There is life after the event lists

Generation of scientific products with SAS

Matteo Guainazzi

(*with contributions by* ***Matthias Ehle***[*(EPIC scientific products)*], ***Carlos Gabriel***[*(source detection)*], ***Rosario Gonzalez-Riestra***[*(RGS)*], ***Antonio Martin-Carrillo***[*(Timing Modes)*], ***Richard Saxton***[*(source catalogs)*])

European Space Astronomy Centre of ESA

Villafranca del Castillo, Spain

XMM-Newton

Science Operations Departement

XMM-Newton Science Operations Center

Important announcement

This is the announcement

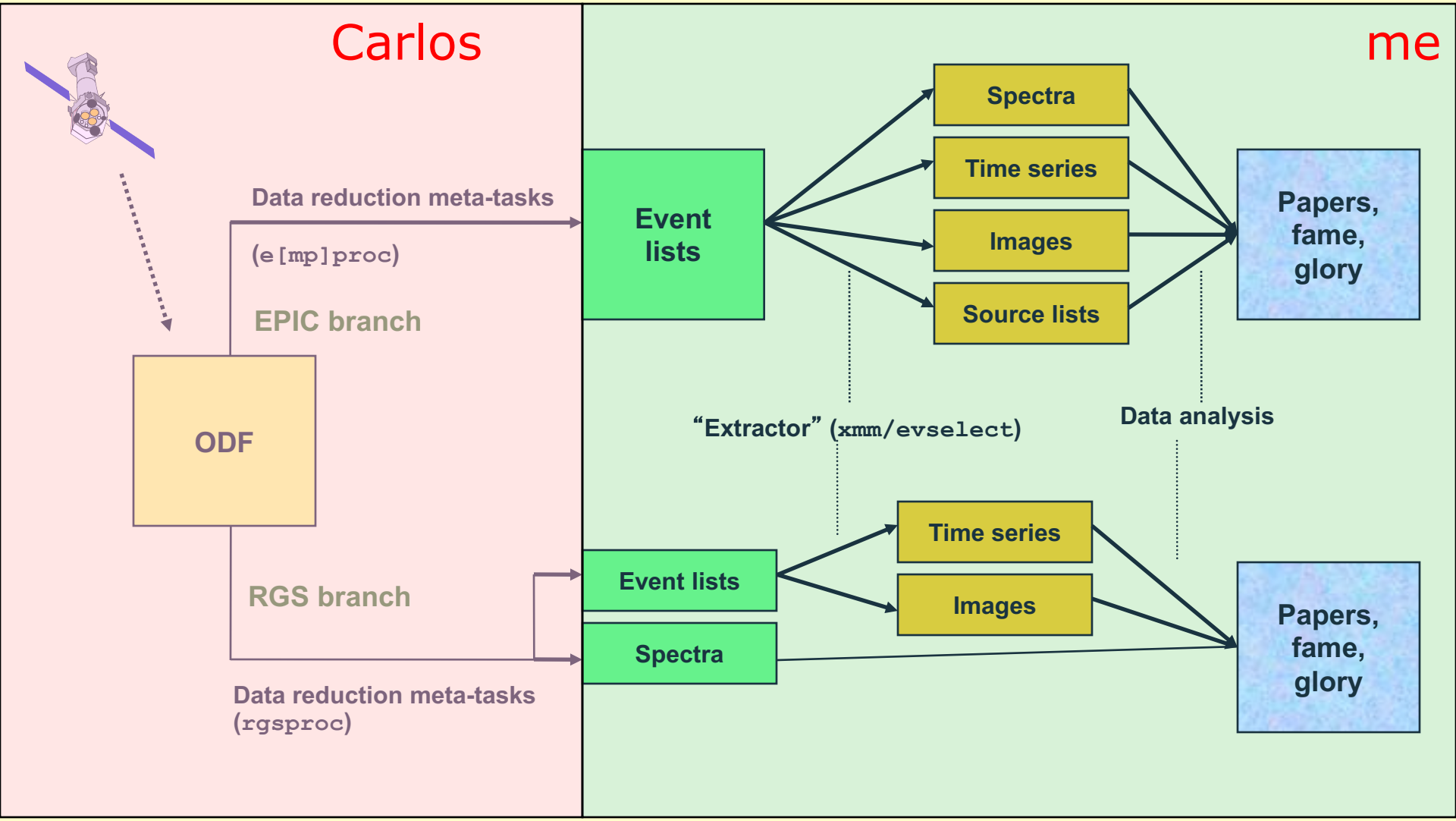
Almost any reduction tasks you may want to accomplish with Chandra or XMM-Newton data is explained in the **data analysis "threads"**

CIAO: `http://cxc.harvard.edu/ciao/threads/index.html`

SAS: `http://xmm.esac.esa.int/sas/current/documentation/threads/`

In this talk I will show you examples of what you can find in the **SAS threads**, pointing to their link

The XMM-Newton grand-scheme



Event lists

When? Where [position]? Who [energy]? What [X-ray or particle]?

	TIME D s	X J 0.05 ARCSECONDS	Y J 0.05 ARCSECONDS	PHA I CHAN	PI I CHAN	PATTERN B	CCDNR B
1	9.506202266412E+07	23743	21330	423	1447	2	1
2	9.506202266412E+07	28728	21990	25	98	0	1
3	9.506202527717E+07	28176	31623	25	97	0	1
4	9.506202527717E+07	29829	30841	327	1131	0	1
5	9.506202527717E+07	23686	19319	541	1854	0	1
6	9.506203046611E+07	25510	32711	1810	6171	0	1
7	9.506203566620E+07	29814	28823	102	360	0	1
8	9.506203826626E+07	26635	30601	2062	7028	0	1
9	9.506204346625E+07	26429	20314	443	1519	4	1
10	9.506204606629E+07	20691	28728	1608	5471	3	1
11	9.506204606629E+07	27989	29777	202	700	0	1
12	9.506204606629E+07	21937	25667	117	402	2	1
13	9.506204866632E+07	28132	32491	462	1589	0	1
14	9.506204866632E+07	27204	29741	904	3095	0	1
15	9.506205126638E+07	22124	20257	290	994	0	1
16	9.506205906643E+07	23193	18795	1398	4771	0	1
17	9.506206166646E+07	23224	19326	276	950	0	1
18	9.506206946653E+07	27755	28979	183	637	0	1
19	9.506207206939E+07	22533	29563	33	118	0	1

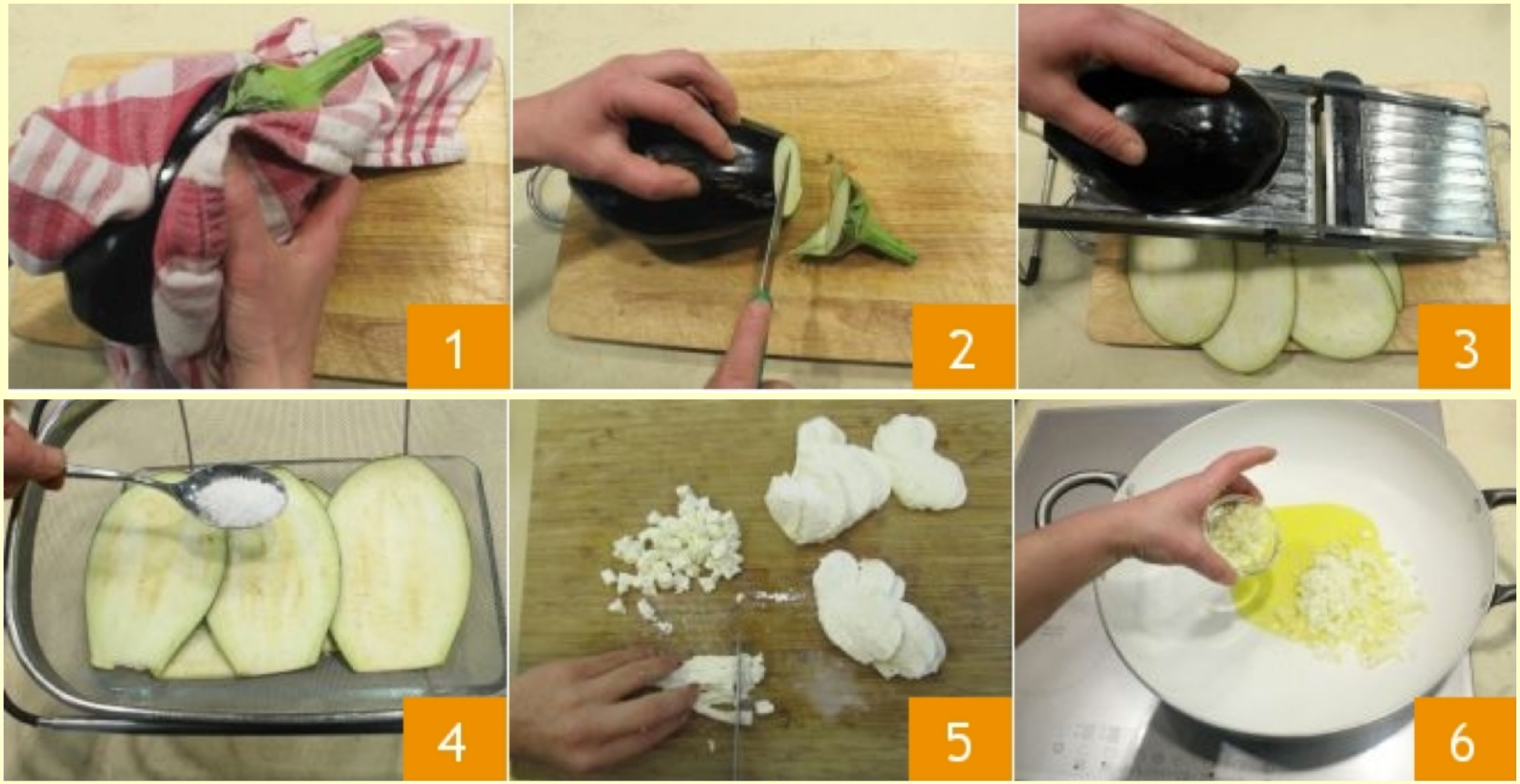
Lecture content

1. How to create EPIC scientific products (spectra, light curves, images)
2. [Interlude: How to optimize the signal-to-noise ratio of your EPIC spectra and images]
3. How to deal with background
4. How to deal with pile-up in EPIC
5. How to calculate the instrument responses (EPIC, and RGS) – `R(I,E)` amd `A(E)` in K.Arnaud's talk
6. `rgsproc` extracts RGS spectra automatically for me (you remember this, don't you?). Can I trust them?

Lecture content

How to create EPIC scientific products

(spectra, light curves, images)



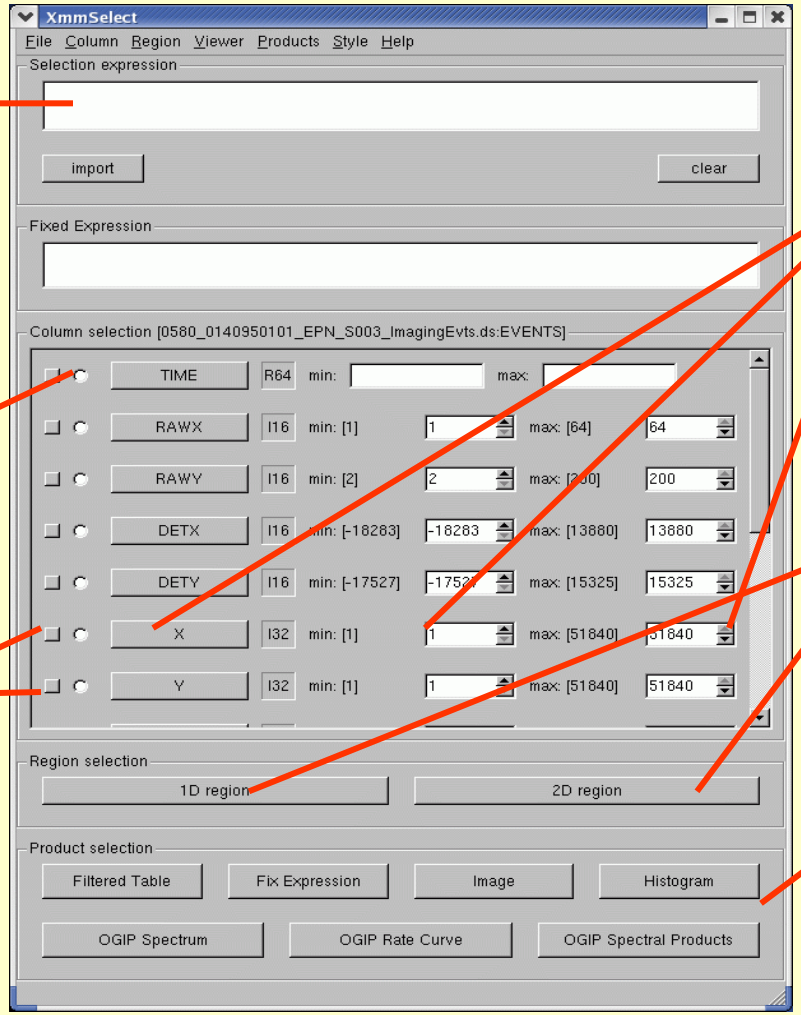
The SAS extractor

```
$> xmmselect table=${event_list} &
```

Here the selection expression is defined.

Circles are used to define the quantities to extract spectra, light curves, histograms.

Checkboxes are used to define the quantities on which to extract an image.

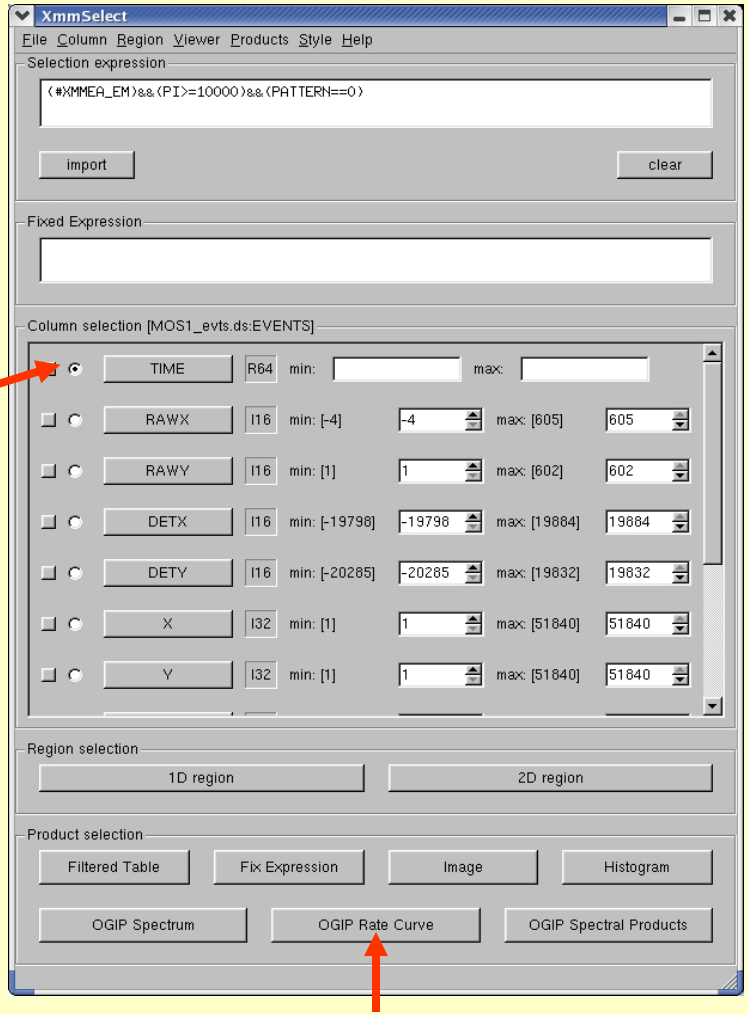


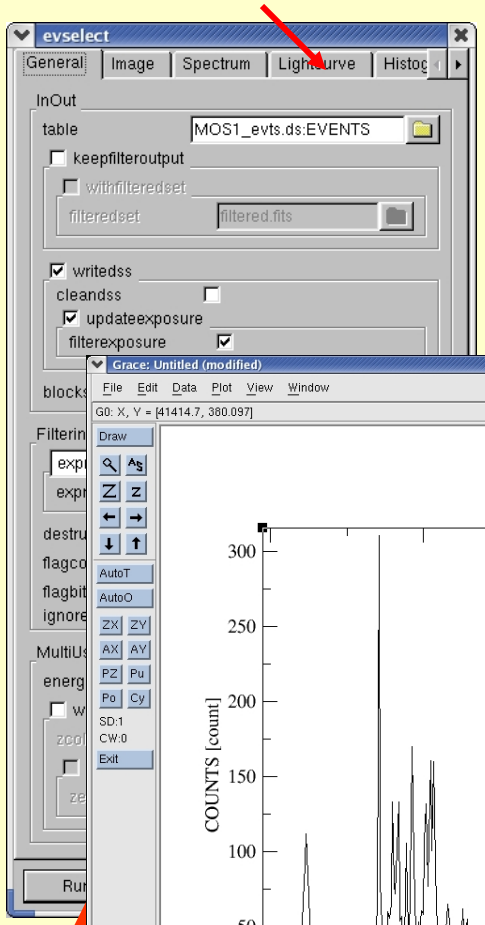
The EVENTS extension columns are listed. Column buttons allow to transfer the ranges defined in the widgets to the selection expression.

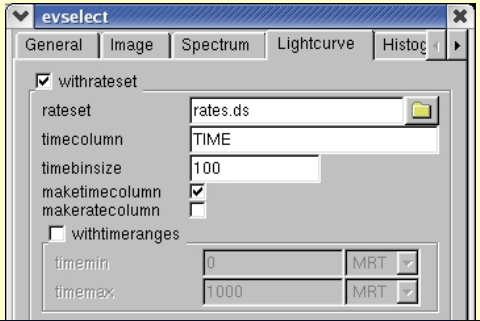
One can transfer selection regions defined in a 1-D or 2-D (image) plots to the selection expression widget

Products which may be extracted: all the above plus filtered event lists.

xmmselect: creation of a rate curve







https://www.cosmos.esa.int/web/xmm-newton/sas-thread-mos-xmmselect-spectrum

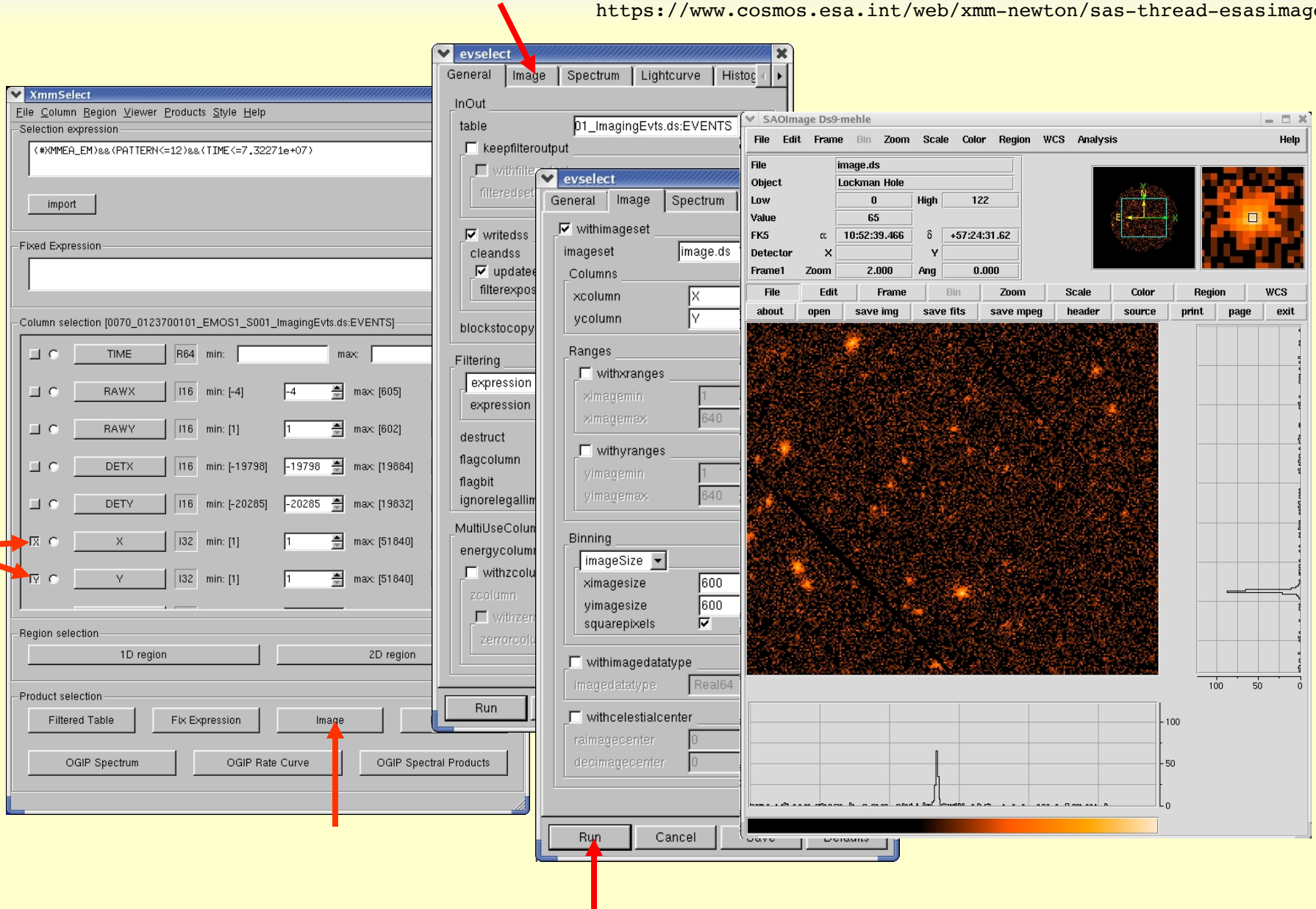
Lecture content

How to create EPIC scientific products

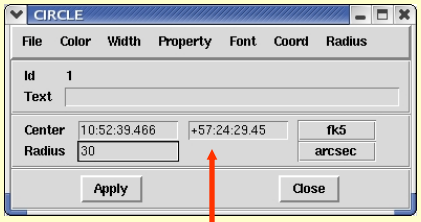
(spectra, light curves, images)

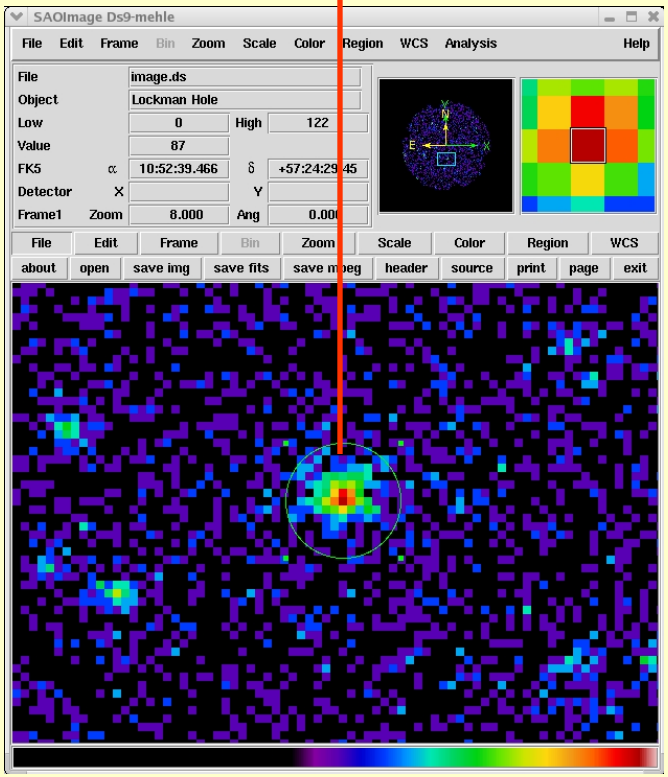
xmmselect: creation of an X-ray image

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



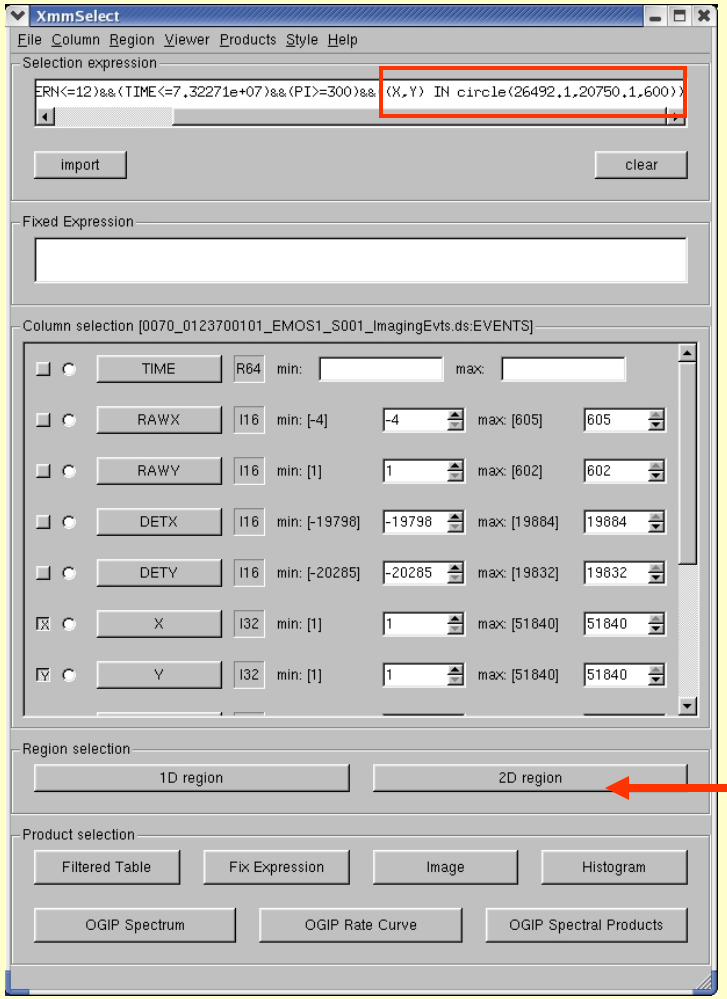
Defining interactively a 2-D spatial region





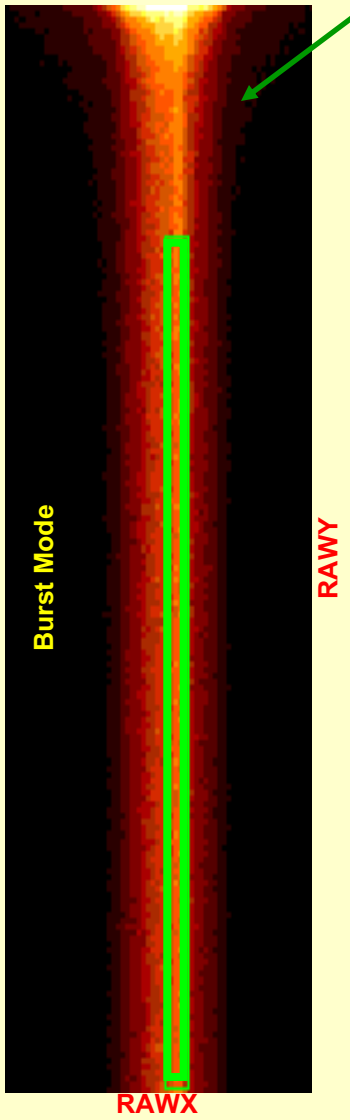
The spatial filter is properly interpreted and ("&&") imported in the selection expression widget!

In `ds9` spatial filters can be selected, defined and modified with the "Region" function



https://www.cosmos.esa.int/web/xmm-newton/sas-thread-pn-xmmselect-spectrum

Source selection in timing EPIC modes

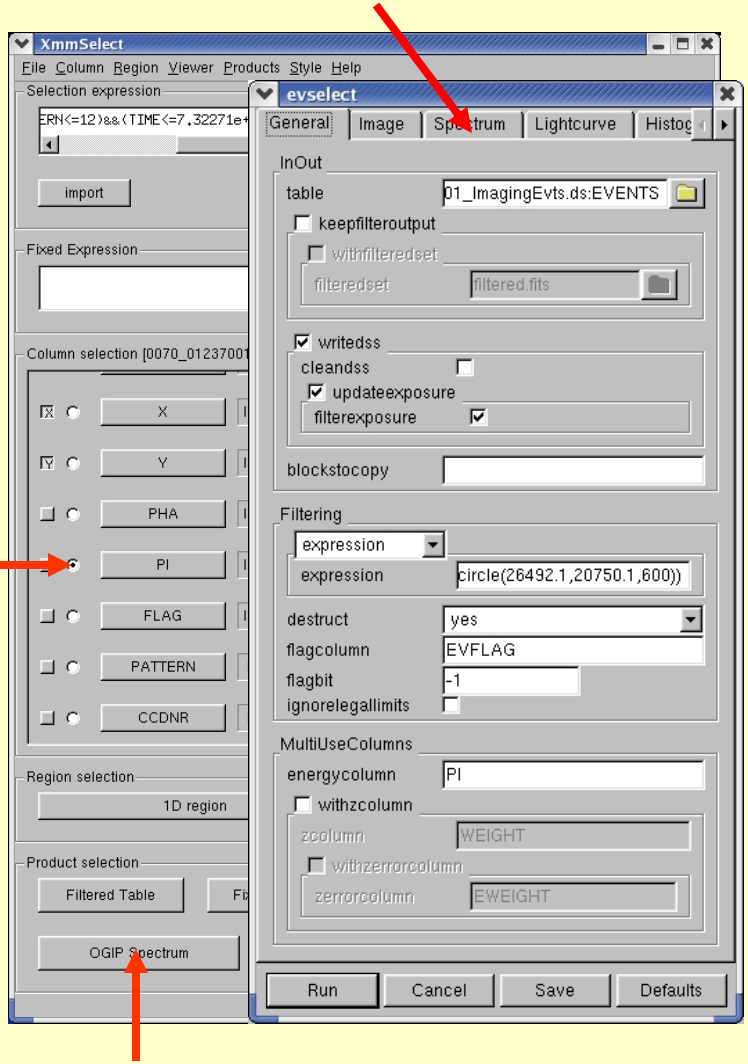


- Timing (MOS/pn) and Burst Modes do not create standard images in detector or raw coordinates. Where to extract the source?
- In pn timing and burst modes take a box in the RAWX and RAWY coordinates plane, *e.g.*

  (RAWX,RAWY) IN box(36.75,100.75,6.75,96.75,0)
- In MOS Timing Mode, create a pseudo-image in the (RAWX,TIME) plane or an histogram in RAWX, and decide the range in RAWX corresponding to your source
- Then proceed with arfgen and rmfgen

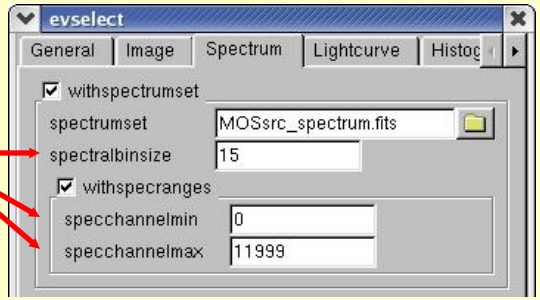
https://www.cosmos.esa.int/web/xmm-newton/sas-thread-pn-spectrum-timing

xmmselect: creation of EPIC spectra

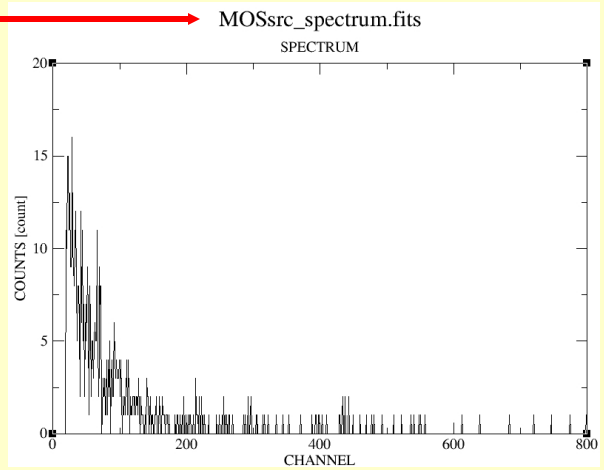


Assuming that one has cleaned the event list for high background & defined a source region (e.g. as a circle).

Parameters set to generate matrices with standard settings



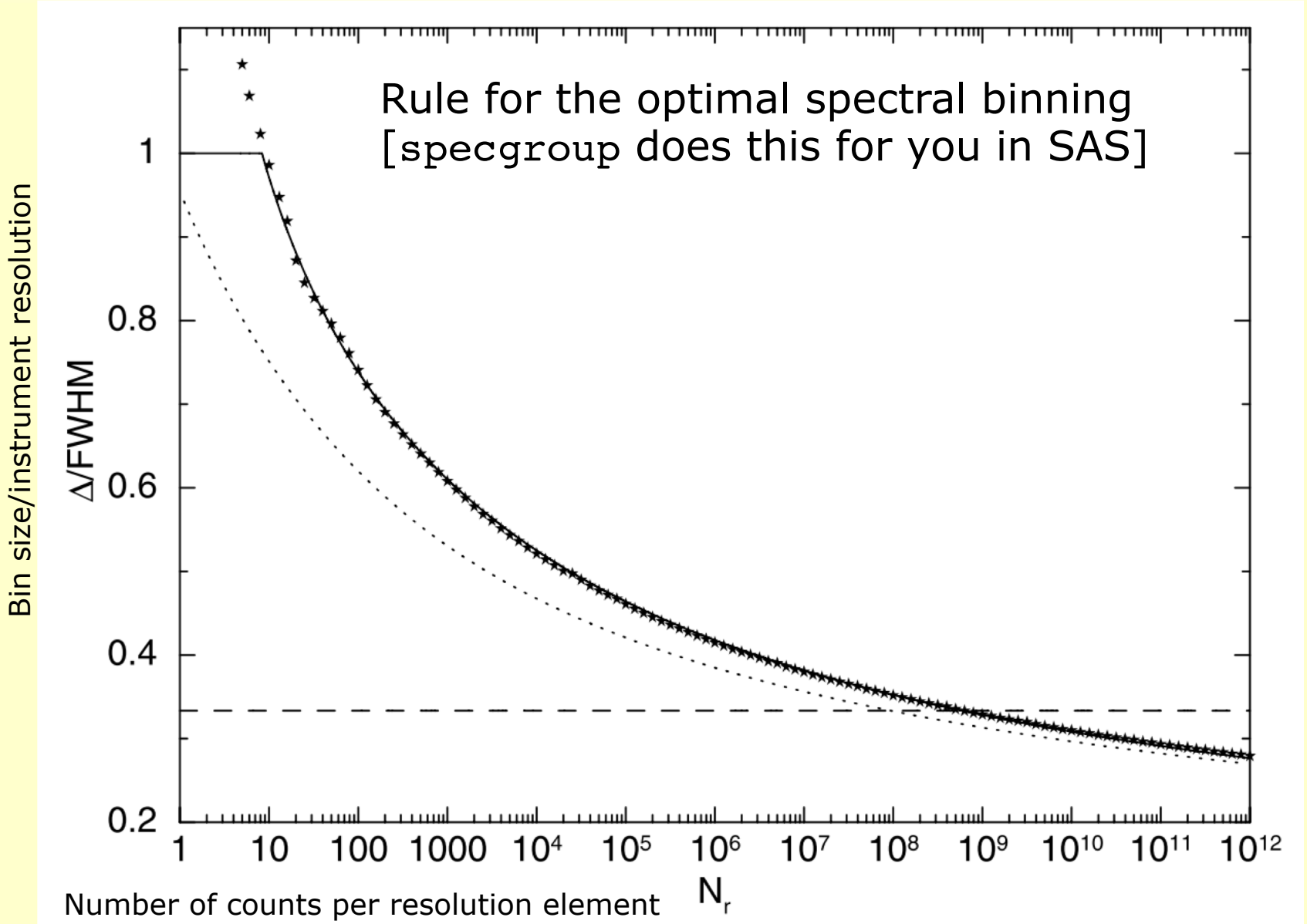
"Run": `xmgrace` window appears with the accumulated spectrum.



https://www.cosmos.esa.int/web/xmm-newton/sas-thread-pn-xmmselect-spectrum

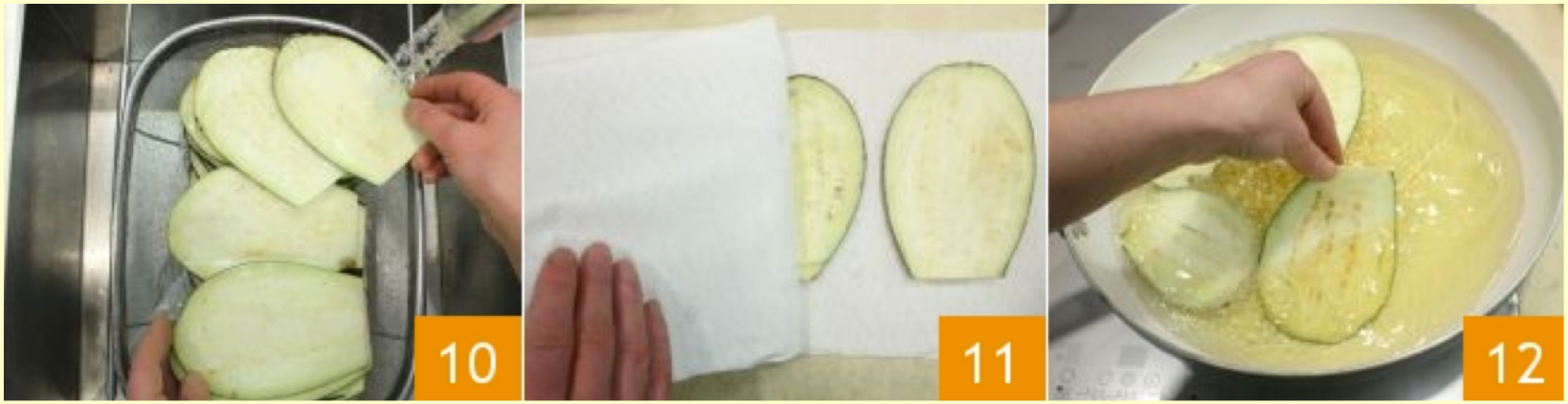
A note on spectral binning

(Kaastra & Bleeker, 2016, A&A, 587, 151)



Lecture content

How to create "background" products (and, by passing) optimizing the signal-to-noise ratio of your data



Whence does background come from?

The full table is available at:
https://www.cosmos.esa.int/web/xmm-newton/epic-background-components

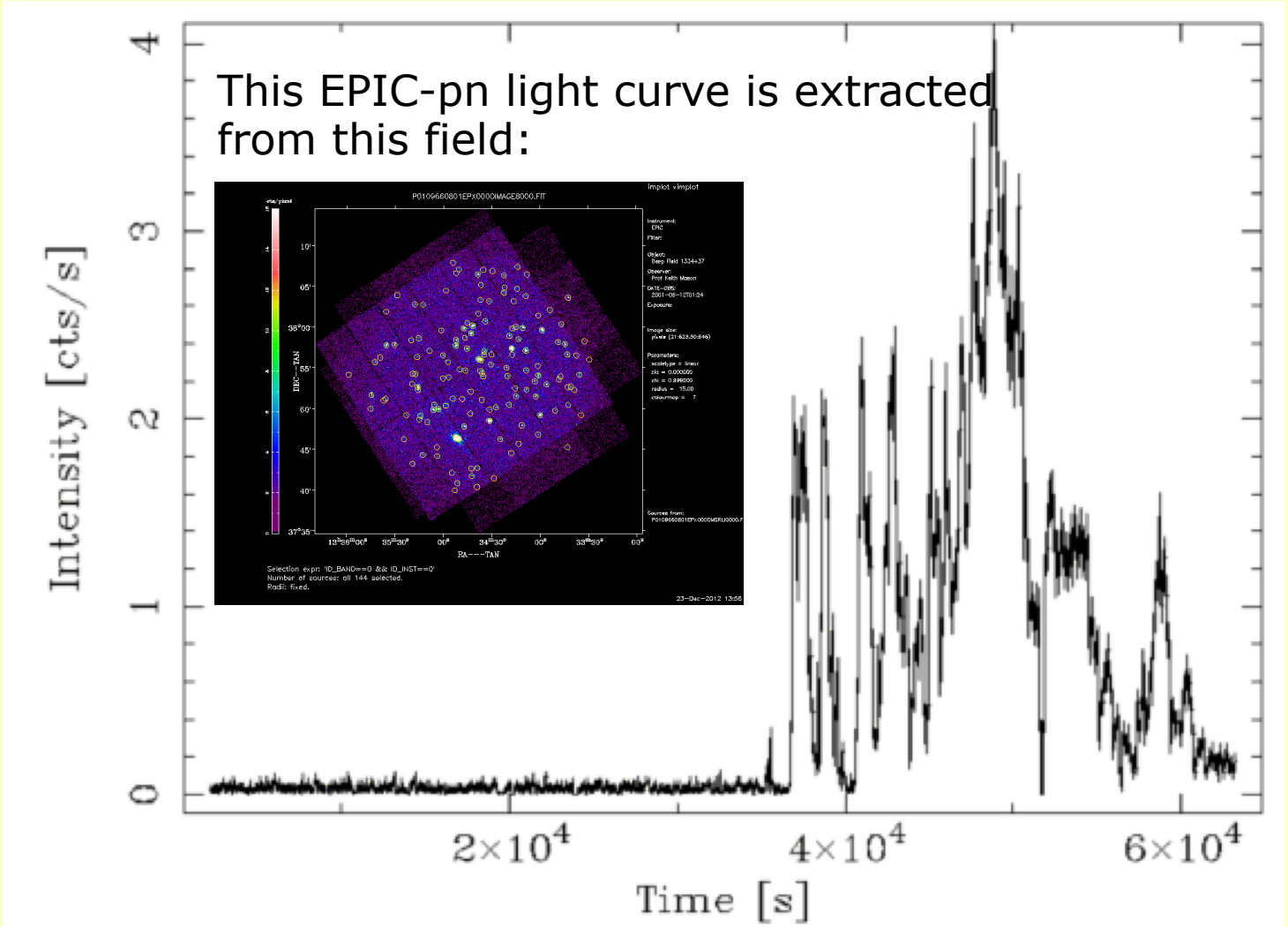
	PARTICLES			PHOTONS	
	SOFT PROTONS	**INTERNAL (cosmic-ray induced)**	**ELECTRONIC NOISE**	**HARD X-RAYS**	**SOFT X-RAYS**
Source	Few x 100 keV solar protons, accelerated by magnetospheric reconnection events. Dominate times of high-BG.	Interaction of High Energy particles (cosmic rays) with detector - associated instrumental fluorescence. Main MOS ref.	(1) Bright pixels & (parts of) columns. (2) CAMEX readout noise (pn). (3) (4) (5)Artificial Low-E enhancements in outer MOS CCDs (Also dark current - thought negligible).	X-ray background (AGN etc), Single Reflections from outside FOV, Out-of-time (OOT) events (pn)	Local Bubble, Galactic Disk, Galactic Halo, Solar Wind Charge Exchange (SWCX) SWCX, Single Reflections from outside FOV, Out-of-time (OOT) events (pn)

remove

model

High background "flares"

XMM-Newton is particularly affected by an annoying problem:



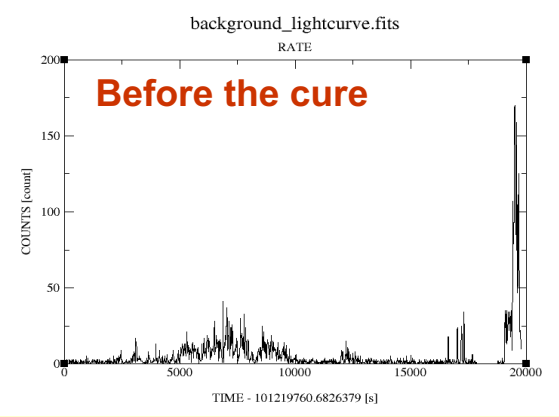
Cleaning high background

XMM-Newton sometimes experiences high flaring background periods (soft protons accelerated by magnetic reconnection), as well as high background close to perigee. They need to be removed before extracting any scientific products:

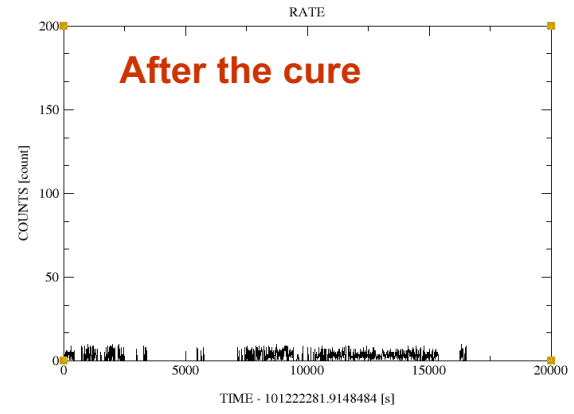
- **extract a high-energy, single event light-curve, with the expression:**
  PN: `(PI in [10000:12000])&&(PATTERN==0)&&#XMMEA_EP`
  MOS: `(PI>10000)&&(PATTERN==0)&&#XMMEA_EM`
- **create GTI, excluding all "flaring" intervals**

```
tabgtigen table=high_energy_curve.fits gtiset=gti.fits
          expression="RATE=<0.4"     for pn  - or -
          expression="RATE=<0.35"    for MOS
```

- **apply above GTI to any scientific products accumulations, adding to the selection expression the string:** `".. gti(gti.fits, TIME) .."`



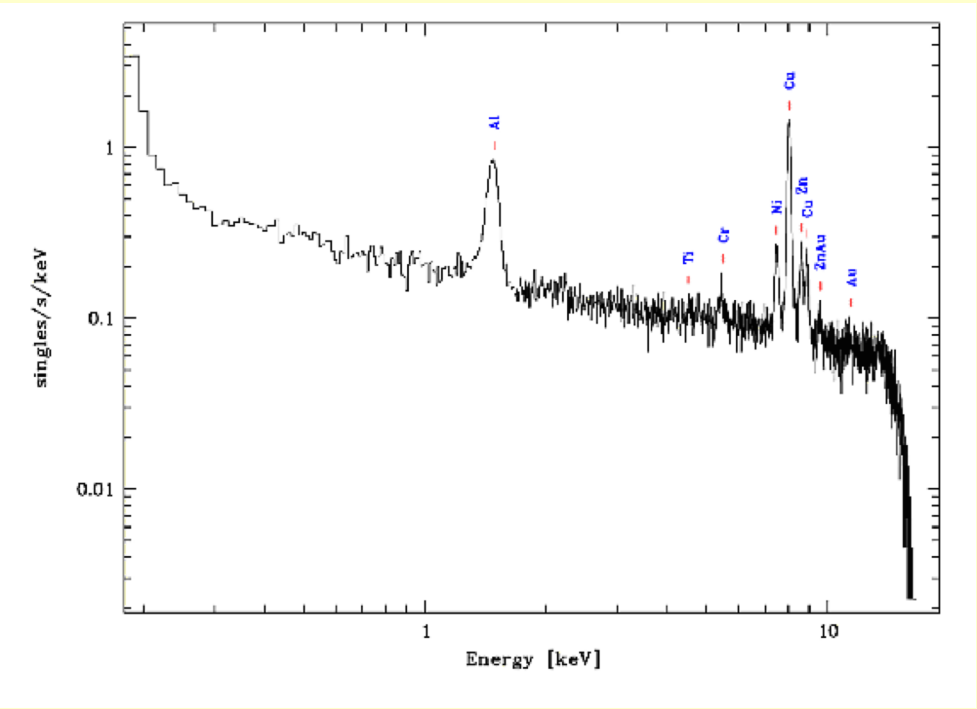
gti.fits



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

Instrumental background is complex

EPIC-pn example



Spectrum of the instrumental background

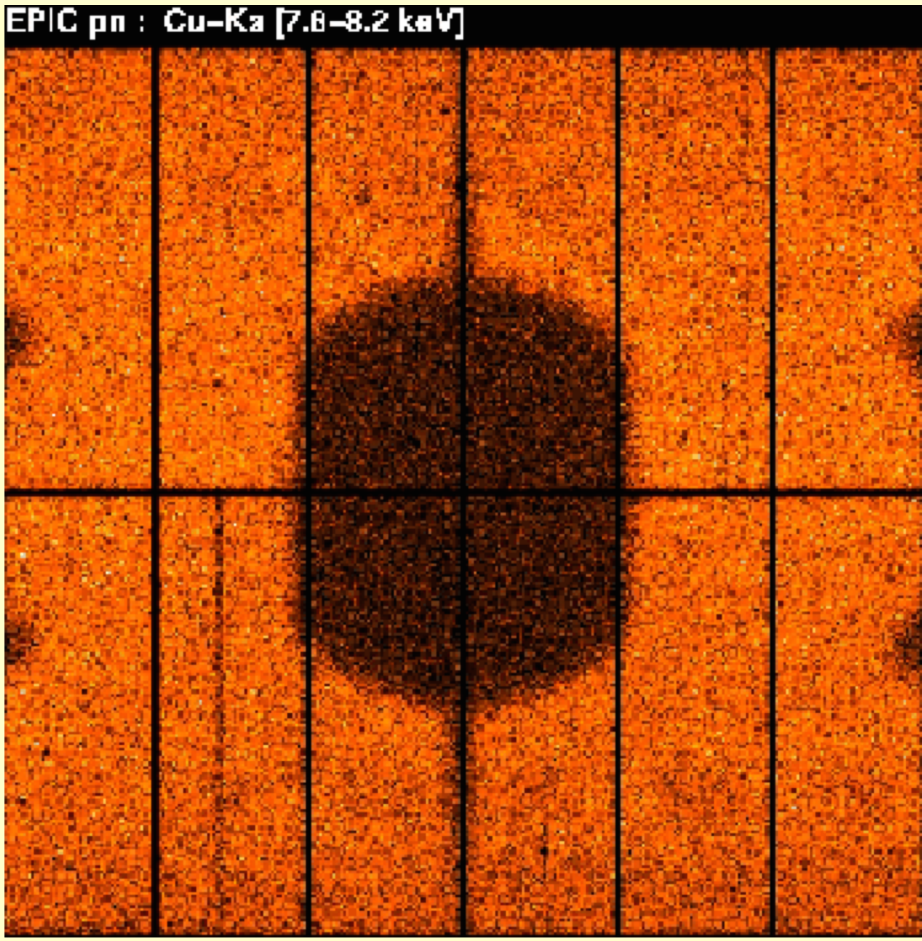
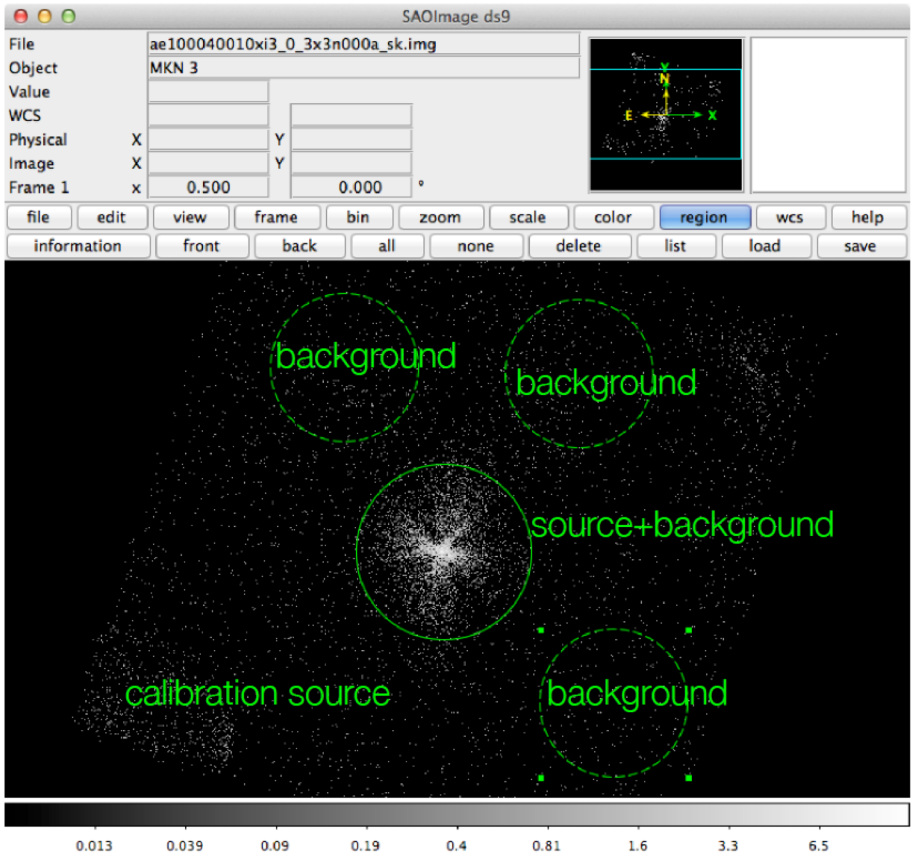
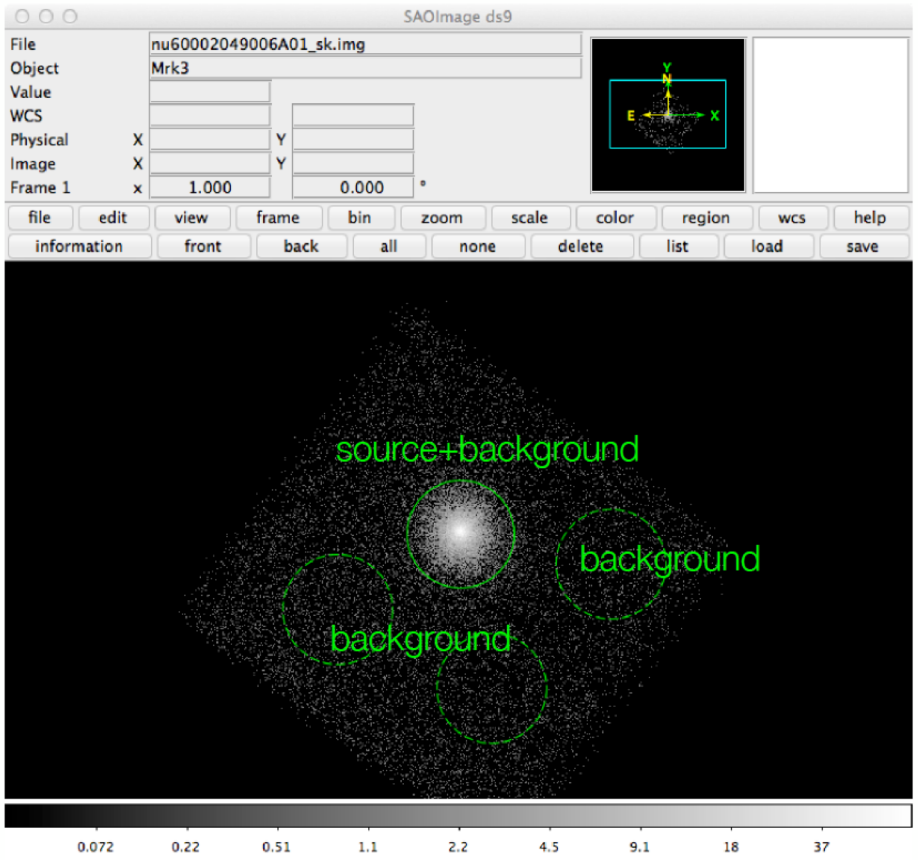


Image of the instrumental background

How to create background products





MOS: an annulus concentric to the "source" is the best choice
pn: avoid annuli, choose a circle close to the "source"

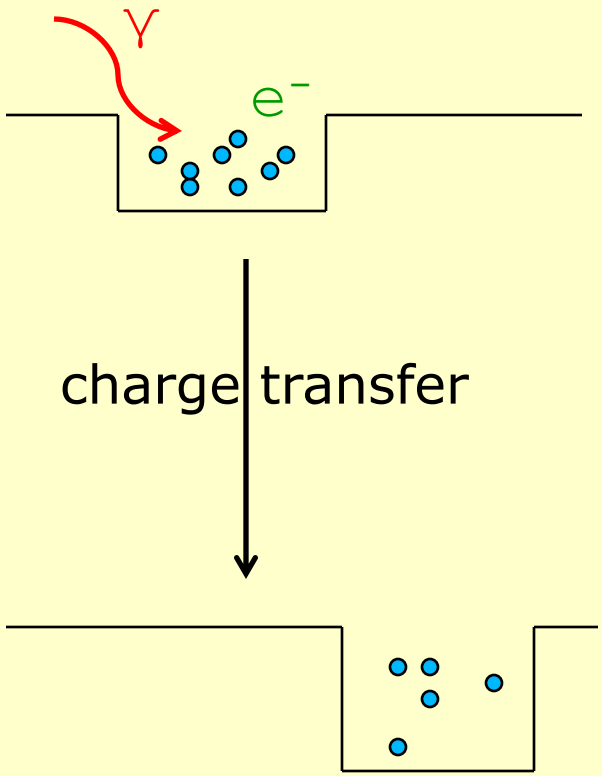
Lecture content

How to deal with "pile-up"

[stay very awake NOW! if you work with bright sources for instance X-ray Binaries]

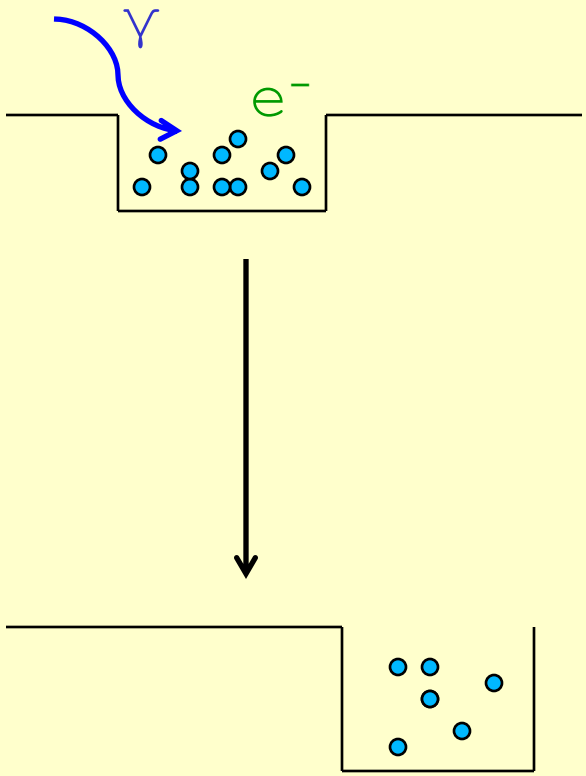
Pile-up – the tale of 1 pixel and 2 photons

Pixel A receives one photon of energy E_1



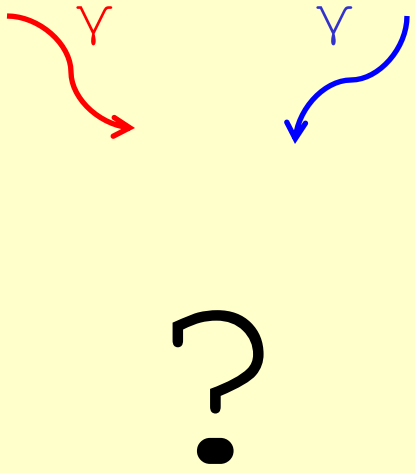
Amplifier reads 5 e⁻

Pixel A receives one photon of energy E_2



Amplifier reads 6 e⁻

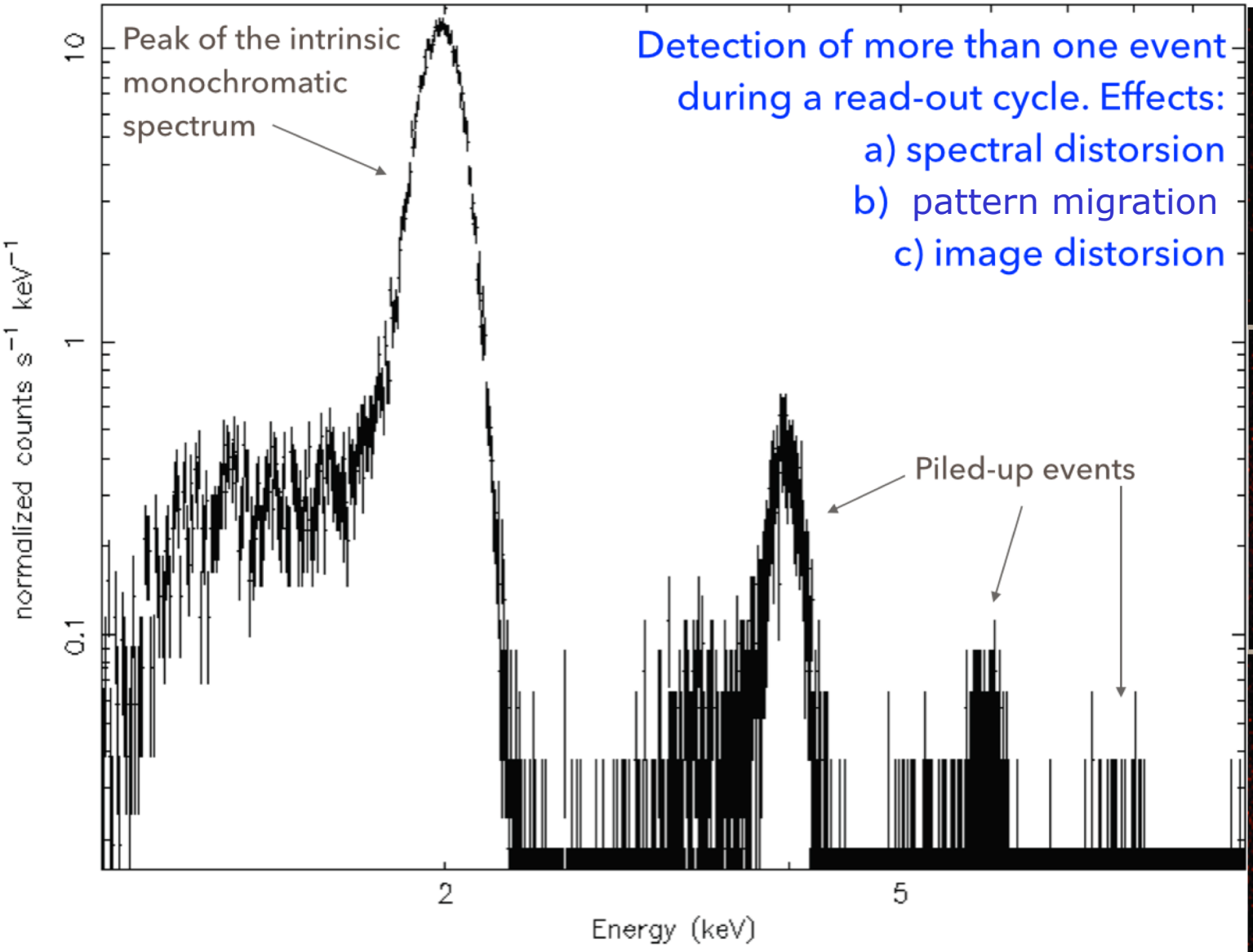
Pixel A receives **two** photons $E_1 + E_2$

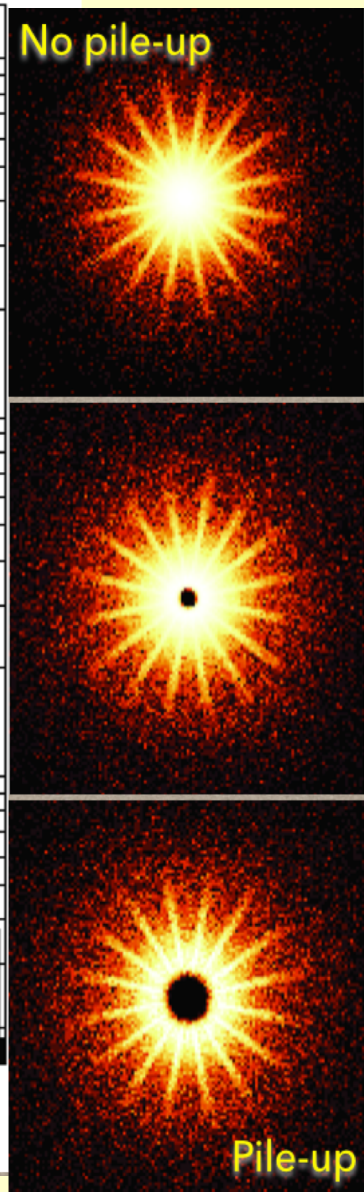


Amplifier reads **11 e⁻**

One photon, energy $E_{\gamma 1}+E_{\gamma 2}$

What is pile-up?





How to correct it?

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

- How to check if there is pile-up?
  - SAS task `epatplot`
  - Compare the count rate of your source with the tables in **Jethwa et al., 2015, A&A, 581, 104**
- How to avoid pile-up?
  - [Choose the correct instrumental mode when proposing something – too late for you here at the Workshop]
  - Remove the core of the PSF affected by pile-up
- How to cure pile-up?
  - `rmfgen […] correctforpileup=yes`
  - **`pileup`** convolution model in XSPEC/ISIS

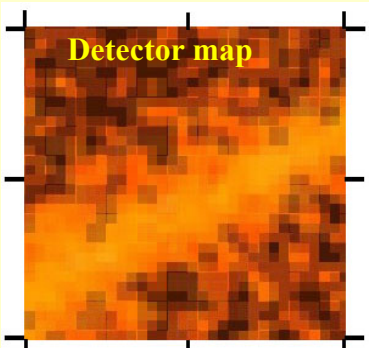
None of these method is perfect. Better avoid piled-up data

Lecture content

How to calculate the EPIC responses

Creation of EPIC responses?

- **rmfgen** - *Calculates the **redistribution matrix** (RMF)*
  - `rmfgen spectrumset=myspec.ds rmfset=myspec.rmf`
- **arfgen** – *Calculates the instrument **effective area** (ARF)*
  - Standard call (point source):
  - `arfgen spectrumset=myspec.ds arfset=myspec.arf`
  - Call for extended sources:
  - `arfgen spectrumset=myspec.ds arfset=myspec.arf extendedsource=yes badpixlocation=myevents.FIT detmaptype=flat`
  - For extended sources it is better to use a detector map:
  - `evselect withimageset=yes imageset=coarseimage.ds xcolumn=DETX ycolumn=DETY expression=<region surrounding the source>`
  - `arfgen spectrumset=myspec.ds arfset=myspec.arf extendedsource=yes detmaptype=dataset detmaparray=coarseimage.ds`



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

Lecture content

You may ask: "Why do you leave RGS at the very end?"

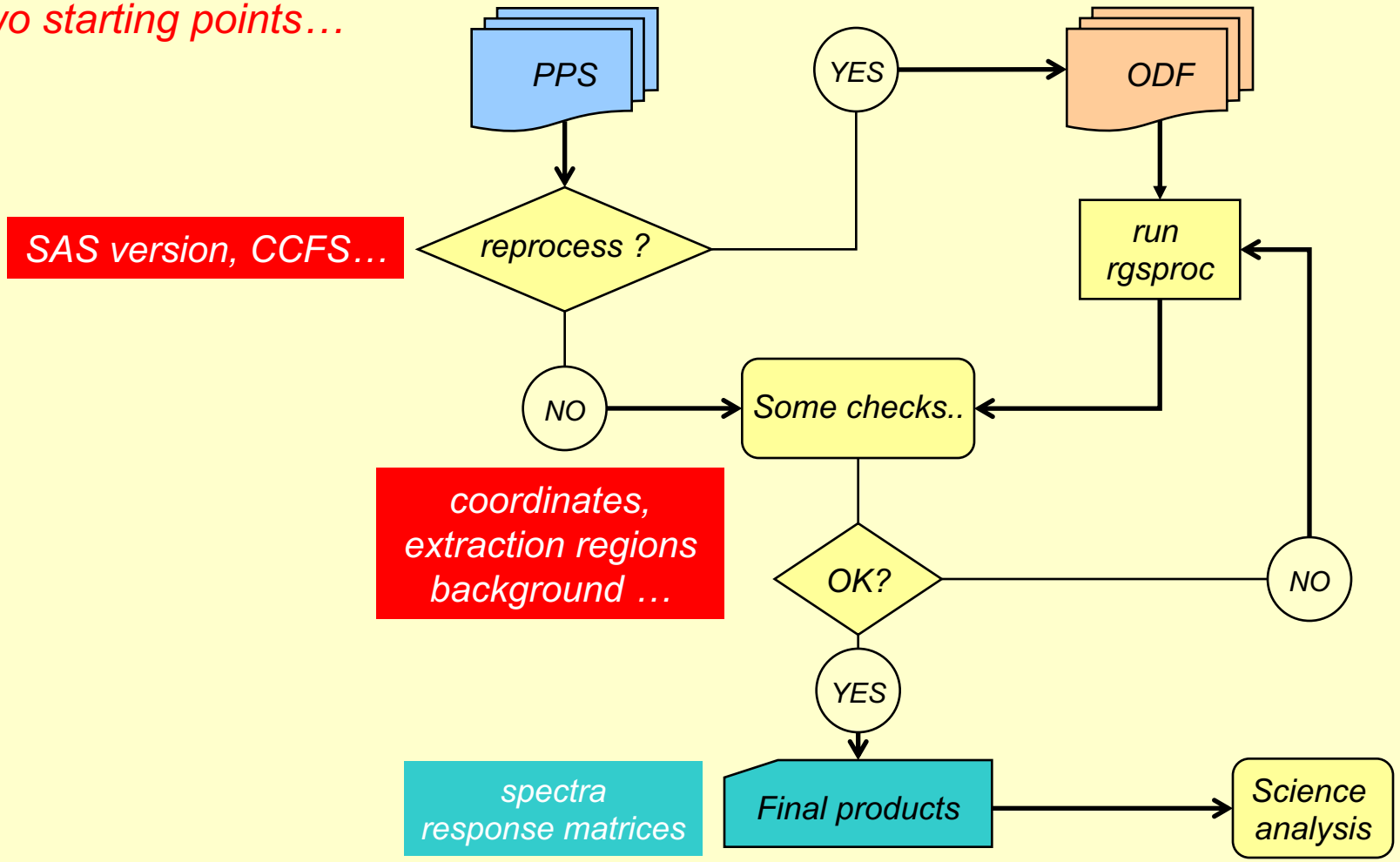
RGS reduction is ludicrously simple

Answer: because in principle all you need to do to create RGS spectra is running:

```
$> rgsproc
```

Analysis of RGS data

Two starting points…

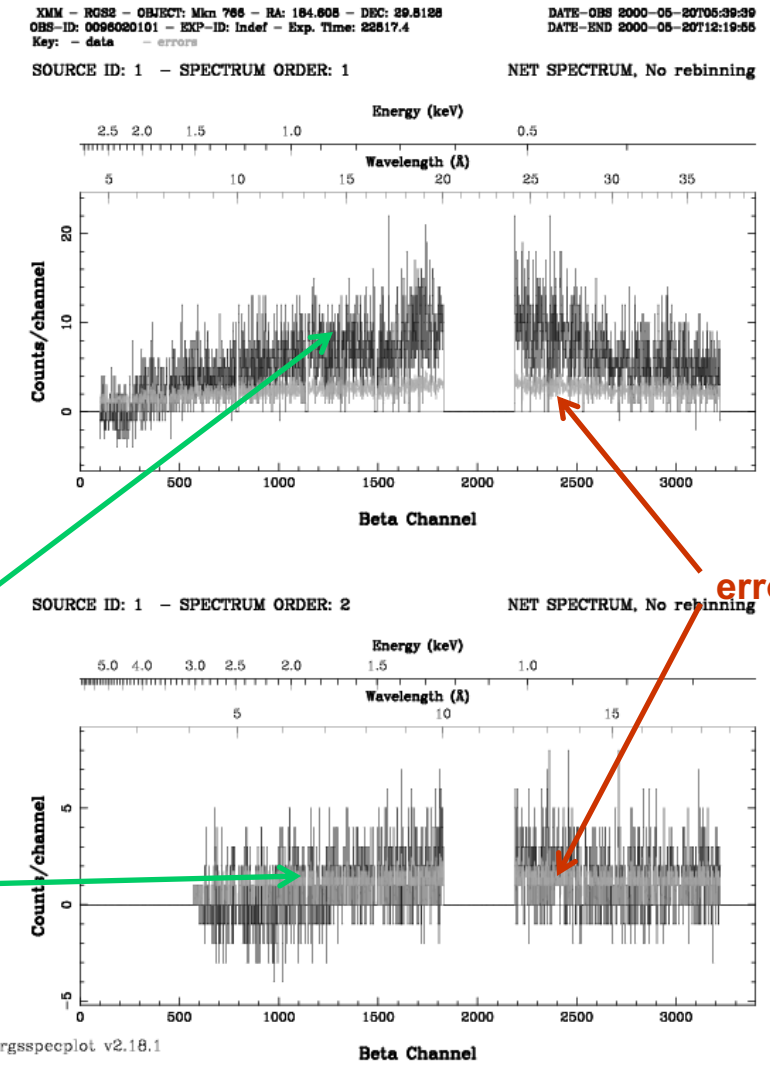


The extracted spectra

By default, spectra are extracted for both orders (1st and 2nd) for the nominal boresight position

- the `rgsproc` default is the total source spectrum (NOT background subtracted) in counts/channel

- the background spectrum and response matrices are also produced → you can start the spectral analysis



spectra

errors

This plot is available in the XSA for quick-look

RGS background subtraction

Two ways to perform RGS background subtraction:

- off-axis areas from the same observation (default in `rgsproc`)

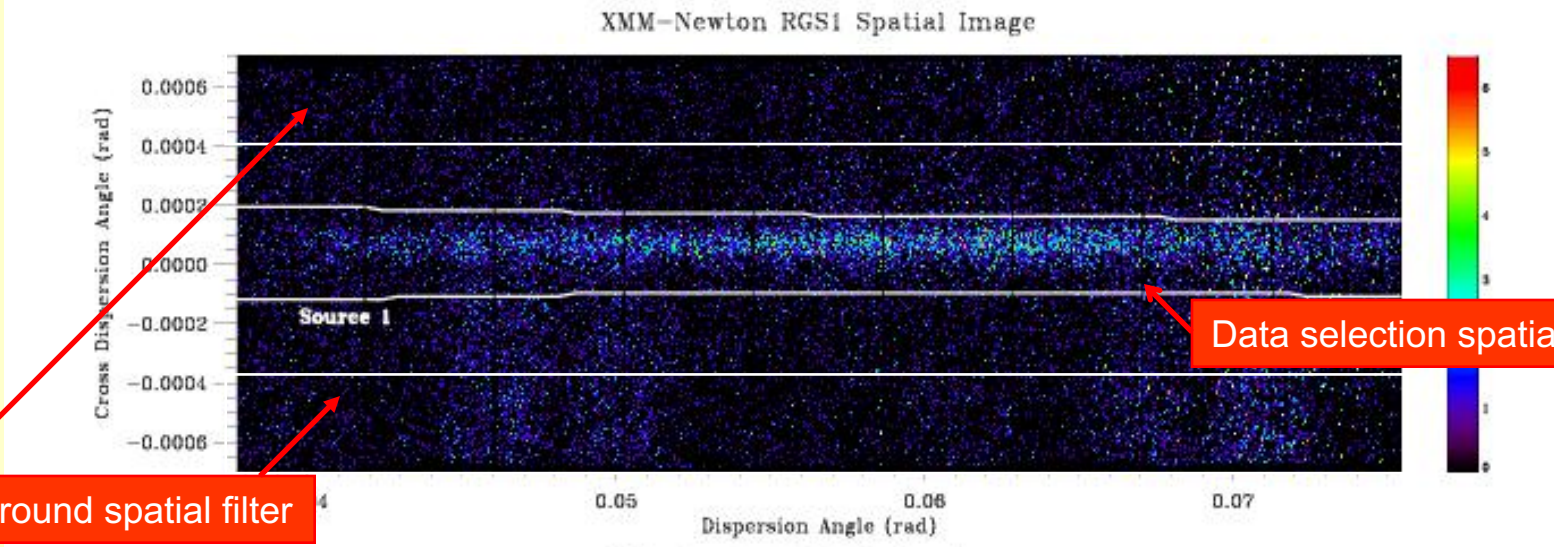
- Templates from blank fields.
  - Advantages:
    - Higher statistics of the background spectra (higher geometrical area, longer exposure time)
    - Avoid source contamination for extended sources
    - Improves detection of weak features
  - Disadvantages:
    - Is it really the background of my observation?

- **`rgsproc withbackgroundmodel=yes`**

- **http://xmm.esac.esa.es/docs/documents/CAL-TN-0058-1-1.ps.gz**

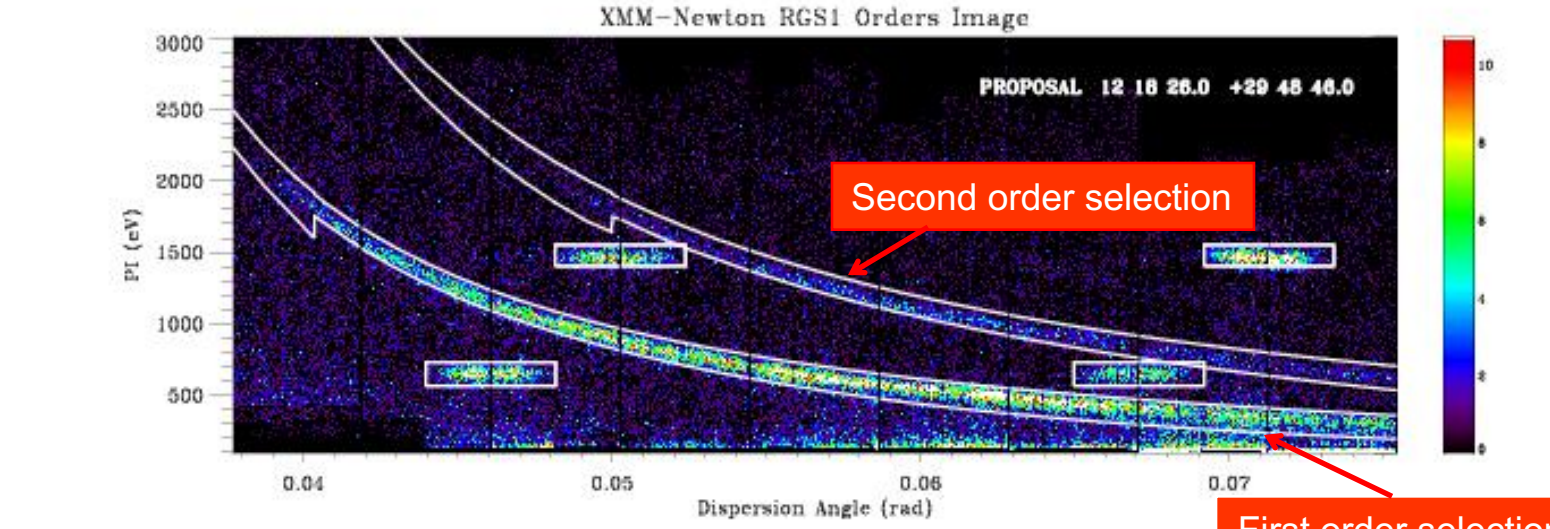
Validity checks I.: extraction regions

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



Background spatial filter

Data selection spatial filter



Second order selection

First order selection

Offset target? Try: `rgsproc withsrc=yes srcra=<RA> srcdec=<Dec>`

Changing source or size of the extraction region

https://www.cosmos.esa.int/web/xmm-newton/sas-thread-rgs2

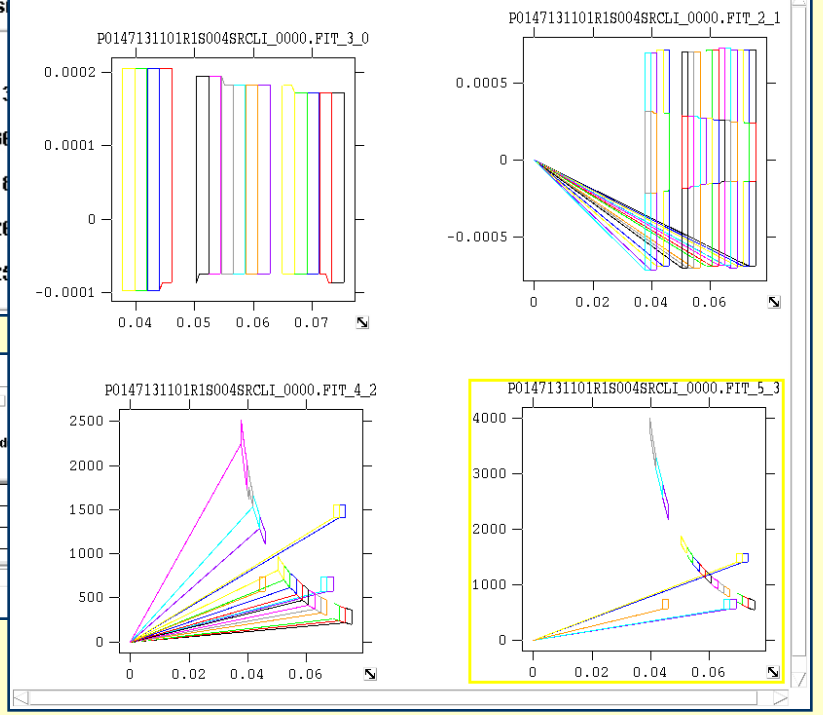
List of coordinates

Extraction regions

File Edit Tools

Index	Extension	Type	Dimens
0	Primary	Image	0
1	SRCLIST	Binary	15 cols X 3
2	RGS1_BACKGROUND	Binary	4 cols X 3
3	RGS1_SRC3_SPATIAL	Binary	4 cols X 1
4	RGS1_SRC3_ORDER_1	Binary	4 cols X 2
5	RGS1_SRC3_ORDER_2	Binary	4 cols X 2

File Edit Colors Tools Zoom Replot Help



File Edit Tools

	INDEX	LABEL	RA	DEC	RATE	DELTA_DISP	DELTA_XDSP	FOV_PHI
	I	20A	E	E	E	E	E	E
			degrees	degrees	cts/s	arcmin	arcmin	degrees
1	2	ONAXIS	184.606900	29.811000	0.00	0.000	0.000	0.000
2	1	PROPOSAL	184.607800	29.788660	0.00	1.000	1.000	131.798
3	3	TARGET	184.611000	29.812670	0.00	0.111	-0.213	-114.948

Go to: Edit cell:

Sources can be added/modified with `rgssources`

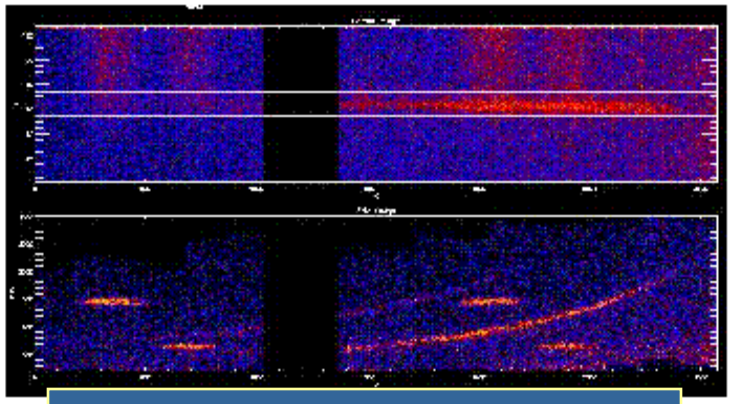
Region definitions can be changed with `rgsregions` or:

```
rgsproc xpsfincl=95 xpsfexcl=98 pdistincl=95
```

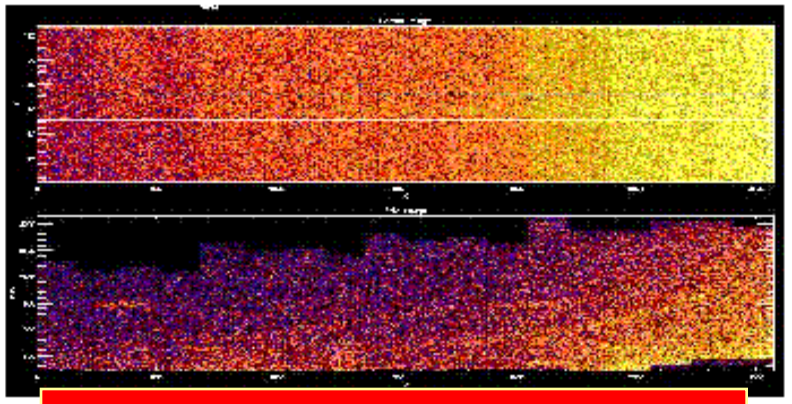
Defaults are:

- source spatial: 95% of x-dispersion PSF inclusion
- background spatial: 98% of x-dispersion PSF exclusion
- order mask: 95% of pulse-height distribution

Validity checks II: high background

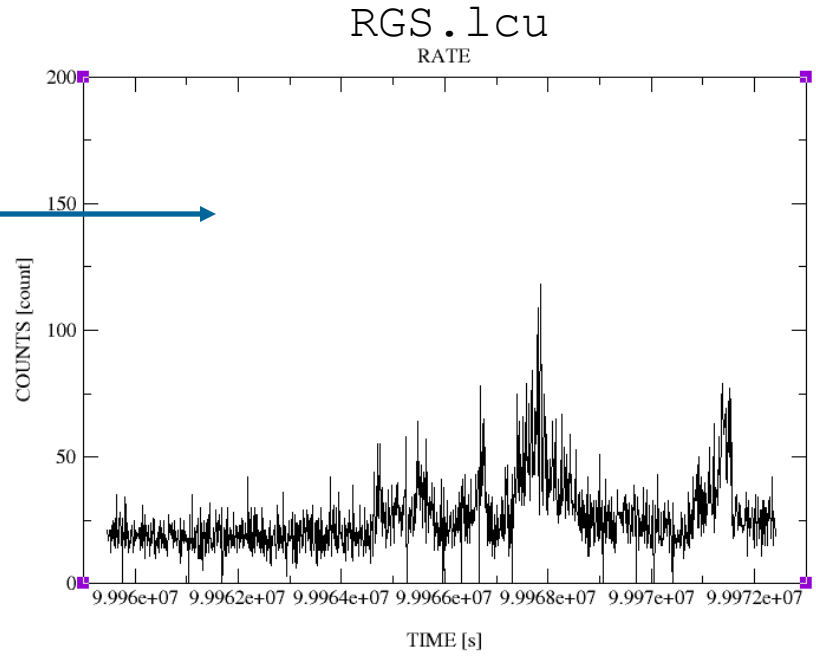


Observation with "normal background"



The same observation with high background

- Create a 10-100 s binned light curve for background region in CCD=9
  - `evselect table=RGSevents.fits withrateset=yes rateset=RGS.lcu expression="CCD==9&&(REGION(PxxxxxxyyyyRleeeeSRCLI_0000.FIT:RGS1_BACKGROUND:BETA_CORR,XDSP_CORR)"`
- Create a GTI file for count rate<0.5 s^{-1}
  - `tabgtigen table=RGS.lcu timebinsize=1 expression="RATE.LE.0.5" gtiset=CCD9.gti`
- Re-run pipeline using the GTI created in the previous step
  - `rgsproc auxgtitables=CCD9.gti entrystage=3:filter finalstage=5:fluxing`



https://www.cosmos.esa.int/web/xmm-newton/sas-thread-rgs2

Conclusion

Cooking is art.

High-energy data reduction is also art. Just following blindly the instructions spoils the soup

[photos are taken from a recipe of the "*melanzane alla parmigiana*": a typical Sicilian dish]