School on

X-rays from Star Forming Regions

DATA PRODUCTS OF X-RAY OBSERVATIONS

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Summary

- Basics of X-ray data from CCD detectors
- Introducing events and related quantities
- From raw data to the event list
- Data filtering and screening
- From data products to science analysis

Observatories and Instruments

- Several devices employed in past, present, and (hopefully) future X-ray observatories

INSTRUMENT		SPACE OBSERVATORY					
		Past		Present			Future
CLASS	TYPE	Einstein	ROSAT	Chandra	XMM	Suzaku	IXO
Gas Proportional Counters		X	X				
Micro-Channel Plates		X	X	X			
Solid-State Detectors	CCDs			X	X	X	X
	Others	X				X	X
	μCal					(X)	X
Dispersive	Crystals	X					
	Gratings	X		X	X		X
Polarimeters							X

X-ray vs. optical data

Optical Observations
Images in different colors or spectra
Source coordinates, photon fluxes
Flat field
Dark (+bias) frame
Lamps
Standard stars

What are the equivalent data in X-ray observations?

X-ray observations of Star Forming Regions: an example

Basics of CCD-based X-ray data

- X-ray detectors are <u>photon-counters</u>
- X-ray data are <u>Poissonian</u>
  - Scientific products may have a few or even zero photons in large space and time ranges
- Data are made of <u>"events"</u>, characterised by:
  - <u>Time</u> of occurrence at the spacecraft
  - <u>Position</u> on the detector
  - <u>Pulse Height</u>, related to the energy of the process which triggered the event
  - <u>Shape</u>, used to separate X-ray events from particles
  - CCD number and other secondary attributes for quality control of the event

Event list

- For each event: when, where, how much, what, etc.

	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

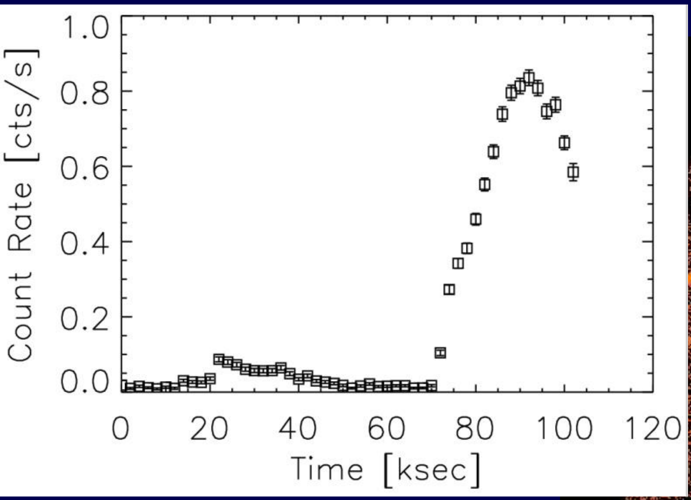
Science products

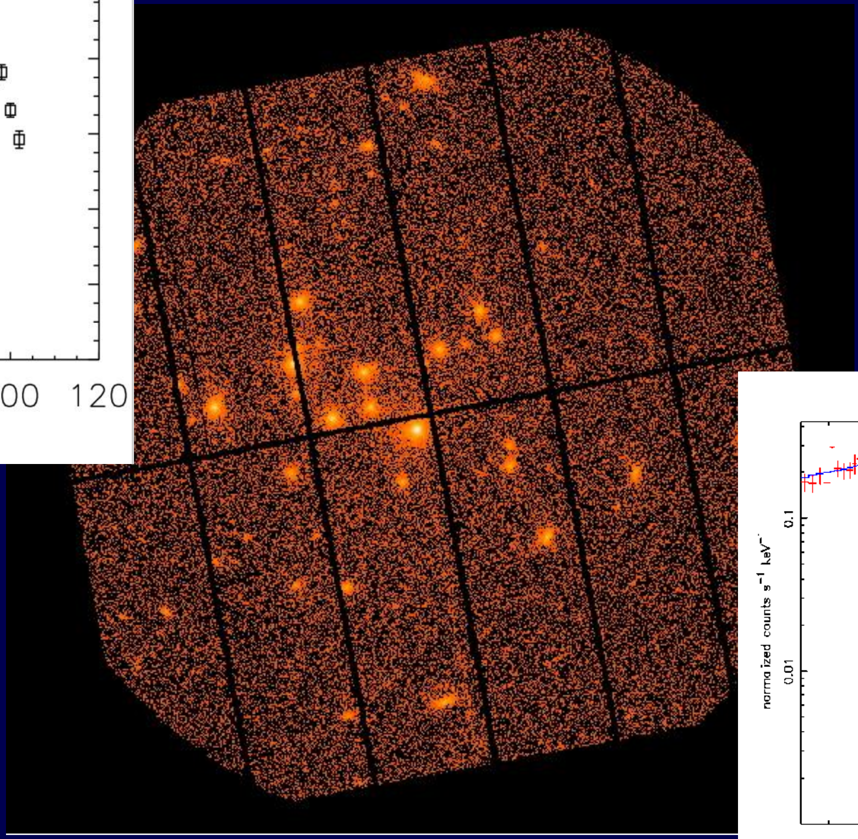
- X-ray science products can be seen as *projections onto different sub-spaces defined by the event physical quantities*
  - In the plane of the spatial coordinates, one gets a 2-D image in units of counts per pixel
  - By ignoring time and space, one gets an energy distribution function (spectrum) in units of counts per energy bin
  - By ignoring space and energy, one gets an intensity time series in units of counts per time bin (X-ray light curve)

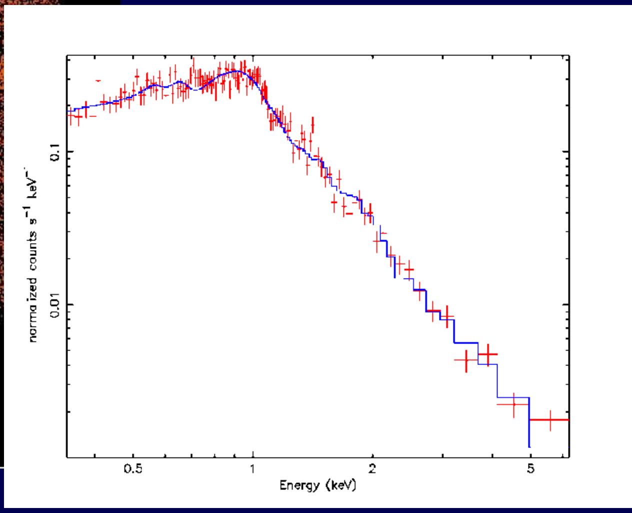
- The aim of the science data analysis is to derive intrinsic physical properties of the celestial sources from these science products
- To this aim a good knowledge of the satellite operation and of the instrument response is required

Science products: examples

- XMM-Newton European Photon Imaging Camera (EPIC) observation of a Star Forming Region with the pn CCD detector



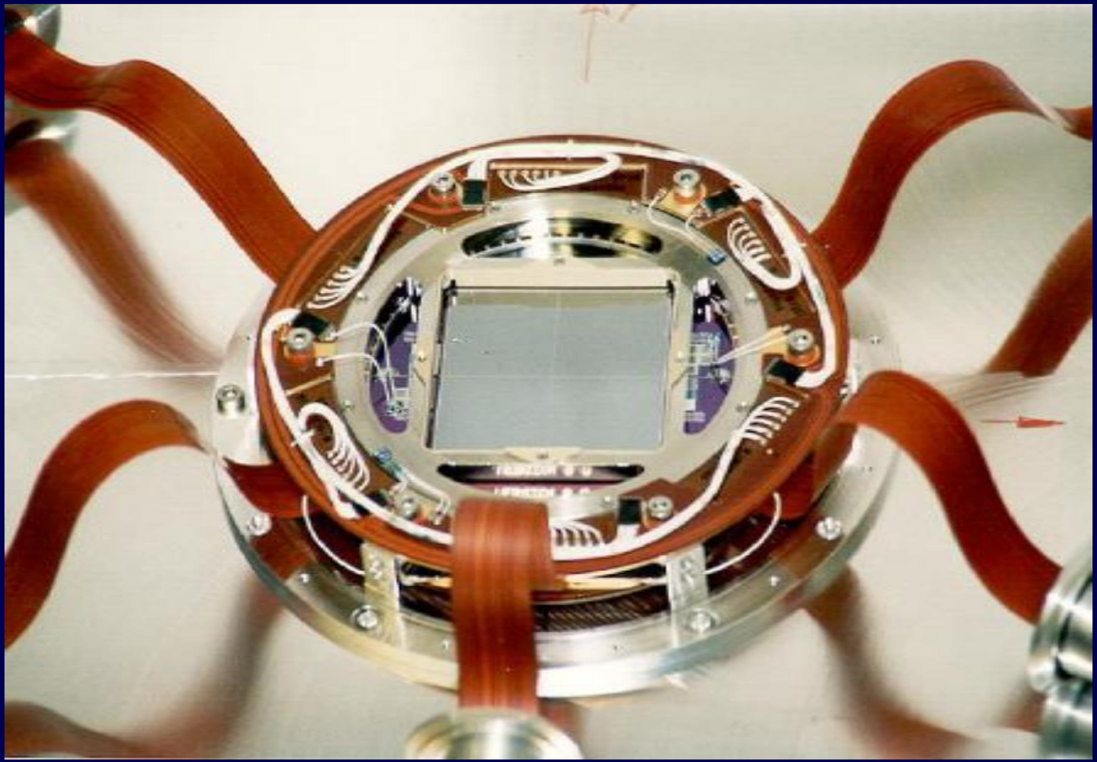




CCD-based X-ray data

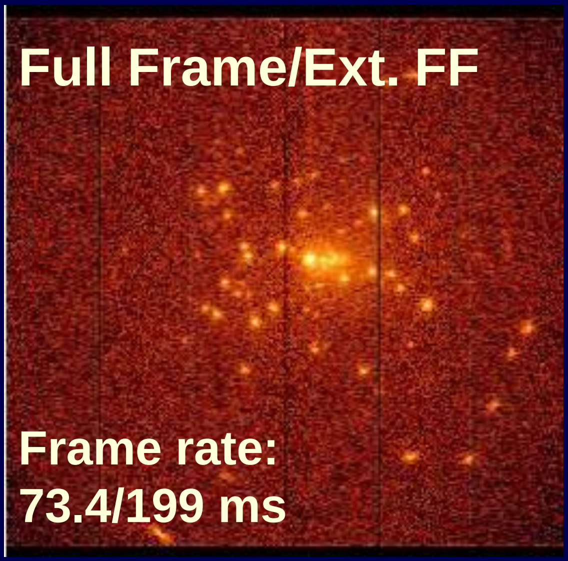
- Charge Coupled Devices sensitive to X-ray photons (low-energy photons are rejected by means of filters)
- The signal number of secondary electrons generated in the Silicon chip is proportional to the photon energy
- A signal may be induced by an X-ray photon simultaneously in two or more pixels
- Signals may be produced also by particles, but recognized by peculiar multi-pixel spatial patterns
- Time-integrated signal charges are read at constant frame rates set by the way the CCD is operated

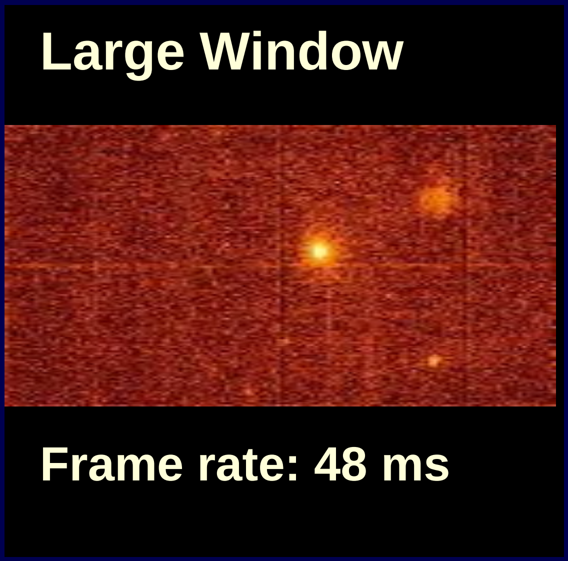
CCDs for X-ray astronomy: an example

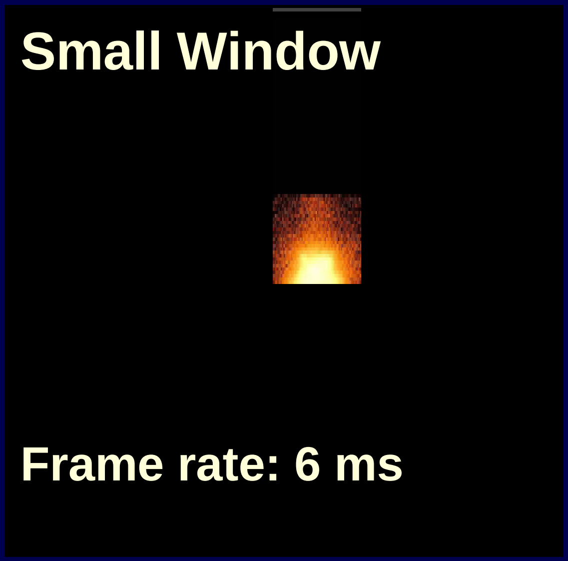


- XMM-Newton EPIC-pn detector
- 12 back-illuminated pn-junctions
- 200 x 64 px each
- Signal readout nodes at one edge
- 5 different operational modes

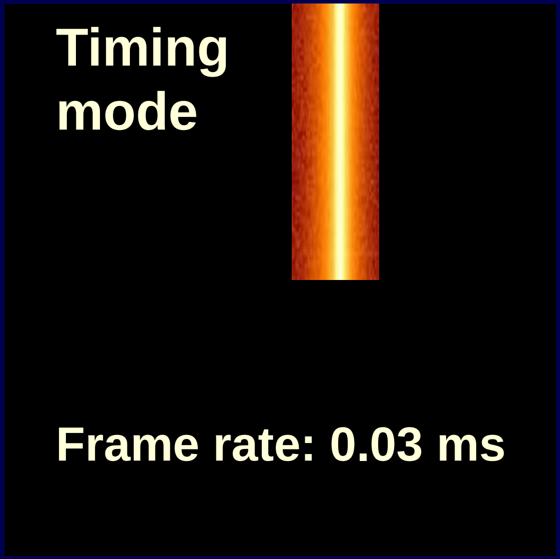
XMM-Newton EPIC/pn operating modes

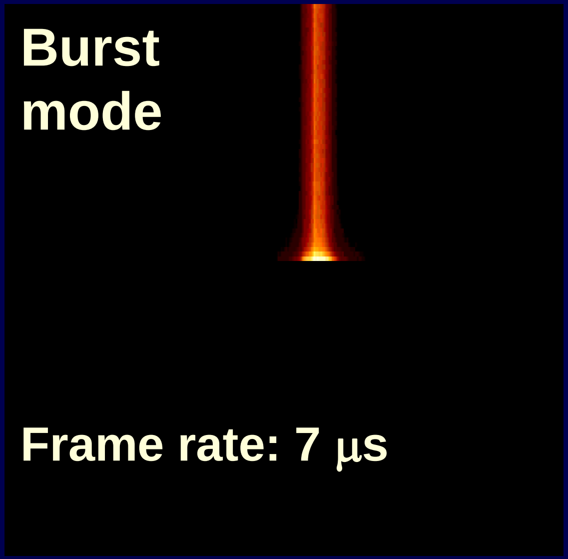






Full Frame usually employed for X-ray observations of Star Forming Regions





From raw data to event files

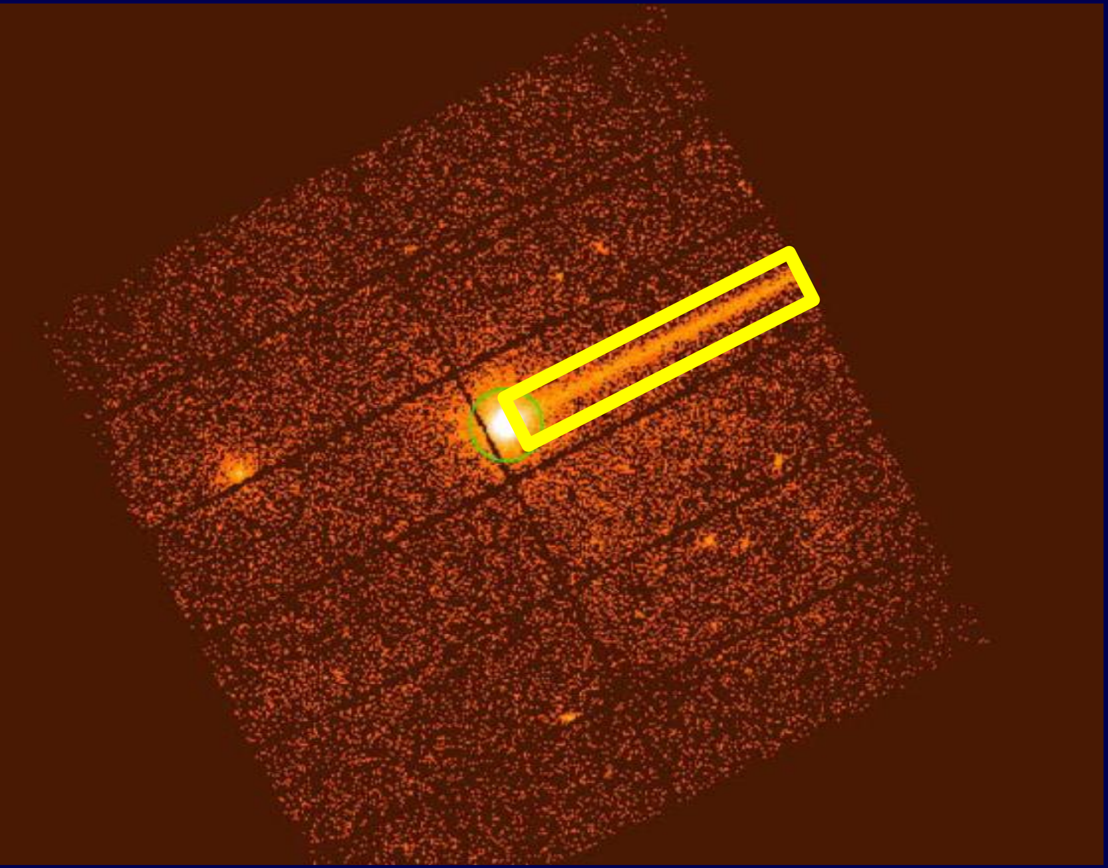
- In order to obtain event files suitable for science analysis a pre-processing of the raw data is required, in which calibrations are applied and observations are (partially) screened

Raw data quantity		Event file quantity	Requirements
FRAME COUNT	→	Time (UTC)	Clock
RAW COORDINATES	→	SKY COORDINATES	Star tracking
PHA (signal amplitude)	→	PI (energy)	Calibration sources
RAW COORDINATES (for gratings data)	→	DISPERSION ANGLE (wavelength)	

From raw data to event files: Timing information

- Time resolution is determined by the frame rate
- The actual exposure time of the observation is shorter than the total on-source time (dead-time correction required)
- Data useful for science analysis are identified by Good Time Intervals (for each CCD)
- Photons arriving during frame read-out times are “incorrectly” identified (Out-of-Time events)

Spatial information issues: Out-of-Time (OoT) events

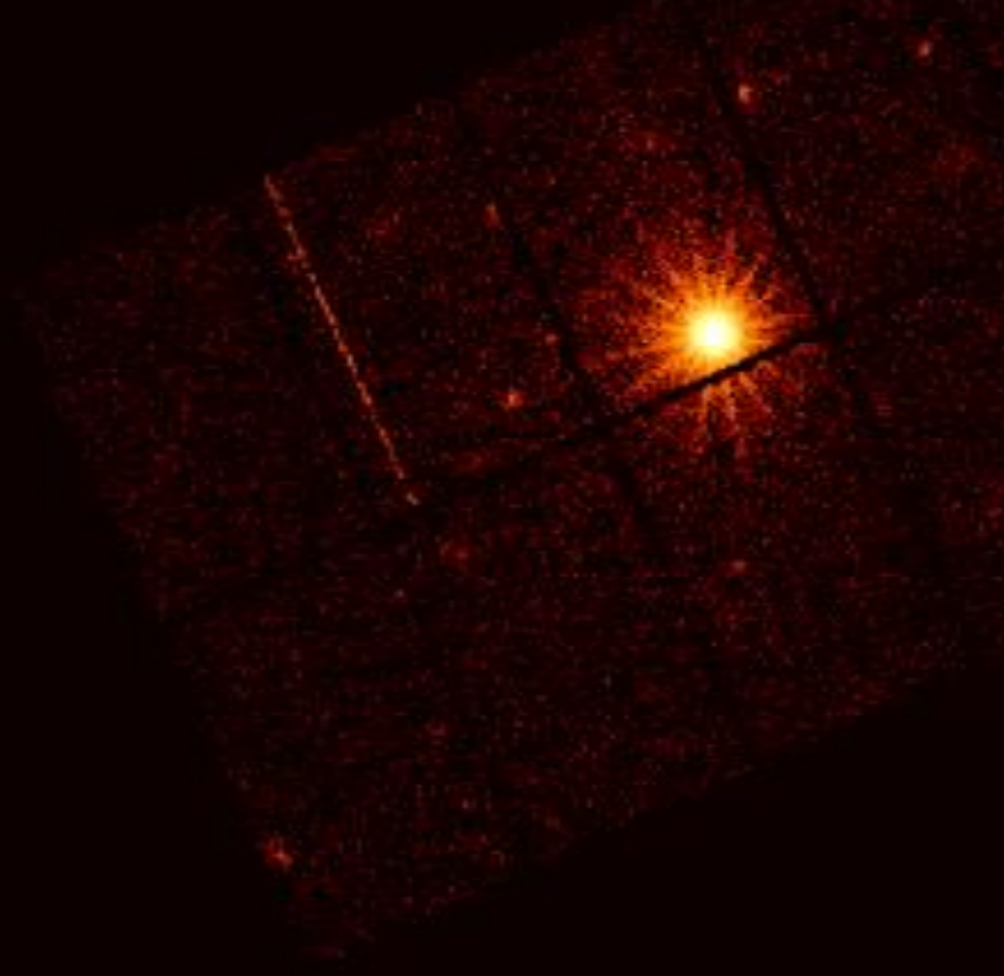


- OoT events: photons registered during CCD read-out
- OoT events create in images a strip of wrongly reconstructed event positions and broaden spectral features in RAWY (see CTE correction issues)

From raw data to event files: Event position

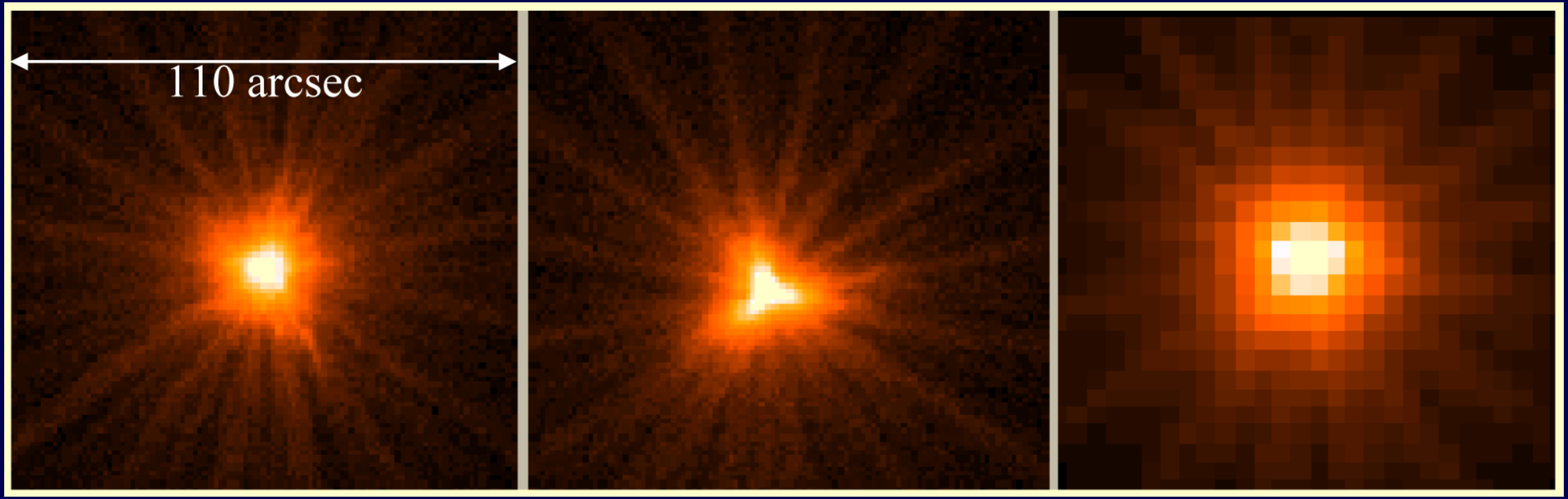
- Absolute Astrometry requires knowledge of space observatory pointing direction
- Accuracy determined by spacecraft attitude reconstruction
- Information from guide star trackers required
- Relative astrometry requires knowledge of detectors geometry

From raw data to event files: Spatial information issues



- Out-of-time events
- CCD gaps
- Bad pixels:
  - Hot pixels: ghost events
  - Dead pixels: no events
  - They are routinely indentified and flagged!
- Bad columns
- Point Spread Function

Point Spread Function

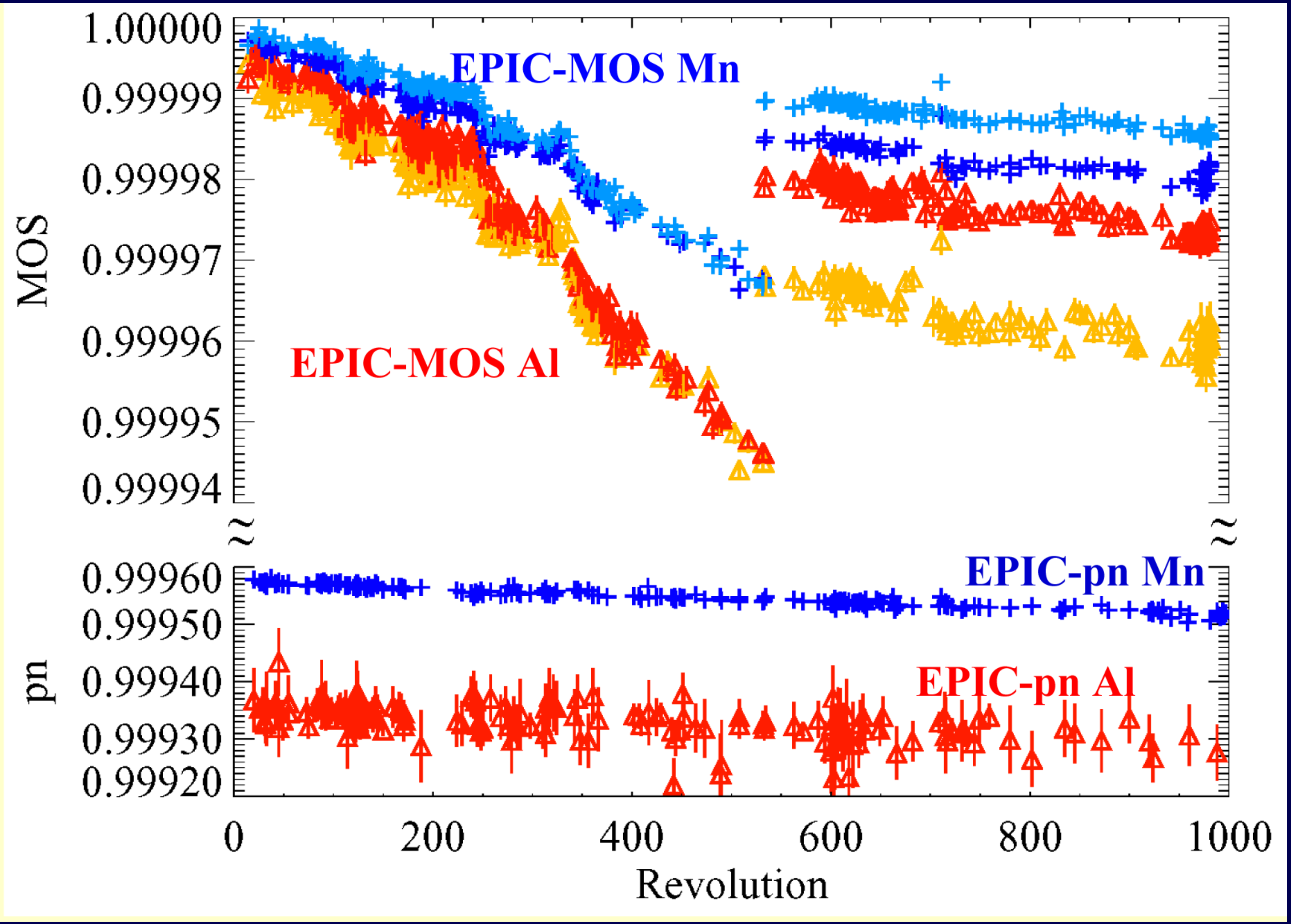


- Spatial distribution of events in the focal plane for a point source
- The PSF integrates to 1 over the infinite focal plane, but **FWHM is 0.5–8″** for Chandra and **4–10″** for XMM
- The PSF depends on:
  - The mirror (i.e. type and quality of the **optics**)
  - The distance from field center (**off-axis angle**)
  - The photon **energy**

From raw data to event files: Energy information

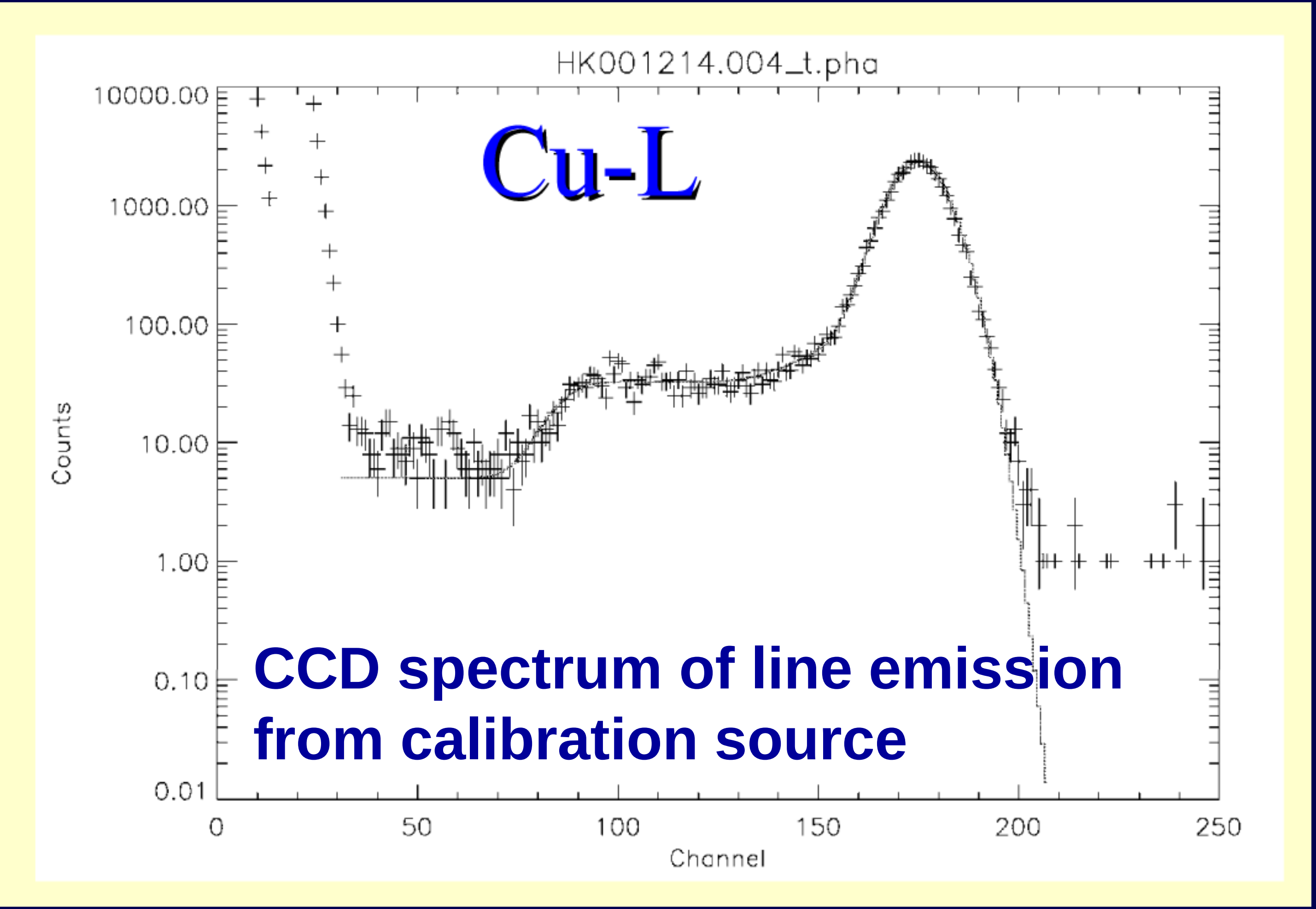
- Photon energy computed from actual signal charge reading
- Gain is the conversion of the charge signal deposited by a detected photon from ADU (Analogue to Digital Unit) into energy (eV)
- Charge Transfer Efficiency (CTE) is the fraction of the signal charge actually transported to the read-out node. It depends on
  - CCD type and operation mode (frame rate)
  - Time of usage (long-term degradation)
- Continuous monitoring of internal calibration sources required

Charge Transfer Efficiency vs. Time



- Energy (spectral) calibration is time-dependent!

Spectral response

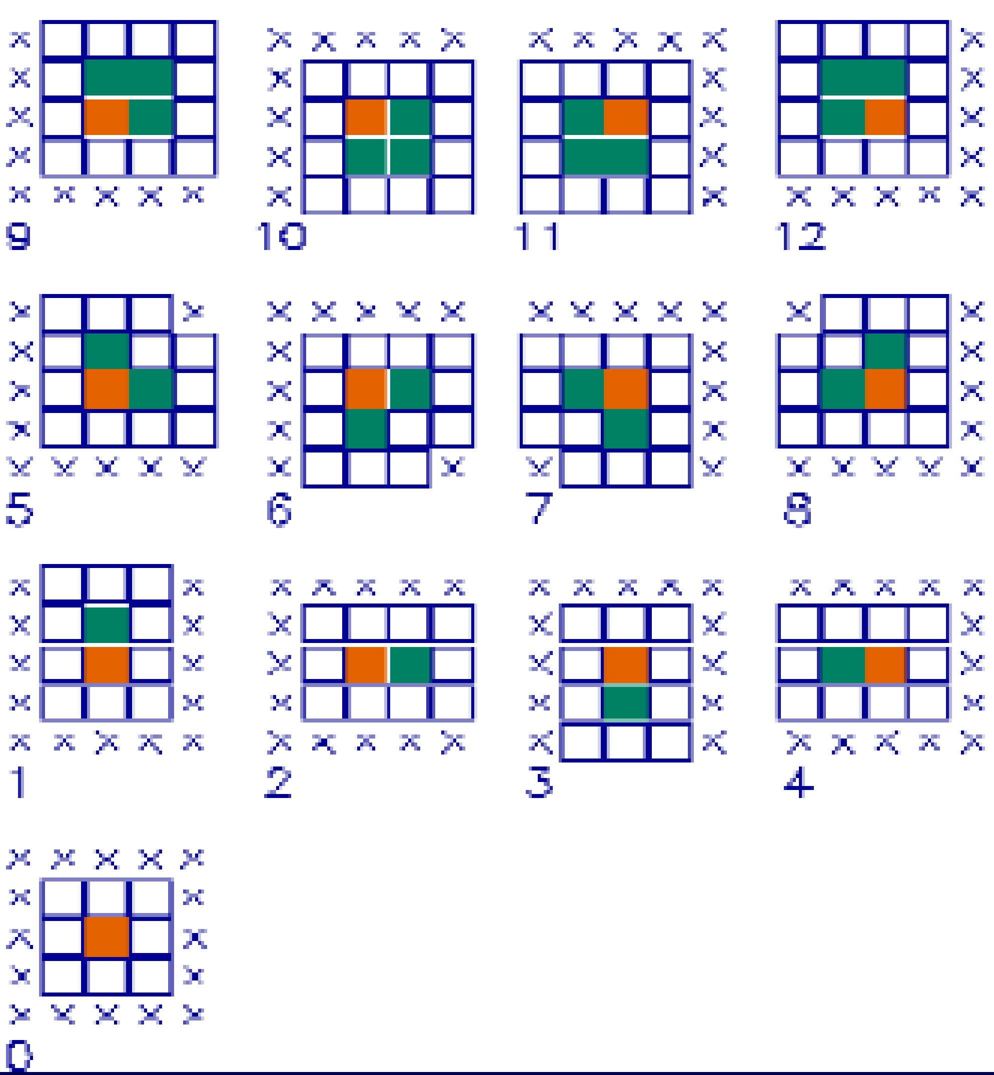


- Monochromatic X-ray photons can induce different signal charges → Probability of energy redistribution

From raw data to event files: Event quality control

- False photon events can be produced also by particles focused by the optics
- Screening possible via
  - High-energy filtering
  - Event patterns (aka grades for Chandra)

Event patterns



- XMM-Newton EPIC-pn detector
- Patterns ≤ 4 (single or double events) are due to true photons (most likely)
- Patterns ≥ 5 are likely spurious events

From raw data to event files

- Raw data (in the *primary/secondary* directories for Chandra or in *ODF* for XMM-Newton) include
  - Uncalibrated CCD events
  - Time correlation files (frame counts vs. UTC time)
  - Spacecraft attitude files (guide star tracking)
  - Spacecraft housekeeping files
  - Other auxiliary data and diagnostics
- Your data analysis will start from pre-processed event files, but the raw data will be required for further science-driven screening and calibration steps

Event data

- The XMM/EPIC imaging-mode table of the calibrated EVENTS contain 14 columns (and similar quantities are in Chandra/ACIS event files):
  - **TIME** → event occurrence time
  - **RAWX, RAWY** → where on the CCD
  - **DETX, DETY** → where on the detector
  - **X, Y** → where from the sky
  - **PHA, PI** → which energy did the event have
  - **FLAG** → event at a critical place in the detector
  - **PATTERN** → event was a true X-ray photon or not
  - **CCDNR** → CCD where the event occurred

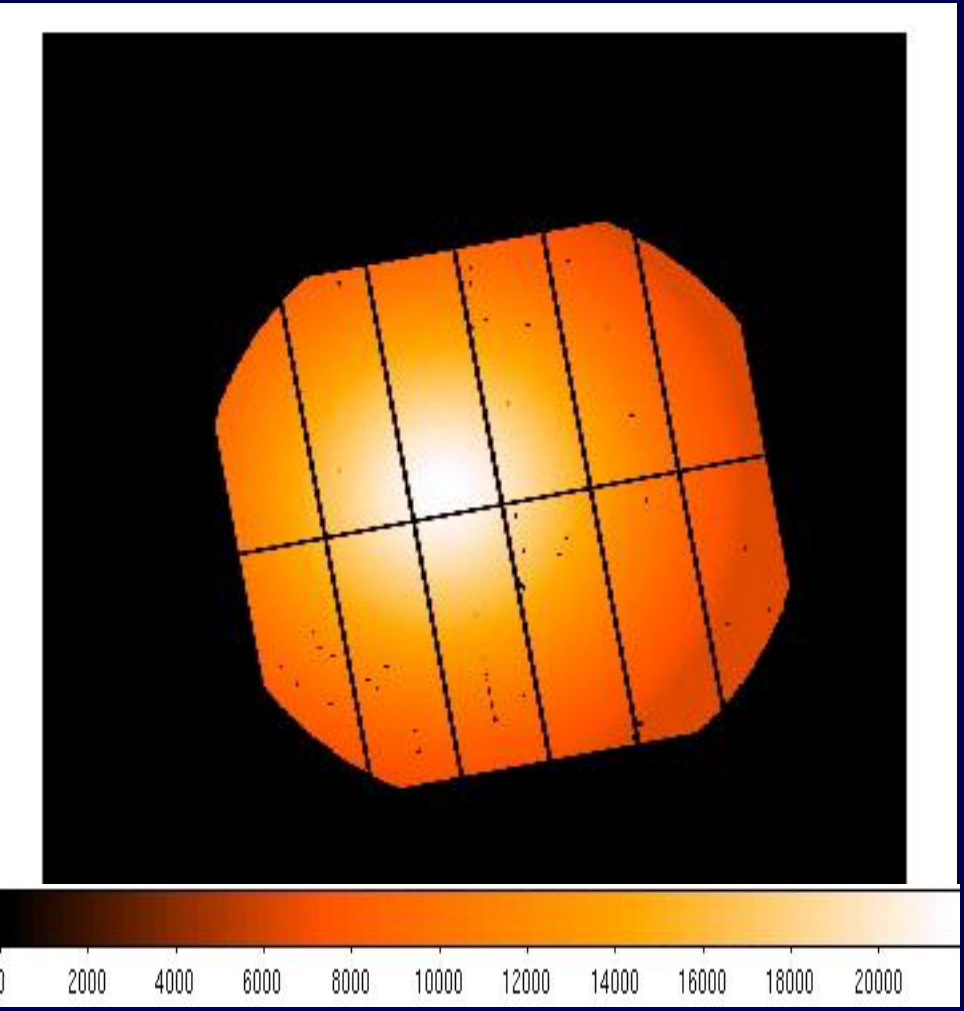
From data products to science analysis

- Standard processing yields quick-look science products, but
- further screening of event files and more data products are usually required for optimal science analysis.
- These steps are left to the user because different choices are possible depending on the science aim
  - Detection of faint X-ray sources requires the lowest noise
  - Variability studies require the best time coverage
  - Spectral analysis requires the best determination of photon energies
  - X-ray photometry in crowded fields requires a good knowledge of the energy-dependent PSF and of the exposure time
  - Source identification requires accurate sky positions
  - Spectral modeling requires knowledge of the instrument response (transfer function)

More data products for science analysis

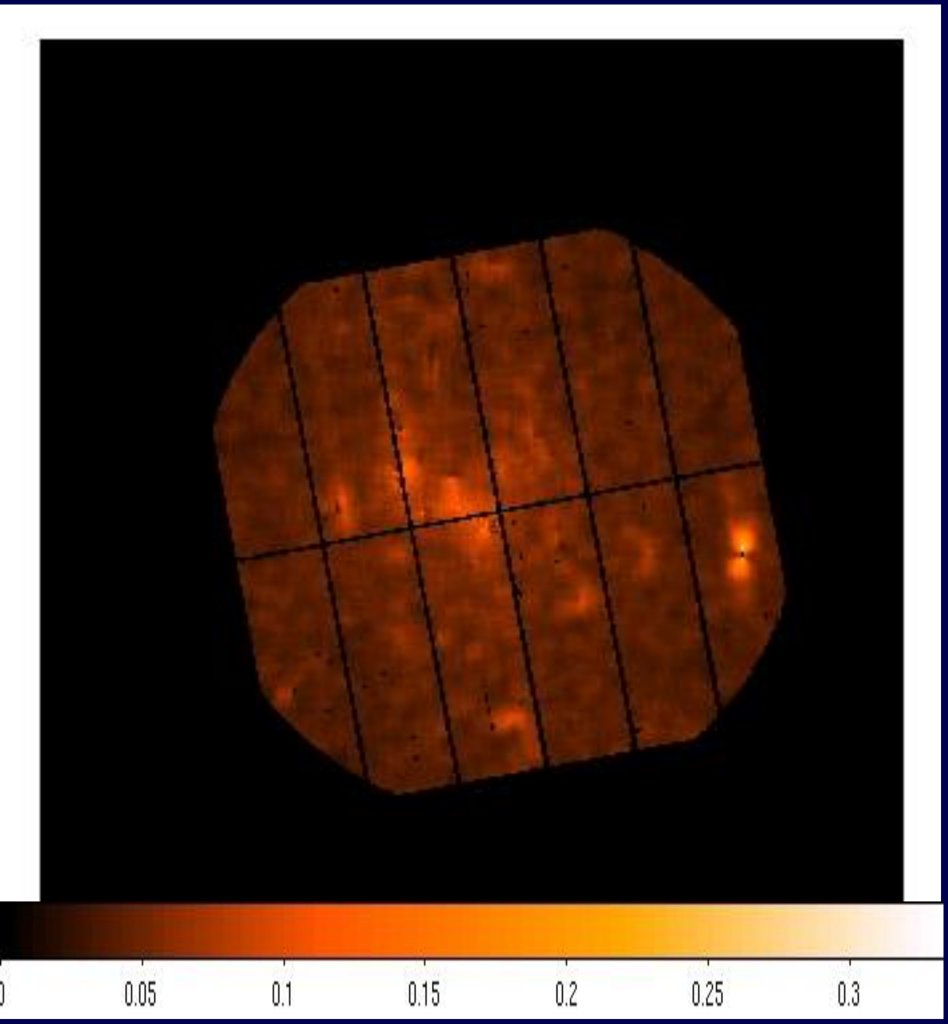
- For source detection and image analysis
  - **Exposure maps**: mirror and detector sensitivity across the field-of-view, taking into account any changes in the spacecraft pointing direction
  - **Background maps**: smoothed maps of the field-of-view background (both of instrumental and cosmic origin)
- For spectral analysis
  - **Effective area**: transfer function of optics+detector as a function of energy and position
  - **Redistribution matrix**: probability that a photon of a given energy is registered in a given channel

Exposure map



- Instrument sensitivity decreases from the center (the **aim point**) toward the edges of the field of view (**vignetting effect**)
- This effect can be described as if the **exposure time decreases with the off-axis angle**
- The exposure map also describes other **obscuration effects** in the field of view
- Required **to compute images in flux units**

Background map



- Background may include
  - Diffuse sky emission
  - Scattered light from very bright X-ray sources just outside the FoV
  - Residual events due to particles
  - Instrumental noise
  - Photons in the PSF tails of actual X-ray sources in the field
- Required for source detection and S/N ratio

X-ray vs. optical data

X-ray Observations (imaging + CCD-resolution spectra)	Optical Observations
Event lists	Images in different colors or spectra
Time, coordinates, energy	Coordinates, photon fluxes
Exposure map	Flat field
Background map (including sky)	Dark (+bias) frame
On board calibration sources	Lamps
Sky calibration sources	Standard stars

Sequence of steps (a summary)

1. Electronic signals of instrumentation on-board
2. Pre-processing on-board
3. Download to ground center (telemetry-limited)
4. From raw data to event files and quick-look science products
5. Event files at user destination
6. Constellation school (A lot of preparatory work!)
7. Science-driven data screening
8. Extraction of science products (images, time series, spectra)
9. Analysis of science products

X-ray data calibration

- A major advantage of X-ray observations with respect to ground-based optical observations:
  - Spacecraft, optics, and detector status is continuously monitored
  - The instrument performance is time-dependent, but updated calibration data and processing software is continuously released and back-compatibility is maintained