XMM-Newton tutorial for data reduction

https://indico.ict.inaf.it/e/labx25

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Outline

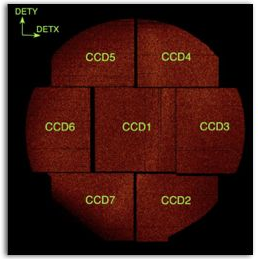
- The spacecraft
- Webpage, software and data download
- Data structure

- SAS
- Data re-processing
- Data reduction:
  -> filtering for high particle background
  -> selection of good time intervals (GTI)
  -> selection of source and background extraction regions
- EPIC science modes
- Pileup

- Extraction of source and background spectra
- RMF & ARF
- Grouping

- Light curve extraction

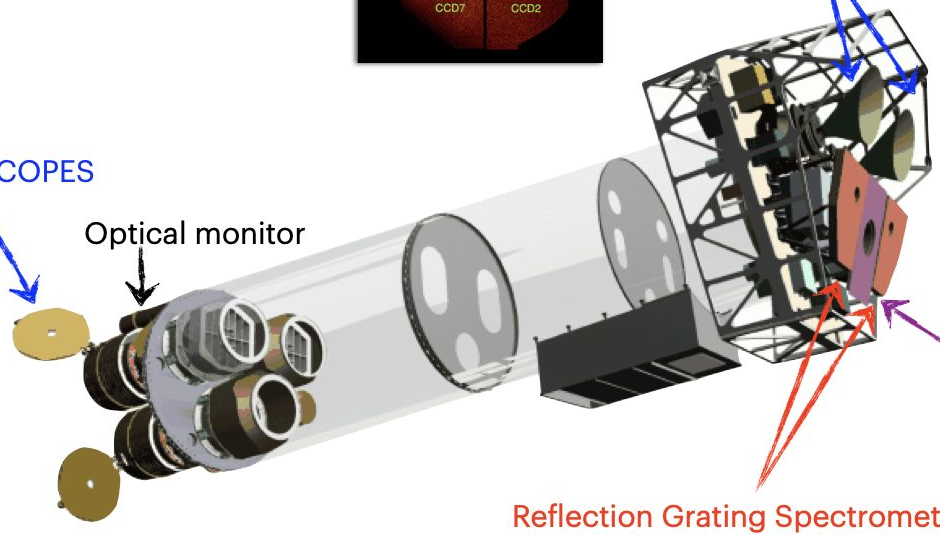
The spacecraft



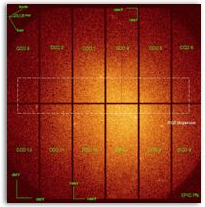
EPIC MOS cameras

X-RAY TELESCOPES

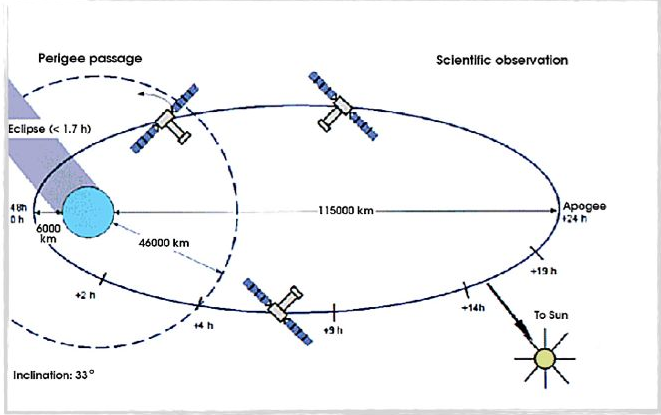
Optical monitor



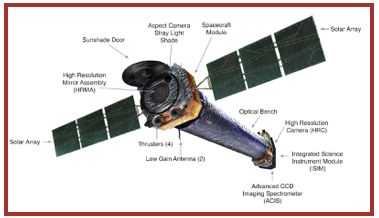
EPIC PN camera



Reflection Grating Spectrometers (RGS)



Highly elliptical orbit around the Earth
Inclination 40 degrees to the Equator



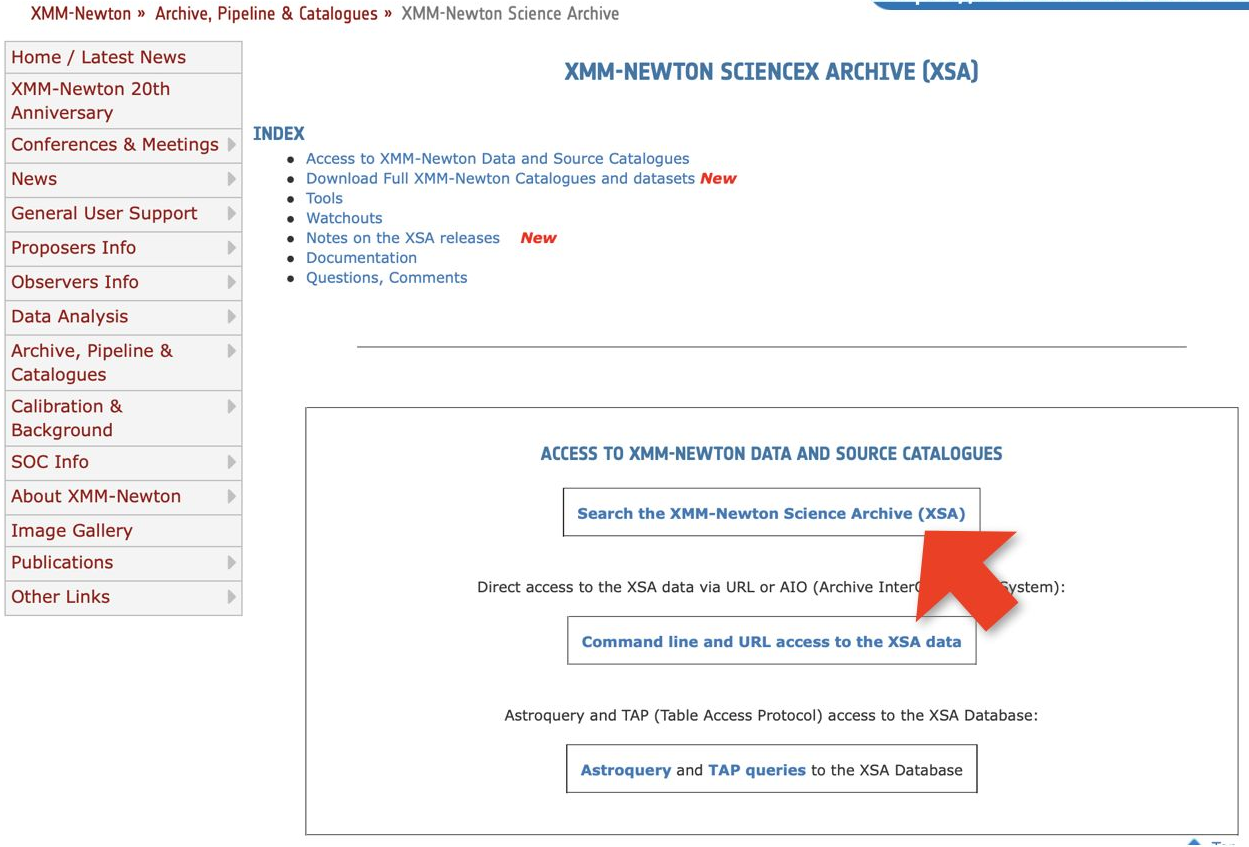
All instruments in the focal plane “active” for each observation

Image courtesy of Dornier Satellitensysteme GmbH and ESA

See M. Dadina’s presentation & C. Vignali’s presentations

XMM-Newton archive & data download

https://www.cosmos.esa.int/web/xmm-newton/xsa



XMM-Newton Science Archive Search

Position | File

- (•) Name
- ( ) Equatorial
- ( ) Galactic

Target in (•) Field Of View ( ) Circle ( ) Box

Name: 3C 33 for Resolve

▶ Observation and Proposal filters

▶ Display options

Reset Form

Catalogue Search > | Submit

		Obs.ID	EPIC	RGS	BKGD	ESASky	Target	RA	DEC	Rev	Distance	Start Date	End Date	Dur.	Target Type	PI name	Prop. Program
☐	⬇	0203280101					3C33	01h 08m 52.85s	+13d 20' 13.8"	745	0.01	2004-01-04 04:49:31	2004-01-04 08:59:23	14992	RADIO GALAXY RADIO LOUD/STEEP SPECT	HARDCASTLE, MARTIN	GO
☑	⬇	[illegible]1					3C33	01h 08m 52.85s	+13d 20' 13.8"	754	0.01	2004-01-21 17:06:11	2004-01-21 19:34:37	8906	RADIO GALAXY RADIO LOUD/STEEP SPECT	HARDCASTLE, MARTIN	GO

ODF
PPS
IMAGES
SOURCES
SPECTRA
LIGHT_CURVES

Public Date	PPS ver	Coord. Obs
Public data	17.56_20190403_1200	-
Public data	17.56_20190403_1200	-

OBSERVATIONS (2)

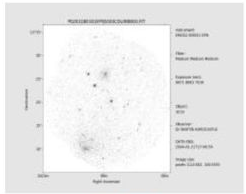
Columns | Column units | Display selected | Add to Basket | Save table as | Send table to | Reprocess | RGS Spectra

			Obs.ID	EPIC	RGS	BKGD	ESASky	Target	RA	DEC	Rev	Distance	Start Date	End Date
☐	⬇	🔎	0203280101					3C33	01h 08m 52.85s	+13d 20' 13.8"	745	0.01	2004-01-04 04:49:31	2004-01-04 08:59:23
☑	⬇	🔎	0203280301					3C33	01h 08m 52.85s	+13d 20' 13.8"	754	0.01	2004-01-21 17:06:11	2004-01-21 19:34:37

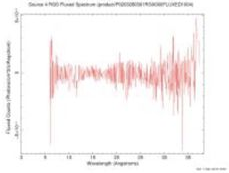
1 of 1 | Page size: 100

Displaying 1-2 of 2

Details for Observation 0203280301



EPIC Image



RGS fluxed spectrum

Summary | Science Exposures | Publications

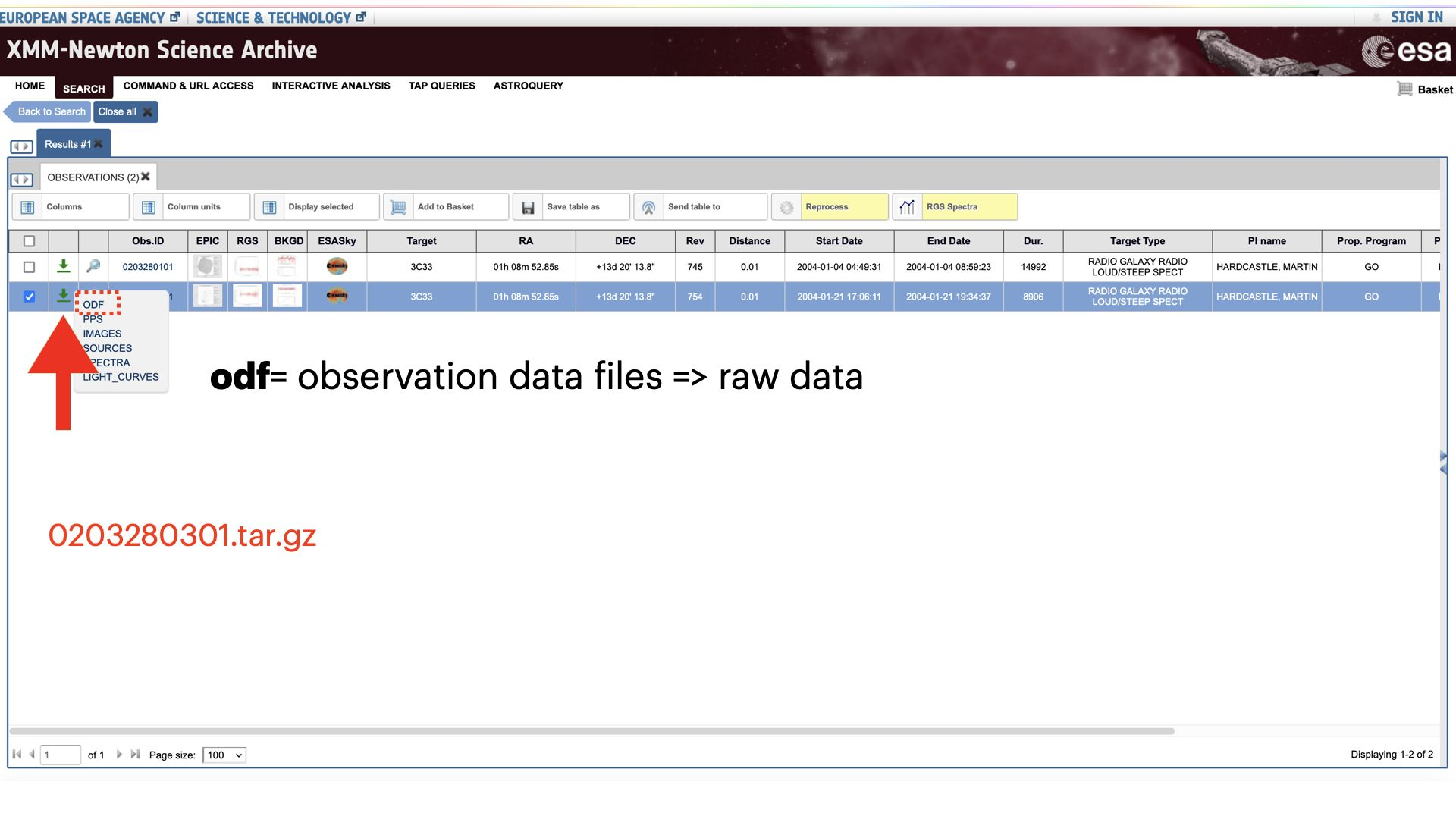
Obs. ID	0203280301
Revolution	754
Target	3C33
Exposures	3 EPIC, 1 OM, 2 RGS

Proposal Abstract

A SEARCH FOR THE GROUP ENVIRONMENTS OF LOW-POWER FRII RADIO GALAXIES

Although a good deal of indirect evidence points towards moderate or poor groups as the environment of low-luminosity (and therefore typical) FRII radio galaxies, there are almost no direct X-ray observations of the required hot, confining medium. An FRII radio source would have a dramatic effect on the gas in a group, heating and potentially expelling a significant fraction of it, with important consequences for our understanding of group evolution. In order to characterize the X-ray environments of typical FRII sources, we propose a small survey of the nearest few FRII sources of intermediate size drawn from the well-studied 3CRR catalogue. Our observations will allow us to detect, and measure the properties of, group-scale emission around our targets.

Show Quality Report


EUROPEAN SPACE AGENCY
SCIENCE & TECHNOLOGY
SIGN IN
XMM-Newton Science Archive
esa
HOME
SEARCH
COMMAND & URL ACCESS
INTERACTIVE ANALYSIS
TAP QUERIES
ASTROQUERY
Basket
Back to Search
Close all
Results #1
OBSERVATIONS (2)
Columns
Column units
Display selected
Add to Basket
Save table as
Send table to
Reprocess
RGS Spectra
Obs.ID
EPIC
RGS
BKGD
ESASky
Target
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Start Date
End Date
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Target Type
PI name
Prop. Program
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3C33
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+13d 20' 13.8"
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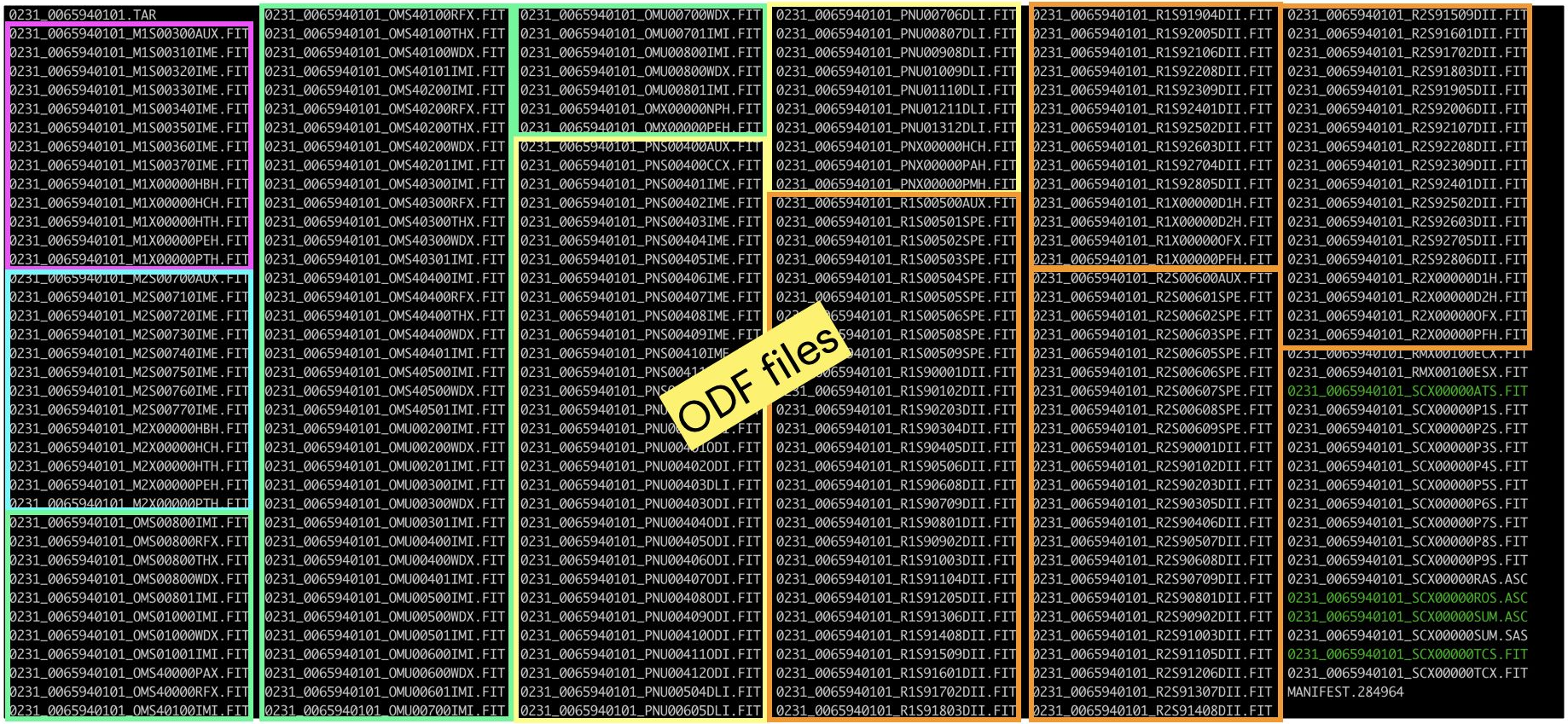
14992
RADIO GALAXY RADIO LOUD/STEEP SPECT
HARDCASTLE, MARTIN
GO
3C33
01h 08m 52.85s
+13d 20' 13.8"
754
0.01
2004-01-21 17:06:11
2004-01-21 19:34:37
8906
RADIO GALAXY RADIO LOUD/STEEP SPECT
HARDCASTLE, MARTIN
GO
ODF
PPS
IMAGES
SOURCES
SPECTRA
LIGHT_CURVES
odf= observation data files => raw data
0203280301.tar.gz
1
of 1
Page size:
100
Displaying 1-2 of 2

Data structure

example: 0203280301.tar.gz -> tar -zxvf 0203280301.tar.gz

-z= unzip
-xvf=untar



MOS1
MOS2

OM

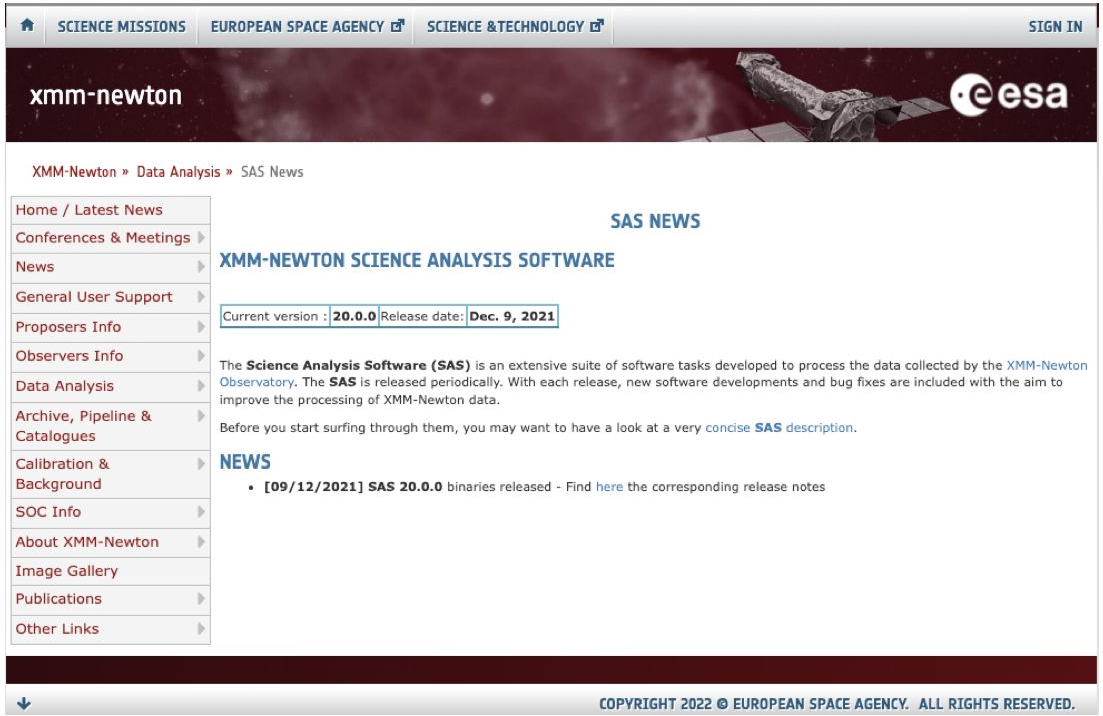
pn

RGS1

RGS2

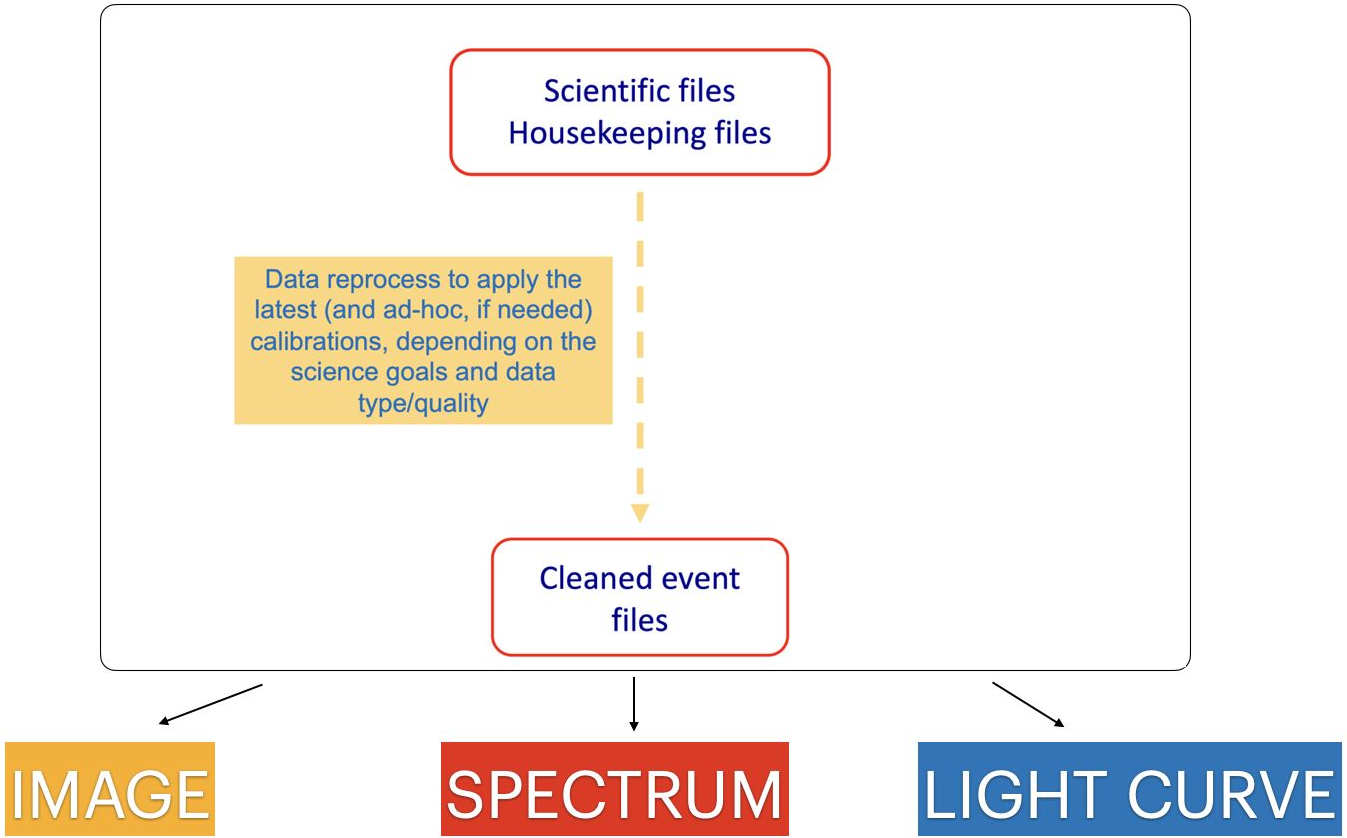
Data reduction

Standard Analysis System (SAS)

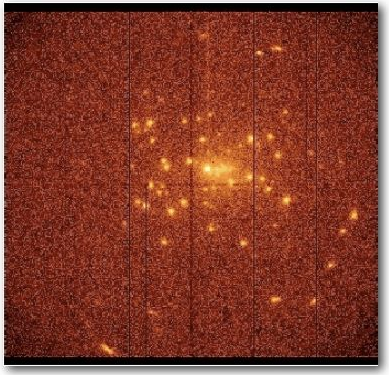


Data reduction

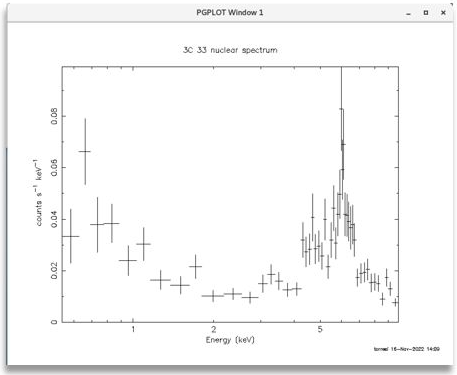
SAS threads



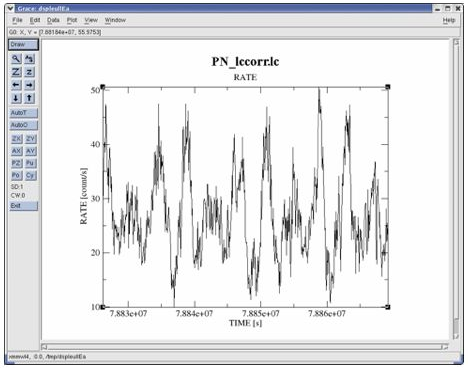
IMAGE



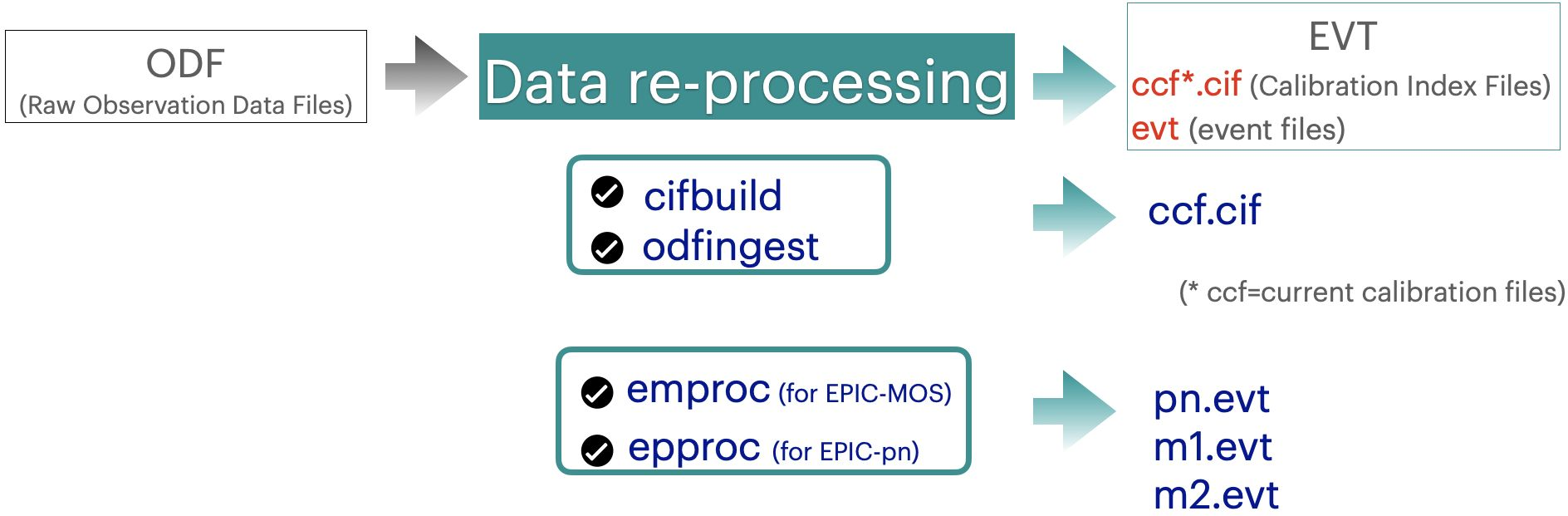
SPECTRUM



LIGHT CURVE

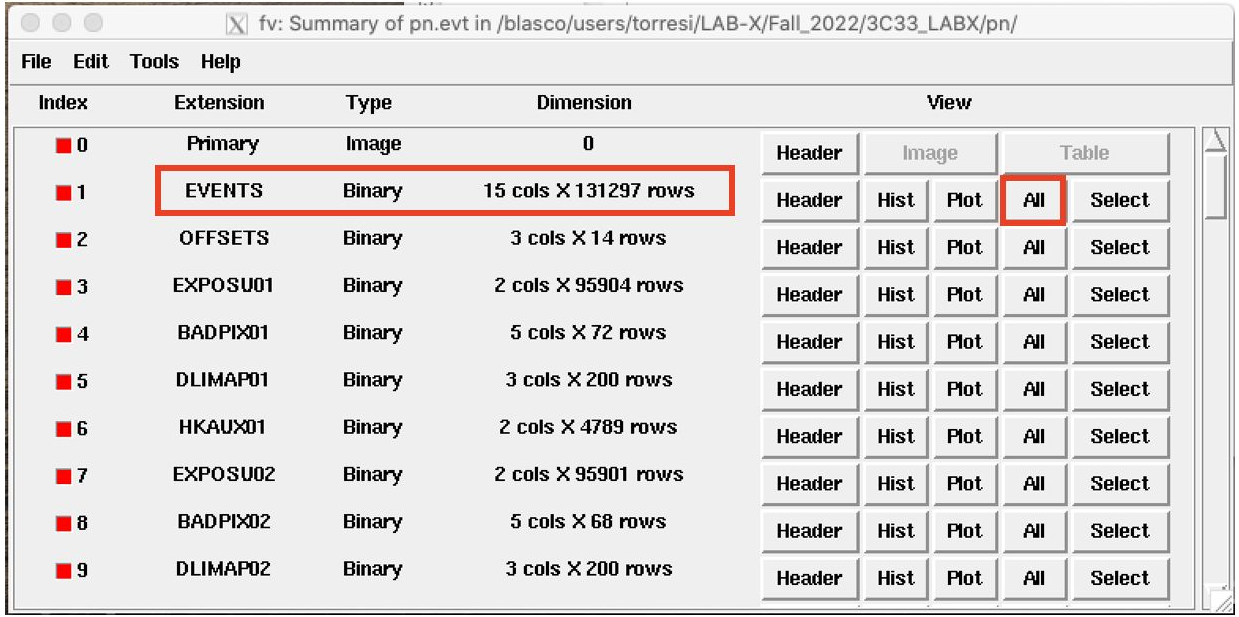


Data re-processing (= creation of **event files**)



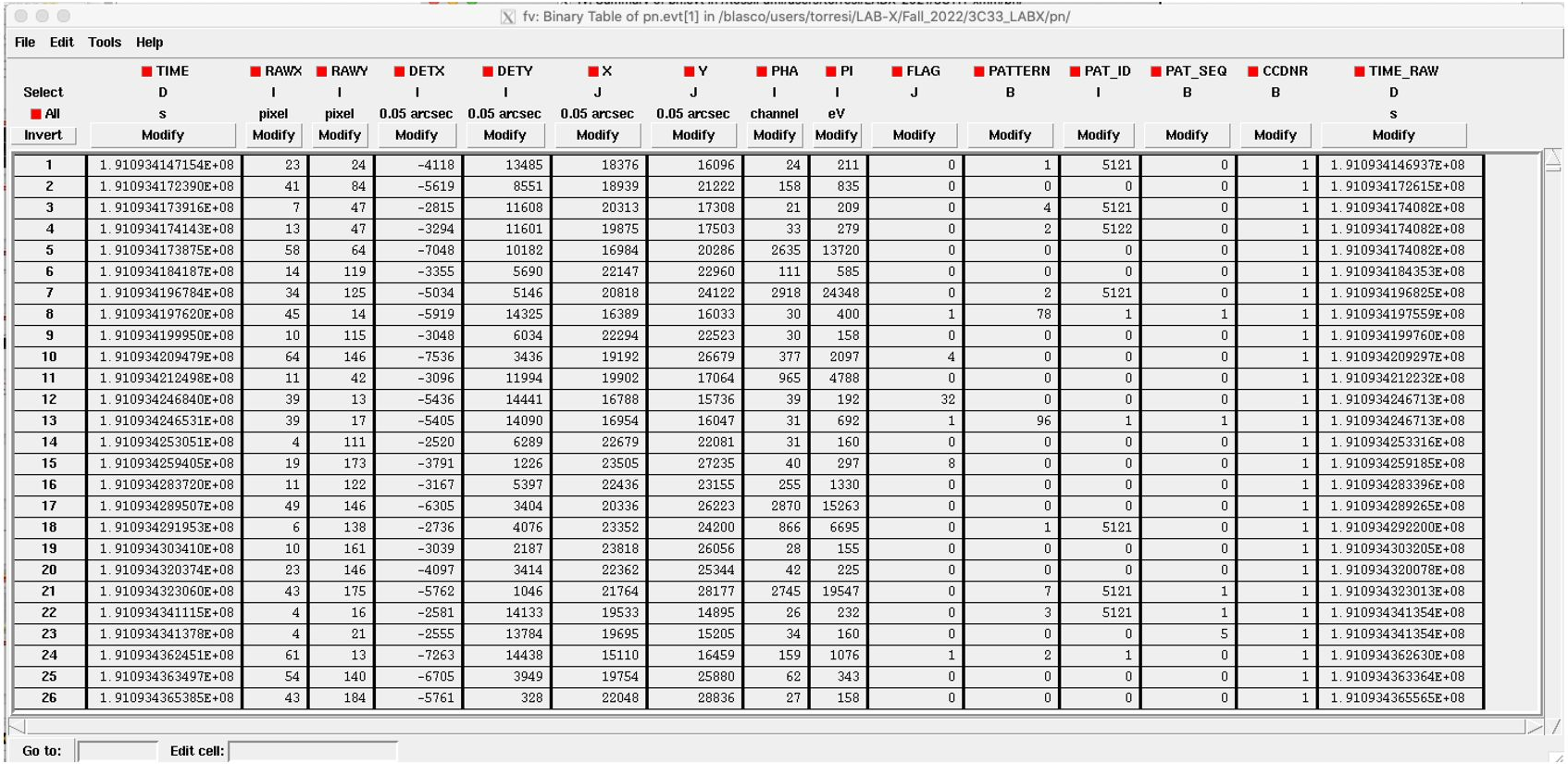
fv pn.evt

#rows=#counts



X,Y -> image
Time -> light curve
PHA, PI -> spectrum

fv pn.evt



fv: Binary Table of pn.evt[1] in /blasco/users/torresi/LAB-X/Fall_2022/3C33_LABX/pn/

File Edit Tools Help

	TIME	RAWX	RAWY	DETX	DETY	X	Y	PHA	PI	FLAG	PATTERN	PAT_ID	PAT_SEQ	CCDNR	TIME_RAW
Select	D	I	I	I	I	J	J	I	I	J	B	I	B	B	D
All	s	pixel	pixel	0.05 arcsec	0.05 arcsec	0.05 arcsec	0.05 arcsec	channel	eV						s
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	1.910934147154E+08	23	24	-4118	13485	18376	16096	24	211	0	1	5121	0	1	1.910934146937E+08
2	1.910934172390E+08	41	84	-5619	8551	18939	21222	158	835	0	0	0	0	1	1.910934172615E+08
3	1.910934173916E+08	7	47	-2815	11608	20313	17308	21	209	0	4	5121	0	1	1.910934174082E+08
4	1.910934174143E+08	13	47	-3294	11601	19875	17503	33	279	0	2	5122	0	1	1.910934174082E+08
5	1.910934173875E+08	58	64	-7048	10182	16984	20286	2635	13720	0	0	0	0	1	1.910934174082E+08
6	1.910934184187E+08	14	119	-3355	5690	22147	22960	111	585	0	0	0	0	1	1.910934184353E+08
7	1.910934196784E+08	34	125	-5034	5146	20818	24122	2918	24348	0	2	5121	0	1	1.910934196825E+08
8	1.910934197620E+08	45	14	-5919	14325	16389	16033	30	400	1	78	1	1	1	1.910934197559E+08
9	1.910934199950E+08	10	115	-3048	6034	22294	22523	30	158	0	0	0	0	1	1.910934199760E+08
10	1.910934209479E+08	64	146	-7536	3436	19192	26679	377	2097	4	0	0	0	1	1.910934209297E+08
11	1.910934212498E+08	11	42	-3096	11994	19902	17064	965	4788	0	0	0	0	1	1.910934212232E+08
12	1.910934246840E+08	39	13	-5436	14441	16788	15736	39	192	32	0	0	0	1	1.910934246713E+08
13	1.910934246531E+08	39	17	-5405	14090	16954	16047	31	692	1	96	1	1	1	1.910934246713E+08
14	1.910934253051E+08	4	111	-2520	6289	22679	22081	31	160	0	0	0	0	1	1.910934253316E+08
15	1.910934259405E+08	19	173	-3791	1226	23505	27235	40	297	8	0	0	0	1	1.910934259185E+08
16	1.910934283720E+08	11	122	-3167	5397	22436	23155	255	1330	0	0	0	0	1	1.910934283396E+08
17	1.910934289507E+08	49	146	-6305	3404	20336	26223	2870	15263	0	0	0	0	1	1.910934289265E+08
18	1.910934291953E+08	6	138	-2736	4076	23352	24200	866	6695	0	1	5121	0	1	1.910934292200E+08
19	1.910934303410E+08	10	161	-3039	2187	23818	26056	28	155	0	0	0	0	1	1.910934303205E+08
20	1.910934320374E+08	23	146	-4097	3414	22362	25344	42	225	0	0	0	0	1	1.910934320078E+08
21	1.910934323060E+08	43	175	-5762	1046	21764	28177	2745	19547	0	7	5121	1	1	1.910934323013E+08
22	1.910934341115E+08	4	16	-2581	14133	19533	14895	26	232	0	3	5121	1	1	1.910934341354E+08
23	1.910934341378E+08	4	21	-2555	13784	19695	15205	34	160	0	0	0	5	1	1.910934341354E+08
24	1.910934362451E+08	61	13	-7263	14438	15110	16459	159	1076	1	2	1	0	1	1.910934362630E+08
25	1.910934363497E+08	54	140	-6705	3949	19754	25880	62	343	0	0	0	0	1	1.910934363364E+08
26	1.910934365385E+08	43	184	-5761	328	22048	28836	27	158	0	0	0	0	1	1.910934365565E+08

Go to: Edit cell:

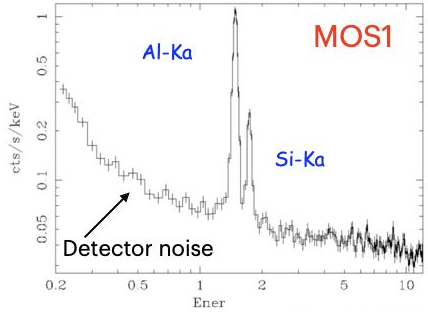
Filtering against high background periods

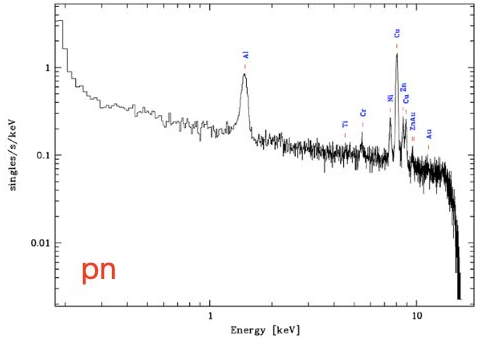
EPIC particle induced background

(above a few keV)

Internal '*quiescent*' component

high-energy particles **interacting with the structure** surrounding the detectors and the detectors themselves





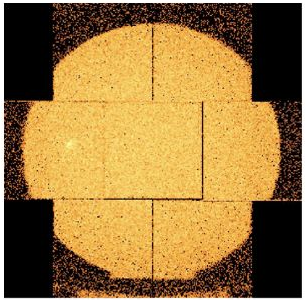
Filtering against high background periods

EPIC particle induced background

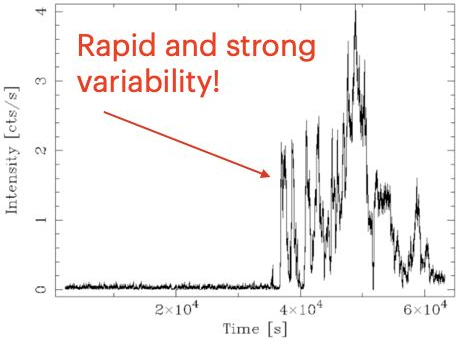
(above a few keV)

External '*flaring*' component

strong and rapid variability; currently attributed to **soft protons (E_p < a few 100 keV)** likely organized in clouds populating the Earth's magnetosphere (above a few keV)



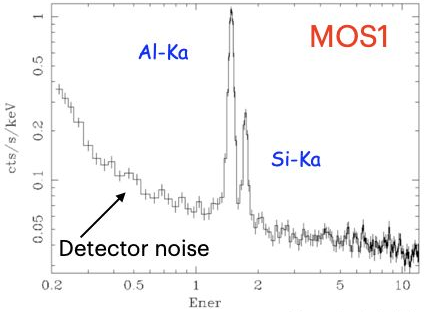
MOS2 observation
badly affected by soft proton flares

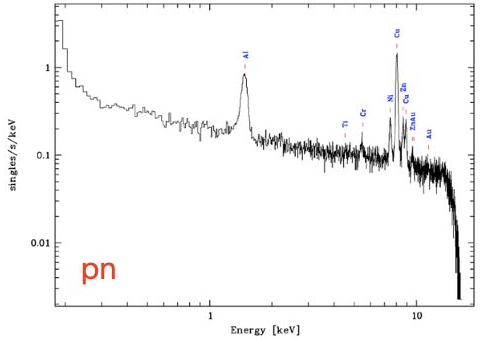


MOS1 light curve
badly affected by soft proton flares

Internal '*quiescent*' component

high-energy particles **interacting with the structure** surrounding the detectors and the detectors themselves





Creation of a light curve above 10 keV

How to filter an EPIC event list for periods of high background *flaring* activity

Extract a **single event (i.e., pattern zero only)**, high energy light curve, from the event file to identify intervals of flaring particle background:

Select only good, single events with energies between 10 and 12 keV.

Notice that the EPIC-pn energy range selected for producing the background light curve includes events only up to 12 keV. The reason for this is to avoid hot pixels being miss-identified as very high energy events.

pn

```
evselect table=pn.evt energycolumn=PI expression='#XMMEA_EP && (PI>10000&&PI<12000) && (PATTERN==0)'
withrateset=yes rateset="lcurve_sup10.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

maketimecolumn=If true, include a time column in the FITS table when creating a time series;

makeratecolumn=If true, produces a lightcurve containing a `RATE`, rather than a `COUNTS` column. An `ERROR` column is also produced.

https://xmmssc-www.star.le.ac.uk/SAS/xmmsas_20121219_1645/doc/evselect/node16.html#1726

Creation of a light curve above 10 keV

skipped

How to filter an EPIC event list for periods of high background *flaring* activity

MOS1

```
evselect table=m1.evt energycolumn=PI expression='#XMMEA_EM && (PI>10000) &&(PATTERN==0)' withrateset=yes
rateset="lcurve_sup10.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

MOS2

```
evselect table=m2.evt energycolumn=PI expression='#XMMEA_EM && (PI>10000) &&(PATTERN==0)' withrateset=yes
rateset="lcurve_sup10.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

What are *event patterns*?

Event selection is performed on-board to allow the transmission of useful data only. Certain X-ray events are not valid because they are empty pixels, while others are expected to be split between pixels.

The SAS software allows these data to be reconstructed to a single value in the event list.

Table 7: *List of EPIC event patterns*

Camera	Mode	X-ray generated pattern					no X-ray [1]
		singles	doubles	triples	quadruples	higher	
MOS	imaging	**0**	**1-4**	**5-8**	**9-12**	13-25	26-31 [2]
	timing	**0**	1				2,3
pn	imaging	**0**	**1-4**	5-8	9-12		> 12
	timing	**0**	**1-4**			5-12	> 12

Calibrated patterns

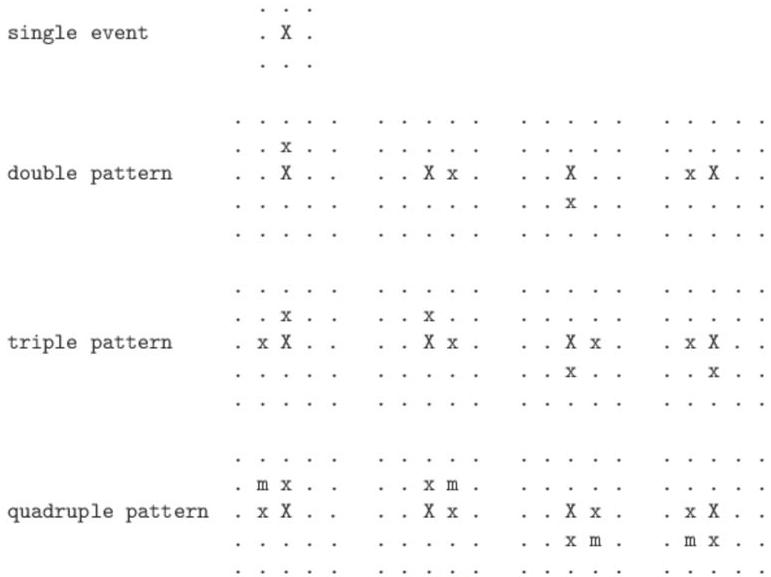
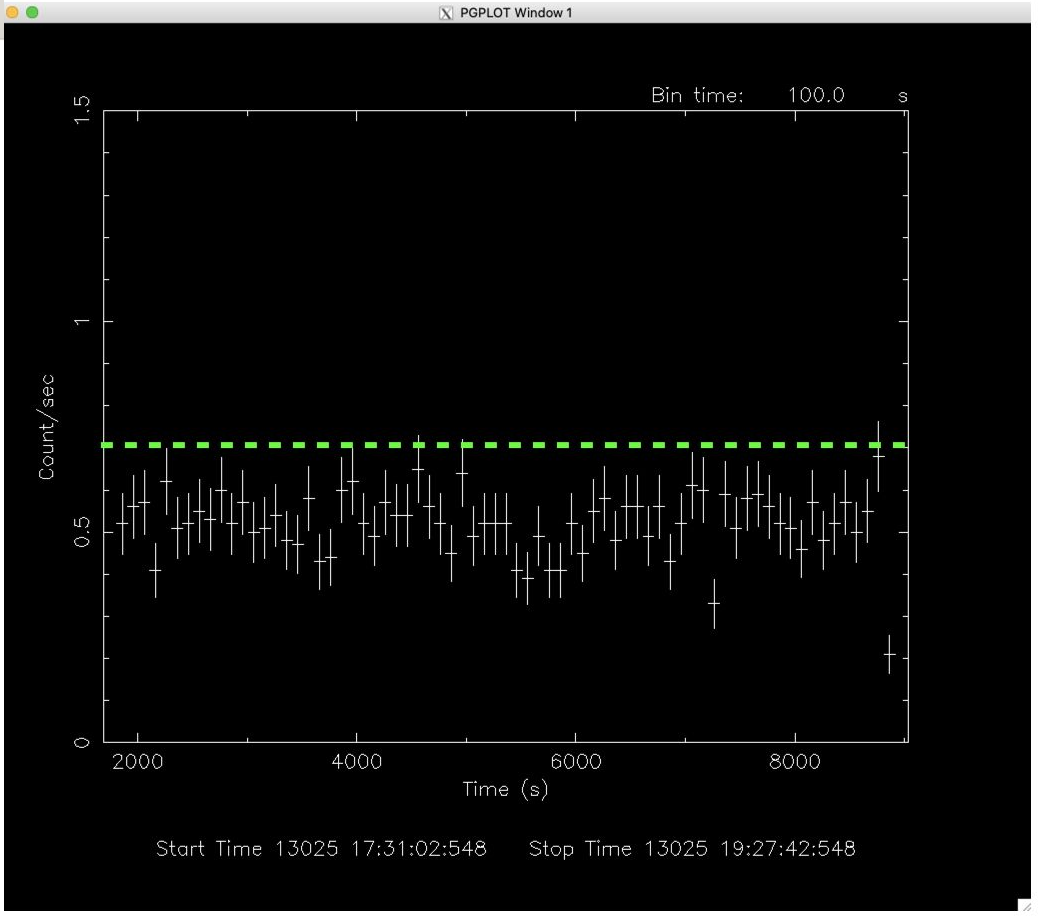


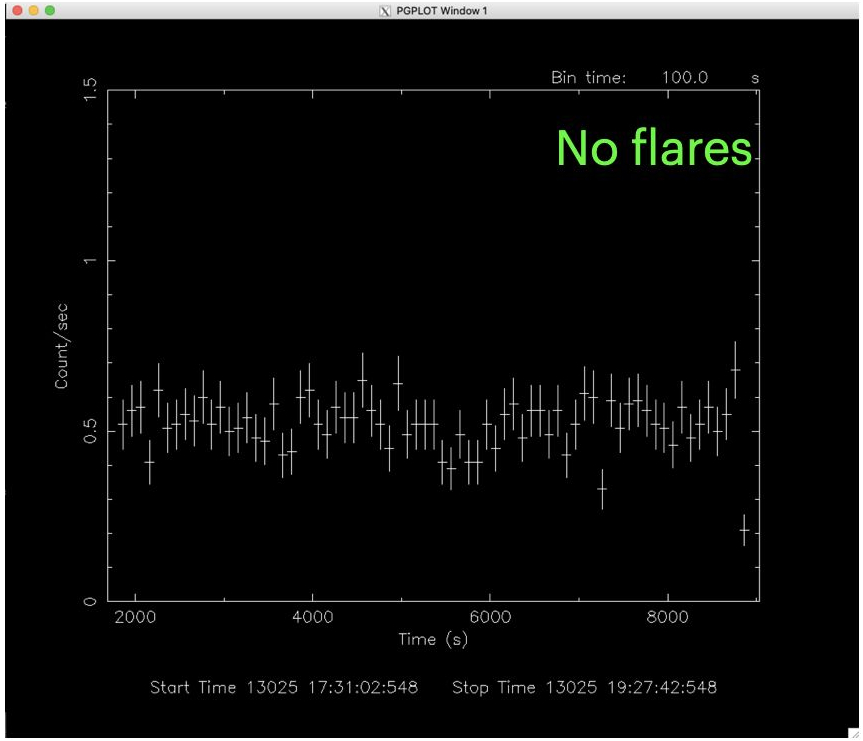
Figure 13: List of valid EPIC-pn patterns (cf. figure 12). Here "." marks a pixel without an event above threshold, "X" is the pixel with the maximum charge ("main pixel"), "x" is the pixel with a non-maximum charge, "m" is the pixel with the minimum charge. These 13 figures refer to the SAS PATTERN codes 0 (singles), 1-4 (doubles), 5-8 (triples) and 9-12 (quadruples), respectively. The RAWX co-ordinate is running rightward and the RAWY co-ordinate running upward

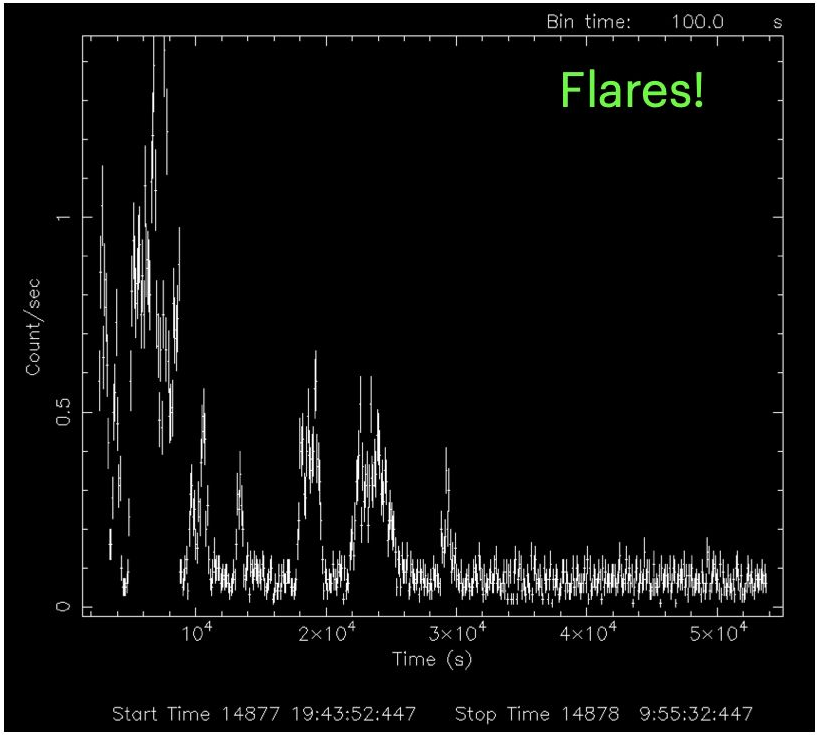
To visualize the produced lightcurve

lcurve

```
torresi@login06:/blasco/users/torresi/LABX2025/3C33/pn — lcurve

lcurve 1.0 (xronos6.0)

Number of time series for this task[1]
Ser. 1 filename +options (or @file of filenames +options)[lcurve_sup10.lc]
 Series 1 file    1:lcurve_sup10.lc

 Selected FITS extensions: 1 - RATE TABLE;

 Source .............                    Start Time (d) .... 13025 17:30:12.548
 FITS Extension ....  1 - `RATE      `   Stop Time (d) ..... 13025 19:27:28.859
 No. of Rows .......          71        Bin Time (s) ......    100.0
 Right Ascension ...                    Internal time sys.. Converted to TJD
 Declination .......                    Experiment ........ XMM      EPN
 Filter ............ Medium
 Corrections applied: Vignetting - No ; Deadtime - No ; Bkgd - No ; Clock - Yes

 Selected Columns:  3- Time;  1- Y-axis;  2- Y-error;

 File contains binned data.

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

 Expected Start ... 13025.72931189543  (days)      17:30:12:548  (h:m:s:ms)
 Expected Stop .... 13025.81075068651  (days)      19:27:28:859  (h:m:s:ms)

 Minimum Newbin Time    100.00000      (s)
 for Maximum Newbin No..               71

 Default Newbin Time is:   100.00000    (s) (to have 1 Intv. of      71 Newbins)
 Type INDEF to accept the default value

Newbin Time or negative rebinning[100]

 Newbin Time ......     100.00000      (s)
 Maximum Newbin No.                71

 Default Newbins per Interval are:          71
 (giving       1 Interval of          71 Newbins)
 Type INDEF to accept the default value

Number of Newbins/Interval[71]
 Maximum of       1 Intvs. with           71 Newbins of       100.000     (s)
Name of output file[test.flc]
Do you want to plot your results?[yes]
Enter PGPLOT device[/xw]

     71 analysis results per interval

100% completed
```



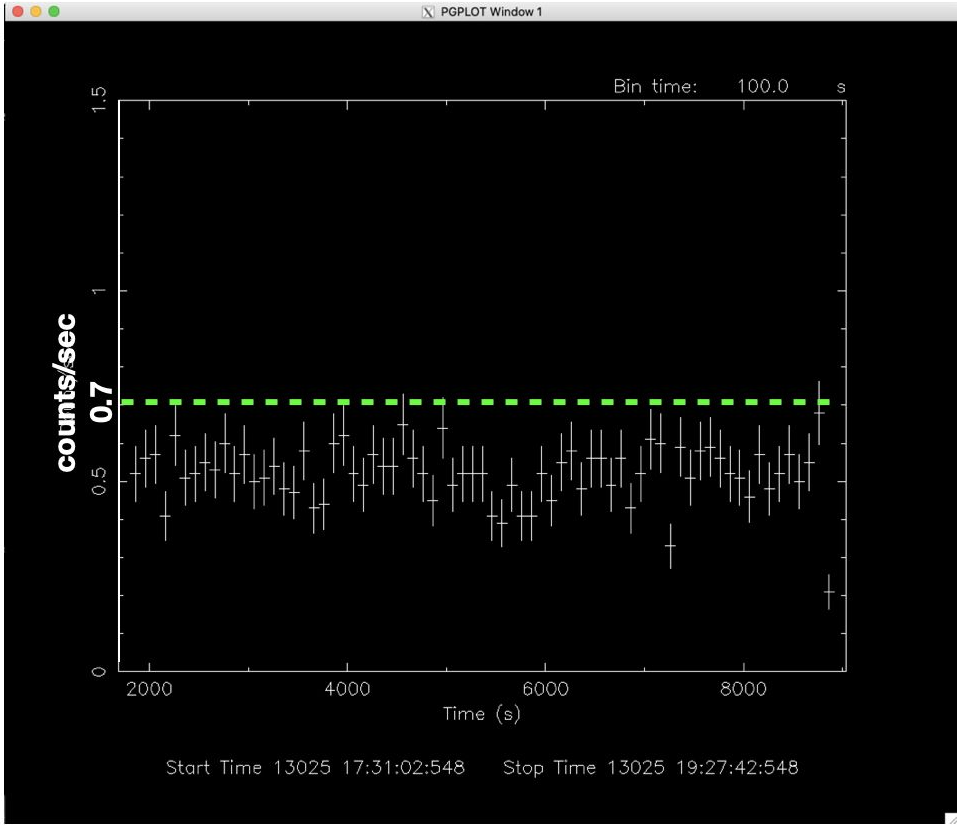




Possible error! **Disconnect from login06 and reconnect**

```
PGPLOT /xw: cannot connect to X server [localhost:12.0]
 To plot  vs. Time (s), please enter
PGPLOT file/type:
```

Selection of **good time intervals**



tabgtigen table=lcurve_sup10.lc gtiset=**good_bkg.gti** expression='RATE<**0.7**'

Generation of a **cleaned event file**

pn

```
evselect table=pn.evt expression='#XMMEA_EP && (PI>150) && (GTI(good_bkg.gti,TIME))' withfilteredset=yes
keepfilteroutput=yes filteredset=pn_new.evt updateexposure=yes cleandss=yes writedss=yes
```

filteredset= the name of the file to which the filtered event list is to be written. If this parameter is set, then **keepfilteroutput** is automatically set to true.

updateexposure= update exposure information in event lists (keywords LIVETIME, LIVETI*nn*, ONTIME, and ONTIME*nn*) and in spectrum files (keyword EXPOSURE).

cleandss= controls the use of data subspace cleaning, which deletes components from the data subspace which select no events from the event list.

writess= controls the writing of data subspace information to the output data files.

Generation of a **cleaned event file**

pn

```
evselect table=pn.evt expression='#XMMEA_EP && (PI>150) && (GTI(good_bkg.gti,TIME))' withfilteredset=yes
keepfilteroutput=yes filteredset=pn_new.evt updateexposure=yes cleandss=yes writedss=yes
```

fv: Binary Table of pn.evt[1] in /blasco/users/torresi/LAB-X/Fall_2022/3C33_LABX/pn/

File Edit Tools Help

Select All / Invert	TIME	RAWX	RAWY	DETX	DETY	X	Y	PHA	PI	FLAG	PATTERN
	D	I	I	I	I	J	J	I	I	J	B
	s	pixel	pixel	0.05 arcsec	0.05 arcsec	0.05 arcsec	0.05 arcsec	channel	eV		
	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	1.910949802434E+08	50	110	7331	-8630	37610	31914	30	151	0	0
2	1.910936738810E+08	28	142	-9935	3770	16856	27317	24	151	0	0
3	1.910987199062E+08	20	183	-11361	-2593	18051	33727	24	151	0	0
4	1.910968628259E+08	35	24	11477	-15702	44206	36781	30	151	65536	0
5	1.910990361903E+08	29	187	-10571	-2284	18655	33132	24	151	0	0
6	1.910961221517E+08	62	98	-7817	-9592	24065	38764	31	151	2097160	0
7	1.910970038855E+08	1	133	3105	4529	28542	21483	26	151	4	0
8	1.910974374096E+08	62	45	-7897	-13947	25707	42799	33	151	2097160	0
9	1.910945815748E+08	48	181	-11601	516	16606	30964	22	151	0	0
10	1.910967549282E+08	15	169	-14269	1567	13740	31049	25	151	0	0
11	1.910971991752E+08	56	151	3922	3037	29881	22532	26	151	0	0
12	1.910989785826E+08	35	162	5695	2135	31866	22663	24	151	0	0
13	1.910968081495E+08	57	186	-13624	-2308	15859	34356	22	151	0	0
14	1.910990163098E+08	48	14	-6206	14311	16131	16159	30	151	0	0
15	1.910954398068E+08	46	116	-16806	5925	9691	28042	27	151	0	0
16	1.910962318820E+08	21	160	-5831	-4511	23889	33312	28	151	0	0
17	1.910999689040E+08	1	167	-2130	-3895	27049	31288	31	151	4	0
18	1.910993828217E+08	57	134	-17669	4455	9477	29733	26	151	0	0
19	1.910989936606E+08	60	164	-12546	1956	15170	30012	22	151	0	0
20	1.910960863435E+08	41	151	-14993	-5262	15764	37611	27	151	0	0
21	1.910968742872E+08	43	185	12176	-2456	39631	24330	24	151	0	0
22	1.910997870684E+08	51	199	2000	-1237	29798	27218	30	151	0	0
23	1.910989410890E+08	44	177	-14728	-3097	15155	35516	22	151	0	0
24	1.910960325198E+08	37	194	-9900	-1697	19041	32328	24	151	0	0
25	1.910967498674E+08	33	154	11287	-5002	39817	27021	26	151	0	0
26	1.910957214857E+08	57	167	-13697	-3921	16427	35868	23	151	0	0

Go to: Edit cell: 151

Generation of a **cleaned event file**

skipped

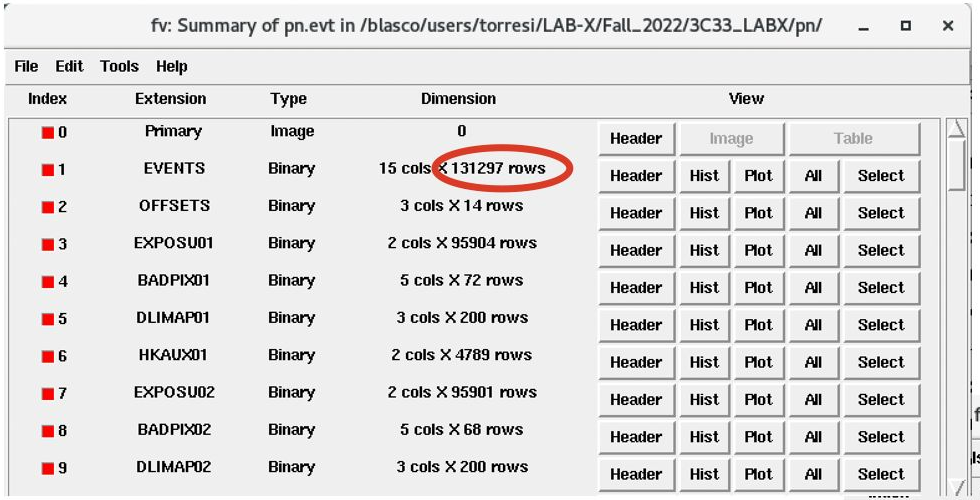
MOS 1

```
evselect table=m1.evt expression='#XMMEA_EM && (PI > 150) && (GTI(good_bkg.gti,TIME))' withfilteredset=yes
keepfilteroutput=yes filteredset=mos1_new.evt updateexposure=yes cleandss=yes writedss=yes
```

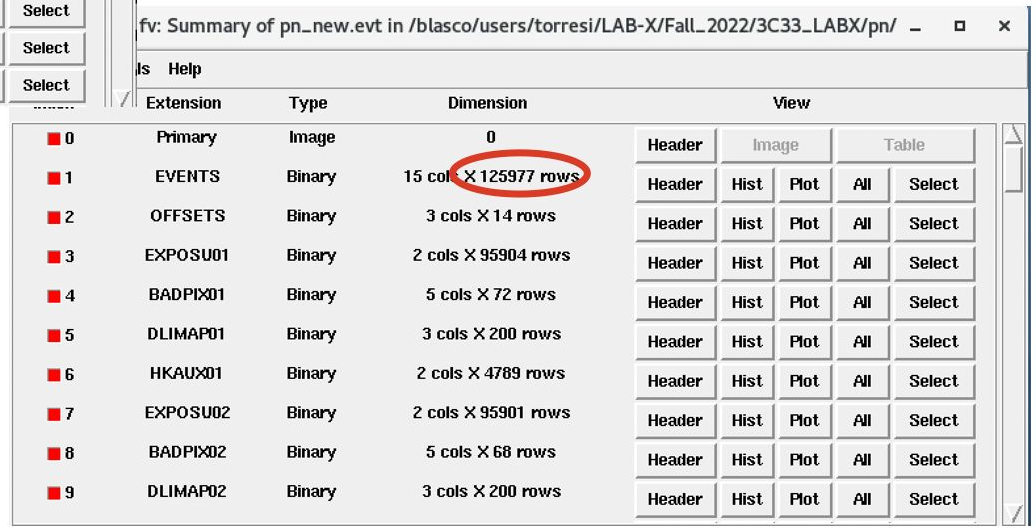
MOS 2

```
evselect table=m2.evt expression='#XMMEA_EM && (PI > 150) && (GTI(good_bkg.gti,TIME))' withfilteredset=yes
keepfilteroutput=yes filteredset=mos2_new.evt updateexposure=yes cleandss=yes writedss=yes
```

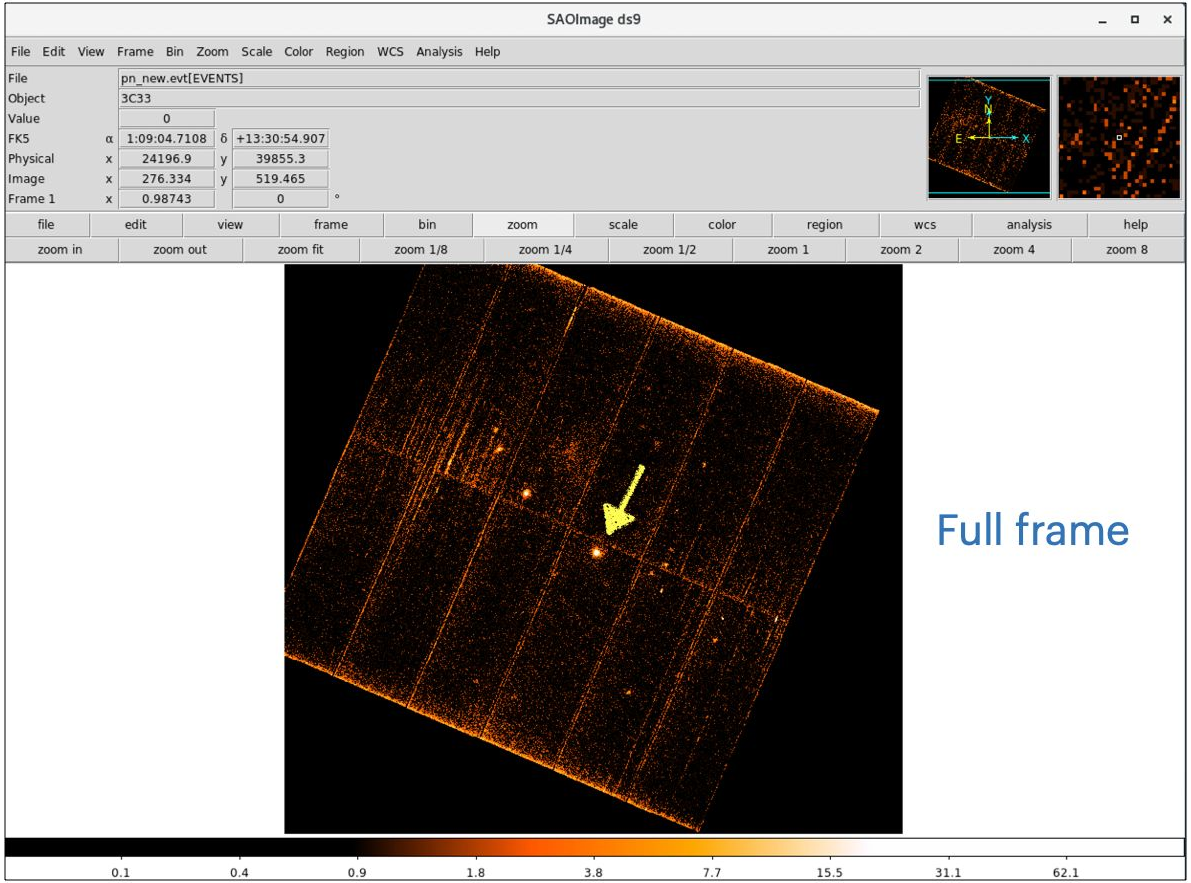
Raw event file (pn.evt)



Cleaned event file (pn_new.evt)



> ds9 pn_new.evt &



Overlay of radio contours

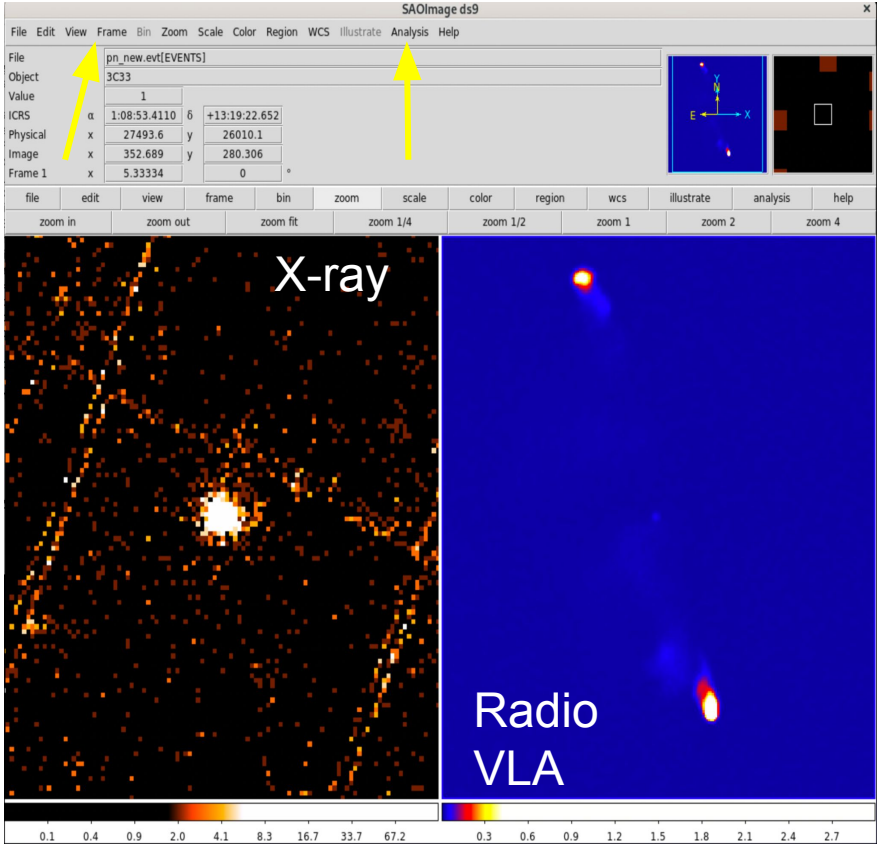
1. Open the radio image
   > ds9 pn_new.evt 3C_33_I_1.5GHz_lbs2003.fits.gz&
   > zoom in (for radio)
   > color b (for radio)

   > scale log (for X-ray)
   > color heat (for X-ray)
   > bin 16 (for X-ray)

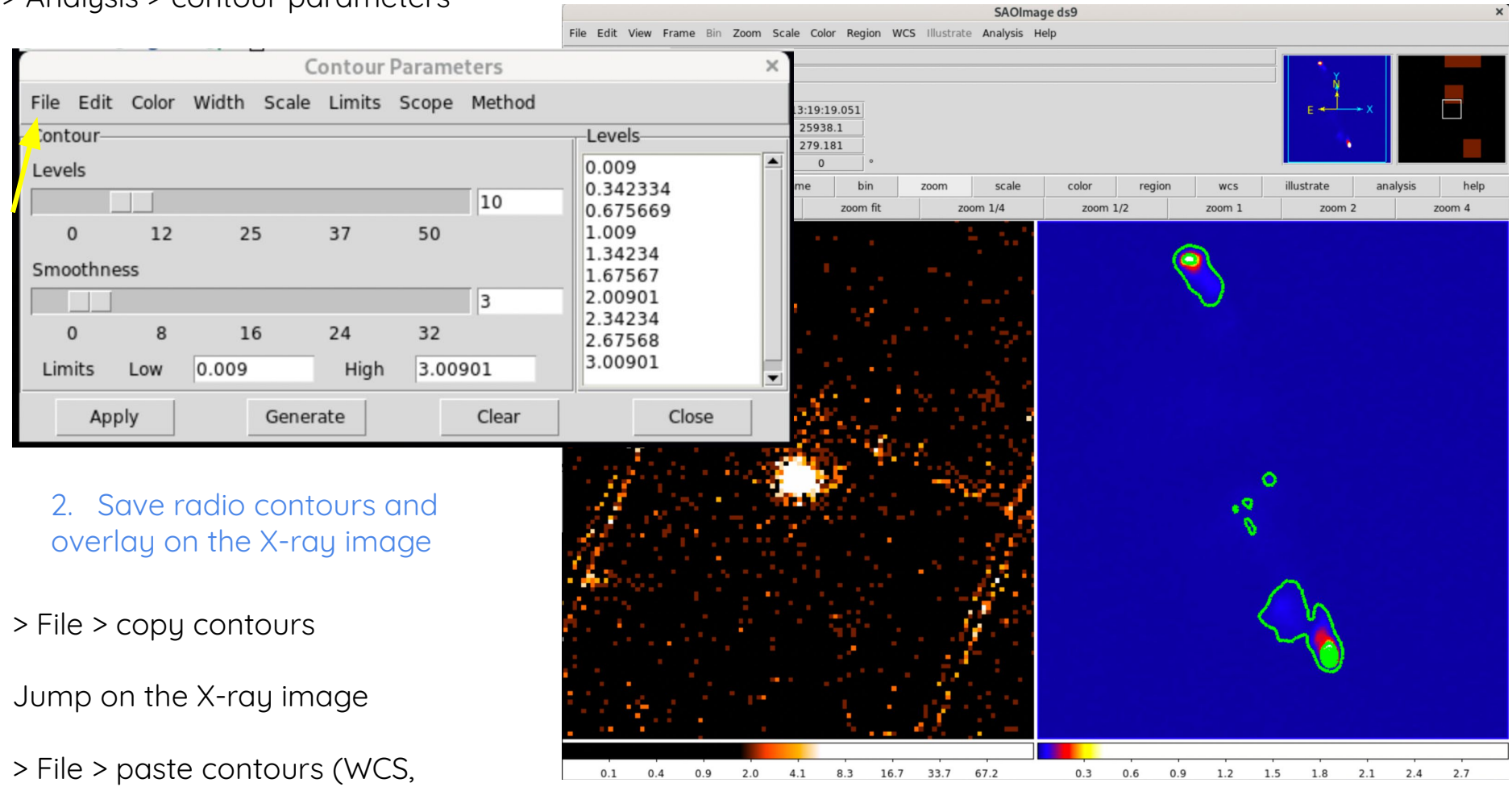
   > Frame -> Match frames -> WCS

On the radio image: Use the *right mouse button* to adjust the image until you're happy with the result.

> Analysis > contour parameters



> Analysis > contour parameters

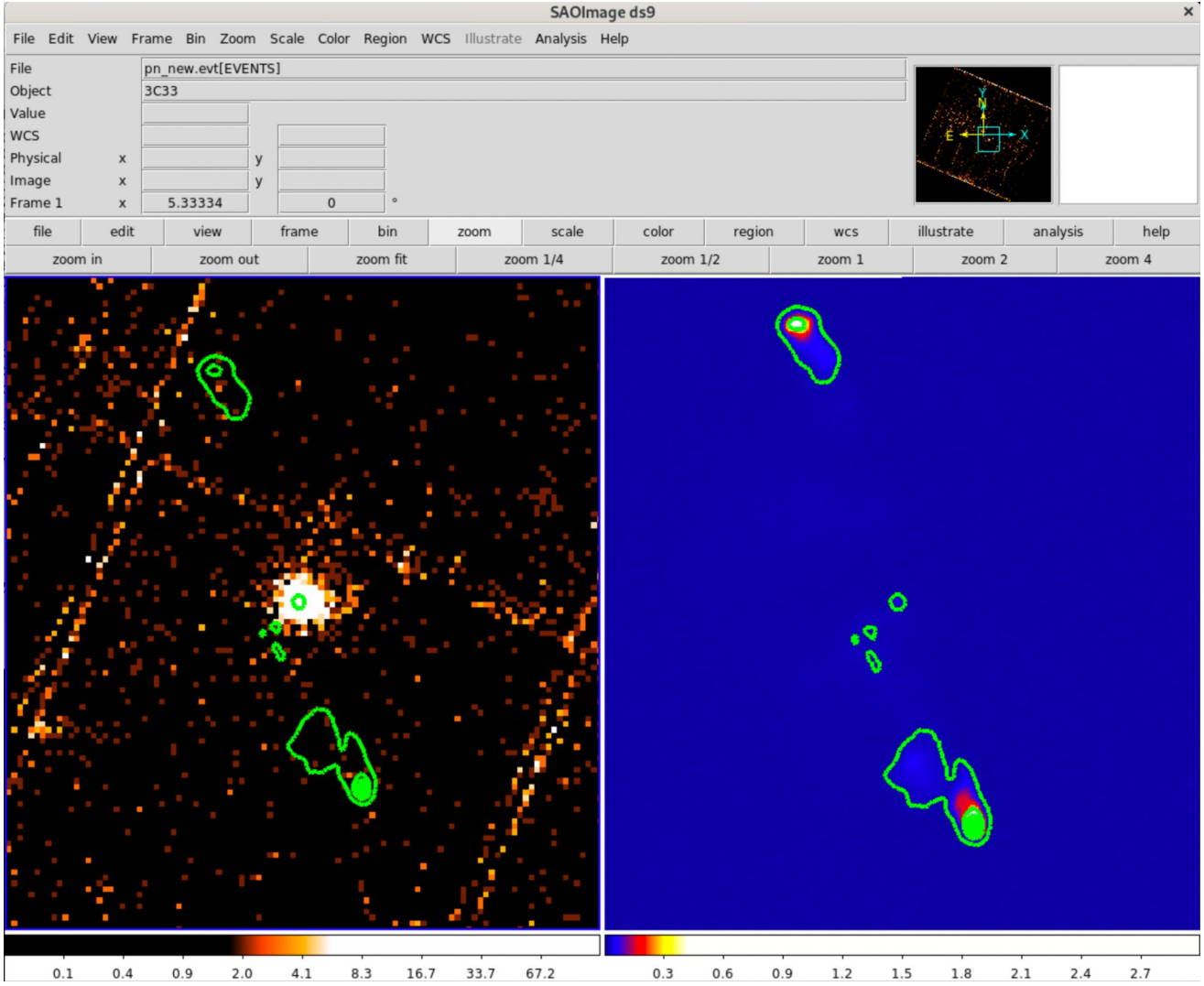


2. Save radio contours and overlay on the X-ray image

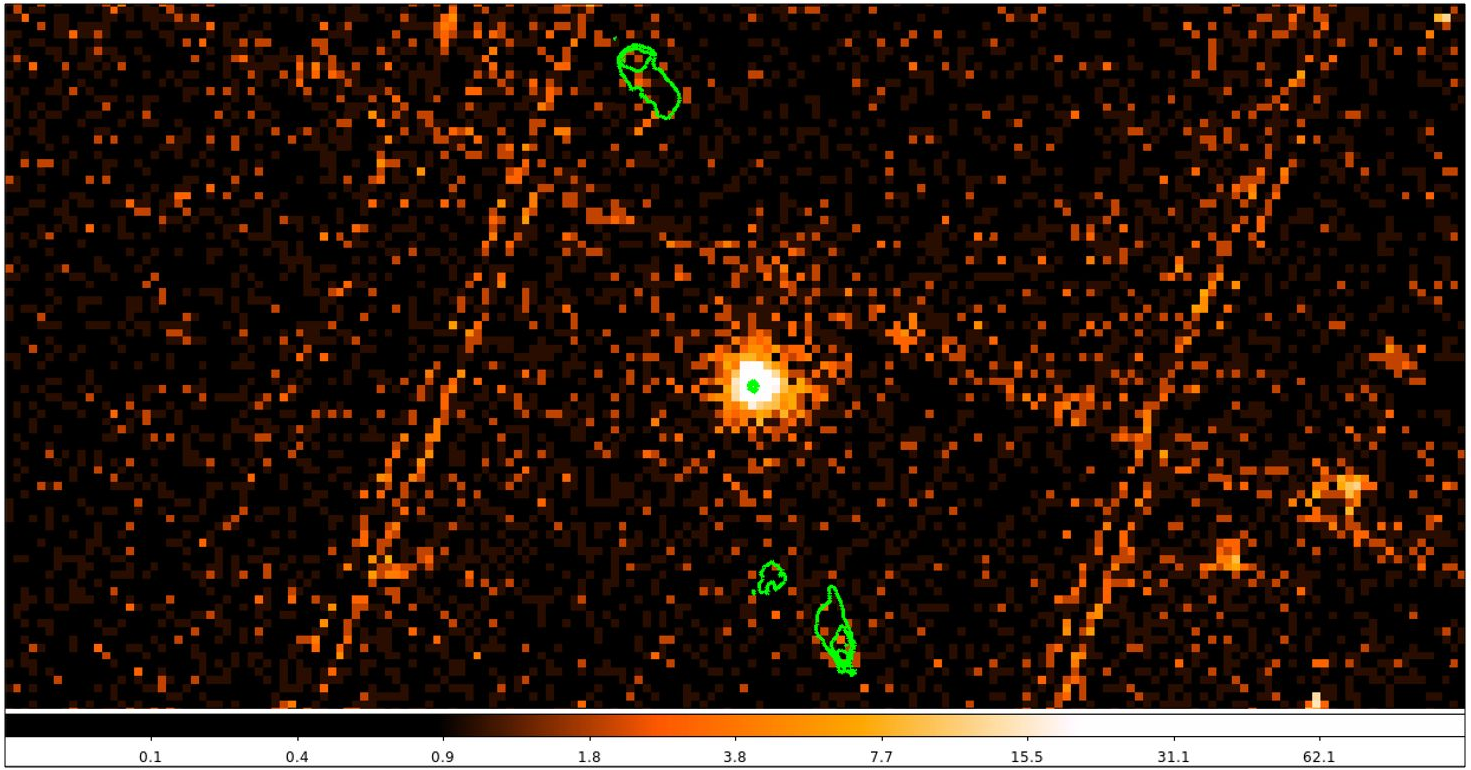
> File > copy contours

Jump on the X-ray image

> File > paste contours (WCS, green, 1)


SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Illustrate Analysis Help
File pn_new.evt[EVENTS]
Object 3C33
Value
WCS
Physical x y
Image x y
Frame 1 x 5.33334 0 °
file edit view frame bin zoom scale color region wcs illustrate analysis help
zoom in zoom out zoom fit zoom 1/4 zoom 1/2 zoom 1 zoom 2 zoom 4
0.1 0.4 0.9 2.0 4.1 8.3 16.7 33.7 67.2
0.3 0.6 0.9 1.2 1.5 1.8 2.1 2.4 2.7

Zoomed image with radio (VLA 5GHz) contours overlaid



Source extraction region

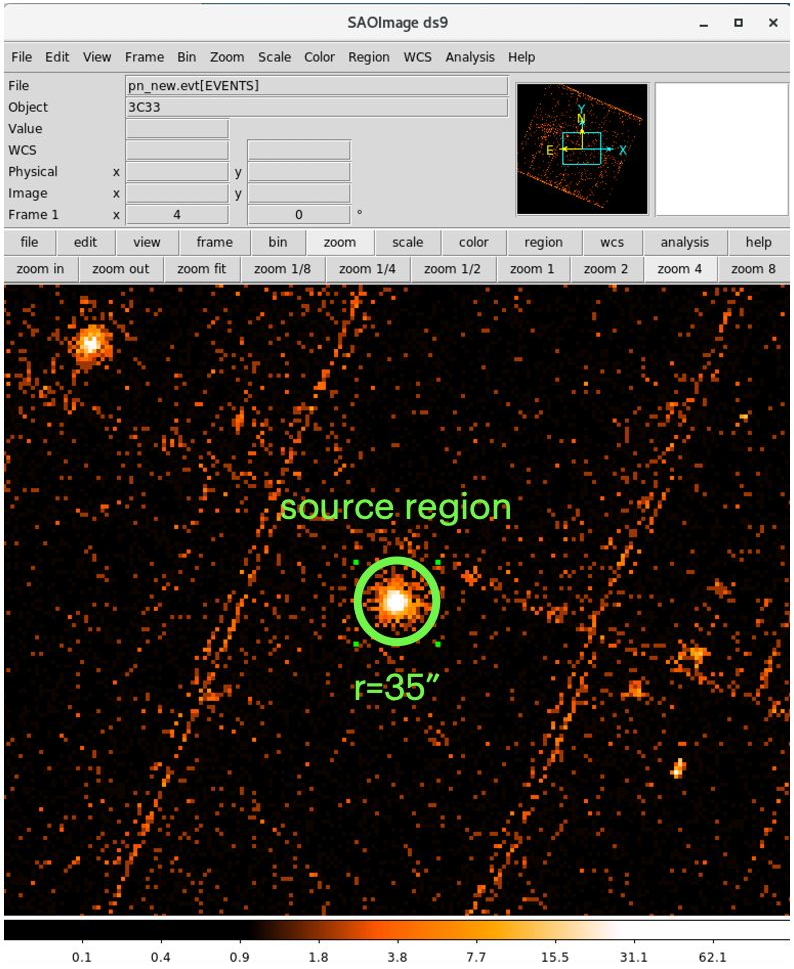
Display the cleaned image with ***ds9***

http://ds9.si.edu/doc/user/binning/index.html

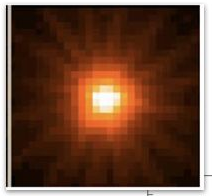
> ds9 pn_new.evt &

> scale log
> bin (block 2, 4, ...)

> Region
> save region
> file format 'ds9'
> coordinates 'physical'
> source.reg

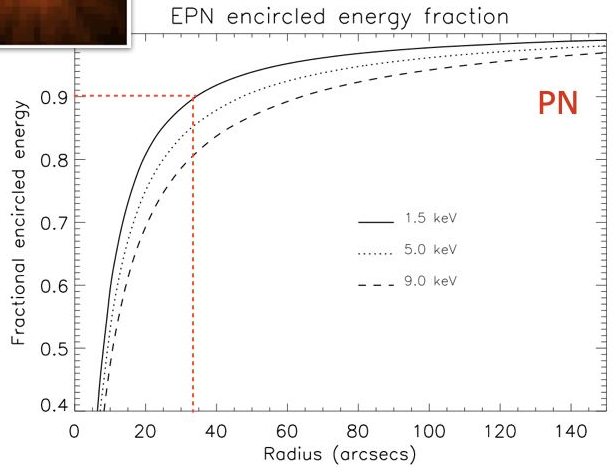


circle(27720.501,27069.104,700.00011)



Fraction encircled energy

Fraction of photons contained within a certain angular radius

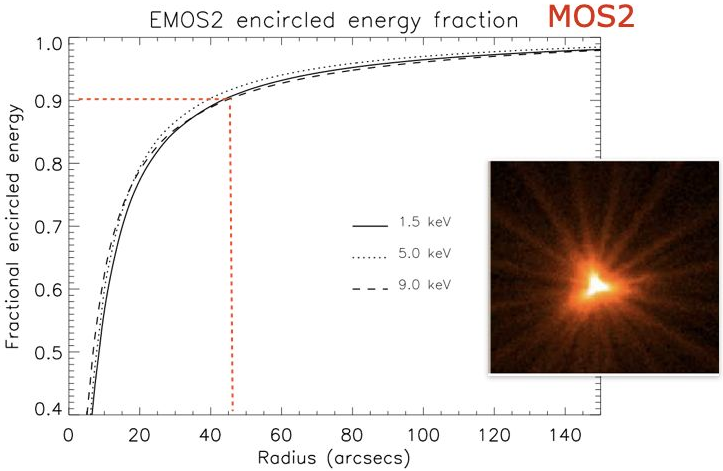


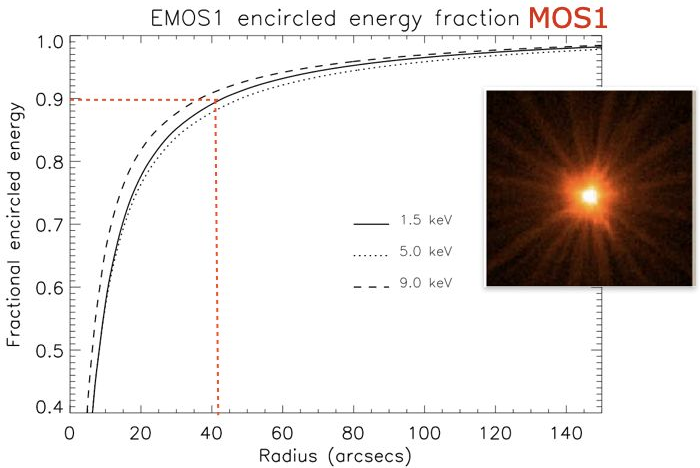
from the center of the PSF

on-axis — point-like source

Extraction radius	Camera		
(arcsec)	MOS-1	MOS2	EPN pointed
15	0.68	0.69	0.71
30	0.83	0.83	0.88
45	0.89	0.89	0.93
60	0.92	0.93	0.95

Each instrument has its own on-axis PSF





The core of XMM on-axis PSF is **narrow** and **varies little** in the 0.1-6 keV band (major XMM strong point!)

see also Dadina's lesson

Background extraction region

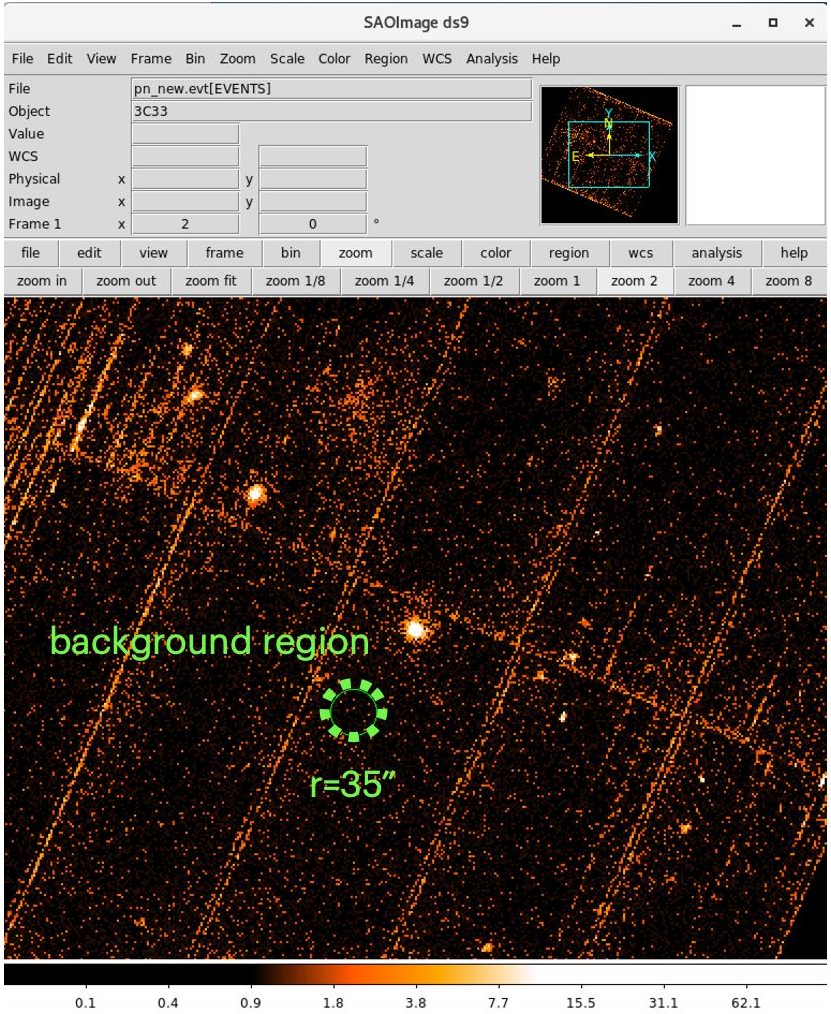
Display the cleaned image with ***ds9***

```
ds9 pn_new.evt &
```

> scale log
> bin (block 2, 4, ...)

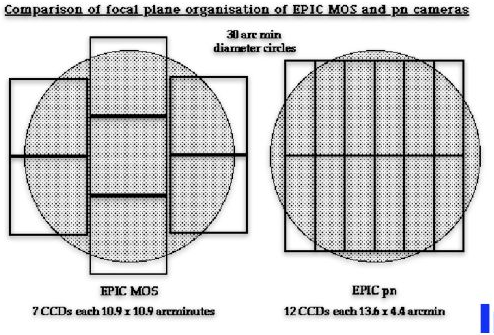
> Region
> save region
> file format ‘ds9’
> coordinates ‘physical’
> back.reg

circle(25864.501,24541.104,700.00011)



EPIC Science Modes

MOS



pn

XMM FoV 30’

Imaging modes

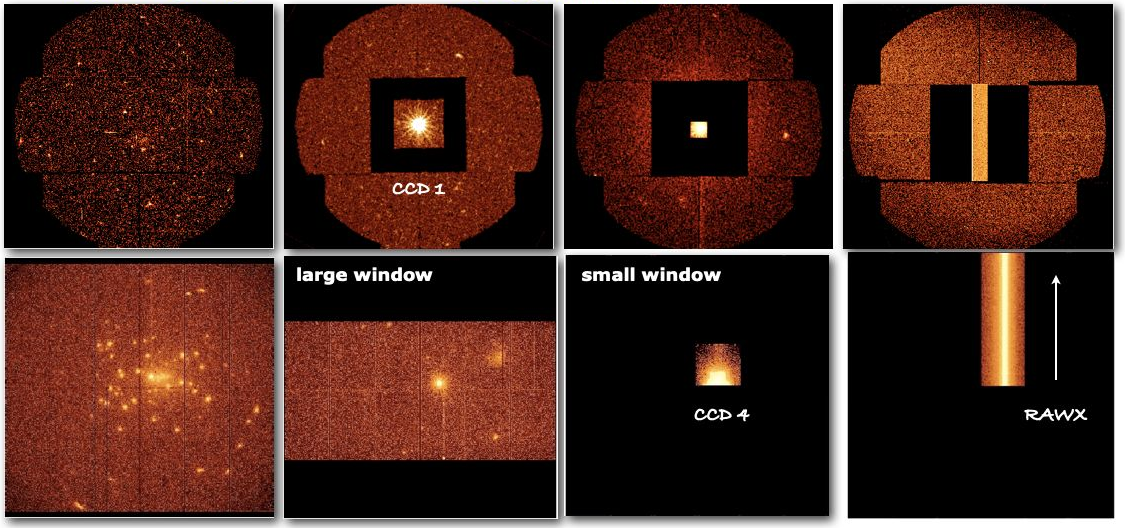
Timing Mode

Full Frame

Partial Window

MOS

pn



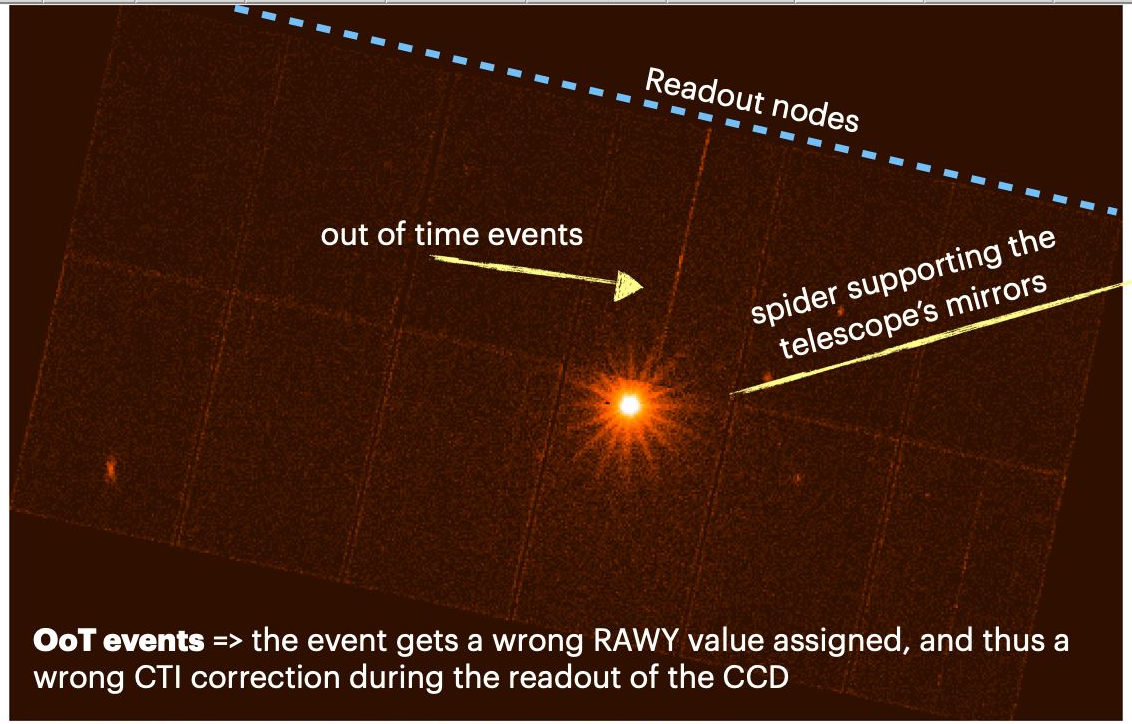
SAOImage ds9

File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help

File	pn_new.evt[EVENTS]			
Object	3C 111			
Value	2			
fk5	α	4:19:16.256	δ	+38:00:21.30
Physical	X	14412.500	Y	25943.500
Image	X	103.000	Y	137.000
Frame 1	x	2.000		0.000 °

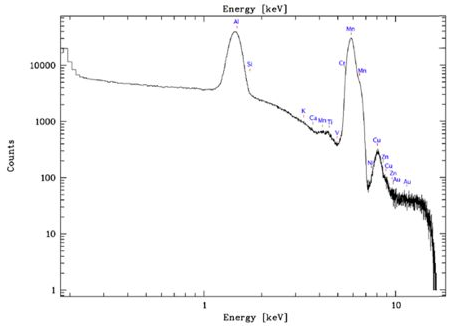
file edit view frame bin zoom scale color region wcs help

- + to fit zoom 1/8 zoom 1/4 zoom 1/2 zoom 1 zoom 2 zoom 4 zoom 8



OoT events => the event gets a wrong RAWY value assigned, and thus a wrong CTI correction during the readout of the CCD

9 28 66 141 293 593 1190 2396 4780



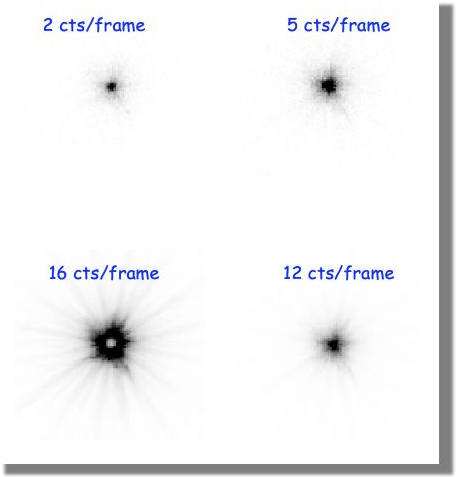
OoT events broaden spectral features in a systematic way

Photon PILE-UP

https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epatplot

Arrival of two or more independent photons at nearby pixels that are erroneously read as one single event (whose energy is the sum of the energies of the individual photons) Jethwa et al. (2015)

Many photons arrive **almost at the same time** in the core of the PSF which results influenced by pile-up



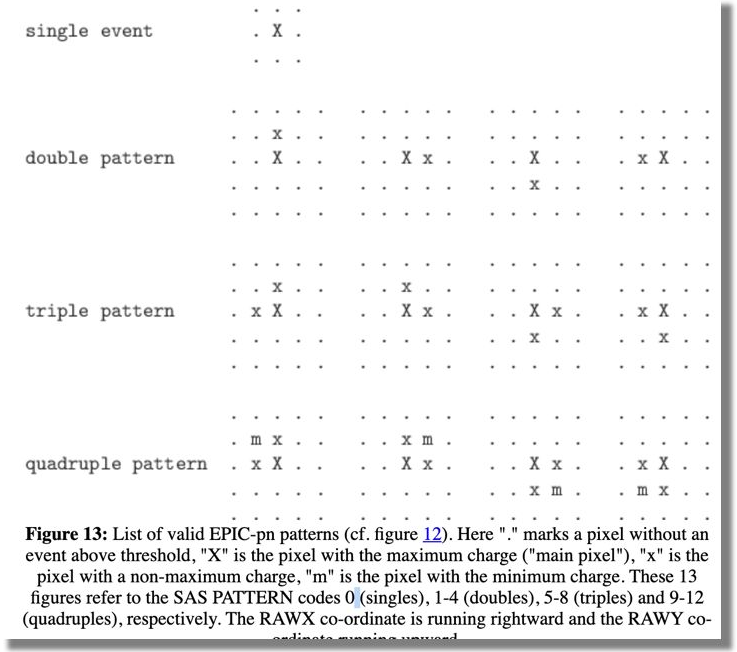


Figure 13: List of valid EPIC-pn patterns (cf. figure 12). Here "." marks a pixel without an event above threshold, "X" is the pixel with the maximum charge ("main pixel"), "x" is the pixel with a non-maximum charge, "m" is the pixel with the minimum charge. These 13 figures refer to the SAS PATTERN codes 0 (singles), 1-4 (doubles), 5-8 (triples) and 9-12 (quadruples), respectively. The RAWX co-ordinate is running rightward and the RAWY co-ordinate running upward

The spectral response is compromised

- Photon loss
- Energy distortion
- Pattern migration

MOS (central CCD; pixels) [1 pixel = 1.1"]	Time resolution	Live time[1] [%]	Max. count rate[2] diffuse[3] (total) [s^{-1}]	Max. count rate[2] (flux) point source [s^{-1}] ([mCrab][4])
Full frame (600×600)	2.6 s	100.0	150	0.50 (0.17)
Large window (300×300)	0.9 s	99.5	110	1.5 (0.49)
Small window (100×100)	0.3 s	97.5	37	4.5 (1.53)
Timing uncompressed (100×600)	1.75 ms	100.0	N/A	100 (35)

pn (array or 1 CCD; pixels) [1 pixel = 4.1"]	Time resolution	Live time[1] [%]	Max. count rate[2] diffuse[3] (total) [s^{-1}]	Max. count rate[2] (flux) point source [s^{-1}] ([mCrab][4])
Full frame[5] (376×384)	73.4 ms	99.9	1000(total)	2 (0.23)
Extended full frame[5,6] (376×384)	199.1 ms	100.0	370	0.7 (0.09)
Large window (198×384)	47.7 ms	94.9	1500	3 (0.35)
Small window (63×64)	5.7 ms	71.0	12000	25 (3.25)
Timing (64×200)	0.03 ms	99.5	N/A	800 (85)
Burst (64×180)	7 μs	3.0	N/A	60000 (6300)

Maximum count rate for point sources, above which the observing mode enters a regime of significant pile-up.

Check for the presence of pile-up

Diagnostic tool for pileup: **epatplot**

evselect table=**pn_new.evt** withfilteredset=yes filteredset=**pnf.evt** keepfilteroutput=yes expression="((X,Y) IN circle (25864.501,24541.104,700.00011))"

epatplot set=**pnf.evt** device="/CPS" plotfile="**pnf_pat.ps**" or device="/GIF" plotfile="**pnf_pat.gif**"

```
[torresi@login06]pn>export SAS_CCF='/blasco/users/torresi/LAB-X/Fall_2022/3C33_LABX/evt/ccf.cif'
[torresi@login06]pn>epatplot set=pnf.evt device="/CPS" plotfile="pnf_pat.ps"
epatplot:- Executing (routine): epatplot set=pnf.evt modifyinset=yes sigma=3 withflag=yes xaxisadu=no device=/CPS o
utdir=./ plotfile=pnf_pat.ps useplotfile=yes withqdp=no withdetxy=no withsrcxy=yes outmaskname=flag0_map_##.dat wit
houtputmask=no backgroundset=bkg_events.fits withbackgroundset=no backscal=1 usermode=0 withusermode=no userrawy=19
0 withuserrawy=no ccdlimits='1 64 1 200 1 12' plotxrange='0 0' plotyrange='0 0' pileupnumberenergyrange='500 2000'
 -w 1 -V 4
epatplot:- epatplot (epatplot-1.22)  [xmmsas_20211130_0941-20.0.0] started:  2022-11-16T10:57:22.000
epatplot:-  epatplot 1.22 is running...
epatplot:-
epatplot:-        s       d       t       q
epatplot:-   0.6375  0.3228  0.0176  0.0220
epatplot:-
epatplot:- 0.5-2.0 keV observed-to-model fractions:
epatplot:- s: 0.955 +/- 0.094   d: 1.168 +/- 0.156
epatplot:-
epatplot:-  PostScript output written to file pnf_pat.ps
epatplot:- epatplot (epatplot-1.22)  [xmmsas_20211130_0941-20.0.0] ended:    2022-11-16T10:57:23.000
[torresi@login06]pn>gv pnf_pat.ps&
```

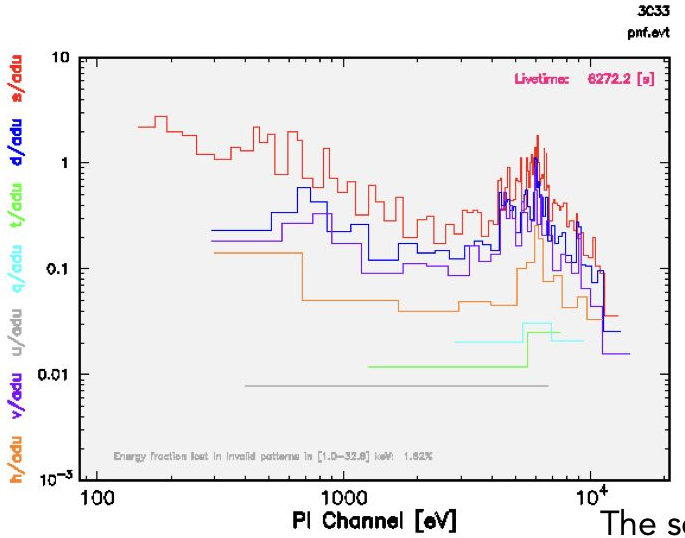
Epatplot compares the ratios of single- and double-events with standard values to check if there is a deviation (hence, pile-up)

How to visualize .ps of .gif files

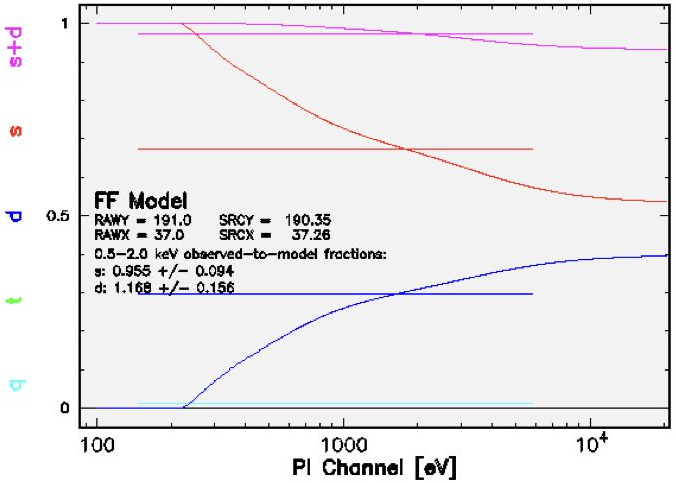
gv **pnf_pat.ps**

evince **pnf_pat.ps**

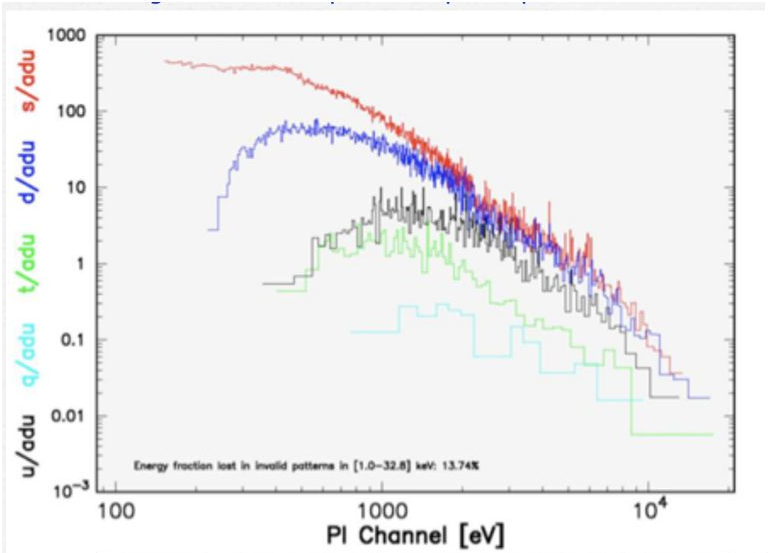
gimp **pnf_pat.gif**

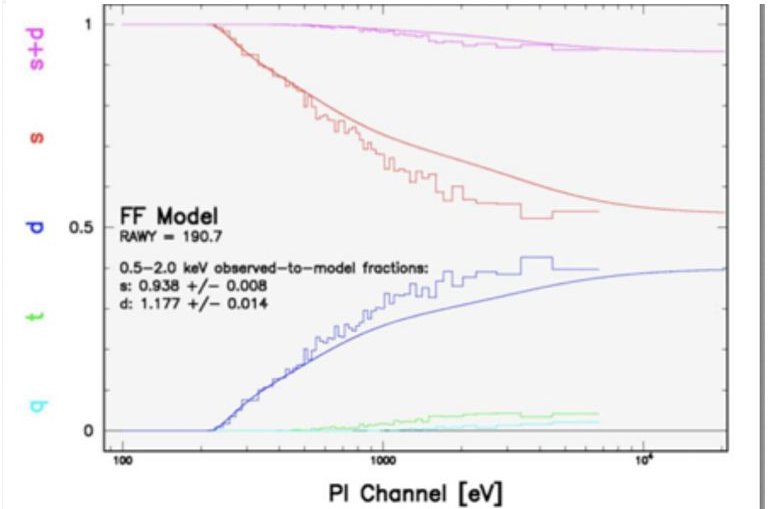


The source is not piled up!



While, in this case, the source **is** piled up





Spectrum extraction

pn

```
evselect table=pn_new.evt withspectrumset=yes spectrumset=source_spectrum.fits energycolumn=PI spectralbinsize=5 withspecranges=yes specchannelmin=0 specchannelmax=20479 expression='(FLAG==0) && (PATTERN<=4) && ((X,Y) IN circle(27874.528,26645.58,699.99999))'
```

source.reg

spectralbinsize= binning factor for spectral creation (size of each bin in instrumental eV)

specchannelmin= the minimum channel number to consider for spectrum creation

specchannelmin= the maximum channel number to consider for spectrum creation

Background extraction

pn

```
evselect table=pn_new.evt withspectrumset=yes spectrumset=back_spectrum.fits energycolumn=PI spectralbinsize=5 withspecranges=yes specchannelmin=0 specchannelmax=20479 expression='(FLAG==0) && (PATTERN<=4) && ((X,Y) IN circle(25864.501,24541.104,700.00011))'
```

back.reg

Spectrum extraction

skipped

MOS 1

```
evselect table=mos1_new.evt withspectrumset=yes spectrumset=source_spectrum.fits energycolumn=PI spectralbinsize=15 withspecranges=yes specchannelmin=0 specchannelmax=11999 expression='(FLAG==0) && (PATTERN<=12) && ((X,Y) IN circle(28090.5,24221.5,775.48791))'
```

MOS 2

```
evselect table=mos2_new.evt withspectrumset=yes spectrumset=source_spectrum.fits energycolumn=PI spectralbinsize=15 withspecranges=yes specchannelmin=0 specchannelmax=11999 expression='(FLAG==0) && (PATTERN<=12) && ((X,Y) IN circle(28090.5,24221.5,775.48791))'
```

Background extraction

skipped

MOS 1

evselect table=**mos1_new.evt** withspectrumset=yes spectrumset=**back_spectrum.fits** energycolumn=PI **spectralbinsize=15** withspecranges=yes **specchannelmin=0** **specchannelmax=11999** expression='(FLAG==0) && **(PATTERN<=12)** && ((X,Y) IN circle (25864.501,24541.104,700.00011))'

MOS 2

evselect table=**mos2_new.evt** withspectrumset=yes spectrumset=**back_spectrum.fits** energycolumn=PI **spectralbinsize=15** withspecranges=yes **specchannelmin=0** **specchannelmax=11999** expression='(FLAG==0) && **(PATTERN<=12)** && ((X,Y) IN circle (25864.501,24541.104,700.00011))'

Backscale

The BACKSCALE task calculates the area of a source region used to make a spectral file.

This task takes into account any bad pixels or chip gaps and writes the result into the BACKSCAL keyword of the SPECTRUM table

The final value is:
AREA= GEOMETRIC AREA-CCD GAPS-BAD PIXELS

pn

backscale spectrumset=**source_spectrum.fits** badpixlocation=**pn_new.evt**
backscale spectrumset=**back_spectrum.fits** badpixlocation=**pn_new.evt**

MOS 1

backscale spectrumset=**source_spectrum.fits** badpixlocation=**mos1_new.evt**
backscale spectrumset=**back_spectrum.fits** badpixlocation=**mos1_new.evt**

MOS 2

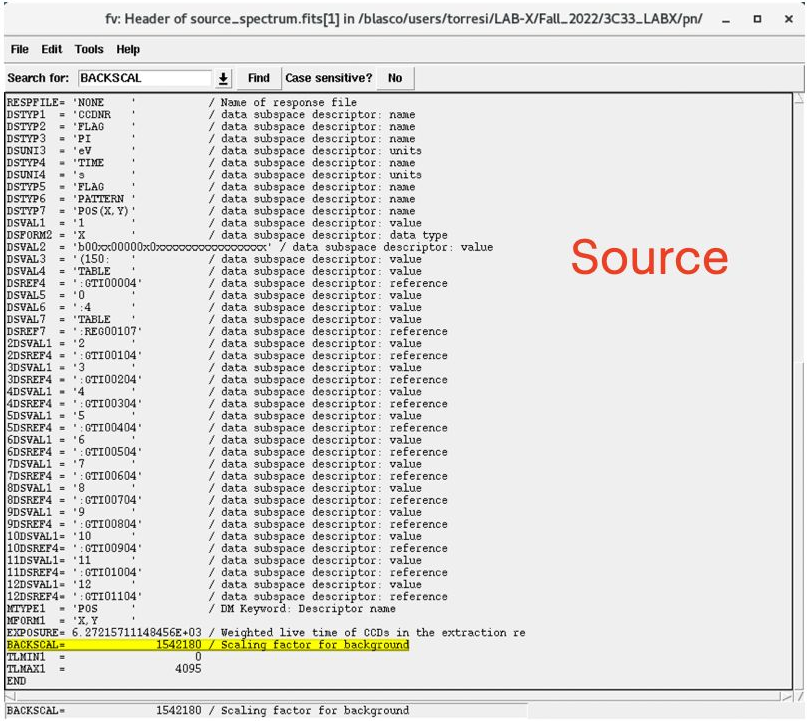
backscale spectrumset=**source_spectrum.fits** badpixlocation=**mos2_new.evt**
backscale spectrumset=**back_spectrum.fits** badpixlocation=**mos2_new.evt**

Backscale

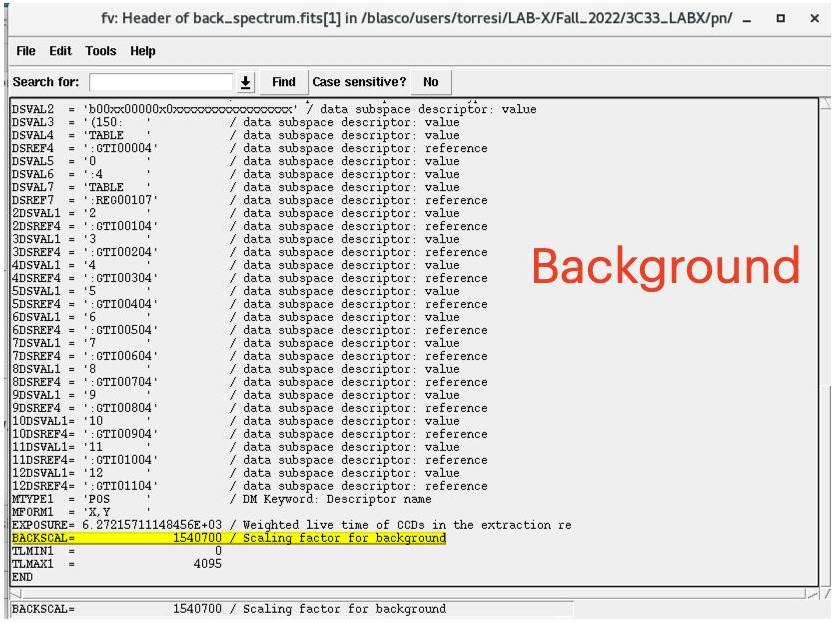
The BACKSCALE task calculates the area of a source region used to make a spectral file.

This task takes into account any bad pixels or chip gaps and writes the result into the BACKSCAL keyword of the SPECTRUM table

The final value is:
AREA= GEOMETRIC AREA-CCD GAPS-BAD PIXELS



Source

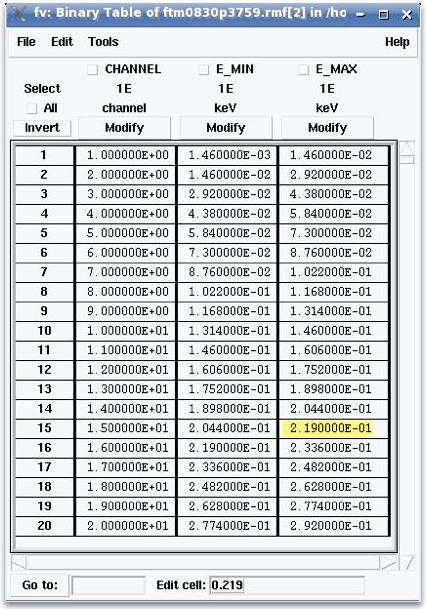


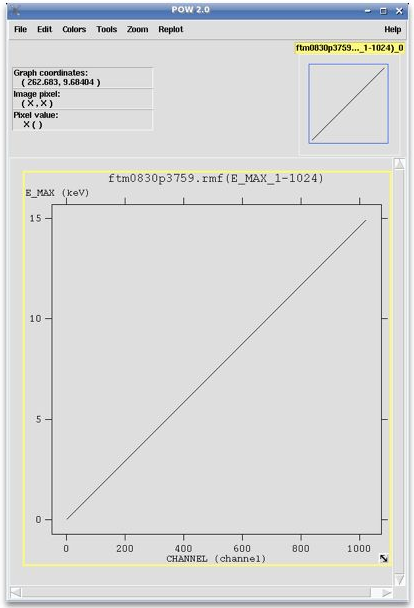
Background

Redistribution Matrix File (RMF)

rmfgen spectrumset=source_spectrum.fits rmfset=pn.rmf

The RMF associates to each instrument channel (I) the appropriate photon energy (E)

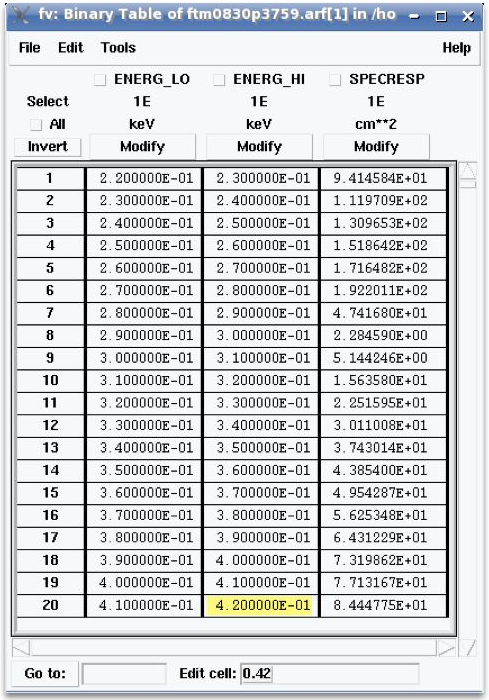


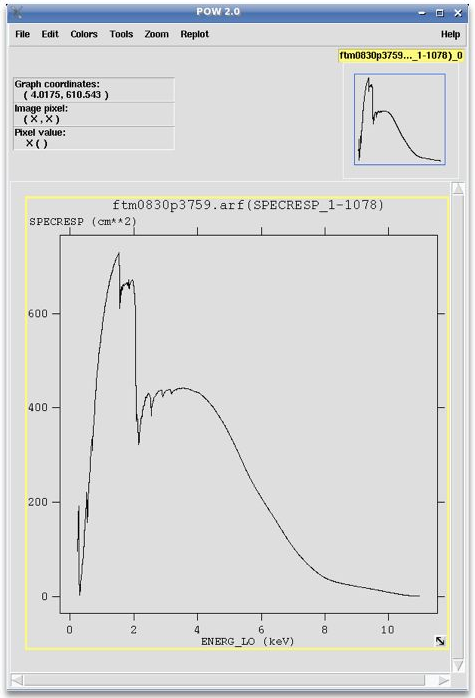


Ancillary Response File (ARF)

arfgen spectrumset=source_spectrum.fits arfset=pn.arf withrmfset=yes rmfset=pn.rmf badpixlocation=pn_new.evt detmaptype=psf (for point sources; for extended sources -> *flat*)

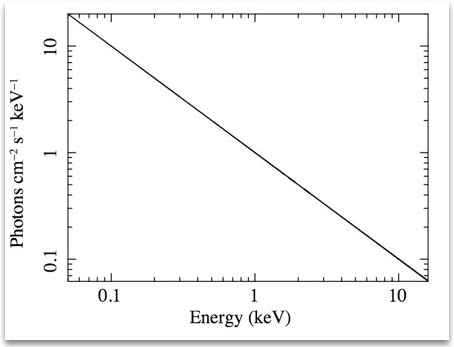
The ARF includes information on the **effective area, filter transmission and any additional energy-dependent efficiencies,** i.e. the efficiency of the instrument in revealing photons

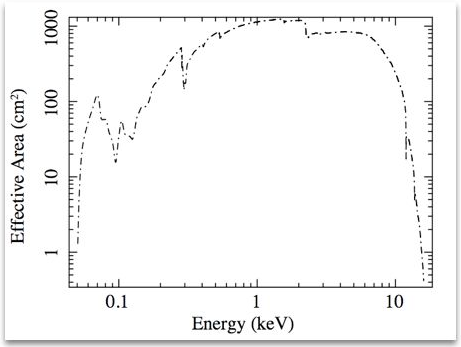


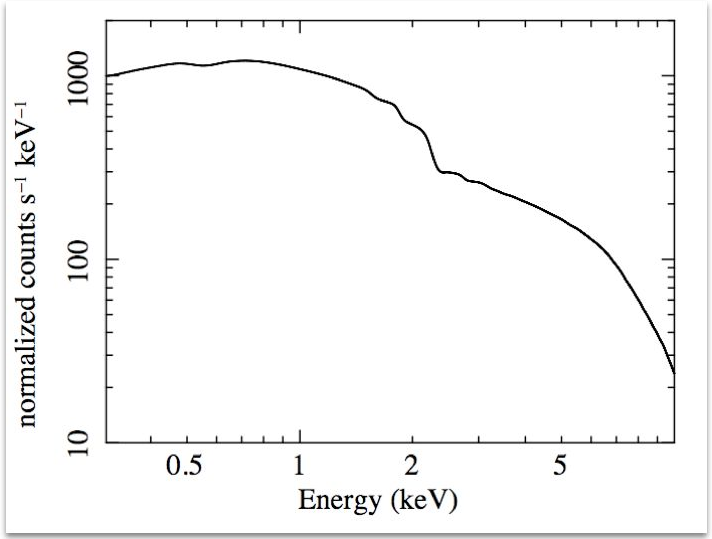


** arfgen: fatal error (NoCifSpecified), `/prod_oasbo/sas/xmmsas_20210317_1624/evt' is neither the name of a directory nor the name of a CIF
>export SAS_CCF='/blasco/users/gruppoXX/datadir/evt/ccf.cif'

The combination of RMF and ARF produces the input spectrum weighted by telescope area and detector efficiencies versus energy







Grouping

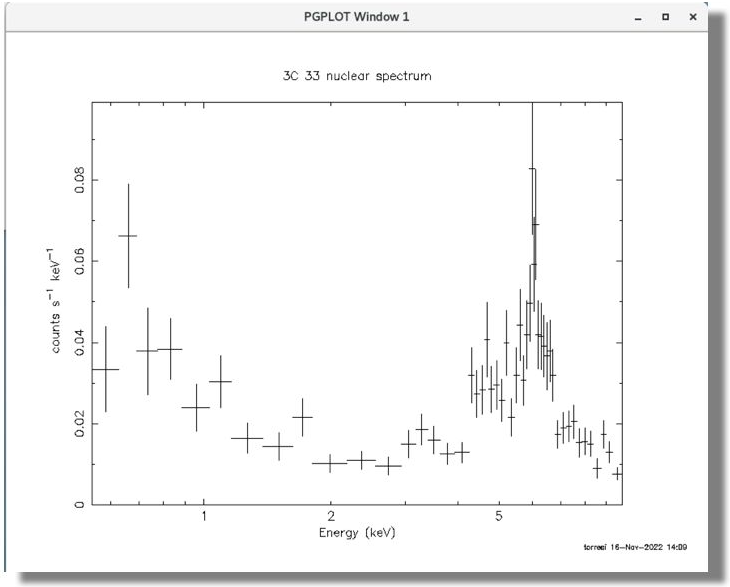
In order to apply the χ^2 statistics (Gaussian distribution) you need to have at least 25 counts in each bin of your spectrum. Otherwise Cash statistics (Poisson distribution) is preferred (see also Statistics Tutorial).

grppha source_spectrum.fits pn_25.grp comm="chkey RESPFILE **pn.rmf** & chkey ANCRFILE **pn.arf** & chkey BACKFILE **back_spectrum.fits** & **group min 25** & exit"

Grouping

In order to apply the χ^2 statistics (Gaussian distribution) you need to have at least 25 counts in each bin of your spectrum. Otherwise Cash statistics (Poisson distribution) is preferred (see also Statistics Tutorial).

grppha source_spectrum.fits pn_25.grp comm="chkey RESPFILE **pn.rmf** & chkey ANCRFILE **pn.arf** & chkey BACKFILE **back_spectrum.fits** & **group min 25** & exit"

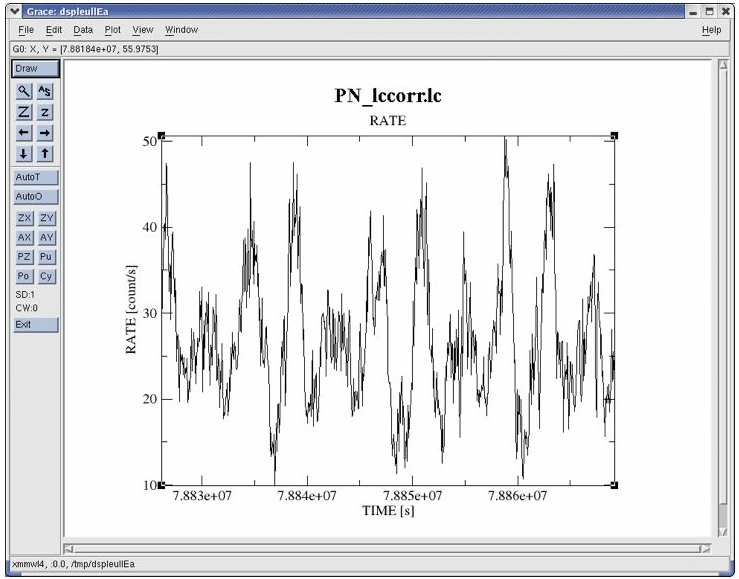


Xspec

see XSPEC tutorial

Light curve

A light curve is the plot of the flux of a source vs time.
It shows if and how the flux of the source varies during a certain time series.
The variability of a source can manifest on different time scales.



https://www.cosmos.esa.int/web/xmm-newton/sas-thread-timing

source+background lightcurve

pn

evselect table=**pn_new.evt** energycolumn=PI expression='#XMMEA_**EP**&&(**PATTERN<=4**)&& ((X,Y) IN circle(25910.5,25870.5,400)&& (PI in **[2000:10000]**))' withrateset=yes rateset="**PN_source_lightcurve_raw.lc**" timebinsize=**100** maketimecolumn=yes makeratecolumn=yes

MOS 1

evselect table=**mos1_new.evt** energycolumn=PI expression='#XMMEA_**EM**&&(**PATTERN<=12**)&& ((X,Y) IN circle(25910.5,25870.5,400)&& (PI in **[2000:10000]**))' withrateset=yes rateset="**MOS1_source_lightcurve_raw.lc**" timebinsize=**100** maketimecolumn=yes makeratecolumn=yes

The longer is the temporal bin the lower is the resolution but the higher is the S/N.

MOS 2

evselect table=**mos2_new.evt** energycolumn=PI expression='#XMMEA_**EM**&&(**PATTERN<=12**)&& ((X,Y) IN circle(25910.5,25870.5,400)&& (PI in **[2000:10000]**))' withrateset=yes rateset="**MOS2_source_lightcurve_raw.lc**" timebinsize=**100** maketimecolumn=yes makeratecolumn=yes

background lightcurve

pn

evselect table=**pn_new.evt** energycolumn=PI expression='#XMMEA_**EP**&&(**PATTERN<=4**)&& ((X,Y) IN circle(25910.5,25870.5,400)&& (PI in **[2000:10000]**))' withrateset=yes rateset="**PN_light_curve_background_raw.lc**" timebinsize=**100** maketimecolumn=yes makeratecolumn=yes

MOS 1

evselect table=**mos1_new.evt** energycolumn=PI expression='#XMMEA_**EM**&&(**PATTERN<=12**)&& ((X,Y) IN circle(25910.5,25870.5,400)&& (PI in **[2000:10000]**))' withrateset=yes rateset="**MOS1_light_curve_background_raw.lc**" timebinsize=**100** maketimecolumn=yes makeratecolumn=yes

MOS 2

evselect table=**mos2_new.evt** energycolumn=PI expression='#XMMEA_**EM**&&(**PATTERN<=12**)&& ((X,Y) IN circle(25910.5,25870.5,400)&& (PI in **[2000:10000]**))' withrateset=yes rateset="**MOS2_light_curve_background_raw.lc**" timebinsize=**100** maketimecolumn=yes makeratecolumn=yes

source-background lightcurve: **epiclccorr**

pn

epiclccorr srctslist=**PN_source_lightcurve_raw.lc** eventlist=**pn_new.evt** outset=**PN_lccorr.lc** bkgtslist=**PN_light_curve_background_raw.lc** withbkgset=yes applyabsolutecorrections=yes

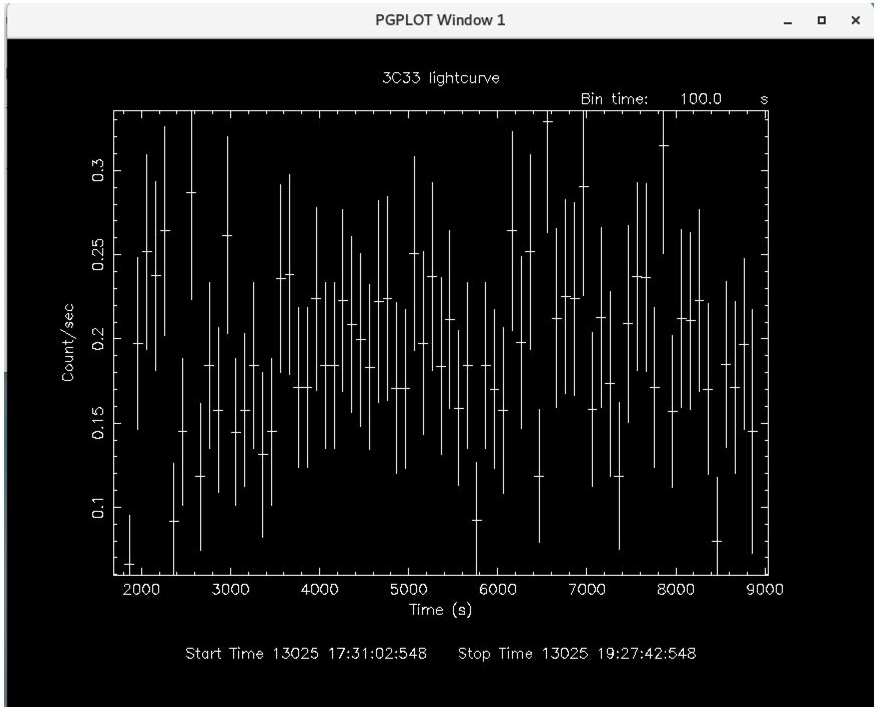
MOS 1

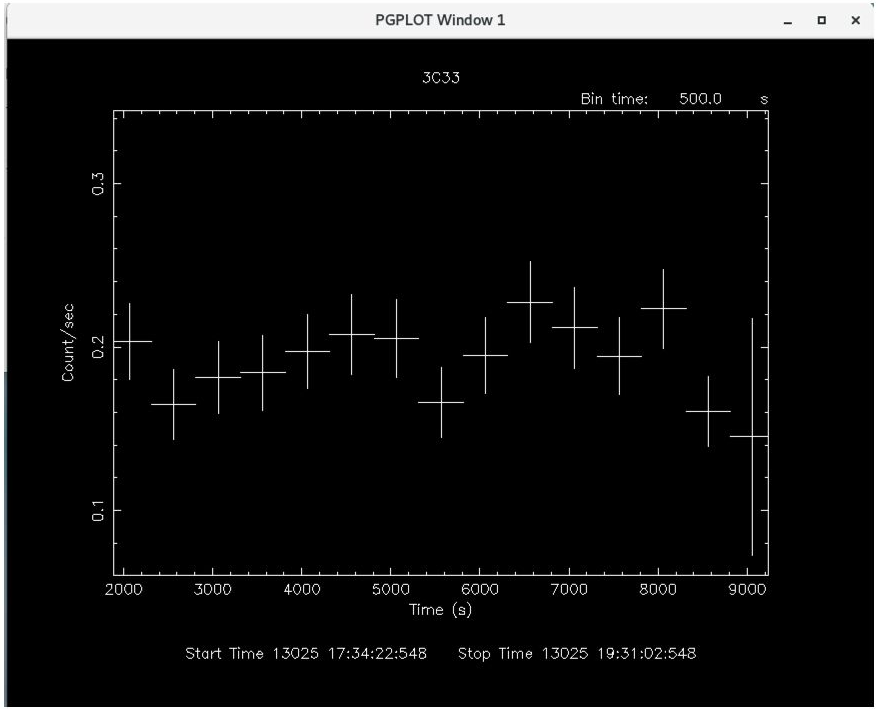
epiclccorr srctslist=**MOS1_source_lightcurve_raw.lc** eventlist=**mos1_new.evt** outset=**MOS1_lccorr.lc** bkgtslist=**MOS1_light_curve_background_raw.lc** withbkgset=yes applyabsolutecorrections=yes

MOS 2

epiclccorr srctslist=**MOS2_source_lightcurve_raw.lc** eventlist=**mos2_new.evt** outset=**MOS2_lccorr.lc** bkgtslist=**MOS2_light_curve_background_raw.lc** withbkgset=yes applyabsolutecorrections=yes

source-background lightcurve: lcurve



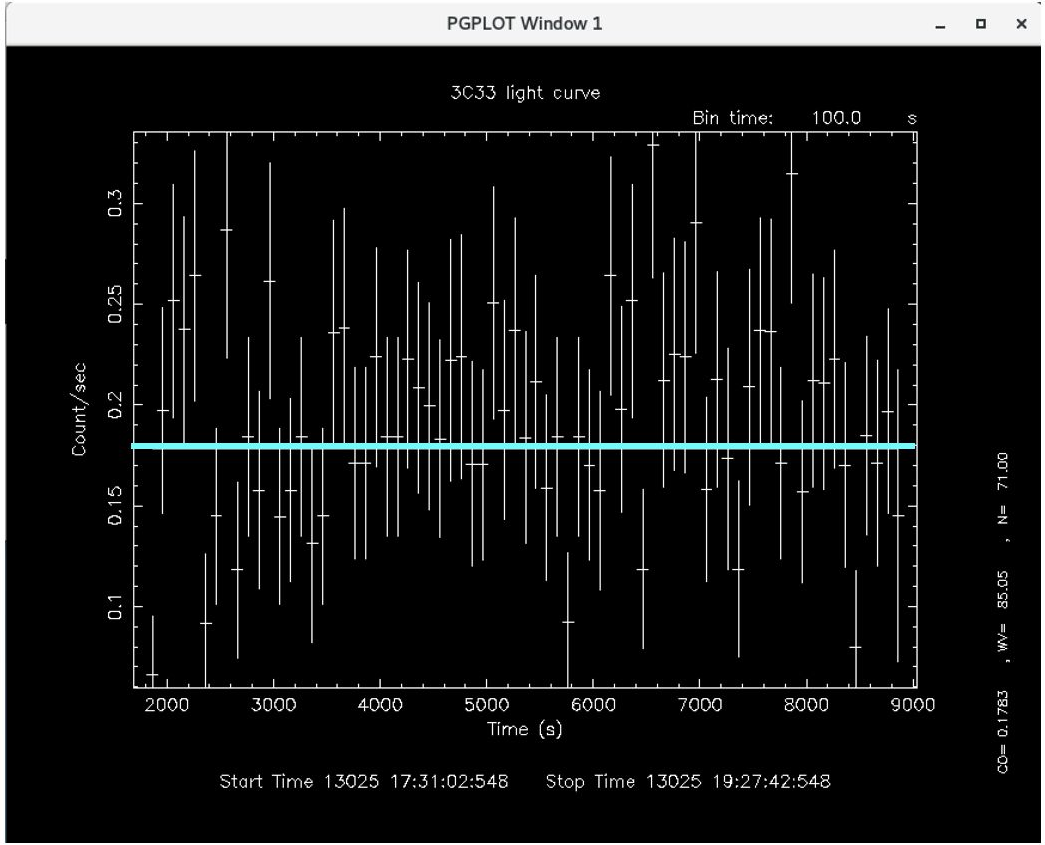


bin=100

The longer is the temporal bin the lower is the resolution but the higher is the S/N.

bin=500

source-background lightcurve: lcurve



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

c_i observed counts in every temporal bin i;
σ_i Poissonian error;
$\langle c \rangle$ average count during the observation;
$\nu = n-1$ degrees of freedom;

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

PLT> fit
 Fitting group   2,  from  1.688E+03 to  9.038E+03
 Fitting      71 points in a band of      71.
   1.00000000
 ( -3)   W-VAR= 85.07
 ( -4)   W-VAR= 85.05
 0.178321302
```

Compute the probability of the result being due to chance

https://www.fourmilab.ch/rpkp/experiments/analysis/chiCalc.html

---

Calculate probability from X^2 and d

One of the most common chi-square calculations is determining, given the measured X^2 value for a set of experiments with a degree of freedom d, the probability of the result being due to chance. Enter the X^2 and d values in the boxes below, press the **Calculate** button, and the probability will appear in the Q box.

Given X^2= 85.05 and d= 70 (71-1)

Calculate

The chance probability, Q, is: 0.192

1-0.192=0.808 the source is variable at ~80% (the acceptance threshold for variability id 99.9%).

Python commands

```
>>> from scipy.stats import chi2

# Insert your values
>>> chi2_value = 80.05     # <-- substitute with your chi²
>>> dof = 70               # <-- substitute with your dof (N - 1)

>>> p_value = 1 - chi2.cdf(chi2_value, df=dof)

print("p-value =", p_value)
print("Significance (1 - p) =", 1 - p_value)
```