- 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

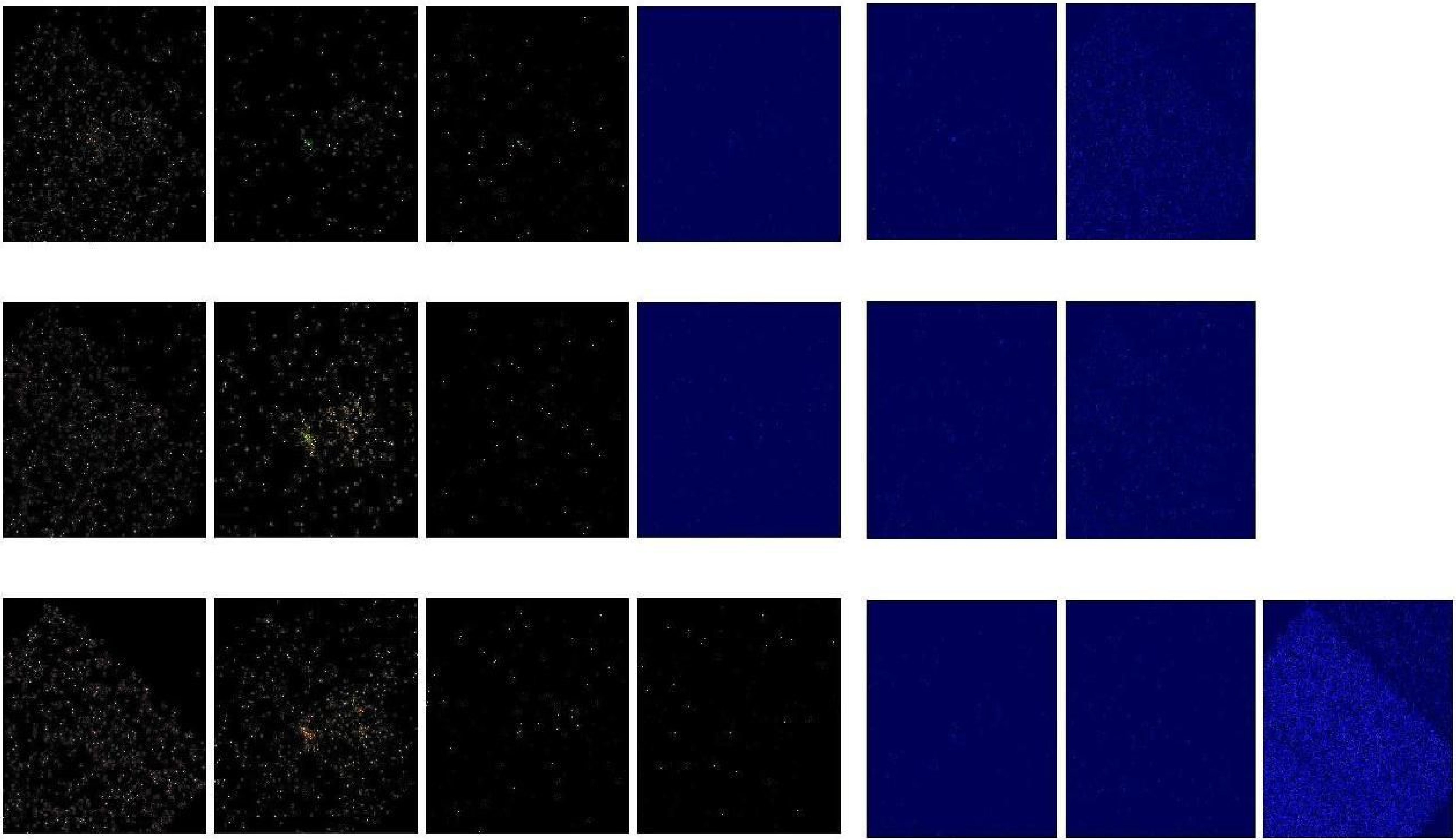
- In optical astronomy, the primary data set is an image. In radio interferometry, it's a visibility array.
- In X-ray astronomy, the primary data set is an event list - a table of (putative) photons
  - Our software makes it easy to generate an image from the event list, so it's easy to forget that's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

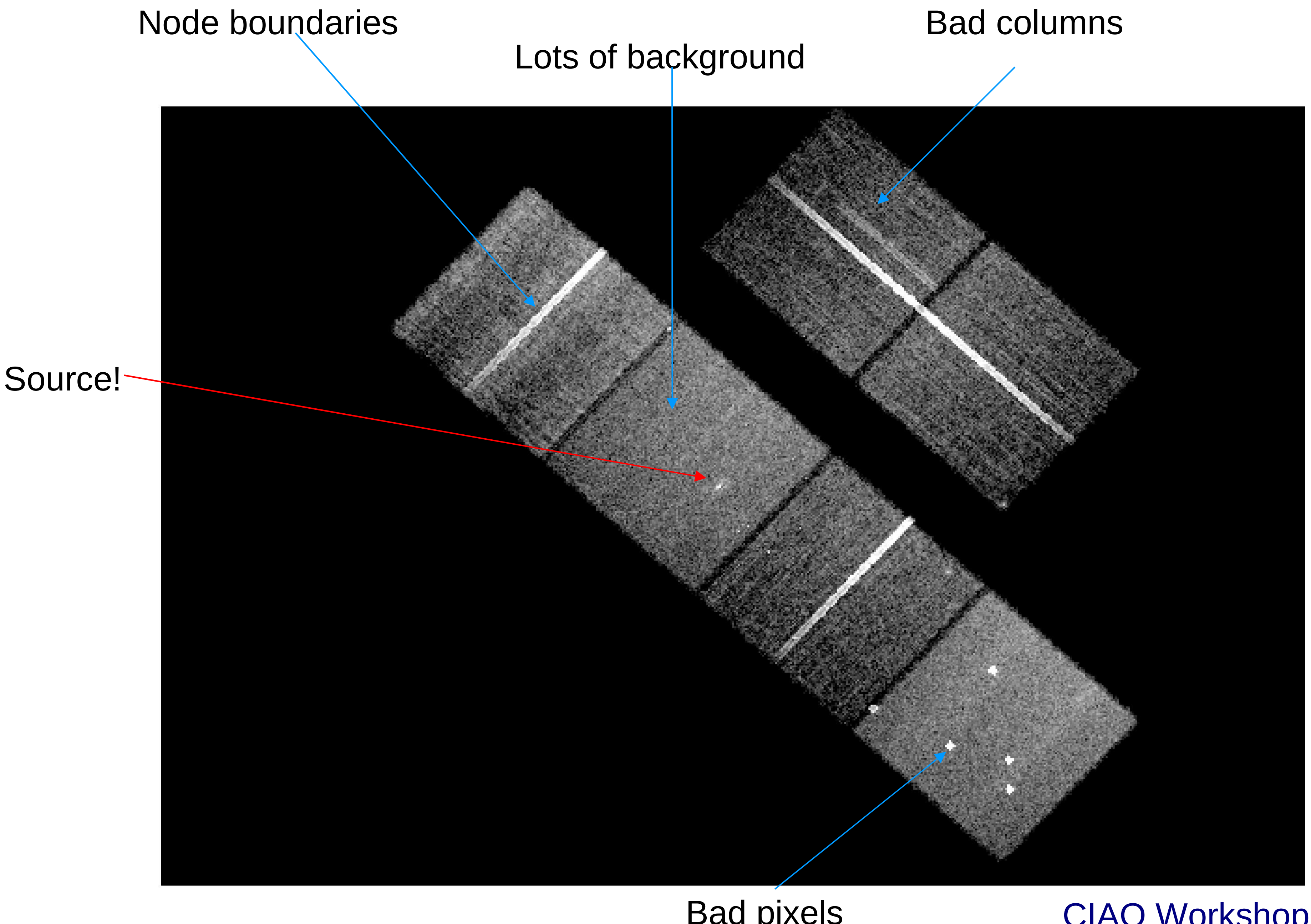
```
jupiter> dmlist acisf03041_001N001_evt3.fits cols

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



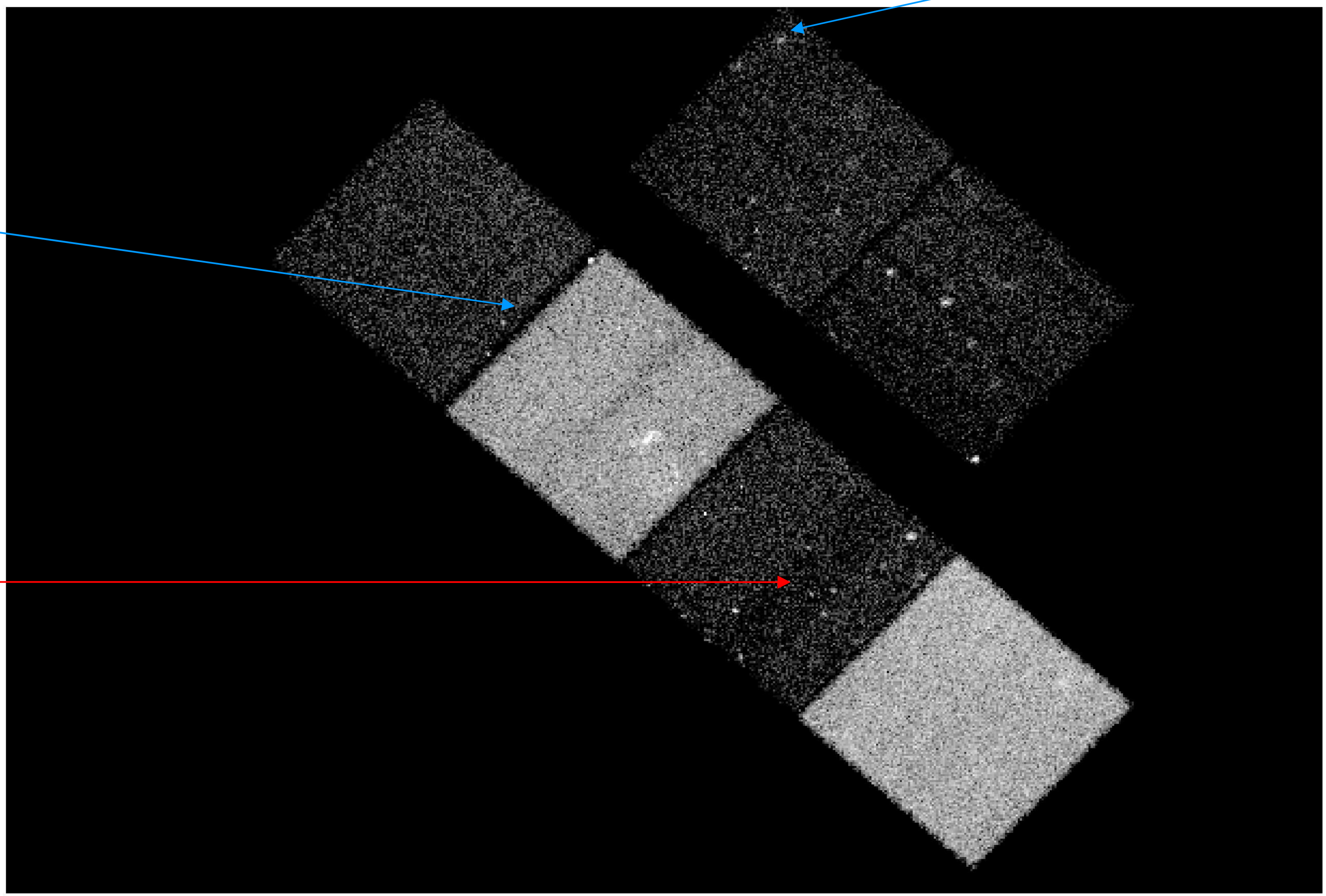
Level 2 event list - cleaned and filtered

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

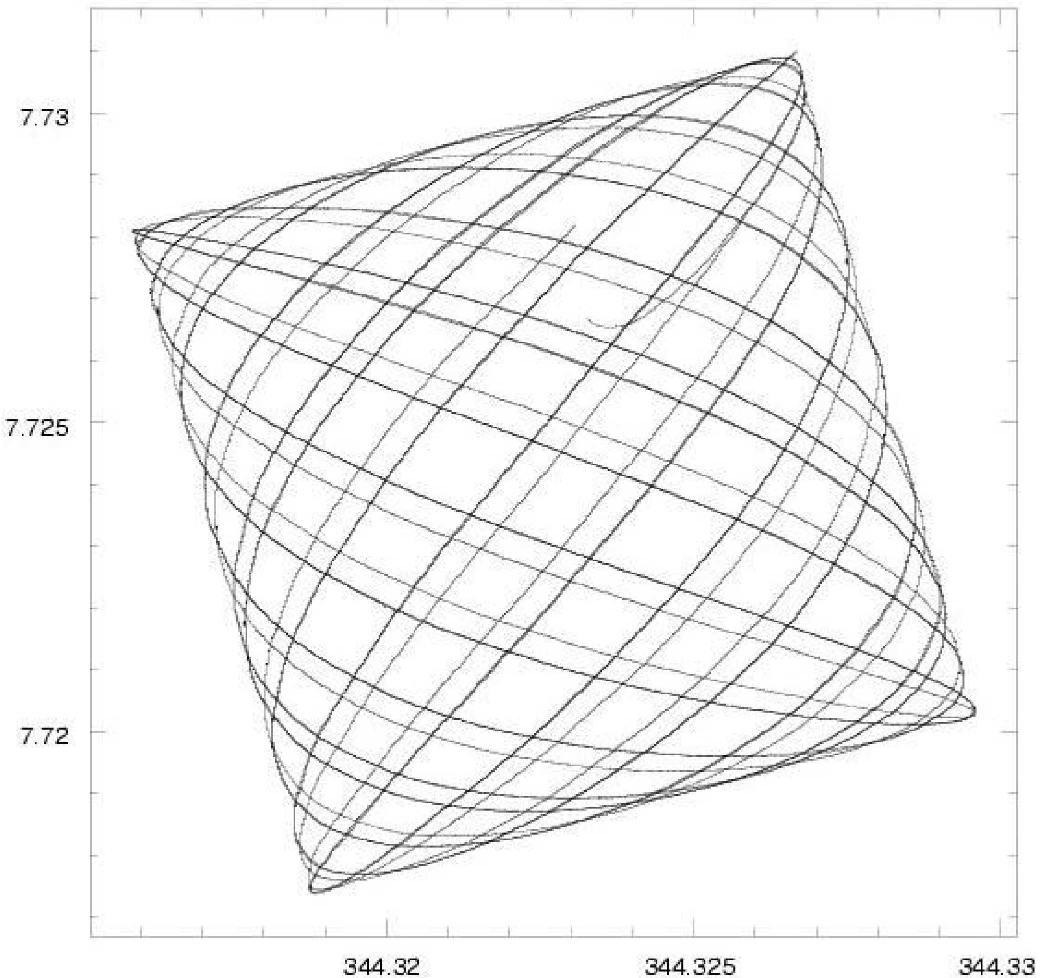
Sources fuzzy far off axis (PSF big)

Beware chip gaps!

More sources!



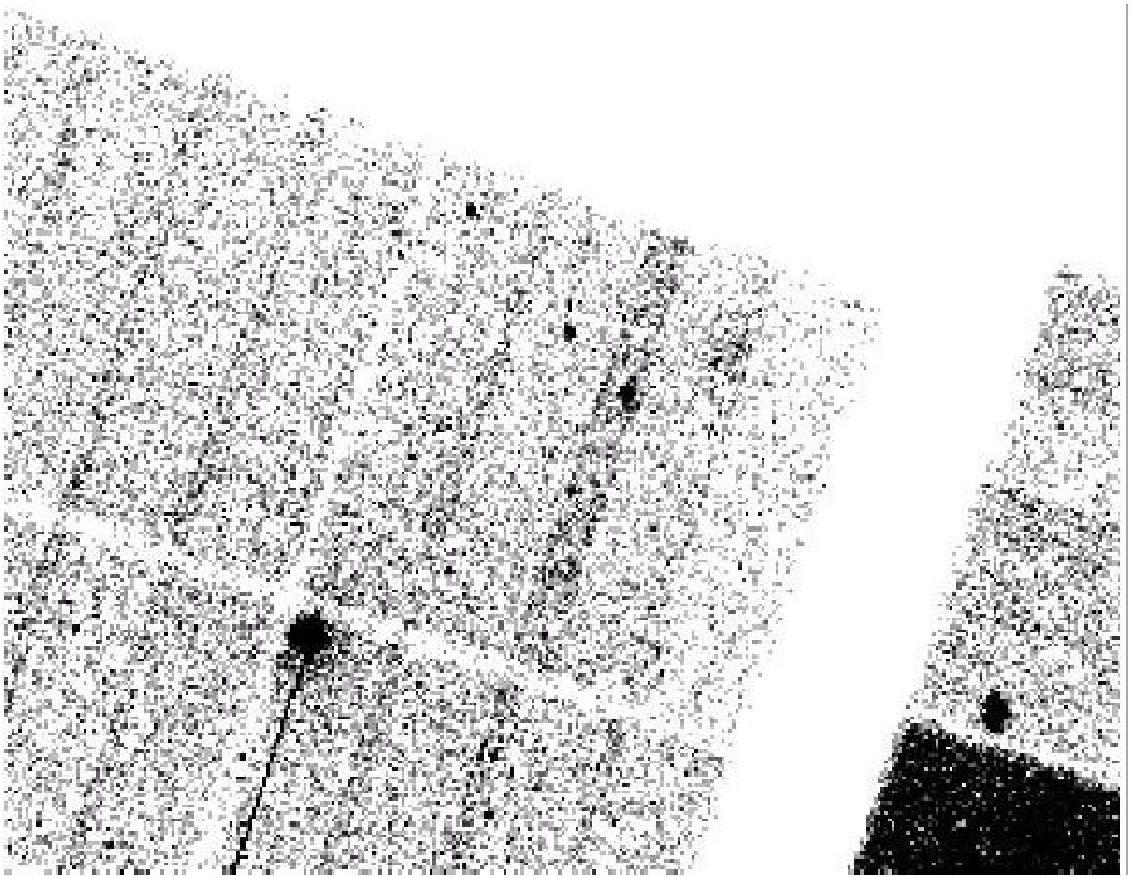
The aspect solution



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.

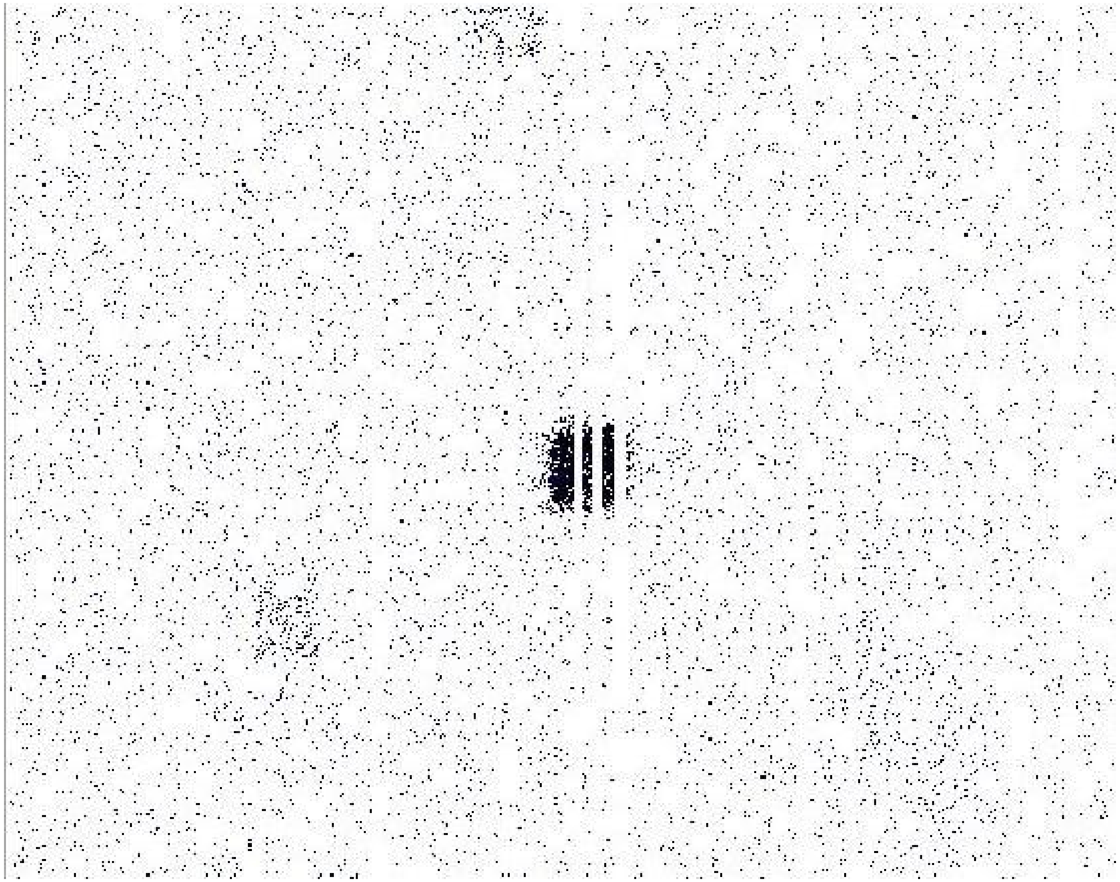
We record the motion of the guide stars in the star tracker so that we can calculate RA and Dec for EACH PHOTON and so reconstruct the image.

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

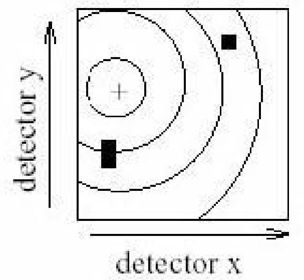
Spatial Response: EXPOSURE MAP

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

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

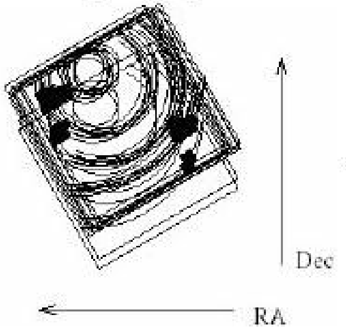
C is the observed counts per spatial bin in a pulse-height bin. S is the source flux, with units of [phot $cm^{-2}s^{-1}Å^{-1}$].

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



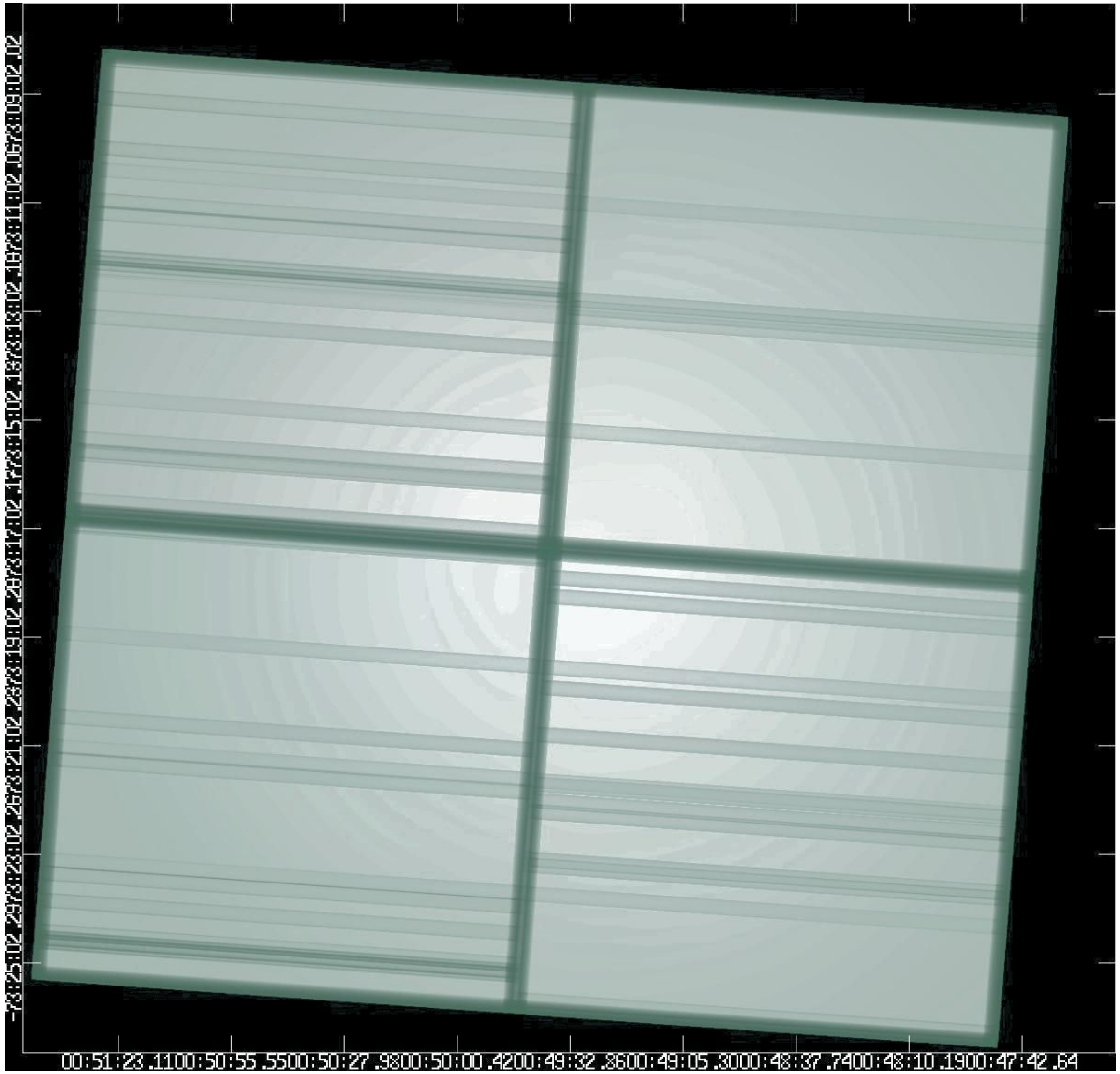
= mirror area x detector QE

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

- 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 (details)

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

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'

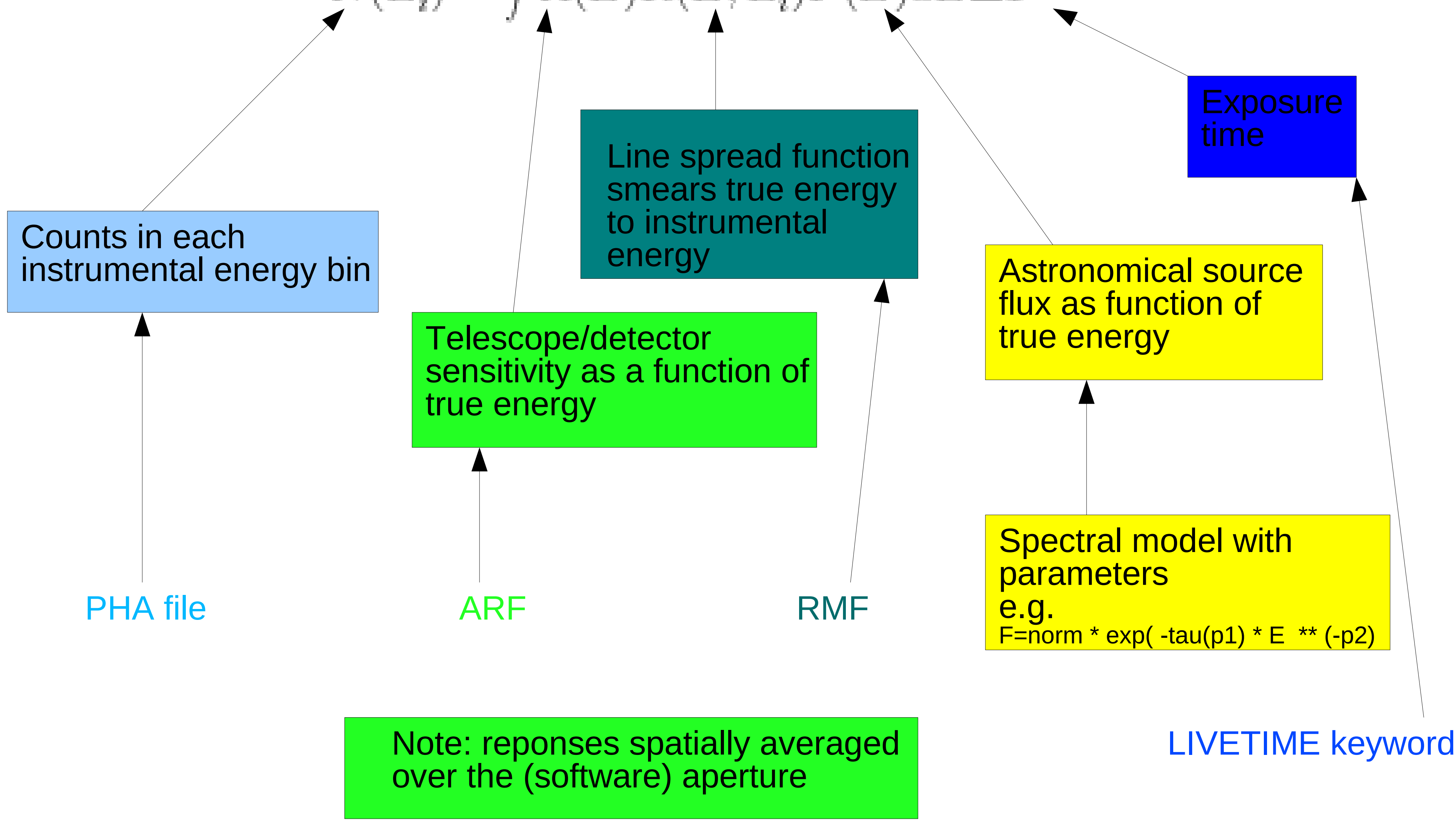
$$N(E'_i,x'_i,y'_i) = \int\int A(E)R(E,Ei)F(E,x,y)P(x-x'_i,y-y'_i)q(E,x'_i,y'_i)dEdxdy\Delta T$$

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)

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

The fundamental eqn of astronomy (simplified)

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



Alternate approach: exposure maps

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

This approach averages over spectral shape

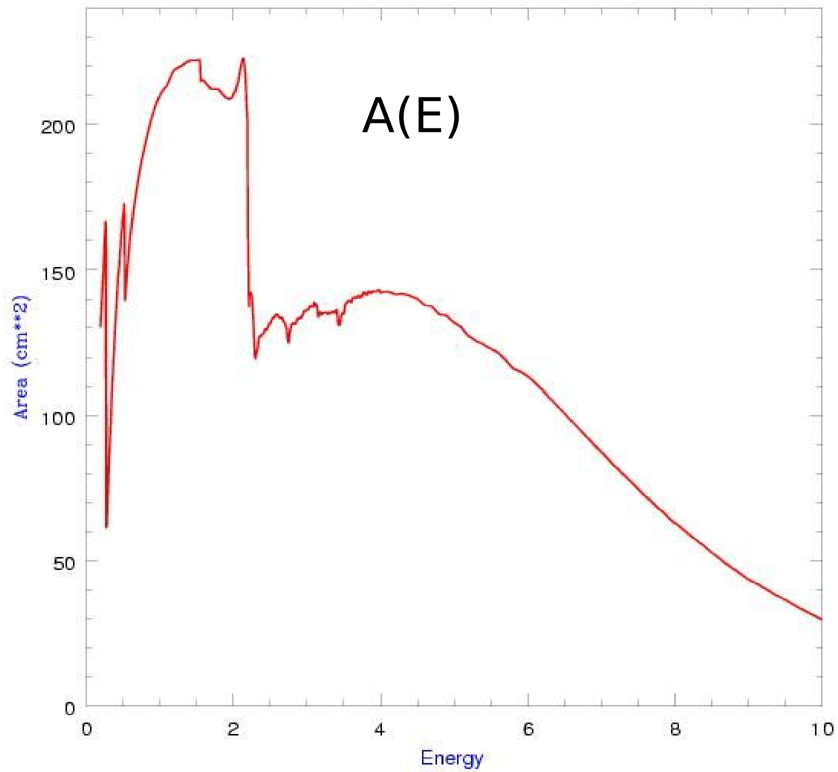
Set F(E) = F0 * f(E), such that Int f(E) dE = 1
Assume we know the spectral shape f(E) and just want the normalization

Then set the exposure map value
M = Int (Int A(E)R(E,E')f(E) dE) dE'* dT

For some instrumental band B, set
r(B,E) = Int(over B) R(E,E') dE'
A(B) = Int A(E) r(B,E) f(E) dE

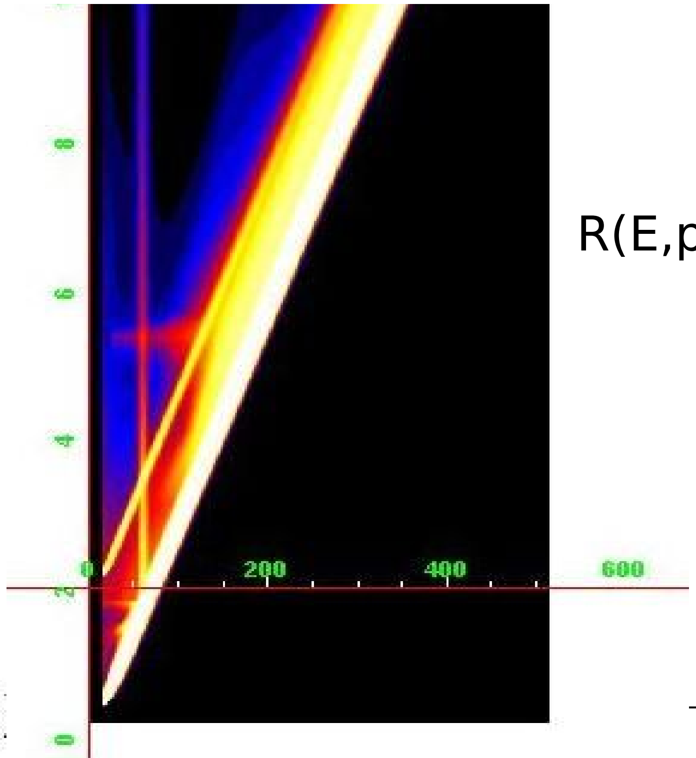
Have N(B) = F0 * A(B) * dT = F0 * M

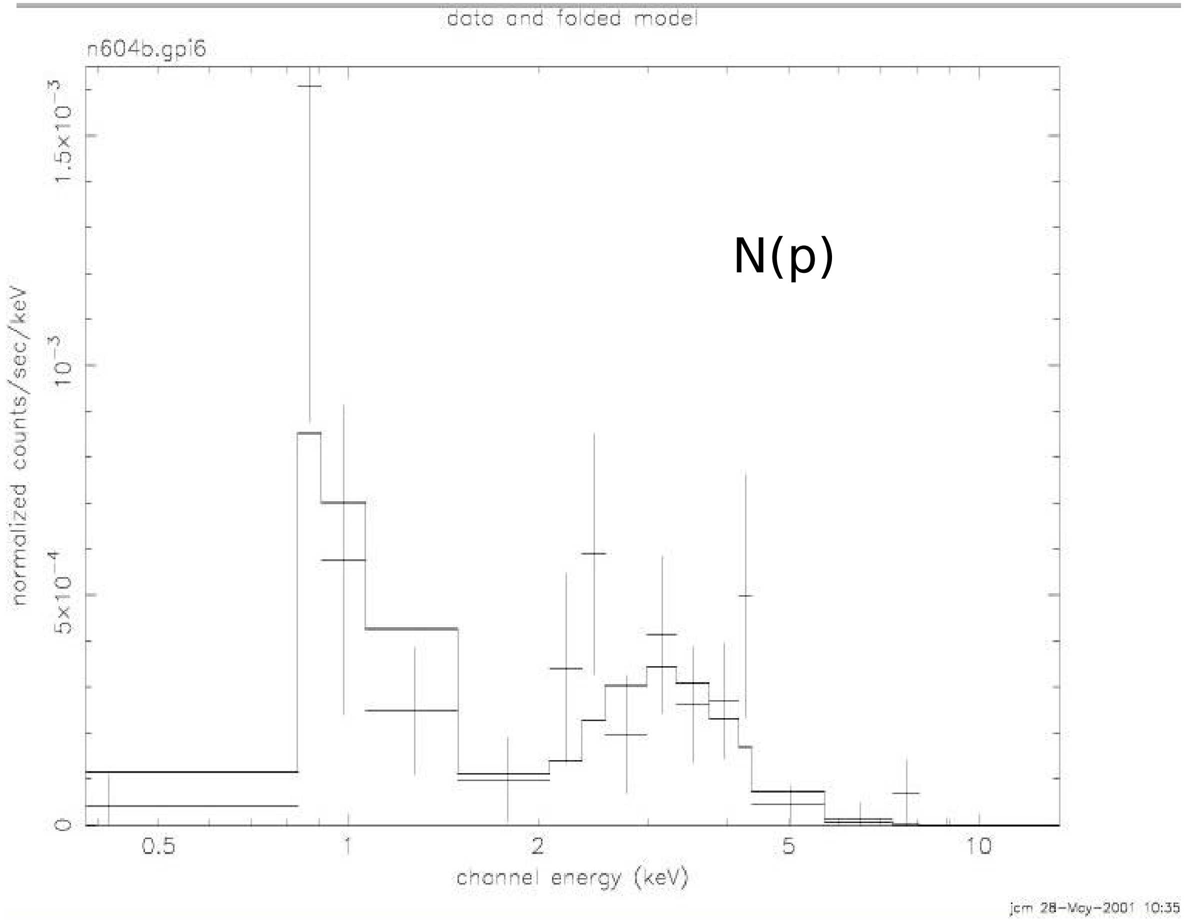
- N(B): Counts in band
- A(B): Band-averaged, spectral-shape-averaged effective area
- dT: Exposure time
- F0: Flux (ph/cm**2/s)
- M: Exposure map (cm**2 s)



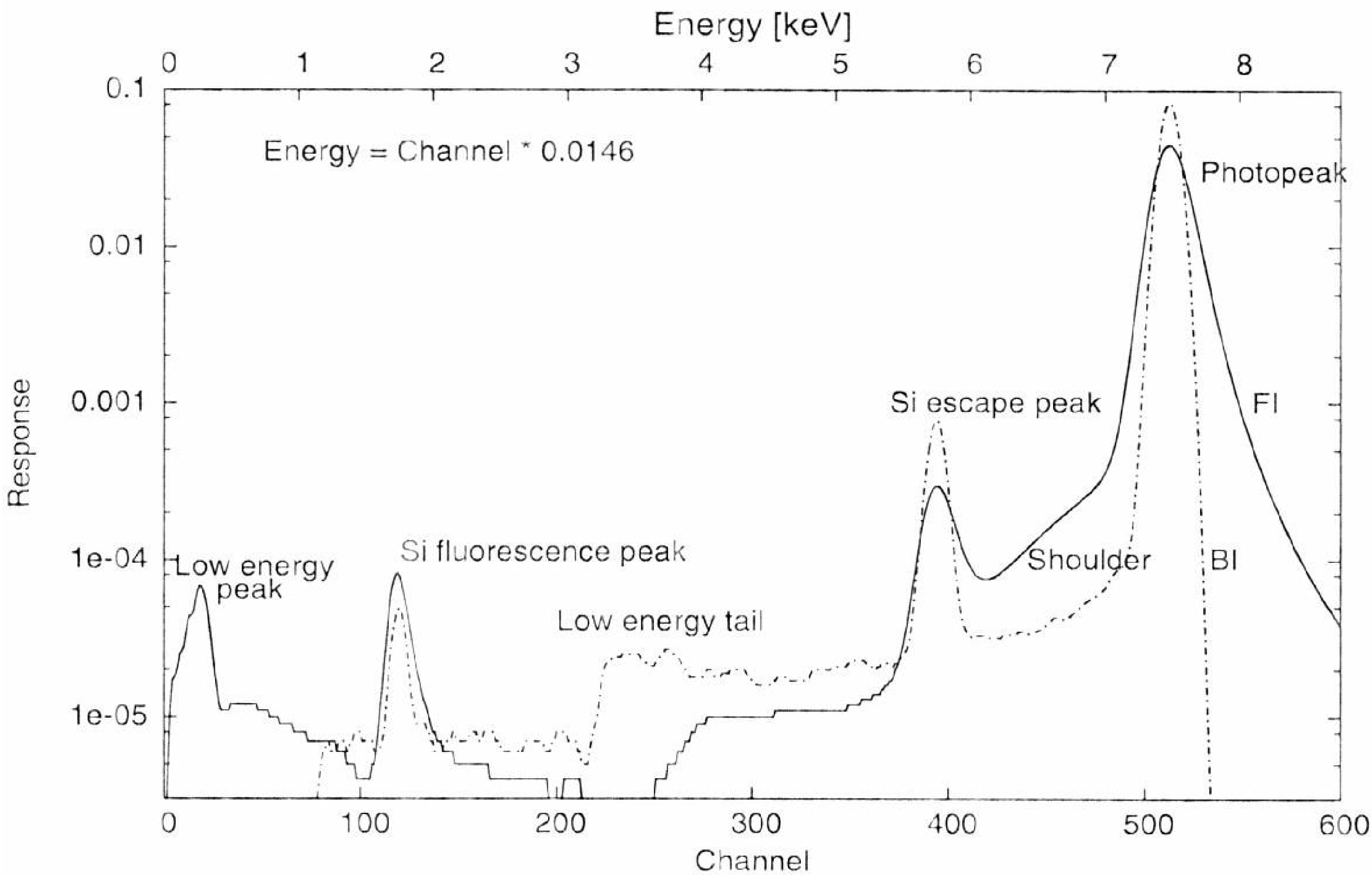
Spectra in Poissonland

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





ACIS CCD line spread function



Spectra in Poissonland

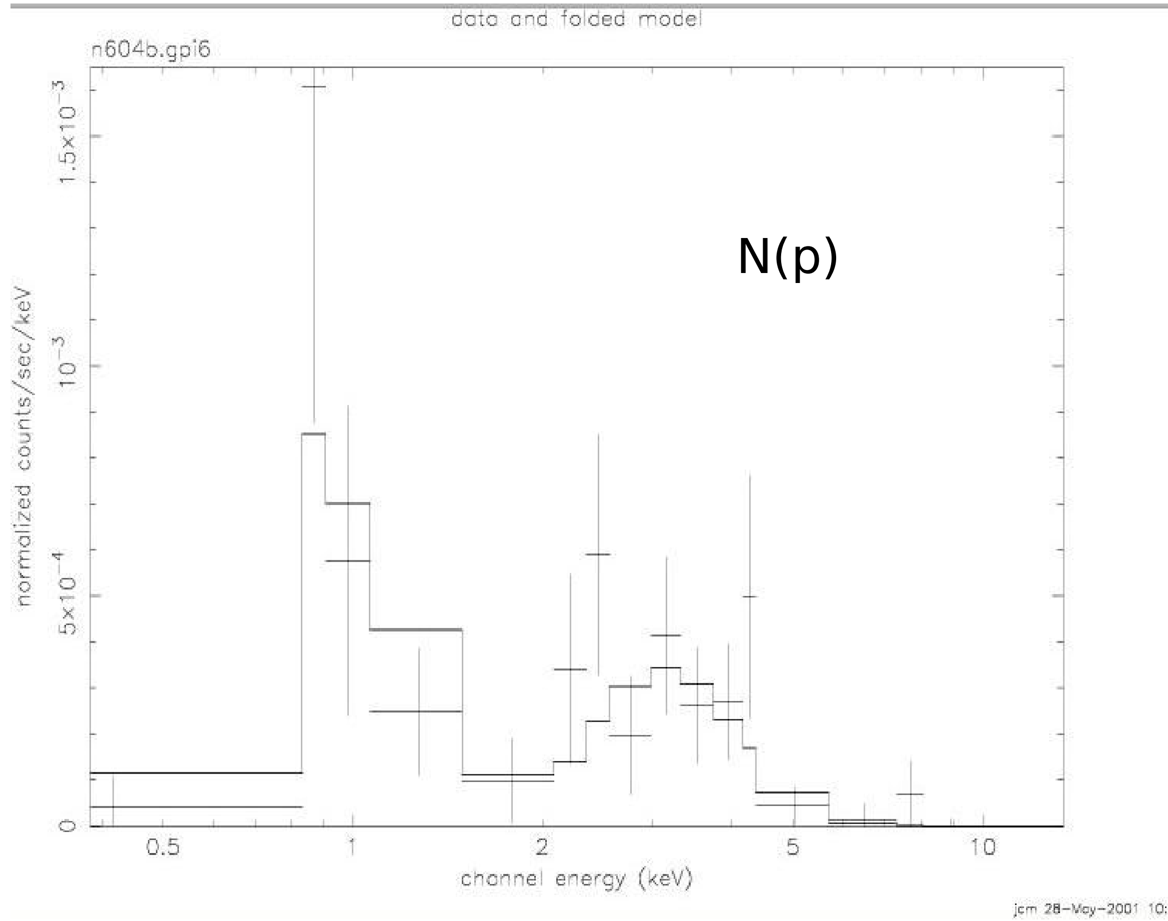
We pick a parameterized F(E) such as warm absorber models, lines, thermal plasma codes. Which F(E)? You must pick one based on expected physics, but match number of free parameters with quality of data.

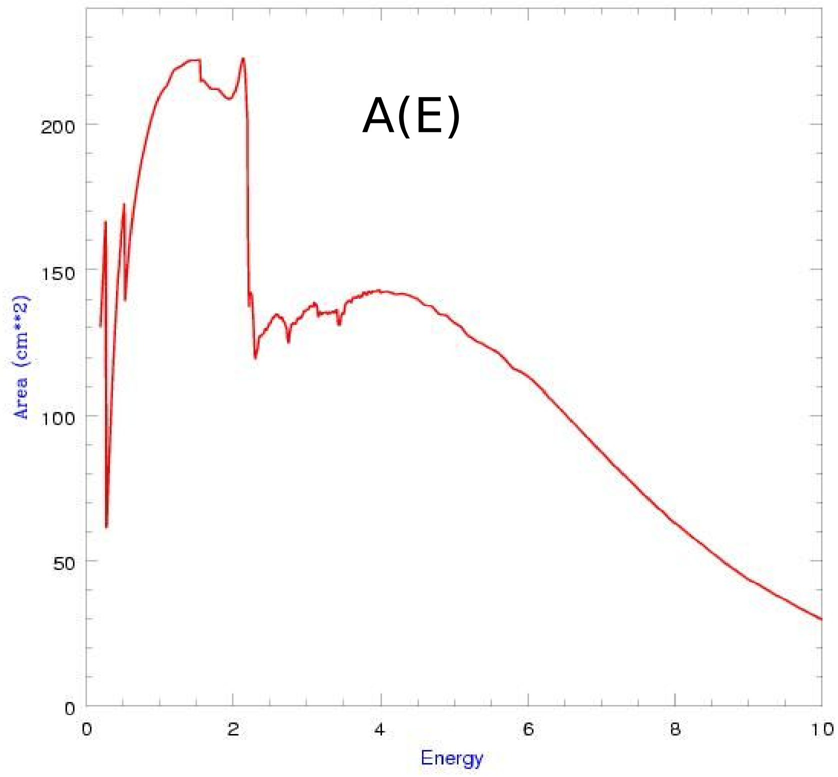
With less than 100 counts, we usually just use count ratios (X-ray colors) for spectral analysis.

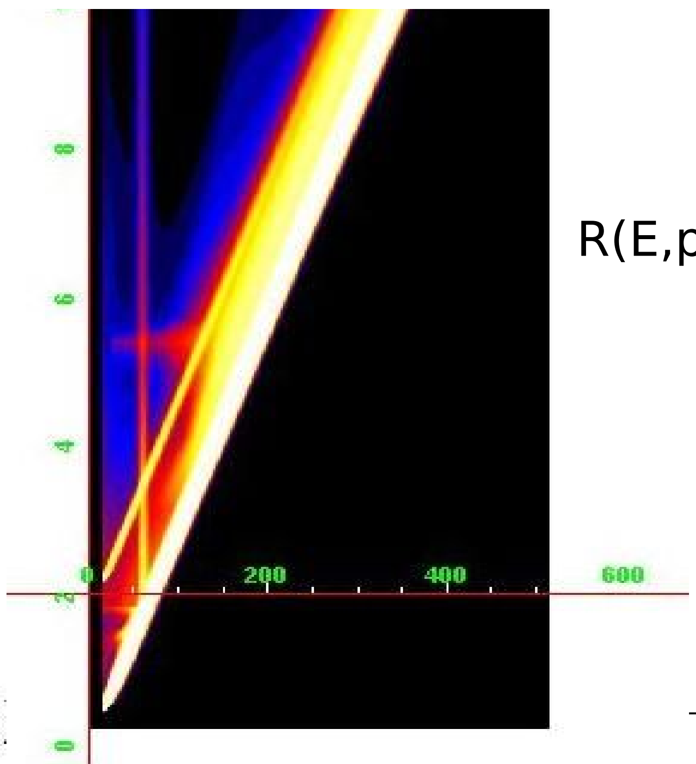
Does one model fit significantly better than another? Be careful that two physically different models may look quite similar in F(E) space.

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.

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







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.