Data Reduction - *Swift* Examples

Tecniche e strumenti di analisi dati per sorgenti astrofisiche e polarimetria nei raggi X

Dipartimento di Fisica - UniTo

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Swift Mission

The Neil Gehrels *Swift* Observatory

- Launched on November 20, 2004
- Nominal Mission Duration: 2 years
- Study the γ-ray bursts and their afterglows
- Total budget $\sim$ 330 M\$
- Burst detection rate: $> 100/\mathrm{yr}$

Swift is a MIDEX Gamma Ray Burst mission led by NASA with participation of Italy and the UK. The *Swift* data are available to the scientific community through data centers in the USA, Italy and the UK.

Participant Institutions

ASI Science Data Center (ASDC)
BeppoSAX/SDC
Caltech
Centre d'Etude Spatiale des Rayonnements, Toulouse
Centre d'Etudes Nucleaires, Saclay
Clemson University
General Dynamics
Goddard Space Flight Center (GSFC)
Institute of Astronomy, University of Cambridge
Institute of Space and Astronautical Science (ISAS)
Istituto di Astrofisica Spaziale e Fisica Cosmica (IASF-INAF)
INTEGRAL Science Data Centre (ISDC)
Liverpool John Moores University
Large Binocular Telescope (LBT)
Lawerence Livermore National Laboratory
Los Alamos National Laboratory (LANL)
Marshall Space Flight Center
Maui Space Surveillance Site (MSSS)
Max-Planck-Institut für extraterrestrische Physik (MPE)
Mullard Space Science Laboratory (MSSL)
National Radio Astronomy Observatory (NRAO)
Observatoire de Haute Provence (OHP)
Omitron
Osservatorio Astronomico di Brera (OAB)
Osservatorio Astronomico, Padova
Osservatorio Astronomico di Roma
Penn State University (PSU)
Princeton University
Rice University
Saitama University
Scuola Normale Superiore
Sonoma State University (SSU)
South African Astronomical Observatory
Southwest Research Institute (SwRI)
Space Telescope Science Institute
Tokyo Institute of Technology
United States Naval Observatory
Universities Space Research Association
University of Arizona
University of Bologna
University of California, Berkeley
University of California, Riverside
University of California, Santa Barbara
University of California, Santa Cruz
University of Chicago
University of Copenhagen
University of Maryland
University of Michigan
University of Pennsylvania
University of Southampton, Highfield
University of Texas, Austin
University of Washington
University of Wyoming
Very Large Telescope, Parnal Observatory
Wayne State University

Italian Contibution

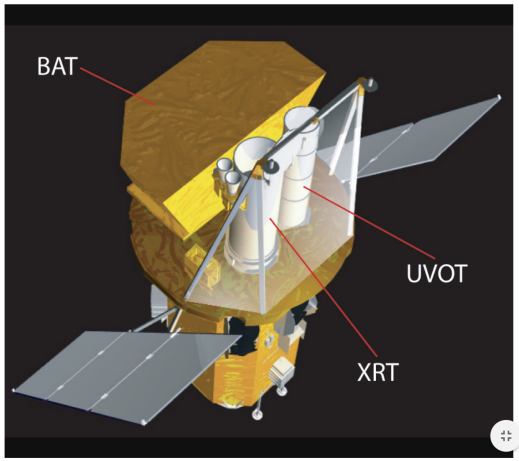
Italy contributes to the mission providing:

- The XRT X-ray mirror
- The Malindi ground station
- XRT data reduction and analysis software

The ASI Science Data Center (ASDC) contributes to the mission providing:

- *Swift* Data Archive Mirror
- On-line XRT & UVOT data analysis
- *Swift* Quick Look Data (XRT & UVOT Interactive Quick Look)
- XRT data simulator
- XRT Helpdesk

Instruments



Burst Alert Telescope (BAT):

- Detecting Area 5200 cm^2
- FoV 2 sr
- PSF 17'
- Location Accuracy 1' - 4'
- Energy Range 15 - 150 keV

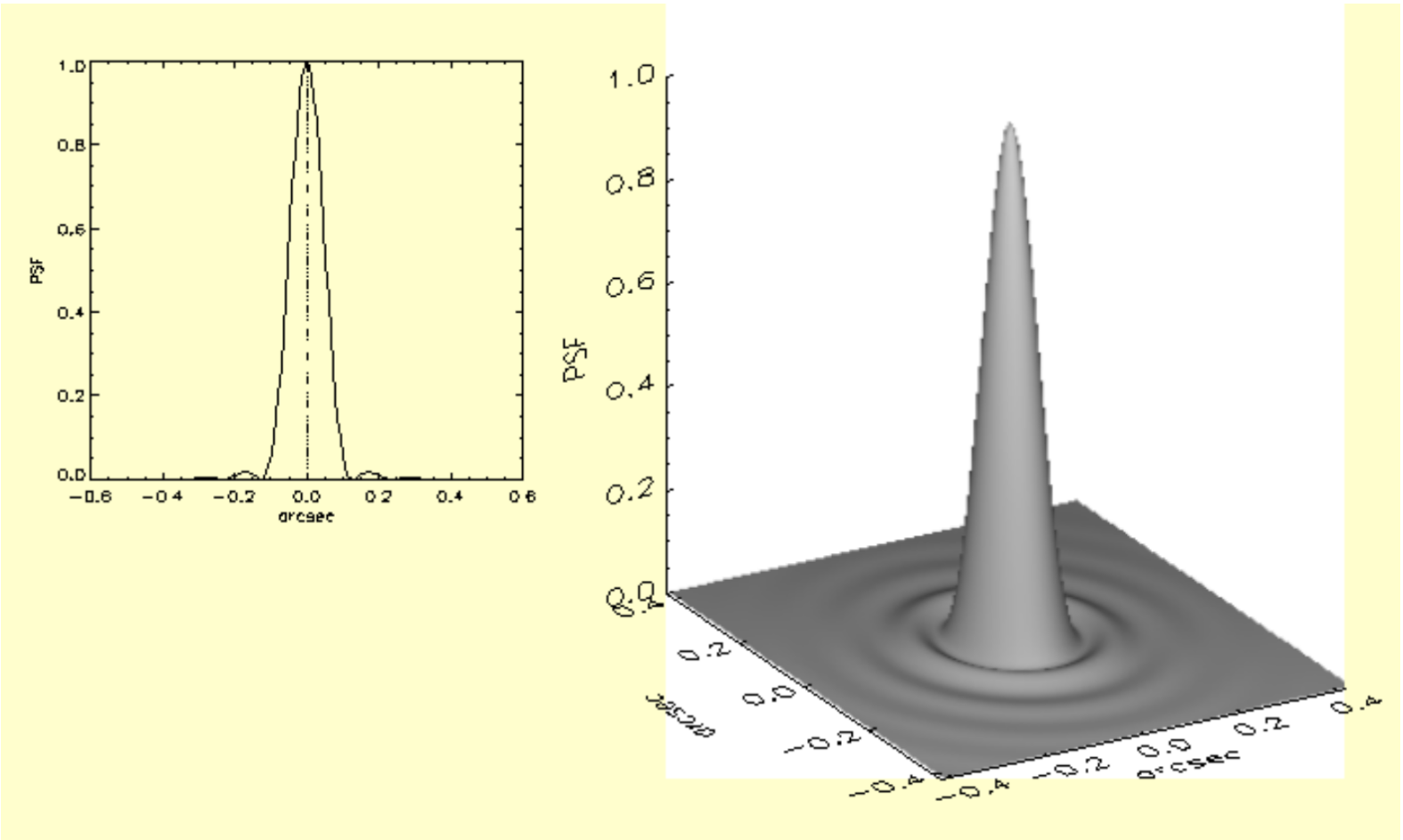
UltraViolet/Optical Telescope (UVOT)

- Colors 6
- $\lambda/\Delta\lambda \sim 200$ @ 400 nm
- FoV 17' x 17'
- PSF 0.9" 350 nm
- Location Accuracy 0.3"
- $\Delta\lambda = 170$ nm - 650 nm

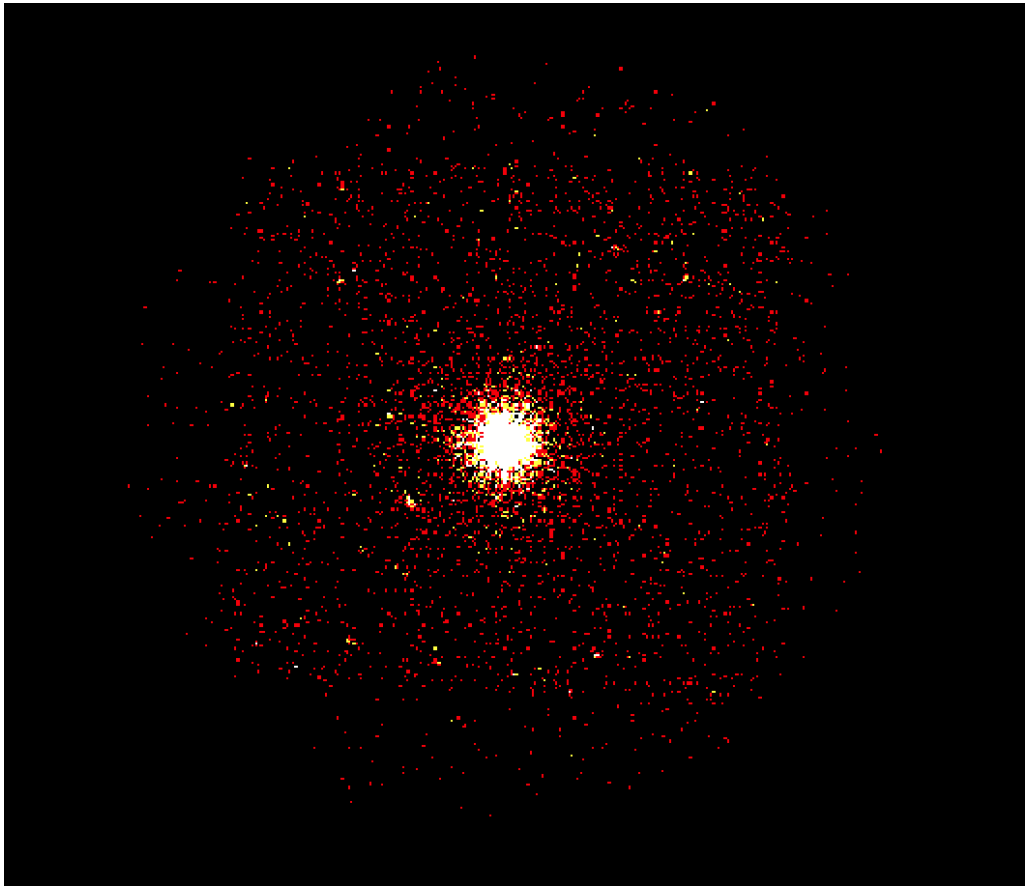
X-ray Telescope (XRT):

- Effective Area 135 cm^2 1.5 keV
- FoV 23.6' x 23.6'
- PSF 18" @ 1.5 keV
- Location Accuracy 3" - 5"
- Energy Range 0.2 - 10 keV

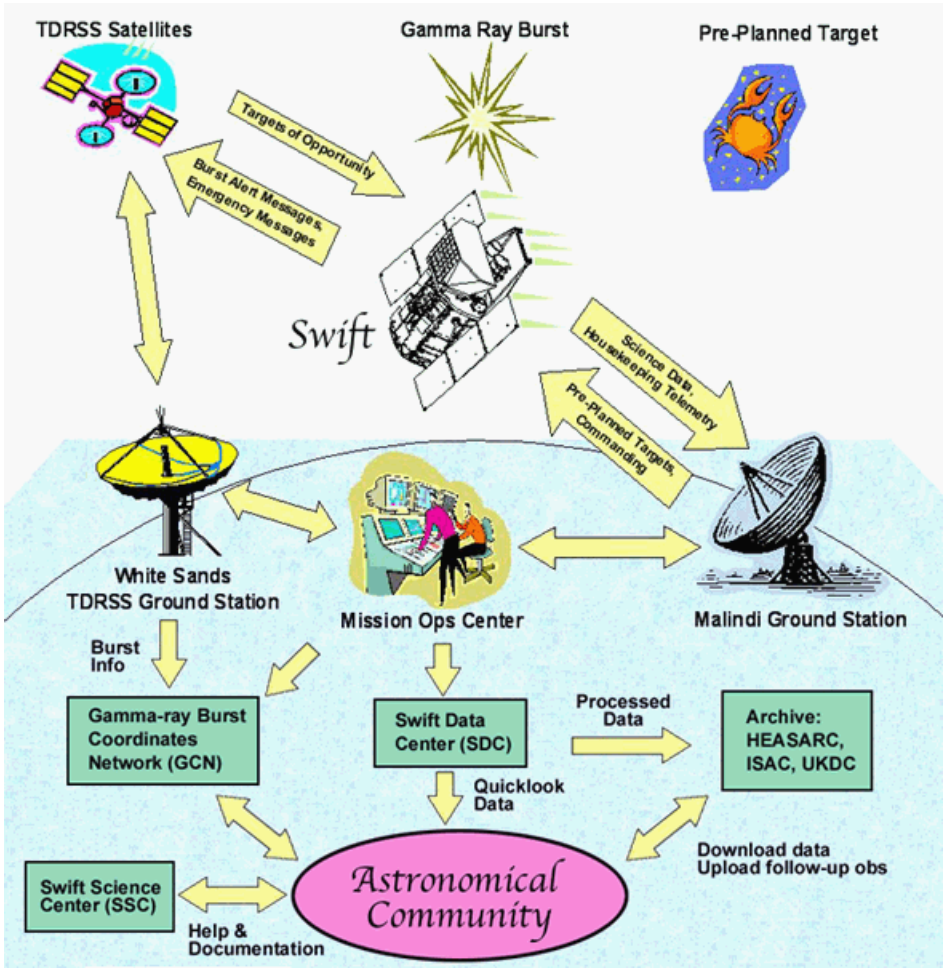
PSF



Point Source



Swift Observing Strategy



Within seconds of detecting a burst, the spacecraft will "swiftly" and autonomously repoint itself to aim the XRT and UVOT at the burst to enable high-precision X-ray and optical positions and spectra to be determined.

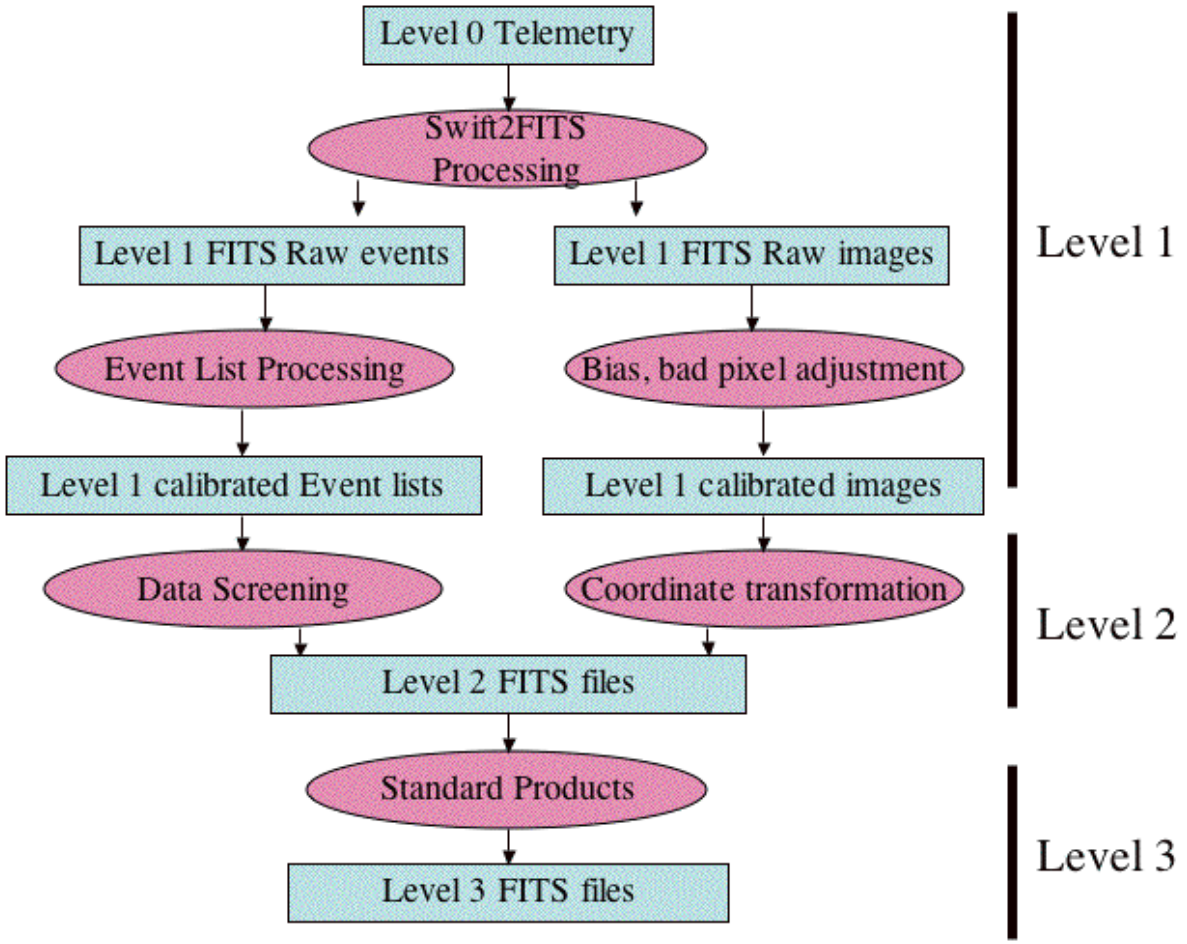
Results

- 1358 GRBs detected, and counting
- *Swift* BAT 105-Month Hard X-ray Survey (1632 sources, Oh et al. 2018, https://swift.gsfc.nasa.gov/results/bs105mon/)
- UVOT Serendipitous Source Catalog (6,200,016 sources, Page et al. 2015, http://www.ucl.ac.uk/mssl/astro/space_missions/swift/uvotssc/)
- XRT Source Catalogs (7-years D'Elia et al. 2013, http://www.asdc.asi.it/1swxrt/, 8-years Evans et al. 2014 http://www.swift.ac.uk/1SXPS/)
- *Swift* AGN & Cluster Survey (Dai et al. 2015)
- *Swift*-XRT Monitoring of Fermi-LAT Sources of Interest (Stroh & Falcone 2013, https://www.swift.psu.edu/monitoring/)
- *More than 2500 papers*

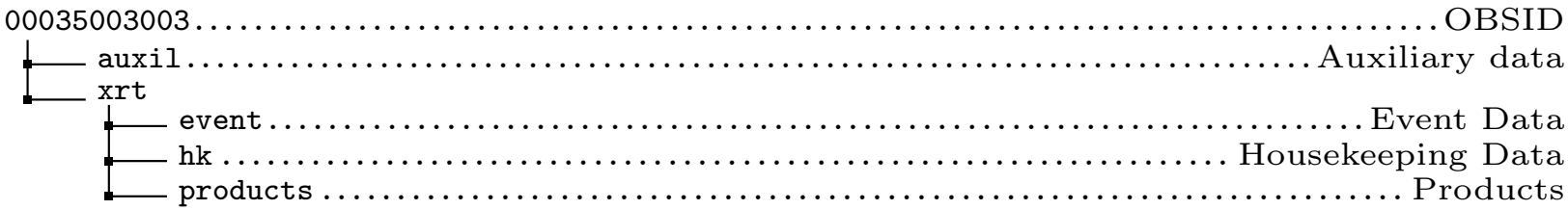
XRT Readout Modes

- Windowed Timing mode: WT mode is a high gain mode to achieve high resolution timing (2.2 ms) with 1-D position information and spectroscopy. This mode is restricted to a 200 column window covering the central 8 arcminutes of the FOV. Window timing mode is useful for fluxes below 50 Crabs and has no pileup for fluxes below 600 m Crabs
- Photon-counting mode: PC mode is the more traditional frame transfer operation of an X-ray CCD. It retains full imaging and spectroscopic resolution, but the time resolution is only 2.5 seconds. The instrument is operated in this mode only at very low fluxes (useful below 1 mCrab).

Data Reduction



XRT Data Structure



Auxiliary data

```
auxil
 ├── sw00035003003sao.fits.gz ..... Attitude and Orbit Data
 ├── sw00035003003pob.cat.gz ..... Catalog of Files
 ├── sw00035003003pjb.par.gz ..... Job Parameter File
 ├── sw00035003003s.mkf.gz ..... Make Filter File
 ├── sw00035003003ppr.par.gz ..... Processing Parameter File
 ├── sw00035003003sat.fits.gz ..... Spacecraft Attitude File
 ├── sw00035003003sen.hk.gz ..... Spacecraft Engineering
 ├── SWIFT_TLE_ARCHIVE.txt.15022.60775370.gz ..... Two-Line Element File
 └── sw00035003003sti.fits.gz ..... UTCF Corrections File
```

XRT Data

```
xrt
├── event
│   ├── sw00035003003xpcw3po_cl.evt.gz ..... XRT Event Level 1 Screened
│   ├── sw00035003003xwtw2po_cl.evt.gz ..... XRT Event Level 1 Screened
│   ├── sw00035003003xpcw3po_uf.evt.gz ..... XRT Event Level 1 Unscreened
│   ├── sw00035003003xwtw2po_uf.evt.gz ..... XRT Event Level 1 Unscreened
│   └── sw00035003003xwtw2po_ufre.evt.gz ..... XRT Event Level 1a Reconstructed
├── hk
│   ├── sw00035003003xbf_rw.img.gz ..... XRT HK Bias Map
│   ├── sw00035003003xen.hk.gz ..... XRT HK Engineering Data
│   ├── sw00035003003xhd.hk.gz ..... XRT HK Header Packets
│   └── sw00035003003xtr.hk.gz ..... HK Trailer Packets
└── products
    ├── sw00035003003xpc_ex.img.gz ..... XRT Products Level 3
    ├── sw00035003003xwt_ex.img.gz ..... XRT Products Level 3
    ├── sw00035003003xpc_sk.img.gz ..... XRT Products Level 3
    └── sw00035003003xwt_sk.img.gz ..... XRT Products Level 3
```

XRTPIPLINE

All tasks required for XRT data processing are performed with the XRTPIPELINE task.

Input files for the XRTPIPELINE are: - XRT Level 1 file; - XRT Bad Pixel Calibration File - XRT On Board Bad Pixel Calibration File - XRT Gain Calibration files - XRT Bias Calibration files - XRT Teldef file - XRT Grades Calibration File - XRT Effective Area Calibration File - XRT Filter Transmission Calibration File - XRT Point Spread Function Calibration File - XRT Vignetting Calibration File - XRT Makefilter Parameters Calibration File - XRT Housekeeping Ranges Calibration File - XRT Events Related Parameters Ranges Calibration File - XRT attitude file - XRT Housekeeping Header Packet file - SWIFT_TLE_ARCHIVE.txt, leapsec.fits, rigidity.data

XRTPIPLINE OUTPUT

- PC Mode: - a Event List Level 1 File with: all the events which fall in bad and hot pixels or from calibration sources flagged as 'bad'; STATUS, PixsAbove, GRADE, PHA, PI columns filled; DETX, DETY, X and Y coordinates calculated;
  - a (optional) Bad pixels list File with all bad pixels taken into consideration to flag events;
  - a (optional) Hot pixels list File with all hot pixels taken into consideration to flag events;
  - a Sky coordinates Image.
- WT Mode: - a Event list level 1 file with: Photon arrival times computed and TIME column filled; STATUS, DETX, DETY, X and Y columns filled
  - a (optional) Bad pixels list File with all bad pixels taken into consideration to flag events;
  - XRT event list level 1a file with: Event reconstruction performed, columns EVTPHA, PHA, PHAS, GRADE, PixsAbove and PI added and filled.
- Common output files: - XRT screened Level 2 Event list - makefilter configuration file - Fits file with attitude and orbit information (s.attorb) - Filter FITS file containing a part of the housekeeping information necessary for screening (s.mkf) - GTI file (one for event file) - Ancillary Response file (PC, WT, PD) - Light Curve (PC, WT, PD) - Spectrum (PC, WT, PD) - Plots of results

XRTPIPLINE syntax

```
xrtpipeline srcra=RA srcdec=DEC indir=OBSID_DIR
outdir=repro/ steminputs=swOBSID
gtiexpr="CCDTemp>=-102 && CCDTemp=<-50"
createexpomap=yes clobber=yes
```

We Select only time intervals with CCD temperatures less than -50° (instead of the standard limit of -47°) since contamination by hot pixels increases the low energy background (D'Elia et al. 2013).

PLIST

Other command parameter can be included on the command line to make subsequent analysis easier. For a full list of these type:

```
plist xrtpipeline
```

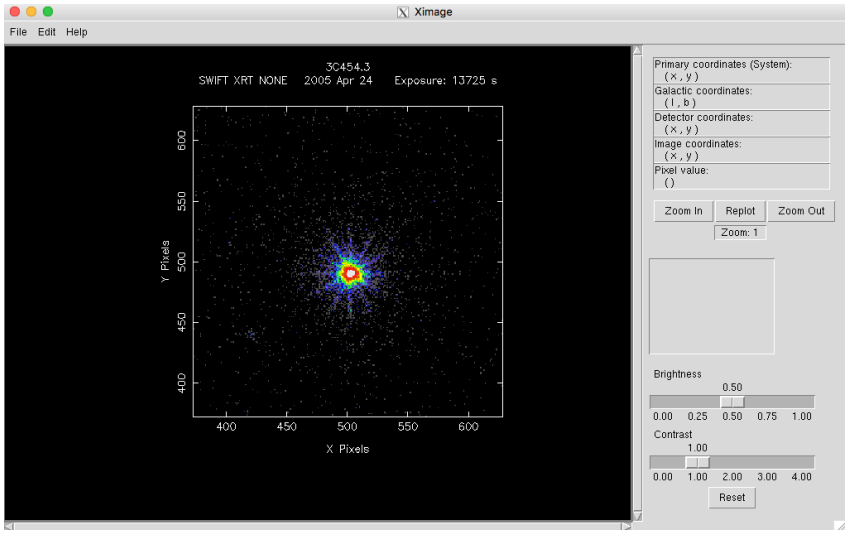
Data Analysis Examples

- Imaging + merging
- Source detection and photometry
- Light curve
- Spectral extraction
- Pileup
- Spectral fitting

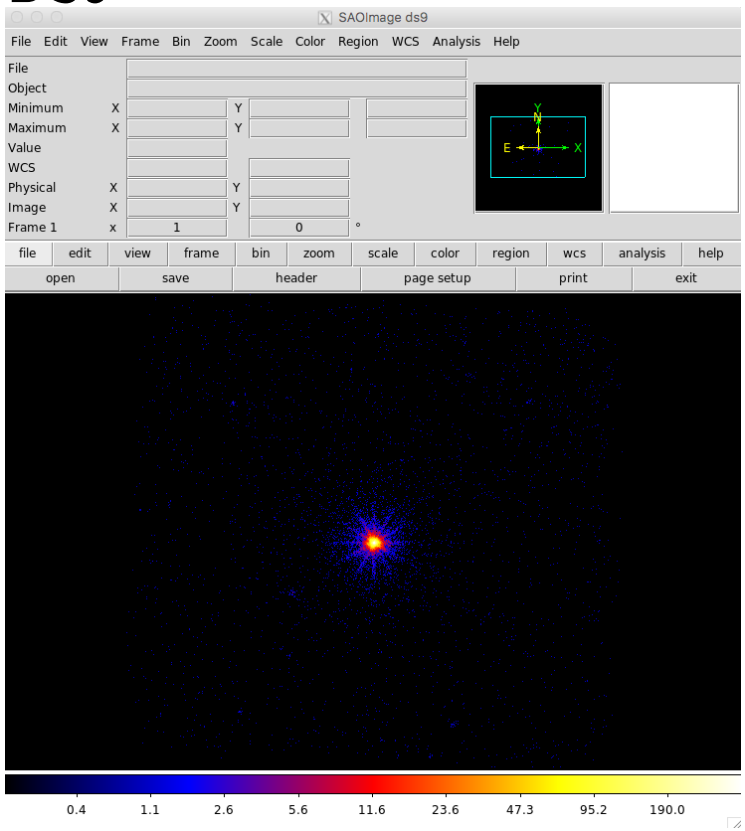
Imaging - Display

PC clean image file `sw00035030001xpcw4po_cl.evt`

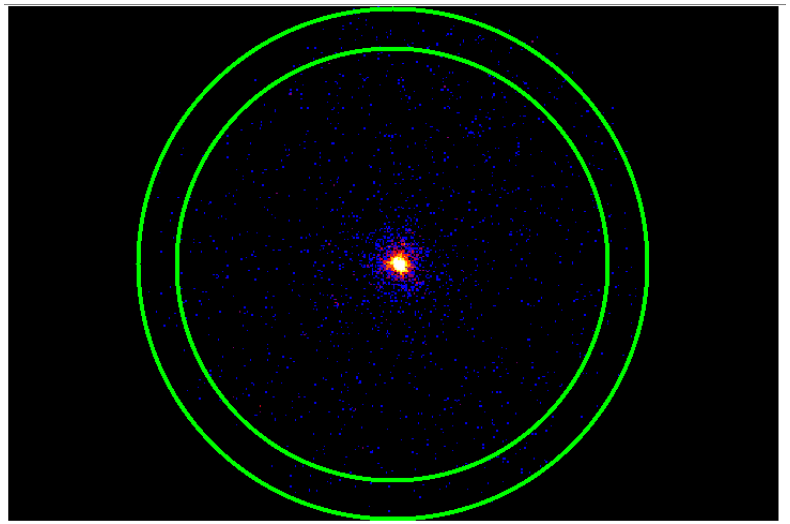
XIMAGE



DS9



Imaging - Filter

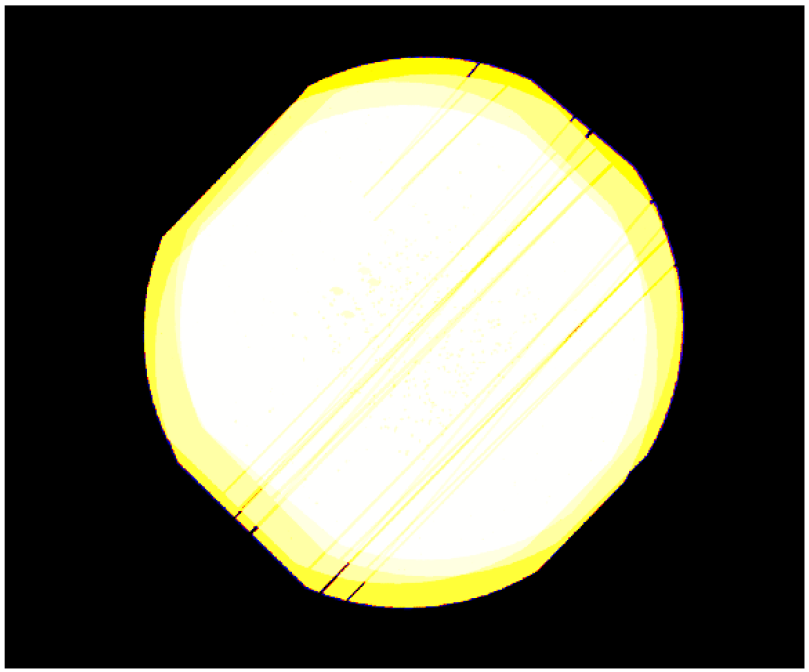


With XSELECT tool:

- filter for time intervals of count rate > 40 cnt/s on the detector edge (11'-13')
- filter for photon energy (i.e., 0.5-7 keV)

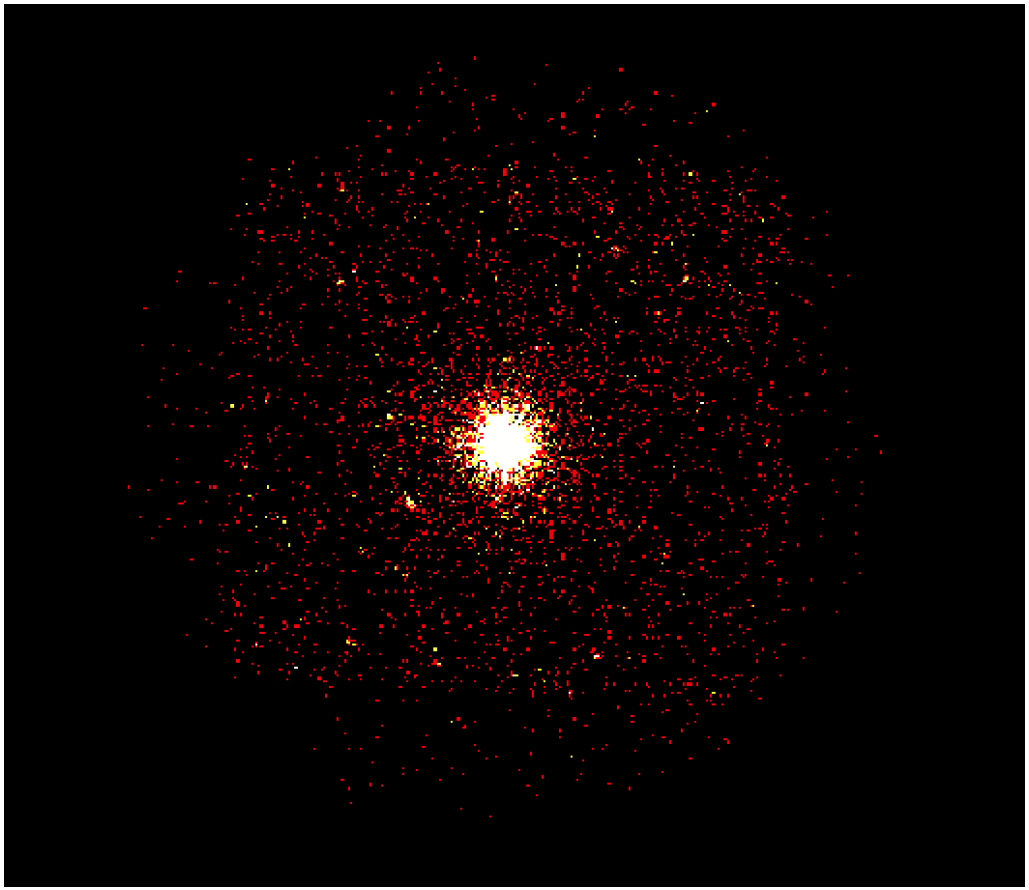
Imaging - Exposure Map

```
xrtexpomap infile=OBSID_pc_filtered.evt
attfile=auxil/swOBSIDpat.fits.gz
hdfile=hk/swOBSIDxhd.hk.gz outdir=./
stemout=OBSID_pc_filters
```



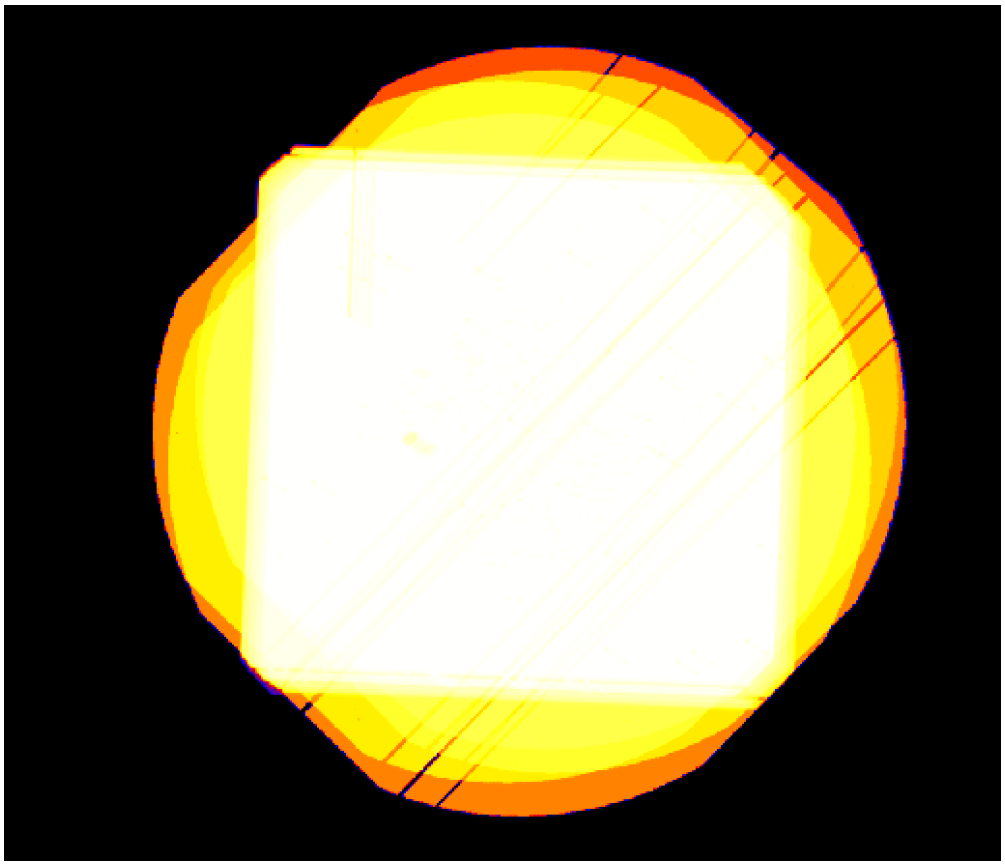
Imaging - Merge Event Files

With XSELECT tool all event files can be merged at once.



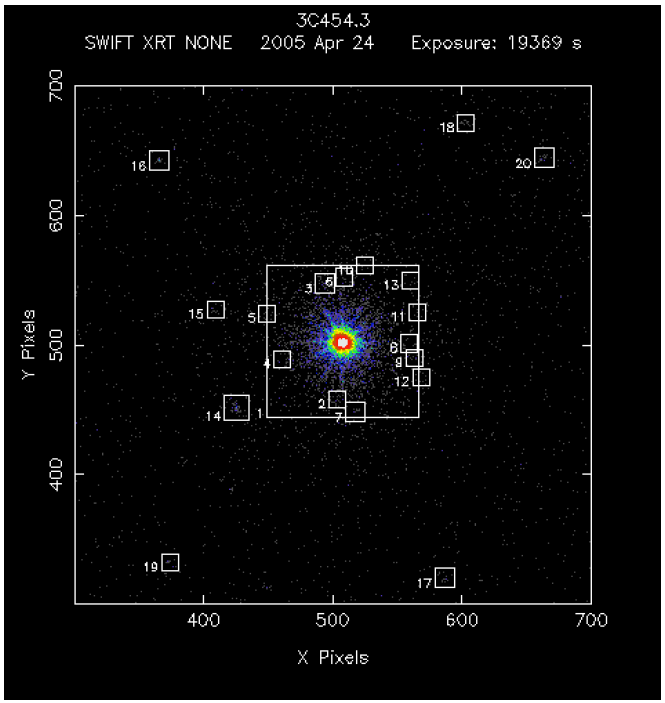
Imaging - Merge Event Files

With XIMAGE tool exposure maps can be merged two at the time.



Source detection and photometry

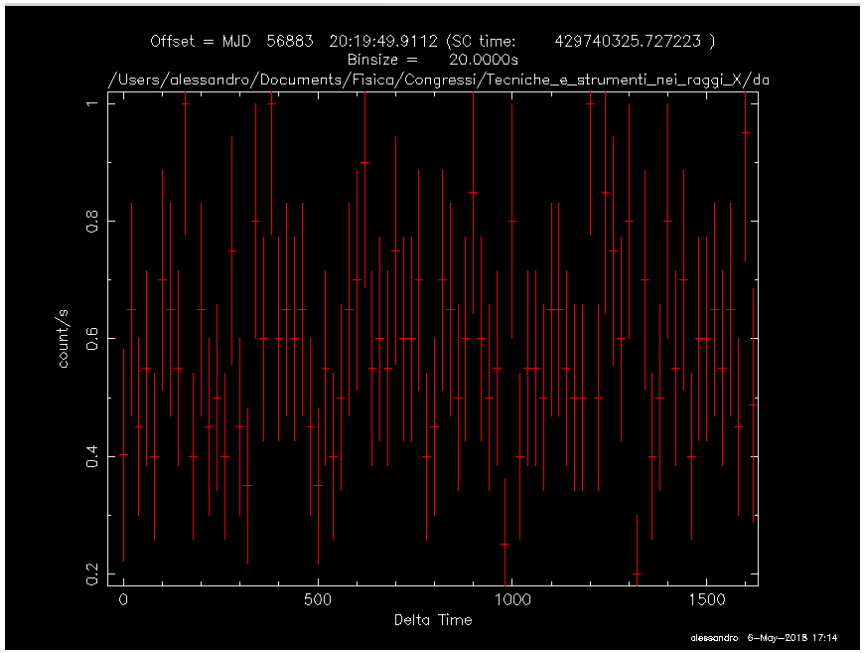
XIMAGE provides a sliding-cell detection algorithm with global (`det`) and local (`sosta`) background.



Uncertainty on source positions can be estimated with the XRTCENTROID tool.

Light curve extraction

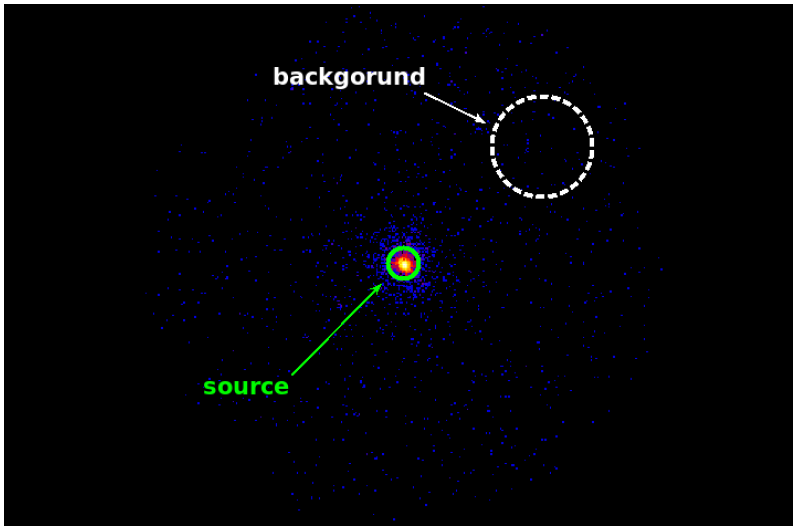
XSELECT provides light curve visualization and interactive time interval selection.



Selected time intervals are saved as GTI filters, and can be applied to the event file with XSELECT.

Spectral extraction and fitting

XRTPRODUCTS is used to extract spectra from the source and background region.



Ancillary spectral files

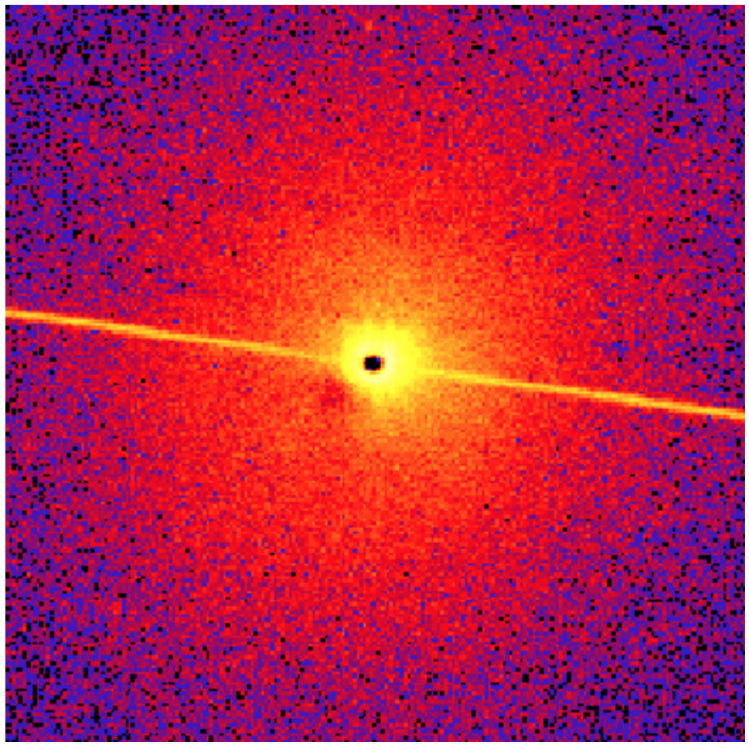
- Redistribution Matrix File (RMF): maps from energy space into detector pulse height (or position) space. Since detectors are not perfect, this involves a spreading of the observed counts by the detector resolution, which is expressed as a matrix multiplication.
- Auxiliary Response File (ARF): Contains the combined telescope/filter/detector areas ("effective area") and the quantum efficiency as a function of energy averaged over time. The effective area is cm^2 and the QE is counts/photon; they are multiplied together to create the ARF, resulting in cm^2 counts/photon.

Putting All Together

FTOOLS GRPPHA tool can be used to set the relevant keywords in the spectrum header and to bin the spectra (i.e, to a minimum number of counts per energy bin).

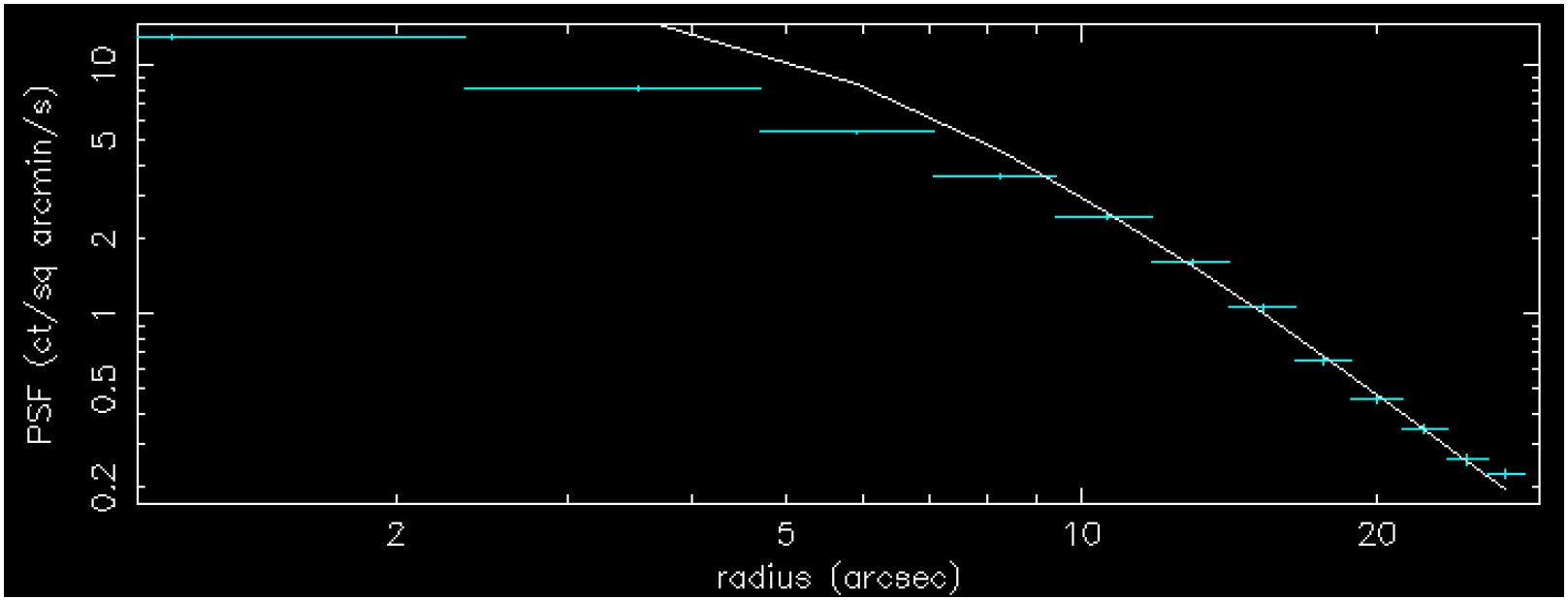
Pileup

Pile-up occurs when multiple photons registered within a given CCD frame have overlapping charge distributions, so that the resulting charge spatial distribution is read as a single event whose energy is the sum of the overlapping events. That is, two or more soft X-ray photons can be registered as a single higher-energy photon. For XRT, this usually occurs at count rates > 0.5 cnt/s.



Pileup 2

The standard procedure to avoid pileup with PC observations is to compare the surface brightness profile of the source with the XRT PSF, and exclude from the spectral extraction the inner pixels where the two profiles diverge.



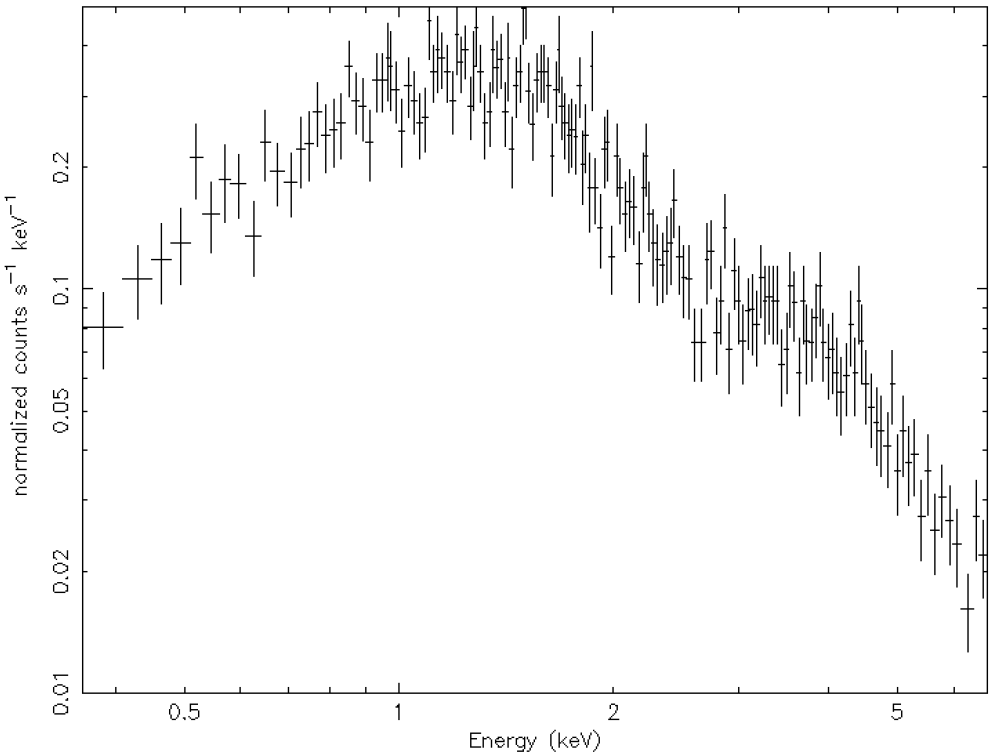
Spectral fitting

The weapon of choice for X-ray spectral fitting is XSPEC (Aranud et al. 1996).
XSPEC is a command-driven (tcl scripting shell), interactive, X-ray spectral-fitting program, designed to be completely detector-independent so that it can be used for any spectrometer.
XSPEC has been used to analyze data from HEAO-1 A2, *Einstein Observatory*, EXOSAT, *Ginga*, ROSAT, BBXRT, ASCA, CGRO, IUE, RXTE, *Chandra*, *XMM-Newton*, *Integral*/SPI, *Fermi*, *Swift*, *Suzaku*, *NuSTAR*, and *Hitomi*.

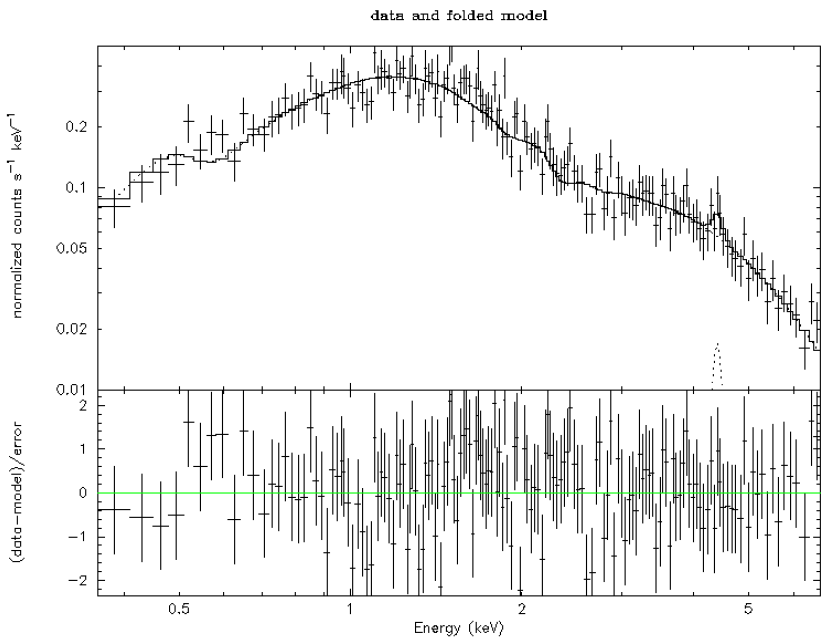
`xspec12@athena.gsfc.nasa.gov`

XSPEC

XSPEC allows for spectral filtering and fitting with a number of pre-made and user-defined models.



XSPEC Fit



More complex procedures, like multiple spectral fitting, 3D deprojection, equivalent width evaluation, confidence contours and pileup modeling are possible, as well as the definition of new models (through the MDEFINE command).