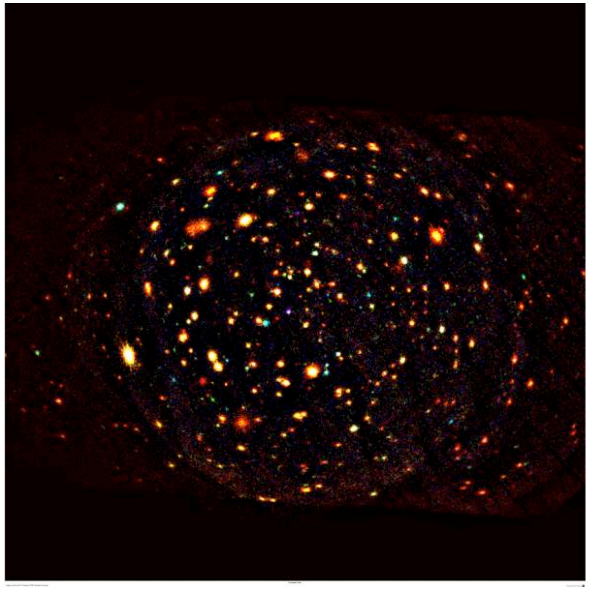
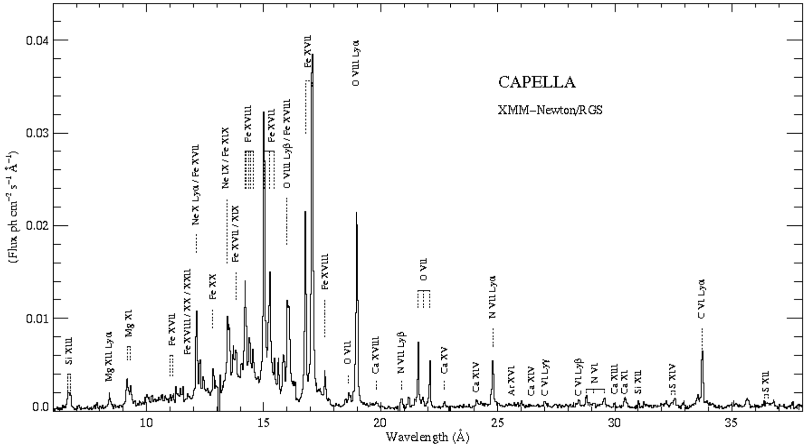
The XMM-Newton Spacecraft and Instruments

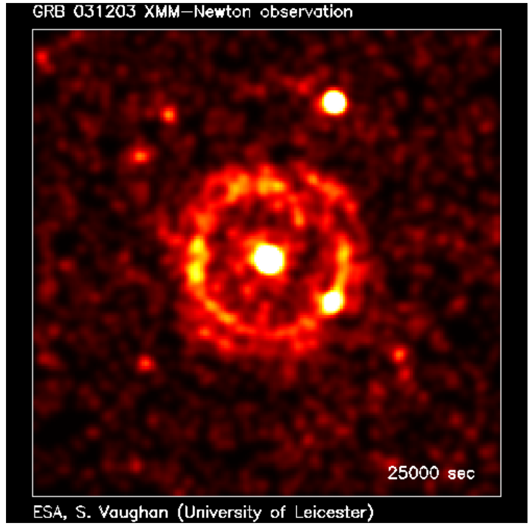
Carlos GABRIEL (+ a lot of colleagues from the)

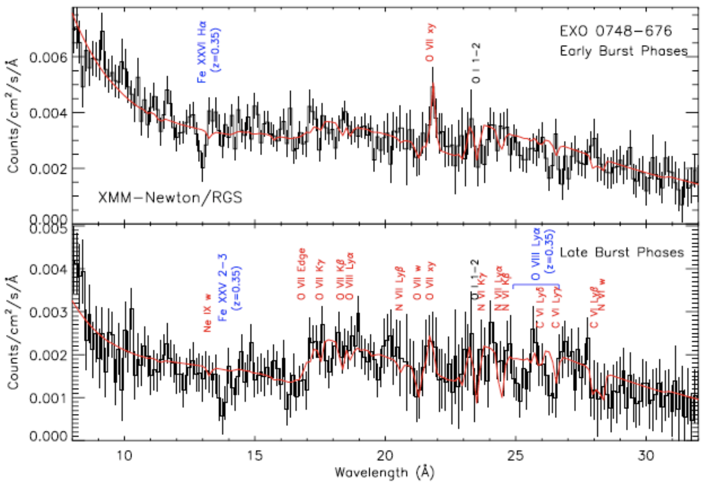
XMM-Newton Science Operations Center – ESA / ESAC

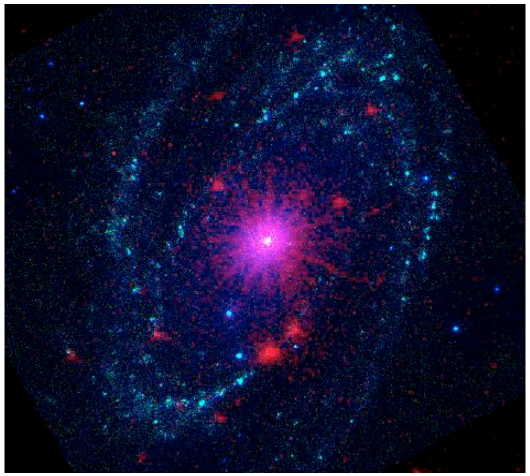
Some (scientific) beautiful things (as seen by XMM)

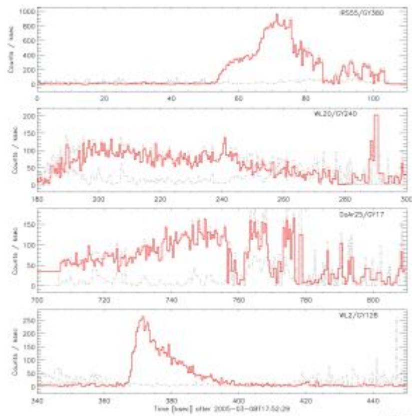


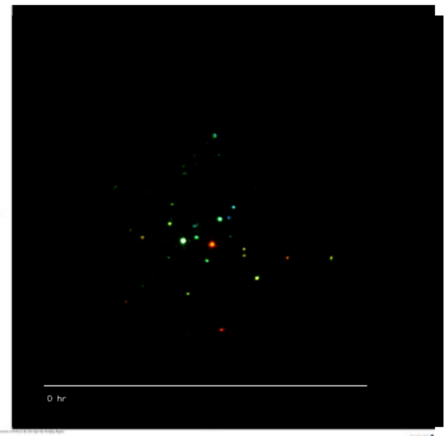












Outline

- **History of the XMM-Newton project**

- Description of the **XMM-Newton** satellite

- Description of instruments and a bit of their calibration

    - X-ray telescopes: XRT
    - X-ray Imaging & low resolution Spectroscopy & Timing: EPIC
    - X-ray High resolution dispersive Spectroscopy: RGS
    - Optical and UV Imaging & Spectroscopy & Timing: OM

- Use of the **XMM-Newton** observatory

History of XMM-Newton

Proposed by ESA's Science Programme committee	1
Approved by the ESA Council of Ministers held in Rome	J
Selection of the prime contractor Dornier Satellitensysteme	O
Start of Development Phase	M
Construction of the spacecraft – Start Total Cost = 689 M€	M
Launch	D
Switch on instruments	January 4, 2000
Start of calibration phase	March 10, 2000
Start of open time observations	July 1, 2000

History of XMM-Newton

Yearly Announcement of Opportunity (AO)	Every year since 2001
4 X-ray CCDs (out of 44) lost - (CCD4 in RGS2, CCD7 in RGS1 and CCDs 6 and 4 in MOS1)	2000, 2005 and 2012
Contact lost with XMM-Newton	18 October 2008
Contact re-established (and everything OK!)	22 October 2008
Number of refereed publications basing on XMM data = 5981	as of Today = 9/3/2019, 10:00 Mohali time

History of XMM-Newton

Two most remarkable events in the last years:

Calibration Scientist Matteo Guainazzi leaves the XMM-Newton SOC...	**September 2015**
A distinguished XMM-Newton observer (and also former Chandra instrument PI), Mariano Méndez, changes status...	**March 2016**

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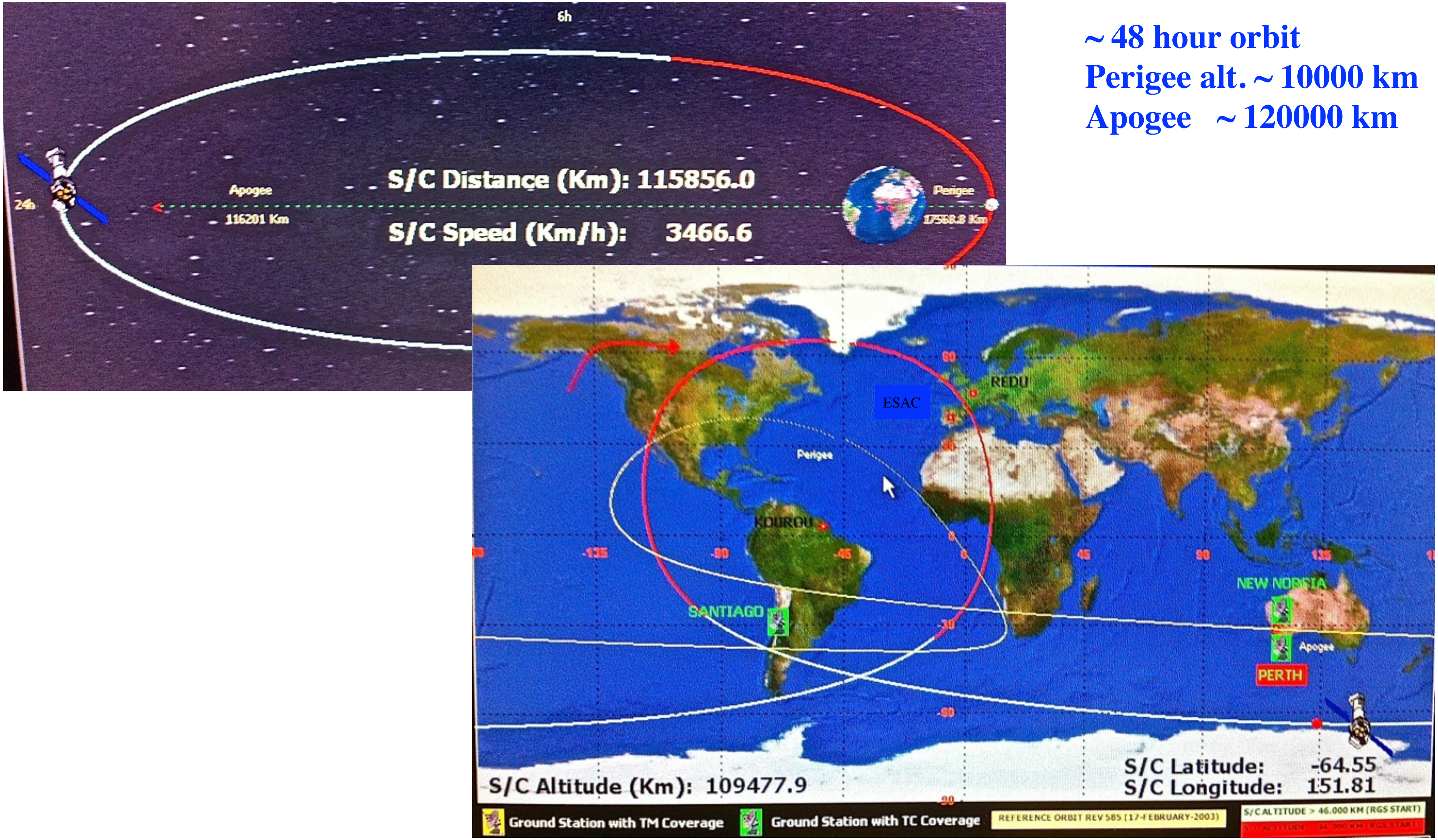
The satellite

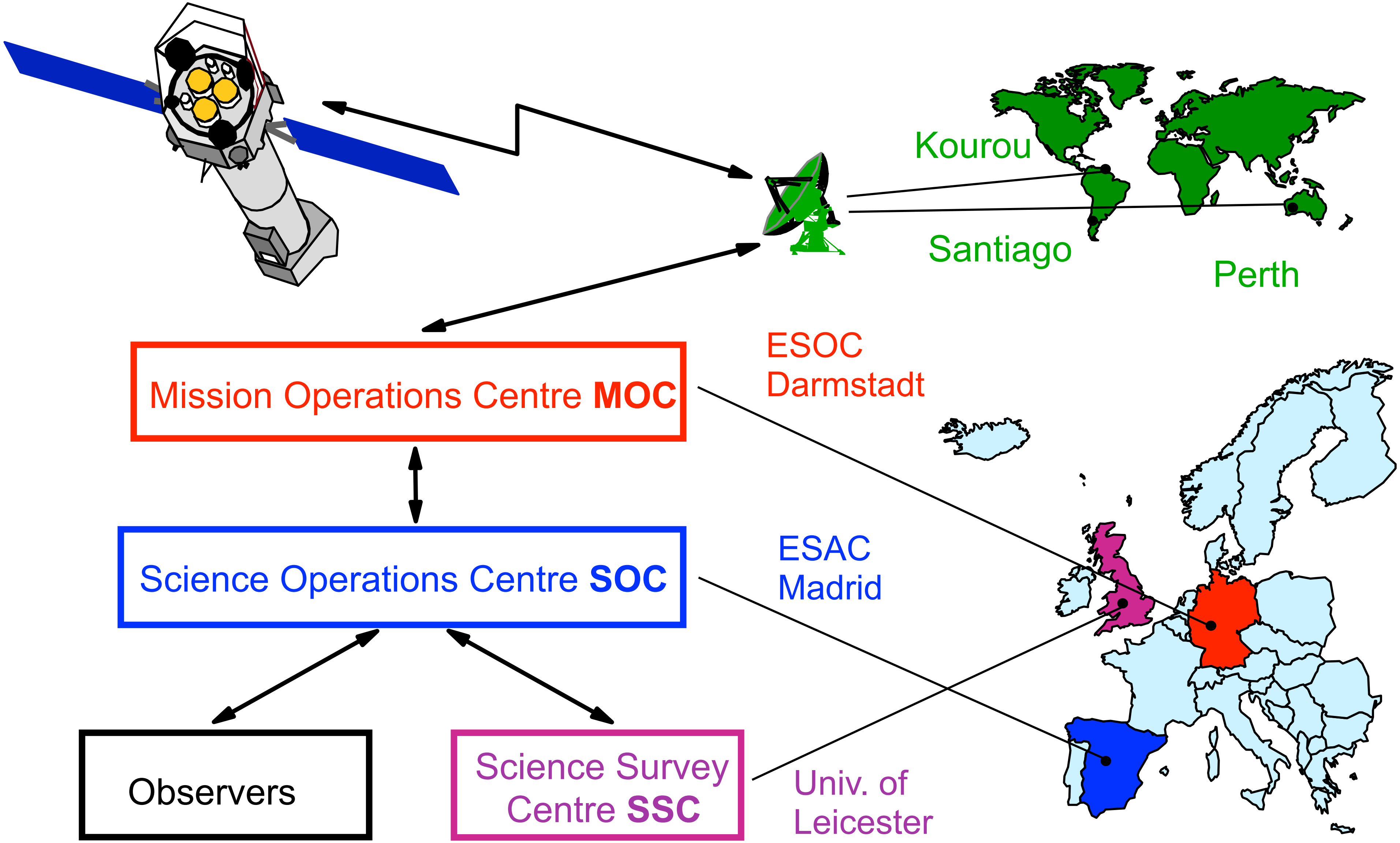
- weight: 3.8 t, length: 10 m
- squarish service module also carrying three 'mirrors modules' at its forward broader end
- the focal plane assembly housing the X-ray cameras and detectors at its other extremity
- 3 Wolter telescopes with 58 mirrors each
- 2 solar panels with 16 metres span

The orbit

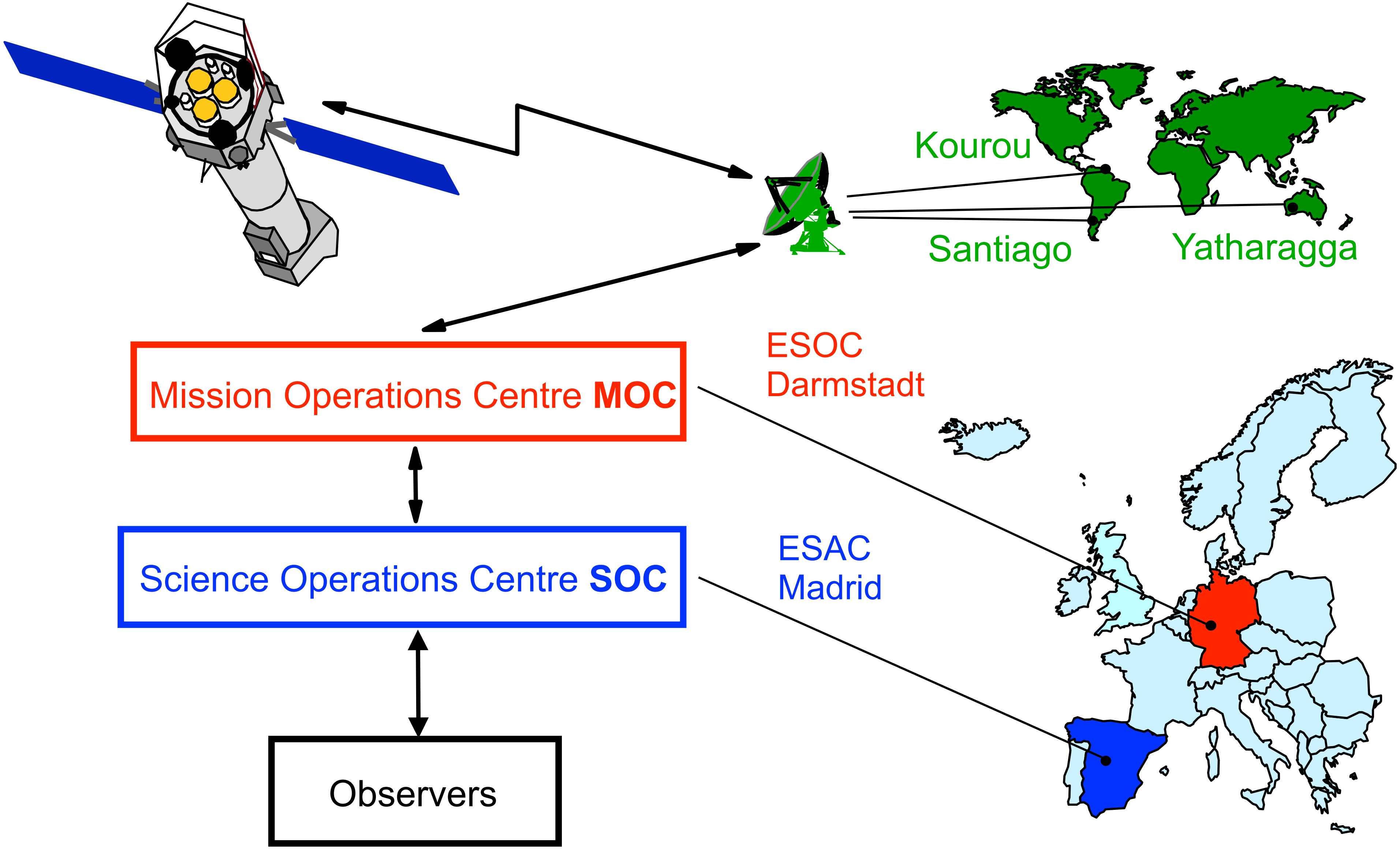


~ 48 hour orbit
Perigee alt. ~ 10000 km
Apogee ~ 120000 km

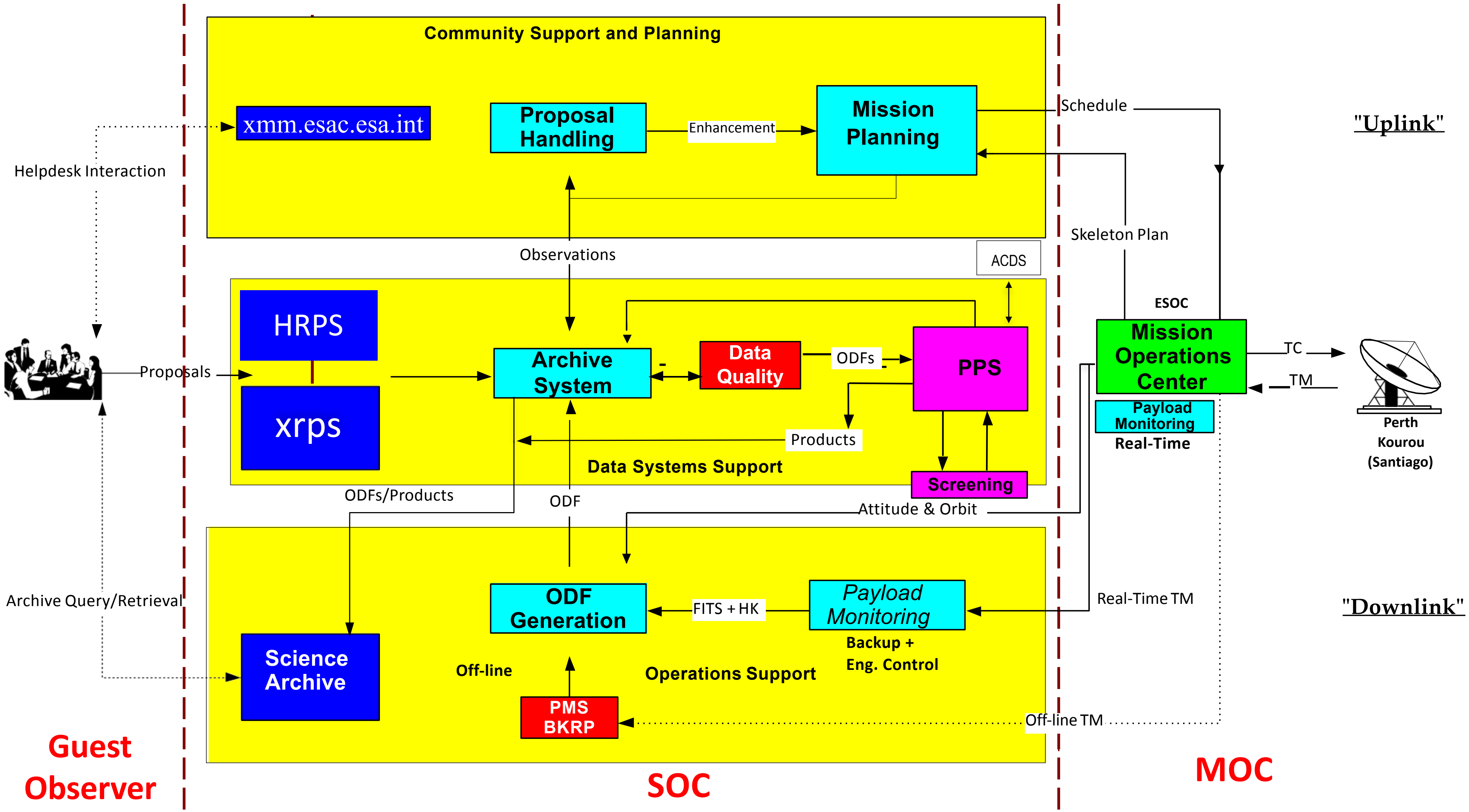
The Ground Segment - until March 2012



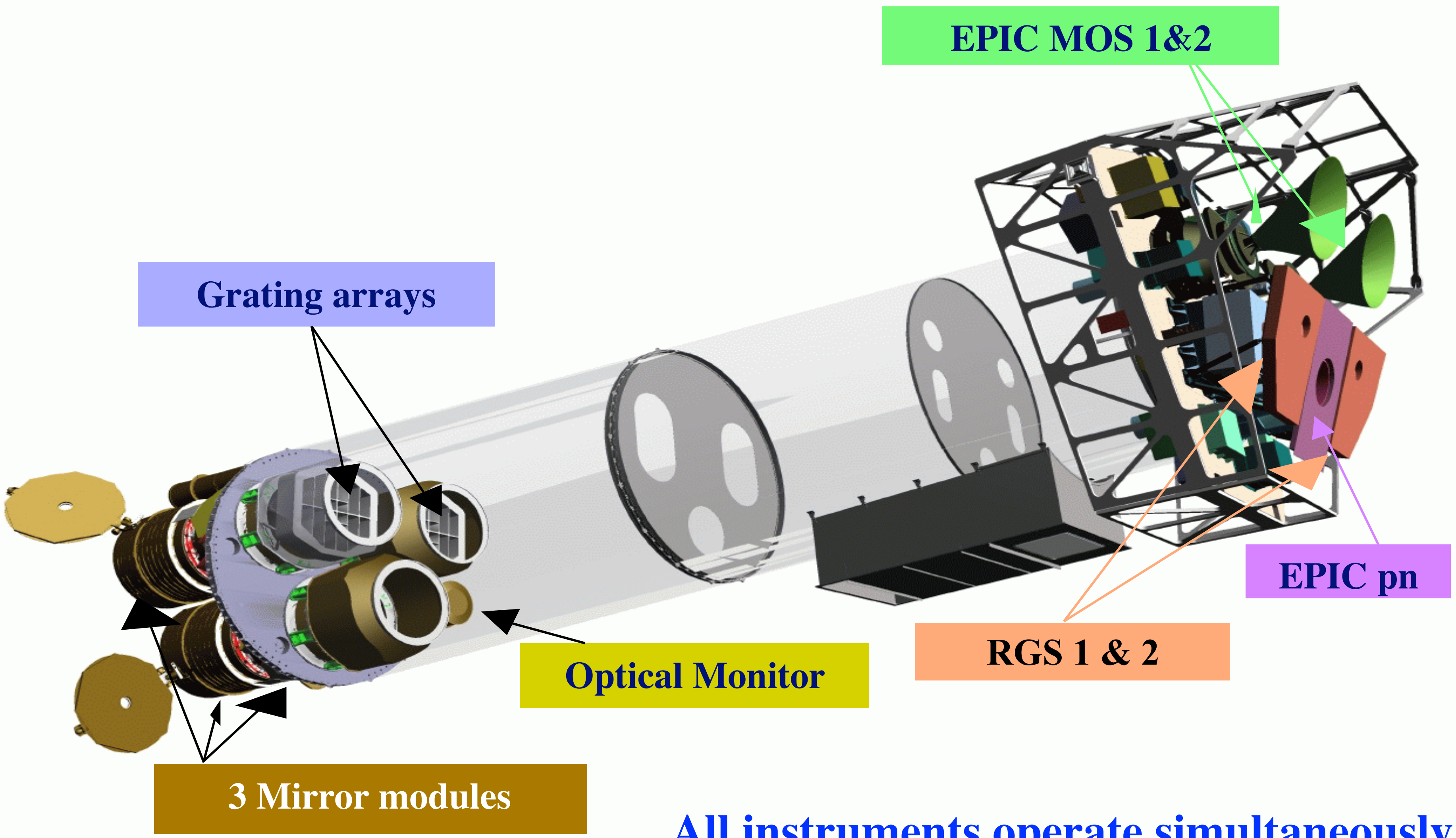
The Ground Segment - today



The Data Flow - today



XMM-Newton layout



All instruments operate simultaneously !!

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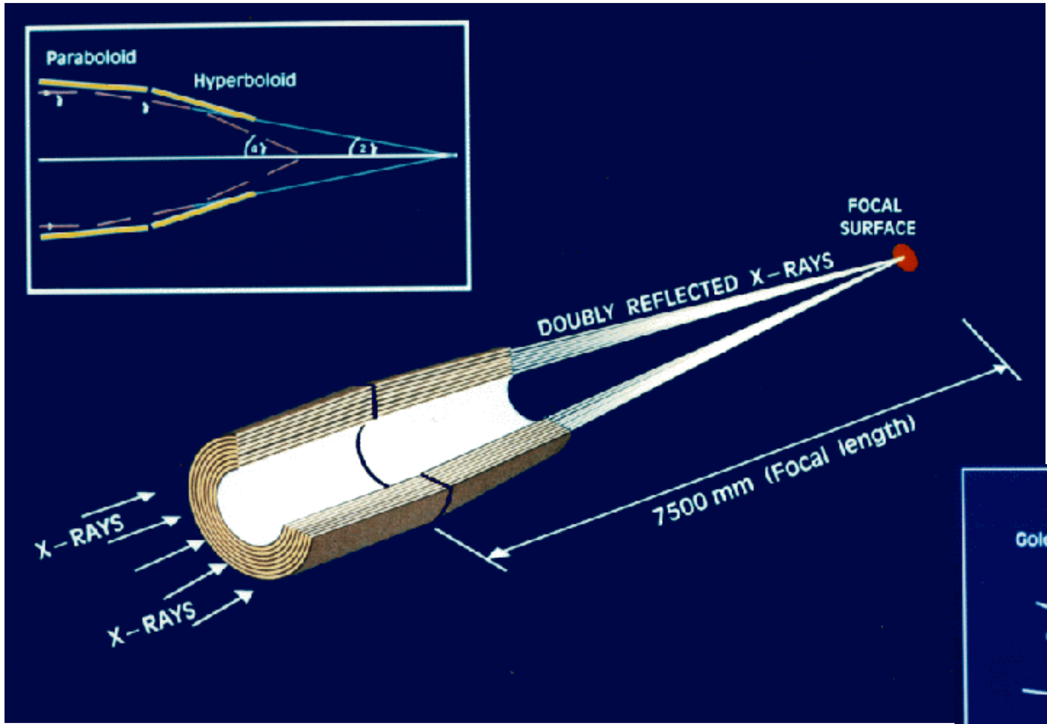
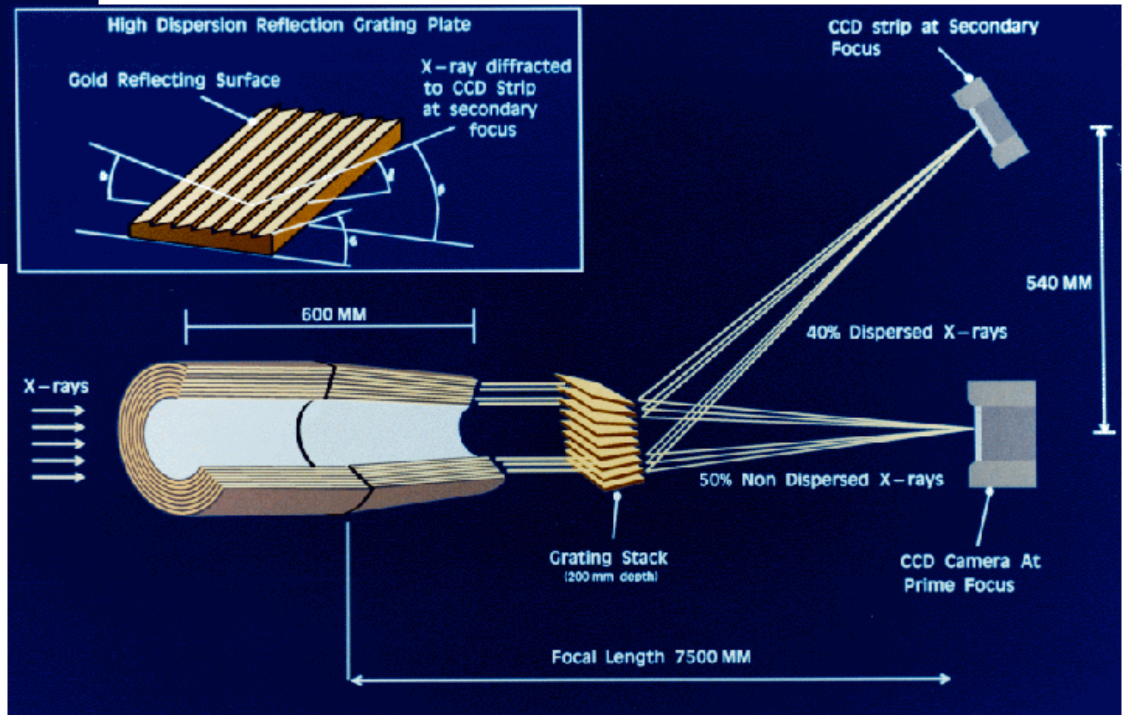
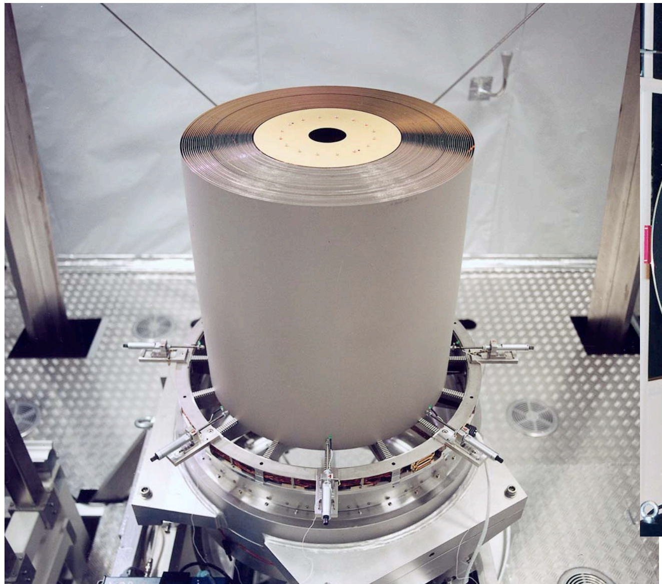
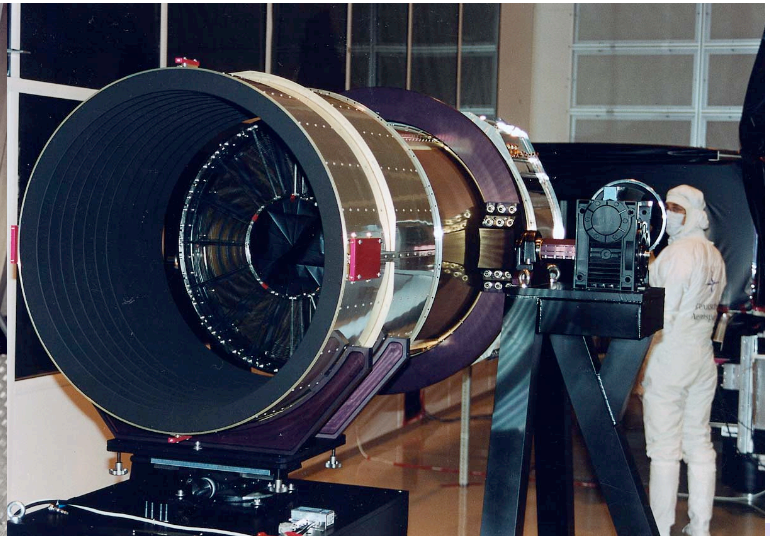
X-ray telescopes

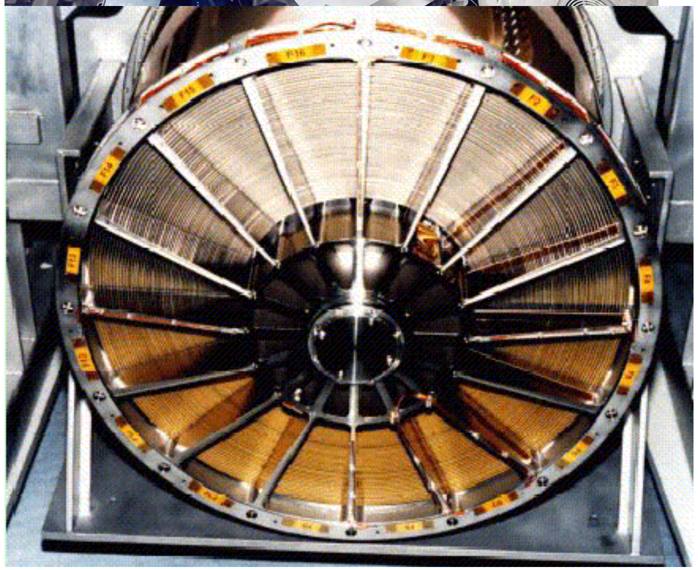


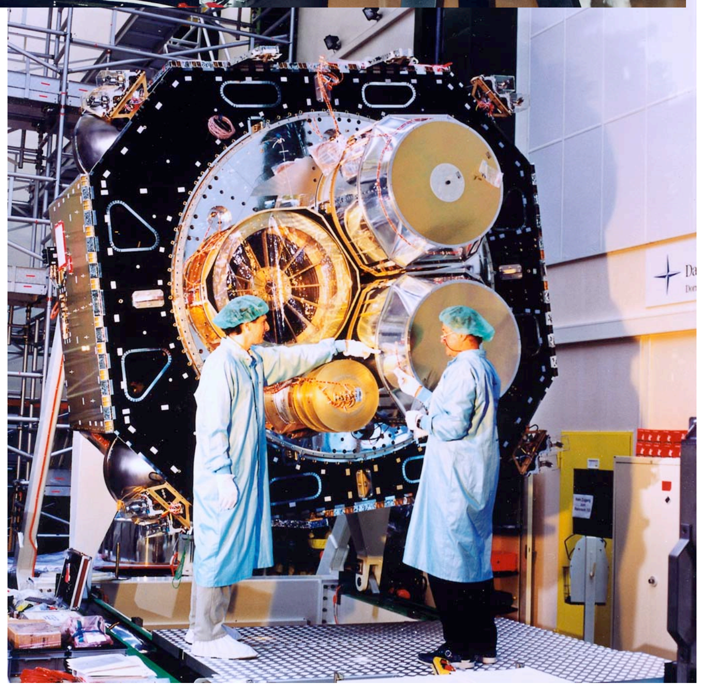


X-ray mirrors





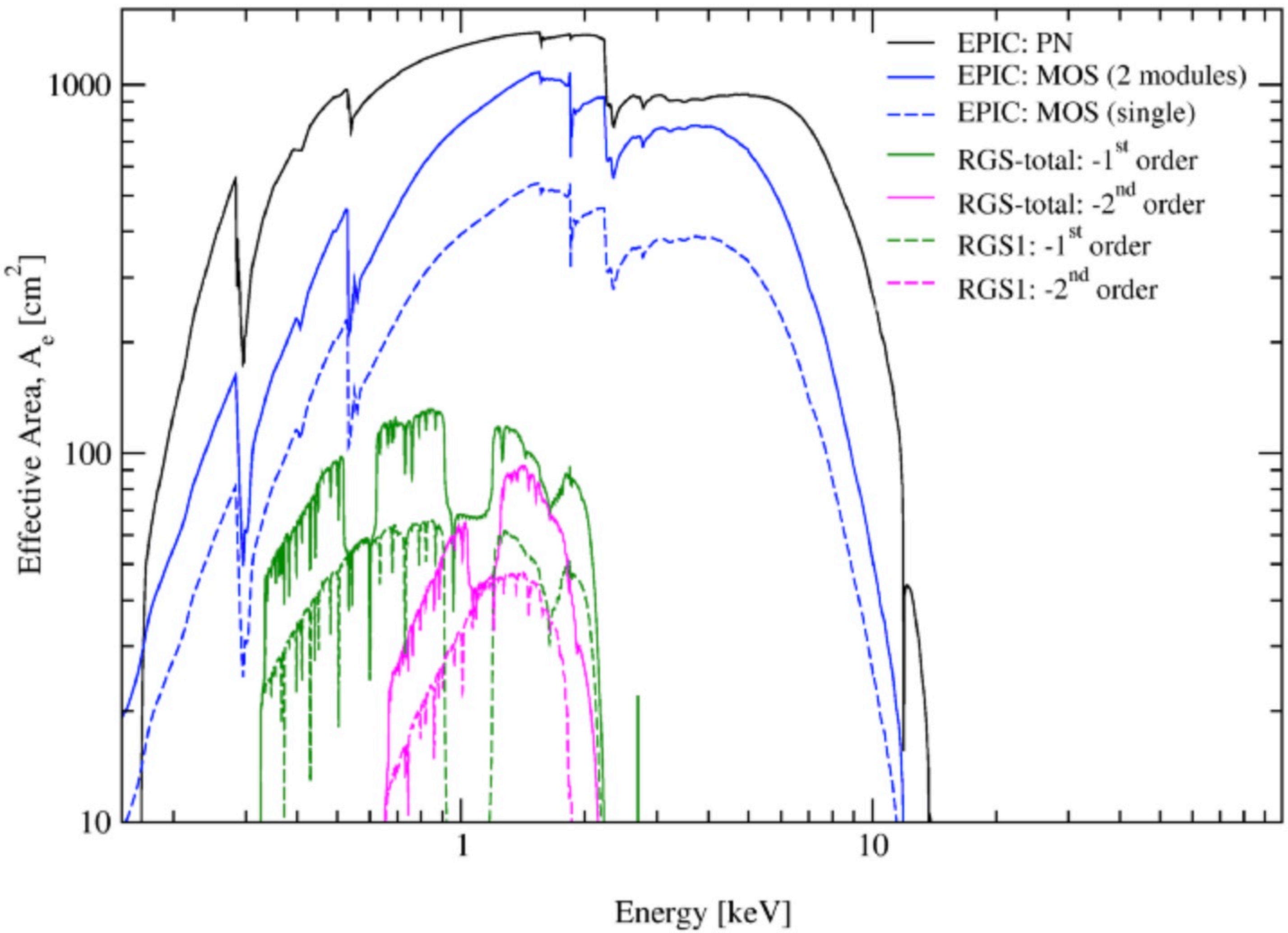




- 58 concentric mirror shells
- Au-coated electroformed nickel shells
- Au-M edge (~ 2.3-3.4 keV) with fine structure
- Held by spider with 16 arms
- 16 scatter wings in PSF
- Triangular PSF (dependent on XRT)

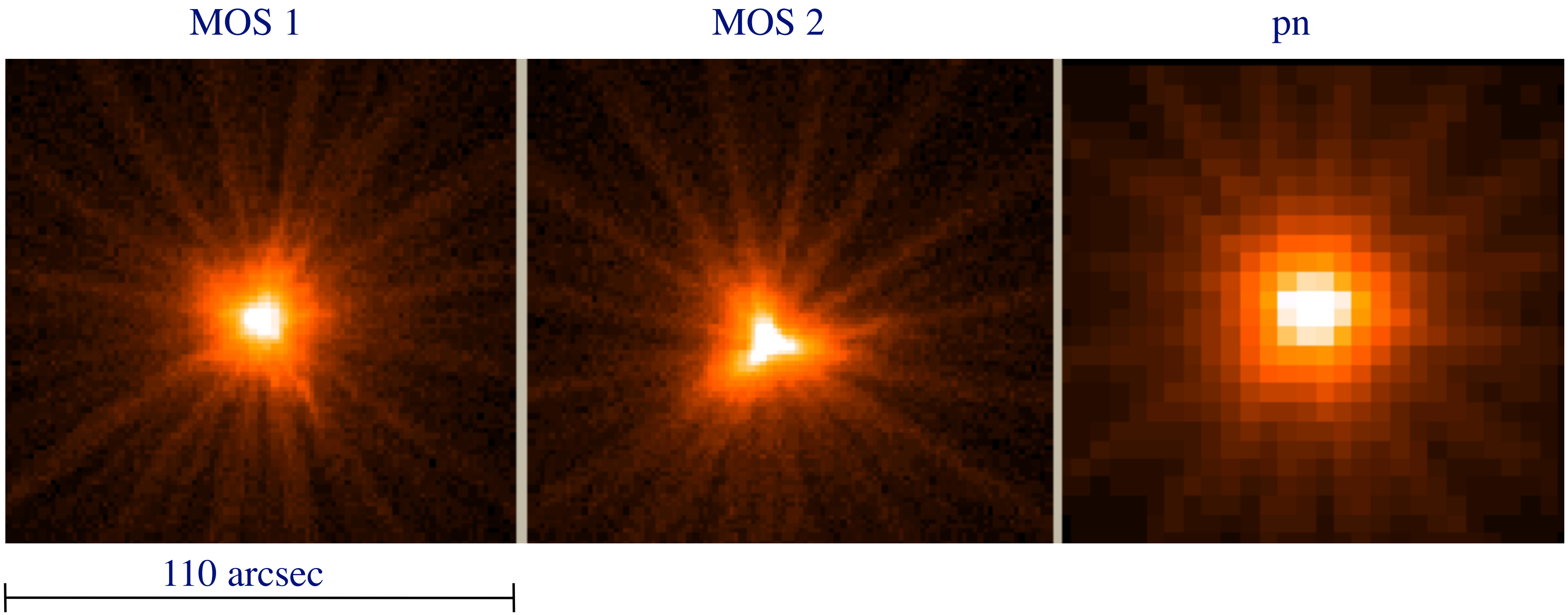
XMM-Newton is photon hungry

Actual Effective area of the XMM-Newton instruments



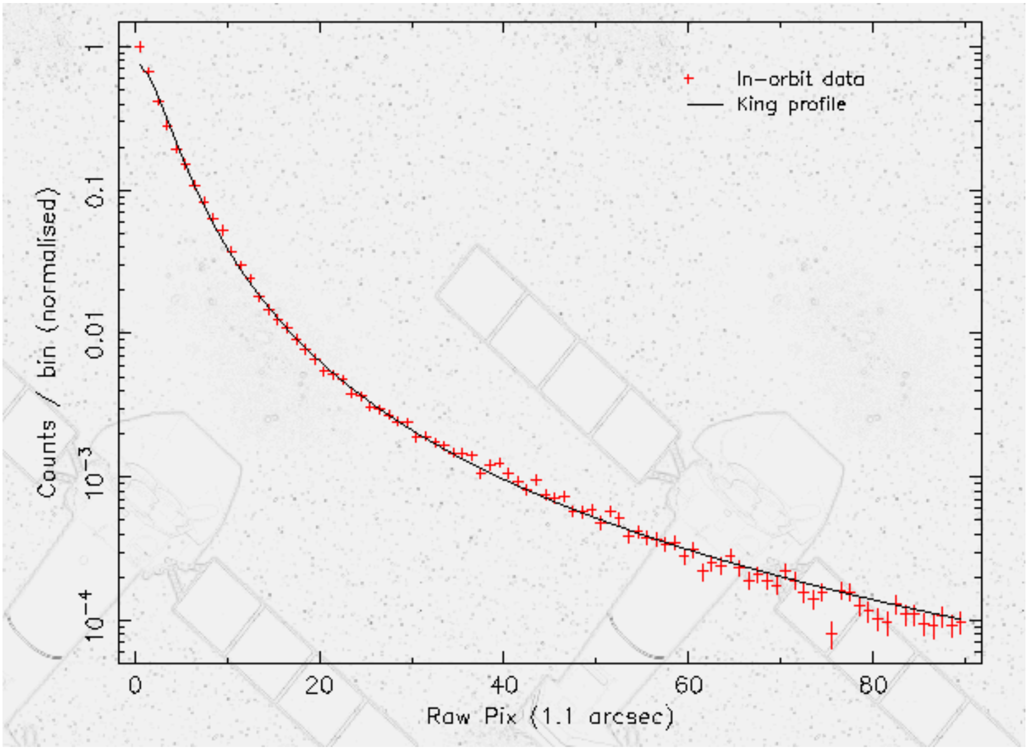
The 3 XMM-Newton PSFs

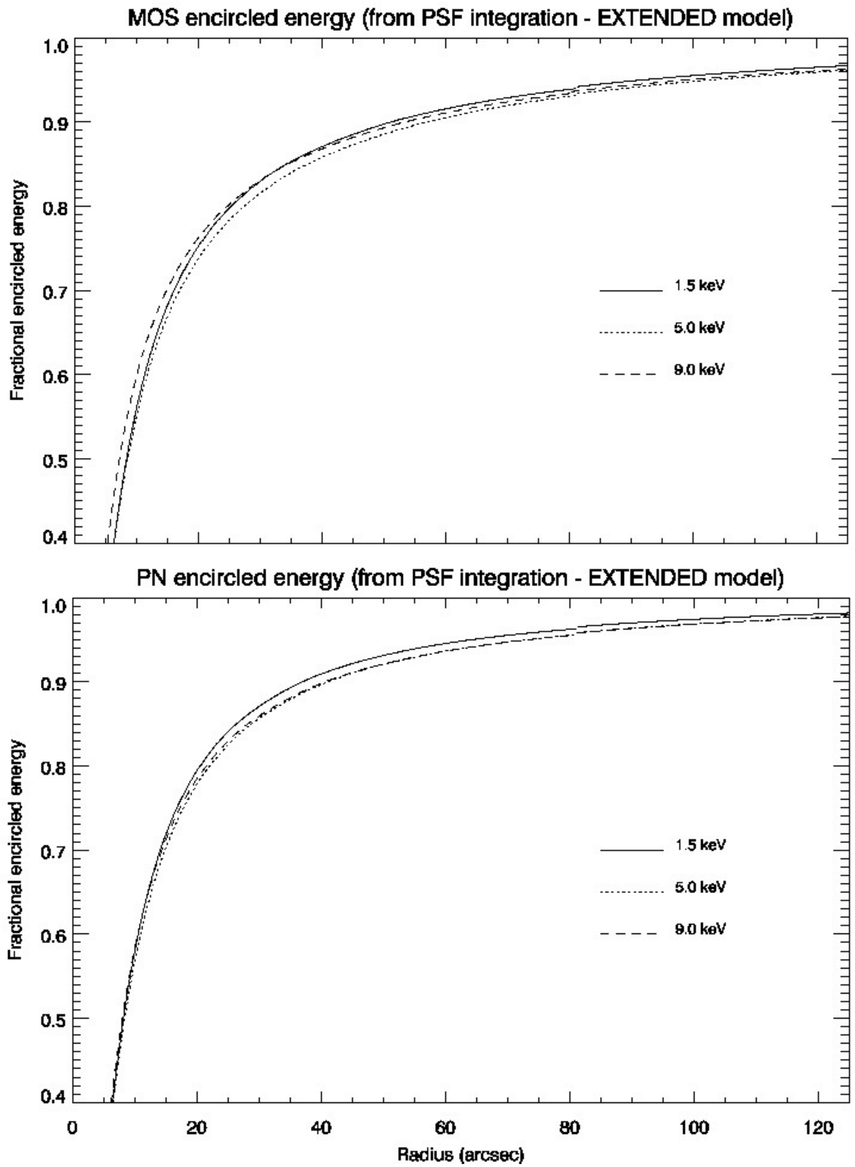
Core PSF of the three telescopes



PSF in some detail

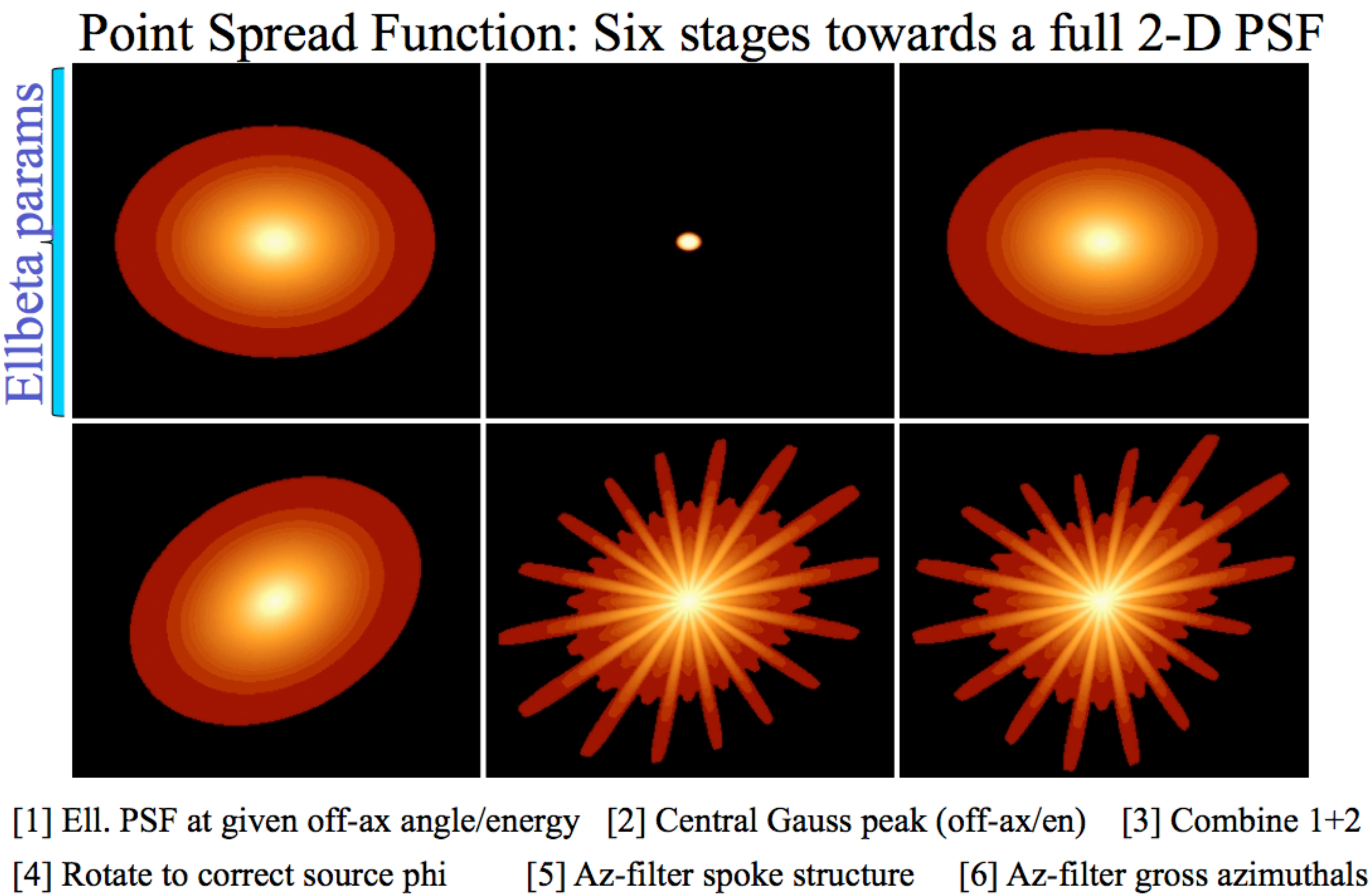
- FWHM ~ 4.5 arcsec
- HEW ~ 13 arcsec
- PSF varies little for $E_\gamma < 4$ keV





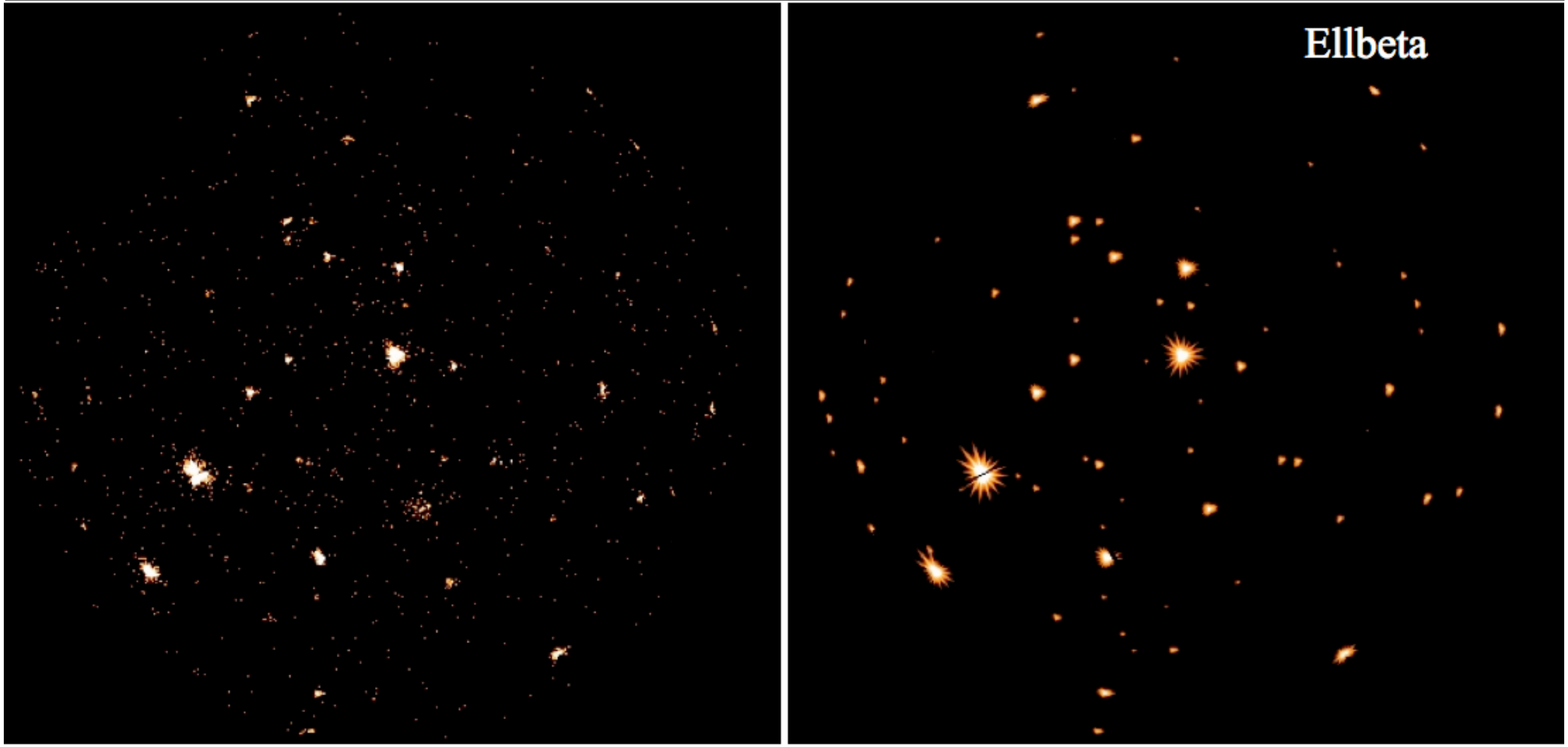
Default since SAS 12: 2D PSF

replaced SciSim generated PSF description through realistic model:



2D PSF in source detection

Source detection running the 2D-PSF model



Data Model

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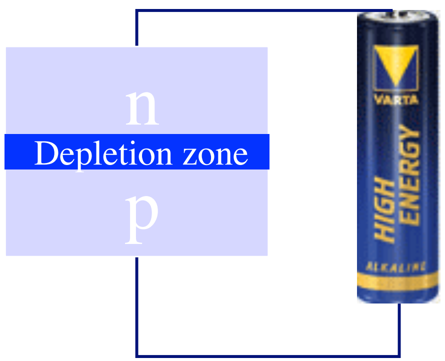
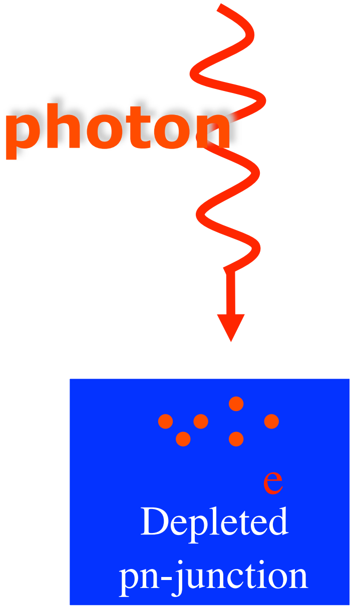
What is a CCD?

- Charge Coupled Device
- you know that from your digital cam or mobile phone
- our CCDs however work also for X-ray photons
- silicon device to measure photons energy, position and time

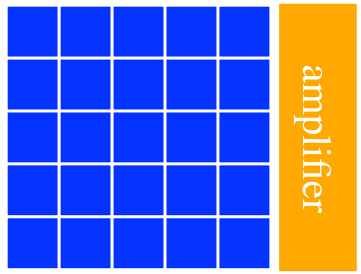
1. Take positive and negative doped silicon

2. Create depletion zone by adding voltage





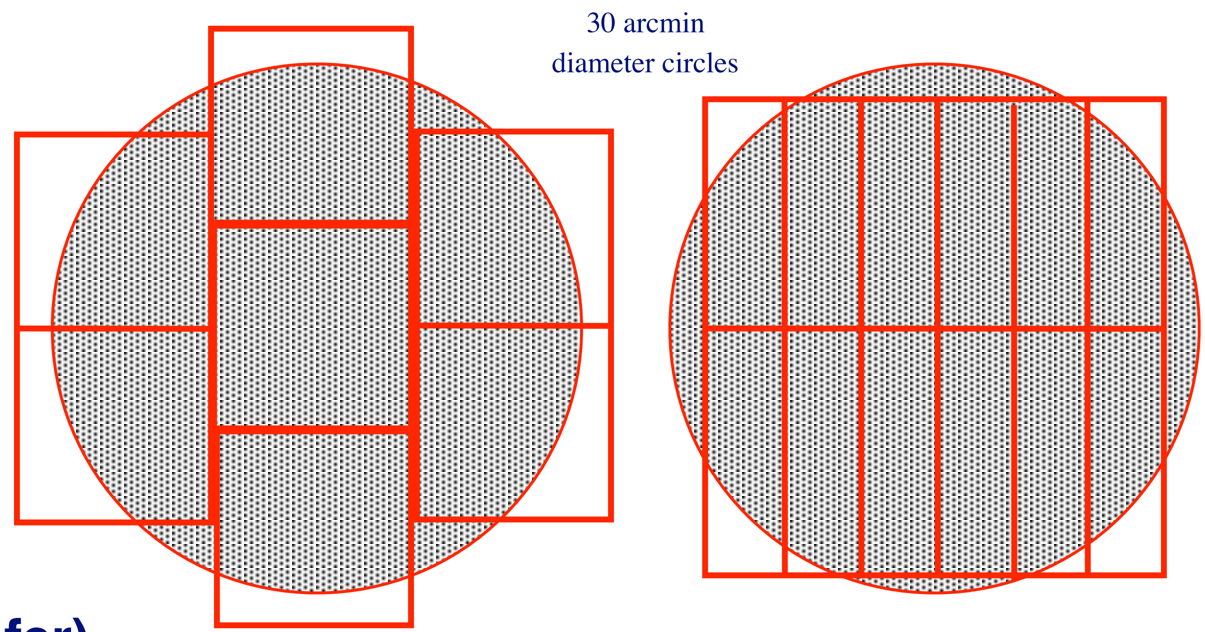
3. Arrange pn-junctions as pixels in structure, that can be read out by changing potentials



! During shifts some electrons may be lost

The imaging cameras - EPIC

Comparison of focal plane organisation of EPIC MOS and pn cameras



EPIC MOS

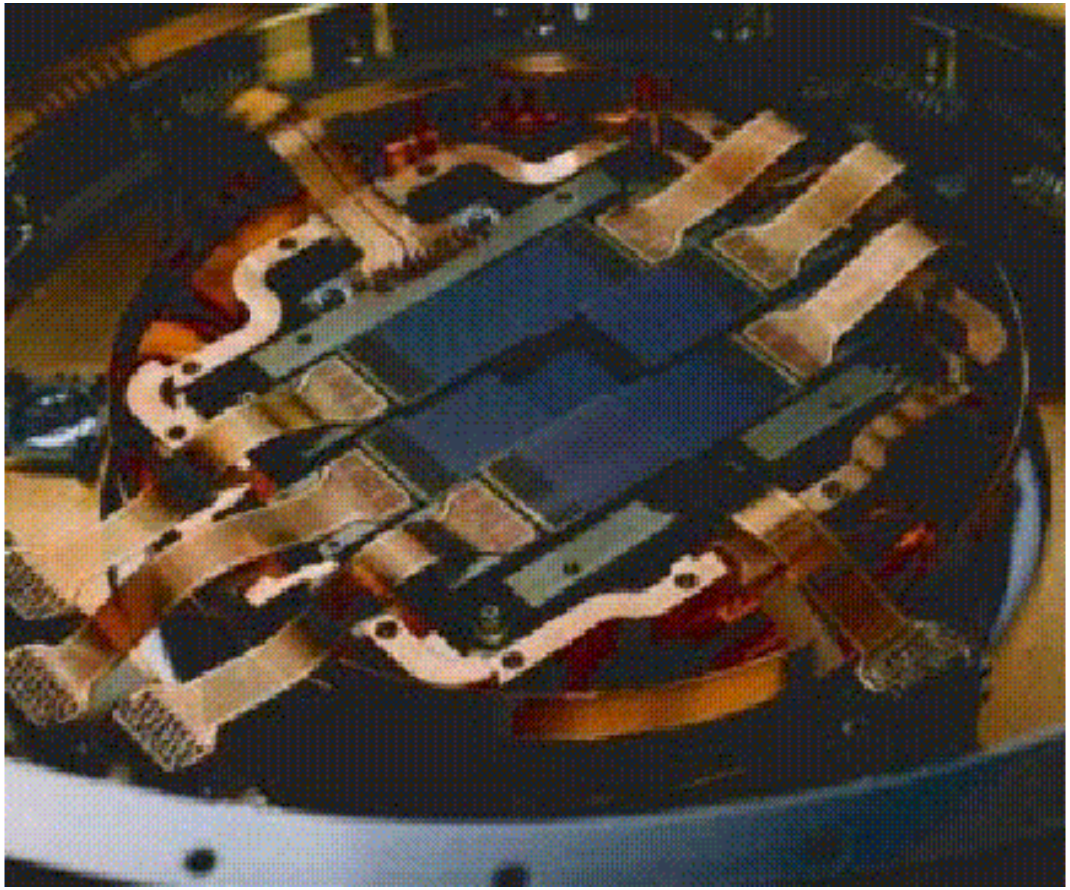
7 CCDs each 10.9 x 10.9 arcminutes

EPIC PN

12 CCDs each 13.6 x 4.4 arcminutes

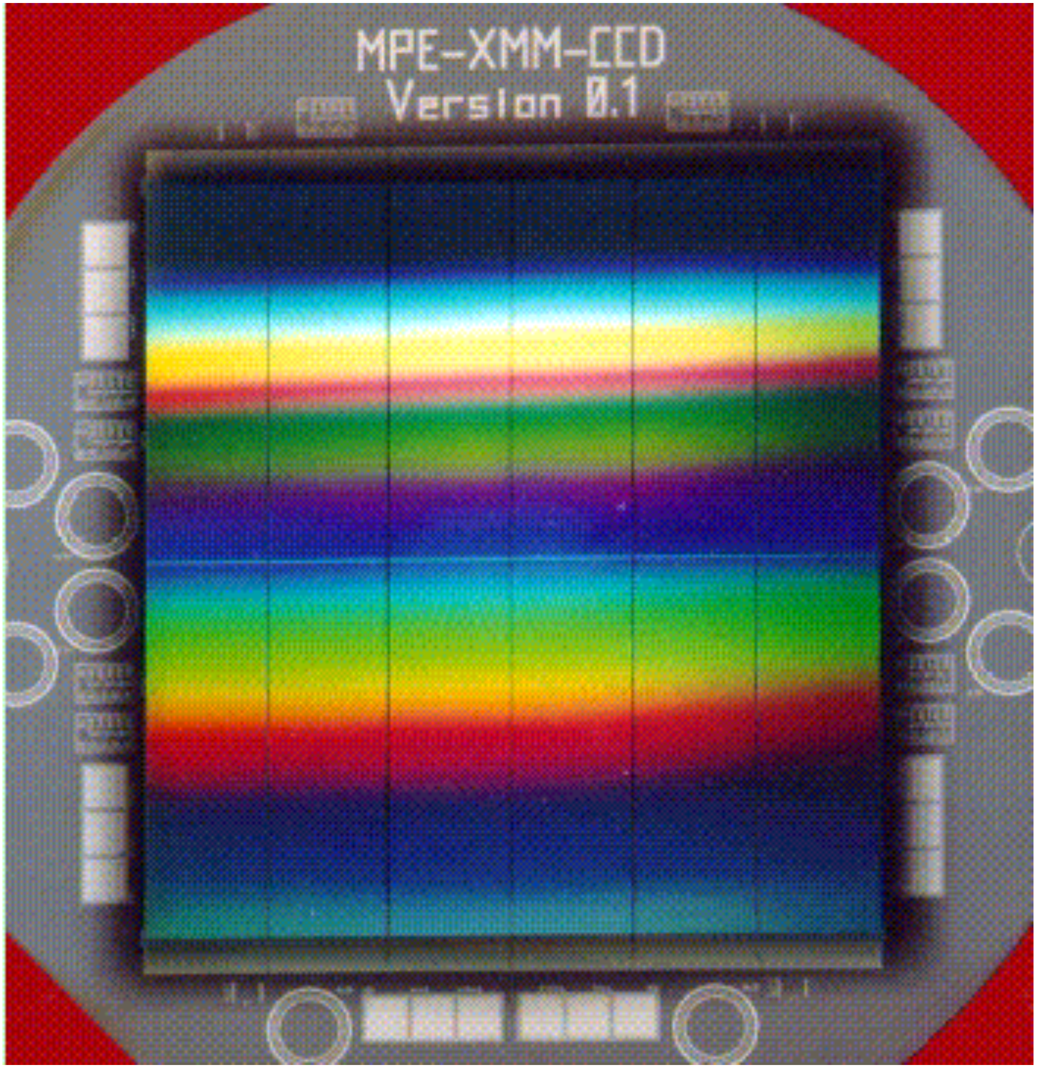
- **2 MOS cameras (7 CCDs each)**
  - Stacked to fit focal curvature
  - Frame store readout
  - 1 CCD: 600 x 600 pixels; per pixel 40 mm, 1.1 arcsec
- **1 pn camera (12 CCDs on one wafer)**
  - Minimizing gaps between CCDs
  - Larger pixel size ⇒ faster readout
  - 1 CCD: 200 x 64 pixels; per pixel 150 mm, 4.1 arcsec
  - Reading all 64 columns in parallel

The EPIC MOS camera



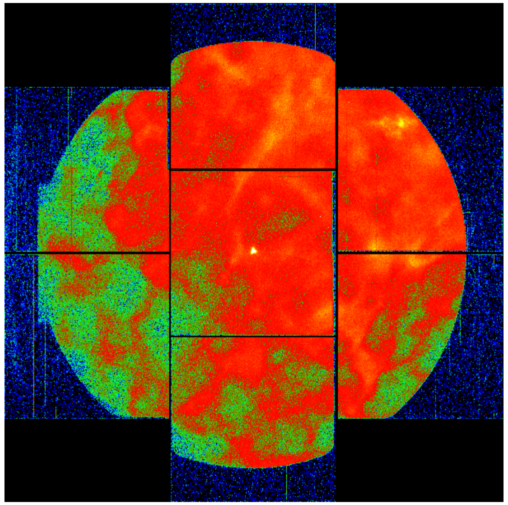
- 7 CCDs, 40 µm, 1.1 arcsec
- Front illuminated: gatting structure in X-ray light path
- Two cameras with different orientation by 90°
- Filters required to reject light from longer (visible) wavelengths

The EPIC pn camera



- 12 CCDs, 150 µm, 4.1 arcsec
- Back illuminated
- Thicker than MOS, good efficiency at high energies
- Same Filters as for MOS cameras

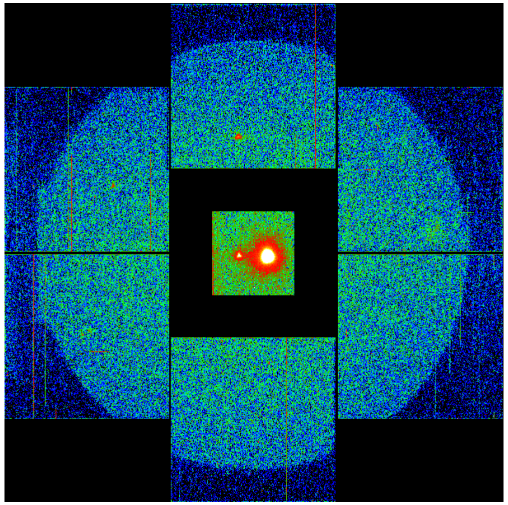
The EPIC MOS operating modes



Full Frame

Time Res.:
2.6 s

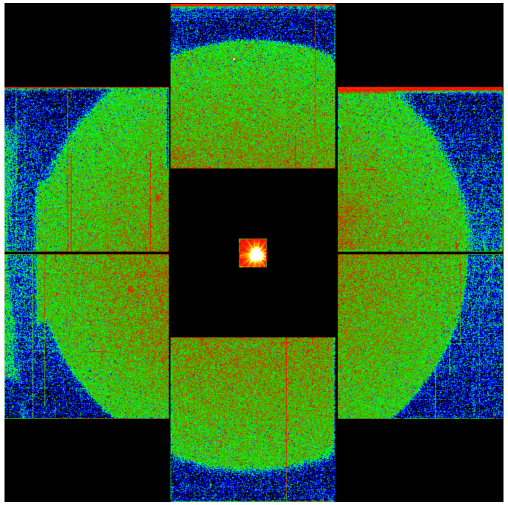
Max. countrate:
0.7/s



Large Window

Time Res:
0.9 s central CCD
2.7 s outer CCDs

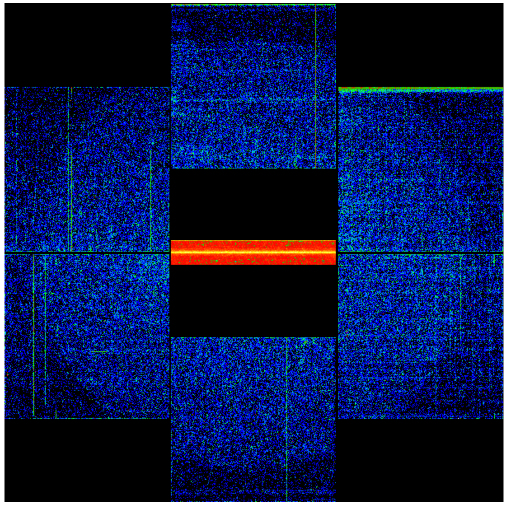
Max.countrate:
1.3/s



Small Window

Time Res.:
0.3 s central CCD
2.7 s outer CCDs

Max. countrate:
5/s

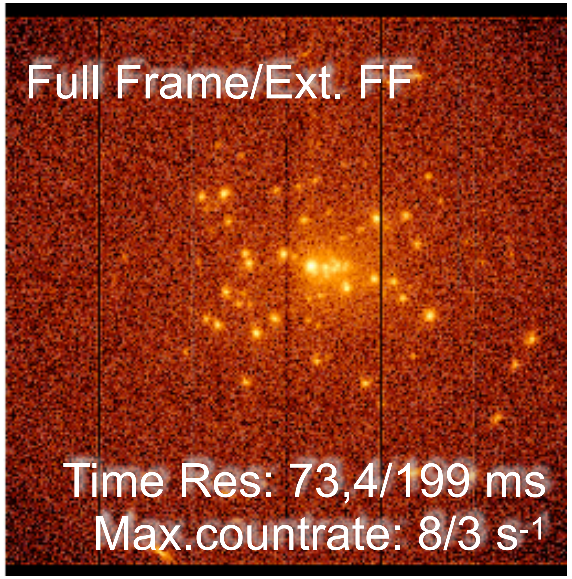


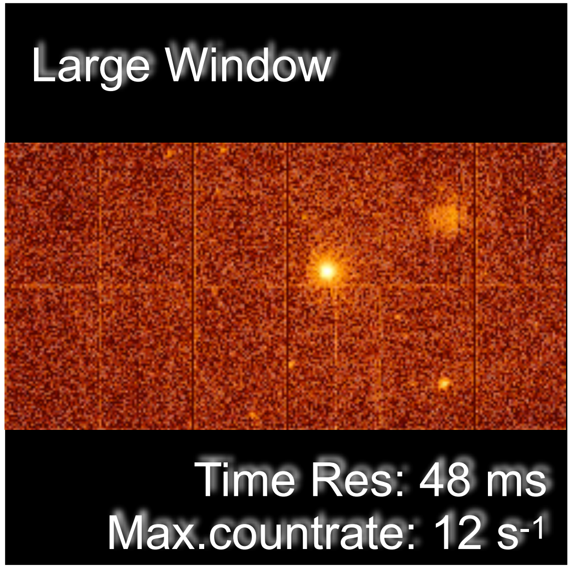
Timing

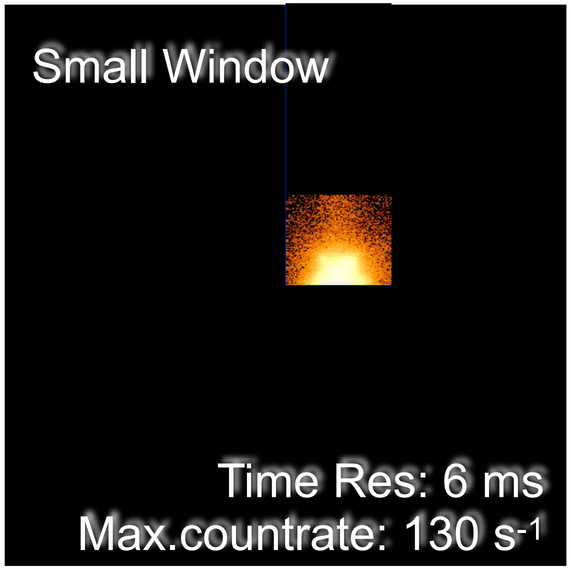
Time res. :
1.8 ms central CCD
2.6 s outer CCDs

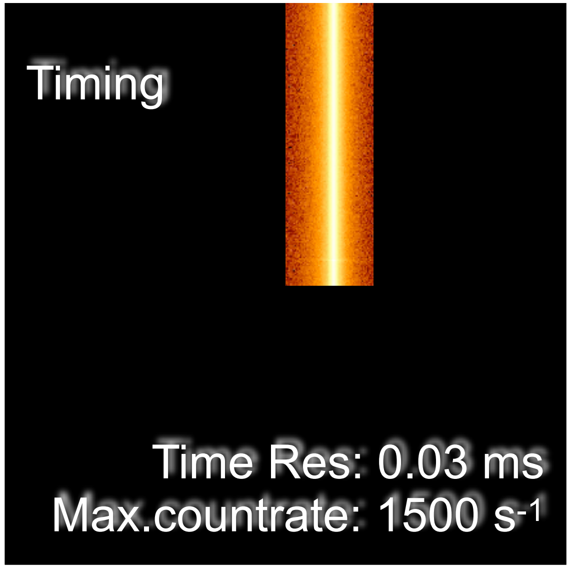
Max. countrate:
100/s

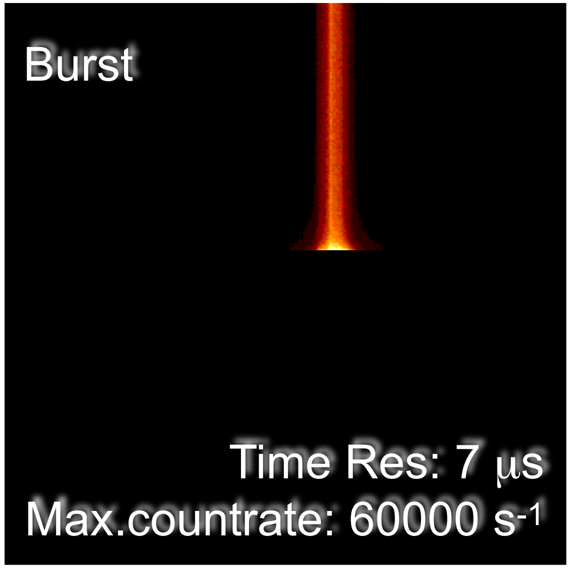
The EPIC pn operating modes





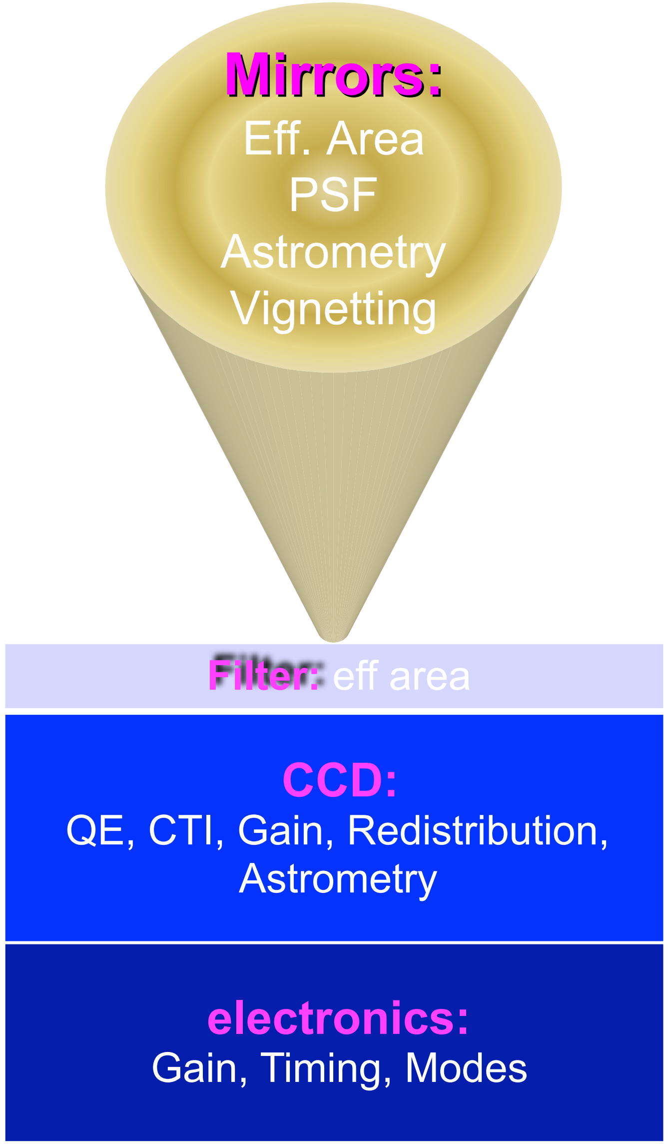






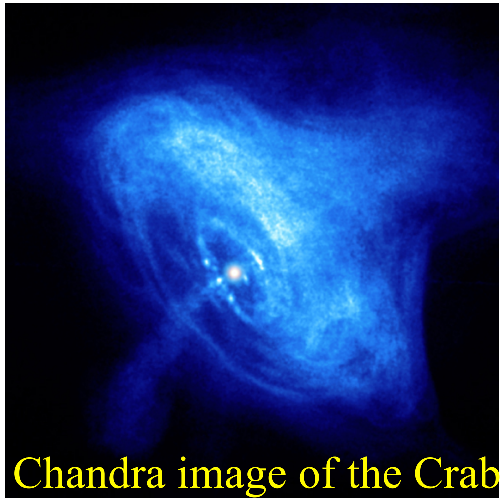
Calibration topics

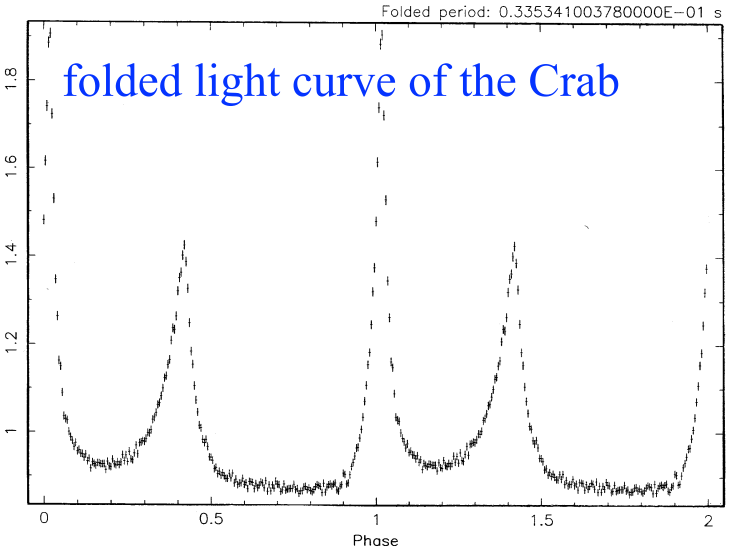
- imaging$_{\text{where}}$
- effective area$_{\text{how many}}$
- energy redistribution$_{\text{effects}}$
- Gain/CTI$_{\text{which}}$
- timing$_{\text{when}}$
- background$_{\text{what}}$



Timing

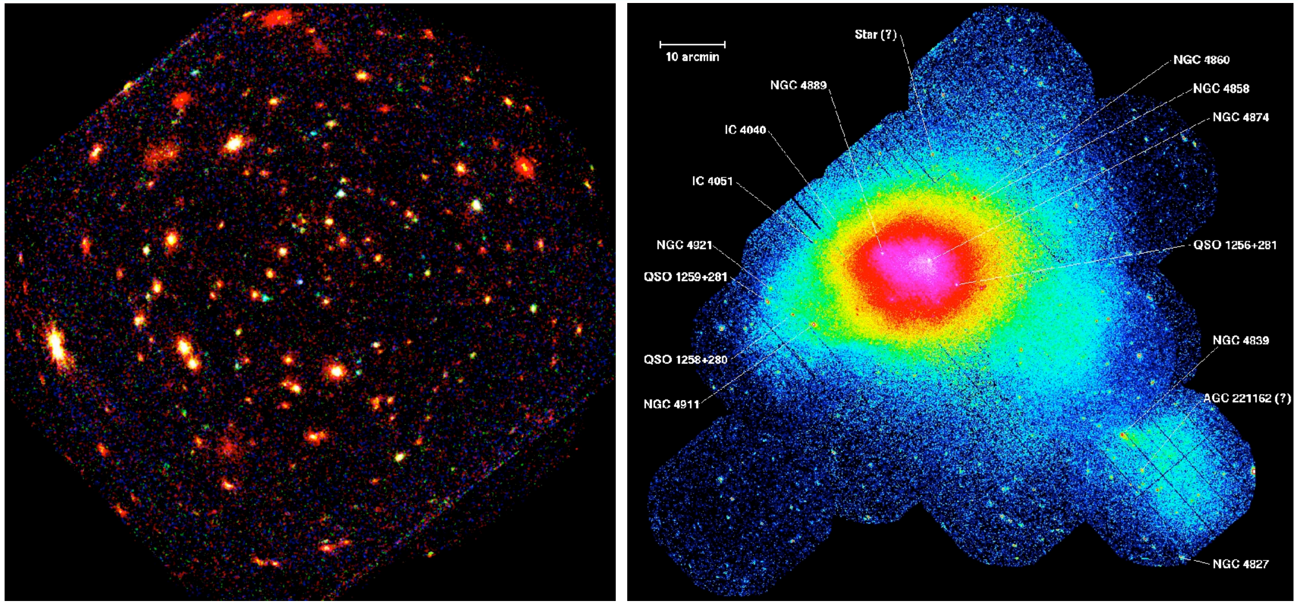
- XMM-Newton:
- pulse analysis
- pulse-phase resolved spectral analysis for ms pulsars
- Current relative time accuracy of EPIC-pn: $\Delta P/P < 10^{-8}$
- Absolute time accuracy < 70 µs



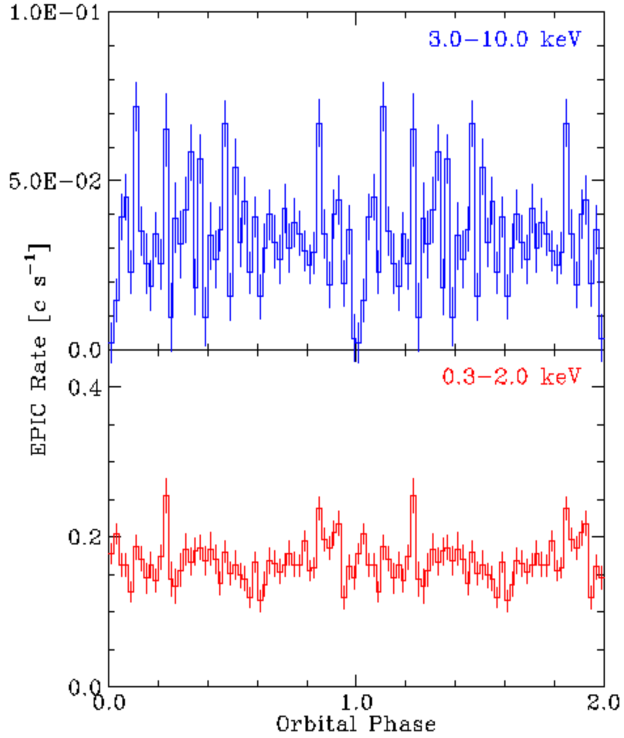


EPIC-pn is the fastest X-ray CCD available at the moment

What can be done with the EPIC cameras?



Imaging: point and extended sources



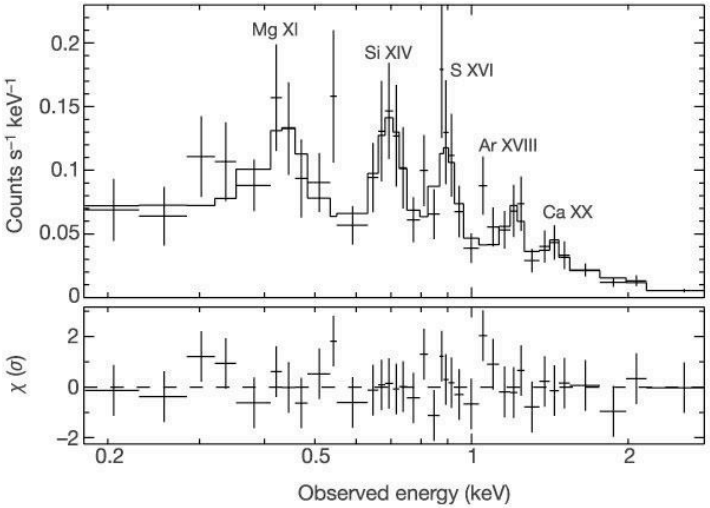
The hard X-ray eclipse of UX UMa

Image courtesy of G.W. Pratt, K. Mukai, et al.

European Space Agency

Timing analysis

Deep low resolution spectroscopy



X-ray spectrum of the afterglow of GRB011211

European Space Agency

EPIC calibration summary

Effect	Max. Error	Energy dependent	Off-axis angle dependent
Relative Astrometry	1.5”(r.m.s.)	NO	YES
Absolute Astrometry	1.2”	NO	YES
Point Spread Function (PSF)	2 %	YES	YES
Relative Effective Area	± 3 / 2% (MOS / pn)	YES	YES
Absolute Effective Area	± 10 %	YES	YES
Absolute Energy Scale	± 10 / 12.5eV (MOS / pn)	YES	YES
Relative Timing	$\Delta P/P < 10^{-8}$	NO	NO
Absolute Timing	< 70 μs	NO	NO

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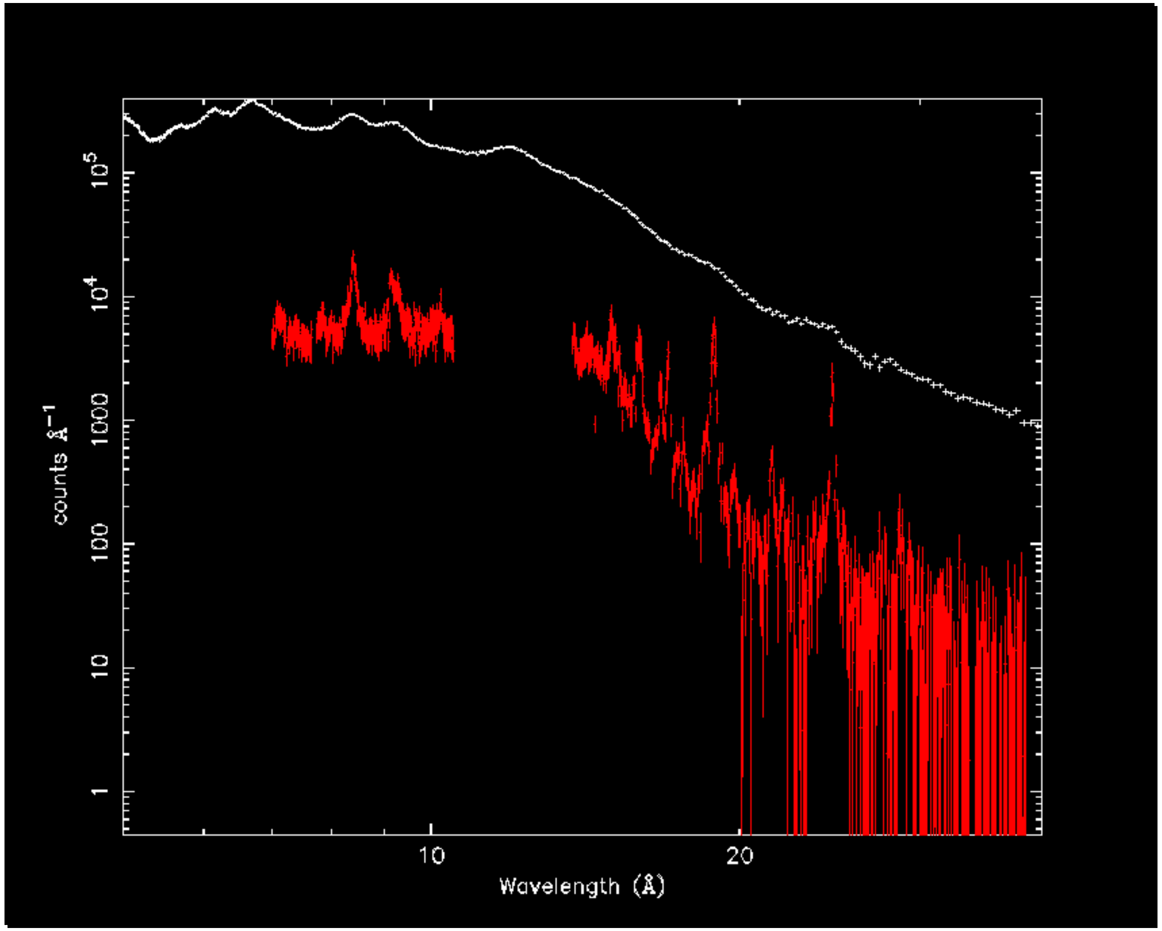
The Reflection Grating Spectrometers

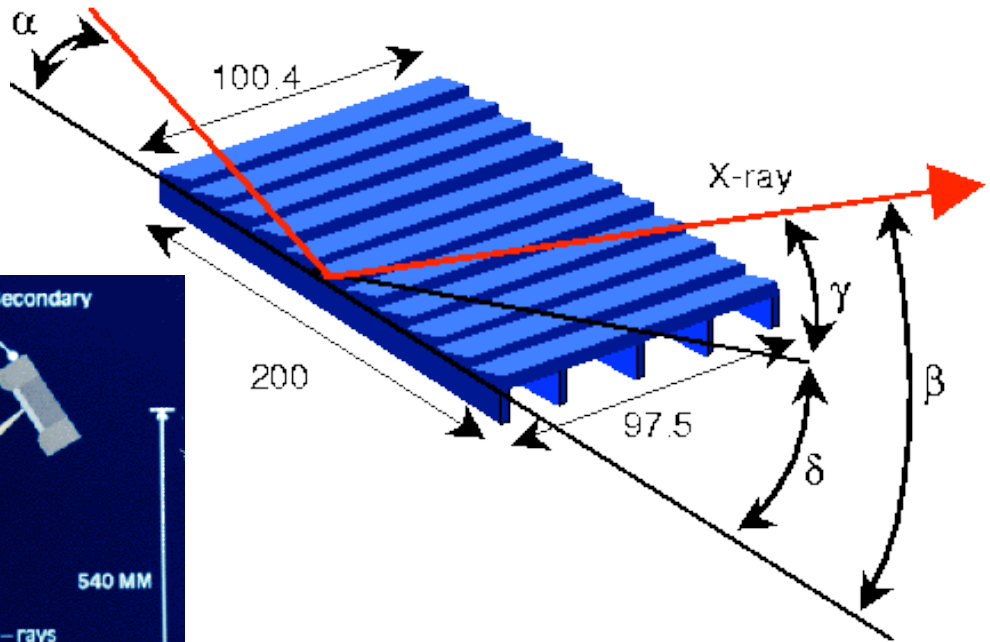


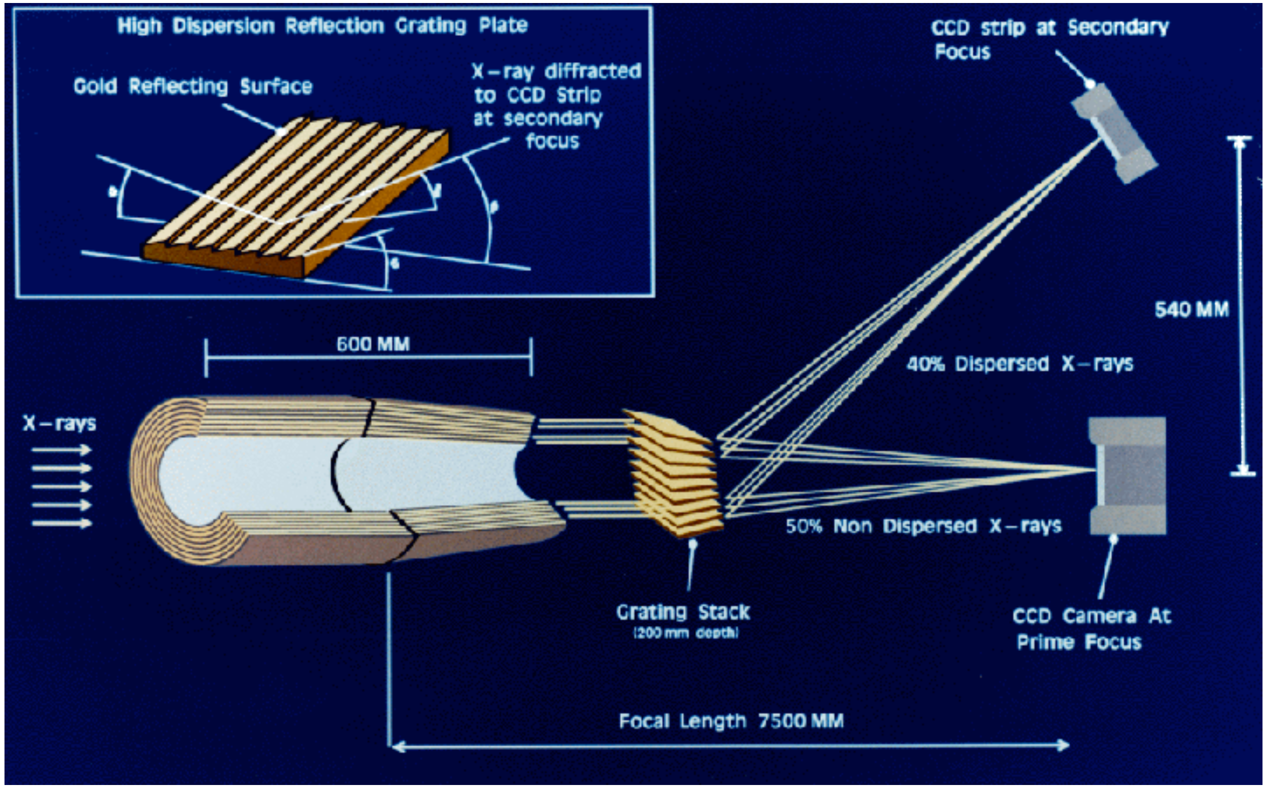
High resolution spectroscopy !

resolution @ 1 keV:

EPIC-pn	10
EPIC-MOS	14
RGS	200 1st order
	400 2nd order

RGS details





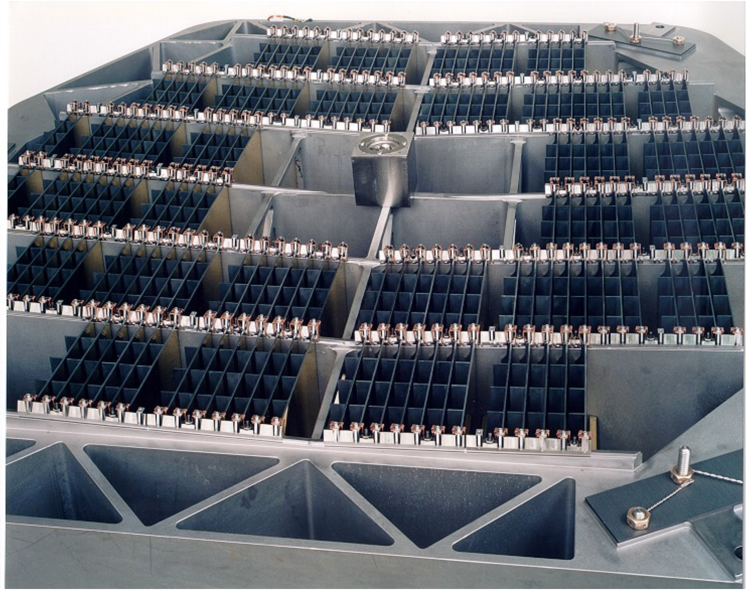
Dispersion equation:

$$\cos\beta = \cos\alpha + m\lambda / d$$

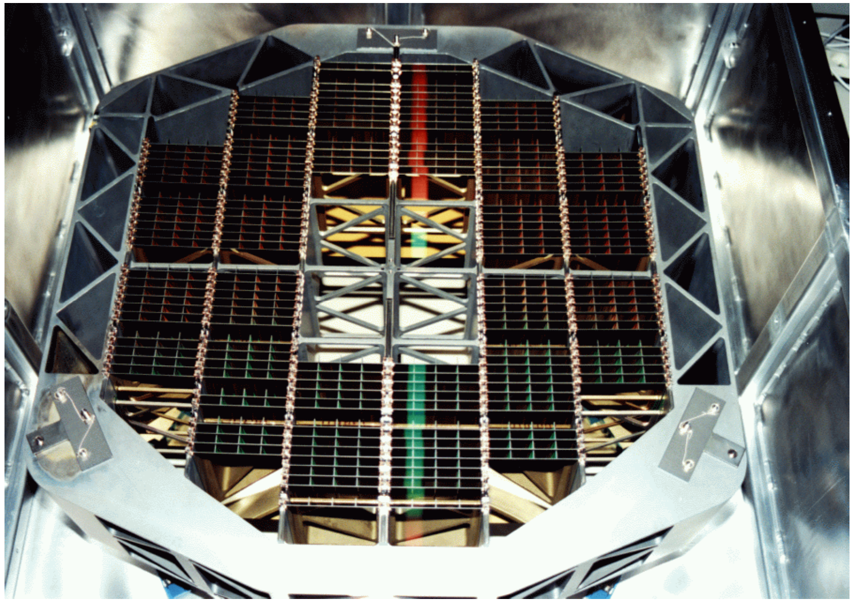
↕

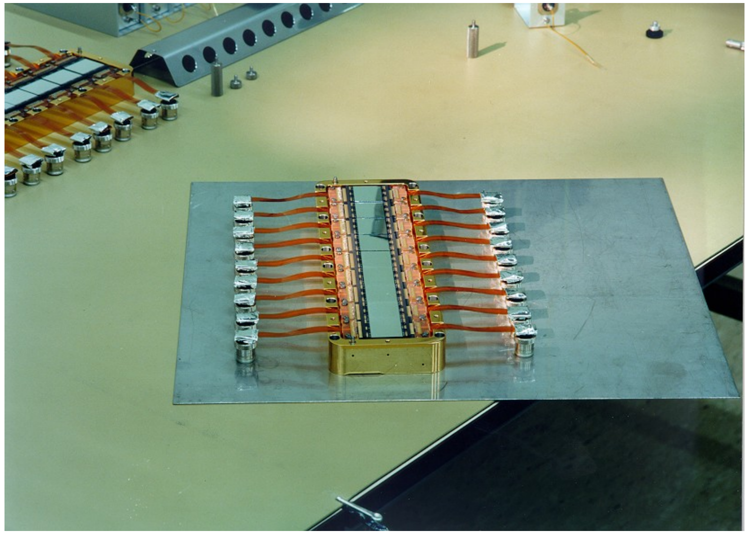
$$\lambda = (\cos\beta - \cos\alpha)\, d / m$$

Some views of the RGS components



The 182 Gratings

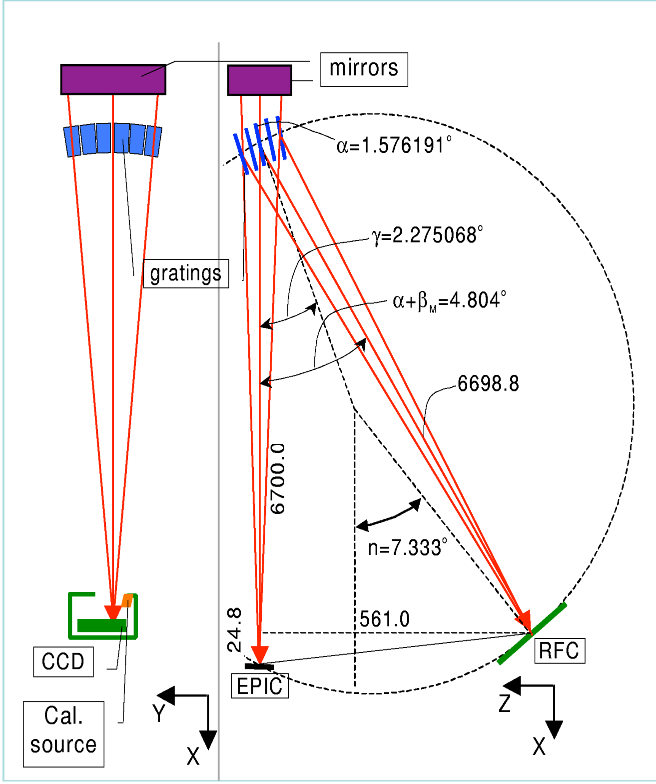




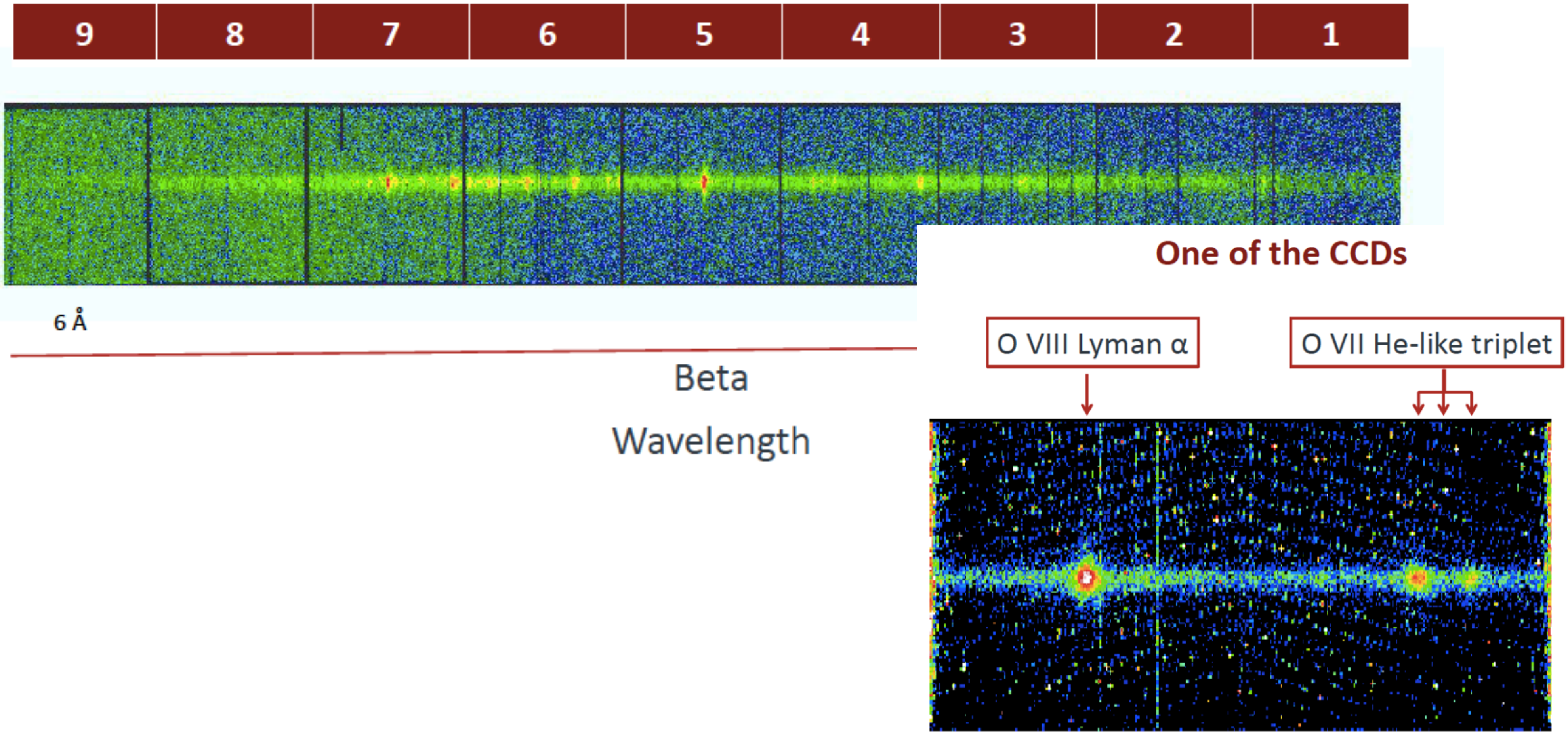
The 9 CCDs

RGS characteristics

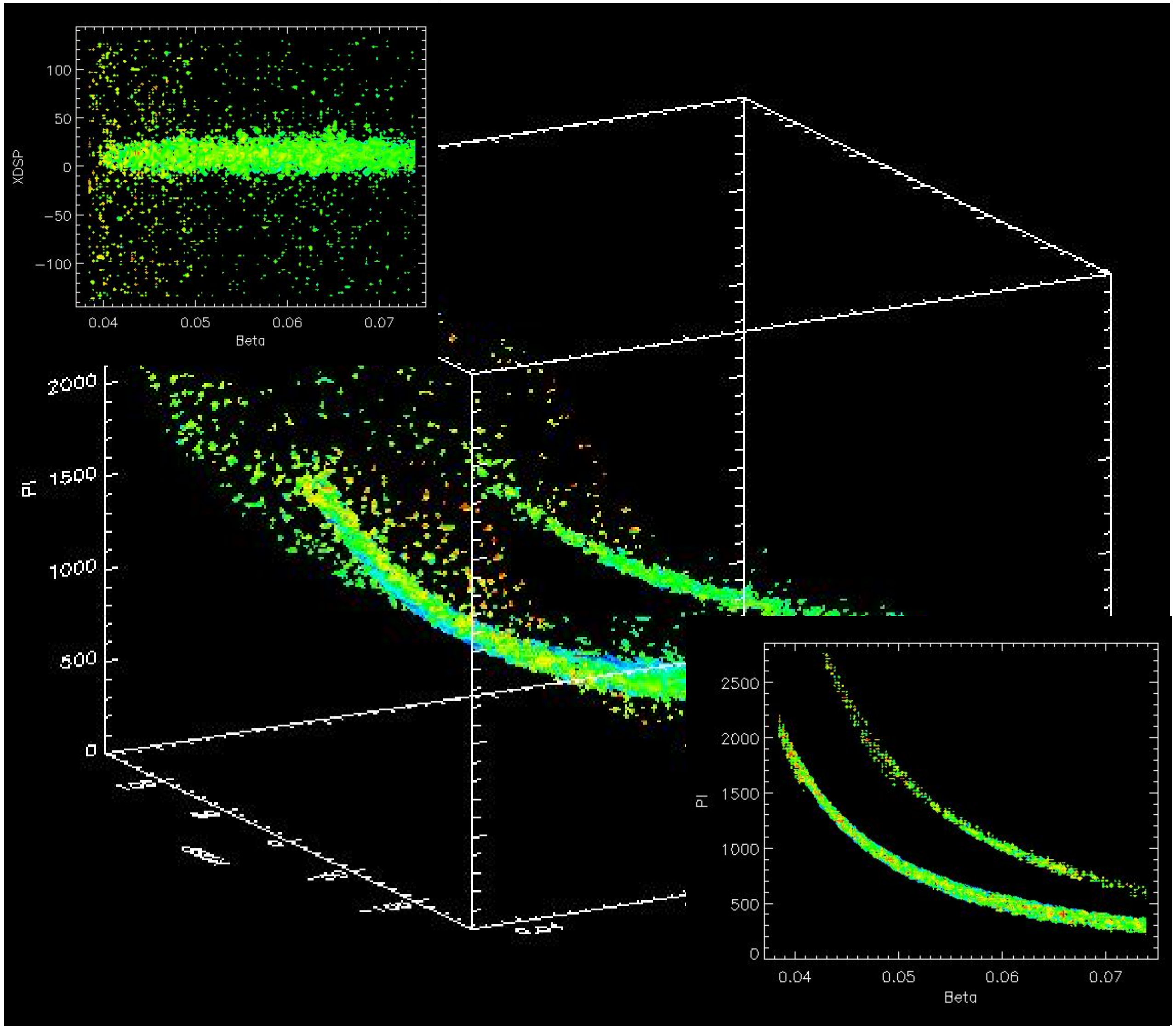
- 2 Reflection Grating Spectrometers behind two of the XRTs
- RGAs continuously in the light-path, non switchable
- High sensitivity and resolution in [0.35-2.5]keV ([5-35]Å)
- Line rich region containing K-shell transitions of low-Z abundant elements (C, N, O, Ne, Si) and the diagnostically important L-shell Fe transitions
- Each spectrometer disperses onto 9 back illuminated CCDs, readout in frame store mode
- 2 CCD readout chains (one per RGS) non-operable
  ⇒ 2 gaps in the spectrum, BUT at different wavelengths
- FOV is ± 2.4 arcmin in cross-dispersion



The CCDs


9
8
7
6
5
4
3
2
1
6 Å
Beta
Wavelength
One of the CCDs
O VIII Lyman α
O VII He-like triplet

RGS data space



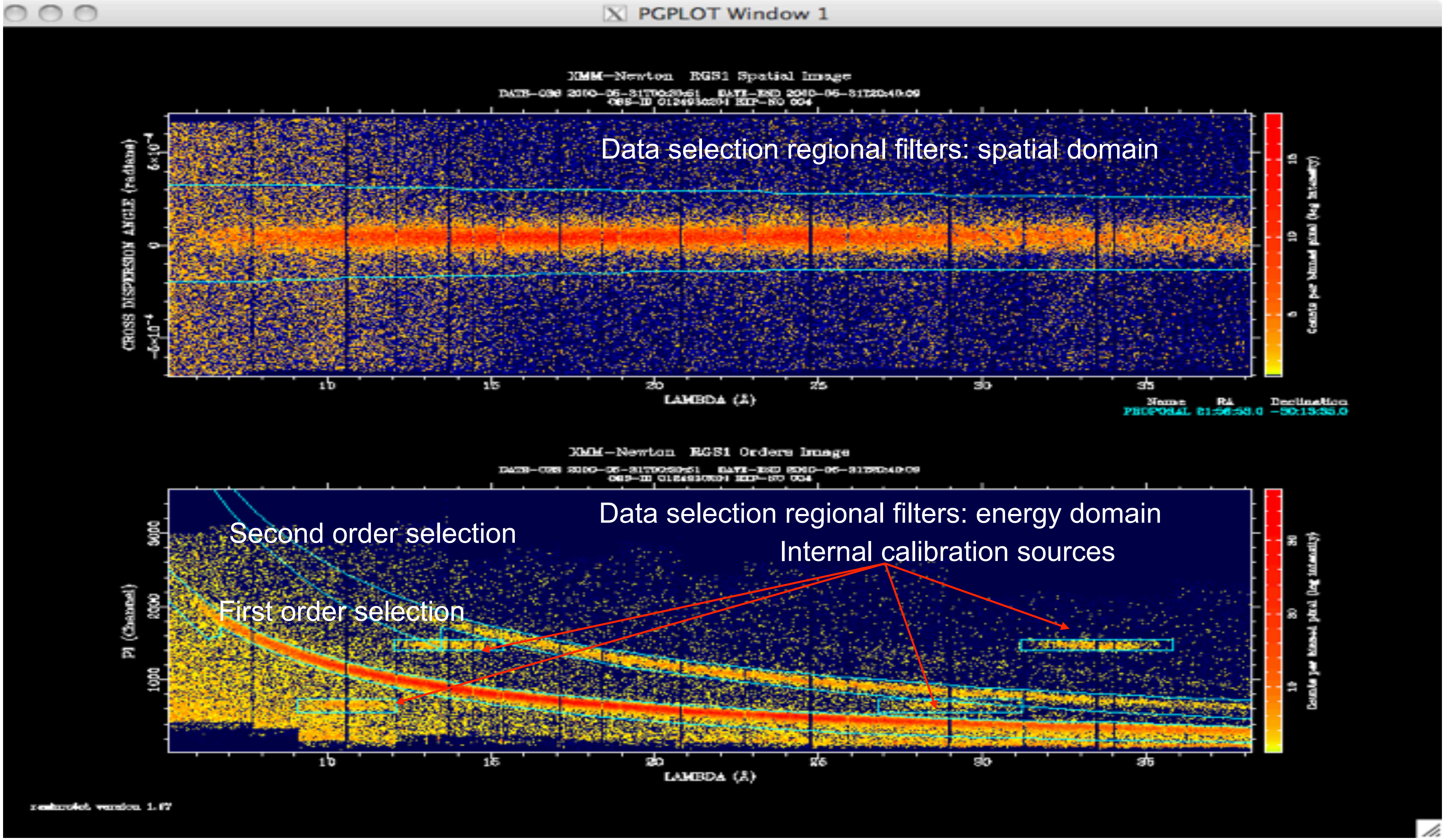
Two basic RGS modes:

Spectroscopy aka Spectro (+ Q)
"High Event Rate with SES"

RGS Small Window
only central 32 CHIPY out of 128 Xdisp rows
>> for very bright sources

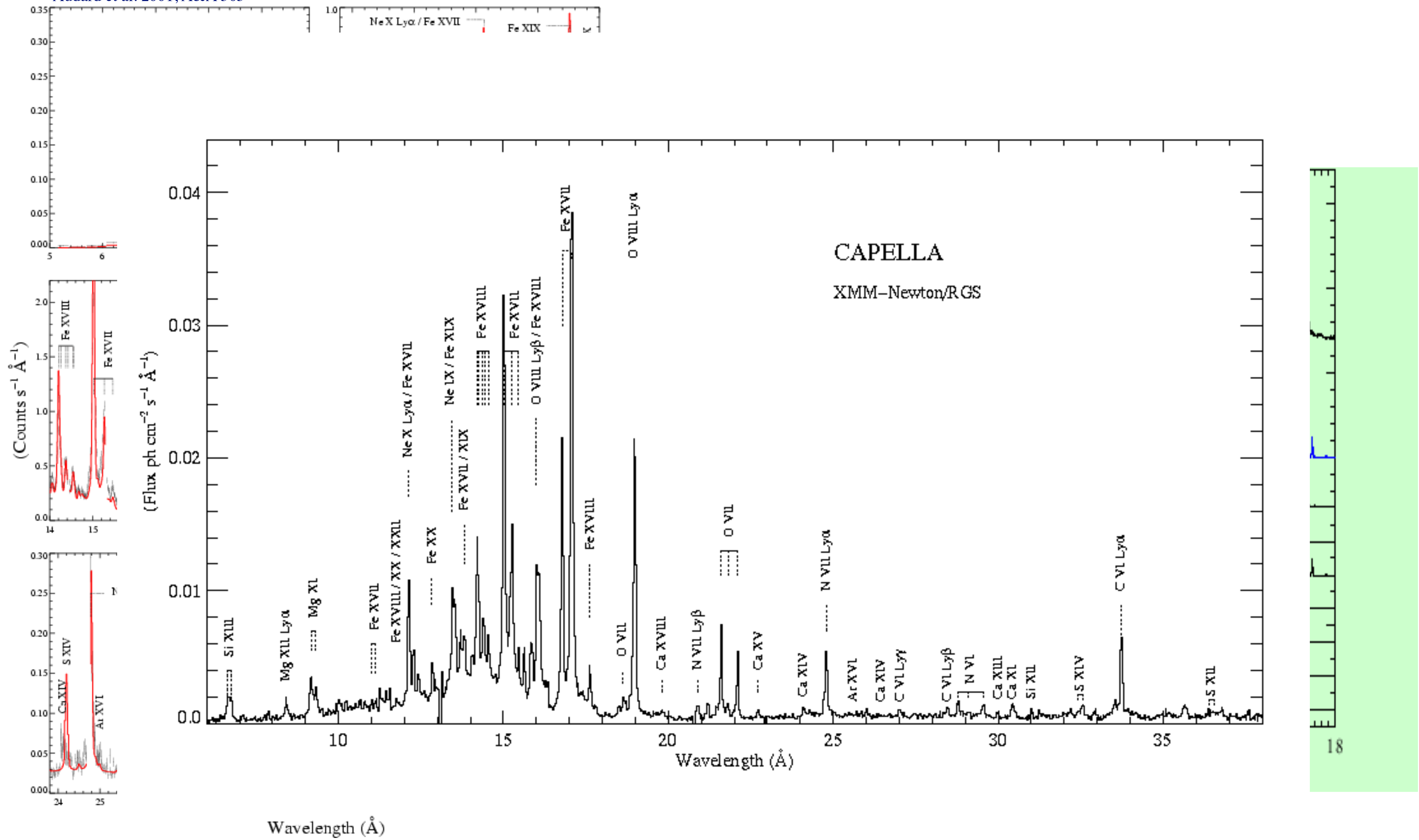
+ a special way of observing:
Multi-pointing mode
0, +/-15", +/-30" == 5 pointings
~ +/- 35 mÅ, +/- 69 mÅ

RGS data space - the projections



RGS spectrum of Capella

Audard et al. 2001, A&A 365



What's happened to the RGS since launch ?

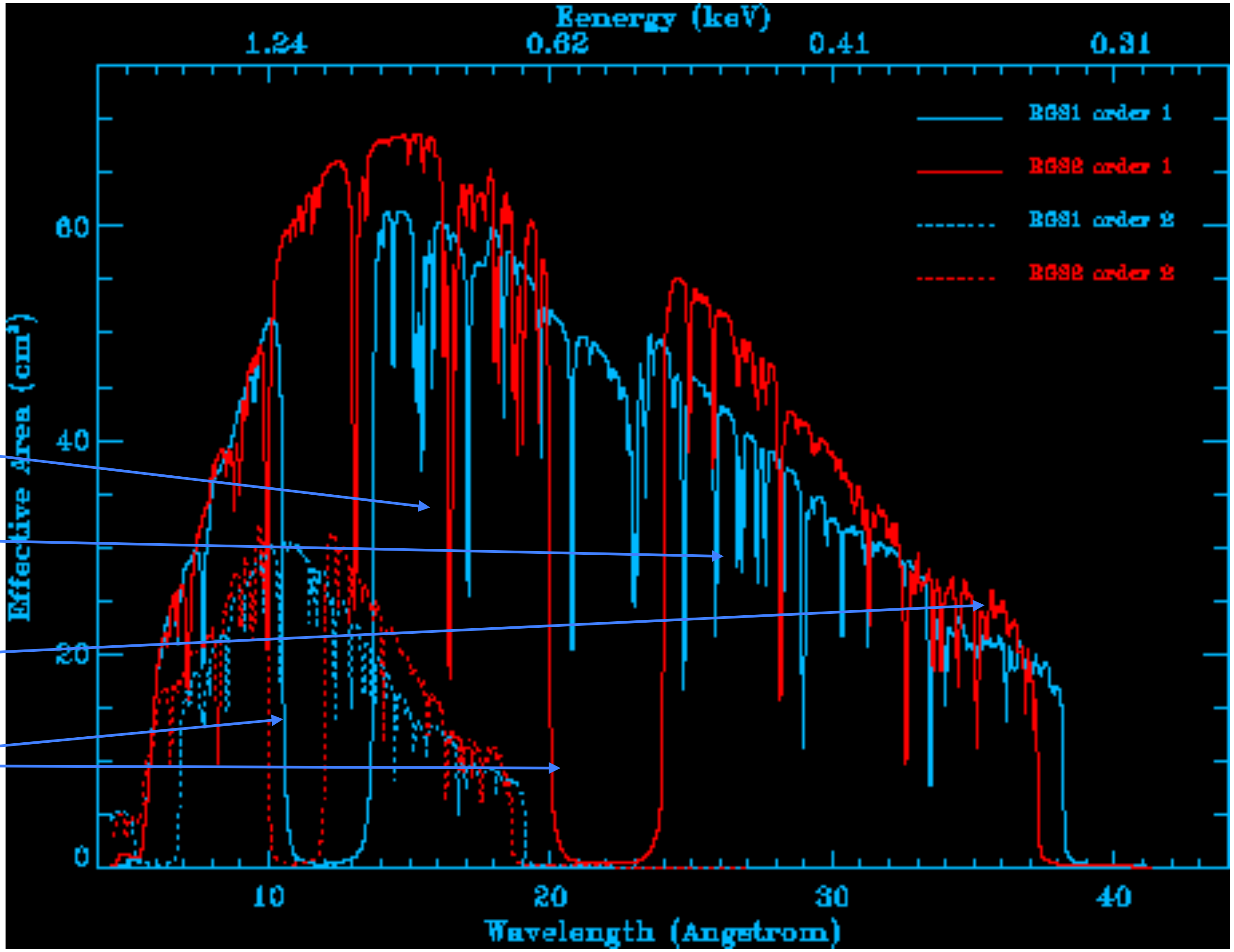
- 2 CCDS have failed
  - after 1 week RGS2 CCD4
    - near the OVII triplet at 21Å
    - covered by RGS1 1st order
  - after 9 months RGS1 CCD7
    - near NeX Lyman α at 12Å
    - covered by RGS1 2nd order and RGS2
- Detector contamination
  - exponential build-up of carbon
  - loss of long-wavelength sensitivity

- RGS2 single-node CCD readout
  - takes longer
- Multi-pointing mode
- Small-window mode

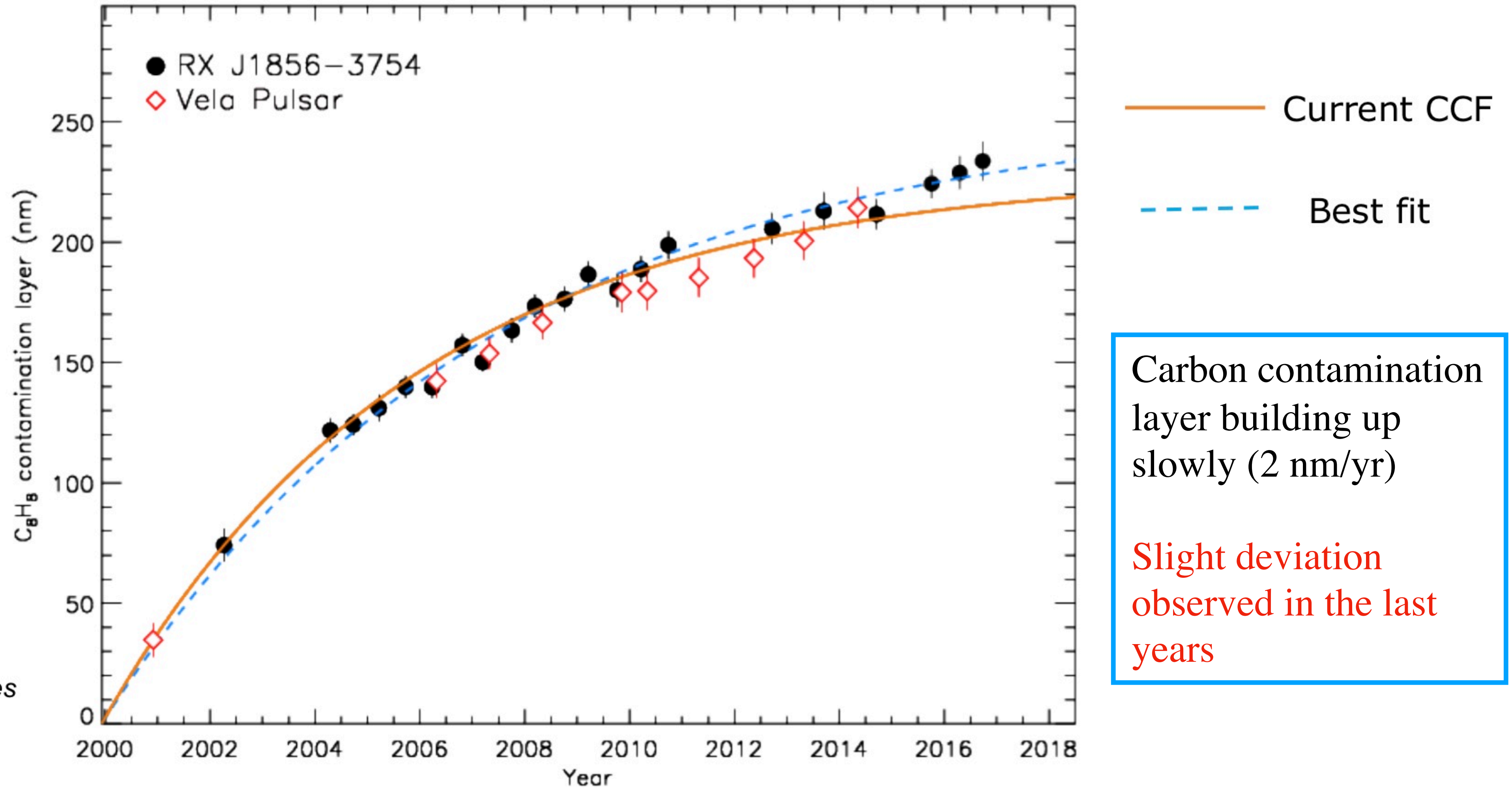
The RGS efficiency

Necessary for the analysis >> response file for each source & order: rgsrmfgen

- **Effective area depends on data selections**
- **Large scattering at short wavelengths**
- **Inter-chip gaps**
- **Signatures of bad columns**
- **Wiggles due to sampling of data selection regions**
- **Failing CCD chains**



RGS contamination



C. de Vries

Carbon contamination layer building up slowly (2 nm/yr)

Slight deviation observed in the last years

RGS calibration summary

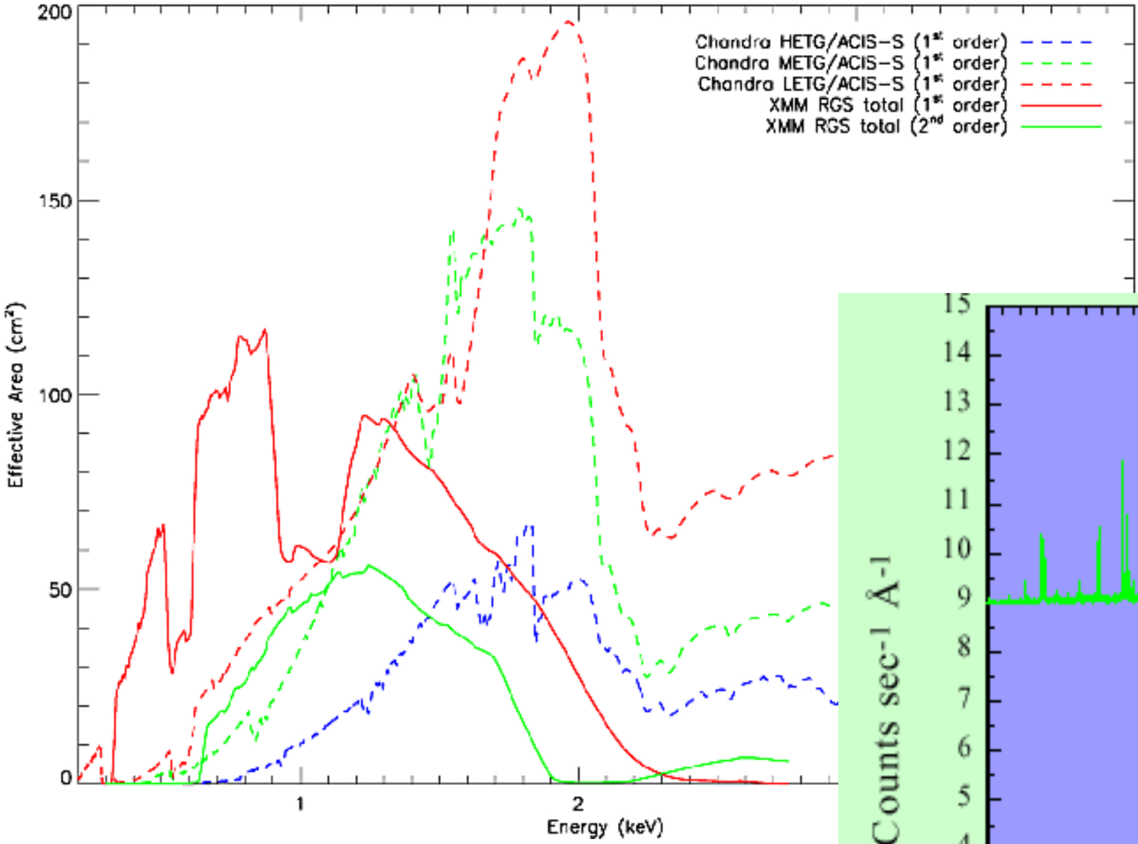
- Relative accuracy of effective area better than
  - 4% in l=[7-36]Å, and better than 15% elsewhere for m = - 1
  - 15% for whole m=-2 spectrum

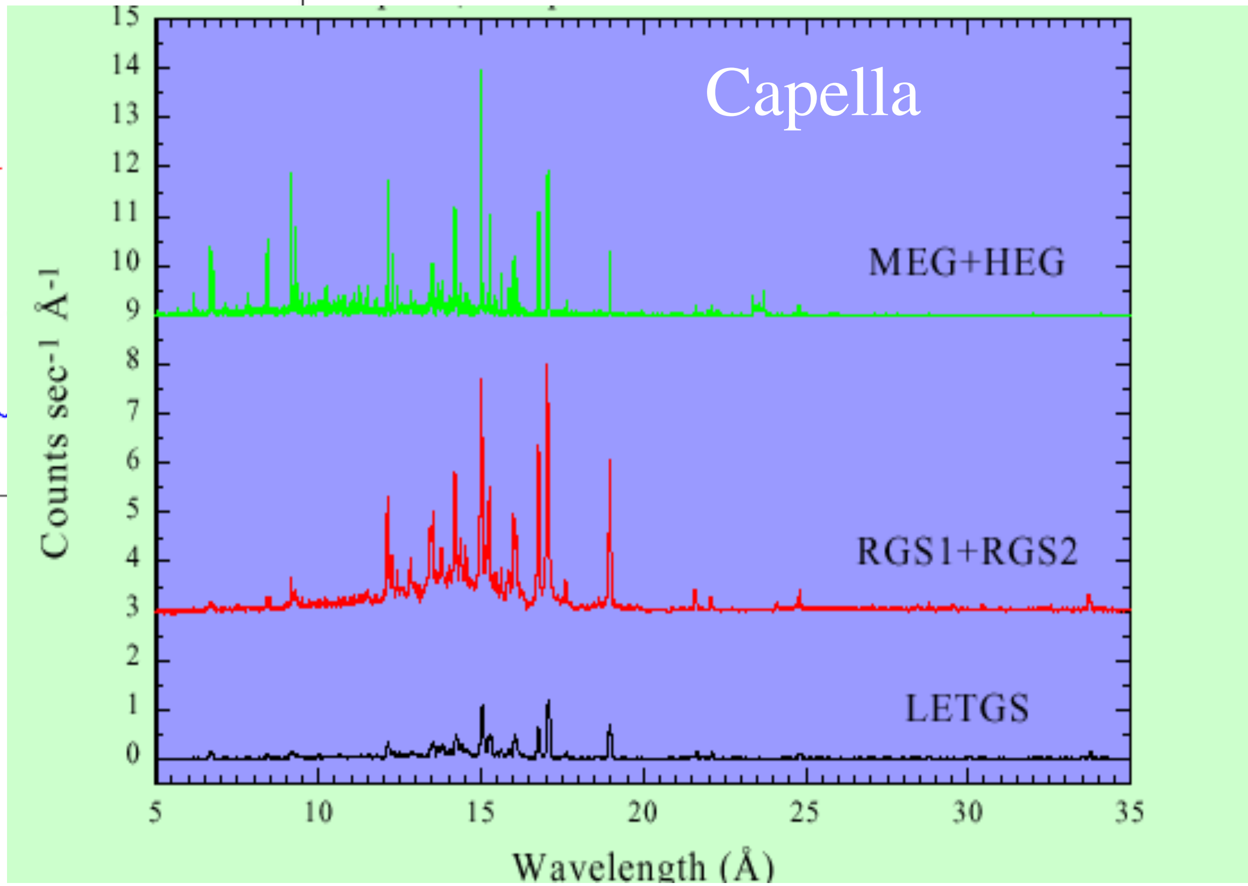
- Wavelength accuracy: s ~ 6 mÅ, mainly limited by uncertainty in pointing reconstruction

- Significant lower number of hot columns, pixels and “low count” columns after cooling

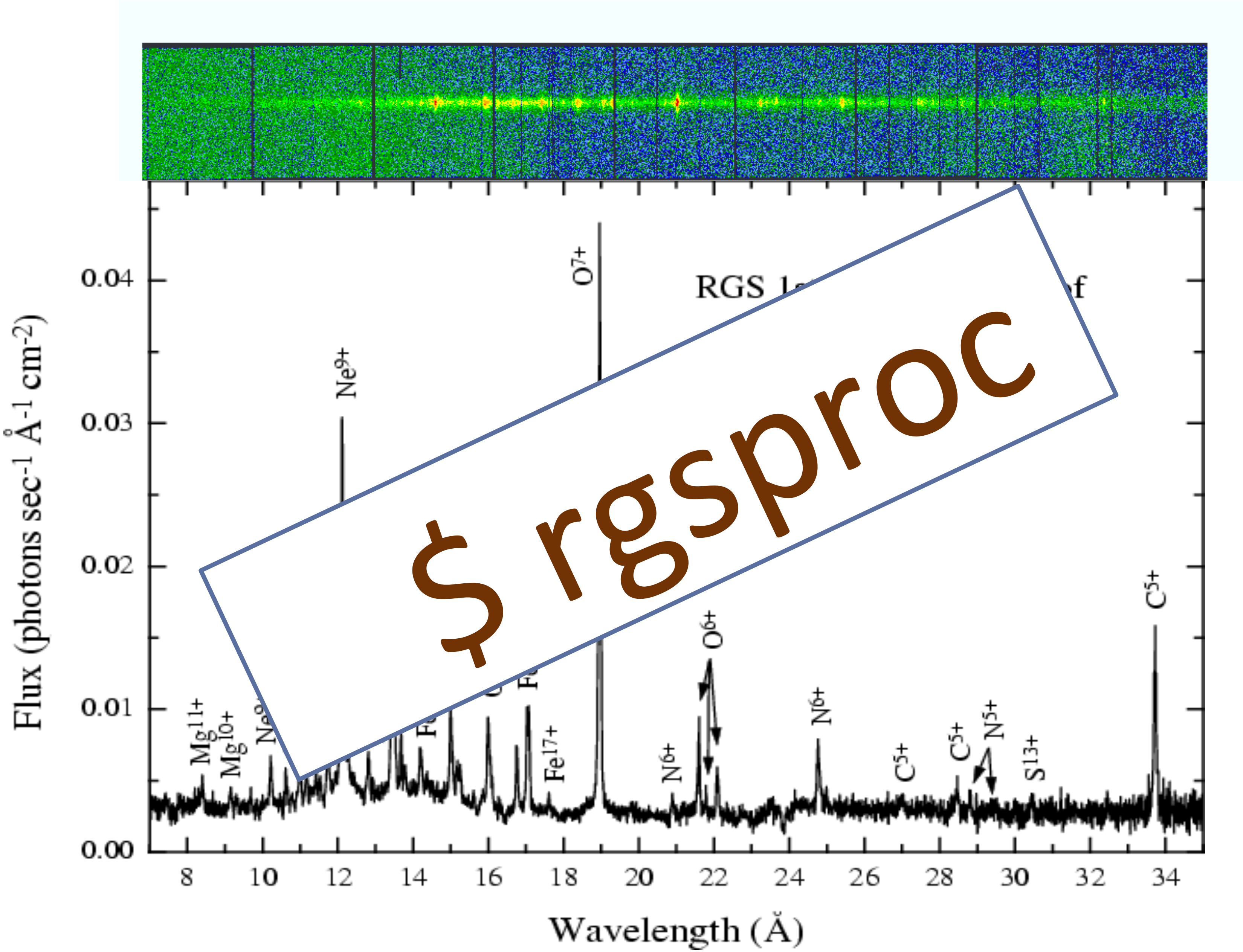
	RGS 1 1st order	RGS 2 1st order	RGS 1 2nd order	RGS 2 2nd order
Wavelength range	6 - 38 Å		6 - 20 Å	
Effective area @15 Å (cm^2)	61	68	15	19
Resolution @15 Å	250 1200 km/s 60 mÅ	215 1400 km/s 70 mÅ	430 700 km/s 35 mÅ	375 800 km/s 40 mÅ
Wavelength accuracy	6 mÅ		5 mÅ	
Time resolution (Spec, 8 CCDs)	4.8 s	9.6 s	4.8 s	9.6 s
Time resolution (Spec, 1 CCD)	0.6 s	1.2 s	0.6 s	1.2 s
Time resolution (SW, 8 CCDs)	1.2 s	2.4 s	1.2 s	2.4 s
Time resolution (SW, 1 CCD)	0.15 s	0.3 s	0.15 s	0.3 s

Chandra gratings vs RGS



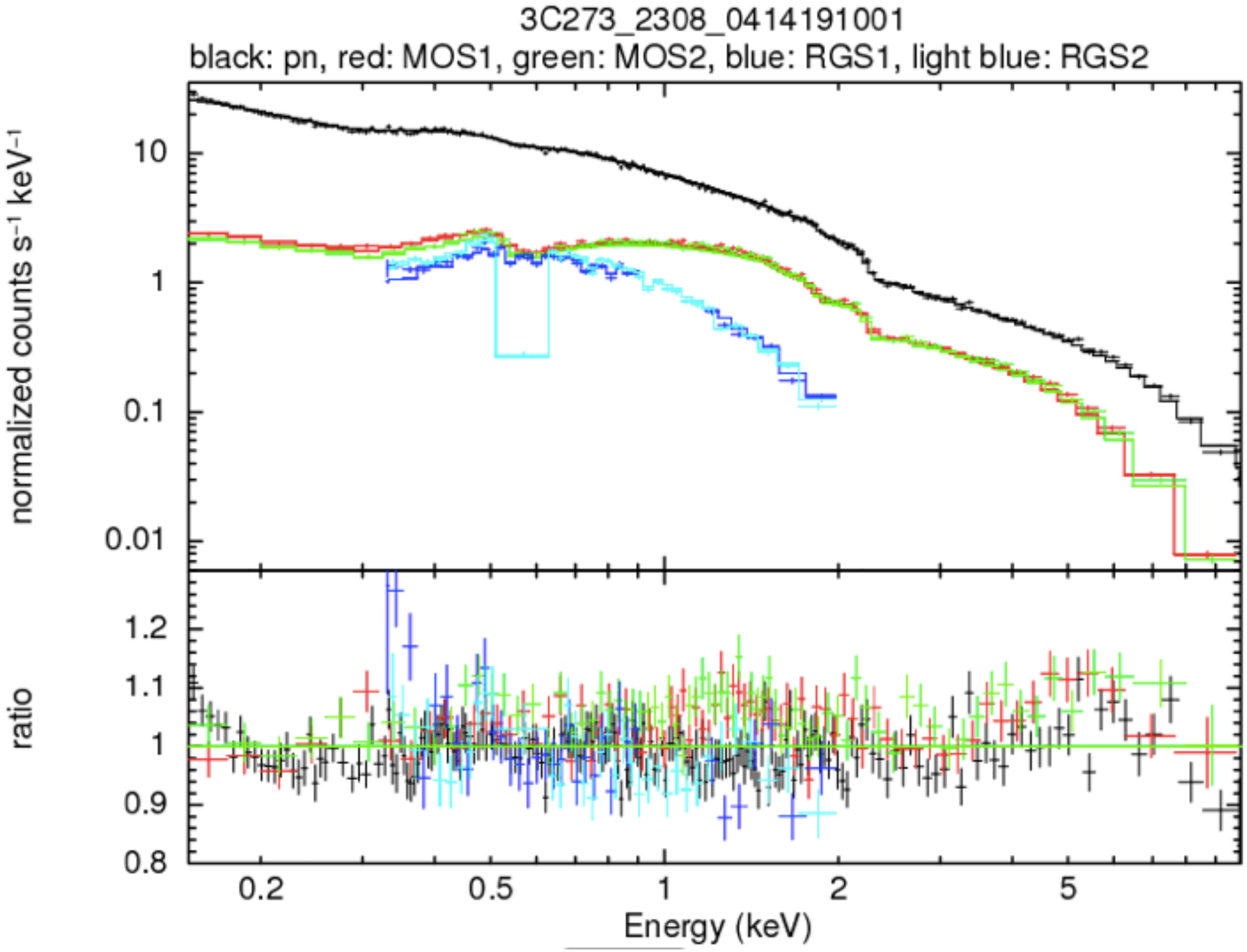


What's next with RGS?



Cross calibration

Instrument's redundancy helps a lot to find / understand calibration defects
Every new SAS version leads to validation of processing and calibration accuracy



Outline

- ➢ History of the **XMM-Newton** project √
- ➢ Description of the **XMM-Newton** satellite √
- ➢ Description of instruments and their calibration
  - ❖ X-ray telescopes: XRT √
  - ❖ X-ray Imaging & mid resolution Spectroscopy & Timing: EPIC √
  - ❖ X-ray High resolution dispersive spectroscopy: RGS √
  - ❖ **Optical and UV Imaging & Spectroscopy & Timing: OM**
- ➢ Use of the **XMM-Newton** observatory

Optical Monitor on board XMM-Newton

Simultaneous & co-aligned UV/optical observation of X-ray sources:

- Broad Band photometry
- Optical/UV spectra
- Fast timing photometry

OM is a 30 cm telescope, f/12.7 modified Ritchey Chrétien optics with:

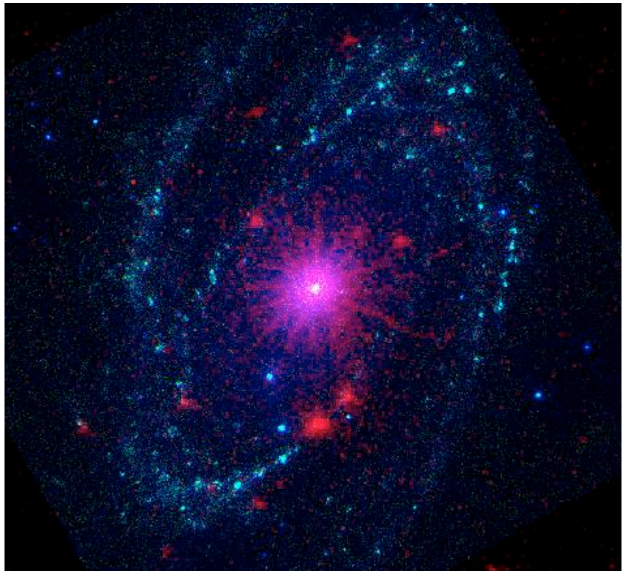
• Total bandwidth	160 - 600 nm
• Spectral bandwidth	160 - 550 nm
• Sensitivity limit	23.5 mag
• Field of view	17’
• PSF (FWHM)	1.6” - 2.3”

• Timing resolution	0.5 s
• Spectral resolution	0.5/1.0 nm
• Spatial resolution	0.5/2.0”
• Brightness limit	$m_V = 7.4$ mag

OM observations - examples

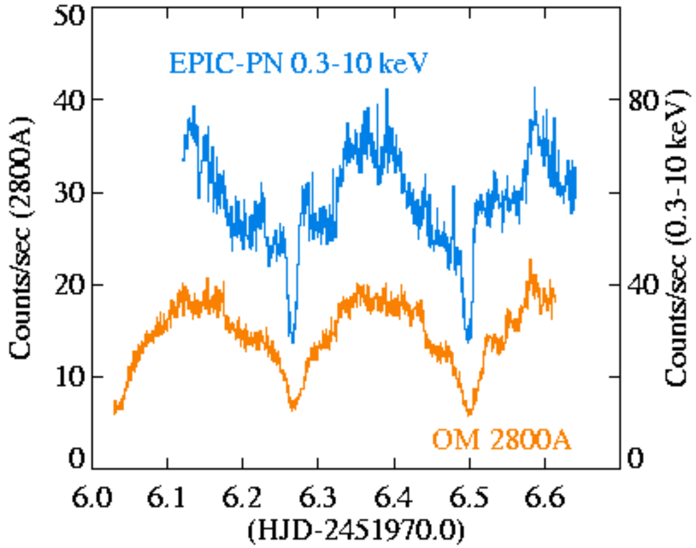
A):
OM UV & MOS Images

(M81)

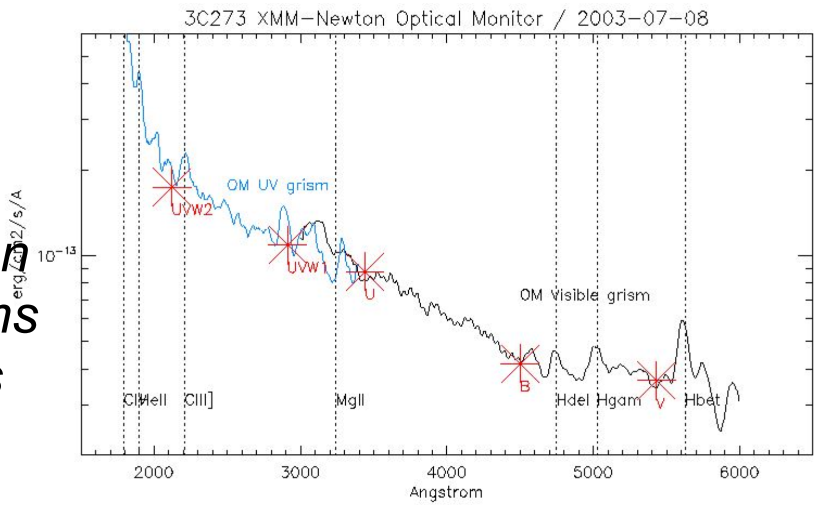


B):
UV & X-ray light curves

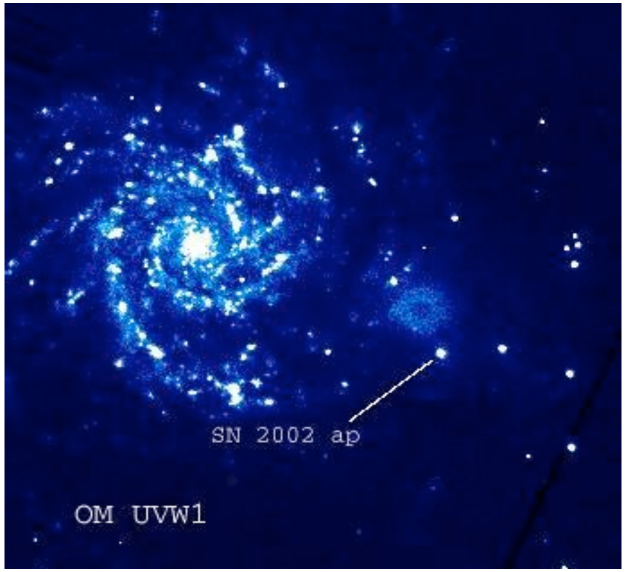
(X1822-371)



C):
Spectral energy distribution with grisms and filters



D):
Supernova 2002p



OM - flexible configurations

Operation modes:

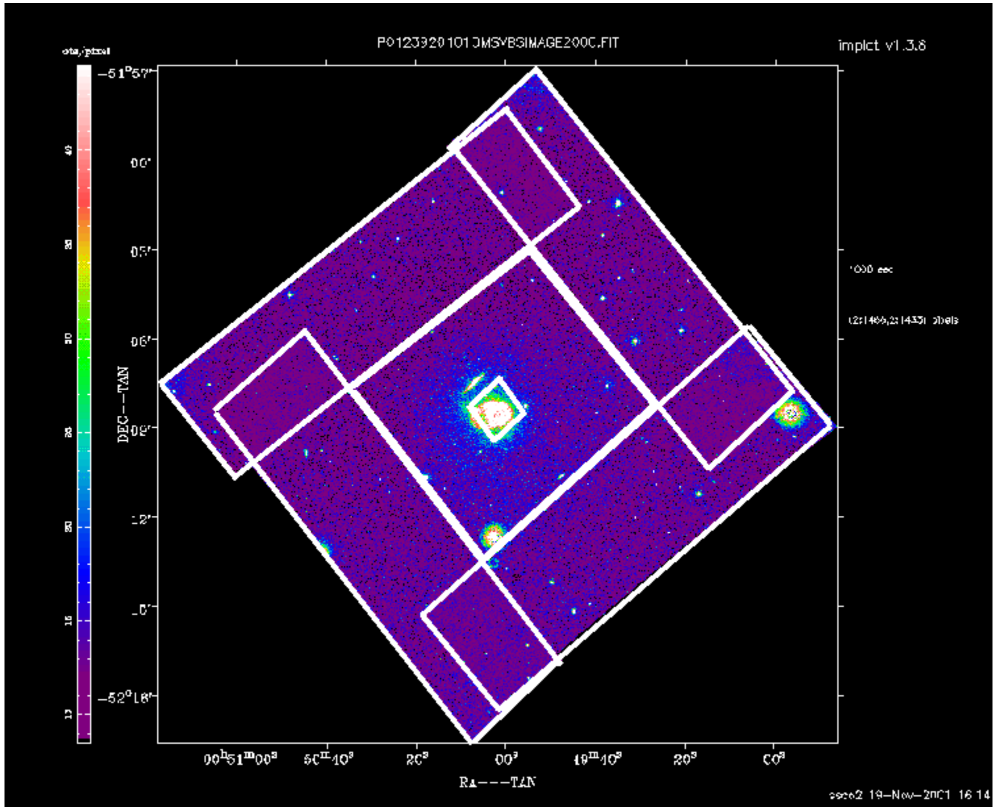
- Image only
- Image + fast
- User defined
- Full-Frame Low-Resolution
- Full-Frame High-resolution

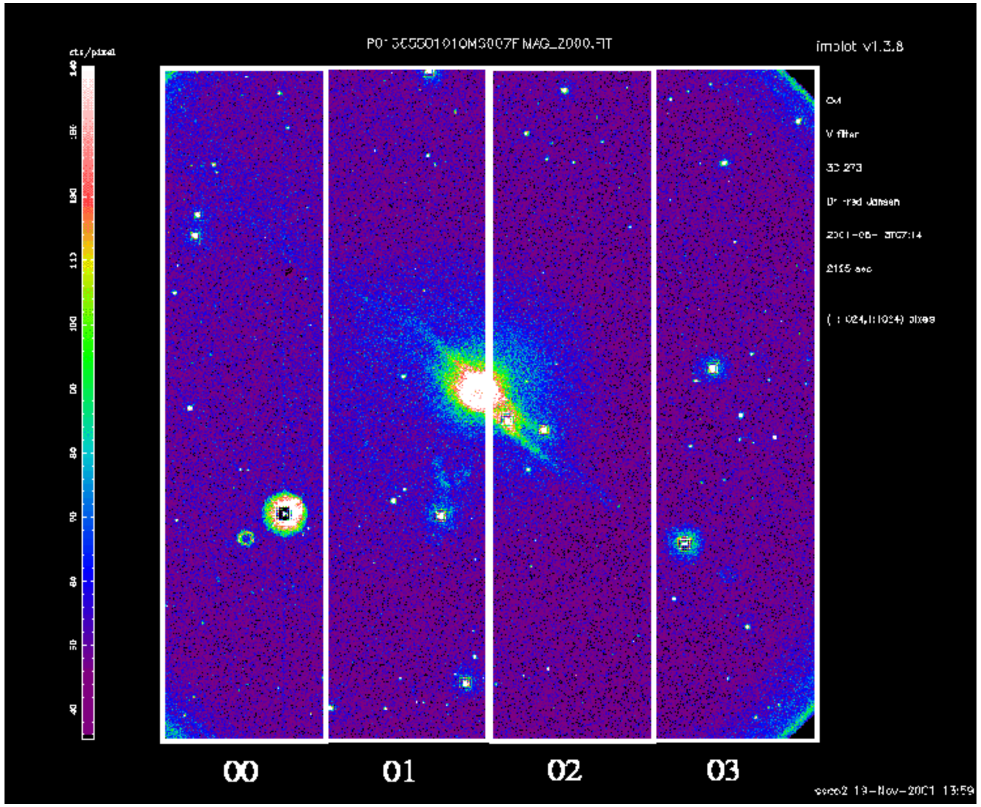
Filters:

(from1600 -6000 A)

V
B
U
UVW1
UVM2
UVW2
white
Visible grism
UV grism

OM - imaging and more





Default: 5 consecutive windows cover entire FOV + continuous central high res. window

+ window in fast mode: time resolution of source
+ grism window: full spectral resolved source

Or: user defined windows (up to 5, 2 in fast mode)

Full-frame imaging: homogeneous sampling of whole FOV ⇒ surveys
> in low resolution (1024x1024 1" pixels)
> in high resolution (2048 x 2048 0.5" pixels)

+ grism: low spectral resolution of all sources in the FOV

OM grisms

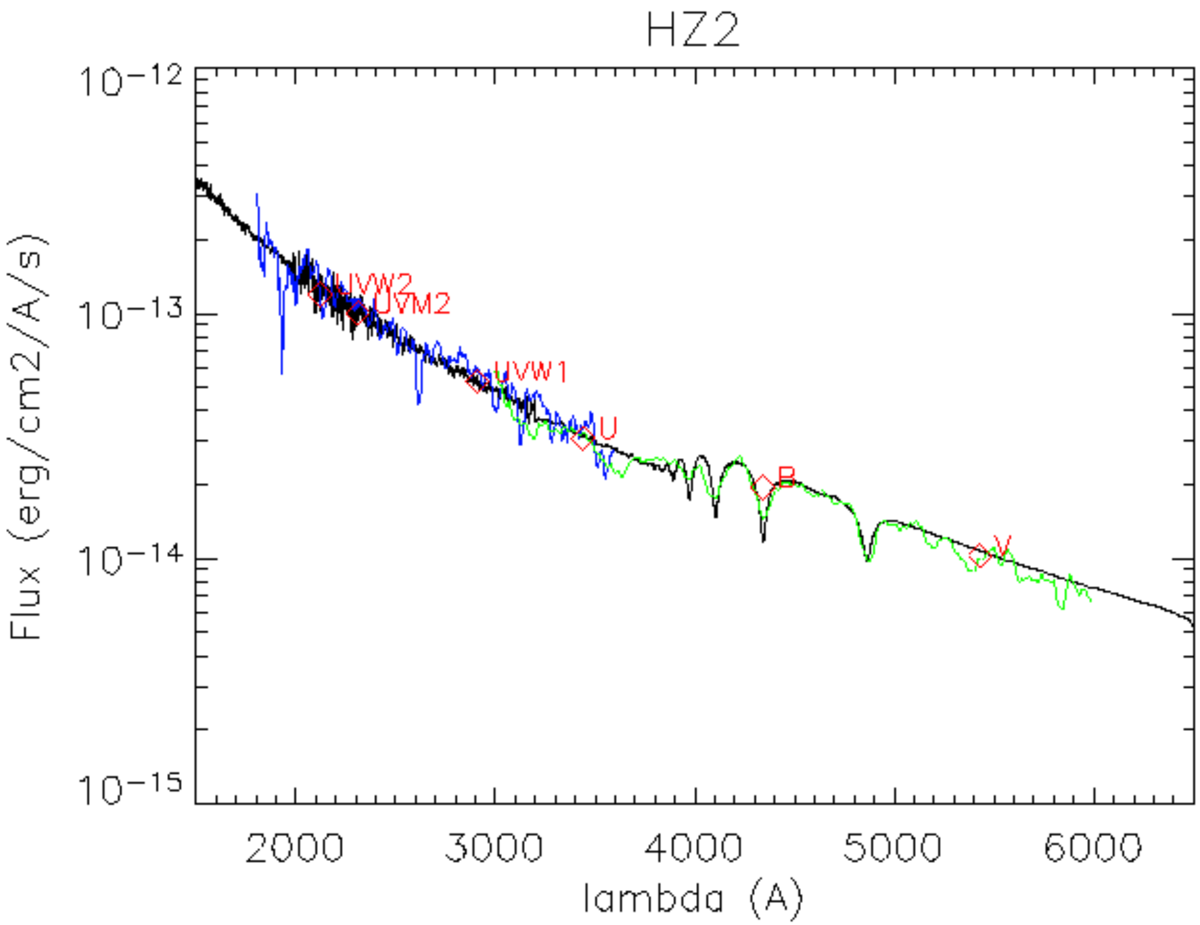
SAS can extract and calibrate the spectra produced by OM grisms automatically.

Accuracy of grism wavelength calibration :

a) 7 Å for UV grism
   < 10 Å for Visible Grism

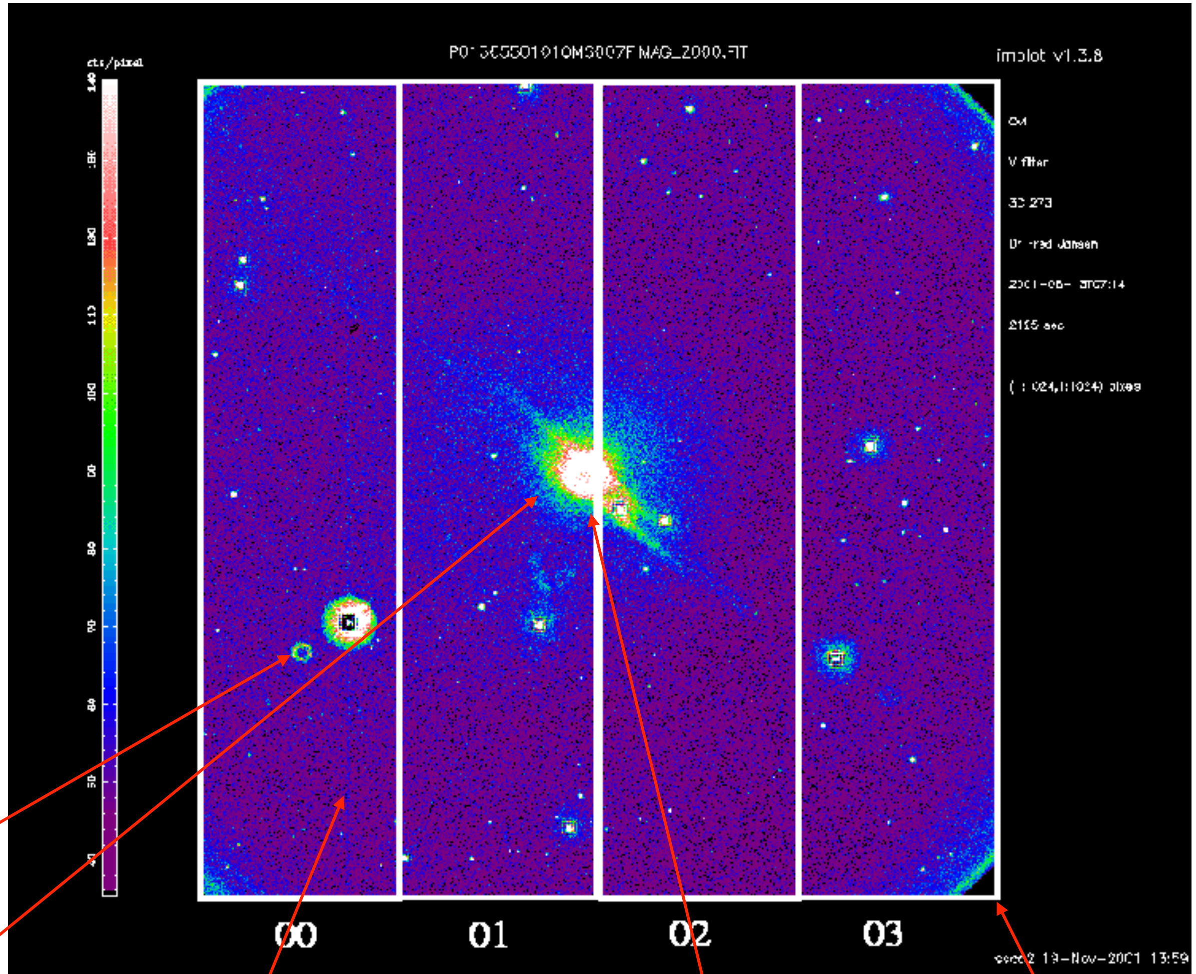
b) zero order centroiding
   may introduce 10 Å syst.unc.

Flux: Comparison to HST within 10%



Artifacts in OM images

- Artifacts are low level
- Noticeable with appropriate scale (here log scale was used)
- Sources can be detected and brightness correctly determined



ghost ring

scattered light features

readout streak

central enhancement

outside FOV

OM vs VLT view of the Crab

OM(231, 291,344 nm) versus VLT(429,657, 673 nm)

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

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- ➢ **Use of the XMM-Newton observatory**

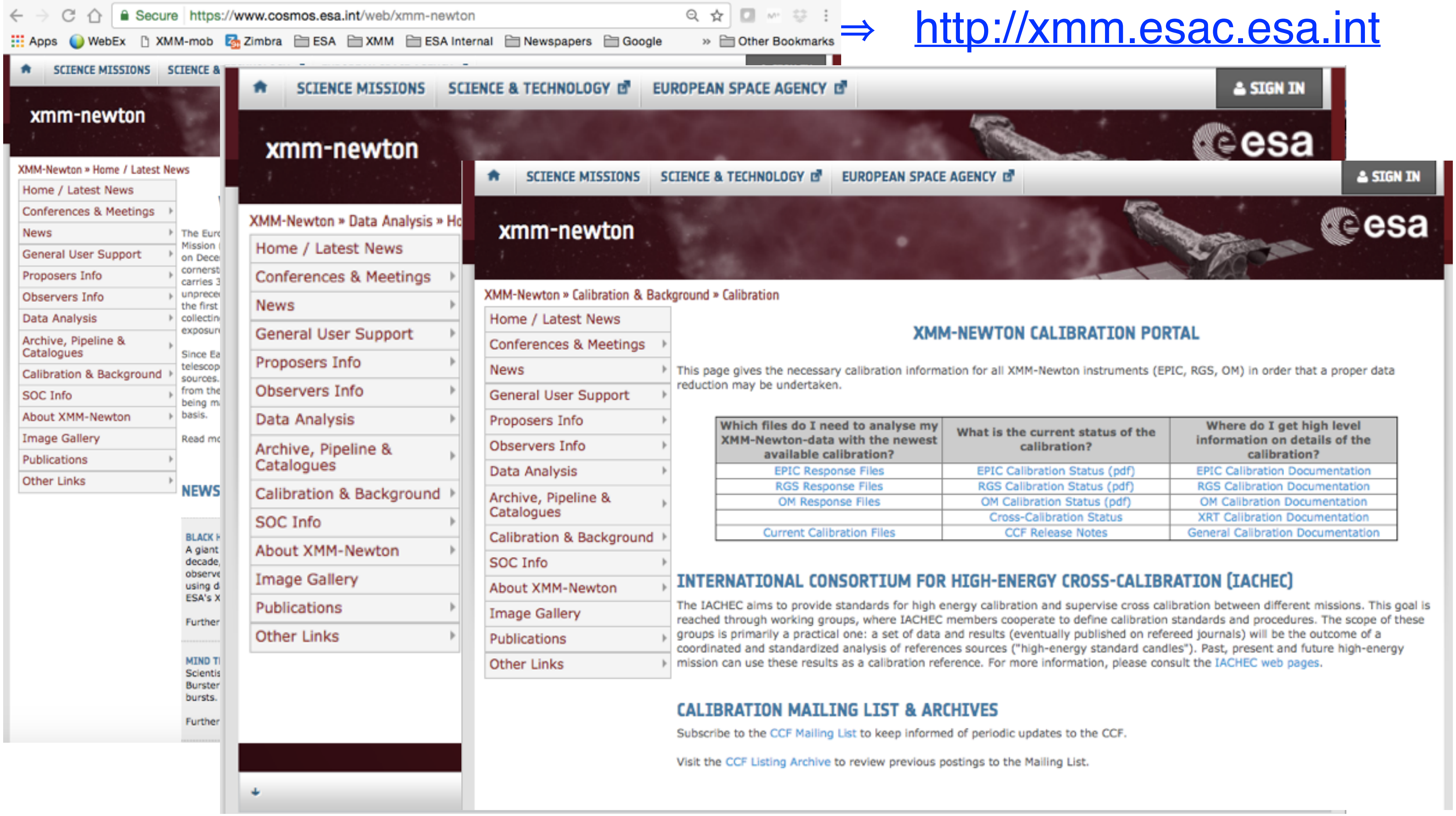
Use of XMM-Newton

- XMM-Newton is an observatory
- Open for applications
- Proposals requested at yearly AO cycles
- Data rights are protected for one year, after that data become publicly available
- XMM-Newton data offered through archive (http://xmm.esac.esa.int/xsa)
- XMM-Newton's lifetime expected to be ~ ~~10~~ ~~12~~ ~~14~~ 25? 28? years

(Almost) Everything you always*

wanted to know about XMM-Newton (but were afraid to ask??)

⇒ http://xmm.esac.esa.int



We have discussed…

- History of the **XMM-Newton** project
- Description of the **XMM-Newton** satellite
- Description of instruments and a bit of their calibration
    - X-ray telescopes: XRT
    - X-ray Imaging & low resolution Spectroscopy & Timing: EPIC
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- Use of the **XMM-Newton** observatory