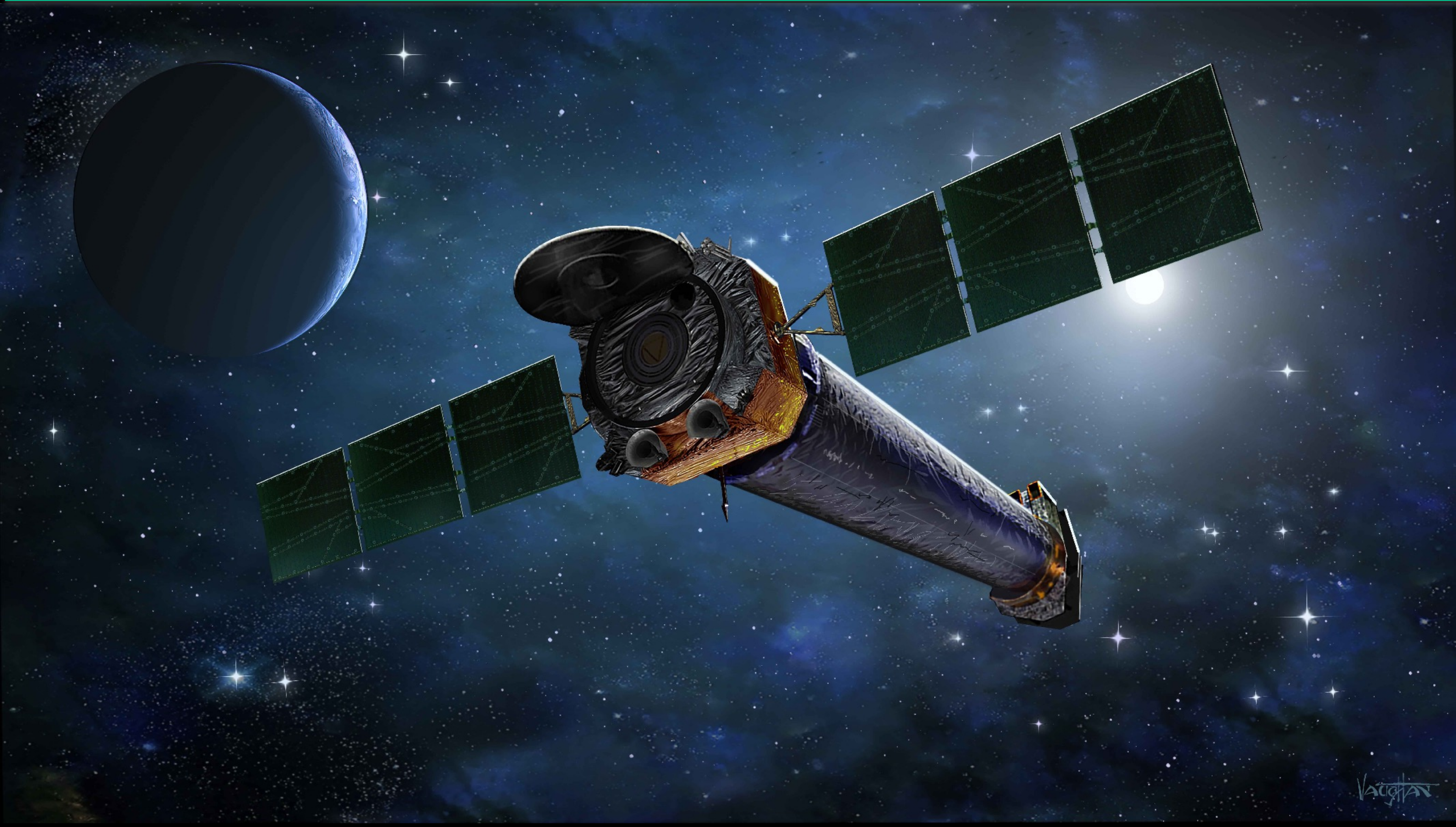
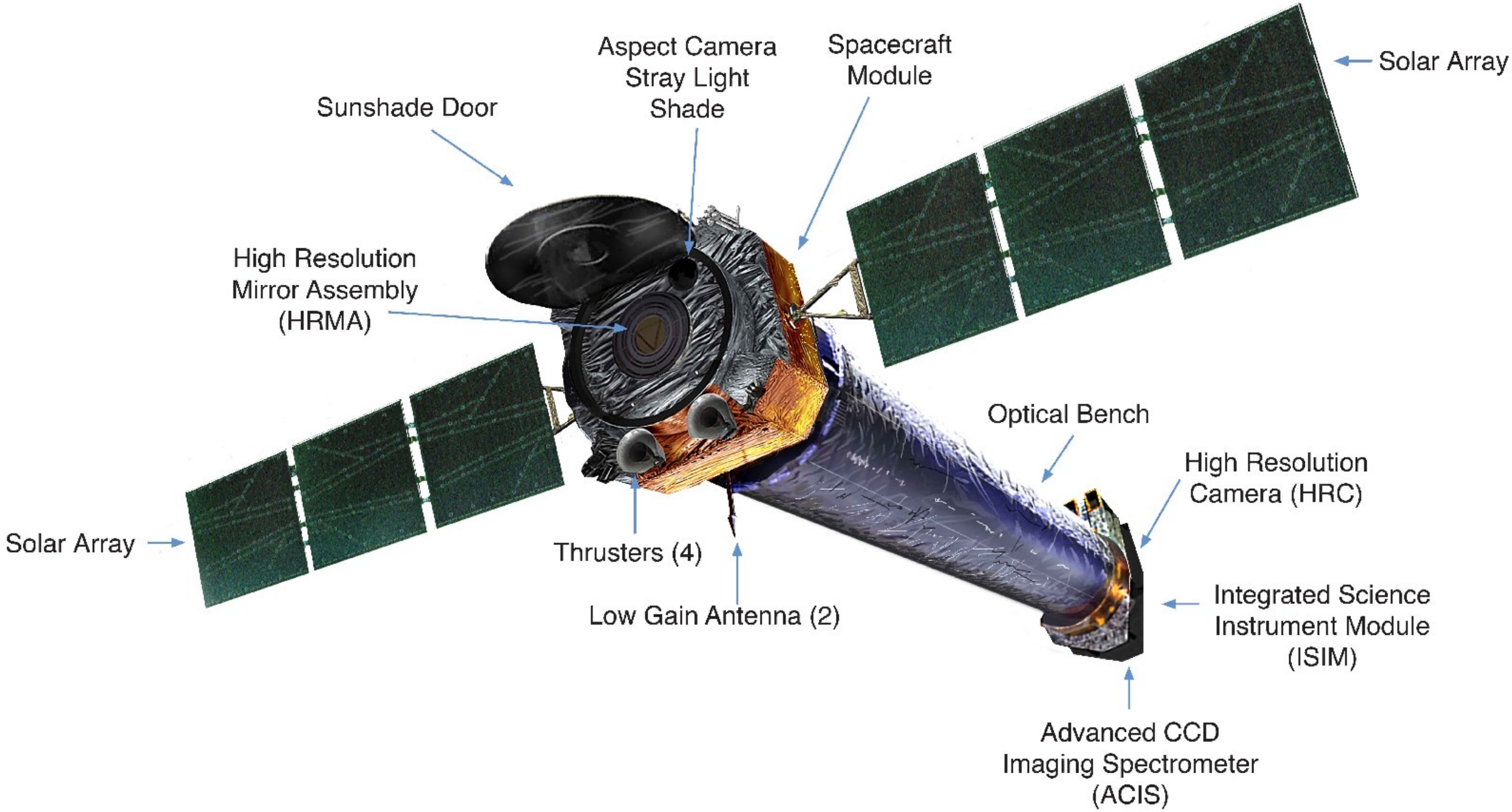
Chandra data analysis: tutorial



Astrophysics Laboratory course – AA2024-25

The spacecraft



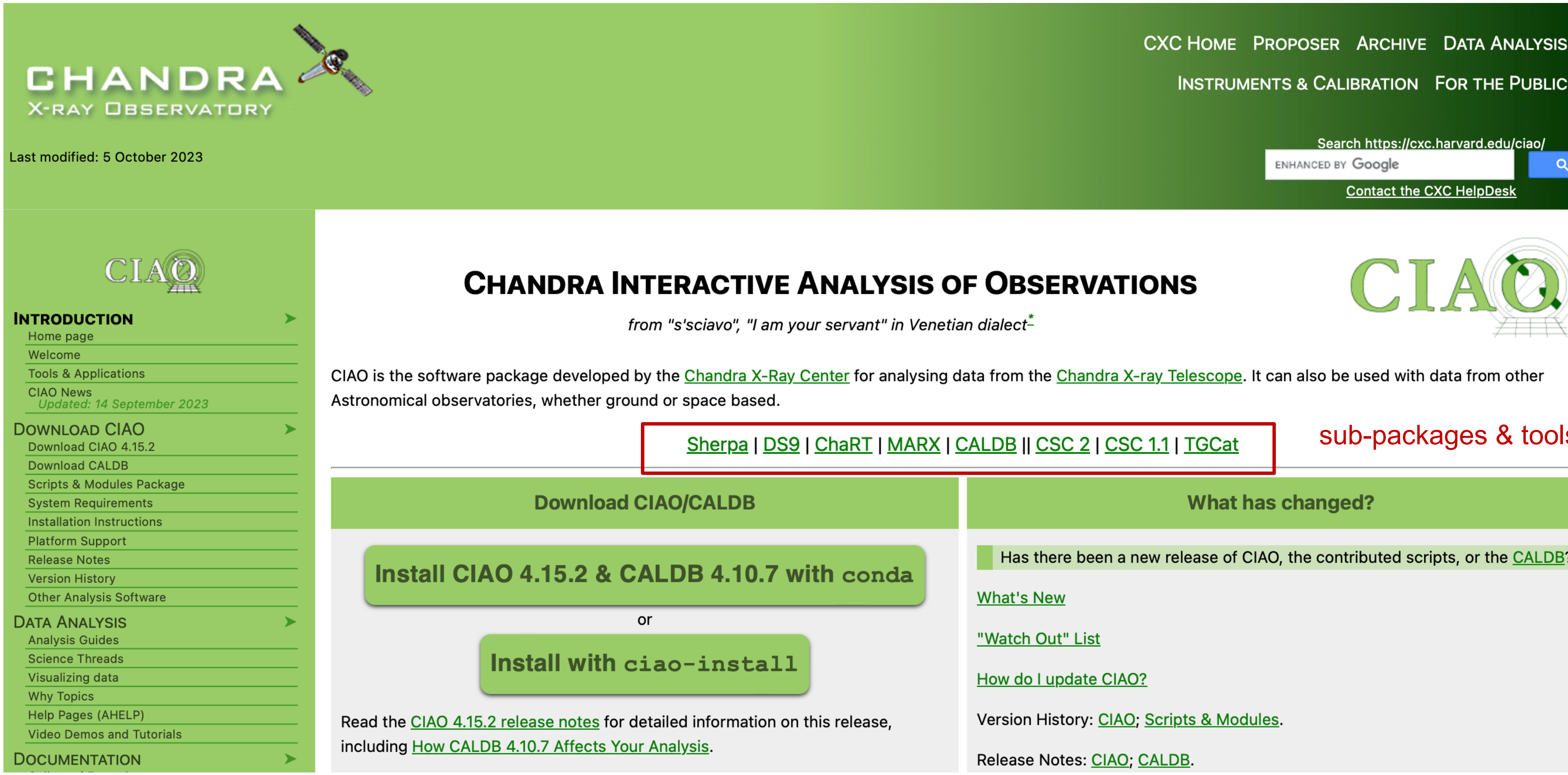
Only one instrument in the focal plane "active" for each observation
(different wrt. XMM-Newton)
Further details in M. Dadina's presentation

Outline of the Chandra tutorial

- ❑ Chandra webpage, software and data download
- ❑ Data structure
- ❑ Chandra threads and main parameter evaluation
- ❑ Data reprocessing and filtering
- ❑ Imaging analysis
  - ❑ Image visualization
  - ❑ Pileup evaluation & Webpimms
  - ❑ Source photon statistics
  - ❑ Smoothing
  - ❑ Contours
  - ❑ Choice of source and background regions
- ❑ Timing analysis: lightcurves & evaluation of variability
- ❑ Spectral extraction

Chandra webpage & software CIAO

Chandra website: https://cxc.cfa.harvard.edu

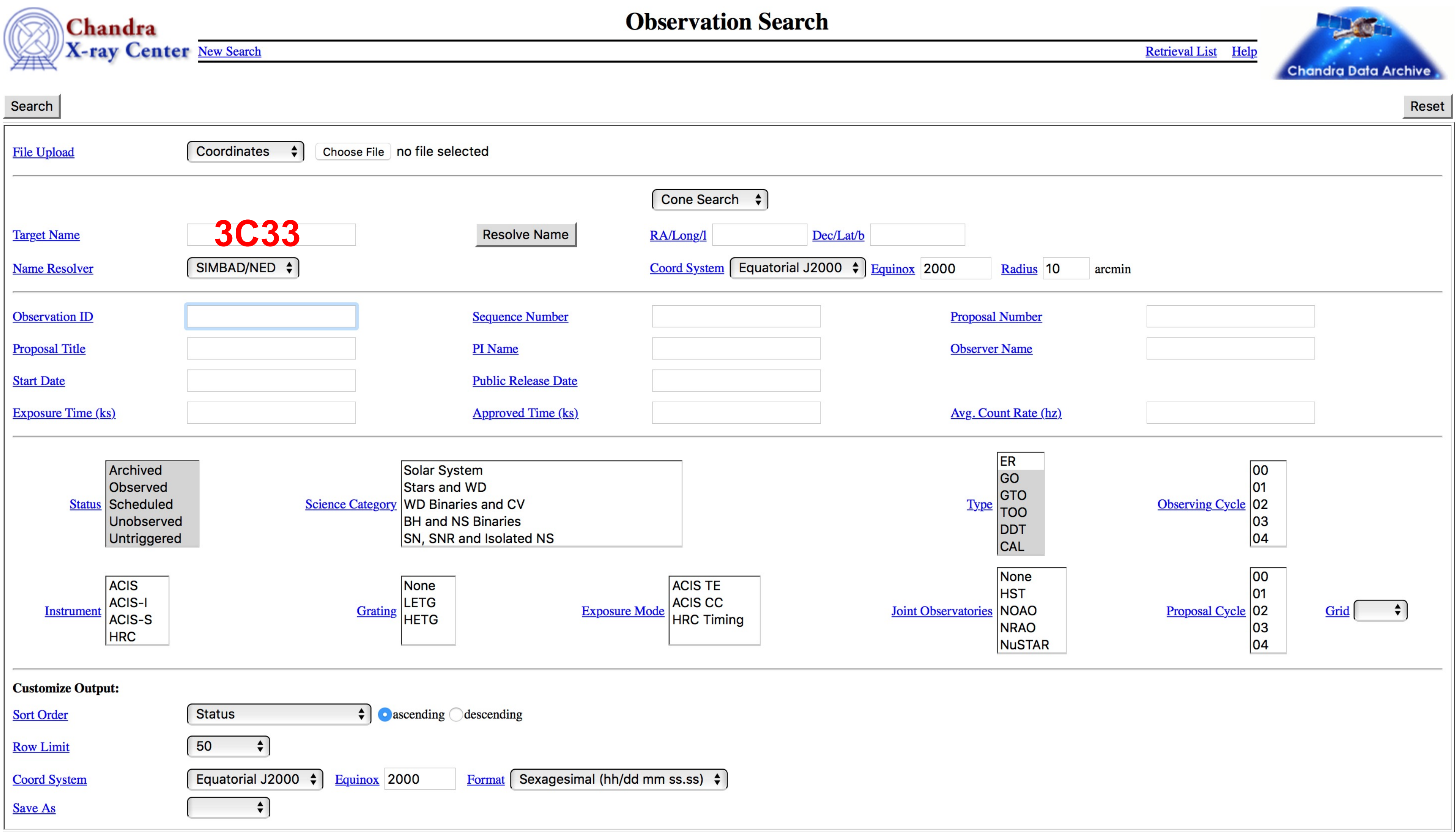


Chandra CIAO website: https://cxc.cfa.harvard.edu/ciao

All relevant documents about telescope + instruments and manuals can be found here

Data download: the Chandra archive

Chandra webchaser: https://cda.harvard.edu/chaser/



Selection possible on the basis of source name/coordinates/PI name/ObsID, etc

Chandra X-ray Center New Search

Search Results

Search Results Retrieval List Help

Chandra Data Archive

View Observation Information

Add Products to Retrieval List

- Primary package
- Secondary package
- Custom selection

Select all | Unselect all

Select	Row	Seq Num	Obs ID	Instrument	Grating	Appr Exp	Exposure	Target Name	PI Name	RA	Dec	Status	Data Mode	Exp Mode	Avg Cnt Rate	Evt Cnt	Start Date	Public Release Date	Proposal	Type	Obs Cycle	Prop Cycle	Science Category
	1	701325	6910	ACIS-S	NONE	20.0	19.91	3C 33	Murray	01 08 51.20	+13 18 36.43	archived	FAINT	TE	8.05	160293	2005-11-08 00:20:44	2005-11-09 06:11:47	07701073	GTO	07	07	ACTIVE GALAXIES AND QUAS
	2	701325	7200	ACIS-S	NONE	20.0	19.92	3C 33	Murray	01 08 51.20	+13 18 36.43	archived	FAINT	TE	8.20	163252	2005-11-12 16:31:10	2005-11-14 17:21:56	07701073	GTO	07	07	ACTIVE GALAXIES AND QUAS

you can view the details of each observation

View Observation Information

Add Products to Retrieval List

- Primary package
- Secondary package
- Custom selection

lect all | Unselect all

Select	Row	Seq Num	Obs ID	Instrument	Grating	Appr Exp	Exposure	Target Name	PI Name	RA	Dec	Status	Data Mode	Exp Mode	Avg Cnt Rate	Evt Cnt	Start Date
	1	701325	6910	ACIS-S	NONE	20.0	19.91	3C 33	Murray	01 08 51.20	+13 18 36.43	archived	FAINT	TE	8.05	160293	2005-11-08 00:20:44
	2	701325	7200	ACIS-S	NONE	20.0	19.92	3C 33	Murray	01 08 51.20	+13 18 36.43	archived	FAINT	TE	8.20	163252	2005-11-12 16:31:10

Seq. # ObsID Instr Expo Target Obs. date

The **first digit** (if 4 numbers) or **the first two digits** (if 5 numbers) tells you the observing Cycle of the observation

Mark one (all) of these boxes to select the observation(s) for the download

An archive (.tar) file will be prepared for the download. This contains both **primary** and **secondary datasets** needed for immediate use for scientific purposes or complete reprocessing using *the most up-to-date calibrations* and CIAO tools

Details of the observation: instrument setup, CCDs in use, abstract of the proposal, pipeline-processed products, etc.

Observation ID: **7200**

Observation ID: **7200**

Add to Retrieval List

- [x] Primary package
- [x] Secondary package
- [ ] Custom selection

- Summary
- Details
- V&V Report
- Proposal Abstract
- Images
- Publications
- Data packages
  - Primary
  - Secondary
- External links
  - Processing Status
  - Sequence Summary
- Related Observations
  - By Sequence
  - By Proposal
  - By Monitor/Followup
  - By Group
  - By Grid

Sequence Number:	701325	**Status:**	archived
Observation ID:	7200	**Proposal Number:**	07701073
Type:	GTO	**Proposal Cycle:**	07
PI Name:	Murray	**Observer:**	Kraft
Science Category:	ACTIVE GALAXIES AND QUASARS	**Joint Observatories:**	None
Target Name:	3C 33	**Grid Name:**	
RA (J2000):	01 08 51.20		
Dec (J2000):	+13 18 36.43		
Instrument:	ACIS-S	**Data Mode:**	FAINT
Grating:	NONE		
Start Date:	2005-11-12 16:31:10	**Observing Cycle:**	07
Approved Time:	20.00 ks	**Public Release Date:**	2005-11-14 17:21:56
Exposure Time:	19.92 ks		

Sequence number (**7**01325 here): six-digit number, the first one provides the category of your observations (7=AGN, 8=clusters, etc.)

ALTERNATIVELY, using a CIAO task

- find_chandra_obsid ‘3c33’

# obsid	sepn	inst	grat	time	obsdate	piname	target
6910	1.7	ACIS-S	NONE	19.9	2005-11-08	Murray	"3C 33"
7200	1.7	ACIS-S	NONE	19.9	2005-11-12	Murray	"3C 33"

- download_chandra_obsid 7200

In case you would like to download more than one dataset:

- download_chandra_obsid 7200, 6910

Data structure

→ package_3974172_221113122215.tar (using webchaser; archive file)

- tar xvf package_ 3974172_221113122215.tar → directory 7200/

```
axaff07200N004_VV001_vv2.pdf
00README
oif.fits
primary
secondary
```

Note: *ciao* tools work also on gzipped (compressed) files

PRIMARY

```
orbitf248097900N001_eph1.fits.gz
pcadf07200_000N001_asol1.fits.gz
acisf07200_000N004_fov1.fits.gz
acisf07200_000N004_bpix1.fits.gz
acisf07200N004_cntr_img2.jpg
acisf07200N004_cntr_img2.fits.gz
acisf07200N004_full_img2.jpg
acisf07200N004_full_img2.fits.gz
acisf07200N004_evt2.fits.gz
```

Scientific data + pointing information + bad pixel file + **fully calibrated events (evt2)**

SECONDARY

Housekeeping files + bias + mask + unfiltered event file (evt1)

```
acisf248199703N004_2_bias0.fits.gz
acisf248199703N004_1_bias0.fits.gz
acisf248199703N004_5_bias0.fits.gz
acisf248199703N004_4_bias0.fits.gz
acisf248199703N004_3_bias0.fits.gz
acisf248200890N004_pbk0.fits.gz
acisf07200_000N004_stat1.fits.gz
acisf07200_000N004_msk1.fits.gz
acisf07200_000N004_flt1.fits.gz
acisf07200_000N004_mtl1.fits.gz
acisf07200_000N004_evt1.fits.gz
axaff07200N004_VV001_vvref2.pdf.gz
aspect
ephem
```

FILE FORMAT

Instrument ObsID evt2

acisf07200N004 _evt2.fits.gz

f=flight file revision file format (.gz: compressed)

- The event file (and most of the files) are in **FITS** (*Flexible Image Transport System*) format
- A single Chandra file can contain multiple “datasets” (e.g., data, Good Time Intervals, weight map, regions) which are stored in ”blocks”
- Blocks can contain image or table data
- The event file is a sort of 4-D array which stores for each event the information about position, energy and time of arrival of the photons + other info
- dmstat and dmlist (ciao tools) and fv (ftool) allows the visualization of these blocks

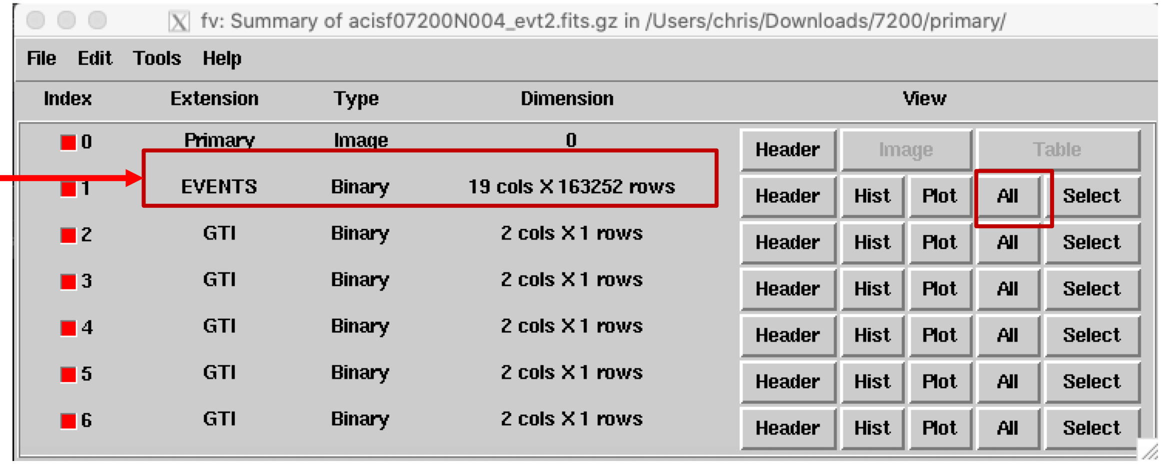
- dmlist acisf07200N004_evt2.fits.gz cols

```
--------------------------------------------------------------------------------
Columns for Table Block EVENTS
--------------------------------------------------------------------------------

ColNo  Name                 Unit        Type             Range              Null
   1   time                 s            Real8          248200333.7314499915:248222518.3199700117 -          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                      9999       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
```

- fv acisf07200N004_evt2.fits.gz (fv: ftool, HEASOFT package)

N(rows)=number of events (total counts for the entire observation)

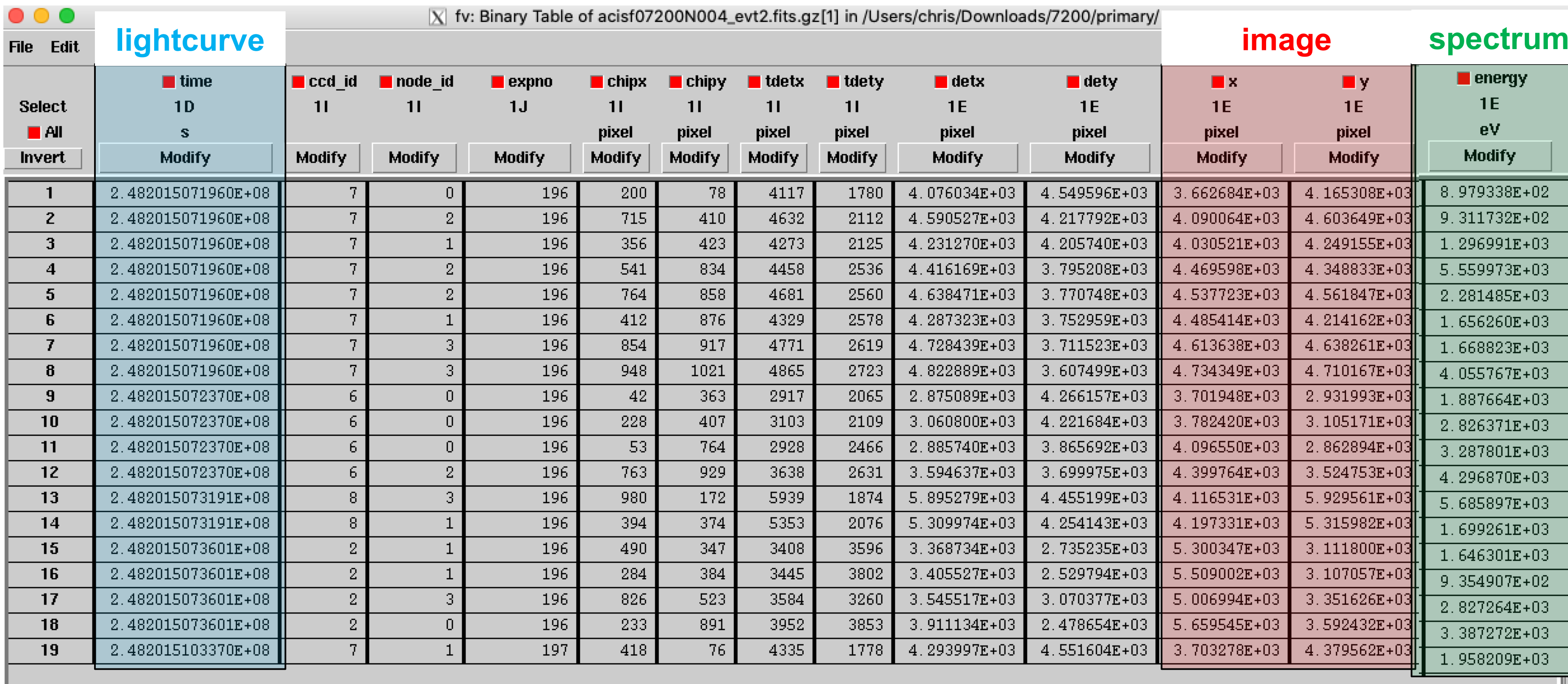


fv: Summary of acisf07200N004_evt2.fits.gz in /Users/chris/Downloads/7200/primary/

File Edit Tools Help

Index	Extension	Type	Dimension	View				
0	Primary	Image	0	Header	Image	Table		
1	EVENTS	Binary	19 cols X 163252 rows	Header	Hist	Plot	All	Select
2	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select
3	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select
4	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select
5	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select
6	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select

- X,Y → image
- Time → lightcurve
- Energy → spectrum



fv: Binary Table of acisf07200N004_evt2.fits.gz[1] in /Users/chris/Downloads/7200/primary/

File Edit

lightcurve | image | spectrum

Select / All / Invert	time 1D s	ccd_id 1I	node_id 1I	expno 1J	chipx 1I pixel	chipy 1I pixel	tdetx 1I pixel	tdety 1I pixel	detx 1E pixel	dety 1E pixel	x 1E pixel	y 1E pixel	energy 1E eV
	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	2.482015071960E+08	7	0	196	200	78	4117	1780	4.076034E+03	4.549596E+03	3.662684E+03	4.165308E+03	8.979338E+02
2	2.482015071960E+08	7	2	196	715	410	4632	2112	4.590527E+03	4.217792E+03	4.090064E+03	4.603649E+03	9.311732E+02
3	2.482015071960E+08	7	1	196	356	423	4273	2125	4.231270E+03	4.205740E+03	4.030521E+03	4.249155E+03	1.296991E+03
4	2.482015071960E+08	7	2	196	541	834	4458	2536	4.416169E+03	3.795208E+03	4.469598E+03	4.348833E+03	5.559973E+03
5	2.482015071960E+08	7	2	196	764	858	4681	2560	4.638471E+03	3.770748E+03	4.537723E+03	4.561847E+03	2.281485E+03
6	2.482015071960E+08	7	1	196	412	876	4329	2578	4.287323E+03	3.752959E+03	4.485414E+03	4.214162E+03	1.656260E+03
7	2.482015071960E+08	7	3	196	854	917	4771	2619	4.728439E+03	3.711523E+03	4.613638E+03	4.638261E+03	1.668823E+03
8	2.482015071960E+08	7	3	196	948	1021	4865	2723	4.822889E+03	3.607499E+03	4.734349E+03	4.710167E+03	4.055767E+03
9	2.482015072370E+08	6	0	196	42	363	2917	2065	2.875089E+03	4.266157E+03	3.701948E+03	2.931993E+03	1.887664E+03
10	2.482015072370E+08	6	0	196	228	407	3103	2109	3.060800E+03	4.221684E+03	3.782420E+03	3.105171E+03	2.826371E+03
11	2.482015072370E+08	6	0	196	53	764	2928	2466	2.885740E+03	3.865692E+03	4.096550E+03	2.862894E+03	3.287801E+03
12	2.482015072370E+08	6	2	196	763	929	3638	2631	3.594637E+03	3.699975E+03	4.399764E+03	3.524753E+03	4.296870E+03
13	2.482015073191E+08	8	3	196	980	172	5939	1874	5.895279E+03	4.455199E+03	4.116531E+03	5.929561E+03	5.685897E+03
14	2.482015073191E+08	8	1	196	394	374	5353	2076	5.309974E+03	4.254143E+03	4.197331E+03	5.315982E+03	1.699261E+03
15	2.482015073601E+08	2	1	196	490	347	3408	3596	3.368734E+03	2.735235E+03	5.300347E+03	3.111800E+03	1.646301E+03
16	2.482015073601E+08	2	1	196	284	384	3445	3802	3.405527E+03	2.529794E+03	5.509002E+03	3.107057E+03	9.354907E+02
17	2.482015073601E+08	2	3	196	826	523	3584	3260	3.545517E+03	3.070377E+03	5.006994E+03	3.351626E+03	2.827264E+03
18	2.482015073601E+08	2	0	196	233	891	3952	3853	3.911134E+03	2.478654E+03	5.659545E+03	3.592432E+03	3.387272E+03
19	2.482015103370E+08	7	1	197	418	76	4335	1778	4.293997E+03	4.551604E+03	3.703278E+03	4.379562E+03	1.958209E+03

Data analysis: Chandra threads

https://cxc.cfa.harvard.edu/ciao/threads/

Description of *ciao* commands/tools to be used, depending on the goals of the project and the kind of analysis to be carried out

Science Threads

WHAT'S NEW | WATCH OUT

Top | All | Intro | Data Prep | Imag | Imag Spec | Grating | Timing | psf | TTT || Sherpa | Proposal | PSF Central

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All threads

A list of all the threads on one page.

Introduction

Beginners should start here. The Introductory threads provide an overview of the main components (GUI applications, parameter files) and concepts (the Data Model, filtering) in the CIAO data analysis software.

Data Preparation

When Chandra data goes through Standard Data Processing (SDP), the most recently available calibration is applied to it. Since this calibration is continuously being improved, one should check whether there are newer files available. Similarly, some science decisions are made during SDP; every user has the option to reprocess the data with different parameters.

Imaging NEW UPDATED

The Imaging threads cover a wide range of topics that include source detection, creating exposure maps and normalized images, and calculating image statistics. How to create color images for publication is addressed, as well as merging data from multiple observations.

Imaging Spectroscopy

After extracting source and background PI or PHA spectra from an imaging observation, the appropriate response files (ARF, RMF) are created so that the data may be modeled and fit. In the case of multiple or extended sources, a weighted ARF and RMF are built for the spectral analysis.

Grating Spectroscopy

Data analysis: main data parameter evaluation

Preliminary checks on some useful data-related parameters

- punlearn dmkeypar — Reset the dmkeypar file
- dmkeypar 7200/primary/*evt2* EXPOSURE echo+ — Nominal exposure time
- dmkeypar 7200/primary/*evt2* DATAMODE echo+ — Data mode (faint/vfaint)
- dmkeypar 7200/primary/*evt2* DETNAM echo+ — Detector in use
- dmkeypar 7200/primary/*evt2* DATE-OBS echo+ — Date of observation

→ **OUTPUTS**

- dmkeypar 20908/primary/*evt2* EXPOSURE echo+
19920.379835851 → T=19.92 ks

- dmkeypar 20908/primary/*evt2* DATAMODE echo+
FAINT → FAINT mode

- dmkeypar 20908/primary/*evt2* DETNAM echo+
*ACIS-236**7**8* → ACIS-S in use (ccd=7: aimpoint of acis-s)

- dmkeypar 20908/primary/*evt2* EXPTIME echo+
2005-11-12T16:32:13 → Nov. 12th, 2005

Data analysis: data reprocessing. I

Scientific files
Housekeeping files

Data reprocess to apply the latest (and ad-hoc, if needed) calibrations, depending on the science goals and data type/quality

Cleaned event files

Data analysis: data reprocessing. II

chandra_repro task

comprehensive of many different tasks

- punlearn chandra_repro
- chandra_repro indir=7200 outdir=7200_new verbose=3 check_vf_pha=no

In case of FAINT data-mode data, check_vf_pha=no; in case of VFAINT: check_vf_pha=yes

'mode' to reduce the impact of the already limited background in Chandra observations

To list all of the options in the parameter file:

- plist chandra_repro

```
Parameters for /Users/chris/cxcds_param4/chandra_repro.par

         indir = ./               Input directory
        outdir =                  Output directory (default = $indir/repro)
         (root = )                Root for output filenames
     (badpixel = yes)             Create a new bad pixel file?
(process_events = yes)             Create a new level=2 event file?
     (destreak = yes)             Destreak the ACIS-8 chip?
   (set_ardlib = yes)             Set ardlib.par with the bad pixel file?
 (check_vf_pha = no)              Clean ACIS background in VFAINT data?
      (pix_adj = default)         Pixel randomization: default|edser|none|randomize
(recreate_tg_mask = no)              Re-run tgdetect and tg_create_mask rather than use the Level 2 region extension?
  (asol_update = yes)             If necessary, apply boresight correction to aspect solution file?
      (cleanup = yes)             Cleanup intermediate files on exit
      (clobber = no)              Clobber existing file
      (verbose = 1)               Debug Level(0-5)
         (mode = ql)
```

Data analysis: filtering

Newly reprocessed files

```
pcadf07200_000N001_asol1.fits
acisf07200_000N004_fov1.fits
acisf07200_000N004_bpix1.fits
acisf07200_000N004_stat1.fits
acisf07200_000N004_msk1.fits
acisf07200_000N004_mtl1.fits
acisf248200890N004_pbk0.fits
axaff07200N004_VV001_vv2.pdf
acisf07200_asol1.lis
acisf07200_repro_bpix1.fits
acisf07200_repro_flt2.fits
acisf07200_repro_evt2.fits
acisf07200_repro_fov1.fits
```

Newly 'reprocessed' event file **evt2**
No selection of the energy band yet

Include only 'good' data (based on grades and status) and select the energy range where Chandra is mostly sensible (keep in mind the effective area; here: 300−7000 eV)

- punlearn dmcopy
- dmcopy "7200_new/acisf07200_repro_evt2.fits[EVENTS] [grade=0,2,3,4,6,status=0,energy=300:7000]" 7200_new/obs7200_037keV_repro_evt2.fits

in one line

Alternatively, you can use the *pset command* to setup everything (one command per line):

- punlearn dmcopy
- pset dmcopy infile="7200_new/acisf07200_repro_evt2.fits[grade=0,2,3,4,6,status=0,energy=300:7000]"
- pset dmcopy outfile=7200_new/obs7200_037keV_repro_evt2.fits
- dmcopy

Data analysis: images in different bands

obs7200_037keV_repro_evt2.fits

ObsID band reprocessed evt2 file

The event file can be visualized as an image in ds9

If you need to use tasks requiring images (not event files), you may proceed in producing them (e.g., in different energy bands to enhance the contrast between different components – nuclear vs. extended emission – and adopting different binning)

Here the images (_bin1) preserve the original pixel size: **1 pix=0.492”** – Note: huge files!

- cd 7200_new/
- punlearn dmcopy
- dmcopy "obs7200_037keV_repro_evt2.fits[bin X=1,Y=1][energy=500:7000]" 3c33_057keV_ima_bin1.fits
- dmcopy "obs7200_037keV_repro_evt2.fits[bin X=1,Y=1][energy=500:2000]" 3c33_052keV_ima_bin1.fits
- dmcopy "obs7200_037keV_repro_evt2.fits[bin X=1,Y=1][energy=2000:7000]" 3c33_27keV_ima_bin1.fits

Suggestion: use appropriate names for your products (e.g., clearly indicating the energy band, whether it is either an image – _*ima* – or an event file – _*evt2* – etc.)

Data analysis: image visualization

- ds9 obs7200_037keV_repro_evt2.fits &

ds9 will open the event file as it were an image (i.e., using the X,Y info)

- ds9 3C33_052keV_ima_bin1.fits &
- ds9 3C33_27keV_ima_bin1.fits &

ds9 will open the images produced in two different energy ranges

- ds9 3C33_052keV_ima_bin1.fits 3C33_27keV_ima_bin1.fits &

two images open at the same time

- ds9 3C33_052keV_ima_bin1.fits –region 3c33_r3.reg &

soft image + region file with source position

Many possible uses of ds9

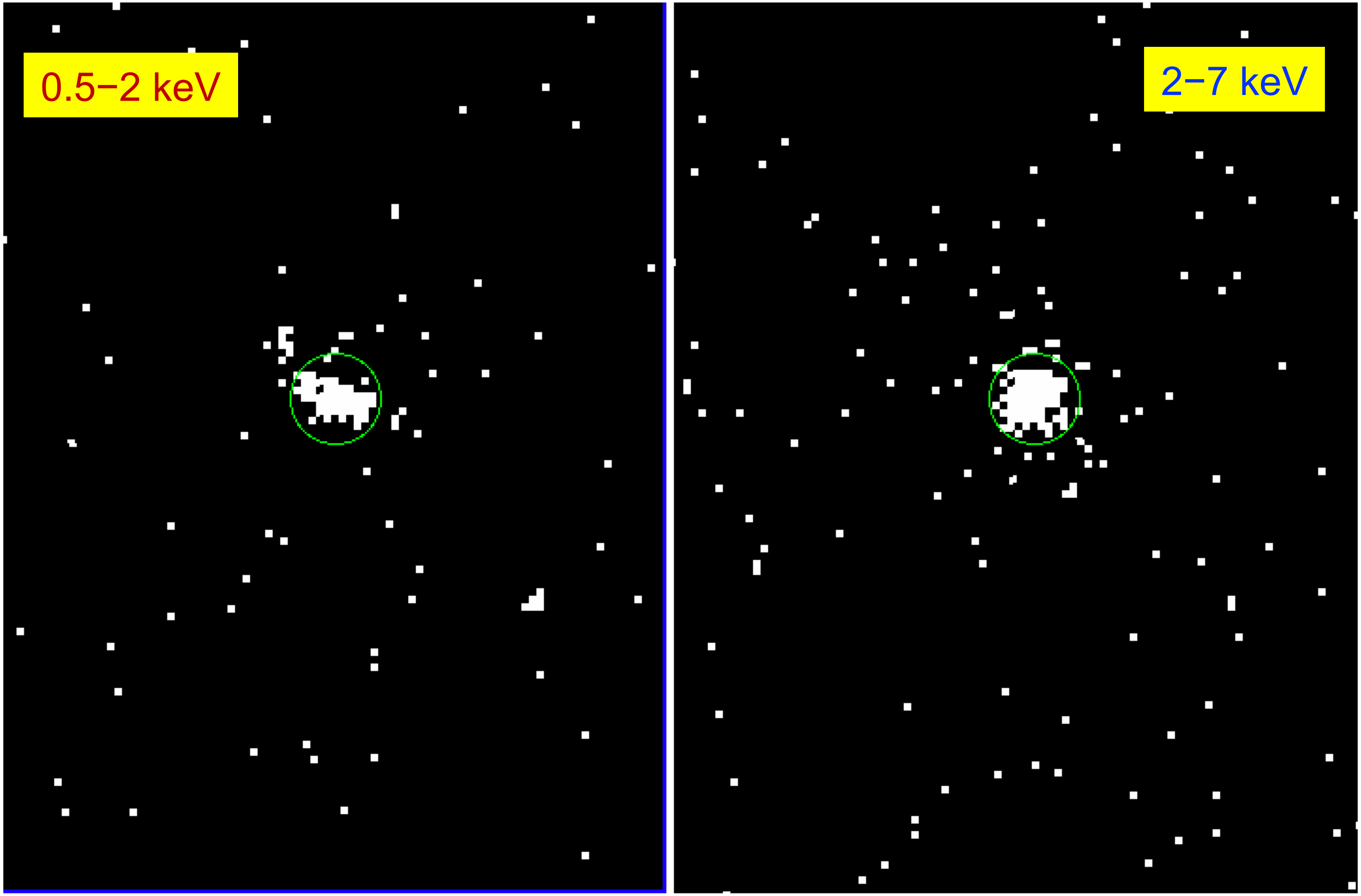
Region file → ascii file with indication of the source position [here two examples: fk5 (WCS, World Coordinates Systems) coordinates and physical (i.e., detector related) coordinates in CIAO format] - Name also the region files properly (e.g., _r3: R_{circle}=3")

3c33_r3_fk5.reg:
fk5;circle(1:08:52.85,+13:20:14.0,3.0")
3c33_r3_phys.reg:
circle(4011.2,4295.5,6.1)

In the following, we will call the source extraction region as 3c33_r3.reg

- ds9 3C33_052keV_ima_bin1.fits –region 3c33_r3.reg 3C33_27keV_ima_bin1.fits –region 3c33_r3.reg &

All in a single line on the terminal

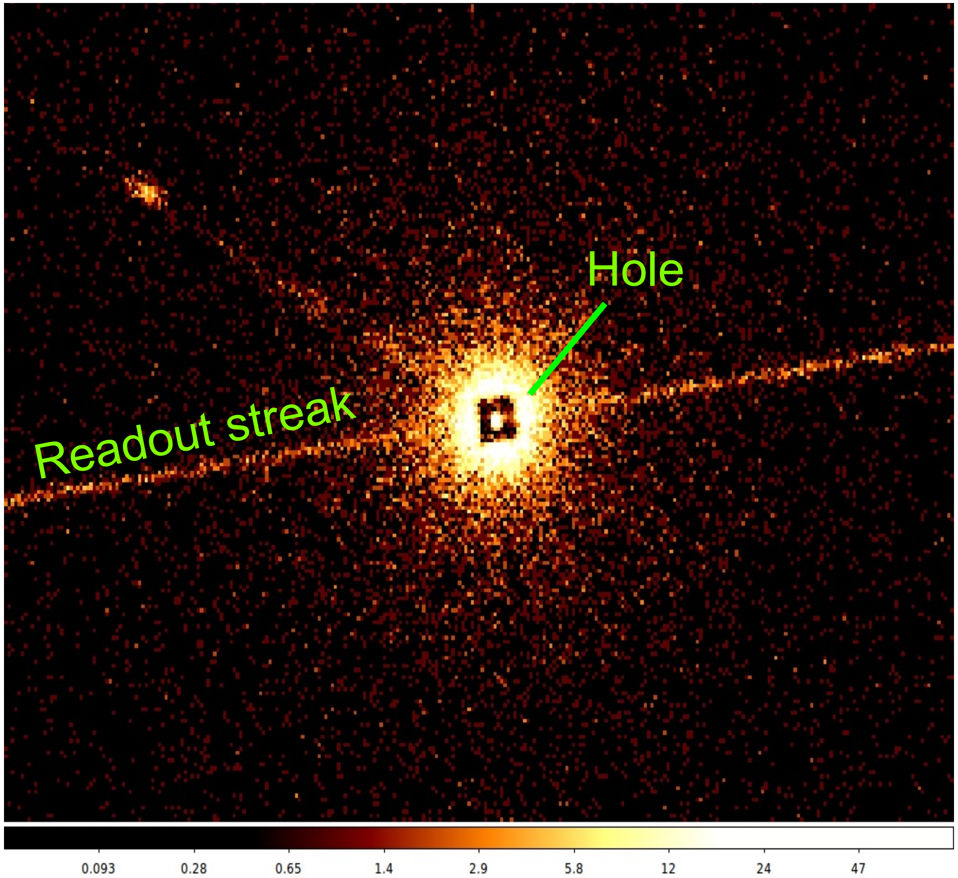


The effective area of X-ray instruments (e.g., Chandra) reaches its peak below 2 keV (currently, decreasing below 1 keV); however, the number of photons collected on the detector depends also on the intrinsic spectrum of the source

Data analysis: pileup. I

http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf

In extreme case: a "hole" at the center of the bright emitting source



Two or more photon are collected during the same read-out in the same pixel, and are read as a single event (with higher energy)

→ loss of information from these events

→ distortion in the observed spectrum (hardening, i.e., 'more' photons in the hard band)

Readout streak: the streak photons are clocked out in the wrong row, hence they are assigned the incorrect CHIPY value

Data analysis: pileup. II

EFFECTS OF PILEUP

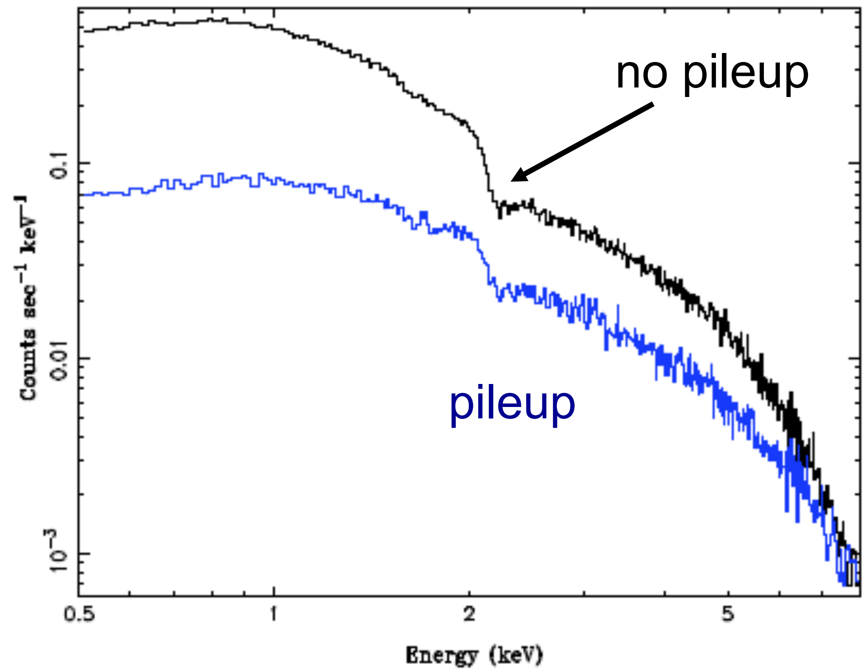
ENERGY MIGRATION photon energies sum to create a detected event with higher energy

GRADE MIGRATION event grades migrate towards values inconsistent with real photon events

→ net decrease in the observed count rate

→ net decrease in the fractional rms variability of the lightcurve

The spectral shape of the source results to be distorted



Avoid/limit pileup:

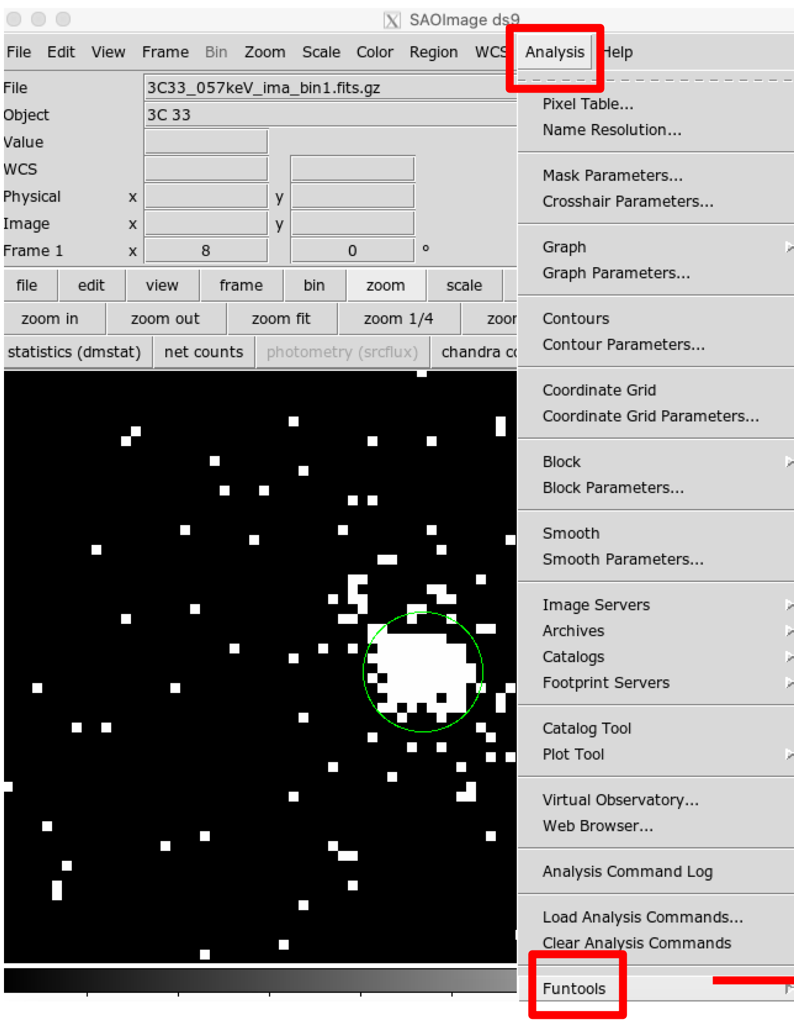
(a) fasten the reading of the CCD (using the subarray option → only a portion of the CCD around the source of interest is read)

(b) extract the spectrum from an annulus centered on the source (hence removing the "inner part" of the source, which is mostly affected by pileup)

Pileup mitigation: use an XSPEC – pileup model

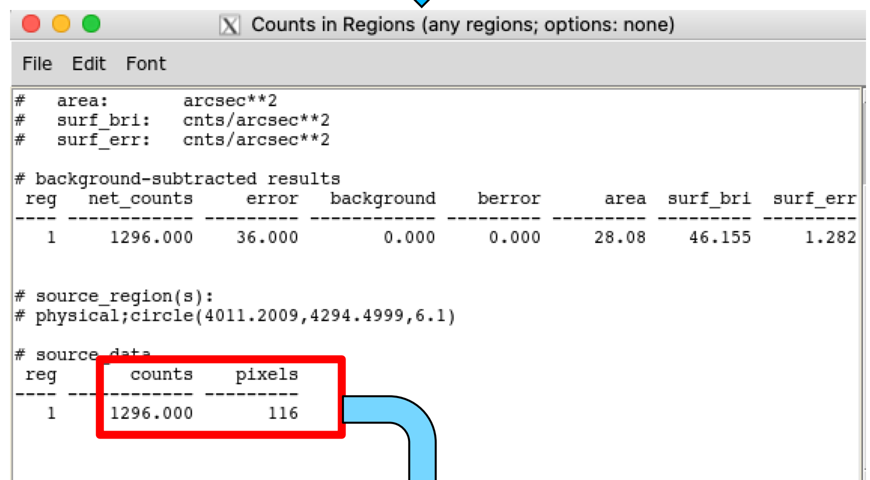
Data analysis: source photon statistics. I

- ds9 3c33_057keV_ima_bin1.fits –region 3c33_r3.reg &



Counts in region

If funtools are installed in ds9:
Analysis → Funtools → Counts in region



Counts in Regions (any regions; options: none)

File Edit Font

```
#   area:       arcsec**2
#   surf_bri:   cnts/arcsec**2
#   surf_err:   cnts/arcsec**2

# background-subtracted results
 reg   net_counts     error   background    berror      area  surf_bri  surf_err
---- ------------ --------- ------------ --------- --------- --------- ---------
   1     1296.000    36.000        0.000     0.000     28.08    46.155     1.282


# source_region(s):
# physical;circle(4011.2009,4294.4999,6.1)

# source_data
 reg       counts    pixels
---- ------------ ---------
   1     1296.000       116
```

Counts(0.5−7 keV)=1296
Area=28.1 $arcsec^2$
Exposure=19.92ks
CR=counts/expo=**0.065 c/s**

Data analysis: source photon statistics. II

Alternatively, using CIAO tools:

- dmstat "3C33_057keV_ima_bin1.fits[sky=circle(1:08:52.85,+13:20:14.0,0.05')]" centroid=no

```
EVENTS_IMAGE
    min:        0              @:       ( 4009 4289 )
    max:        250            @:       ( 4011 4295 )
   mean:        11.172413793
  sigma:        33.636565659
    sum:        1296
   good:        116
   null:        66
```

Counts(0.5−7 keV)=1296
Area=116 pix^2 (1 pix=0.492”)

Values should be very similar to the previous ones

Data analysis: pileup. III

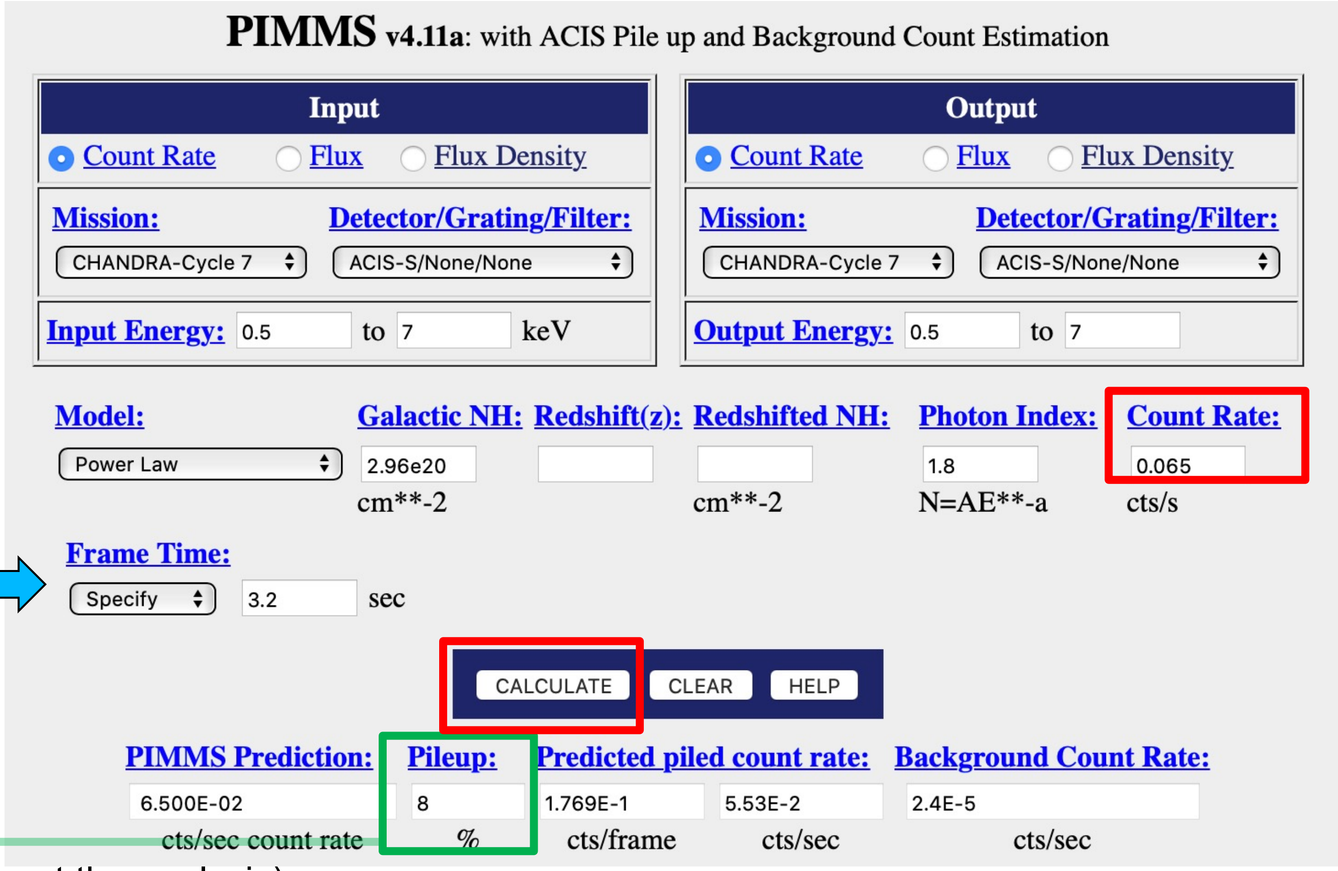
https://cxc.harvard.edu/toolkit/pimms.jsp

Use **pimms/webpimms** to convert fluxes into count rates and viceversa. In this case, we use it *to estimate the pileup fraction in our Chandra observation*

Input values

- Cycle 7 observation
- Instr: ACIS-S (none=no grating)
- Band=0.5−7 keV
- CR=0.065 cps
- Model: powerlaw with Γ=1.8 (assumption)
- $N_{H,Gal}=2.96 \times 10^{20}$ cm^{-2}

Lowering the *frame time* (CCD reading time) using a subarray configuration would have provided a lower pileup fraction (PI's choice)



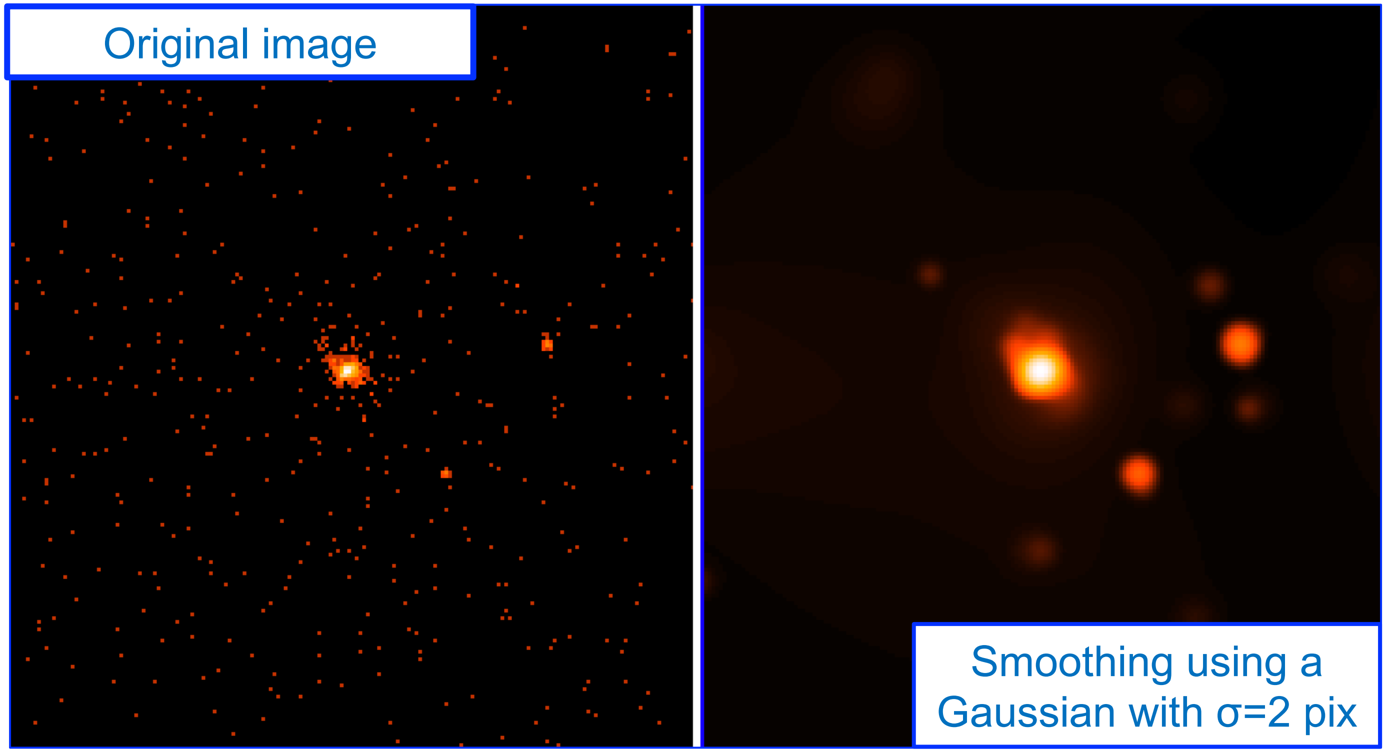
Output value

- Pileup fraction=8%

(not so high to significantly impact the analysis)

Data analysis: smoothing the image

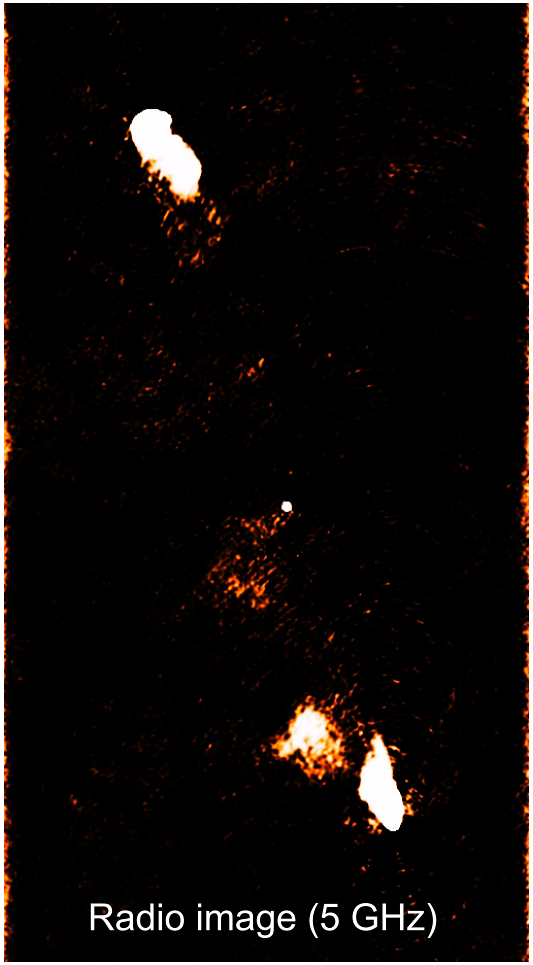
Smoothing is used to enhance faint structures. It consists of substituting the value of each pixel by the value obtained by weighting the nearby pixels using a given function (e.g., a Gaussian)



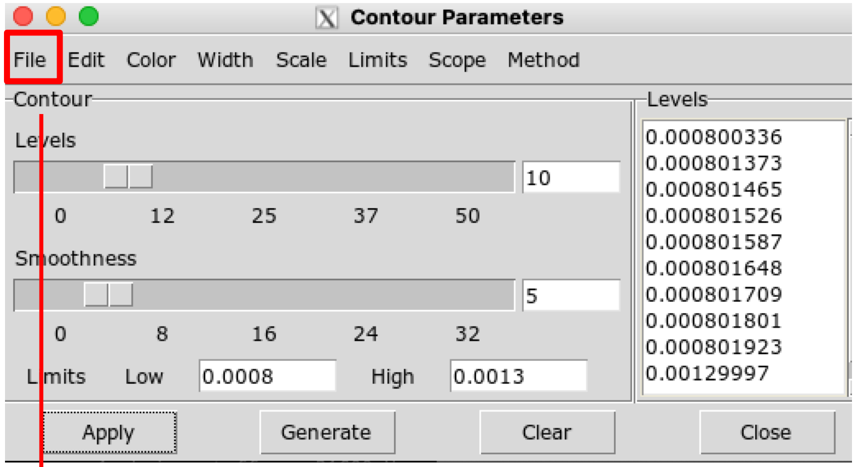
ds9 → Analysis → Smoothing & Smooth Parameters

Alternatively: use ciao tool *csmooth*

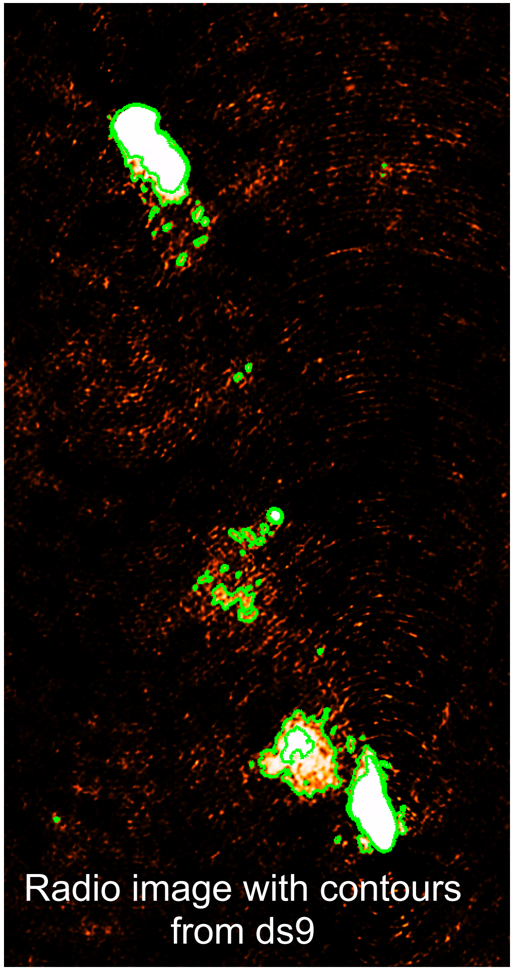
Data analysis: contours. I



ds9 radio_image → Analysis → Contours & Contour Parameters



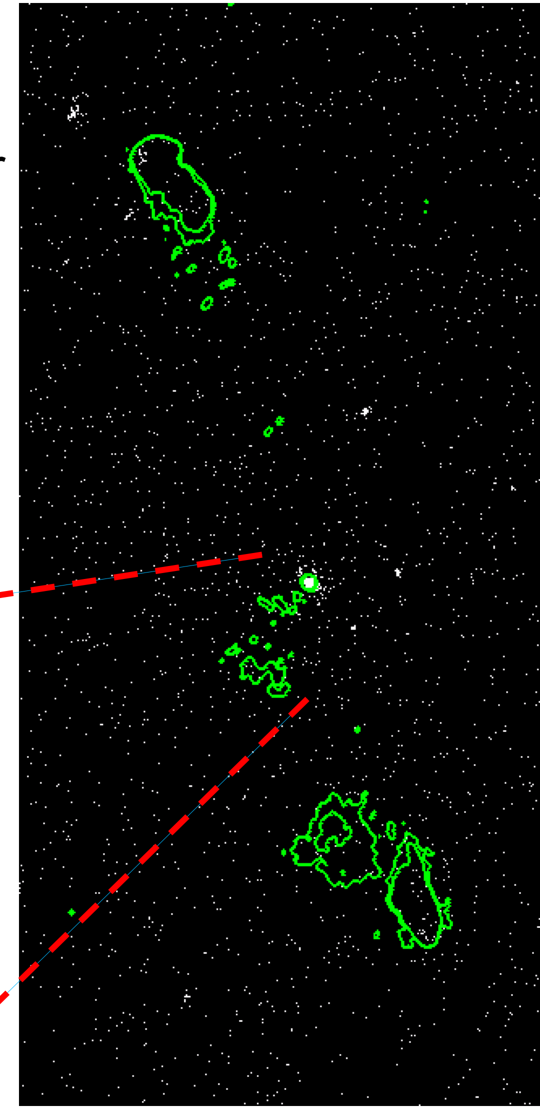
File → Save → radio.ctr



Analysis → Contour parameters → File → Open → radio.ctr

Data analysis: contours. II

Load the e.g. radio contours on the X-ray image

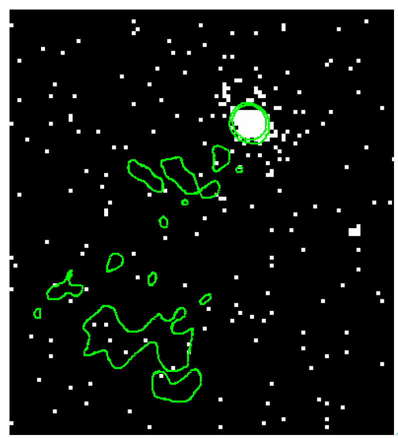


- ds9 obs7200_037keV_repro_evt2.fits -contour load radio.ctr

Alternatively:

- ds9 obs7200_037keV_repro_evt2.fits & → Analysis
→ Contour Parameters → File → Open → radio.ctr

Overlay of contours of one image onto another image (both with good astrometry) at different wavelengths allows for a quick comparison of the emissions. Remember that sensitivity and spatial resolution issues may limit the comparison

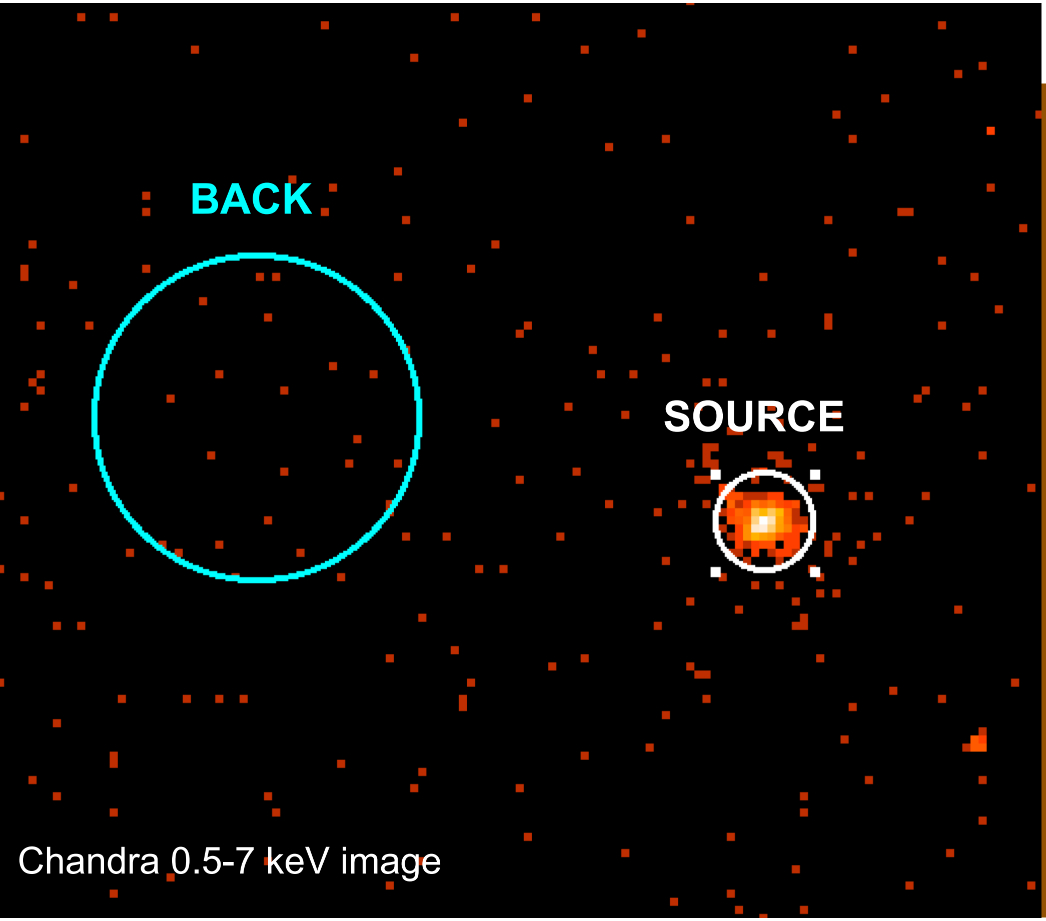


Data analysis: selection of source and back regions

source extraction region (ascii file)

- ds9 3C33_057keV_ima_bin1.fits -region 3c33_r3.reg -region back.reg &

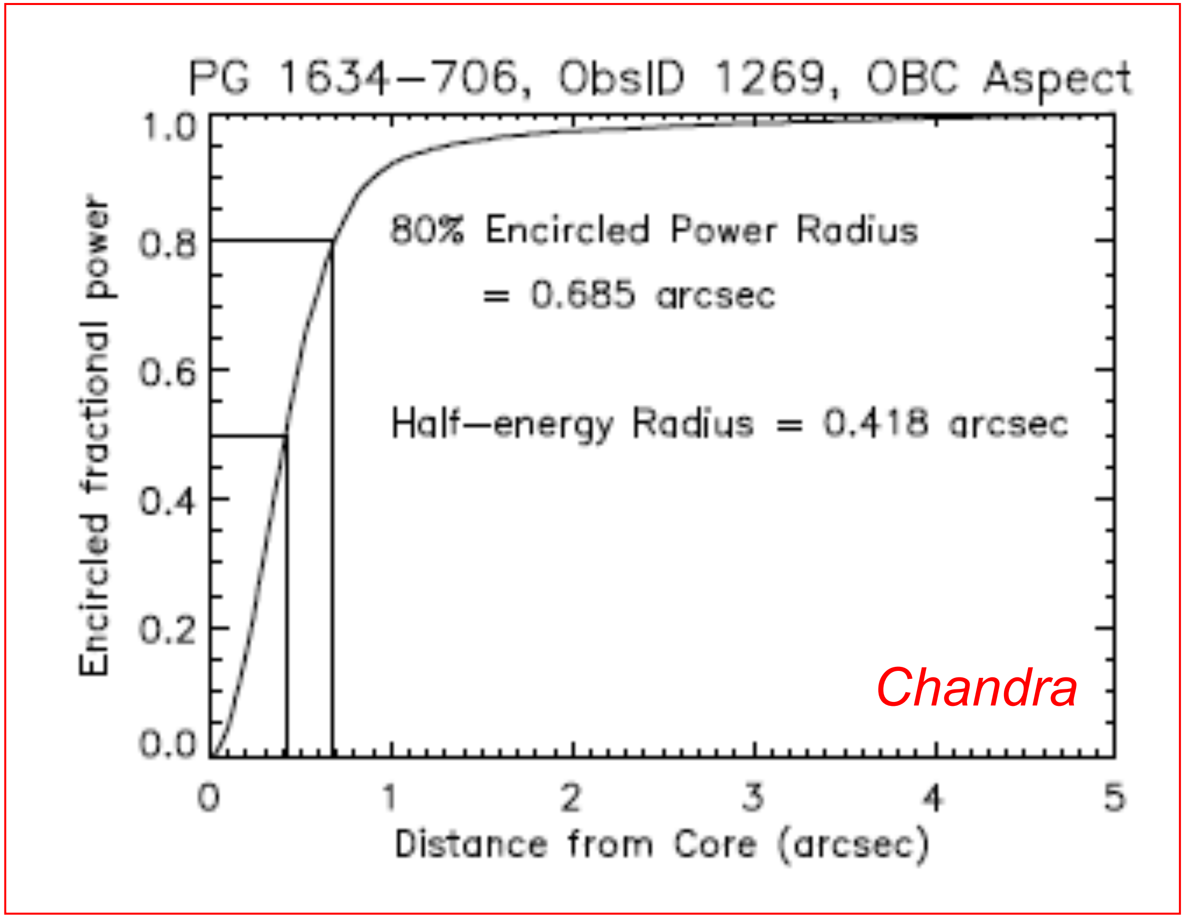
background extraction region (ascii file)



Source
- in case of pointlike emission, refer to the encircled energy fraction (EEF; see manuals) for the choice of the extraction region
- number of counts vs. signal-to-noise ratio ‘compromise’: for faint/weak sources, smaller extraction regions are usually preferred

Background
- close to the source and large enough to adequately ‘sample’ the local level of background

The Encircled Energy Fraction (EEF)

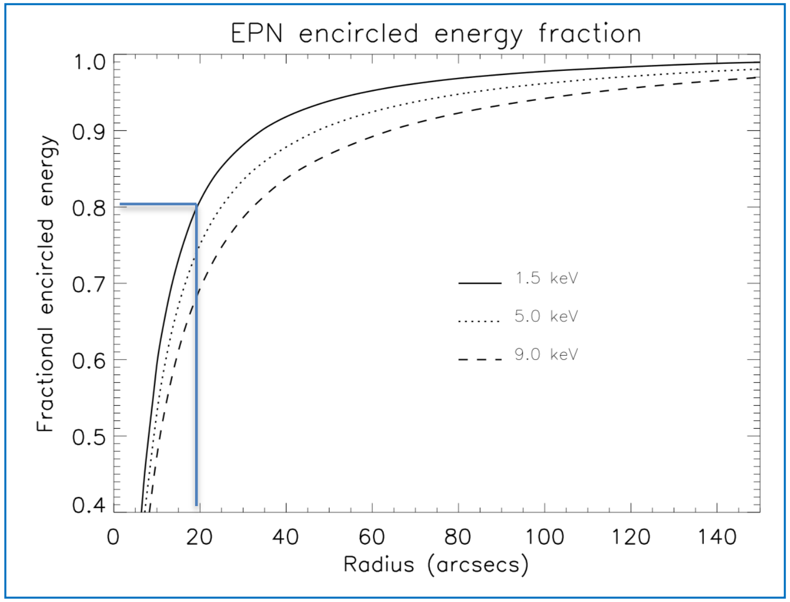


see also the lesson of M. Dadina

Angular resolution is often “replaced” by the **encircled energy fraction**, i.e., the *fraction of photons collected within a given aperture (extraction radius) centered on the source position*.
It depends on the energy and the position (x, y, θ) in the detector (being worse/larger at large off-axis angles θ). It is also referred to as the bi-dimensional PSF

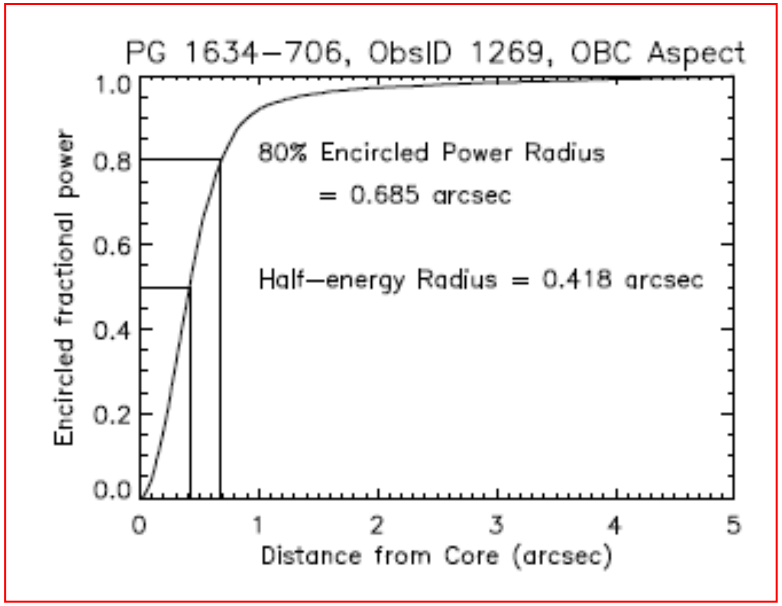
Chandra vs. XMM-Newton EEF

XMM-*Newton* vs. *Chandra*



EEF=0.8: ~20 arcsec (XMM) vs. ~1 arcsec (*Chandra*)

Chandra has a much better spatial (angular) resolution than XMM-*Newton*



Angular resolution is often "replaced" by the **encircled energy fraction**, i.e., the *fraction of photons collected within a given aperture (extraction radius) centered on the source position*.
It depends on the energy and the position (x, y, θ) in the detector (being worse/larger at large off-axis angles θ). It is also referred to as the bi-dimensional PSF

Data analysis: timing. I

Creare a background-subtracted light curve

Source region → source_r3.reg
circle(4011.2,4294.5,6.1)

- Background region → back.reg
circle(3948.5,4307.5,20)

Choice of physica lcoordinates here

MIN:MAX:BIN → Binning=1000 s
(depending on the flux of the source)

- punlearn dmextract
- pset dmextract infile="obs7200_037keV_repro_evt2.fits[sky=region(source_r3.reg)][bin time=::1000]"
- pset dmextract outfile="3C33_src_lc_1ks.fits" ← resulting light curve
- pset dmextract bkg="obs7200_037keV_repro_evt2.fits[sky=region(back.reg)]"
- pset dmextract opt="ltc1"
- dmextract
- […]

To visualize the columns of the output lightcurve file:

- dmlist 3C33_src_lc_1ks.fits cols

Data analysis: timing. II

Visualization of the source lightcurve using the FTOOL package **lcurve**

- punlearn lcurve — Reset the lcurve (ftool) parameter file
- lcurve — Run lcurve

```
lcurve 1.0 (xronos6.0)

Number of time series for this task[1]
Ser. 1 filename +options (or @file of filenames +options)[file1] 3C33_src_lc_1ks.fits
 Series 1 file    1:3C33_src_lc_1ks.fits

 Selected FITS extensions: 1 - RATE TABLE;

 Source ............ 3C 33              Start Time (d) .... 13686 16:32:13.731
 FITS Extension ....  1 - `LIGHTCURVE`   Stop Time (d) ..... 13686 22:41:58.320
 No. of Rows .......            23        Bin Time (s) ......    1000.
 Right Ascension ... 1.7208233688112E    Internal time sys.. Converted to TJD
 Declination ....... 1.3310165045310E    Experiment ........ CHANDRA  ACIS

 Corrections applied: Vignetting - No ; Deadtime - No ; Bkgd - No ; Clock - Yes

 Selected Columns:  3- Time;  5- Y-axis;  6- Y-error;

 File contains binned data.

Name of the window file ('-' for default window)[-]

 Expected Start ... 13686.68904781771  (days)      16:32:13:731  (h:m:s:ms)
 Expected Stop .... 13686.94581388854  (days)      22:41:58:320  (h:m:s:ms)

 Minimum Newbin Time    1000.0000      (s)
 for Maximum Newbin No..               23

 Default Newbin Time is:   1000.0000    (s) (to have 1 Intv. of      23 Newbins)
 Type INDEF to accept the default value

Newbin Time or negative rebinning[4.6692607009327] 1000.

 Newbin Time ......     1000.0000      (s)
 Maximum Newbin No.                23

 Default Newbins per Interval are:          23
 (giving       1 Interval of           23 Newbins)
 Type INDEF to accept the default value

Number of Newbins/Interval[10] 23
 Maximum of       1 Intvs. with           23 Newbins of       1000.00     (s)
Name of output file[default]
Do you want to plot your results?[yes]
Enter PGPLOT device[/XW]

      23 analysis results per interval

100% completed

 Intv    1   Start 13686 16:40:33
     Ser.1     Avg 0.5743E-01    Chisq  165.6        Var 0.4135E-03 Newbs.     23
               Min  0.000          Max 0.7800E-01expVar 0.5743E-04  Bins      23
PLT>
```

Lightcurve previously produced using dmextract

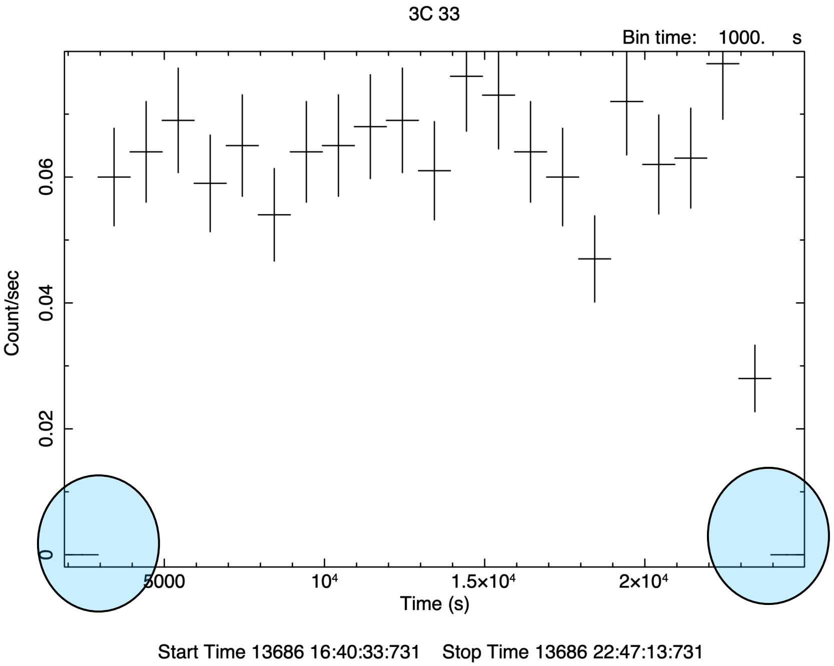
Information contained in the lightcurve FITS file.
Bin time=1000s (you may adopt a different binning within lcurve)
→ 23 datapoints (roughly, exposure/1000s)

Newbin Time = 1000s (as the original)
→ 23 time bins → You may decide here to apply a different bin interval (>1000s implies a lower number of bins, hence higher S/N in each bin but overall losing time resolution) → compromise considering all these 'effect'
→ It depends on how bright the source is

Default PGPLOT (plotting) window: /xw

Data analysis: timing. III

Resulting light curve



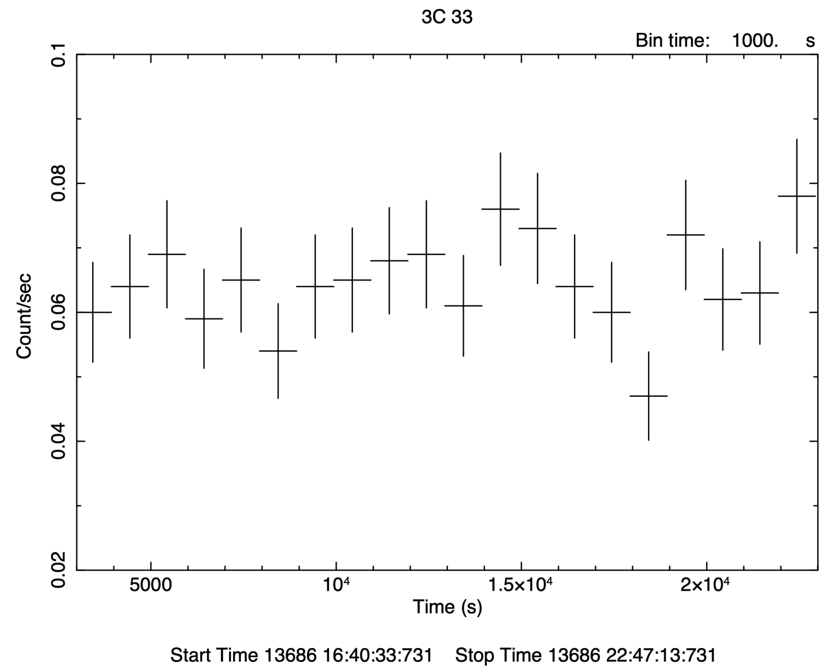
At the beginning and at the end of the observation, the program may have some problems (count rate ~0) – it may happen some time (i.e., problems in correctly reading some lcurve entries)

To overcome these issues, we may rescale the x-axis to include only reasonably "good" datapoints

- PLT > rescale x 3000 23000
- PLT > rescale y 0.02 0.1

Data analysis: timing. IV

"Cleaned" light curve



Then we may want to verify whether the source is variable within the observation (i.e., the count rate distribution plotted in the y-axis is not consistent with a constant value)

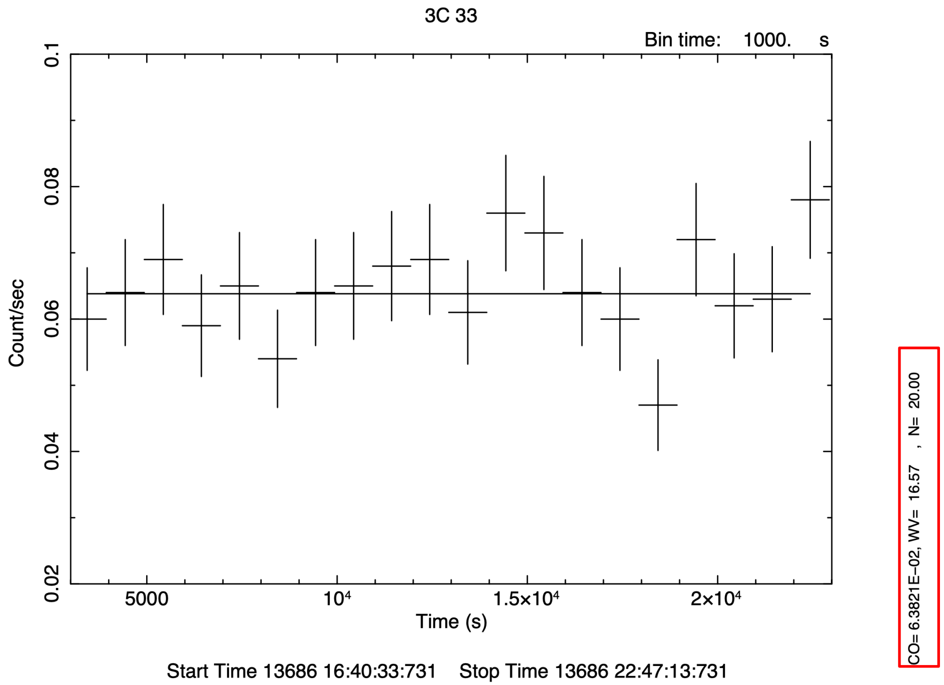
```
[PLT> mo cons
  1 CO: VAL(  1.000    ), SIG(  0.000    ), PLO(  0.000    ), PHI(  0.000    )?

[PLT> fit
 Fitting group   2,  from  3.000E+03 to  2.300E+04
 Fitting       20 points in a band of      20.
   1.00000000
 ( -3)   W-VAR= 16.85
 ( -4)   W-VAR= 16.57
 ( -5)   W-VAR= 16.57
   6.38213754E-02
[PLT> plot
```

χ^2 (chi-squared)=16.57

CR (cons)=6.38E-2 counts/sec

Data analysis: timing. V

“Cleaned” light curve +
fit using a constant model



- CR (cons)=6.38E-2 counts/sec
- χ^2 (chi-squared)=16.57
- N=20 points → 19 (N_{points}-1) degrees of freedom (d.o.f.)

Is the source variable?

You may save the light curve in a postscript file

- PLT > hardcopy 3c33_lc_1ks.ps/ps
- PLT > quit

Data analysis: timing. VI

Is the source variable? Apply the χ^2 test

Binning is a compromise between the SNR of each time bin and the temporal resolution (higher SNR in each bin ←→ lower number of temporal bins). It should be adjusted on the basis of the source photon statistics and the length of the observation.

To establish whether a source is variable during the observation, we can apply the **χ^2 test**

Reduced χ^2

$$\chi^2_\nu = \frac{1}{\nu} \sum_{i=1}^{n} \frac{(c_i - <c>)^2}{\sigma_i^2}$$

C_i: observed number of counts in each temporal bin i (or count rate in each time interval)

<C>: average number of counts over the entire observation

σ_i: Poissonian error associated with the number of counts C_i

ν=n-1: degrees of freedom (n=number of datapoints)

Compute the null-hypothesis probability that the source is not variable (see more on this in E. Torresi's tutorial on XMM-Newton data). The probability of the results being due to chance can be estimated using http://www.fourmilab.ch/rpkp/experiments/analysis/chiCalc.html

Data analysis: spectral extraction

Four files are needed for X-ray spectral analysis and will be produced by **specextract**:

- Source spectrum
- Background spectrum
- Ancillary Response File (ARF)
- Redistribution Matrix File (RMF)

- punlearn specextract
- pset specextract infile="obs7200_037keV_repro_evt2.fits[sky=region(source_r3.reg)]"
- pset specextract bkgfile="obs7200_037keV_repro_evt2.fits[sky=region(back.reg)]"
- pset specextract outroot=3C33_r3
- pset specextract asp= pcadf07200_000N001_asol1.fits
- pset specextract mskfile= acisf07200_000N004_msk1.fits
- pset specextract badpixfile=acisf7200_repro_bpix1.fits
- pset specextract weight=no → produces an ARF for a point-like source
- pset specextract correct=yes → energy-dependent point-source aperture correction (EEF)
- pset specextract verbose=2

The opposite (weight=yes & correct=no) for extended src

- pset specextract grouptype=NONE
- pset specextract binspec=NONE

} Data can be rebinned either here or later using the ftool **grppha** (see the XSPEC tutorial)

- specextract

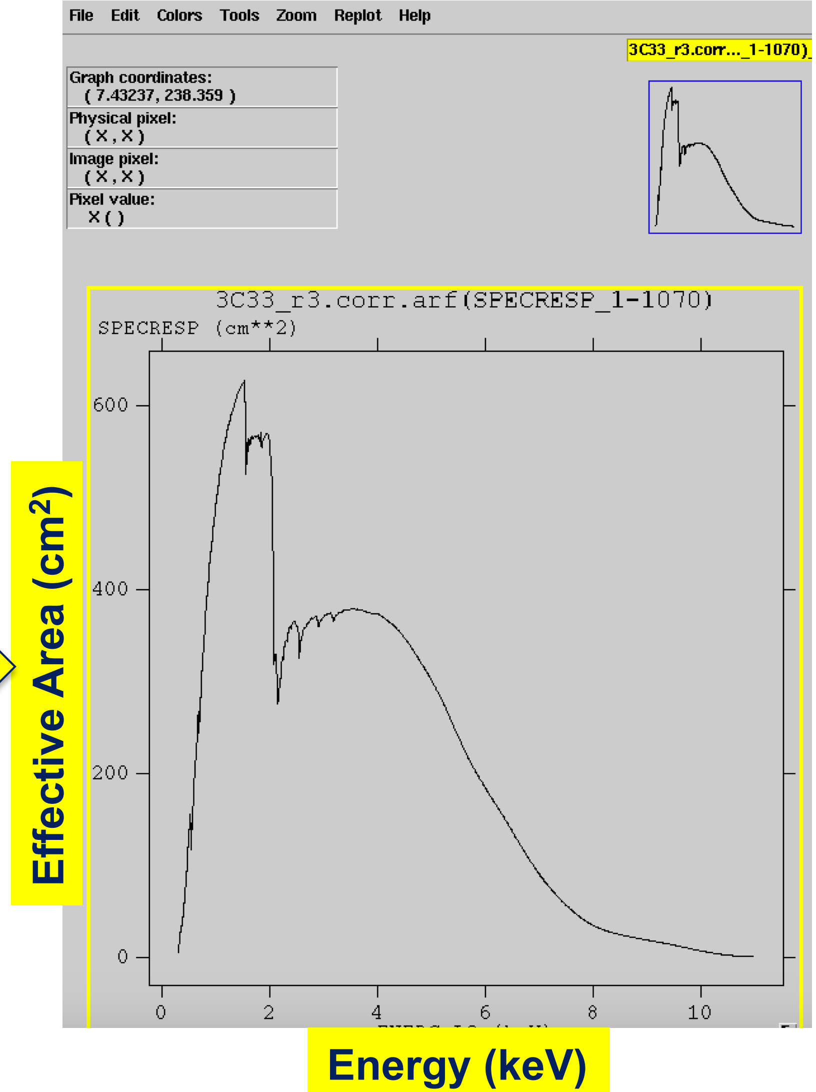
Response matrices: ARF

ARF: indicates the effective response (hence sensitivity) of the mirrors+instrument at a given source position on the detector

- fv 3C33_r3.corr.arf

File Edit Tools Help

Select	ENERG_LO	ENERG_HI	SPECRESP	PSF_FRAC
	1E	1E	1E	1D
All	keV	keV	cm**2	
Invert	Modify	Modify	Modify	Modify
1	3.000000E-01	3.100000E-01	3.886596E+00	9.729960747434E-01
2	3.100000E-01	3.200000E-01	1.144929E+01	9.729424863851E-01
3	3.200000E-01	3.300000E-01	1.601507E+01	9.728888978671E-01
4	3.300000E-01	3.400000E-01	2.089009E+01	9.728353095087E-01
5	3.400000E-01	3.500000E-01	2.528668E+01	9.727817211504E-01
6	3.500000E-01	3.600000E-01	2.901072E+01	9.727281326324E-01
7	3.600000E-01	3.700000E-01	3.212375E+01	9.726745442740E-01
8	3.700000E-01	3.800000E-01	3.583970E+01	9.726209559157E-01
9	3.800000E-01	3.900000E-01	4.098644E+01	9.725673675574E-01
10	3.900000E-01	4.000000E-01	4.640701E+01	9.725137790394E-01
11	4.000000E-01	4.100000E-01	4.873587E+01	9.724601906810E-01
12	4.100000E-01	4.200000E-01	5.367477E+01	9.724066023227E-01
13	4.200000E-01	4.300000E-01	6.376080E+01	9.723530138047E-01
14	4.300000E-01	4.400000E-01	7.226711E+01	9.722994254463E-01
15	4.400000E-01	4.500000E-01	7.973080E+01	9.722458370880E-01
16	4.500000E-01	4.600000E-01	8.869151E+01	9.721922485700E-01
17	4.600000E-01	4.700000E-01	9.731506E+01	9.721386602116E-01
18	4.700000E-01	4.800000E-01	1.062349E+02	9.720850718533E-01
19	4.800000E-01	4.900000E-01	1.150116E+02	9.720314833353E-01
20	4.900000E-01	5.000000E-01	1.239493E+02	9.719778949770E-01



PSF_FRAC: a sort of aperture correction (see EEF concept)

The ‘meaning’ of ARF

see lesson by M. Dadina

Mirrors | Detector

$$A_{effective}(E,\theta,x,y) = A_{geometric} \times R(E) \times V(E,\vartheta) \times QE(E,x,y)$$

Effective area — Geometric area — Reflectivity — Vignetting — Quantum Efficiency

Most quantities in X-rays depend on the energy of the photons

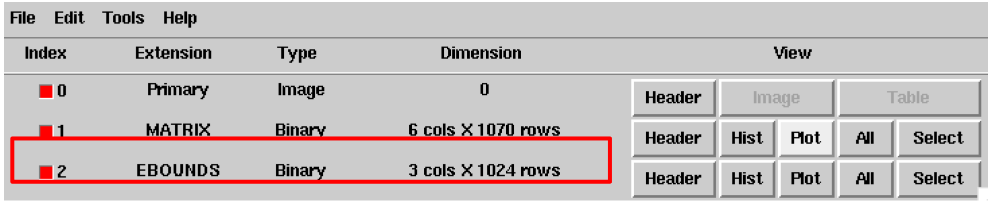
- **Effective area** – in cm^2
- **Geometric area** – ‘cross section’ (i.e., entrance aperture) of the telescope
- **Reflectivity** – fraction of photons reflected by the mirrors (grazing incidence)
- **Vignetting** – fraction of photons ‘lost’ as a function of the distance wrt. the optical axis (ϑ). This effect is maxim for high-energy photons
- **Quantum Efficiency** – fraction of incident photons registered by the detector. (x,y) represents the position on the detector

The effective area represents the capability of the telescope+detector to collect photons

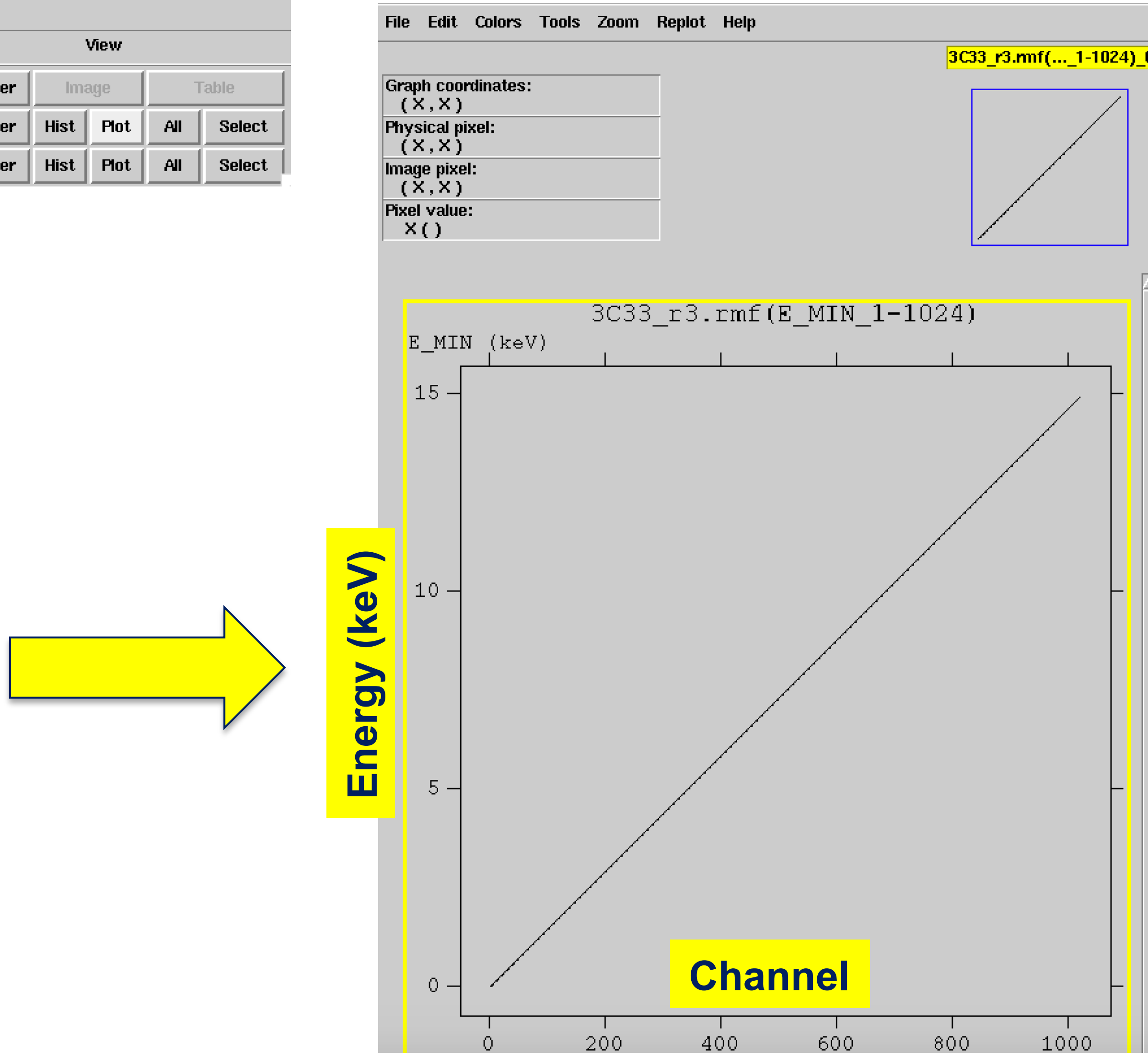
Response matrices: RMF

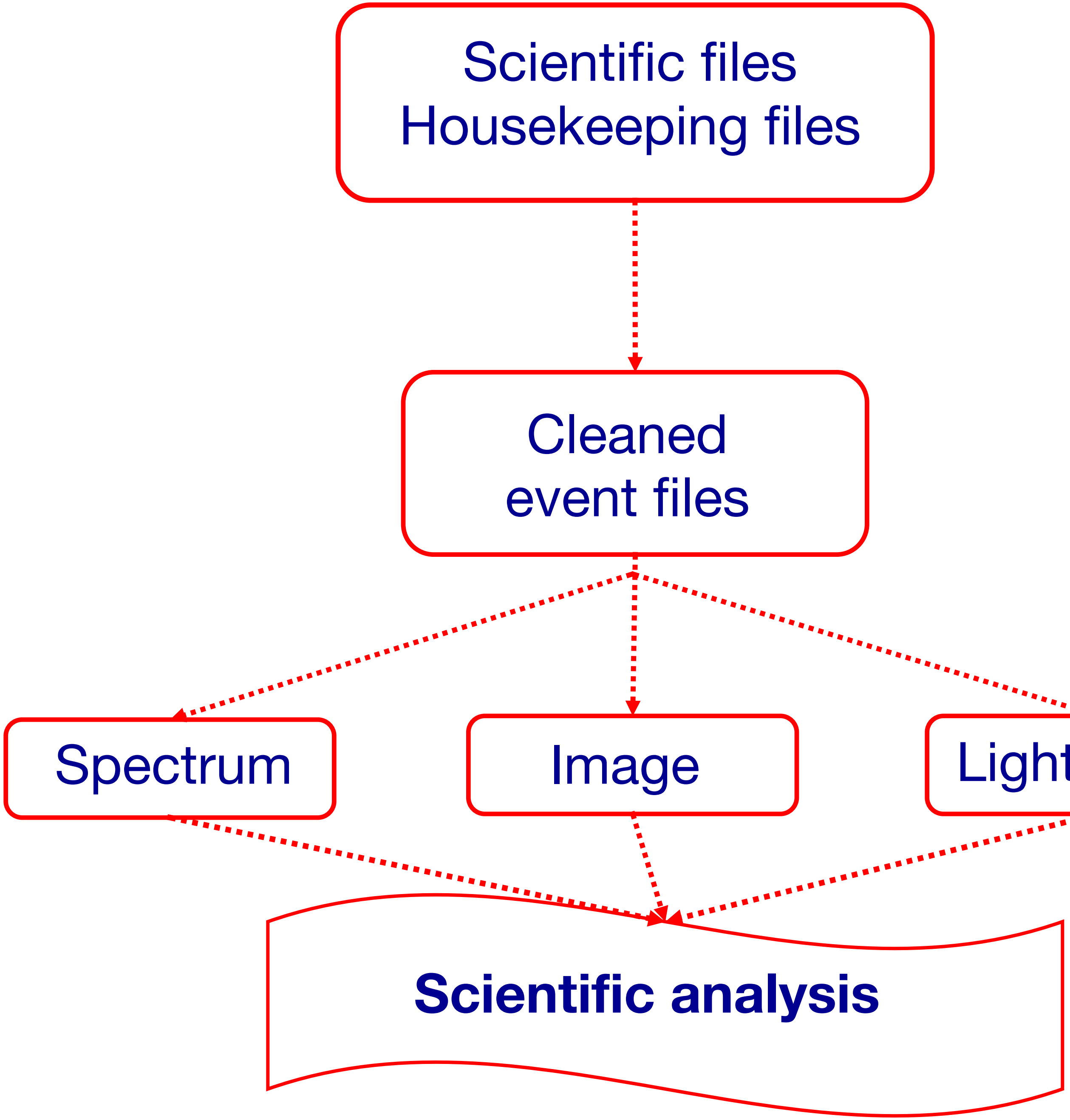
RMF: links the instrumental channel scale with the physical energy (wavelength) scale

- fv 3C33_r3.rmf



Select	CHANNEL (1J, channel)	E_MIN (1E, keV)	E_MAX (1E, keV)
1	1	7.300000E-03	1.460000E-02
2	2	1.460000E-02	2.920000E-02
3	3	2.920000E-02	4.380000E-02
4	4	4.380000E-02	5.840000E-02
5	5	5.840000E-02	7.300000E-02
6	6	7.300000E-02	8.760000E-02
7	7	8.760000E-02	1.022000E-01
8	8	1.022000E-01	1.168000E-01
9	9	1.168000E-01	1.314000E-01
10	10	1.314000E-01	1.460000E-01
11	11	1.460000E-01	1.606000E-01
12	12	1.606000E-01	1.752000E-01
13	13	1.752000E-01	1.898000E-01
14	14	1.898000E-01	2.044000E-01
15	15	2.044000E-01	2.190000E-01
16	16	2.190000E-01	2.336000E-01
17	17	2.336000E-01	2.482000E-01
18	18	2.482000E-01	2.628000E-01
19	19	2.628000E-01	2.774000E-01
20	20	2.774000E-01	2.920000E-01





XSPEC tutorial