Introduction to X-ray Astronomy

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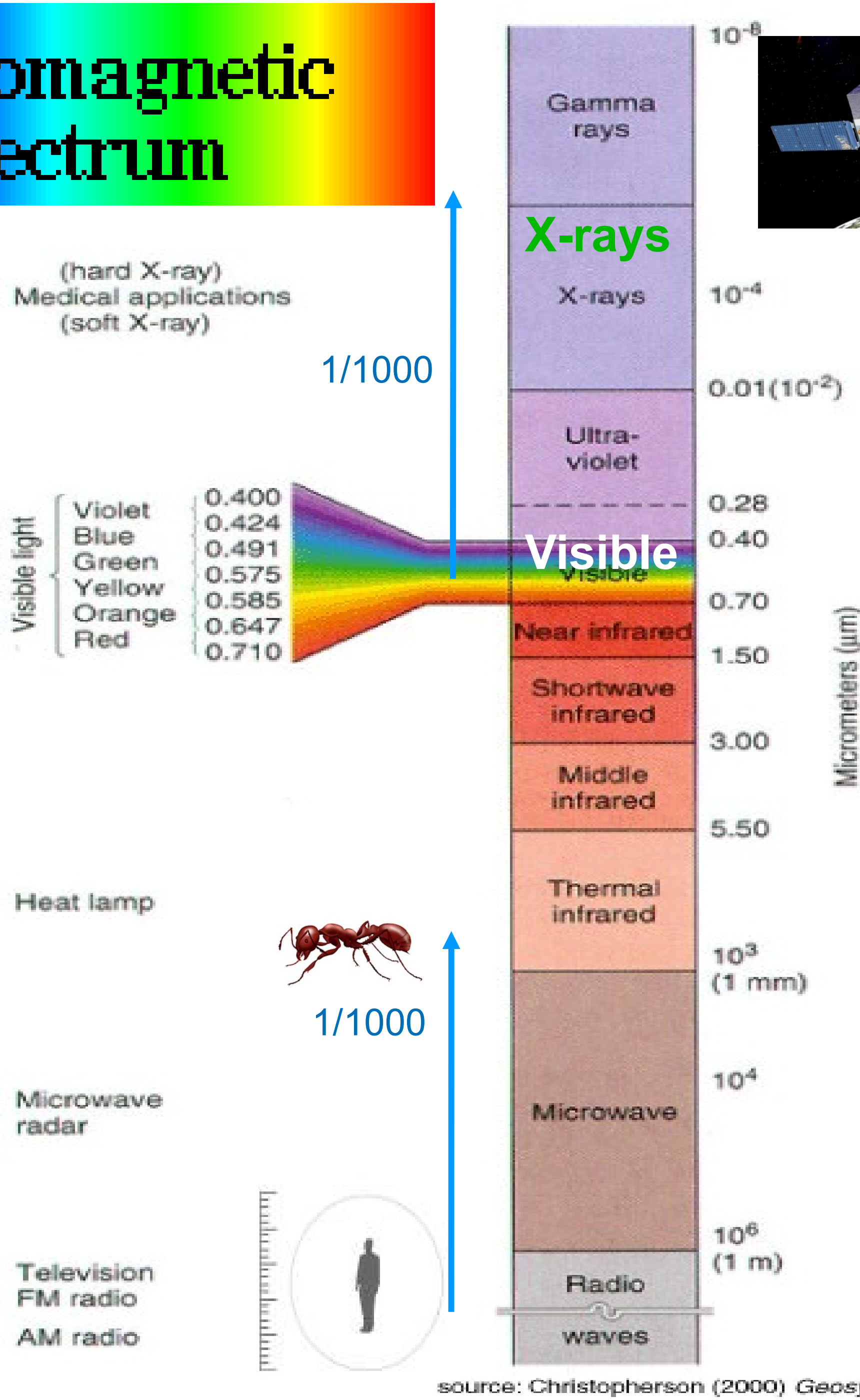
We are now in the era of multiwaveband astronomy

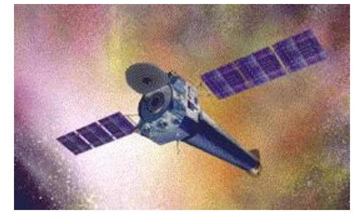
Electromagnetic Spectrum

10^{15} range of wavelength in astronomy

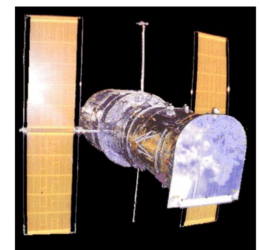



Whipple 10 meter

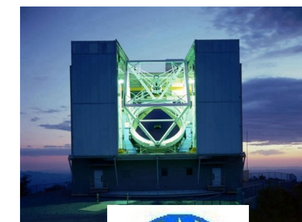
Fermi gamma-ray Observatory



Chandra

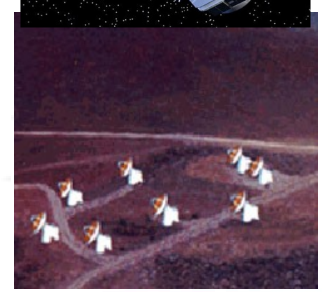


Hubble

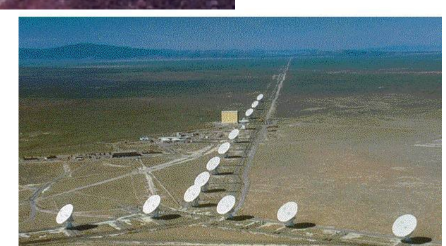


MMT

Spitzer



Sub-millimeter array



VLA

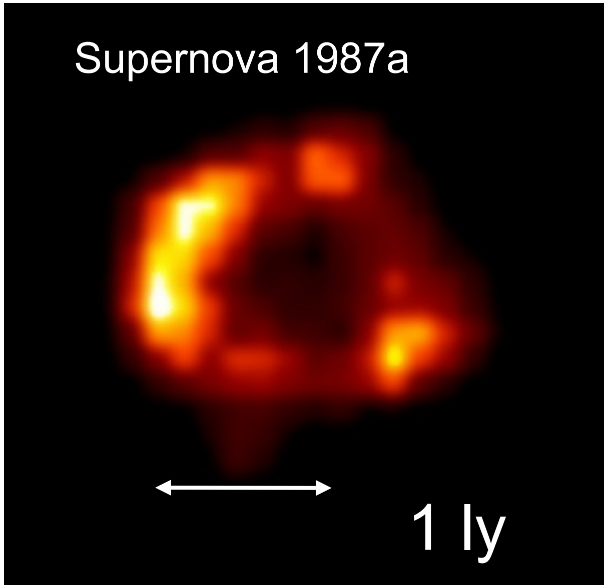
Sources of X-rays

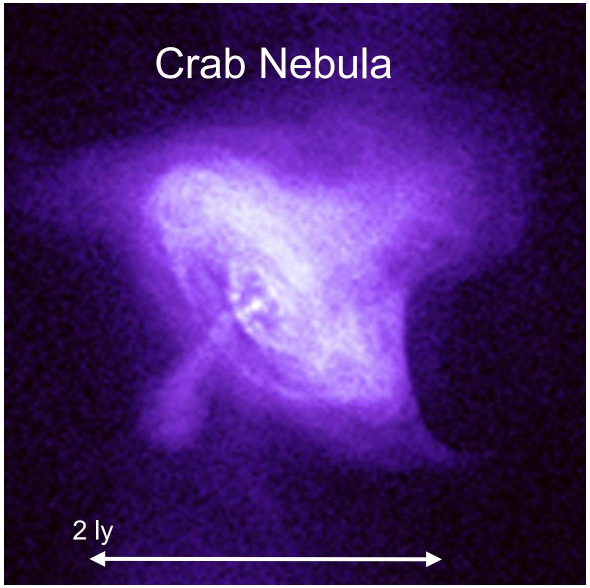
- Shock waves in plasma (ionized gas)
- "Synchrotron" caused by energetic particles in magnetic fields (like a natural particle accelerator)
- Energy release from gravity ("accretion" power)

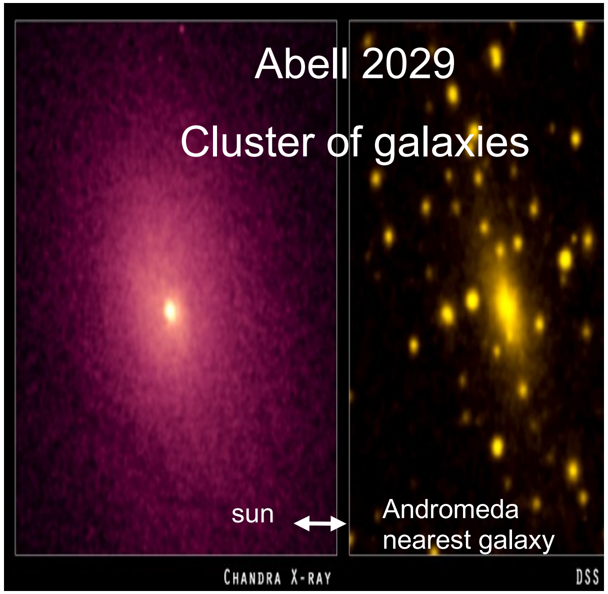
Explosions: Supernovae and their remnants

Particles moving near the **speed of light in magnetic fields**

Matter falling into **deep gravitational wells**





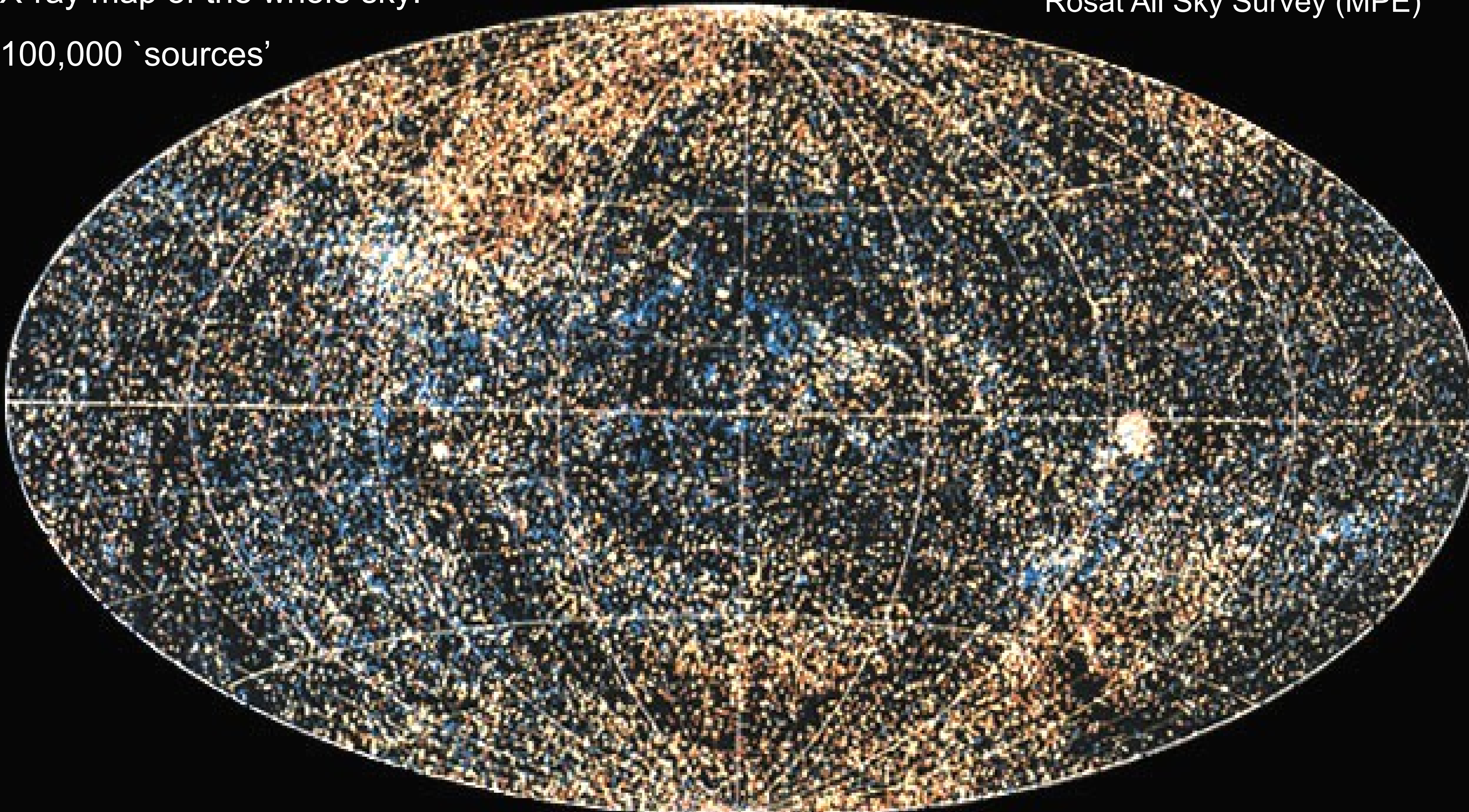


Powerful sources of X-rays

X-ray map of the whole sky:

100,000 `sources'

Rosat All Sky Survey (MPE)



A power source entirely different from the nuclear fusion that drives the Sun and stars

…and much more efficient

The Chandra X-ray Observatory

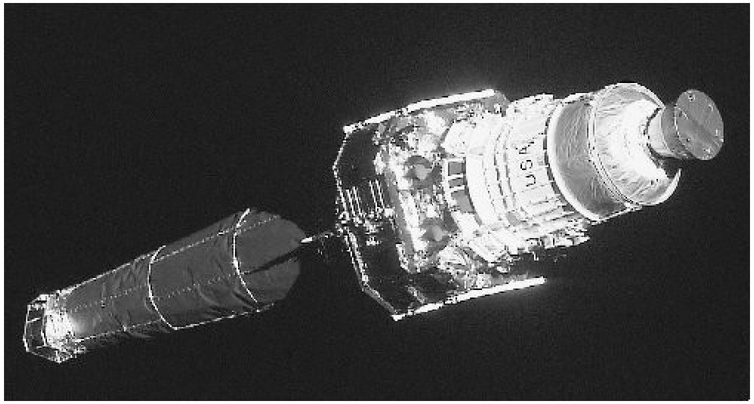
Launched 26 years ago 23 July 1999

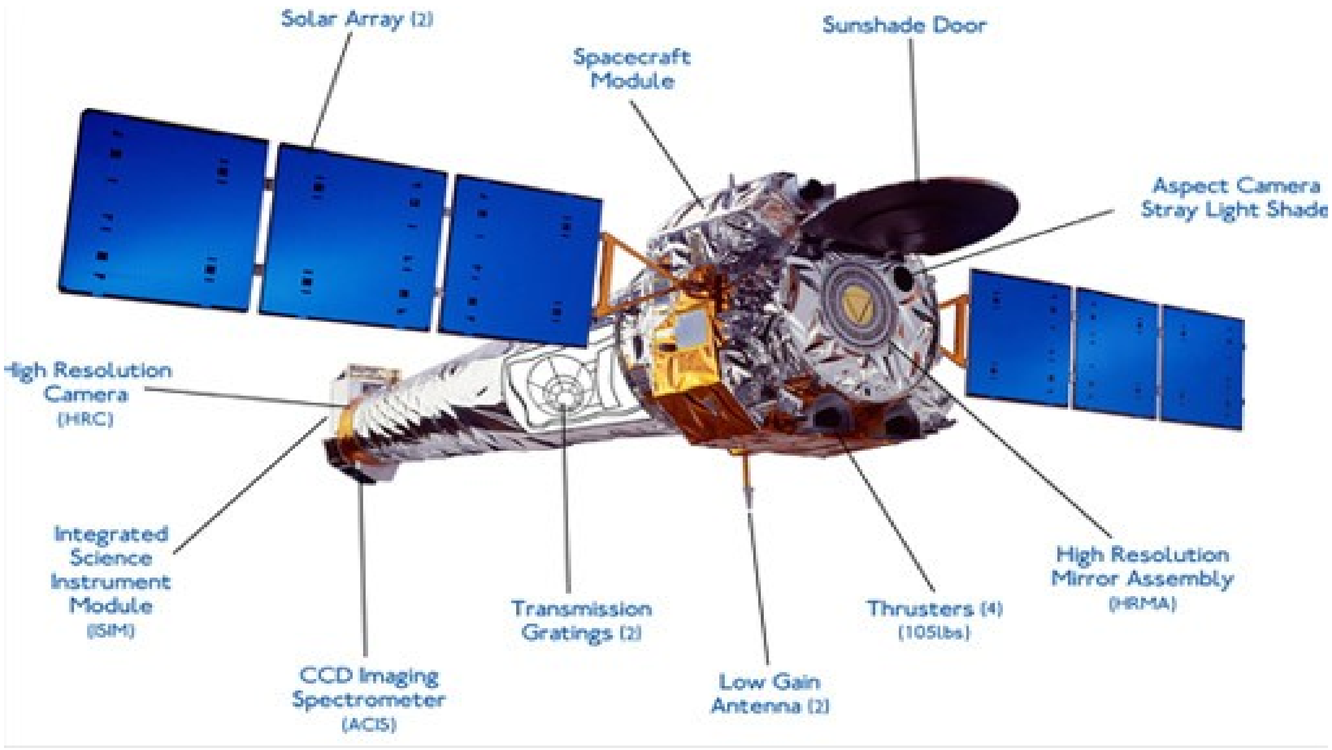
A revolution in X-ray astronomy

and astronomy in general

Chandra

- Highest-spatial-resolution X-ray telescope
- Launched July 1999 – still doing great science!
- Operated by the Chandra X-ray Center (Cambridge, MA, USA) – includes support for worldwide users.
  - Our goal is to make it easy for “non X-ray” astronomers to get science done with Chandra





5 tonne spacecraft in 1411 x 147395 km x 38.5 deg orbit

Cameras:

ACIS (Advanced CCD Imaging Spectrometer)

HRC (High Resolution Camera)

Chandra Detectors 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 ~0.5-7 keV

HRC-I and HRC-S: High Resolution Camera

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

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

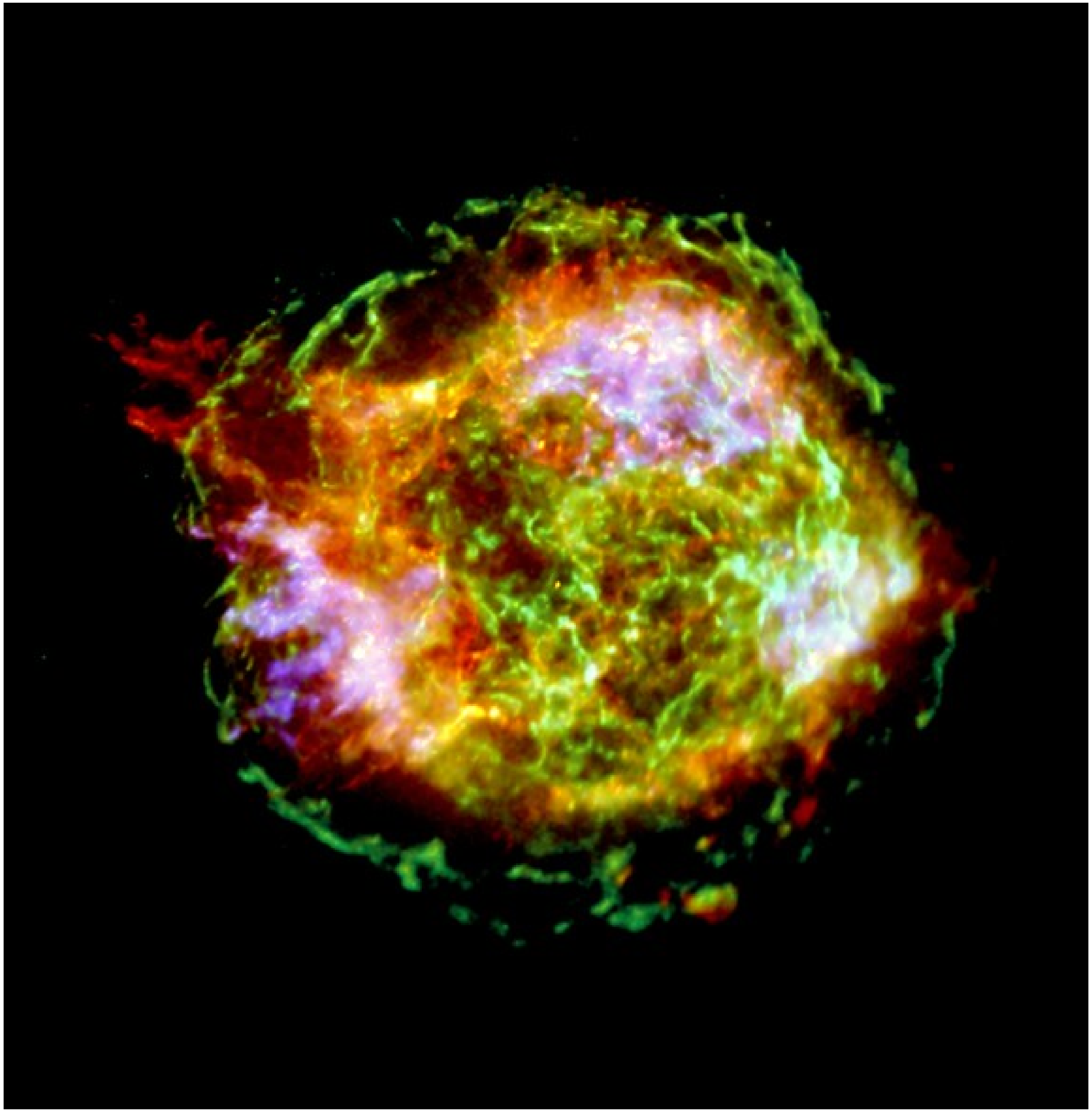
What Chandra can do

- Deep searches for photometry and astrometry of faint point sources
  - ACIS Imaging Mode (ACIS-I or ACIS-S)
  - ACIS-S slightly superior in low energy response, but not much to choose from these days
  - ACIS-I has bigger field of view
- Integral field spectroscopy of bright extended sources
  - ACIS-I FOV is 16' x 16' (but spatial resn degrades off-axis)
  - Each pixel has spectral resolution R about 50-100
  - Background per pixel is low
- High resolution spectroscopy of bright point sources
  - HETG (High Energy Transmission Grating)
  - Resolution E/dE = 1000 at 1 keV
  - Energy range 0.4-10 keV
  - Measure equivalent widths, line centers

A sampling of Chandra science..

- I will concentrate on results from the ACIS X-ray CCD imager
- Lots of great results from high resolution transmission gratings, addressed in a later talk

Cas A – fresh elements



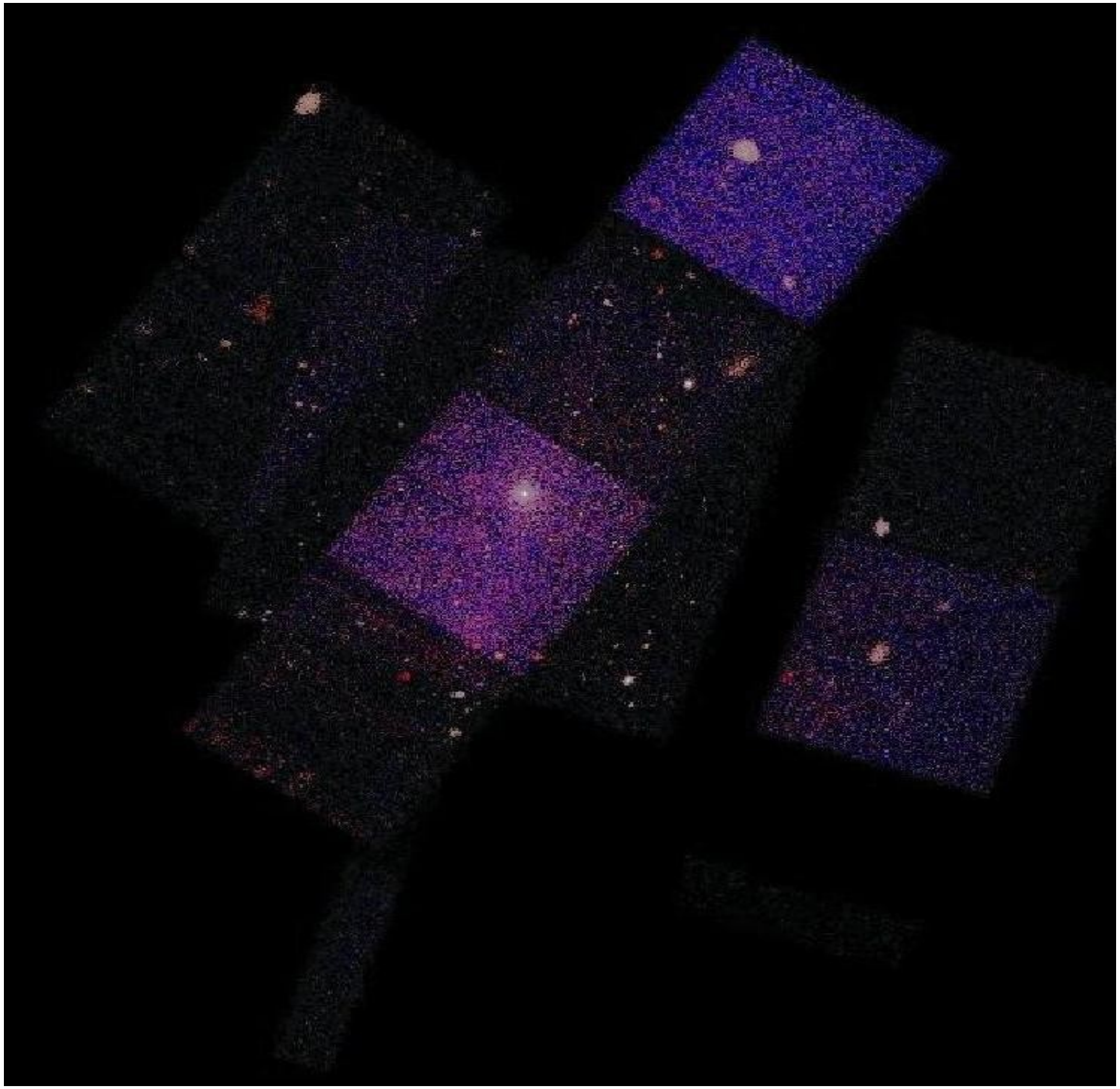
Green: continuum shock

Red: silicon line

Blue: iron line

Hwang et al 2004

M33 – compact populations



X-ray binaries
Supernova remnants
Hot gas in HII regions

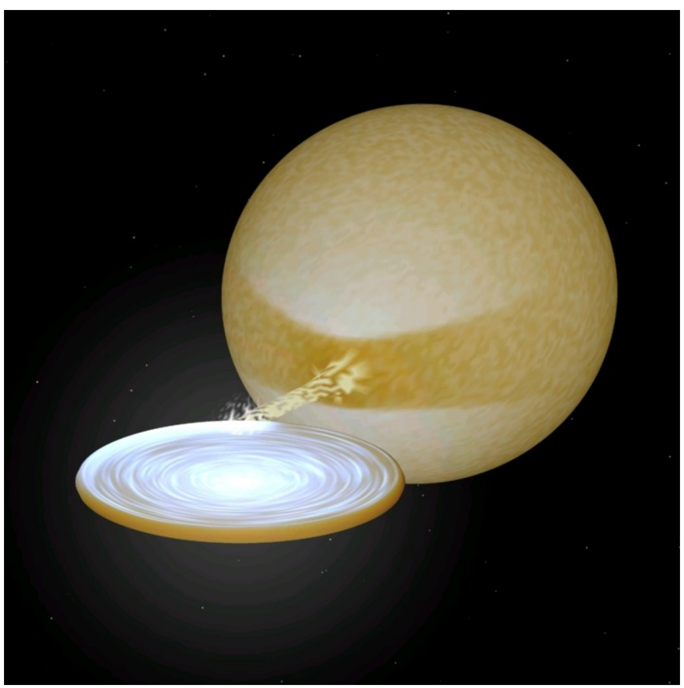
McDowell et al 2002,
Grimm et al 2005

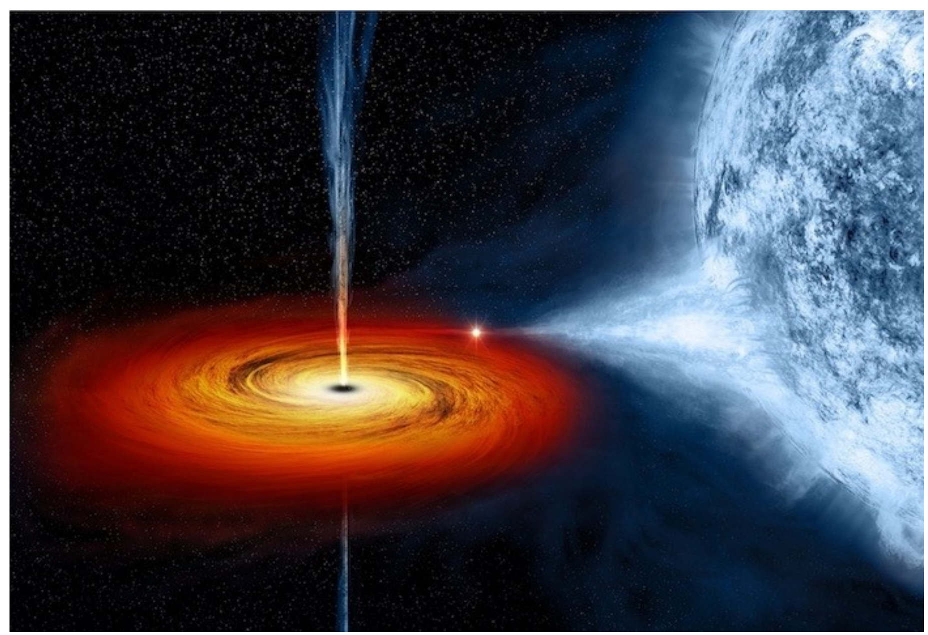
Nearby galaxies in the X-rays

LMXBs (low mass X-ray binaries) trace the older population. Roche Lobe overflow of MS star
HMXBs (high mass X-ray binaries) the current star formation. Wind capture from supergiant

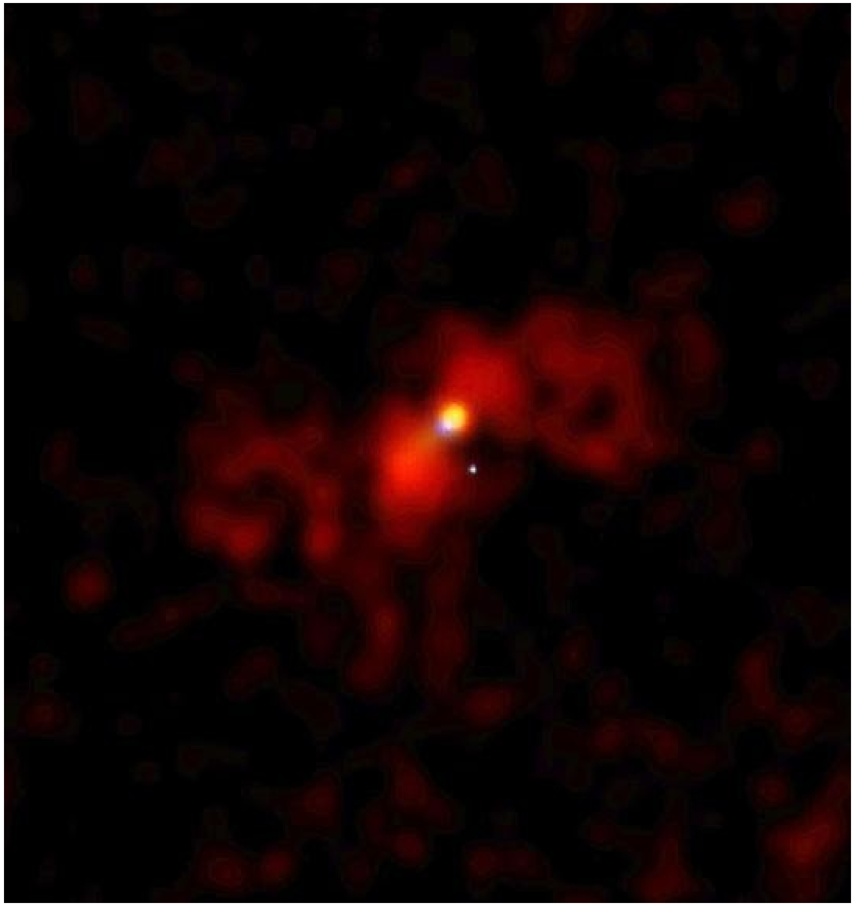
These are mostly log(Lx/erg/s) ~ 35 to 38

ULX (ultraluminous X-ray sources, log(Lx)>=39) are still a bit mysterious – mixture of beamed jets and intermediate-mass black holes?

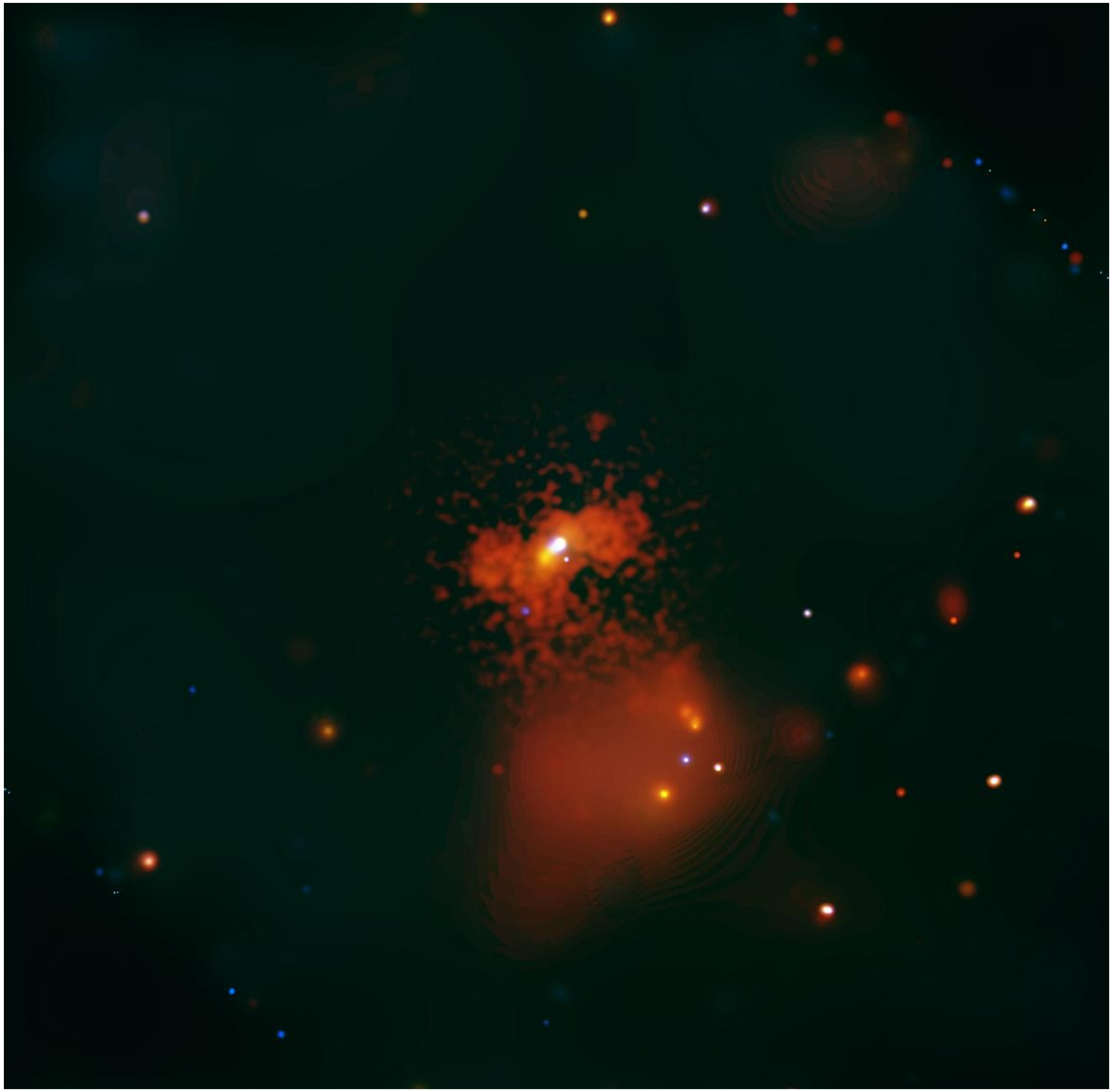




Merging galaxies



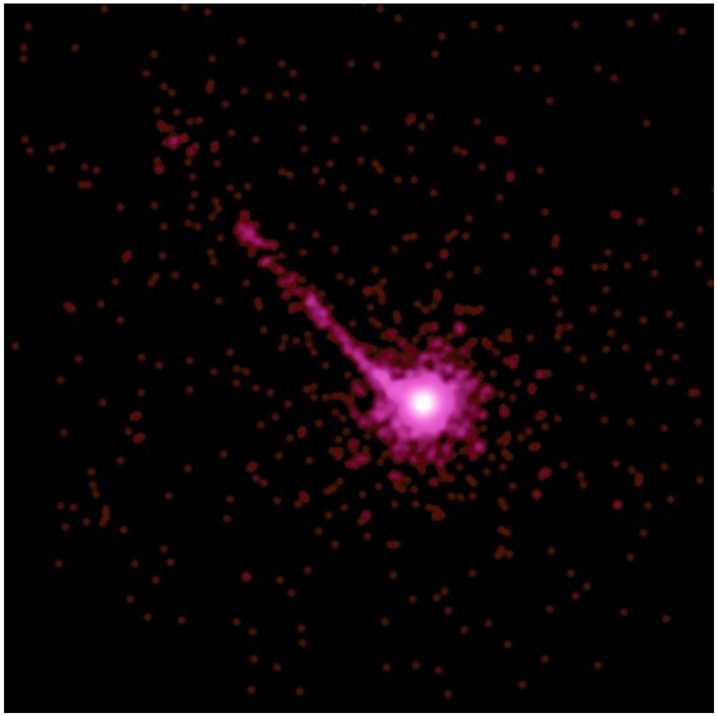
Arp 220 – merging galaxy
McDowell et al 2003



Shocked hot gas at 1-10 million degrees
Hot gas in starbursts
Ultraluminous X-ray binaries

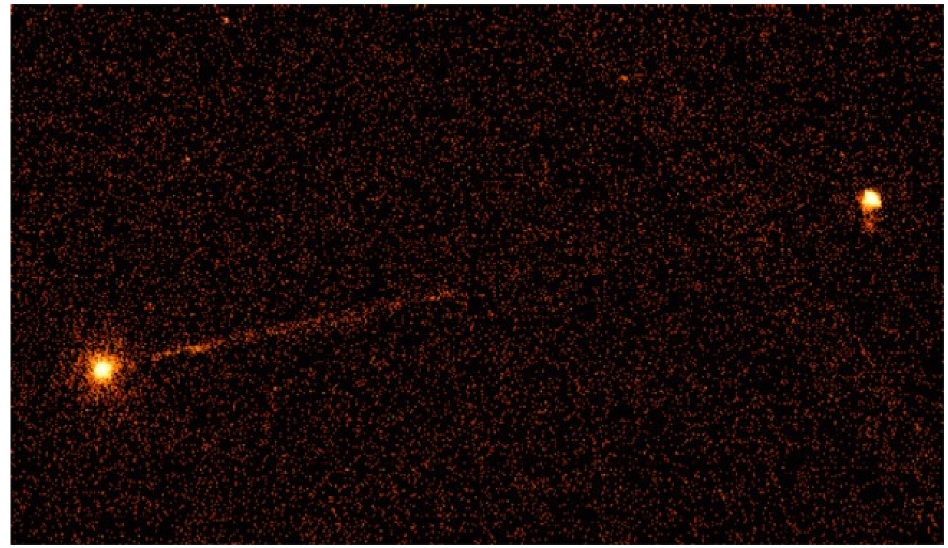
Background galaxy cluster: hot gas

AGNs with Jets

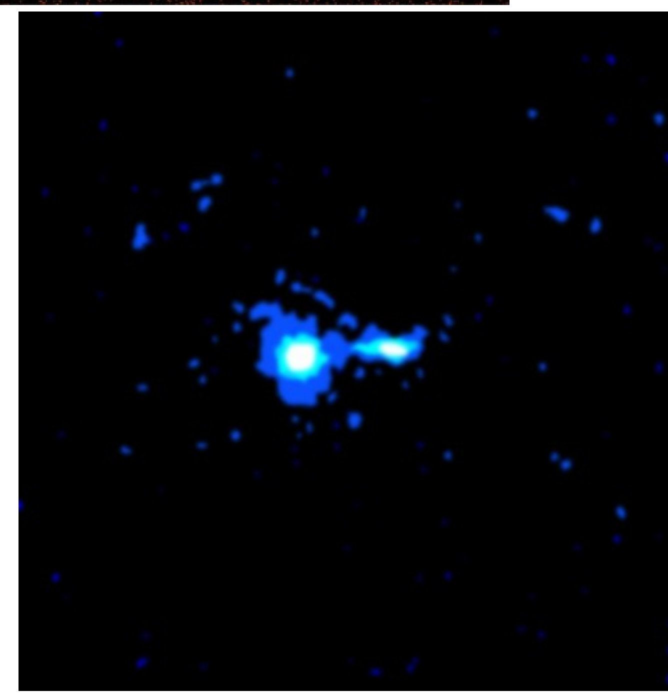


PKS 1127-145 - Siemiginowska, Bechtold

Pictor A - Wilson



PKS 0637-75 - Chandra first focus image

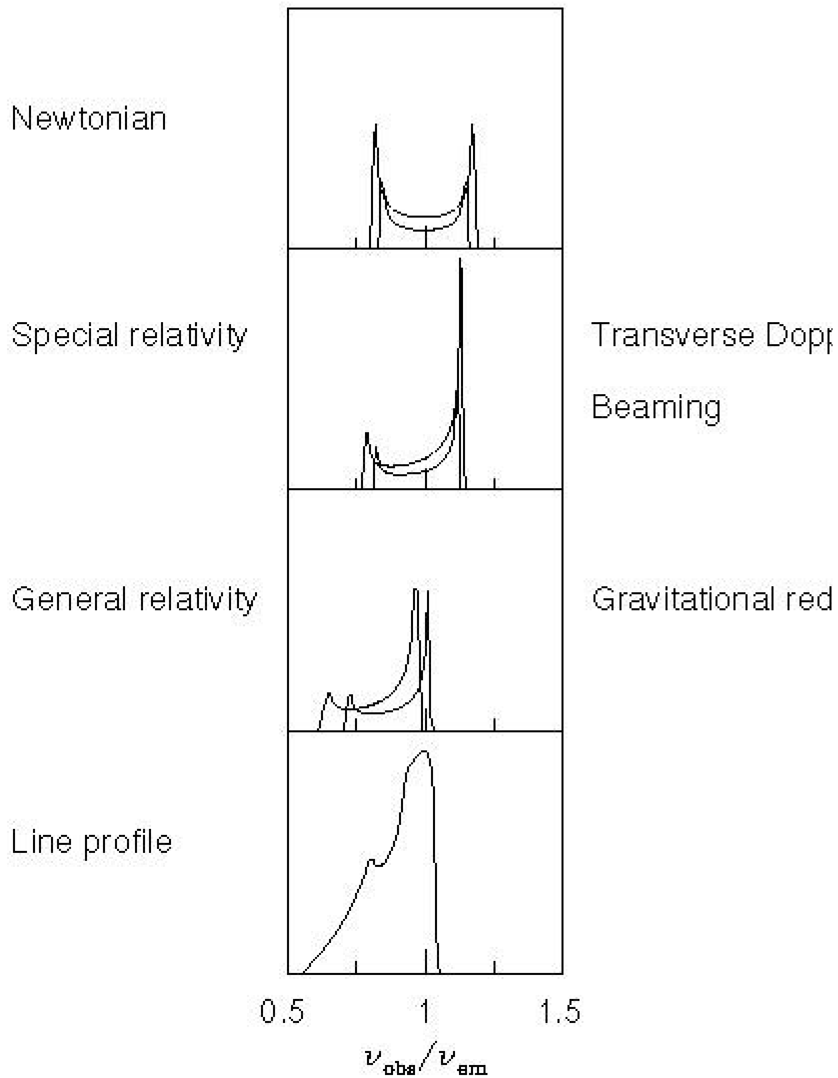


Accretion onto supermassive black holes

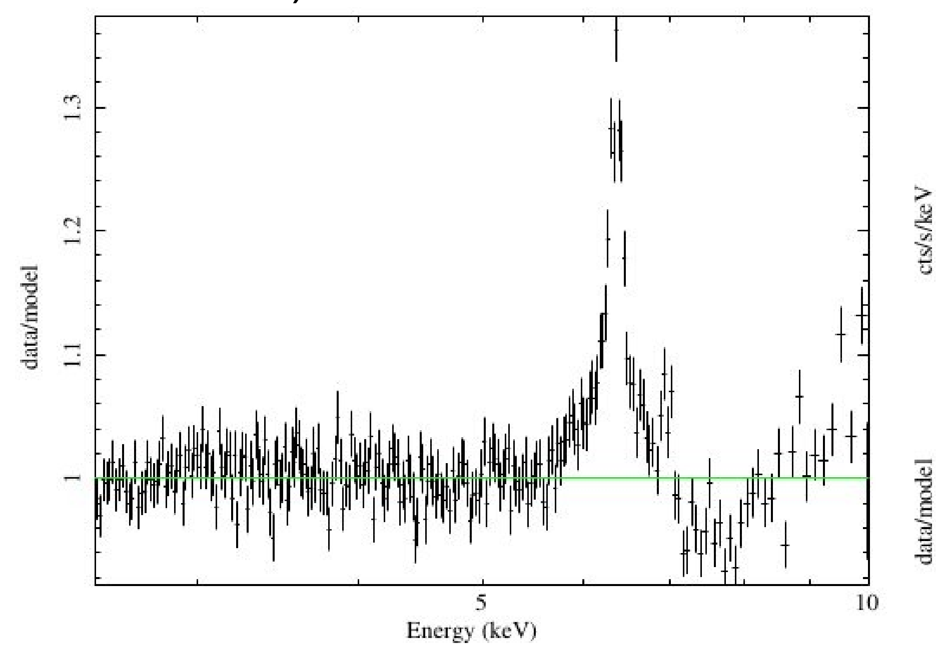
Relativistic particle jets

Active Galactic Nuclei

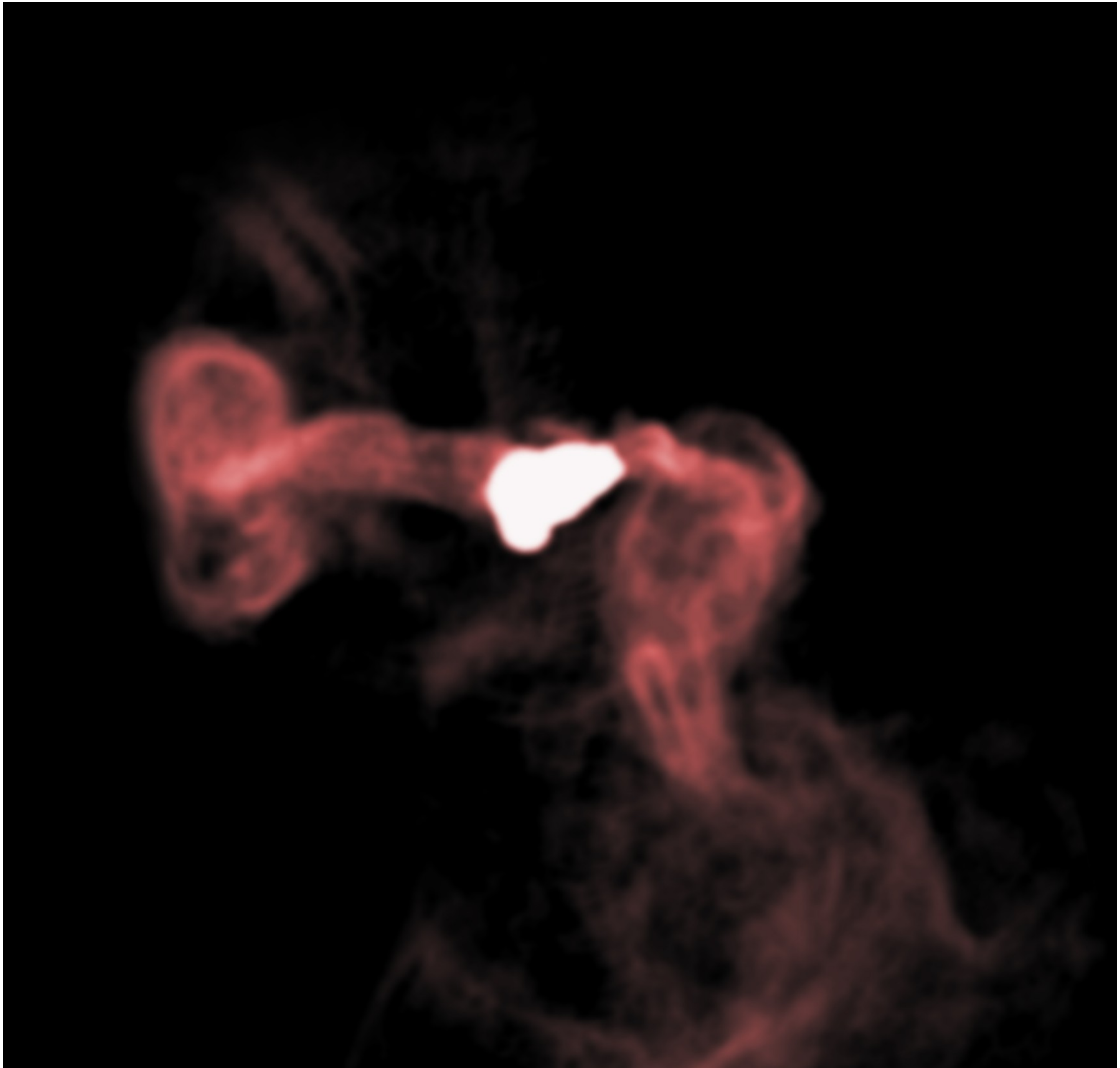
The X-rays in AGN come from gas close to the black hole. We can detect emission from iron atoms: the Fe Kalpha flourescence line. Its spectral shape is distorted by the effects of general relativity!

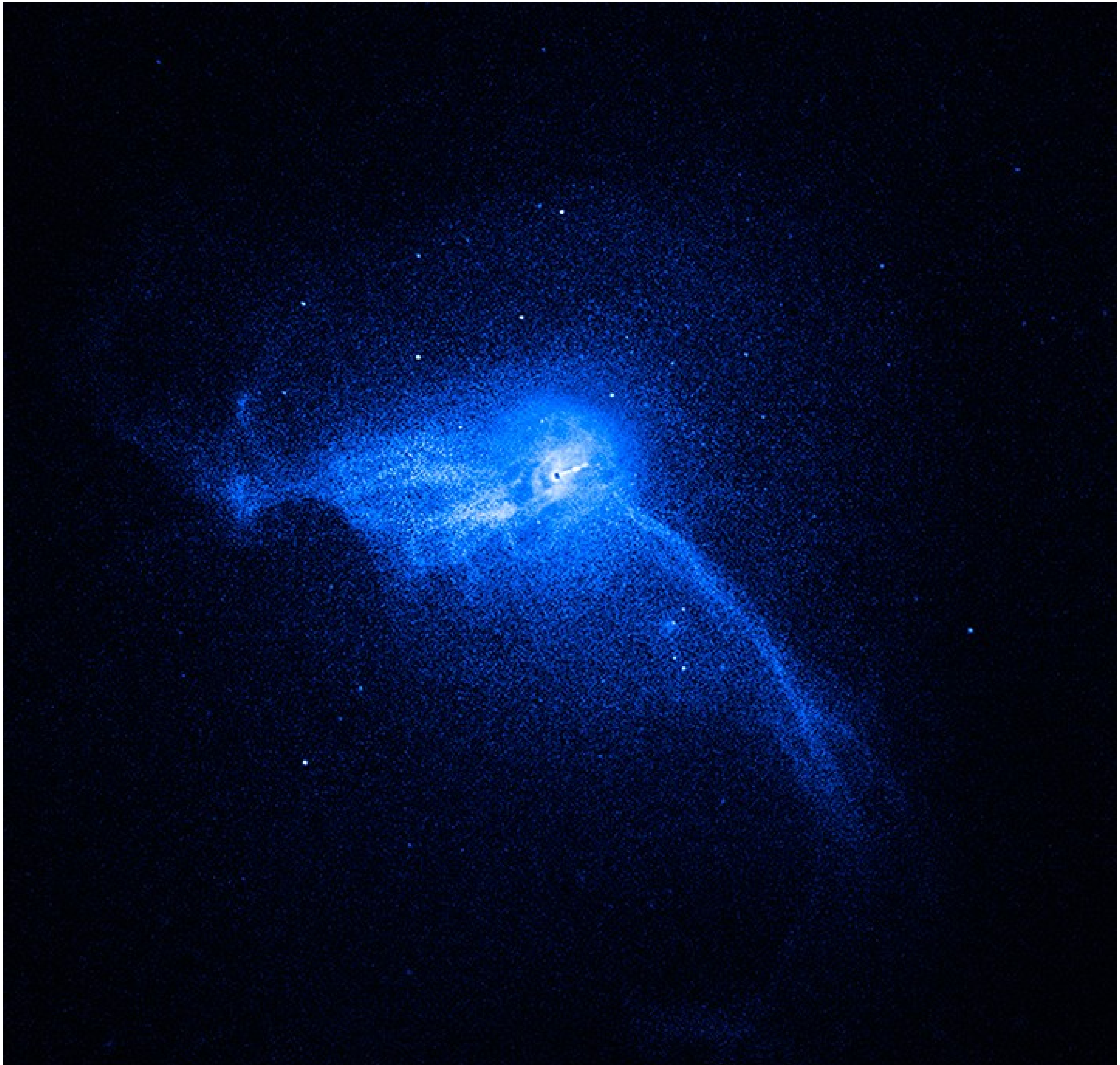


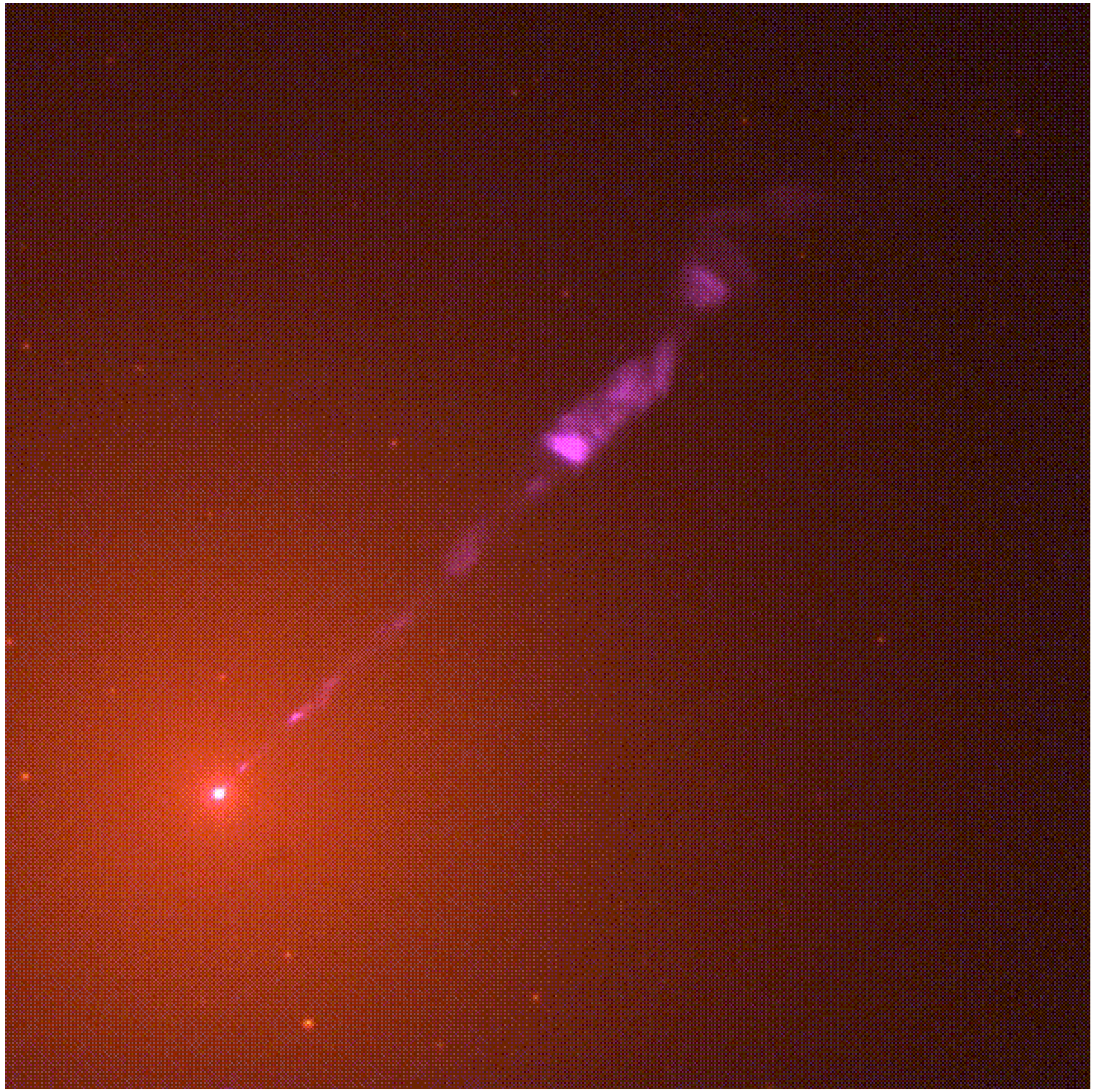
MCG- 5-23-16
XMM spectrum
(Brenneman & Reynolds
2009)

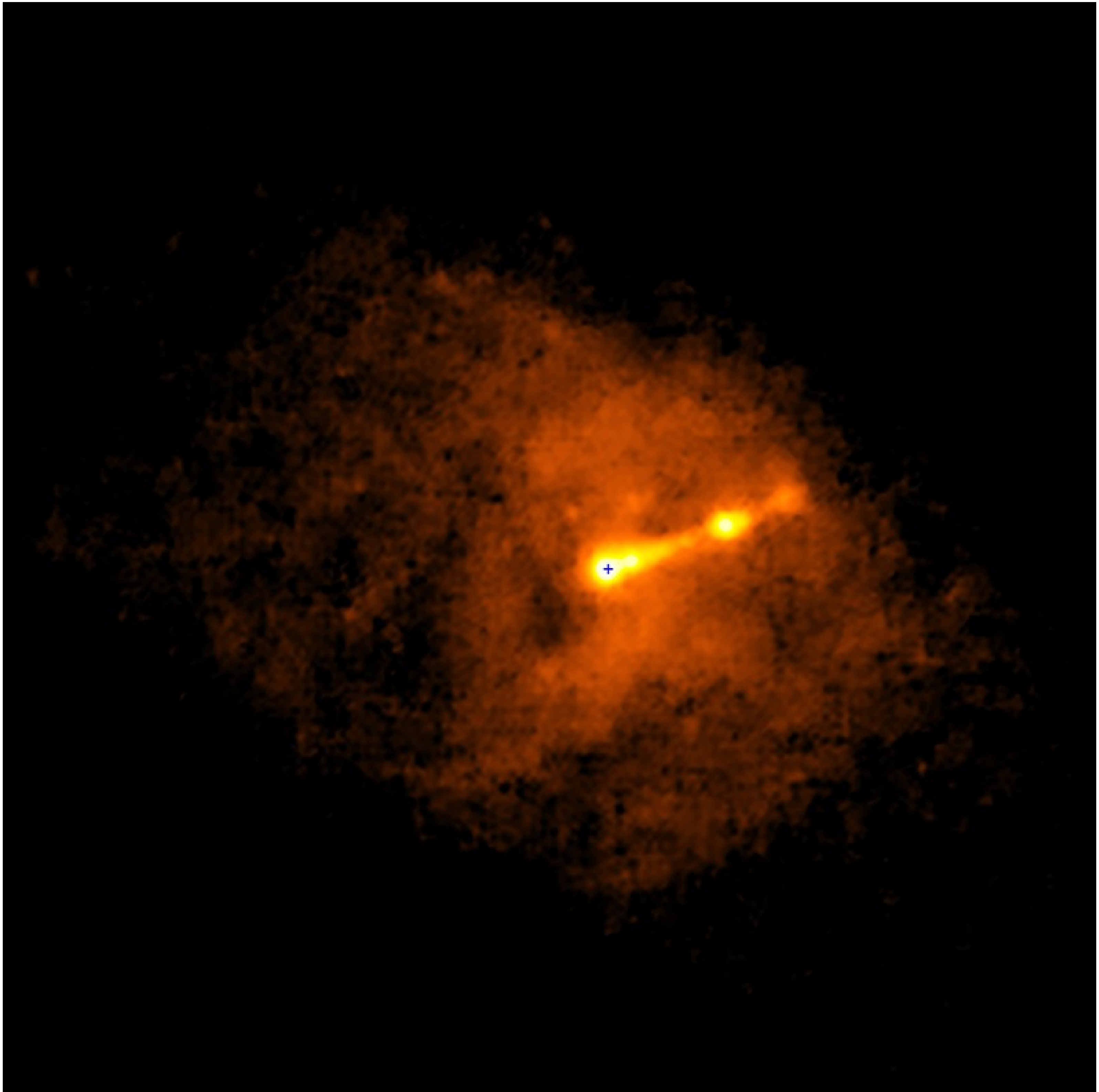


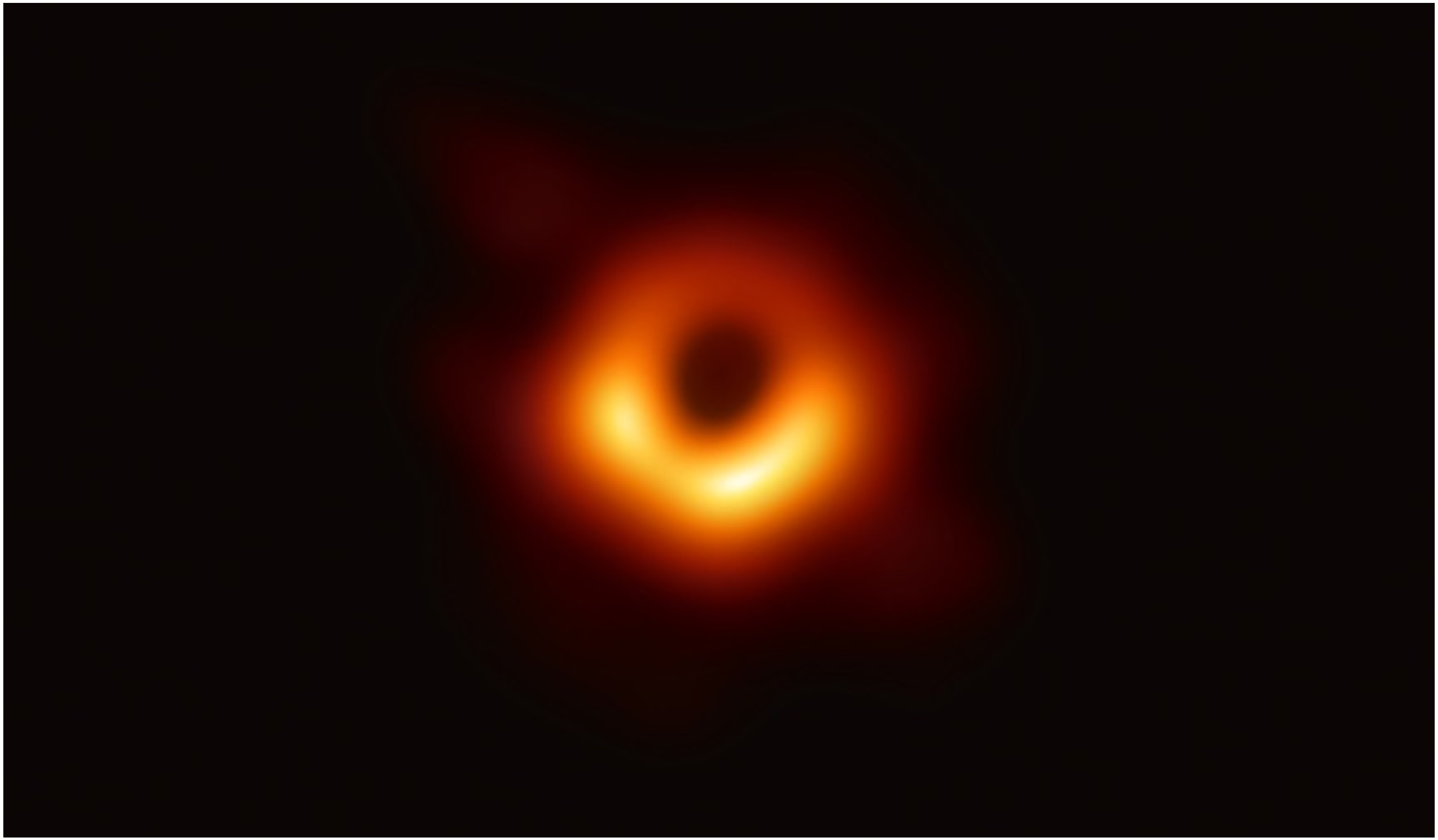
M87 (Messier 87)
Virgo A



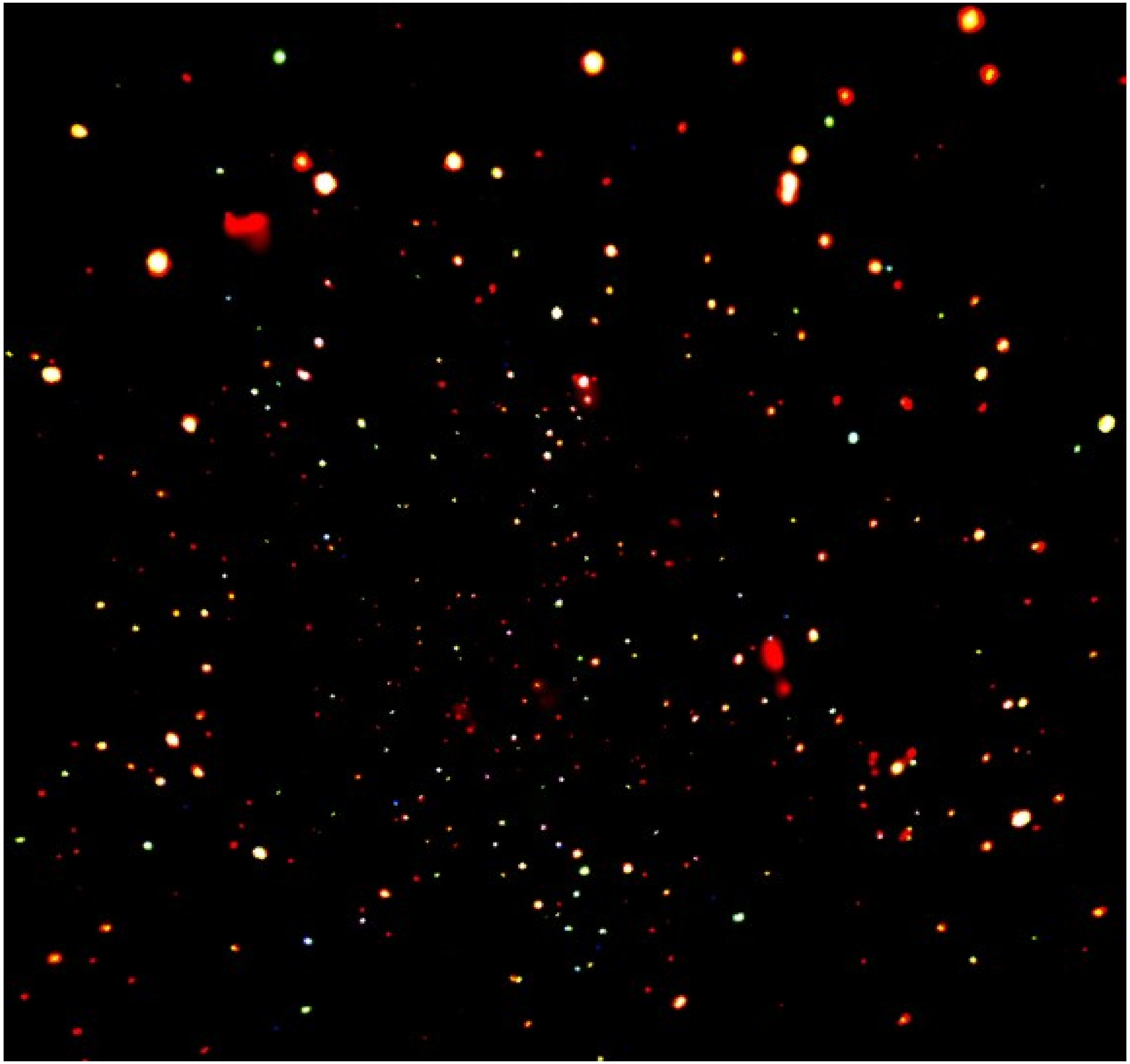








Chandra Deep Field North



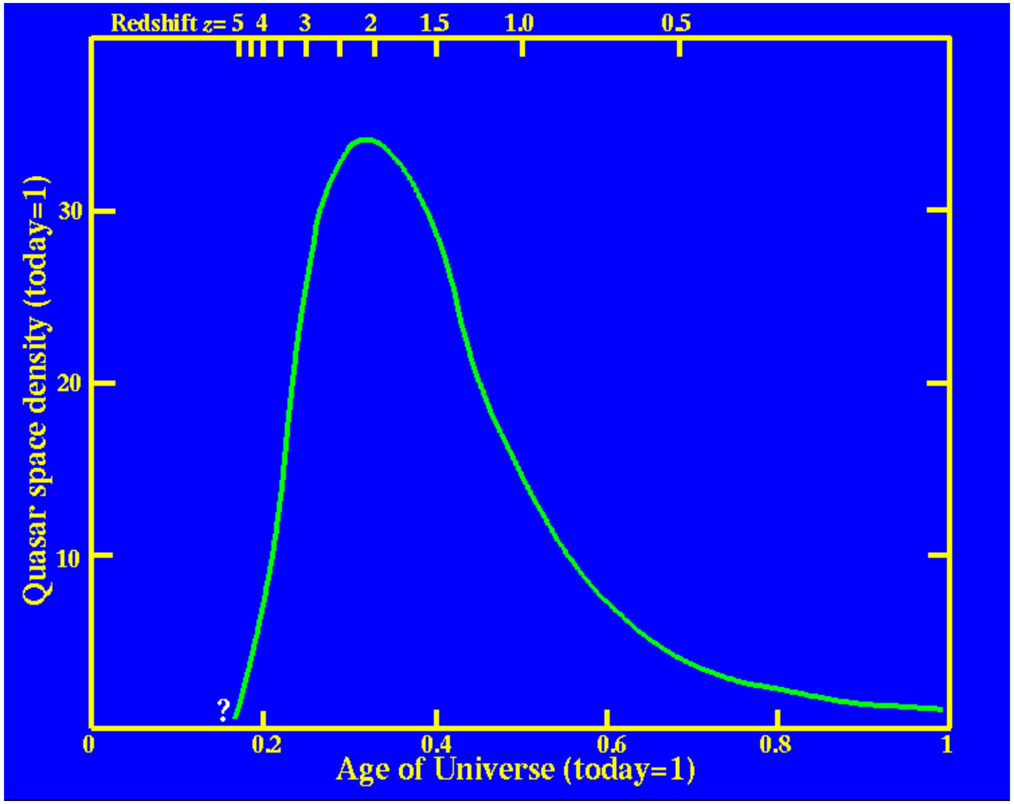
Accretion onto supermassive black holes....

lots and lots of them!

Bauer, Brandt, Hornschemeier, etc
2002-2005

Evolution of AGN

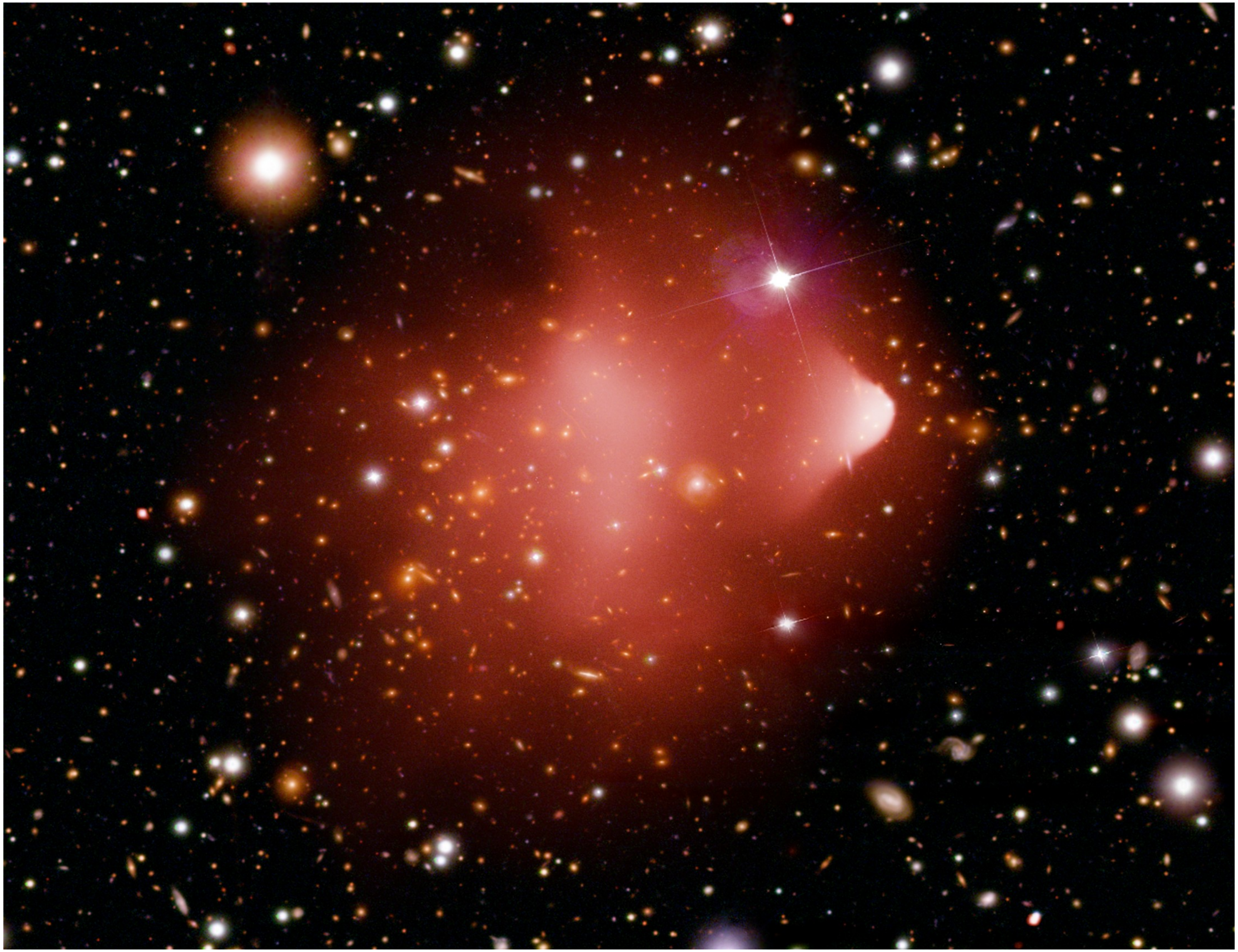
Galactic nuclear activity was much more common, and extreme, in the past. There are many more high-luminosity quasars seen at z=2 than today



Credit: W. Keel

Clusters of galaxies

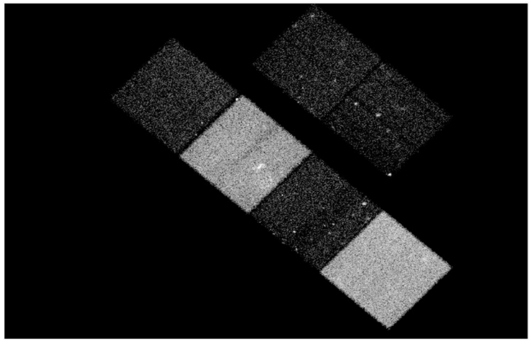
Bullet cluster: merging pair of clusters
Red: X-rays (hot gas)
superimposed on visible-light image of galaxies

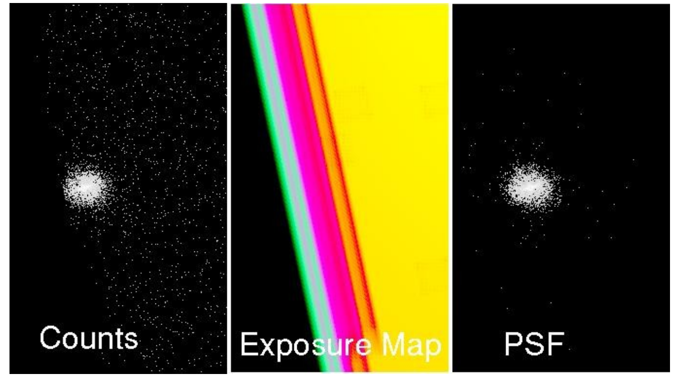


X-ray Data Analysis

Data processing

Standard dataset calibration

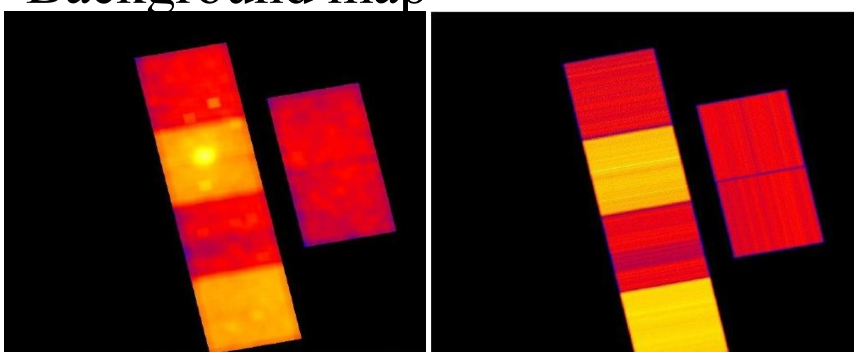




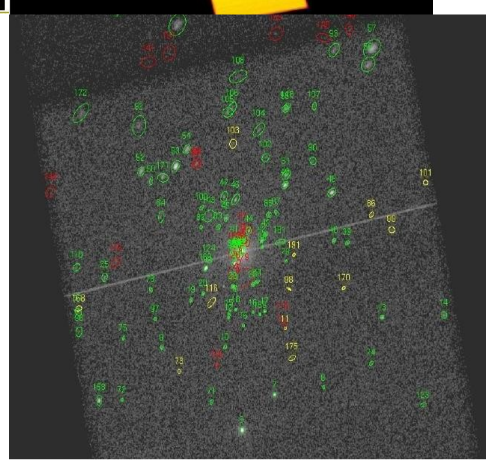
For each source region, we calculate the spatial exposure variation and run our ray trace code to get a model PSF.

Flare removal

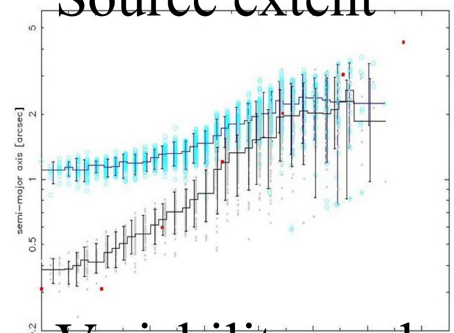
Background map



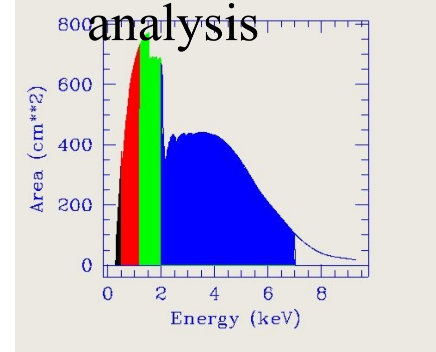
Source detection



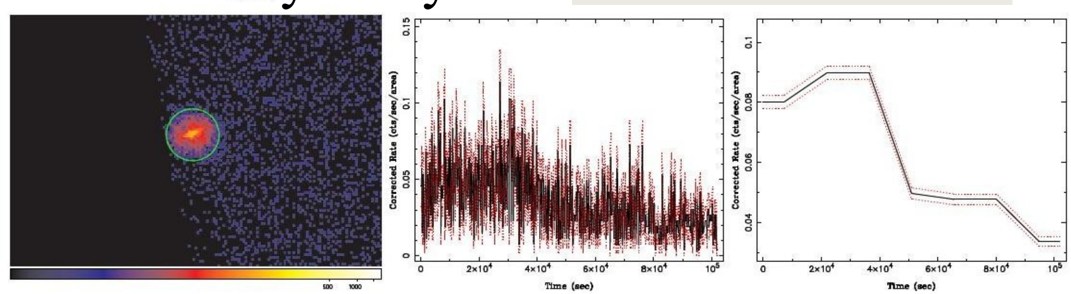
Source extent



Spectral analysis

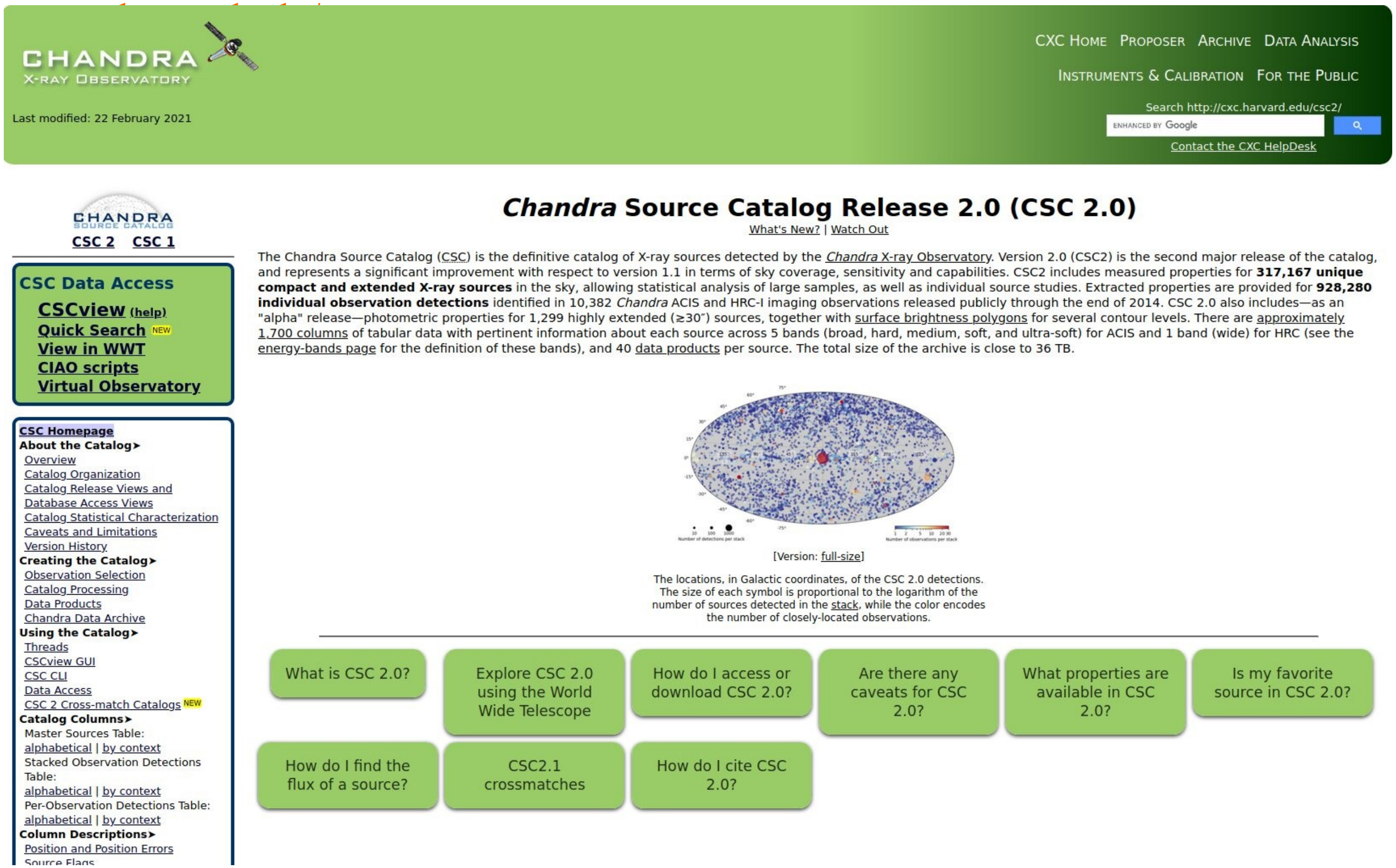


Variability analysis



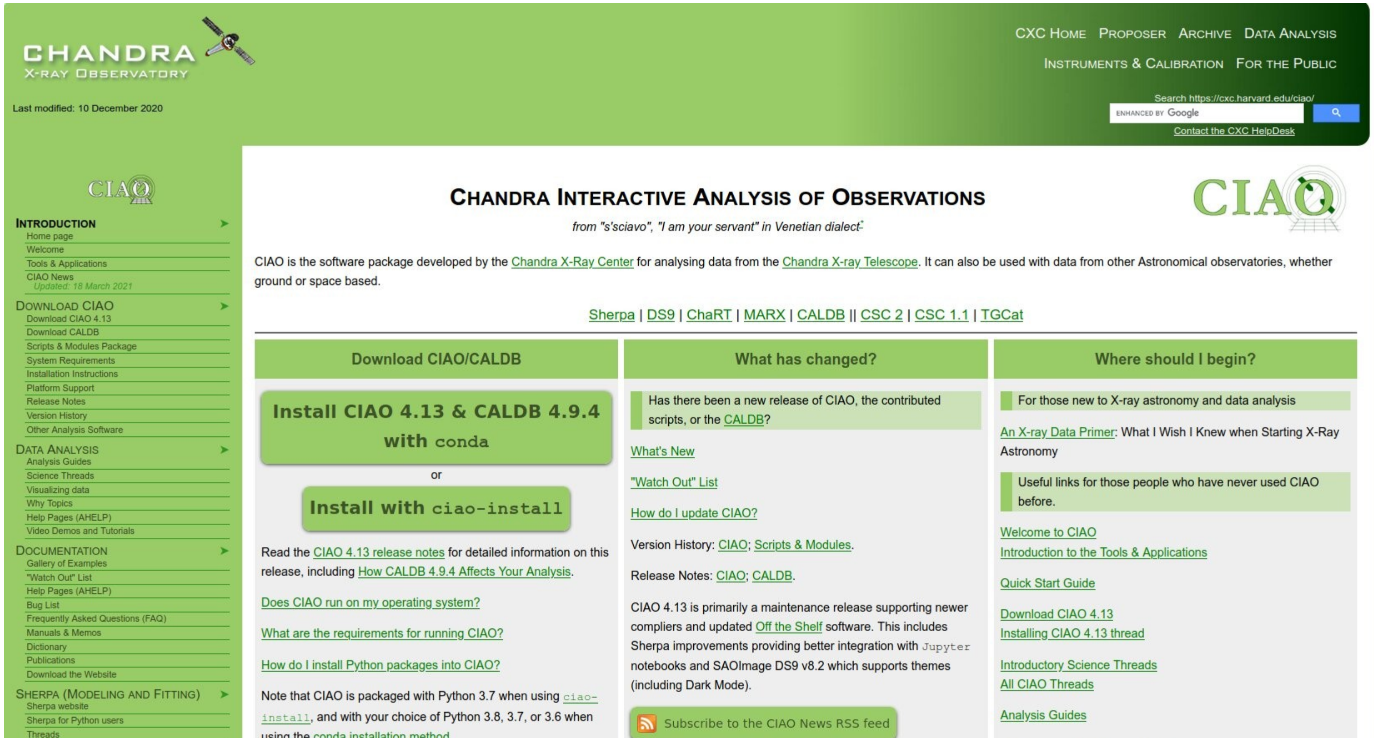
Chandra Source Catalog

- Release 2.0 contains 317167 X-ray sources in data public prior to 2014
- 1 arcsecond absolute astrometry
- X-ray photometry in 3 bands (0.5-1.2, 1.2-2.0, 2.0-7.0 keV)
- Associated data products
-



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



CIAO is:

Free and open source

Runs on Linux or Mac [NOT Windows]

Full install about 9 Gbyte including calibration data

Command line unix tools working on FITS files

Extensively documented!!

The Fundamental Equation of Astronomy:

We observe the sky – a field of incoming light which varies with celestial lon/lat x,y, time t and energy E

$S(x,y,t,E)$

[n.b. Energy, wavelength, frequency, color interchangeable]

Our telescope/instrument/data pipeline gives us a signal as a function of **instrumental** position, time, energy

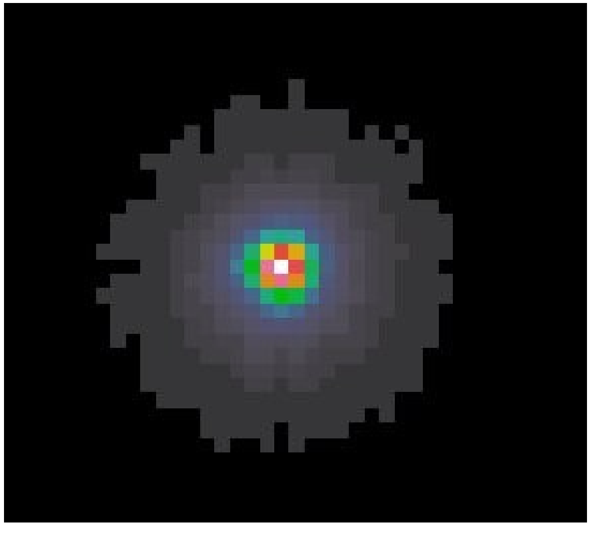
$N(x',y',t',E')$

The observation multiplies S with a sensitvity (“Effective Area”) A and convolves (smears) it with the observational response R

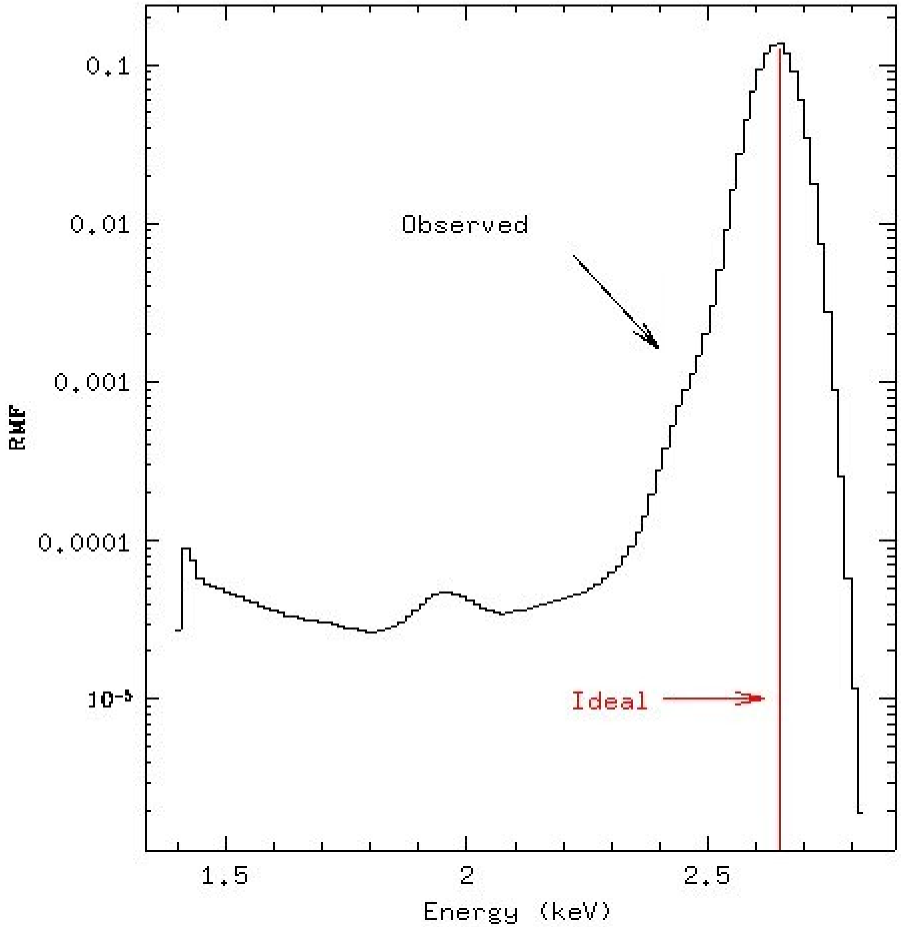
$$N(x',y',t',E') = \int S(x,y,t,E)\, A(x,y,t,E) R(x,y,t,E,x',y',t',E')\, dx\, dy\, dt\, dE$$

Our game is to invert this integral (we want S but we have N). Usually we assume R is separable into (x,y), t, E parts

The spatial response is called the
POINT SPREAD FUNCTION (PSF)
- how much does a starlike point get smeared in the image?

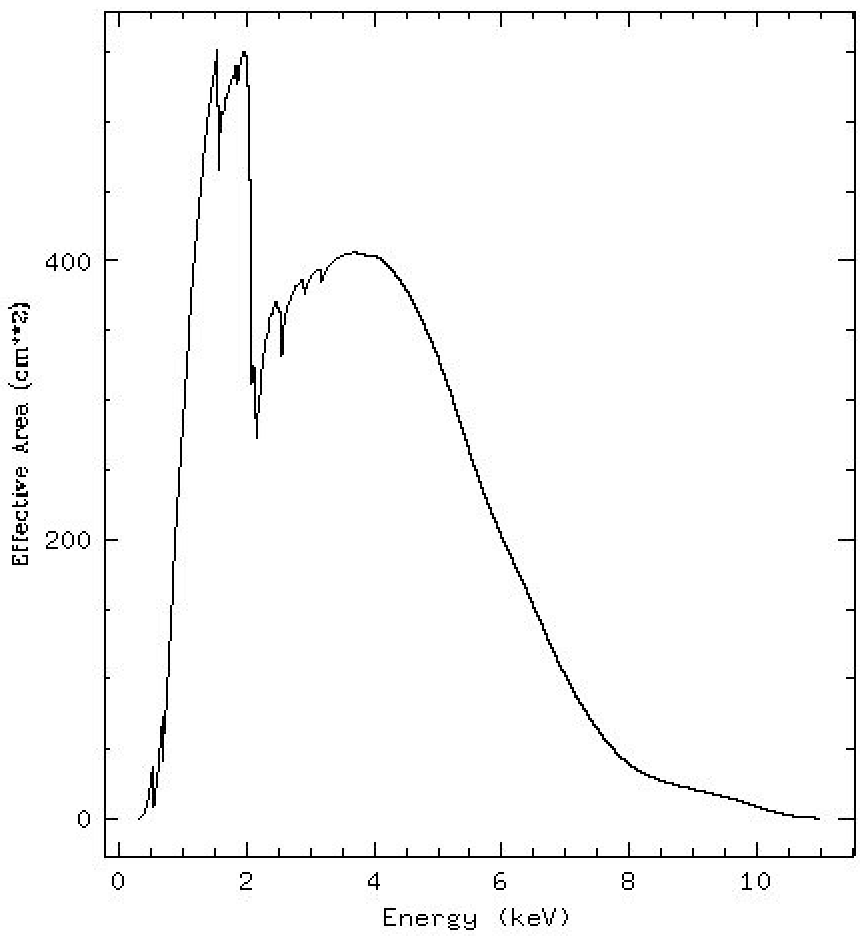


The energy response is called the
LINE SPREAD FUNCTION (LSF)
or, in low spectral resolution X-ray astronomy, the
REDISTRIBUTION MATRIX FUNCTION (RMF)
- how much does a monochromatic color get smeared in energy space?



The sensitivity curve in X-ray astronomy is called the EFFECTIVE AREA (Aeff)

It is the geometric area of the telescope aperture times an efficiency factor (which depends on x,y,t,E)



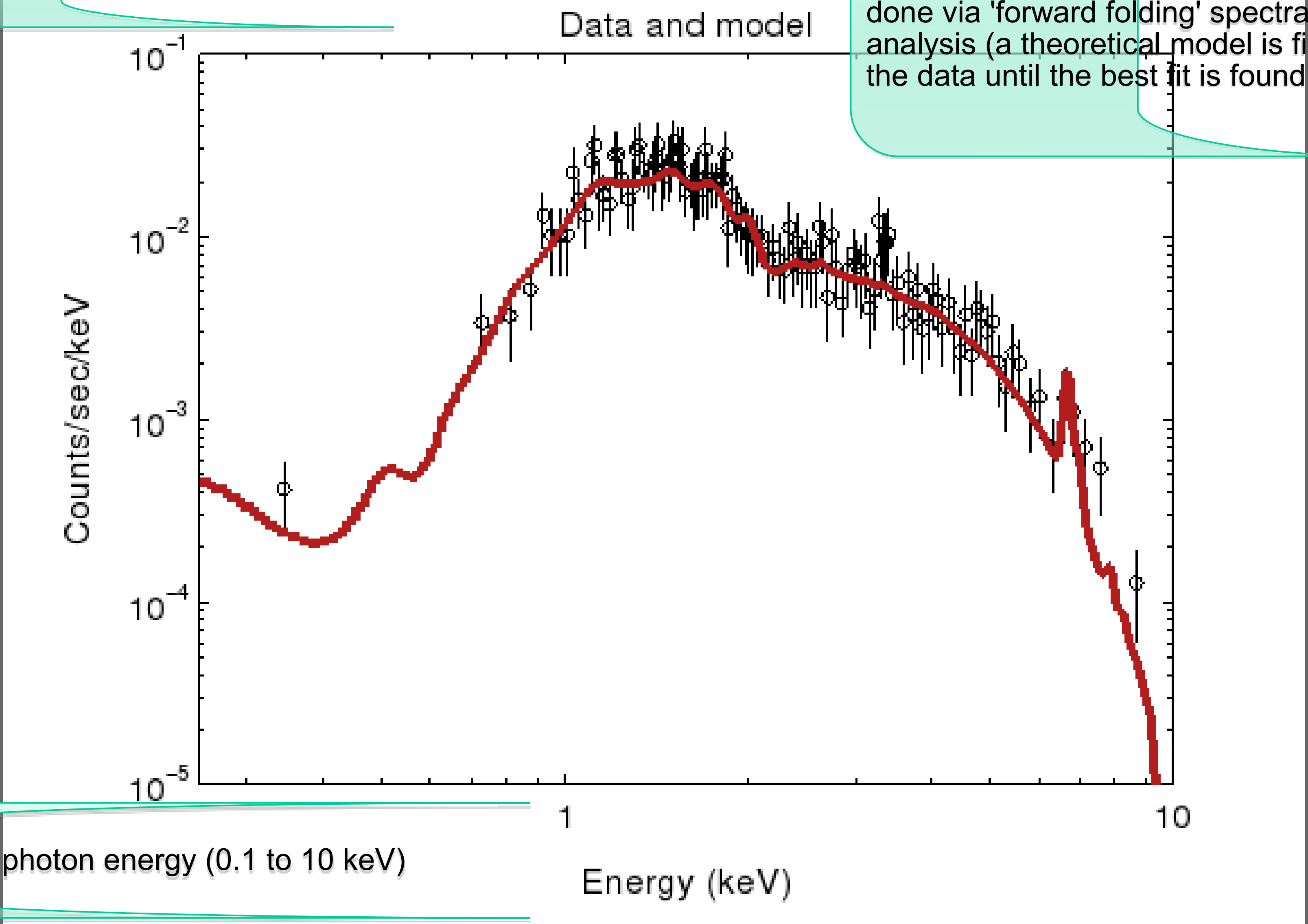
Introduction to X-ray Data Analysis

- 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)

Complexities in X-Ray and Chandra Data Analysis

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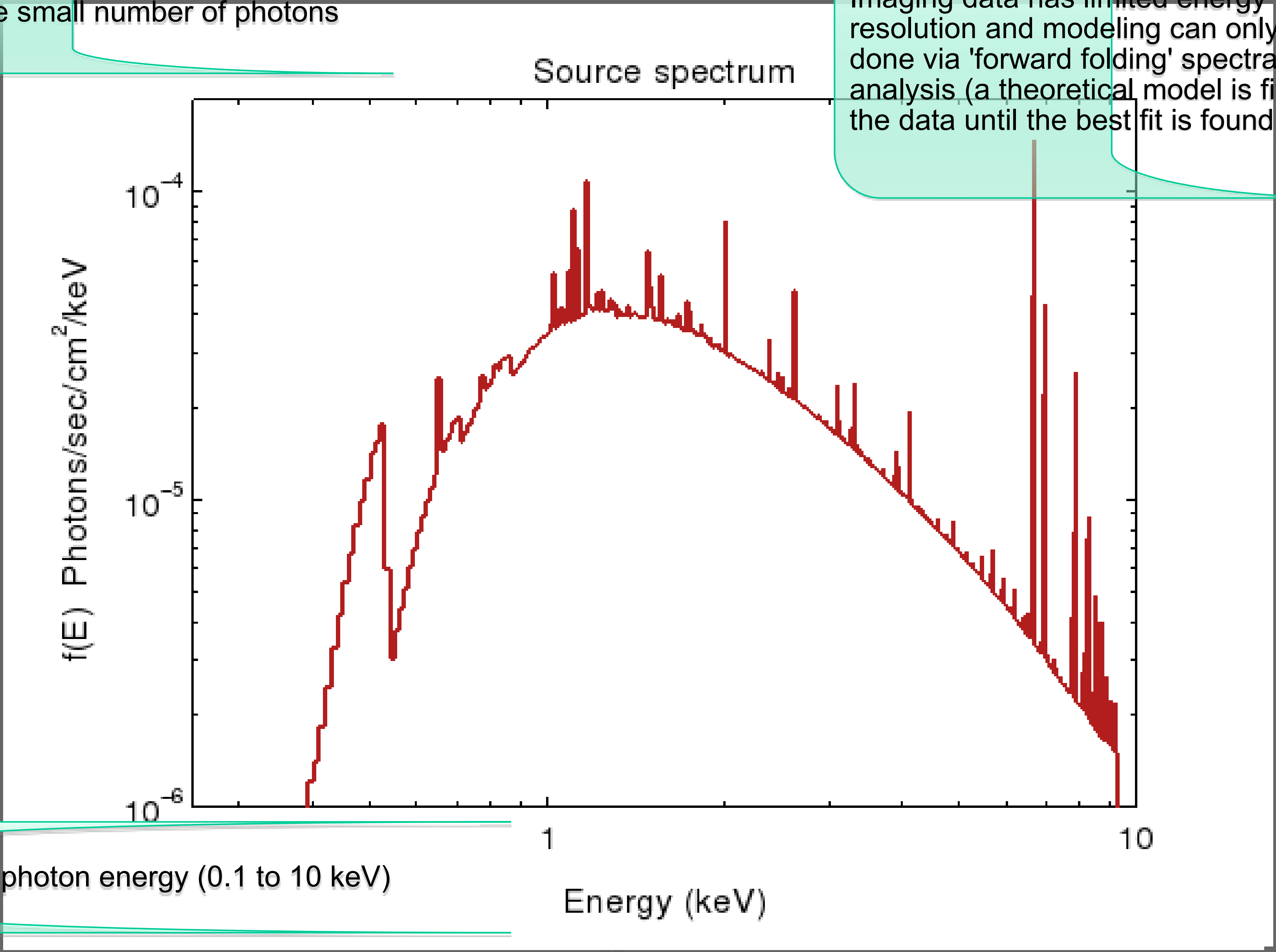


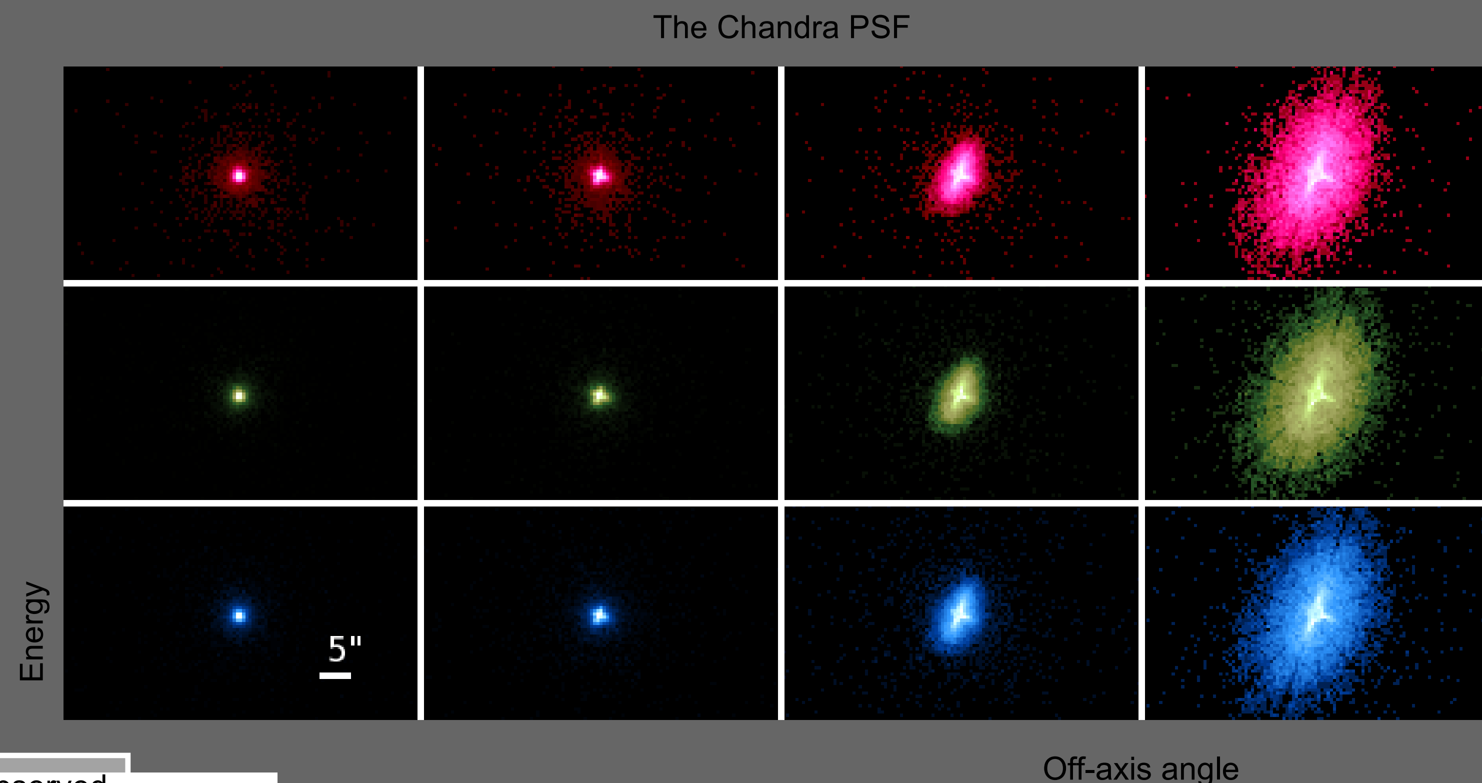
2 decades of photon energy (0.1 to 10 keV)

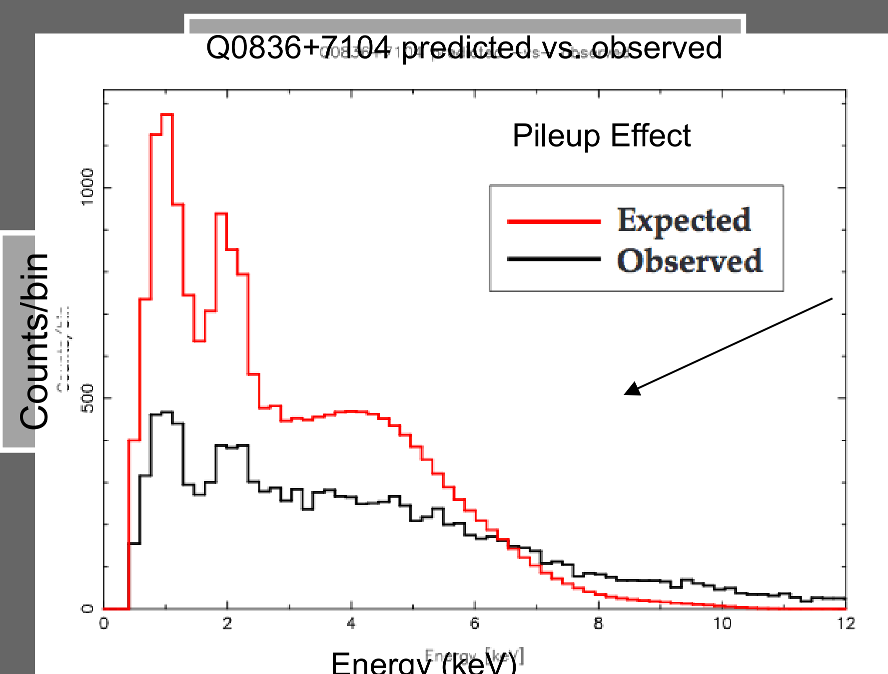
Complexities in X-Ray and Chandra Data Analysis

Every aspect of the observation varies with

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

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

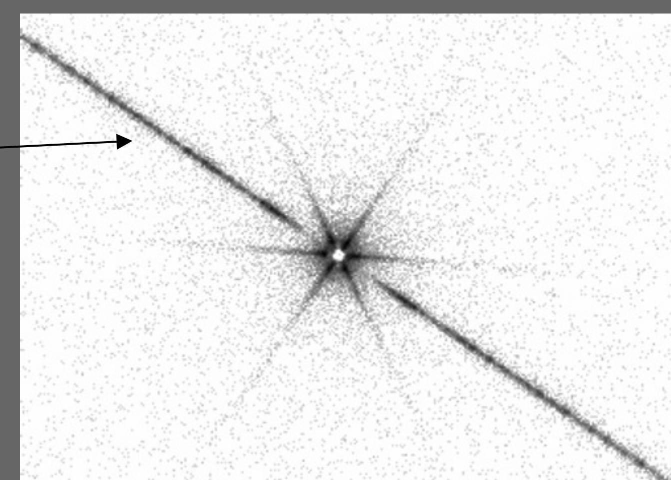




Specific instrumental effects eg.

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)
  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

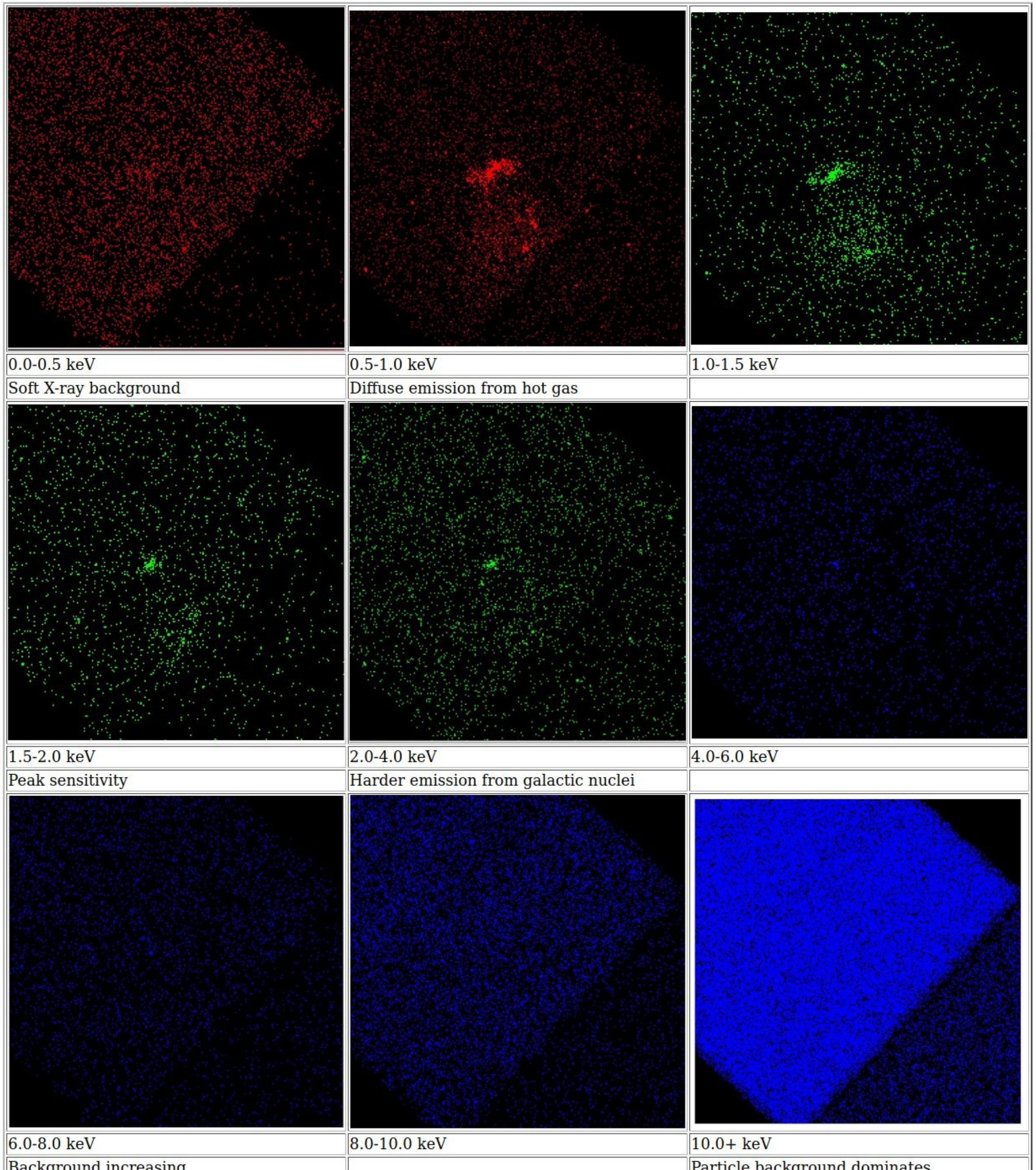
- In optical astronomy, the primary data set is an image.
- In radio interferometry, it's a visibility array.
- In X-ray astronomy, the primary data set is an **event list** - a table of (putative) photons
  - Our software makes it easy to generate an image from the event list, so it's easy to forget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



Each ACIS observation is not a 2D image – it has time and energy dimensions.

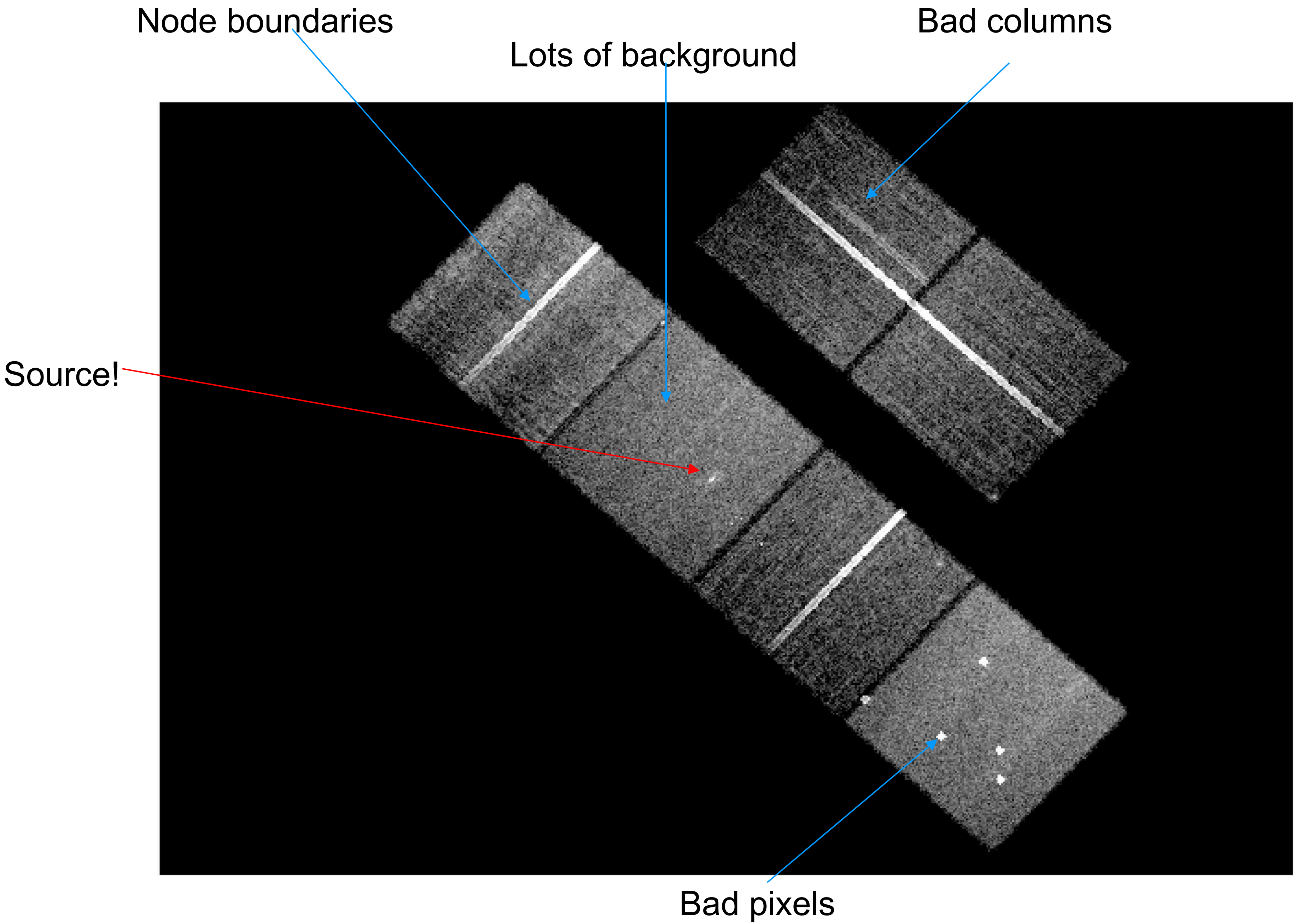
Here is part of obsid 869 showing energy slices through the data

Spatial binning of 4

Made by (e.g.):

dmcopy evt2.fits"[energy=4000:6000][bin x=3600:4600:4,y=3600:4600:4]" img.fits

Level 1 Event List - Calibrated but Dirty



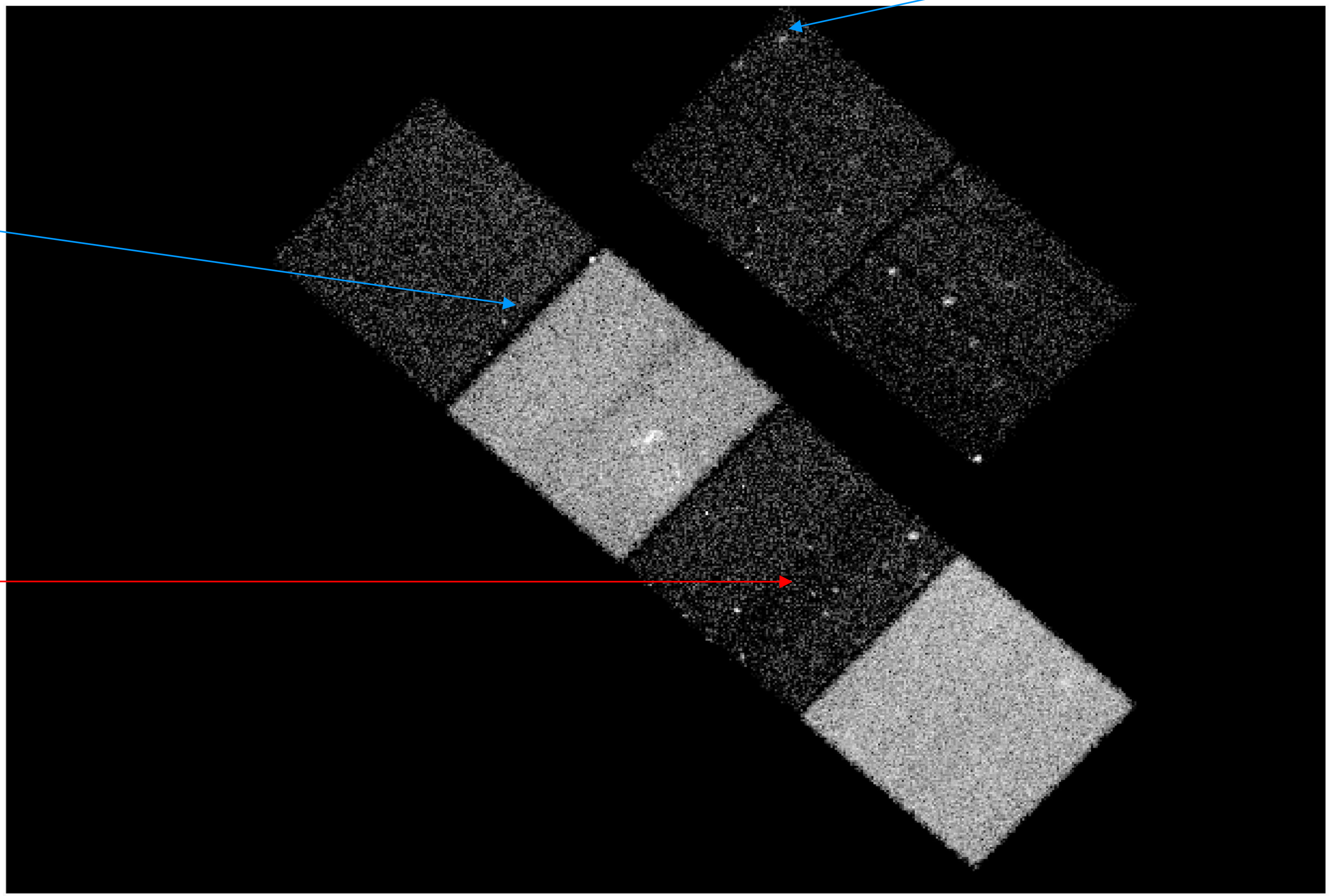
Level 2 event list - cleaned and filtered

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

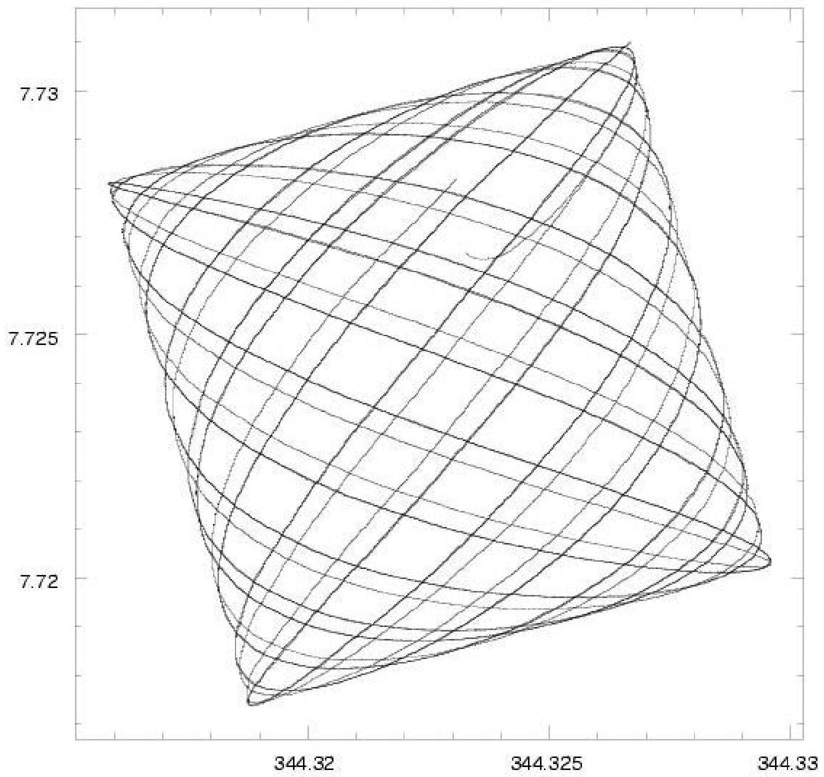
Sources fuzzy far off axis (PSF big)

Beware chip gaps!

More sources!



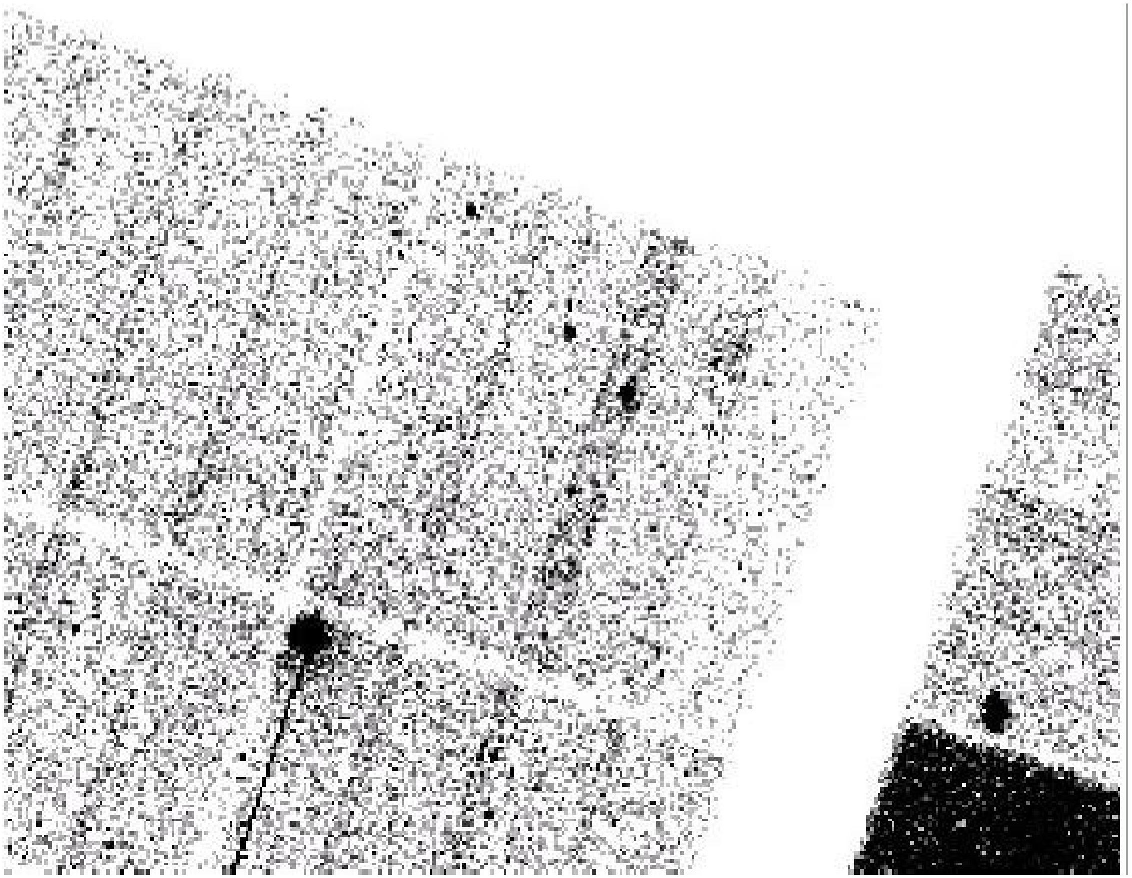
The aspect solution



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.

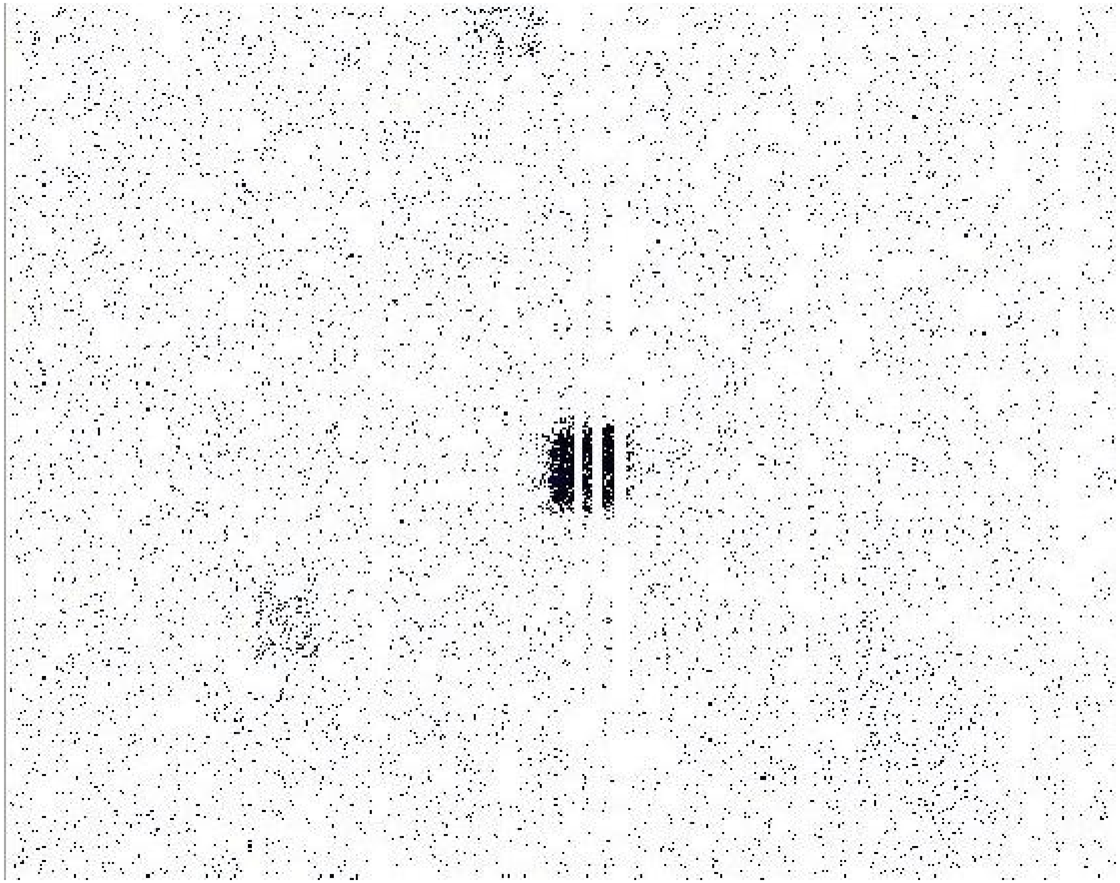
We record the motion of the guide stars in the star tracker so that we can calculate RA and Dec for EACH PHOTON and so reconstruct the image.

Chandra aspect-corrected data



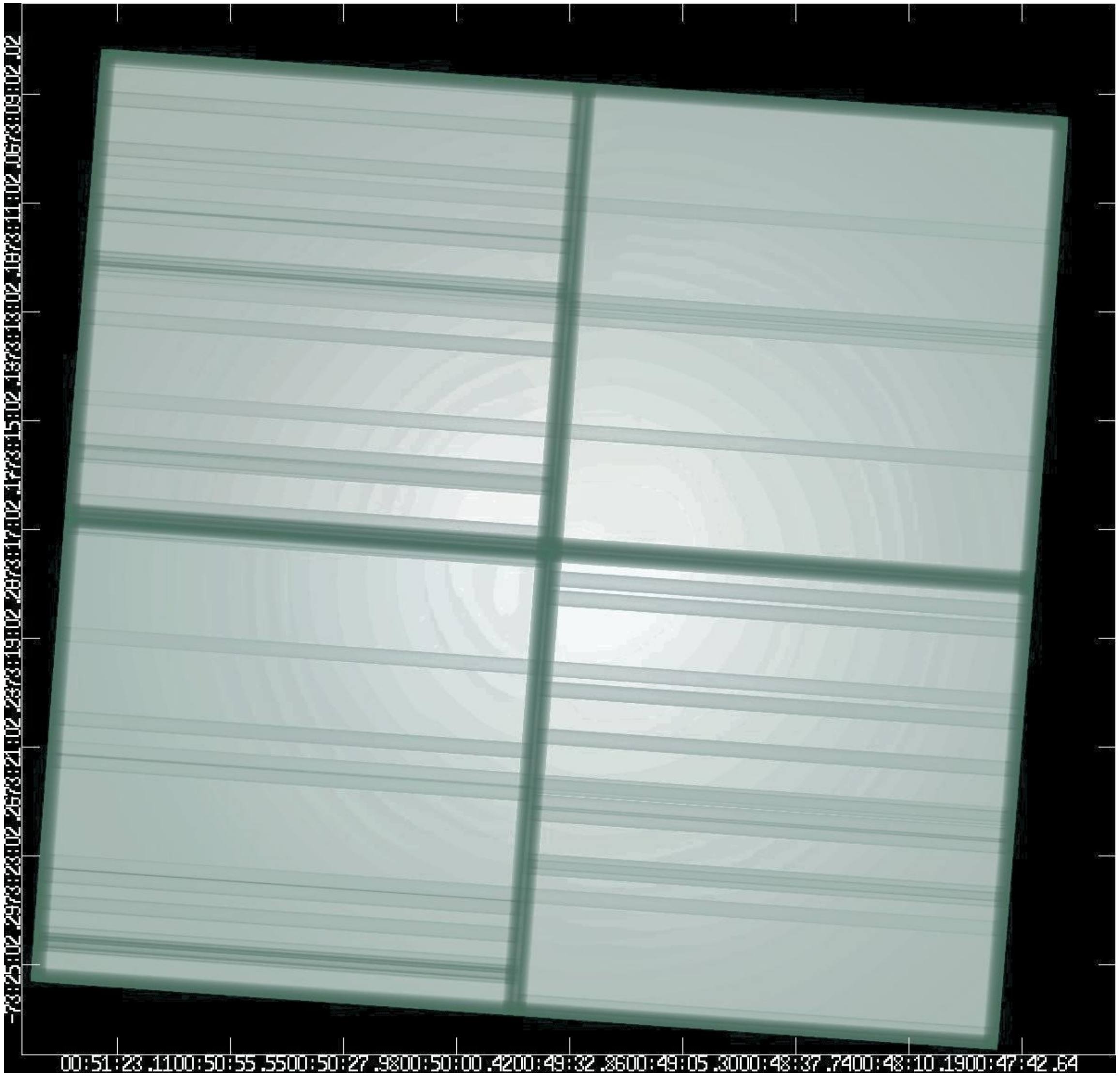
This is what you get after calibration but before cleaning the data. Note the sharp point sources near the center.

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

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 again:

$$N(x',y',t',E') = \int S(x,y,t,E)\, A(x,y,t,E) R(x,y,t,E,x',y',t',E')\, dx\, dy\, dt\, dE$$

Integrate over dx dy over a region that contains almost all the PSF (and estimate correction factor P for fraction outside)
Assume R is independent of t over observing time T
Then

$$N(E') = \int S(E)\, A(E) R(E,E')\; T\, dE$$

‘PHA file’
src.pha
extracted from evt file

Sherpa source model
Parameterized precoded spectral shape

‘ARF file’
src.arf
for that position and date

‘RMF file’
src.rmf
for that position and date

‘Livetime’
from header

Spectra in Poissonland

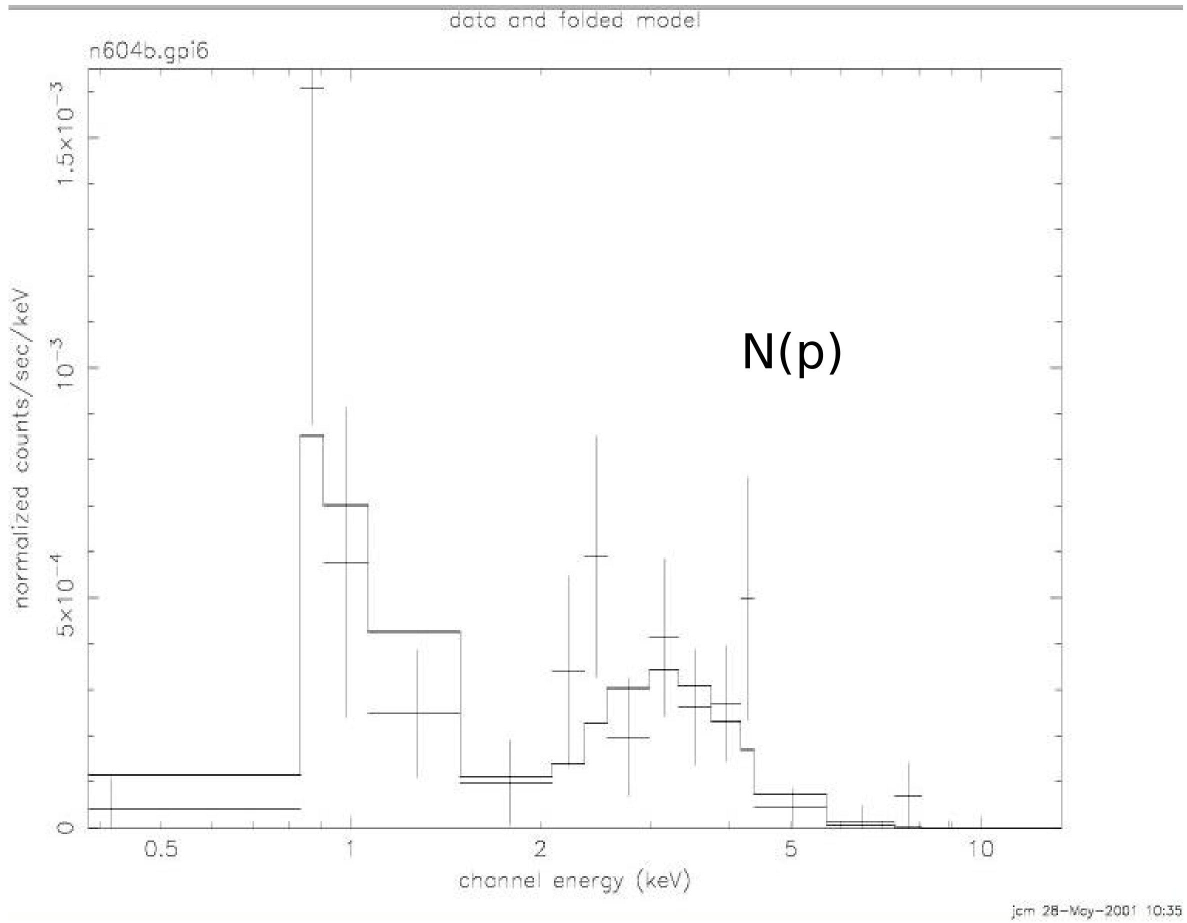
$$N(p) = \int R(E,p)A(E)F(E)dE$$

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.

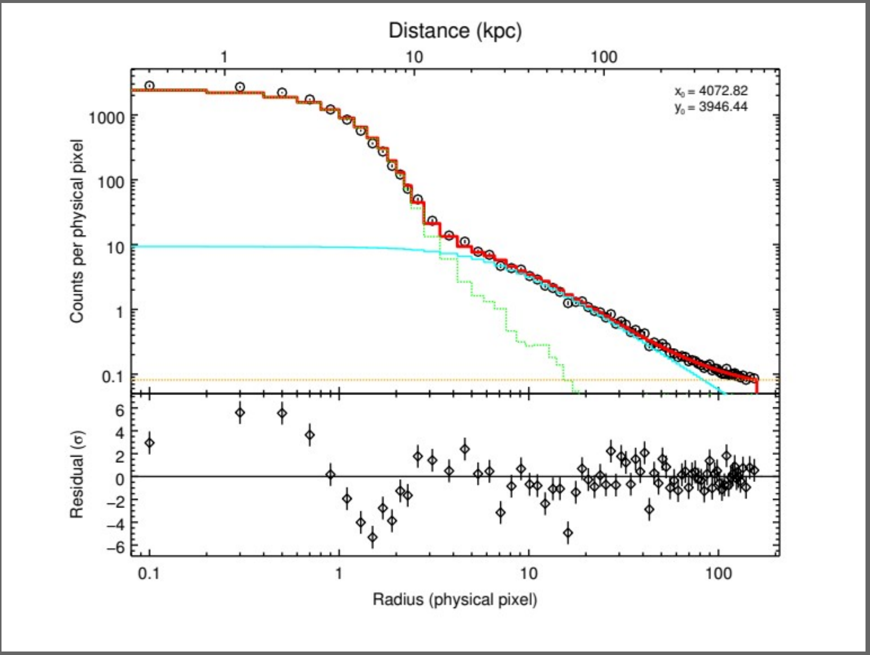
Incompletely calibrated instrumental features may show up in residuals, limiting factor in high S/N spectra – these features may include edges. Beware apparent science in regions where A(E) is changing rapidly.

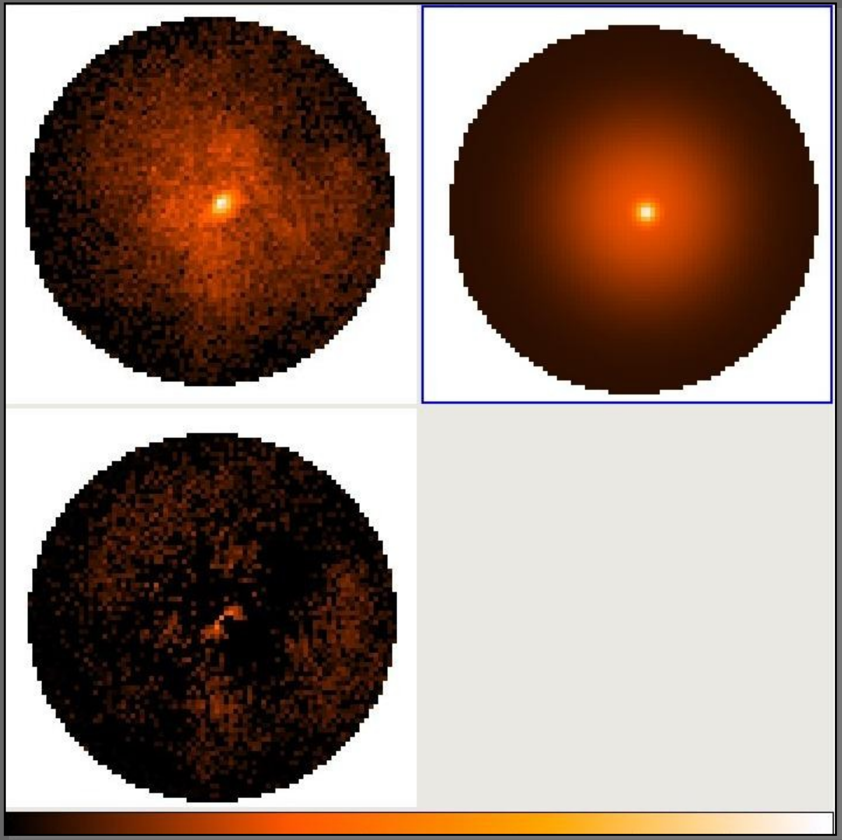


Sherpa: Modeling and Fitting in Python

Sherpa

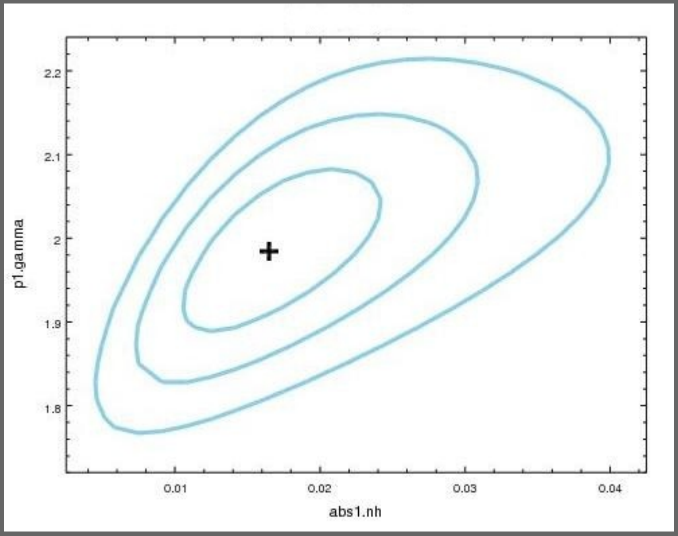
Modeling and fitting for 1-D and 2-D datasets **in any waveband** including: spectra, images, surface brightness profiles, light curves, general ASCII data.





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: Modeling and Fitting in Python

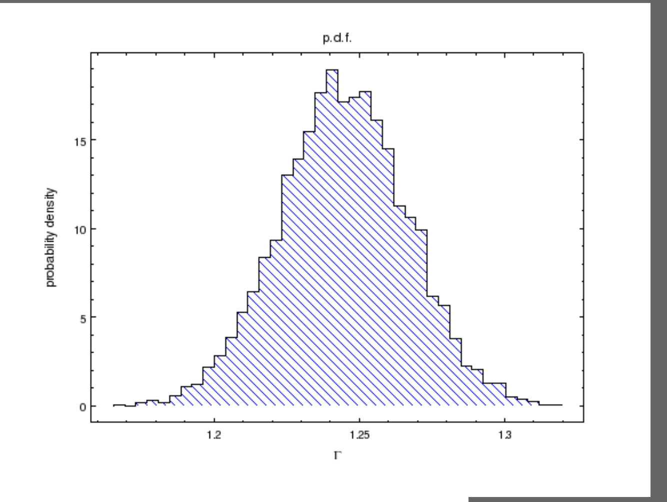
Sherpa

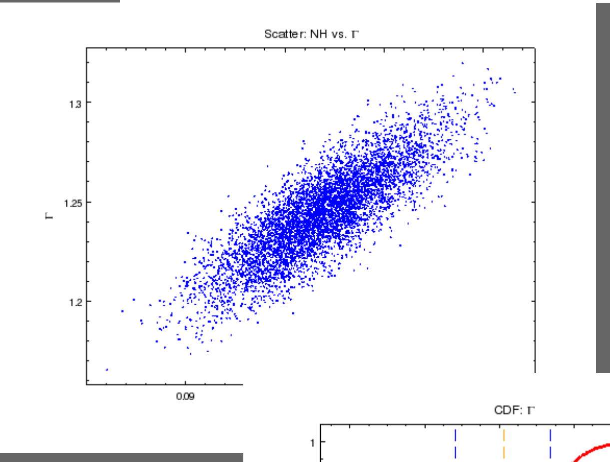
- comes with well-tested, robust optimization methods - e.g. Levenberg-Marquardt, Nelder-Mead Simplex or Monte Carlo/Differential Evolution

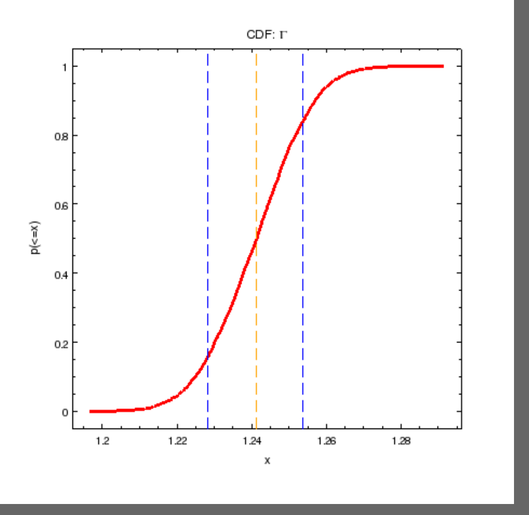
- comes with statistics for modeling Poisson or Gaussian data

- 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





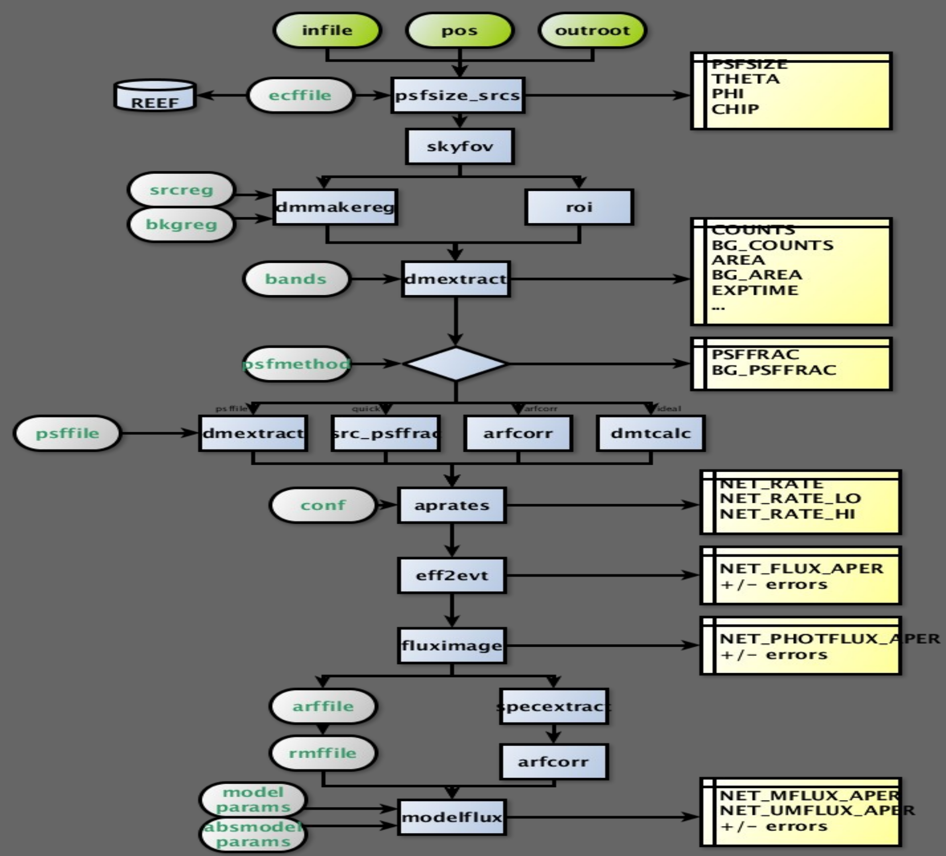


CALDB

- 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)

Your Chandra Observation 801589 Inbox ×

arcops@head.cfa.harvard.edu
to jcm, arcops

Dear Dr. McDowell,

This message is to let you know that your observation
SeqNum 801589, ObsId 18265
is available for downloading by you by going to the following web page:

http://cda.harvard.edu/chaser/obsRetrieveEntry.do?obsid=18265

Please log in using the following account information:

Username: [redacted]
Password: [redacted]

Untarring the data will create a directory
18265
in the current directory, containing a small directory tree with the data.

Note that only the primary and/or secondary data products are available for download and that there may be defects in these data products; please consult the V&V report.

```
download_chandra_obsid 18265
ls 18265; ls 18265/primary
```

```
andromeda> ls 18265
00README  axaff18265N003_VV001_vv2.pdf  oif.fits  primary/  secondary/
andromeda> ls 18265/primary
acisf18265N003_cntr_img2.fits.gz  acisf18265N003_evt2.fits.gz       acisf18265N003_full_img2.jpg      acisf18265_000N003_fov1.fits.gz   pcadf18265_000N001_asol1.fits.gz
acisf18265N003_cntr_img2.jpg      acisf18265N003_full_img2.fits.gz  acisf18265_000N003_bpix1.fits.gz  orbitf605707505N001_eph1.fits.gz
andromeda> []
```

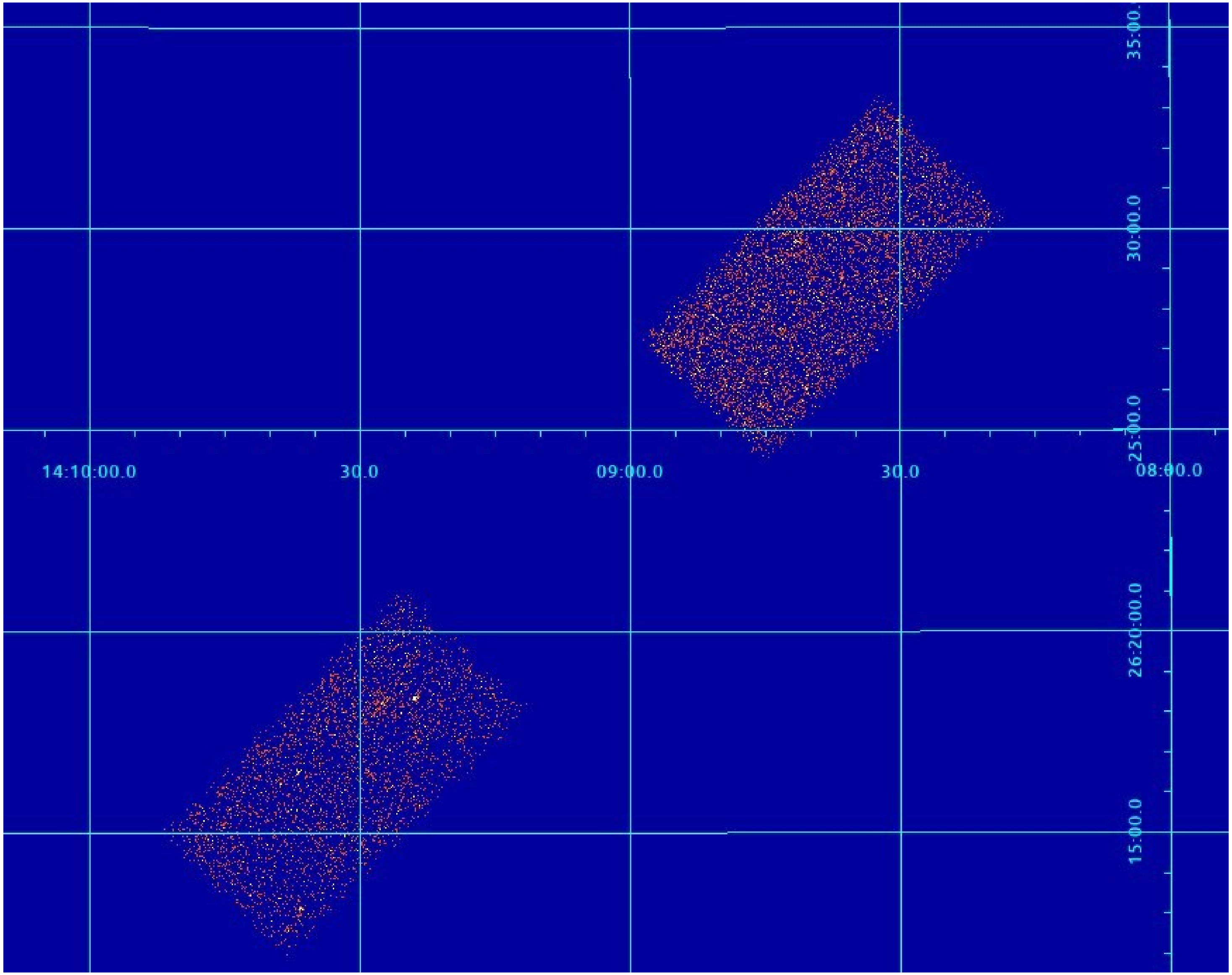
```
chandra_repro 18265            # reprocess
ls 18265
ls 18265/repro
```

```
andromeda> ls 18265
00README  axaff18265N003_VV001_vv2.pdf  oif.fits  primary/  repro/  secondary/
andromeda> ls 18265/repro
acisf18265_000N003_bpix1.fits  acisf18265_000N003_msk1.fits  acisf18265_000N003_stat1.fits  acisf18265_repro_bpix1.fits  acisf18265_repro_flt2.fits  acisf605870200N002_pbk0.fits
acisf18265_000N003_fov1.fits   acisf18265_000N003_mtl1.fits  acisf18265_asol1.lis           acisf18265_repro_evt2.fits   acisf18265_repro_fov1.fits  pcadf18265_000N001_asol1.fits
andromeda> []
```

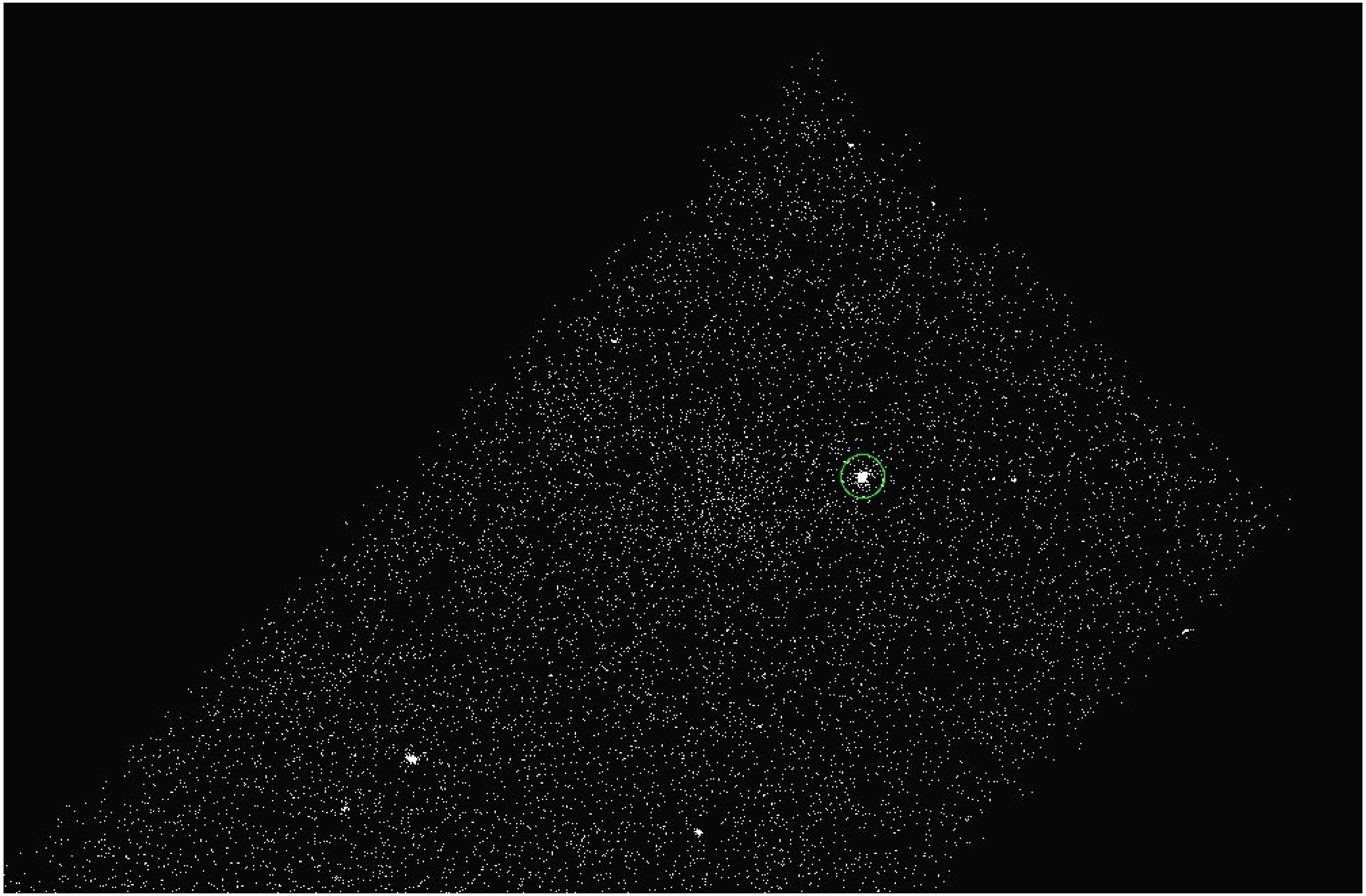
evt file

asol file

```
cd 18265/repro
ln -s  acis18265_repro_evt2.fits  evt                  # lazy!
dmcopy “evt[energy=300:8000]” evt03.80        # broad band
ds9  evt03.80 &
```

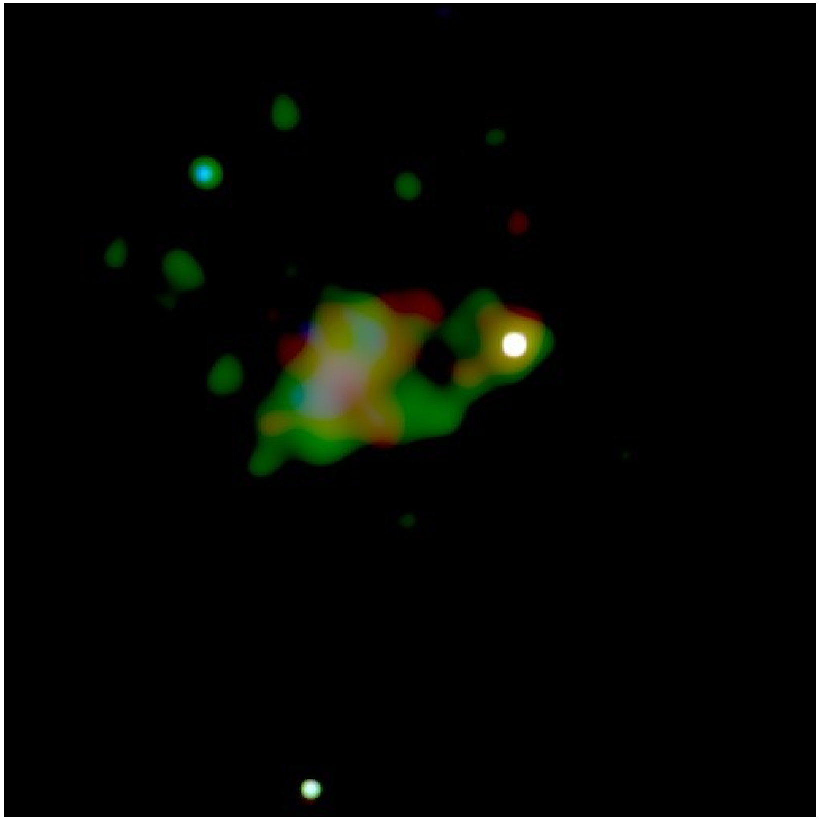


This observation was made with 2 chips (5&7). Each chip had only the central 512 rows read out to reduce pileup. Looks like something interesting at the lower left, let’s zoom in

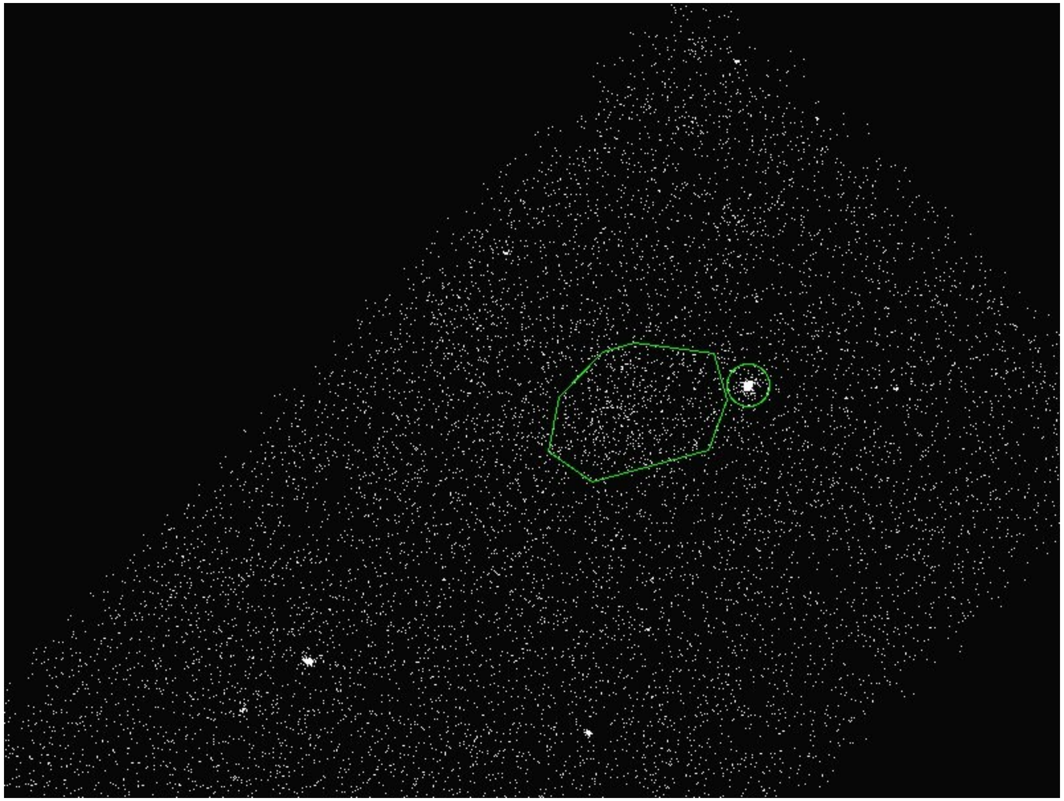


We can certainly see the quasar which was my target
Can you see the slight fuzz to the left of it?
This looks like a job for adaptive smoothing

```
dmcopy "evt[energy=500:1200][bin x=3800:4312,y=3800:4312]"  red
dmcopy "evt[energy=1200:2000][bin x=3800:4312,y=3800:4312]" green
dmcopy "evt[energy=2000:7000][bin x=3800:4312,y=3800:4312]" blue

csmooth red red.s sigmin=2.5 sigmax=3 sclmin=2 sclmax=10
csmooth green green.s sigmin=2.5 sigmax=3
csmooth blue blue.s sigmin=2.5 sigmax=3

dmimg2jpg red.s green.s blue.s rgb.jpg scalefunc=log scaleparam=3

display rgb.jpg
```



Yep, there's really something there!



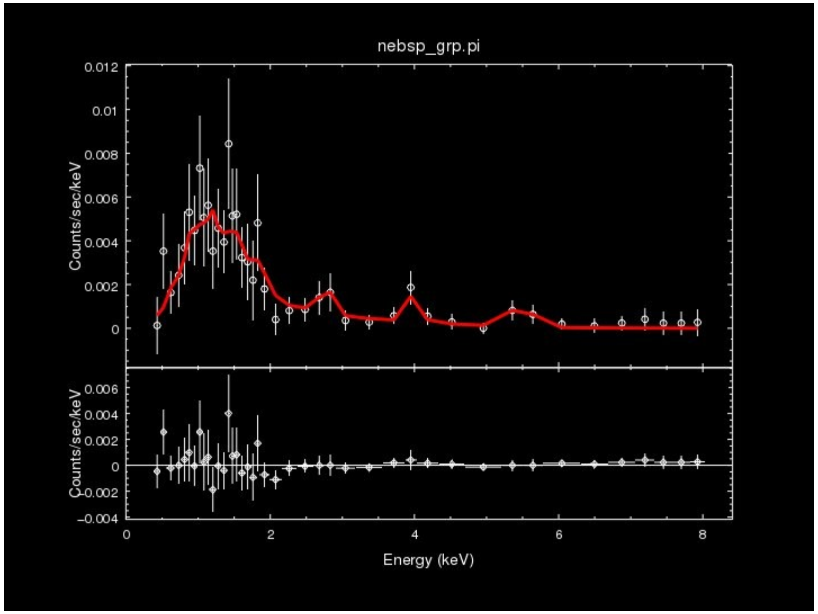
Use the jpg to define a region, extracting counts from the original data

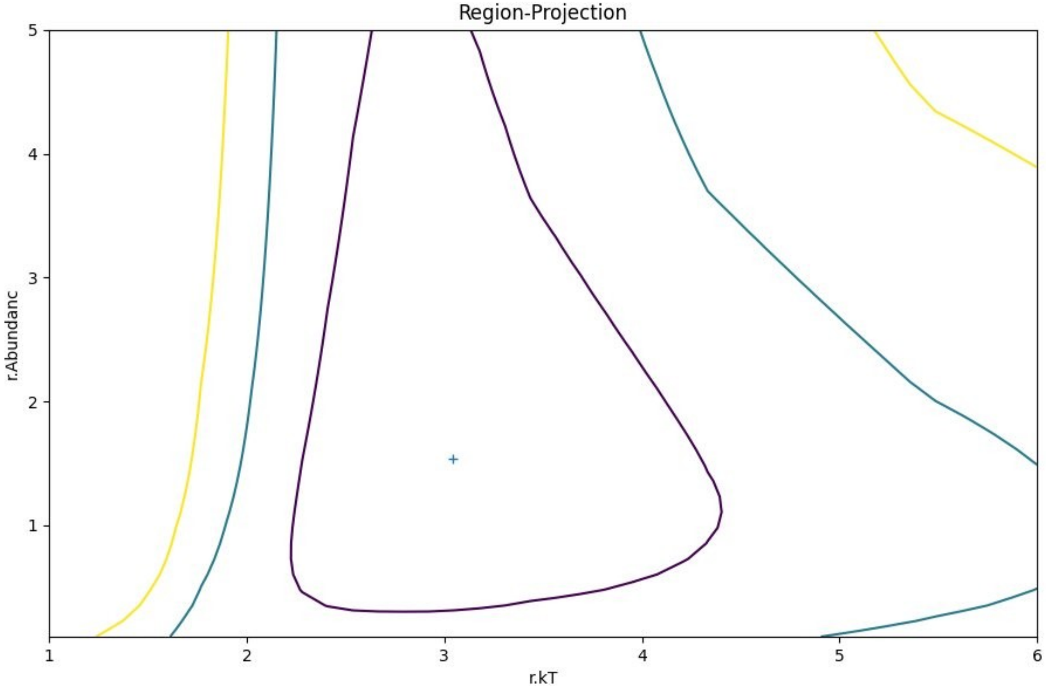
```
specextract evt[sky=region(neb.reg) nspec bkg="evt[sky=region(bg.reg)]"
  grouptype=NUM_CTS binspec=15 weight=yes
sherpa
 >  load_pha("nspec_grp.pi")
 >  subtract()
 >  notice(0.5,7.0)
 >  plot_data()
```

Use Sherpa commands to fit the model and look at
contours of chi-sq in parameter space

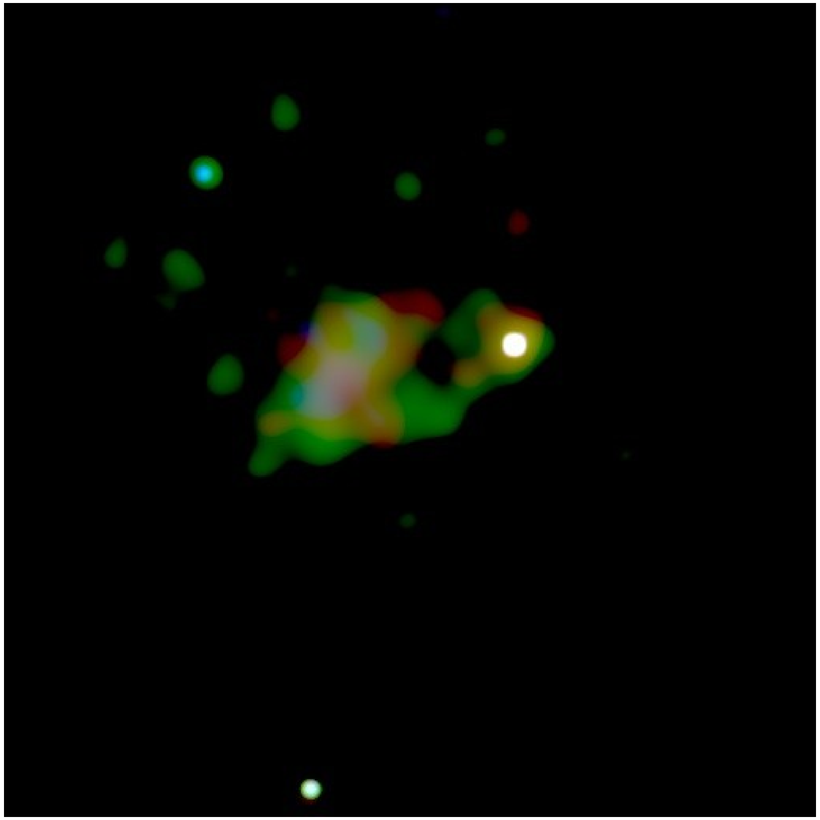
```
set_source(xsphabs.a*(xsapec.r+gauss1d.g))
fit()
plot_fit_resid()
reg_proj(r.kt,r.Abundanc,min=(1,0.2),max=(6,5),nloop=(40,40)
```

We have a result! Cluster temperature is about 3 keV



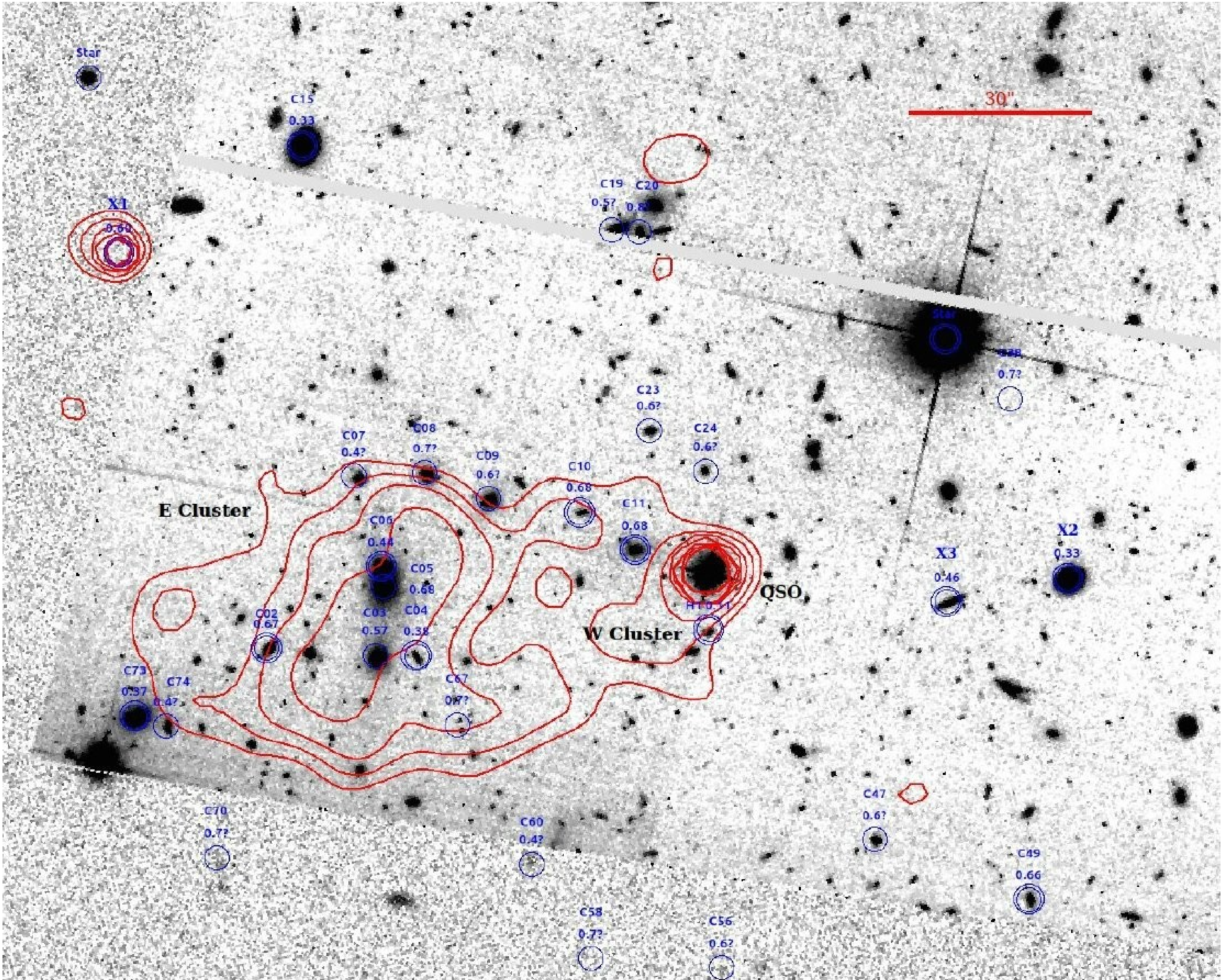


```
dmcopy "evt[energy=500:1200][bin x=3800:4312,y=3800:4312]"  red
dmcopy "evt[energy=1200:2000][bin x=3800:4312,y=3800:4312]" green
dmcopy "evt[energy=2000:7000][bin x=3800:4312,y=3800:4312]" blue

csmooth red red.s sigmin=2.5 sigmax=3 sclmin=2 sclmax=10
csmooth green green.s sigmin=2.5 sigmax=3
csmooth blue blue.s sigmin=2.5 sigmax=3

dmimg2jpg red.s green.s blue.s rgb.jpg scalefunc=log scaleparam=3

display rgb.jpg
```



Yep, there's really something there!

McDowell et al
2021
ApJ 919, 22


30"
Star
C15
0.33
X1
0.60
C19
0.5?
C20
0.8?
Star
C23
0.6?
C24
0.6?
C07
0.4?
C08
0.7?
C09
0.6?
C10
0.68
C11
0.68
E Cluster
C06
0.44
C05
0.68
C03
0.57
C04
0.38
C02
0.67
QSO
W Cluster
X3
0.46
X2
0.33
C73
0.37
C74
0.4?
C67
0.7?
C47
0.6?
C70
0.7?
C60
0.4?
C49
0.66
C58
0.7?
C56
0.6?

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
- The catalog makes it even easier to use X-ray data and provides the first astrometric all-sky (but not complete) catalog at high energies.