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

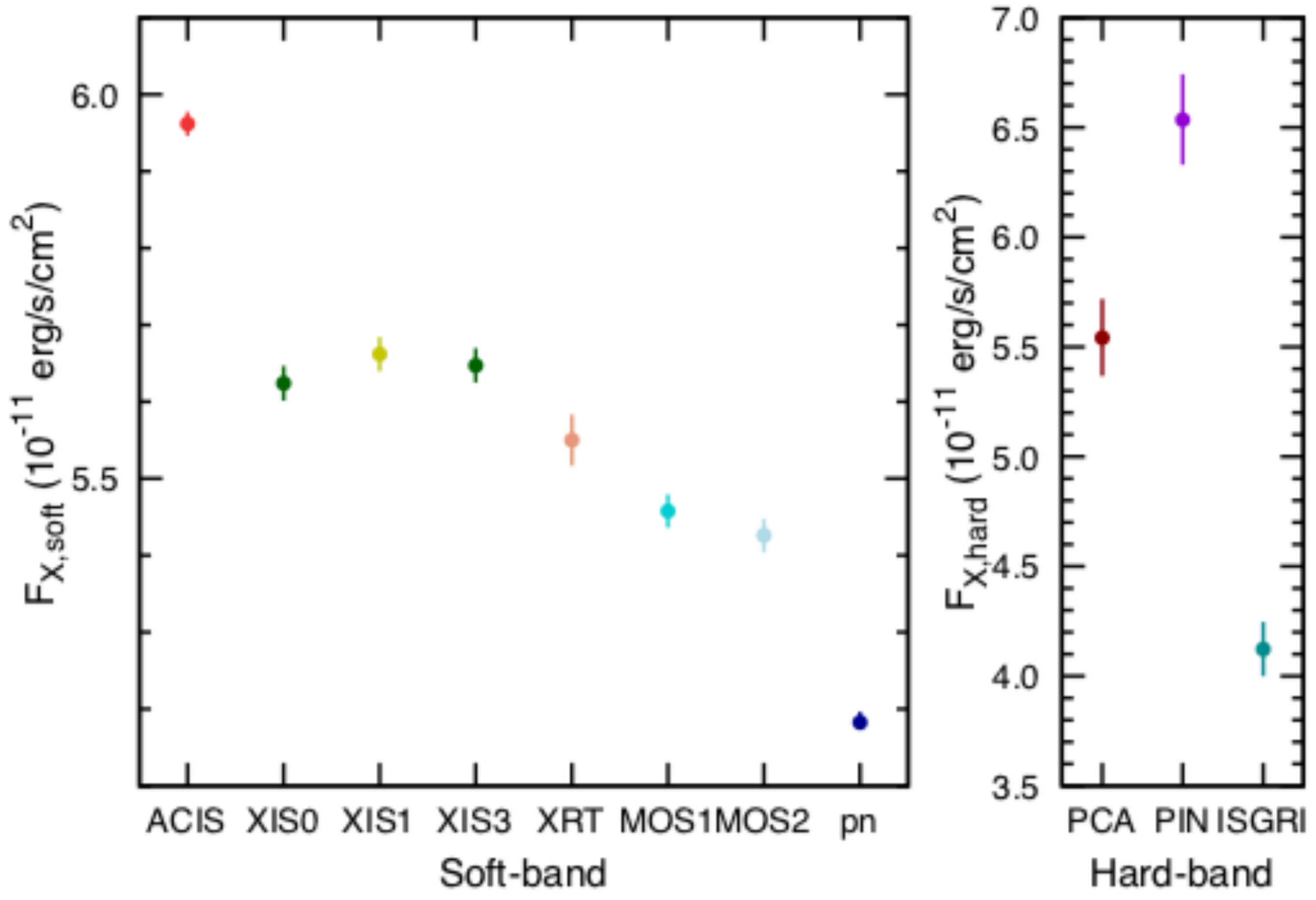
➡ Let flux $f_{ij} = c_{ij}/T_{ij}/a_i$

where a_i = prior on A_i

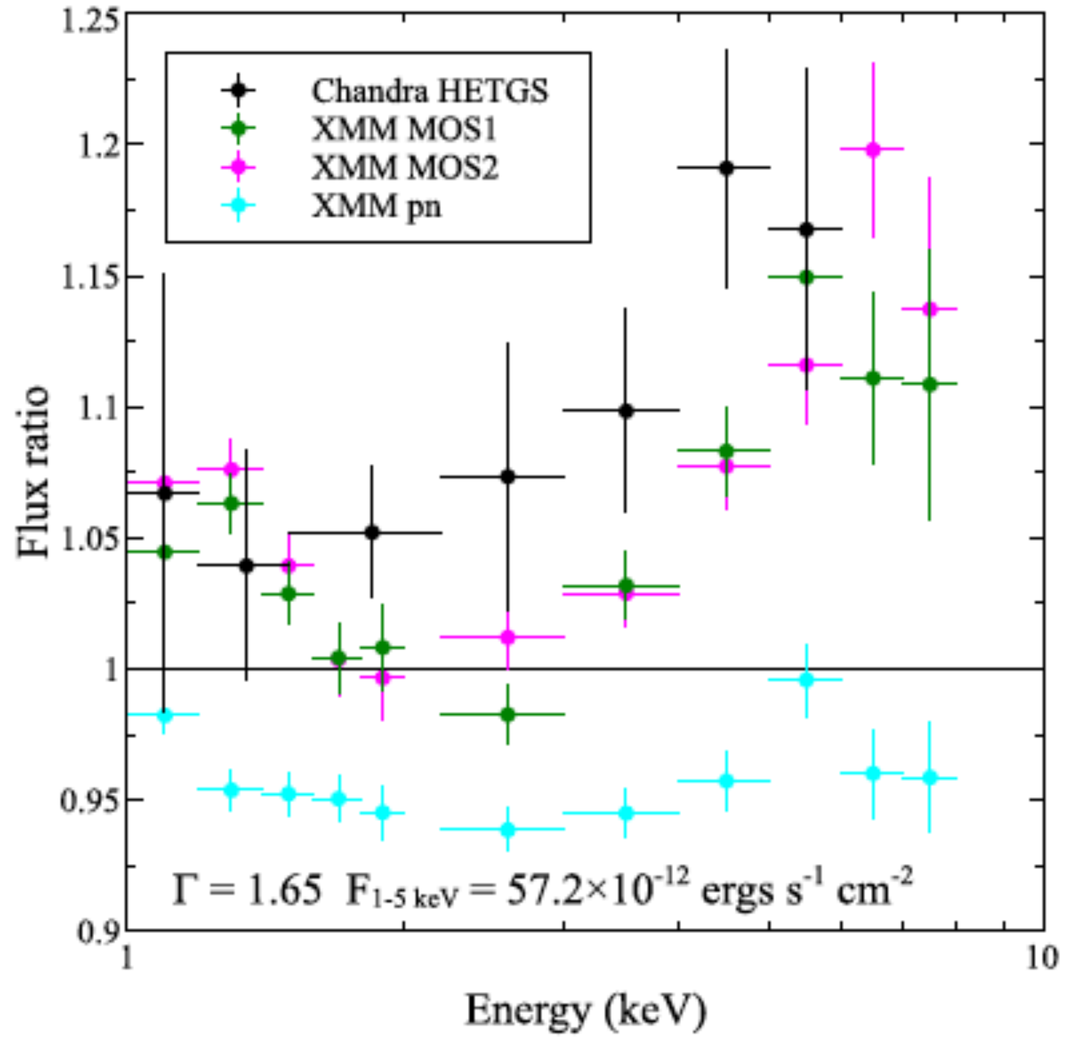
c_{ij} = observed counts

T_{ij} = known exposure time

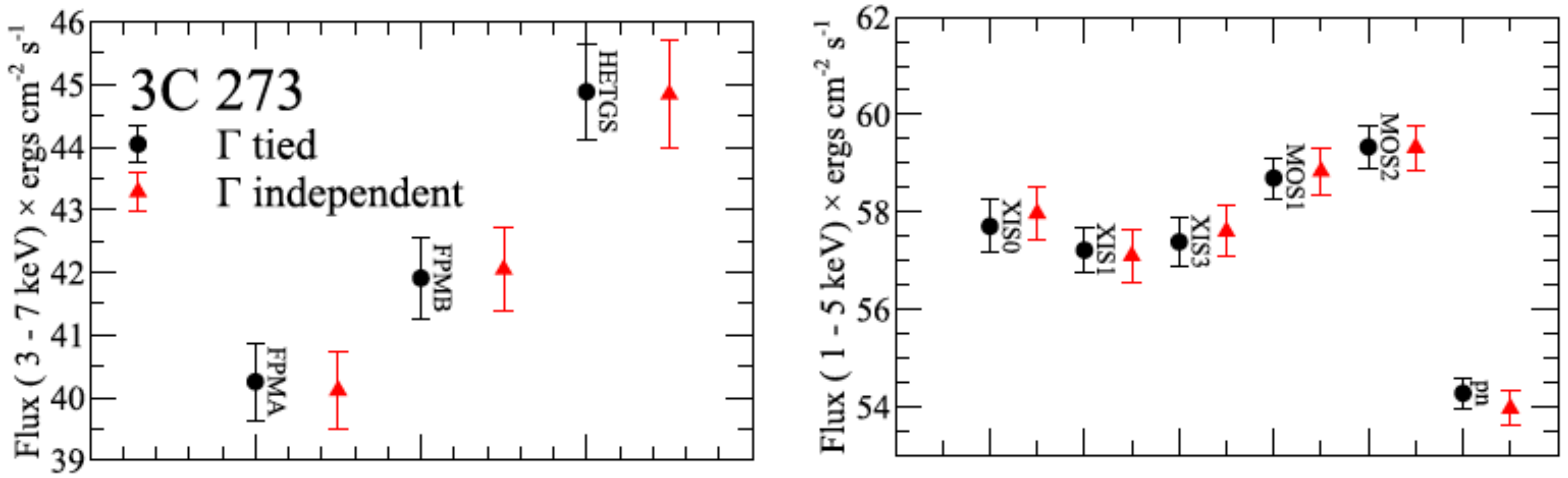
Some Previous Cross-Cal Work

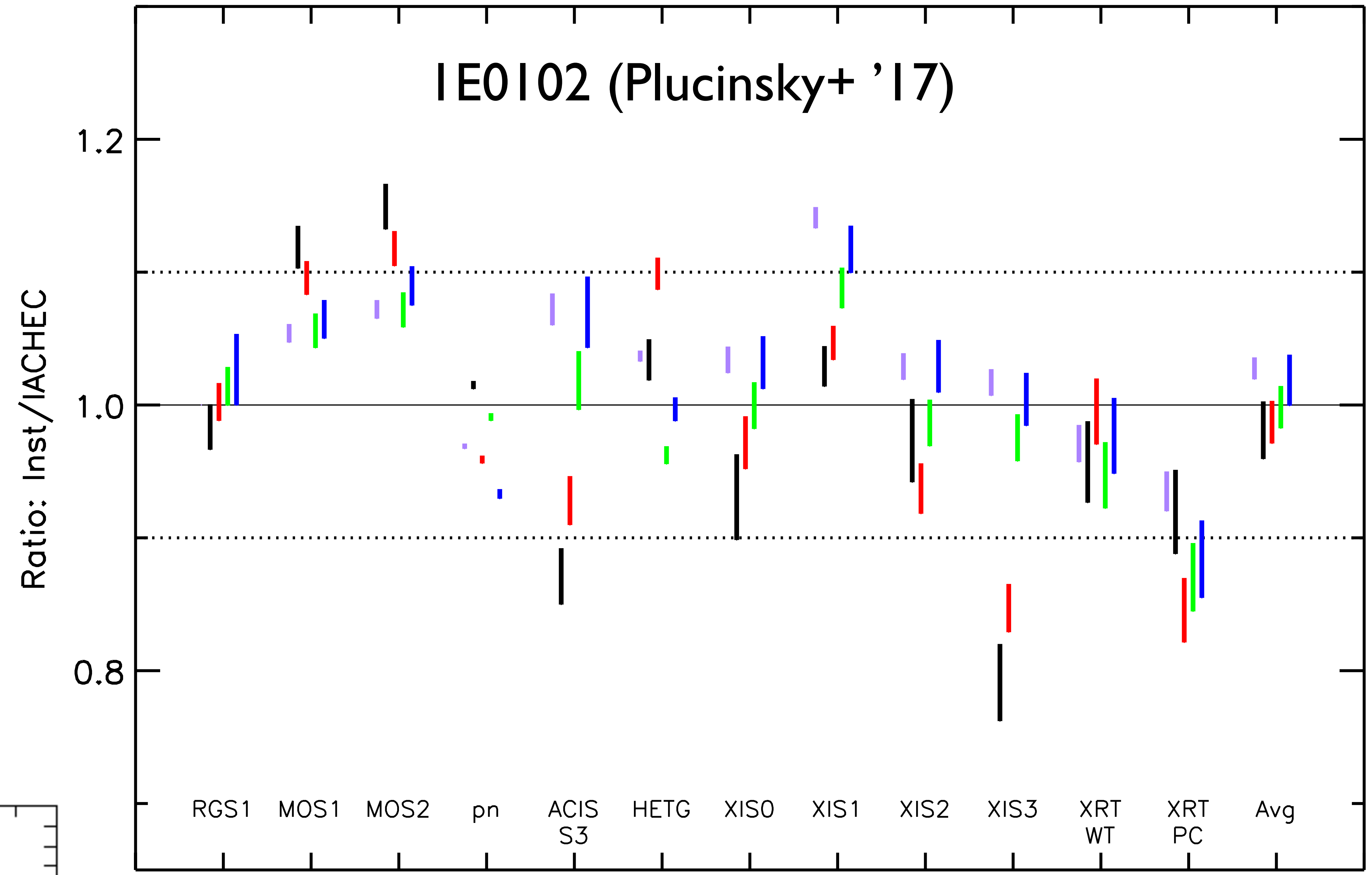


G21.5-0.9 (Tsujimoto + '10)



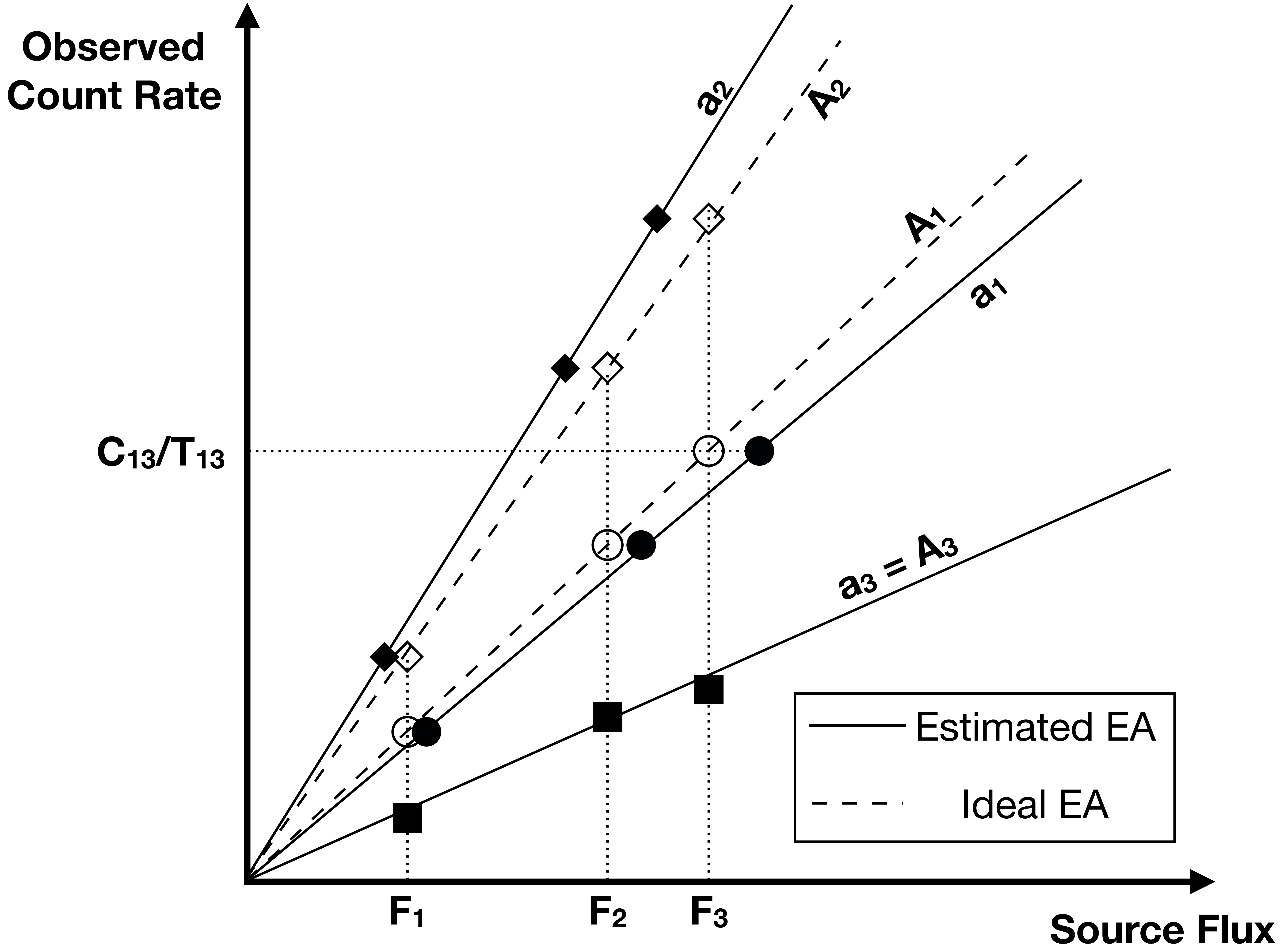
3C 273 (Kruse Madsen + '17)





1E0102 (Plucinsky+ '17)

The Problem, Graphically



Some Poor Methods

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

➡ 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

Better: Mult. Shrinkage (Chen+ '19)

$$y_{ij} = B_i + G_j - \frac{1}{2\sigma_i^2} + e_{ij} \quad , \quad y_{ij} \equiv \log(c_{ij}/T_{ij}) \quad , \quad B_i \equiv \log A_i \quad , \quad G_j \equiv \log F_j$$

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

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

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

See Y. Chen's talk!

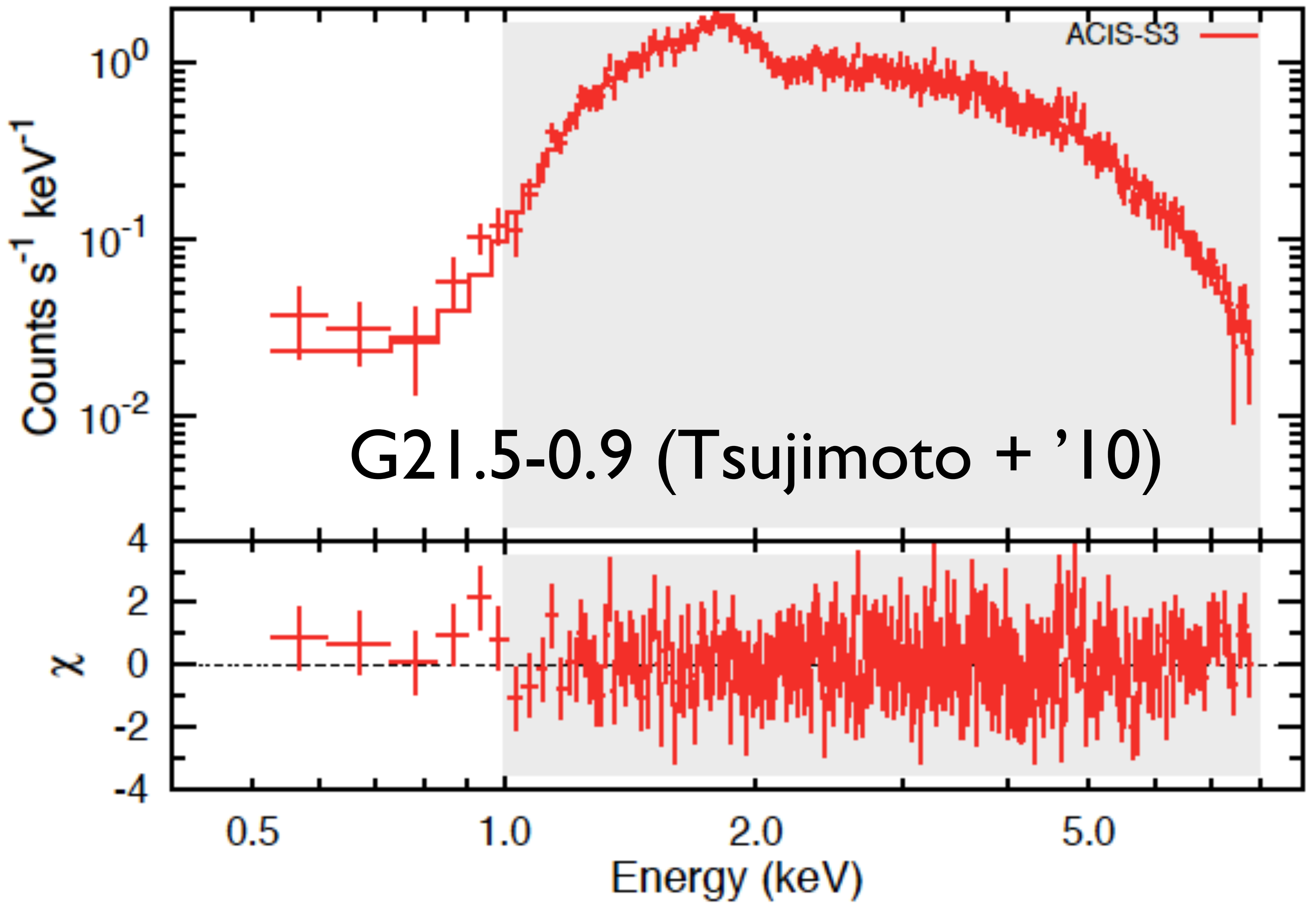
Complications I: Flux Measurements

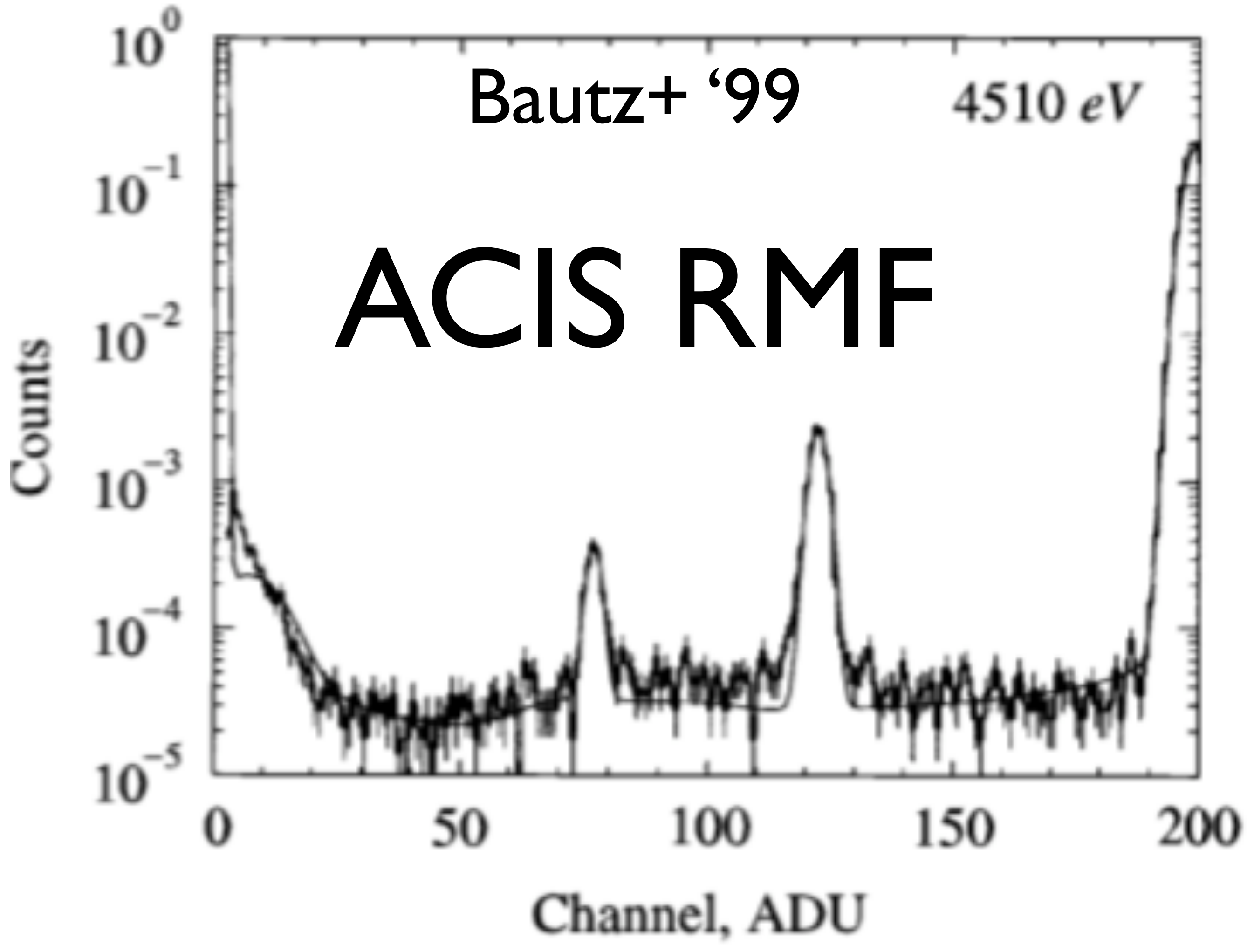
Concordance: find A_i where $C_{ij} = T_{ij} A_i F_j \quad , \quad A(E) = A_i \alpha_i(E)$

- 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 $C'_{ijk} = t_{ij} a_i f_{ij} \dfrac{\int_{E_1}^{E_2} \alpha_i(E) q_j(E) \Phi_k(E) dE}{\int_{E_1}^{E_2} q_j(E) dE} = T_{ijk} a_i f_{ij}$

where $f_{ij} = \displaystyle\int_{E_1}^{E_2} n_E(\Theta_{ij}) dE = n_{ij} \int_{E_1}^{E_2} q_j(E) dE$ 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 $\displaystyle\sum_k \Phi_k(E) = 1$

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





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 $\rho_{i,i'} = \frac{1}{\sqrt{\tau(E_i)\tau(E_{i'})}} \int [\tilde{B}(E_i; \overrightarrow{\xi}) - \hat{B}(E_i)][\tilde{B}(E_{i'}; \overrightarrow{\xi}) - \hat{B}(E_{i'})] p(\overrightarrow{\xi}) d\overrightarrow{\xi}$
- In reality, a Monte Carlo method is used to compute the correlations…

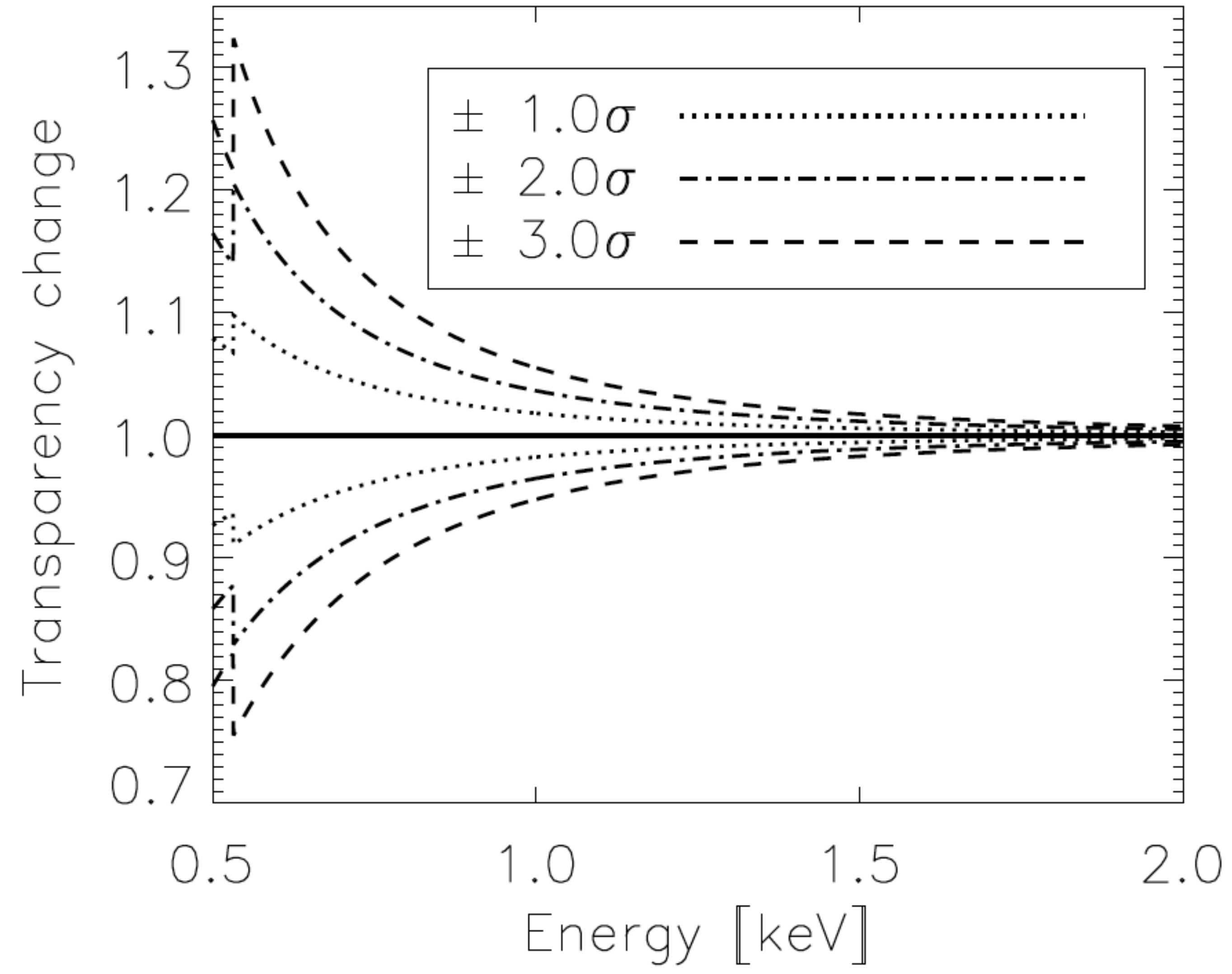


Table 8. Correlation matrix for 2XMM and XCAL Analyses

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.

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 corrlations 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.)

Paper I Published

Calibration Concordance for Astronomical Instruments via Multiplicative Shrinkage

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We present analytical solutions in the form of power shrinkage in special cases and develop reliable Markov chain Monte Carlo (MCMC) algorithms for general cases, both of which are available in the Python module *CalConcordance*. We apply our method to several data sets including a combination of observations of *active galactic nuclei* (AGN) and spectral line emission from the *supernova remnant* E0102, obtained with a variety of X-ray telescopes such as *Chandra*, XMM-*Newton*, *Suzaku*, and *Swift*. The data are compiled by the *International Astronomical Consortium for High Energy Calibration* (IACHEC). We demonstrate that our method provides helpful and practical guidance for astrophysicists when adjusting for disagreements among instruments.

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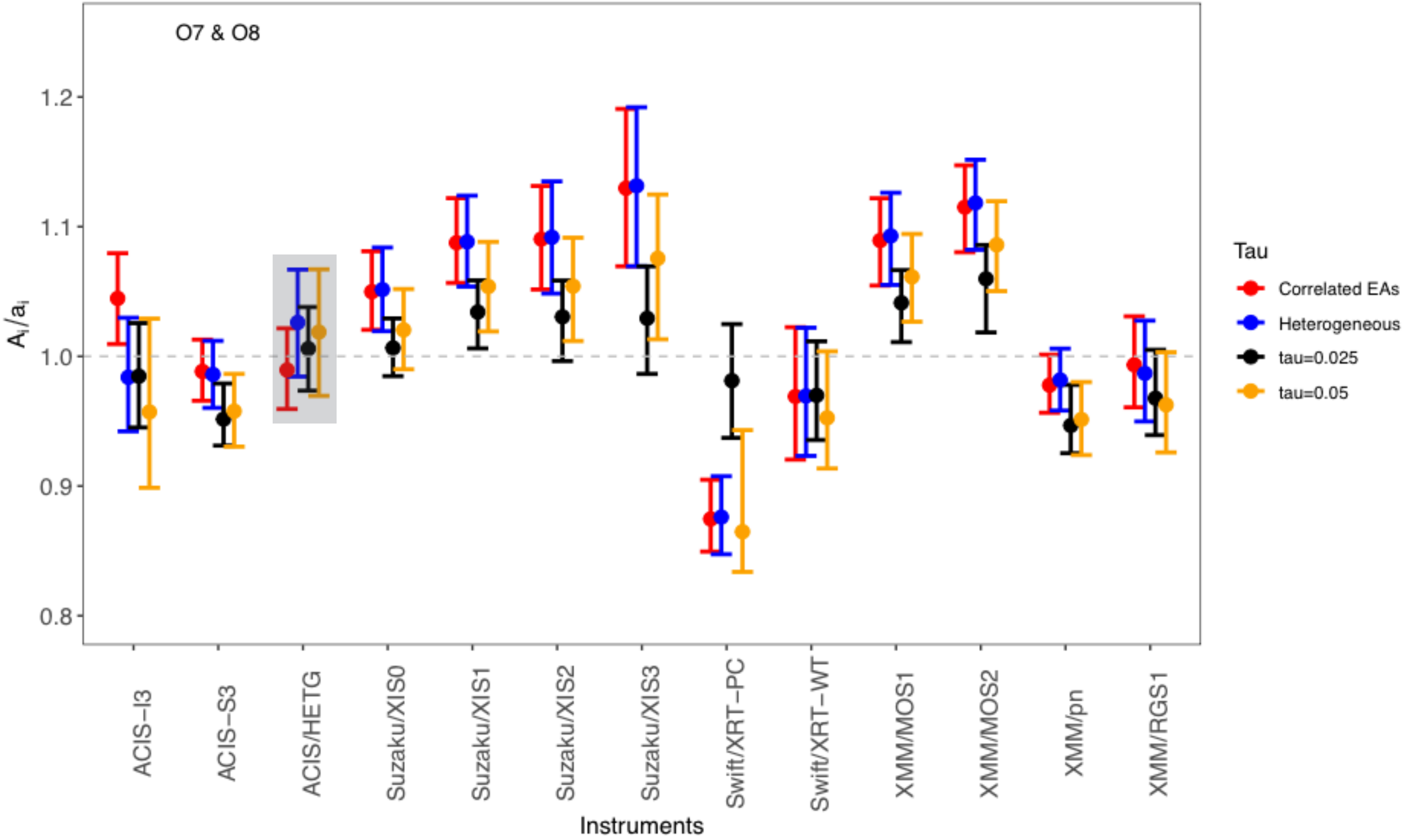
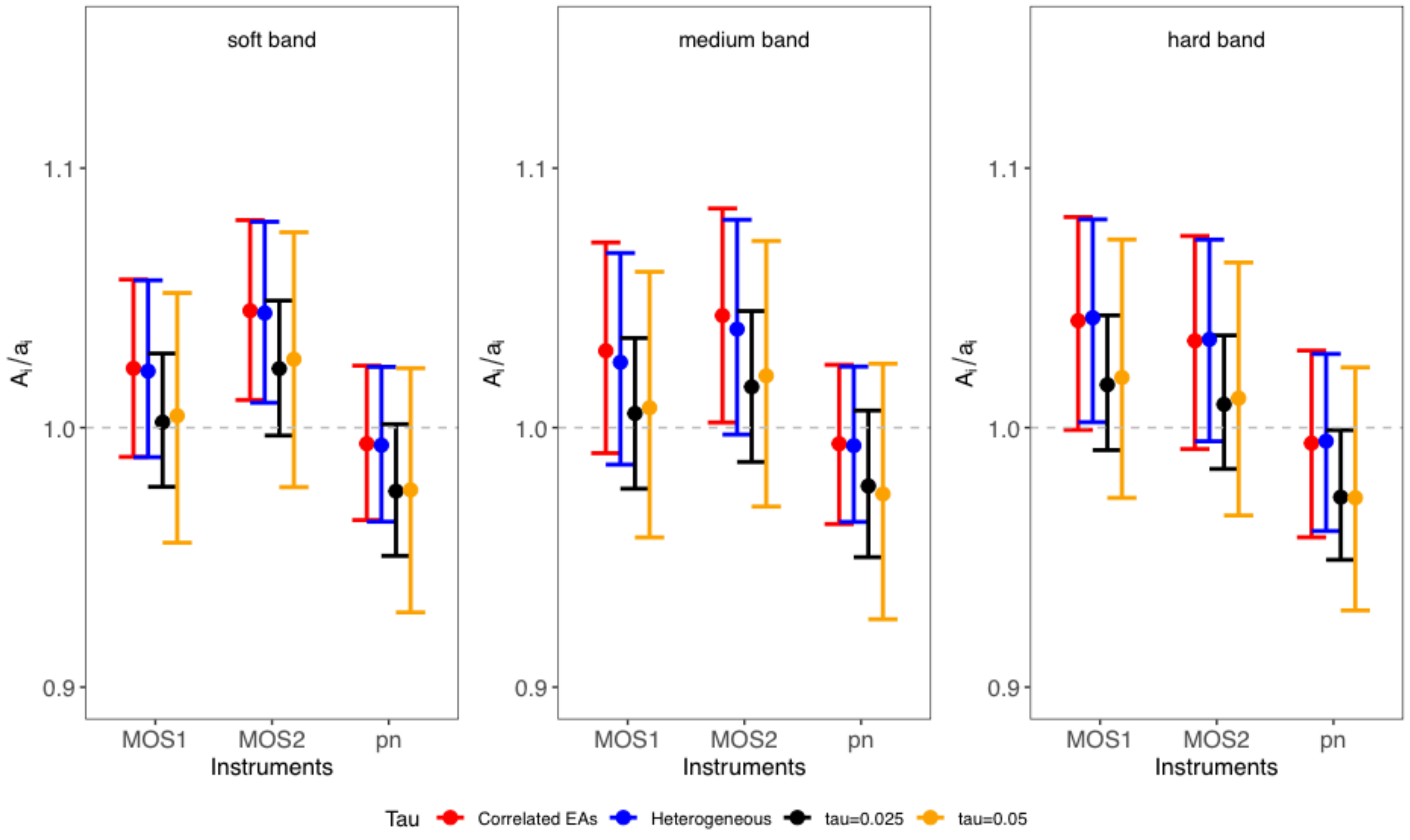
Concordance I: 1E0102



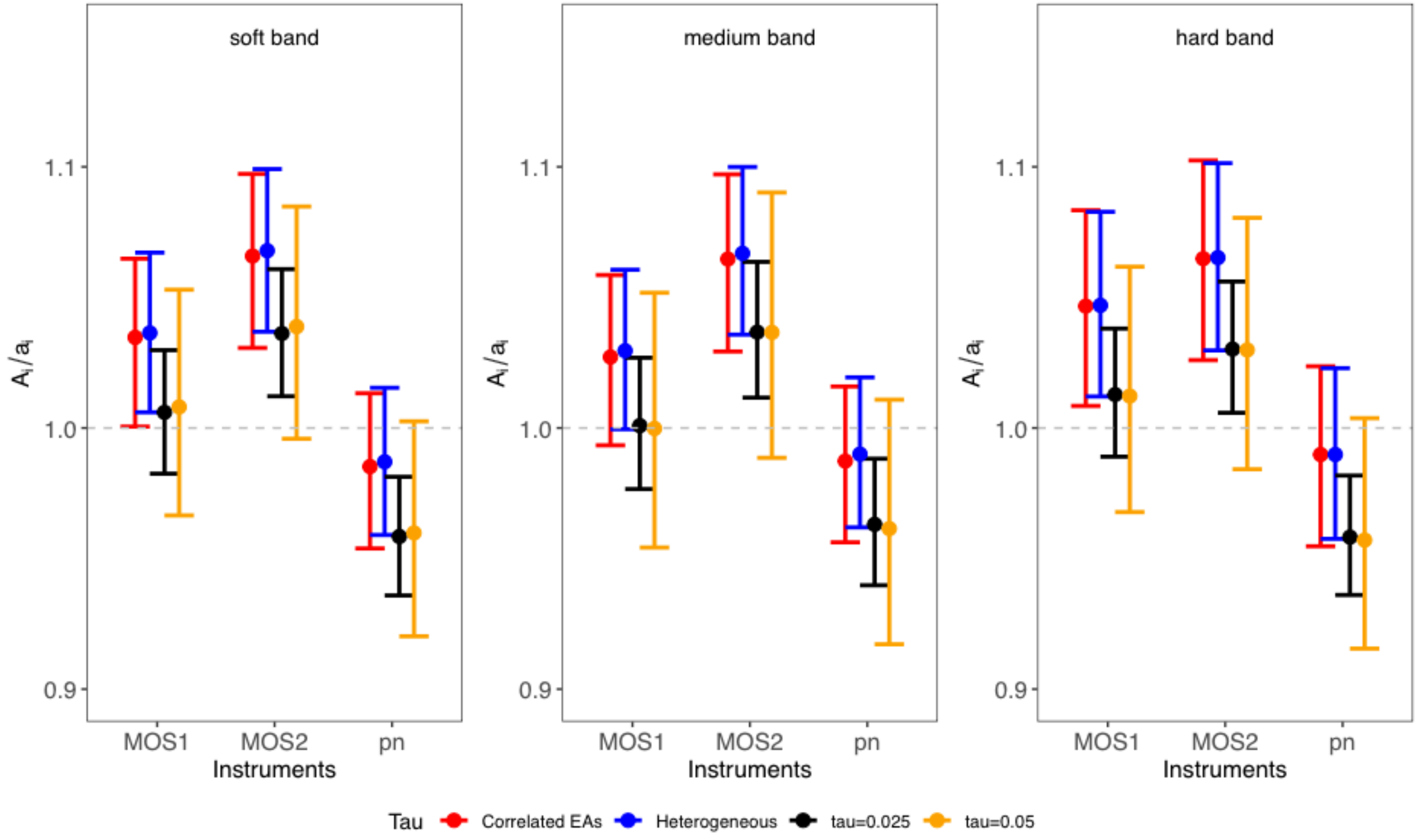
Concordance 2: 2XMM

- 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



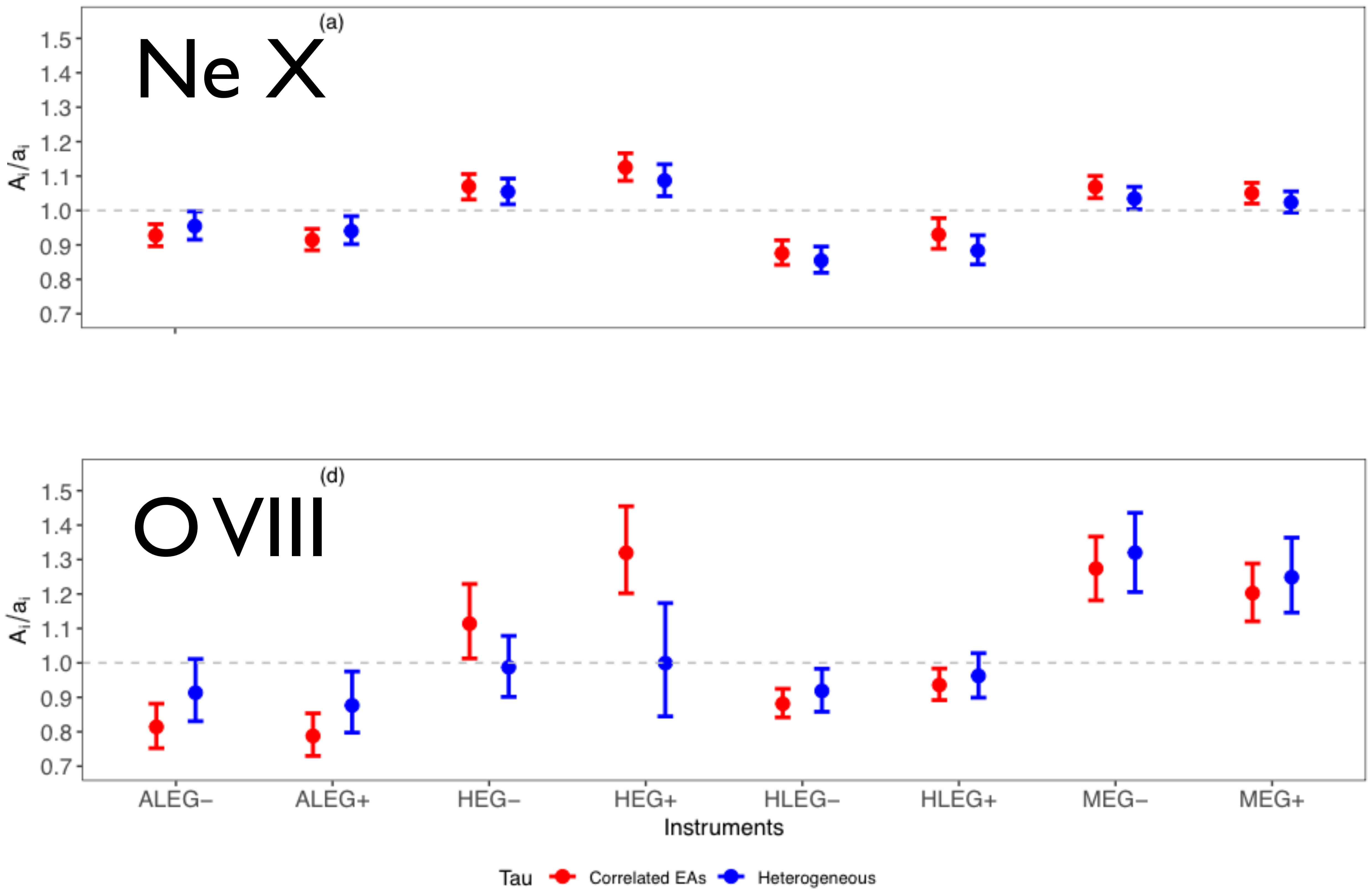
Concordance 3: XMM Blazars

- 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

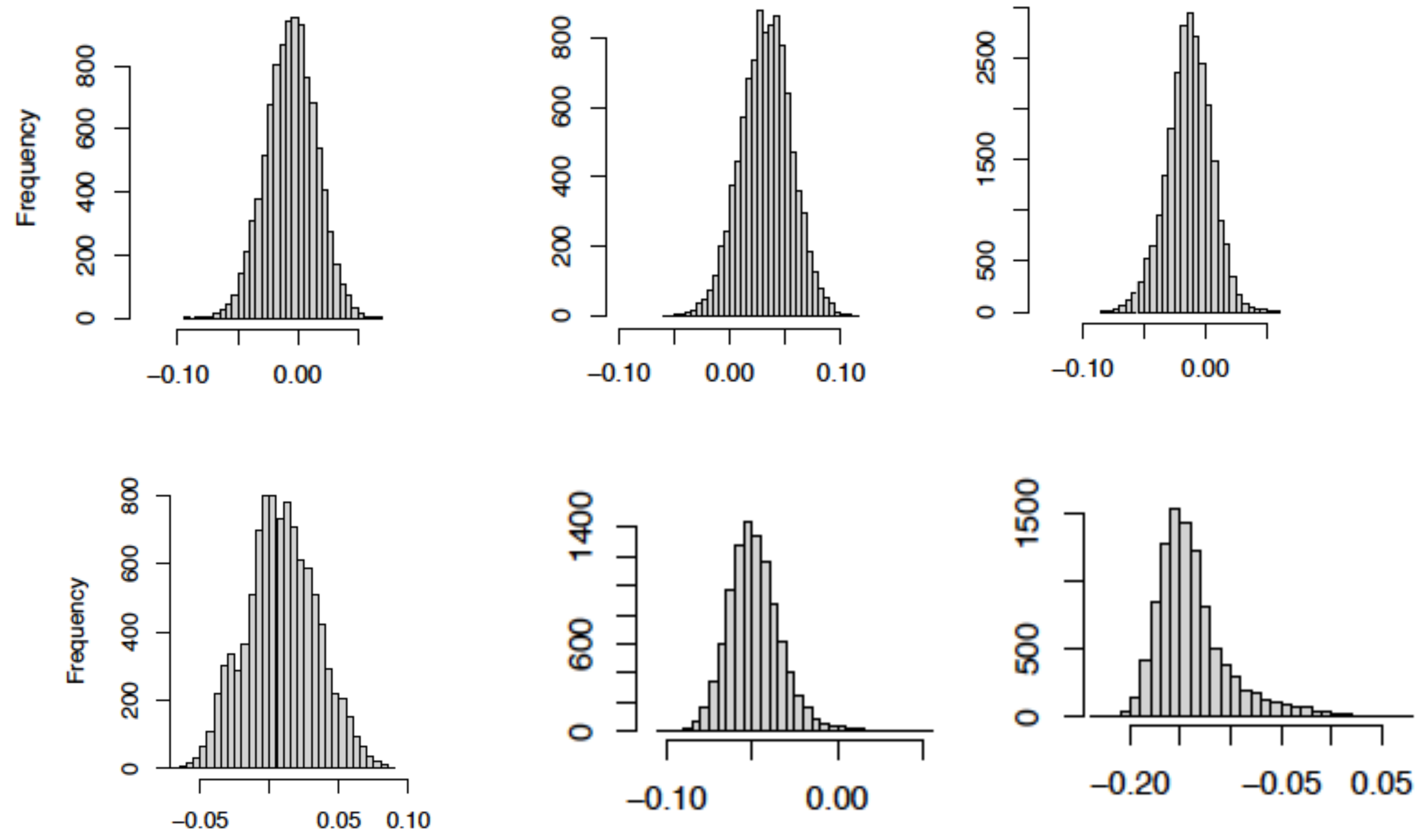
- Lines from Chandra grating spectra
  - Ne x, Fe xxvii (15 Å), Fe xxvii (17 Å), O VIII
- 5 sets of adjacent observations compared
- Not all instruments used each time
- Result: ±1 generally consistent, LETGS are low of HETGS



Marshall+ in prep.

Posterior Distributions?

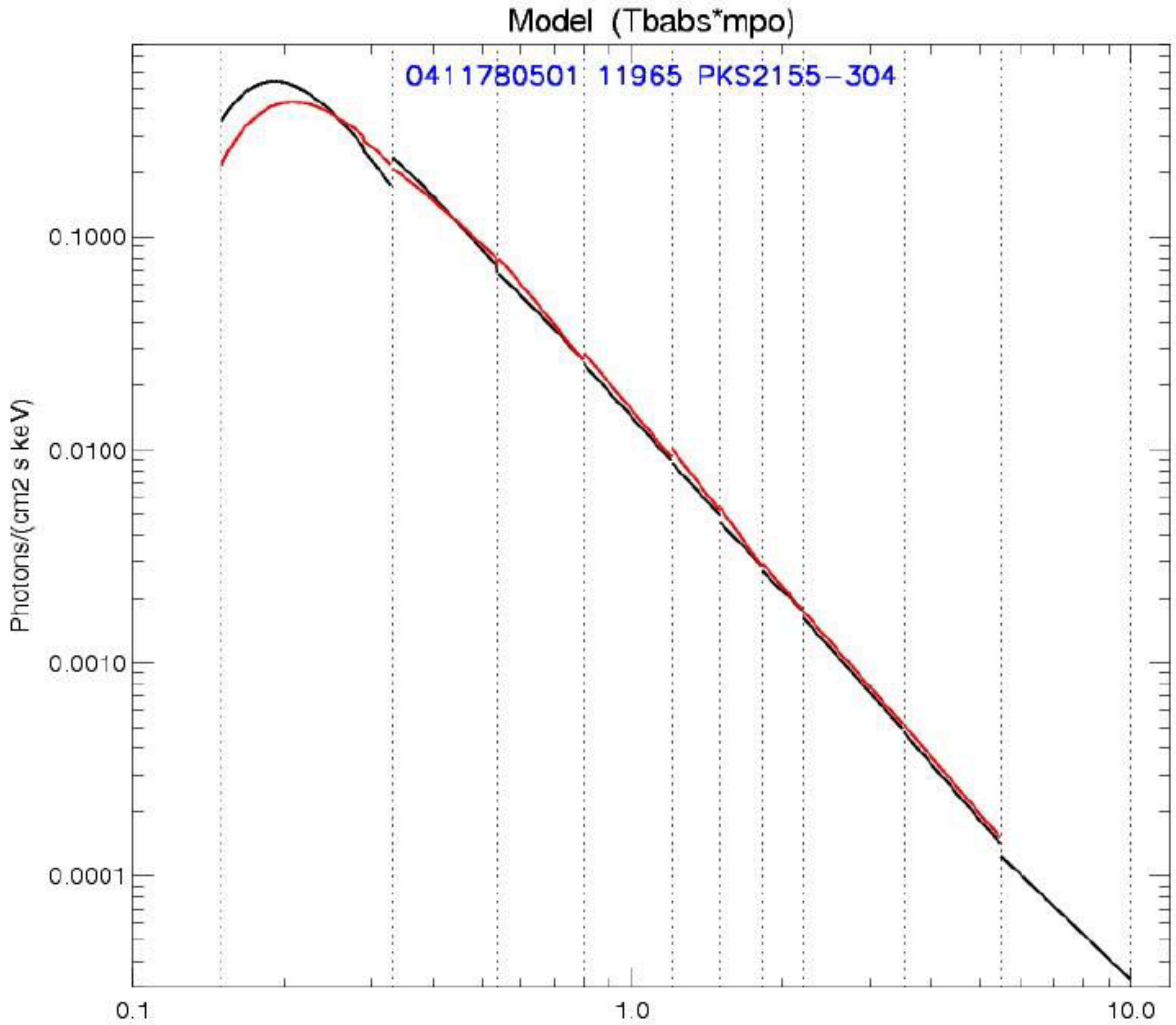
- Most posterior distributions look Gaussian
- Few have skew, tails



a) 2XMM, hard, corr'd τ, pn
b) 2XMM, hard, hetero τ, MOS2
c) XCAL medium, corr'd τ, pn
d) XCAL, soft τ=0.05, MOS1
e) E0102, O, τ=0.025, i=5
f) E0102, O, τ=0.05, i=13

Conclusions

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



Preview: XMM v. Chandra