- 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)

Scope

- Caveat: will cover ACIS imaging data only
- Basics the same for HRC and gratings, but with extra wrinkles

The Event File

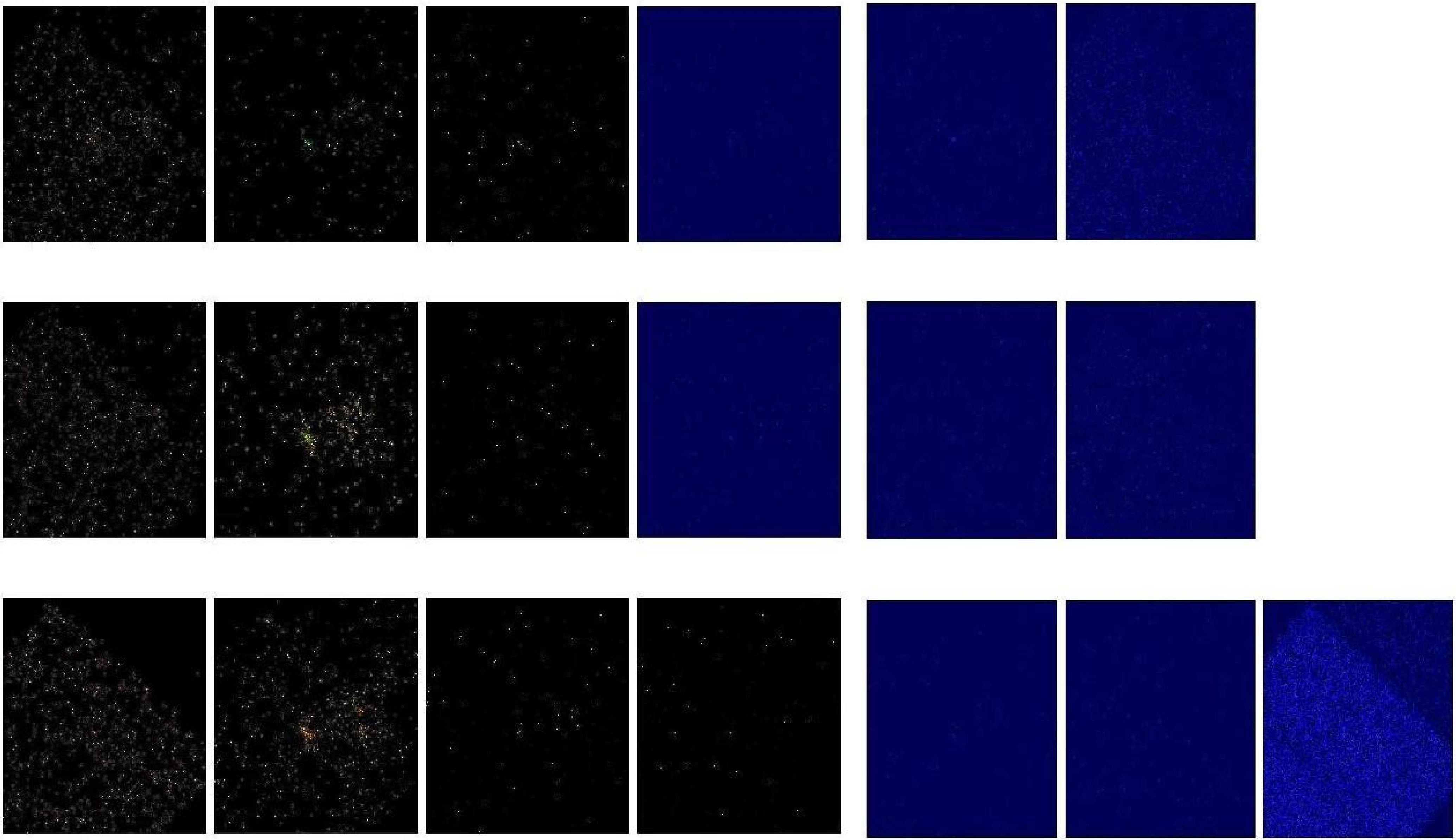
- In optical astronomy, the primary data set is an image. In radio interferometry, it's a visibility array.
- In X-ray astronomy, the primary data set is an event list - a table of (putative) photons
    - Our software makes it easy to generate an image from the event list, so it's easy to forget that's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

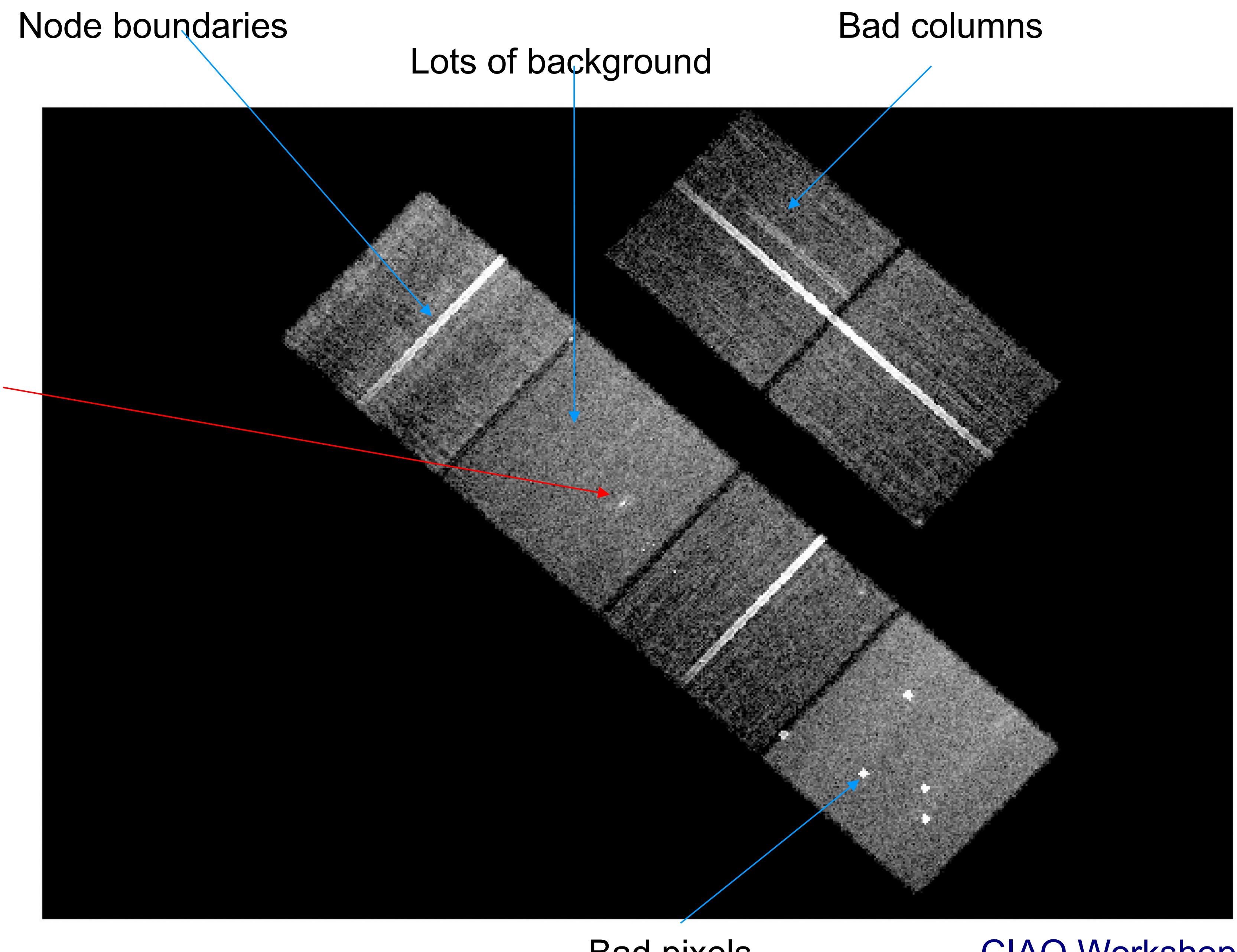
```
jupiter> dmlist acisf03041_001N001_evt3.fits cols

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



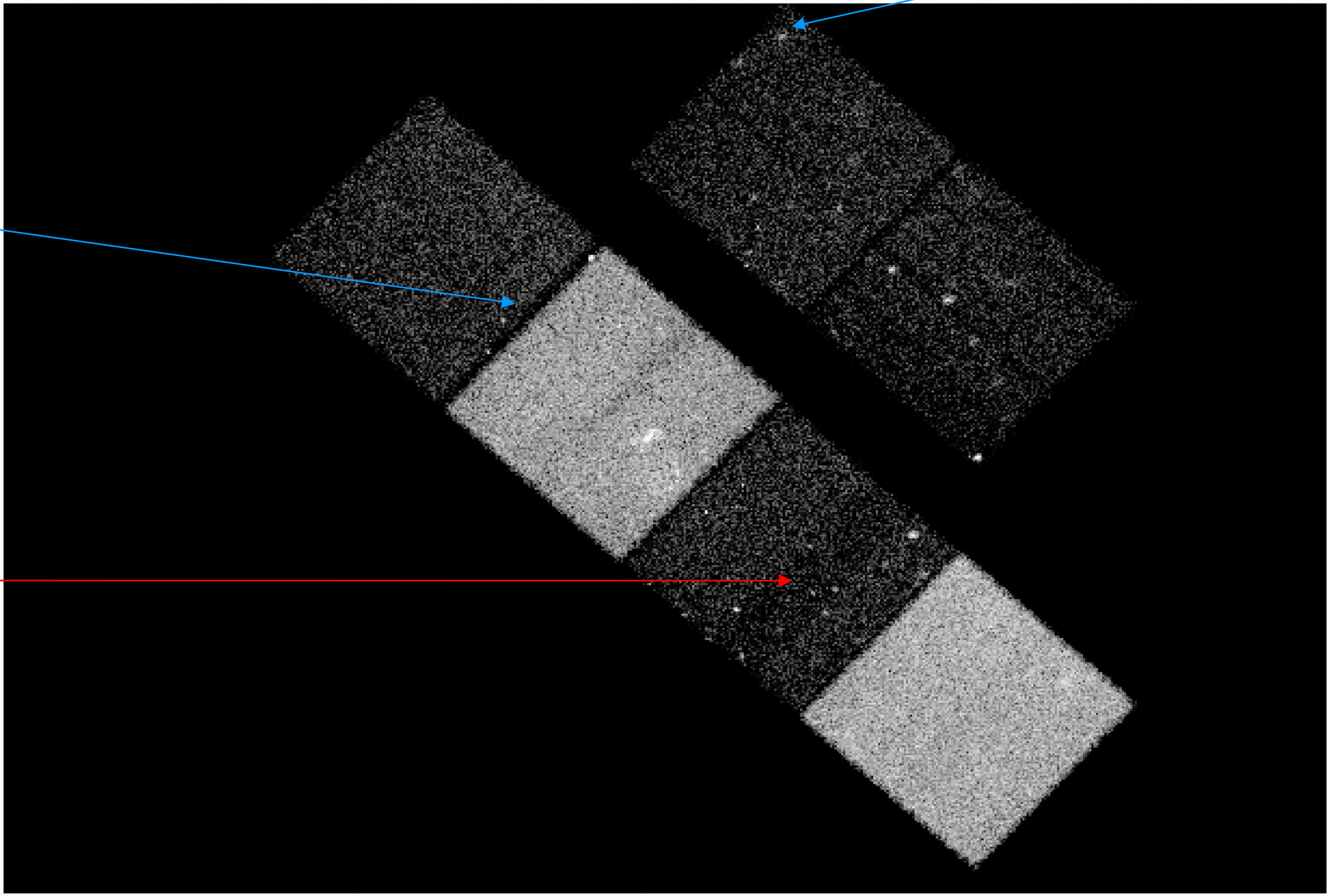
Level 2 event list - cleaned and filtered

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

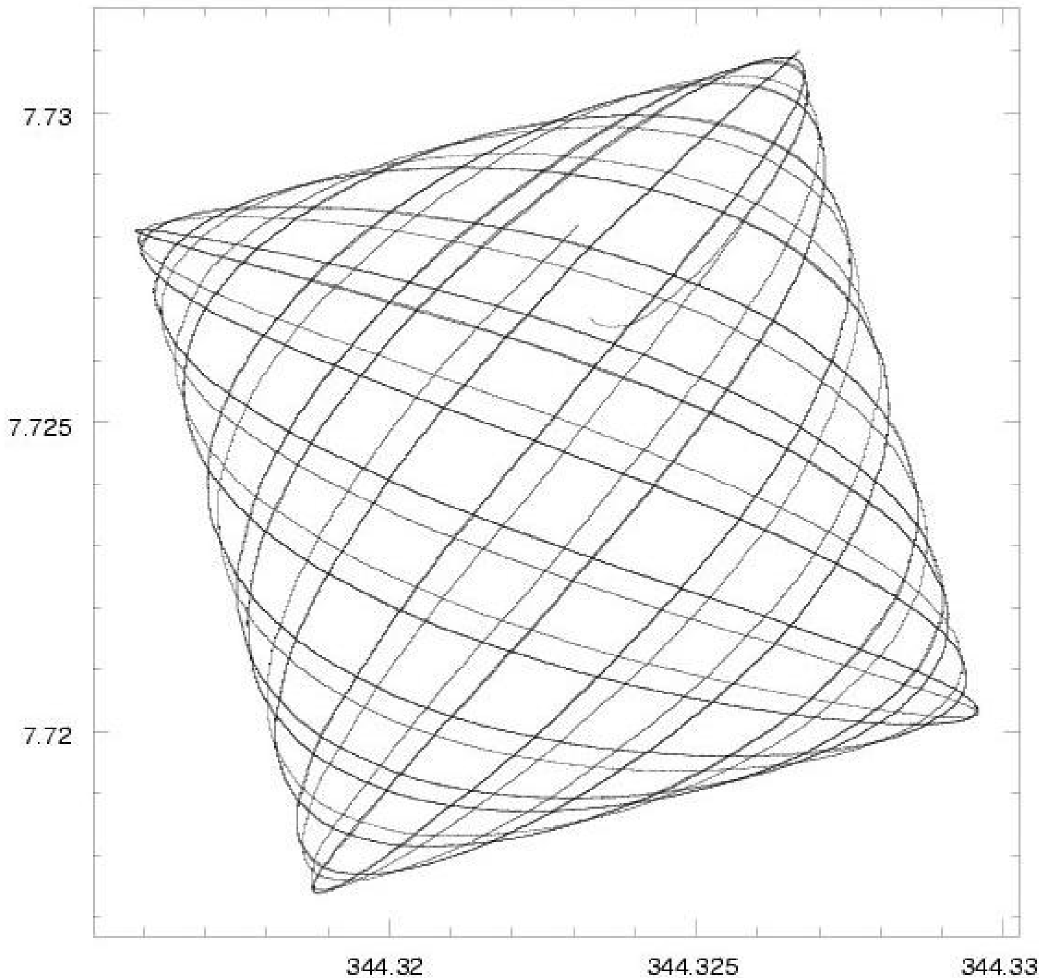
Sources fuzzy far off axis (PSF big)

Beware chip gaps!

More sources!



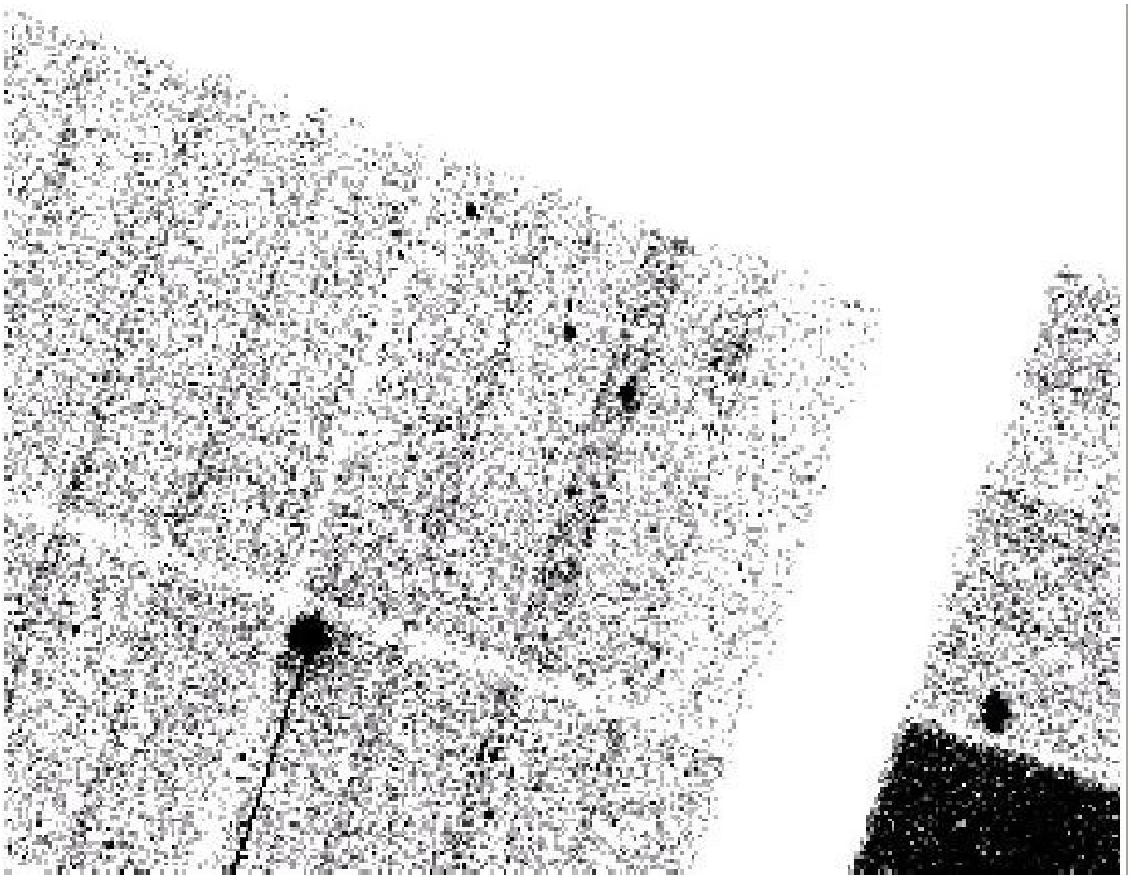
The aspect solution



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.

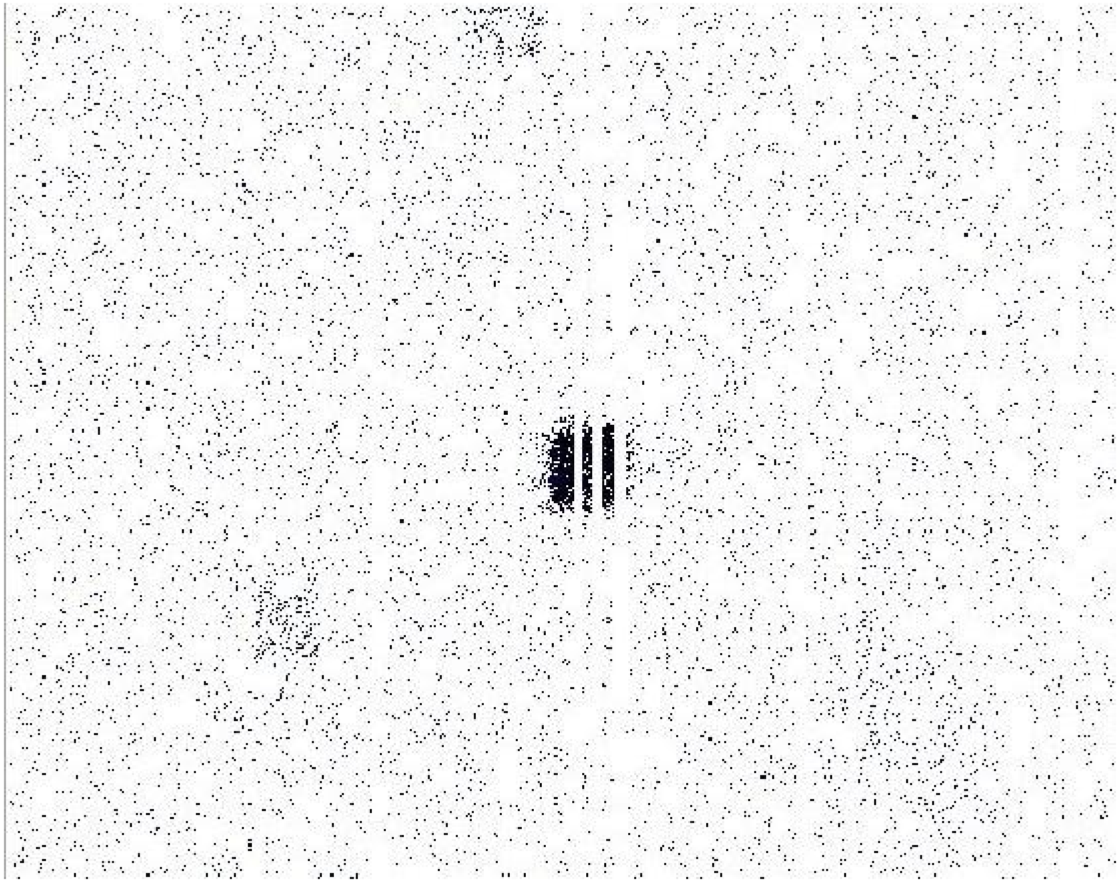
We record the motion of the guide stars in the star tracker so that we can calculate RA and Dec for EACH PHOTON and so reconstruct the image.

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

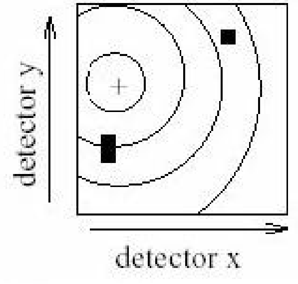
Spatial Response: EXPOSURE MAP

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

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

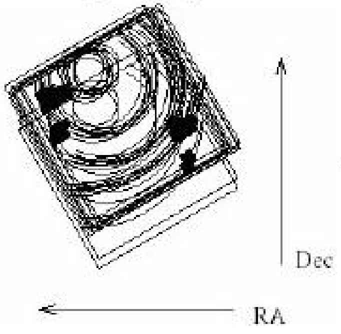
C is the observed counts per spatial bin in a pulse-height bin. S is the source flux, with units of [phot $\mathrm{cm}^{-2}\mathrm{s}^{-1}\text{Å}^{-1}$].

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



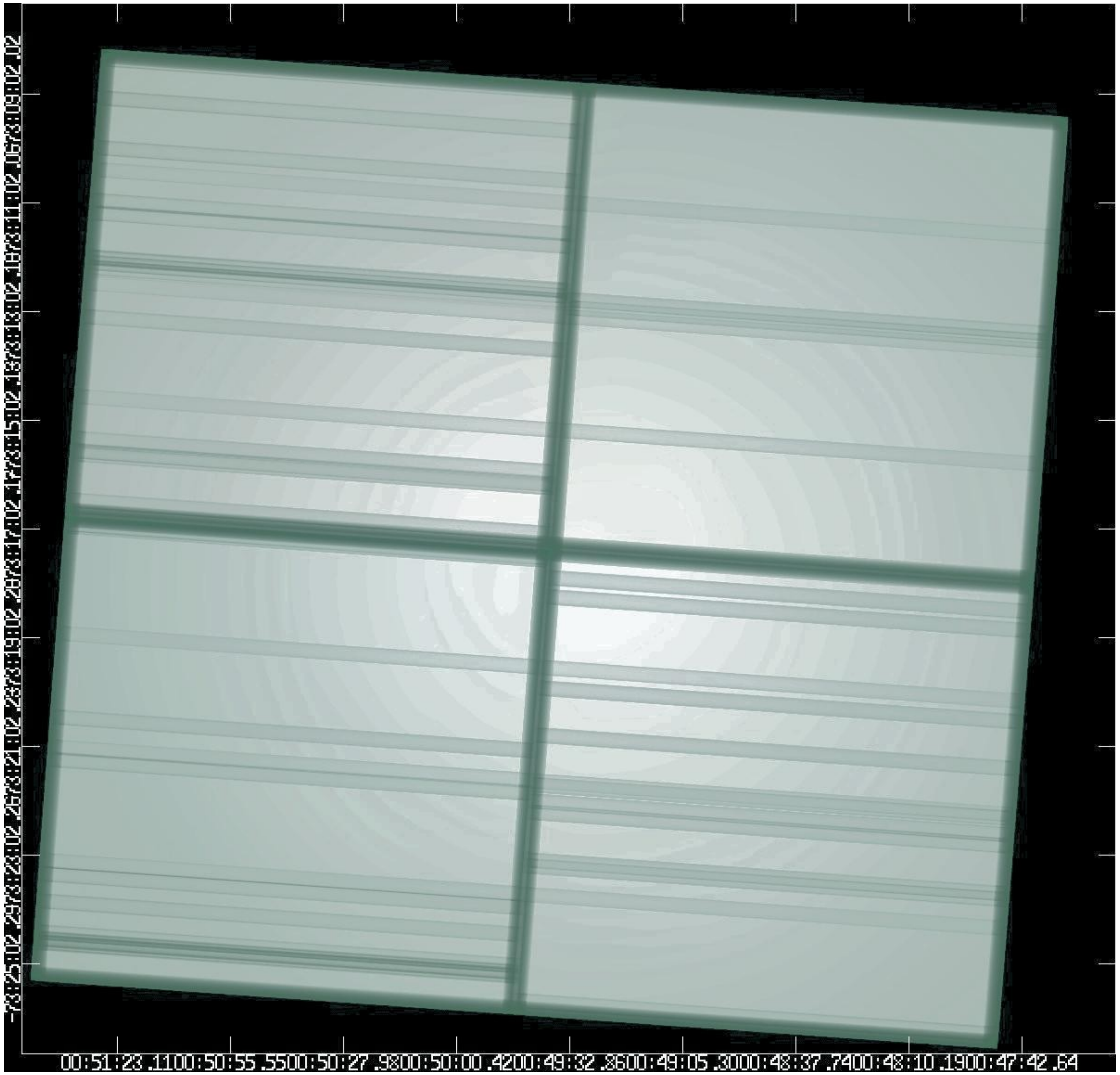
= mirror area x detector QE

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

- 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

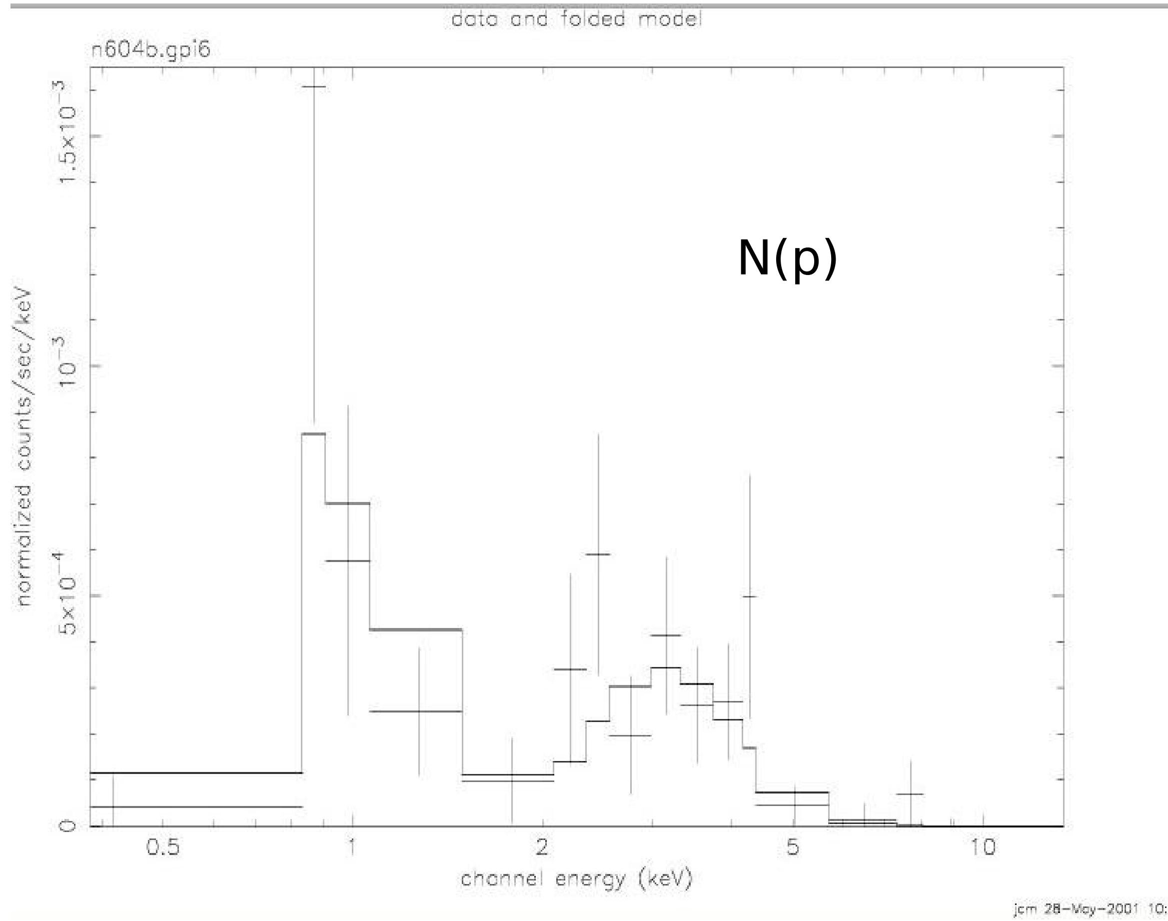
We pick a parameterized F(E) such as warm absorber models, lines, thermal plasma codes. Which F(E)? You must pick one based on expected physics, but match number of free parameters with quality of data.

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

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.



- 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.