X-ray cross-calibration with clusters of galaxies

Jukka Nevalainen

Tartu University, Estonia

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Contents

1) Introduction

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~~5) Calibration uncertainty effect on cluster mass – based cosmology~~

1) Introduction

Cross-calibration

of effective area

$= A_{eff} \times \text{transmission} \times \text{QE}$

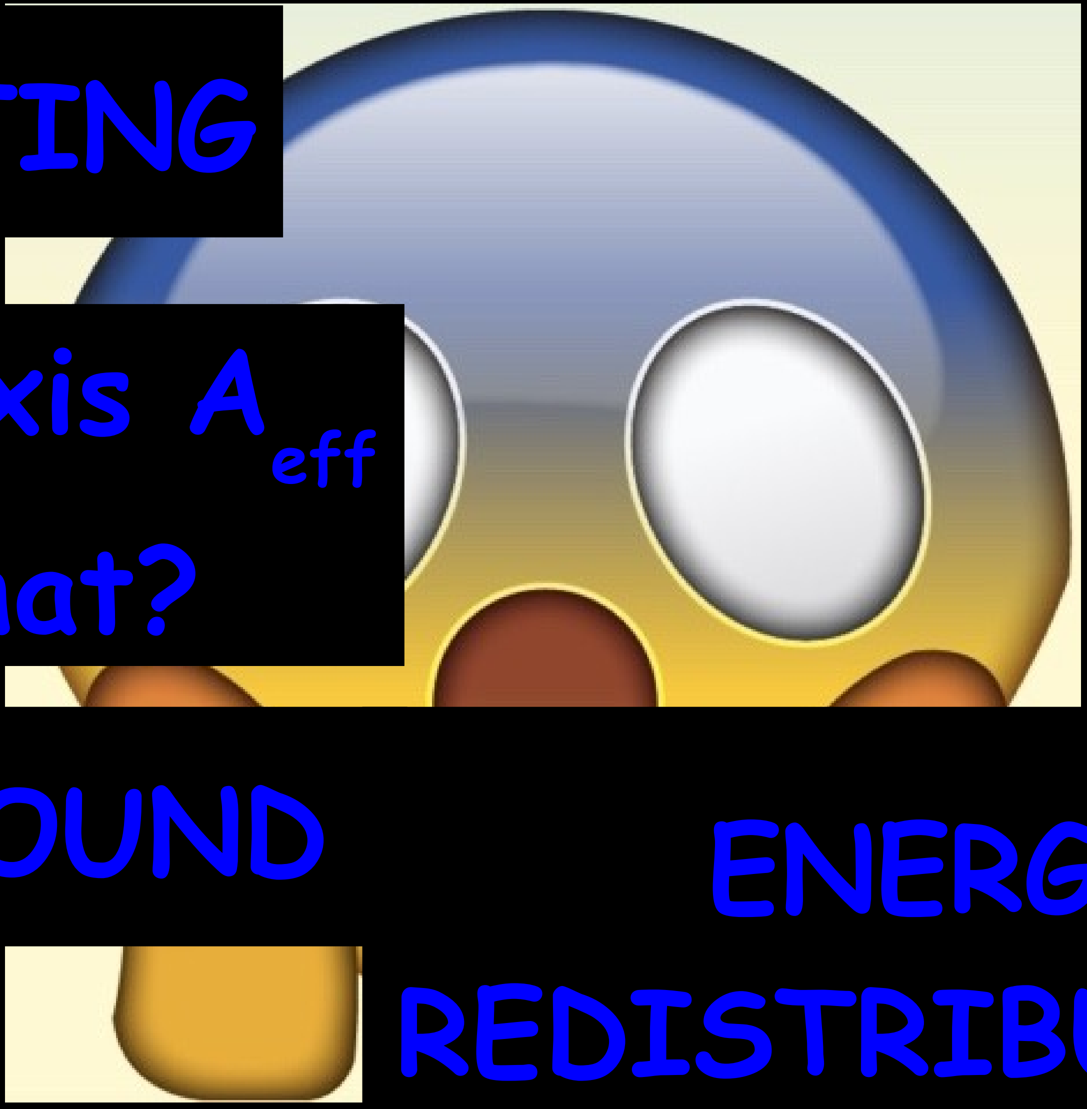
- Ground calibration done but...

- International Astronomical Consortium for High Energy Calibration (IACHEC)

1.1) Why clusters of galaxies?

Clusters are bright and stable

Problems with clusters



VIGNETTING

PSF

Not on-axis A_{eff} but what?

BACKGROUND

ENERGY REDISTRIBUTION

2) Controlling systematics

Systematics

- REQUIREMENT: Keep the systematics below the statistical precision requirement of 1%
- What we can do: to vary the extraction region and to pick the best clusters

2.1) Redistribution minimisation

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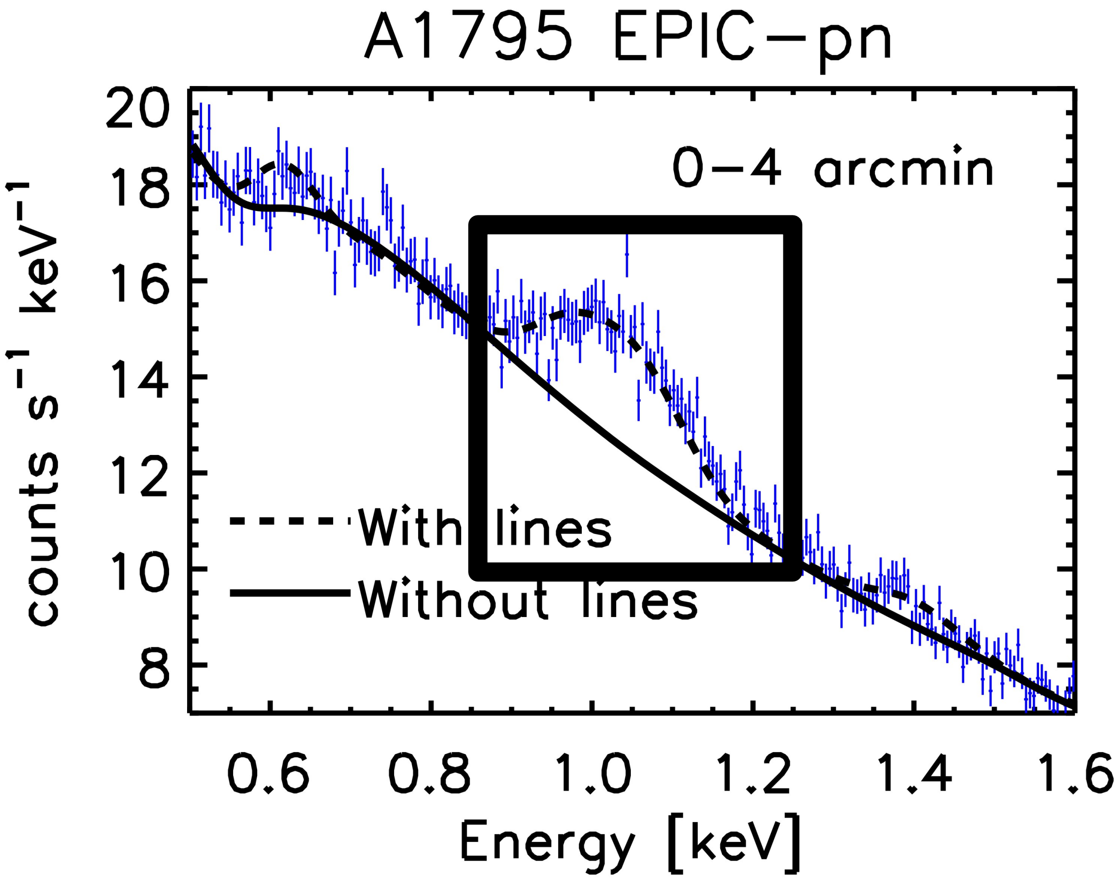
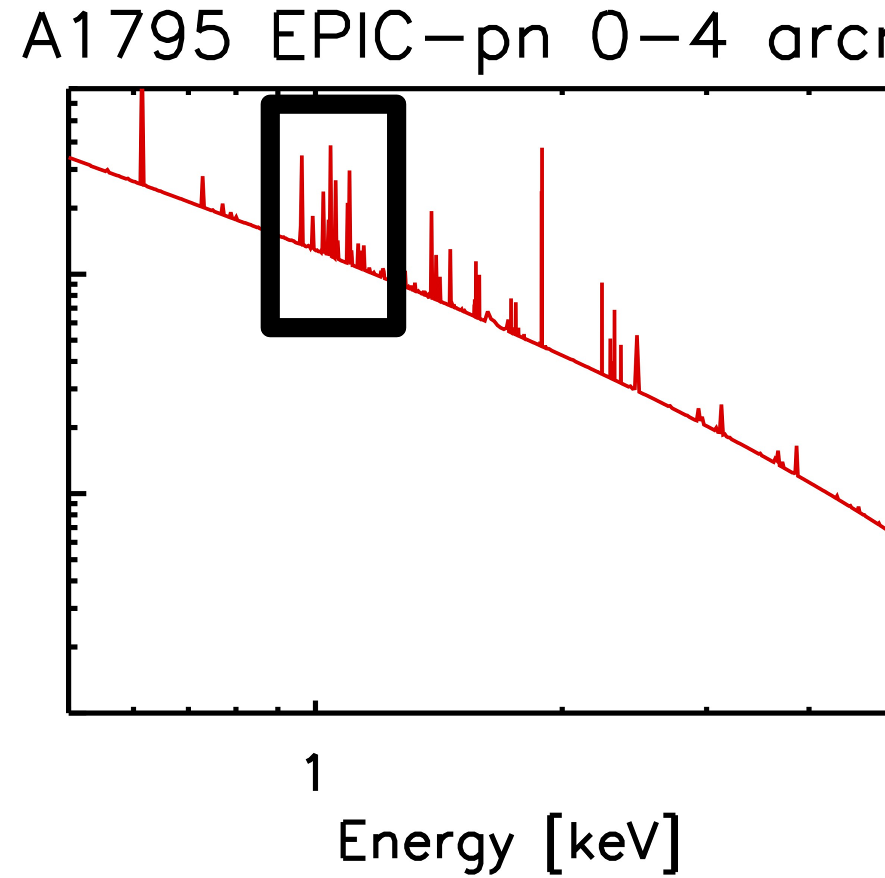
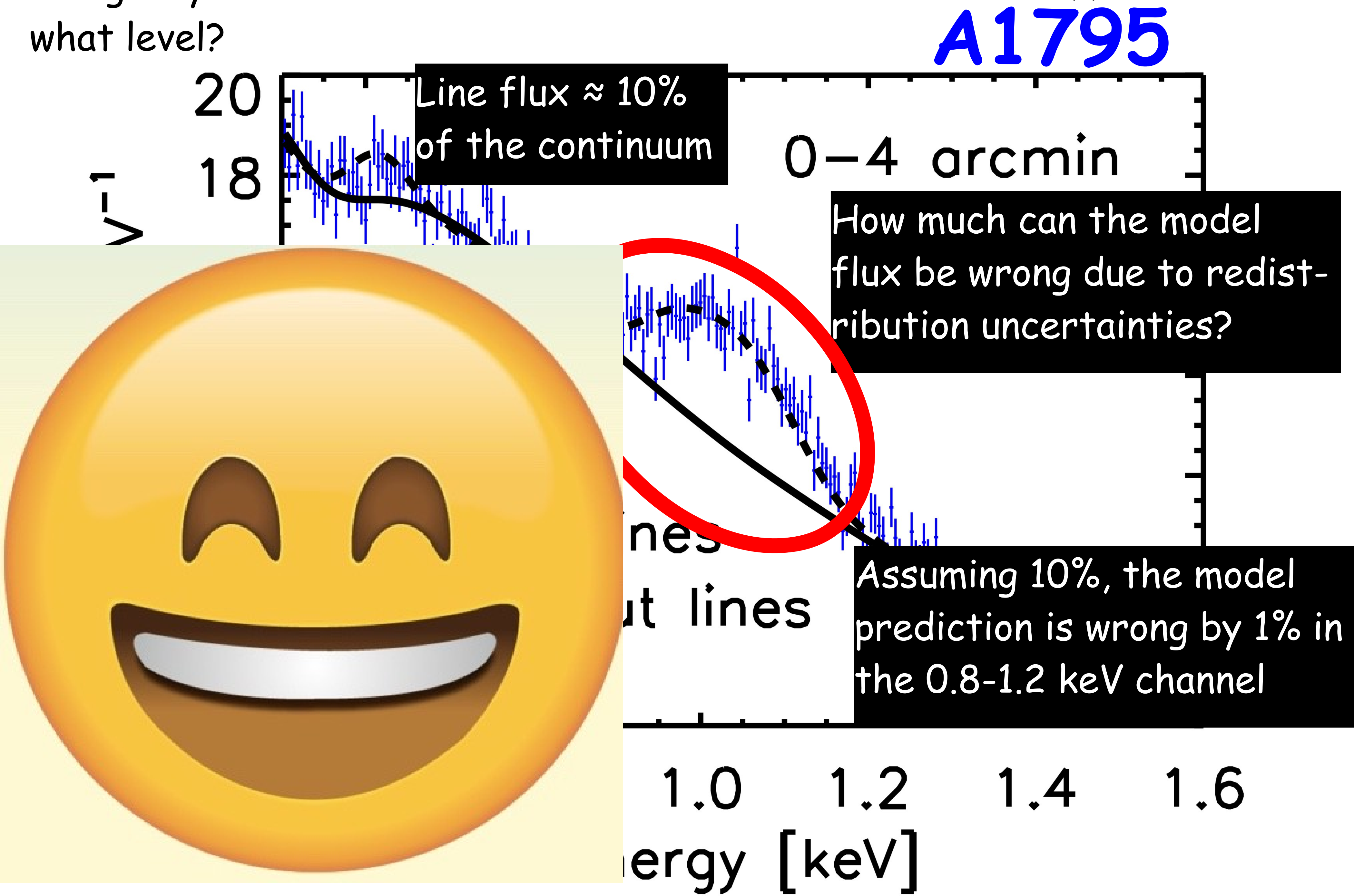
- If the redistribution is not perfectly calibrated, the complex line emission at 1 keV (from the cool core) and 6 keV may produce effects that mimick an effarea calibration problem



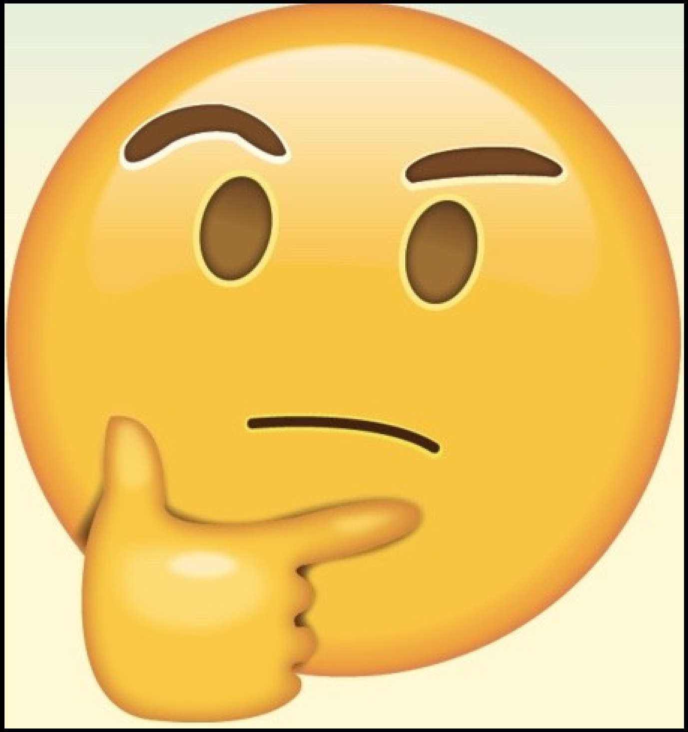


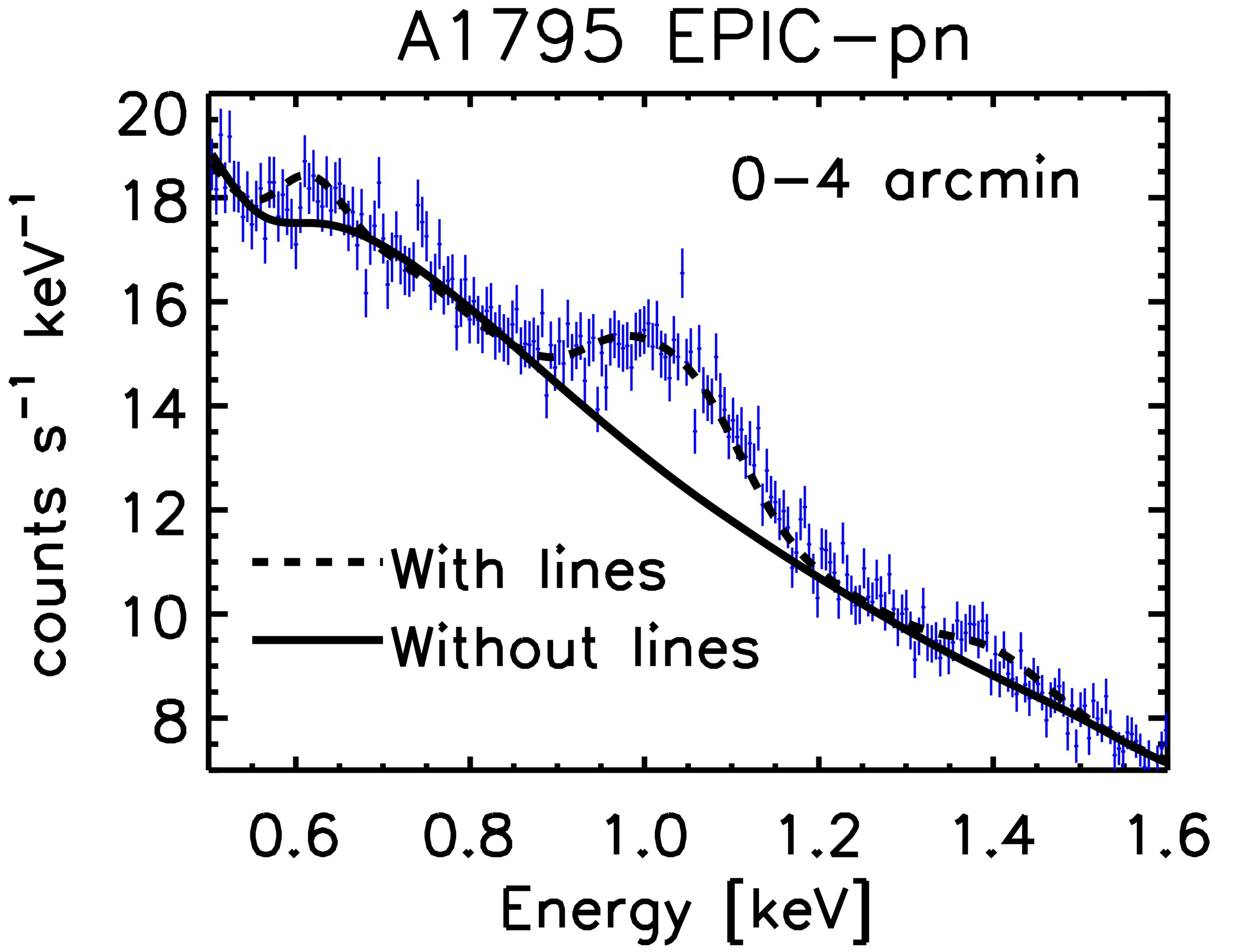
Using only the hottest clusters **kT > 6 keV** reduces this effect. To what level?



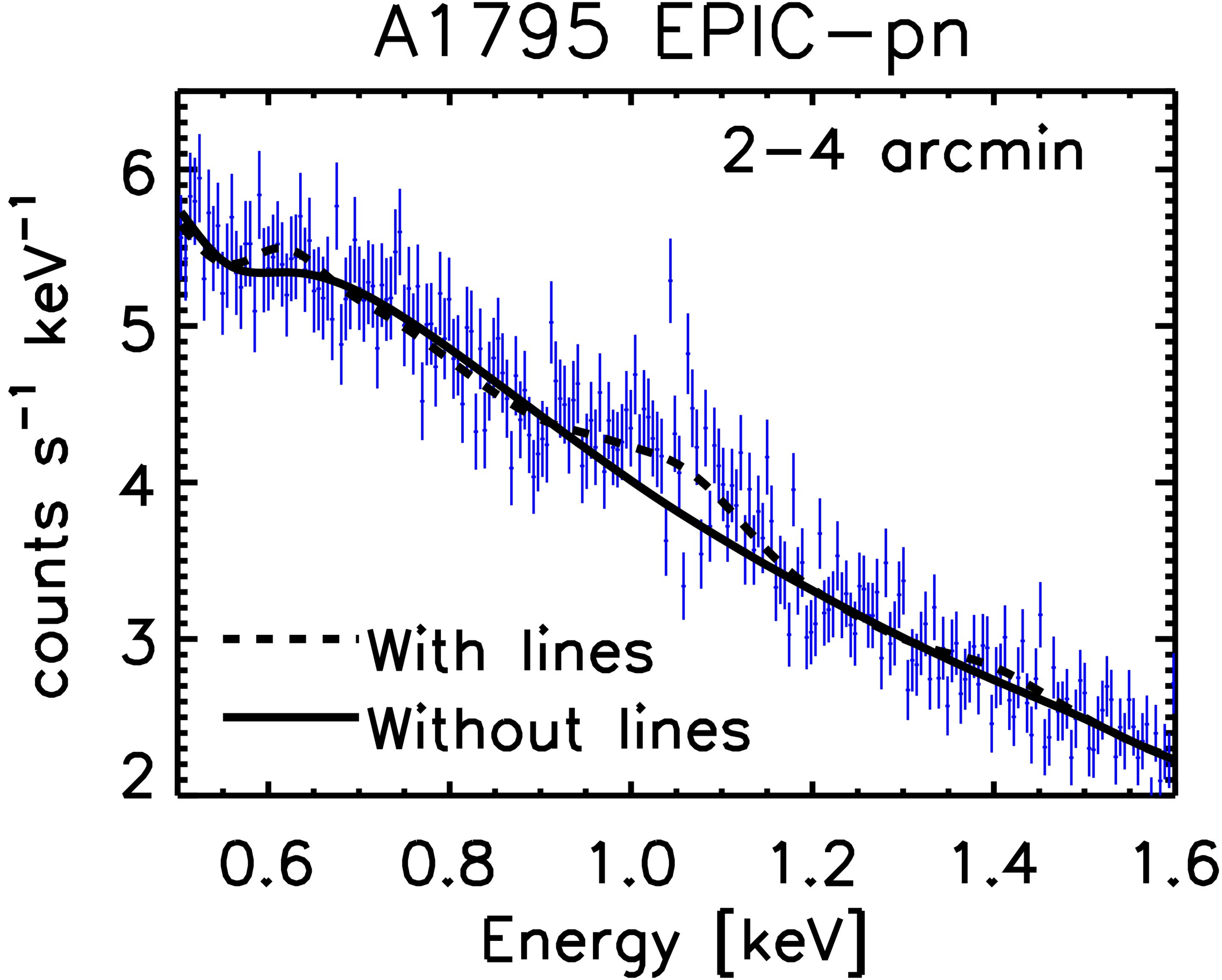
Quick and dirty

- If uncertanties much bigger, remove cool cores from the extraction region
- Central 2 arcmin (= 100 kpc at z = 0.05) cool core region





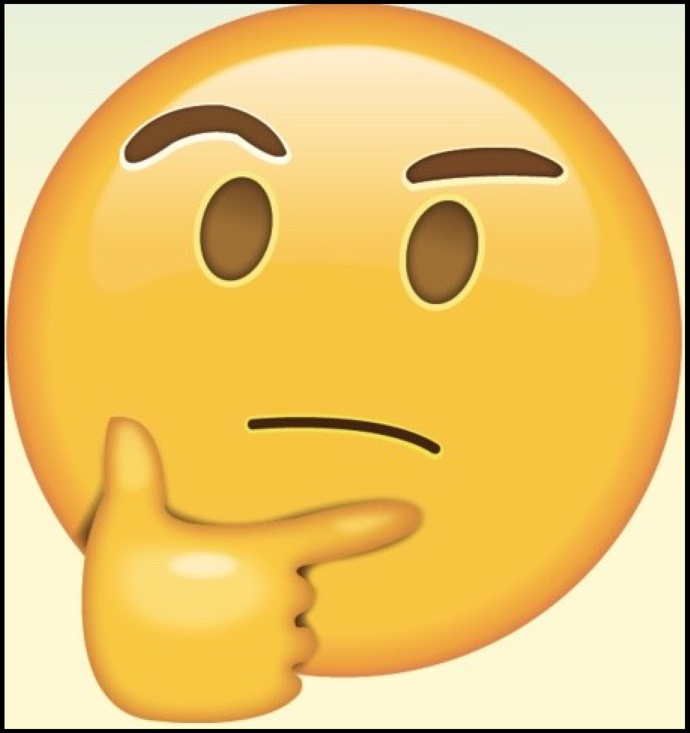
A1795 EPIC-pn
0-4 arcmin
With lines
Without lines
counts s^{-1} keV^{-1}
Energy [keV]
20
18
16
14
12
10
8
0.6
0.8
1.0
1.2
1.4
1.6



A1795 EPIC-pn
2-4 arcmin
counts s^{-1} keV^{-1}
Energy [keV]
With lines
Without lines
6
5
4
3
2
0.6
0.8
1.0
1.2
1.4
1.6

Quick and dirty

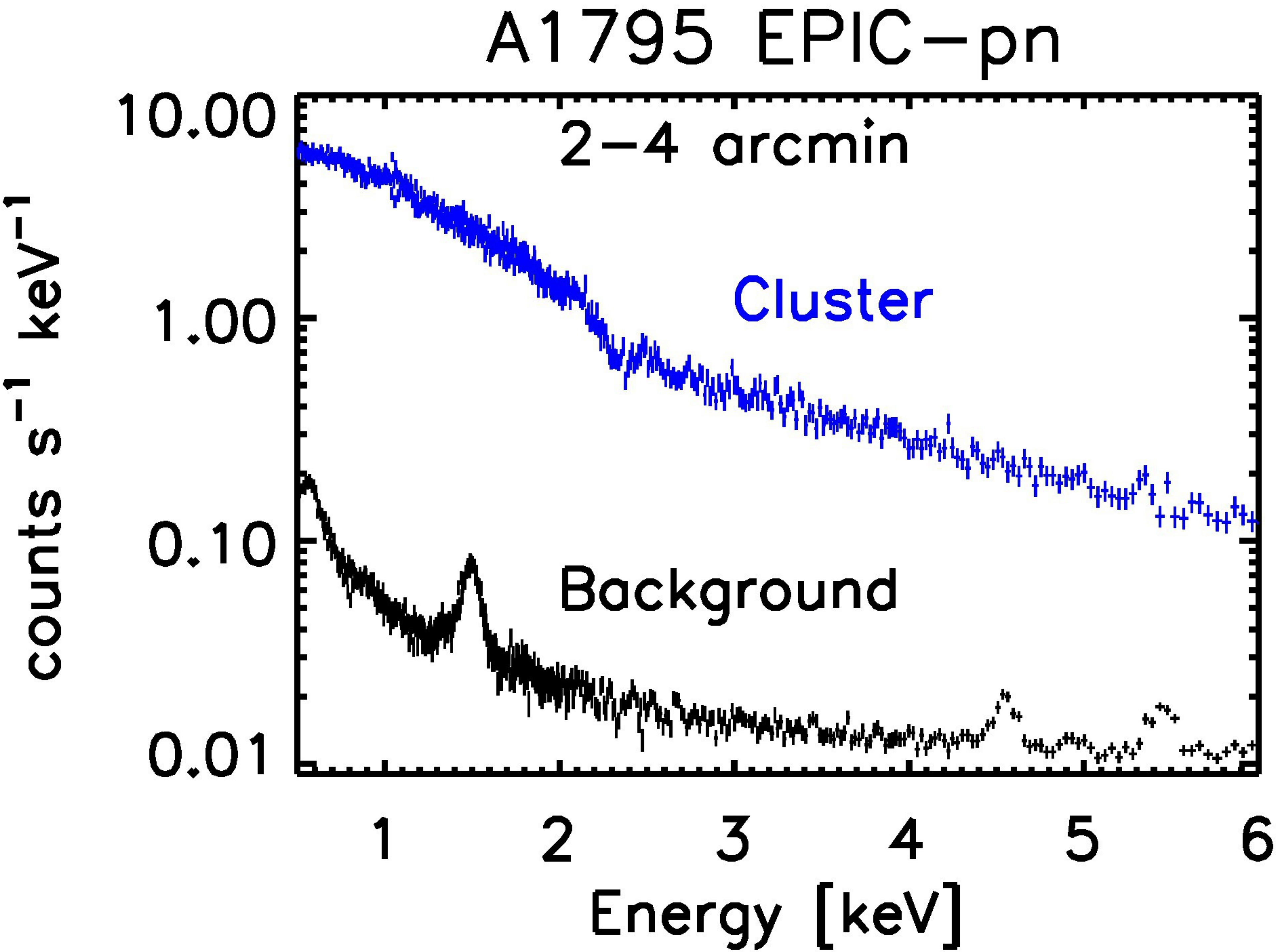
- The downside is a huge reduction of counts
- If the redistribution of the cool core lines is a significant problem, exclude the 0.8-1.2 keV bin from the analysis
- Similar estimates TBD for the Fe XXV and XXVI lines at 6-7. Currently we cut the spectra at 6 keV.



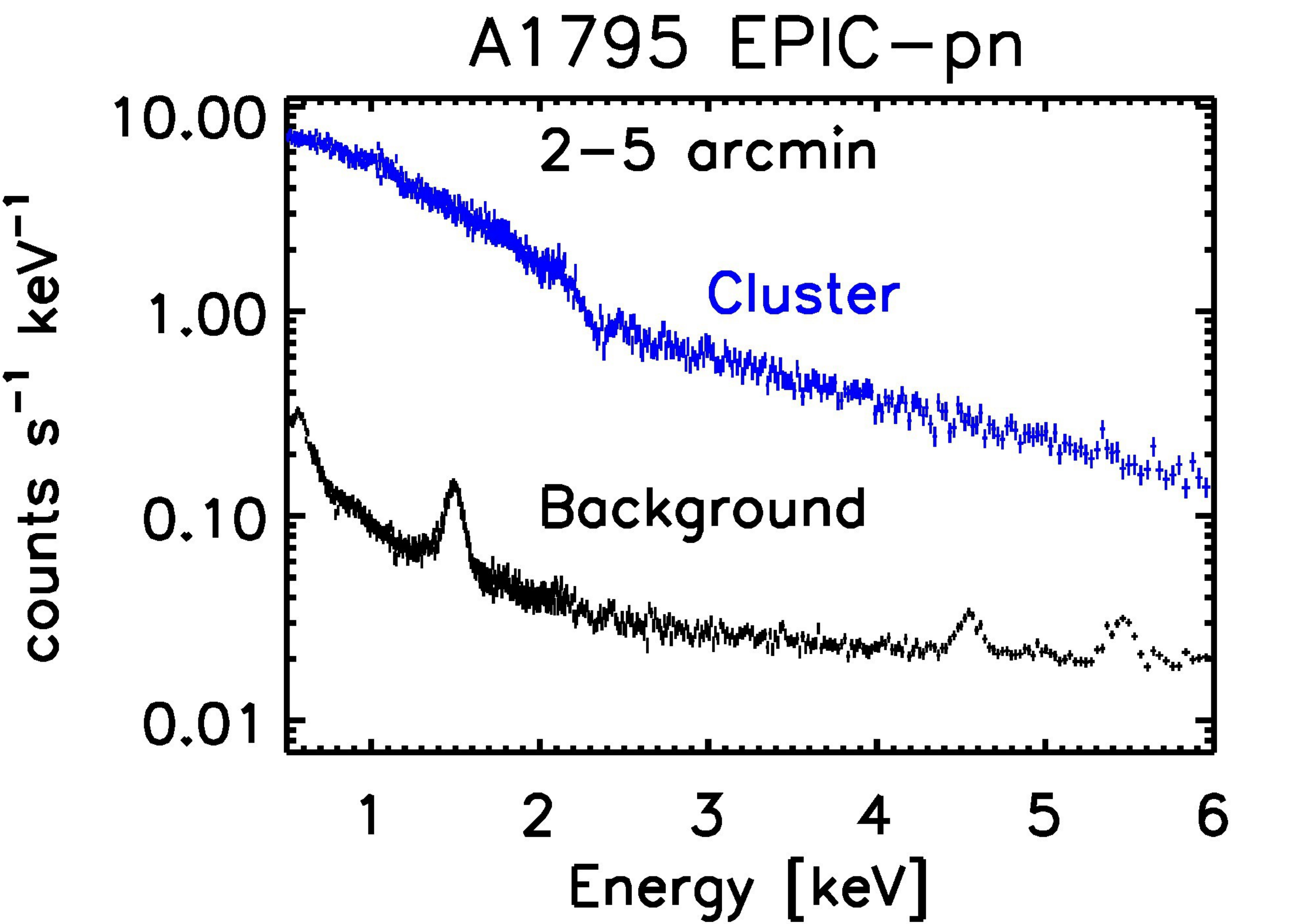
2.2) Background minimisation

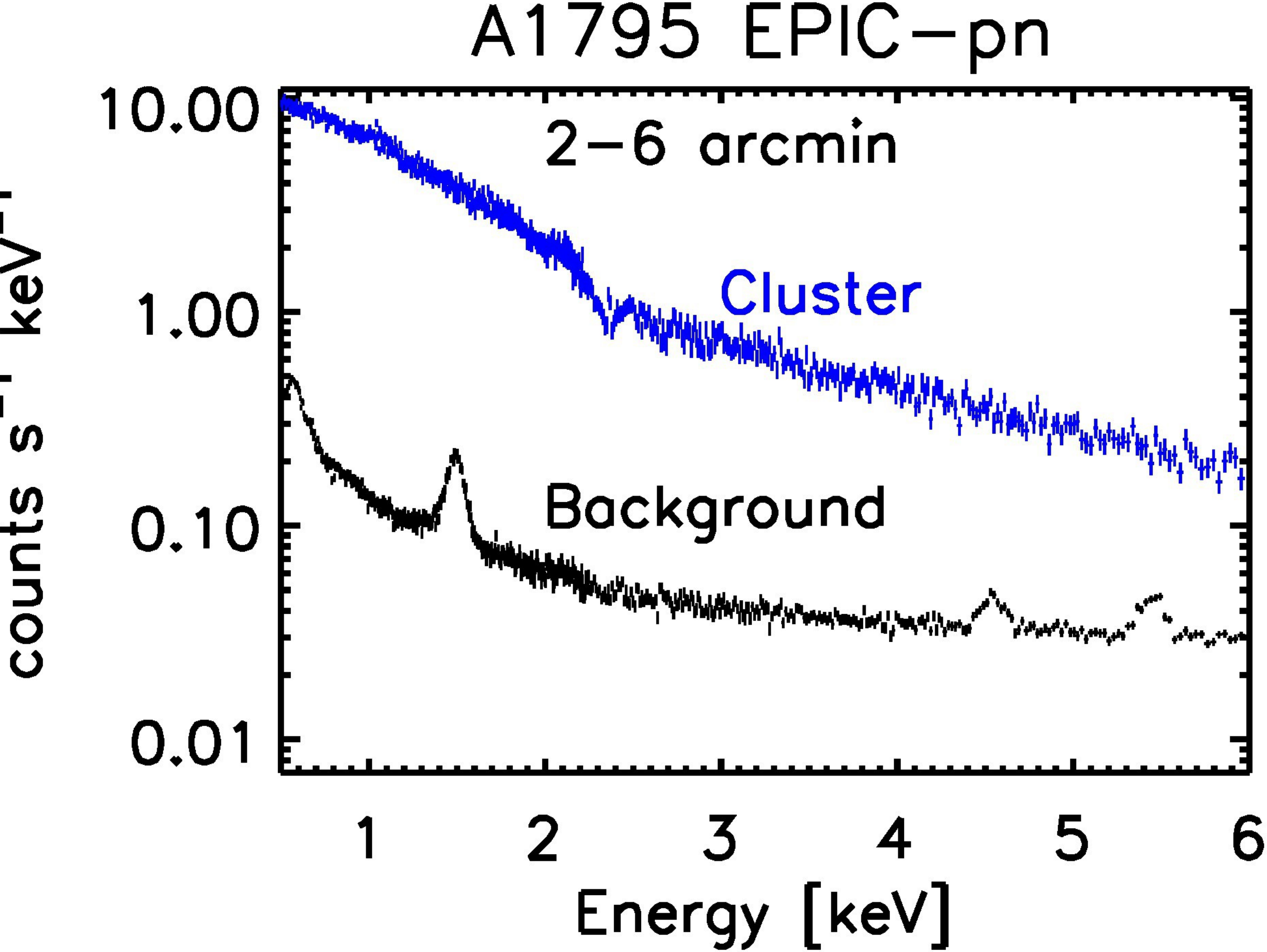
3.2) Background minimisation

- Best signal in 0.5-7.0 keV band from the hottest nearby clusters
- Bigger outer extraction radius r_{out} increases the photon statistics, but the background/source ratio increases and the background modelling uncertainties become a bigger problem
- If assuming 10%??? systematic uncertainties for the background modelling in the 0.5-6.0 keV band, **the background must remain below 10% of cluster signal so that the consequent effect on the measured cluster signal is less than 1%**
- Examples of A1795 spectra and bkg, excluding the central 2 arcmin (worst case redistribution scenario)



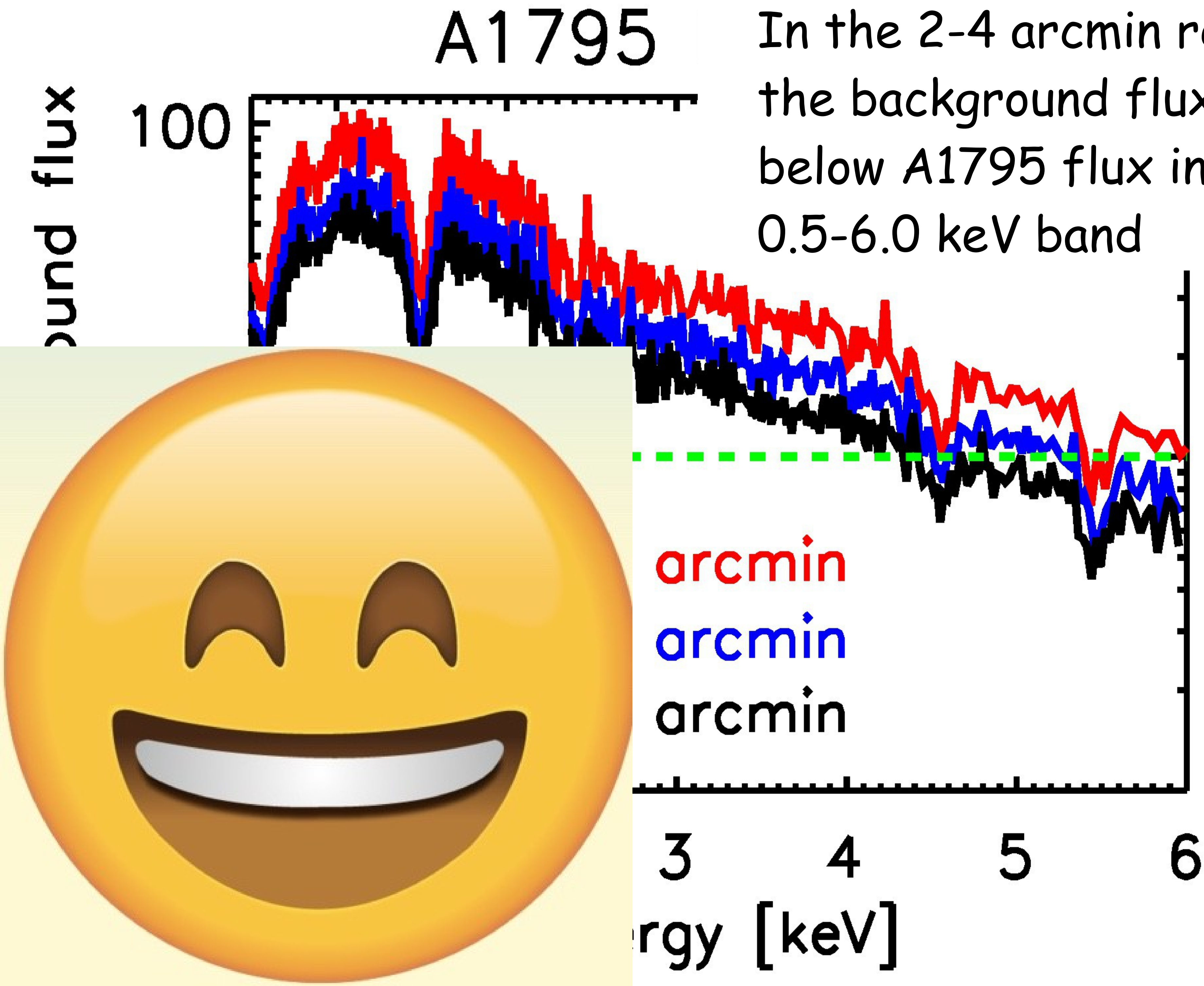
A1795 EPIC-pn
2-4 arcmin
Cluster
Background
10.00
1.00
0.10
0.01
counts s^{-1} keV^{-1}
1
2
3
4
5
6
Energy [keV]


A1795 EPIC−pn
2−5 arcmin
Cluster
Background
10.00
1.00
0.10
0.01
counts s^{-1} keV^{-1}
1
2
3
4
5
6
Energy [keV]



A1795 EPIC-pn
2-6 arcmin
Cluster
Background
counts s^{-1} keV^{-1}
10.00
1.00
0.10
0.01
1
2
3
4
5
6
Energy [keV]

In the 2-4 arcmin region the background flux is below A1795 flux in the 0.5-6.0 keV band



2.3) PSF scatter minimisation

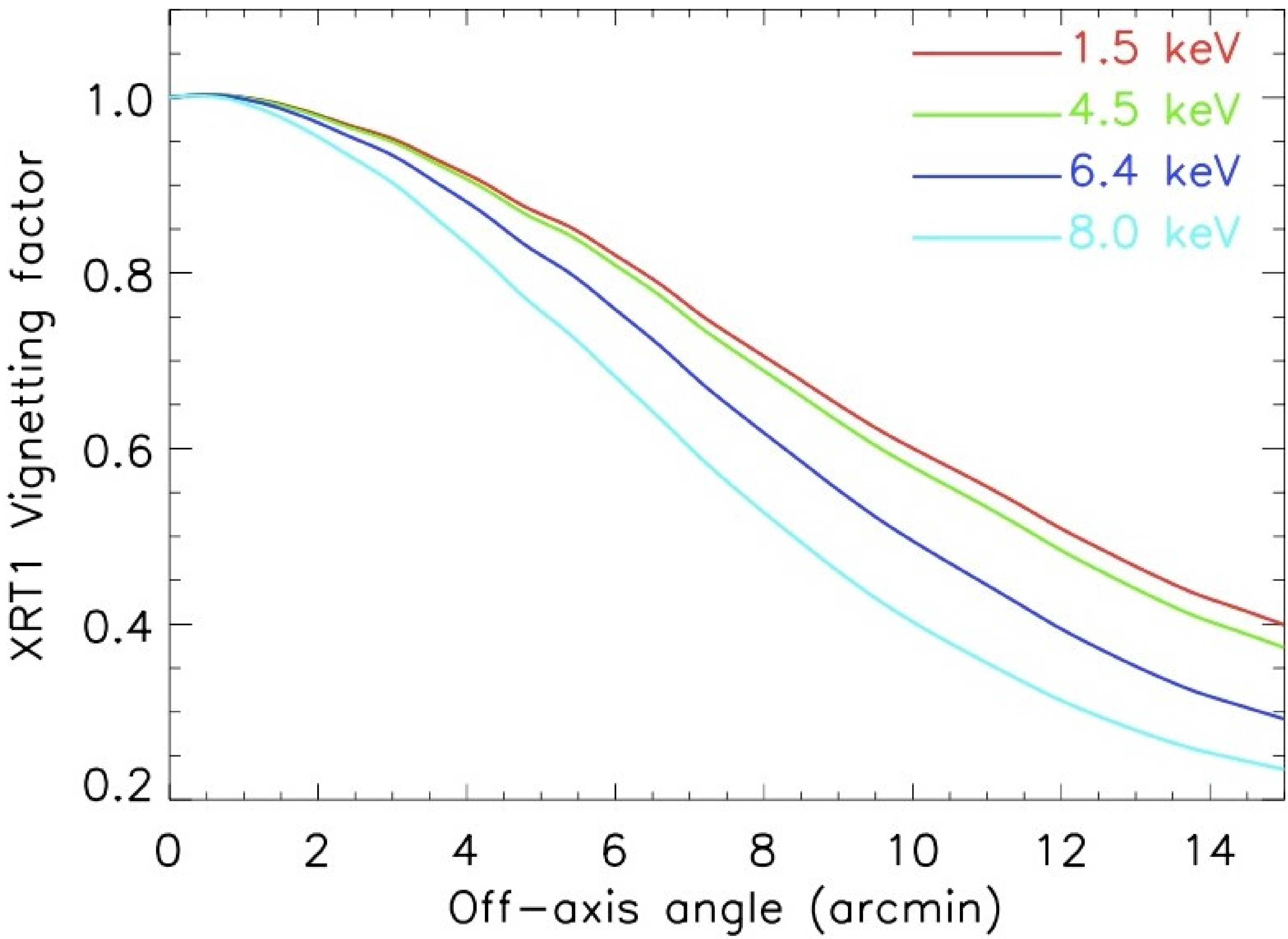
3.3) PSF scatter minimisation

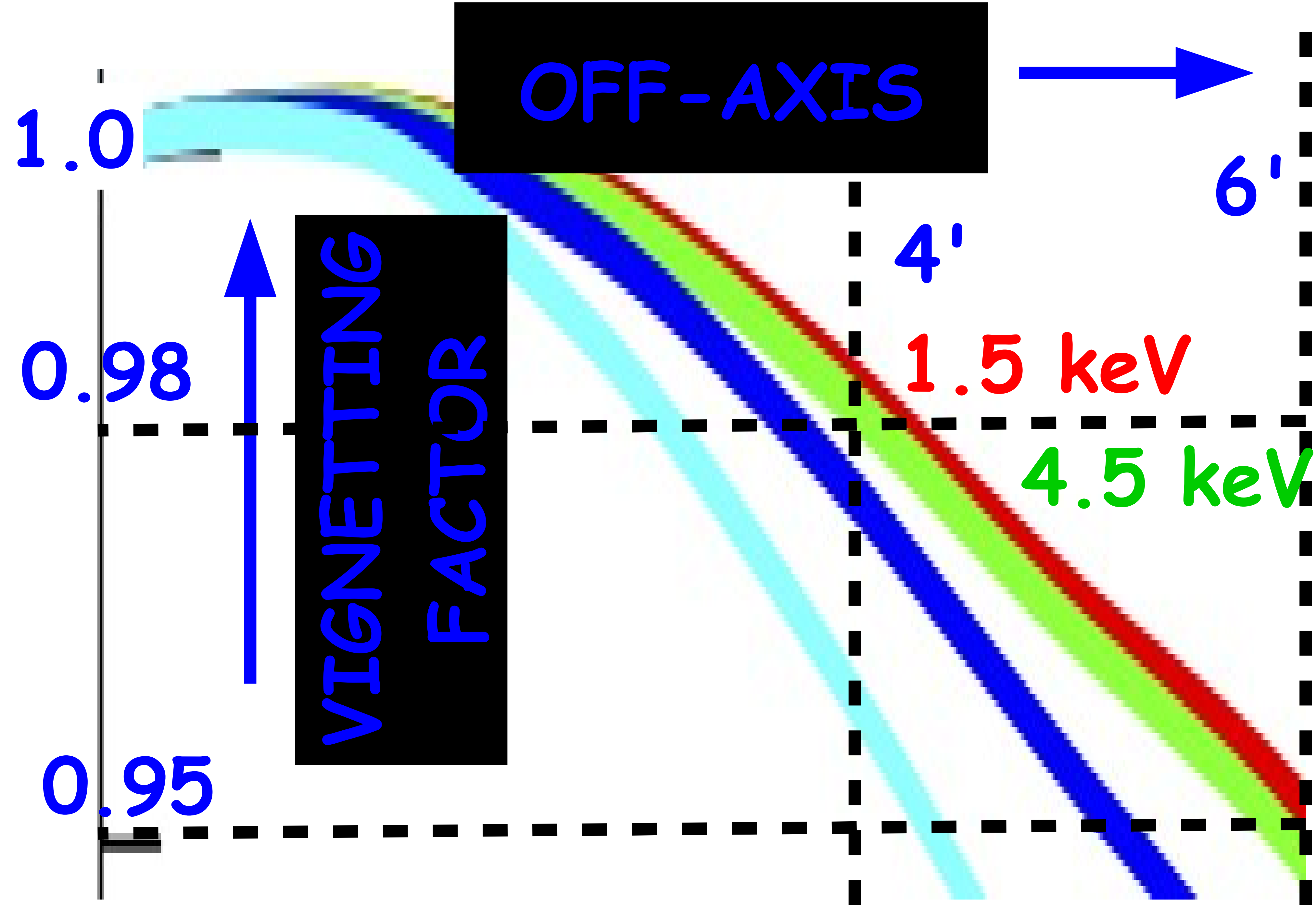
- Extraction region cannot be too small so that the PSF scatter **from** the studied region **to** the studied region dominates
- The EPIC PSF has 40-50 arcsec 90% encircled energy radius. **Our extraction regions must have larger scales than 1 arcmin.** How much bigger?
- It would be good to include the cool core in the extraction region

3.3) PSF scatter minimisation

- In N10+ I convolv  ess profiles with the PSF to es
- In N10+ I had exc the outer r > 0.3 r500 (to stay
- In case of A1795,
- Results: The PSF 0.1% level of the original cluste in annulus
- If we use bigger the bkg requirement), the
- If we include the center in our extraction regions, the effect is zero

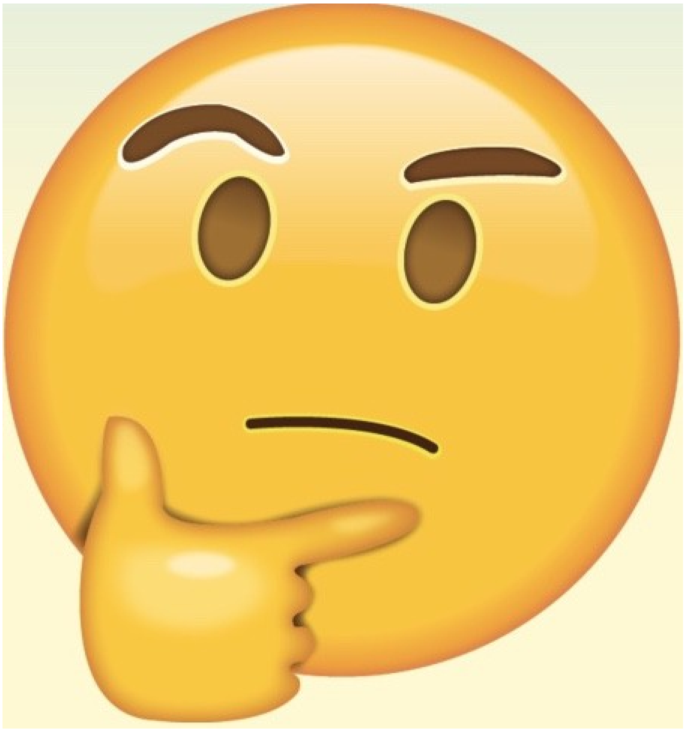
2.4) Vignetting minimisation

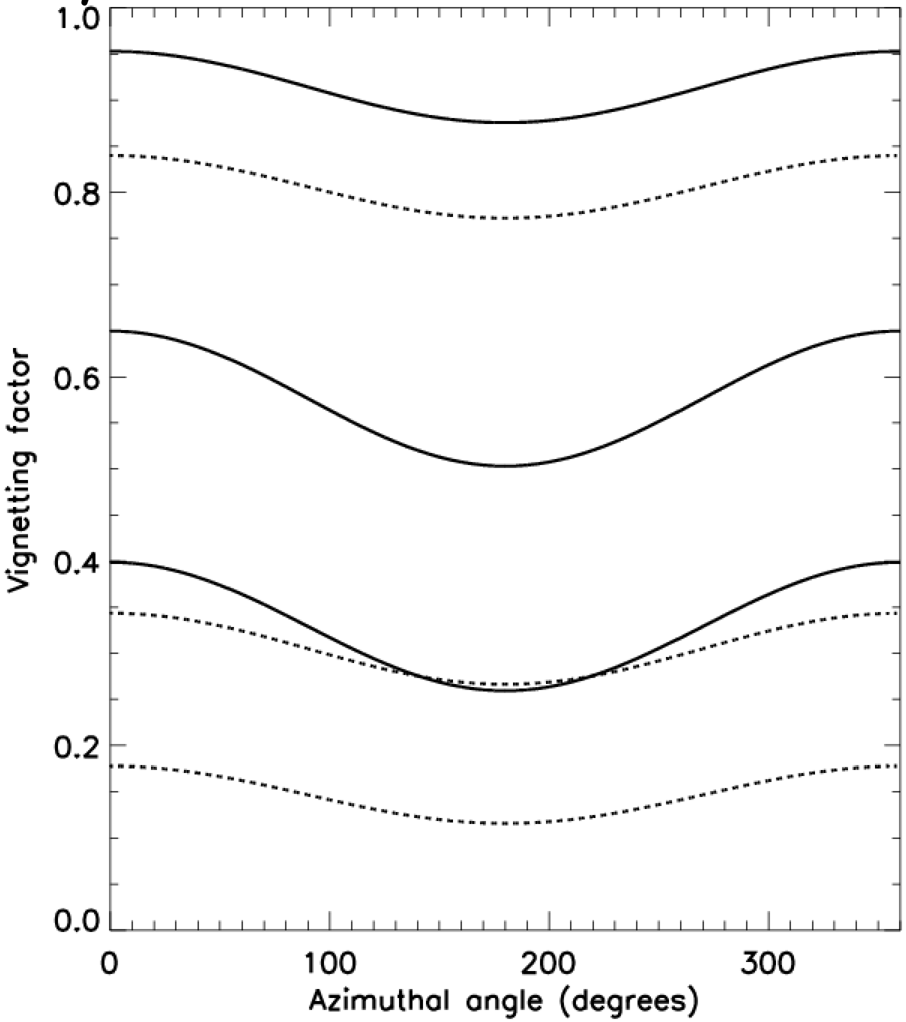

1.5 keV
4.5 keV
6.4 keV
8.0 keV
XRT1 Vignetting factor
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
Off-axis angle (arcmin)


OFF-AXIS
1.0
0.98
0.95
VIGNETTING FACTOR
4'
6'
1.5 keV
4.5 keV

- Within 4-6 arcmin, the emission – weighted vignetting factor is 0.98-0.95
- Allowing 10% uncertainties??? for the vignetting calibration (i.e. vignetting factor values), the consequent uncertainties on the effective area are at a level of 0.1%.
- Using cluster spectra extracted within central 4-6 arcmin we study **almost** the on-axis effective area

- MOS units have additional azimuthal variation in the vignetting due to RGS:s.
- What is the consequent effect of the effective area reduction and its uncertainty?





3.5) Extraction region requirements summary

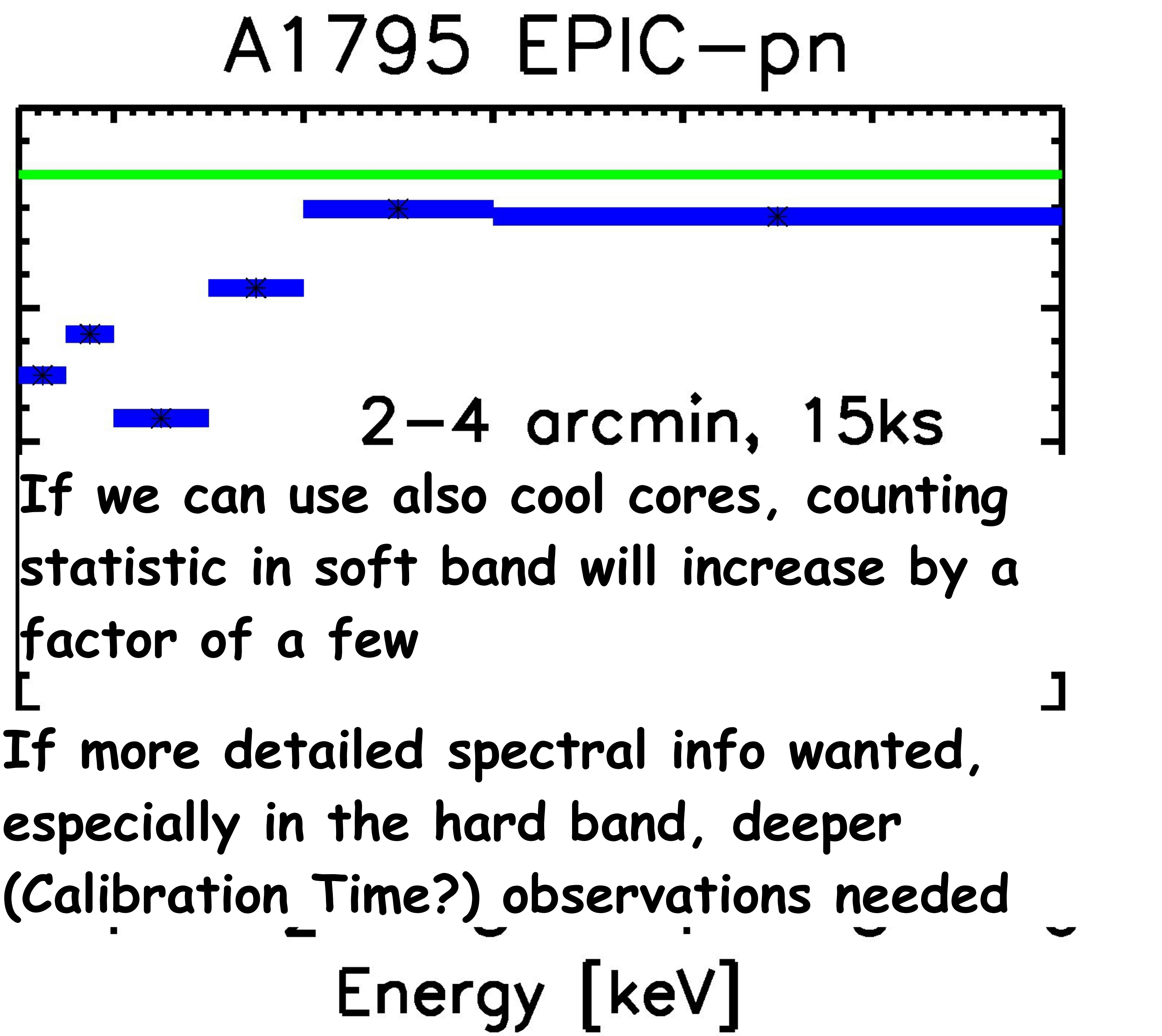
3.5) Extraction region summary

- **Redistribution:** perhaps exclude cool core **(TBD):**
  $R_{in} \geq$ (0-)2 arcmin
- **Background:** outer extraction radius not too large:
  $R_{out} \leq$ 4(-6) arcmin
- **Vignetting:** outer radius not too large
  R_{in} = 0 , $R_{out} \leq$ 6 arcmin
- **PSF:** No problem as long as **extraction region scale larger than 1 arcmin**

☛ **R_{in} = (0-)2 arcmin, R_{out} = 4(-6) arcmin**

3.6) Are there enough counts within the allowed extraction region?

We reach 1% statistical precision requirement with 15 ks pn exposure in 6 spectral bins



If we can use also cool cores, counting statistic in soft band will increase by a factor of a few

If more detailed spectral info wanted, especially in the hard band, deeper (Calibration_Time?) observations needed

3) Our method for evaluating cross-cal uncertainties

- Residual ratio (RR) to evaluate the effective area cross-calibration:
  - At the moment we use EPIC-pn as a reference instrument **ref**
  - For instrument **i** that we compare against the reference instrument calculate the ratio

Data of instrument i

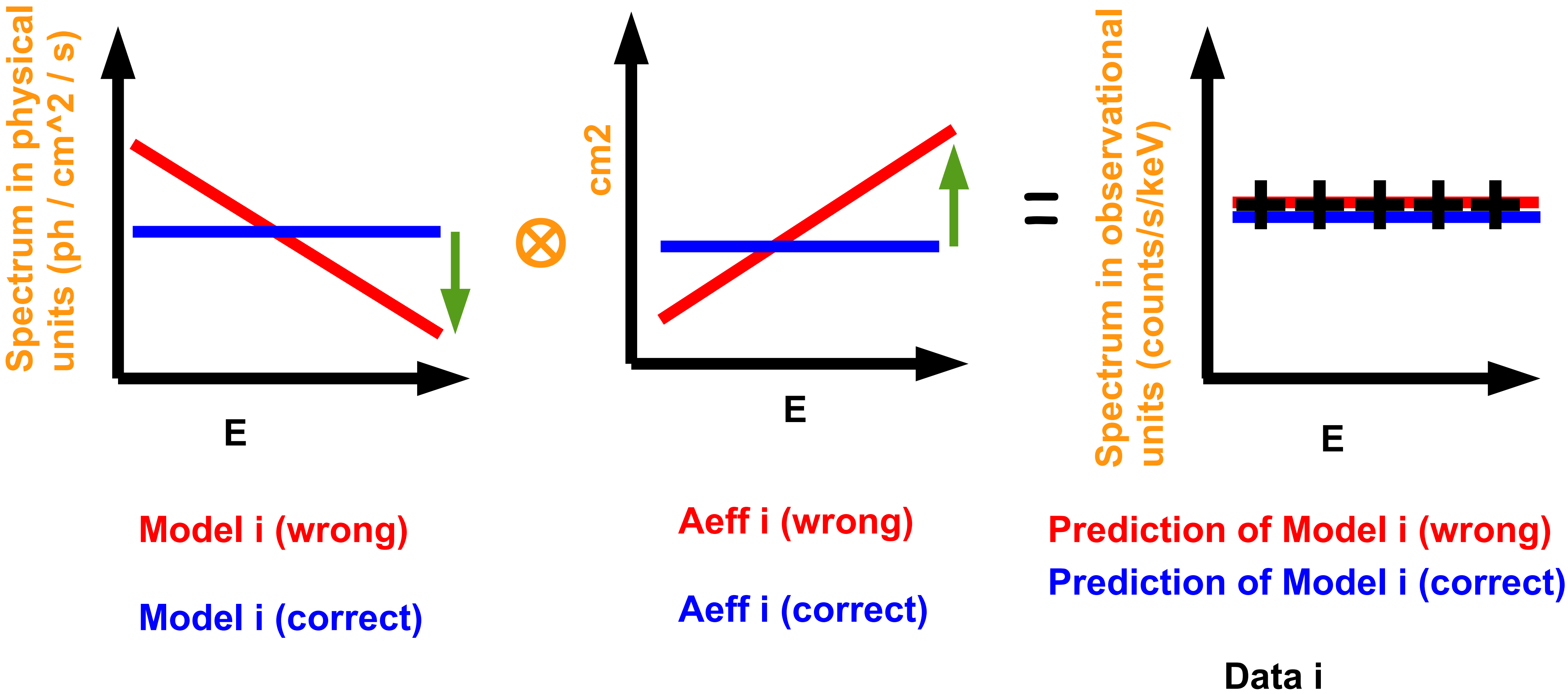
Best-fit model of the reference instrument

Residuals of the reference instrument

$$RR_{i/ref} = \frac{data_i}{model_{ref}\ \hat{u}\ resp_i} \times \frac{model_{ref}\ \hat{u}\ resp_{ref}}{data_{ref}}$$

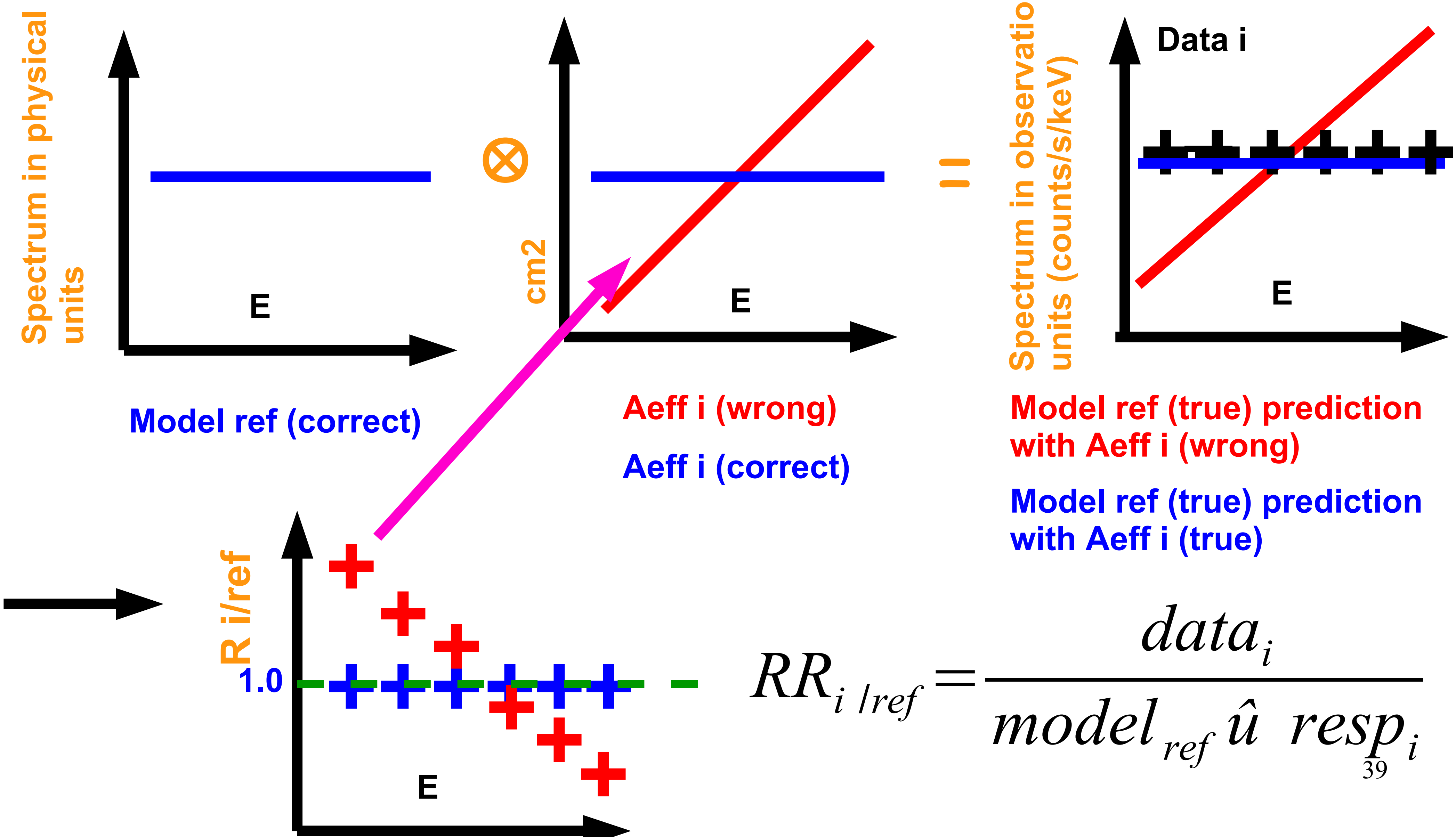
Prediction for instrument **i**

Instrument i, calibration incorrectly implemented



Biased best-fit model obtained

Instrument ref model (correct) prediction compared with Instrument_i data

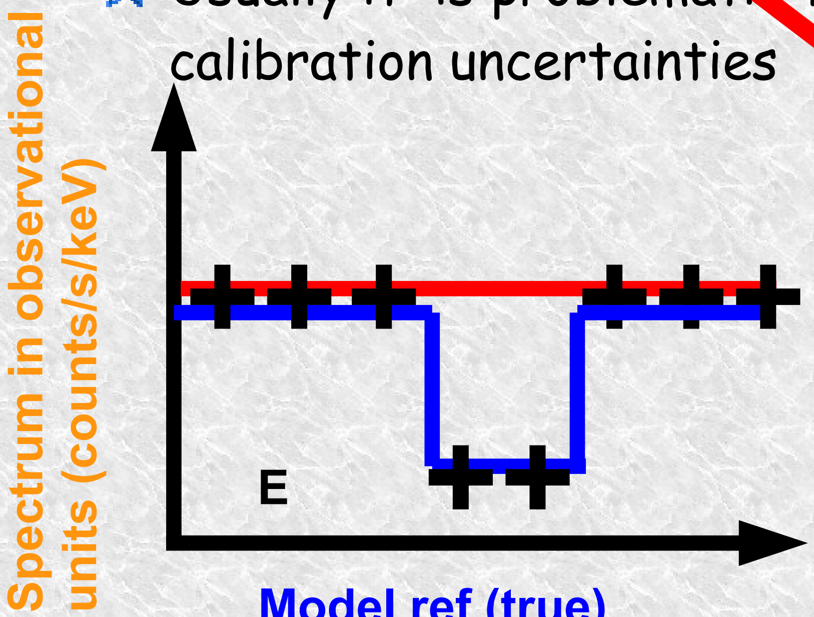


$$RR_{i\ /ref} = \frac{data_i}{model_{ref}\ \hat{u}\ \ resp_i}$$

- Deviation from unity tells that there is a mismatch between the model prediction of Instrument ref and the data of Instrument i
- Because we "know" that Instrument i calibration wrong, the residuals tell by how much at each energy
- In practise we do not know which, if any, instrument is accurately calibrated
- Residual ratio tells that the combined effect of the calibration inaccuracies of the two instruments is at the level indicated by the residuals
- The **RELATIVE** cross-calibration uncertainties evaluated

A complication

- Above we assumed that the Model of the reference instrument ($model_{ref}$) describes the data ref accurately
- If the reference instrument model does not describe accurately the reference data, its prediction with **a correct Aeff i** is problematic to interpret
- Usually it is problematic to fit the data accurately when there are calibration uncertainties



Model ref (true)

Model ref (wrong)

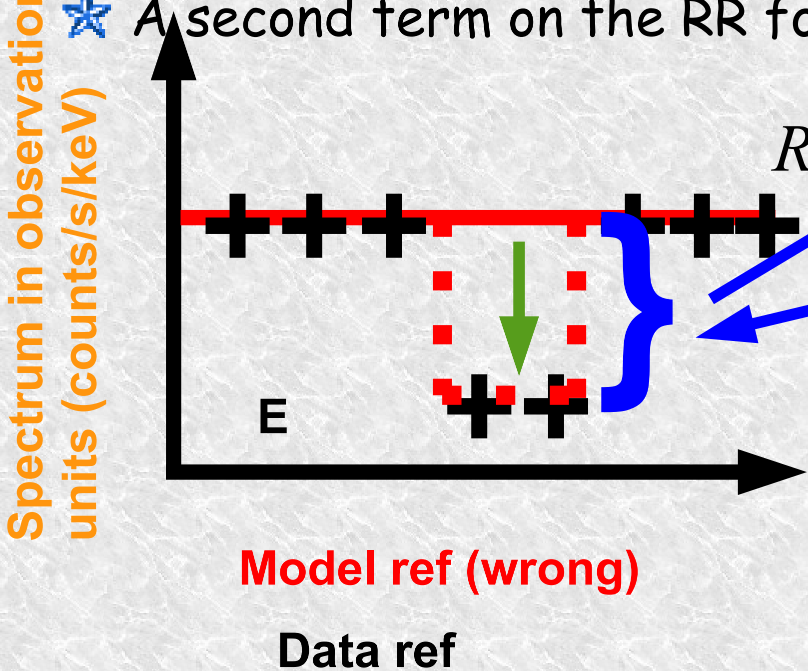
Data ref

$$R_{i/ref} = \frac{data_i}{model_{ref}\ \hat{u}\ resp_i}$$

Solution

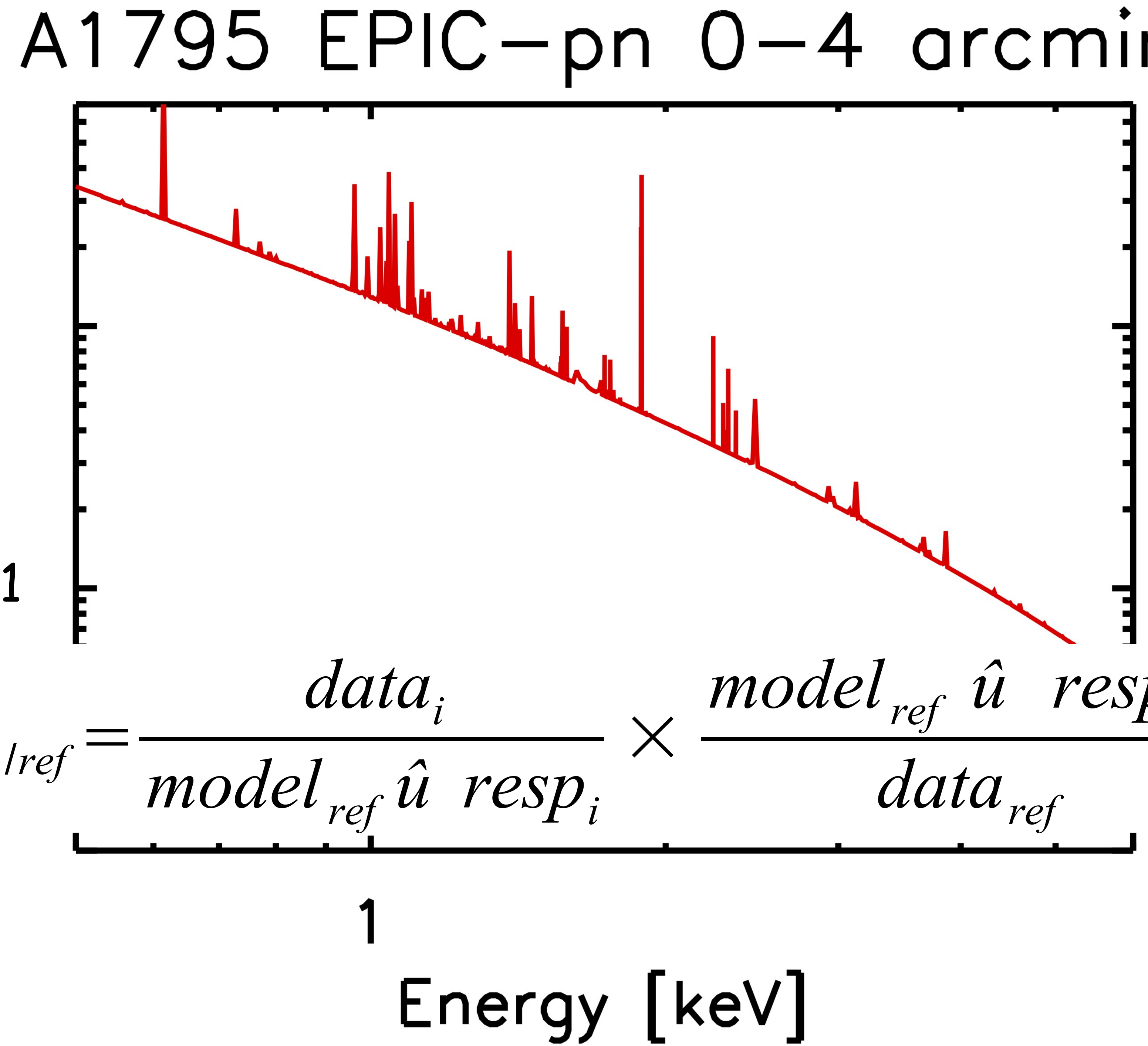
- A phenomenological mathematical model that fits the data is OK for cross-cal
  - Since we know the **relative** difference between the data and the problematic model prediction of the reference instrument, we can use this info to correct the model prediction to match the data (fudge factor kind of thing)
  - A second term on the RR formula does exactly that

$$R_{i/ref} = \frac{data_i}{model_{ref}\ \hat{u}\ resp_i} \times \frac{model_{ref}\ \hat{u}\ resp_{ref}}{data_{ref}}$$



- Caveat: due to statistical uncertainties you will never reach the absolutely correct model, whatever method you use
- Keep statistical uncertainties small compared to the calibration effects
- In other words given the statistical uncertainty level, one can only study systematic effects bigger than this
- In cluster sample we aim to keep statistical uncertainties at 1% level.

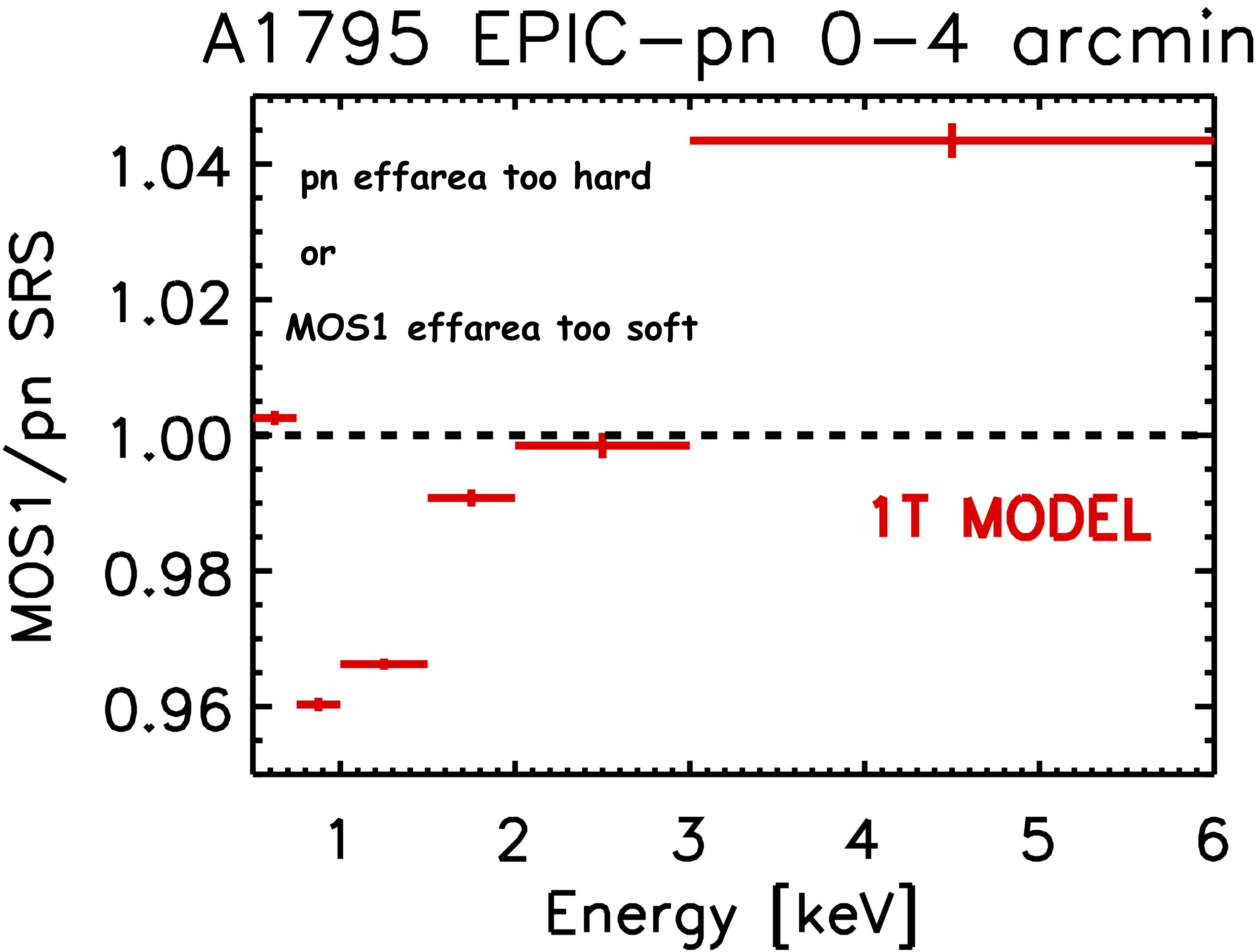
RR for A1795



ref = pn

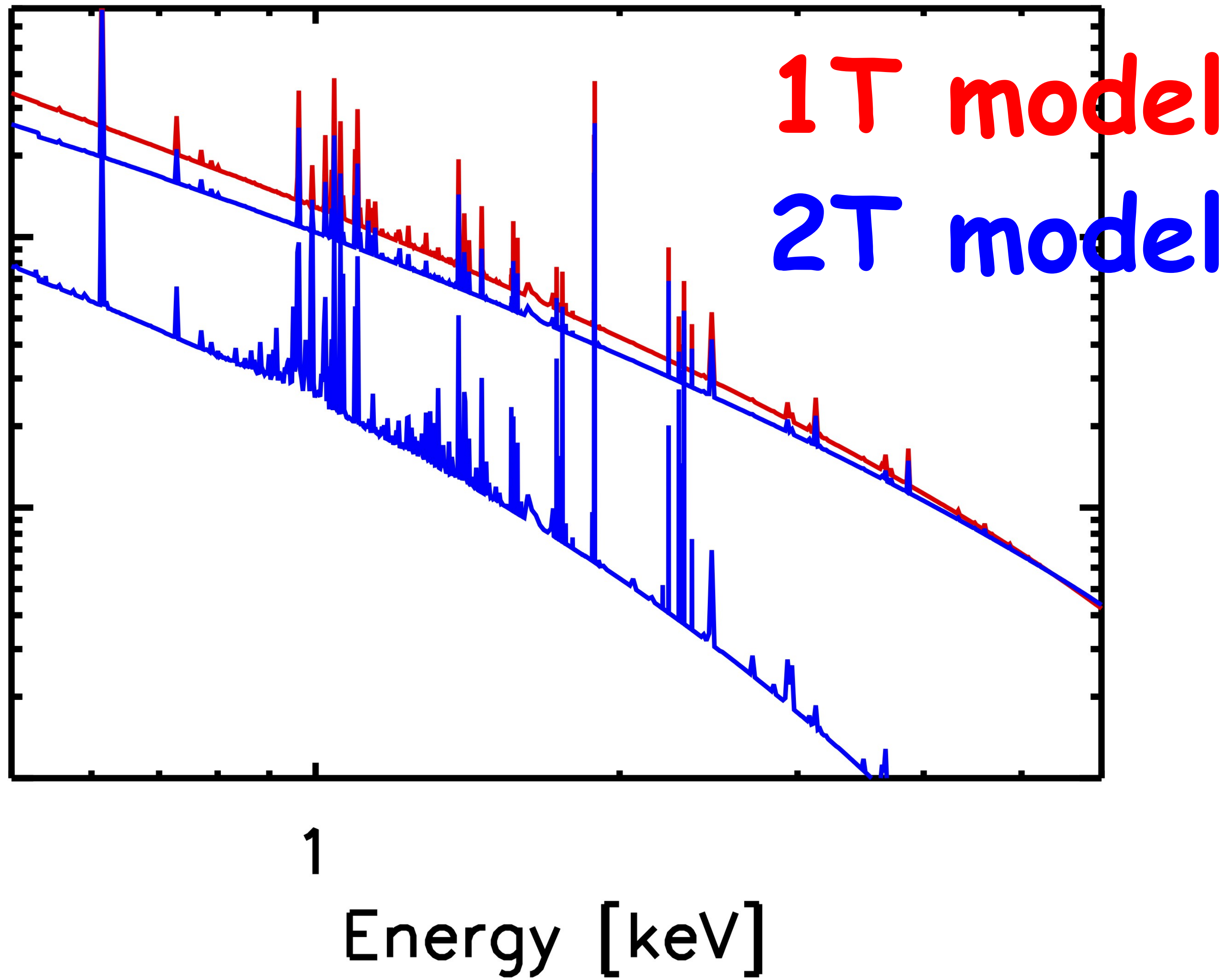
i = MOS1

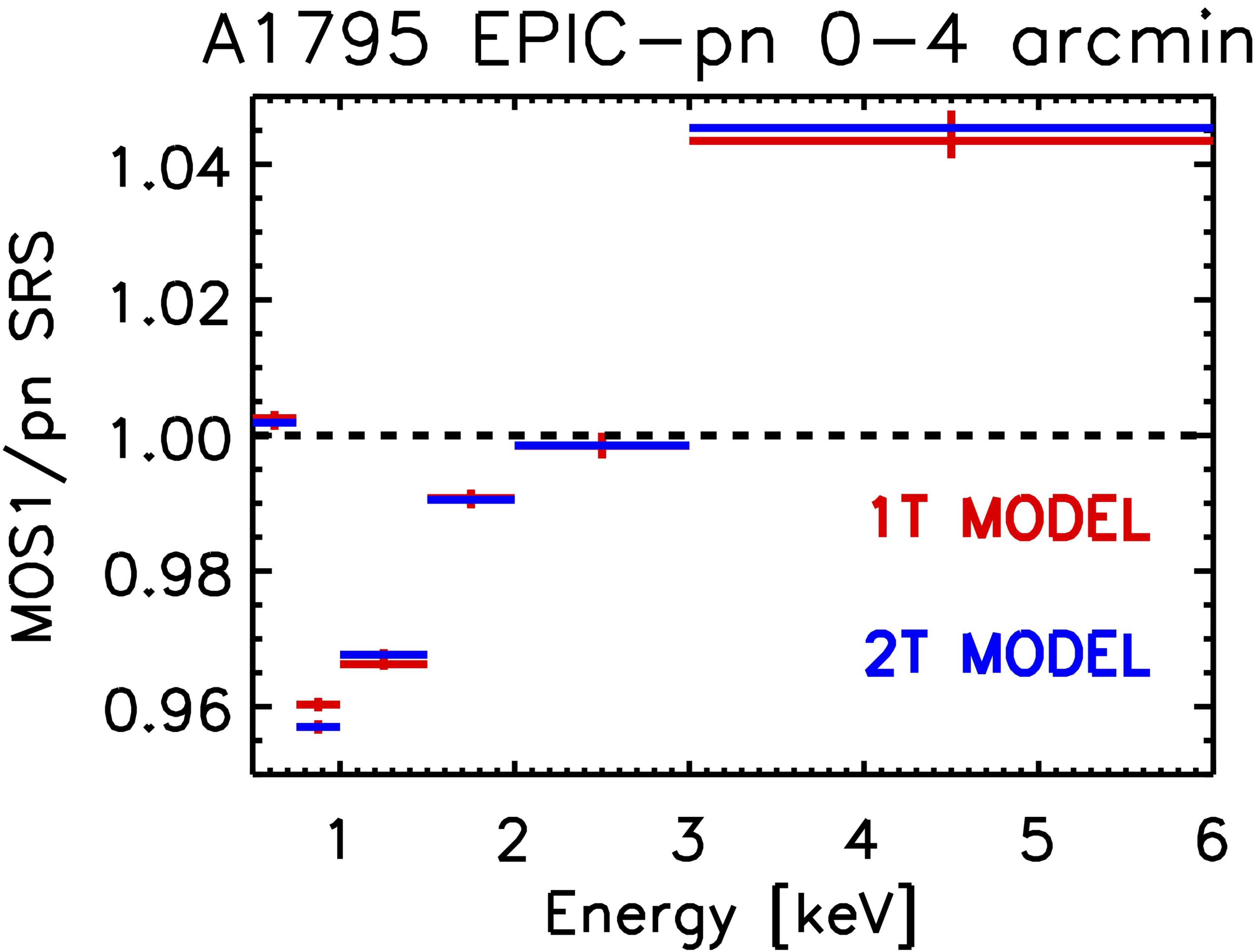
$$RR_{i\,/ref} = \frac{data_i}{model_{ref}\ \hat{u}\ \ resp_i} \times \frac{model_{ref}\ \hat{u}\ \ resp_{ref}}{data_{ref}}$$


A1795 EPIC-pn 0-4 arcmin
pn effarea too hard
or
MOS1 effarea too soft
1T MODEL
MOS1/pn SRS
1.04
1.02
1.00
0.98
0.96
1
2
3
4
5
6
Energy [keV]

3.1) Reference model accuracy does not matter for the RELATIVE calibration PROOF:

A1795 EPIC-pn 0-4 arcmin





A1795 EPIC-pn 0-4 arcmin
MOS1/pn SRS
1.04
1.02
1.00
0.98
0.96
1T MODEL
2T MODEL
1
2
3
4
5
6
Energy [keV]

- If we minimise the line emission (see below) and have only continuum, then

$$model\,\hat{u}\;\;resp \approx model \times arf \rightarrow$$

$$R_{i\,/ref} = \frac{data_i}{model_{ref}\,\hat{u}\;\;resp_i} \times \frac{model_{ref}\;\hat{u}\;\;resp_{ref}}{data_{ref}} \rightarrow$$

$$R_{i\,/ref} = \frac{data_i}{model_{ref} \times arf_i} \times \frac{model_{ref} \times arf_{ref}}{data_{ref}} \rightarrow$$

$$R_{i\,/ref} = \frac{data_i}{arf_i} \times \frac{arf_{ref}}{data_{ref}}$$

we do not need the refence model at all

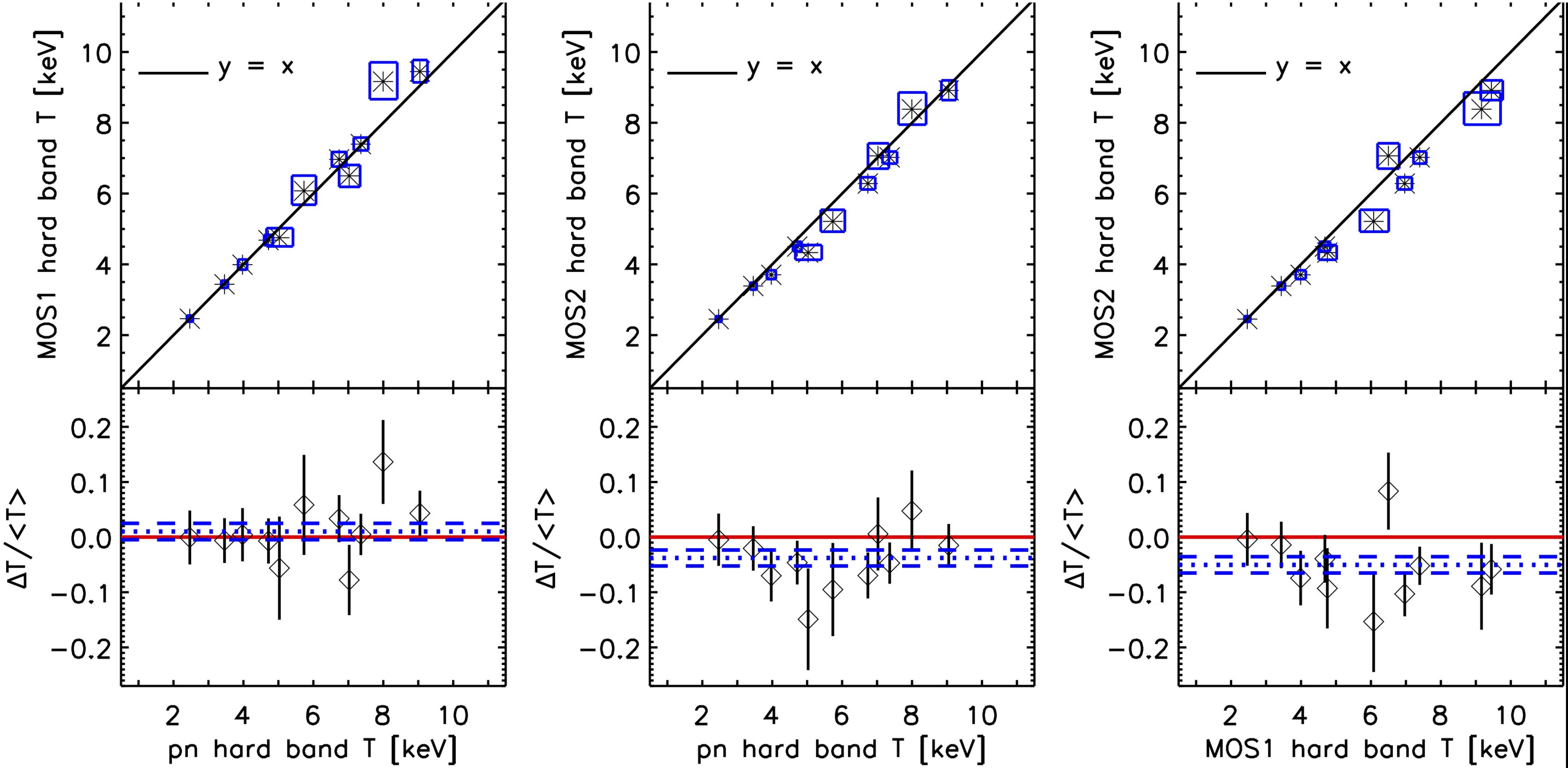
4) Results

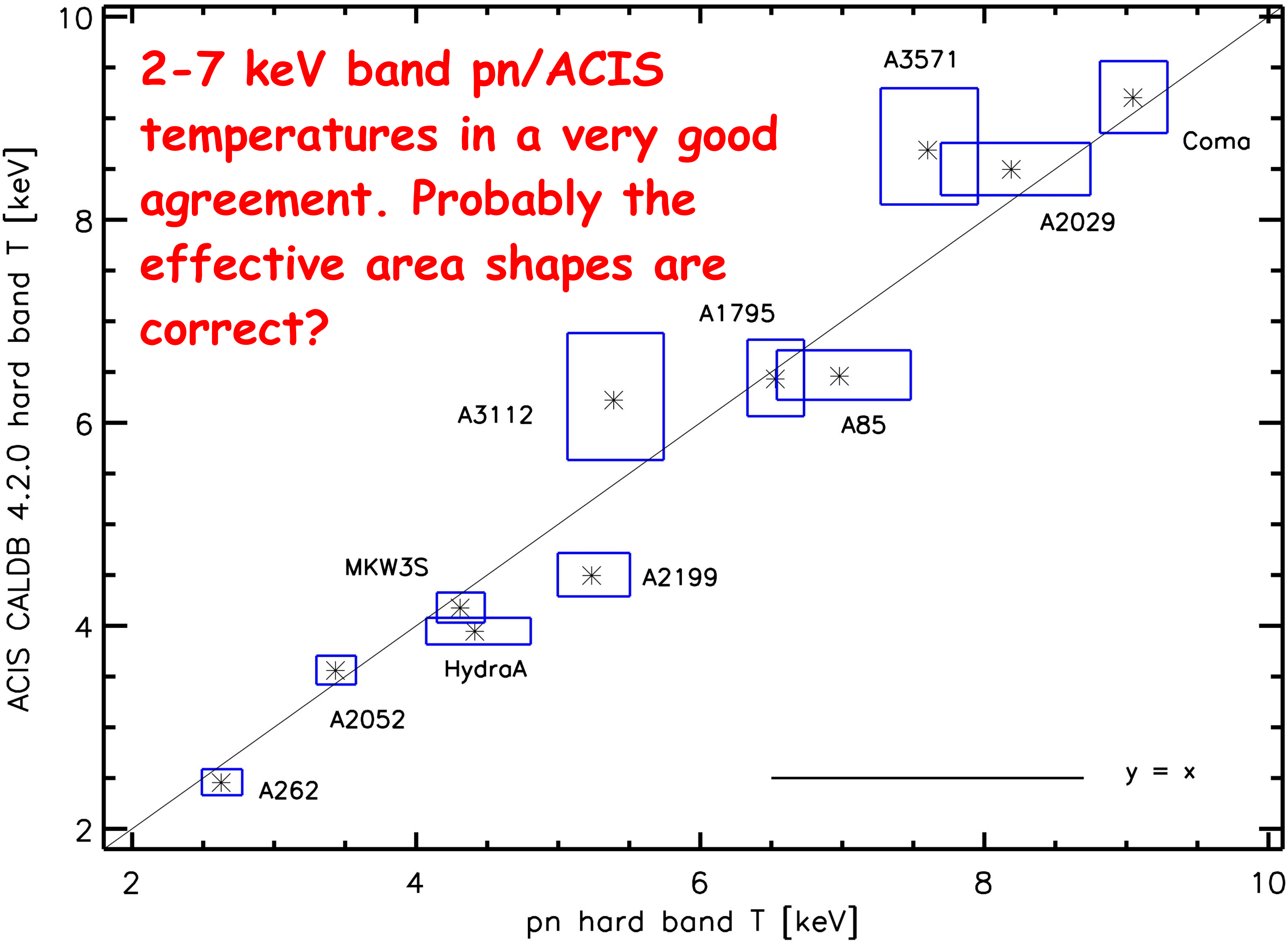
Cross-calibrating X-ray detectors with clusters of galaxies: an IACHEC study

J.Nevalainen et al. , 2010, A&A, 523, 22 (N10+)

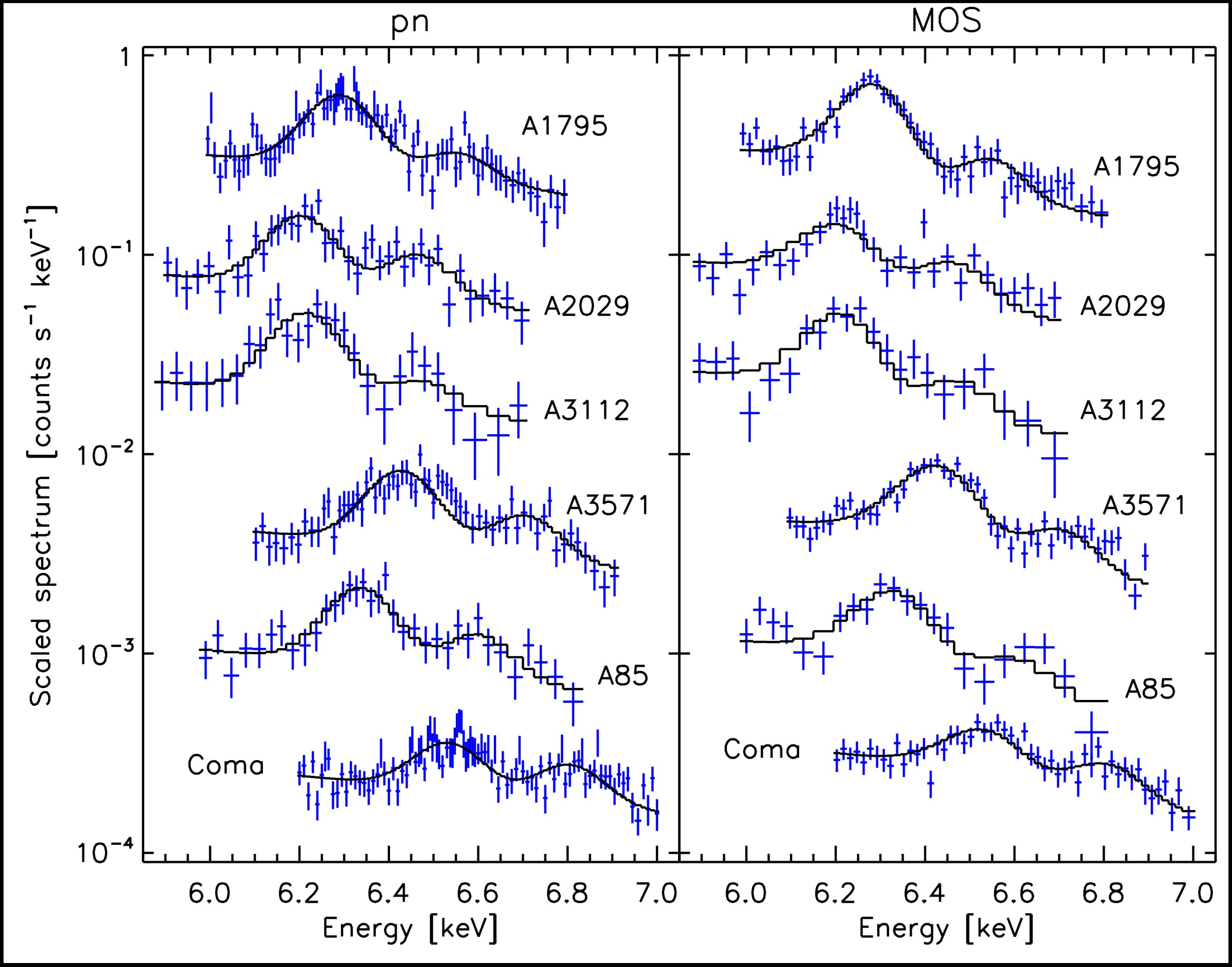
- At the early days, we used temperature comparisons to study the effective area cross-calibration
- Use used the quite isothermal regions 0.1-0.3 r_{500}

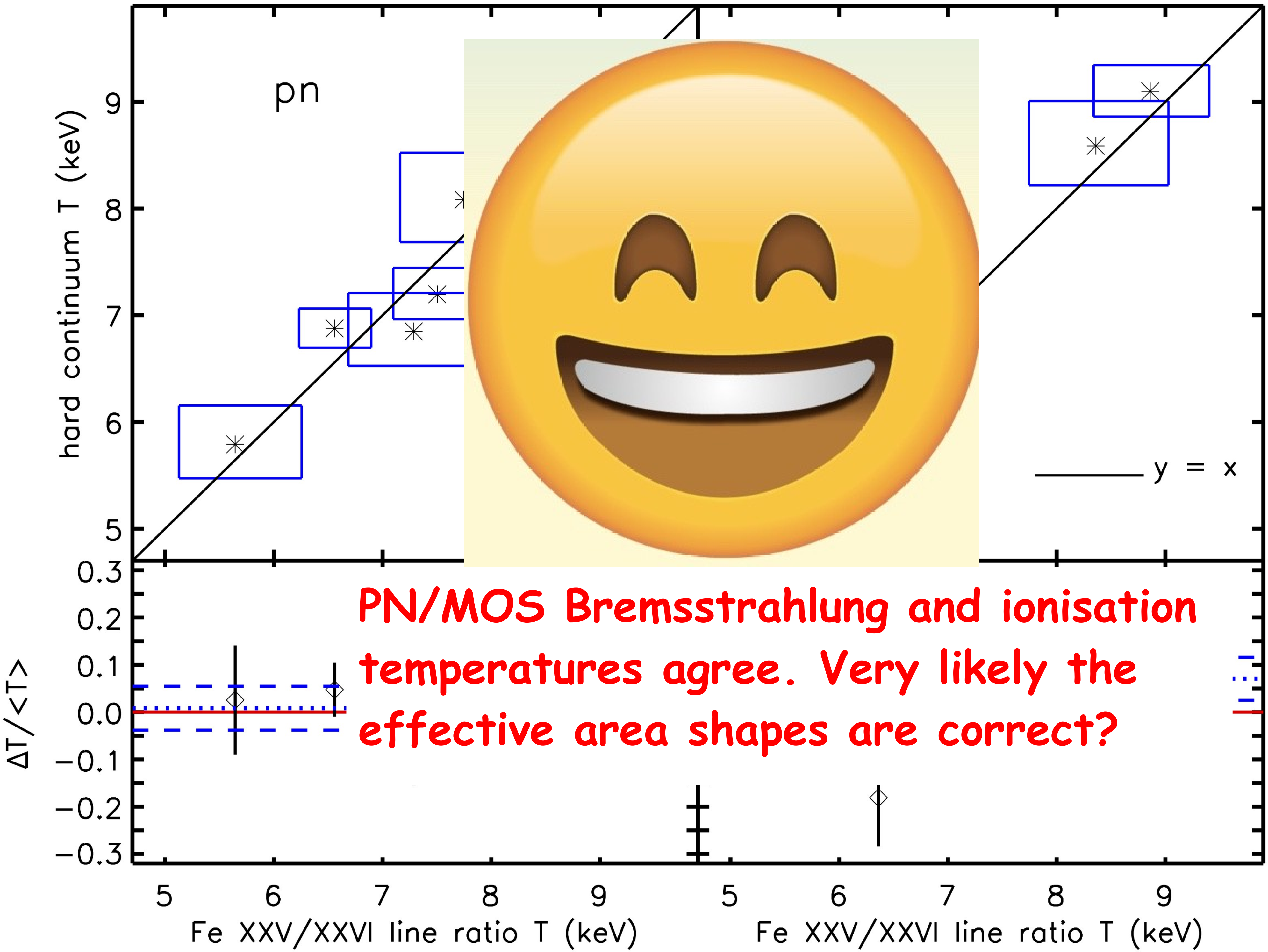
2-7 keV band pn/MOS1/MOS2 temperatures in a very good agreement. Perhaps the effective area shapes are correct?




2-7 keV band pn/ACIS temperatures in a very good agreement. Probably the effective area shapes are correct?
A3571
Coma
A2029
A1795
A3112
A85
MKW3S
A2199
HydraA
A2052
A262
y = x
ACIS CALDB 4.2.0 hard band T [keV]
pn hard band T [keV]
2
4
6
8
10

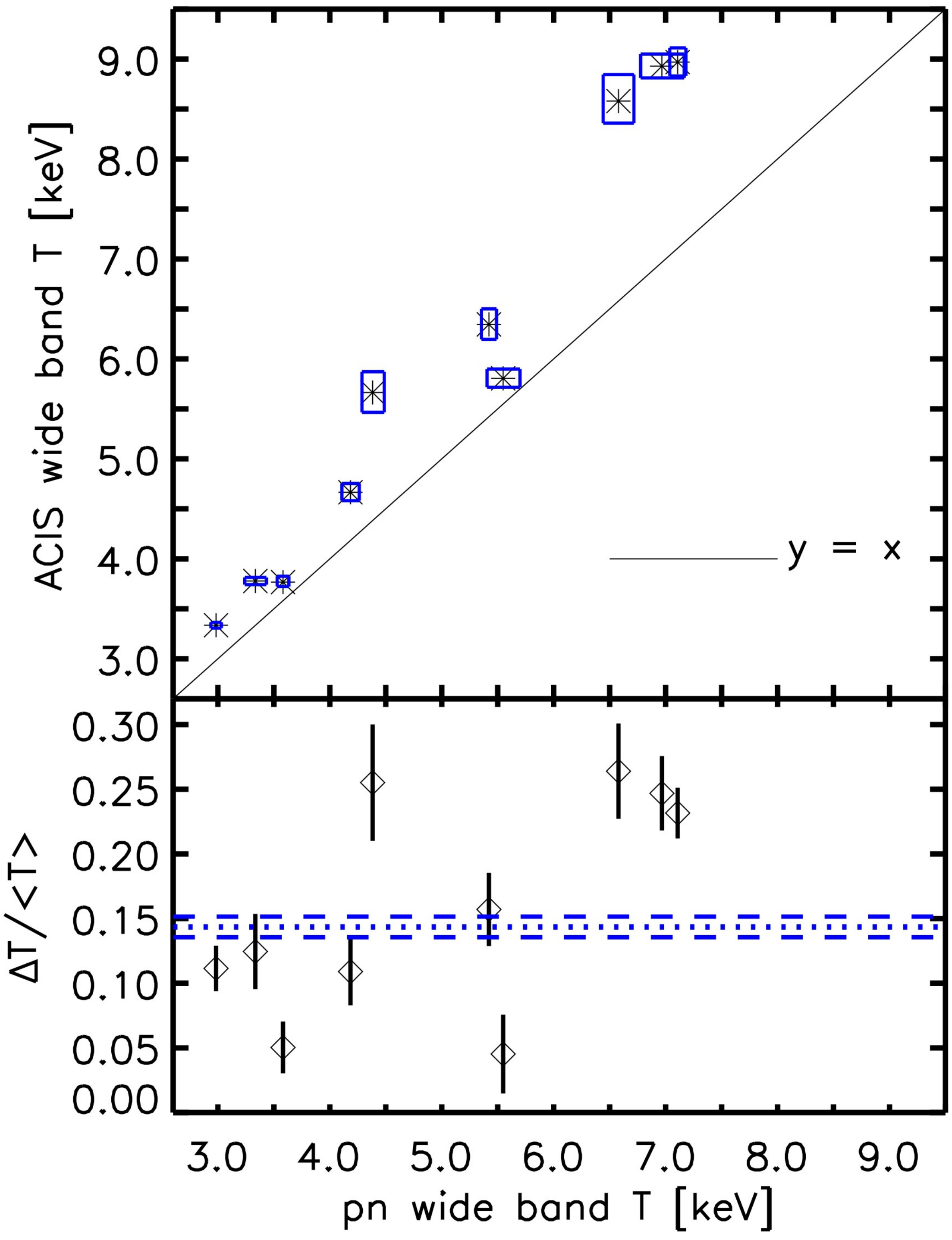
T(bremmstrahlung) v.s. T(ionisation) test




pn
hard continuum T (keV)
y = x
ΔT/<T>
PN/MOS Bremsstrahlung and ionisation temperatures agree. Very likely the effective area shapes are correct?
Fe XXV/XXVI line ratio T (keV)
Fe XXV/XXVI line ratio T (keV)

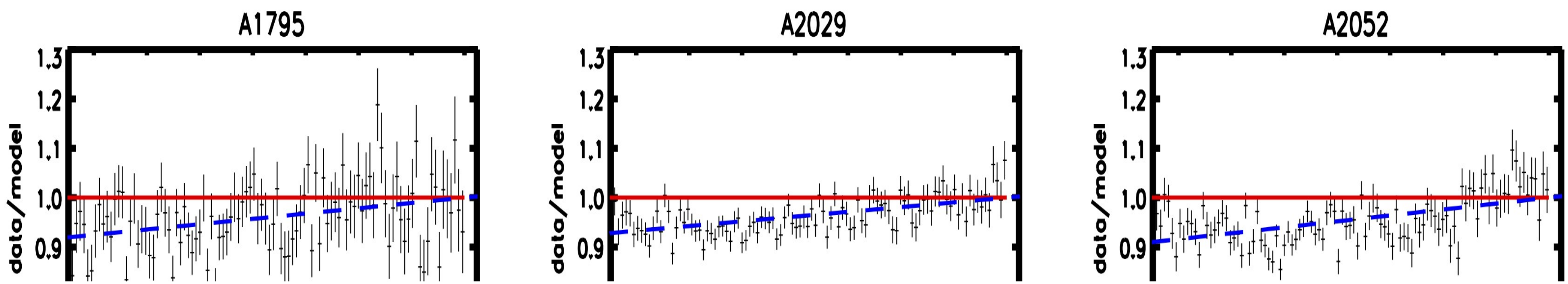
How about the full 0.5-7.0 keV band?

ACIS gives much higher wide band temperatures than pn

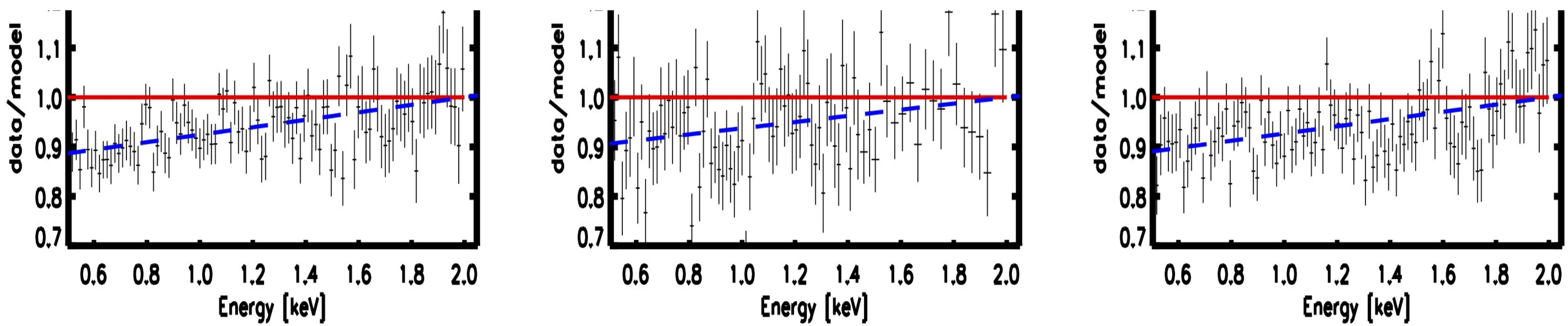


Residuals ratio

pn model x ACIS ARF v.s. ACIS data

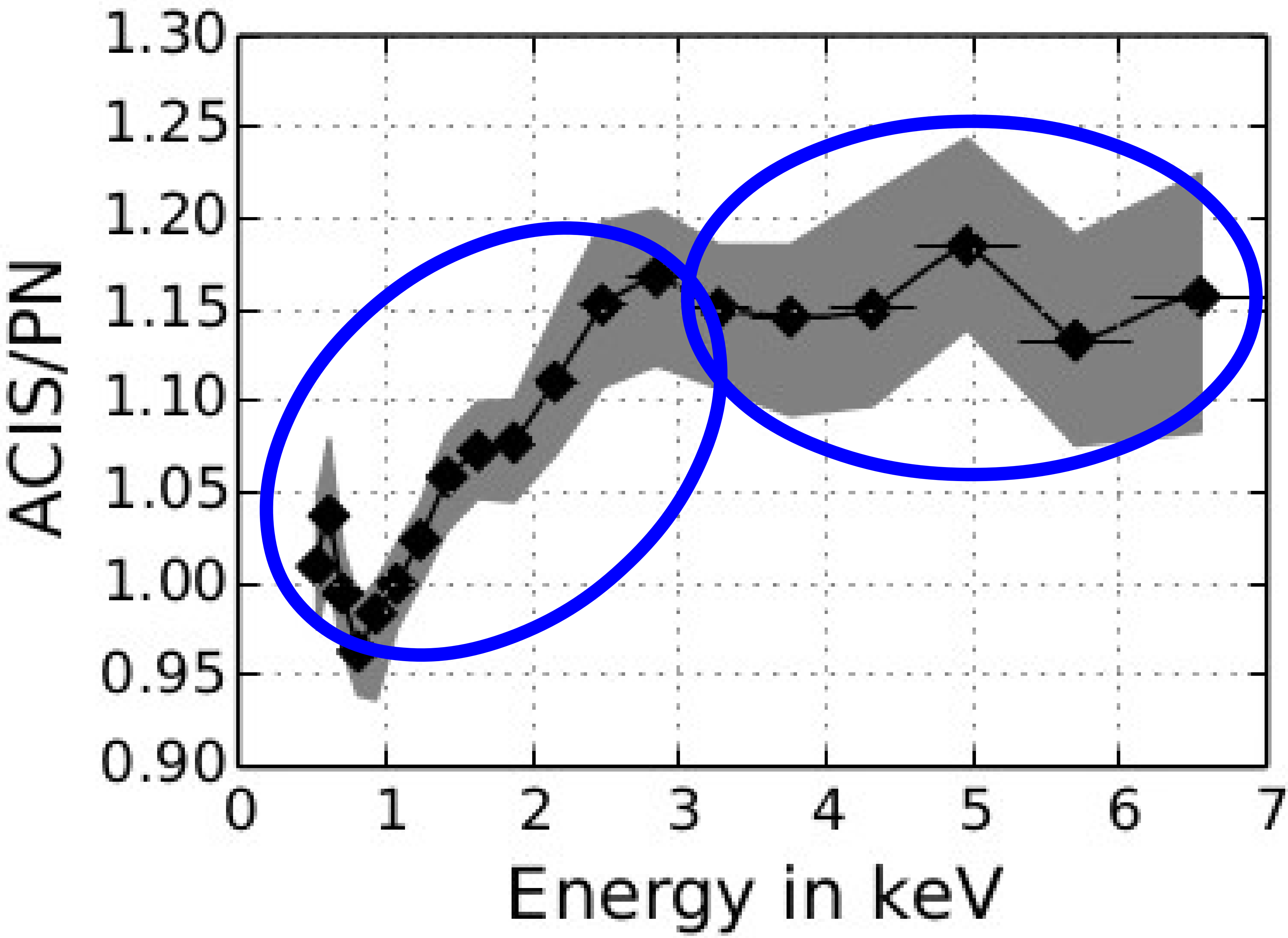


If ACIS A_{eff} shape correctly calibrated, pn model too soft, i.e. pn effarea too hard

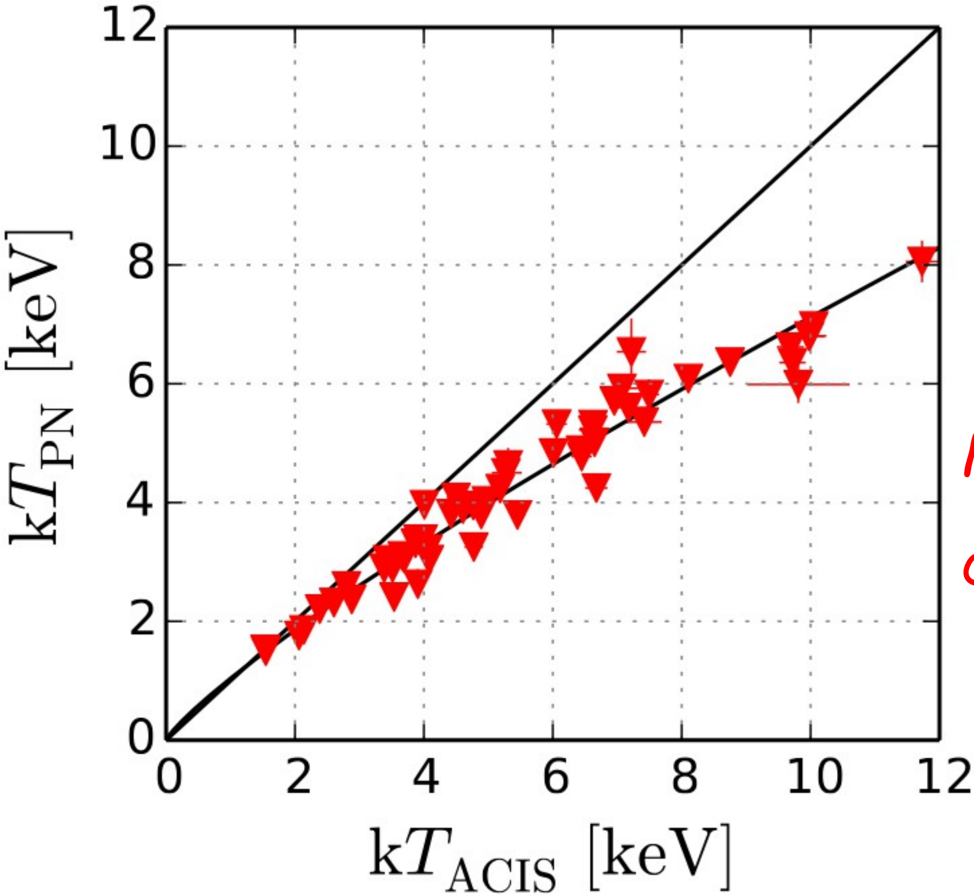


HIFLUGCS
Schellenberger et al., 2015, A&A, 575, 30

Similar as in N10+



Scaling between ACIS and pn 0.7-7.0 keV band temperatures



$M_{X\text{-}ray}$(XMM) ≠ $M_{X\text{-}ray}$(Chandra) ....
cosmology

$$\log \frac{\{kT_{pn}\}}{\{1\,keV\}} = 0.836 \times \log \frac{\{kT_{ACIS}\}}{\{1\,keV\}} + 0.016$$

- MODARF - Python-Script for modification of XMM-Newton/EPIC and Chandra/ACIS effective areas according to the stack residual ratios in Schellenberger et al. 2015, A&A, 575, 30
- MODARF tool in the IACHEC WIKI page:

https://wikis.mit.edu/confluence/display/iachec/Data3

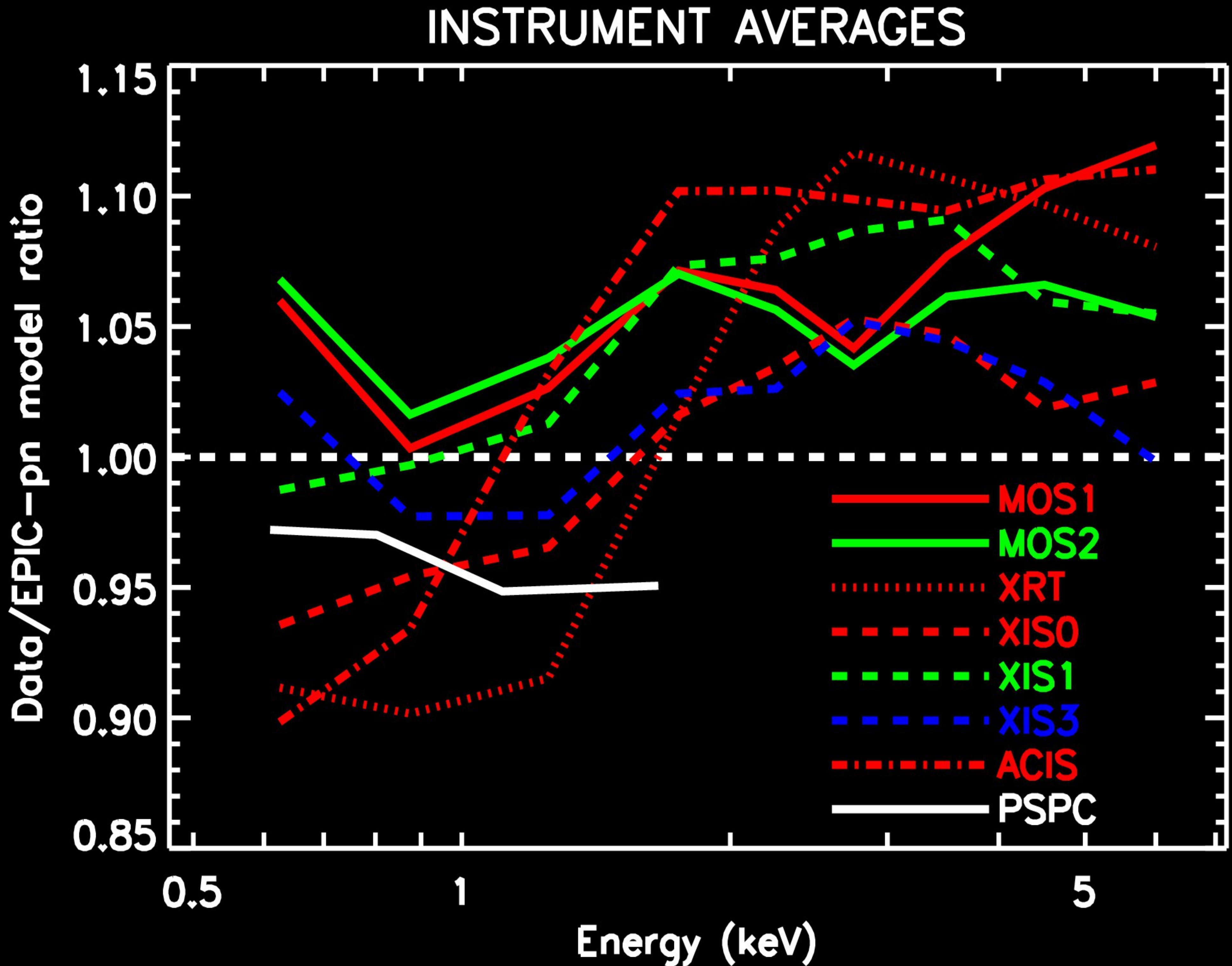
- Modifies the input arf, assuming the user-defined reference instrument arf is accurately calibrated

Multi-Mission Study

J. Nevalainen, A. Beardmore, L. David, E. Miller, S. Snowden

Multi-Mission Study

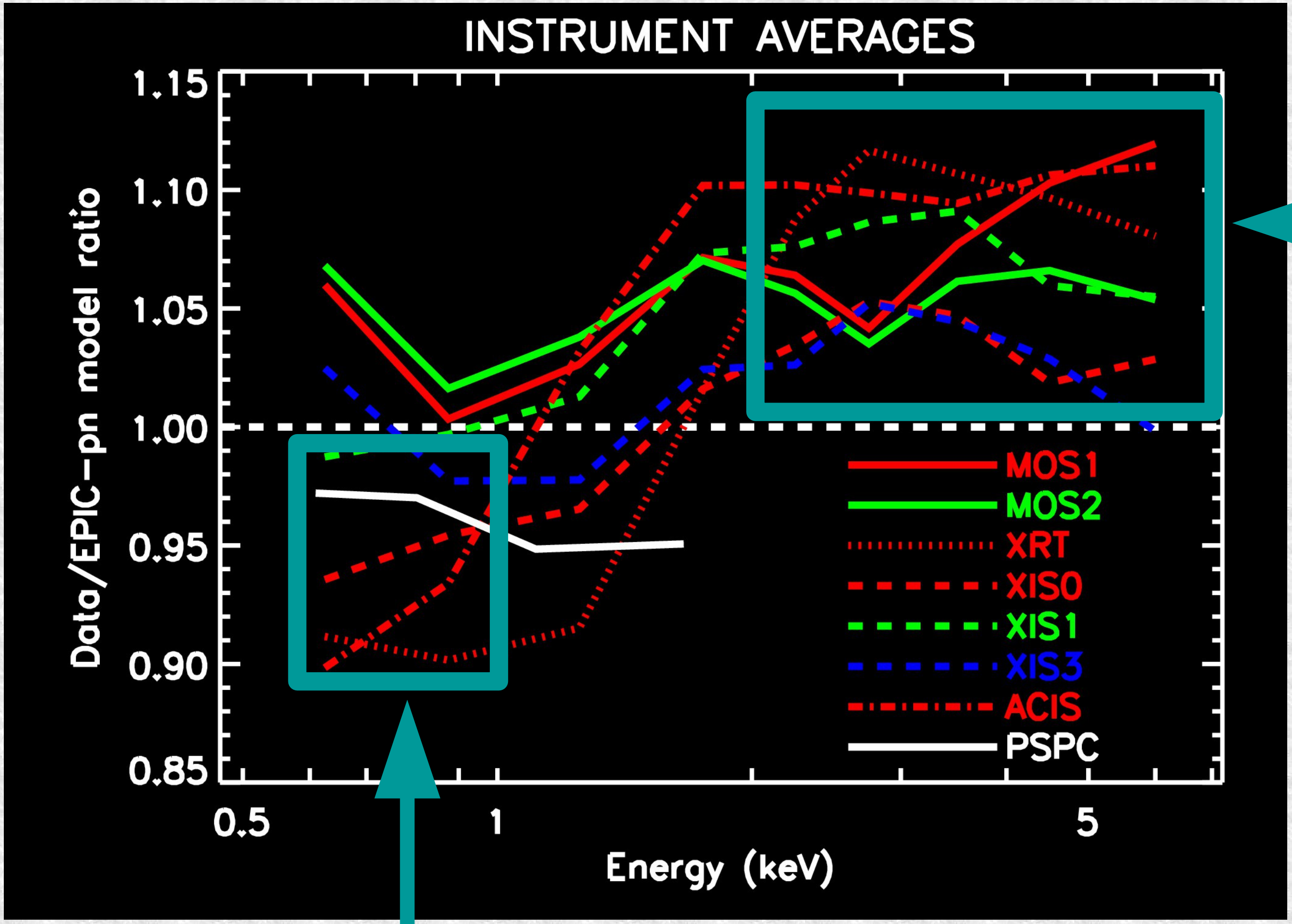
- Cross-calibration of XMM-Newton/EPIC, Chandra/ACIS, Suzaku/XIS ROSAT/PSPC and SWIFT/XRT
- 0-6 arcmin extraction region centered at the X-ray peak
- Systematics for other missions TBD
- EPIC-pn as a reference instrument
- Preliminary results for 4 clusters



INSTRUMENT AVERAGES
Data/EPIC-pn model ratio
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.5
1
5
Energy (keV)
MOS1
MOS2
XRT
XIS0
XIS1
XIS3
ACIS
PSPC

Residuals ratios

The average instr/pn residual ratio of each pair

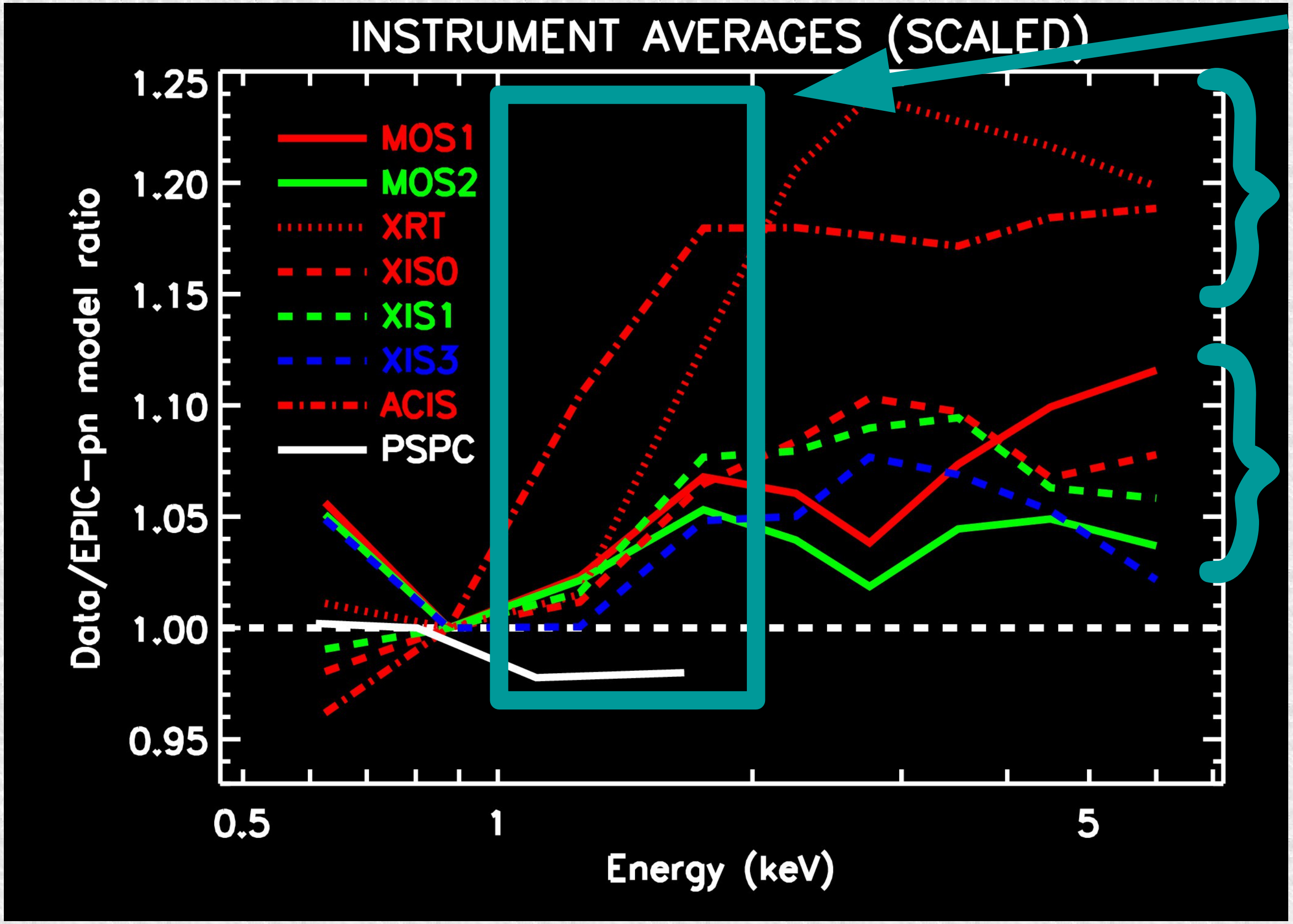


All instruments show higher flux than pn at > 2 keV, but with a varying degree (0-15%)

Most instruments show lower flux than pn at < 1 keV, but with a varying degree (0-10%)

Scaled residuals ratios

The average instr/pn residual ratio of each pair, scaled to unity at 0.75-1.0 keV

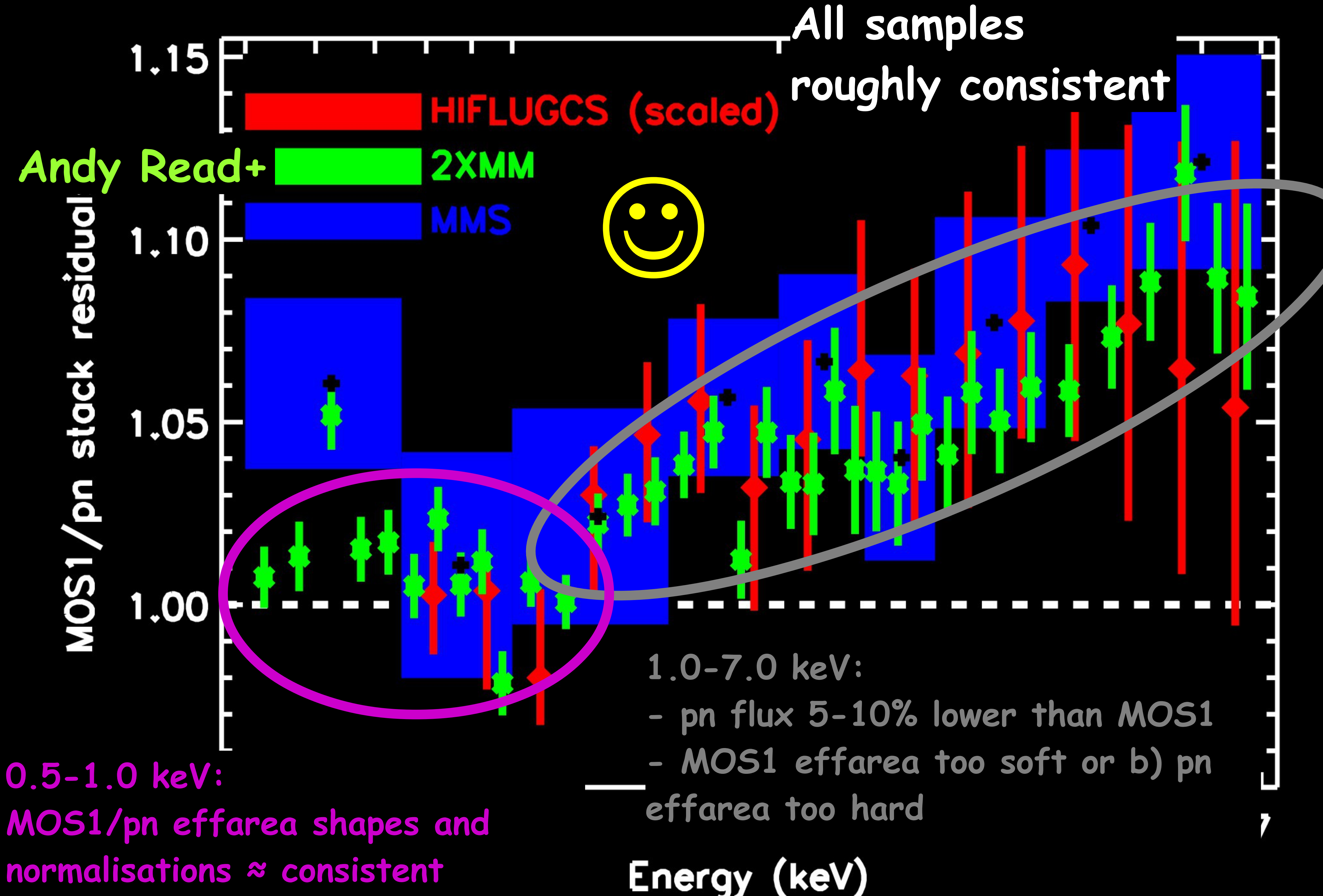


The 1-2 keV gradient:

1) Swift/XRT and Chandra/ACIS similar: 20% increase

2) XMM/MOS and Suzaku/XIS similar: 5% increase

➔ Not a single instrument is guilty


All samples roughly consistent
HIFLUGCS (scaled)
Andy Read+
2XMM
MMS
1.15
1.10
1.05
1.00
MOS1/pn stack residual
Energy (keV)
1.0-7.0 keV:
- pn flux 5-10% lower than MOS1
- MOS1 effarea too soft or b) pn effarea too hard
0.5-1.0 keV:
MOS1/pn effarea shapes and normalisations ≈ consistent

SUMMARY

- Using clusters we can obtain cross-calibration information btw. EPIC instruments at 1% systematical and statistical uncertainty level
- Clusters and blazars give a consistent picture of pn/MOS effective area cross-calibration
- Clusters show significant pn/MOS and EPIC/ACIS problems
- The different calibration teams should try to figure out TOGETHER what is causing this