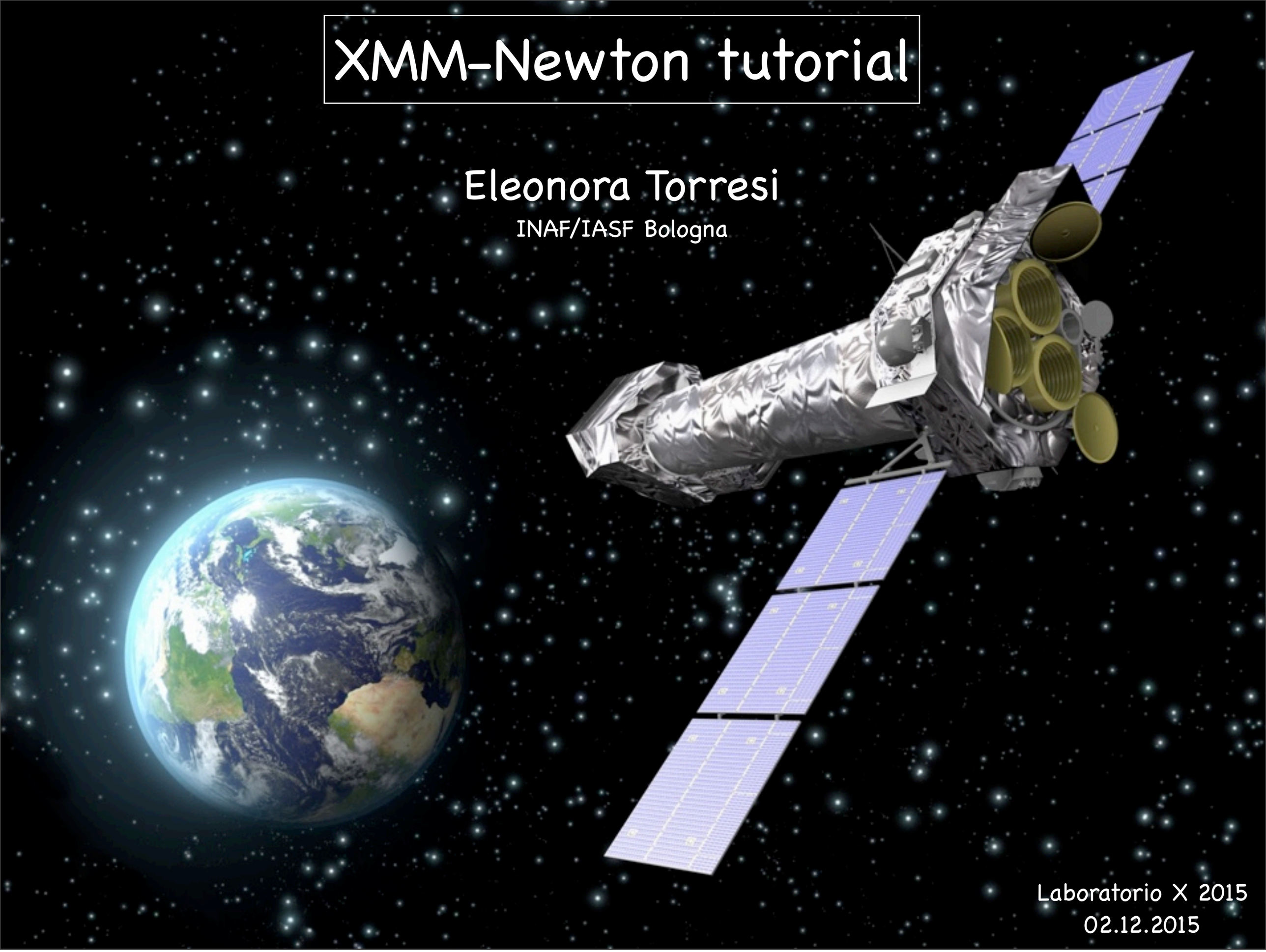
XMM-Newton tutorial

Eleonora Torresi
INAF/IASF Bologna



Laboratorio X 2015
02.12.2015

OUTLINE

- Download XMM-Newton data from the public archive

- PN, MOS1 and MOS2 data reduction:

  - selection of Good Time Intervals (GTI)
  - generation of the cleaned event file
  - source and background regions selection
  - check for the presence of pile-up
  - spectrum extraction (of both source and background)
  - creation of the Response Matrix Function (RMF)
  - creation of the Ancillary Response Function (ARF)
  - grouping of the spectra

- Extraction of a light curve from a point-like source

XMM-Newton payload

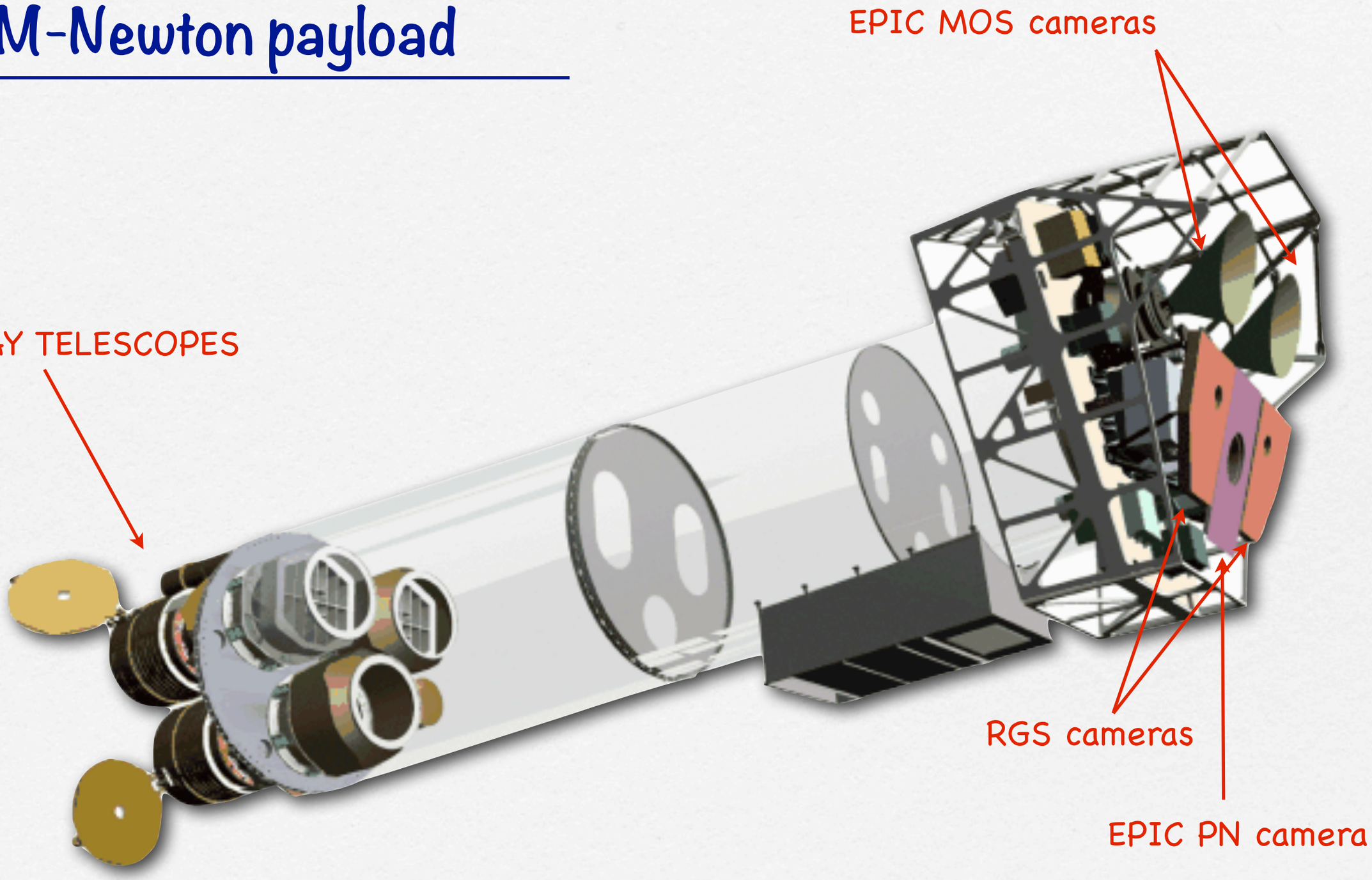


Image courtesy of Dornier Satellitensysteme GmbH and ESA

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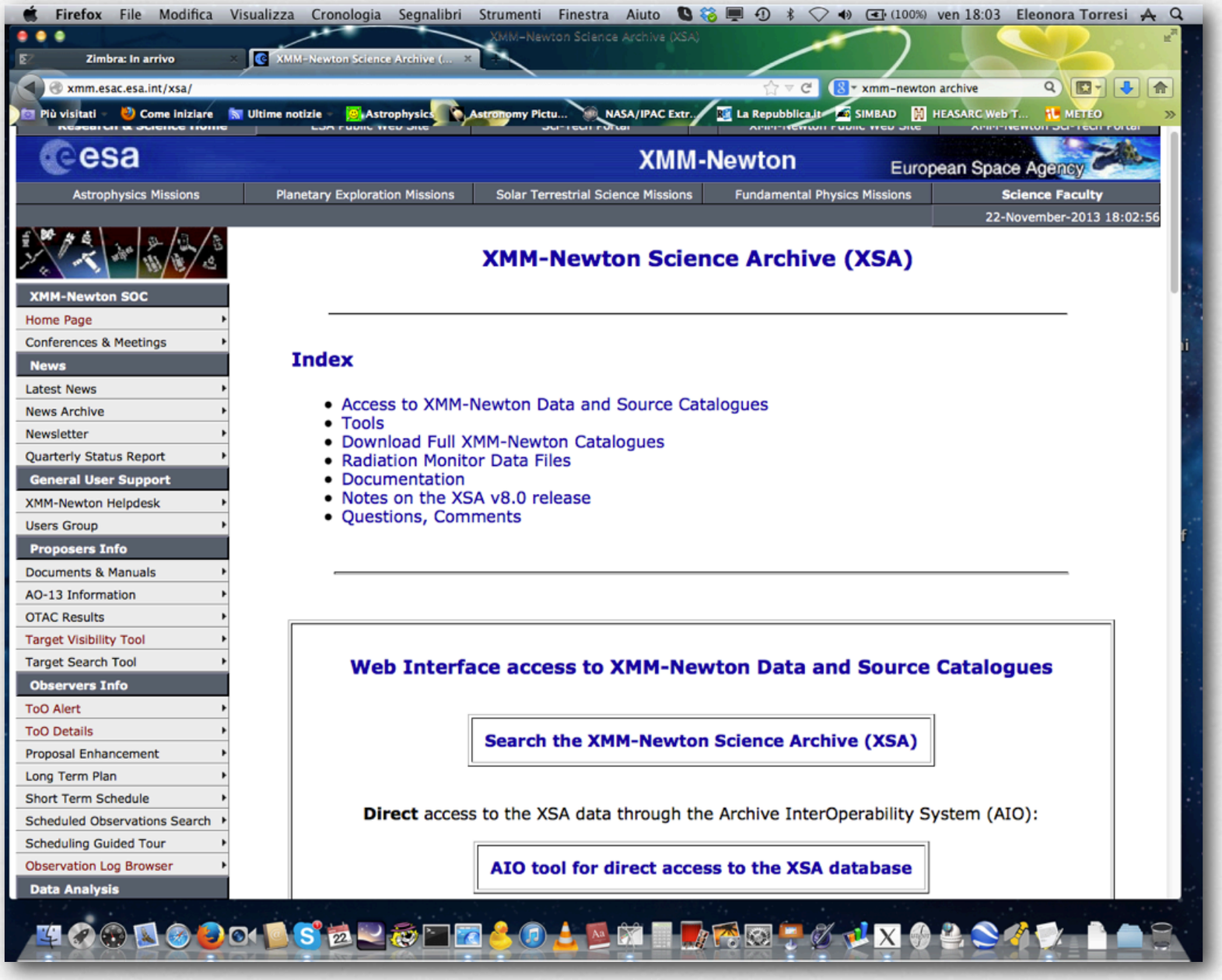

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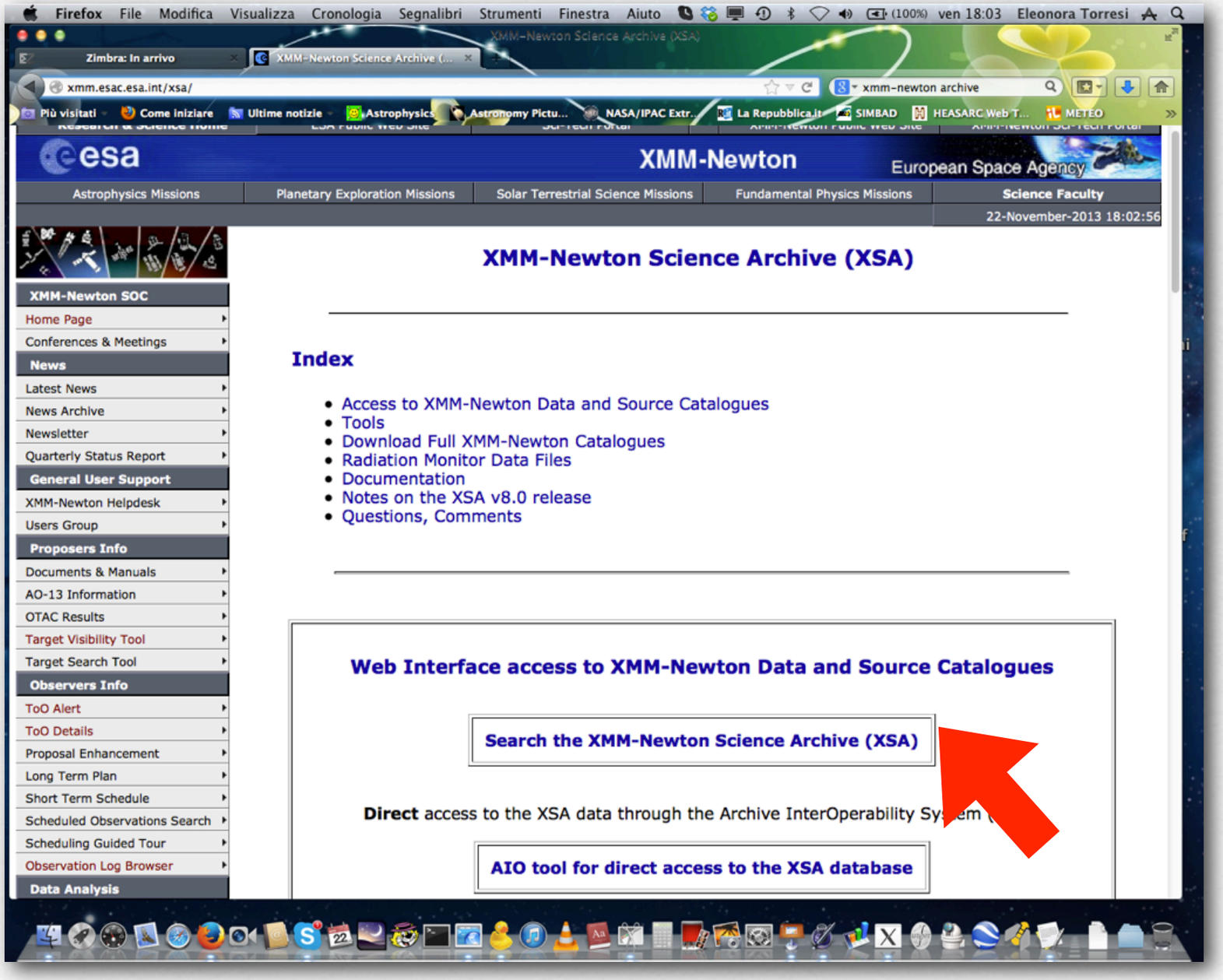

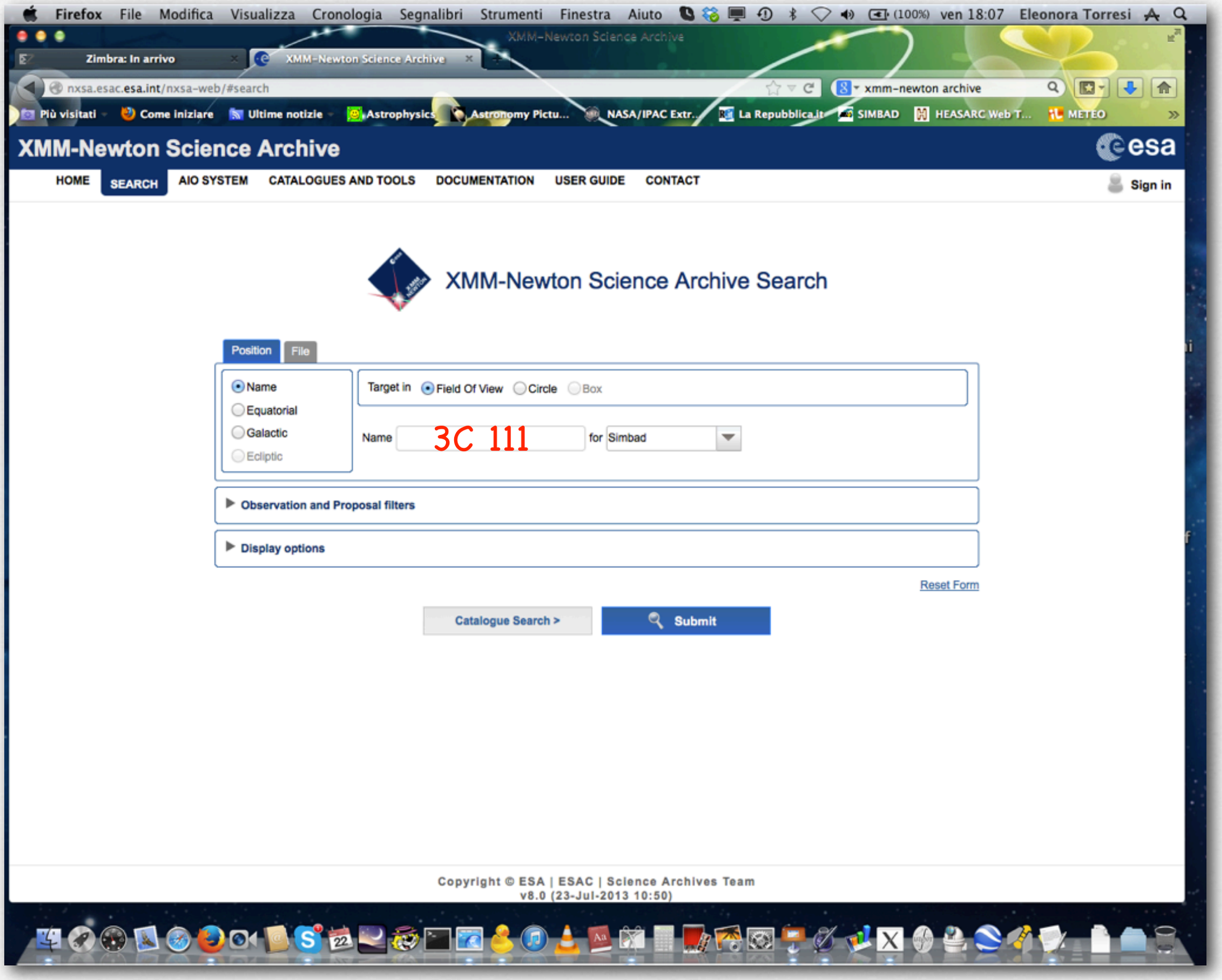
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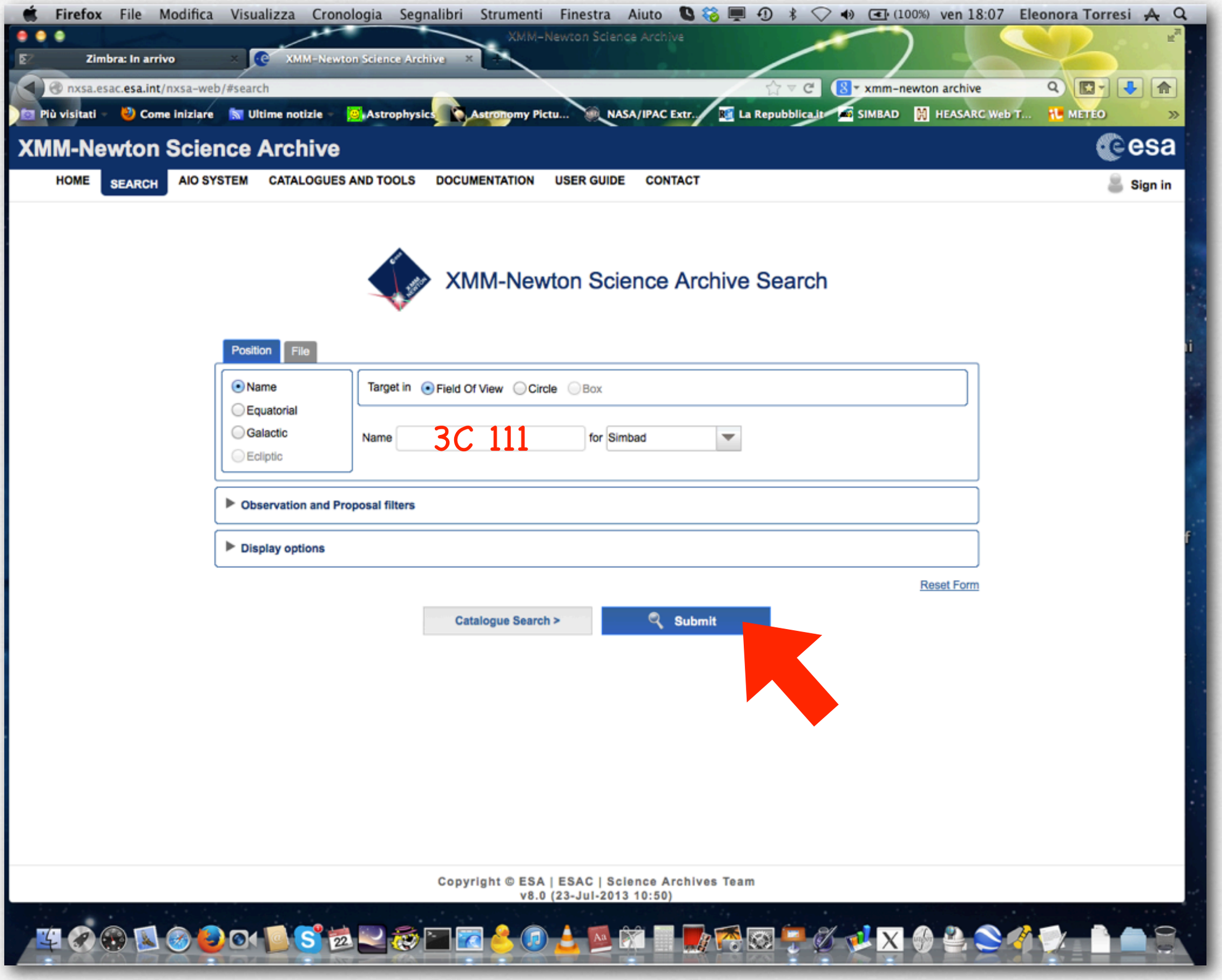
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			Obs.ID	EPIC	RGS	Target	RA	Dec	PA	Rev	Distance	Start Date	End Date
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☑			0552180101			3C111	04h 18m 21.27s	+38d 01' 35.7"	262.9	1683	0	2009-02-15 17:25:11	2009-02-17 04:(
☐			...201	N/A	N/A	3C111	04h 18m 21.27s	+38d 01' 35.7"	262.9	1683	0	2009-02-15 14:44:57	2009-02-15 16:5

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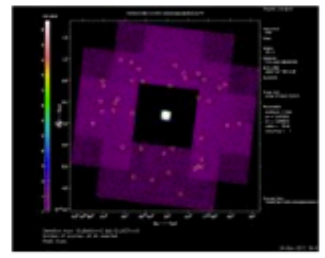
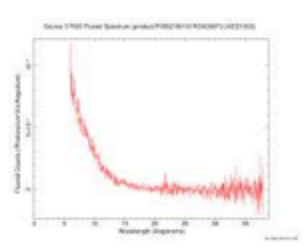
Displaying 1-3 of 3

Details for Observation 0552180101





Summary | Exposures | Publications

Obs. ID	0552180101
Revolution	1683
Target	3C111
Exposures	3 EPIC, 59 OM, 2 RGS

Proposal Abstract

The investigators request a 130 ks `stare' of 3C 111 in order to measure the high-frequency end of the power spectral density (PSD) of the X-ray flux variations. Combined with long-term monitoring with RXTE that is sampling the intermediate and low frequencies, the data will define the break in the PSD. This will add an FR II radio galaxy to the relationship between break frequency, black-hole mass, and accretion rate of both AGNs and XRBs. The long-term light curves display dips in X-ray flux that precede the appearance of superluminal knots in the radio jet. The lag between the start of an X-ray event and the first appearance of a knot in the jet `core' will determine the length scale of the jet, which we can relate to the black hole's gravitational radius.

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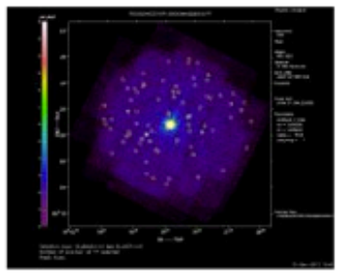
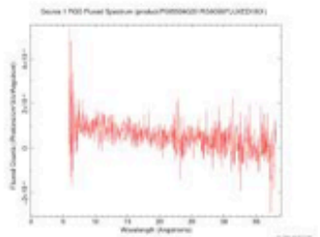
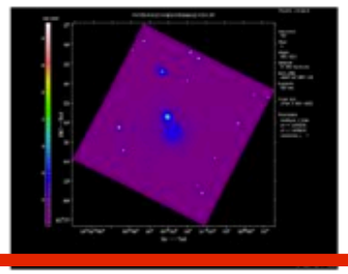
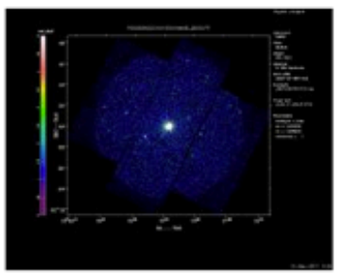






ExposureID	S006
Instrument	OM
Mode	Image
Filter	U



ExposureID	S001
Instrument	EMOS1
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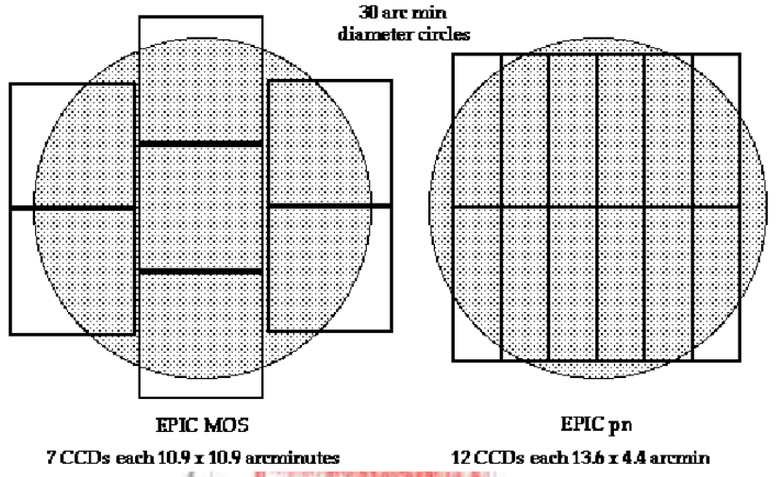
Details for Observat

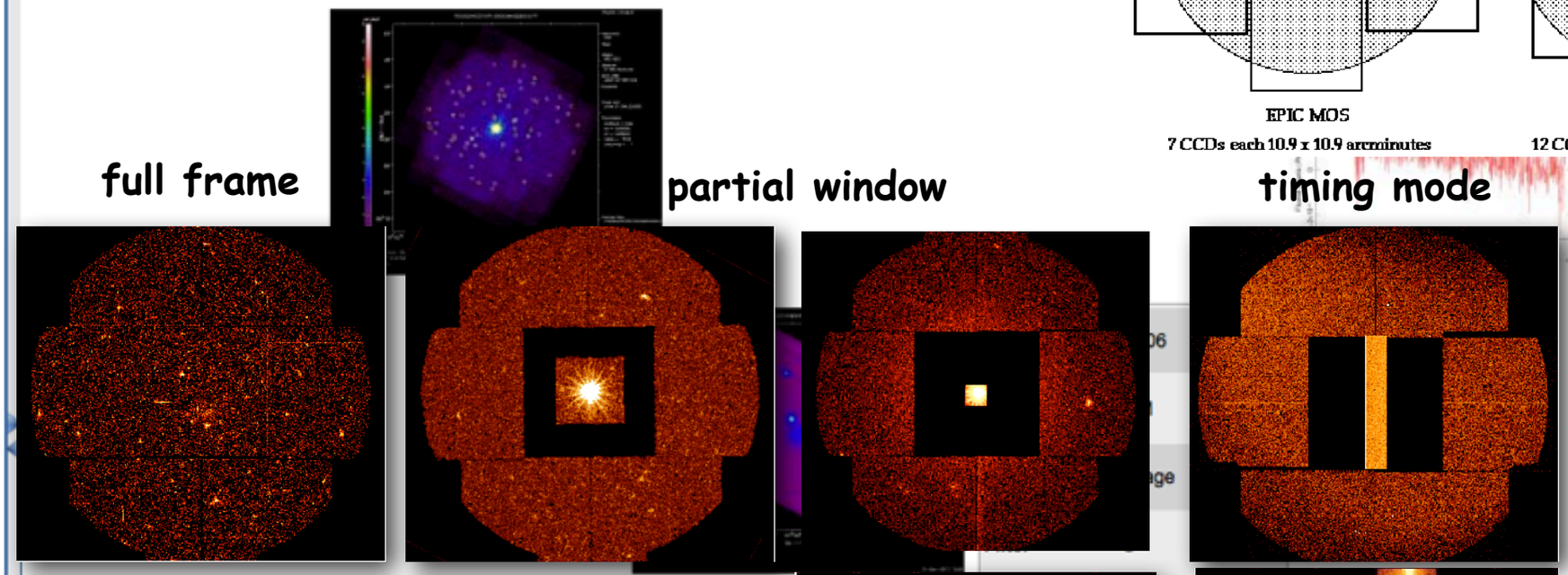
Comparison of focal plane organisation of EPIC MOS and pn cameras



full frame

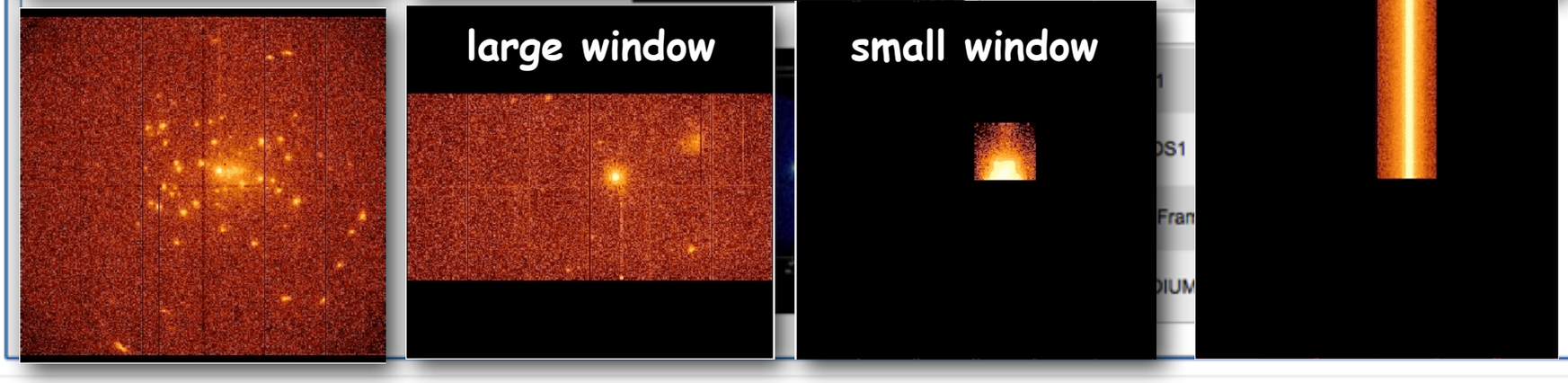
partial window

timing mode



large window

small window



MOS

pn

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☑						3C111	04h 18m 21.27s	+38d 01' 35.7"	262.9	1683	0	2009-02-15 17:25:11	2009-02-17 04:01:23	124572	RADIO GALAXY RADIO LOUD/FLAT SPECT FLAT RADIO SP
☐				N/A	N/A	3C111	04h 18m 21.27s	+38d 01' 35.7"	262.9	1683	0	2009-02-15 14:44:57	2009-02-15 16:55:09	7812	RADIO GALAXY RADIO LOUD/FLAT SPECT FLAT RADIO SP

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PPS
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SPECTRA
LIGHT_CURVES

ODF (Observation Data Files): row data that need to be reprocessed

PPS (Processing Pipeline Files): already reprocessed data using standard pipelines

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ODF
PPS
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☑ Download XMM-Newton data from the public archive

☐ PN, MOS1 and MOS2 data reduction:

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- generation of the cleaned event file
- source and background regions selection
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- creation of the Ancillary Response Function (ARF)
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☐ Extractiou of a light curve from a point-like source

ssh -X groupX@ -> login01.iasfbo.inaf.it
-> login02.iasfbo.inaf.it
-> morgana.iasfbo.inaf.it

Loading of data reduction and analysis packages

-> source setup_all.sh

XMM

-> heainit
-> sas14
-> heainit

Chandra

-> ciao

XSPEC

-> heainit

ODF files

Default

Default

```
[eleonora@MacBook]ODF>ls
2205_0675400101_M1S00100AUX.FIT 2205_0675400101_PNU10112ODI.FIT
2205_0675400101_M1S00110IME.FIT 2205_0675400101_PNX00000HCH.FIT
2205_0675400101_M1S00120IME.FIT 2205_0675400101_PNX00000PAH.FIT
2205_0675400101_M1S00130IME.FIT 2205_0675400101_PNX00000PMH.FIT
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2205_0675400101_M1X00000PTH.FIT 2205_0675400101_R1S91205DII.FIT
2205_0675400101_M2S00200AUX.FIT 2205_0675400101_R1S91306DII.FIT
2205_0675400101_M2S00210IME.FIT 2205_0675400101_R1S91408DII.FIT
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```

Revolution number

FITS files

ObsID

Instrument (pn, MOS1, MOS2)

Content

FITS files

Data produced by the satellite are stored in **FITS (Flexible Image Transport System)** format.

All the information of your observation are contained in the header of the fits file.
You can visualize it by using the FTOOL command fv:

```
> fv nomefile.fits
```

But before you must have set the correct environment...

Creation of event files

ODF → (SAS: epproc-emproc-cifbuild) → evt

event files: pn.evt, m1.evt, m2.evt

CCF
calibration index file (CIF): ccf.cif

PN, MOS1 & MOS2 DATA REDUCTION

After reprocessing the row data you are ready to start the reduction

1. Extraction of a high energy light curve (>10 keV) to identify interval of flaring particle background

EPIC background

Cosmic X-ray background

Instrumental background

detector noise component
(important below 300 eV)

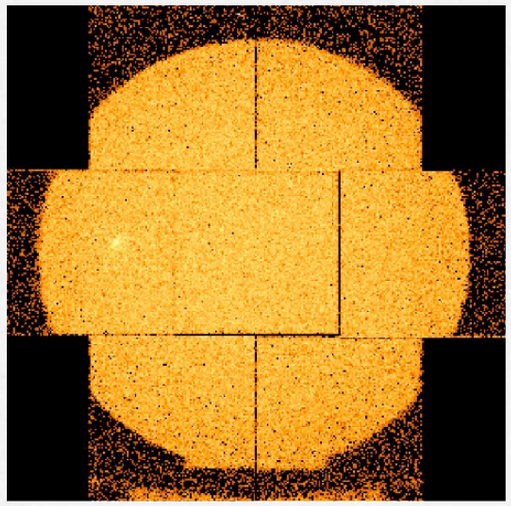
second component due to the interaction of particles with the detectors and the structures surrounding them
(important at high energies, e.g. above a few keV)

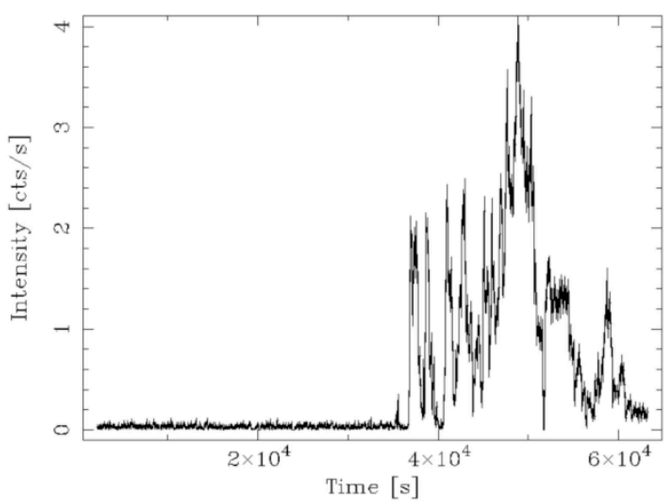
For more information refer to the XMM-Newton User's Handbook

EPIC particle induced background

External 'flaring' component

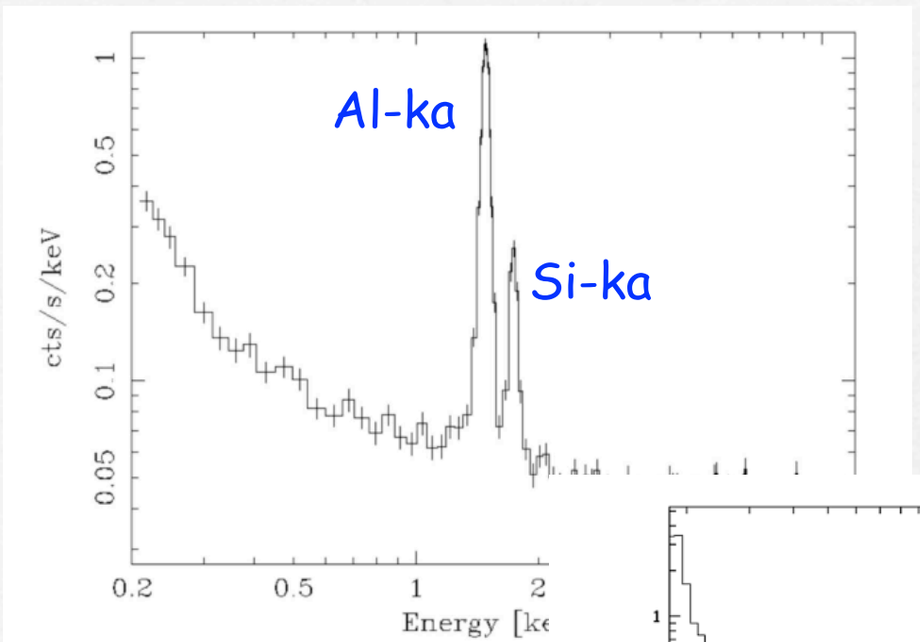
strong and rapid variability; currently attributed to soft protons (E_p < a few 100 keV) likely organized in clouds populating the Earth's magneto-sphere





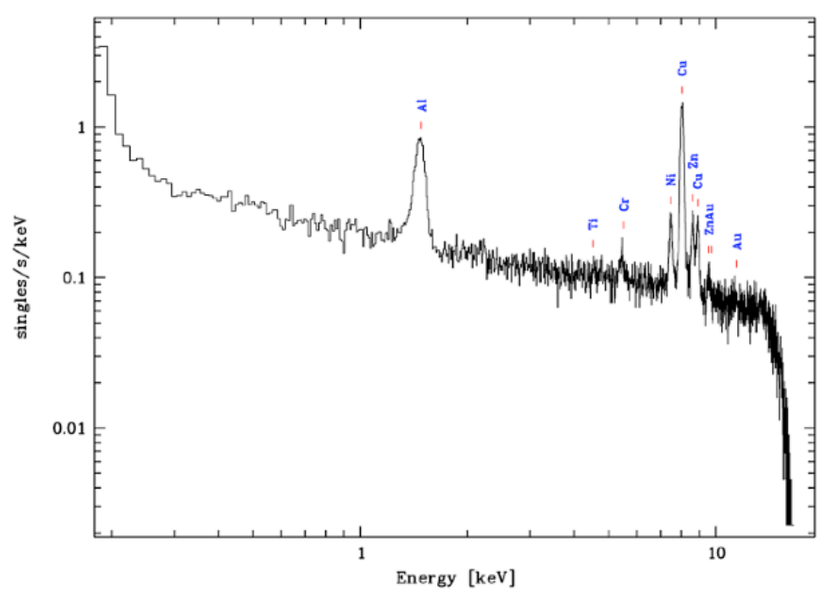
Internal 'quiescent' component

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



MOS1

pn



PN, MOS1 & MOS2 DATA REDUCTION

After reprocessing the row data you are ready to start the reduction

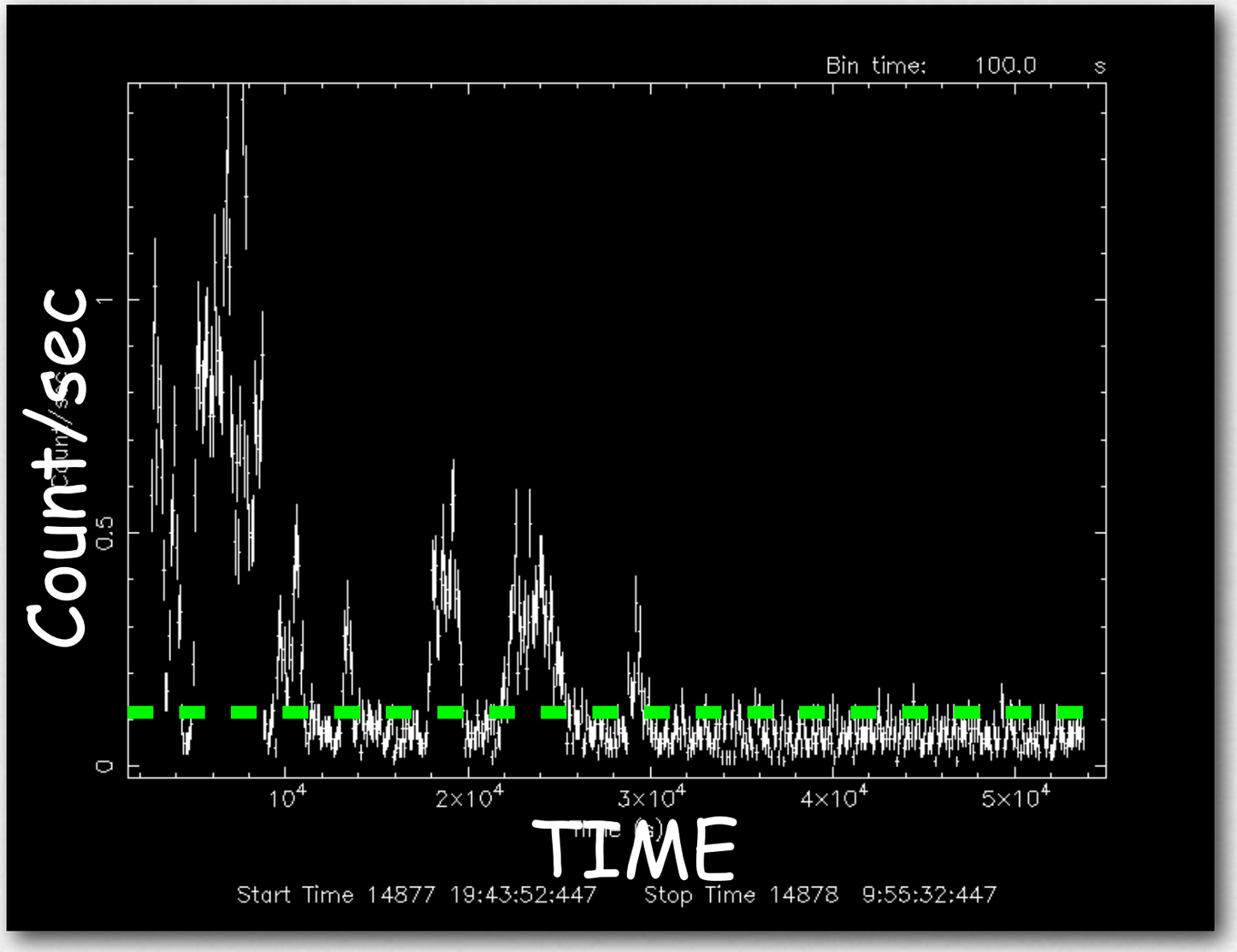
1. Extraction of a high energy light curve (>10 keV) to identify interval of flaring particle background

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

```
lcurve
```

Light curve above 10 keV

pn < 0.4 cts/s
MOS < 0.35 cts/s



2. Selection of GOOD TIME INTERVALS (GTI)

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

3. Generation of the cleaned event file

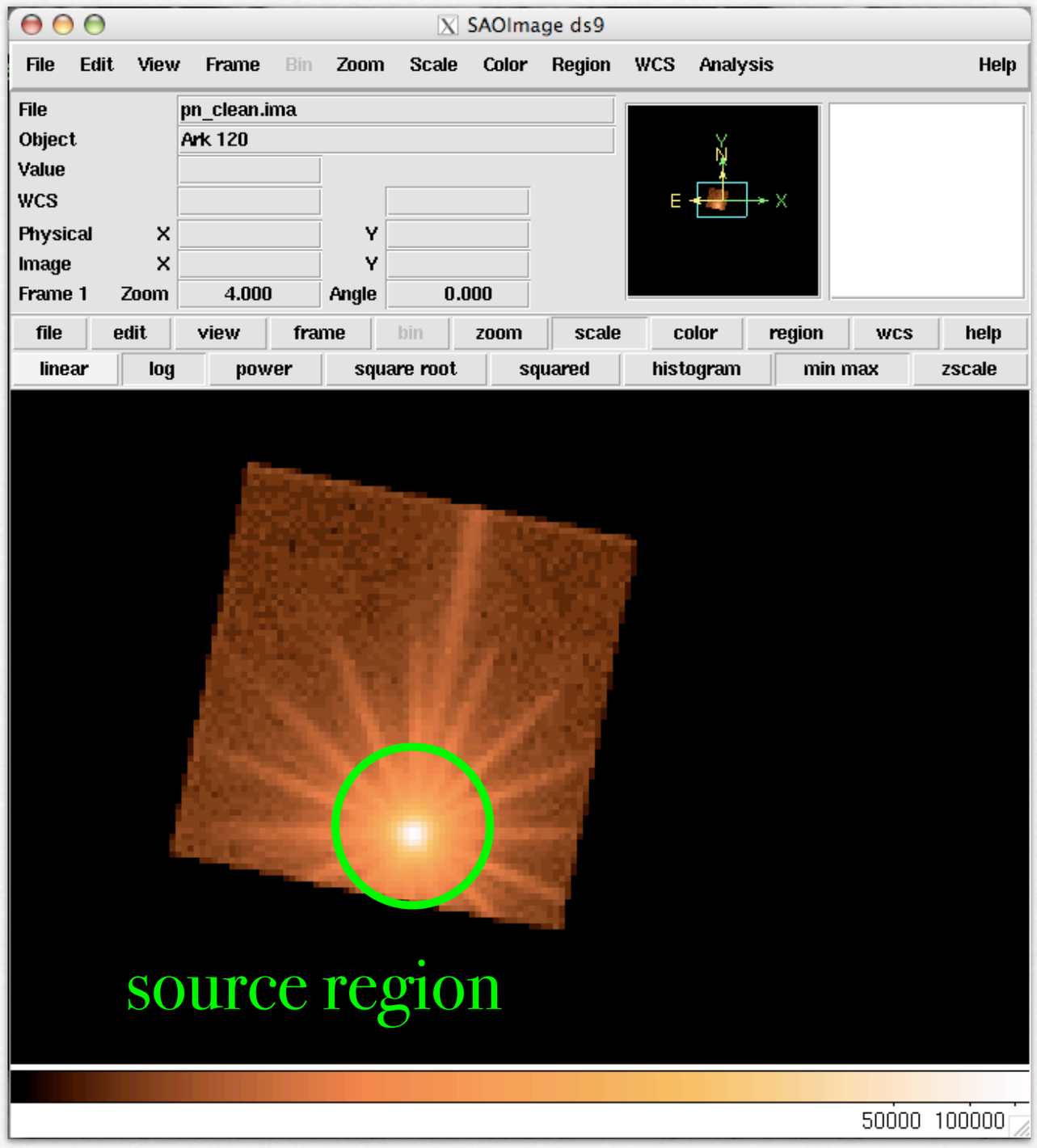
```
evselect table=pn.evt expression='#XMMEA_EP (EM) && (PI > 150) &&
(GTI(good_bkg.gti,TIME))' withfilteredset=yes keepfilteroutput=yes
filteredset=pn_new.evt(mos1_new.evt)updateexposure=yes cleandss=yes
writedss=yes
```

```
pn_new.evt
mos1_new.evt
mos2_new.evt
```

4. Source and background regions selection

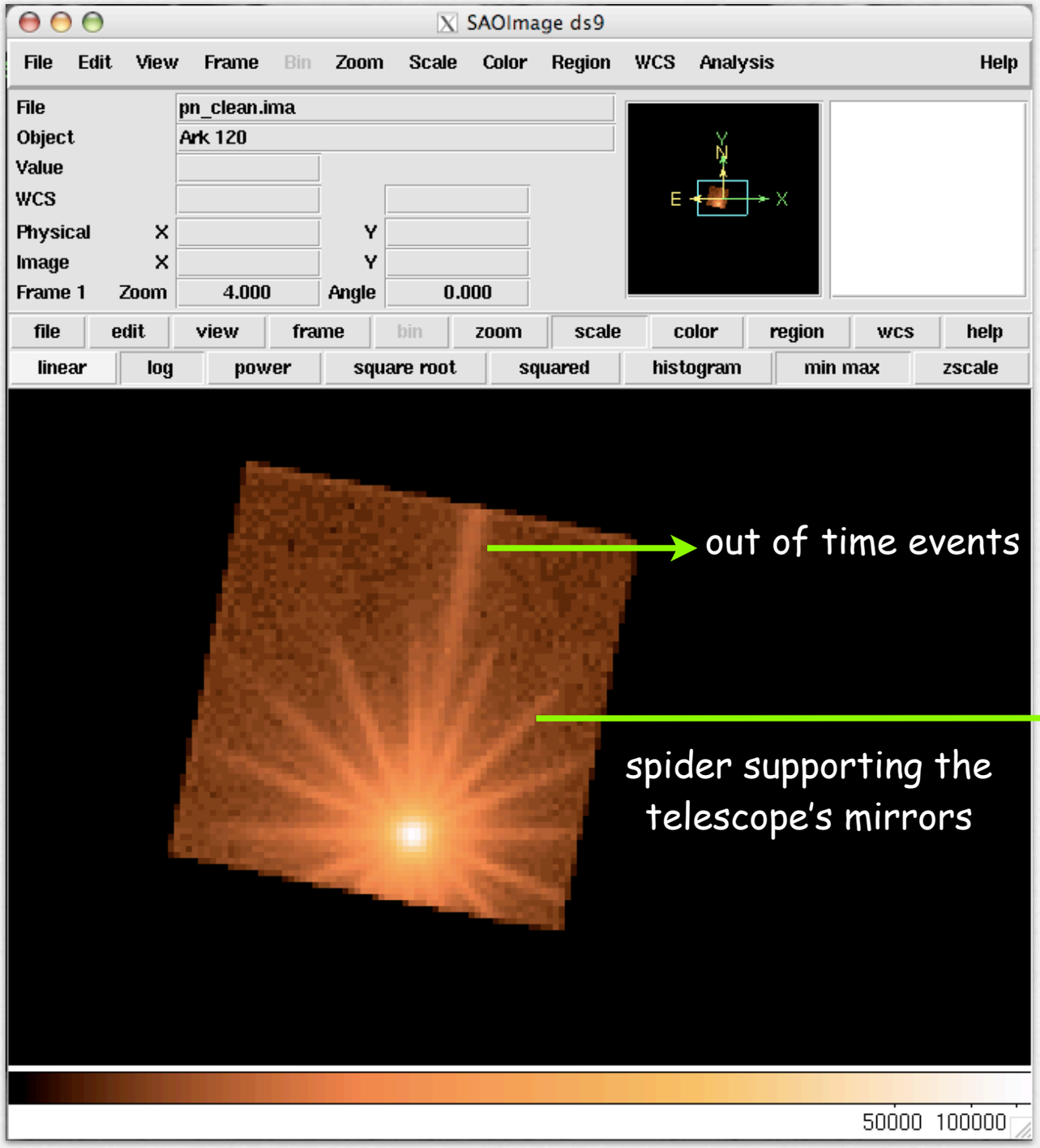
open event list file with ds9

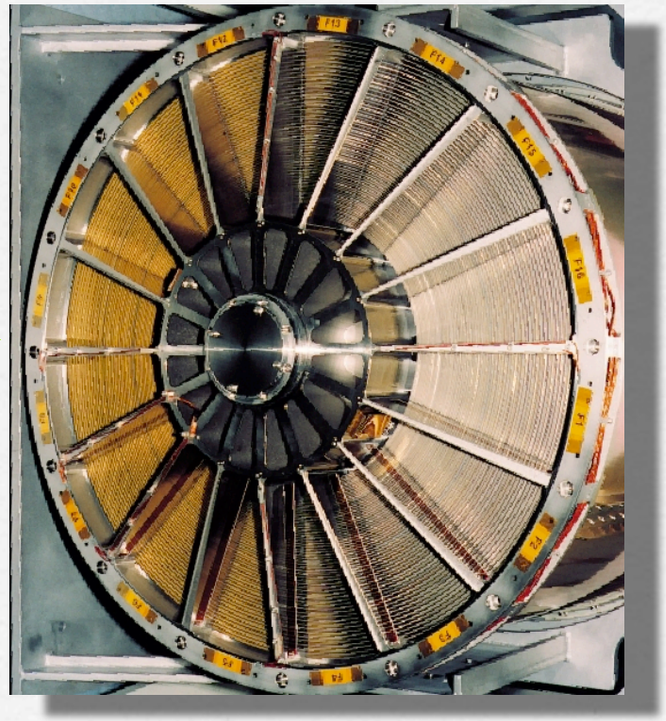
```
> ds9 pn_new.evt &
```



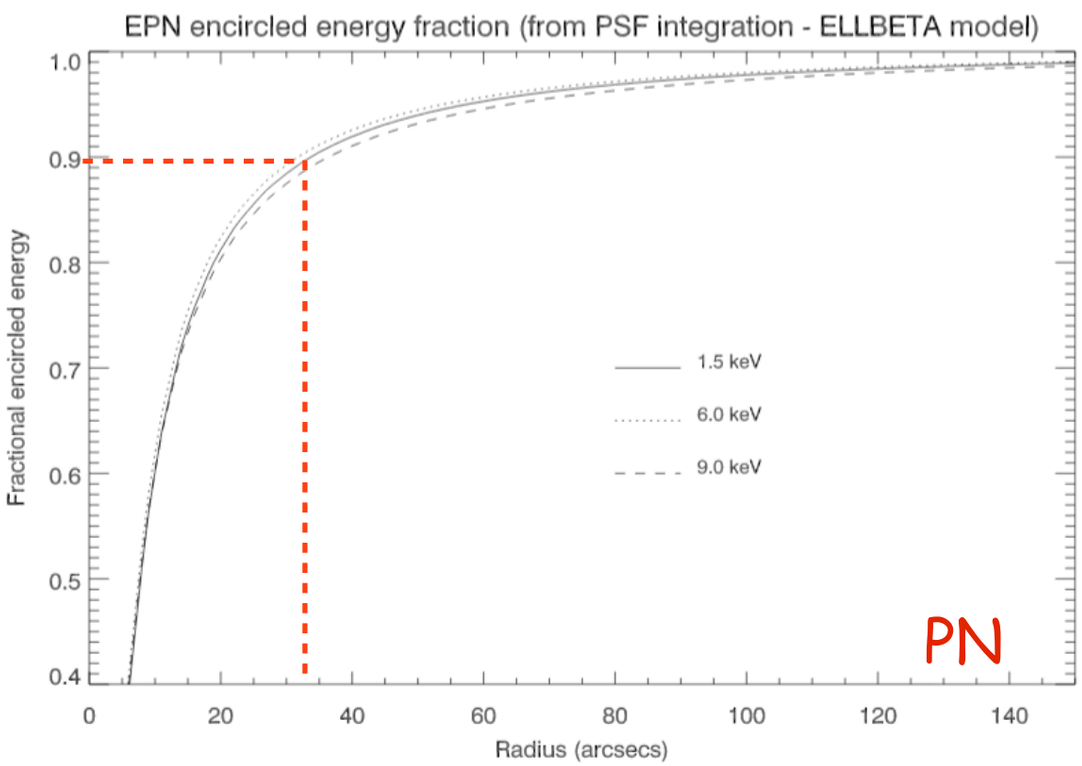

```
> Region
> save region
> file format ‘ds9’
> coordinates ‘physical’
> source.reg
```

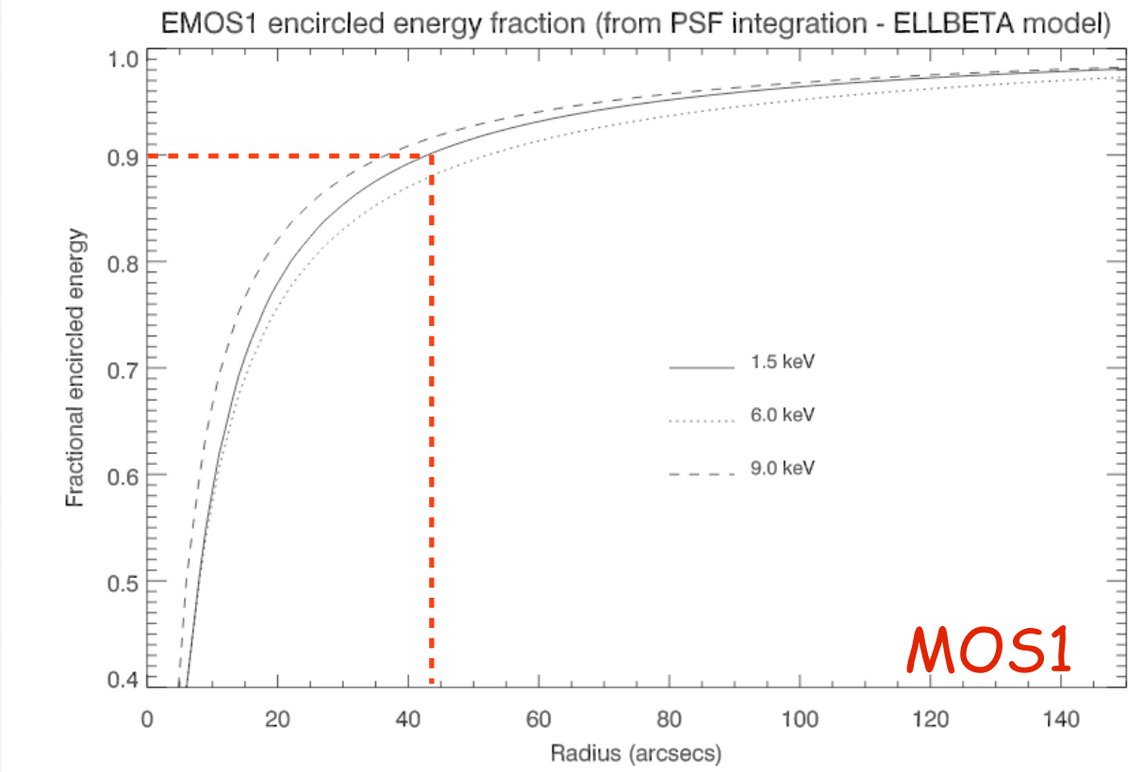
http://ds9.si.edu/doc/ref/


SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File pn_clean.ima
Object Ark 120
Value
WCS
Physical X Y
Image X Y
Frame 1 Zoom 4.000 Angle 0.000
Y
N
E
X
file edit view frame bin zoom scale color region wcs help
linear log power square root squared histogram min max zscale
out of time events
spider supporting the telescope's mirrors
50000 100000



Fractional encircled energy



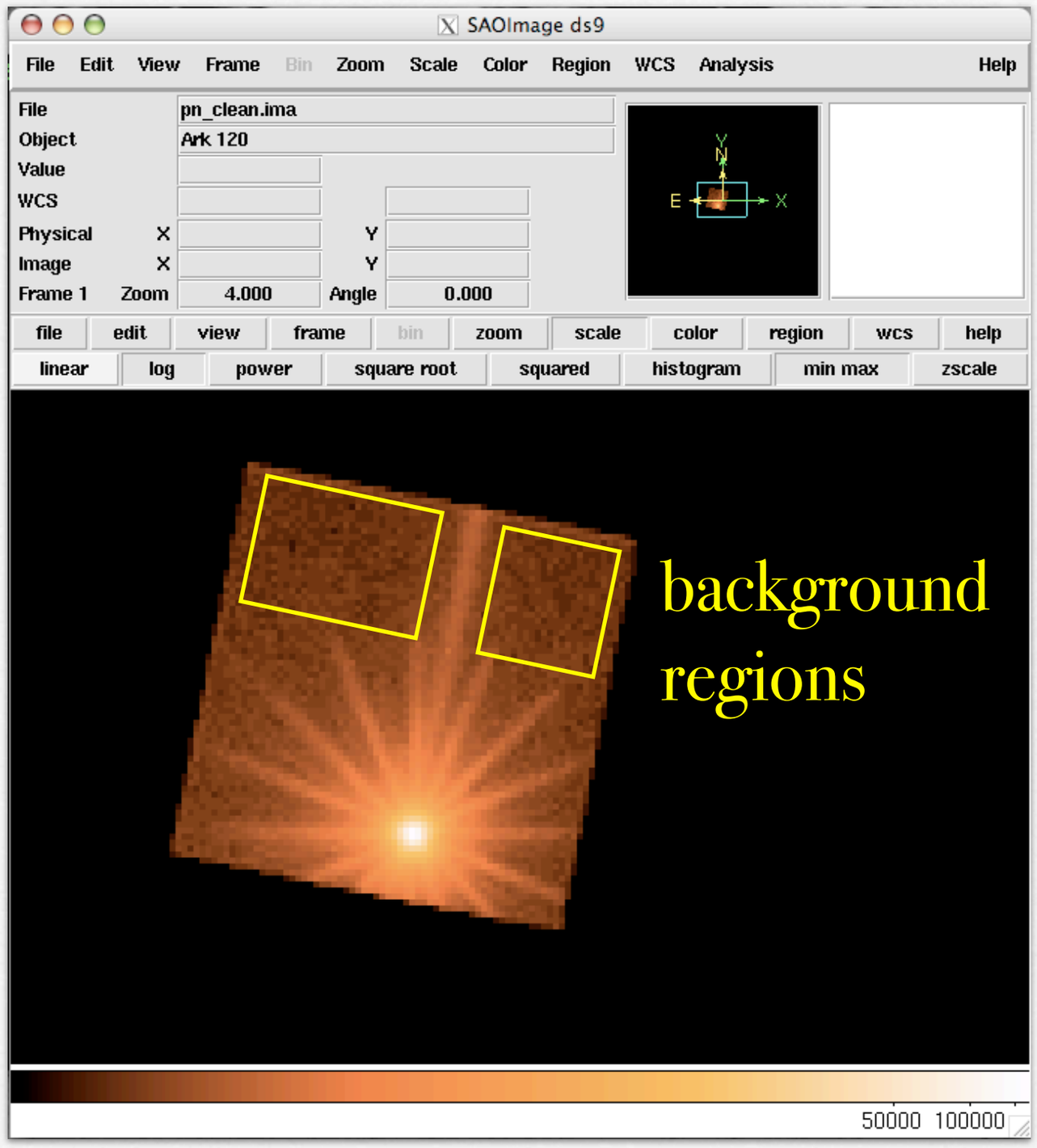


Dependence of the radius at which 90% of the total energy is encircled on the off-axis angle

4. Source and background regions selection

open event list file with ds9

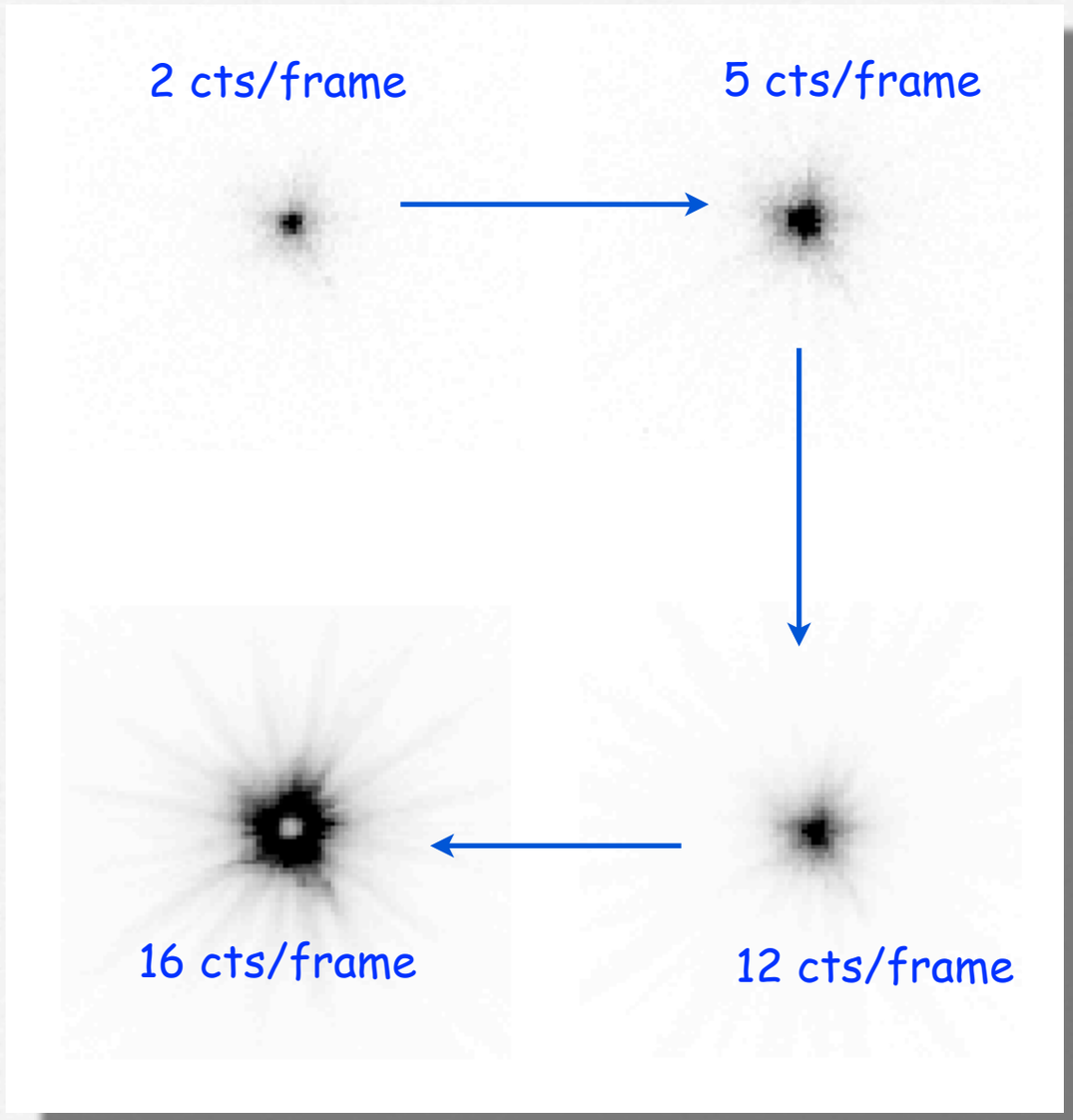
```
> ds9 pn_new.evt &
```




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

5. Check for the presence of photon pile-up

Arrival of more than one X-ray photon in one camera pixel or in an adjacent pixel before it is read out



Can affect the PSF (in its core many photons arrive at almost the same time) and the EPIC spectral response (artificial "hard" X-ray photons are created where there have been two or more soft photons)

EPIC MOS

Single- double- triple- quadruple- events are the four types of valid events which can be created by an X-ray photon

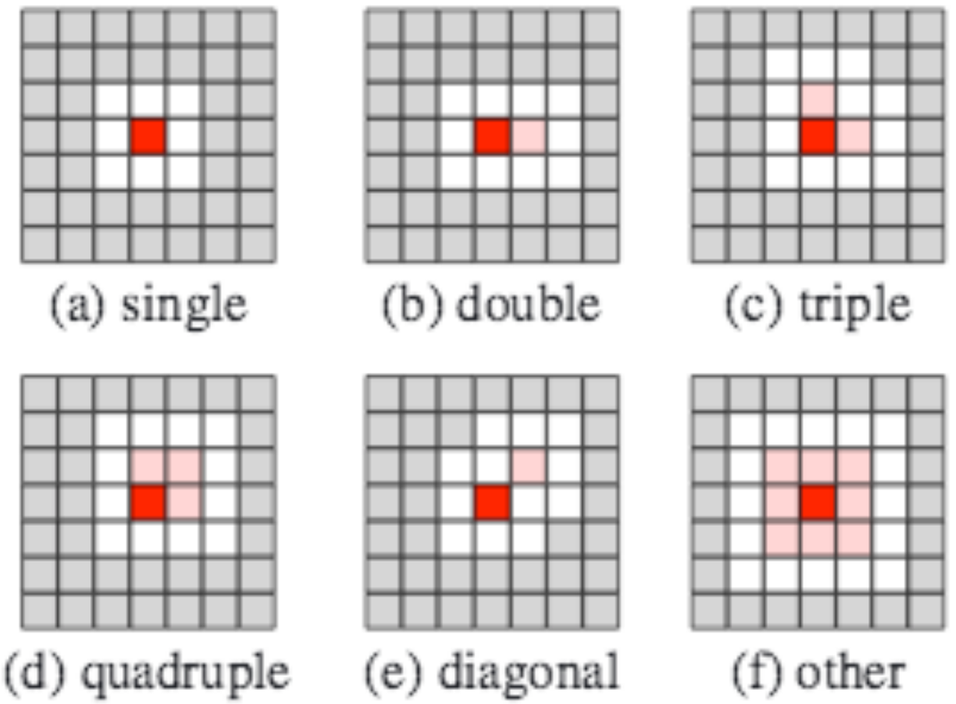


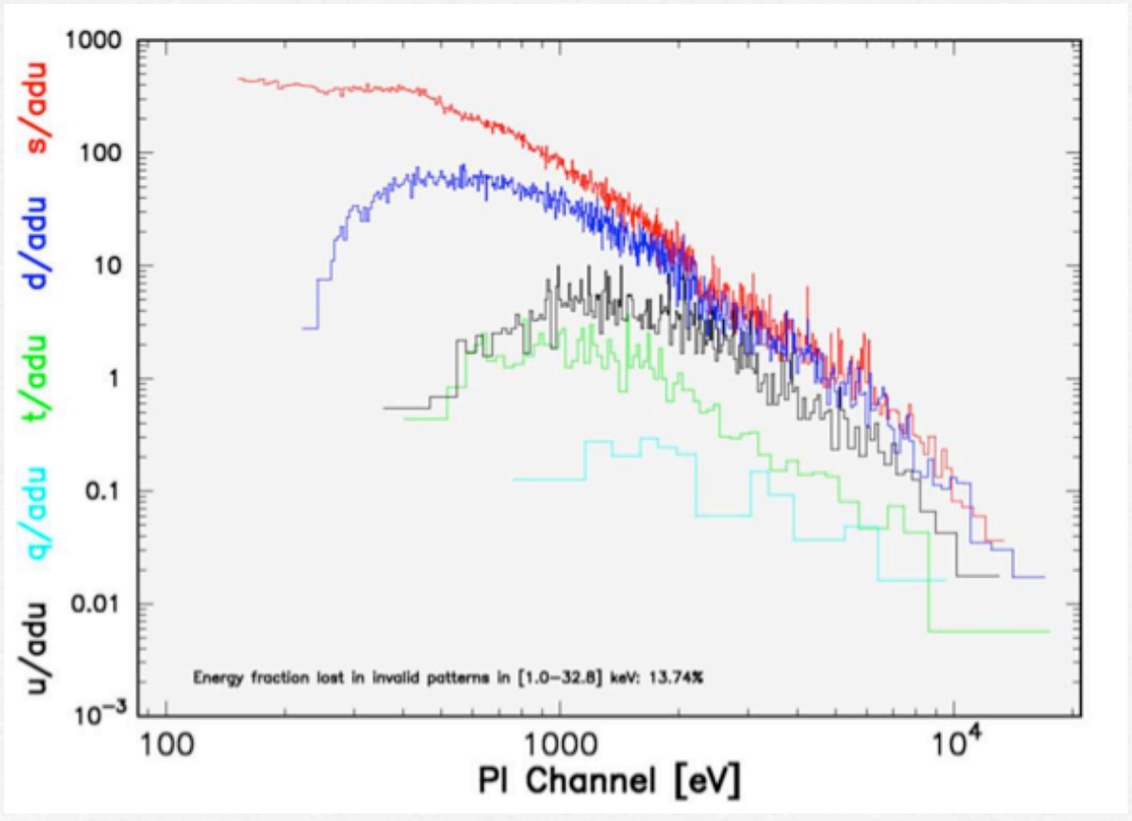
Fig. 1. Examples of EPIC pattern classifications. In each case the dark red pixel contains maximum charge, light red pixels have charge above a threshold value whereas white pixels are necessarily below this threshold. Grey pixels do not influence the pattern classification of the event.

Jethwa et al. 2015

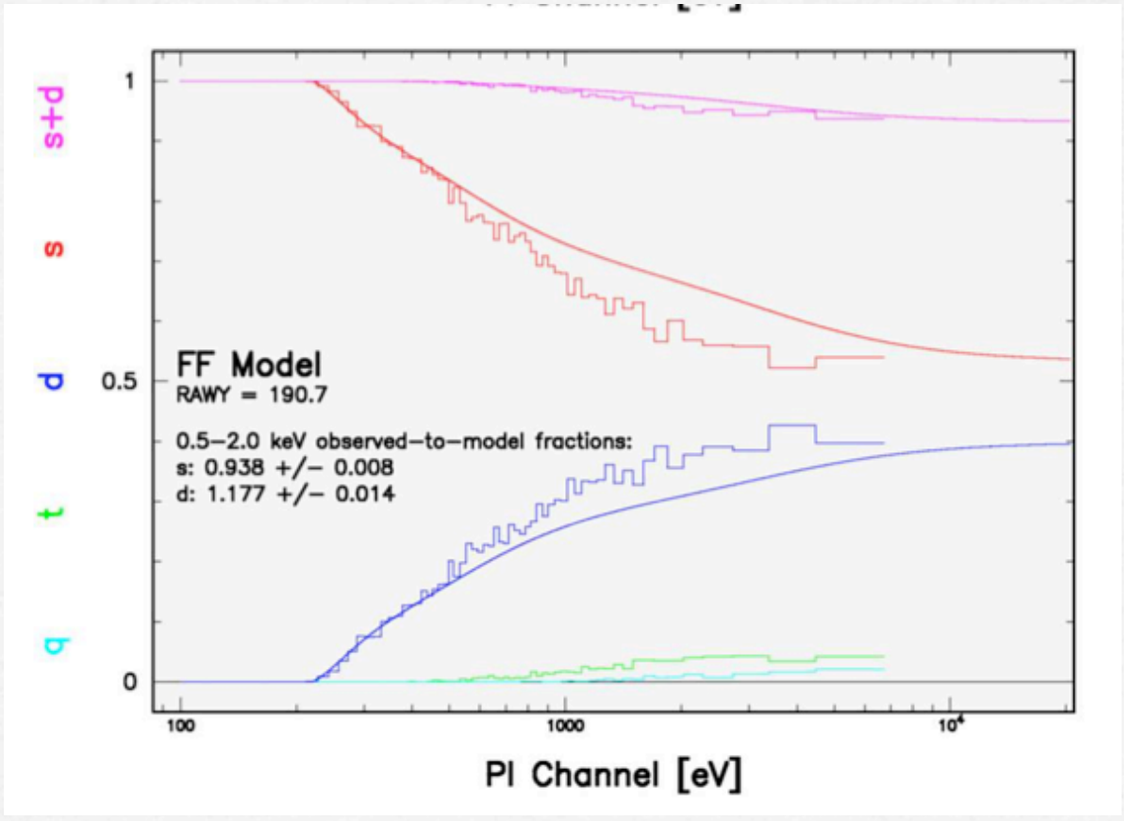
Double events can be produced only if the energy of both events is above the event threshold. Triple (quadruples) events start at 3 (4) times the event threshold.

```
> evselect table=pn_new.evt withfilteredset=yes
filteredset=pnf.evt keepfilteroutput=yes expression="((X,Y)
IN circle (source region))"

> epatplot set=pnf.evt device="/CPS" plotfile="pnf_pat.ps"

> gv pnf_pat.ps
```

spectral distributions as function of PI channels for single- double- triple- and quadruple- events



fraction of the four valid event types



see also Jethwa et al. 2015

6. Spectrum extraction (source)

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))'
```

MOS

```
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))'
```

PATTERN==0 (single events); PATTERN==[1-4] (double events); PATTERN==[5-12] (triple and quadruple events)

6. Spectrum extraction (background)

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
(27874.528,26645.58,699.99999))'
```

MOS

```
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
(28090.5,24221.5,775.48791))'
```

If you have more than one background region:

```
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( )) ||
((X,Y) IN circle( )))'
```

8. Calculate the area of source and background regions used to make the spectral files

```
backscale spectrumset=source_spectrum.fits badpixlocation=pn_new.evt

backscale spectrumset=back_spectrum.fits badpixlocation=pn_new.evt
```

The backscale task takes into account any bad pixels o chip gaps and writes the result into the BACKSCAL keyword of the spectrum table

9. Creation of the Redistribution Matrix File (RMF)

```
rmfgen spectrumset=source_spectrum.fits rmfset=pn.rmf
```

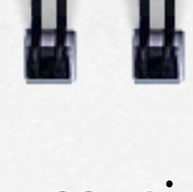
The Redistribution Matrix File (RMF): associates to each instrument channel (I) the appropriate photon energy (E)

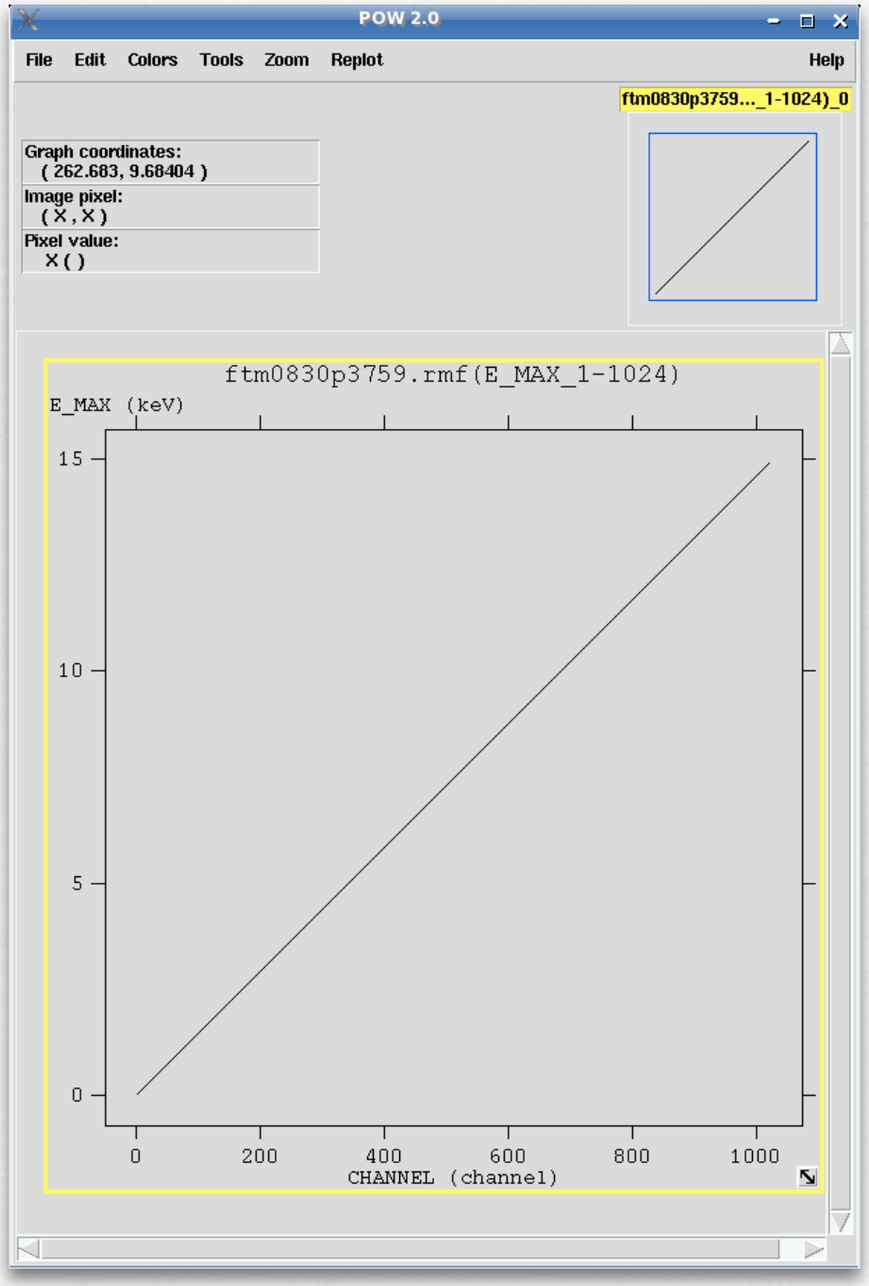
fv: Binary Table of ftm0830p3759.rmf[2] in /ho

File Edit Tools Help

Select	CHANNEL	E_MIN	E_MAX
All	1E	1E	1E
Invert	channel	keV	keV
	Modify	Modify	Modify
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

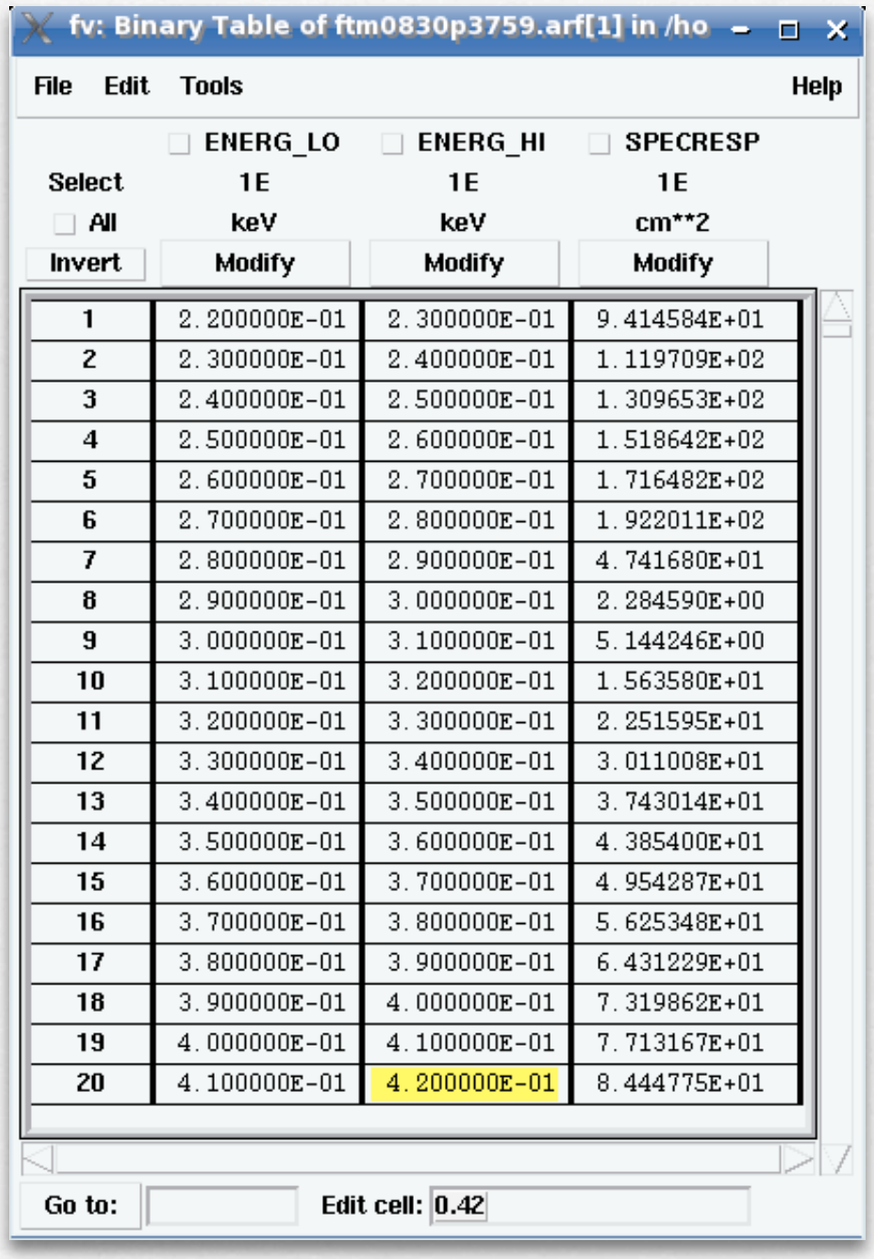


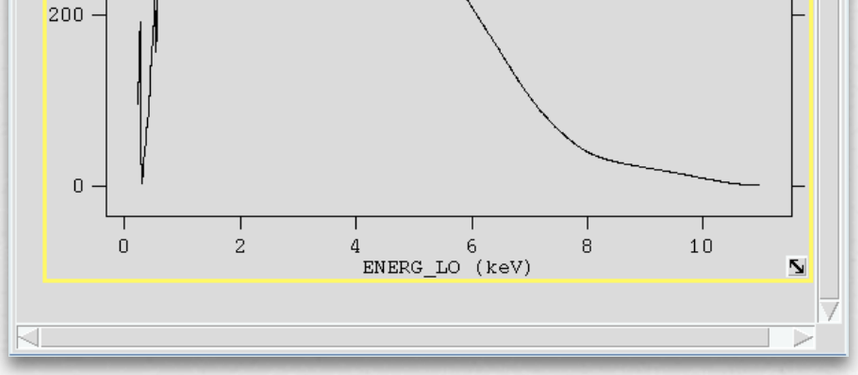


9. Creation of the Auxiliary Response File (ARF)

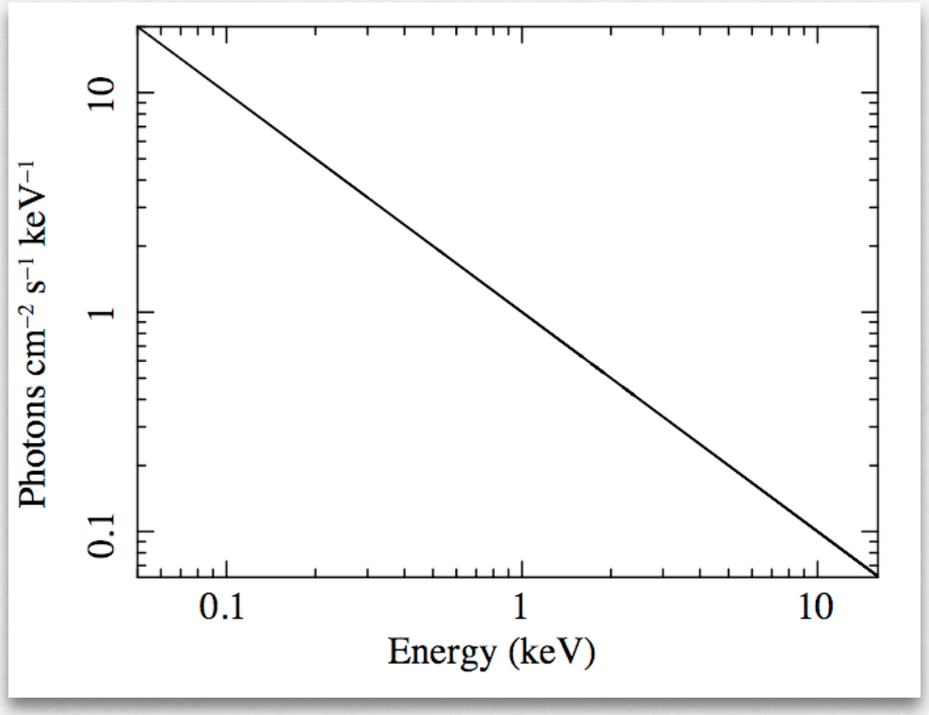
```
arfgen spectrumset=source_spectrum.fits arfset=pn.arf withrmfset=yes
rmfset=pn.rmf badpixlocation=pn_new.evt detmaptype=psf
```

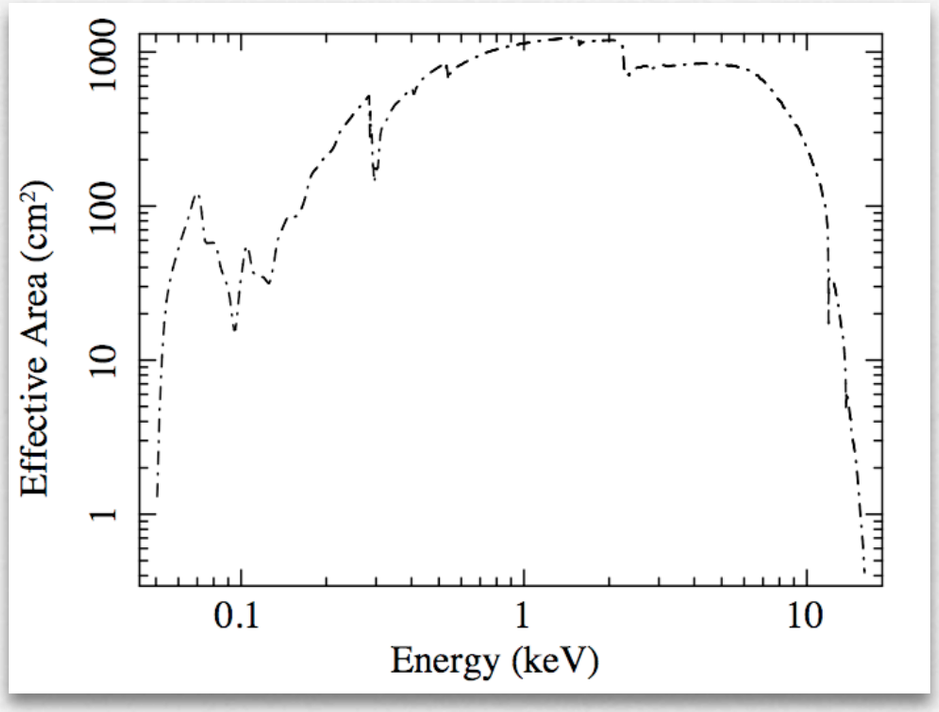
The Auxiliary Response File (ARF) includes information on the effective area, filter transmission and any additional energy-dependent efficiencies, i.e. the efficiency of the instrument in revealing photons



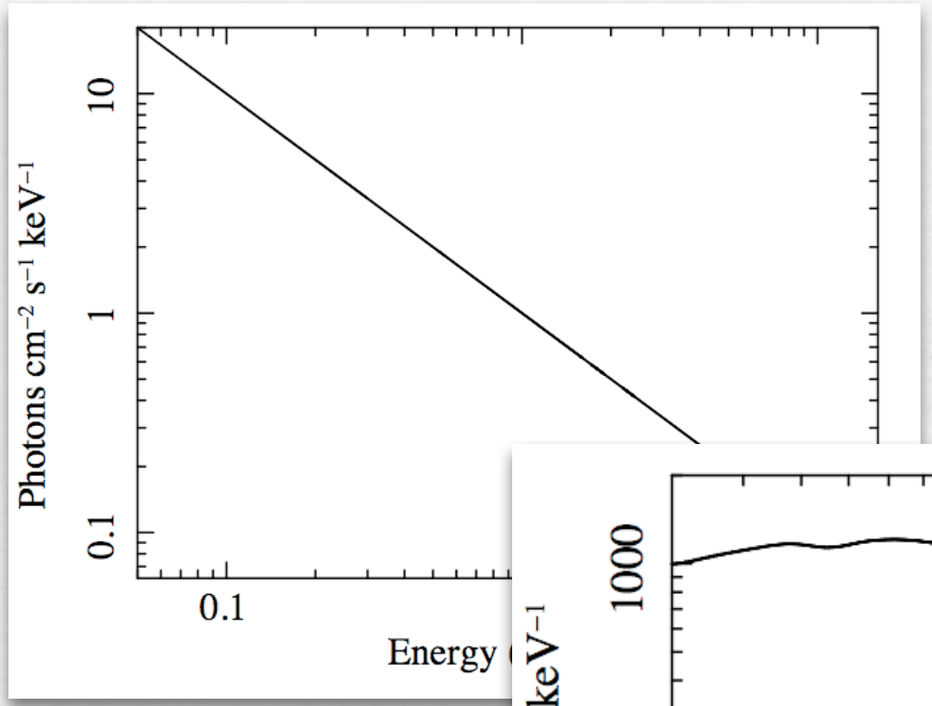


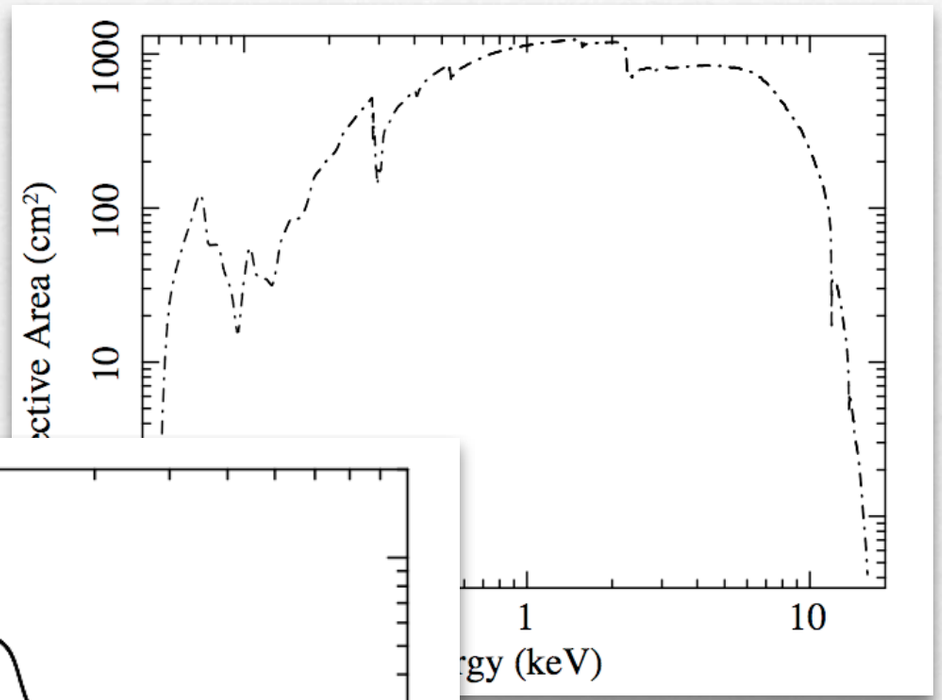
The combination of RMF and ARF produces the input spectrum weighted by telescope area and detector efficiencies versus energy.

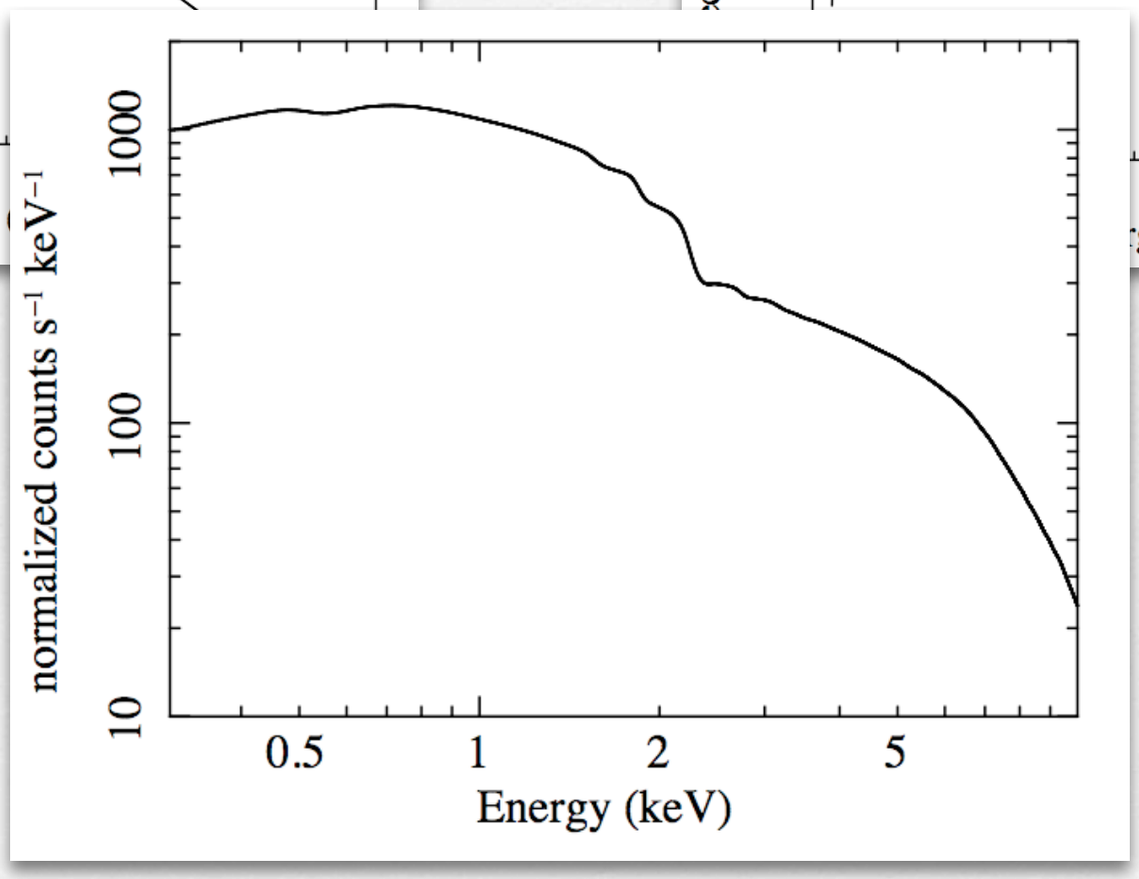




The combination of RMF and ARF produces the input spectrum weighted by telescope area and detector efficiencies versus energy.







10. Grouping of the spectra

In order to apply the chi2 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"
```

☑ Download XMM-Newton data from the public archive

☑ PN, MOS1 and MOS2 data reduction:

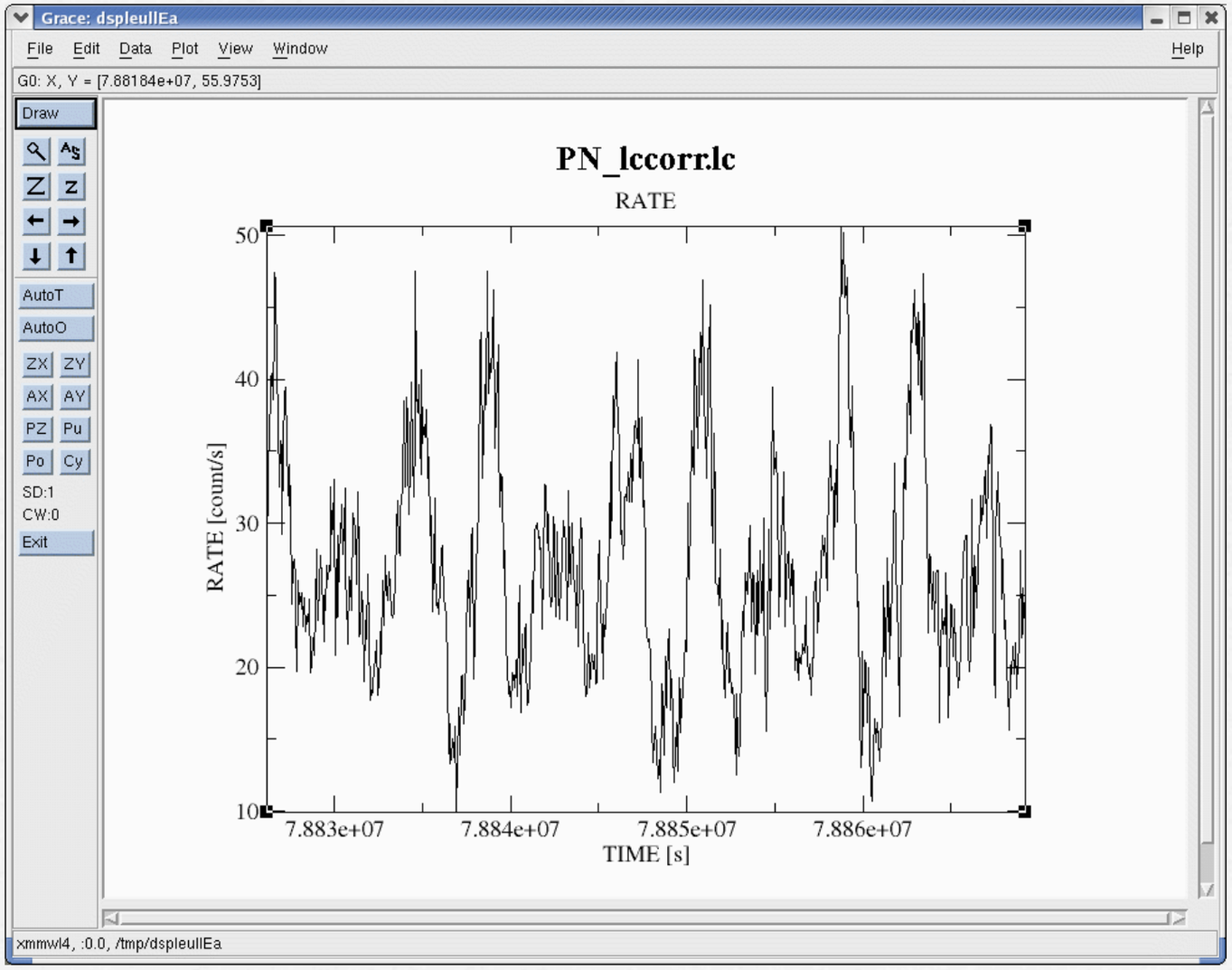
- selection of Good Time Intervals (GTI)
- generation of the cleaned event file
- source and background regions selection
- check for the presence of pile-up
- spectrum extraction (of both source and background)
- creation of the Response Matrix Function (RMF)
- creation of the Ancillary Response Function (ARF)
- grouping of the spectra

☐ Extraction of a light curve from a point-like source

EXTRACTION OF A LIGHT CURVE FROM A POINT-LIKE SOURCE

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.



A light curve can be build in different temporal bins, e.g. if the observation is 1000 s long it is possible to extract light curves of 10 s and 100 s.

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

To establish if a source varied during the observation we can apply the chi^2 test:

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

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;

A probability of chi$^2 \leq 10^{-3}$ suggests that the source is varied. This test should be repeated for several temporal bins.

EXTRACTION OF A LIGHT CURVE FROM A POINT-LIKE SOURCE

- Source+background light curve between 2-10 keV

```
evselect table=pn_new.evt energycolumn=PI expression='#XMMEA_EP[M]&&(PATTERN<=4[12])&&((X,Y) IN circle(source.reg))&&(PI in [200:10000])' withrateset=yes rateset="PN_source_lc_raw.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

- Background light curve between 2-10 keV

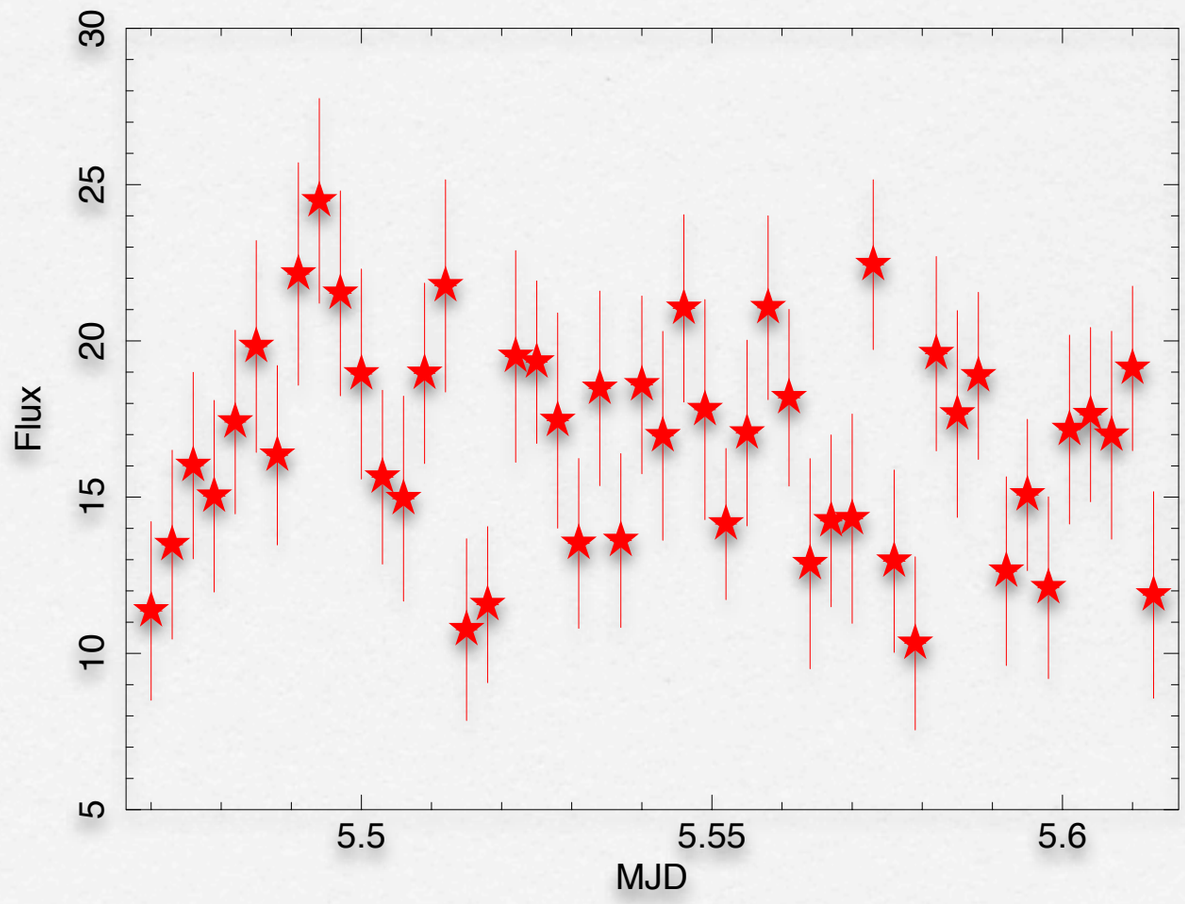
```
evselect table=pn_new.evt energycolumn=PI expression='#XMMEA_EP [M]&&(PATTERN<=4[12])&&((X,Y) IN circle(back.reg))&&(PI in [200:10000])' withrateset=yes rateset="PN_back_lc_raw.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

- Corrected light curve between 2-10 keV

```
epiclccorr    srctslist=PN_source_lc_raw.lc    eventlist=pn_new.evt
outset=PN_lccorr.lc    bkgtslist=PN_back_lc_raw.lc    withbkgset=yes
applyabsolutecorrections=yes
```

- Corrected light curve between 2-10 keV

```
epiclccorr    srctslist=PN_source_lc_raw.lc    eventlist=pn_new.evt
outset=PN_lccorr.lc    bkgtslist=PN_back_lc_raw.lc    withbkgset=yes
applyabsolutecorrections=yes
```



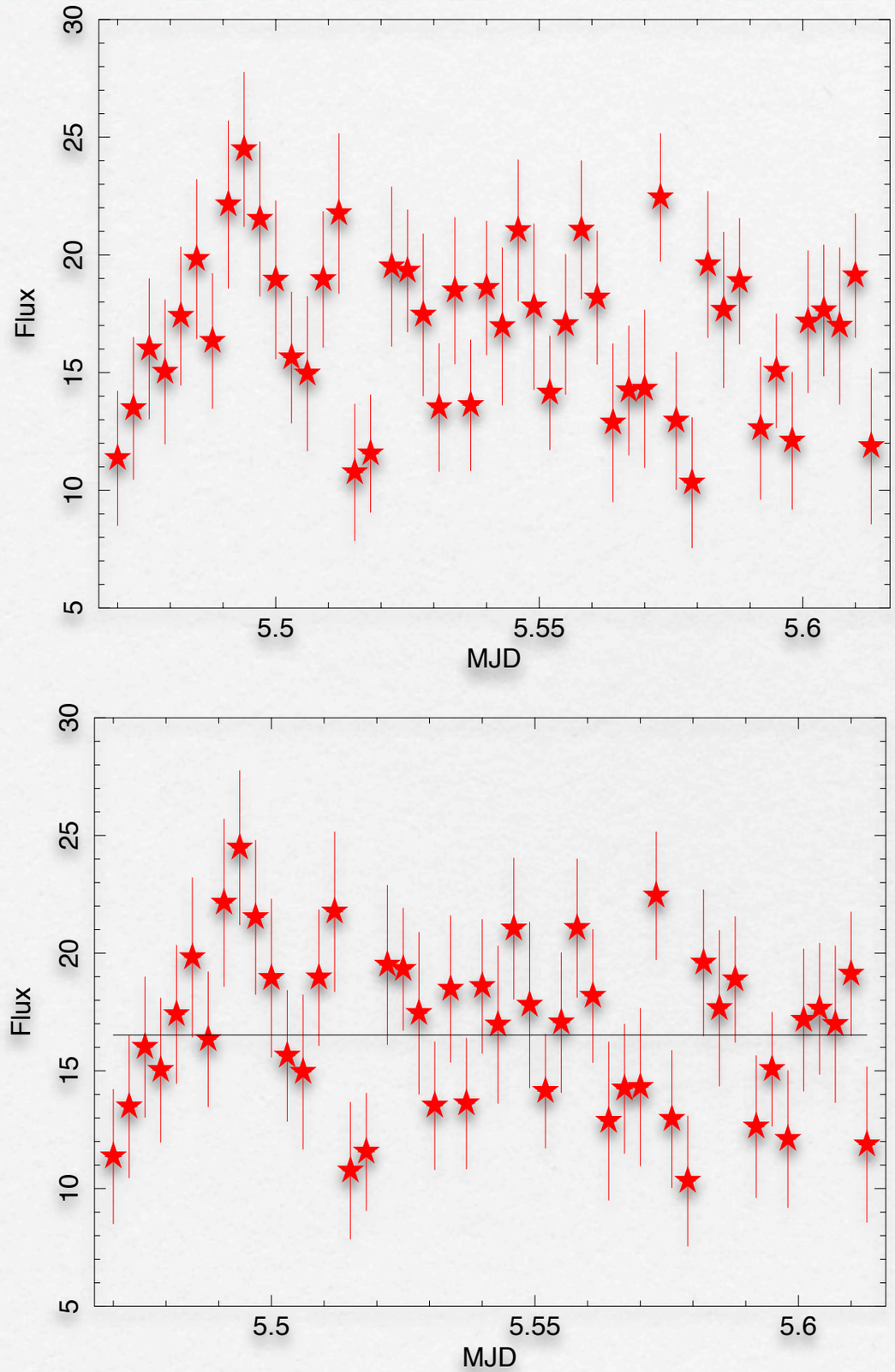
Example:

> `lcurve  PN_lccorr.lc`

> `mo cons` (fit di una costante)

> `fit`

```
Fitting group  2,  from  5.47    to  5.62
Fitting  48 points in a band of  48.
  1.0000000
( -3)  W-VAR=  62.47
( -4)  W-VAR= 62.47
  16.526085
```



> `lcurve  PN_source_lc_raw.lc`

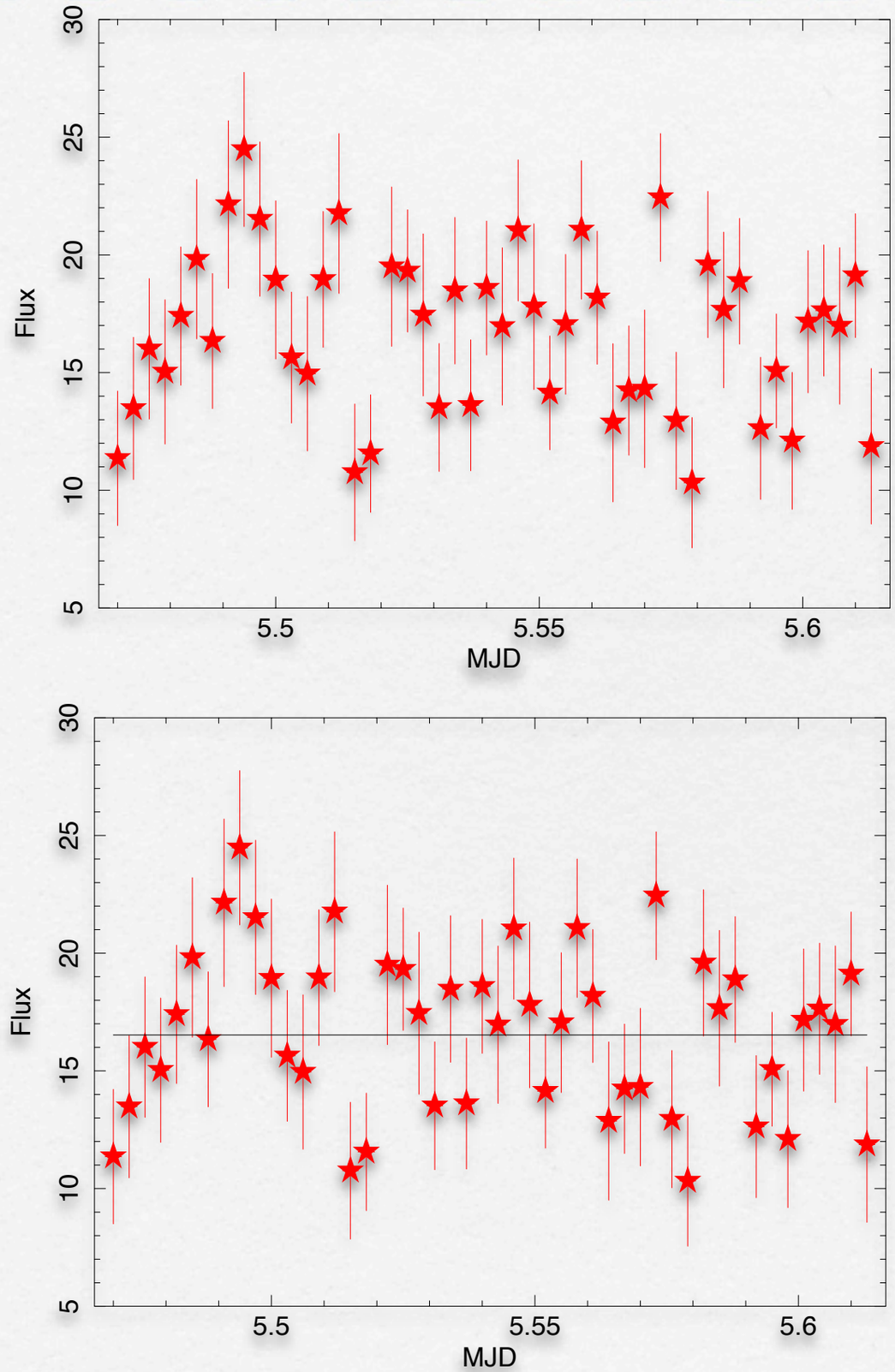
> `mo cons` (fit di una costante)

> `fit`

Fitting group 2, from 5.47 to 5.62
Fitting 48 points in a band of 48.
1.0000000
(-3) W-VAR= 62.47
(-4) W-VAR= 62.47
16.526085

The chance probability (Q) is 0.0648 (= the probability that this results is due to chance)

1-0.0648=0.9352 the source is variable at 93%.
Our acceptance threshold of variability is 99.9%



http://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= 62.47 and d= 48-1

Calculate

The chance probability, Q, is: 0.0648