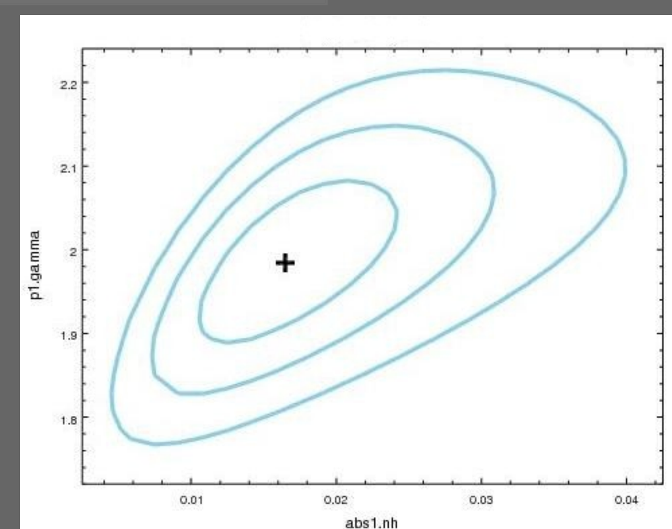




Coded in a Python environment – familiar to the new generation of astronomers and used in other missions

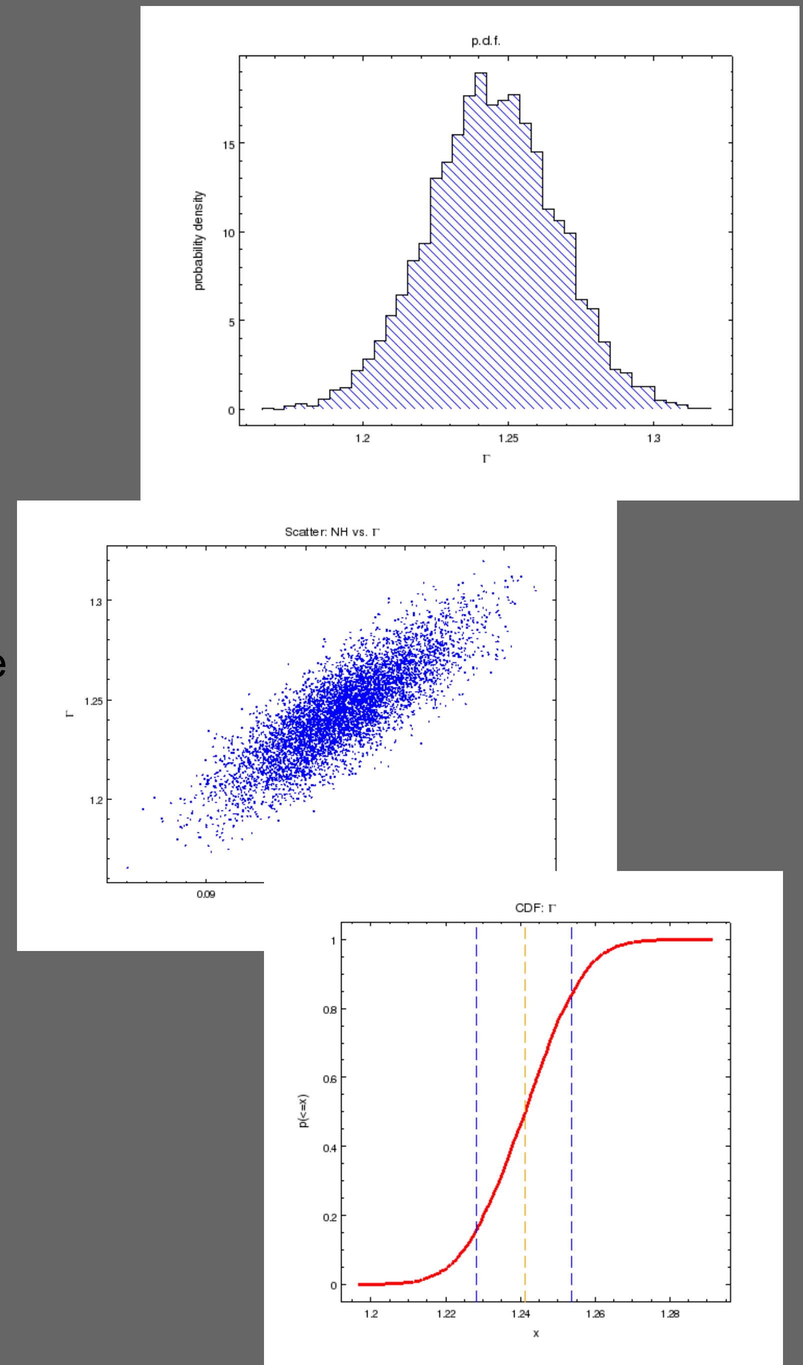
Model Poisson and Gaussian data

Calculate confidence levels on the best-fit model parameters



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

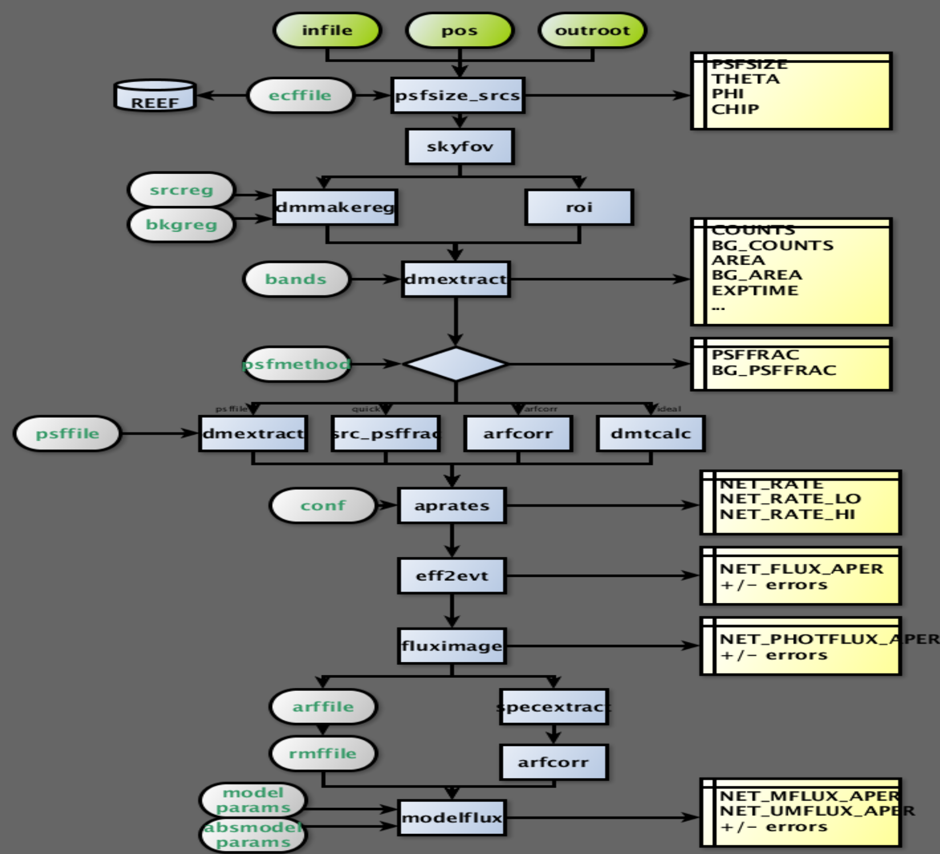
- The CALDB (Calibration Database) contains everything you need that's not part of your specific observation.
- It's designed as a multimission directory structure. The Chandra files are in $CALDB/data/chandra
- Within that, they are arranged by instrument and kind of calibration. But, with luck, the 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