From events to science

Imaging, imaging spectroscopy and the Chandra Source Catalog with CIAO



25 years of Chandra · Chandra Photo Album

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Today’s path

A closer look at what you do with Chandra data: from the event file to images, spectra and catalog measurements. Many of these steps you can also run by clicking in DS9 with dax: that is the next talk.

1 Imaging

bin, filter, clean; exposure maps and fluxed images; finding sources

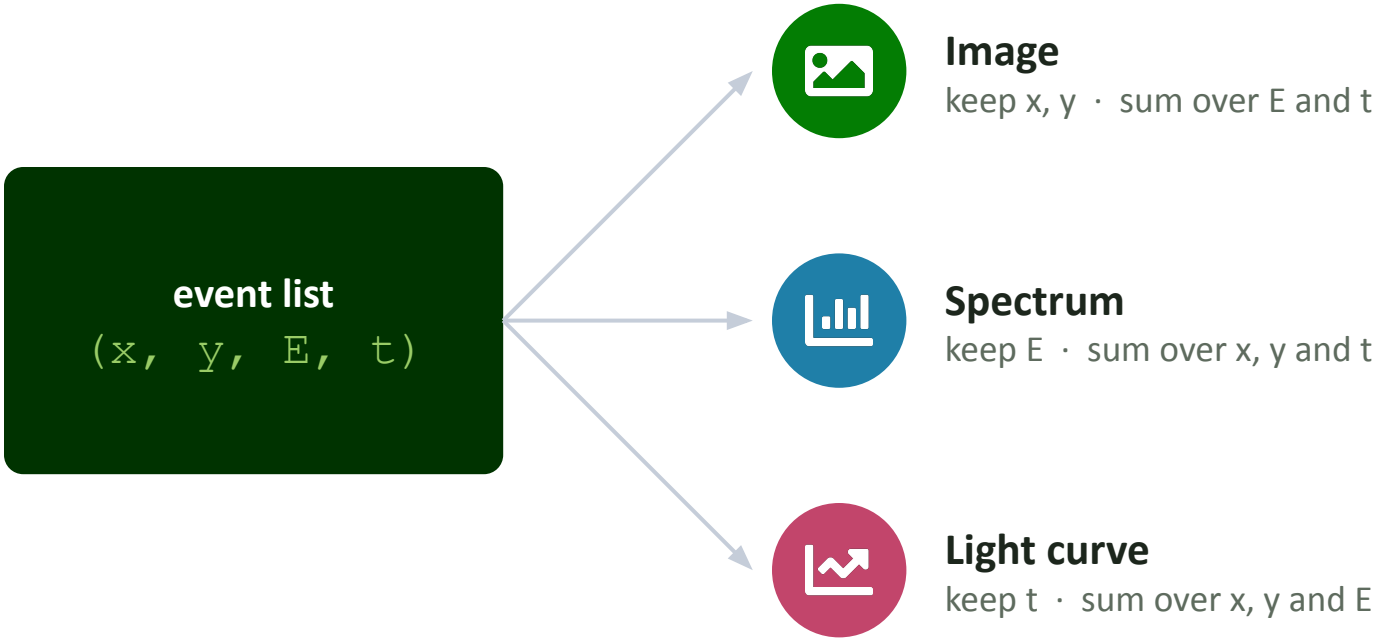
2 Imaging spectroscopy

spectra and responses with specextract; a first look at fitting

3 Chandra Source Catalog

430,000+ sources already measured for you

Every analysis is a projection of the event list



Binning always throws information away, so choose the projection that answers your question. You can always go back to the events.

PART 1

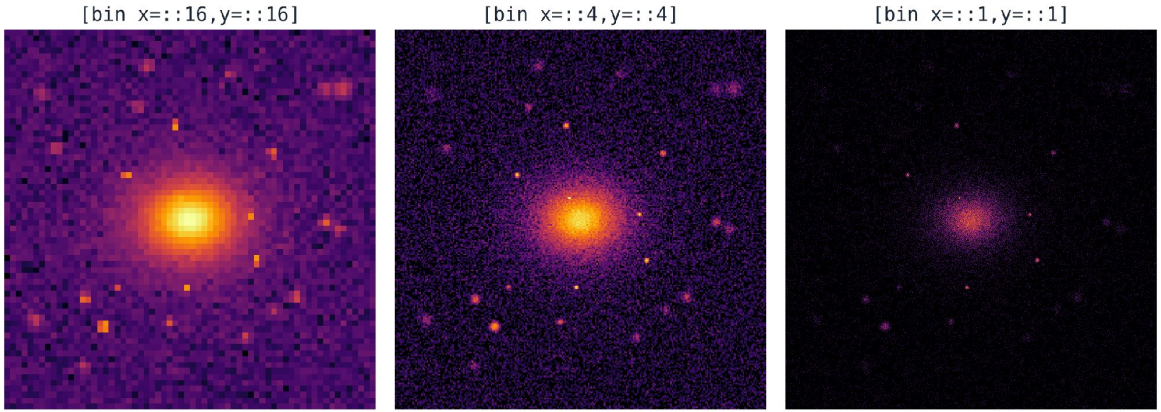
Imaging

Chandra’s superpower: ~0.5 arcsec images, with an energy for every event



Bullet Cluster · Chandra Photo Album

Binning: choose your pixel size



Simulated data, same events binned three ways · ahelp dmbinning

```
% dmcopy "evt2.fits[bin x=::4,y=::4]" img4.fits
% dmcopy "evt2.fits[bin sky=1]" img1.fits
```

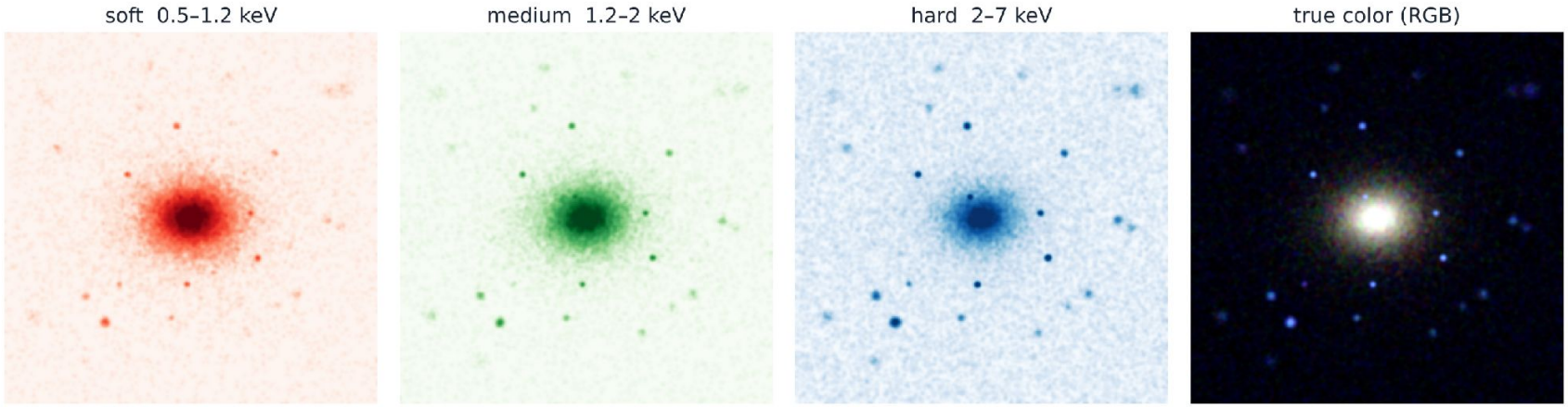
1 sky pixel
= 0.492″ (ACIS)

Big bins
show faint, diffuse emission

Small bins
show sharp point sources

Sub-pixel
possible, but for experts

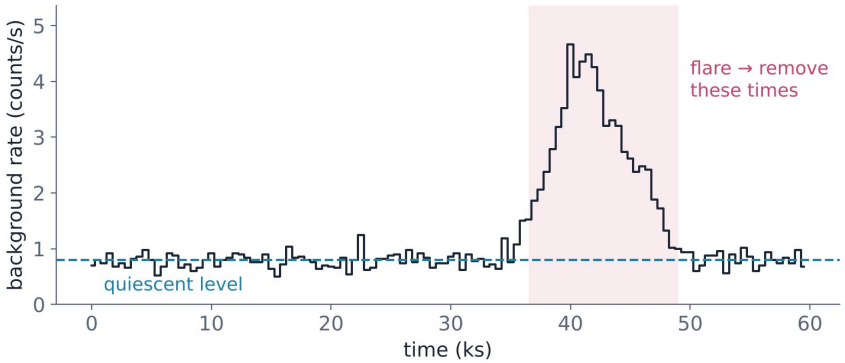
Energy filtering: same sky, different physics




```
% dmcopy "evt2.fits[energy=500:1200][bin sky=4]" soft.fits
% dmcopy "evt2.fits[energy=1200:2000][bin sky=4]" medium.fits
% dmcopy "evt2.fits[energy=2000:7000][bin sky=4]" hard.fits
```

Simulated: soft thermal gas from a cluster vs. hard point sources (AGN). Combine the bands in DS9 (Frame → RGB) or with dmimg2jpg. True-color thread

Clean first: remove background flares



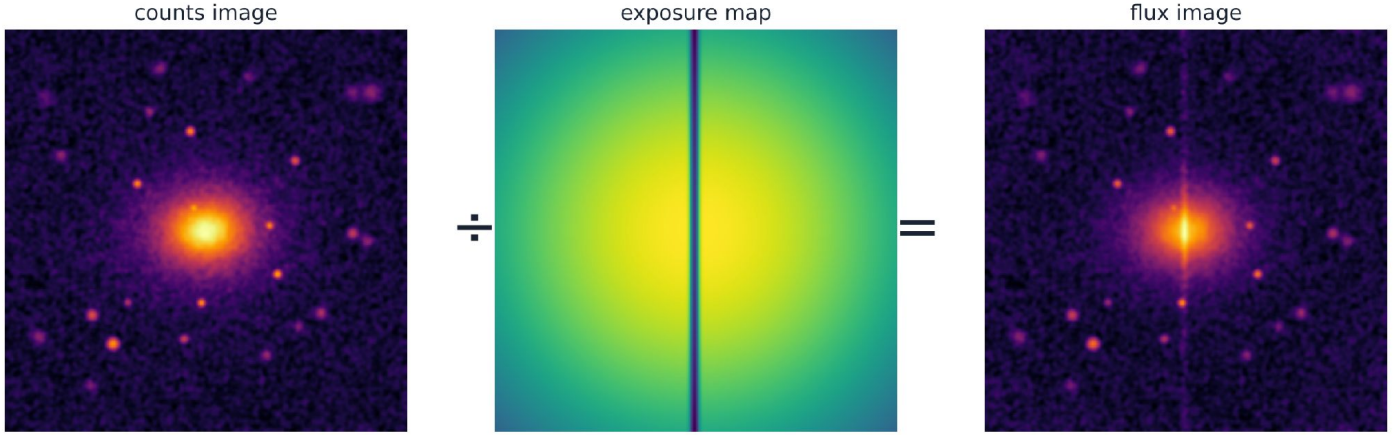
Simulated background light curve

Flares come from charged particles in Chandra's orbit. They add background but no signal, and they matter most for faint and extended sources.

```
# 1. light curve, source-free region
% dmextract "evt2.fits[sky=region(bkg.reg)]
    [bin time=::200]" bkg.lc opt=ltc1
# 2. find the good times
% deflare bkg.lc clean.gti method=clean
# 3. keep only the good times
% dmcopy "evt2.fits[@clean.gti]" \
    clean_evt2.fits
```

The GTI and the exposure time update automatically. Flare thread · ahelp deflare

Counts are not flux: exposure maps



counts(x, y) ÷ **exposure(x, y)** = **flux(x, y)**

[counts] [cm^2 s counts $photon^{-1}$] [photons cm^{-2} s^{-1}]

exposure = effective area [cm^2 counts $photon^{-1}$] × **time** [s], for every pixel · Thread

fluximage: fluxed images in one step

By hand: five tools

1. **dmcopy** counts image
2. **mkinstmap** instrument map
3. **mkexpmap** exposure map
4. **dmregrid** match & combine
5. **dmimgcalc** counts ÷ exposure

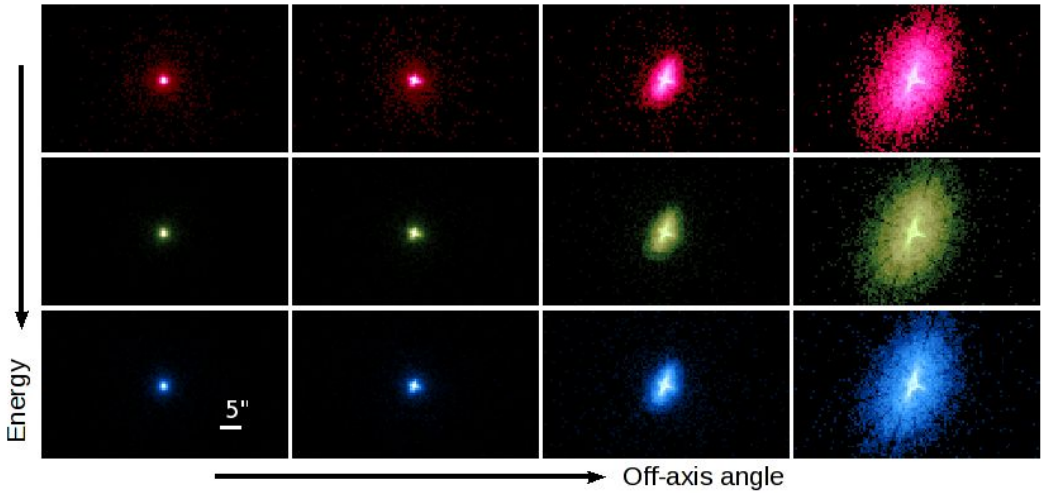
```
% fluximage evt2.fits out/ \
    bands=broad binsize=2
```



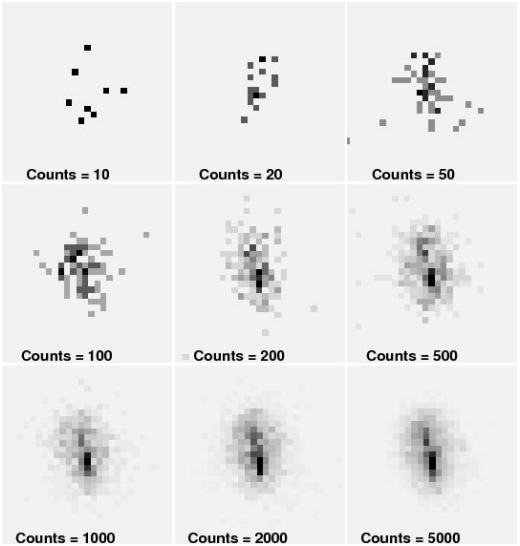
`out/broad_thresh.img` counts
`out/broad_thresh.expmap` exposure
`out/broad_flux.img` flux

fluximage finds the aspect, bad-pixel and mask files itself. **Several ObsIDs? merge_obs** reprojects and combines them in the same way.

What is the PSF?



simulated PSFs: further off-axis →, higher energy ↓



one off-axis source, 10 → 5000 counts

PSF = point spread function: the image a point source makes on the detector. Chandra's is ~0.5″ on-axis, but it grows and gets distorted off-axis and at higher energy, so a faint off-axis point source can look extended.

You need it to detect sources, correct apertures, test if a source is extended and simulate it. **CIAO PSF pages**

Finding sources: wavdetect

```
# PSF size at each pixel
% mkpsfmap out/broad_thresh.img psfmap.fits \
    energy=2.3 ecf=0.393

% wavdetect infile=out/broad_thresh.img \
    psffile=psfmap.fits \
    expfile=out/broad_thresh.expmap \
    scales="1 2 4 8 16" outfile=src.fits \
    scellfile=scell.fits imagefile=recon.fits \
    defnbkgfile=nbkg.fits
```

Why the PSF?

Chandra's PSF grows strongly off axis: 0.5″ at the center, several arcsec at the edge

Output

source list (src.fits) with positions, counts and significance; load it in DS9 as regions

Alternatives

celldetect (fast), vtpdetect (extended)

srcflux: count rate and flux for a source

```
% srcflux evt2.fits "03:29:29.25 +31:18:34.73" out/myflux
```

```
Summary of source fluxes   (0.5-7.0 keV, 90% confidence)

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    (4.20E-13 - 4.57E-13)
```

Example output from a previous CIAO workshop. srcflux bundles logic from six threads. Crowded field? Give your own src/bkg regions. ahelp srcflux · Fluxes thread

Also in DS9: Analysis → CIAO tools (DAX) → fluxes · next talk

Automatic regions
source and background apertures from the PSF

Corrections
PSF fraction and exposure, at the source position

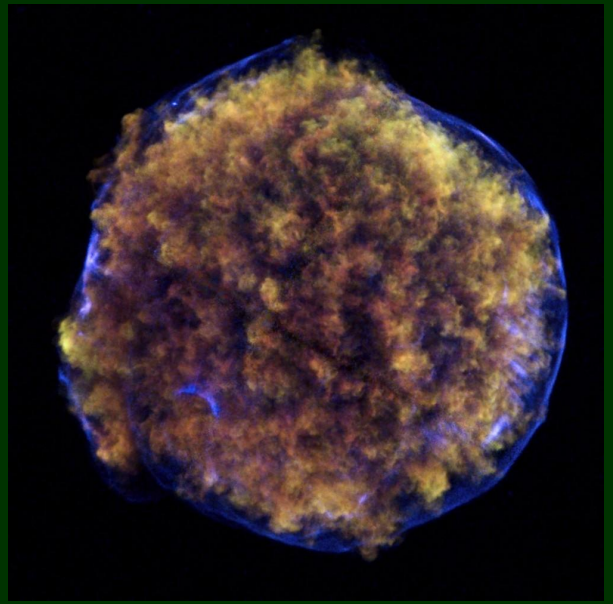
Errors & upper limits
confidence intervals, even for no detection

Model flux
for an assumed spectrum (e.g. absorbed power law)

PART 2

Imaging spectroscopy

Spectra of sources from ACIS images (gratings are a separate topic)



Tycho’s supernova remnant · Chandra Photo Album

What a spectrum tells you

Composition

emission lines: Fe, Si, S, O…

Temperature

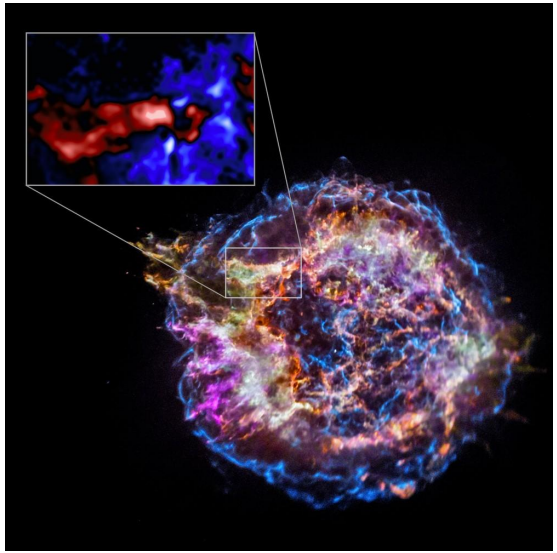
shape of thermal emission from hot gas

Absorption

gas along the line of sight: hydrogen column density NH

Emission process

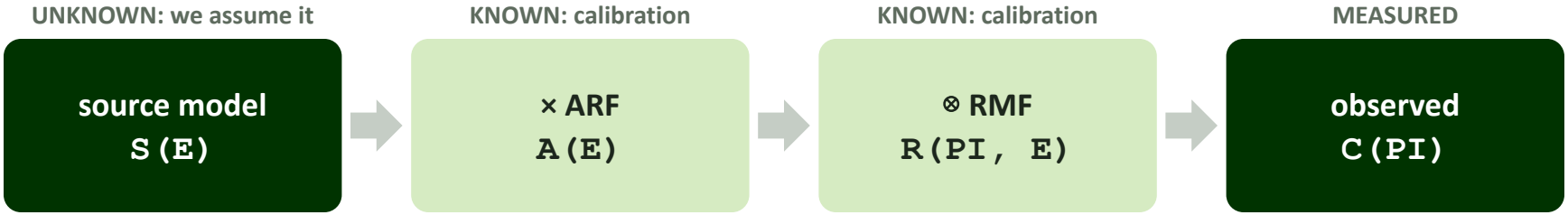
thermal plasma vs. power law (accretion, jets)



Cas A: colors trace elements · Chandra Photo Album

Plus the flux and luminosity in any band: $L = 4\pi d^2 F$

What you measure is not the source spectrum



fitting goes backward: from the measured counts to a model of the source

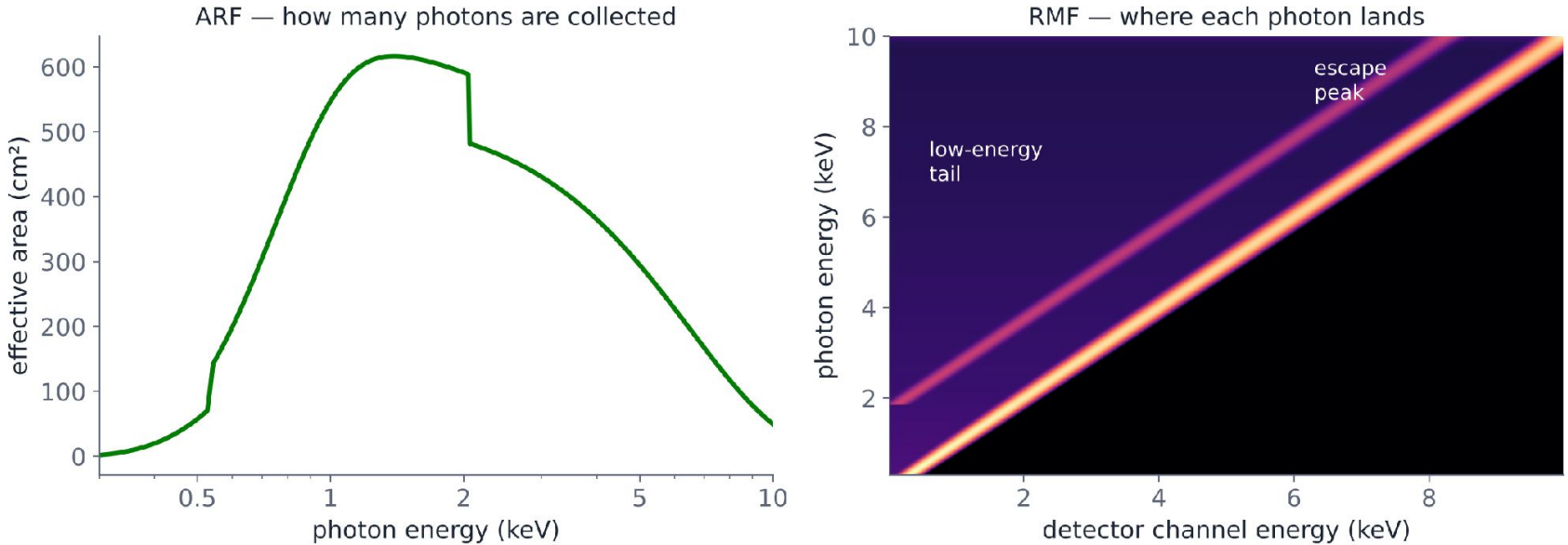
$$C(PI) = t \times \int R(PI, E) \times A(E) \times S(E)\,? \; dE$$

[counts] [s] [probability] [cm² counts photon⁻¹] [photons cm⁻² s⁻¹ keV⁻¹] [keV]

We cannot invert this integral. So we **assume** a model S(E; N_H, Γ, …), fold it through the ARF and RMF, compare with C(PI) and adjust: a fit in Sherpa.

```
ACIS channels: PI ≈ E / 14.6 eV + 1   (1024 channels)
```

The two responses: ARF and RMF



ARF depends on where the source is (vignetting, chip, time). **RMF** is nearly diagonal for a CCD, with tails and escape peaks.

Schematic curves for illustration, not calibration products

specextract: spectra + responses in one go

Draw src.reg and bkg.reg in DS9

Set the parameters

Run: spectra + ARF + RMF

Also in DS9: Analysis → CIAO tools (DAX) · next talk

Replaces dmextract, mkacisrmf, mkarf, asphist…
ahelp specextract · threads: point · extended · multiple

```
% punlearn specextract
% pset specextract \
  infile="evt2.fits[sky=region(src.reg)]"
% pset specextract \
  bkgfile="evt2.fits[sky=region(bkg.reg)]"
% pset specextract outroot=spec
% pset specextract correctpsf=yes weight=no
% pset specextract grouptype=NUM_CTS binspec=15
% specextract
```

The decisions are yours

Background	subtract or model it? Is the source bright compared with the background?	`bkgfile=`
Point source	correct the ARF for PSF photons outside the aperture	`correctpsf=yes`
Extended source	weight the responses by the counts across the region	`weight=yes`
Many regions	one spectrum per region, or combine them	`combine=yes`
Grouping	minimum counts per bin for χ^2 fitting	`grouptype=NUM_CTS` `binspec=15`

What comes out

File	What it is
`spec.pi`	source spectrum (counts per PI channel)
`spec_grp.pi`	grouped spectrum
`spec.arf` / `spec.corr.arf`	effective area (PSF-corrected if correctpsf=yes)
`spec.rmf`	redistribution matrix
`spec_bkg.pi`	background spectrum
`spec_bkg.arf` / `.rmf`	background responses (bkgresp=yes)



Linked for you

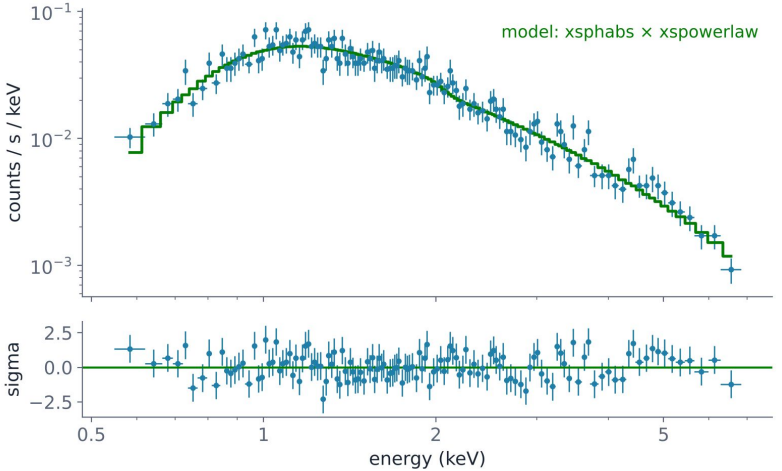
The spectrum header points to its background, ARF and RMF, so Sherpa loads all four with one command.

Sherpa threads

Next step: fit the spectrum in Sherpa

```
from sherpa.astro.ui import *

load_pha("spec_grp.pi")  # + bkg, ARF, RMF
subtract()
notice(0.5, 7.0)
set_source(xsphabs.abs1 * xspowerlaw.p1)
fit()
plot_fit_delchi()
conf()
```



Simulated spectrum (absorbed power law, ~3000 counts). Results: NH, photon index, flux, with confidence intervals from conf(). Few counts? See the statistics talk. *Sherpa threads*

Watch out for

Pile-up
bright point sources: two photons read as one, spectrum too hard. Check with pileup_map.

Few counts
Poisson, not Gaussian: cstat/wstat, careful grouping

Off-axis PSF
far from the aim point sources are blurred: use bigger regions and correctpsf

Old calibration
run chandra_repro with the current CALDB

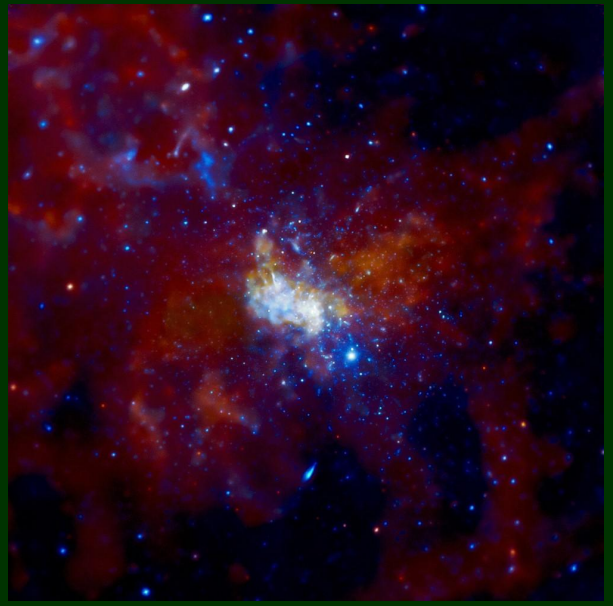
Background
dominates faint and extended sources: choose the region carefully, deflare

The threads and the "Watch out" notes in ahelp cover each of these.

PART 3

The Chandra Source Catalog

Every source in every public ACIS and HRC-I observation, measured the same way



Galactic Center, Sgr A* field · Chandra Photo Album

CSC 2.2 in numbers

432,713

unique X-ray sources (compact + extended)

1.43 M

detections in individual observations

17,879

observations, in 11,317 stacks

786 deg²

sky area (~2% of the sky)

100+

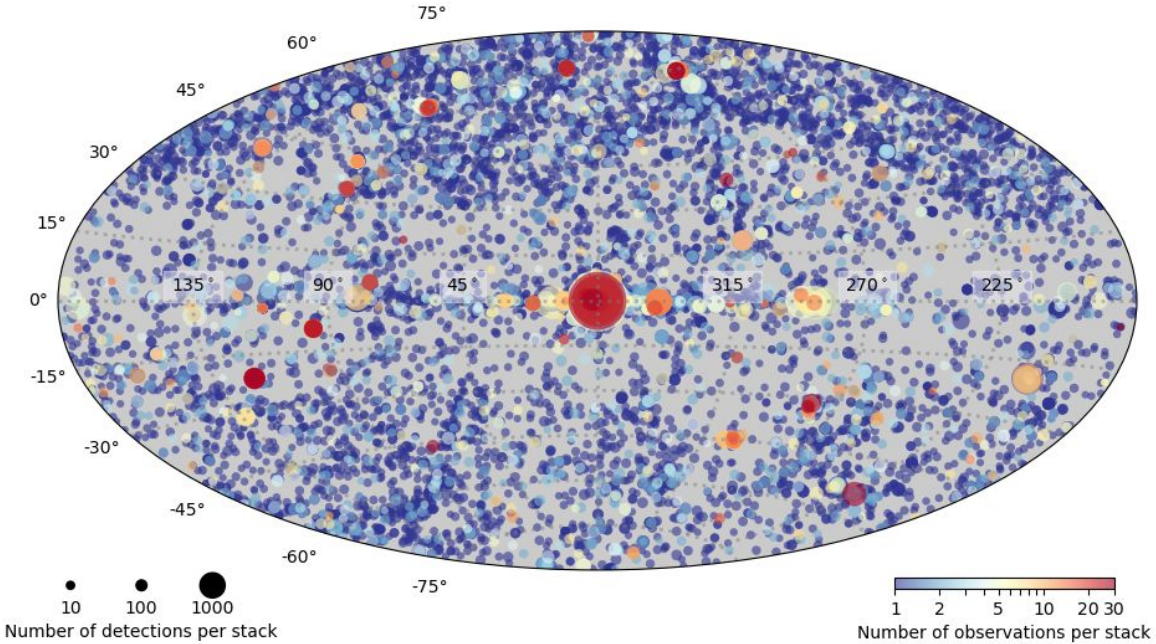
properties per source

NEW

aperture-photometry posterior draws

Release 2.2, 6 October 2026 · +6% sources, +8% sky area vs CSC 2.1 · What's new · cxc.cfa.harvard.edu/csc

Where the catalog looks



Every circle is a stack · color: observations per stack · size: detections per stack · Fig. 1, CSC home page

Three levels: observation, stack, master source

Observation
each ObsID analyzed on its own: variability within an observation

Stack
overlapping observations (pointings within ~1′) co-added for detection

Master source
one entry per object on the sky, combining all its detections

Which level do I use?

- Master source: “what is this object like on average?”
- Per-observation: “did it change between observations?”
- Stack: deepest view of a field

What the catalog gives you

Band	Energy (keV)
b broad	0.5 – 7.0
u ultrasoft	0.2 – 0.5
s soft	0.5 – 1.2
m medium	1.2 – 2.0
h hard	2.0 – 7.0
w wide (HRC)	≈ 0.1 – 10

The spectra come with responses: ready to fit in Sherpa, as in Part 2.

Properties

Positions & errors
Fluxes in each band
Hardness ratios
Variability
Spectral fits
Source extent
Upper limits

Data products

Event files & images
Spectra + ARF + RMF
Light curves
Source regions
PSF models
Sensitivity maps
Photometry draws (new)

Ways in

CSCview
full queries (ADQL),
cross-matches, downloads

Quick Search
web cone search or cross-match

WorldWide Telescope
browse sources on the sky

Virtual Observatory
cone search, TAP, SIA from Python
(pyvo)

CIAO
query and download from the
command line

With CIAO: `search_csc` · `obsid_search_csc` · all access options

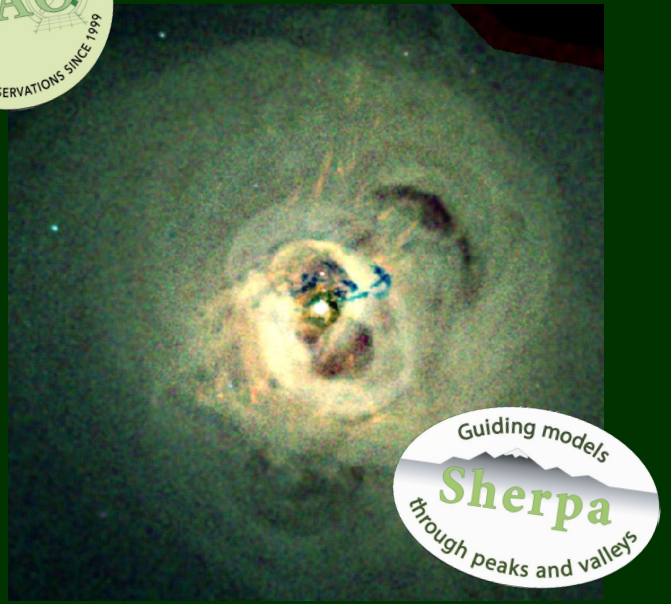
```
% search_csc pos="16:26:24.16 -24:24:49.4" radius=0.6 \
    outfile=rho_oph.tsv download=all root=./csc \
    filetypes=pha,arf,rmf,reg catalog=latest
% obsid_search_csc obsid=1843 outfile=1843_csc.tsv catalog=latest
```

radius in arcmin; catalog=latest = newest release; download=all gets products ready for Sherpa

TAKE-HOME

Your toolkit for this afternoon

- Images: dmcopy to bin and filter, deflare, fluximage, wavdetect, srcflux
- Spectra: specextract → spectrum + ARF + RMF → Sherpa
- Catalog: check the CSC first; its products are ready to use
- Next: SAOImageDS9 and dax, the same CIAO tools from DS9 menus; then statistics



Perseus Cluster · Chandra Photo Album