Cross-calibrating the XMM EPIC effective areas for a default empirical correction

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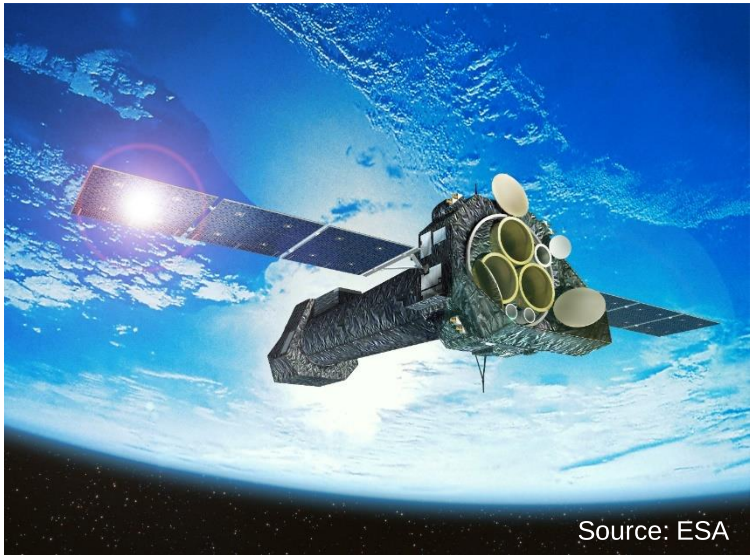
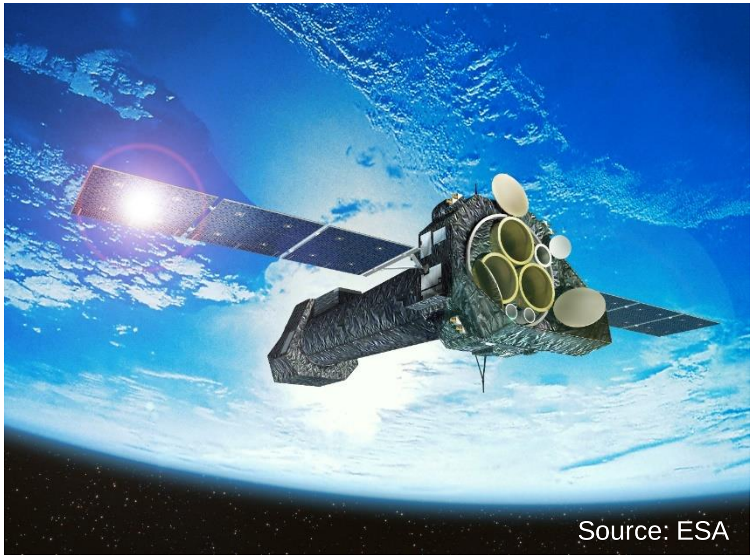
Outline



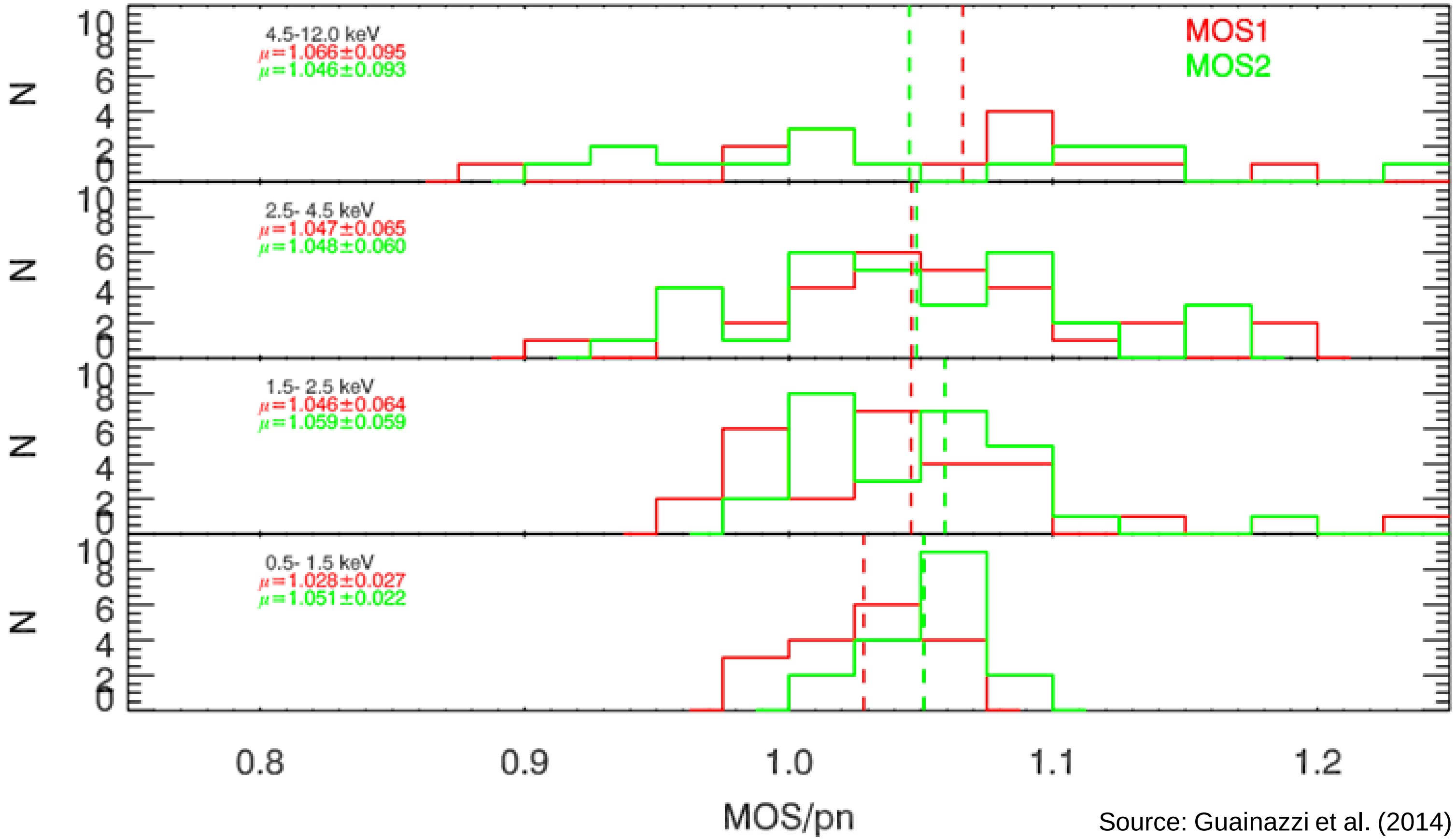
Outline



Source: ESA

1 Introduction: CORRAREA

MOS to pn flux ratios:



Source: Guainazzi et al. (2014)

sample of 46 sources
calculated with SAS v13.5 and according calibrations

1 Introduction: CORRAREA

Since SAS v14.0 (Guainazzi et al., 2014):

- non-default option *applyxcaladjustment* in SAS task *arfgen*
- empirically corrects the EPIC effective areas by an energy-dependent multiplicative factor
- **CORRAREA**: extension of the according constituents (XAREAEF) in the current calibration files (CCFs)

→ determine the relative cross-calibration accuracy of the **on-axis** effective areas

→ a tool to **estimate** the astrophysical impact that the systematic EPIC effective area uncertainties have

GOALS

- make it a default empirical correction in the future
- recalibration and further validation
- automation

1 Introduction: CORRAREA

- Starting point: Source selection, screening & stacking method according to Read et al. (2014)

- Sources selected from the **XMM-Newton Serendipitous Source Catalogue**, 2XMMi-DR3 (2010), with ~ 5000 observations up to October 2009:

  (i) point-like
  (ii) full frame mode
  (iii) thin/medium filter
  (iv) number of counts (0.2-12 keV: MOS > 5000, pn > 15 000)
  (v) low count rate (MOS: 0.70 cts/s, pn: 6 cts/s)
  (vi) sources near on-axis (boresight-to-source distance < 2')
  (vii) out of the plane of the Galaxy (galactic latitude > 15 deg)

- **Screen** for crowded fields, short good time intervals (< 1 ks), close chip gaps & bad CCD columns, extended emission, chip loss

1 Introduction: CORRAREA

→ 46 sources, out of > 350 000 detections, with a total good time interval (GTI) exposure of 1751.9 ks

Stacked residual method:

- "stack and fit": model a stacked spectrum
- determine the residual ratio α: value for each energy bin would be unity if the cross-calibration of the effective areas was consistent

$$\alpha = \frac{data_i}{model_{\mathrm{pn}} \otimes response_i} \times \frac{model_{\mathrm{pn}} \otimes response_{\mathrm{pn}}}{data_{\mathrm{pn}}}$$

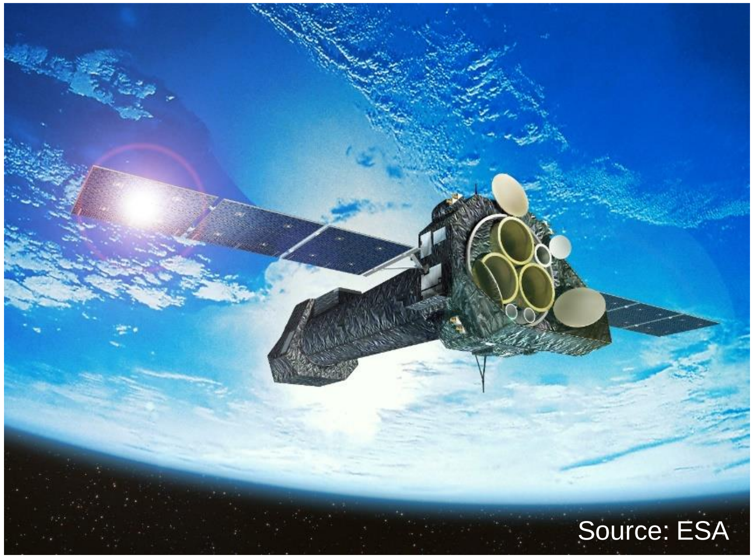
i: MOS indices (1, 2)

- pn chosen as reference instrument (appears to be extremely stable)

OBSID	Rev.	Count rate (0.2–10 keV; s^{-1})			Exp. GTI
		pn	MOS1	MOS2	(ks)
0303340101	1102	3.07	0.62	0.63	44.7
0084140501	0395	1.53	0.44	0.44	12.4
0084140101	0217	1.40	0.39	0.40	35.3
0200480101	0915	1.68	0.38	0.39	30.2
0300630301	1120	1.01	0.28	0.27	17.6
0106860101	0157	0.92	0.31	0.30	23.4
0086360401	0230	1.11	0.31	0.31	26.9
0086360301	0230	1.66	0.43	0.45	54.5
0101441501	0410	1.68	0.42	0.42	37.1
0101440601	0138	2.33	0.57	0.60	34.7
0153250101	0615	1.90	0.38	0.38	54.7
0300910301	1068	1.71	0.38	0.39	13.0
0201290301	0813	0.99	0.29	0.29	18.2
0112521001	0428	2.18	0.68	0.69	7.9
0151390101	0630	0.71	0.21	0.21	46.3
0112850201	0469	1.87	0.60	0.60	16.5
0112880101	0565	2.02	0.50	0.52	28.1
0205010101	0816	1.74	0.47	0.48	26.3
0306630201	1103	1.34	0.32	0.32	91.4
0124900101	0082	2.17	0.60	0.61	29.7
0204040301	0841	1.47	0.39	0.39	56.4
0204040101	0823	1.95	0.52	0.52	75.6
0300240501	1129	1.17	0.39	0.40	25.8
0206580101	0939	0.64	0.17	0.17	36.9
0147670201	0576	1.59	0.48	0.47	12.1
0152940101	0660	1.29	0.43	0.43	39.4
0205390301	0831	0.73	0.18	0.19	49.1
0092850501	0373	1.09	0.28	0.28	38.9
0207130401	0948	2.08	0.54	0.55	11.7
0067750101	0311	1.23	0.31	0.32	23.6
0100240701	0127	2.15	0.61	0.65	15.5
0056340201	0420	2.18	0.64	0.66	12.4
0146390101	0604	1.66	0.59	0.57	17.3
0147920601	0539	2.12	0.67	0.69	12.1
0402560901	1291	0.71	0.22	0.22	48.0
0405090101	1255	0.88	0.28	0.28	96.1
0304320201	1017	1.52	0.41	0.41	68.5
0304320301	1016	1.40	0.37	0.37	36.1
0304320801	1189	1.98	0.52	0.52	37.8
0405690501	1275	0.85	0.23	0.24	25.8
0405690201	1272	1.15	0.31	0.32	36.1
0510181701	1528	1.59	0.51	0.52	44.6
0502220301	1441	0.31	0.10	0.09	69.1
0555020201	1558	2.16	0.60	0.61	24.9
0555650201	1598	0.64	0.18	0.18	96.4
0555650301	1599	0.63	0.17	0.17	92.8

Source: Read et al. (2014)

Outline


Source: ESA

2 Automation

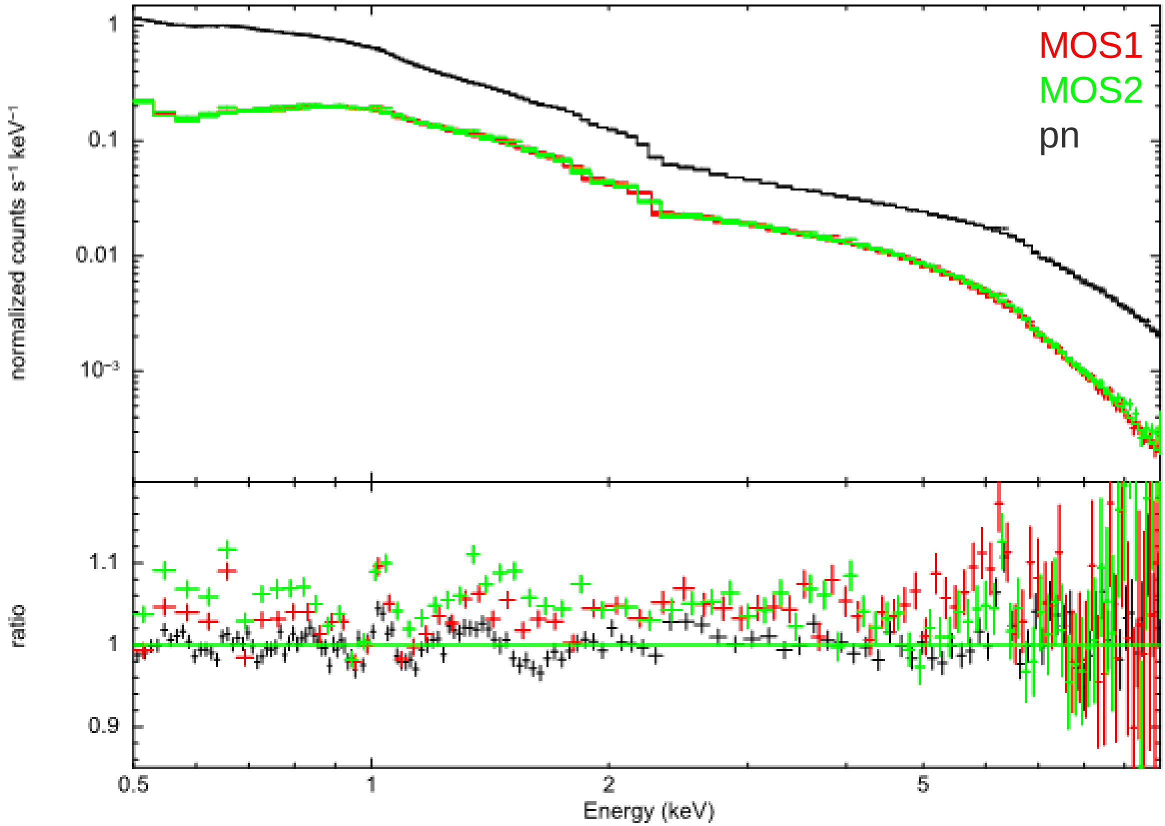
Mainly done via bash, python & idl scripts:

1. initial data processing (analysis date flexible)
2. filter the event files with a **common GTI** file for each observation
3. create images for visual screening
4. eased **region selection**
5. create source and background **spectra**, as well as the Redistribution Matrix and Ancillary Response Files (RMFs and ARFs)
6. **stacking** for each detector:
   - source & background spectra: summing up counts per bin, summing up exposures, exposure-weighting BACKSCAL values
   - exposure-weighted RMFs and ARFs
7. phenomenological **reference model** fit to **pn data**:

$$wabs \times [power + power + Gauss + Gauss + Gauss] \times edge$$

2 Automation

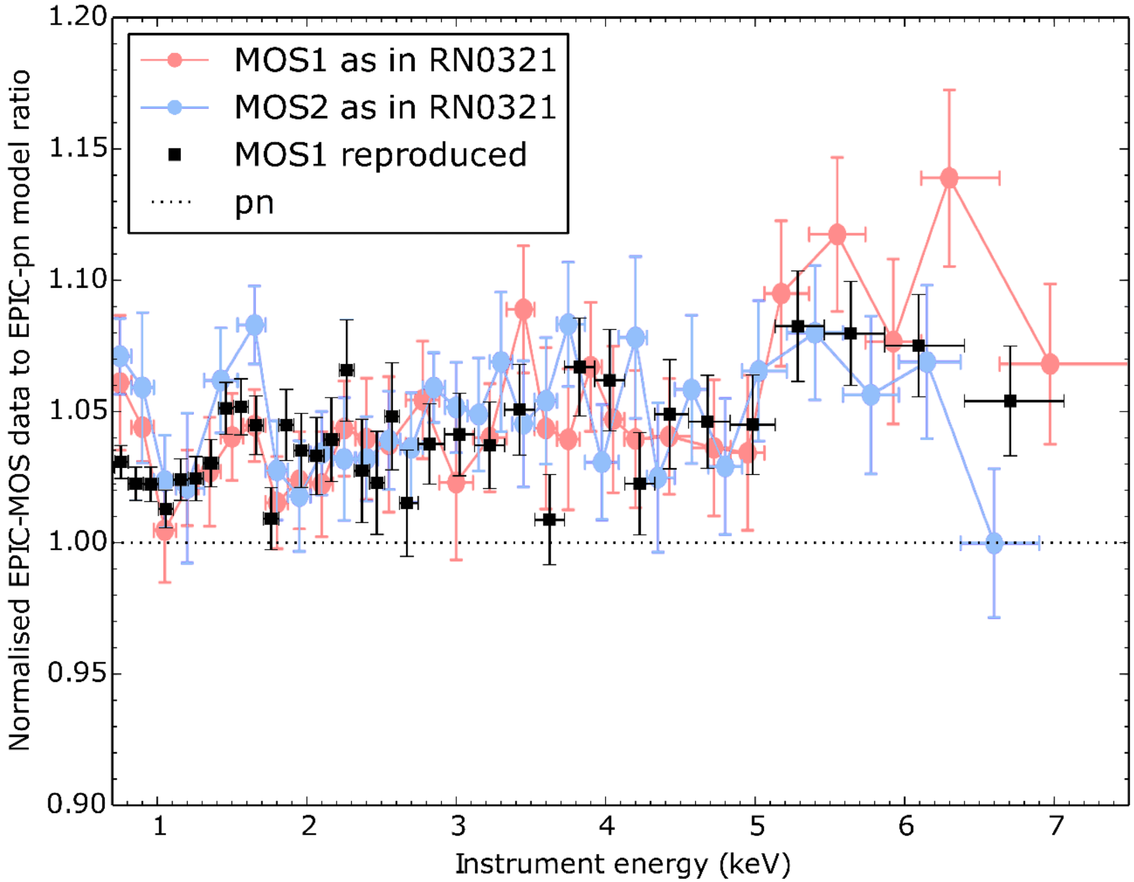
8. reference model convolved with the instrument responses of MOS1 and MOS2



pn fit: red. χ^2 is 1.08 for 1888 degrees of freedom
calculated with SAS v13.5 and according calibrations

2 Automation

9. realignment of the residuals to a new, uniform energy grid
10. calculation of the residual ratio (with an optional SNR rebinning)



2 Automation

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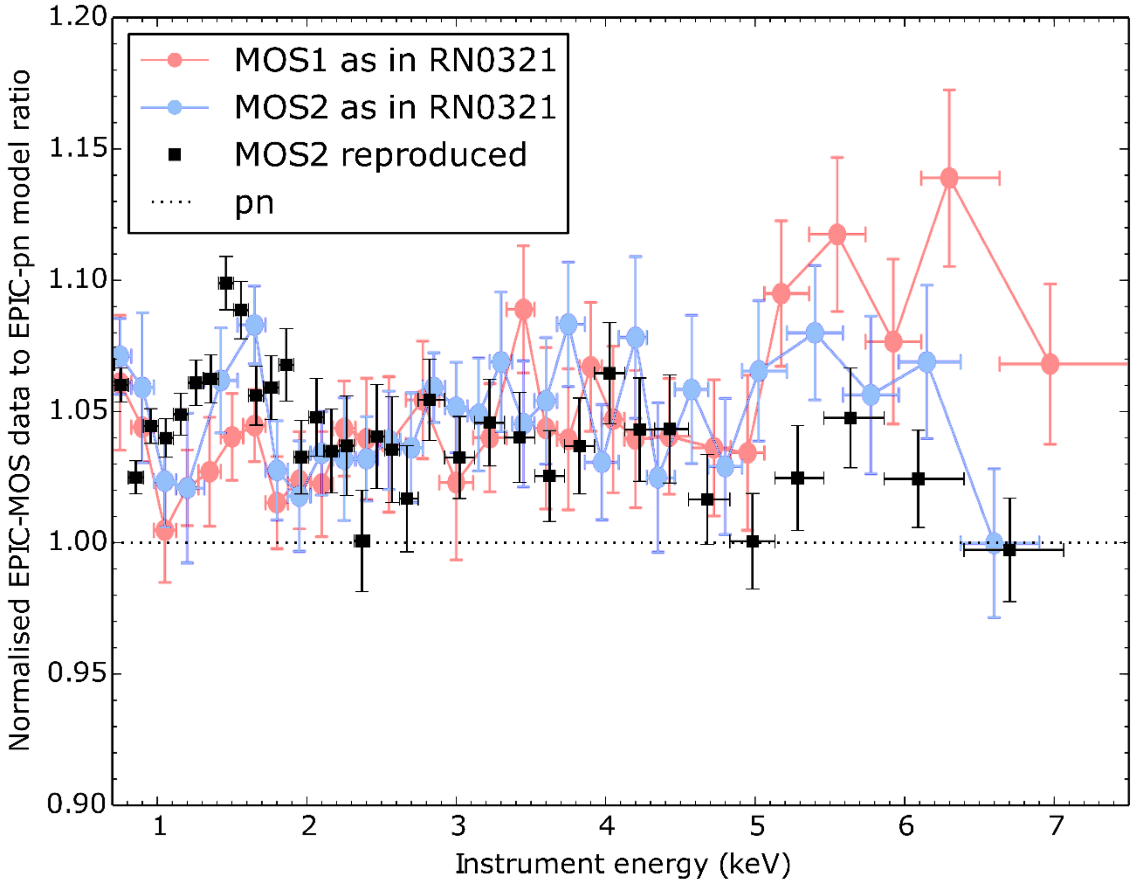


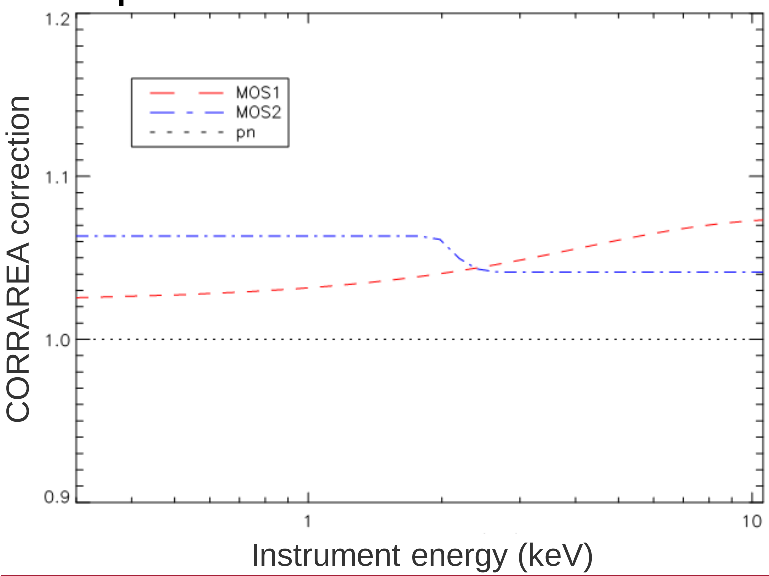
11.eased fitting of the residual ratio

current CORRAREA function:

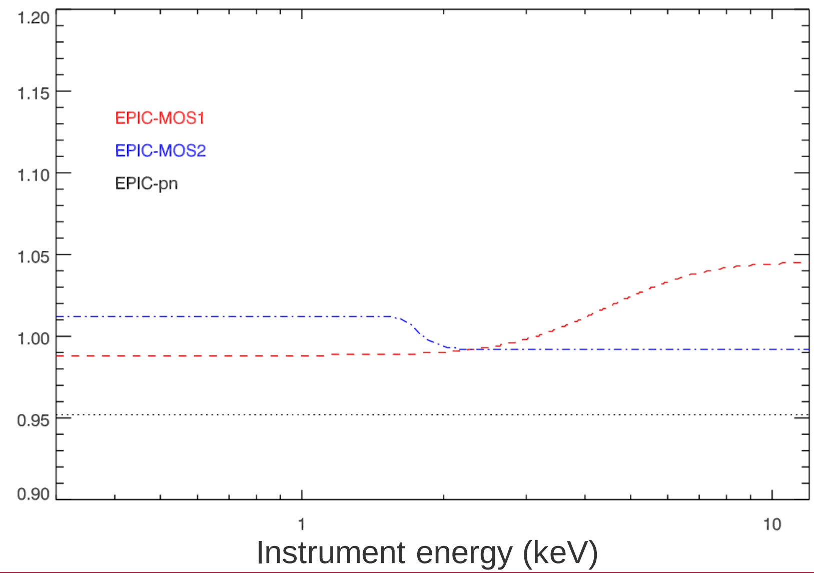
$$R_i(E) = a_i + a_{\mathrm{pn}} + b_i \times \mathrm{e}^{-c_i \times \mathrm{e}^{-d_i \times E}}$$

R_i: MOS to pn empirical correction factor
i: MOS indices (1, 2)
E: energy
$a \dots d$: best fit parameters

reproduced:

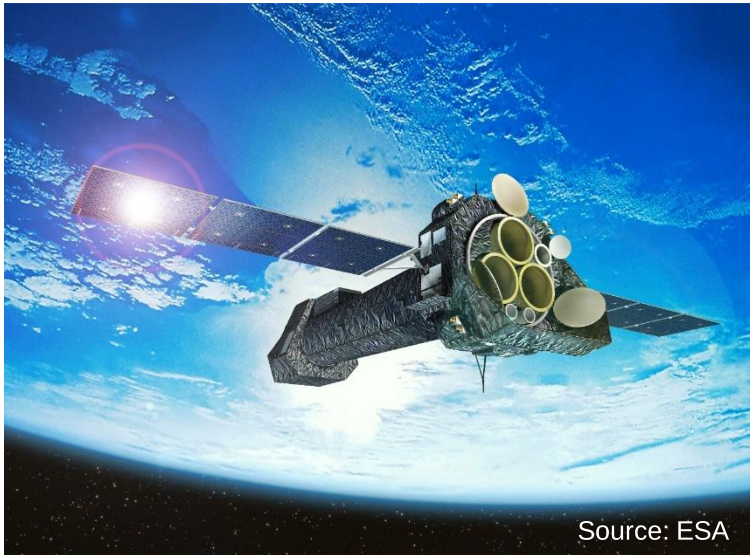


RN 0321:



Source: Guainazzi et al. (2014)

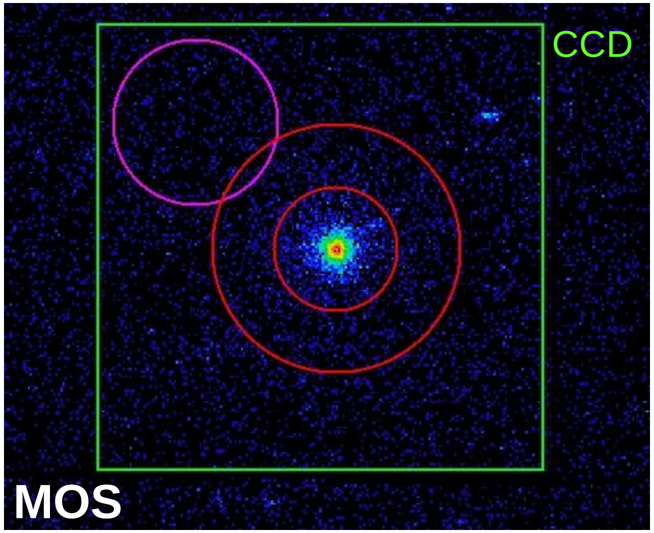
Outline

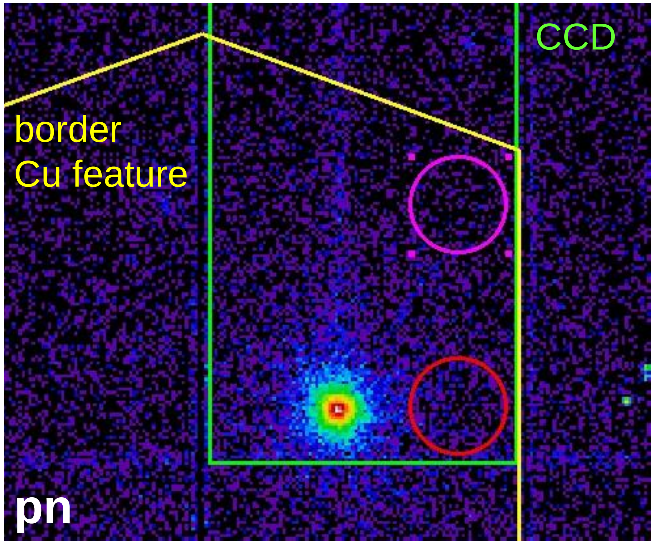


- so far: annulus (90-180“) around the source taken as background
- some observations excluded due to the uniform region selection
- problem with the pn-background:
  - spatially inhomogeneous **Cu-feature**
  - chip gaps included
  - same CCD & RAWY position as for source region preferred

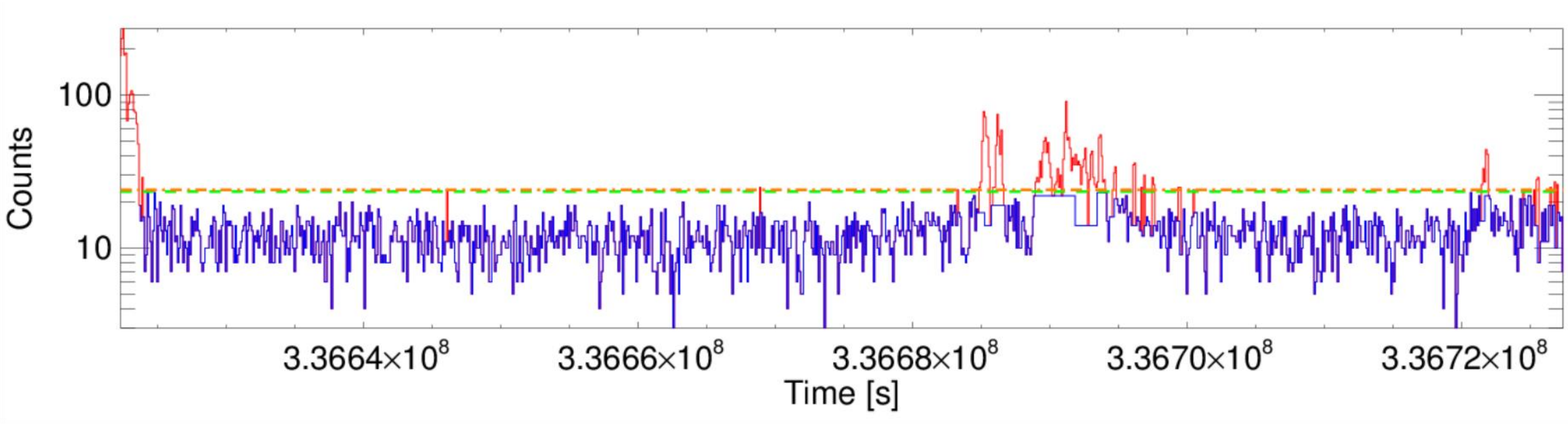
→ new background region selection
red: first choice background
magenta: second choice background

→ one observation excluded:
source too close to the Cu feature region (now 45 observations)





- so far: GTIs uniformly defined as those bins containing less than 130 (pn) or 40 (MOS) counts per bin
- a method to define GTIs individually for each observation wanted:
  1. lightcurves with > 10 keV (MOS) or 10-12 keV (pn) are prepared
  2. a histogramm is created and a gaussian applied: **gaussian threshold** set at three times the standard deviation above mean ($\mu + 3\sigma$)
  3. the maximum signal-to-noise ratio (snr) provides the **snr threshold**
  4. the more conservative one of the thresholds is chosen



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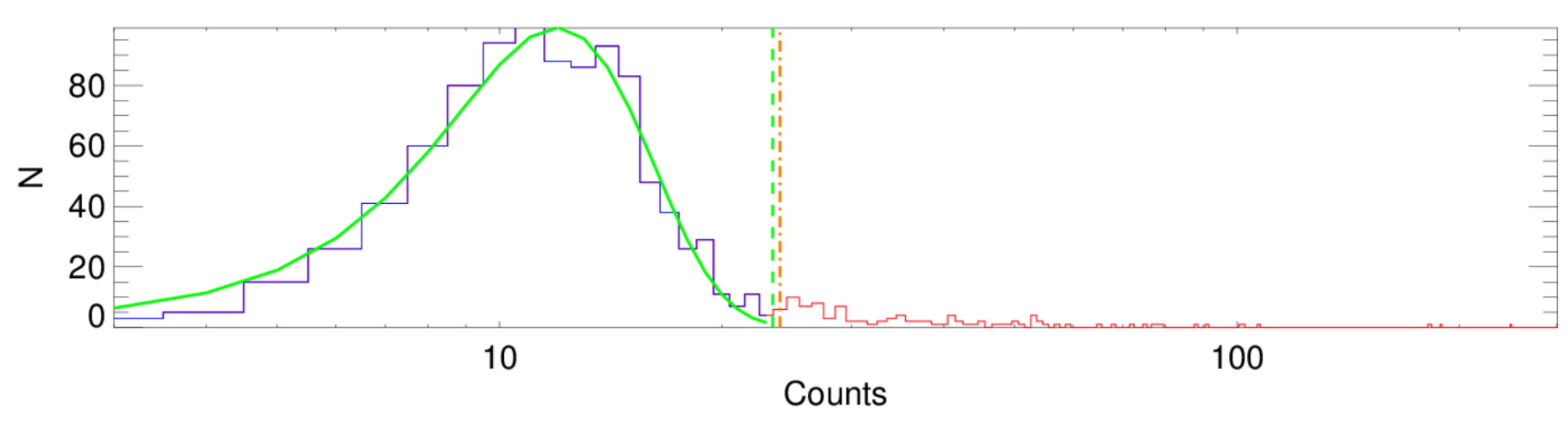
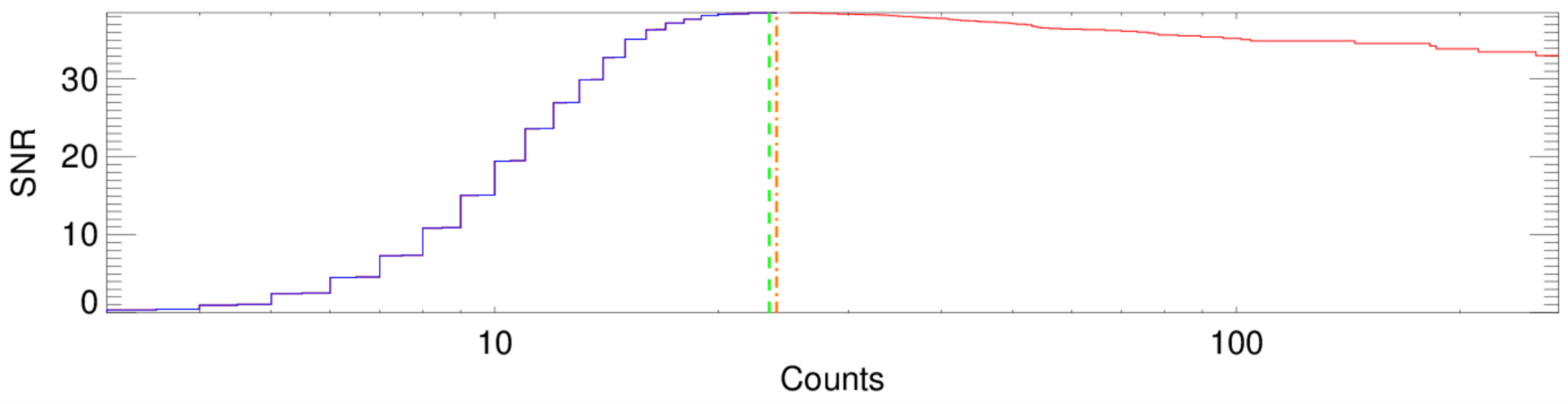


3 Recalibration

3.2 Good-Time-Intervals

- so far: GTIs uniformly defined as those bins containing less than 130 (pn) or 40 (MOS) counts per bin
- a method to define GTIs individually for each observation wanted:

1. lightcurves with > 10 keV (MOS) or 10-12 keV (pn) are prepared
2. a histogramm is created and a gaussian applied: **gaussian threshold** set at three times the standard deviation above mean ($\mu + 3\sigma$)
3. the maximum signal-to-noise ratio (snr) provides the **snr threshold**
4. the more conservative one of the thresholds is chosen

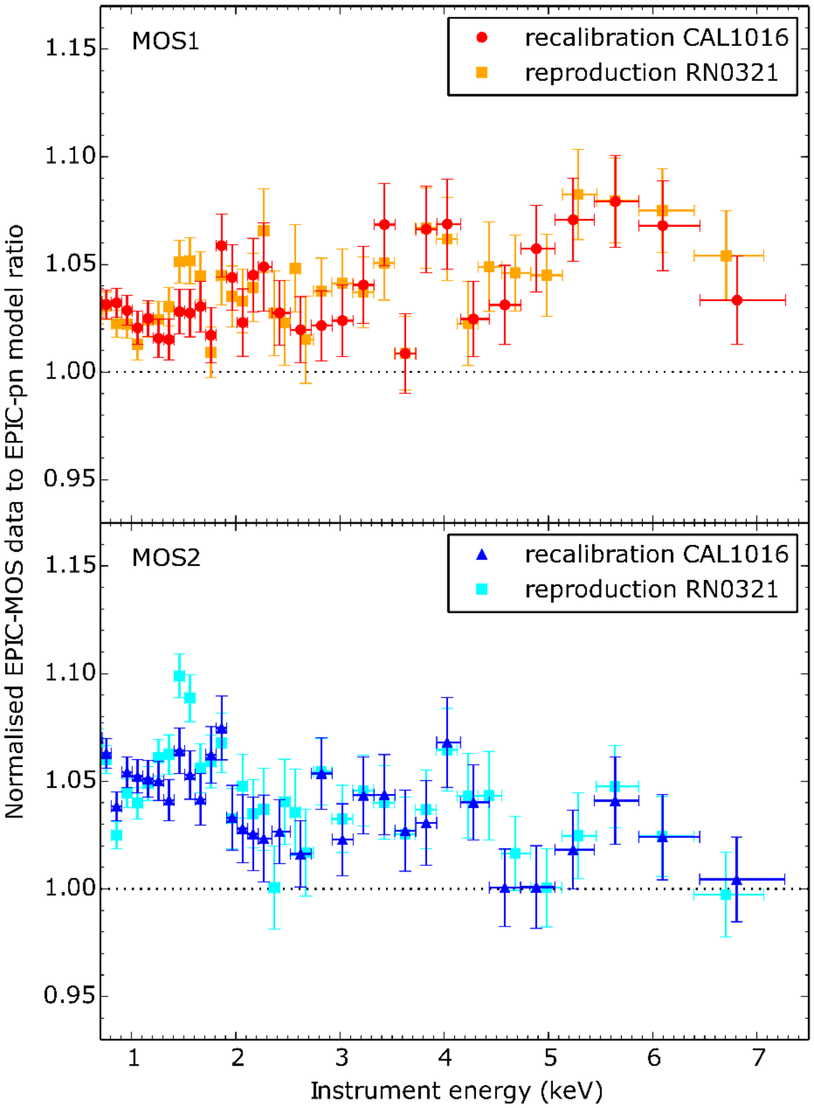


3 Recalibration

3.3 First New Fit

recalibration with

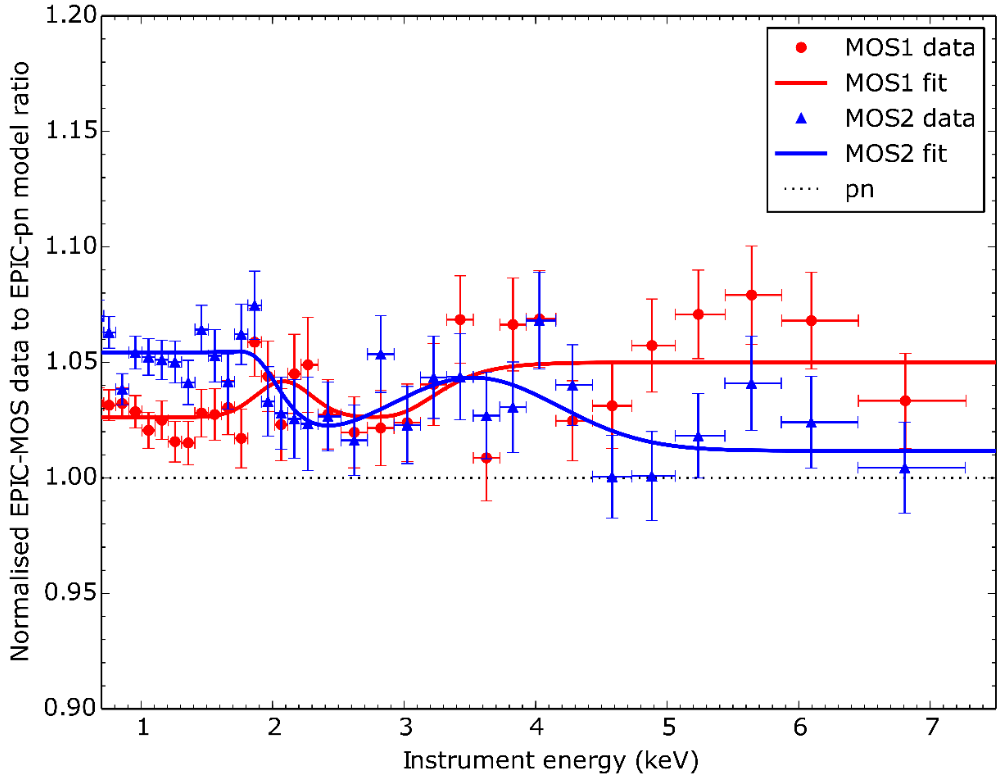
- SAS v15.1
- the calibration files public in October 2016
- 45 of the original sources
- new background regions (source regions still 40“)
- individual GTIs



3 Recalibration

3.3 First New Fit

$$R_i(E) = a_i + a_{\mathrm{pn}} + b_i \times \mathrm{e}^{-c_i \times \mathrm{e}^{-d_i \times E}} + f_i \times \mathrm{e}^{-\frac{1}{2}\left(\frac{E-g_i}{h_i}\right)^2}$$



R_i: MOS to pn empirical correction factor

i: MOS indices (1, 2)

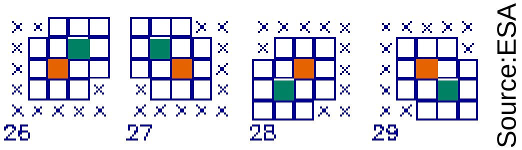
E: energy

$a \ldots d, f \ldots h$: best fit parameters

3 Recalibration

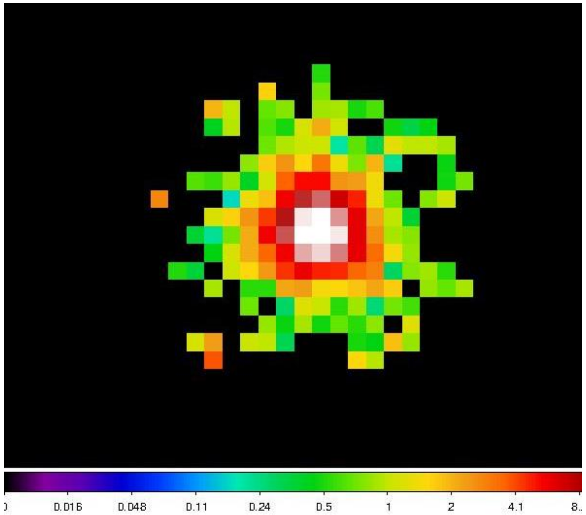
3.4 Pile-Up Check

- so far: maximum count rate (as in XMM-Newton Users Handbook v.2.10) given as a source selection criterium to limit pile-up
- more precise method: MOS diagonal events are produced almost exclusively from the pile-up of two single pixel events



→ useful to estimate the pile-up level (fraction of diagonal events)

- obtained by dividing an image of diagonal events by an image of ‘clean’ #XMMEA_EM events (excluding e.g. events near hot pixels or outside of the field of view)



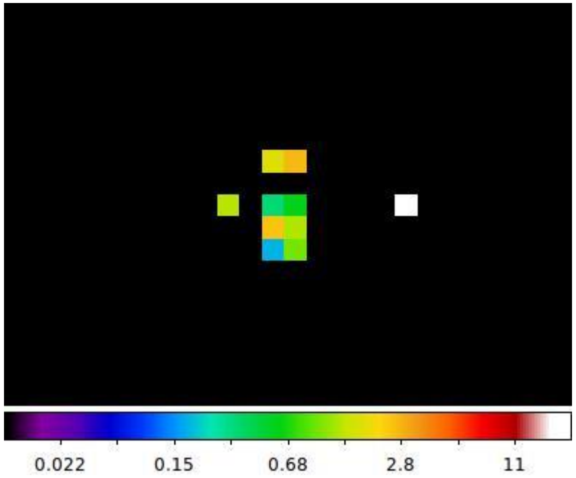
highly piled-up example: obs. 0134540601
MOS1 pile-up level > 16% (> 8 cts/s)

3 Recalibration

3.4 Pile-Up Check

- maximum value within the central region taken as the pile-up level (but there is not always a clear center; the maximum value is not necessarily in the center)

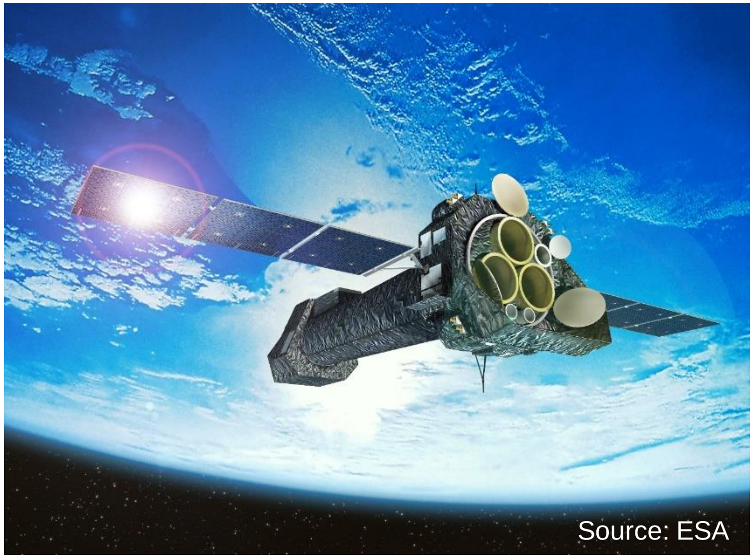
  observation 0405690201:
  MOS1 pile-up level 2.47% (~0.32 cts/s)



- excluding piled-up sources (pile-up level > 1.5) would have led to an almost empty sample with only 5 (MOS1) / 4 (MOS2) observations left

- larger sample, and particularly a larger non-piled-up sample, needed for comparing subsamples with different pile-up levels (can be achieved by including large and small window mode data)

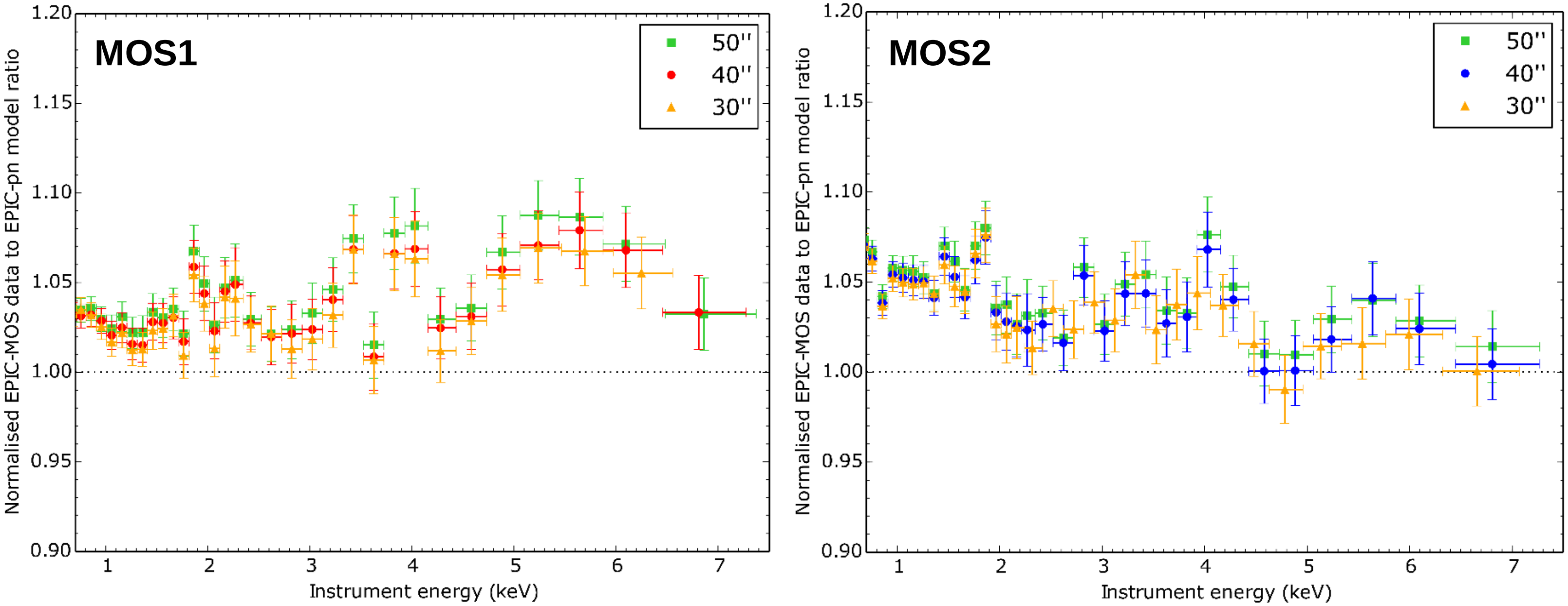
Outline



4 Validation

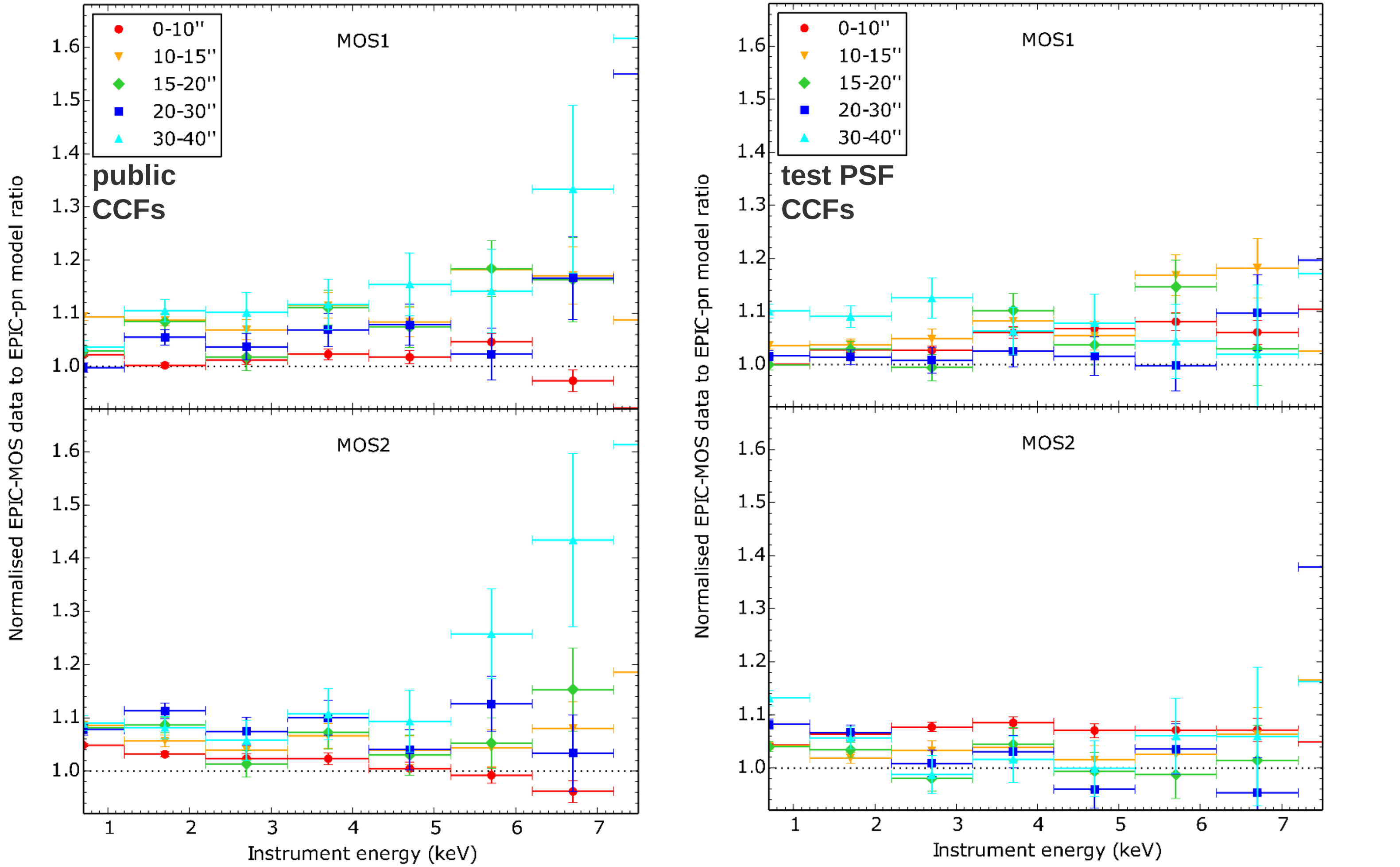
4.1 Source Region Size

- the residual ratios for source region radii of 30“, 40“ and 50“ were compared with each other
- MOS1 shows a systematic worsening of residuals towards larger radii across the complete band; MOS2 shows something similar above ~4keV
- this should be an issue of the point spread function (PSF) wings



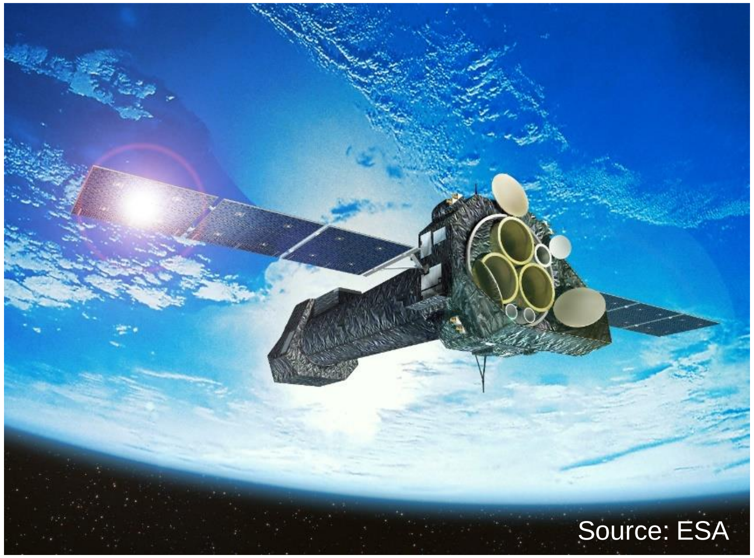
4 Validation

4.2 Nested Annuli



→ recalibrated, not yet public CCFs were tested with our tools to get an additional, independent validation

Outline



5 Outlook & Summary

- CORRAREA is intended to become a default empirical correction for the EPIC on-axis effective area in the future.
- The automation to get the residual ratio and the correction function is done to a large degree.
- The screening has been revised (GTIs, background, pile-up).
- We are close to releasing a new CORRAREA correction.
- Further recalibration and validation planned:
  - increased source sample (new XMM Serendipitous Source Catalogue 3XMM-DR6, large and small window mode data, thick filter data, pn number of counts set to 13 500)
    → up to 252 additional sources (currently subject to screening and further selection criteria)
  - compare different subsamples
  - cross calibration with instruments on other observatories
- Our tools can also be used to validate other calibration works.

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Thank you!

References:

http://www.esa.int/

http://xmmssc-www.star.le.ac.uk/Catalogue/

https://heasarc.gsfc.nasa.gov/

Guainazzi et al., 2014, XMM-Newton CCF Release Note XMM-CAL-SRN0321

Read et al., 2014, Cross-calibration of the XMM-Newton EPIC pn and MOS on-axis effective areas using 2 XMM sources

XMM-Newton Users Handbook, v.2.14