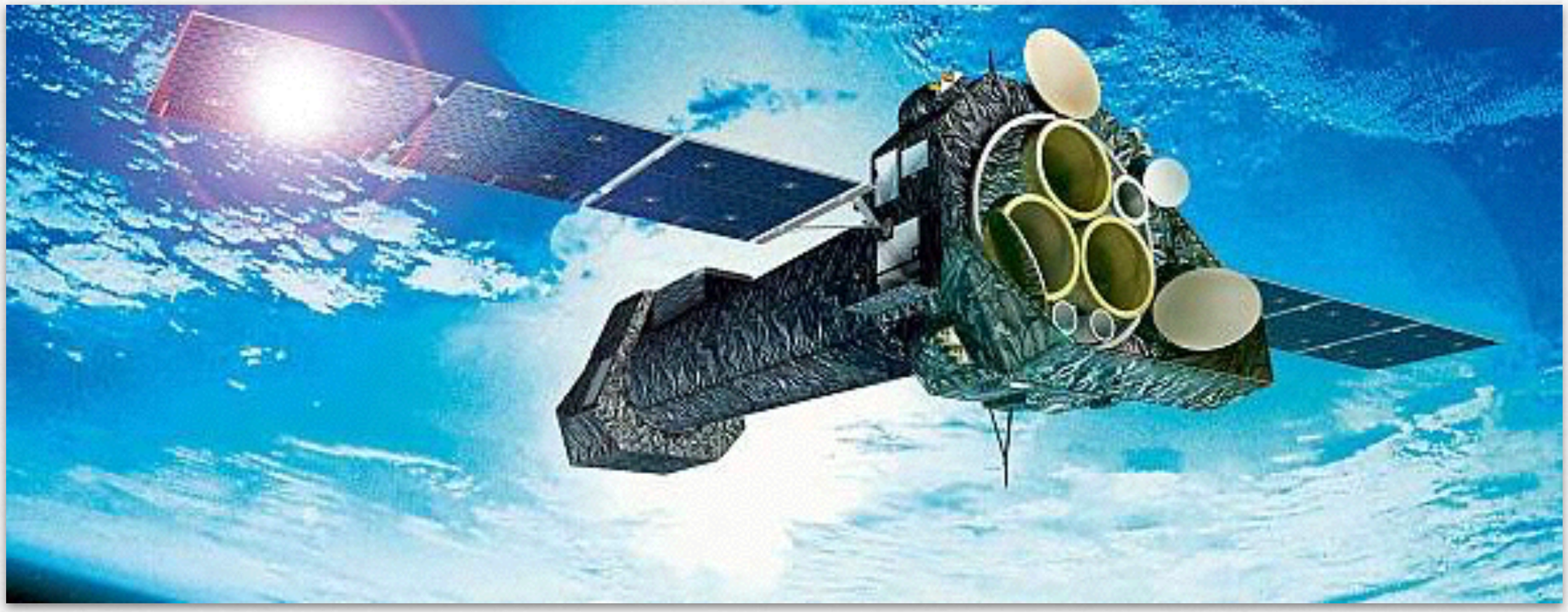
XMM-Newton tutorial



Eleonora Torresi
DIFA & INAF/IASF Bologna

LABORATORIO X 2017
7.11.2017

XMM-Newton payload

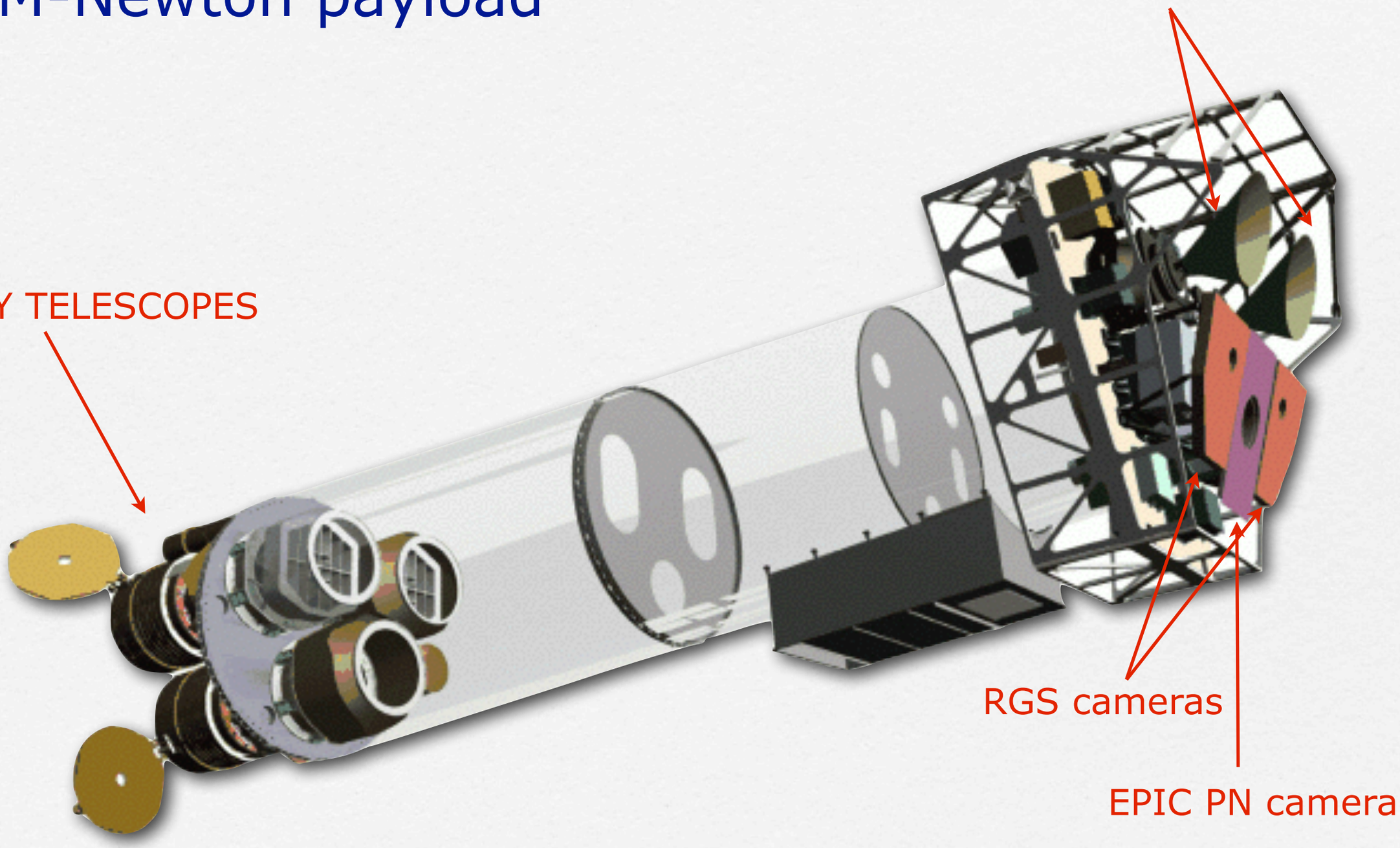
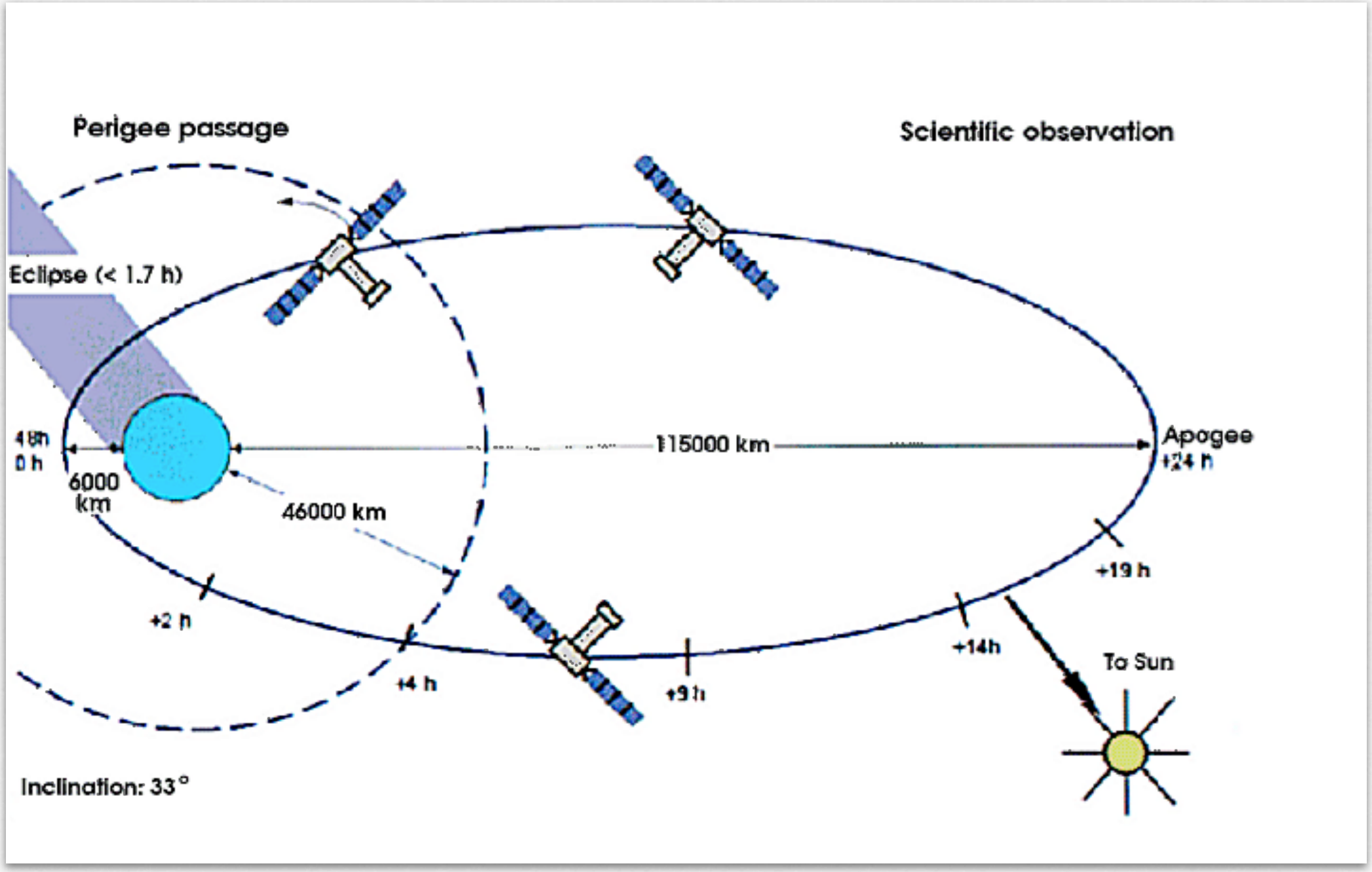


Image courtesy of Dornier Satellitensysteme GmbH and ESA

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

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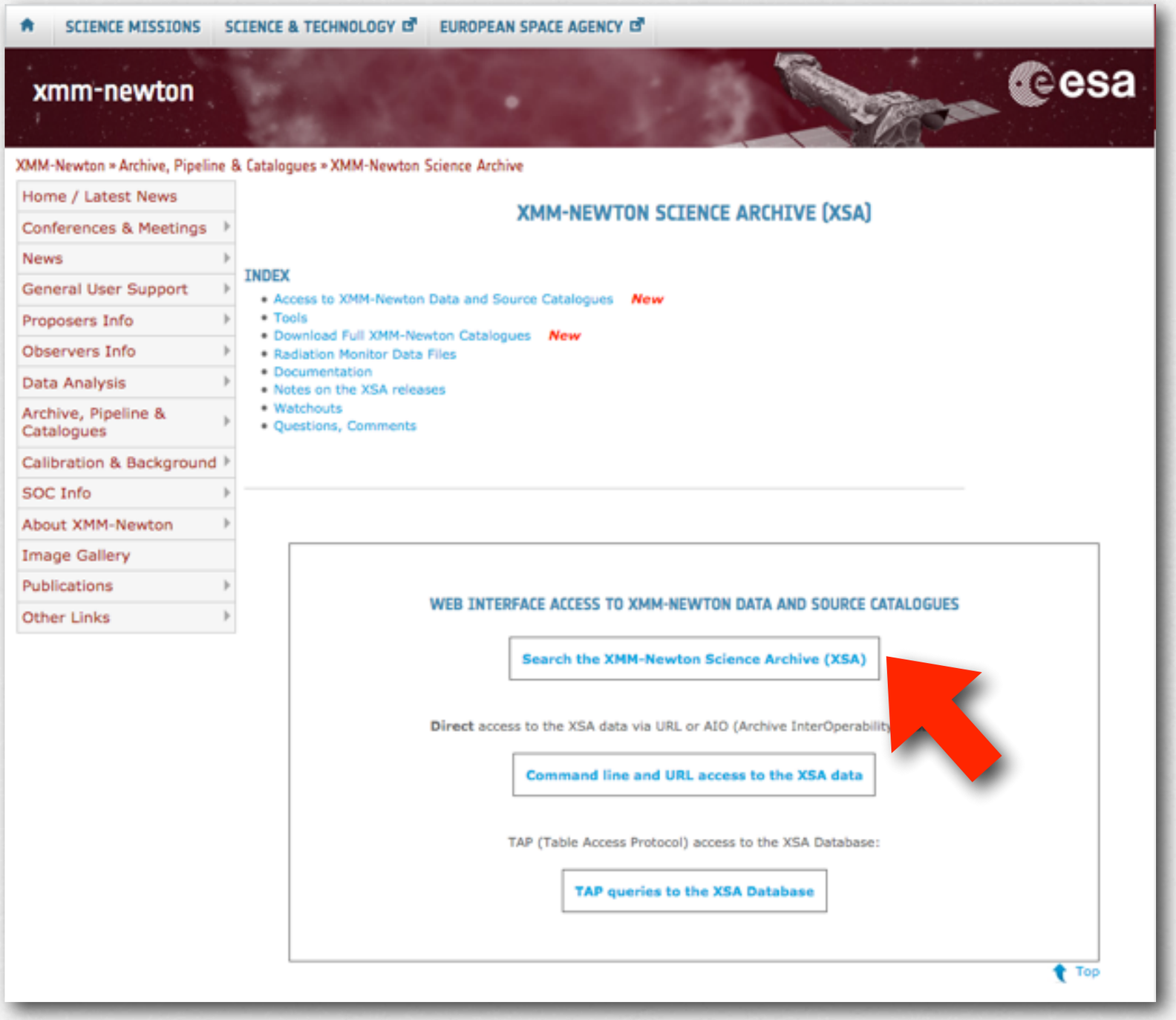
XMM-Newton Science Operations Centre (ESA-Vilspa, Spain)

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



Firefox File Modifica Visualizza Cronologia Segnalibri Strumenti Finestra Aiuto (100%) ven 18:07 Eleonora Torresi

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Position | File

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- Galactic
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Target in: Field Of View | Circle | Box

Name: 3C 111 for Simbad

▶ Observation and Proposal filters

▶ Display options

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Results #1

OBSERVATIONS (3)

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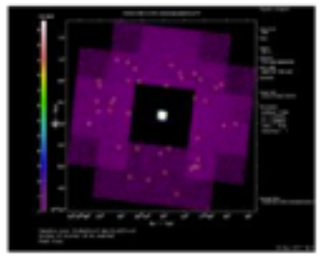
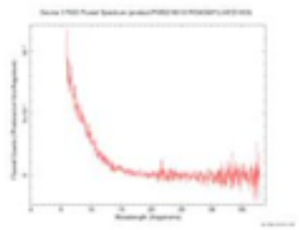
			Obs.ID	EPIC	RGS	Target	RA	Dec	PA	Rev	Distance	Start Date	End Date
☐			0065940101			3C 111	04h 18m 21.07s	+38d 01' 32.6"	257.1	231	4	2001-03-14 12:56:44	2001-03-15 01:2
☑			0552180101			3C111	04h 18m 21.27s	+38d 01' 35.7"	262.9	1683	0	2009-02-15 17:25:11	2009-02-17 04:(
☐			201	N/A	N/A	3C111	04h 18m 21.27s	+38d 01' 35.7"	262.9	1683	0	2009-02-15 14:44:57	2009-02-15 16:5

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

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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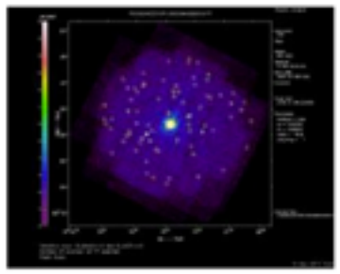
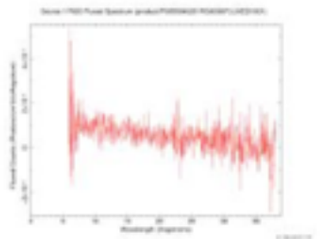
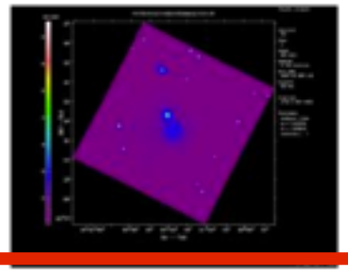
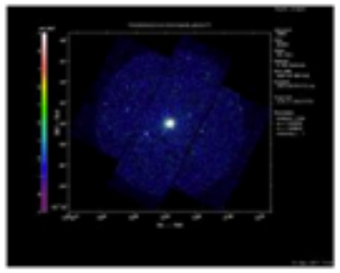
Details for Observation 0056340201







ExposureID	S006
Instrument	OM
Mode	Image
Filter	U



ExposureID	S001
Instrument	EMOS1
Mode	Full Frame
Filter	MEDIUM

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EPIC FILTERS

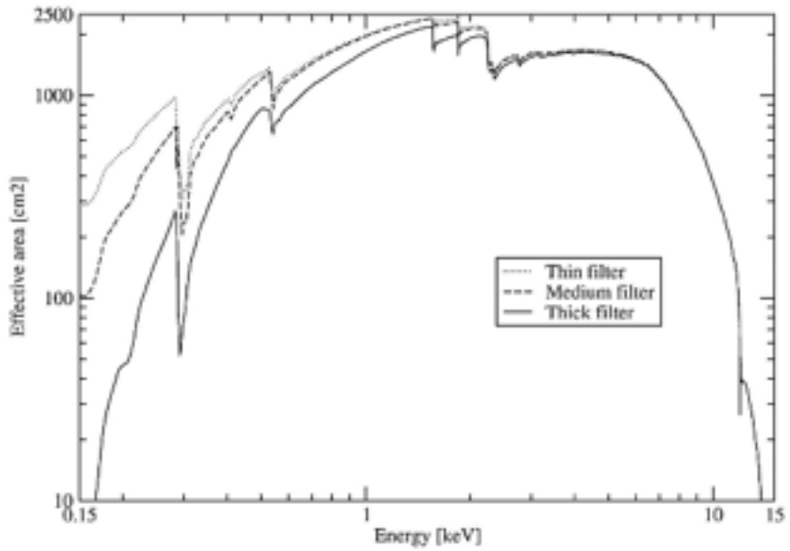
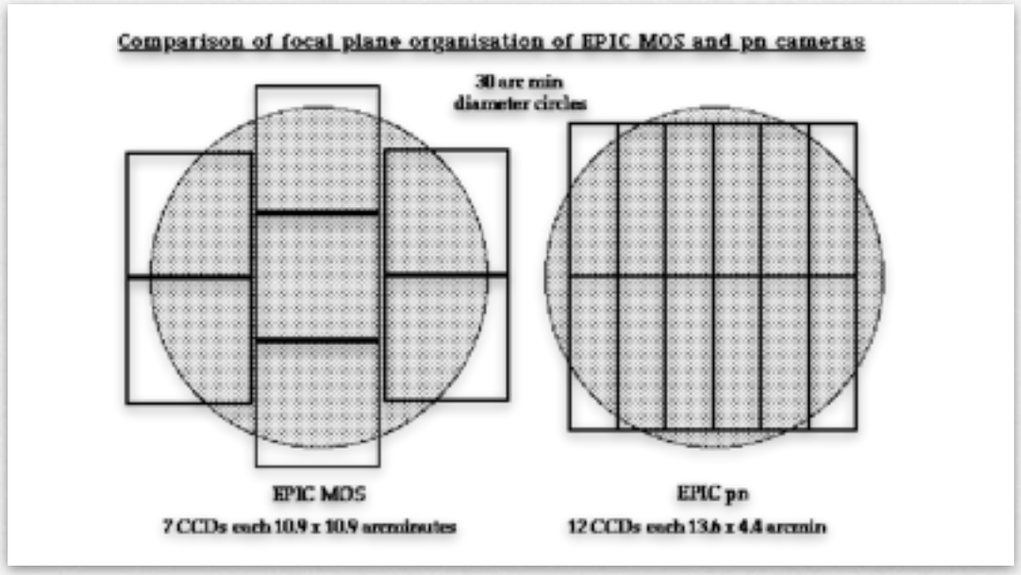


Figure 31: *Combined effective area of all telescopes assuming that the EPIC cameras operate with the same filters, either thin, medium or thick.*

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

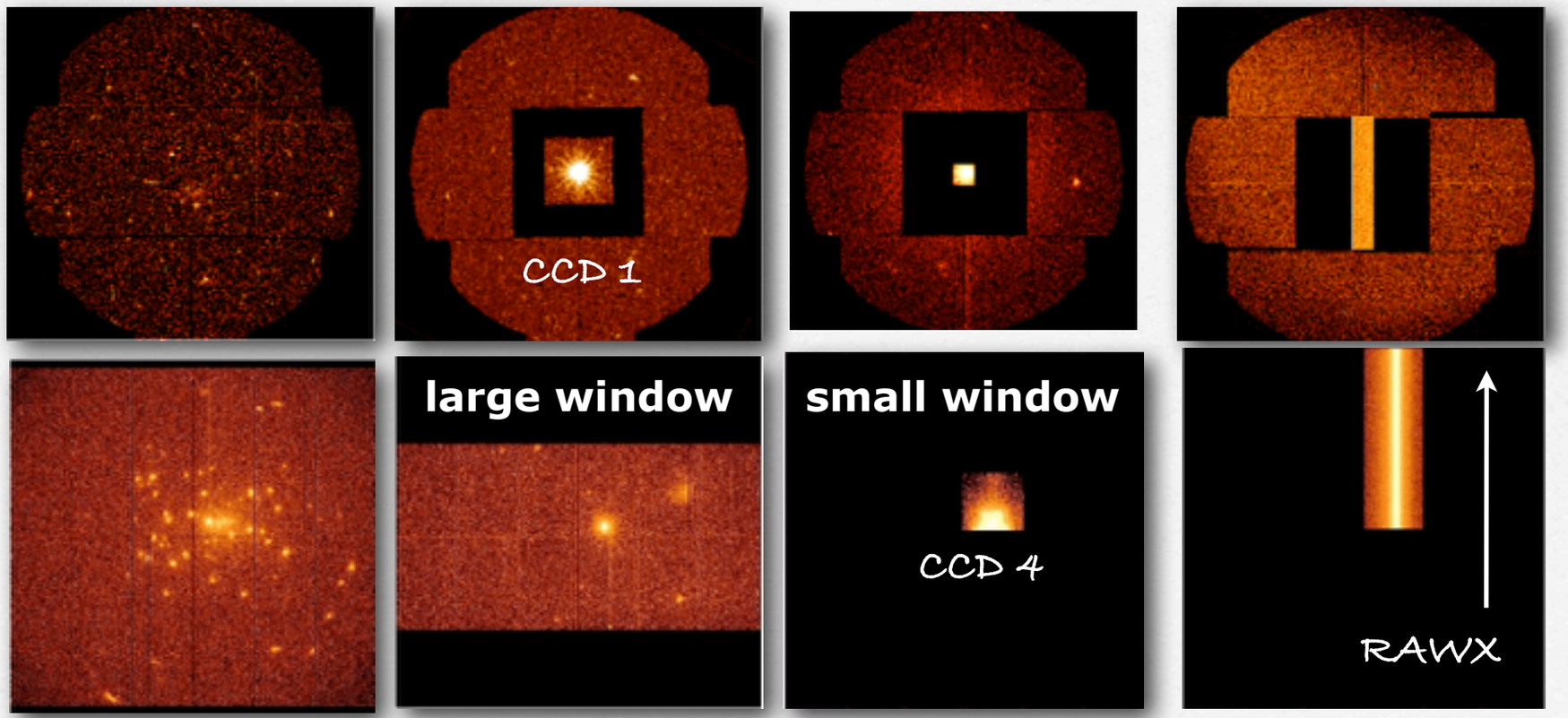
EPIC SCIENCE MODES

MOS



pn

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



MOS

pn

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OBSERVATIONS (3)

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			Obs.ID	EPIC	RGS	Target	RA	Dec	PA	Rev	Distance	Start Date	End Date	Dur.	Target Type
☐			0065940101			3C 111	04h 18m 21.07s	+38d 01' 32.6"	257.1	231	4	2001-03-14 12:56:44	2001-03-15 01:23:52	44828	SEYFERT RADIO LOUD STEEP RADIO SP
☑						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

ODF
PPS
IMAGES
SPECTRA
LIGHT_CURVES

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

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

1 of 1 Page size: 100

ODF files

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
2205_0675400101_M1S00140IME.FIT 2205_0675400101_R1S00400AUX.FIT
2205_0675400101_M1S00150IME.FIT 2205_0675400101_R1S00401SPE.FIT
2205_0675400101_M1S00170IME.FIT 2205_0675400101_R1S00402SPE.FIT
2205_0675400101_M1U00200AUX.FIT 2205_0675400101_R1S00403SPE.FIT
2205_0675400101_M1U00210IME.FIT 2205_0675400101_R1S00404SPE.FIT
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2205_0675400101_M1U00300AUX.FIT 2205_0675400101_R1S90102DII.FIT
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2205_0675400101_M1U00320IME.FIT 2205_0675400101_R1S90304DII.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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2205_0675400101_M2S00230IME.FIT 2205_0675400101_R1S91601DII.FIT
2205_0675400101_M2S00240IME.FIT 2205_0675400101_R1S91702DII.FIT
```

Revolution number

FITS files

ObsID

Instrument (pn, MOS1, MOS2)

Content

FITS files

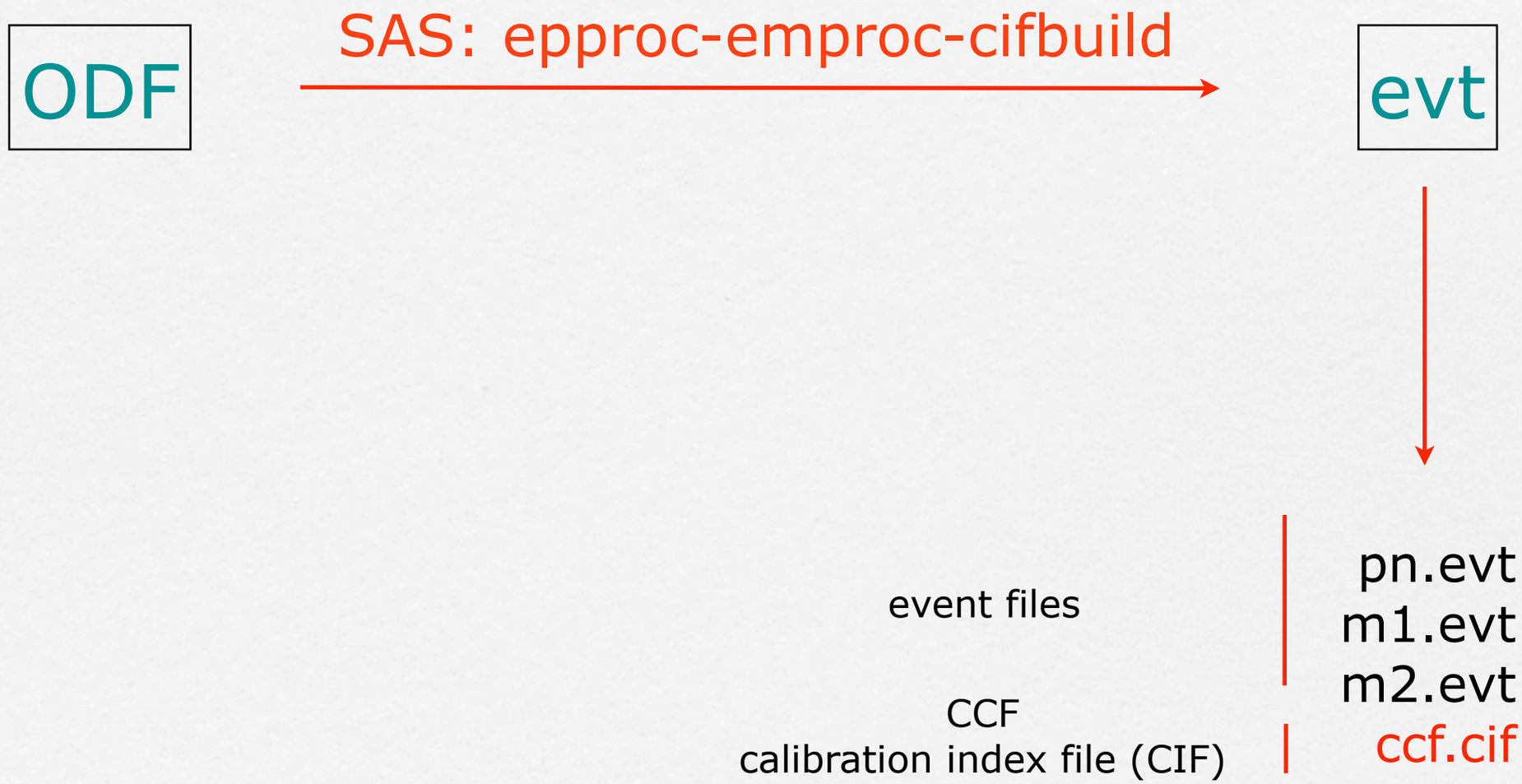
Data produced by the satellite are stored in **FITS (Flexible Image Transport System)** format.

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



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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Instrumental background

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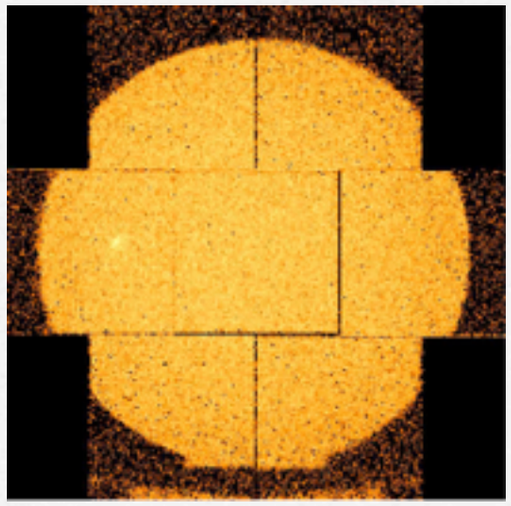
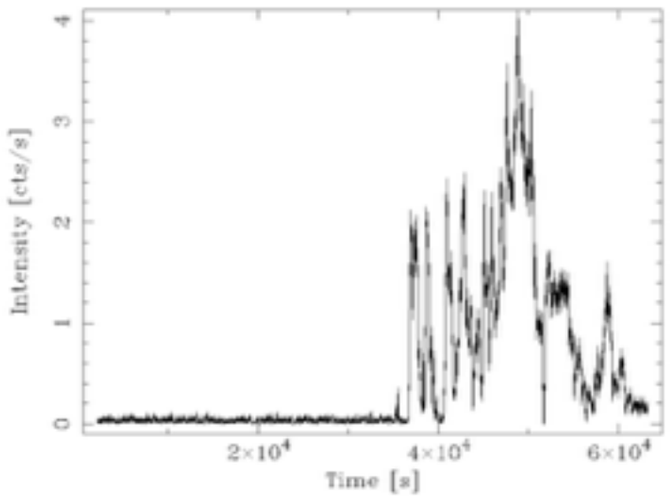
EPIC particle induced background

External 'flaring' component

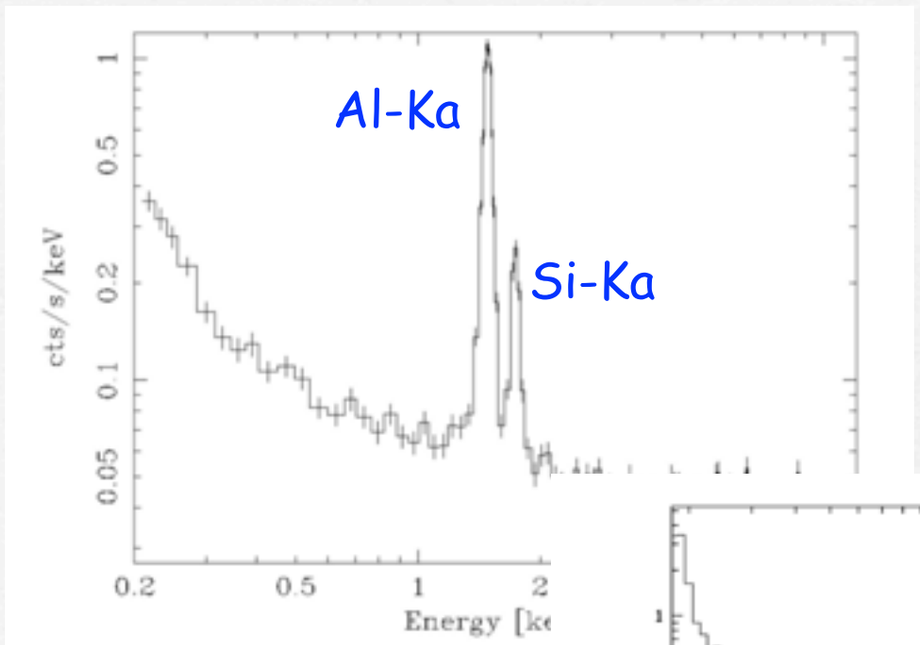
strong and rapid variability; currently attributed to soft protons (E_p < a few 100 keV) likely organized in clouds populating the Earth's magneto-sphere





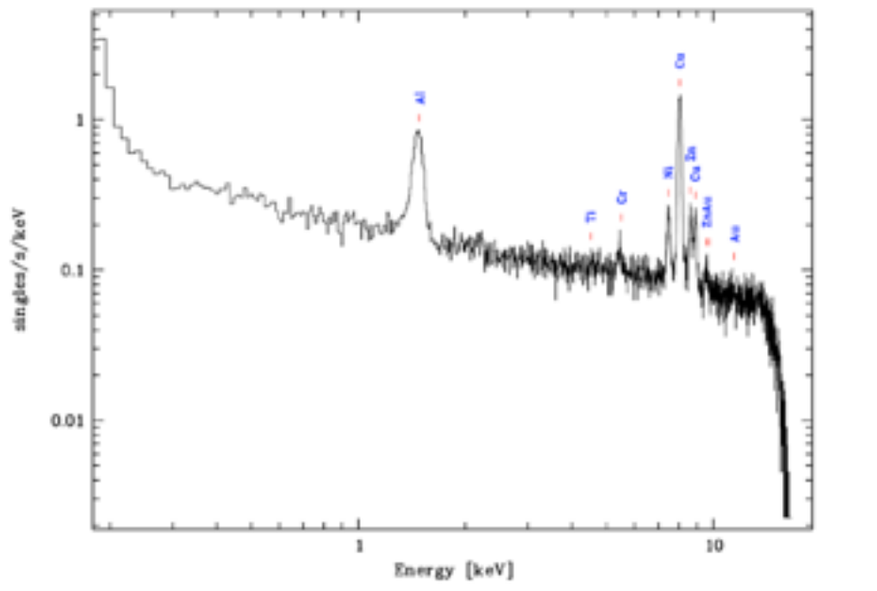
Internal 'quiescent' component

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



MOS1

pn



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

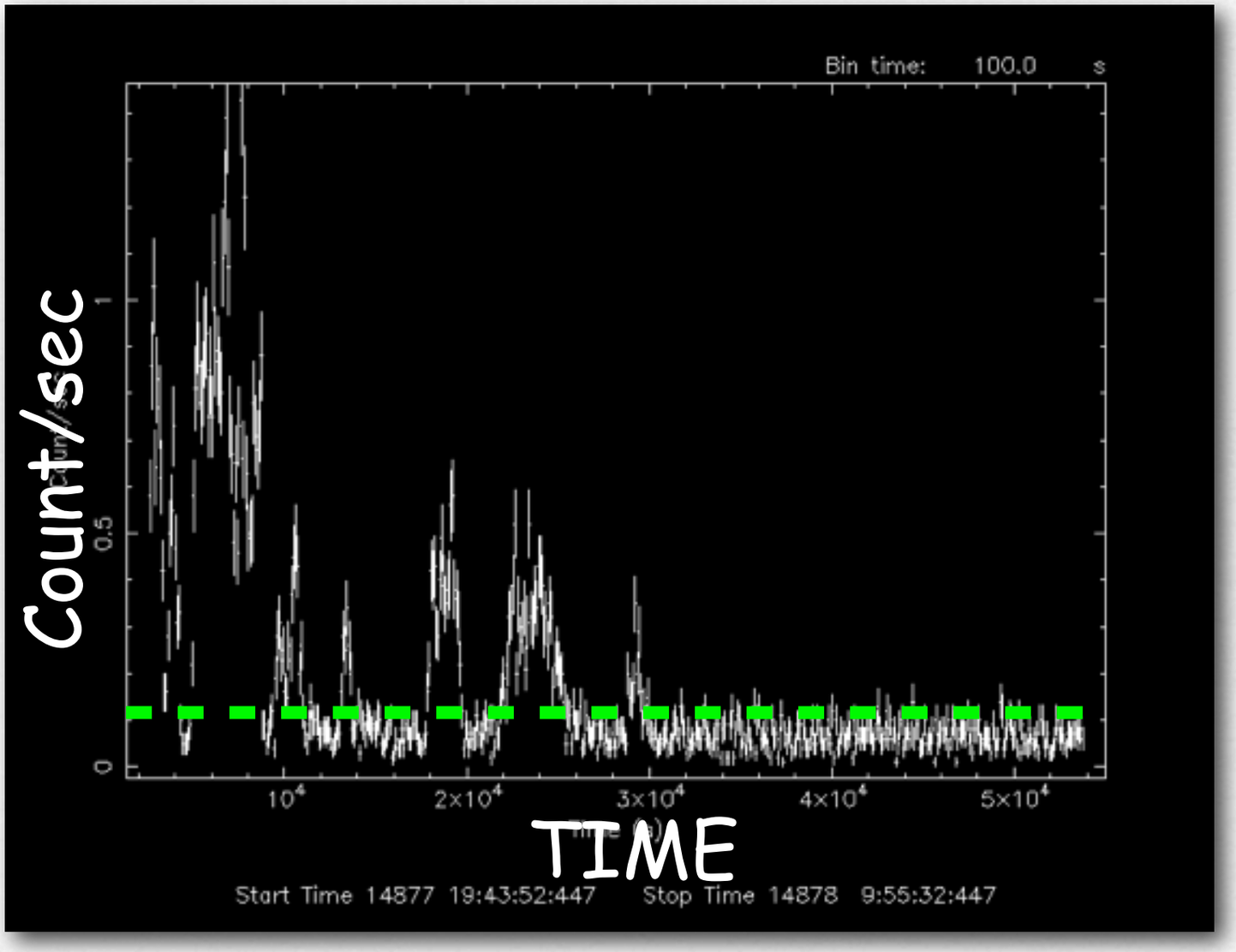
```
evselect table=pn.evt energycolumn=PI expression='#XMMEA_EP && (PI>10000) && (PATTERN==0)' withrateset=yes rateset="lcurve_sup10.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

lcurve

Light curve
above 10 keV

pn < 0.4 cts/s

MOS < 0.35 cts/s



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

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

OUTLINE

1. Download XMM-Newton data from the public archive

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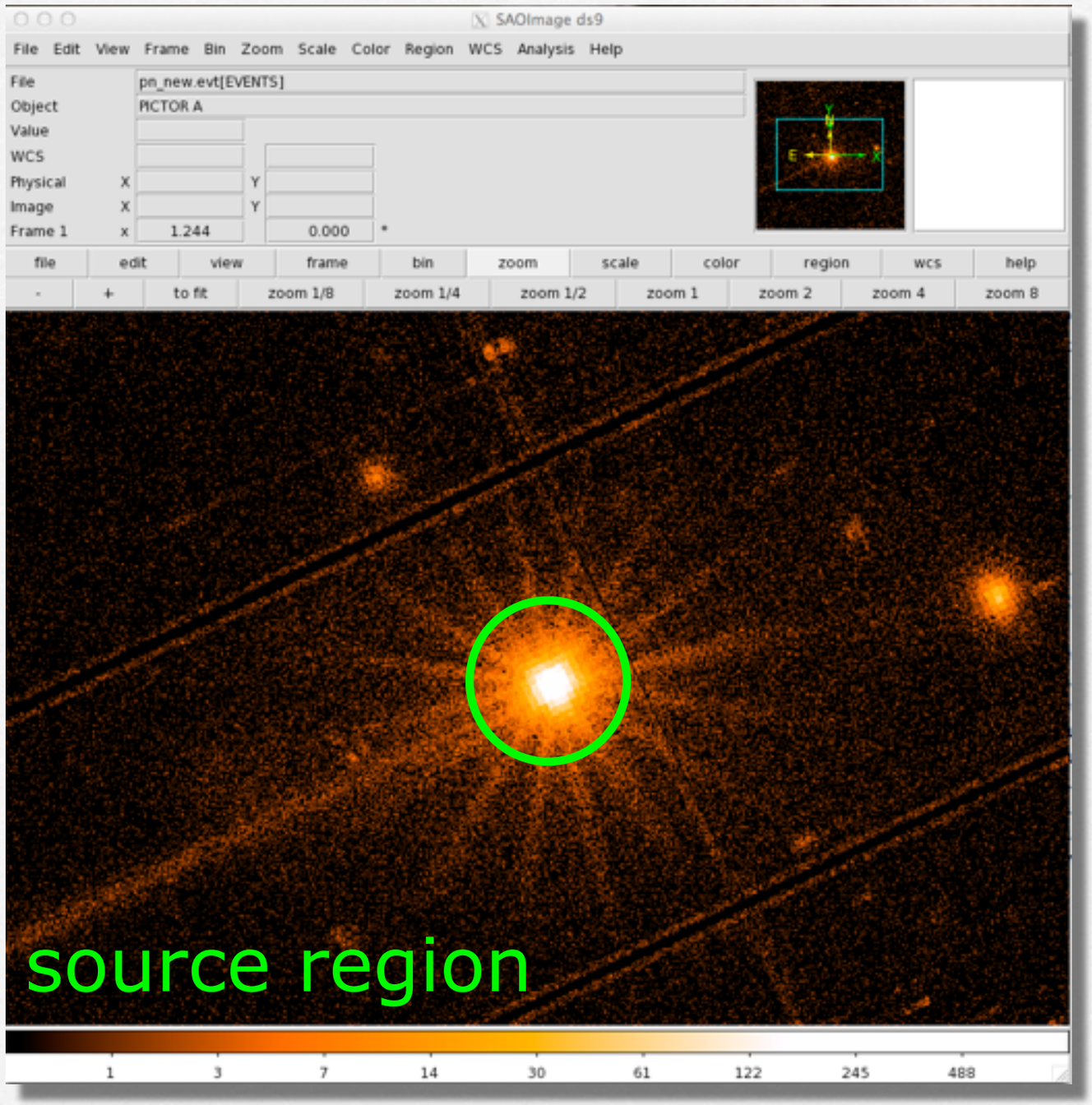
3. Extraction of a light curve from a point-like source

Source and background regions selection

open event list file with ds9

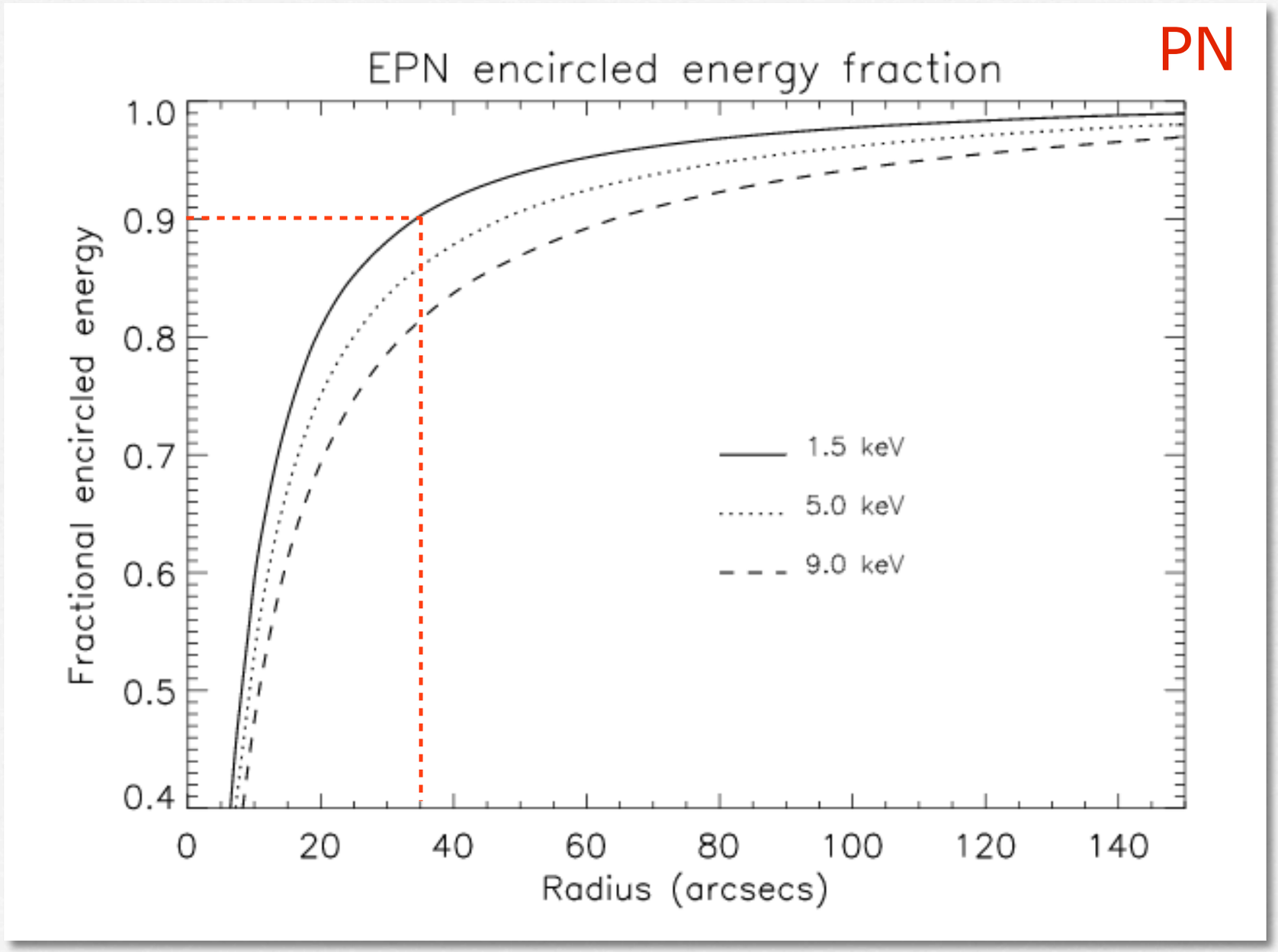
> ds9 pn_new.evt &



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

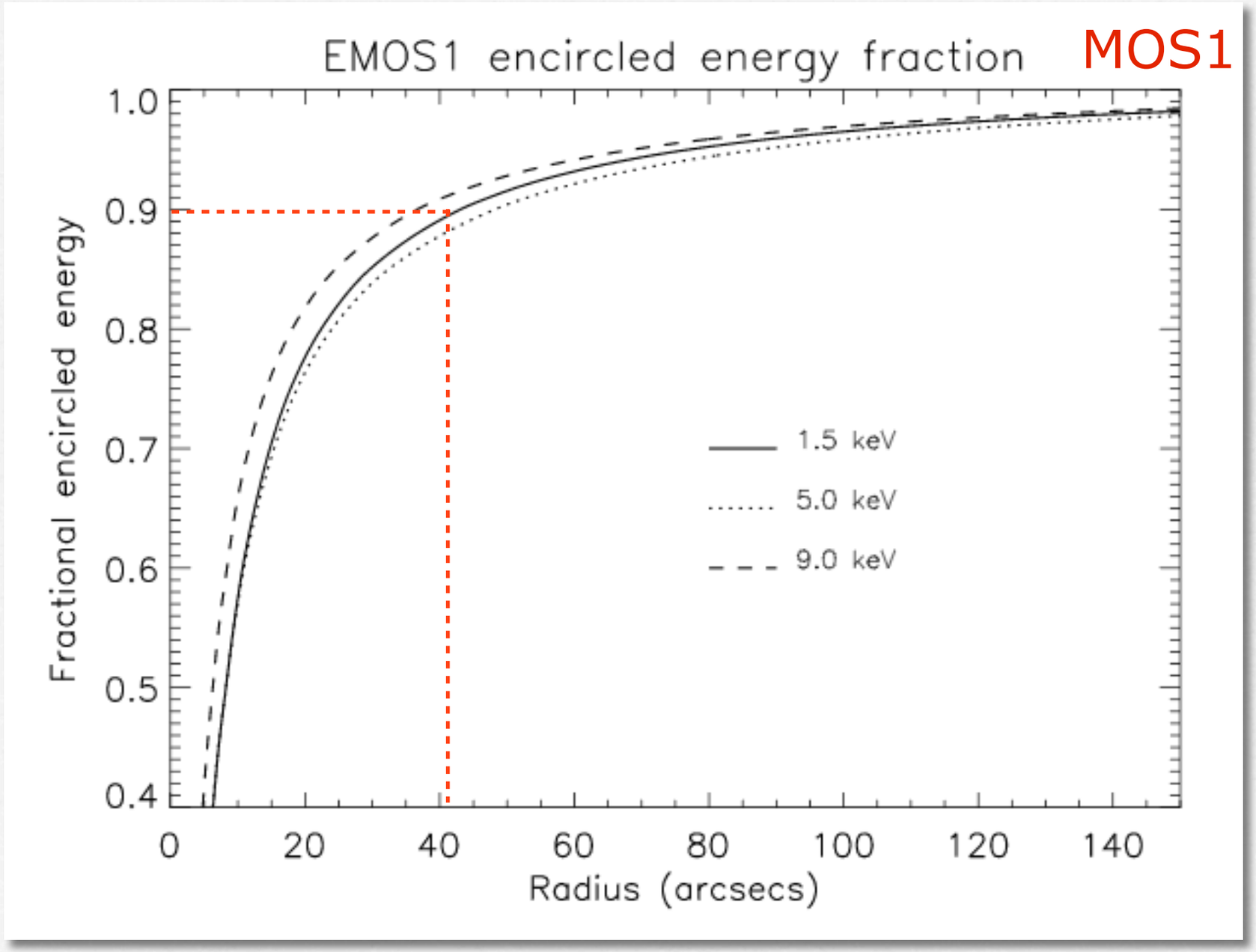
Fractional encircled energy

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



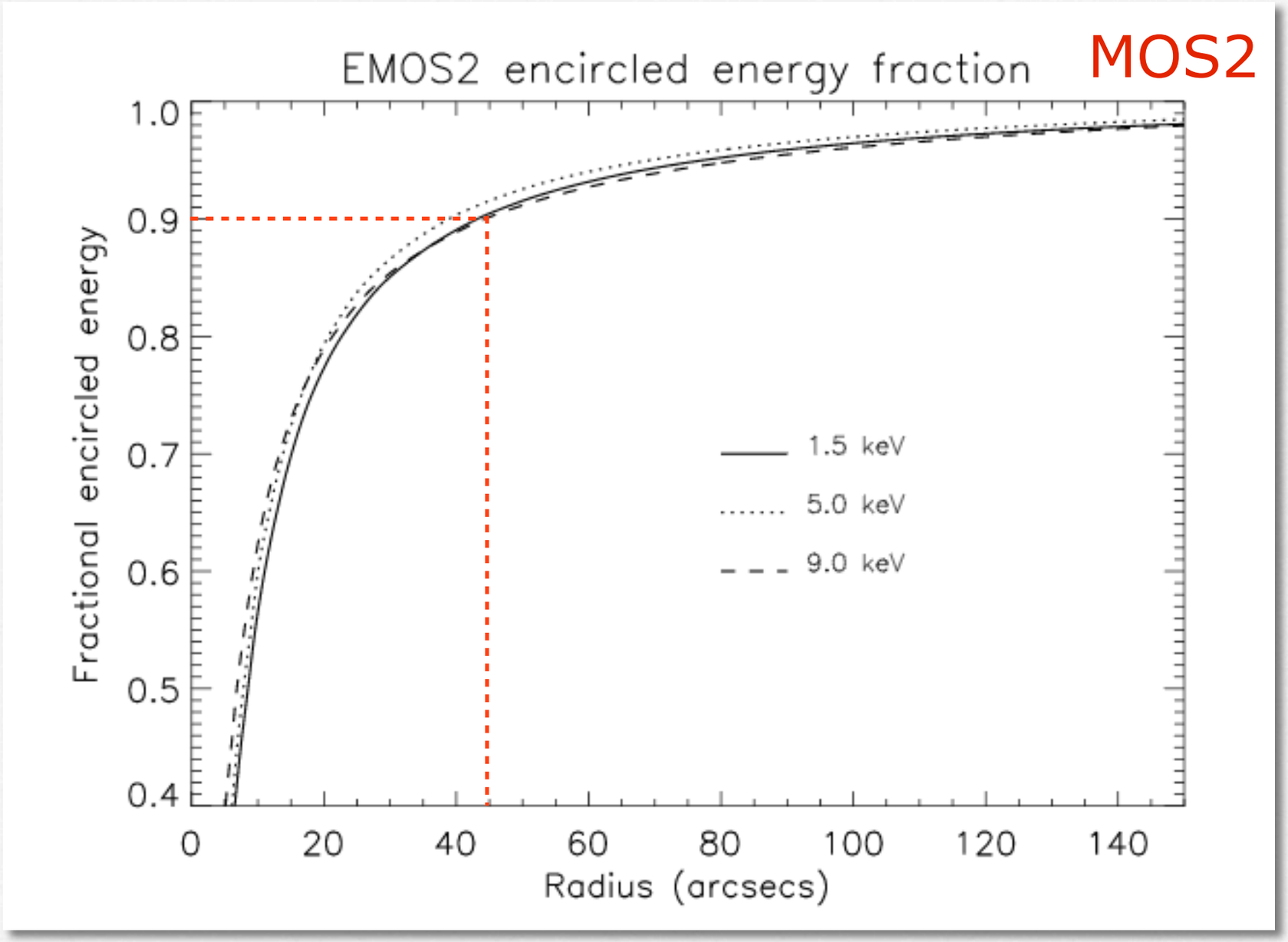
Fractional encircled energy

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



Fractional encircled energy

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



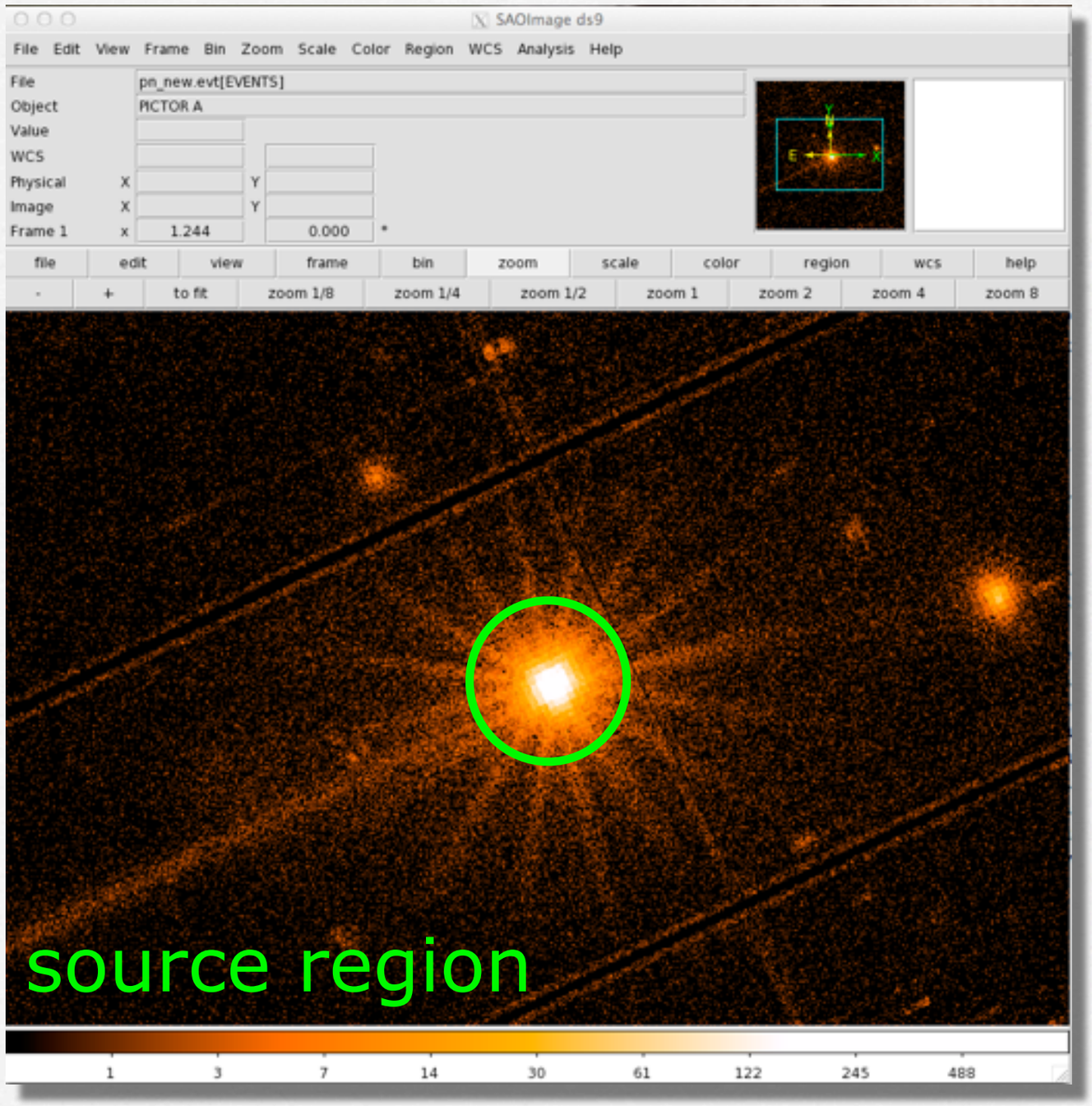
Source and background regions selection

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/

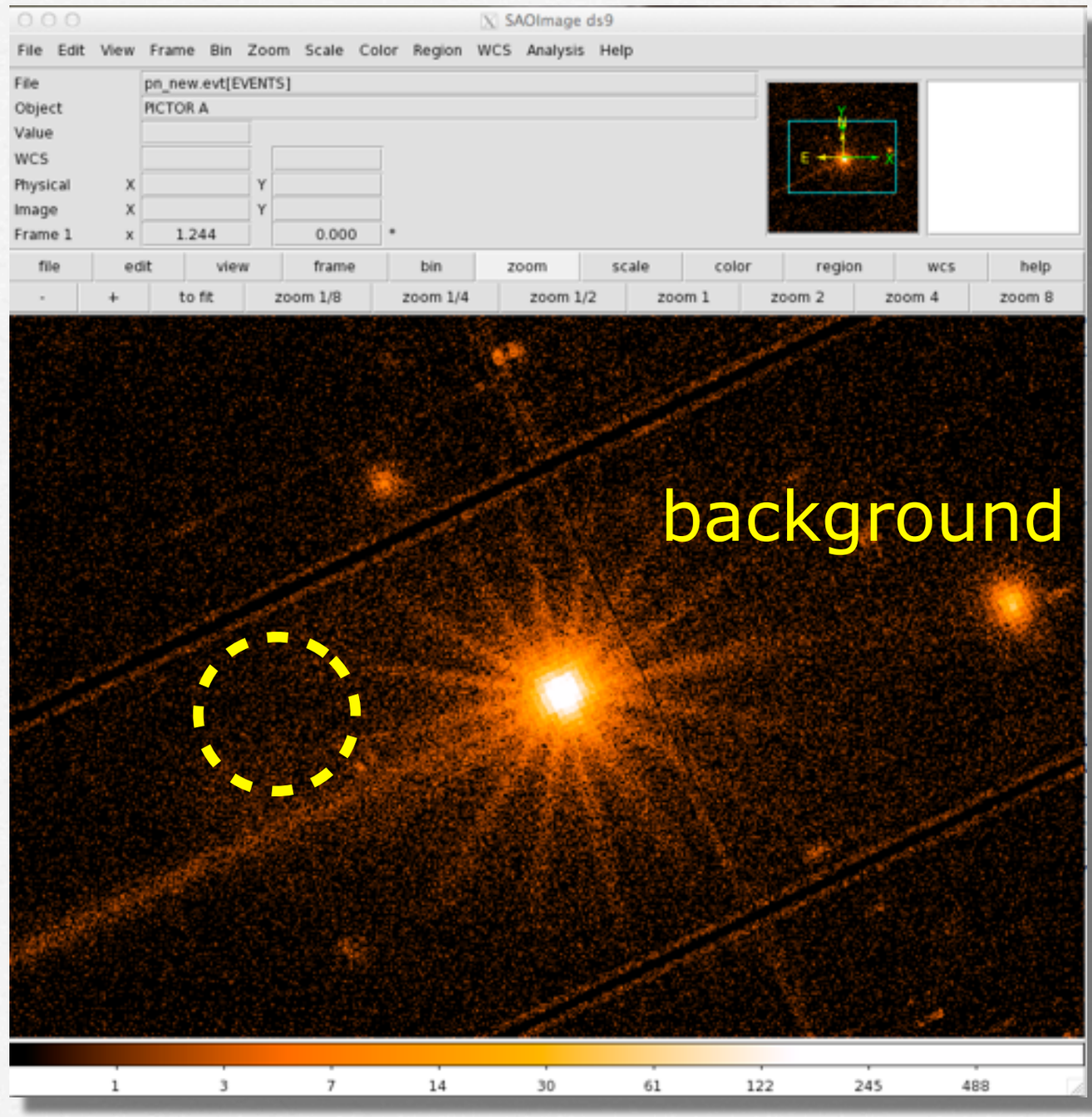


Source and background regions selection

open event list file with ds9

> ds9 pn_new.evt &

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



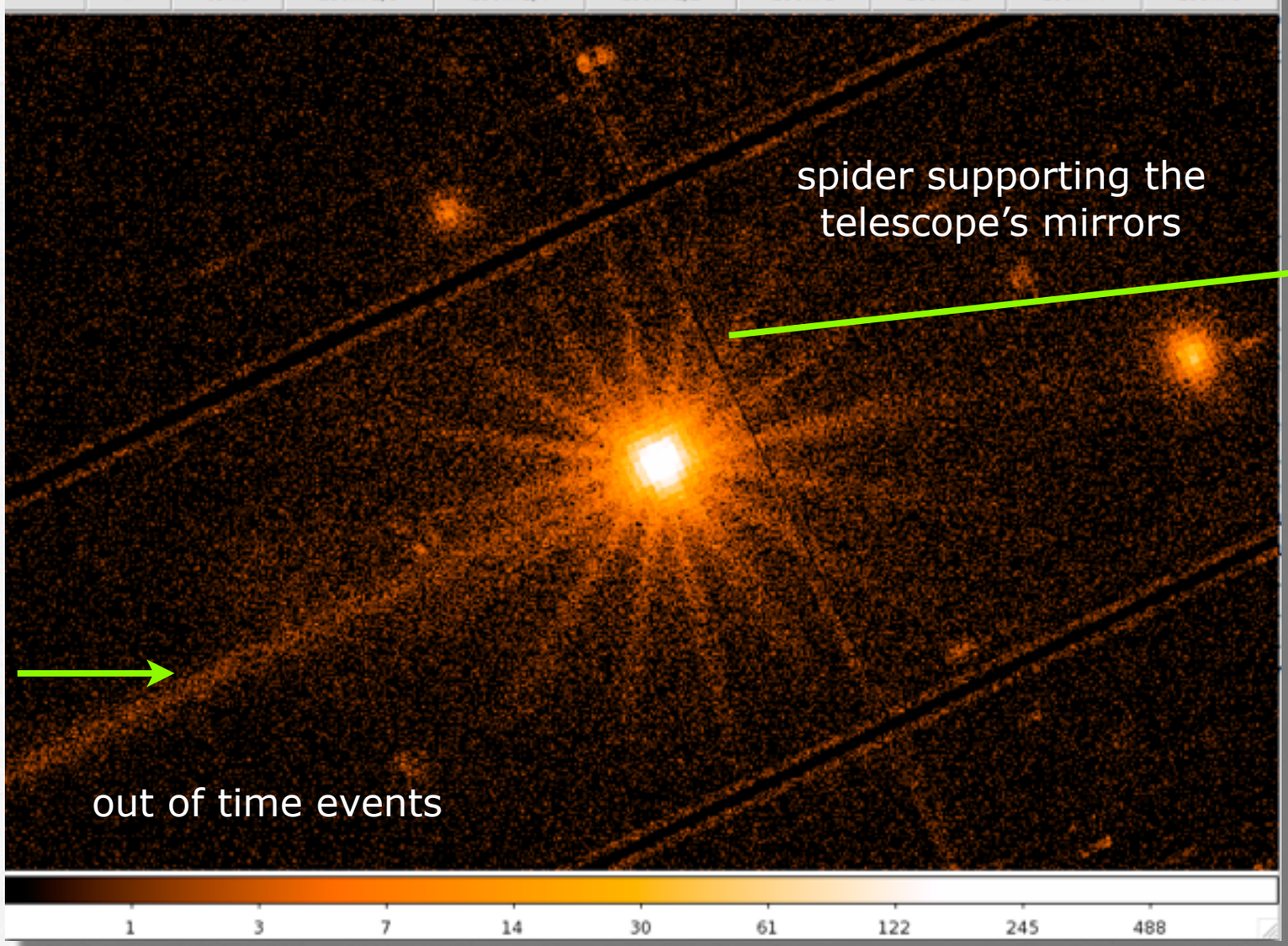
SAOImage ds9

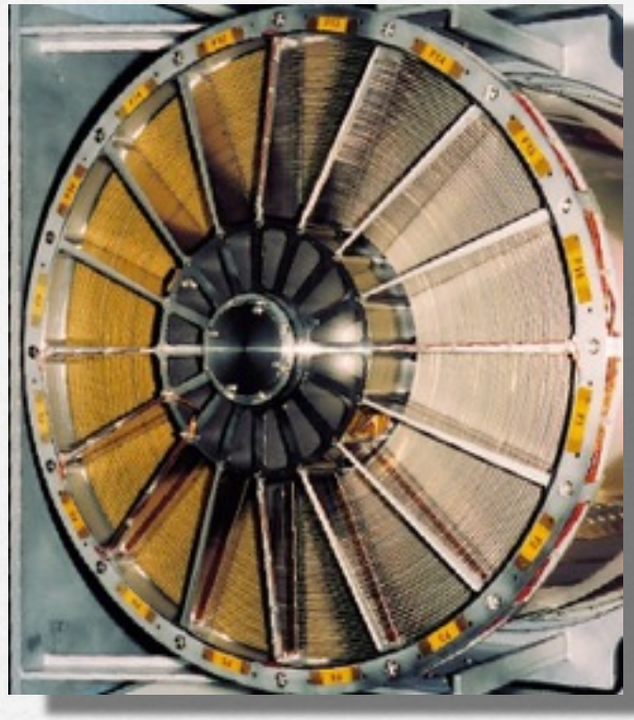
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help

File	pn_new.evt[EVENTS]			
Object	PICTOR A			
Value				
WCS				
Physical	X		Y	
Image	X		Y	
Frame 1	x	1.244	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





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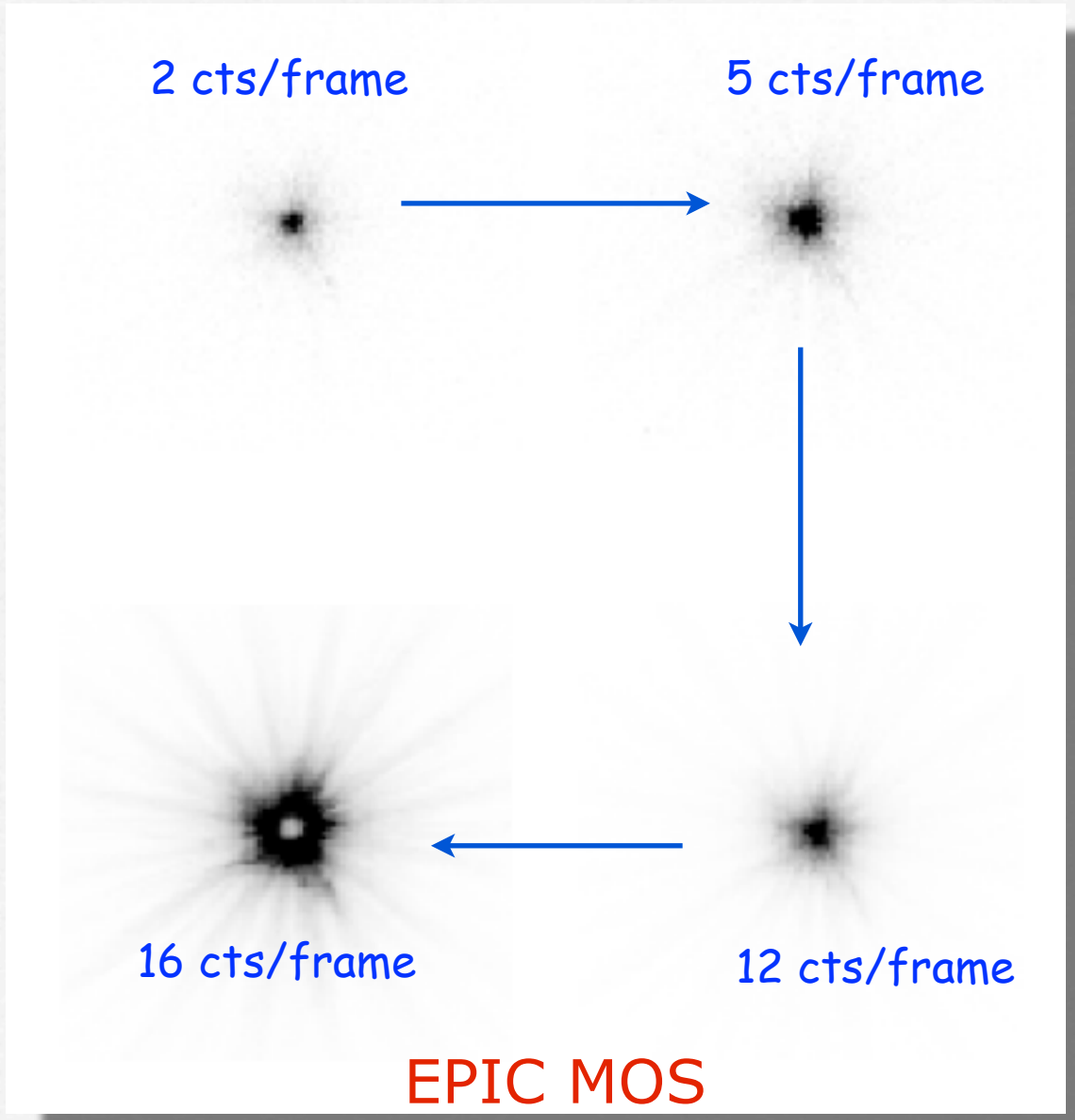
PILE-UP

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)

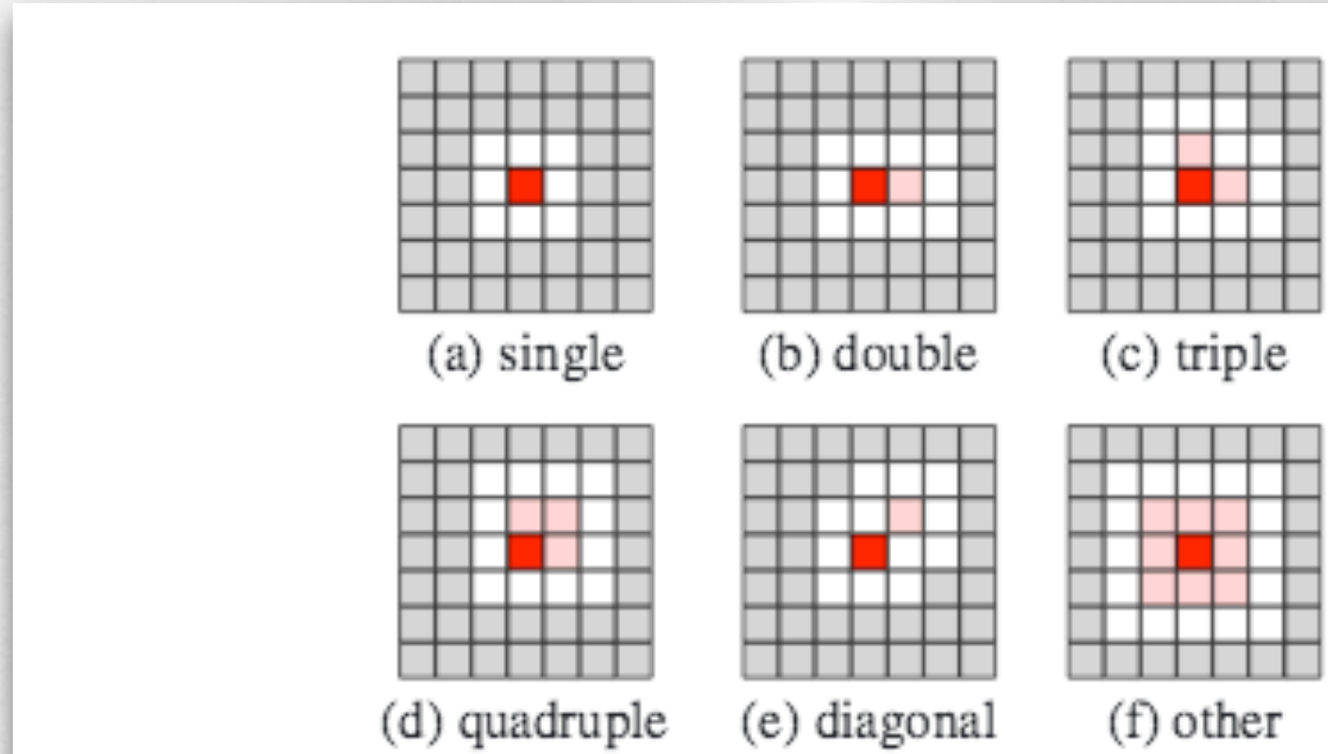


Fig. 1. Examples of EPIC pattern classifications. In each case the dark red pixel contains maximum charge, light red pixels have charge above a threshold value whereas white pixels are necessarily below this threshold. Grey pixels do not influence the pattern classification of the event.

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)

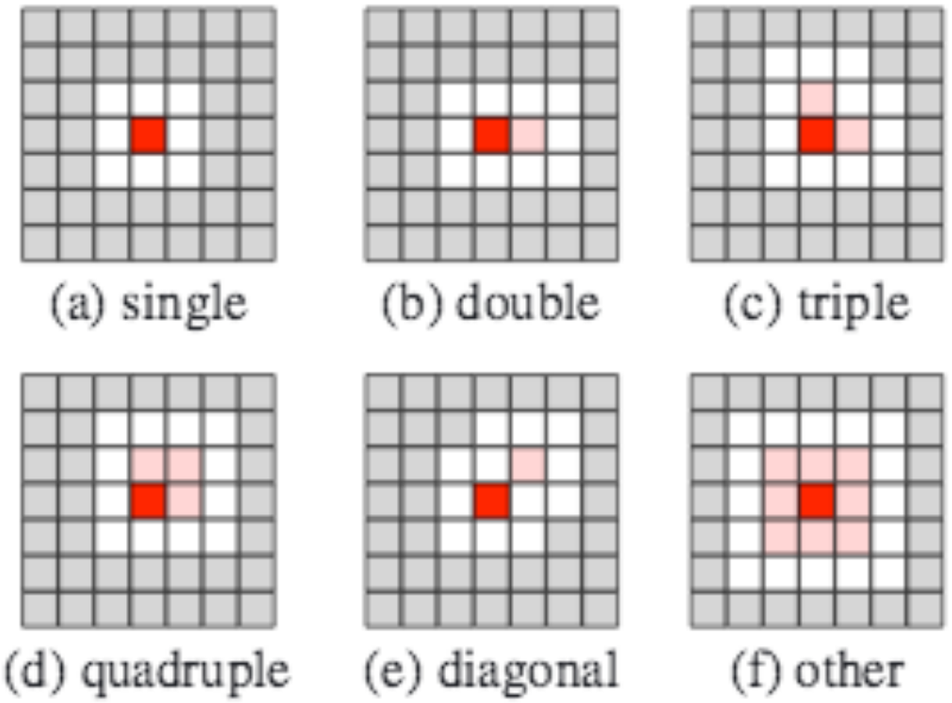
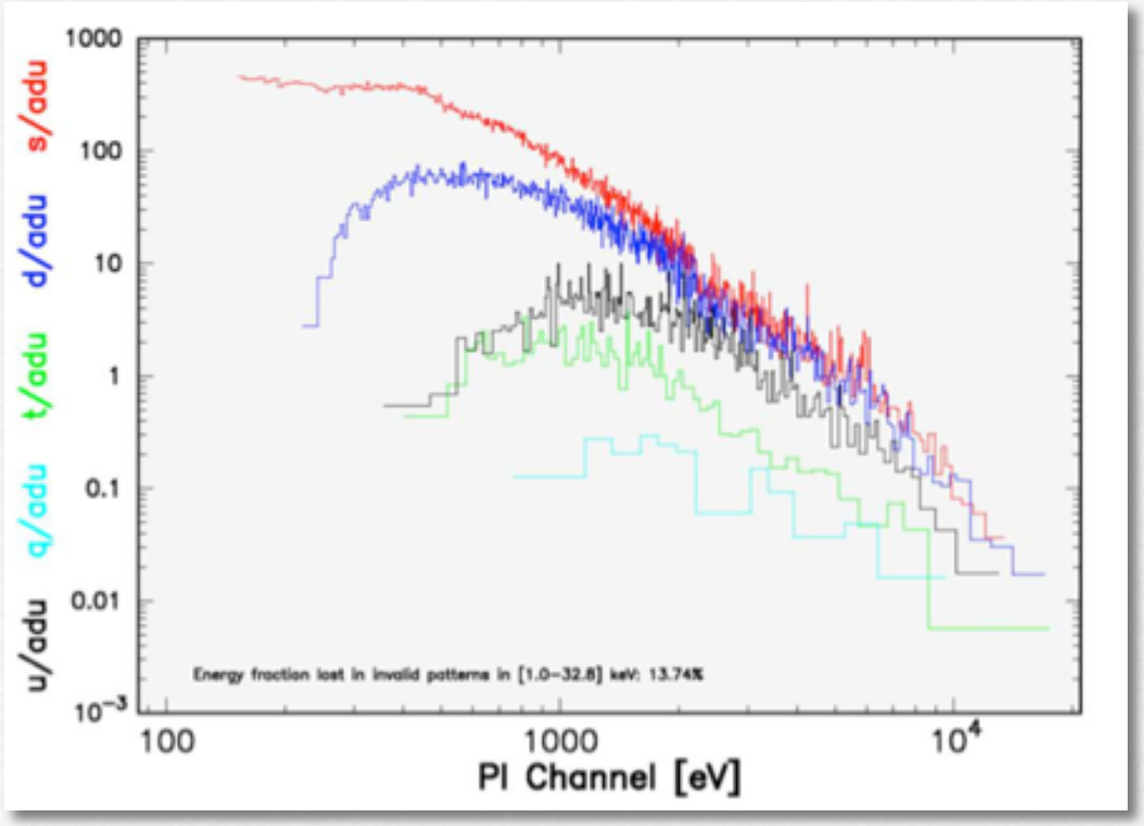


Fig. 1. Examples of EPIC pattern classifications. In each case the dark red pixel contains maximum charge, light red pixels have charge above a threshold value whereas white pixels are necessarily below this threshold. Grey pixels do not influence the pattern classification of the event.

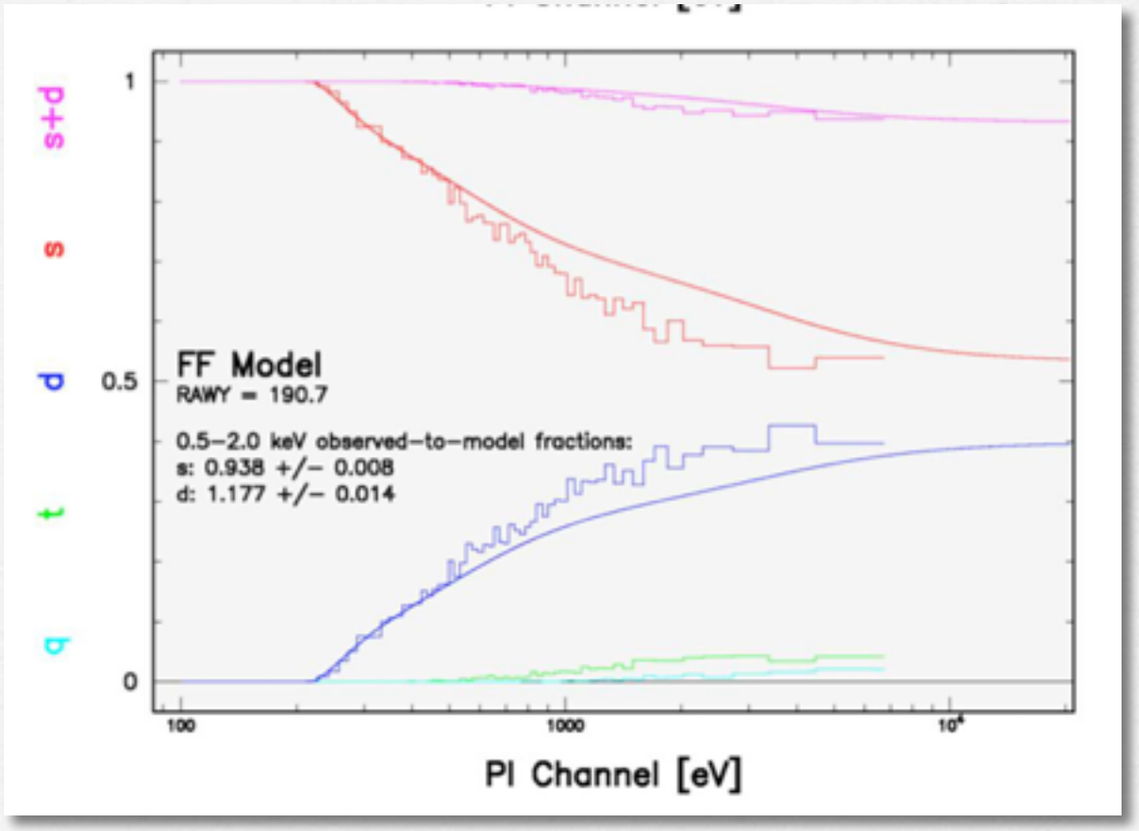
Double events can be produced only if the energy of both events is above the event threshold. Triple (quadruples) events start at 3 (4) times the event threshold.

```
> 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

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Creation of the Redistribution Matrix File (RMF)

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

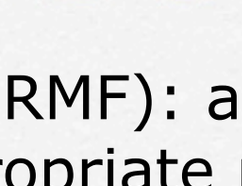
The Redistribution Matrix File (RMF): associates to each instrument channel (I) the appropriate photon energy (E)

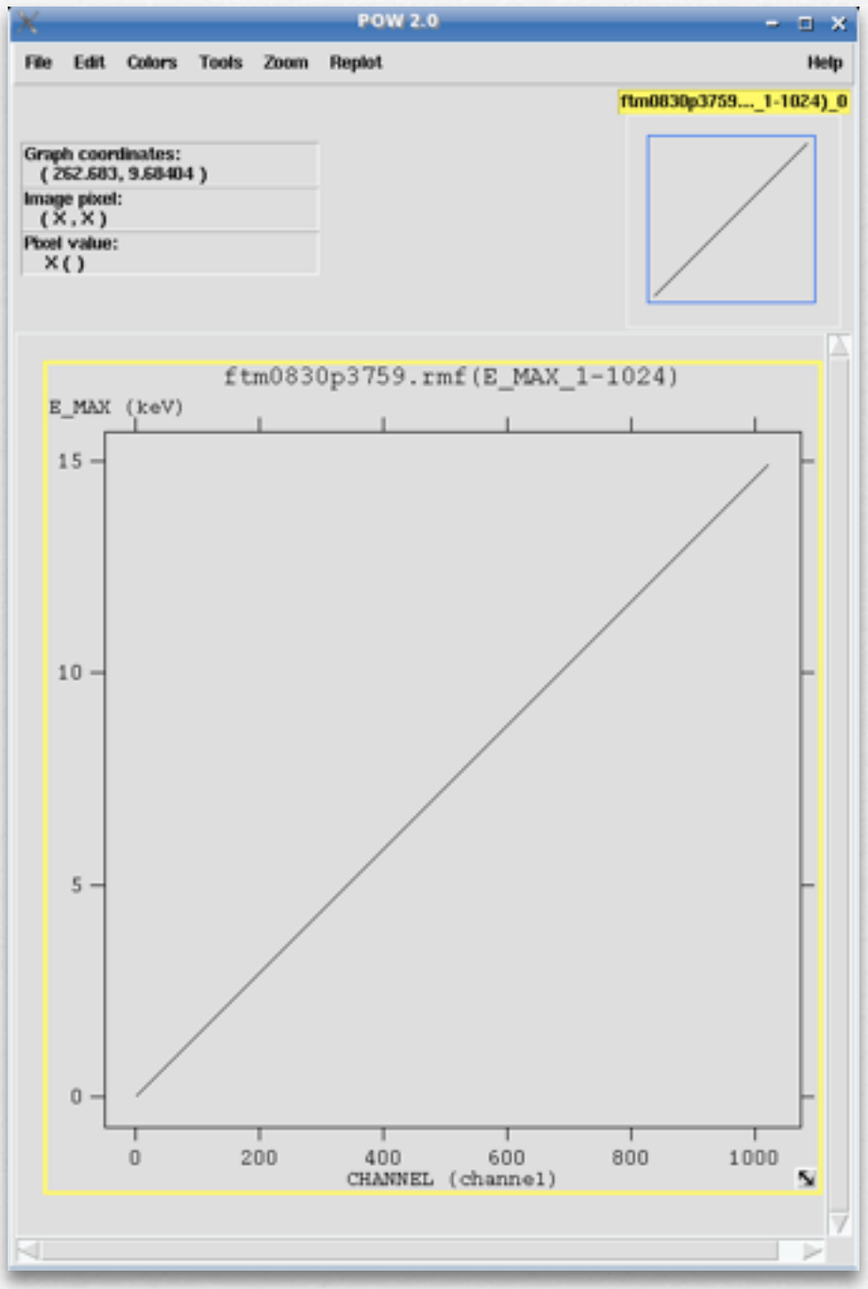
fv: Binary Table of ftm0830p3759.rmf[2] in /ho

File Edit Tools Help

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

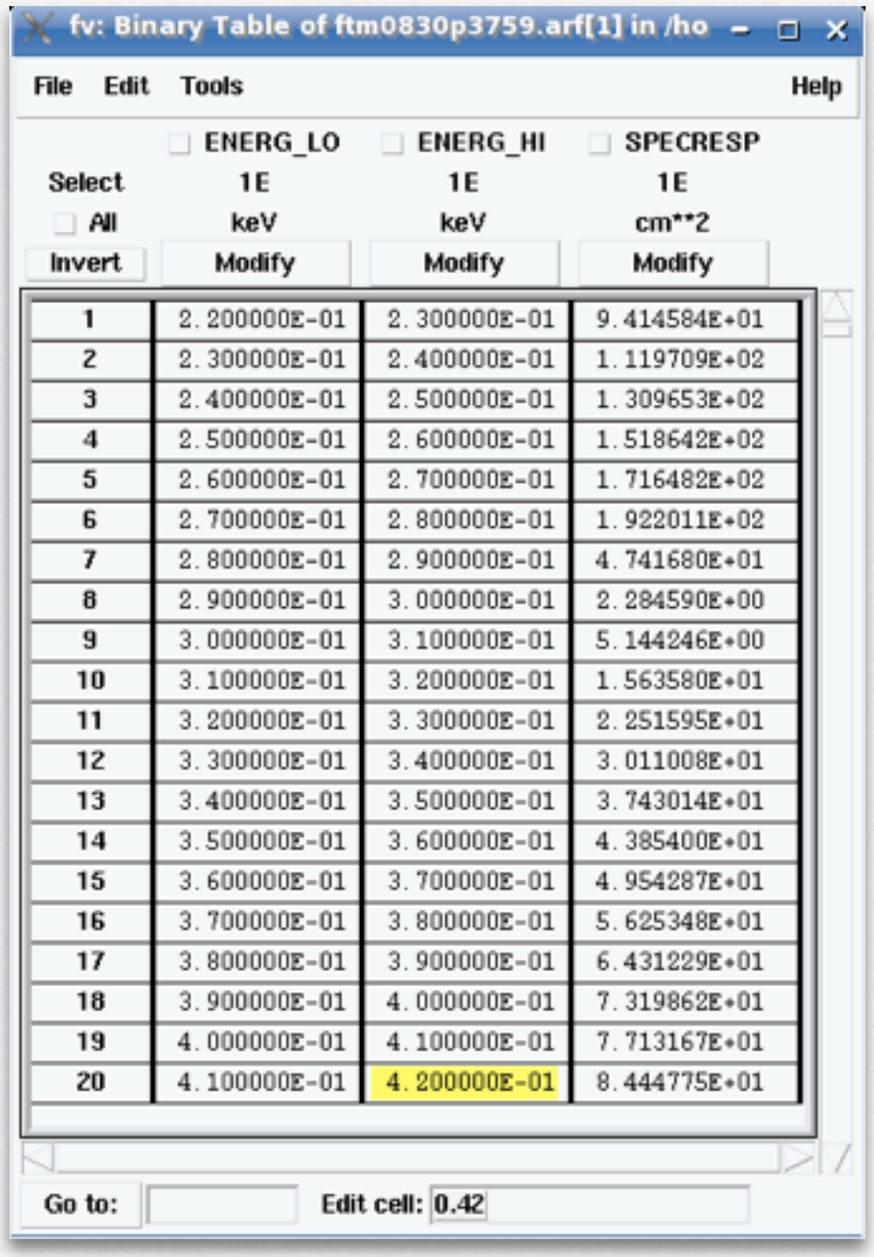


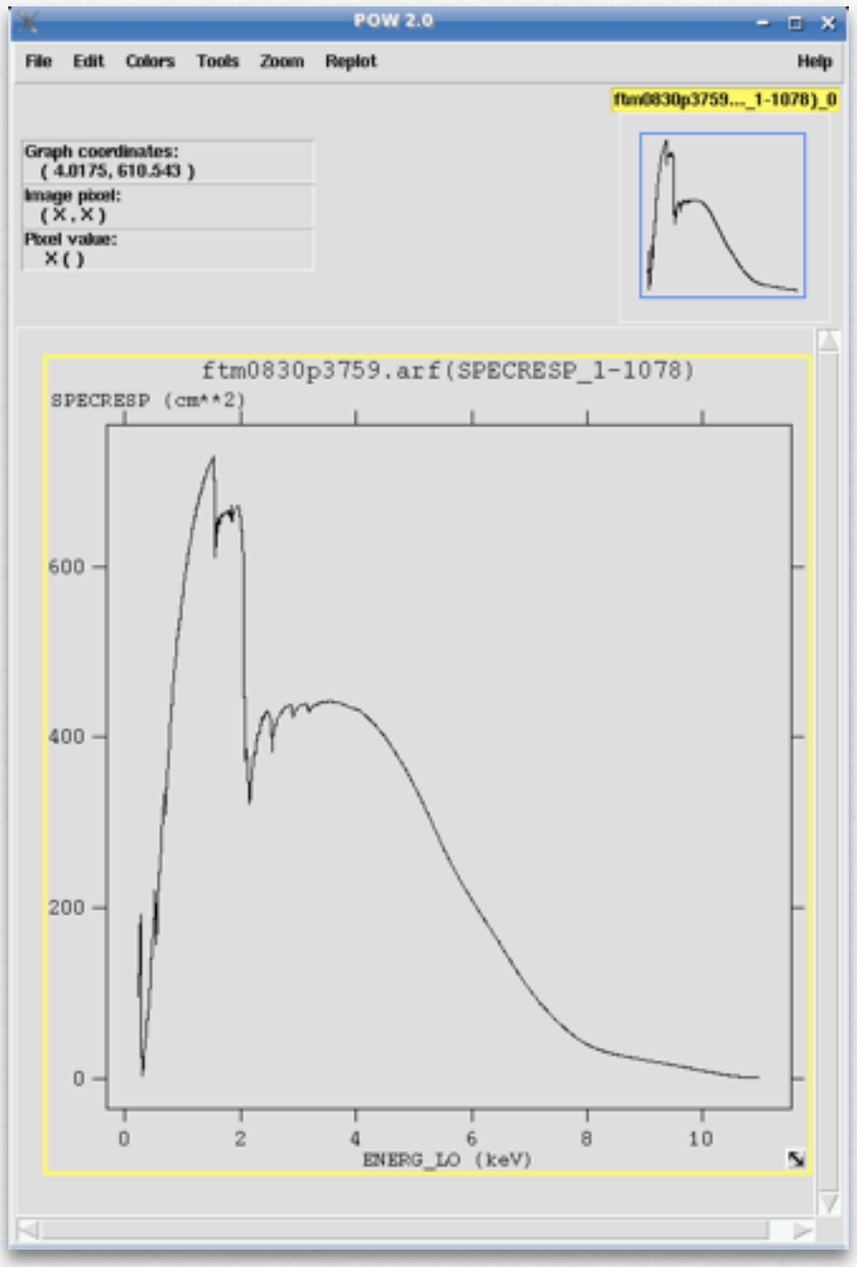


Creation of the Auxiliary Response File (ARF)

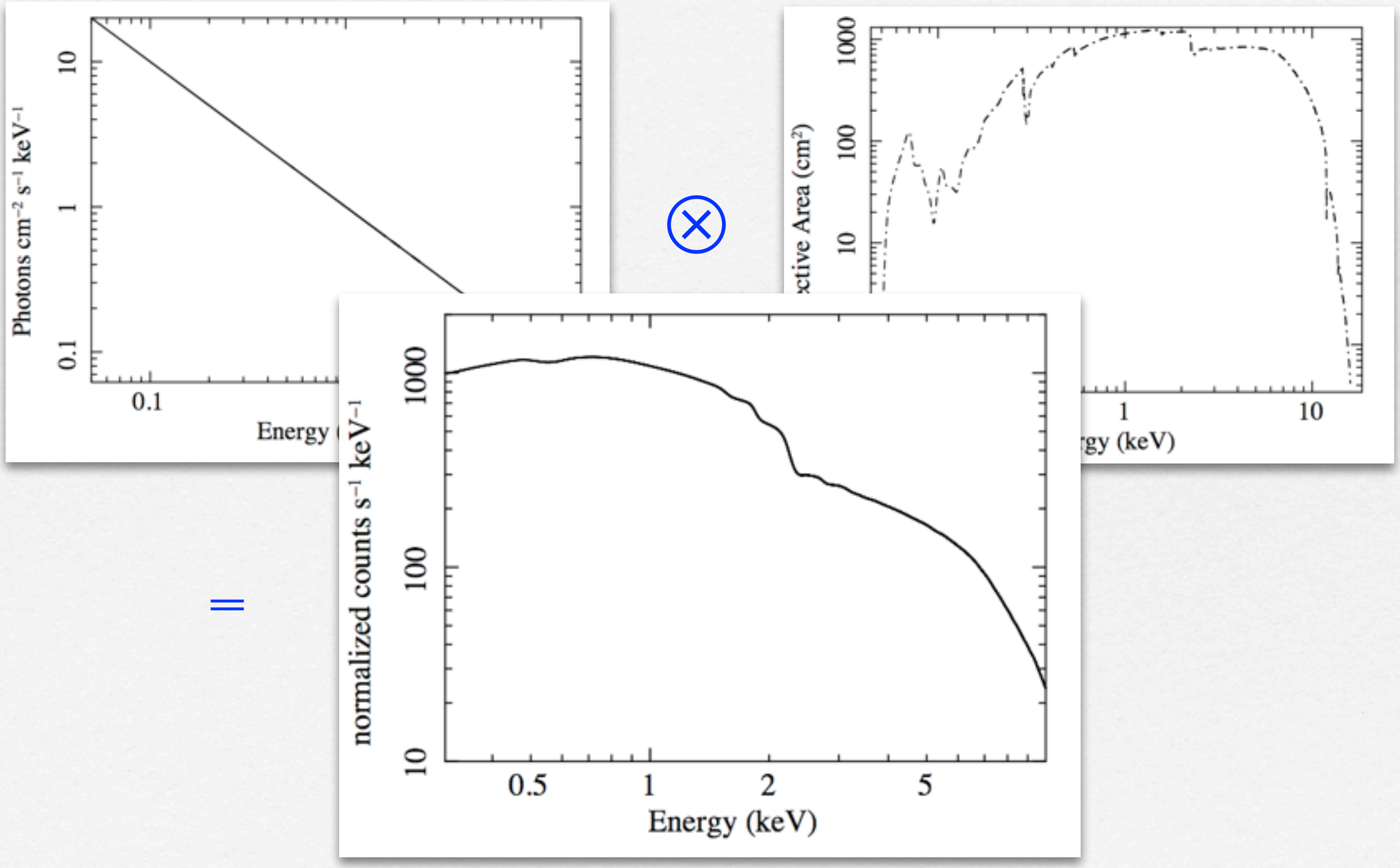
```
arfgen spectrumset=source_spectrum.fits arfset=pn.arf
withrmfset=yes rmfset=pn.rmf badpixlocation=pn_new.evt
detmaptype=psf
```

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.



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"
```

LabX2017

> 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 in pile up in un'osservazione XMM

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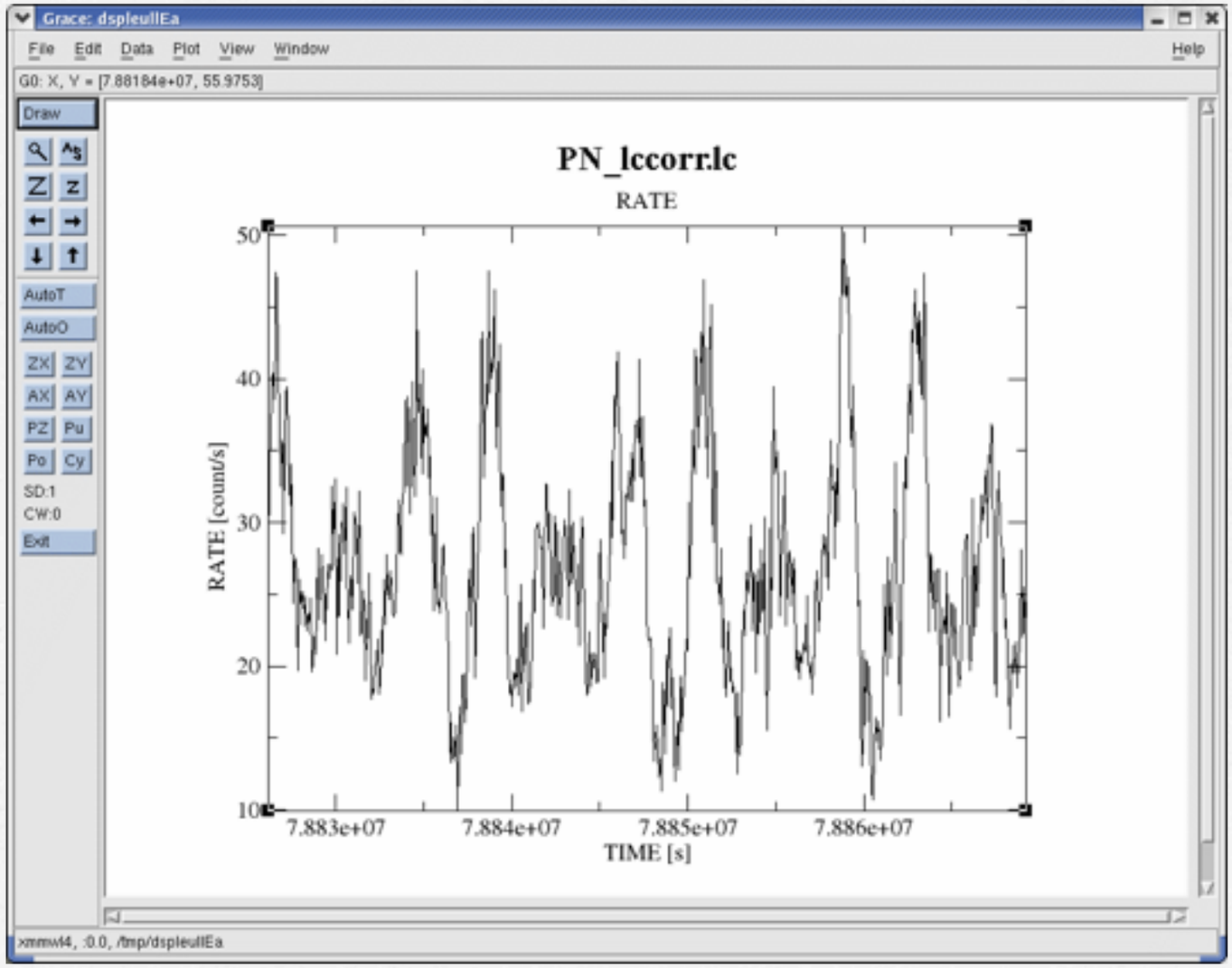
EXTRACTION OF A LIGHT CURVE FROM A POINT-LIKE SOURCE

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:

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

c_i observed counts in every temporal bin i;
σ_i Poissonian error;
<c> average count during the observation;
ν**=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

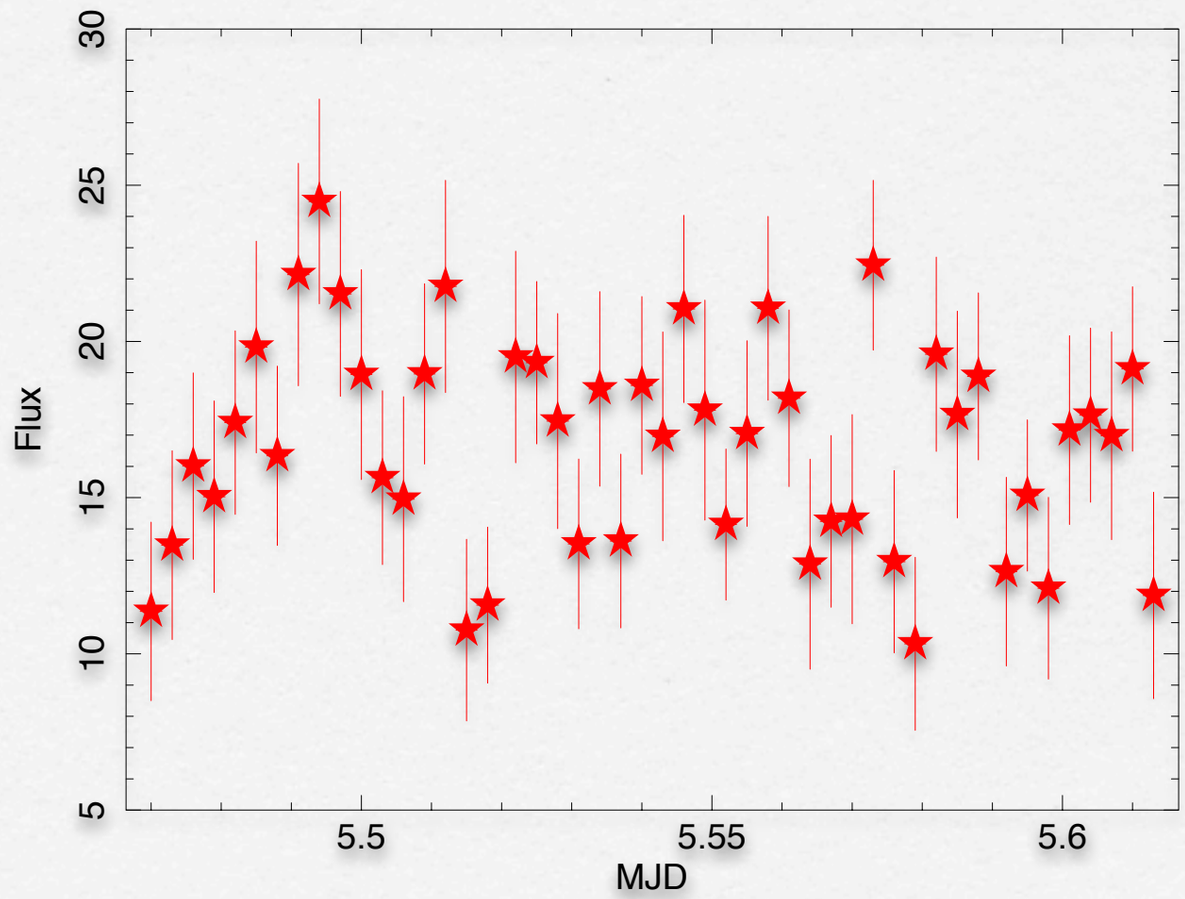
```
evselect table=pn_new.evt energycolumn=PI expression='#XMMEA_EP[M] && (PATTERN<=4[12]) && ((X,Y) IN circle(source.reg)) && (PI in [200:10000])' withrateset=yes rateset="PN_source_lc_raw.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes
```

- 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
```



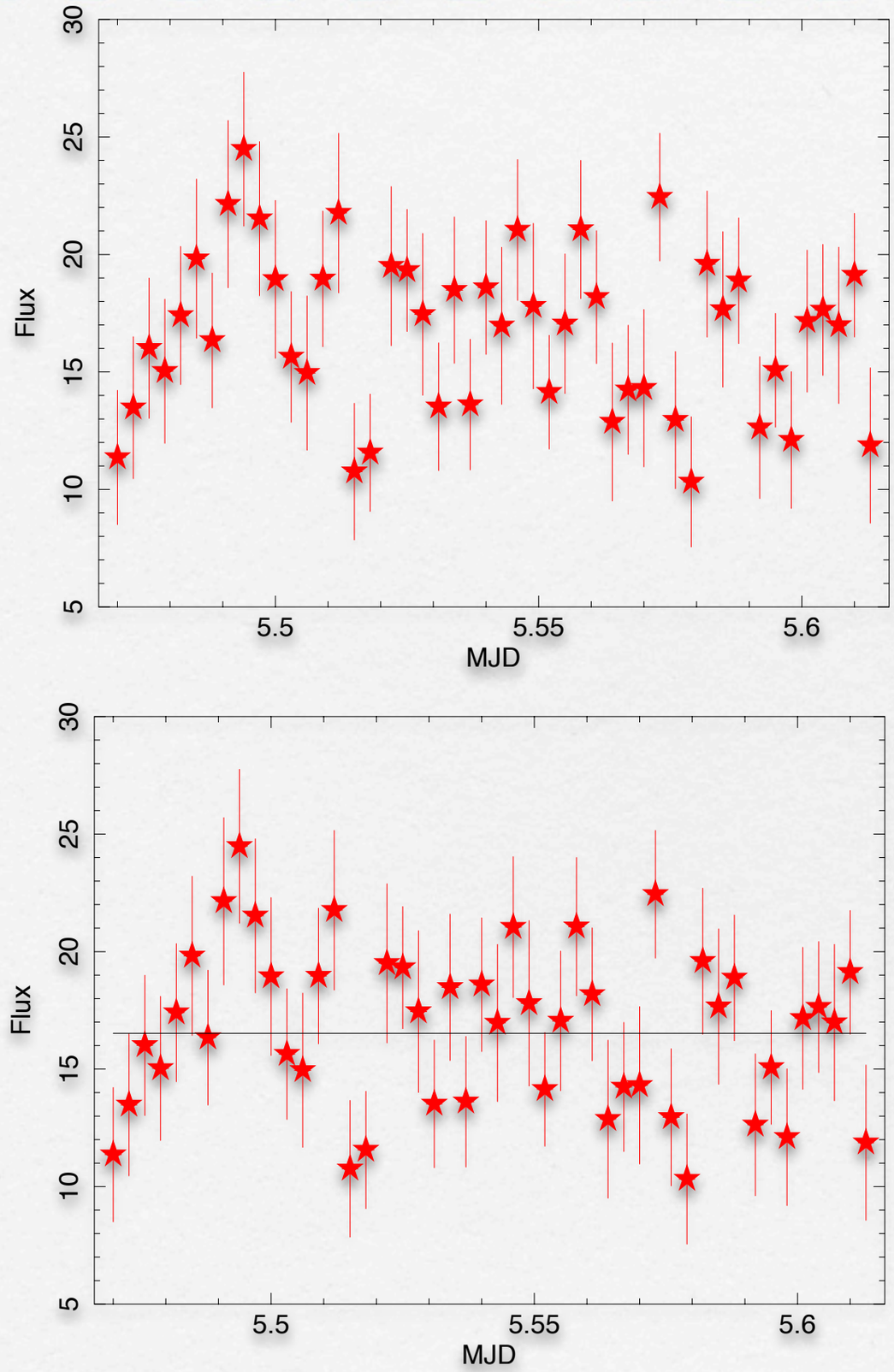
Example:

> 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

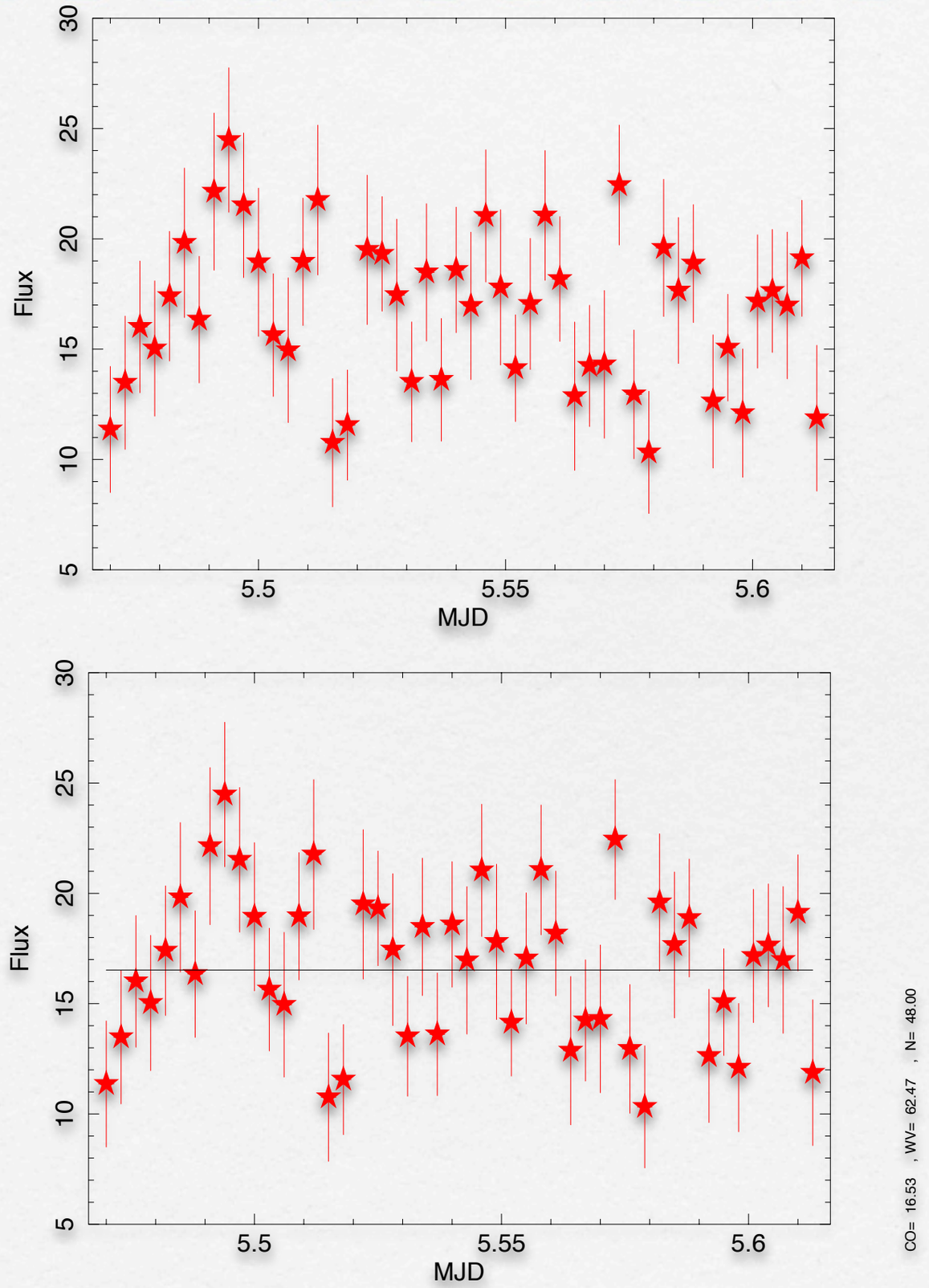
Example:

> 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%