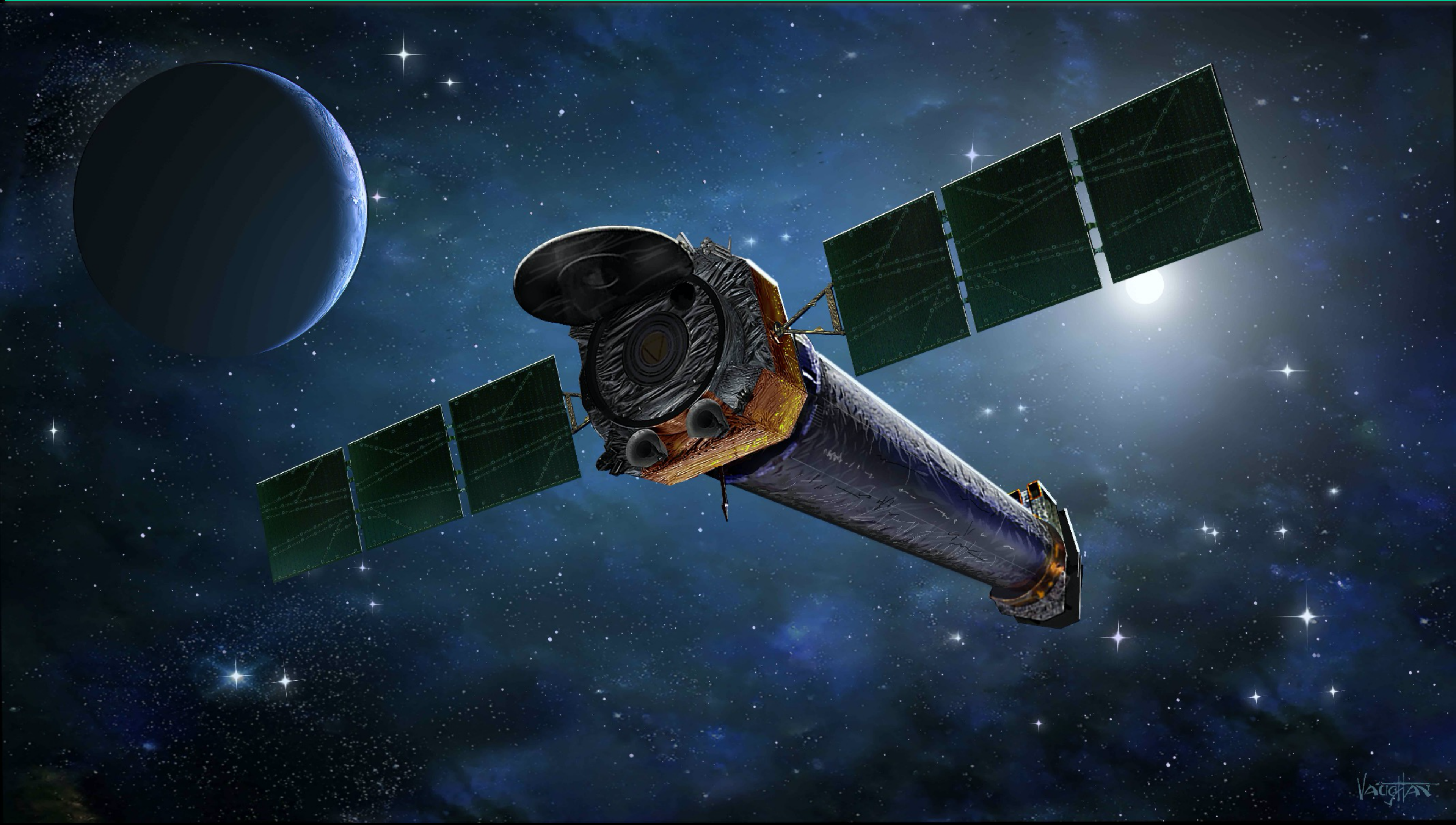
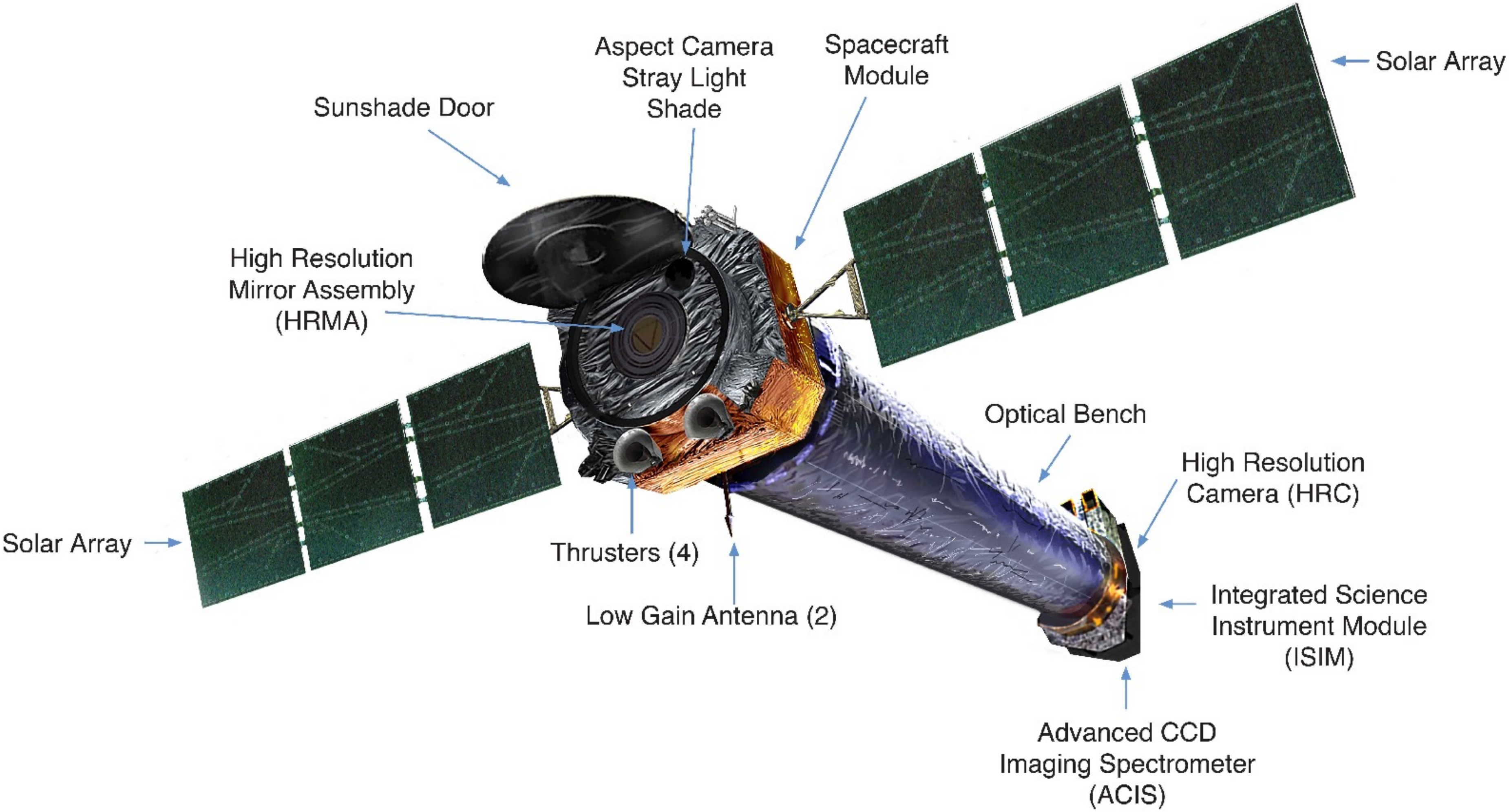
Chandra data analysis: tutorial



Astrophysics Laboratory course – AA2020-21

The spacecraft

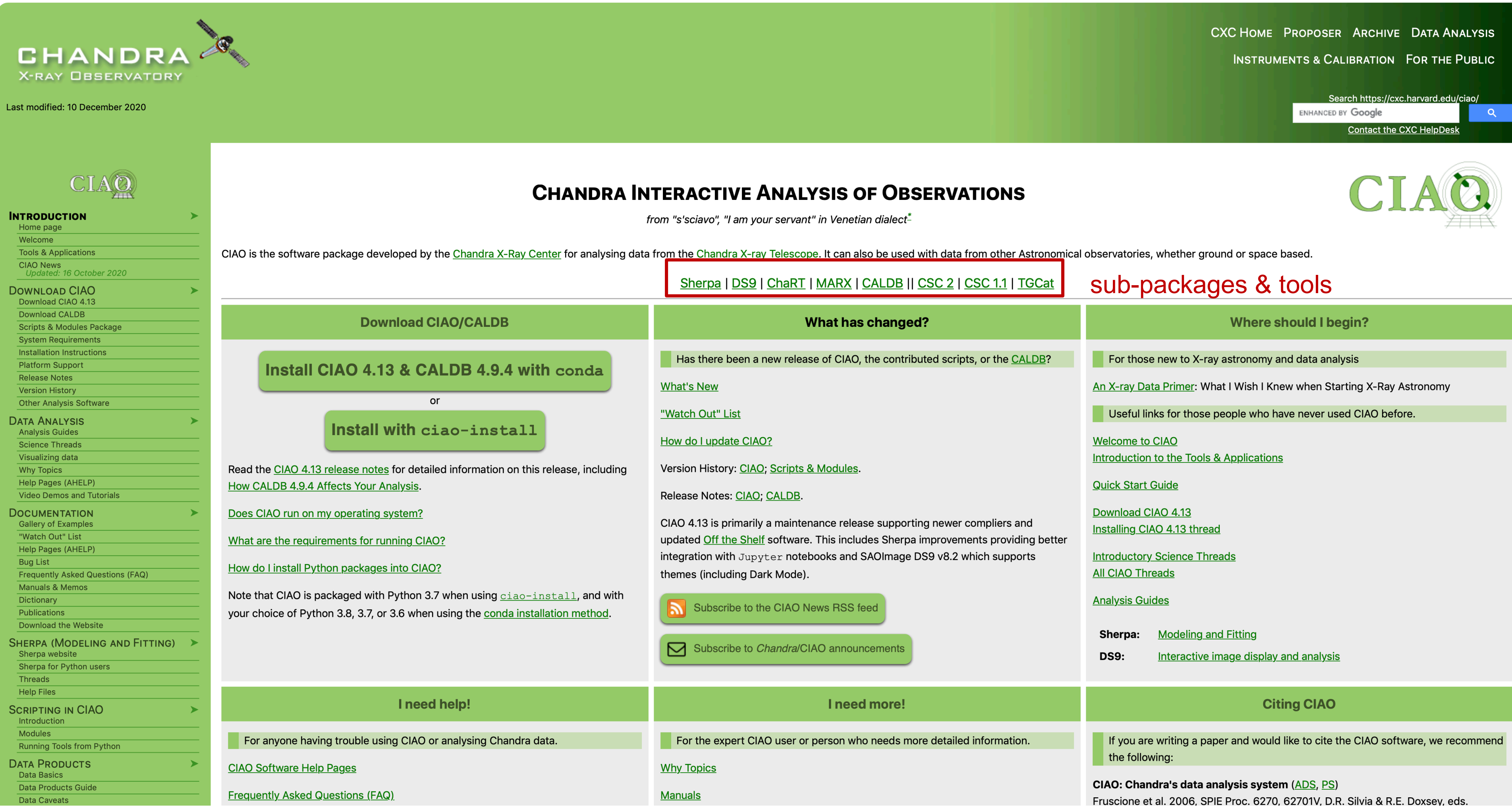


Only one instrument in the focal plane “active” for each observation

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 & Webpimms
  - ❑ Source photon statistics
  - ❑ Destreak (in case of pileup)
  - ❑ Smoothing
  - ❑ Contours
  - ❑ Choice of source and background regions
- ❑ Timing analysis: lightcurves & evaluation of variability
- ❑ Spectral extraction

Chandra webpage & software CIAO

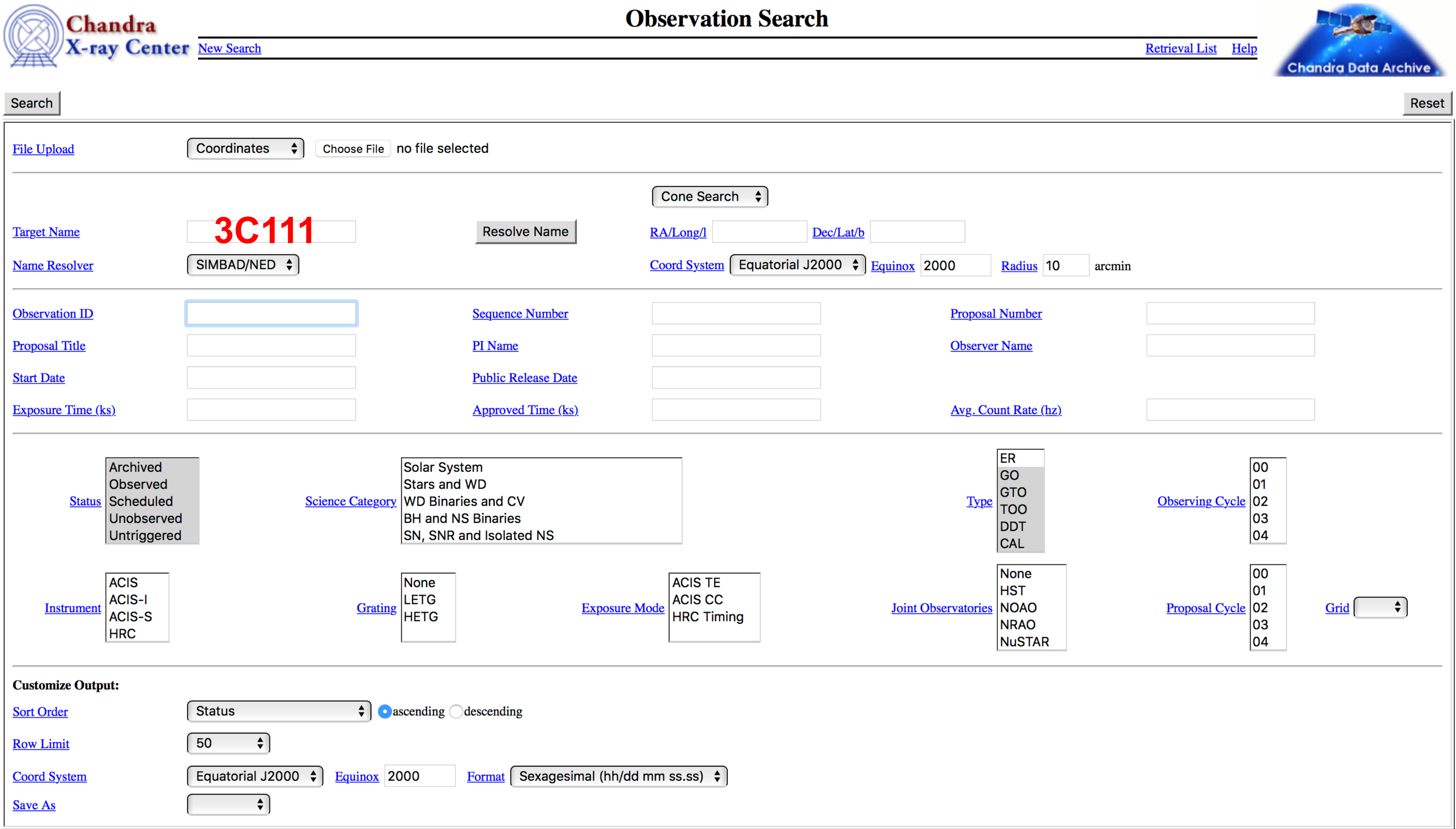


https://cxc.cfa.harvard.edu
https://cxc.cfa.harvard.edu/ciao

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

Search Results

New Search

Search Results | Retrieval List | Help

View Observation Information

Add Products to Retrieval List

- [x] Primary package
- [x] 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	Joint
☐	1	702798	14990	ACIS-S	NONE	127.0	92.1	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	5.65	520726	2013-01-10 04:29:04	2014-01-15 01:50:57	14700630	GO	14	14	ACTIVE GALAXIES AND QUASARS	HST
☐	2	703007	16219	ACIS-S	HETG	150.0	143.41	3C 111	Tombesi	04 18 21.30	+38 01 35.80	archived	FAINT	TE	7.64	1095075	2014-11-04 10:48:56	2015-11-07 05:25:42	15700397	GO	15	15	ACTIVE GALAXIES AND QUASARS	None
☐	3	703412	19615	ACIS-S	NONE	26.0	22.54	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	3.07	69154	2017-12-26 15:46:41	2019-01-02 16:11:57	18700471	GO	18	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	4	703412	20907	ACIS-S	NONE	32.0	28.16	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	2.97	83648	2017-12-29 03:21:51	2019-01-02 16:11:57	18700471	GO	18	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	5	703412	20908	ACIS-S	NONE	32.0	27.23	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	2.93	79812	2017-12-29 18:15:31	2019-01-02 16:11:57	18700471	GO	18	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	6	703413	19616	ACIS-S	NONE	24.0	23.5	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.78	159244	2019-01-03 10:22:18	2020-01-08 07:02:05	18700471	GO	19	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	7	703413	22023	ACIS-S	NONE	16.0	15.69	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.60	103548	2018-12-30 08:04:59	2020-01-08 07:02:05	18700471	GO	19	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	8	703413	22024	ACIS-S	NONE	20.0	19.6	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.74	132160	2018-12-29 06:55:26	2020-01-08 07:02:05	18700471	GO	19	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	9	703413	22025	ACIS-S	NONE	17.0	16.18	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.48	104876	2019-01-06 08:00:32	2020-01-08 07:02:05	18700471	GO	19	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
☐	10	703413	22026	ACIS-S	NONE	13.0	12.76	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.54	83434	2019-01-07 03:32:32	2020-01-08 07:02:05	18700471	GO	19	18	ACTIVE GALAXIES AND QUASARS	HST+NuSTAR
Totals						0.00	0.00									0								

you can view the details of each observation

Chandra X-ray Center

Search Results

New Search

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
☐	1	702798	14990	ACIS-S	NONE	127.0	92.1	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	5.65	520726	2013-01-10 04:29:0
☐	2	703007	16219	ACIS-S	HETG	150.0	143.41	3C 111	Tombesi	04 18 21.30	+38 01 35.80	archived	FAINT	TE	7.64	1095075	2014-11-04 10:48:5
☐	3	703412	19615	ACIS-S	NONE	26.0	22.54	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	3.07	69154	2017-12-26 15:46:4
☐	4	703412	20907	ACIS-S	NONE	32.0	28.16	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	2.97	83648	2017-12-29 03:21:5
☐	5	703412	20908	ACIS-S	NONE	32.0	27.23	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	2.93	79812	2017-12-29 18:15:3
☐	6	703413	19616	ACIS-S	NONE	24.0	23.5	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.78	159244	2019-01-03 10:22:1
☐	7	703413	22023	ACIS-S	NONE	16.0	15.69	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.60	103548	2018-12-30 08:04:5
☐	8	703413	22024	ACIS-S	NONE	20.0	19.6	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.74	132160	2018-12-29 06:55:2
☐	9	703413	22025	ACIS-S	NONE	17.0	16.18	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.48	104876	2019-01-06 08:00:3
☐	10	703413	22026	ACIS-S	NONE	13.0	12.76	3C 111	Perlman	04 18 21.30	+38 01 36.00	archived	VFAINT	TE	6.54	83434	2019-01-07 03:32:3
Totals						0.00	0.00									0	

Seq. # **ObsID** **Expo**

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: 20908

Observation ID: **20908**

Add to Retrieval List

- Primary package
- 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:	703412	**Status:**	archived
Observation ID:	20908	**Proposal Number:**	18700471
Type:	GO	**Proposal Cycle:**	18
PI Name:	Perlman	**Observer:**	Perlman
Science Category:	ACTIVE GALAXIES AND QUASARS	**Joint Observatories:**	HST+NuSTAR
Target Name:	3C 111	**Grid Name:**	
RA (J2000):	04 18 21.30		
Dec (J2000):	+38 01 36.00		
Instrument:	ACIS-S	**Data Mode:**	VFAINT
Grating:	NONE		
Start Date:	2017-12-29 18:15:31	**Observing Cycle:**	18
Approved Time:	32.00 ks	**Public Release Date:**	2019-01-02 16:11:57
Exposure Time:	27.23 ks		

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

ALTERNATIVELY

- find_chandra_obsid '3c111'

# obsid	sepn	inst	grat	time	obsdate	piname	target
9279	0.0	ACIS-S	NONE	9.2	2008-12-08	Lister	"QSO B0415+379"
14990	0.0	ACIS-S	NONE	92.1	2013-01-10	Perlman	"3C 111"
16219	0.0	ACIS-S	HETG	143.4	2014-11-04	Tombesi	"3C 111"
19615	0.0	ACIS-S	NONE	22.5	2017-12-26	Perlman	"3C 111"
19616	0.0	ACIS-S	NONE	23.5	2019-01-03	Perlman	"3C 111"
20907	0.0	ACIS-S	NONE	28.2	2017-12-29	Perlman	"3C 111"
20908	0.0	ACIS-S	NONE	27.2	2017-12-29	Perlman	"3C 111"
22023	0.0	ACIS-S	NONE	15.7	2018-12-30	Perlman	"3C 111"
22024	0.0	ACIS-S	NONE	19.6	2018-12-29	Perlman	"3C 111"
22025	0.0	ACIS-S	NONE	16.2	2019-01-06	Perlman	"3C 111"
22026	0.0	ACIS-S	NONE	12.8	2019-01-07	Perlman	"3C 111"

- download_chandra_obsid 20908

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

- download_chandra_obsid 20908, 22023

Data structure

→ package_4715_210211112723.tar

- tar xvf package_4715_210211112723.tar → directory 20908/

```
axaff20908N002_VV001_vv2.pdf
00README
oif.fits
primary
secondary
```

PRIMARY

```
orbitf630504305N001_eph1.fits.gz
pcadf20908_000N001_asol1.fits.gz
acisf20908_000N002_bpix1.fits.gz
acisf20908_000N002_fov1.fits.gz
acisf20908N002_cntr_img2.jpg
acisf20908N002_full_img2.jpg
acisf20908N002_full_img2.fits.gz
acisf20908N002_evt2.fits.gz
acisf20908N002_cntr_img2.fits.gz
```

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

SECONDARY

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

```
acisf630958962N002_2_bias0.fits.gz
acisf630958962N002_1_bias0.fits.gz
acisf630959617N002_pbk0.fits.gz
acisf630958962N002_4_bias0.fits.gz
acisf630958962N002_3_bias0.fits.gz
acisf20908_000N002_stat1.fits.gz
acisf20908_000N002_flt1.fits.gz
acisf20908_000N002_msk1.fits.gz
acisf20908_000N002_mtl1.fits.gz
acisf20908_000N002_evt1.fits.gz
axaff20908N002_VV001_vvref2.pdf.gz
aspect
ephem
```

FILE FORMAT

Instrument ObsID evt2

acisf20908N002_evt2.fits

f=flight file revision file format

- 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 bloks

dmlist acisf20908N002_evt2.fits cols

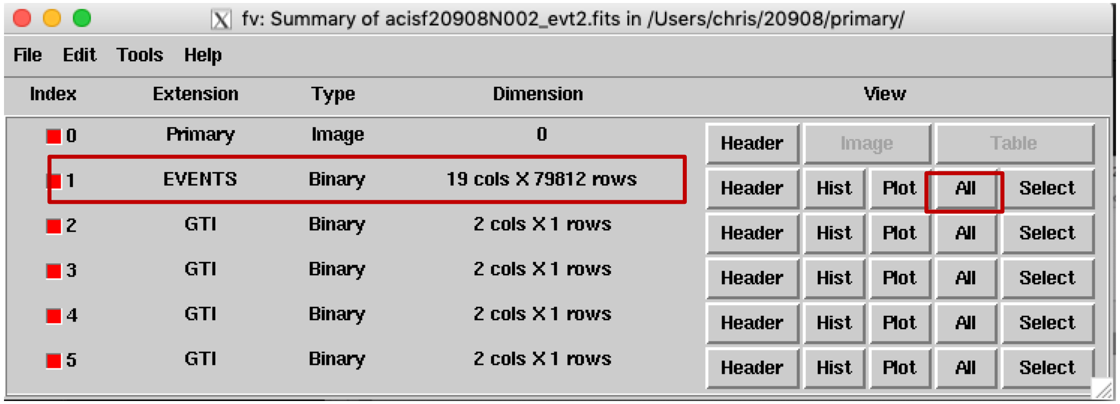
```
--------------------------------------------------------------------------------
Columns for Table Block EVENTS
--------------------------------------------------------------------------------

ColNo  Name                 Unit        Type             Range              Null
   1   time                 s            Real8          630958599.7406699657:630989571.1424900293 -         S/C TT correspond
ing 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 containin
g 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 acisf20908N002_evt2.fits &

N(rows)=number of events (counts)

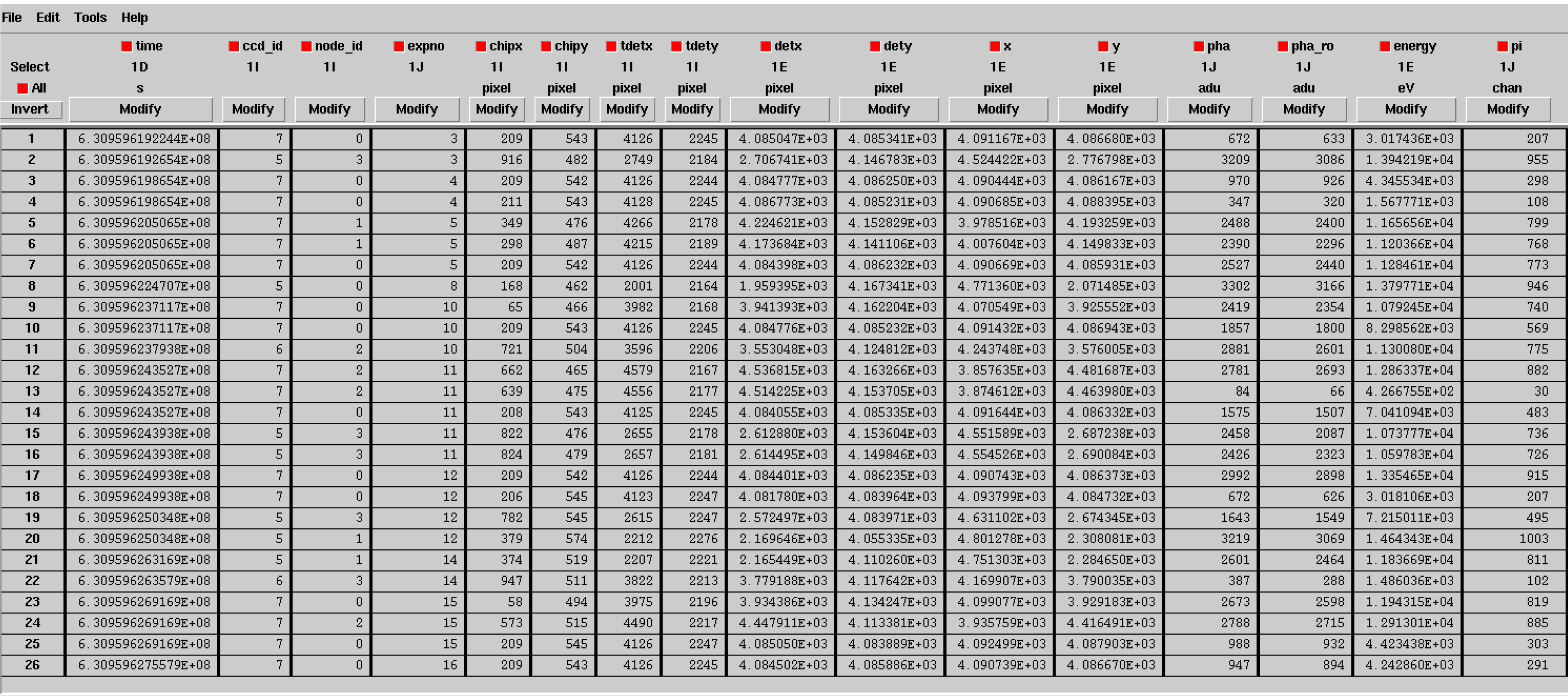
X,Y → image
Time → lightcurve
Energy → spectrum



fv: Summary of acisf20908N002_evt2.fits in /Users/chris/20908/primary/

File Edit Tools Help

Index	Extension	Type	Dimension	View				
0	Primary	Image	0	Header	Image	Table		
1	EVENTS	Binary	19 cols X 79812 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



File Edit Tools Help

Select	time	ccd_id	node_id	expno	chipx	chipy	tdetx	tdety	detx	dety	x	y	pha	pha_ro	energy	pi
	1D	1I	1I	1J	1I	1I	1I	1I	1E	1E	1E	1E	1J	1J	1E	1J
All	s				pixel	pixel	pixel	pixel	pixel	pixel	pixel	pixel	adu	adu	eV	chan
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	6.309596192244E+08	7	0	3	209	543	4126	2245	4.085047E+03	4.085341E+03	4.091167E+03	4.086680E+03	672	633	3.017436E+03	207
2	6.309596192654E+08	5	3	3	916	482	2749	2184	2.706741E+03	4.146783E+03	4.524422E+03	2.776798E+03	3209	3086	1.394219E+04	955
3	6.309596198654E+08	7	0	4	209	542	4126	2244	4.084777E+03	4.086250E+03	4.090444E+03	4.086167E+03	970	926	4.345534E+03	298
4	6.309596198654E+08	7	0	4	211	543	4128	2245	4.086773E+03	4.085231E+03	4.090685E+03	4.088395E+03	347	320	1.567771E+03	108
5	6.309596205065E+08	7	1	5	349	476	4266	2178	4.224621E+03	4.152829E+03	3.978516E+03	4.193259E+03	2488	2400	1.165656E+04	799
6	6.309596205065E+08	7	1	5	298	487	4215	2189	4.173684E+03	4.141106E+03	4.007604E+03	4.149833E+03	2390	2296	1.120366E+04	768
7	6.309596205065E+08	7	0	5	209	542	4126	2244	4.084398E+03	4.086232E+03	4.090669E+03	4.085931E+03	2527	2440	1.128461E+04	773
8	6.309596224707E+08	5	0	8	168	462	2001	2164	1.959395E+03	4.167341E+03	4.771360E+03	2.071485E+03	3302	3166	1.379771E+04	946
9	6.309596237117E+08	7	0	10	65	466	3982	2168	3.941393E+03	4.162204E+03	4.070549E+03	3.925552E+03	2419	2354	1.079245E+04	740
10	6.309596237117E+08	7	0	10	209	543	4126	2245	4.084776E+03	4.085232E+03	4.091432E+03	4.086943E+03	1857	1800	8.298562E+03	569
11	6.309596237938E+08	6	2	10	721	504	3596	2206	3.553048E+03	4.124812E+03	4.243748E+03	3.576005E+03	2881	2601	1.130080E+04	775
12	6.309596243527E+08	7	2	11	662	465	4579	2167	4.536815E+03	4.163266E+03	3.857635E+03	4.481687E+03	2781	2693	1.286337E+04	882
13	6.309596243527E+08	7	2	11	639	475	4556	2177	4.514225E+03	4.153705E+03	3.874612E+03	4.463980E+03	84	66	4.266755E+02	30
14	6.309596243527E+08	7	0	11	208	543	4125	2245	4.084055E+03	4.085335E+03	4.091644E+03	4.086332E+03	1575	1507	7.041094E+03	483
15	6.309596243938E+08	5	3	11	822	476	2655	2178	2.612880E+03	4.153604E+03	4.551589E+03	2.687238E+03	2458	2087	1.073777E+04	736
16	6.309596243938E+08	5	3	11	824	479	2657	2181	2.614495E+03	4.149846E+03	4.554526E+03	2.690084E+03	2426	2323	1.059783E+04	726
17	6.309596249938E+08	7	0	12	209	542	4126	2244	4.084401E+03	4.086235E+03	4.090743E+03	4.086373E+03	2992	2898	1.335465E+04	915
18	6.309596249938E+08	7	0	12	206	545	4123	2247	4.081780E+03	4.083964E+03	4.093799E+03	4.084732E+03	672	626	3.018106E+03	207
19	6.309596250348E+08	5	3	12	782	545	2615	2247	2.572497E+03	4.083971E+03	4.631102E+03	2.674345E+03	1643	1549	7.215011E+03	495
20	6.309596250348E+08	5	1	12	379	574	2212	2276	2.169646E+03	4.055335E+03	4.801278E+03	2.308081E+03	3219	3069	1.464343E+04	1003
21	6.309596263169E+08	5	1	14	374	519	2207	2221	2.165449E+03	4.110260E+03	4.751303E+03	2.284650E+03	2601	2464	1.183669E+04	811
22	6.309596263579E+08	6	3	14	947	511	3822	2213	3.779188E+03	4.117642E+03	4.169907E+03	3.790035E+03	387	288	1.486036E+03	102
23	6.309596269169E+08	7	0	15	58	494	3975	2196	3.934386E+03	4.134247E+03	4.099077E+03	3.929183E+03	2673	2598	1.194315E+04	819
24	6.309596269169E+08	7	2	15	573	515	4490	2217	4.447911E+03	4.113381E+03	3.935759E+03	4.416491E+03	2788	2715	1.291301E+04	885
25	6.309596269169E+08	7	0	15	209	545	4126	2247	4.085050E+03	4.083889E+03	4.092499E+03	4.087903E+03	988	932	4.423438E+03	303
26	6.309596275579E+08	7	0	16	209	543	4126	2245	4.084502E+03	4.085886E+03	4.090739E+03	4.086670E+03	947	894	4.242860E+03	291

Data analysis: Chandra threads

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

Science Threads

All threads

A list of all the threads on one page.

Introduction NEW UPDATED

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 UPDATED

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
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 addr
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 ex
the spectral analysis.

Grating Spectroscopy

If new calibration has been applied to the event file, the grating spectrum should be re-extracted as well. It is then possible to build grating response files (gARF, gRMF) in order to model and fit the data.

Timing Analysis

In order to perform absolute timing analysis on a dataset, a barycenter correction must first be applied to the data. One may then create lightcurves and phase-binned spectra to look for variability in the source. T
data taken in the ACIS continuous clocking (CC) mode.

PSF Simulations

Data analysis: main data parameter evaluation

Preliminary checks on some useful data-related parameters

- punlearn dmkeypar — Reset the dmkeypar file
- dmkeypar 20908/primary/*evt2* EXPOSURE echo+ — ObsID nominal exposure
- dmkeypar 20908/primary/*evt2* DATAMODE echo+ — Data mode (faint/vfaint)
- dmkeypar 20908/primary/*evt2* DETNAM echo+ — Detector in use
- dmkeypar 20908/primary/*evt2* NROWS echo+ — # rows read in the det.
- dmkeypar 20908/primary/*evt2* EXPTIME echo+ — CCD readout time

→ **OUTPUTS**

/Users/chris> dmkeypar 20908/primary/*evt2* EXPOSURE echo+
27225.700092981 → T=27.23 ks

/Users/chris> dmkeypar 20908/primary/*evt2* DATAMODE echo+
VFAINT → VFAINT mode

/Users/chris> dmkeypar 20908/primary/*evt2* DETNAM echo+
ACIS-5678 → ACIS-S in use (ccd=7 t the aimpoint)

/Users/chris> dmkeypar 20908/primary/*evt2* NROWS echo+
128 → 128 rows/1024 → 1/8 subarray used in case of bright sources to limit pileup → frame time ~3.2s (standard)/8 (0.6s here)

/Users/chris> dmkeypar 20908/primary/*evt2* EXPTIME echo+
0.6

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=20908 outdir=20908_new verbose=3 check_vf_pha=yes

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

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

```
pcadf20908_000N001_asol1.fits
acisf20908_000N002_fov1.fits
acisf20908_000N002_bpix1.fits
acisf20908_000N002_stat1.fits
acisf20908_000N002_mtl1.fits
acisf20908_000N002_msk1.fits
acisf630959617N002_pbk0.fits
acisf20908_asol1.lis
acisf20908_repro_bpix1.fits
acisf20908_repro_flt2.fits
acisf20908_repro_evt2.fits
acisf20908_repro_fov1.fits
```

New ('reprocessed') event file (no selection of the energy band)

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 "20908_new/acisf20908_repro_evt2.fits[EVENTS][grade=0,2,3,4,6,status=0,energy=300:7000]" 20908_new/obs20908_037keV_repro_evt2.fits

in one line

Alternatively, you can use the *pset command*:

- punlearn dmcopy
- pset dmcopy infile="20908_new/acisf20908_repro_evt2.fits[grade=0,2,3,4,6,status=0,energy=300:7000]"
- pset dmcopy outfile=20908_new/obs20908_037keV_repro_evt2.fits
- pset dmcopy

Data analysis: images in different bands

obs20908_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 – nucleus vs. extended emission – and with different binning)
Here the original pixel size is preserved: 1 pix=0.492" – Note: huge files!)

- cd 20908_new/
- punlearn dmcopy
- dmcopy "obs20908_037keV_repro_evt2.fits[bin X=1,Y=1][energy=500:7000]" 3c111_057keV_ima_bin1.fits
- dmcopy "obs20908_037keV_repro_evt2.fits[bin X=1,Y=1][energy=500:2000]" 3c111_052keV_ima_bin1.fits
- dmcopy "obs20908_037keV_repro_evt2.fits[bin X=1,Y=1][energy=2000:7000]" 3c111_27keV_ima_bin1.fits

Use appropriate names for your products (e.g., clearly indicating the energy band, whether it is either an image or an event file, etc.)

Data analysis: image visualization

- ds9 obs20908_037keV_repro_evt2.fits.gz &

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

- ds9 3c111_052keV_ima_bin1.fits &
- ds9 3c111_27keV_ima_bin1.fits &

ds9 will open the images produced in two different energy ranges

- ds9 3c111_052keV_ima_bin1.fits 3c111_27keV_ima_bin1.fits &

two images at the same time

- ds9 3c111_052keV_ima_bin1.fits –region 3c111_r4.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 coordinates and physical (i.e., detector related) coordinates in CIAO format]

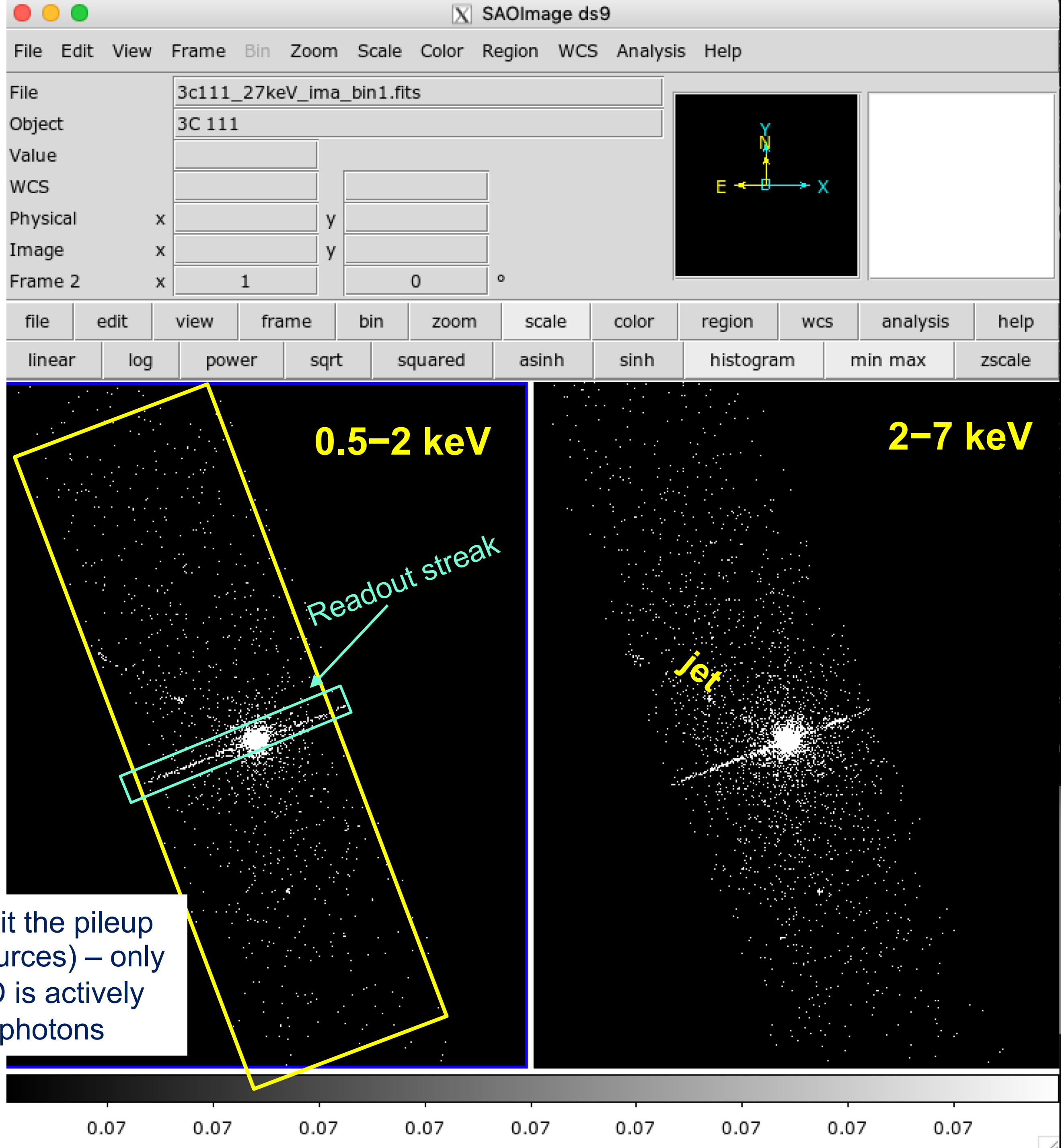
Name also the region files properly (e.g., _r4: R_{circle}=4")

3c111_r4.reg:

fk5;circle(4:18:21.2767,+38:01:35.685,4.0")

3c111_r4_phys.reg:

circle(4090.2,4086.2,8.13)



Sub-array to limit the pileup (due to bright sources) – only a part of a CCD is actively 'registering' photons

Data analysis: pileup. I

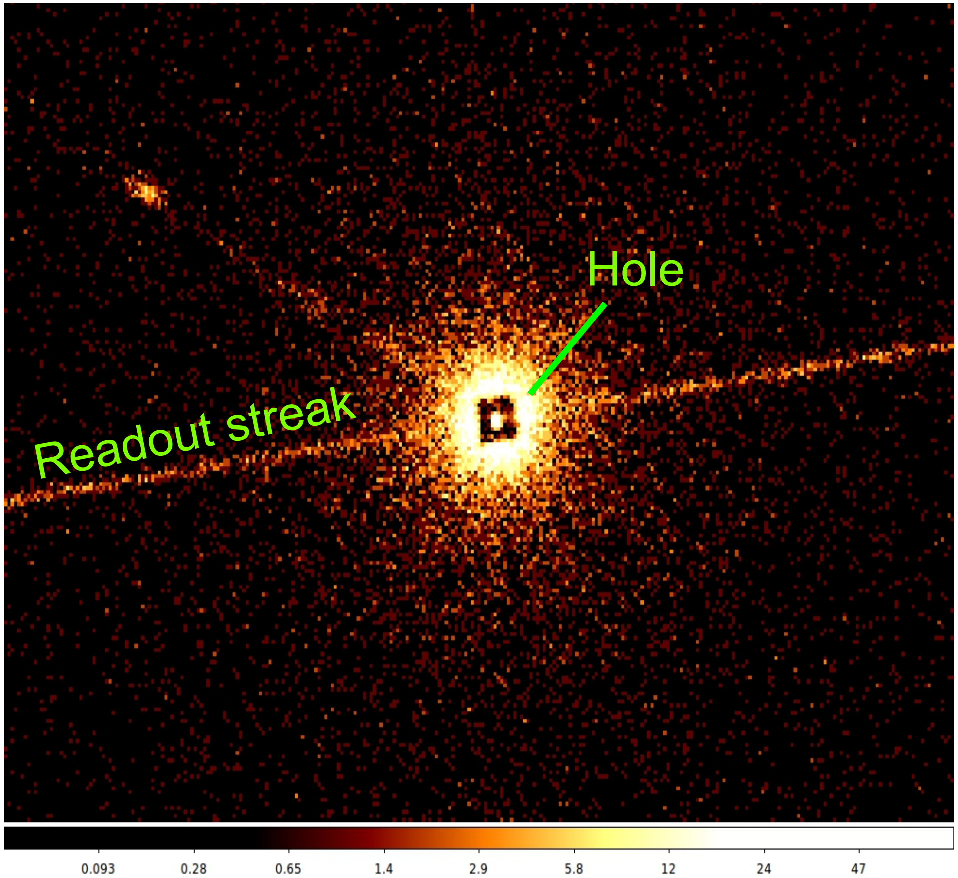
http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf

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)

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



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

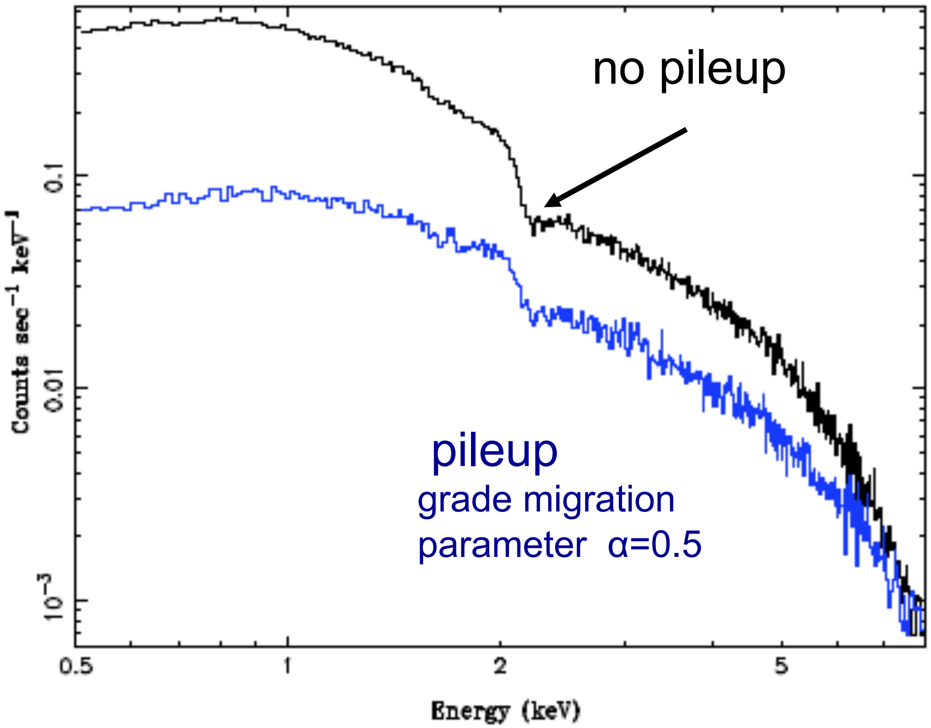
ENERGY MIGRATION photon energies sum to create a detected event with higher energy

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

→ net decrease of 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)

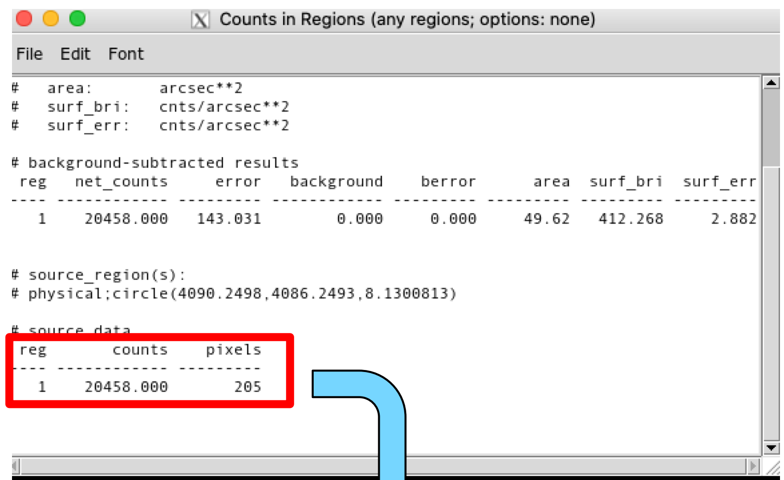
(b) extract the spectrum from an annulus centered on the source (hence removing the “inner part” of the source)

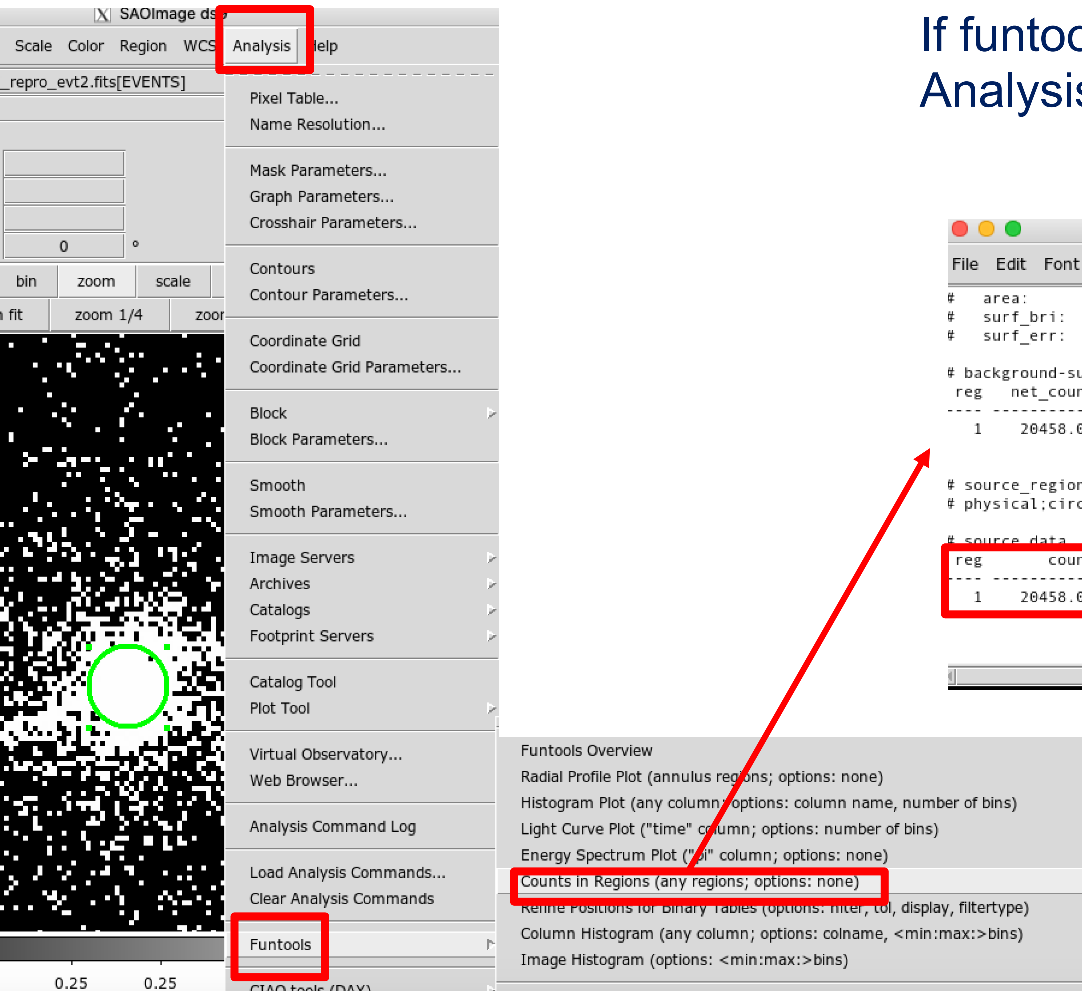
Pileup mitigation: use an XSPEC – pileup model

Data analysis: source photon statistics. I

- ds9 3c111_057keV_ima_bin1.fits.gz –region 3c111_r4.reg &

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





Counts(0.5−7 keV)=20458
Area=205 pix
Exposure=27.23ks
CR=0.75 c/s

Data analysis: source photon statistics. II

Alternatively, using CIAO tools:

- dmstat "3c111_057keV_ima_bin1.fits[sky=circle(4:18:21.2767,+38:01:35.68,0.067')]" centroid=no

```
EVENTS_IMAGE
    min:        0               @:          ( 4095 4092 )
    max:        4058            @:          ( 4090 4087 )
   mean:        97.937799043
  sigma:        476.06752462
    sum:        20469
   good:        209
   null:        80
```

Counts(0.5−7 keV)=20469
Area=209 pix

Values are very close to the previous ones

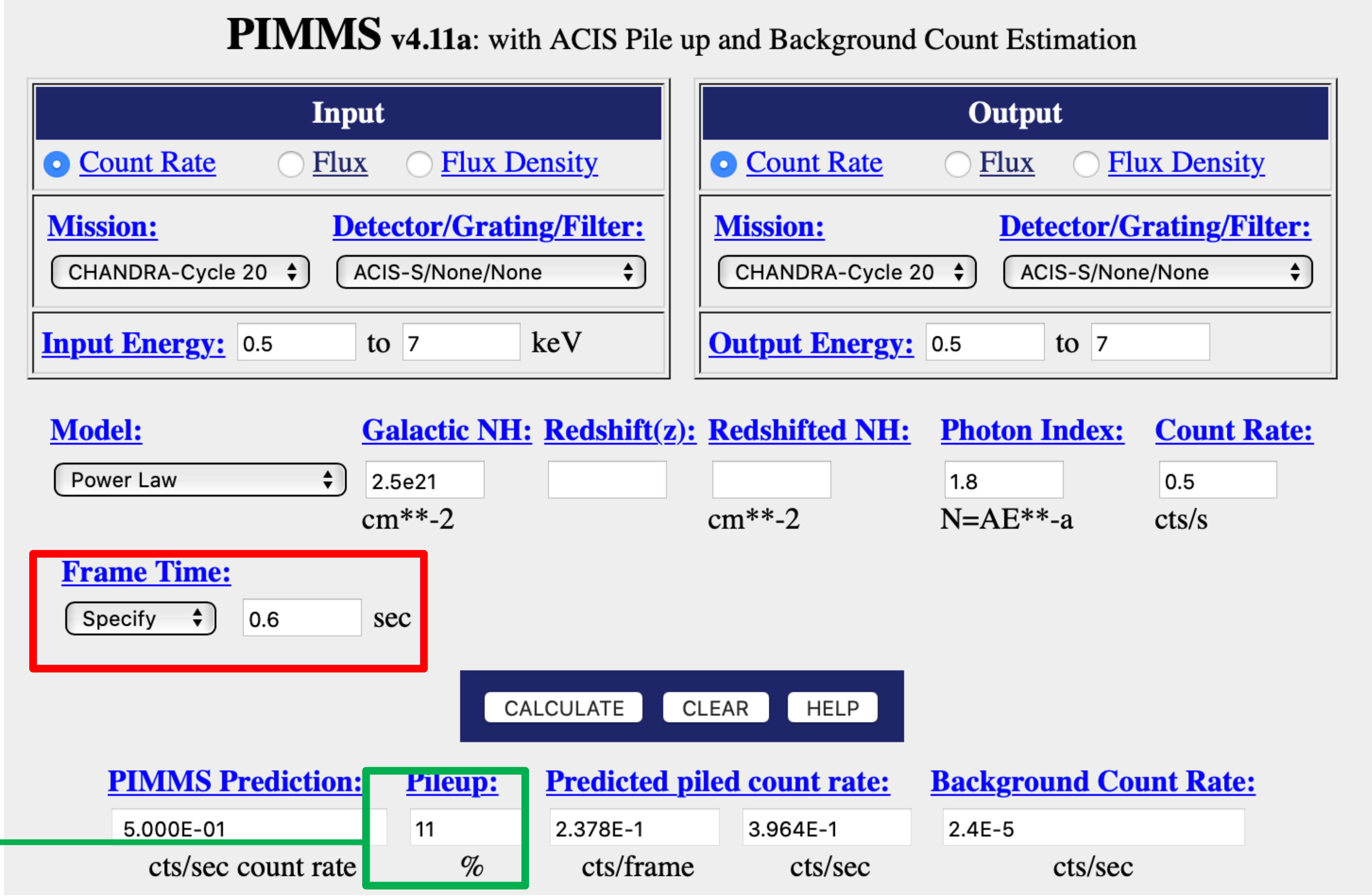
Data analysis: pileup. III

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 20 observation
- Instr: ACIS-S
- Band=0.5−7 keV
- CR=0.75 cps
- Model: powerlaw with Γ=1.8 (assumption)
- $N_{H,Gal}=2.85\times10^{21}$ cm^{-2}
- Frame Time=0.6s (as previously determined due to subarray configuration, instead of the nominal 3.2s)



Output value

- Pileup fraction=11%

Data analysis: removing the readout streak. I

Most of the Chandra observations are already good enough to be used without further work. This set of instructions are to be adopted in case of bright sources to remove the readout streak

1. Get the exact source location from dmstat
2. Create a background spectrum (ciao, physical coordinates)
3. Correct for a bug in **acisreadcorr** in case of observations with subarrays (as in this example)
4. Run acisreadcorr and define the dx,dy size of the region to be cleaned

   dx: width in pixels of the region to be cleaned

   dy: number of rows to be avoided around a source; it can be estimated by drawing a circle in ds9 and finding its diameter

   These dx,dy values determine the width of the region to be cleaned and how close to get to the source, respectively

Data analysis: removing the readout streak. II

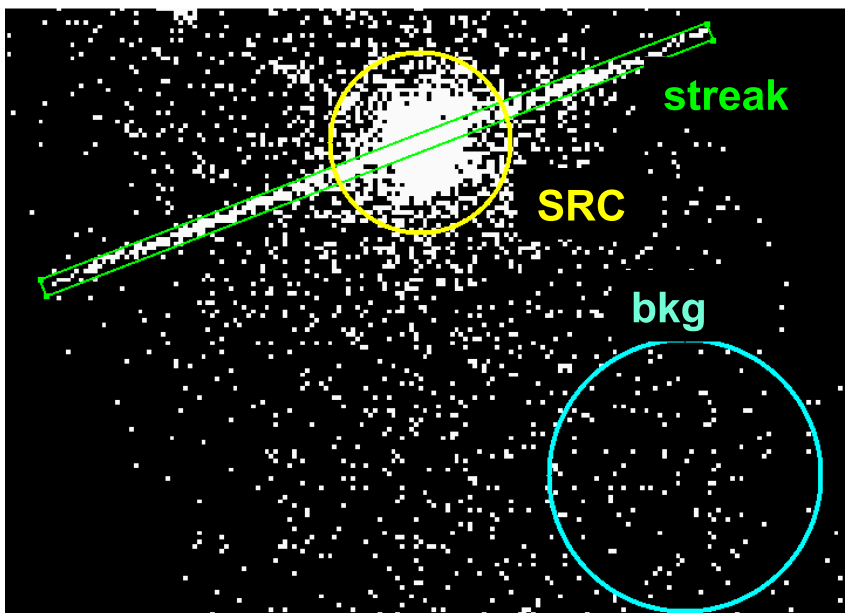
Step 1

- punlearn dmstat
- dmstat "obs20908_037keV_repro_evt2.fits[sky=circle(4090.2,4086.2,20)][bin sky=1]" centroid+ sig- med-

R=20 pixel to have a proper estimate of the source centroid

```
EVENTS_IMAGE(x, y)
    min:          0              @:         ( 4086.7 4066.7 )
    max:          6831           @:         ( 4090.7 4086.7 )
cntrd[log] :      ( 20.909379749 20.921029608 )
cntrd[phys]:      ( 4090.6093797 4086.6210296 )
   good:          1264
   null:          336
```

Centroid (X,Y)=(4090.6,4086.6)



Data analysis: removing the readout streak. III

Step 2

- punlearn dmextract
- pset dmextract infile="obs20908_037keV_repro_evt2.fits[sky=region(bkg.reg)][bin pi=1:1024:1]"
- pset dmextract outfile=bkg_pi.fits   Background file
- dmextract verbose=3

Step 3 [needed because BACKSCAL is not properly computed in the background spectrum in case of subarray observations]

- dmkeypar bkg_pi.fits BACKSCAL echo+

→ 4.2132040682894e-5

To be multiplied by 8 (subarray is 1/8 of the original CCD size in this example)

→ BACKSCAL=0.0003371

- dmhedit infile=bkg_pi.fits filelist="" operation=add key=BACKSCAL value=0.0003371 unit="[pixel]" comment="Fractional area"
- dmkeypar bkg_pi.fits BACKSCAL echo+

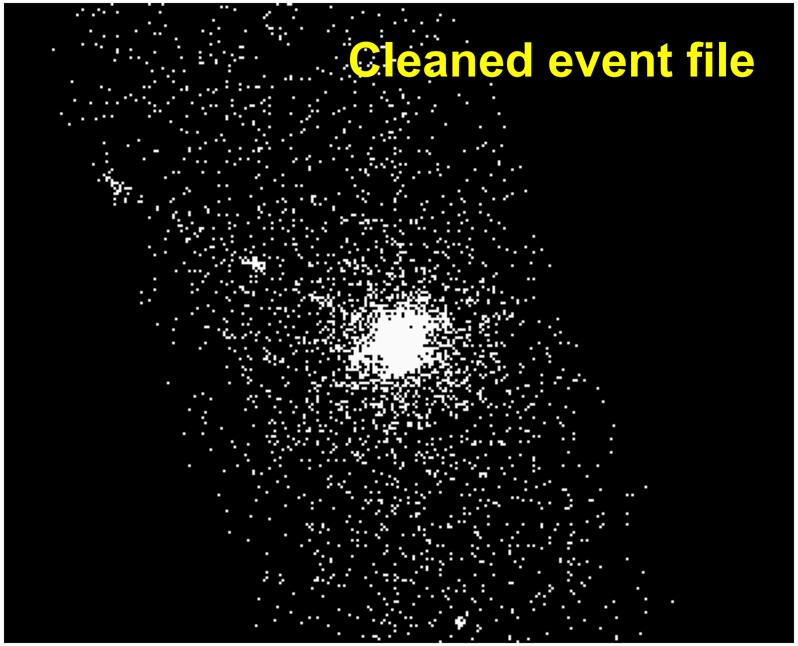
→ 0.0003371

Background BACKSCAL keyword properly corrected

Data analysis: removing the readout streak. IV

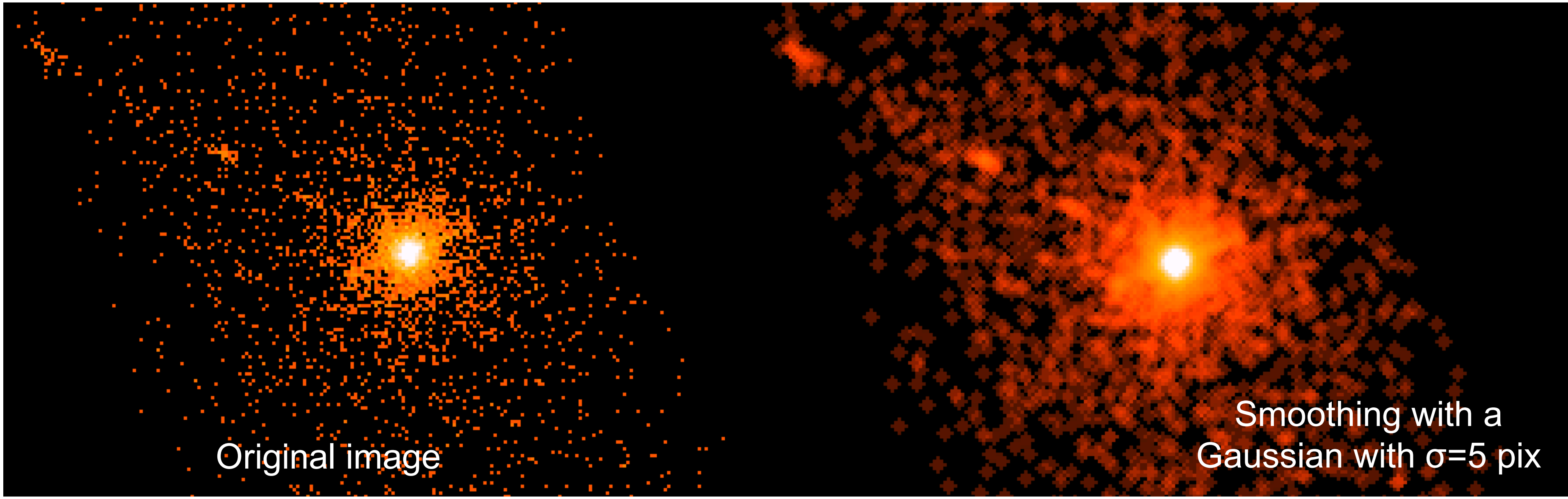
Step 4

- punlearn acisreadcorr
- pset acisreadcorr infile=obs20908_037keV_repro_evt2.fits — Input file
- pset acisreadcorr outfile=obs20908_037keV_repro_corr_evt2.fits — Output file
- pset acisreadcorr aspect=@acisf20908_asol1.lis — Aspect solution
- pset acisreadcorr x=4090.6 y=4086.6 — X,Y of the centroid
- pset acisreadcorr dx=5 dy=40 — Size of the region to be cleaned
- pset acisreadcorr bkg=bkg_pi.fits — Background file
- acisreadcorr



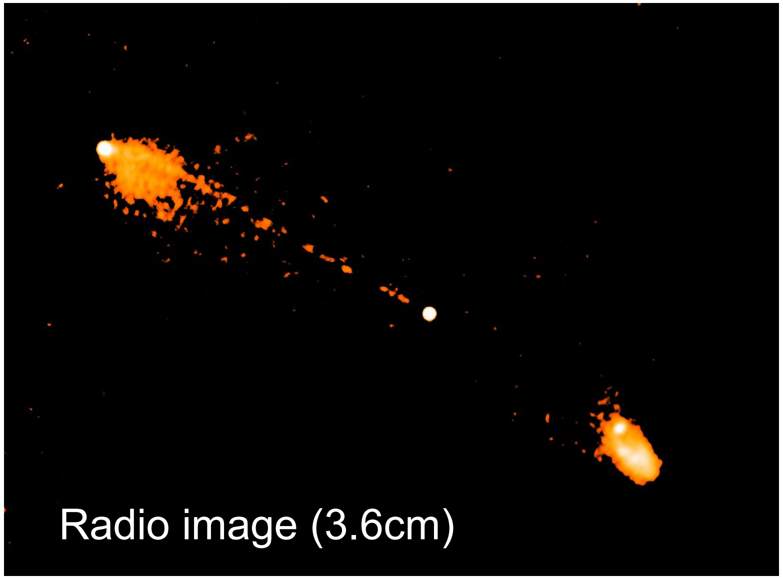
Data analysis: smoothing the image

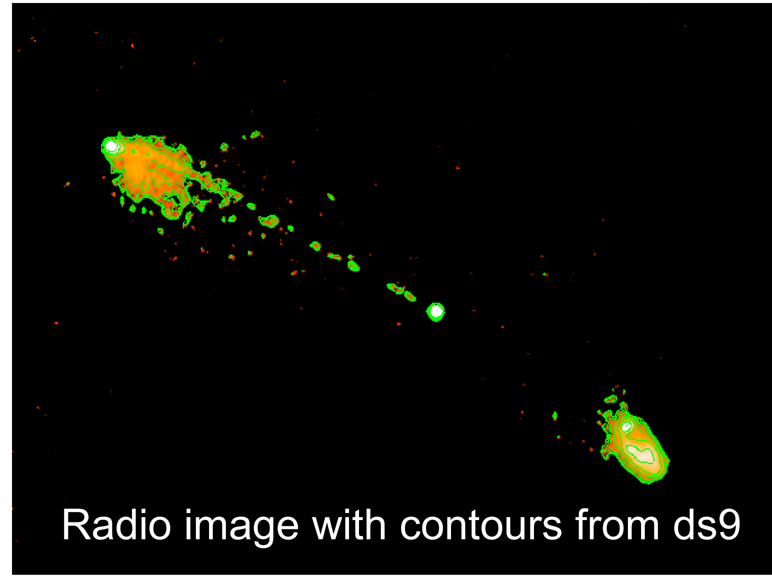
Smoothing is used to enhance faint structures. It consists of substituting the value of each pixel by the value obtained by weighting the nearby pixels using a given function (e.g., a Gaussian)



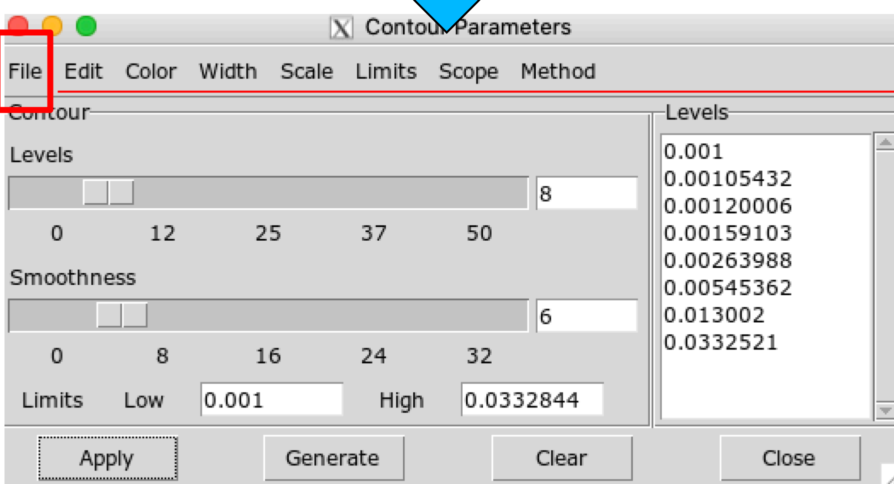
ds9 → Analysis → Smoothing & Smooth Parameters

Data analysis: contours. I





ds9 radio_image → Analysis → Contours & Contour Parameters



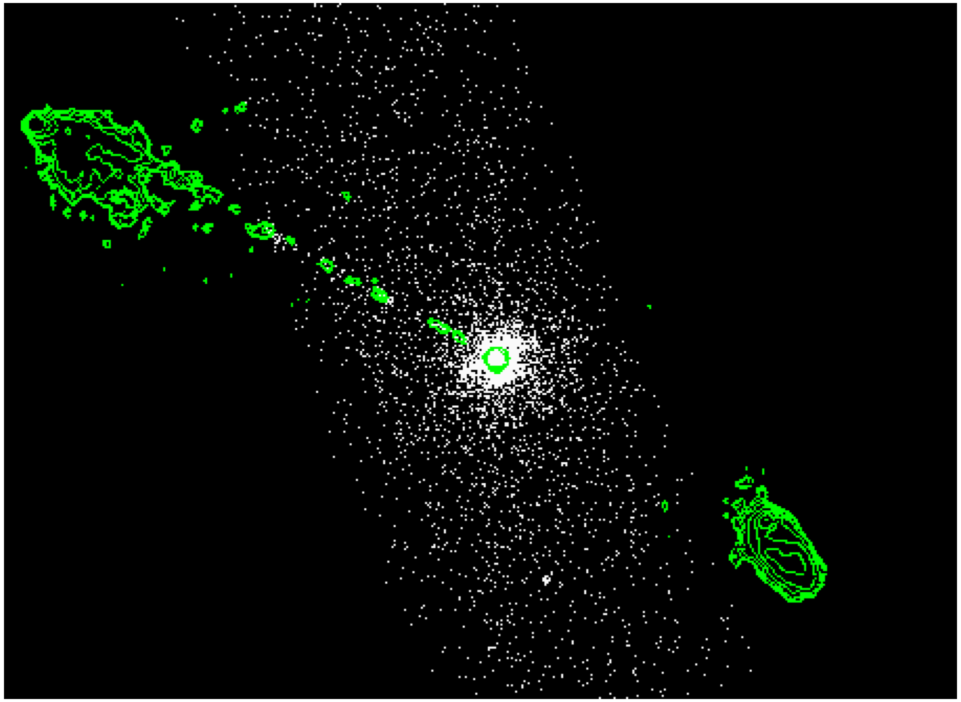
File → Save → radio.ctr

Analysis → Contours

Data analysis: contours. II

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

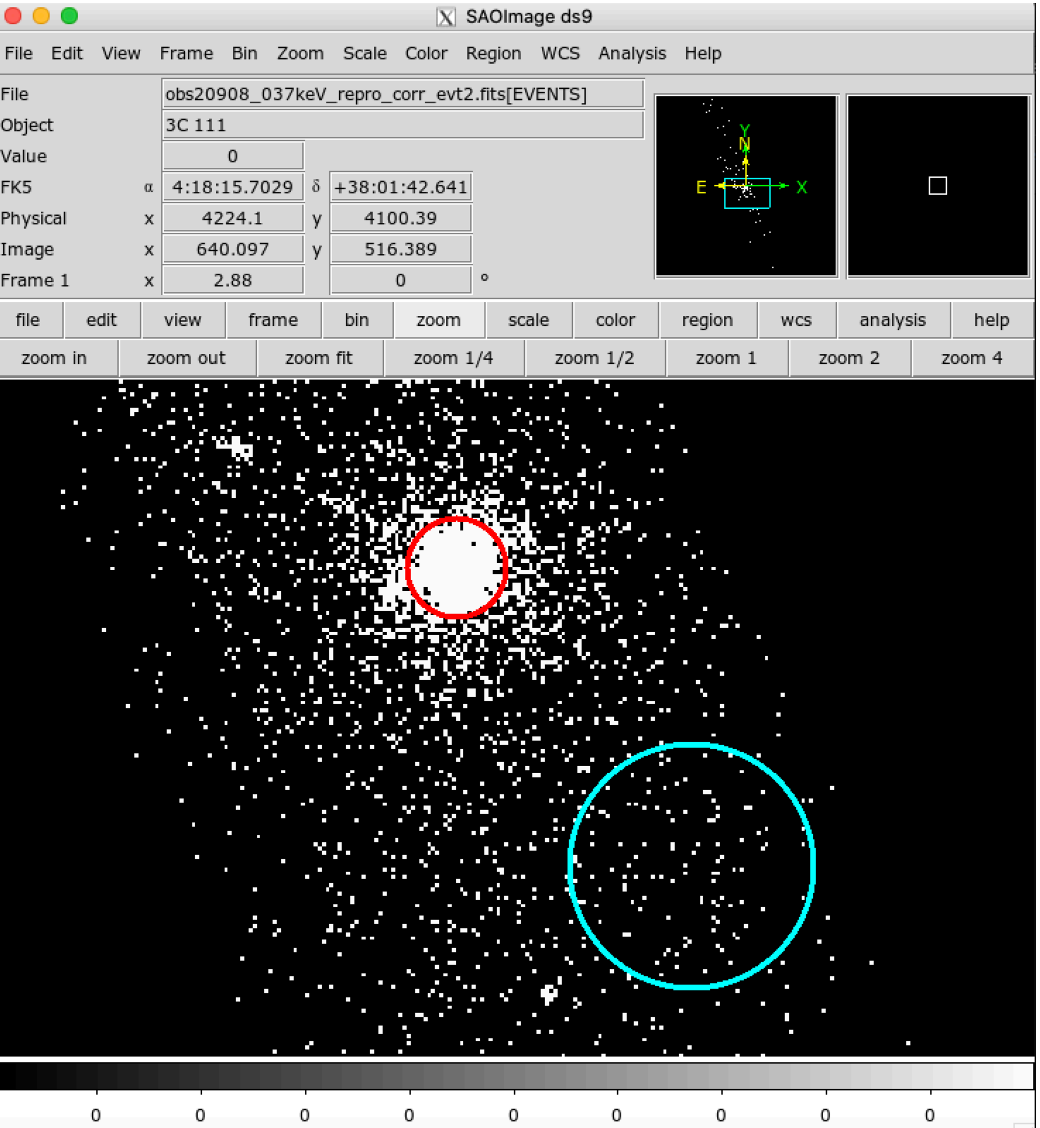
- ds9 obs20908_037keV_repro_corr_evt2.fits -contour load radio.ctr &



Alternatively

ds9 obs20908_037keV_repro_corr_evt2.fits & → Analysis → Contour Parameters → File → Open → radio.ctr

Data analysis: selection of source and back regions



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

Data analysis: timing. I

Creare a background-subtracted light curve

- Source region → source_r6.reg

circle(4091.1,4085.9,12.2)

- Background region → bkg.reg

circle(4148.6,4012.5,30)

- punlearn dmextract
- pset dmextract infile="obs20908_037keV_repro_corr_evt2.fits[sky=region(source_r6.reg)][bin time=::500]" MIN:MAX:BIN → Binning=500 s (depending on the flux of the source)
- pset dmextract outfile="3c311_src_lc.fits"
- pset dmextract bkg="obs20908_037keV_repro_corr_evt2.fits[sky=region(bkg.reg)]"
- pset dmextract opt="ltc1"
- dmextract
- […]

To visualize the columns of the output lightcurve file:

- dmlist 3c311_src_lc.fits cols

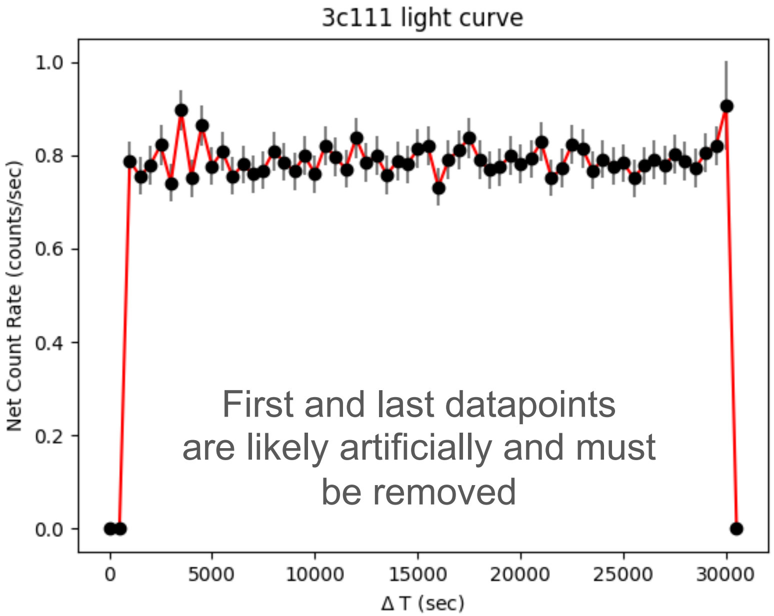
Data analysis: timing. II

Visualization of the source lightcurve. Method I with python and sherpa (CIAO package)

- sherpa
- from pycrates import read_file
- import matplotlib.pylab as plt
- tab = read_file("3c311_src_lc.fits")
- dt = tab.get_column("dt").values
- rate = tab.get_column("net_rate").values
- erate = tab.get_column("err_rate").values
- plt.errorbar(dt, rate, yerr=erate, marker="o", color="red", mfc="black",mec="black", ecolor="grey")
- plt.xlabel("Δ T (sec)")
- plt.ylabel("Net Count Rate (counts/sec)")
- plt.title("3c111 light curve")

Sherpa: Chandra package

Source lightcurve



Data analysis: timing. III

Visualization of the source lightcurve. Method II with the FTOOL package **lcurve**

- lcurve

```
lcurve 1.0 (xronos6.0)

Number of time series for this task[1]
Ser. 1 filename +options (or @file of filenames +options)[file1] 3c311_src_lc.fits
 Series 1 file    1:3c311_src_lc.fits

 Selected FITS extensions: 1 - RATE TABLE;

 Source ............ 3C 111             Start Time (d) .... 18116 18:16:39.741
 FITS Extension ....  1 - `LIGHTCURVE`  Stop Time (d) ..... 18117 02:52:51.142
 No. of Rows .......            62      Bin Time (s) ......    500.0
 Right Ascension ... 6.4587556654073E    Internal time sys.. Converted to TJD
 Declination ....... 3.8027986653567E    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 ... 18116.76157107257  (days)      18:16:39:741  (h:m:s:ms)
 Expected Stop .... 18117.12003637141  (days)       2:52:51:142  (h:m:s:ms)

 Minimum Newbin Time    500.00000      (s)
 for Maximum Newbin No..               62

 Default Newbin Time is:   500.00000    (s) (to have 1 Intv. of      62 Newbins)
 Type INDEF to accept the default value

Newbin Time or negative rebinning[4.6692607009327] 500

 Newbin Time ......     500.00000      (s)
 Maximum Newbin No.                62

 Default Newbins per Interval are:          62
 (giving       1 Interval of          62 Newbins)
 Type INDEF to accept the default value
```

Lightcurve previously produced using dmextract

Information contained in the lightcurve file, Bin time=500s (you may rebin within lcurve)
→ 62 datapoints (=exposure/500s)

Default window

Newbin Time = 500 (as the original)
→ 62 time bins

Data analysis: timing. IV

```
Number of Newbins/Interval[10] 62
 Maximum of        1 Intvs. with          62 Newbins of       500.000     (s)
Name of output file[default] 3c111_lc
Do you want to plot your results?[yes]
Enter PGPLOT device[/XW]

      62 analysis results per interval

100% completed

 Intv    1   Start 18116 18:20:49
     Ser.1     Avg 0.6948        Chisq  1348.       Var 0.3020E-01 Newbs.     62
               Min  0.000          Max 0.8400    expVar 0.1390E-02  Bins     62
PLT> r x 1500 31000
PLT> r y 0.6 0.9
PLT> pl
PLT> fit
 PLT--You must define a model first.
PLT>
PLT> mo cons
  1 CO: VAL(  1.000    ), SIG(  0.000    ), PLO(  0.000    ), PHI(  0.000    )?

PLT> fit
 Fitting group   2,  from  1.500E+03 to  3.100E+04
 Fitting      58 points in a band of      58.
   1.00000000
 ( -3)   W-VAR= 29.64
 ( -4)   W-VAR= 29.64
  0.738529861
PLT> plot
PLT> hard 3c111_lc_500s.ps/ps
PLT> quit
Writing output file: 3c111_lc.flc
```

Name of the output file

Plotting device: /xw

iplot environment:

Rescale the X (time) axis to remove the first and last time bins if their behaviour is unusual

Fit with a constant model ('constant' lightcurve, i.e., no variability)

Save the lightcurve in a PS file

Data analysis: timing. V

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**

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

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

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="obs20908_037keV_repro_corr_evt2.fits[sky=region(source_r6.reg)]"
- pset specextract bkgfile="obs20908_037keV_repro_corr_evt2.fits[sky=region(bck.reg)]"
- pset specextract outroot=3c111_r6
- pset specextract asp=pcadf20908_000N001_asol1.fits
- pset specextract mskfile=acisf20908_000N002_msk1.fits
- pset specextract badpixfile=acisf20908_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

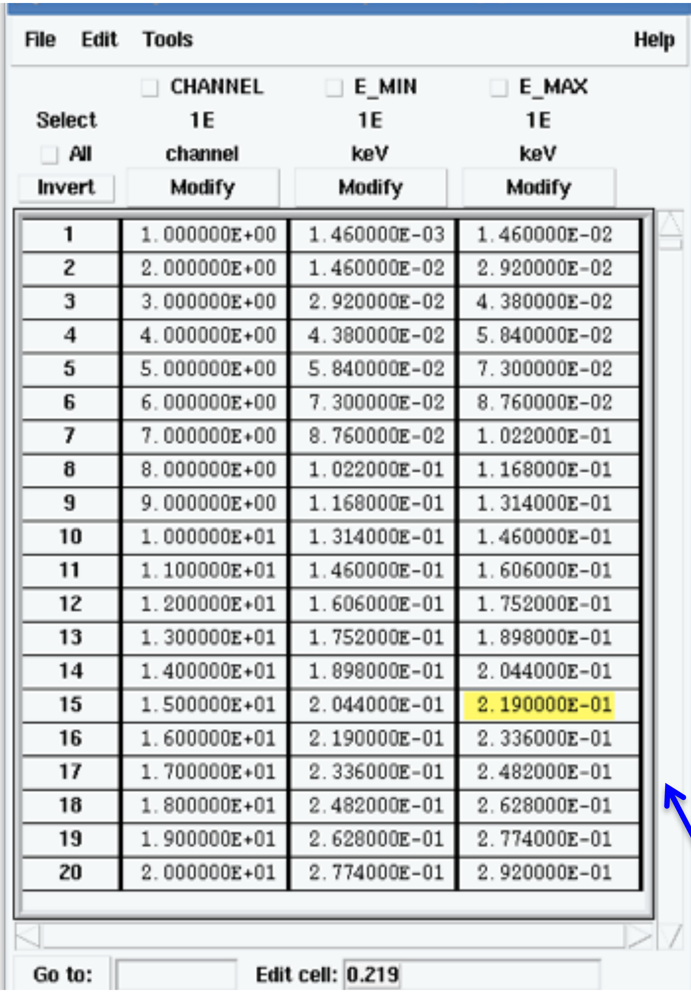
The opposite (weight=yes & correct=no) for extended src

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

Data can be rebinned either here or later using **grppha**

Response matrices: RMF

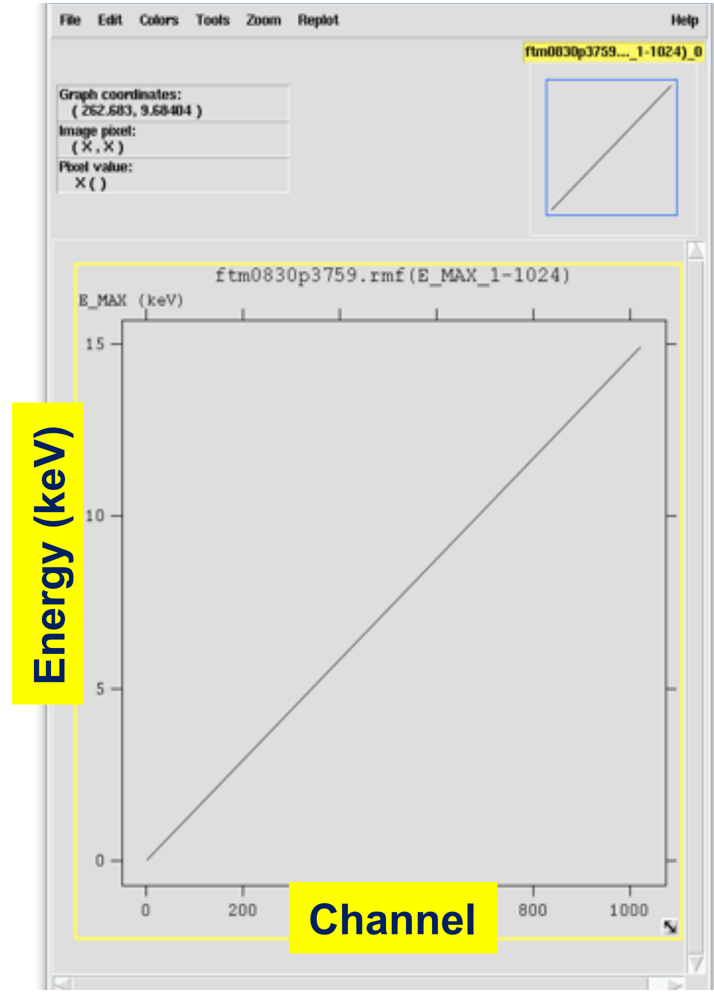
RMF: links the instrumental channel scale with the physical energy (wavelength) scale



File Edit Tools Help

Select / All / Invert	CHANNEL 1E channel	E_MIN 1E keV	E_MAX 1E keV
1	1.000000E+00	1.460000E-03	1.460000E-02
2	2.000000E+00	1.460000E-02	2.920000E-02
3	3.000000E+00	2.920000E-02	4.380000E-02
4	4.000000E+00	4.380000E-02	5.840000E-02
5	5.000000E+00	5.840000E-02	7.300000E-02
6	6.000000E+00	7.300000E-02	8.760000E-02
7	7.000000E+00	8.760000E-02	1.022000E-01
8	8.000000E+00	1.022000E-01	1.168000E-01
9	9.000000E+00	1.168000E-01	1.314000E-01
10	1.000000E+01	1.314000E-01	1.460000E-01
11	1.100000E+01	1.460000E-01	1.606000E-01
12	1.200000E+01	1.606000E-01	1.752000E-01
13	1.300000E+01	1.752000E-01	1.898000E-01
14	1.400000E+01	1.898000E-01	2.044000E-01
15	1.500000E+01	2.044000E-01	2.190000E-01
16	1.600000E+01	2.190000E-01	2.336000E-01
17	1.700000E+01	2.336000E-01	2.482000E-01
18	1.800000E+01	2.482000E-01	2.628000E-01
19	1.900000E+01	2.628000E-01	2.774000E-01
20	2.000000E+01	2.774000E-01	2.920000E-01

Go to: Edit cell: 0.219



Visualization of the RMF file using the **ftool** ***fv***

Response matrices: ARF

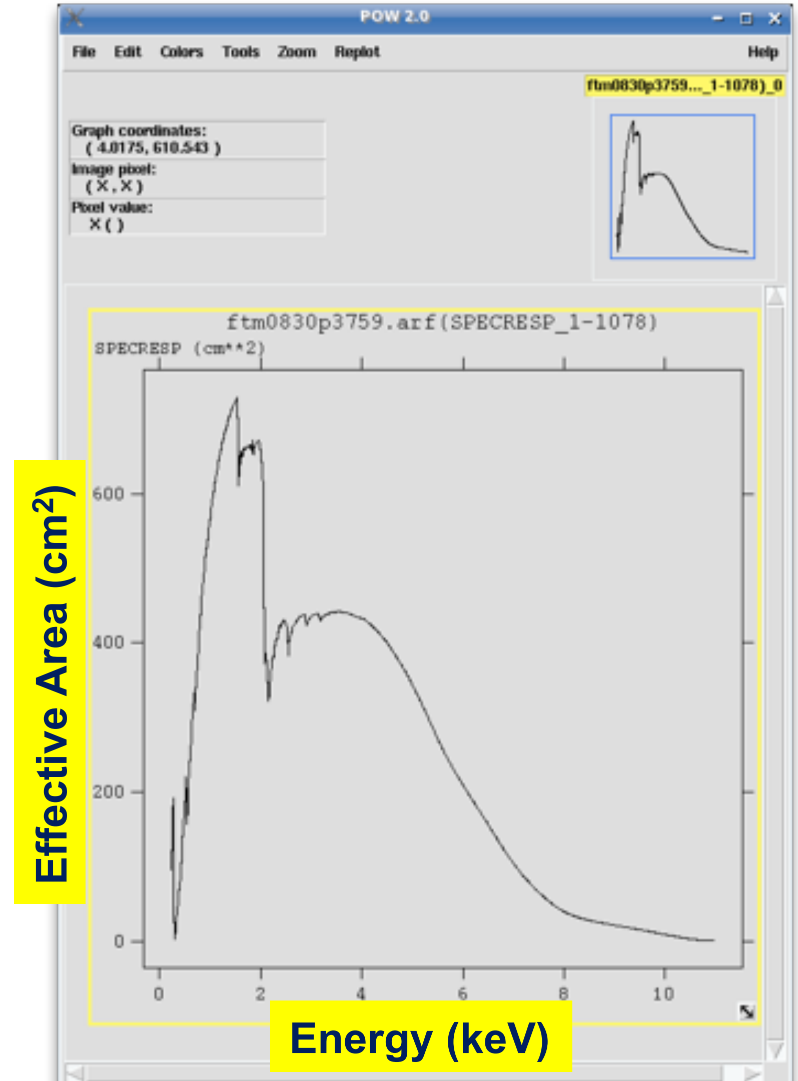
ARF: indicates the effective response (hence sensitivity) of the mirrors+instrument at a given source position on the detector

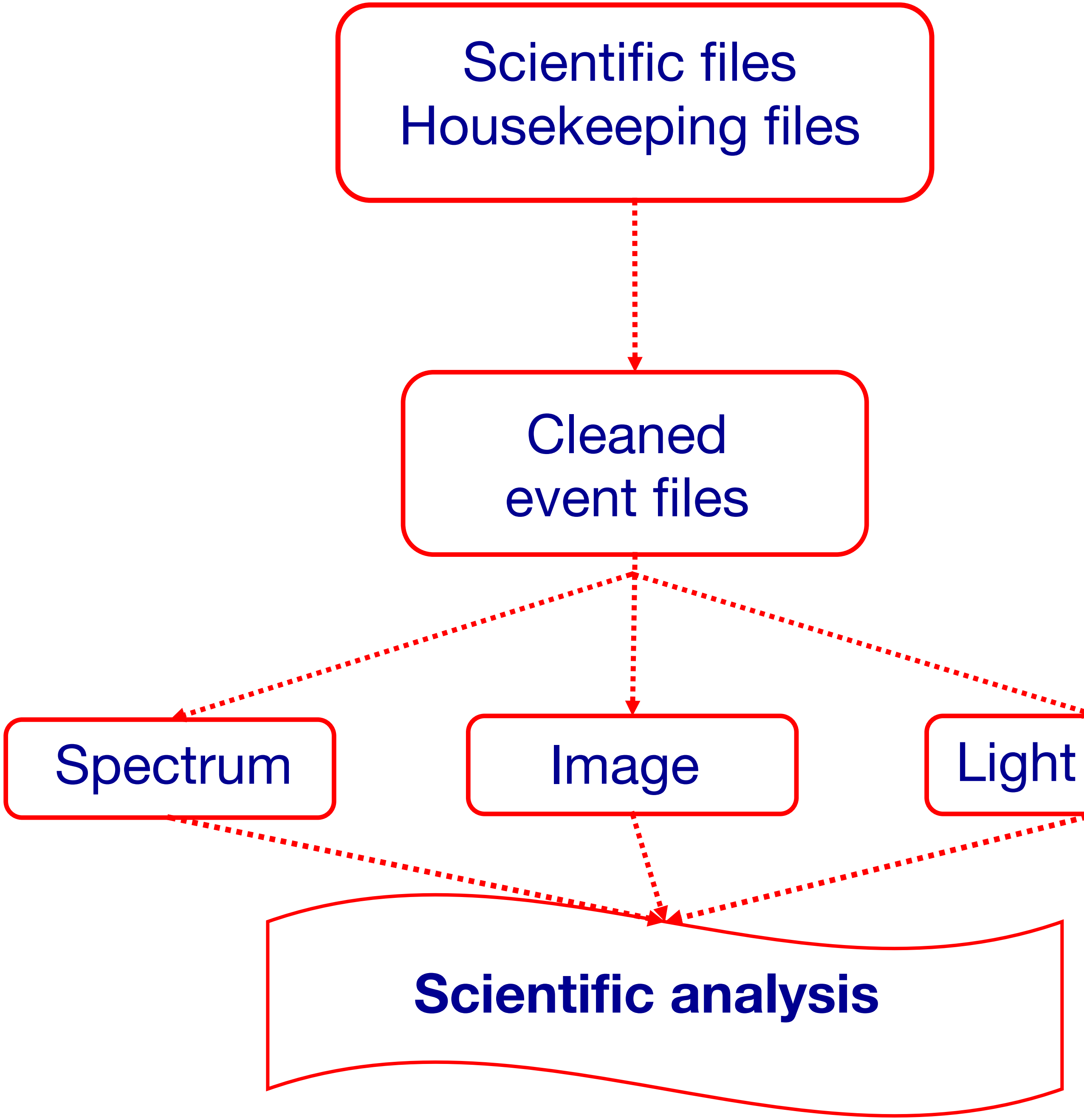
fv: Binary Table of ftm0830p3759.arf[1] in /ho

File Edit Tools Help

Select	ENERG_LO	ENERG_HI	SPECRESP
All	1E keV	1E keV	1E cm**2
Invert	Modify	Modify	Modify
1	2.200000E-01	2.300000E-01	9.414584E+01
2	2.300000E-01	2.400000E-01	1.119709E+02
3	2.400000E-01	2.500000E-01	1.309653E+02
4	2.500000E-01	2.600000E-01	1.518642E+02
5	2.600000E-01	2.700000E-01	1.716482E+02
6	2.700000E-01	2.800000E-01	1.922011E+02
7	2.800000E-01	2.900000E-01	4.741680E+01
8	2.900000E-01	3.000000E-01	2.284590E+00
9	3.000000E-01	3.100000E-01	5.144246E+00
10	3.100000E-01	3.200000E-01	1.563580E+01
11	3.200000E-01	3.300000E-01	2.251595E+01
12	3.300000E-01	3.400000E-01	3.011008E+01
13	3.400000E-01	3.500000E-01	3.743014E+01
14	3.500000E-01	3.600000E-01	4.385400E+01
15	3.600000E-01	3.700000E-01	4.954287E+01
16	3.700000E-01	3.800000E-01	5.625348E+01
17	3.800000E-01	3.900000E-01	6.431229E+01
18	3.900000E-01	4.000000E-01	7.319862E+01
19	4.000000E-01	4.100000E-01	7.713167E+01
20	4.100000E-01	4.200000E-01	8.444775E+01

Go to: Edit cell: 0.42





XSPEC tutorial