EPIC Calibration

Michael Smith, on behalf of XMM-Newton SOC and Instrument Teams
23rd XMM-Newton Users' Group Meeting, 16 May 2022

EPIC calibration recommendations from the 2021 UG

Recommendation 2020-06-08/07: The UG strongly appreciate the efforts made by the EPIC calibration team to further improve the cross-calibration of the XMM-Newton instruments and the cross-calibrate between the XMM-Newton EPIC detectors with the NUSTAR one (to resolve discrepancies between the two observatories in inferred spectral shape and normalizations). The UG strongly recommends to continue these efforts and that the final outcomes (e.g., the improved CORRAREA correction) are incorporated into SAS.

Recommendation 2020-06-08/09: The UG recommends to continue the investigations into the pn empirical RMF modelling (e.g., expand to energies >1.7 keV, include other modes, epochs, and spatial regions) and incorporate the outcome into SAS.

Recommendation 2020-06-08/10: The UG recommends to implement the spatial and temporal refinement of the pn energy scale as presented in Sanders et al. (2020, A&A 633, 42) as a calibration product.

Recommendation 2020-06-08/11: The UG recommends to continue the investigations into the off-axis flux calibration of the EPIC cameras.

Recommendation 2021-06-10/09: The UG recommends to finalize the analysis of the possibility of a column by column rate-dependent PHA correction of pn in Burst and Timing modes and publish the conclusions.

Recommendation 2021-06-10/10: The UG recommends to continue to improve the MOS redistribution and determine the impact any improvement has on the MOS-to-PN cross calibration at low energies.

Updated CORRAREA correction

Recalibration of the CORRAREA correction: an empirical correction of MOS A_{eff} to PN

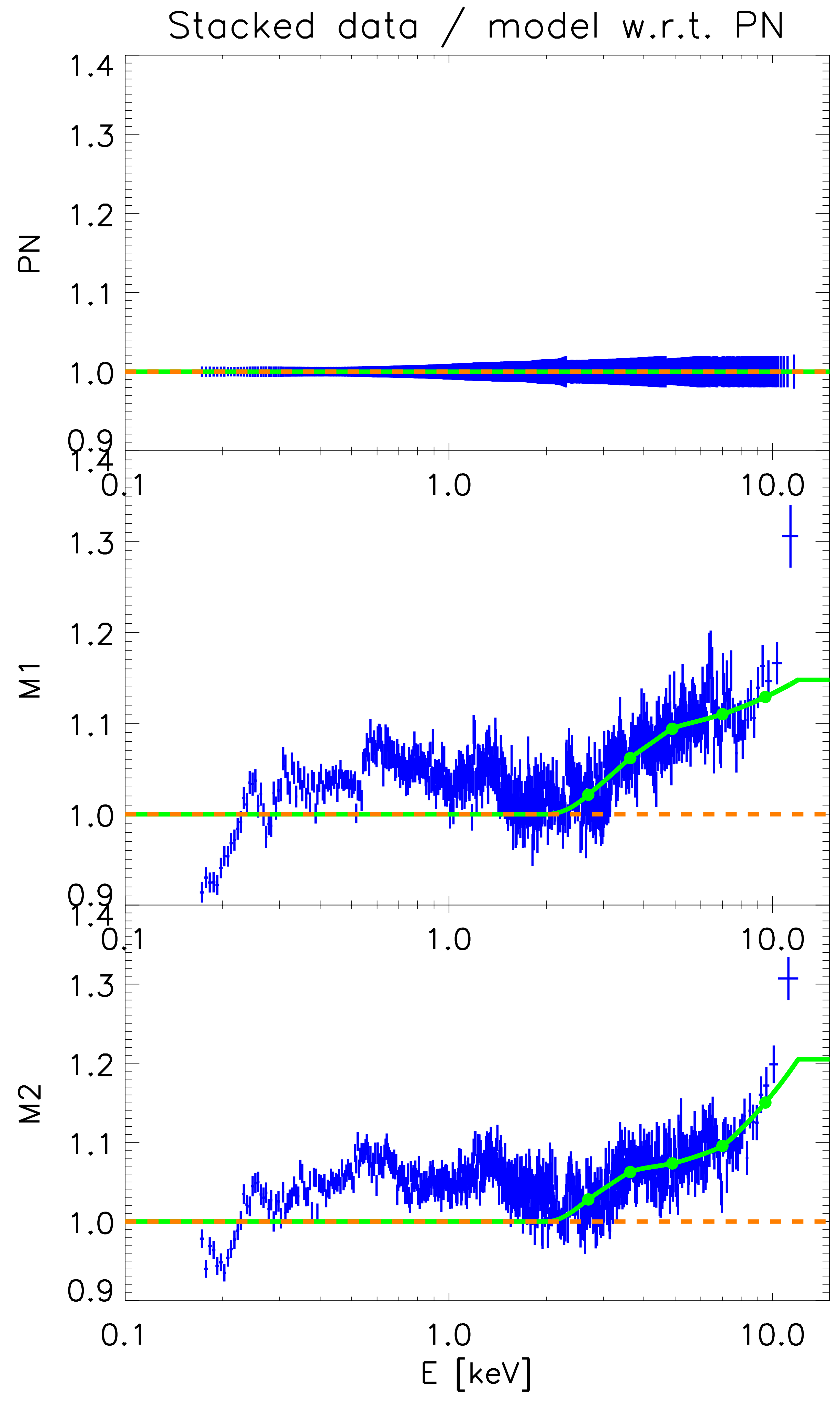
Sample of ~ 120 sources:
- On-axis, point source, non-piled up

Per observation:
- Derive best-fit PN model
- Apply PN model to MOS1 & MOS2

Per instrument, stack
- Data
- Model (= expected cts + scaled bkg)

Determine stacked data / model ratios and normalise to PN

Derive energy-dependent A_{eff} correction function (spline) to minimise residuals:
- correction to MOS A_{eff} > 2.0 keV
- null correction < 2.0 keV (where redistribution effects may be significant)



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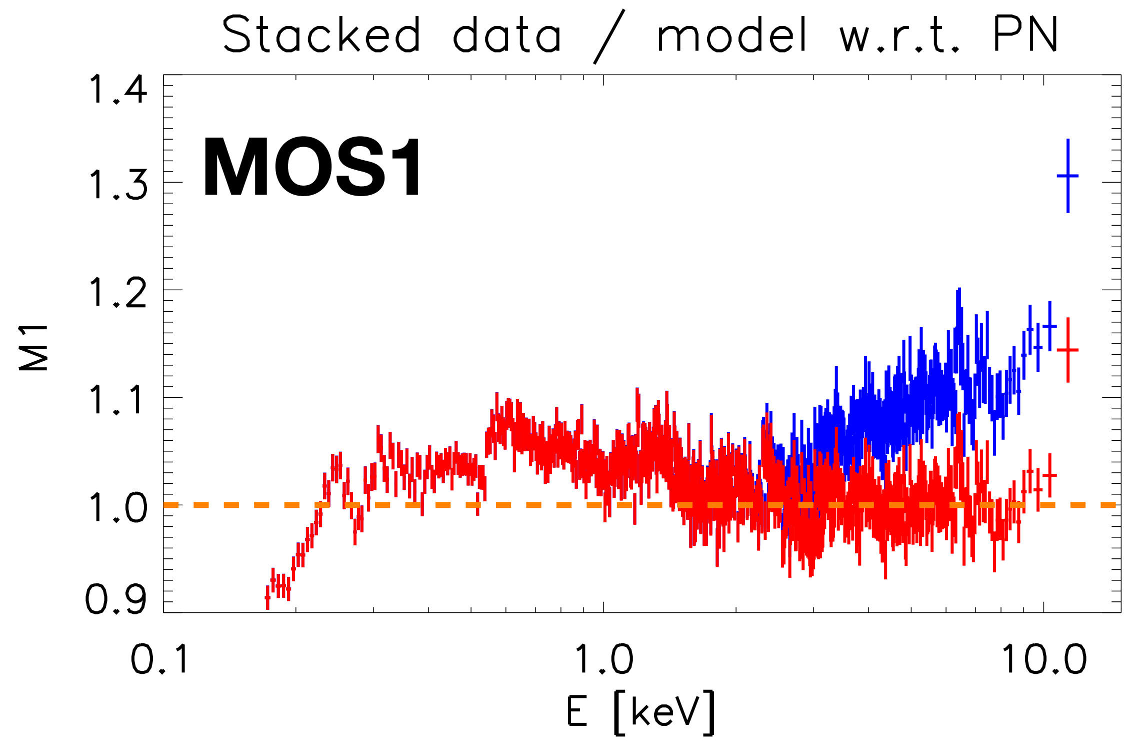
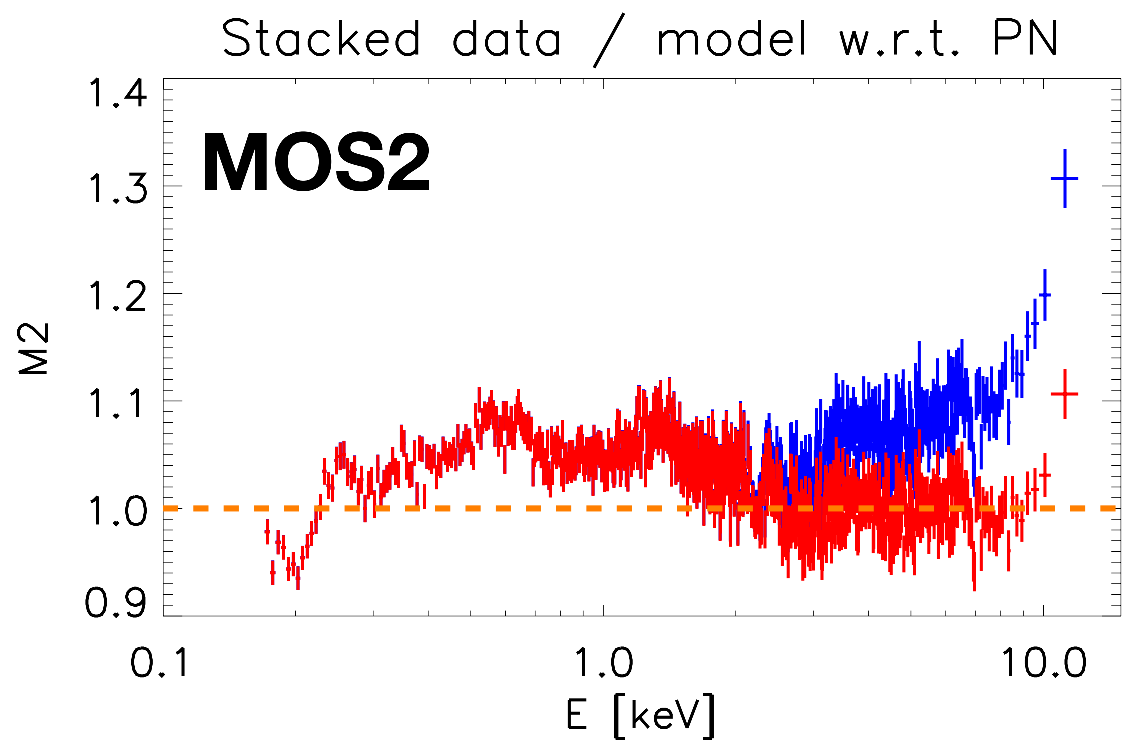
Calibration released in July 2021: RN XMM-CCF-REL-382

Must be explicitly invoked:

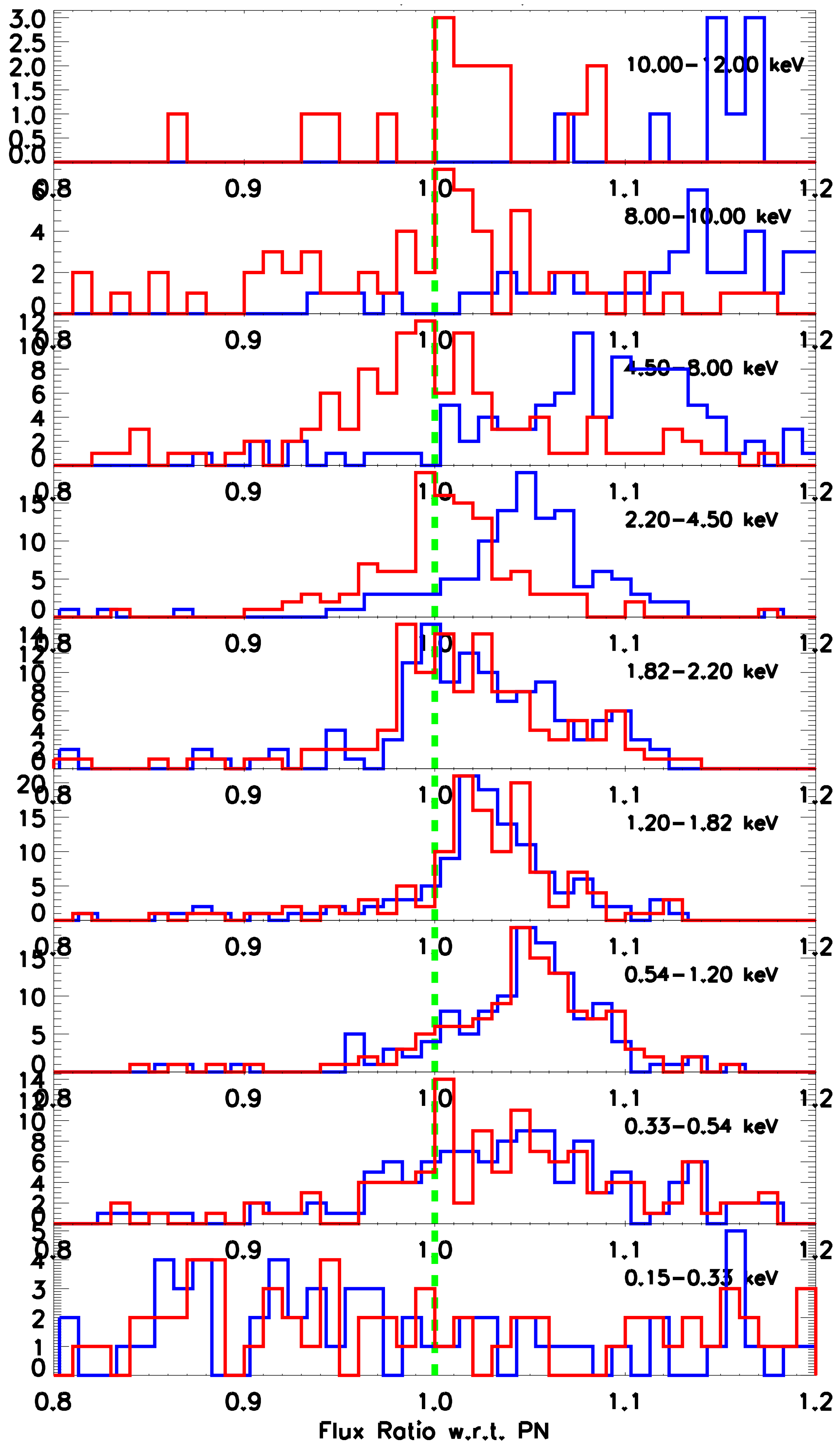
```
arfgen applyxcaladjustment=yes
```





MOS1 / PN flux ratios

before correction - after correction



E-band (keV)

10.0–12.0

8.00–10.0

4.50–8.00

2.20–4.50

1.82–2.20

1.20–1.82

0.54–1.20

0.33–0.54

0.15–0.33

Cross-calibration with NuSTAR

Empirical correction of the EPIC effective area to better reconcile EPIC-pn with NuSTAR FPMA & FPMB

See dedicated presentation by F. Fuerst

Calibration released April 2022: RN XMM-CCF-REL-388

Must be explicitly invoked (SAS 20):

```
arfgen applyabsfluxcorr=yes
```

Can be combined with CORRAREA correction, e.g.:

```
arfgen applyabsfluxcorr=yes applyxcaladjustment=yes
```

Empirical corrections which link MOS with PN, and PN with NuSTAR:

When applying these corrections the instruments cannot be considered fully independent.

Off-axis flux calibration

Calibration issues reported concerning off-axis flux calibration:
- Matteos et al., A&A 496 (2009)
- Lusso, Astron. Nachr. 340, 4 (2019)

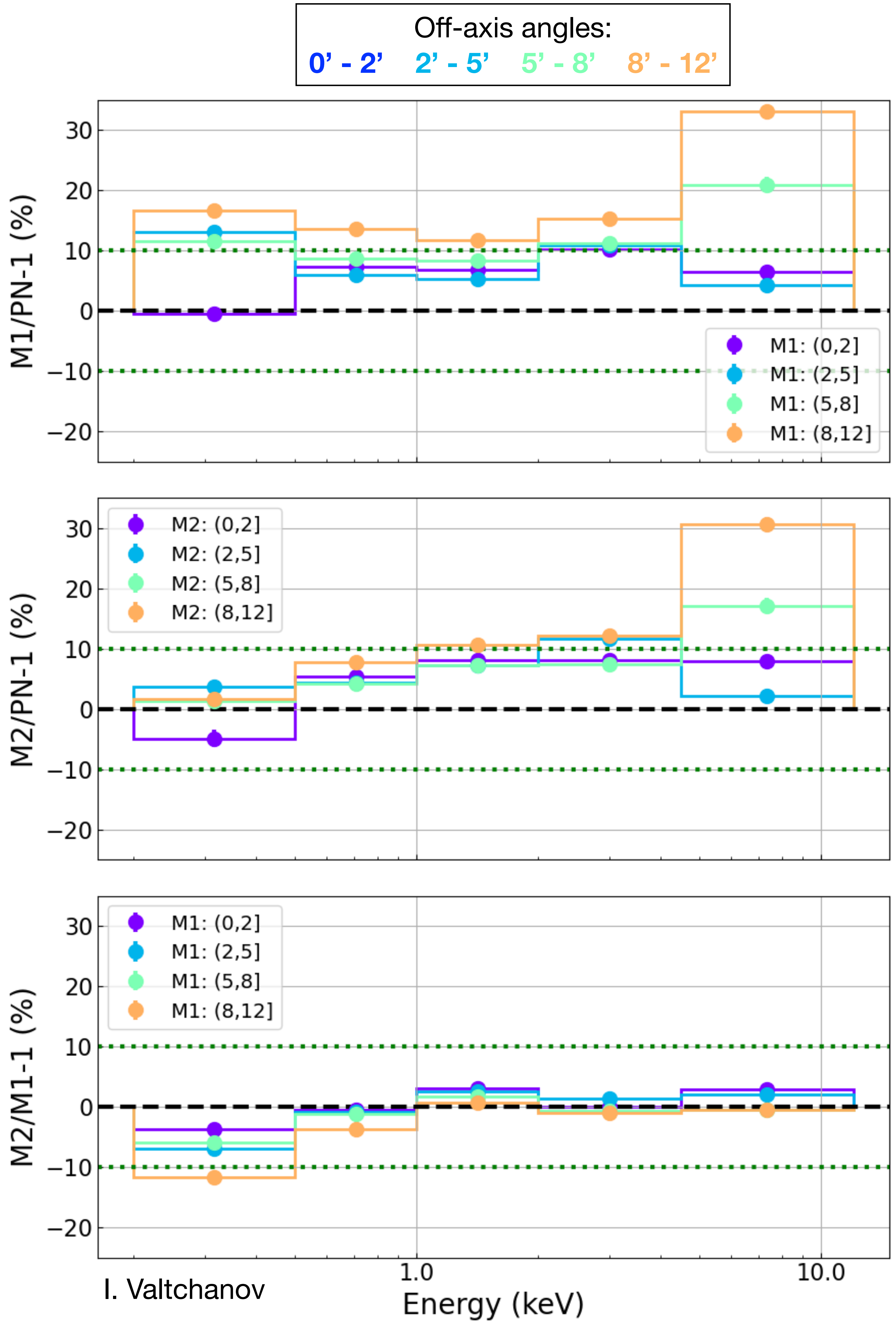
Analysis based on 2XMM / 3XMM EPIC flux comparisons:
- Show radial dependency of flux ratios
- Also, possible azimuthal dependency

Results were reproduced with 4XMM, however interpretation not straightforward due to:
- Count rates – to – flux conversion
- Background
- Source variability

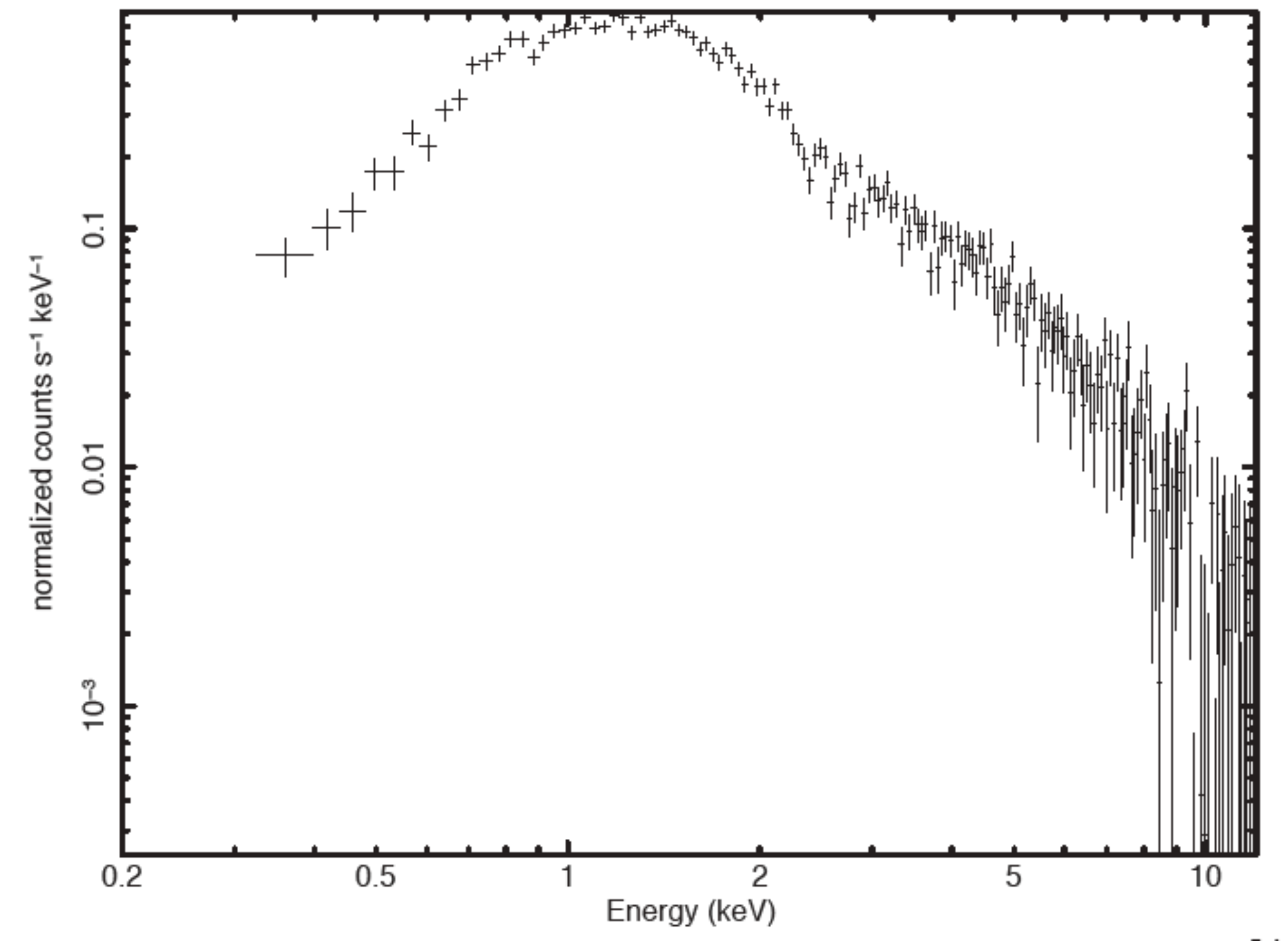
Vignetting calibration?

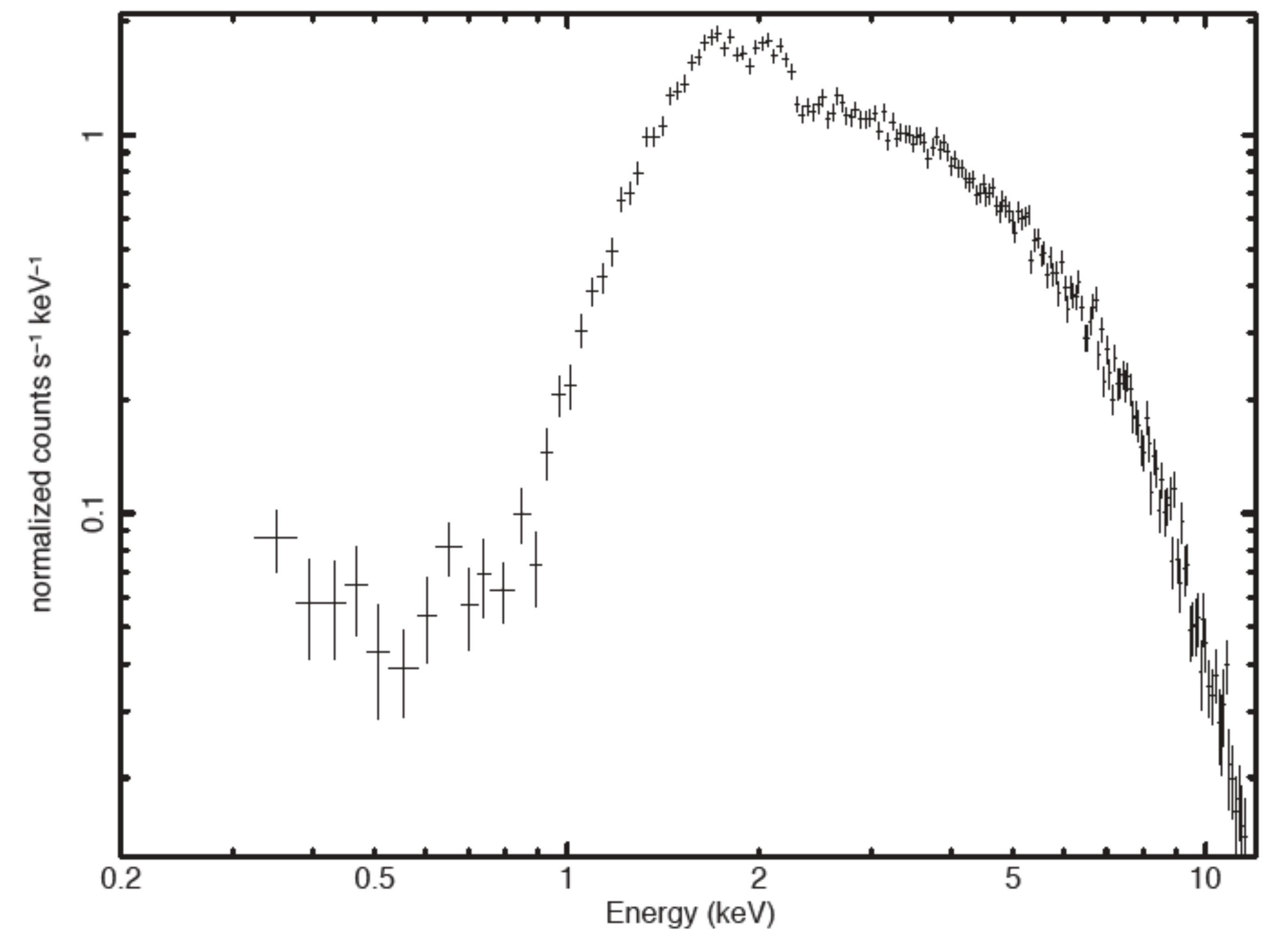
Investigation ongoing:
- Revisit archival raster scan data
- Look at individual sources

Relative flux differences v. energy



Off-axis flux calibration



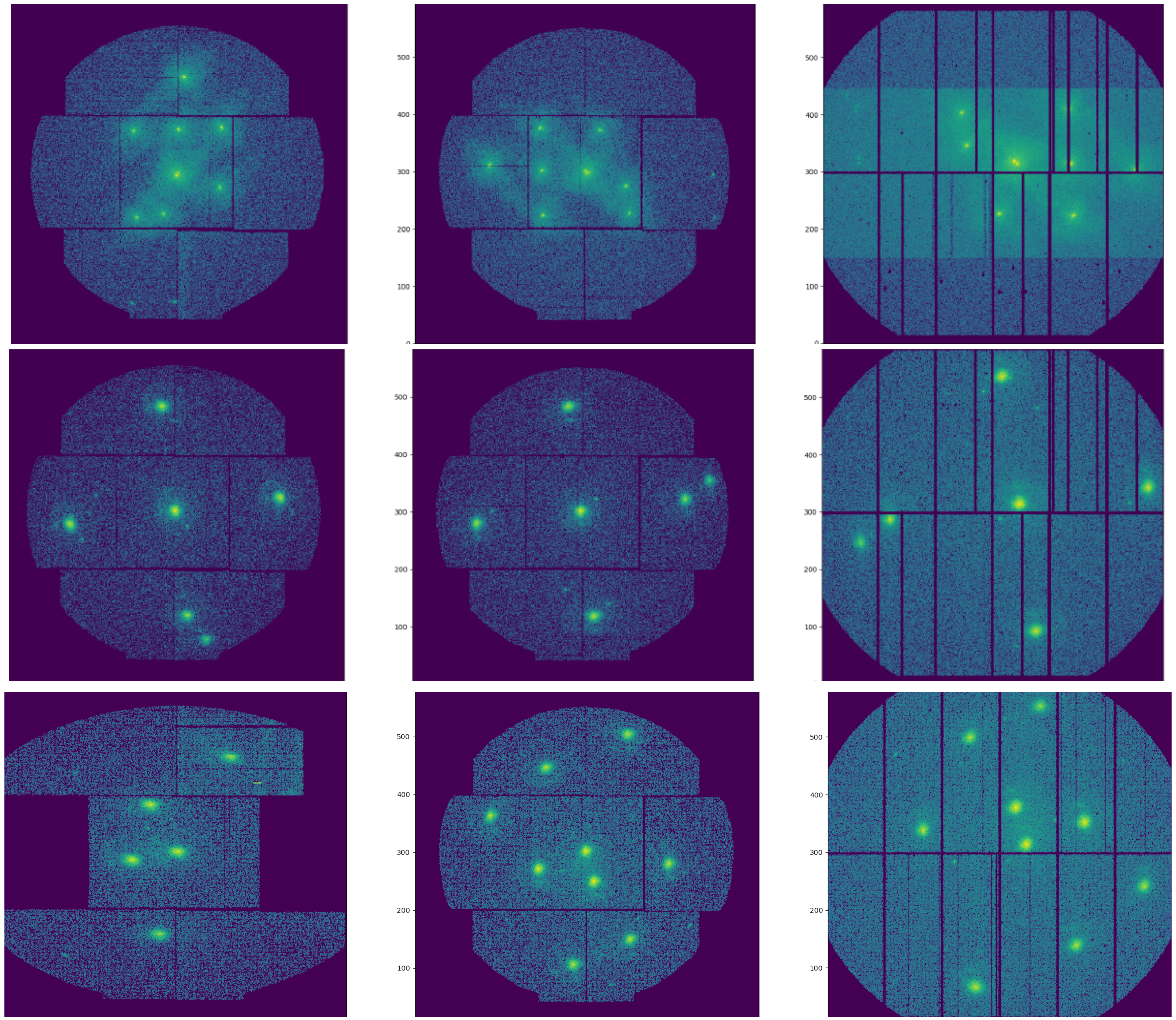


Raster scan observations (in DET coordinates)

SNR 3C58 (2000/2002)

SNR G21.5-09 (2000/2001)

SNR G21.5-09 (2021)



Off-axis flux calibration

PN:
   vignetting correction accurate
   to ~ ± 5%

MOS1:
   Low E band:
   - vignetting correction within ~ 5%;
   - 3C58 results depend on choice of
     normalising obs
   High E band:
   - larger deviations at moderate
     radial distance (esp. 3C58)

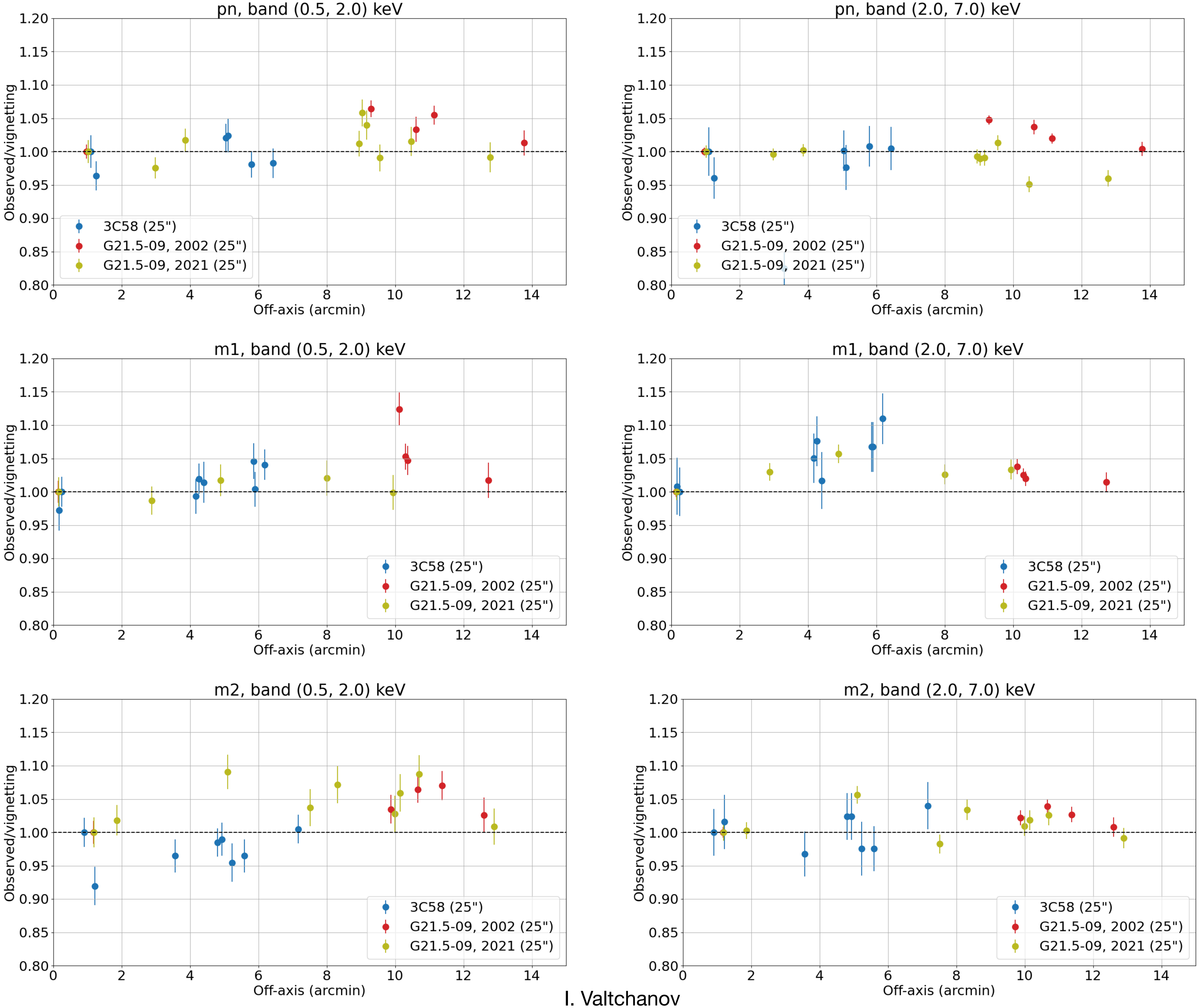
MOS2:
   3C58 and G21.5 consistency
   strongly dependent on choice of
   3C58 normalising observation (8%
   effect)

Normalised vignetting-corrected count rates

PN

MOS1

MOS2



3C58 normalised
to rev 47

I. Valtchanov

Off-axis flux calibration

PN:
vignetting correction accurate to ~ ± 5%

MOS1:
Low E band:
- vignetting correction within ~ 5%;
- 3C58 results depend on choice of normalising obs

High E band:
- larger deviations at moderate radial distance (esp. 3C58)

MOS2:
3C58 and G21.5 consistency strongly dependent on choice of 3C58 normalising observation (8% effect)

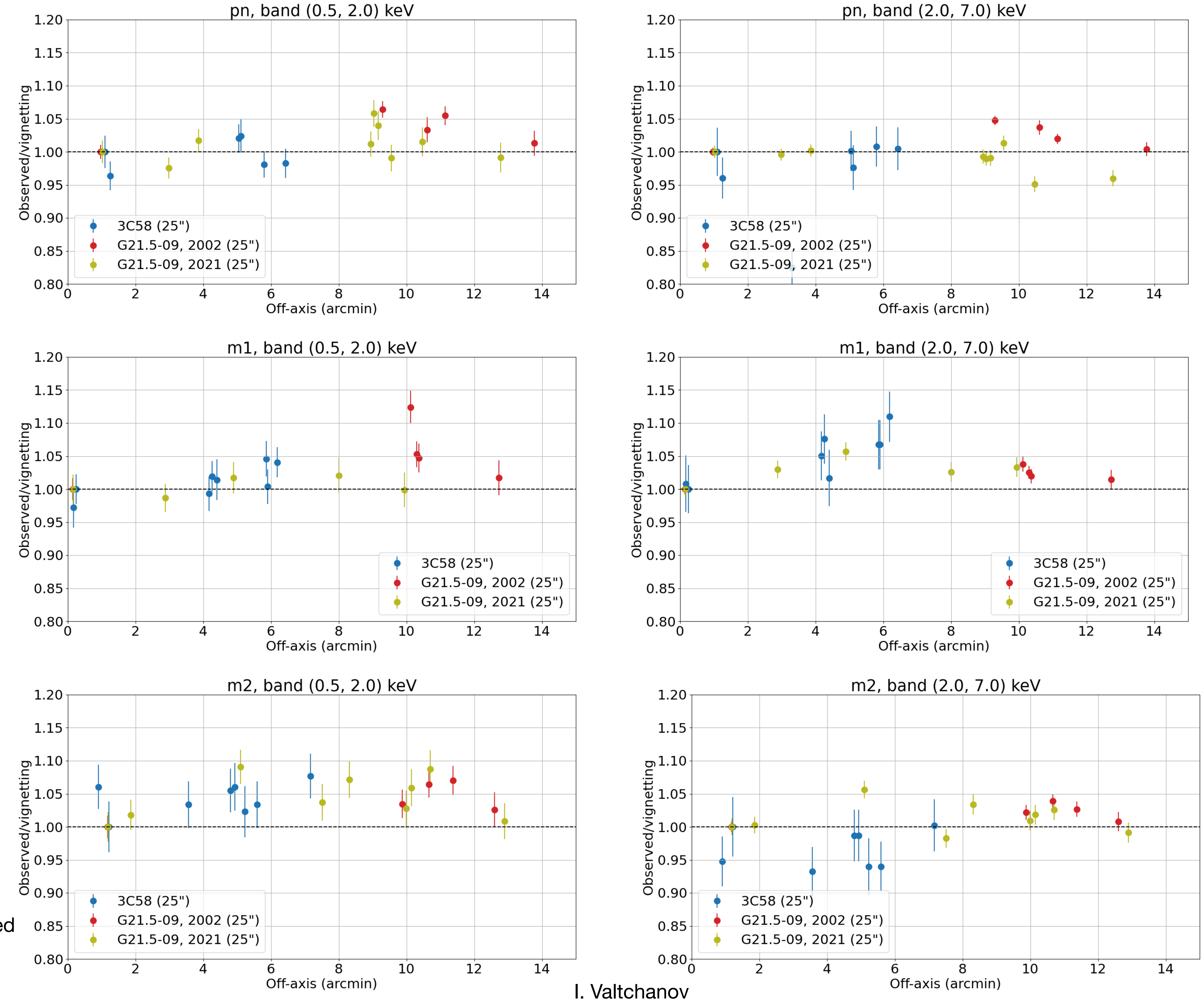
Work in progress...

Normalised vignetting-corrected count rates

PN

MOS1

MOS2



3C58 normalised to rev 506

I. Valtchanov

PN energy scale refinement

Spatial and temporal refinement of the PN energy scale (Sanders et al. A&A 633, 2020): increased accuracy to ~ 150 km/s (from ~ 550 km/s) @ Fe K

Aim is to implement this for FF and EFF modes as calibration product (in collaboration with the MPE group)

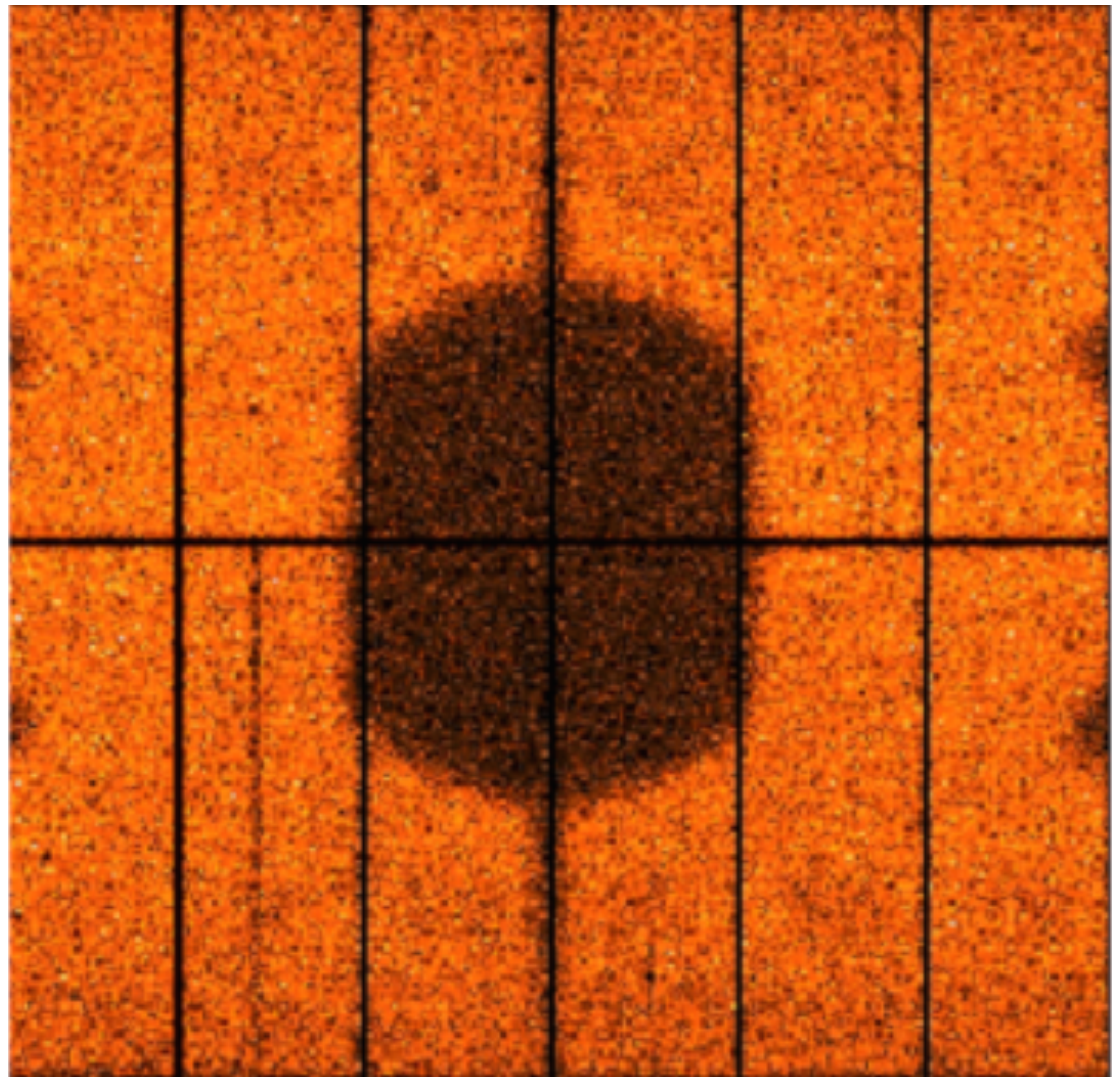
Refinement consists of three steps:

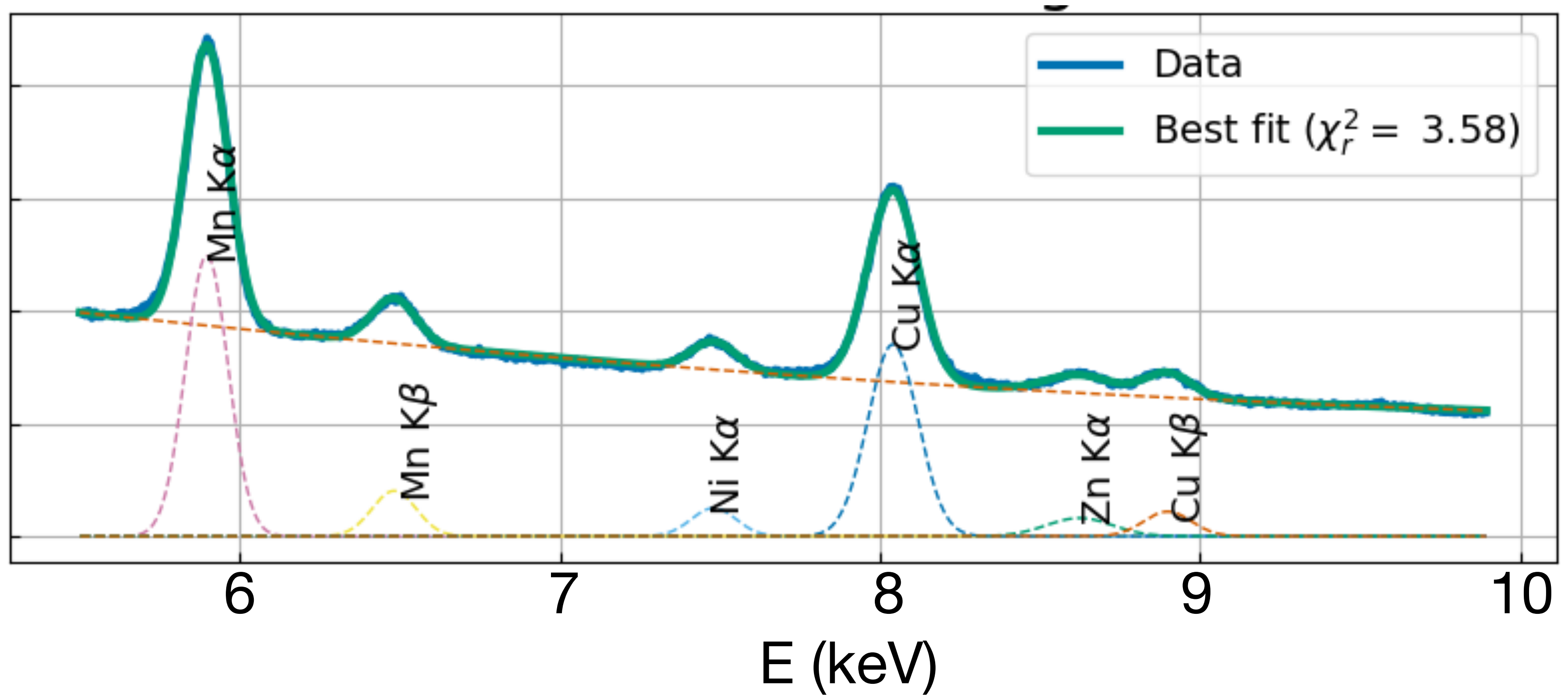
1. CCD averaged time-dependent correction at Cu Kα (8.0 keV)
2. Spatial correction (epoch dependent) at Cu Kα
3. Further energy scale refinement using additional instrumental lines (6 - 9 keV)

Cannot just “copy and paste” the Sanders et al. products:

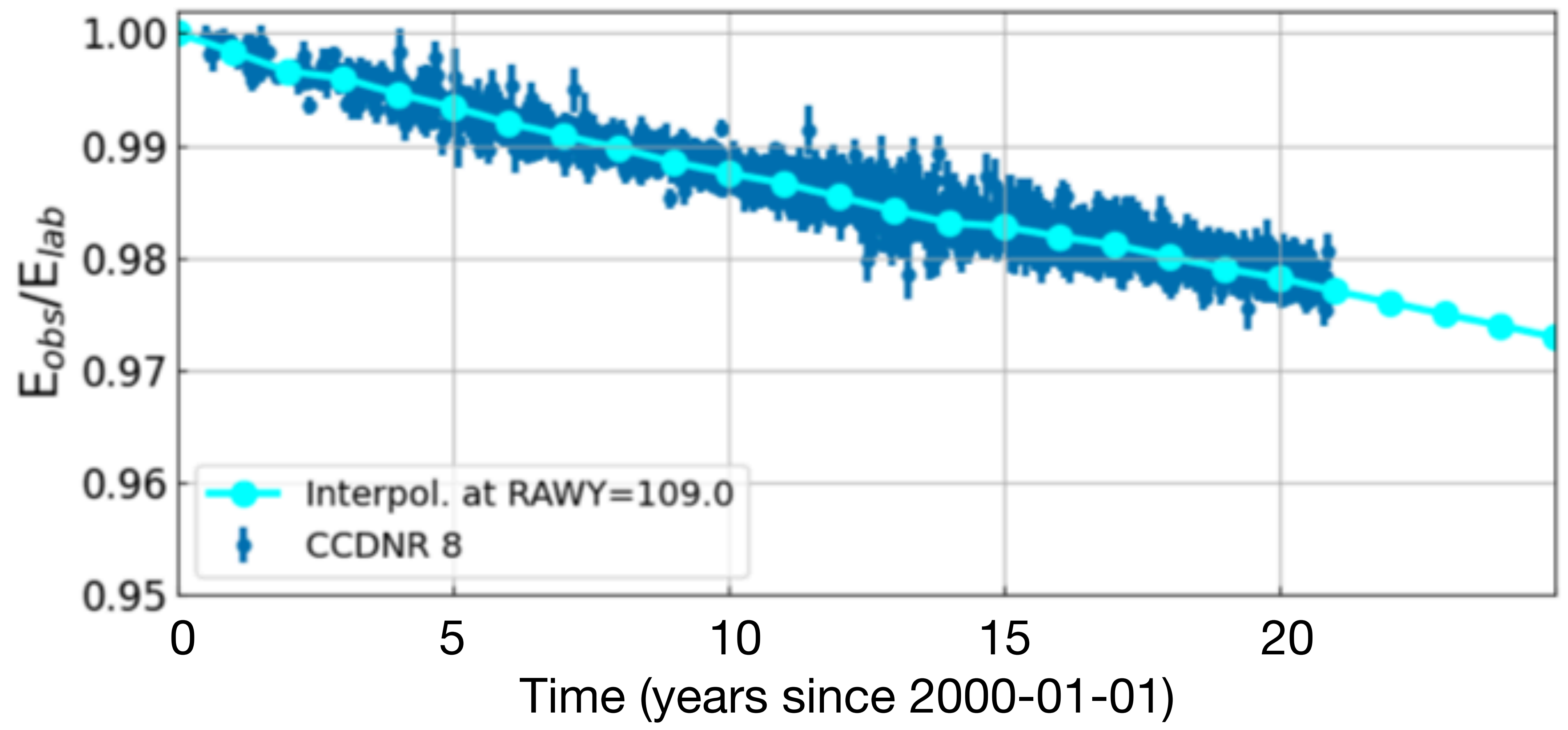
- Compatible s/w and cal products need to be created
- SOC tools to maintain calibration in view of future changes
- The Sanders method calibration needs to be aligned with current energy scale calibration

Cu Kα fluorescence emission





PN energy scale refinement



Step 1: CCD averaged time-dependent correction at Cu Kα

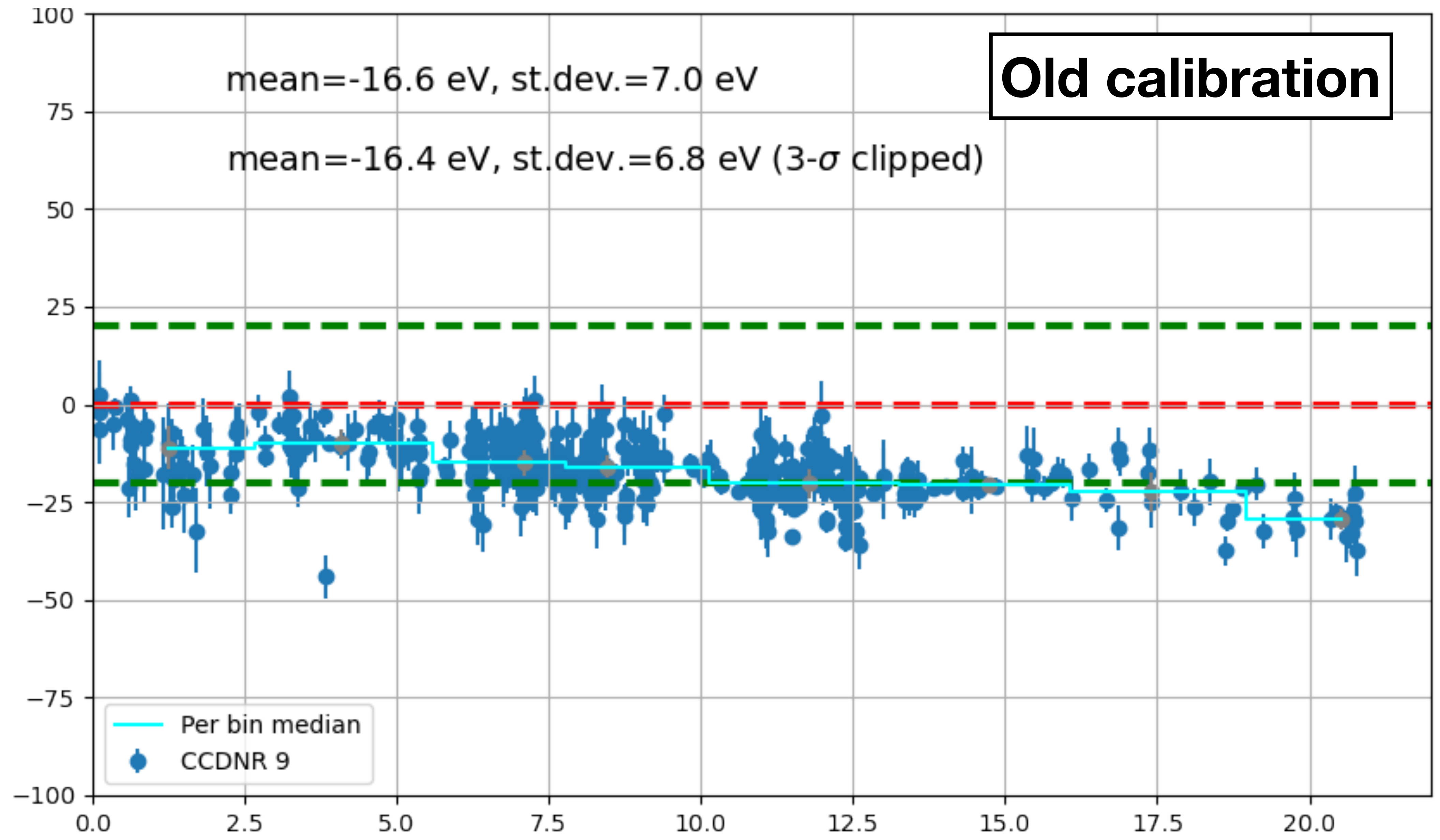
Empirically model the non-long-term-CTI corrected Cu Kα line centroids with a suitable function

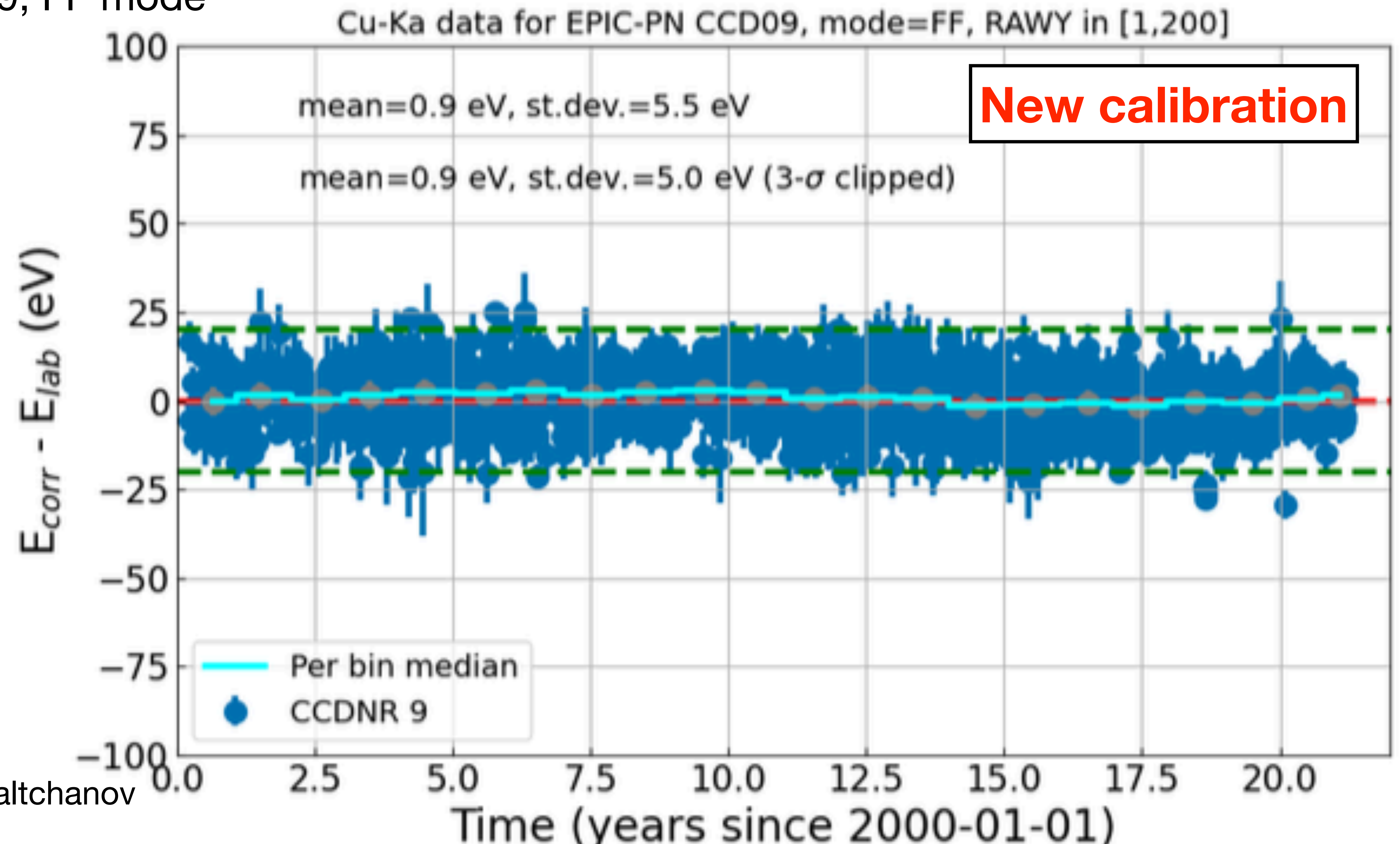
Yields an approximation of CTI(t) at Cu Kα per CCD and per mode (FF, EFF)

Include CTI(t) at Cu Kα in the calibration file
(in addition to the already existing CTI(t) at Al Kα and Mn Kα)

New calibration released March 2022: RN XMM-CCF-REL-389

Energy scale reconstruction at Cu Kα
e.g. CCD 09, FF mode





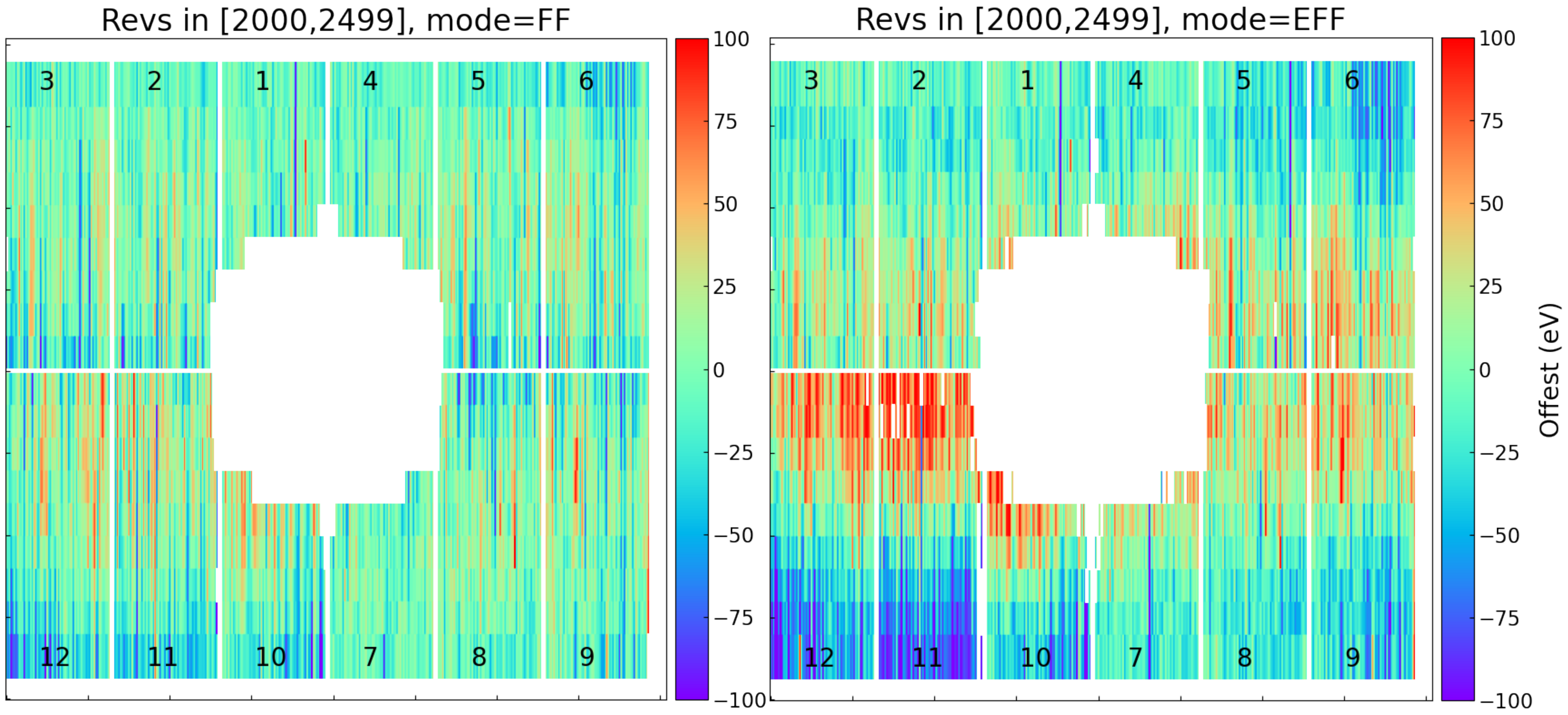
PN energy scale refinement

Step 2: Spatial correction (epoch dependent) at Cu Kα

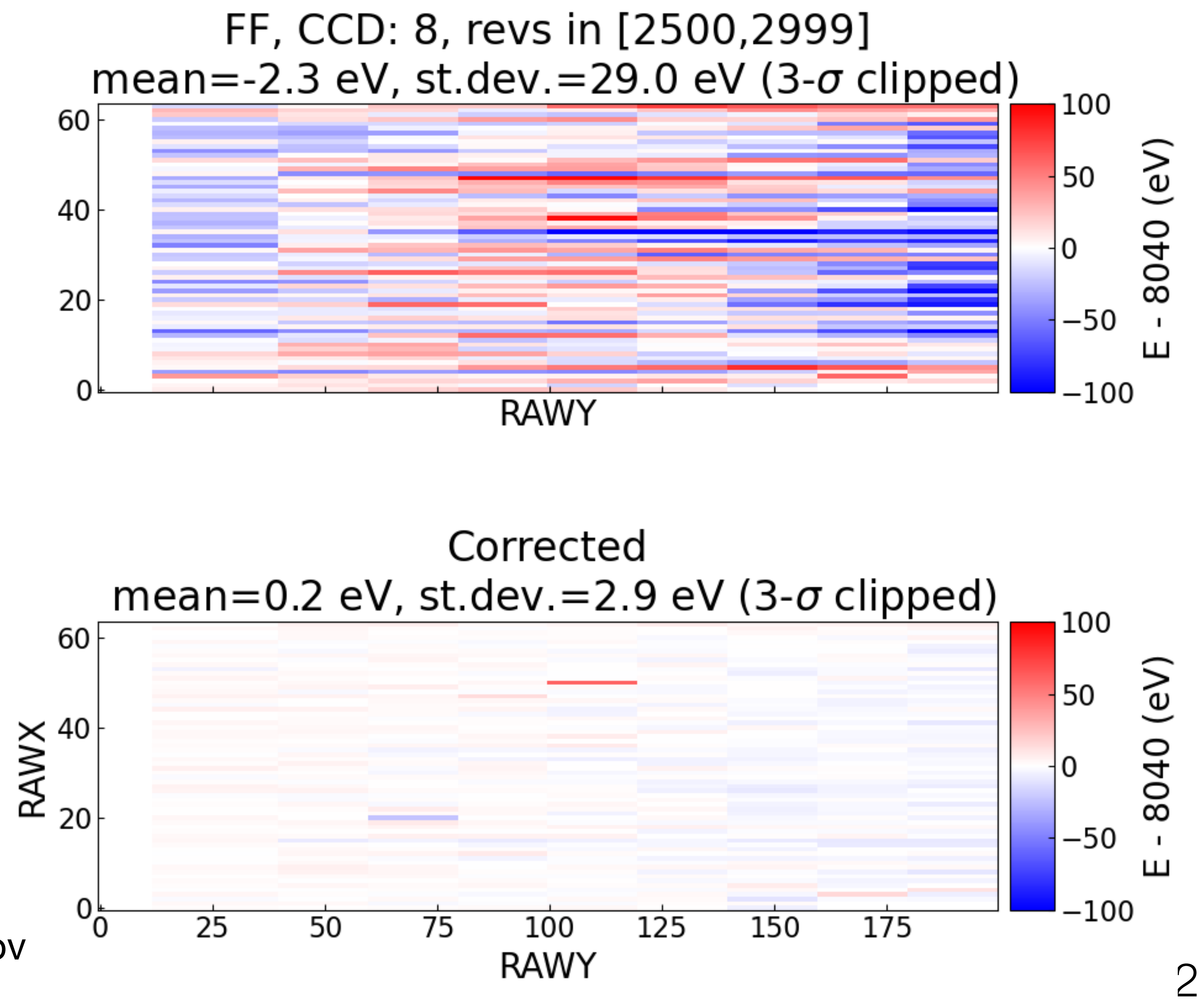
Following Sanders et al. (2020):

- Apply the per-CCD long-term CTI correction for Cu Kα
- Stack event lists in bins of 500 revolutions, with step 250 (overlap)
- For each stacked table, extract spectra for each CCD, RAWX (64) and in bins of 20 pixels on RAWY
- Fit the Cu Kα line and derive the residual the spatial offsets as function of epoch, CCDNR, RAWX and RAWY segment

Implementation of the correction requires SAS code changes (aim is for SAS 21 - 2022)



Before / after applying spatial correction:



I. Valtchanov

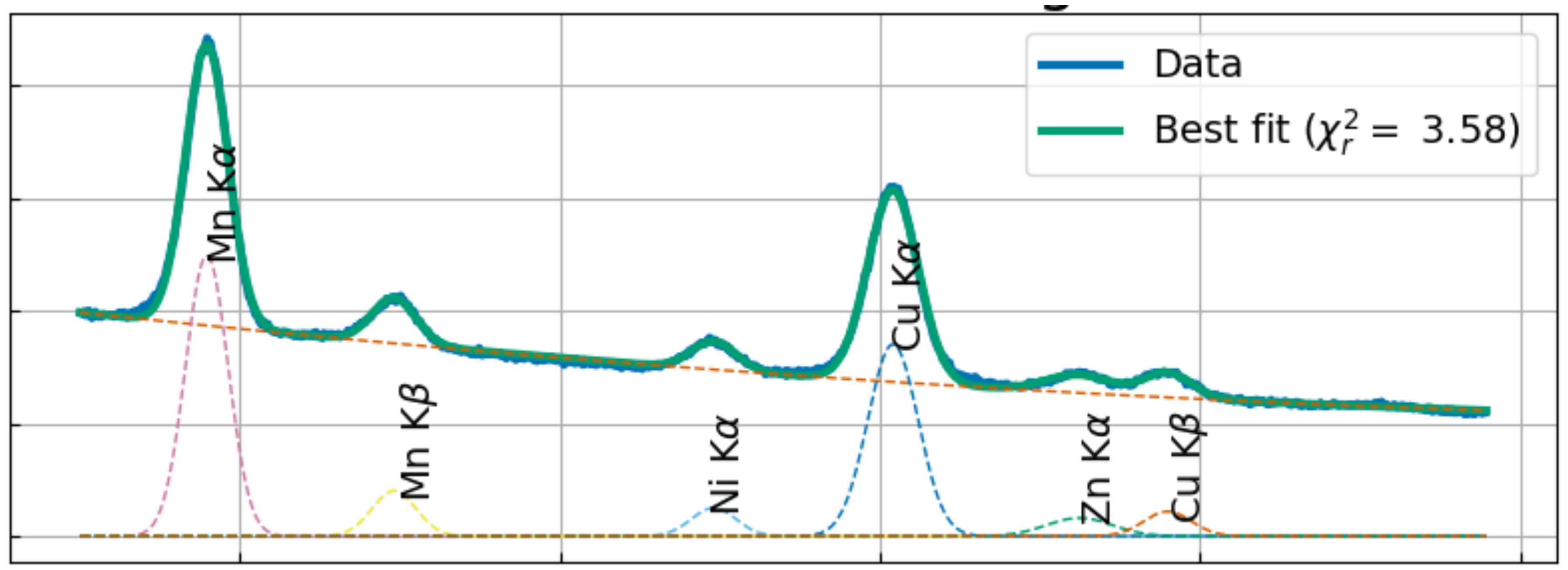
PN energy scale refinement

Further steps:

- Check if applying the spatial energy offsets derived at Cu Kα will improve the spatial energy calibration at Mn Kα (5.9 keV).

- Apply the spatial energy offsets to Perseus cluster (and other mosaic observations, Virgo); check if the Fe line redshifts are in agreement with reported results (Sanders et al. 2020, Gatuzz et al. 2022).

- “Step 3”: energy scale refinement in 6 — 9 keV with six line model (if needed)



Empirical PN RMF modelling

EPIC PN empirical RMF modelling (K. Dennerl, MPE):

- So far work has concentrated on low E response, for SW mode data

- Expand beyond 1.7 keV, include other modes, epochs, spatial regions

- Prototype RMF (SW mode, singles, Thin filter, epoch ~ rev 4000) has recently been provided
    - Incorporation into SAS and calibration products under investigation
    - Possible testing on suitable sources (below 1.7 keV)

Work in progress…

MOS redistribution and contamination

MOS cameras show time dependent changes in response due to

- contamination (A_{eff} change < ~ 1 keV) - up to now assuming a pure C contaminant

- spatially dependent redistribution
    - patch core: r<14”
    - patch wings: 14<r<36”
    - off-patch: r> 40”

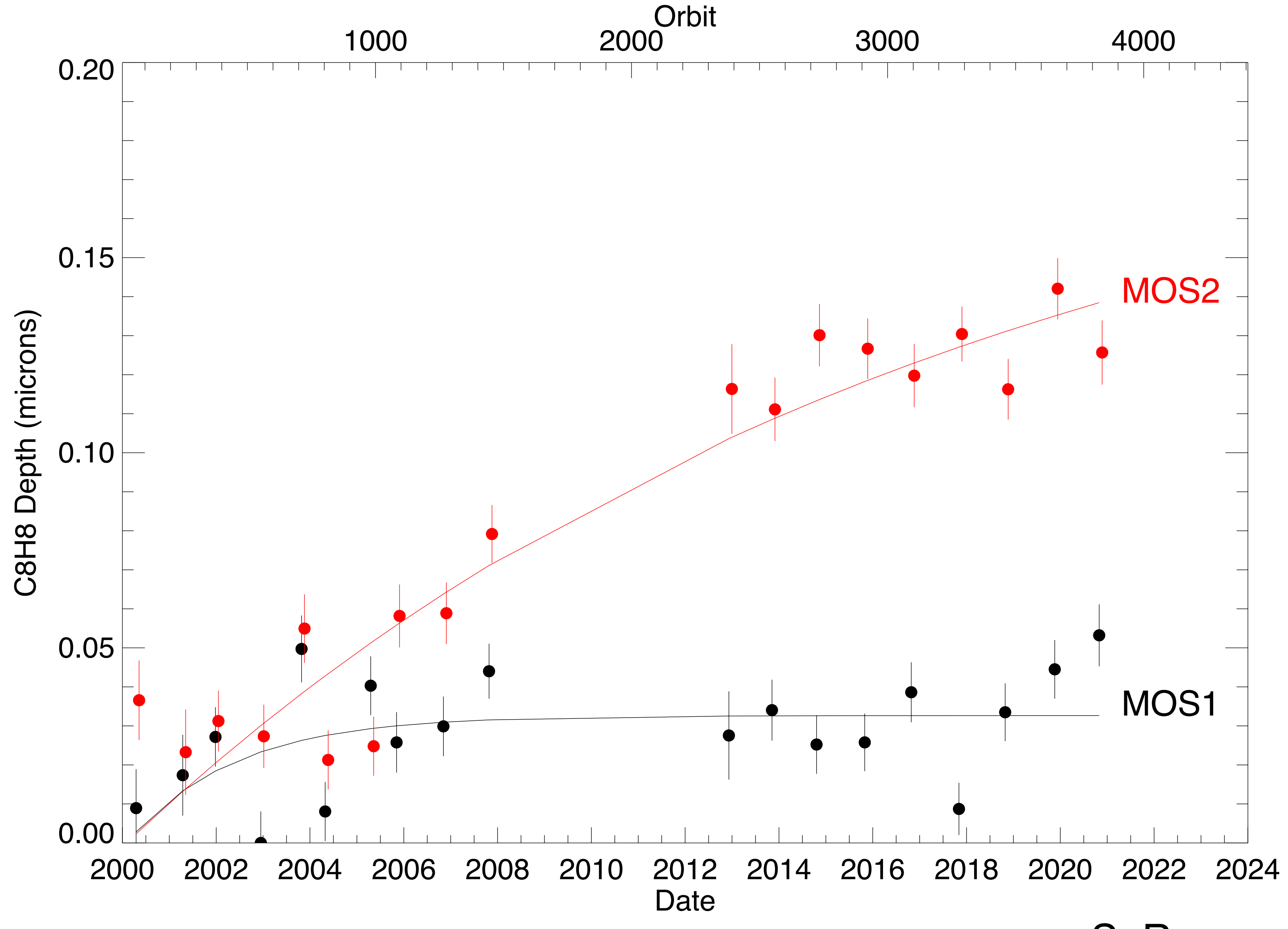
  where main photo peak “shoulder” flattens into a “shelf” in patch

Are corrected for in calibration (contaminant model; epoch & spatial dependent RMFs) but need periodic updates.

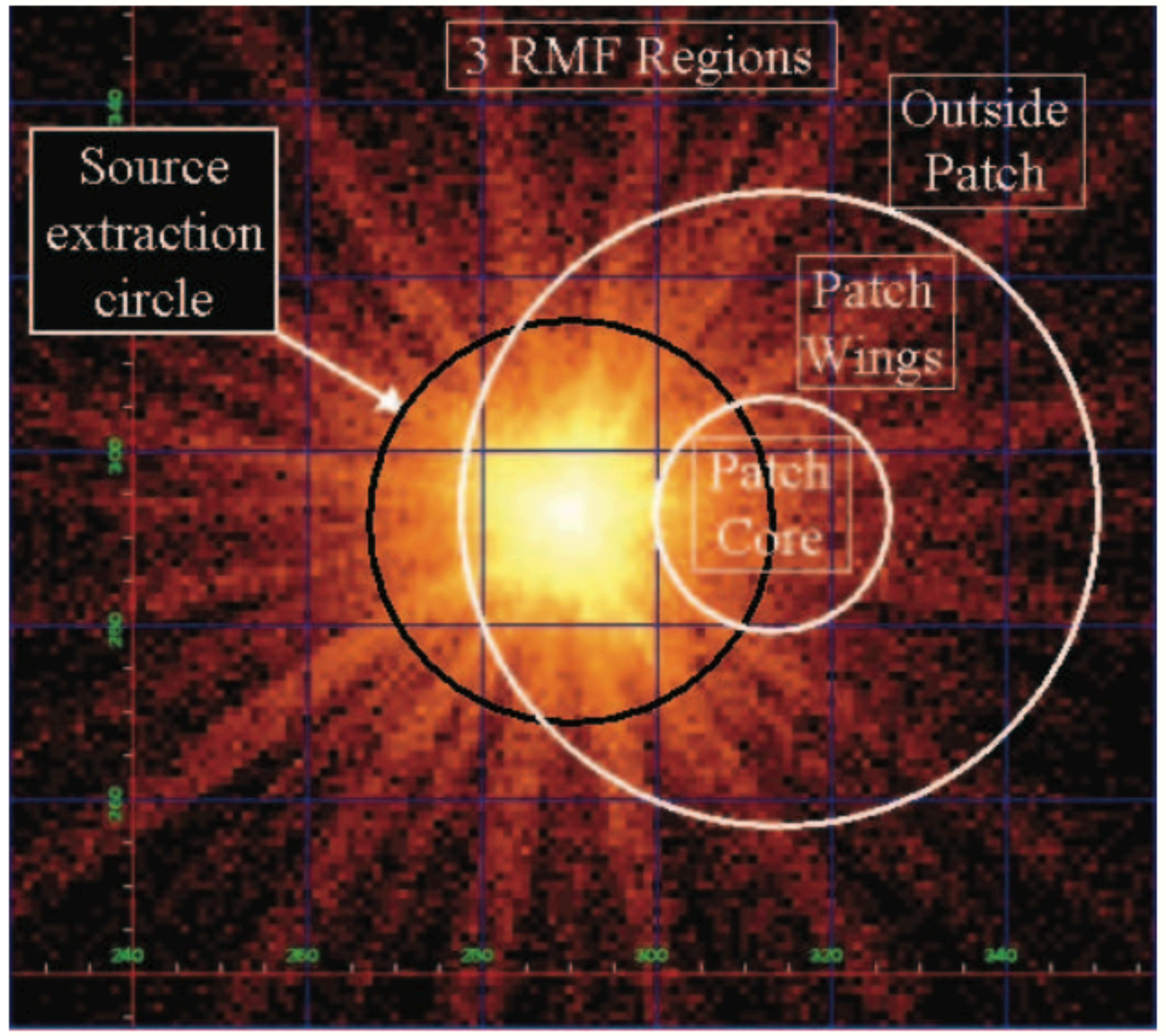
Degeneracy: a given RMF solution is dependent on the A_{eff}
1. Update contaminant model (off-patch data from SNR 1E 0102)
2. Update RMF with new A_{eff} estimate

Existing RMF + contaminant give acceptable results for previous epochs. But update for recent data is required.

Latest Carbon-based contamination analysis from 1ES0102



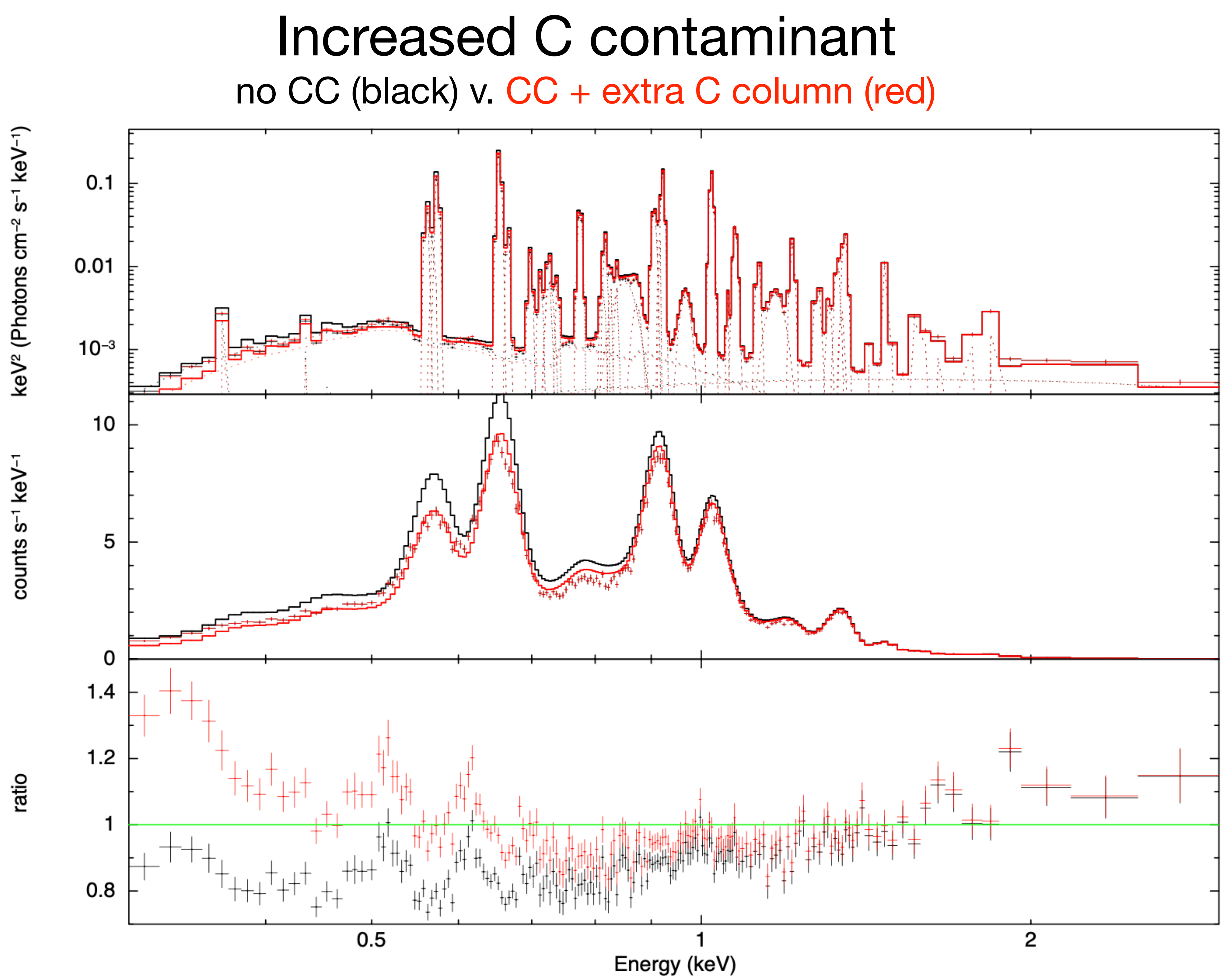
S. Rosen

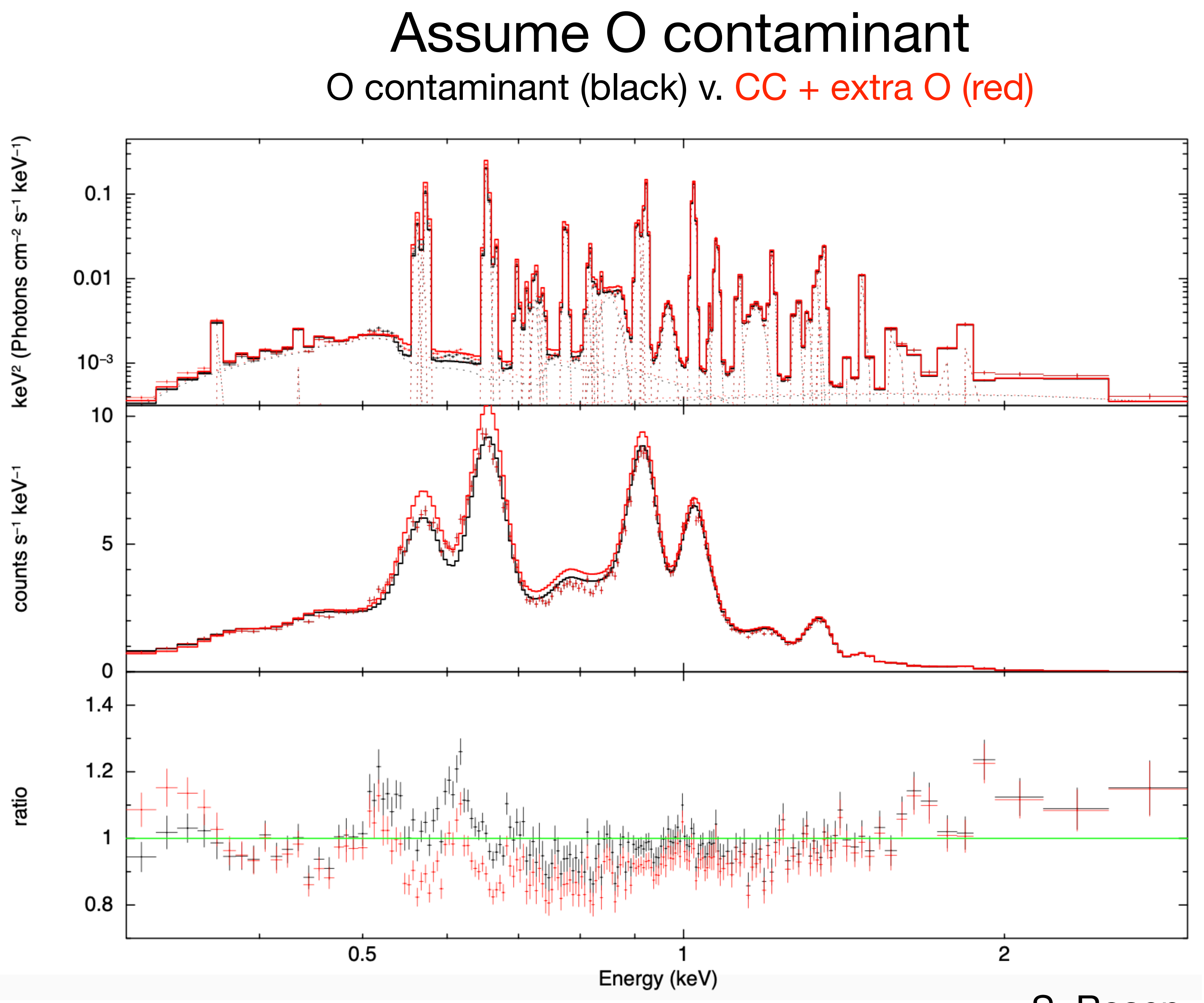


MOS redistribution and contamination

1E 0102 off-patch (rev 3652):

MOS2 low energy residuals reduced if contaminant assumed to be Oxygen-dominated instead of Carbon.





S. Rosen

However, other calibration sources yield confusing/conflicting results.

- RX J1856: clearly needs a C contaminant, not O
- N132D: MOS2 hints at Carbon-based contaminant
  MOS1 better with Oxygen (but, MOS1 contamination << MOS2).

Current plan:

- update contamination based on previous carbon contaminant model (also for consistency with previous epochs)
- update the RMF for latest epoch - check whether this yields consistent results

Per-column rate-dependent PHA correction

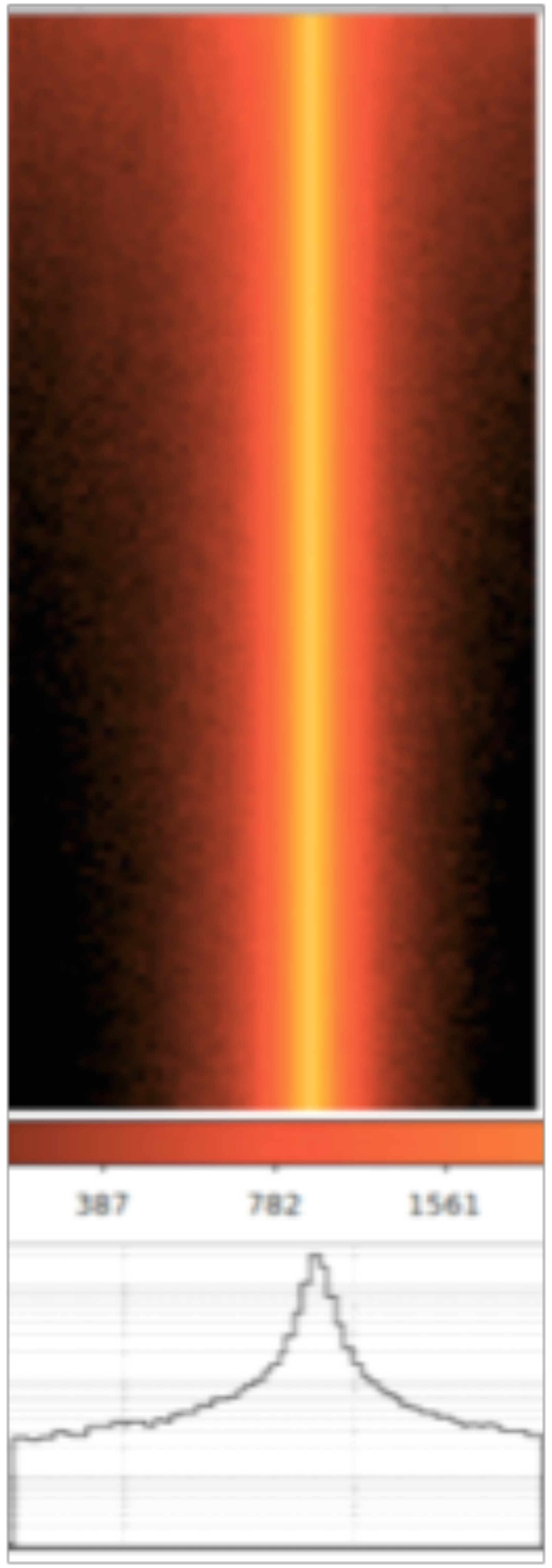
PN Timing and Burst mode energy scale shows a dependency on rate of shifted charge

- Corrected through the RDPHA correction
- Calibrated at the Si K, Au M and Au L-edges
- Timing mode RDPHA correction already available since 2013 (updated in 2019)
- Burst mode RDPHA implemented in SAS 19 (Nov 2020)

Current RDPHA implementation uses a global rate of shifted charge.

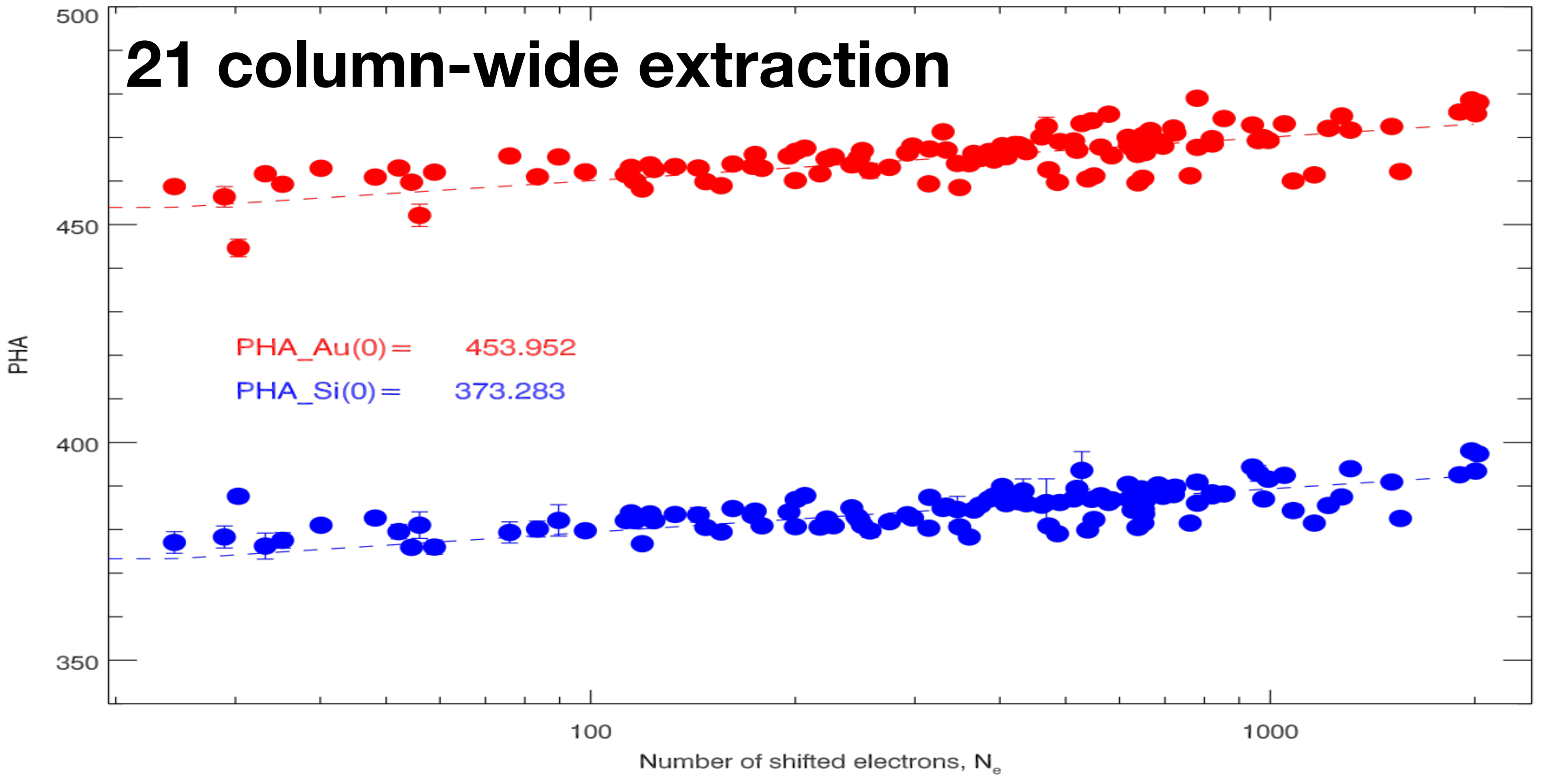
Does not take into account column dependency of the rate

-> blurring of energy scale across PSF



Per-column rate-dependent PHA correction

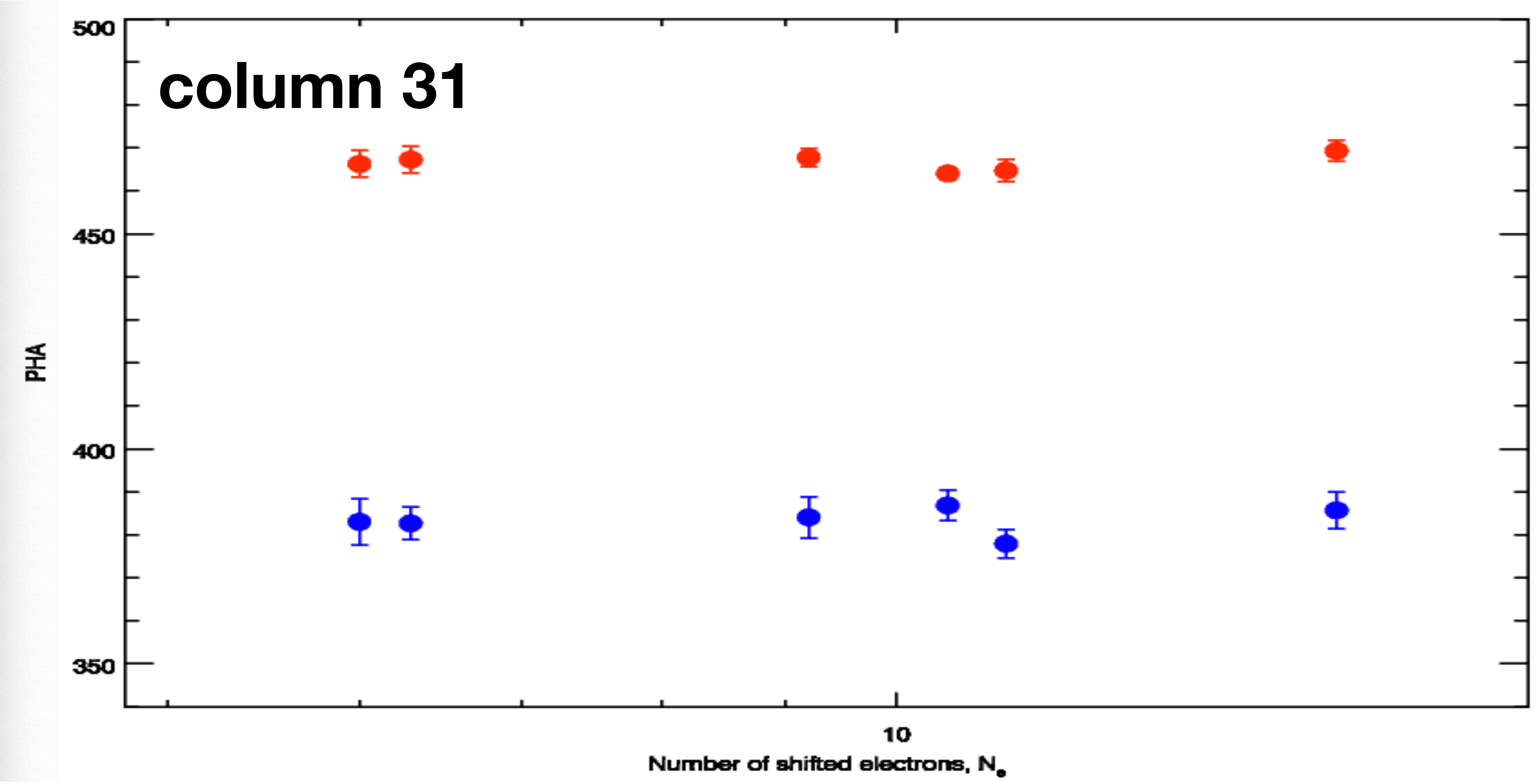
Current calibration based on 21 column-wide extraction:

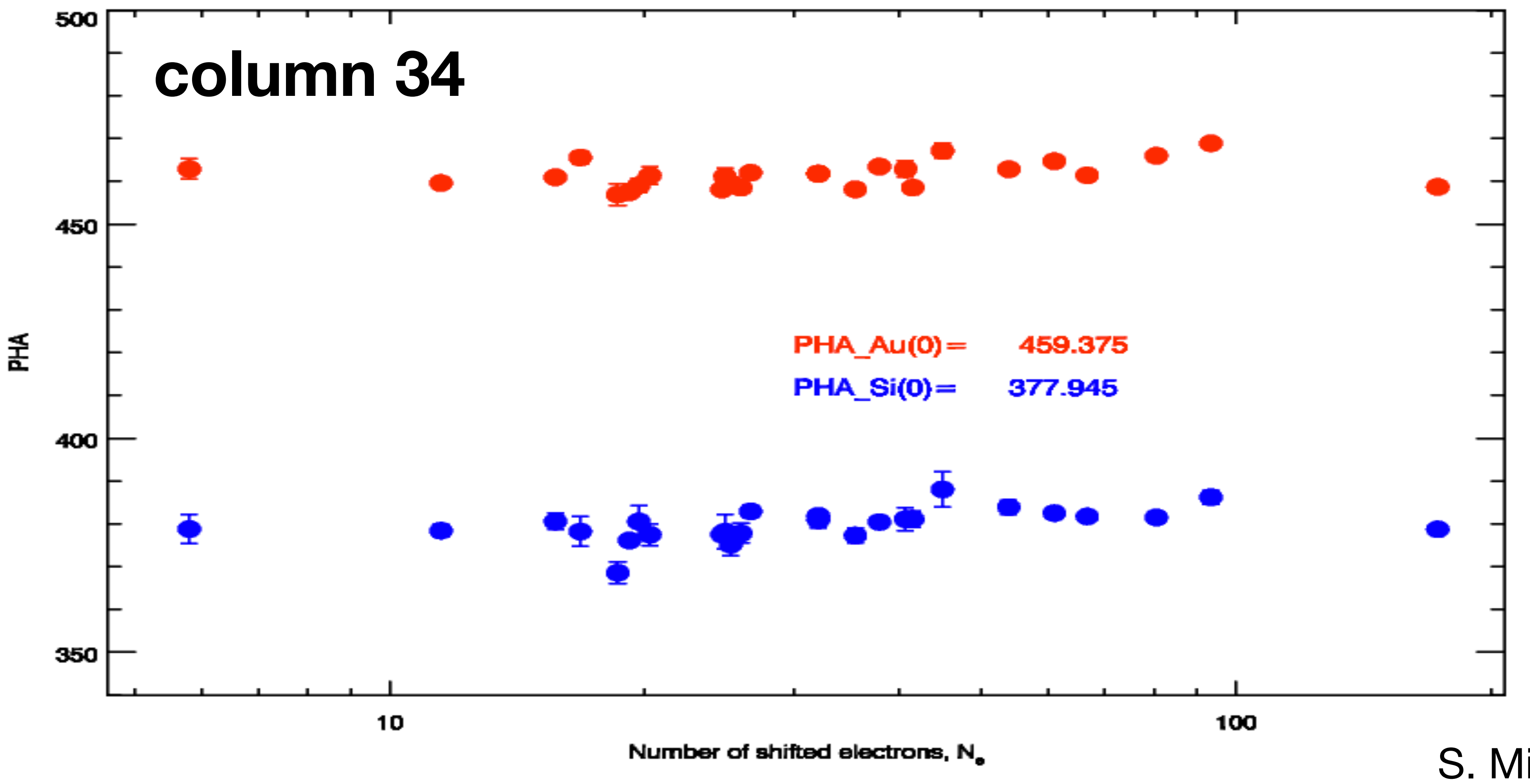


Deriving rate-dependency for individual columns complicated by:

- Lower count rate dynamic range
- Fewer counts overall
- Fewer useful observations

Nominally different rate-dependencies per column, with large uncertainties in fit parameters:





S. Migliari

Conclusion: column-by-column analysis cannot be used to improve significantly the RDPHA correction

Technical Note to be made public imminently.

Current / future work

Analysis guide for observation specific rate-dependent PHA correction (PN Burst & Timing modes):
- will allow users to derive the RDPHA correction for a specific observation (given sufficient data quality)

Fully incorporate energy scale calibration at Cu Kα with that at Al Kα and Mn Kα:
scope for improving the two main components affecting time-dependency:
- long-term CTE degradation
- quiescent background dependent gain correction (additional data point in E-space, 2 solar cycles)

Verify pattern fractions:
- sufficient in-orbit data to compare with expected pattern fractions
- pattern fractions directly impact QE
- preliminary data shows MOS flux discrepancies between s and s,d,t,q spectra

Proton response matrix:
- “Design and characterisation of a prototype proton response matrix for the XMM-Newton mission” Fioretti et al. Proc. SPIE, V 11822, id. 118221F (2021)
- proton response matrix would allow a better understanding of the proton radiation environment, with the aim of modelling the in-flight non X-ray background
- intention is to make matrices available via a SAS task

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Calibration released (July 2021 and April 2022)

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In progress

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"Step 1": calibration released (March 2022)
"Step 2": aiming for SAS 21 (2022)

Recommendation 2020-06-08/11: The UG recommends to continue the investigations into the off-axis flux calibration of the EPIC cameras.

In progress

Recommendation 2021-06-10/09: The UG recommends to finalize the analysis of the possibility of a column by column rate-dependent PHA correction of pn in Burst and Timing modes and publish the conclusions.

Analysis finalised; documentation imminent

Recommendation 2021-06-10/10: The UG recommends to continue to improve the MOS redistribution and determine the impact any improvement has on the MOS-to-PN cross calibration at low energies.

In progress