XMM-Newton tutorial

hands-on session

Eleonora Torresi
DIFA & INAF/IASF Bologna

LABORATORIO X 2018
21.11.2018

XMM-Newton payload

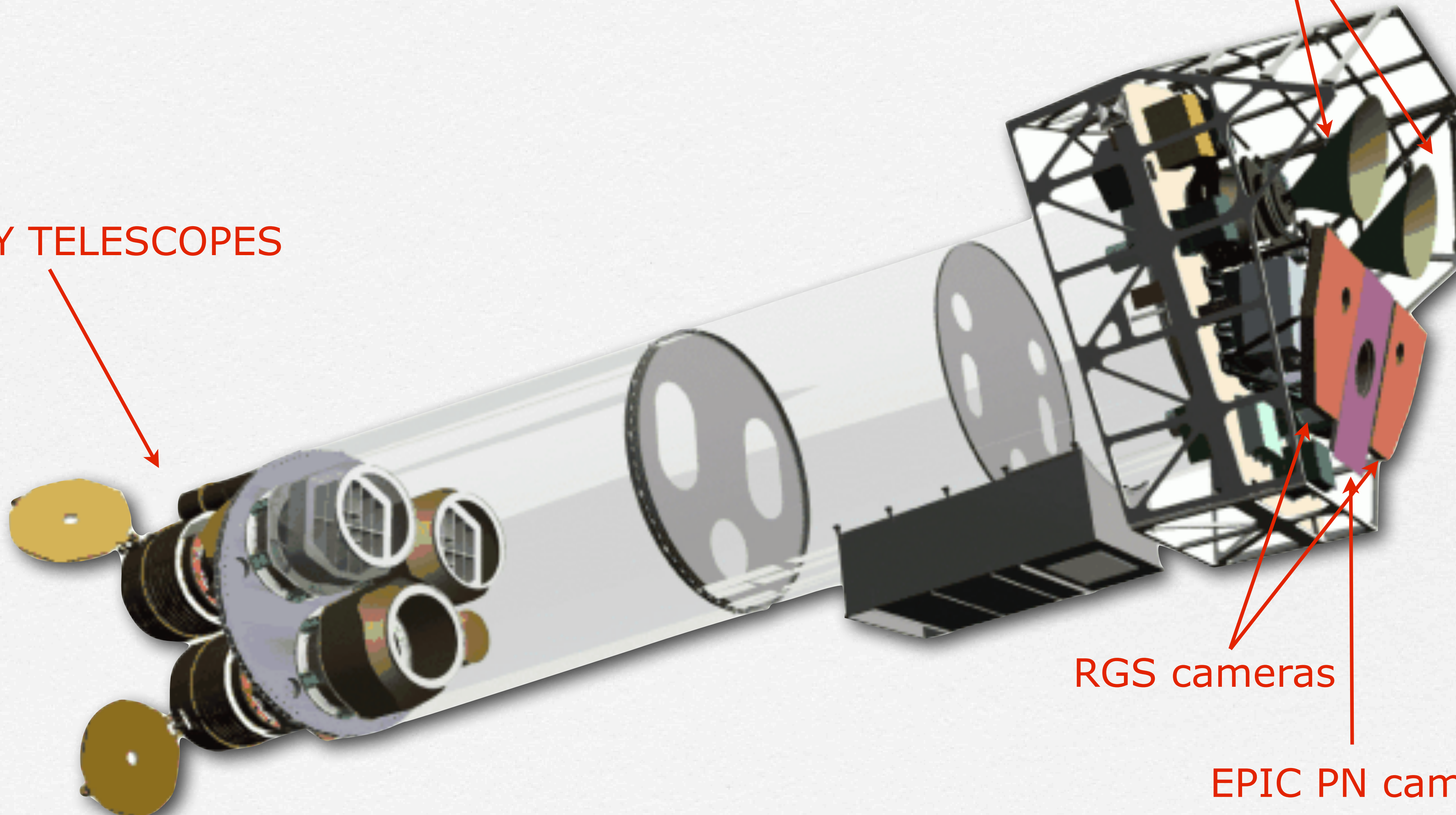
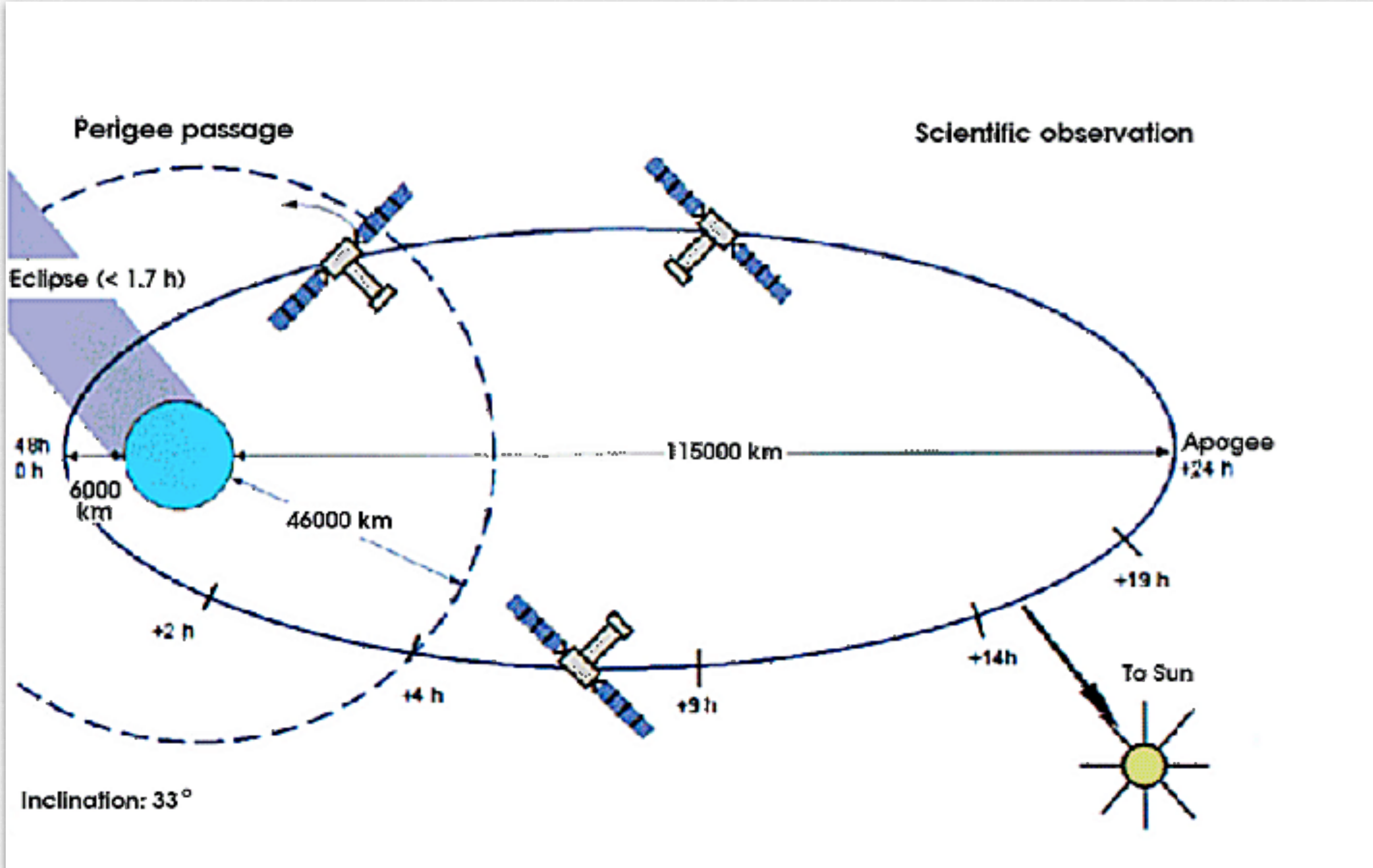


Image courtesy of Dornier Satellitensysteme GmbH and ESA

Eccentric 48-hour orbit around the Earth
Inclination 40 degrees to the Equator



OUTLINE

1. Download XMM-Newton data from the public archive

2. PN, MOS1 and MOS2 data reduction:
    - selection of Good Time Intervals (GTI)
    - generation of cleaned event files
    - source and background regions selection
    - check for the presence of pile-up
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    - grouping of the spectra

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

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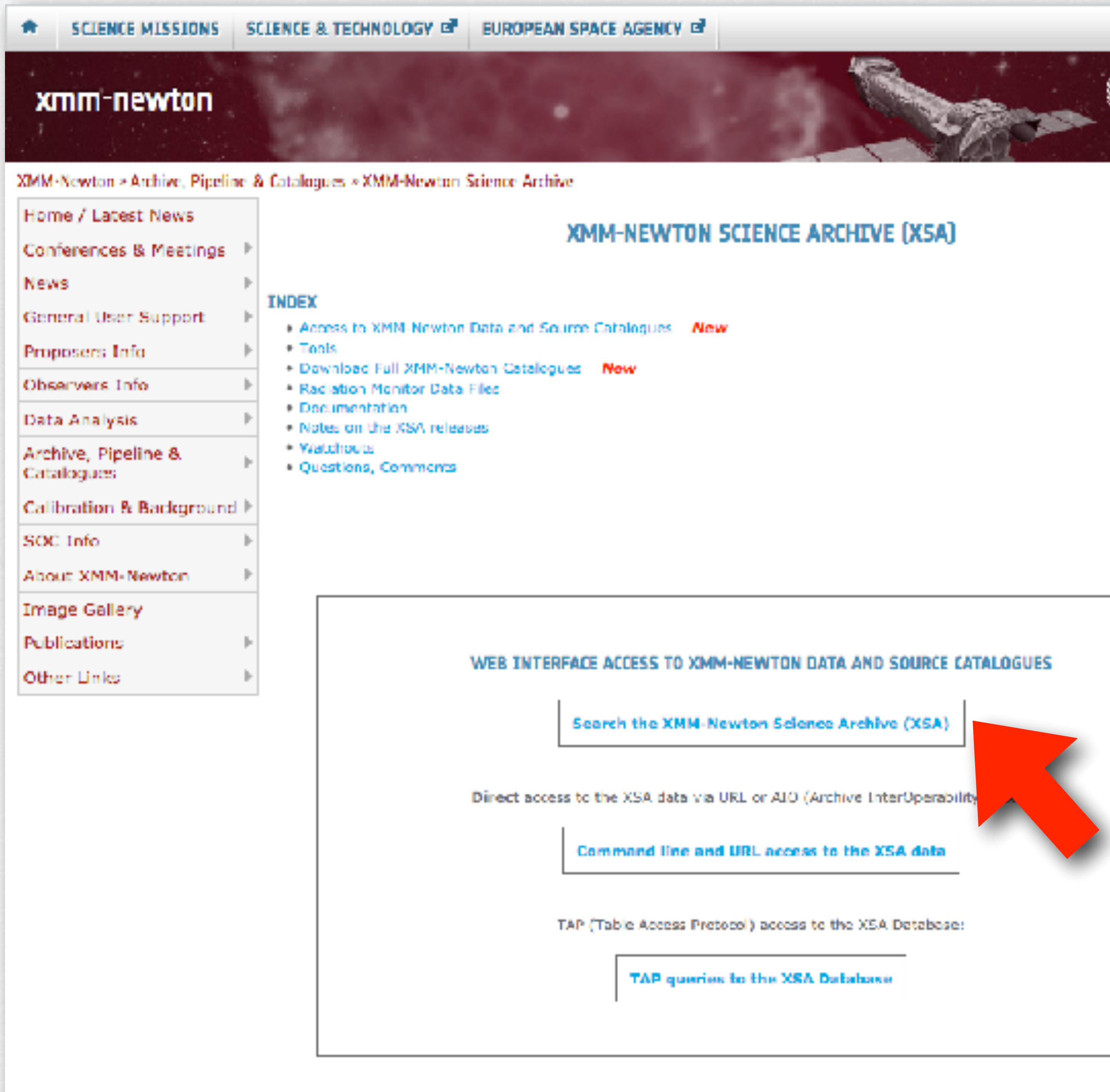
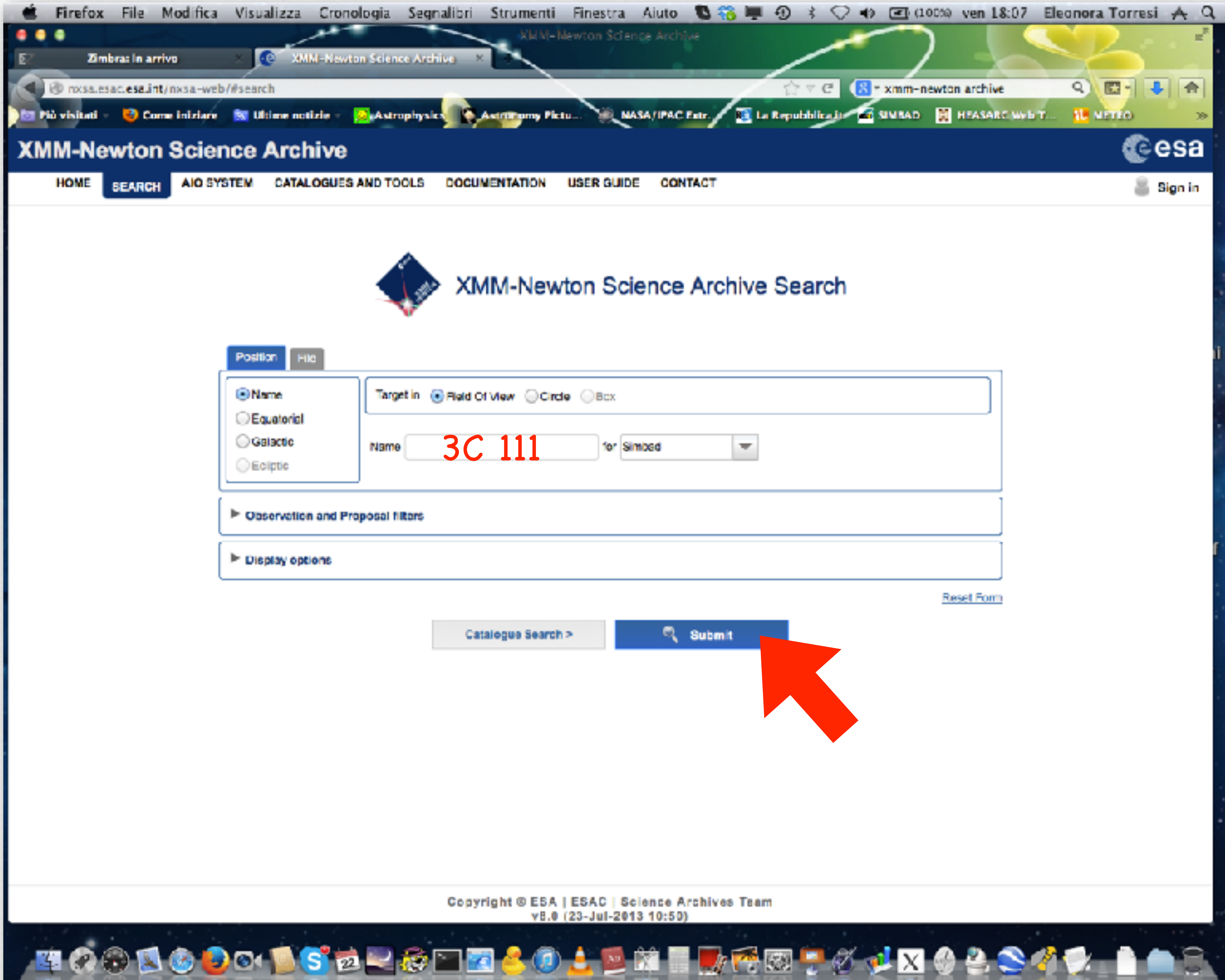
XMM-Newton Science Operations Centre (ESA-Vilspa, Spain)

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

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XMM-Newton Science Archive
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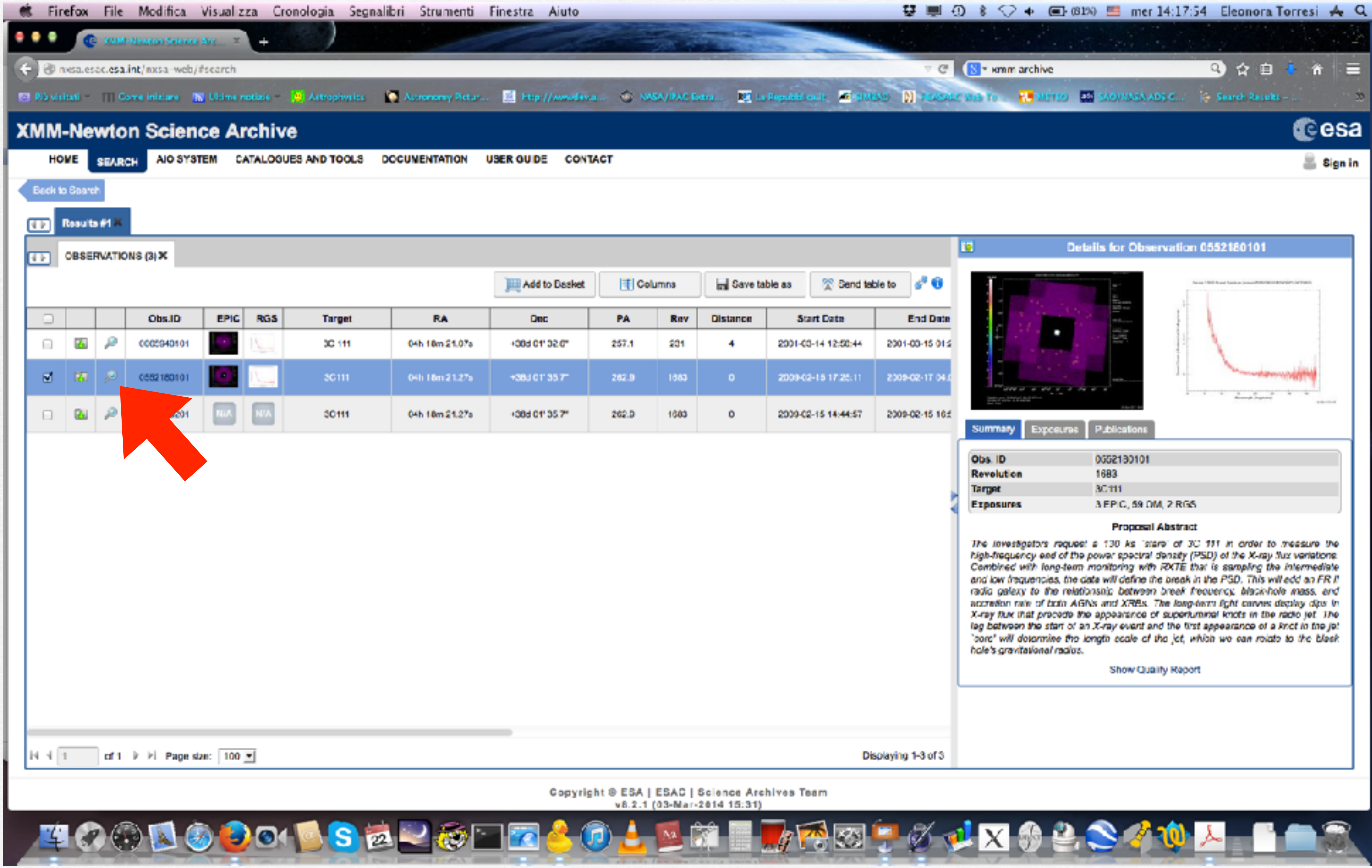

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Save table as
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EPIC
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End Date
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N/A N/A 3C111 04h 18m 21.27s +38d 01' 35.7" 262.9 1683 0 2009-02-15 14:44:57 2009-02-15
of 1
Page size: 100
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
Show Quality Report
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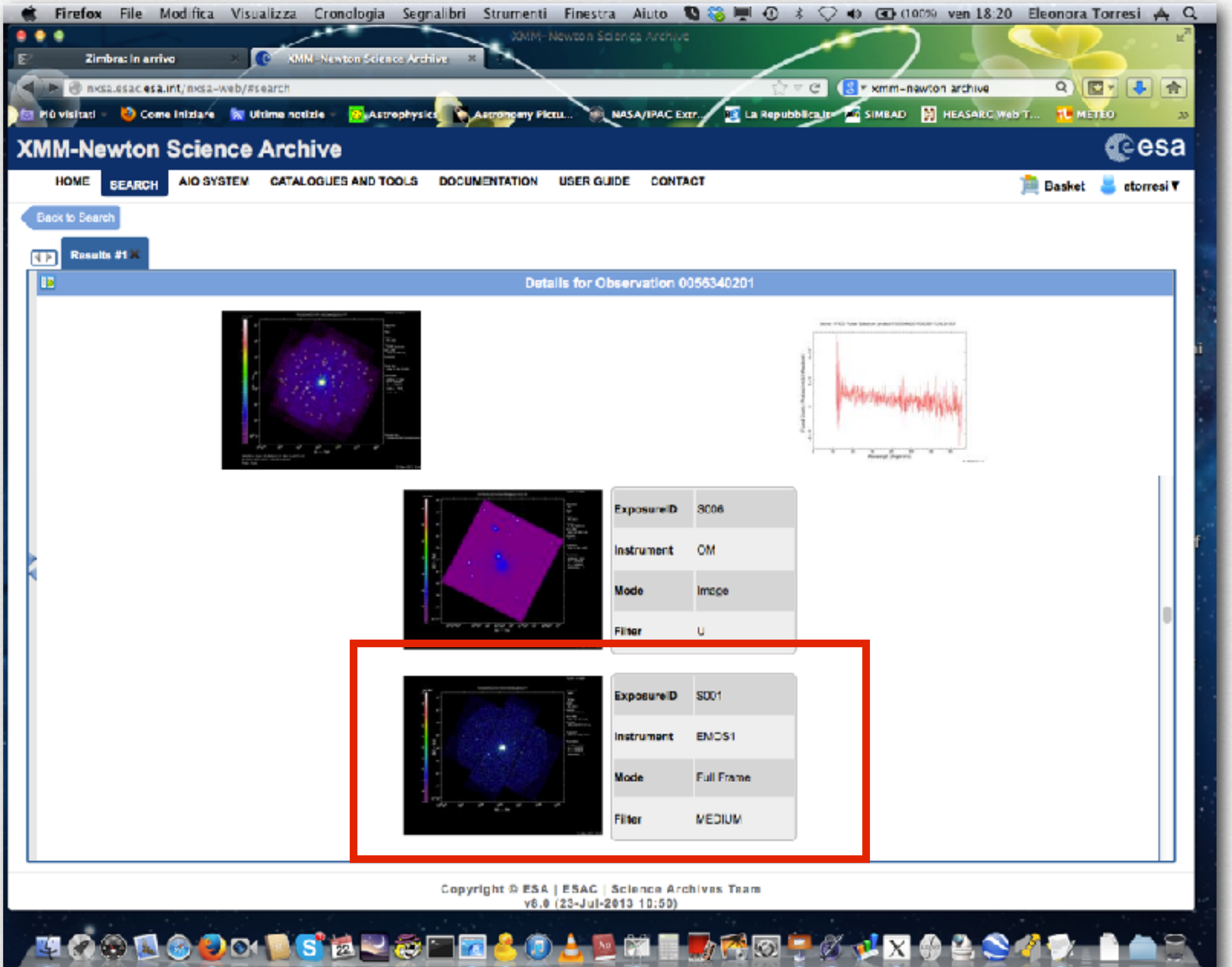
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ven 18:20 Eleonora Torresi
XMM-Newton Science Archive
Zimbra: In arrivo
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Più visitati
Come iniziare
Ultime notizie
Astrophysics
NASA/IPAC Extr...
La Repubblica.it
SIMBAD
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Details for Observation 0056340201
ExposureID S006
Instrument OM
Mode Image
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EPIC FILTERS

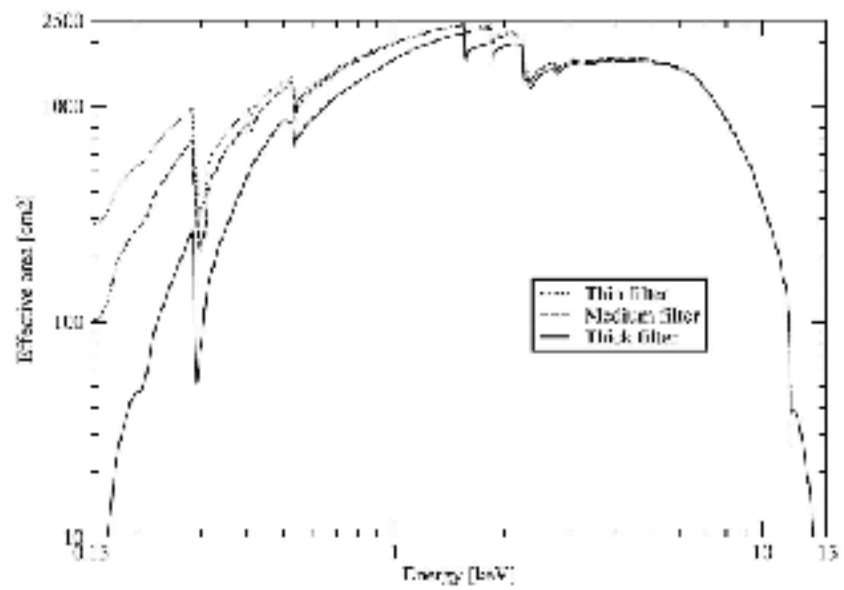
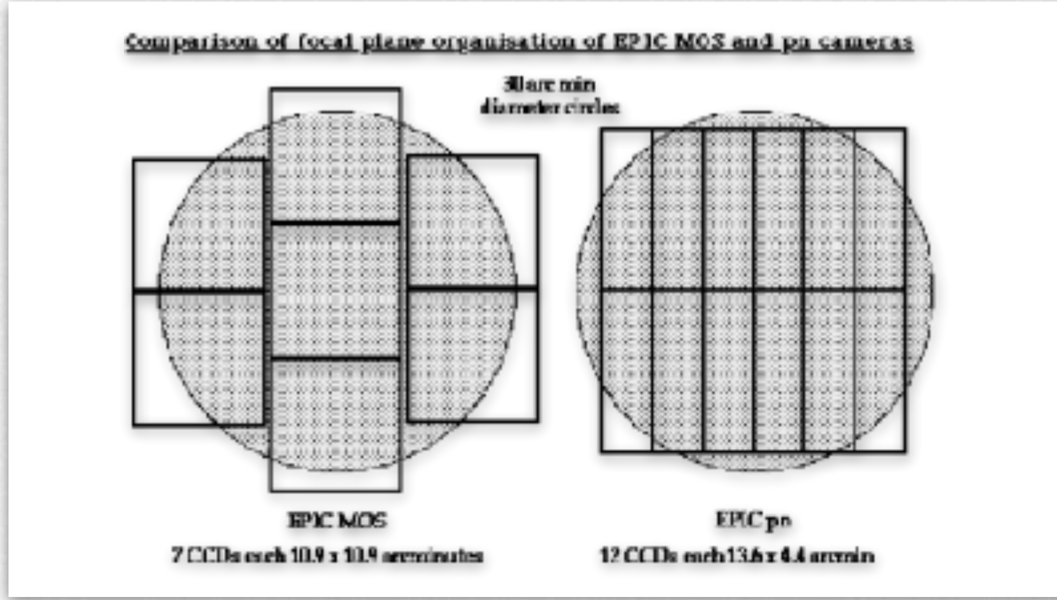


Figure 31: *Combined effective area of all telescopes assuming that the EPIC cameras operate with the same filters, either thin, medium or thick.*

http://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/XMM_UHB.pdf

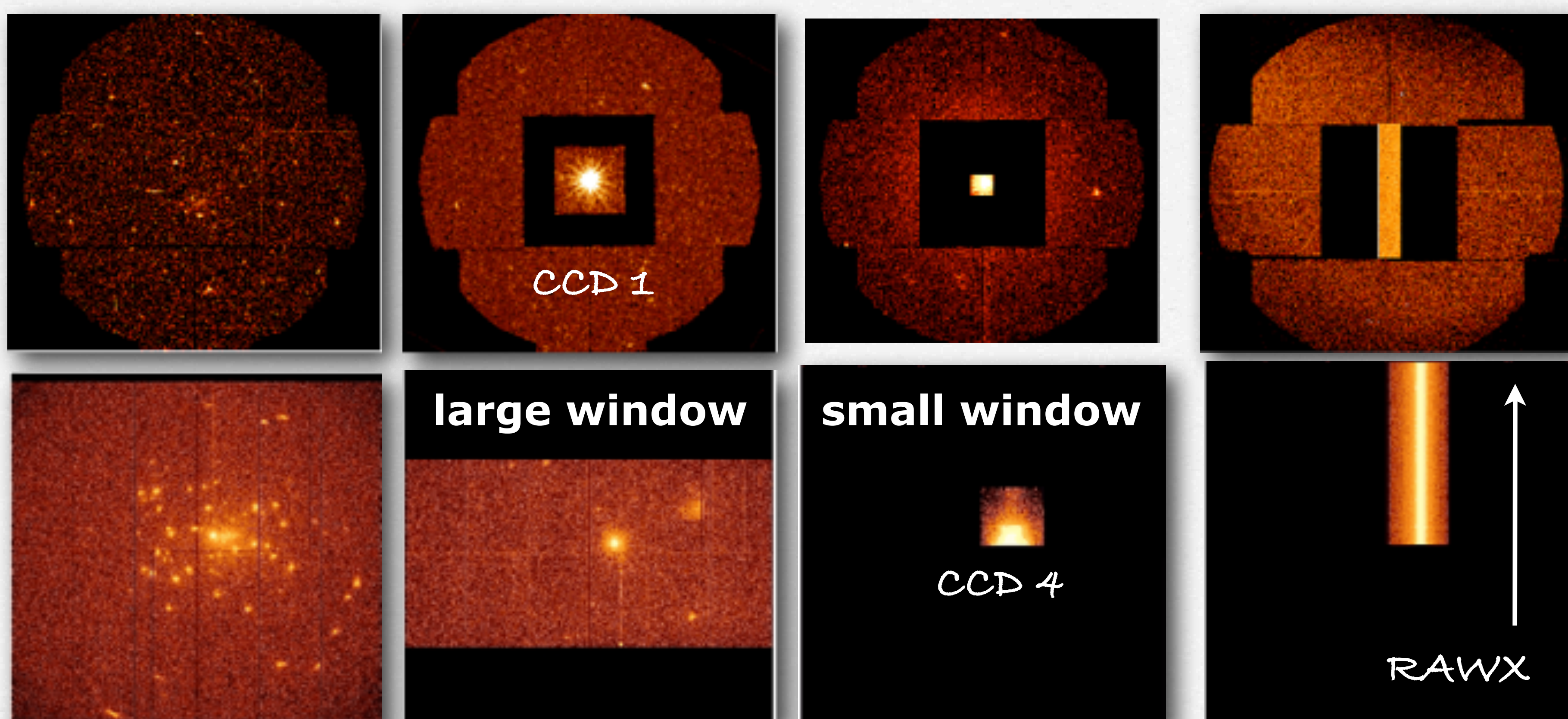
EPIC SCIENCE MODES

MOS



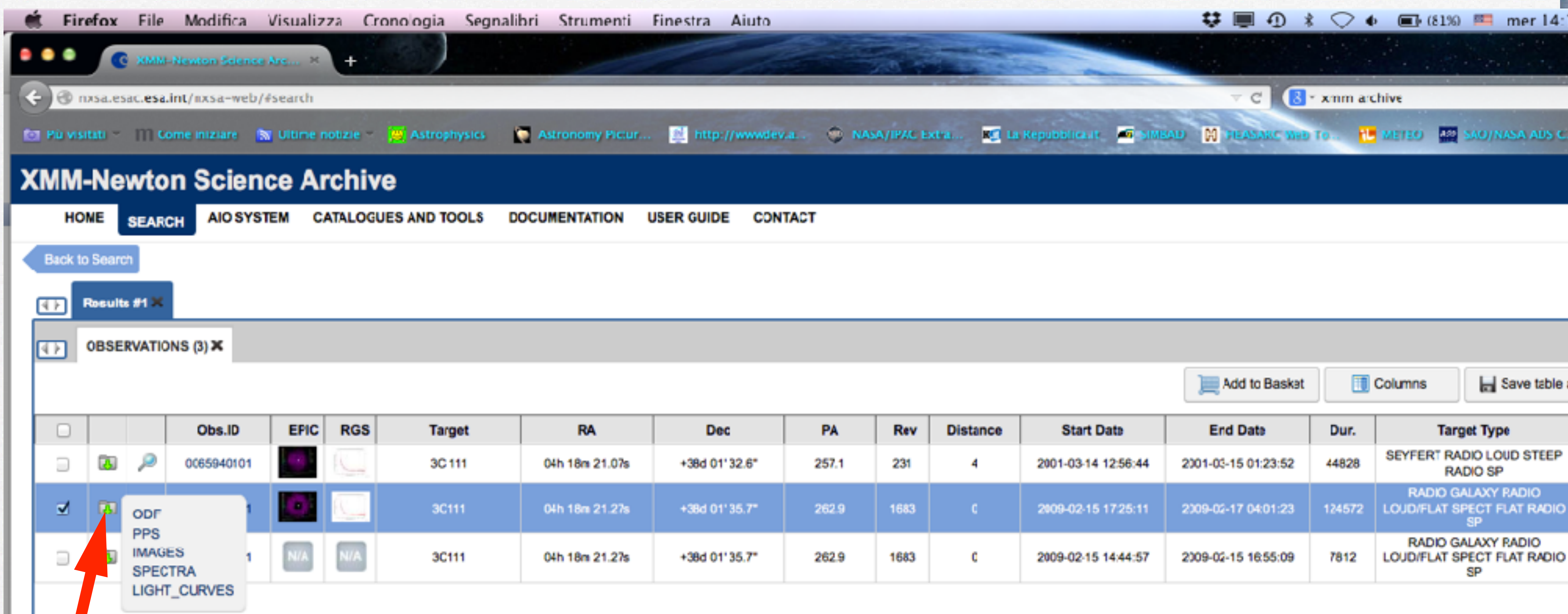
pn

full frame **partial window** **timing mode**



MOS

pn



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

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

ODF files

```
[eleonora@MacBook]ODF>ls
2205_0675400101_M1S00100AUX.FIT 2205_0675400101_PNU101120DI.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_M1S00150IME.FIT 2205_0675400101_R1S00401SPE.FIT
2205_0675400101_M1S00170IME.FIT 2205_0675400101_R1S00402SPE.FIT
2205_0675400101_M1U00200AUX.FIT 2205_0675400101_R1S00403SPE.FIT
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2205_0675400101_M1U00270IME.FIT 2205_0675400101_R1S90001DII.FIT
2205_0675400101_M1U00300AUX.FIT 2205_0675400101_R1S90102DII.FIT
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2205_0675400101_M1U00370IME.FIT 2205_0675400101_R1S90709DII.FIT
2205_0675400101_M1X00000HBH.FIT 2205_0675400101_R1S90801DII.FIT
2205_0675400101_M1X00000HCH.FIT 2205_0675400101_R1S90902DII.FIT
2205_0675400101_M1X00000HTH.FIT 2205_0675400101_R1S91003DII.FIT
2205_0675400101_M1X00000PEH.FIT 2205_0675400101_R1S91104DII.FIT
2205_0675400101_M1X00000PTH.FIT 2205_0675400101_R1S91205DII.FIT
2205_0675400101_M2S00200AUX.FIT 2205_0675400101_R1S91306DII.FIT
2205_0675400101_M2S00210IME.FIT 2205_0675400101_R1S91408DII.FIT
2205_0675400101_M2S00220IME.FIT 2205_0675400101_R1S91509DII.FIT
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2205_0675400101_M2S00240IME.FIT 2205_0675400101_R1S91702DII.FIT
```

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

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

EPIC background

Cosmic X-ray background (CXB)

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

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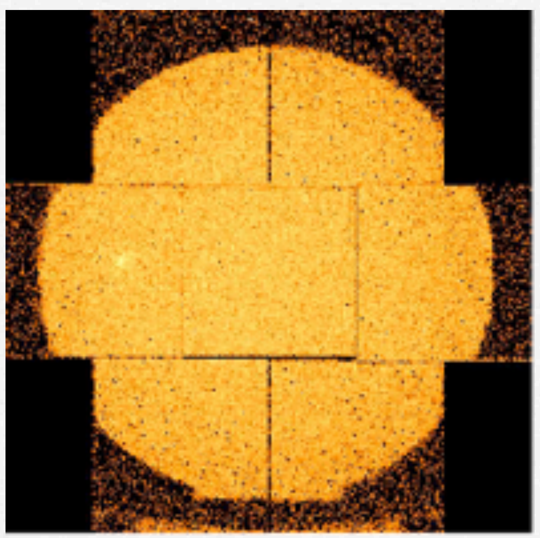
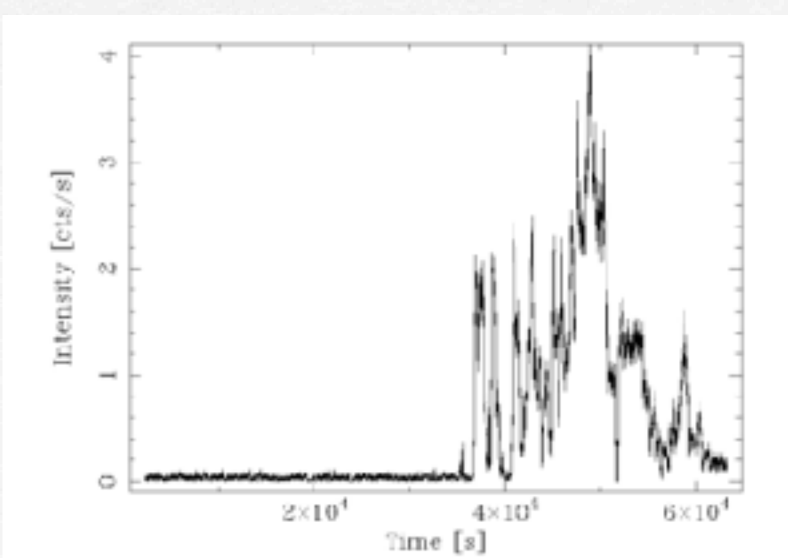
EPIC particle induced background

External ‘flaring’ component

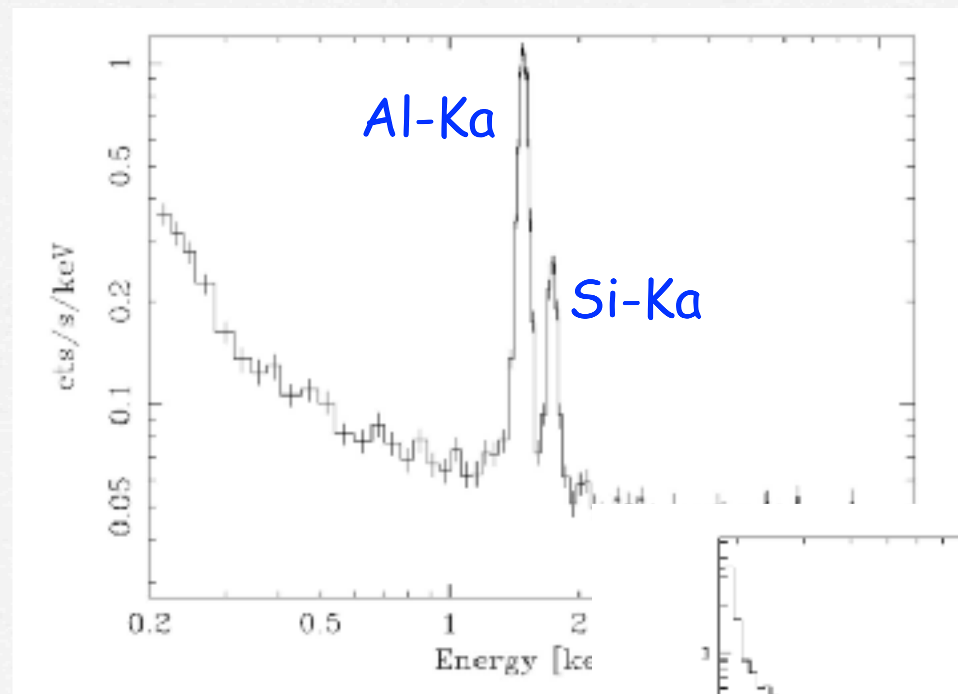
strong and rapid variability; currently attributed to soft protons (E_p < a few 100 keV) likely organized in clouds populating the Earth’s magneto-sphere

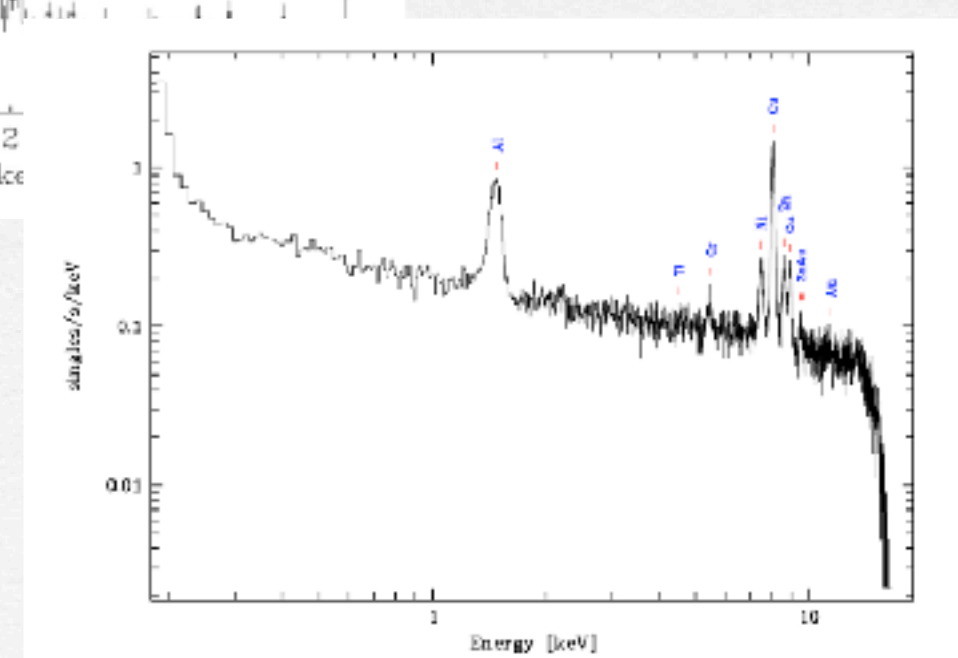




Internal ‘quiescent’ component

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





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

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

```
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
```

```
lcurve
```

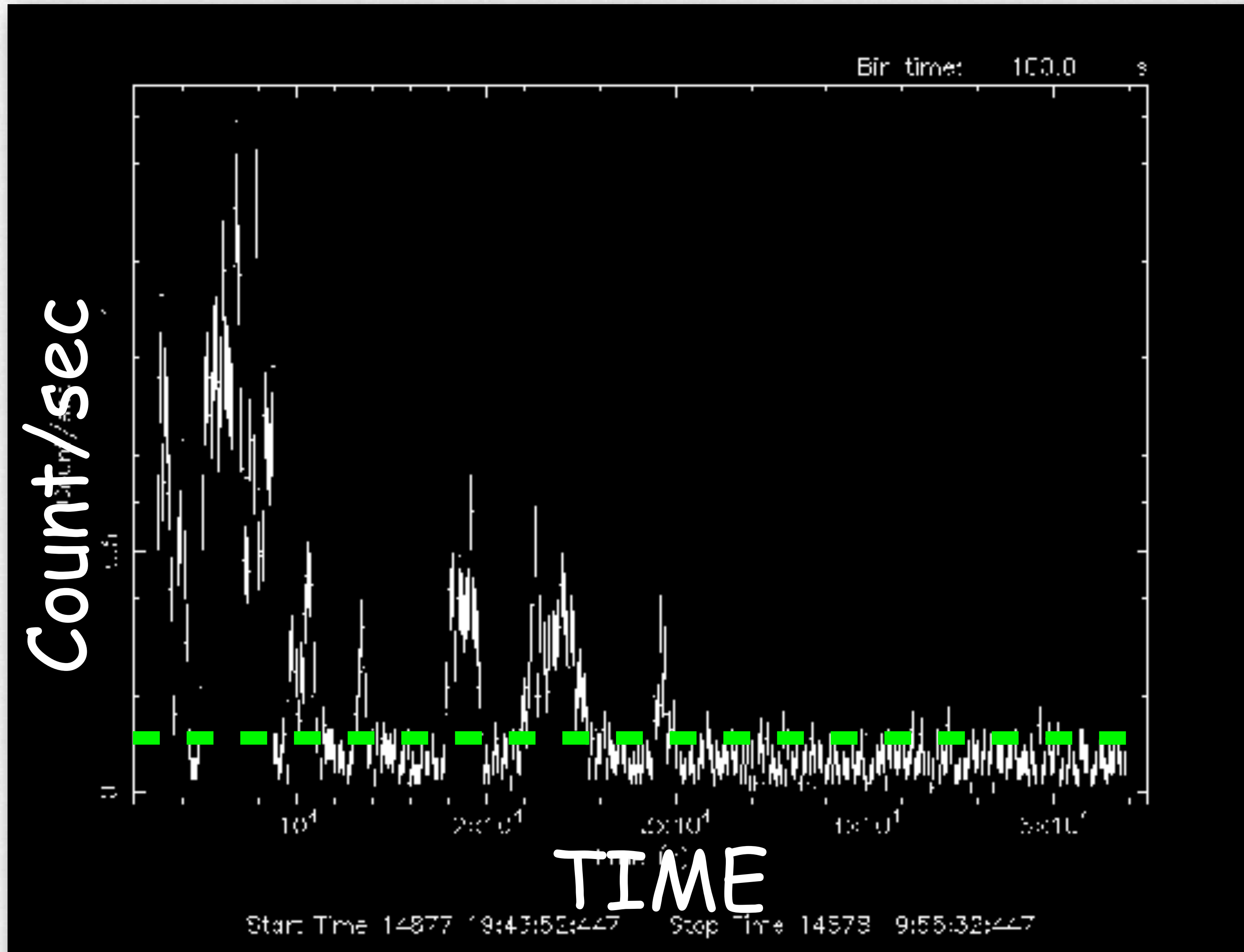
Light curve above 10 keV

Determine where the light curve is *low* and *steady*.

Choose a threshold just above the low steady background to define the *"low background" intervals*, to create the corresponding GTI file:

pn < 0.4 cts/s

MOS < 0.35 cts/s



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Selection of GOOD TIME INTERVALS (GTI)

```
tabgtigen table=lcurve_sup10.lc gtiset=good_bkg.gti expression='RATE<0.4'
```

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

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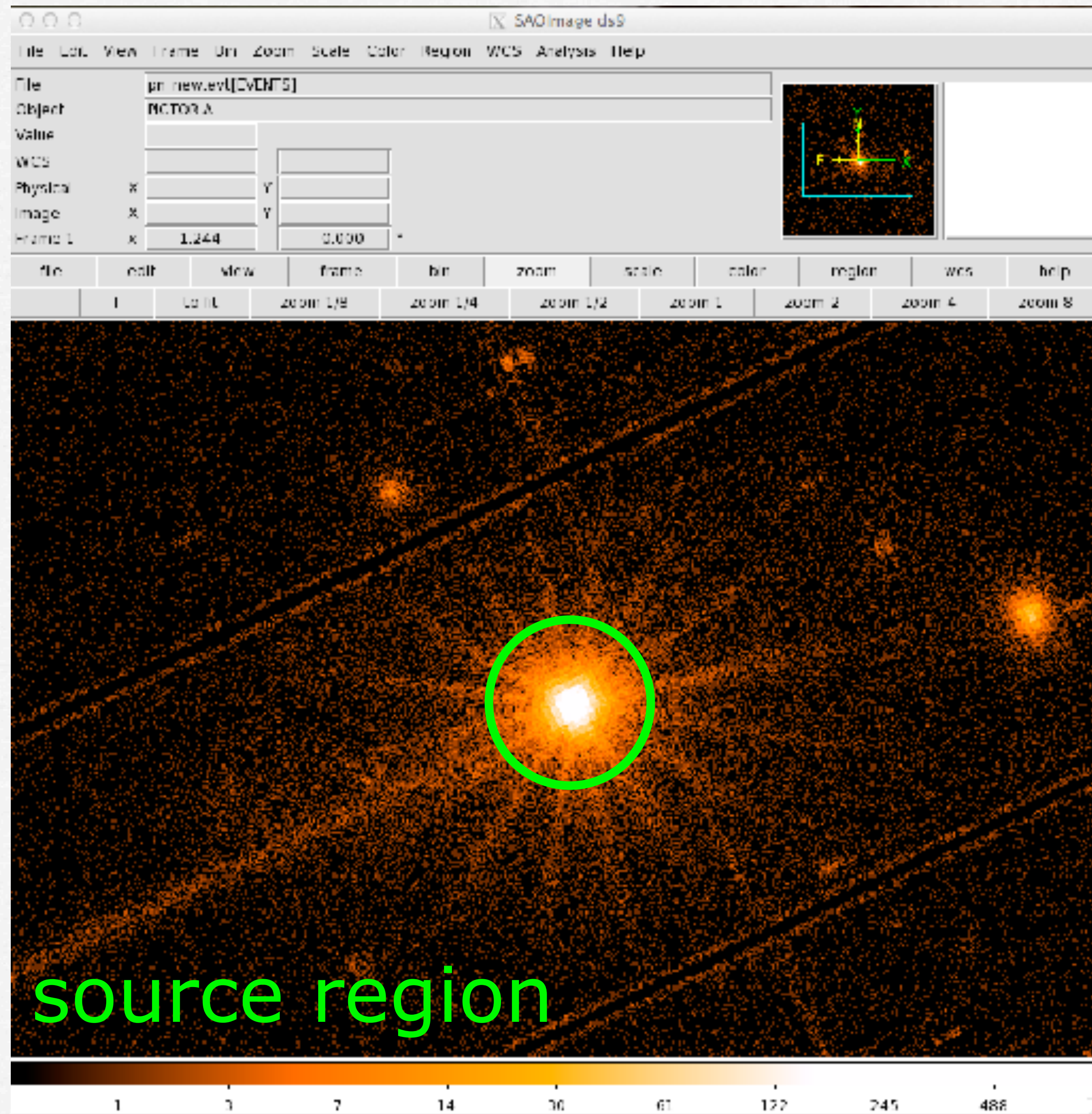
Source and background regions selection

open event list file with ds9

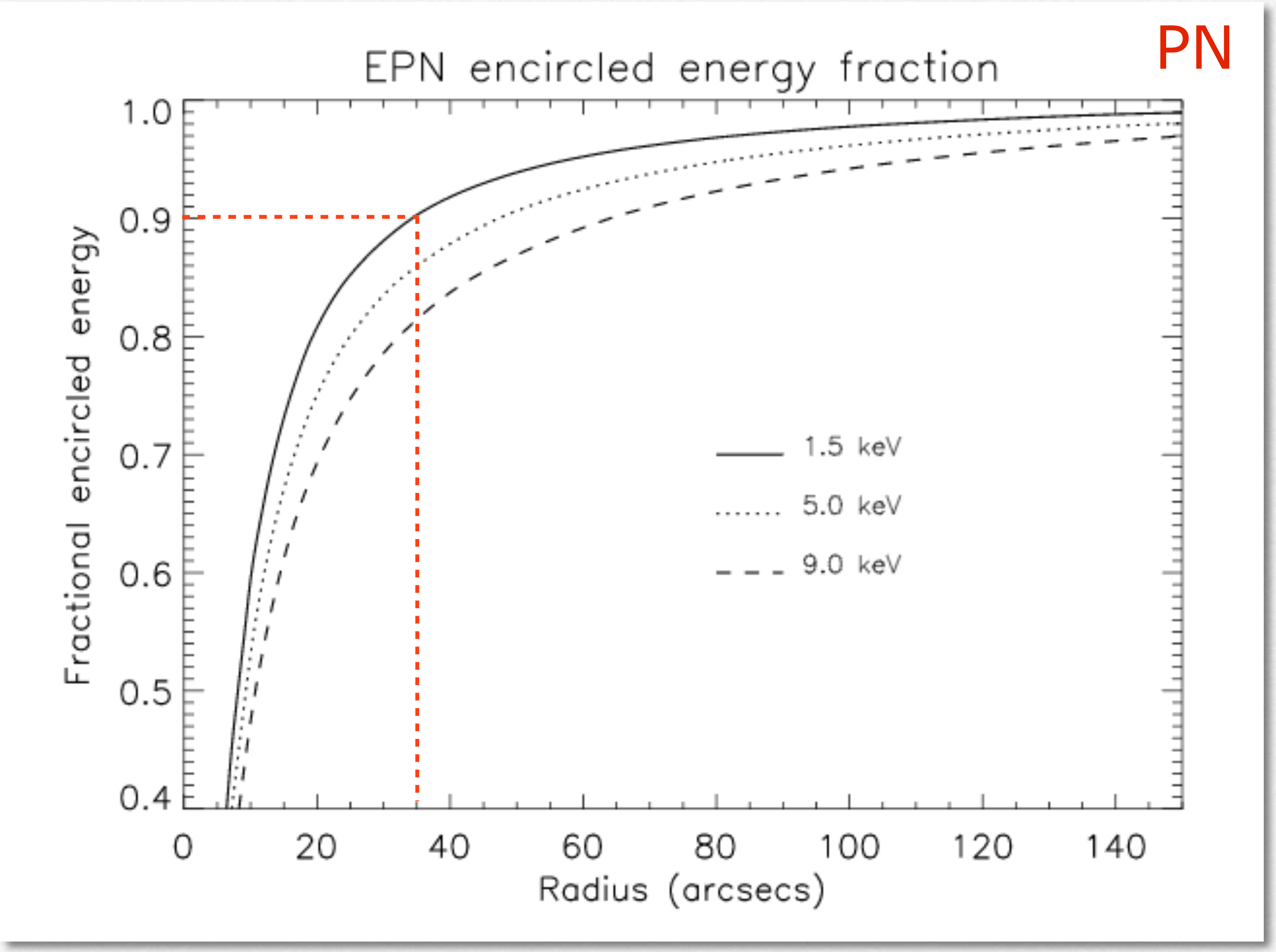
```
> ds9 pn_new.evt &
```



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

Fractional encircled energy

Fraction of photons contained within a certain radius (in arcsec).
This quantity is function of the angular radius (on-axis)



Fractional encircled energy

Fraction of photons contained within a certain radius (in arcsec).
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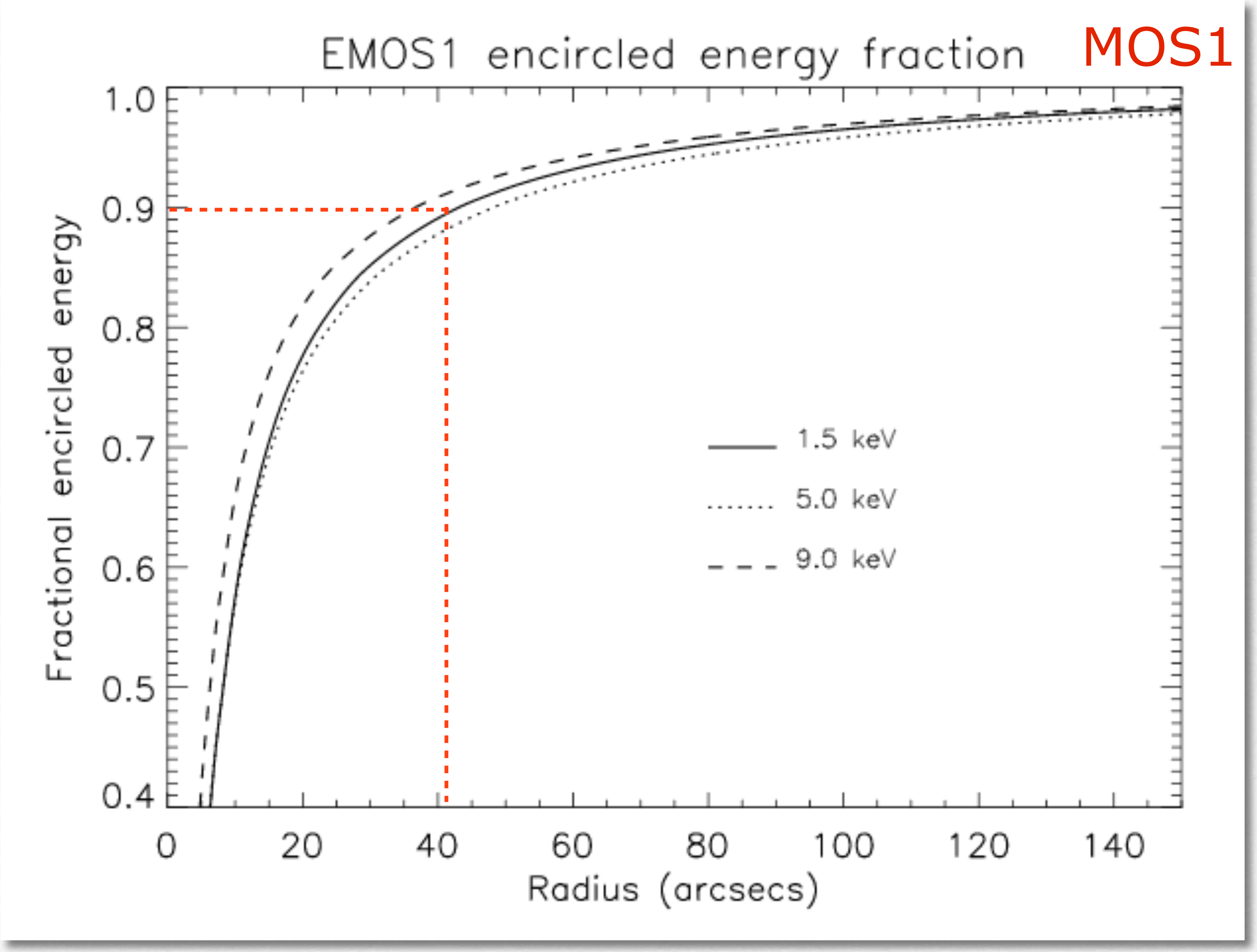

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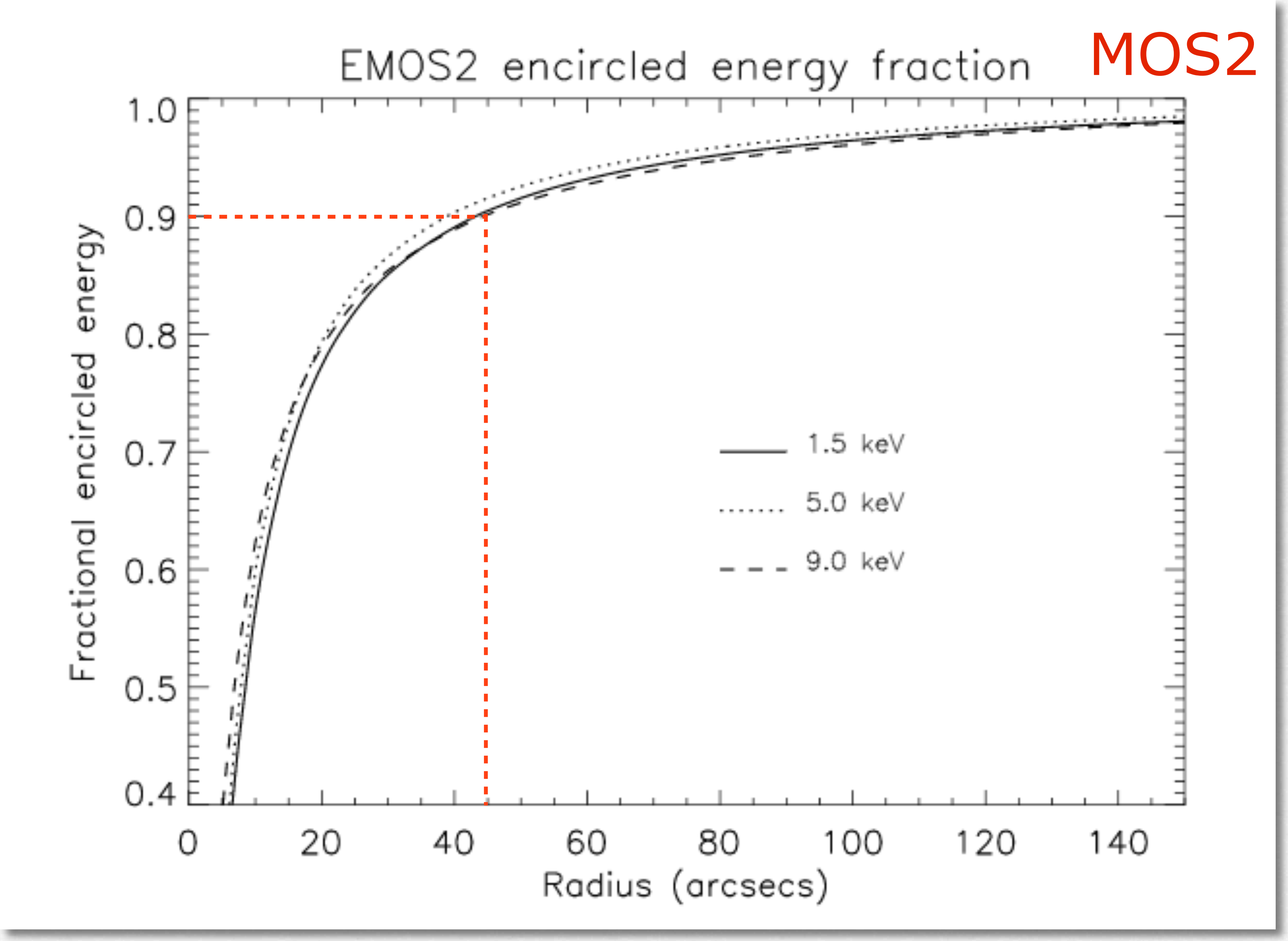
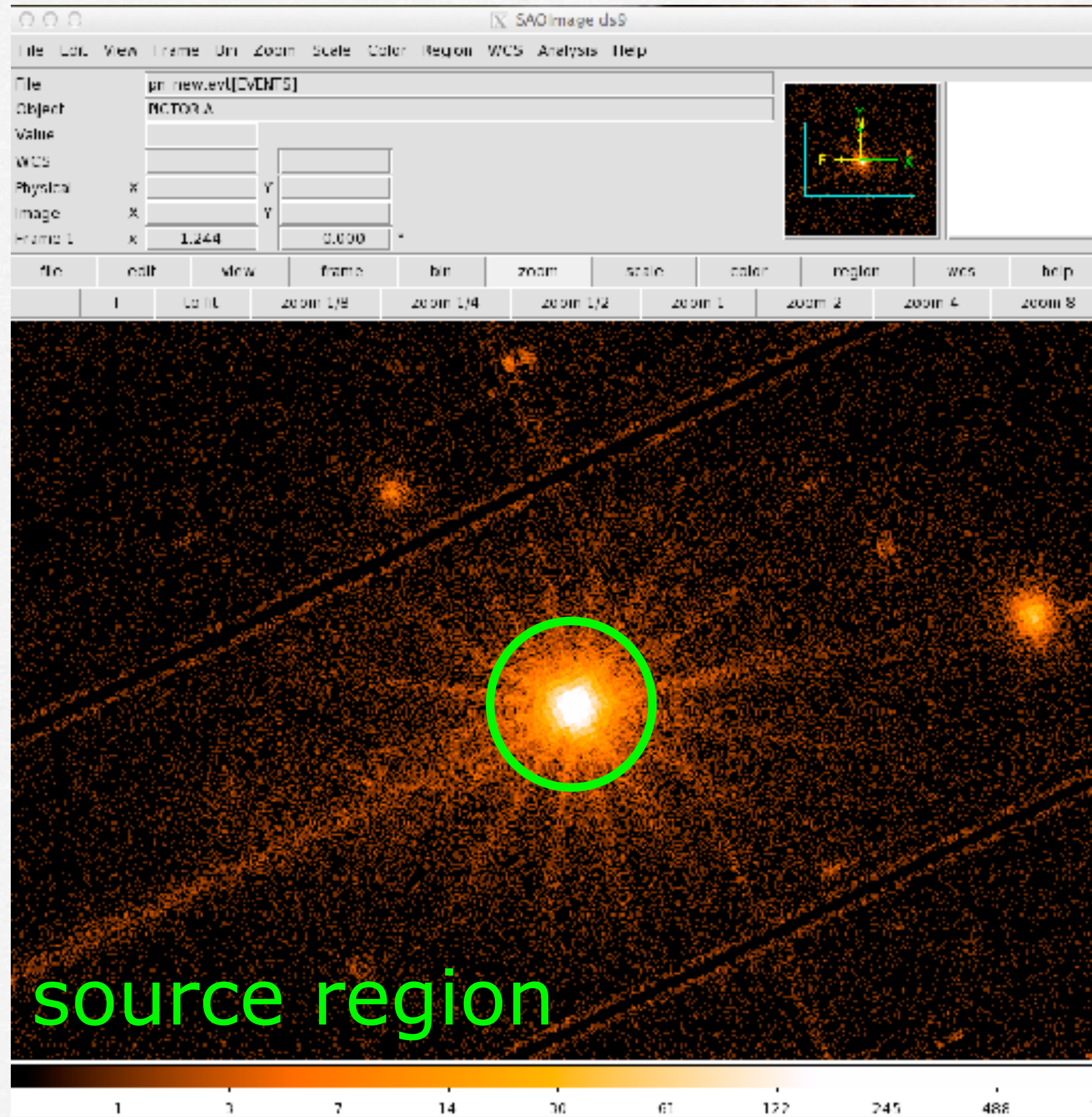


Source and background regions selection

open event list file with ds9

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



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

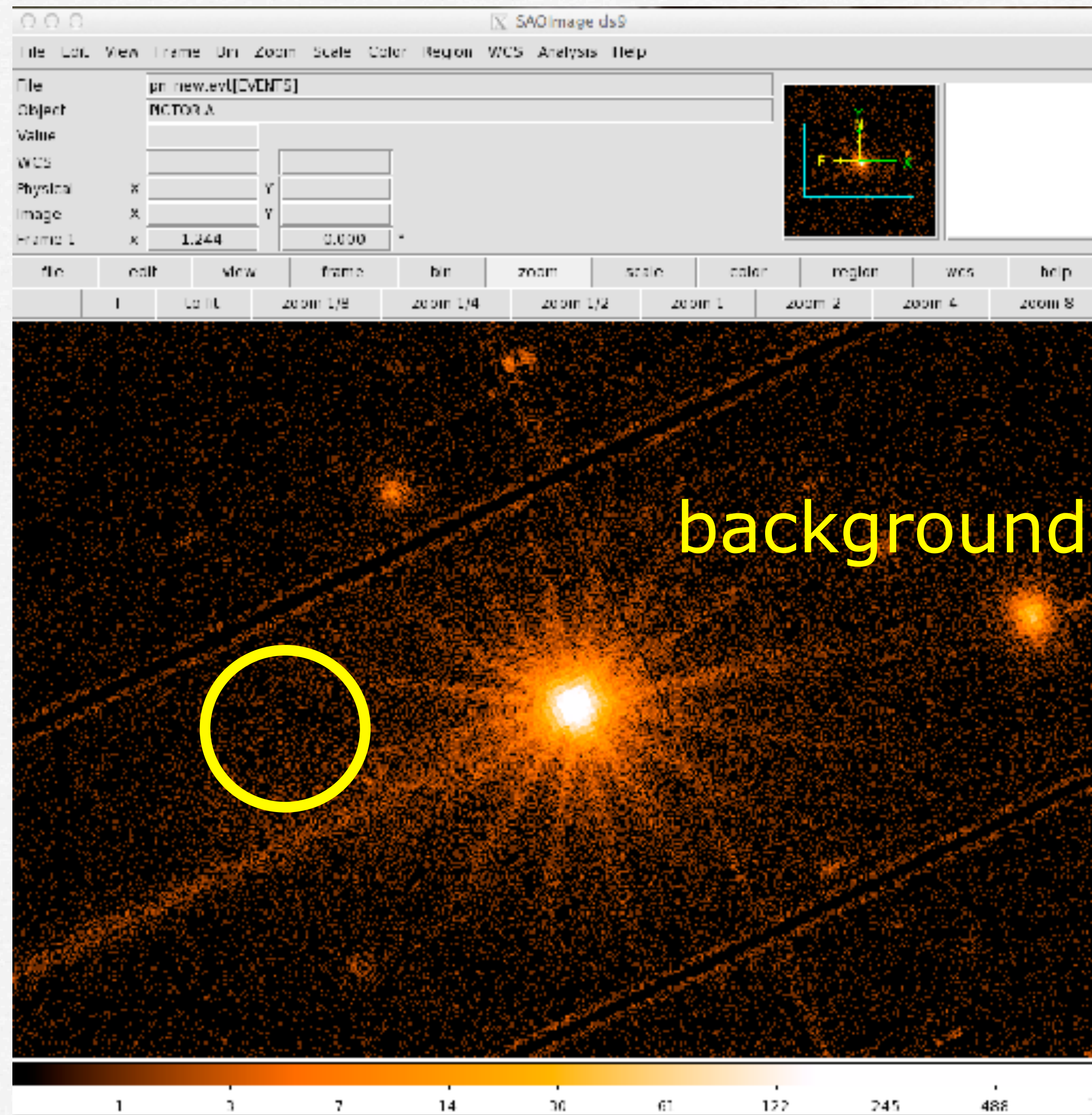
http://ds9.si.edu/doc/ref/

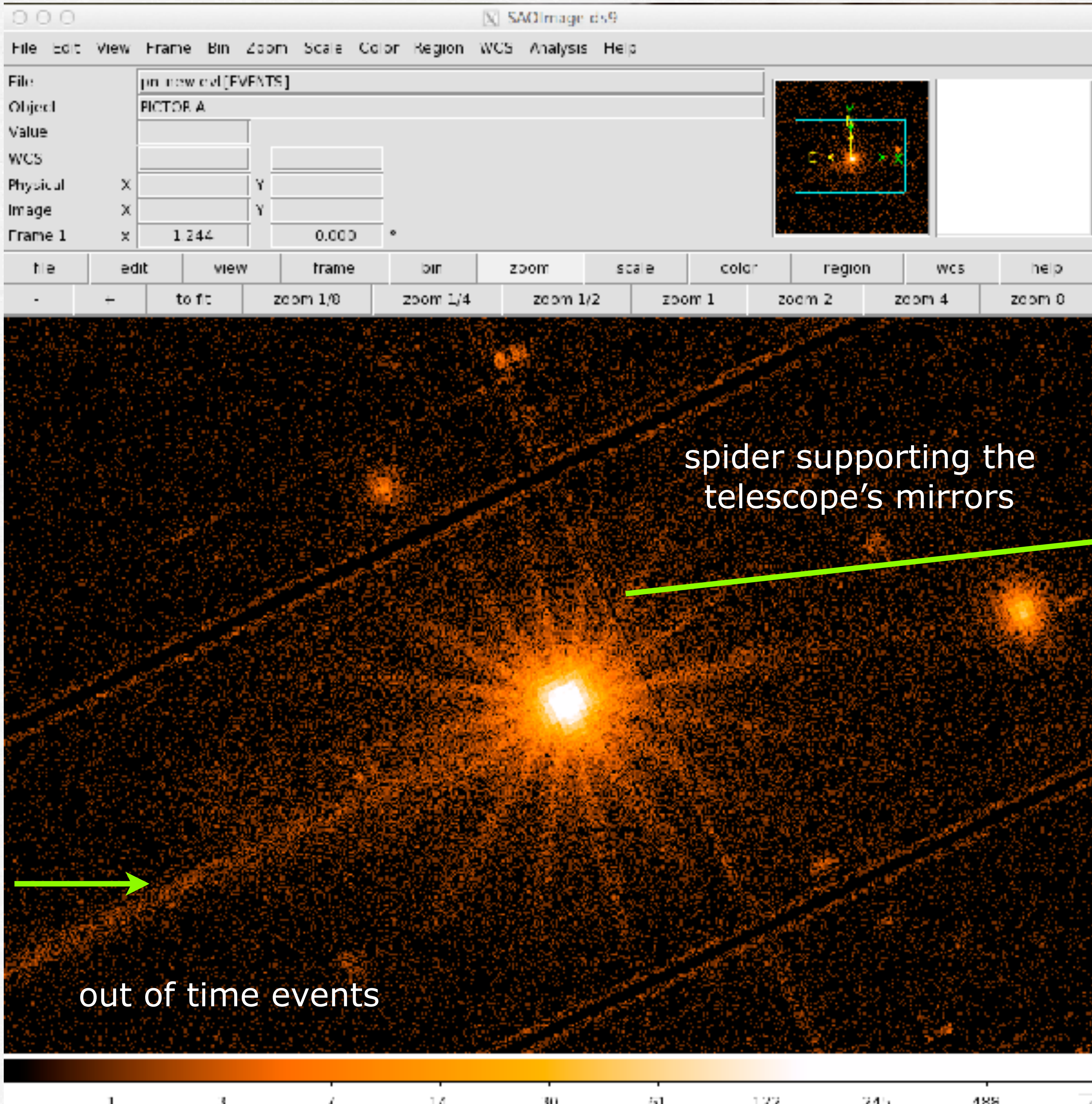
Source and background regions selection

open event list file with ds9

> ds9 pn_new.evt &

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





spider supporting the telescope's mirrors

out of time events

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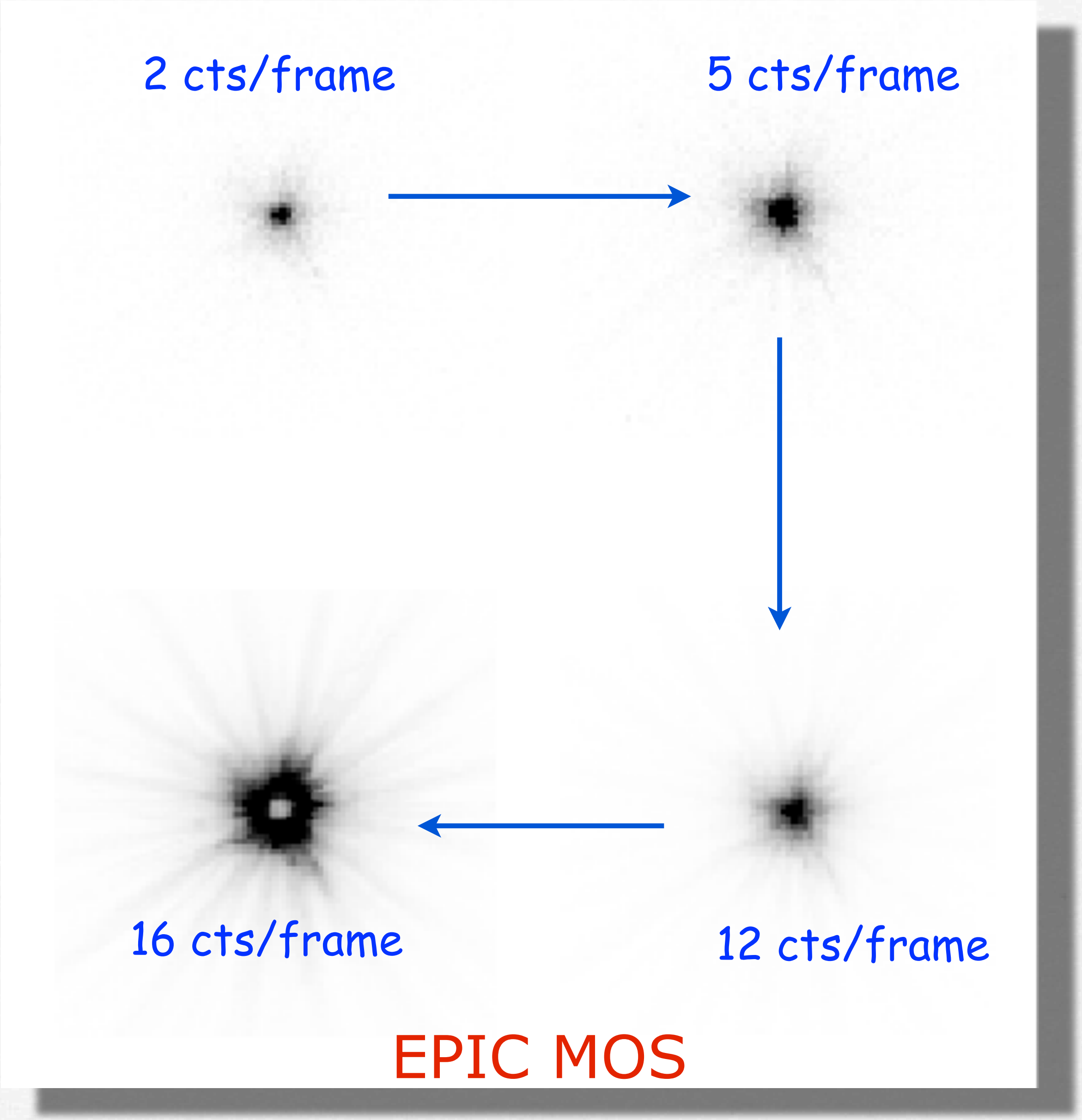
PILE-UP

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)



Can affect the PSF (in its core many photons arrive at almost the same time) and the EPIC spectral response distorting the spectral shape:

-> by hardening the observed spectrum

-> by suppressing flux due to the creation of invalid patterns

-> by joining separate mono-pixel into a single multi-pixel event (pattern migration)

Jethwa et al. (2015)

The term *'pattern'* indicates the distribution of pixels over which a charge cloud spreads (= *'grade'* in Chandra/ACIS)

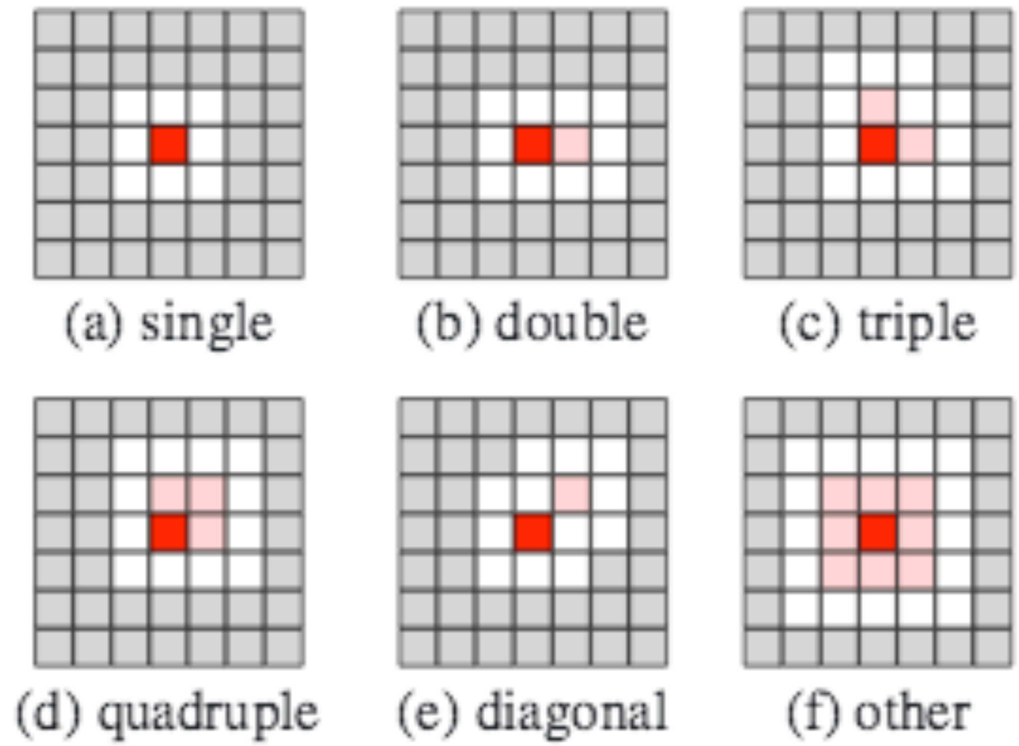


Fig. 1. Examples of EPIC pattern classifications. In each case the dark red pixel contains maximum charge, light red pixels have charge above a threshold value whereas white pixels are necessarily below this threshold. Grey pixels do not influence the pattern classification of the event.

An X-ray photon can generate a variety of patterns. The probability of each pattern is a function of the photon's energy.

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

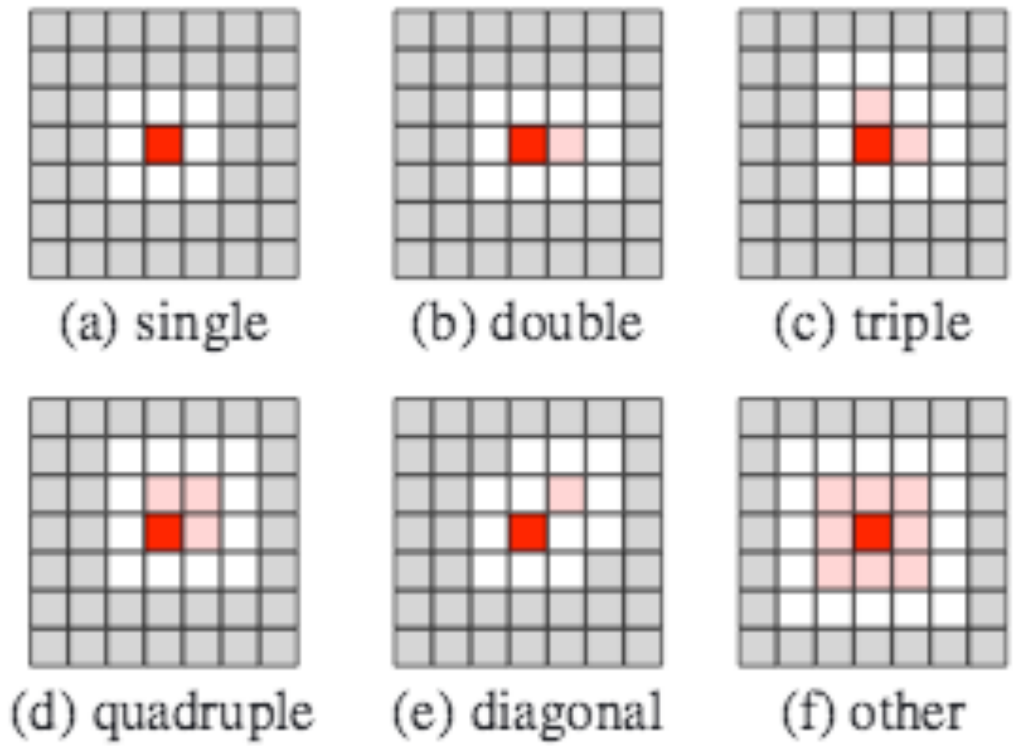
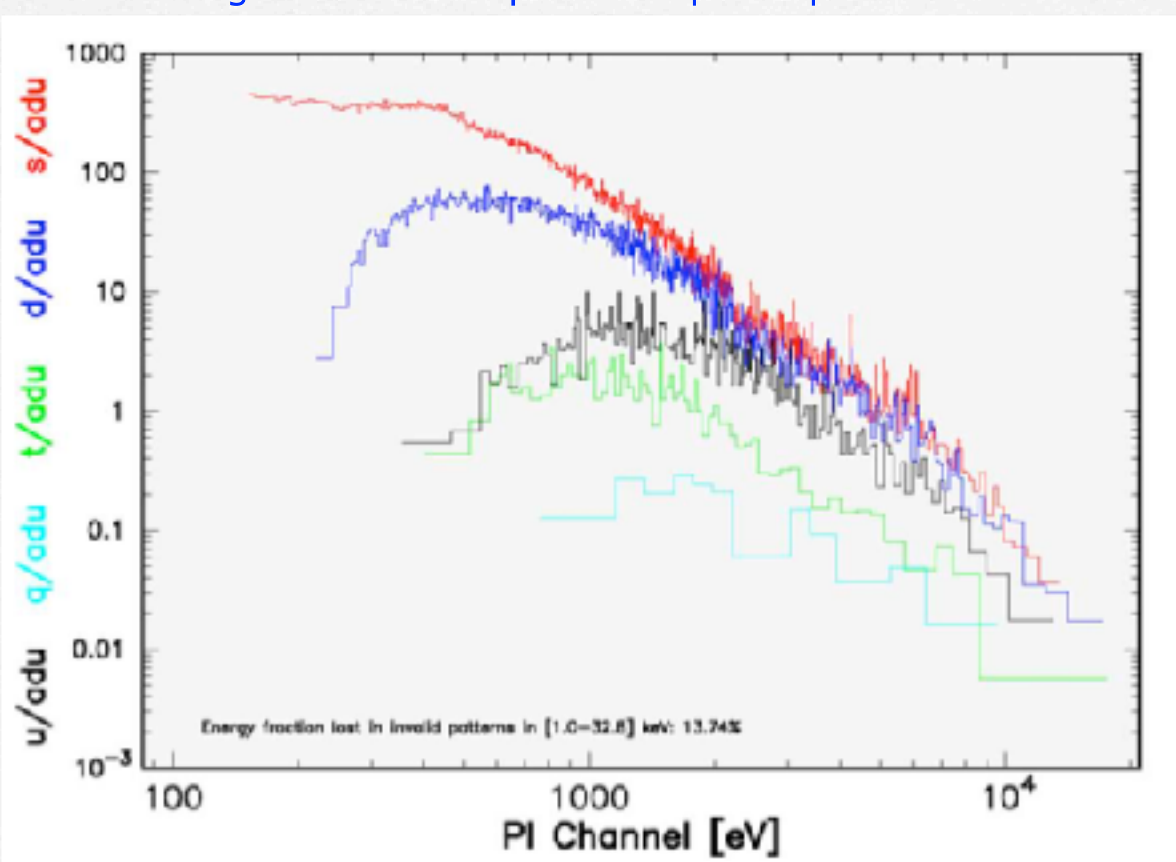


Fig. 1. Examples of EPIC pattern classifications. In each case the dark red pixel contains maximum charge, light red pixels have charge above a threshold value whereas white pixels are necessarily below this threshold. Grey pixels do not influence the pattern classification of the event.

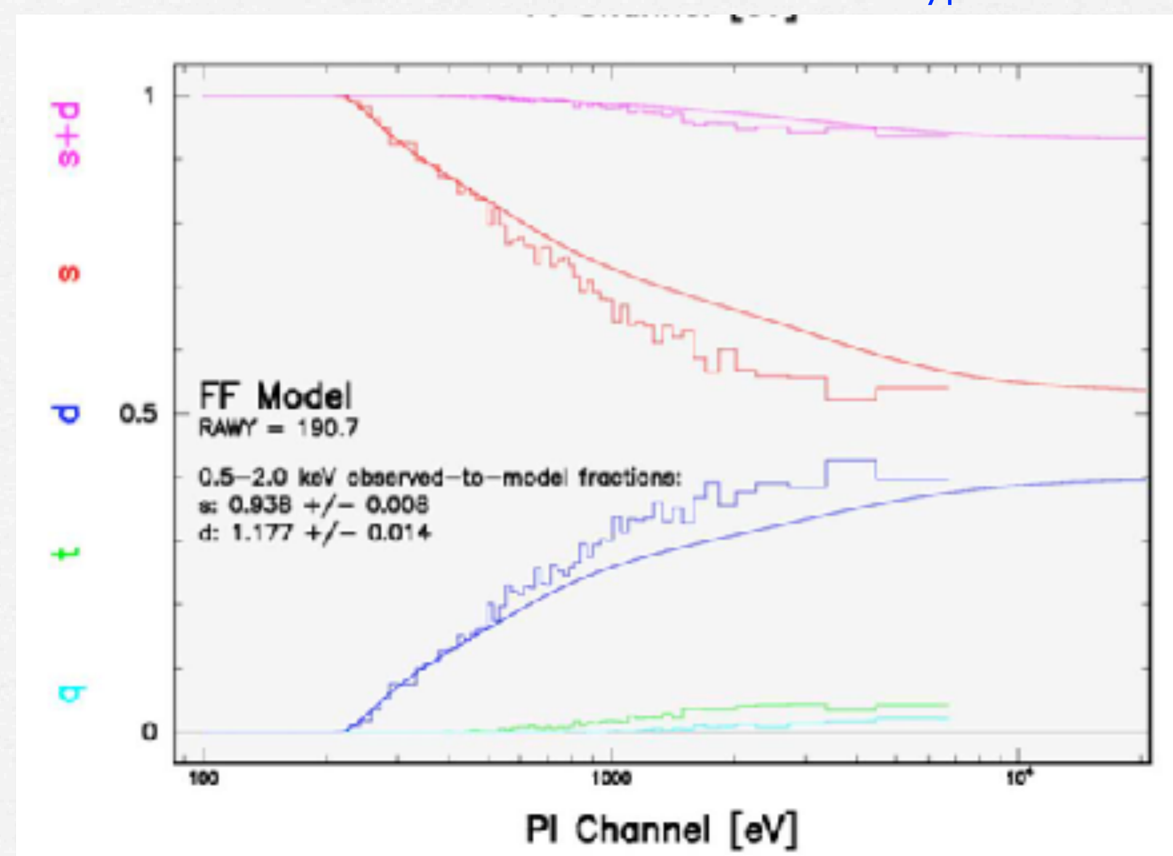
Double events can be produced only if the energy of both events is above the event threshold. Triple (quadruples) events start at 3 (4) times the event threshold.

```
> evselect table=pn_new.evt withfilteredset=yes filteredset=pnf.evt keepfilteroutput=yes expression="((X,Y) IN circle (27874.528,26645.58,699.99999))"

> 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



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

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)

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( )))'
```

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 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

OUTLINE

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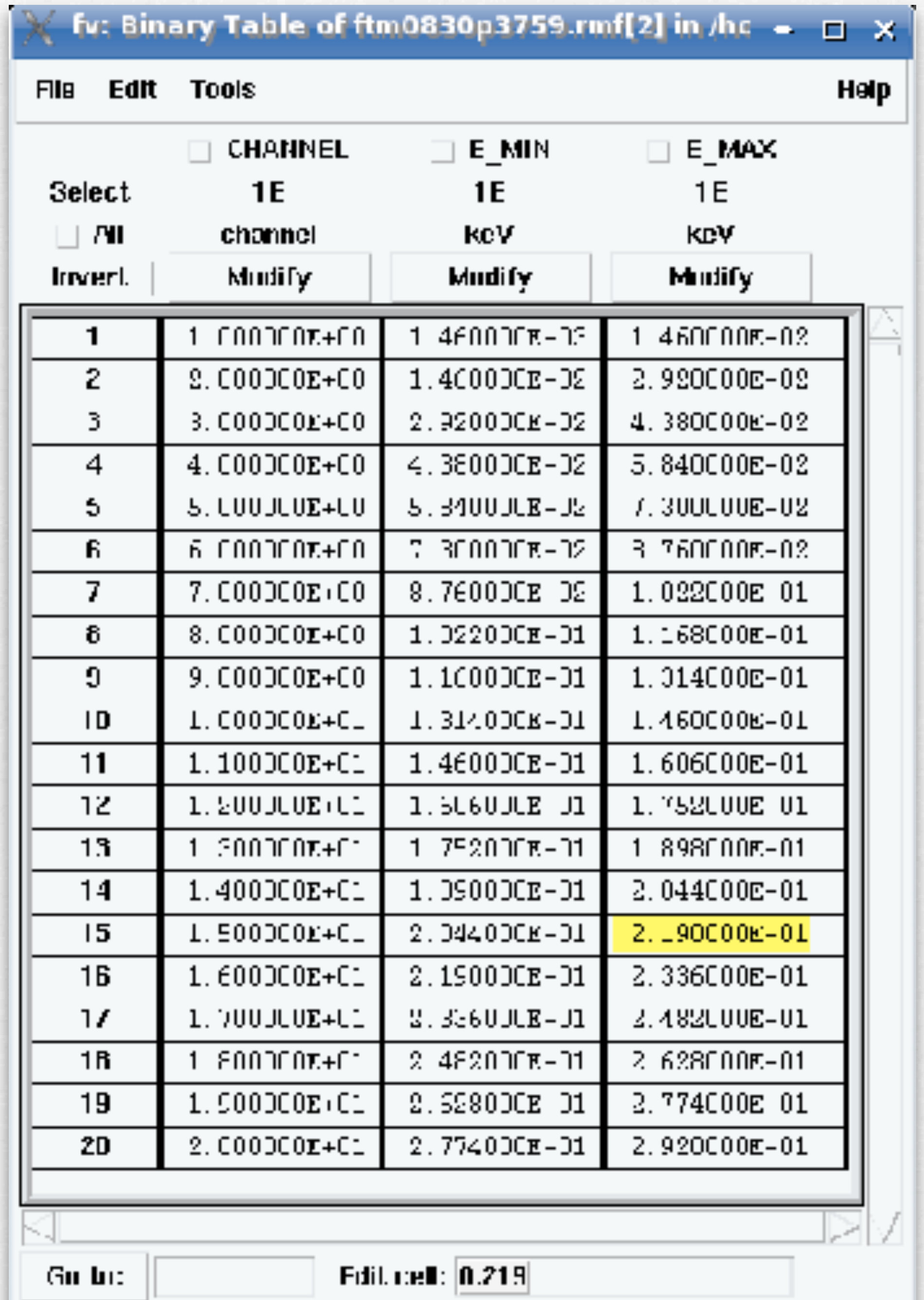
3. Extraction of a light curve from a point-like source

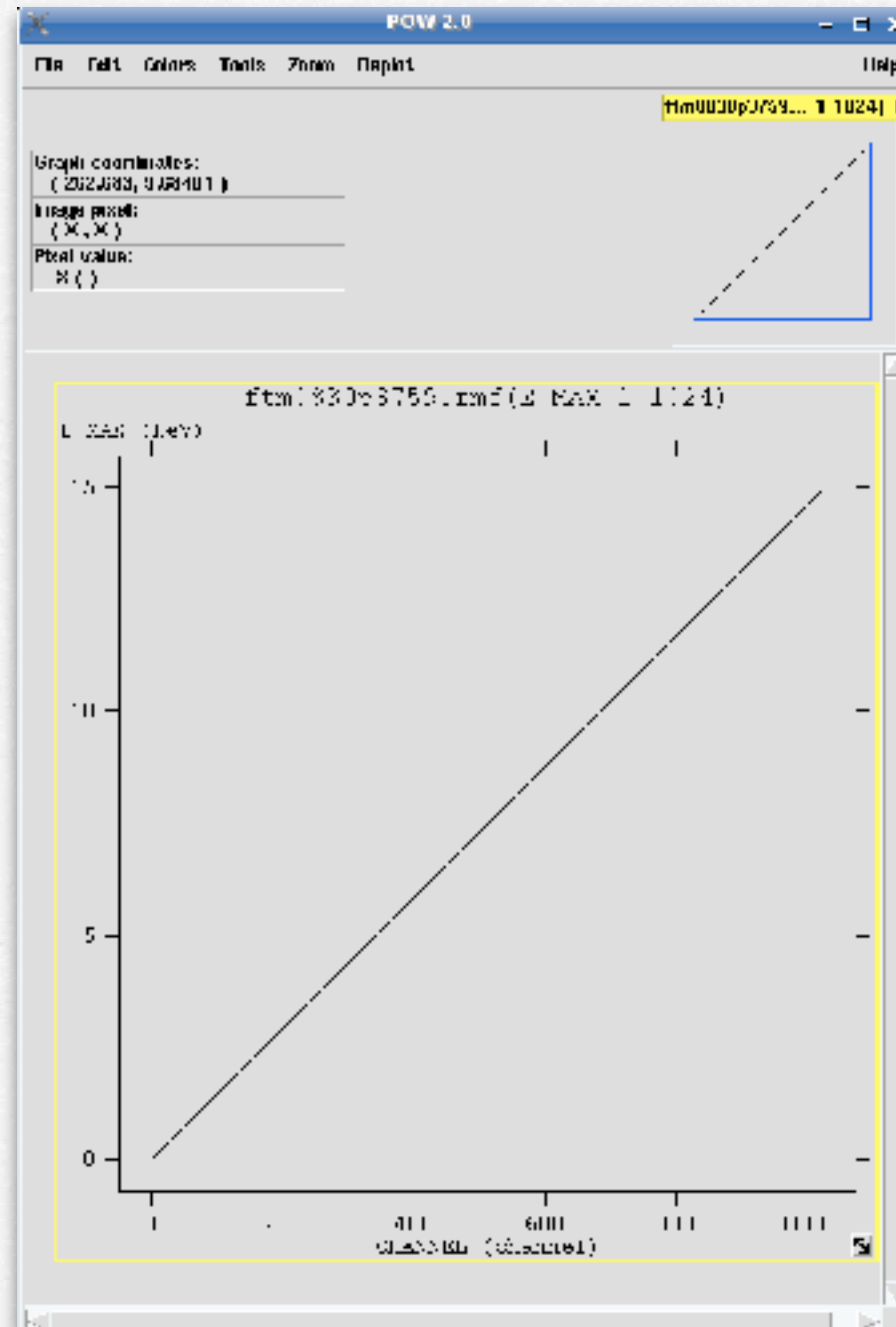
Creation of the Redistribution Matrix File (RMF)

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

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



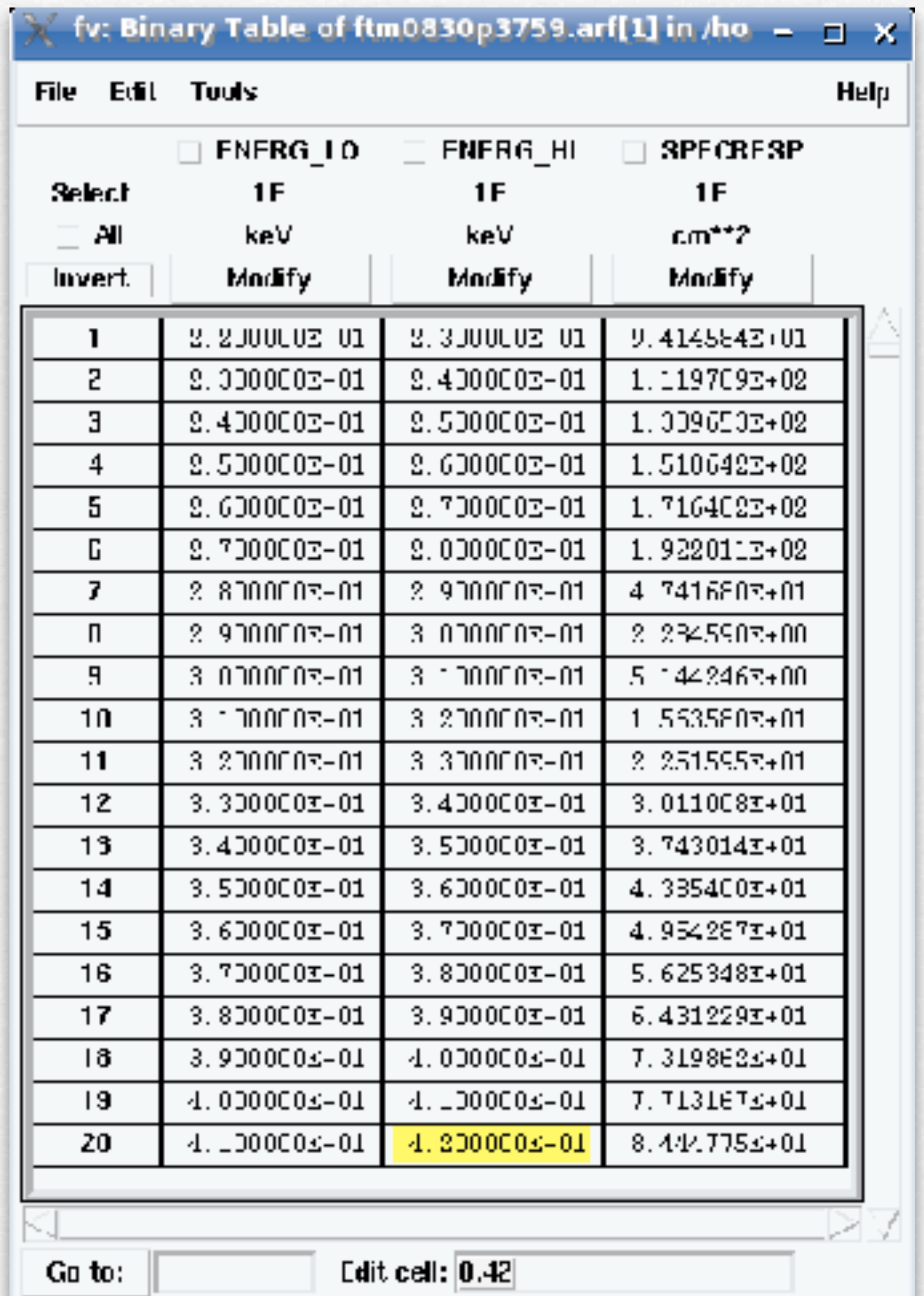
	CHANNEL 1E channel	E_MIN 1E keV	E_MAX 1E keV
1	1.000000E+00	1.460000E-02	1.460000E-02
2	2.000000E+00	1.460000E-02	2.920000E-02
3	3.000000E+00	2.920000E-02	4.380000E-02
4	4.000000E+00	4.380000E-02	5.840000E-02
5	5.000000E+00	5.840000E-02	7.300000E-02
6	6.000000E+00	7.300000E-02	8.760000E-02
7	7.000000E+00	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



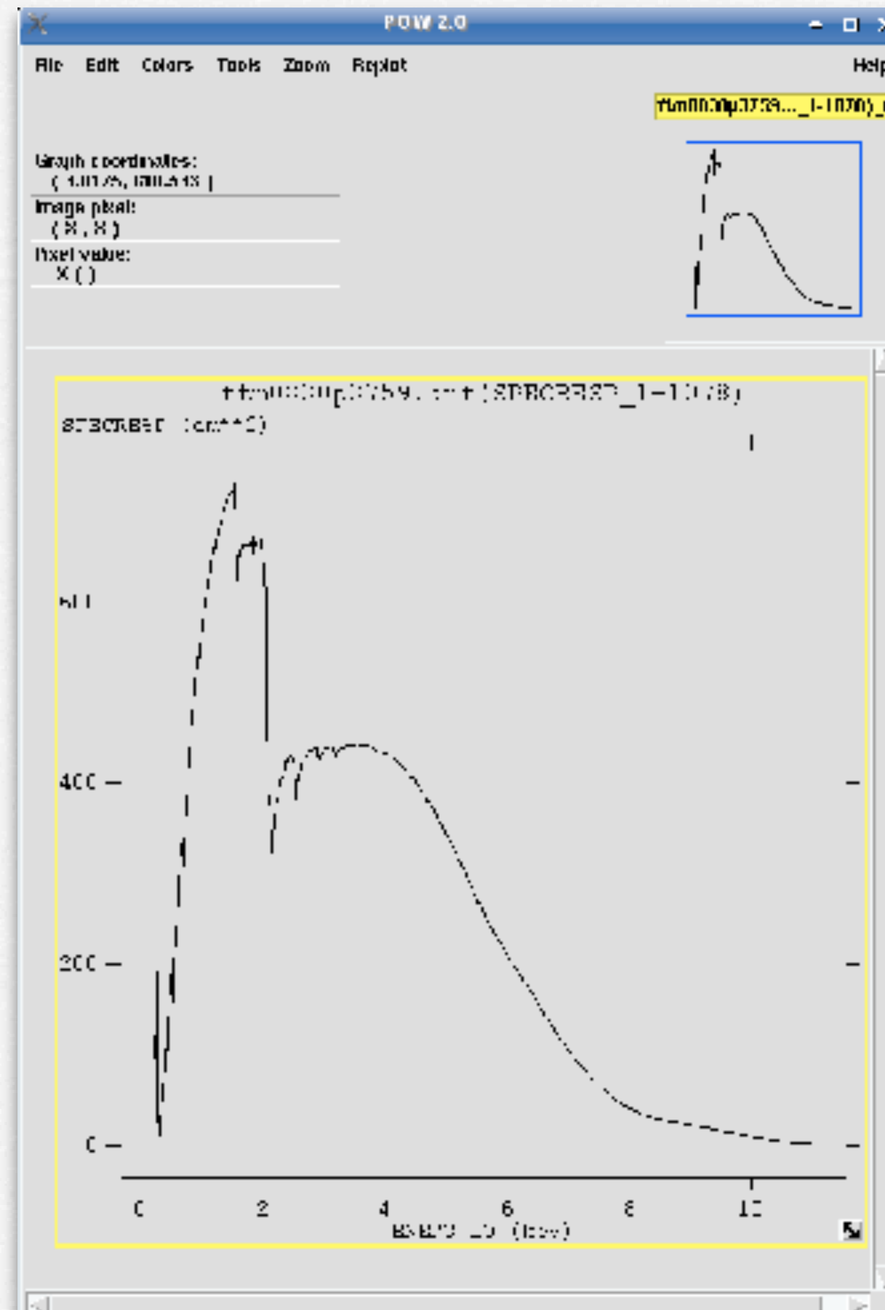
Creation of the Auxiliary Response File (ARF)

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

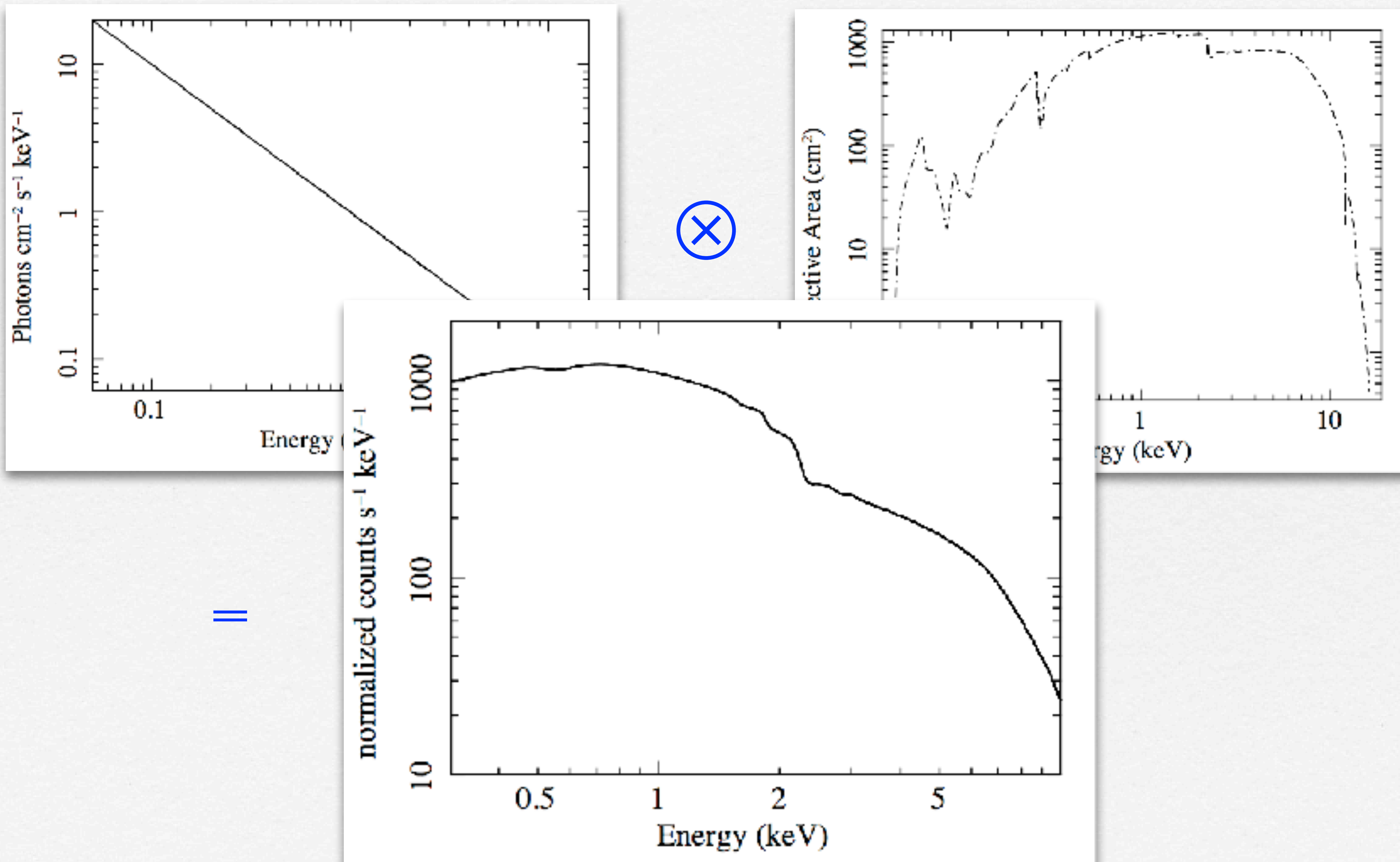
The Auxiliary Response File (ARF) includes information on the effective area, filter transmission and any additional energy-dependent efficiencies, i.e. the efficiency of the instrument in revealing photons



Select	ENERG_LO	ENERG_HI	SPECRESP
	1E	1E	1E
All	keV	keV	cm**2
Invert	Modify	Modify	Modify
1	2.200000E-01	2.300000E-01	9.414564E+01
2	2.300000E-01	2.400000E-01	1.119709E+02
3	2.400000E-01	2.500000E-01	1.339650E+02
4	2.500000E-01	2.600000E-01	1.510642E+02
5	2.600000E-01	2.700000E-01	1.716402E+02
6	2.700000E-01	2.800000E-01	1.922011E+02
7	2.800000E-01	2.900000E-01	4.741660E+01
8	2.900000E-01	3.000000E-01	2.234550E+00
9	3.000000E-01	3.100000E-01	5.144246E+00
10	3.100000E-01	3.200000E-01	1.553560E+01
11	3.200000E-01	3.300000E-01	2.251555E+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	4.335400E+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	8.447775E+01



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



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"
```

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"
```

LabX2018

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> XMM-Newton (SAS):

- XMM-Newton ABC Guide: Introduzione all'analisi dati del satellite XMM-Newton
- SAS Users Guide: manuale completo per la riduzione dei dati del satellite XMM-Newton
- XMM-Newton threads: principali istruzioni per la riduzione dei dati XMM-Newton (EPIC pn, MOS1, MOS2)
- XMM-Newton Users Handbook: informazioni sulla strumentazione a bordo del satellite XMM-Newton
- XMM-Newton pile up: informazioni su come valutare il pile up in un'osservazione XMM

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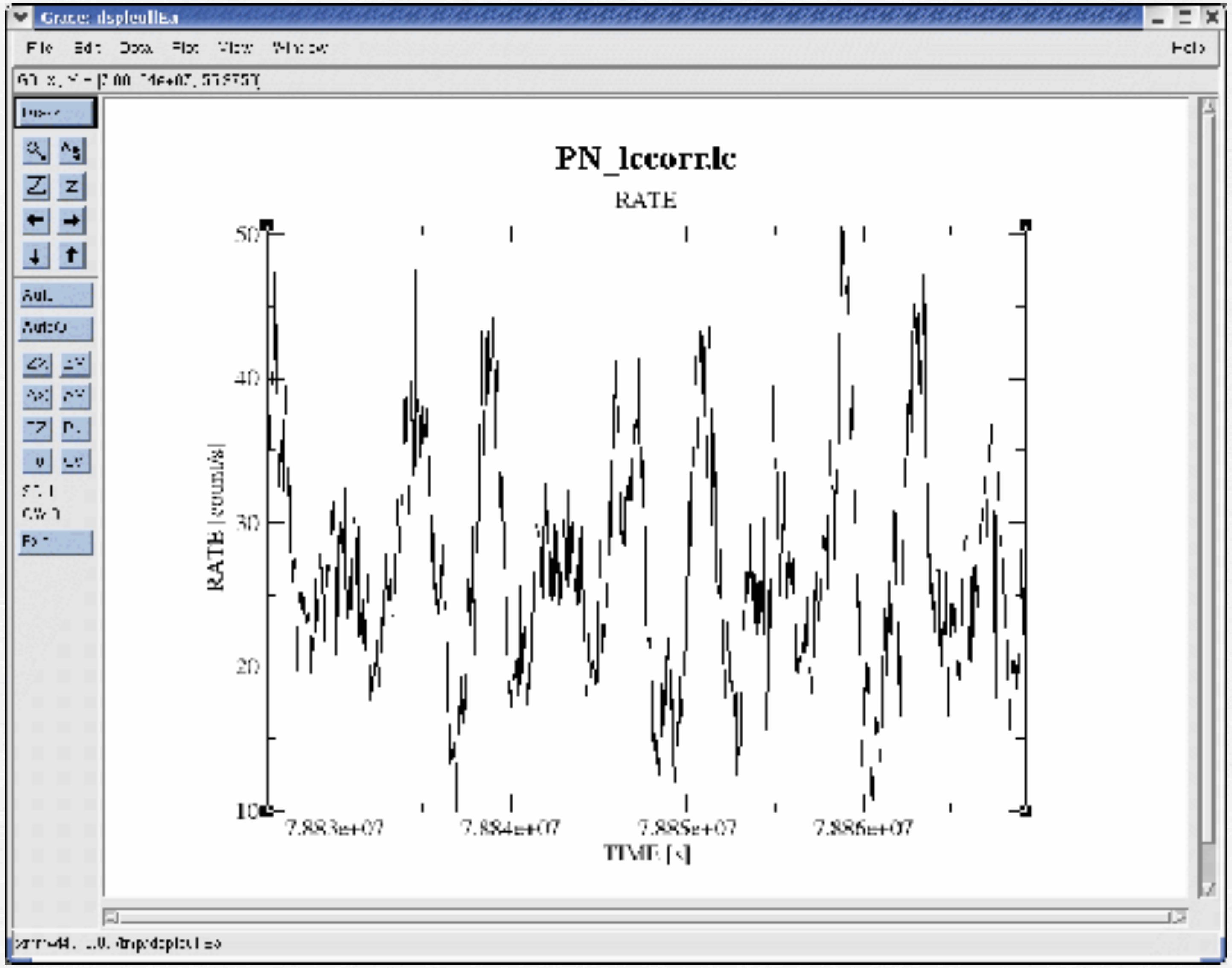
3. Extraction of a light curve from a point-like source

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 built in different temporal bins, e.g. if the observation is 1000 seconds long it is possible to extract light curves of 10 sec and 100 sec. **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:

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

c_i observed counts in every temporal bin i;
σ_i Poissonian error;
<c> average count during the observation;
v**=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 (background corrected)

- Source+background light curve between 2-10 keV

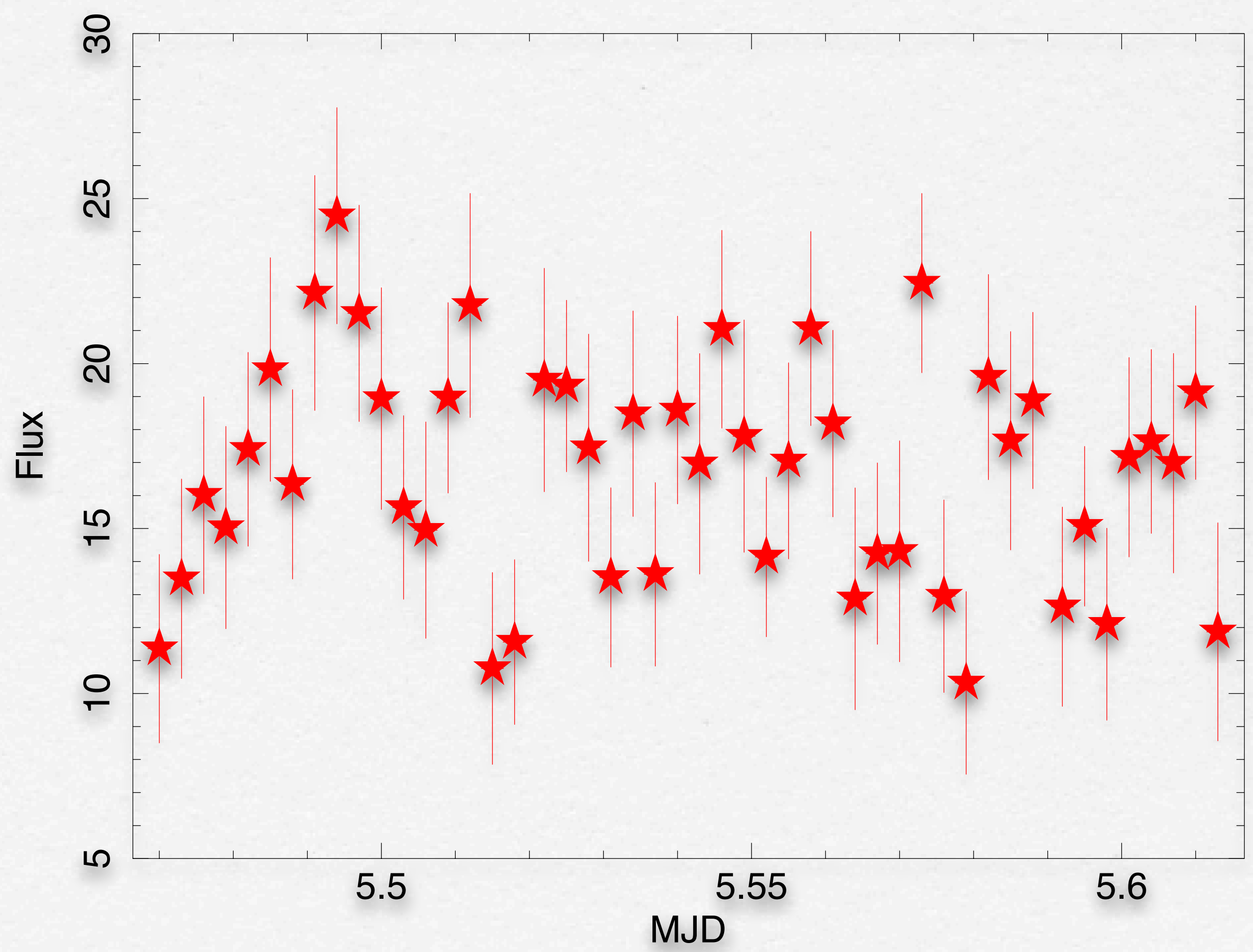
```
evselect table=pn_new.evt energycolumn=PI expression='#XMMEA_EP[M] && (PATTERN<=4[12]) && ((X,Y) IN circle(source.reg)) && (PI in [200:10000])' withrateset=yes rateset="PN_source_lc_raw.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

- 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
```



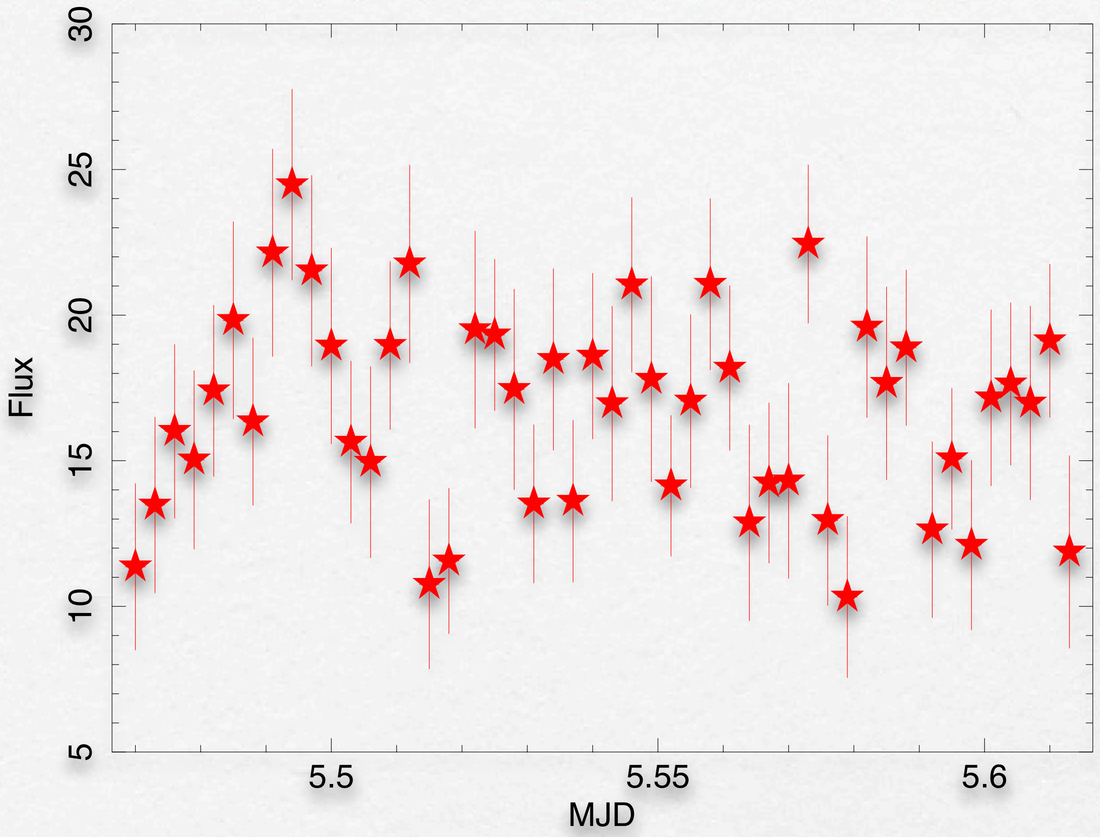
Example:

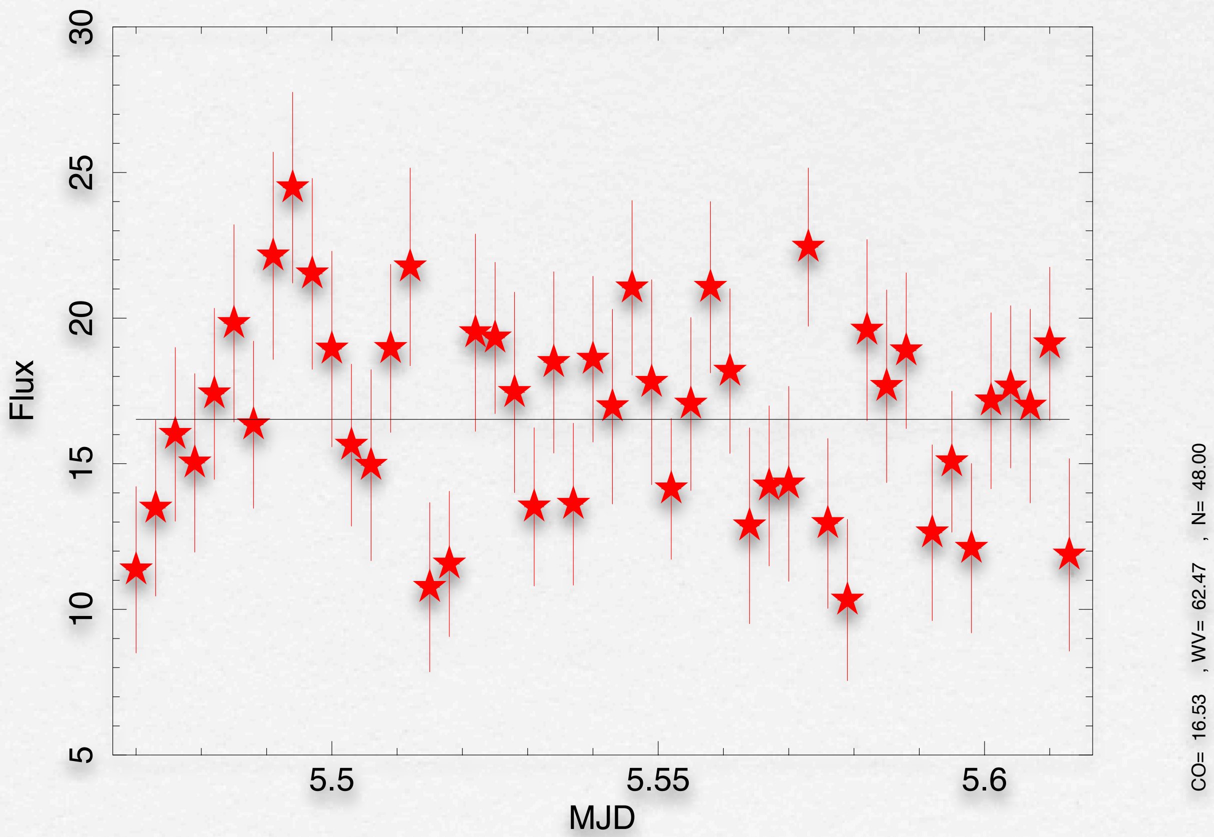
> lcurve **PN_source_lc_raw.lc**

> 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
```





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

Example:

> 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%