Concordance:
In-Flight Calibration of X-ray Telescopes
without
Absolute References

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The Goal

- The problems
  - Discrepant results from X-ray observatories in orbit
    - Cluster temperatures and fluxes
    - Blazar fluxes from simultaneous observations
    - SNR line fluxes
  - Imperfect ground cal, performance changes in flight
    - Instrument area priors a_i differ from "true values" A_i
  - No absolute calibrators across all bands in flight: no "true" F_j
- Specific task: derive $\hat{A}_i$ for optimal agreement

➡ Let flux $f_{ij} = c_{ij}/T_{ij}/a_i$

where a_i = prior on A_i

c_{ij} = observed counts

T_{ij} = known exposure time

Some Poor Methods

- Use the average flux as the 'true' flux: $F_j = < f_{ij} >$
  - If statistical weighting, answer depends on T_{ij} and a_i
  - If no weighting, then "agnostic" but not stable
  - Problematic statistical inference: $\hat{A}_i = \dfrac{c_{ij}}{T_{ij}F_j}$
- Use one instrument as "given": $F_j = f_{Xj}$ for some X
  - Reference choice is subjective
  - Still problematic statistically

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Better: Multiplicative Shrinkage
(Chen+ '19)

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$$y_{ij} = B_i + G_j - \frac{\sigma_i^2}{2} + e_{ij} \quad , \quad y_{ij} \equiv \log(c_{ij}/T_{ij}) \quad , \quad B_i \equiv \log A_i \quad , \quad G_j \equiv \log F_j$$

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$\hat{B}_i = W_i(\bar{y}'_{i\cdot} - \bar{G}_i) + (1 - W_i)b_i$ and $\hat{G}_j = \bar{y}'_{\cdot j} - \bar{B}_j$

$$W_i = \frac{M\sigma_i^{-2}}{\tau_i^{-2} + M\sigma_i^{-2}}$$

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EA prior uncertainties

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EA prior uncertainties

Data uncertainties

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$$\hat{B}_i = W_i(\bar{y}'_{i\cdot} - \bar{G}_i) + (1 - W_i)b_i \quad \text{and} \quad \hat{G}_j = \bar{y}'_{\cdot j} - \bar{B}_j$$

$$\tilde{y}'_{ij} = \tilde{y}_{ij} + 0.5\sigma_i^2 \ , \ \bar{y}'_{i\cdot} = \frac{\sum_{j=1}^{M} \tilde{y}'_{ij}\sigma_i^{-2}}{\sum_{j=1}^{M} \sigma_i^{-2}}, \quad \bar{y}'_{\cdot j} = \frac{\sum_{i=1}^{N} \tilde{y}'_{ij}\sigma_i^{-2}}{\sum_{i=1}^{N} \sigma_i^{-2}}, \quad \bar{G}_i = \frac{\sum_{j=1}^{M} \hat{G}_j\sigma_i^{-2}}{\sum_{j=1}^{M} \sigma_i^{-2}}, \quad \bar{B}_j = \frac{\sum_{i=1}^{N} \hat{B}_i\sigma_i^{-2}}{\sum_{i\in I_j} \sigma_i^{-2}}$$

$$W_i = \frac{M\sigma_i^{-2}}{\tau_i^{-2} + M\sigma_i^{-2}}$$

EA prior uncertainties (τ_i^{-2}) — Data uncertainties ($M\sigma_i^{-2}$)

Input Data

- Paper I
  - 1E0102 with 13 instruments (N=13), O & Ne (M=2)
  - 2XMM catalog targets, N=3, M=41; soft, medium, hard
  - XCAL bright targets, N=3, M=94-108; soft, medium, hard
- New paper (Marshall+, in prep.)
  - Same 3 sets as in Paper I
  - Also Capella with Chandra gratings, N=8, M=15
  - Added correlations of XMM hard, medium, soft
  - Added correlations of O, Ne fluxes of 1E0102
  - Used heterogeneous tau values

Table 5. *2XMM* Concordance Fluxes – Medium Band[a]

Target	pn		MOS1		MOS2	
	f_{ij}	σ_{ij}	f_{ij}	σ_{ij}	f_{ij}	σ_{ij}
1127-145	0.481	0.049	0.496	0.053	0.490	0.052
1E0919+515	0.053	0.053	0.069	0.066	0.068	0.065
4C06.41	0.131	0.015	0.142	0.017	0.143	0.018
APM08279+5255	0.085	0.041	0.088	0.042	0.082	0.040
CenX-4	0.088	0.035	0.089	0.022	0.091	0.023
CoD-33 7795	0.275	0.136	0.287	0.143	0.276	0.136
ESO323-G077	0.425	0.184	0.438	0.202	0.439	0.203
GRB080411	0.348	0.006	0.415	0.008	0.419	0.009
Holmberg IX	0.514	0.083	0.517	0.084	0.556	0.090
IRAS13197-1627	0.938	0.818	0.914	0.793	1.000	0.873
LBQS1228+1116	0.154	0.009	0.156	0.010	0.162	0.010
M31 NN1	0.173	0.005	0.196	0.007	0.195	0.007
MS0205.7+3509	0.283	0.087	0.304	0.095	0.293	0.092
MS1229.2+6430	0.326	0.086	0.356	0.092	0.355	0.101
NGC 1313	0.200	0.021	0.212	0.023	0.215	0.023
NGC 4278	0.281	0.032	0.291	0.035	0.307	0.037
NGC 5204 X-1	0.140	0.032	0.140	0.033	0.148	0.036
NGC 5204 X-1	0.192	0.034	0.195	0.035	0.196	0.036
NGC 5252	0.326	0.092	0.327	0.095	0.328	0.091

Sample Data (Marshall+ in prep.)

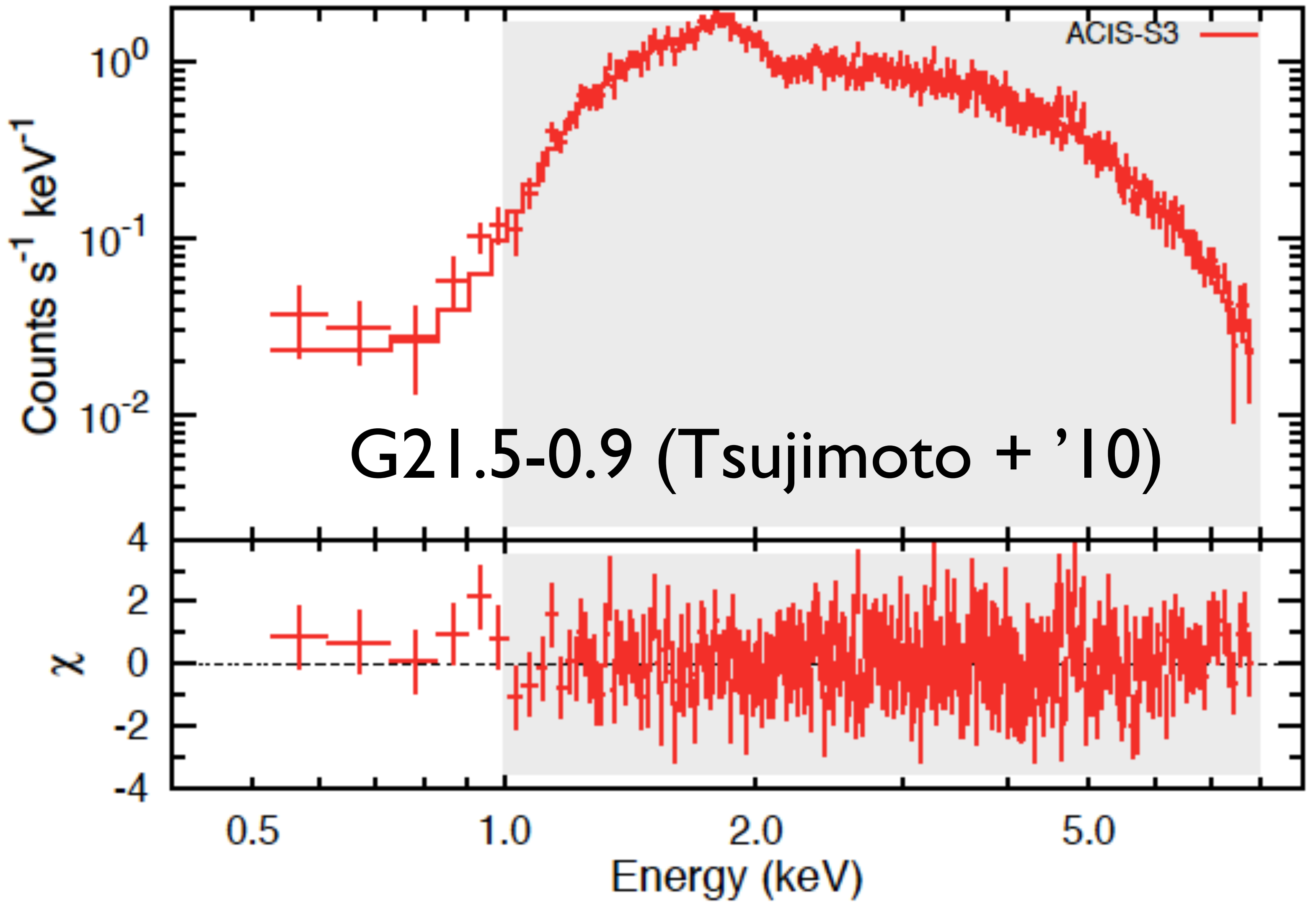
Complications I: Flux Measurements

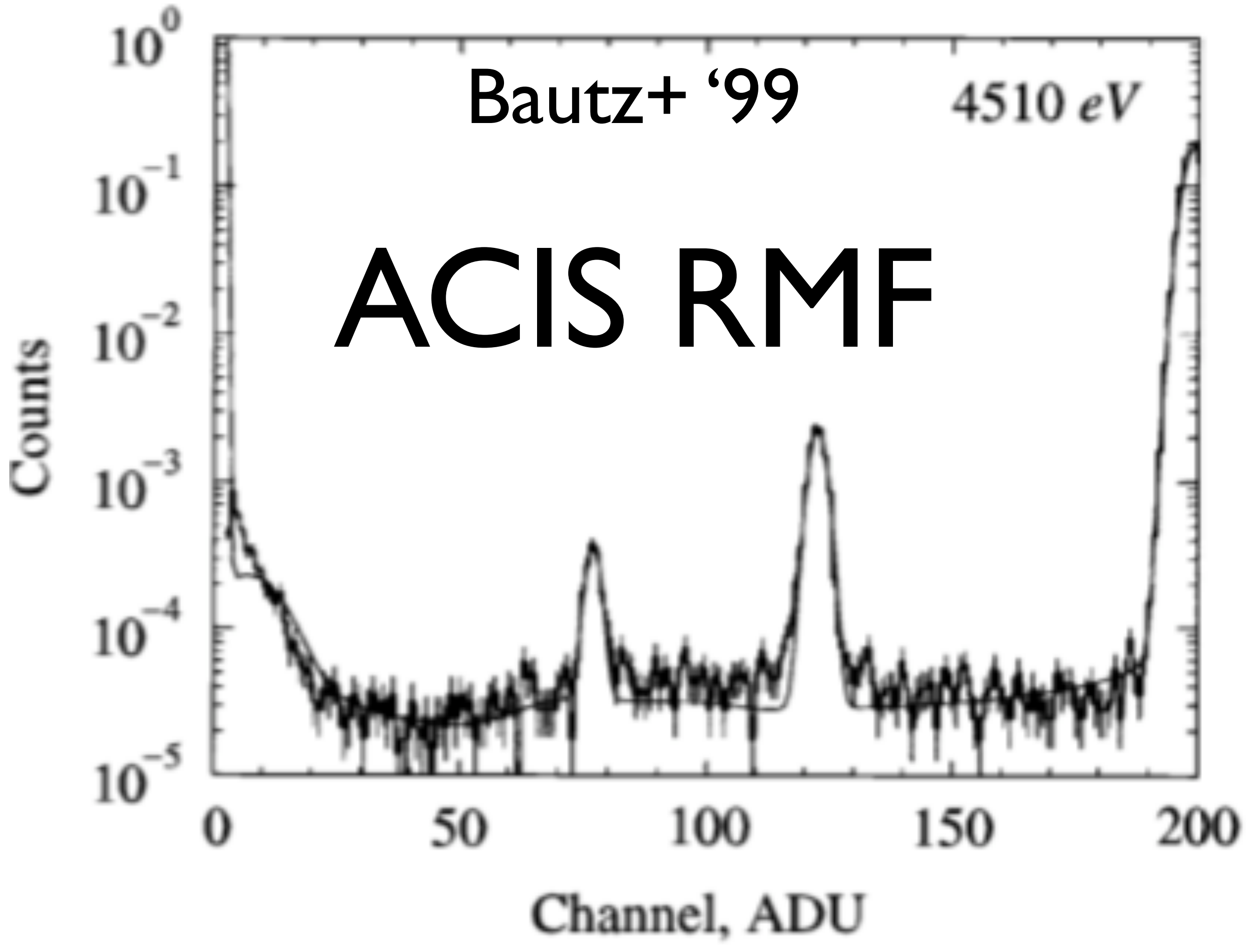
Concordance: find A_i where $C_{ij} = T_{ij}A_iF_j \quad , \quad A(E) = A_i\alpha_i(E)$

- Fluxes in band (E_1, E_2) derived by an inversion process
- Input: observation c_{ijk} for counts in channel k
- Then fit to model $C'_{ijk} = t_{ij}a_if_{ij}\frac{\int_{E_1}^{E_2}\alpha_i(E)q_j(E)\Phi_k(E)dE}{\int_{E_1}^{E_2}q_j(E)dE} = T_{ijk}a_if_{ij}$

where $f_{ij} = \int_{E_1}^{E_2} n_E(\Theta_{ij})dE = n_{ij}\int_{E_1}^{E_2} q_j(E)dE$ and $\tilde{A}(E) = a_i\alpha_i(E)$ define shape functions $q_j(E)$ and $\alpha_i(E)$, the detector response is $\Phi_k(E)$, and $\sum_k \Phi_k(E) = 1$

Now, $C_{ij} = \sum_k C_{ijk} \quad , \quad T_{ij} = \sum_k T_{ijk}$





Complications II: Eff. Area Correlations

- Assume we have EA parameters $\overrightarrow{\xi}$ giving $\log \tilde{A}(E; \overrightarrow{\xi}) = \tilde{B}(E; \overrightarrow{\xi})$ with $p(\overrightarrow{\xi})$
- Then $\hat{B}(E) = \int \tilde{B}(E; \overrightarrow{\xi}) p(\overrightarrow{\xi}) d\overrightarrow{\xi}$ is the best (prior) estimate of B and $\tau^2(E) = \int [\tilde{B}(E; \overrightarrow{\xi}) - \hat{B}(E)]^2 p(\overrightarrow{\xi}) d\overrightarrow{\xi}$ should be the prior's variance
- Consider two energies, E_i and $E_{i'}$, then the correlation between these is $\rho_{i,i'} = \frac{1}{\tau(E_i)\tau(E_{i'})} \int [\tilde{B}(E_i; \overrightarrow{\xi}) - \hat{B}(E_i)][\tilde{B}(E_{i'}; \overrightarrow{\xi}) - \hat{B}(E_{i'})] p(\overrightarrow{\xi}) d\overrightarrow{\xi}$
- In reality, a Monte Carlo method is used to compute the correlations…

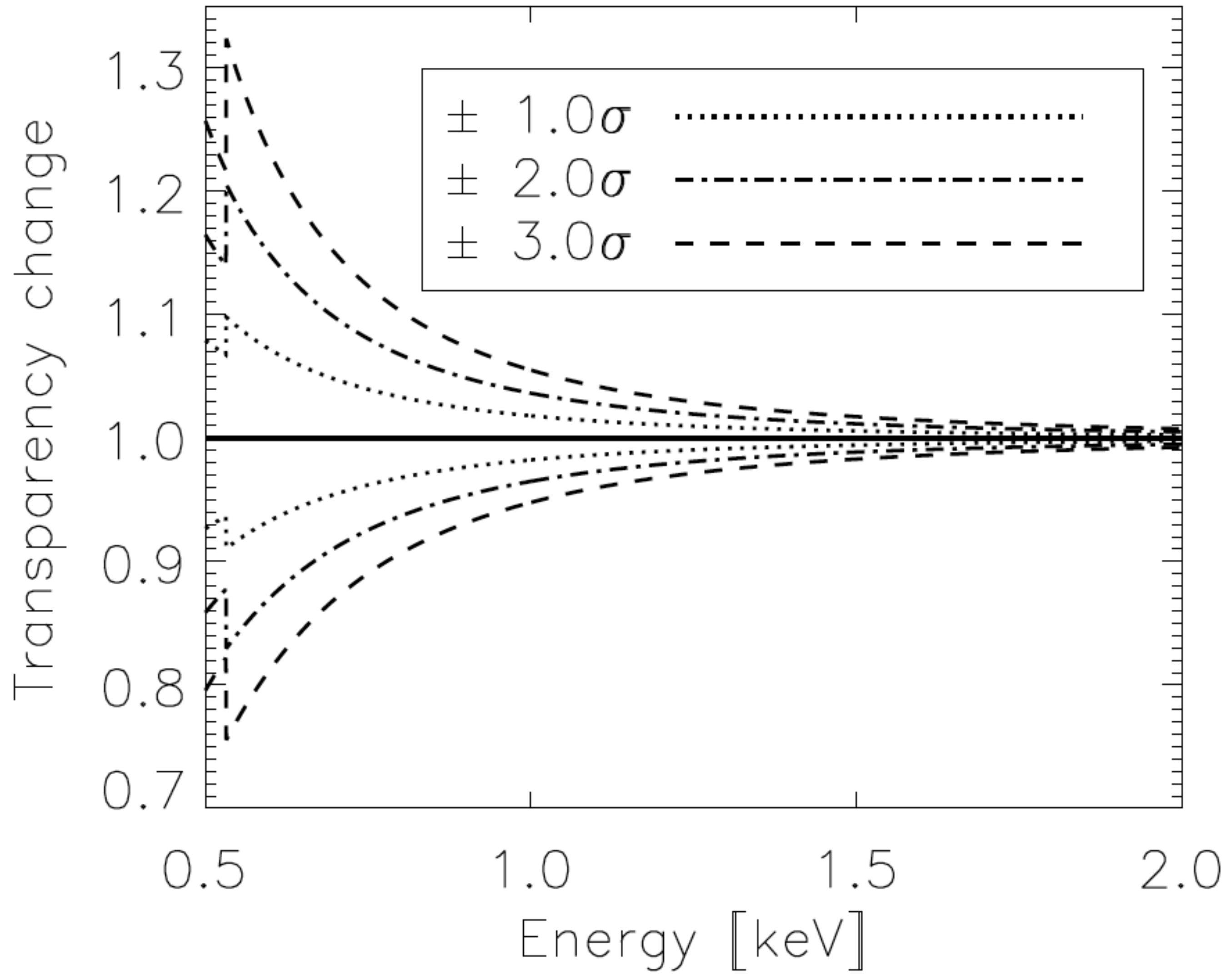


Table 8. Correlation matrix for 2XMM and XCAL Analyses

Band	Soft band	Medium band	Hard band
Soft band	1	0.60	0.13
Medium band	0.60	1	0.53
Hard band	0.13	0.53	1

Complications III: Assessing Priors

- Collecting ***prior*** (fractional) uncertainties on effective areas
- Cal scientists assessed their instruments

Table 1. Effective Area Uncertainty Priors (τ_i)[a]

	Energy Bands (keV)								
Instrument	0.15-0.33	0.33-0.54	0.54-0.8	0.8-1.2	1.2-1.8	1.8-2.2	2.2-3.5	3.5-5.5	5.5-10
Astrosat SXT	···	15	15	10	10	10	10	10	10
Chandra ACIS	3	3	3	3	2.6	3.3	3.3	4.9	5
Chandra HETGS	···	···	10	5	4	4	4	5	7
Chandra LETGS	5	7	7	7	7	7	7	10	10
ROSAT PSPC	10	10	10	10	10	10	···	···	···
Suzaku XIS1	···	20	15	10	10	15	5	5	5
Suzaku XIS0,2,3	···	···	15	10	10	15	5	5	5
Swift PC/WT	···	15	10	7.5	7.5	10	5	5	5
XMM MOS1,2	20	10	6	6	6	6	6	6	10
XMM pn	2	2	2	2	2	2	2	2	3
XMM RGS	···	8	5	5	5	···	···	···	···

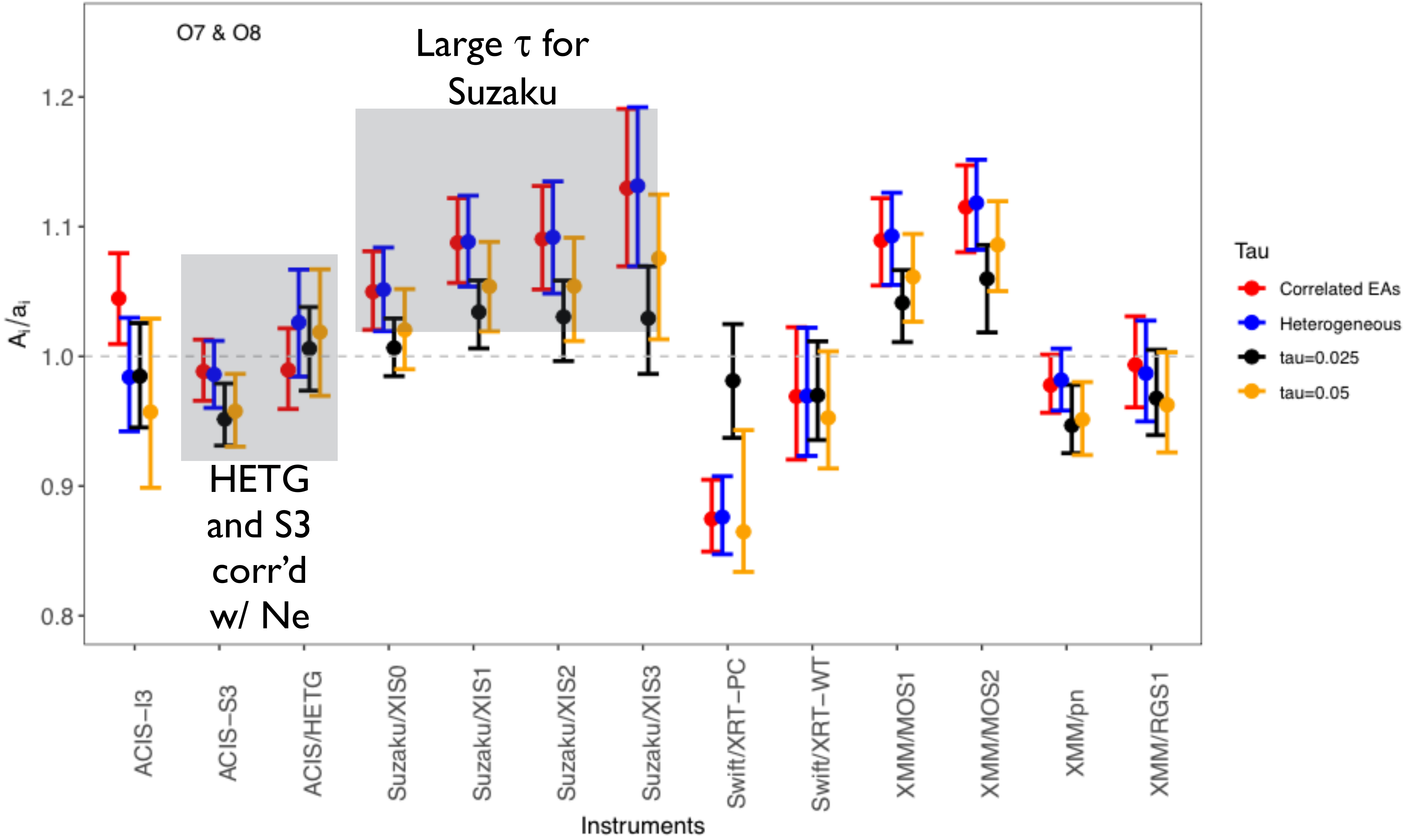
[a]The τ_i values are given as percentages. The ellipses indicate bandpasses where the instrument has an insignificant effective area.

Table 2. Effective Area Uncertainty Priors (τ_i)[a]

	Energy Bands (keV)						
Instrument	2.2-3.5	3.5-5.5	5.5-10	15-25	25-50	50-100	100-300
Astrosat CZTI	···	···	···	··· 20	20	20	25
Astrosat LAXPC	···	15	15	15	15	20	···
INTEGRAL IBIS	···	···	···	···	8	15	20
INTEGRAL SPI	···		···	···	5	5	5
NuSTAR	···	4	3	3	15	20	···
RXTE PCA	5	10	3	3	10	50	···
RXTE HEXTE	···	···	···	5	5	5	···
Suzaku HXD	···	···	···	20	20	20	20
Swift BAT	···	···	···	15	4	4	12

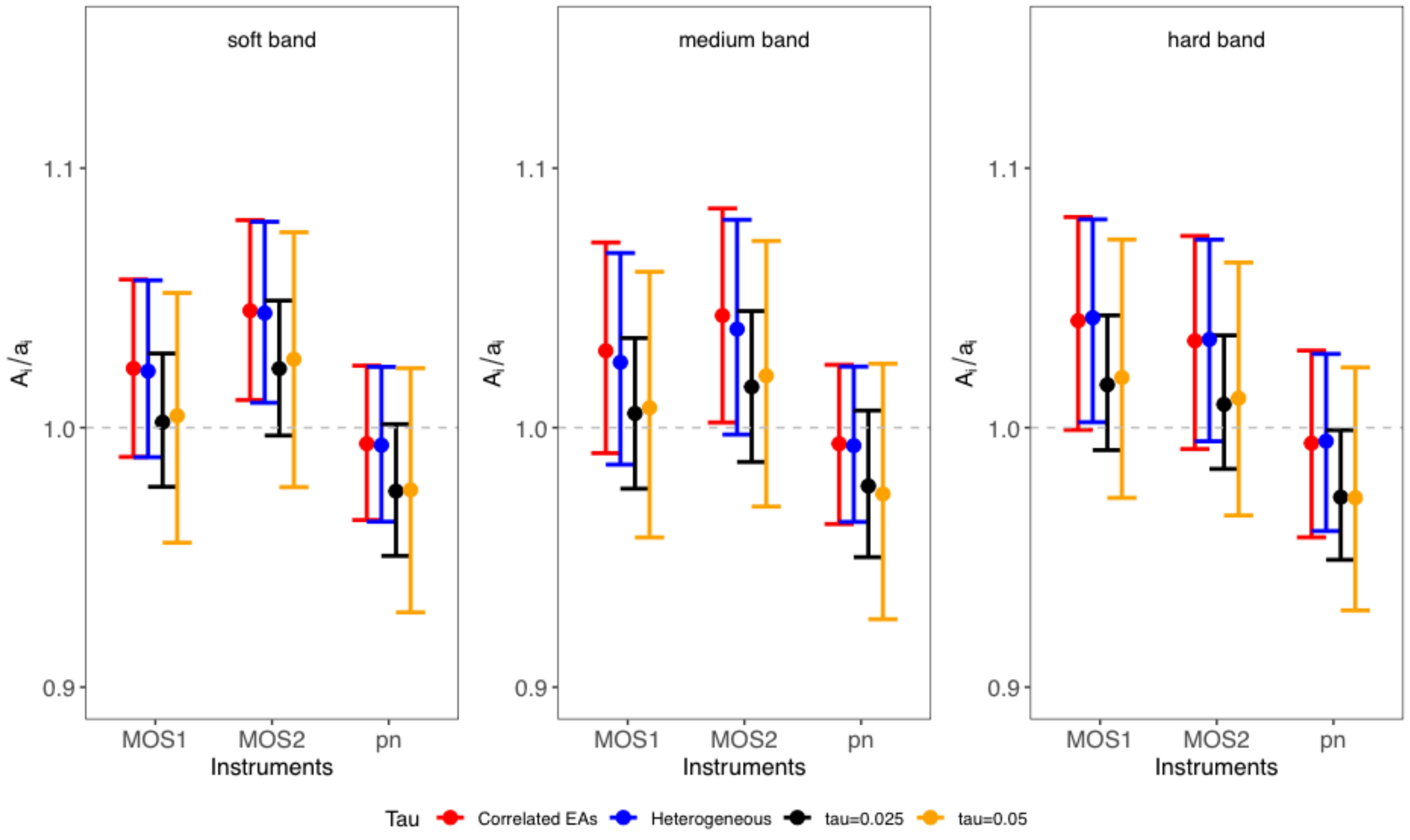
[a]The τ_i values are given as percentages.

Concordance 1: 1E0102



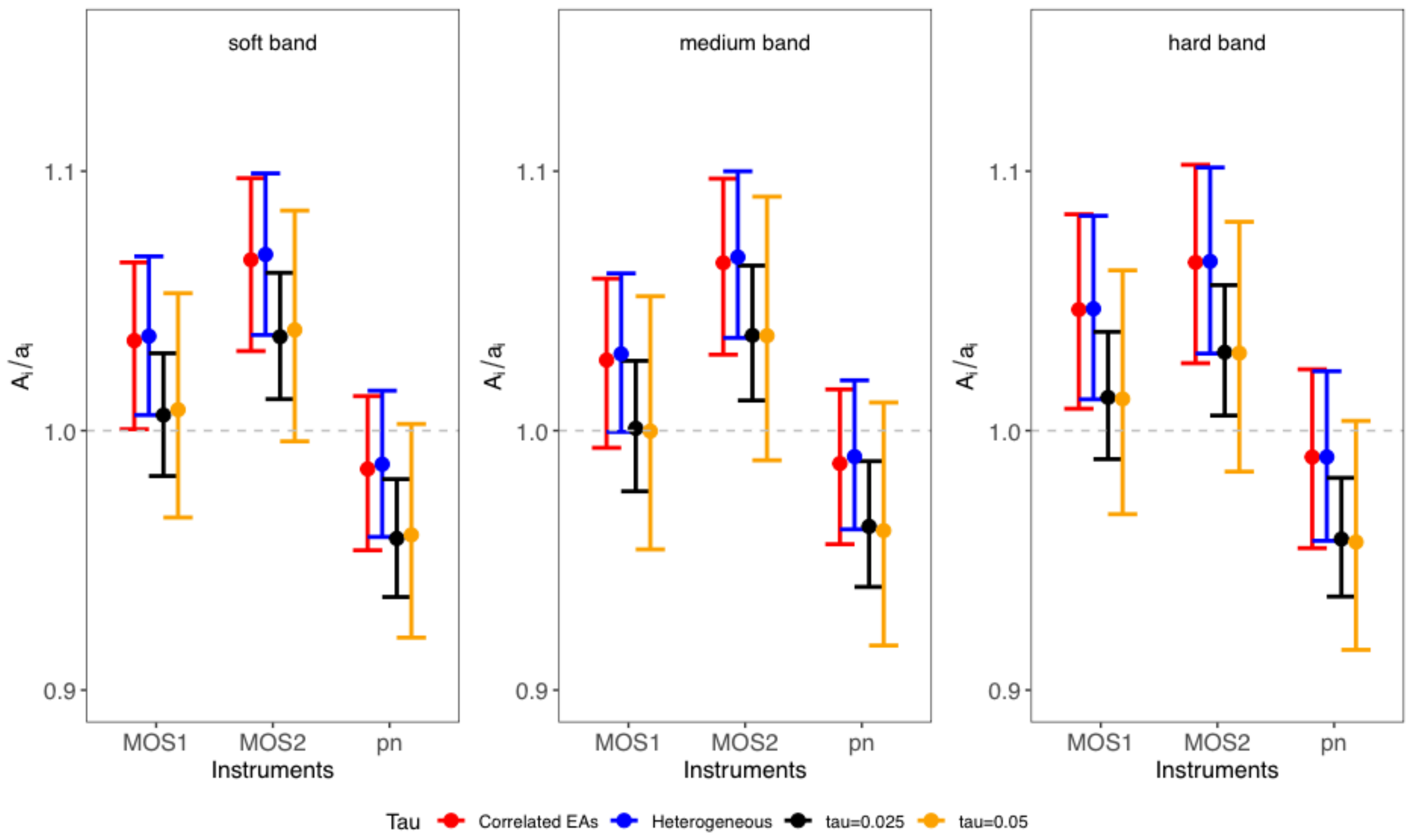
Concordance 2: 2XMM

- Based on 42 sources from the 2XMM catalog
- Unaffected by pileup
- Fixed τ: no EA change required
- Result (hetero. τ): 1% for pn indicated, 5-7% for MOS



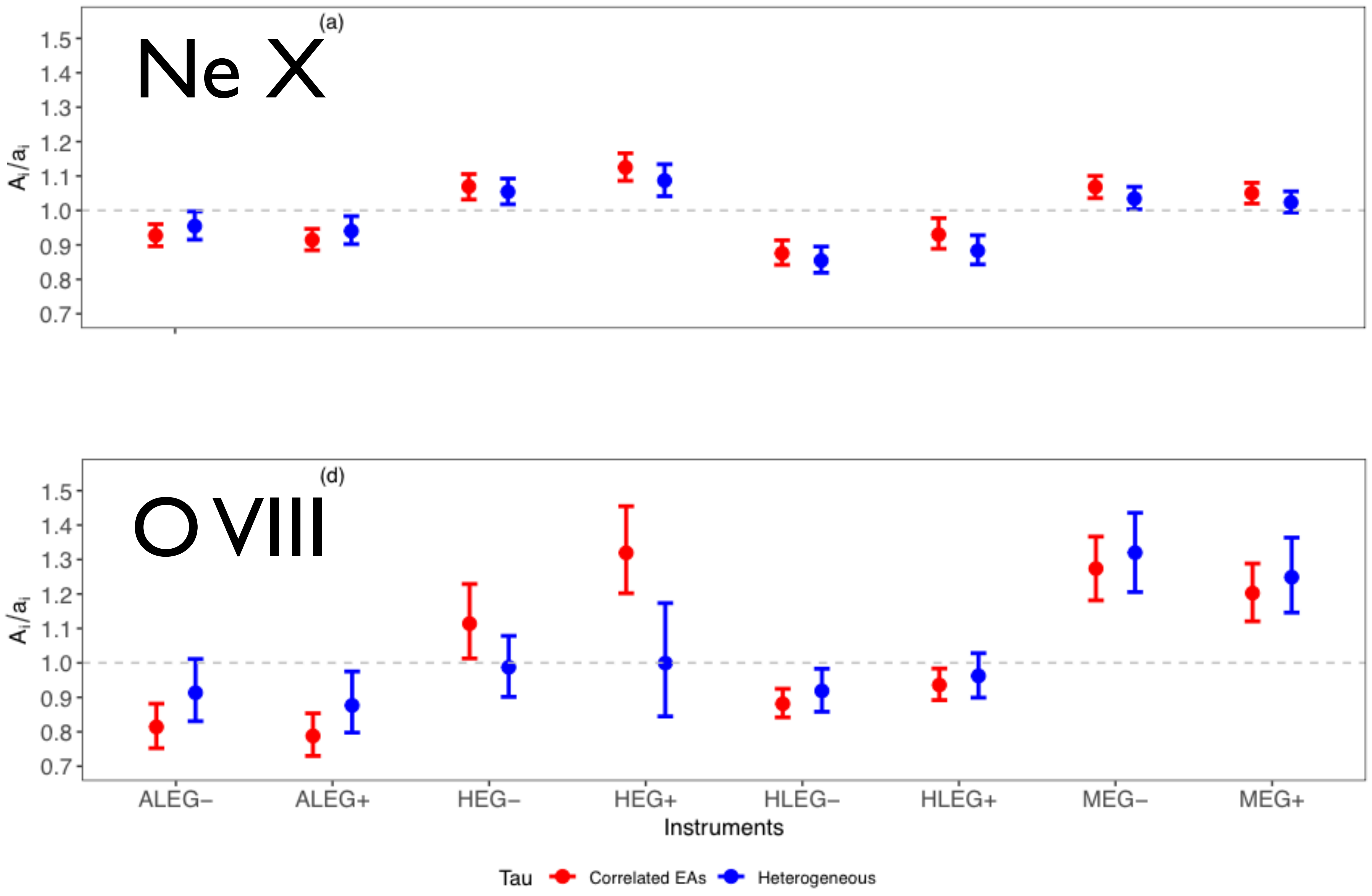
Concordance 3: XMM Blazars

- 117 bright XMM sources from Matteo Guainazzi
- PSF clipped to reduce effect of pileup
- Result (fixed τ): 5% adjustment to pn indicated, 1-2% for MOS
- Result (hetero. τ): 1% for pn indicated, 5-7% for MOS



Concordance 4: Capella

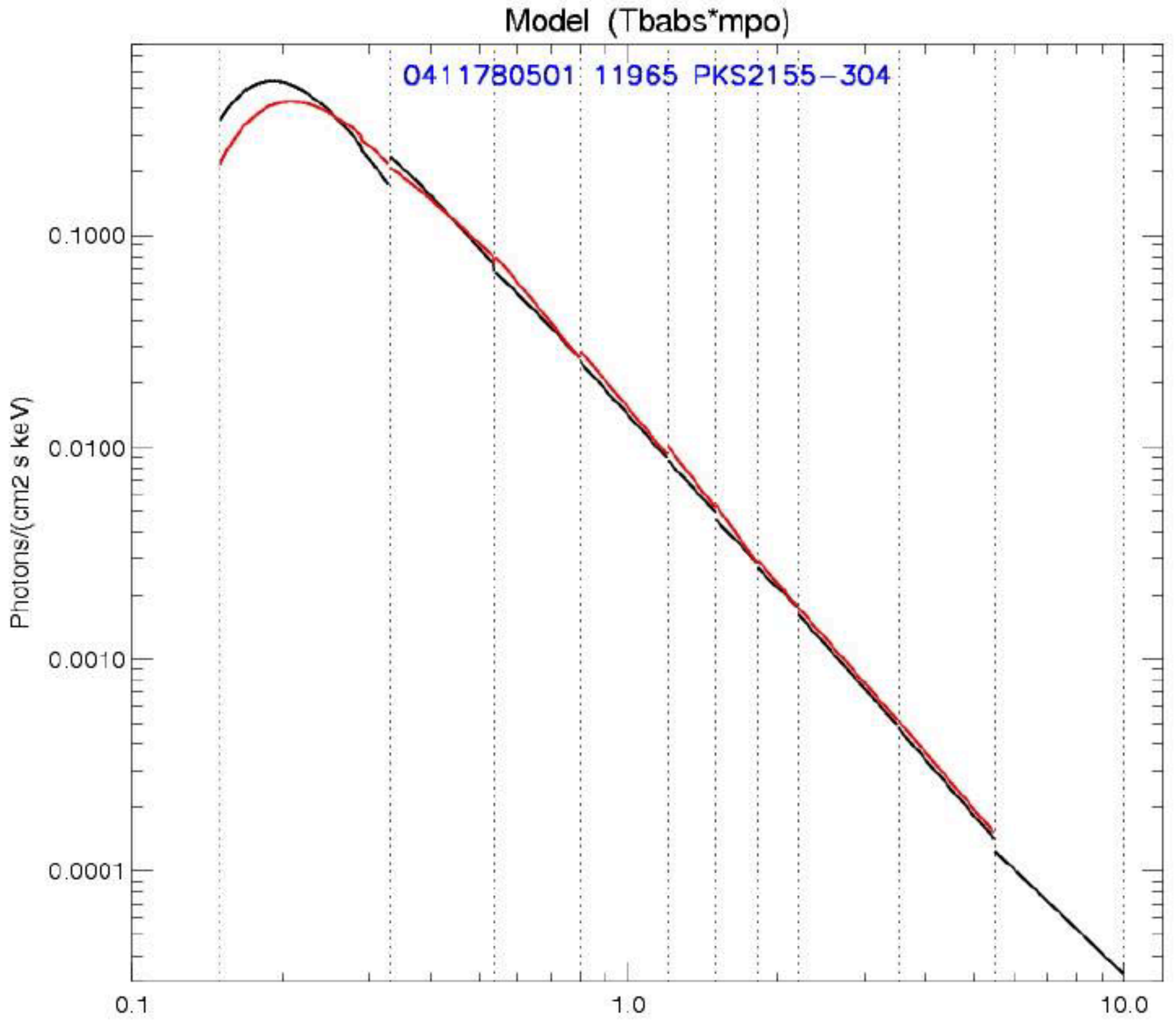
- Lines from Chandra grating spectra
  - Ne x, Fe xxvii (15 Å), Fe xxvii (17 Å), O VIII
- 5 sets of adjacent observations compared
- Not all instruments used each time
- Result: ±1 generally consistent, LETGS are low of HETGS



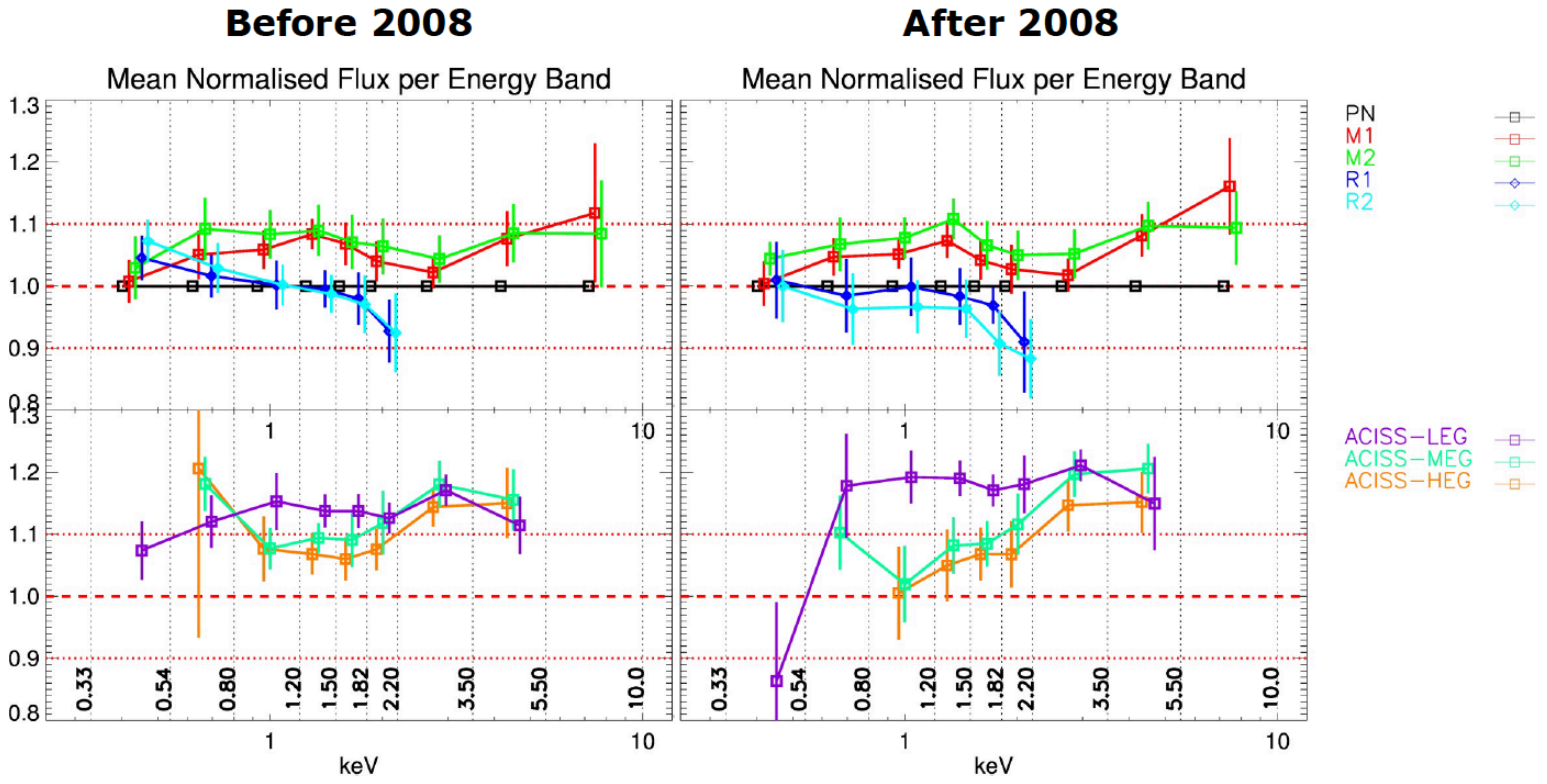
Marshall+ in prep.

Conclusions

- We can bring observations into Concordance
- Simple situations give reasonable answers: consistent with other analyses
- More complex situations:
  - Outliers handled with t distribution
  - Fluxes in bands are related globally, not independent
  - Instrument areas are time-dependent



Preview: XMM v. Chandra



XMM-Newton - Chandra Cross-Calibration with Blazars | M. Smith | 14th IACHEC, 20-23 May 2019 | Pag. 17

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