IACHEC Concordance — Progress!

Extended Bayesian Estimation for In-flight Calibration of Space-based Instruments

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To be submitted to RAS Techniques and Instruments

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

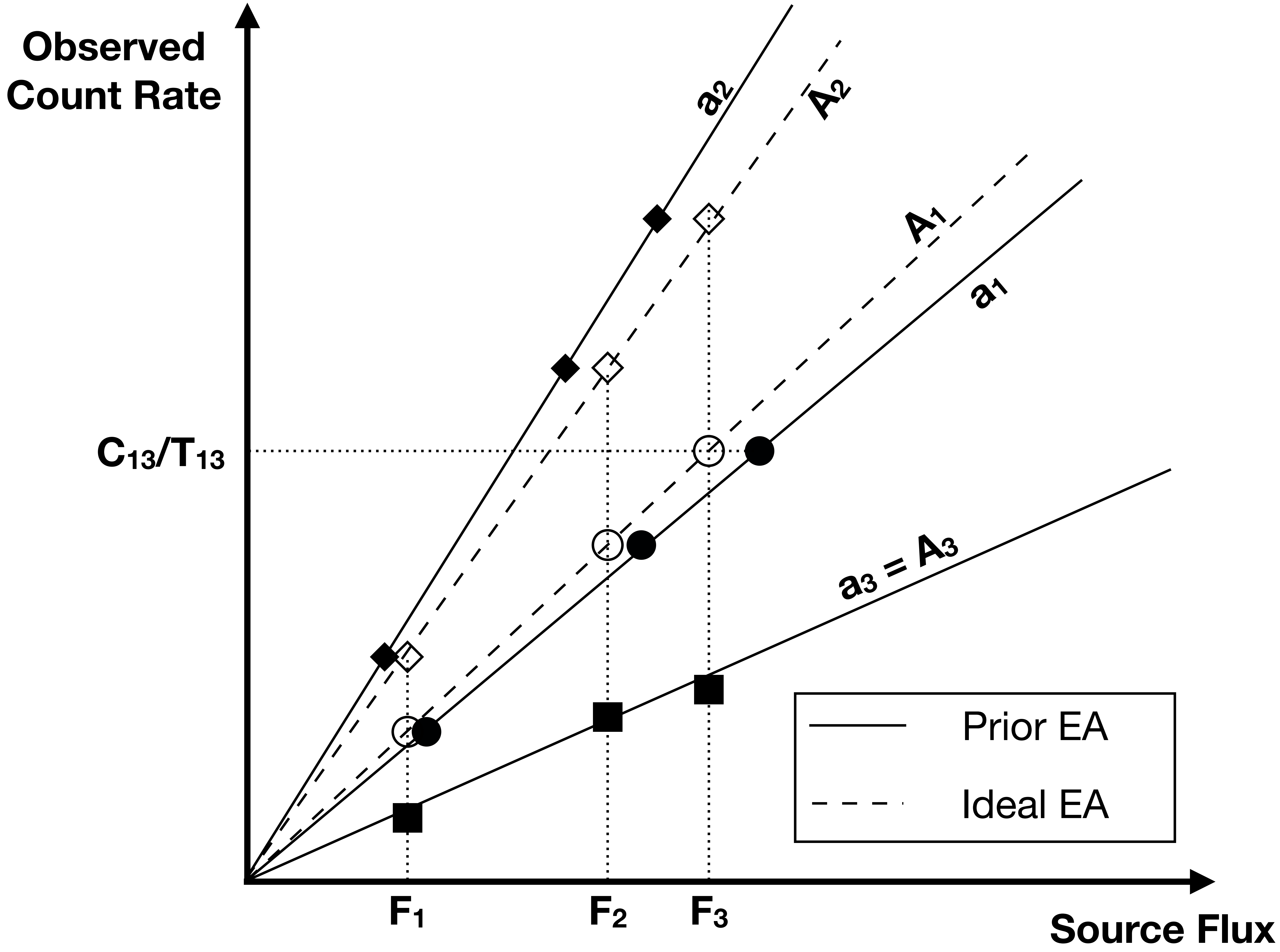
➡ Let flux $f_{ij} = c_{ij}/T_{ij}/a_i$

where a_i = prior on A_i

c_{ij} = observed counts

T_{ij} = known exposure time

The Problem, Graphically



Multiplicative Shrinkage

(Chen+ '19, JASA)

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

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

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

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

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

Previously: Eff. Area Correlations

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

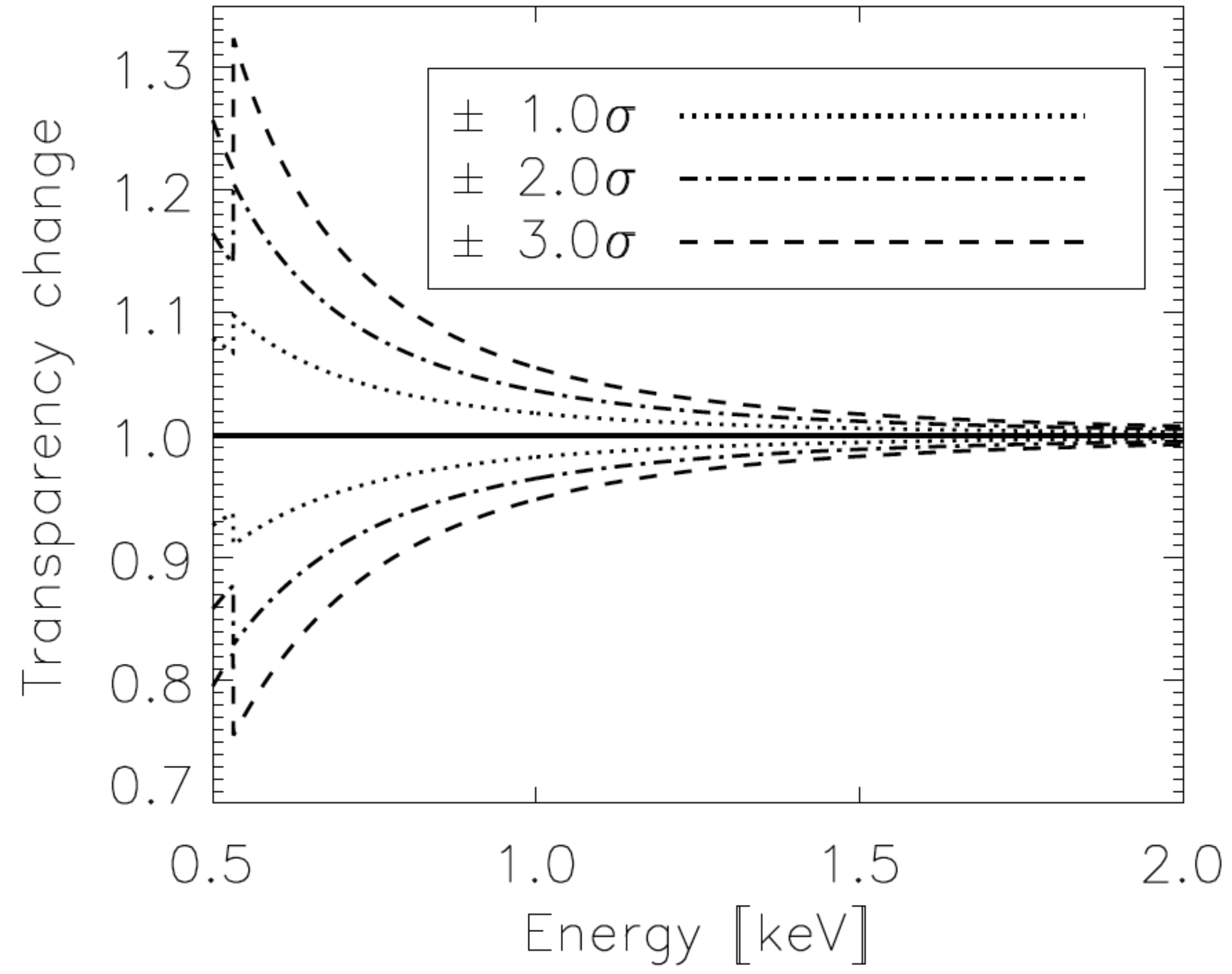


Table 8. Correlation matrix for 2XMM and XCAL Analyses

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

Previously: Prior Uncertainties

- 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 1 (Chen+, 2019, JASA)
  - 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
- Paper 2 (Marshall+, 2021, *AJ*, 162, 254)
  - Same 3 sets as in Paper 1
  - 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

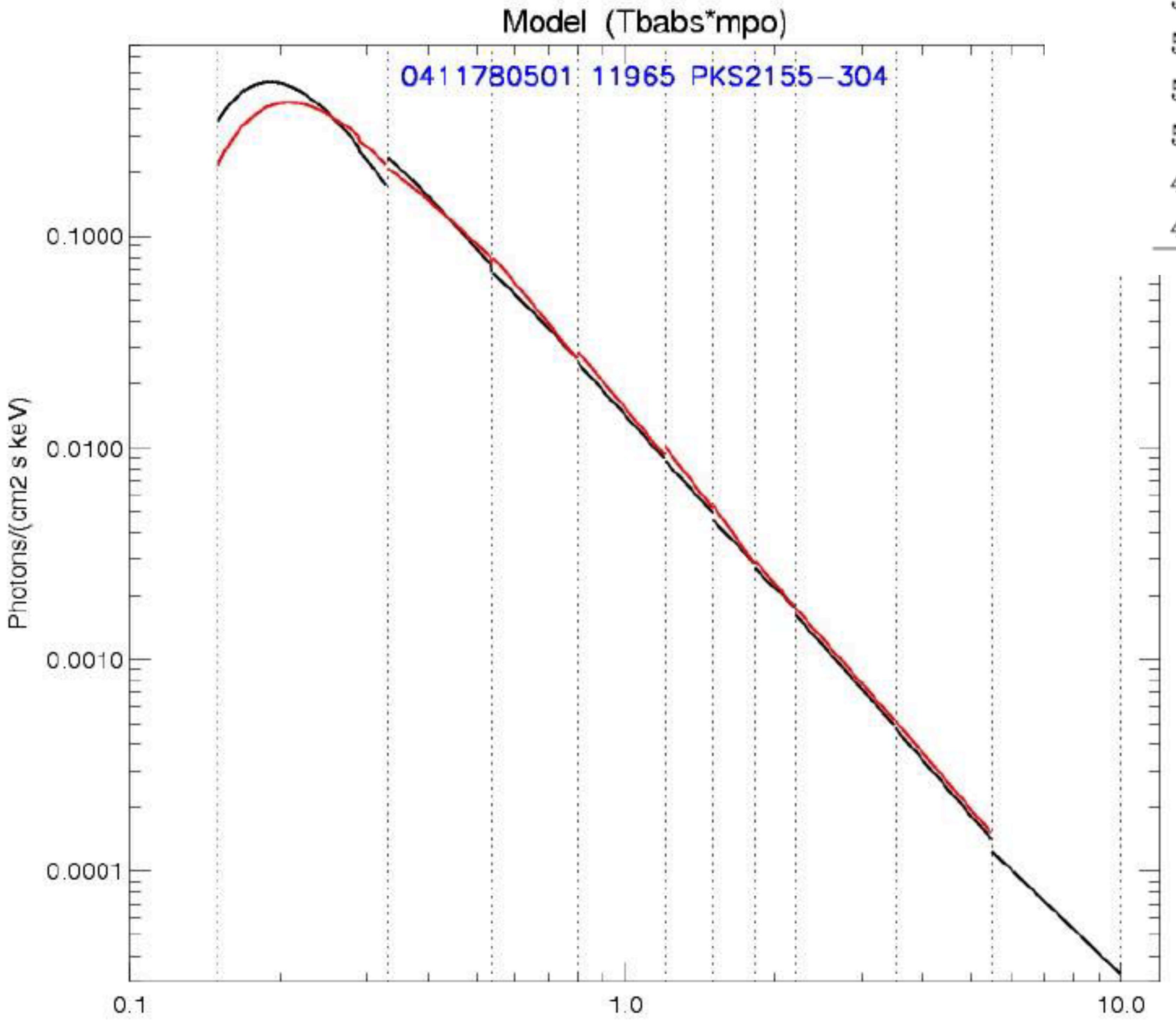
Sample Data (Marshall+ 2021)

Paper 3: XMM/Chandra XCAL

- Processing by Michael Smith
- Simultaneous XMM-Newton/ Chandra observations
  - Five XMM instruments involved — pn, MOS1, MOS2, RGS1, RGS2
  - Five Chandra grating configurations — HEG, MEG, LEG/ACIS, LEG/HRC-S, LEG/HRC-I
- PKS 2155, 3C 273, 1H1426, Mk 590
  - Observations labeled by GTI (ObsID)
  - 45 GTIs, 10 bands, 9 instruments
- Fits to PLs w/ fixed N_H values, each GTI/band/instrument independently
- Data: 2098 fluxes (10^{-11} erg/cm^2/s)

Table 3. Joint instrument observation frequencies of 10 sources and 10 passbands for 10 out of 45 sources. The ten passbands are represented by their indices.

Source	Passband Indices									
	1	2	3	4	5	6	7	8	9	10
2462	4	6	6	6	6	6	4	4	4	3
2463	3	6	6	7	7	7	5	5	5	5
2464A	3	6	6	6	5	5	4	4	4	4
2464B	3	6	6	6	6	6	4	4	4	4
5169A	2	4	5	6	6	6	3	4	4	4
5169B	2	5	6	7	7	7	5	5	5	4
5170A	3	6	6	6	5	5	4	4	4	4
5170B	2	6	6	6	6	6	4	4	4	4
4430	3	6	6	6	6	6	4	4	4	4
4431	3	6	6	6	6	6	4	4	4	4



Concordance Math

- i = 1..10 (instrument), p=1..10 (bandpass), s=1..45 (source)
- Spectral shape $q(E;\tilde{\theta}_s) = \dfrac{E\ n_E(\theta_s)}{E_0\ n_s}$, n_s is in ph/cm²/s/keV at $E_0 = 1$ keV
- $q(E;\tilde{\theta}_s) = \left(\dfrac{E}{E_0}\right)^{1-\Gamma_s+\gamma_s \log(E/E_0)} e^{-N_H\sigma(E)}$, where $\tilde{\theta}_s = [\Gamma_s, \gamma_s]$
- then bandpass fluxes are $F_{sp} = \int_{\mathscr{E}_p} E\ n_E(\theta_s)\ \mathrm{d}E = n_s E_0 \int_{\mathscr{E}_p} q(E;\tilde{\theta}_s)\ \mathrm{d}E$
- Ansatz: fits in narrow bands give accurate F_{sp} regardless of true $[\Gamma_s, \gamma_s]$

Multiplicative Shrinkage Math

- Replace

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

- with $y_{isp} = B_{ip} + G_{sp} - \frac{\sigma_i^2}{2} + e_{isp}$,

$$y_{isp} \equiv \log \hat{f}_{isp} = \log[E_0 C_{isp}/(\hat{T}_{isp} a_{ip})], B_{ip} \equiv \log(A_{ip}/a_{ip}), G_{sp} \equiv \log F_{sp}$$

- and we assume $\hat{T}_{isp}(\theta_s) = t_{is} \sum_k \frac{\int_{\mathscr{E}_p} \alpha_i(E) \frac{E_0}{E} q(E;\theta_s) \Phi_{ik}(E)\, \mathrm{d}E}{\int_{\mathscr{E}_p} q(E;\theta_s)\, \mathrm{d}E}$ is not correlated with errors in effective area over narrow bands

Multiplicative Shrinkage Math

- Replace

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

- with $y_{isp} = B_{ip} + G_{sp} - \frac{\sigma_i^2}{2} + e_{isp}$,

This is our goal:
Effective area corrections

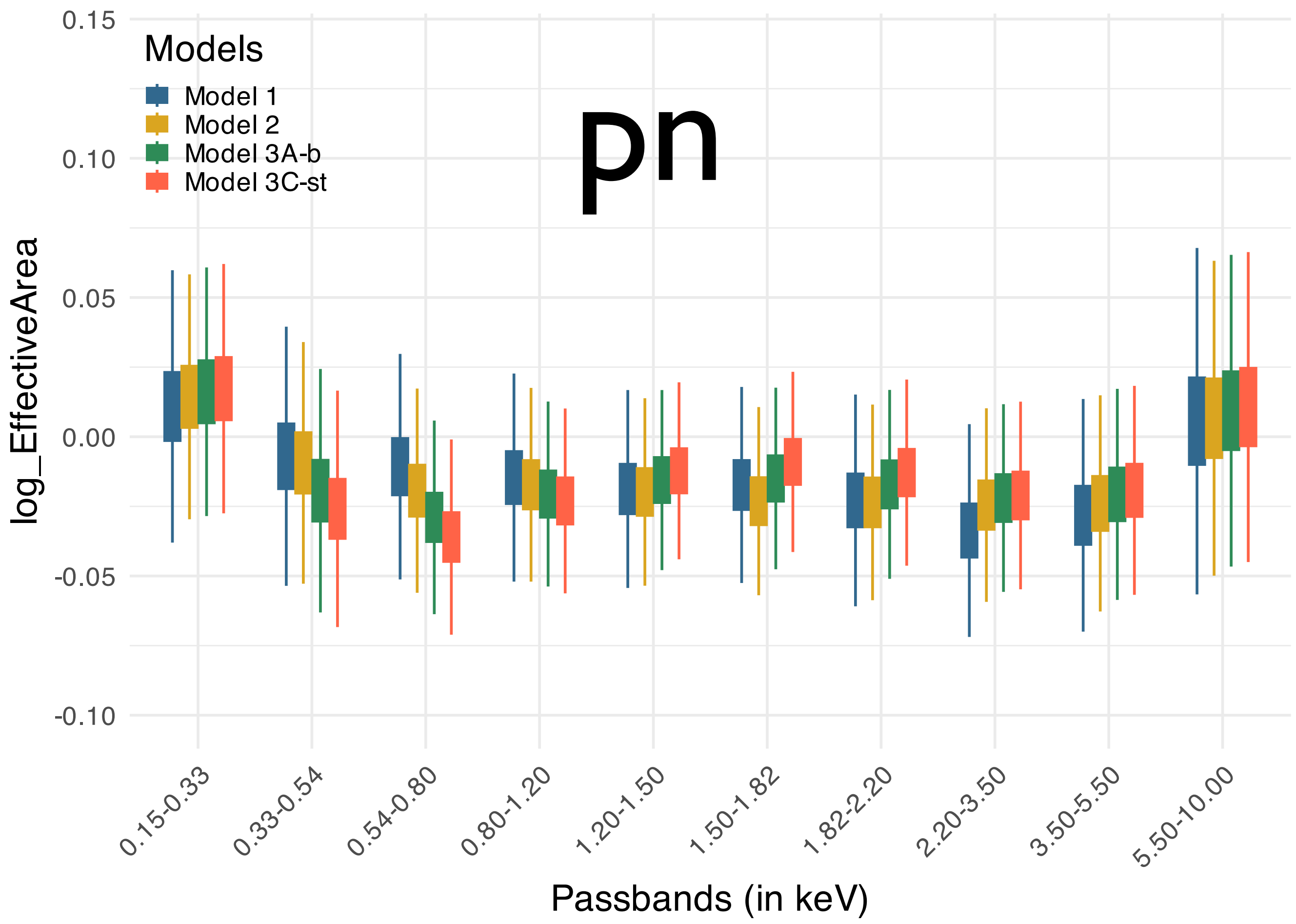
$$y_{isp} \equiv \log \hat{f}_{isp} = \log[E_0 C_{isp}/(\hat{T}_{isp} a_{ip})], B_{ip} \equiv \log(A_{ip}/a_{ip}), G_{sp} \equiv \log F_{sp}$$

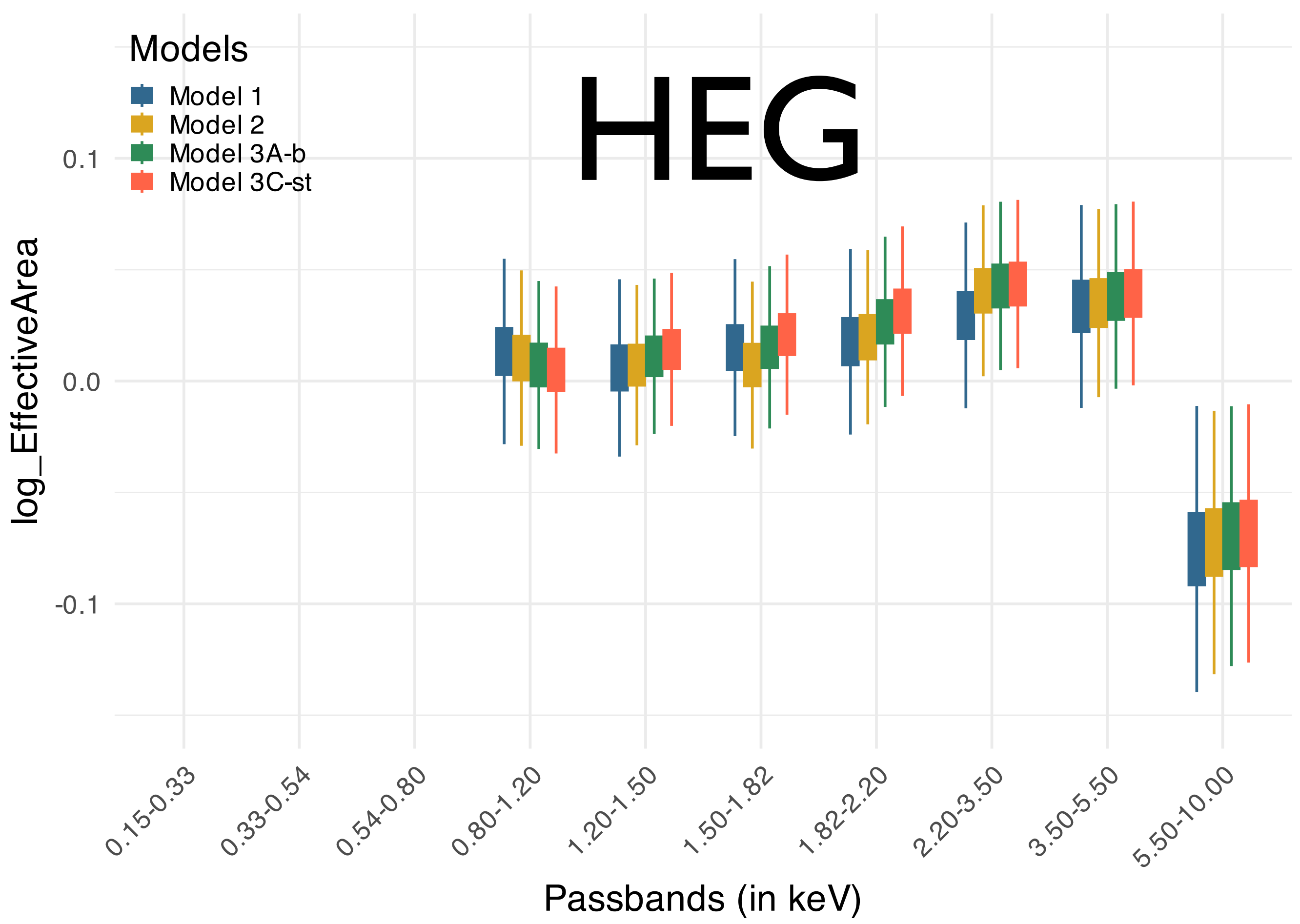
- and we assume $\hat{T}_{isp}(\theta_s) = t_{is} \sum_k \frac{\int_{\mathscr{E}_p} \alpha_i(E) \frac{E_0}{E} q(E;\theta_s) \Phi_{ik}(E)\, \mathrm{d}E}{\int_{\mathscr{E}_p} q(E;\theta_s)\, \mathrm{d}E}$ is not correlated with errors in effective area over narrow bands

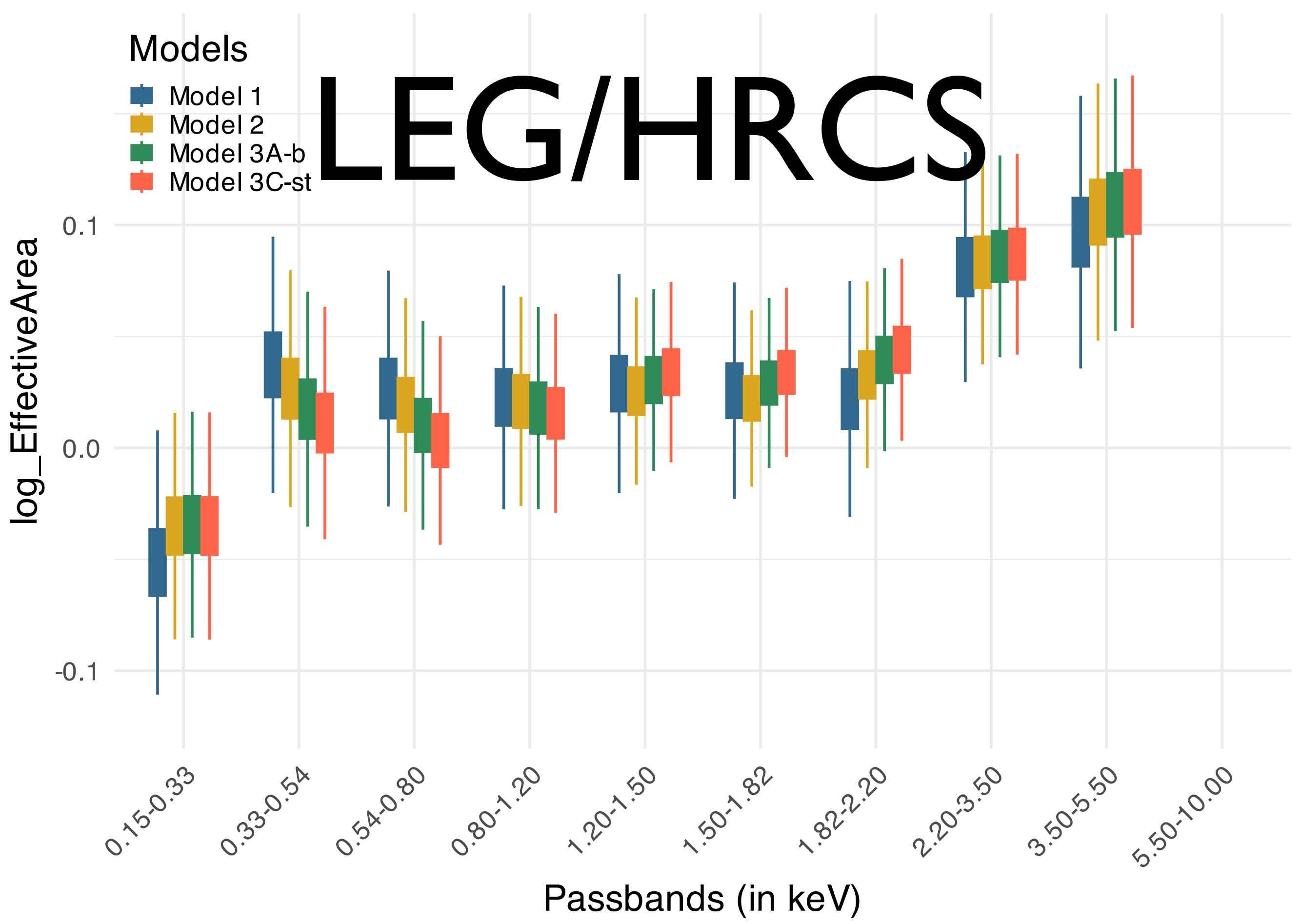
Paper 3 Features

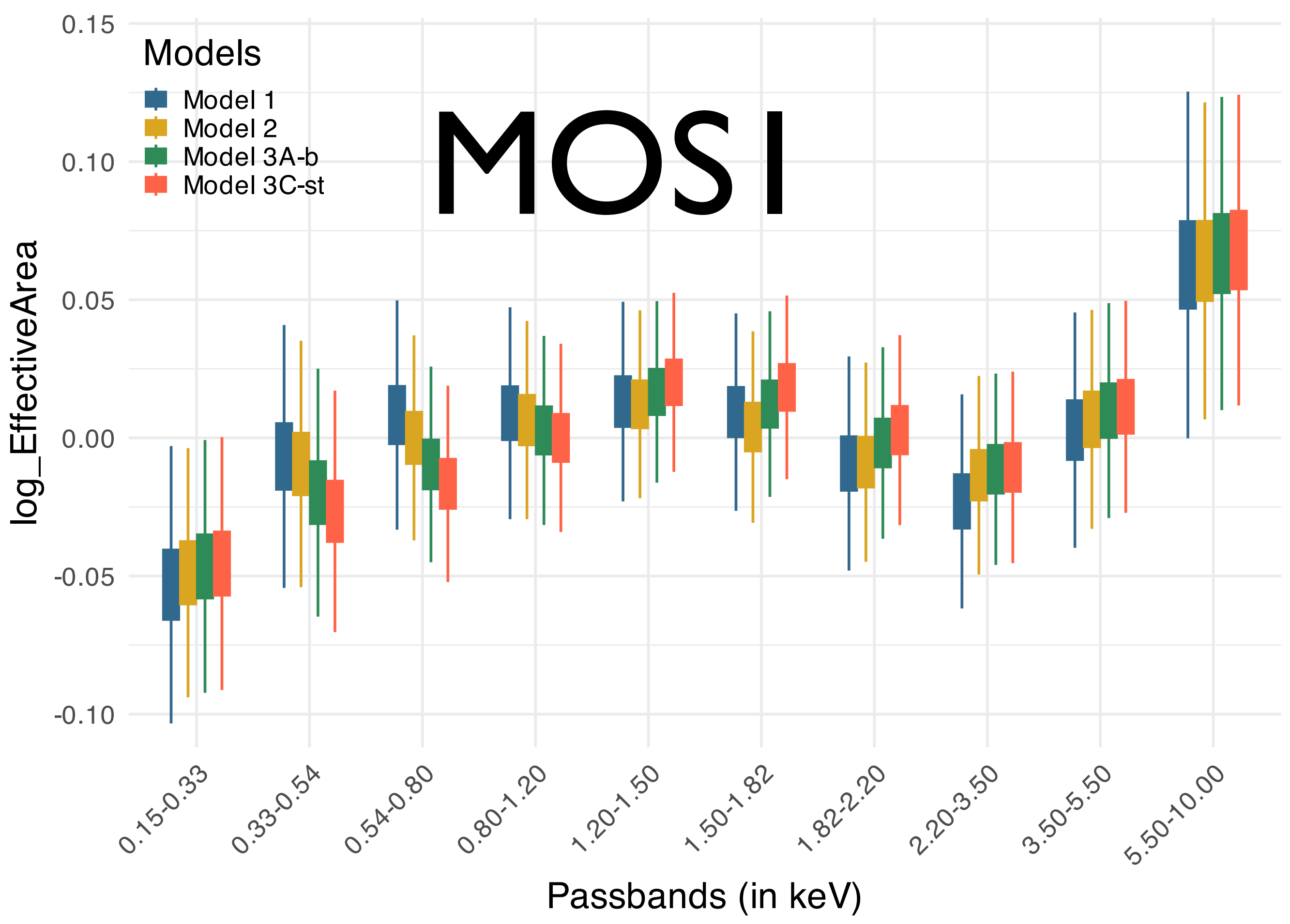
- Data prepared for analysis — "cleaned" of outliers
  - Fit set of log fluxes for a given source to narrow band approximation: $\log F_p(\theta_s) = \log F_p(n_s, \Gamma_s, \gamma_s) = \log n_s + K_p - \xi_p \Gamma_s + \xi_p^2 \gamma_s$ where $K_p = \xi_p + d_p - N_{\mathrm{H}} \sigma_p, \;\; \xi_p \equiv \log(E_{2p} + E_{1p}), \;\; d_p \equiv \log(E_{2p} - E_{1p})$
  - Eliminate instrument-bandpass sample if $|\log \hat{f}_{isp} - \log F_p(\hat{\theta})| > 0.5$
- Statistical models
  - 1 - No use of bandpass EA covariances, spectral correlation (Chen+ '19)
  - 2 - Bandpass EA covariances, no spectral correlation (Marshall+ '21)
  - 3 - EA and spectral correlation across bands (Paper 3)
    - Variants: all sources have same $[\Gamma, \gamma]$ or targets have specific $[\Gamma, \gamma]$
- Model time-dependence

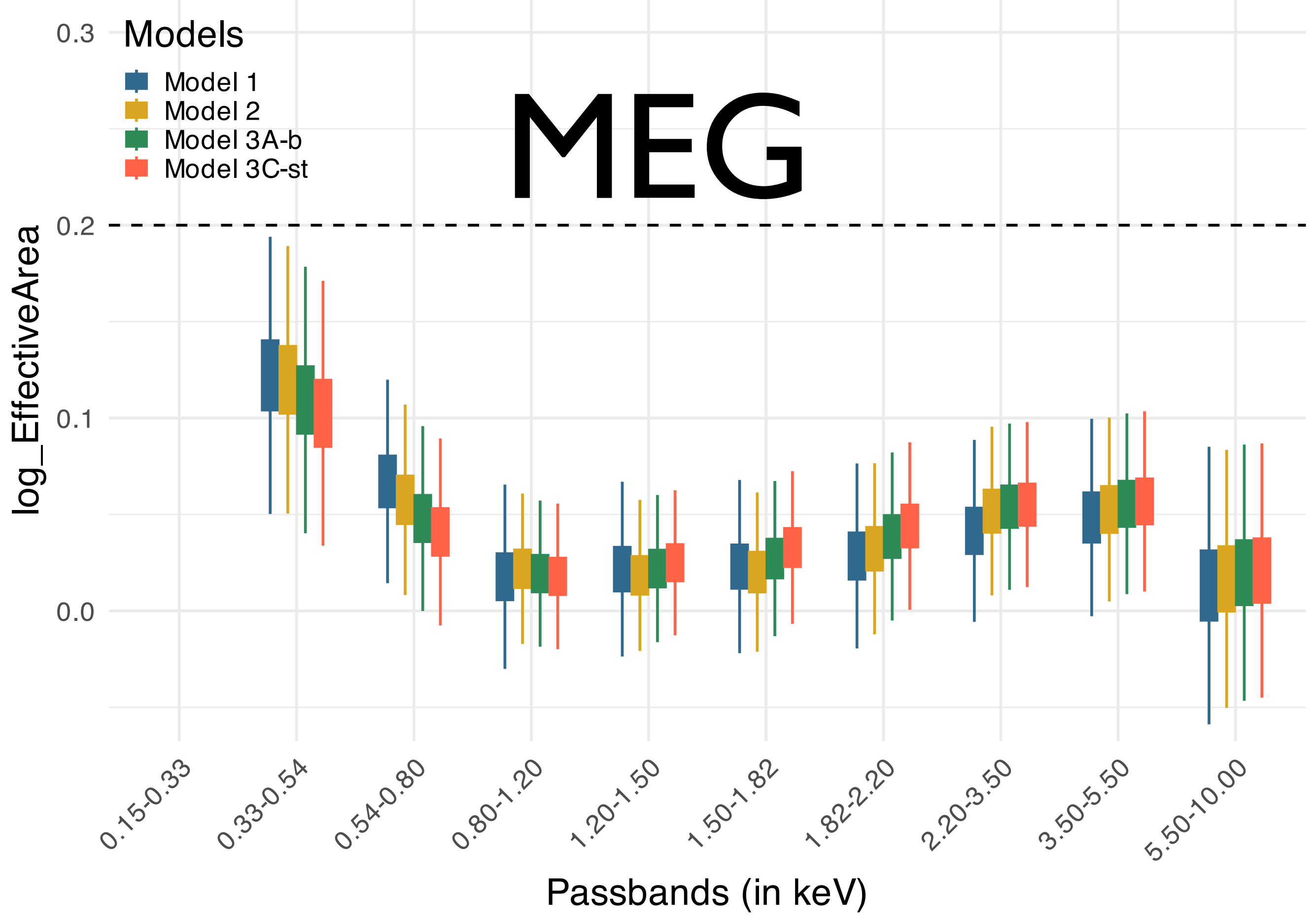
Concordance Results: EA corrections

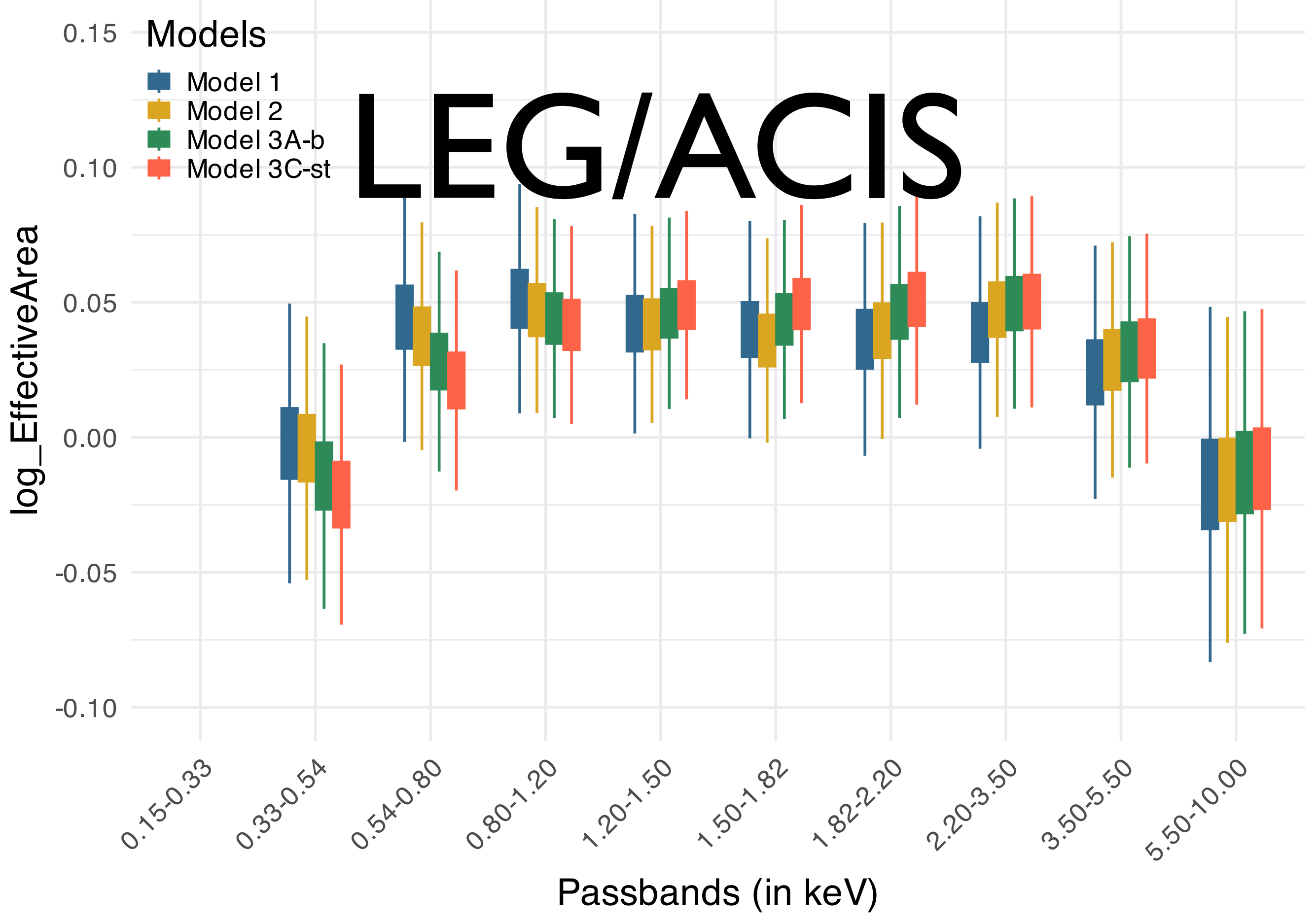




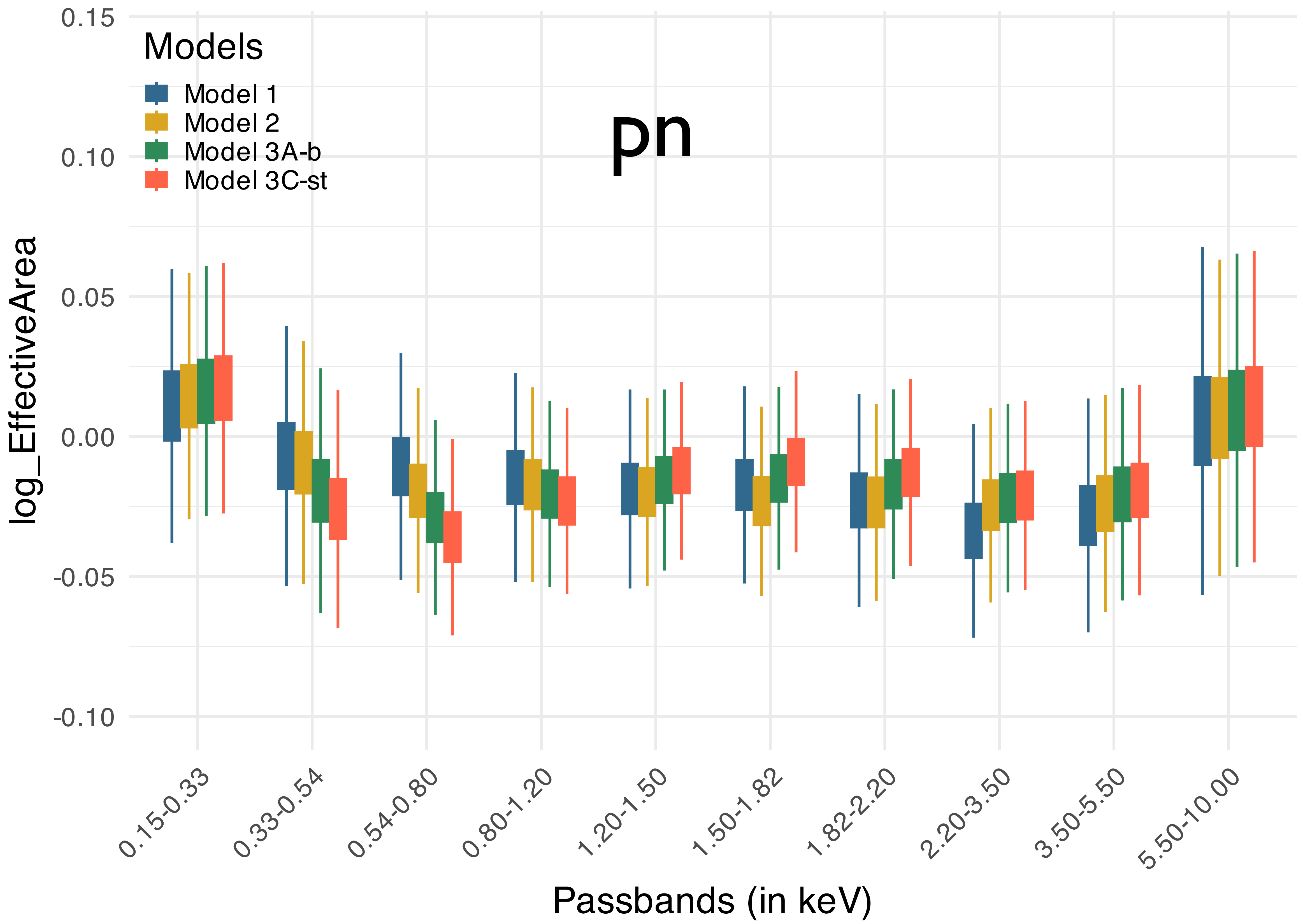


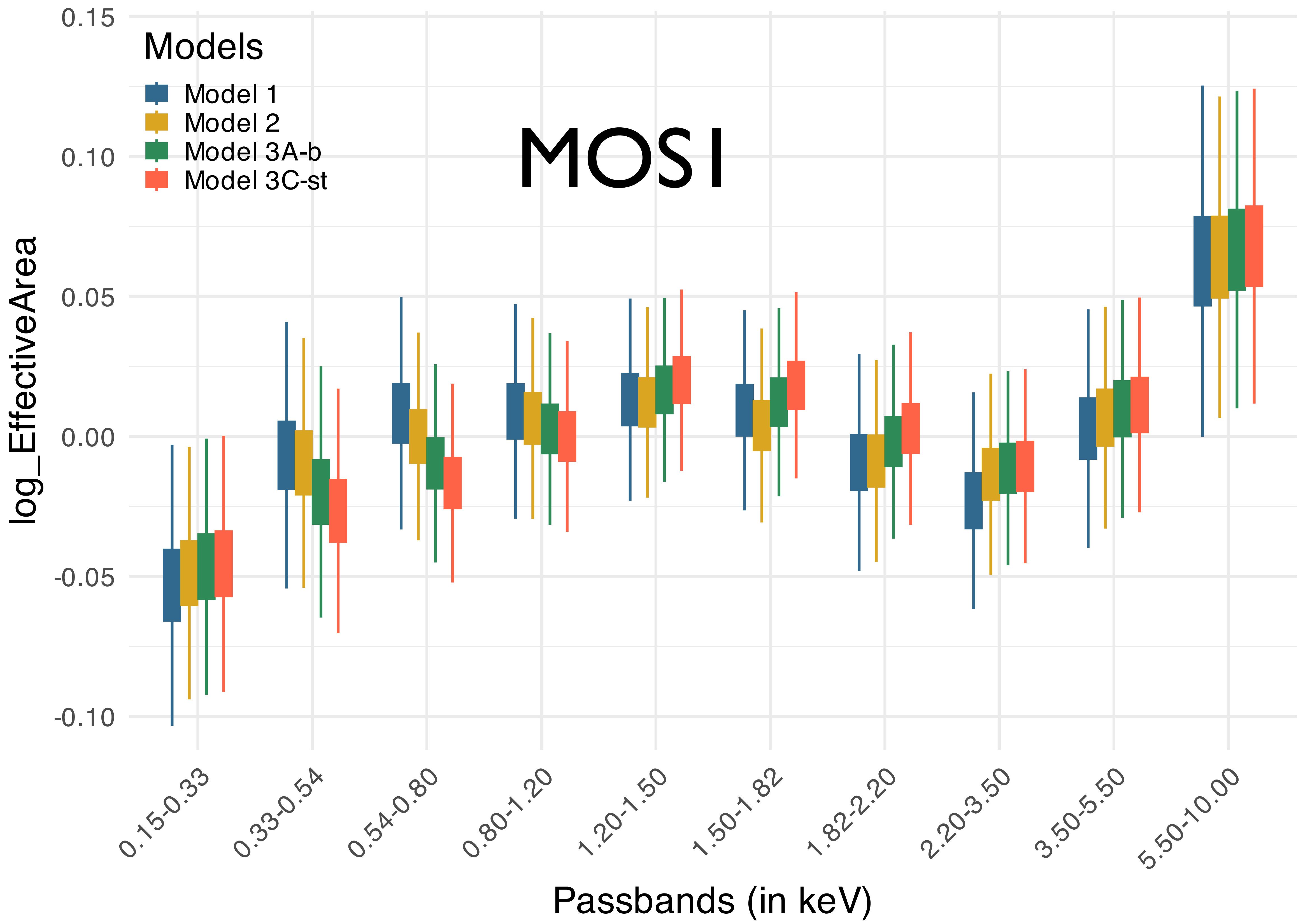




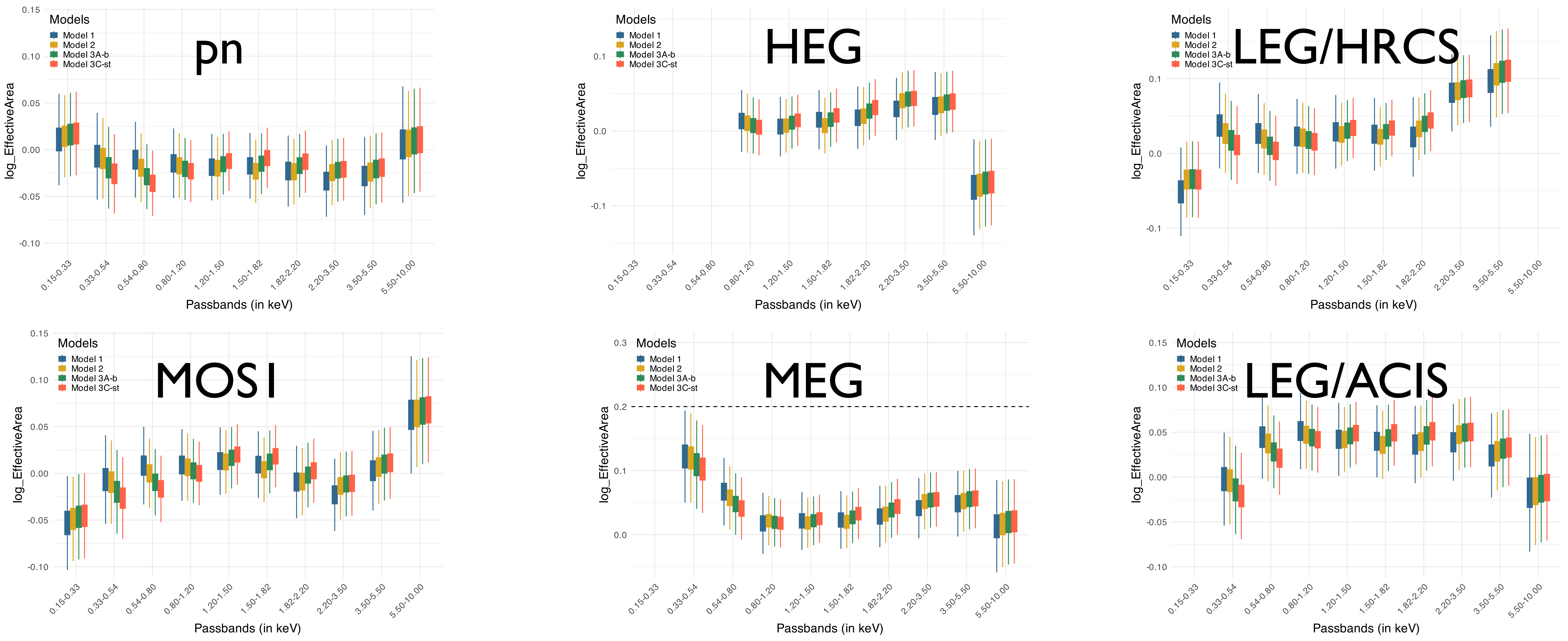


Concordance Results: EA corrections

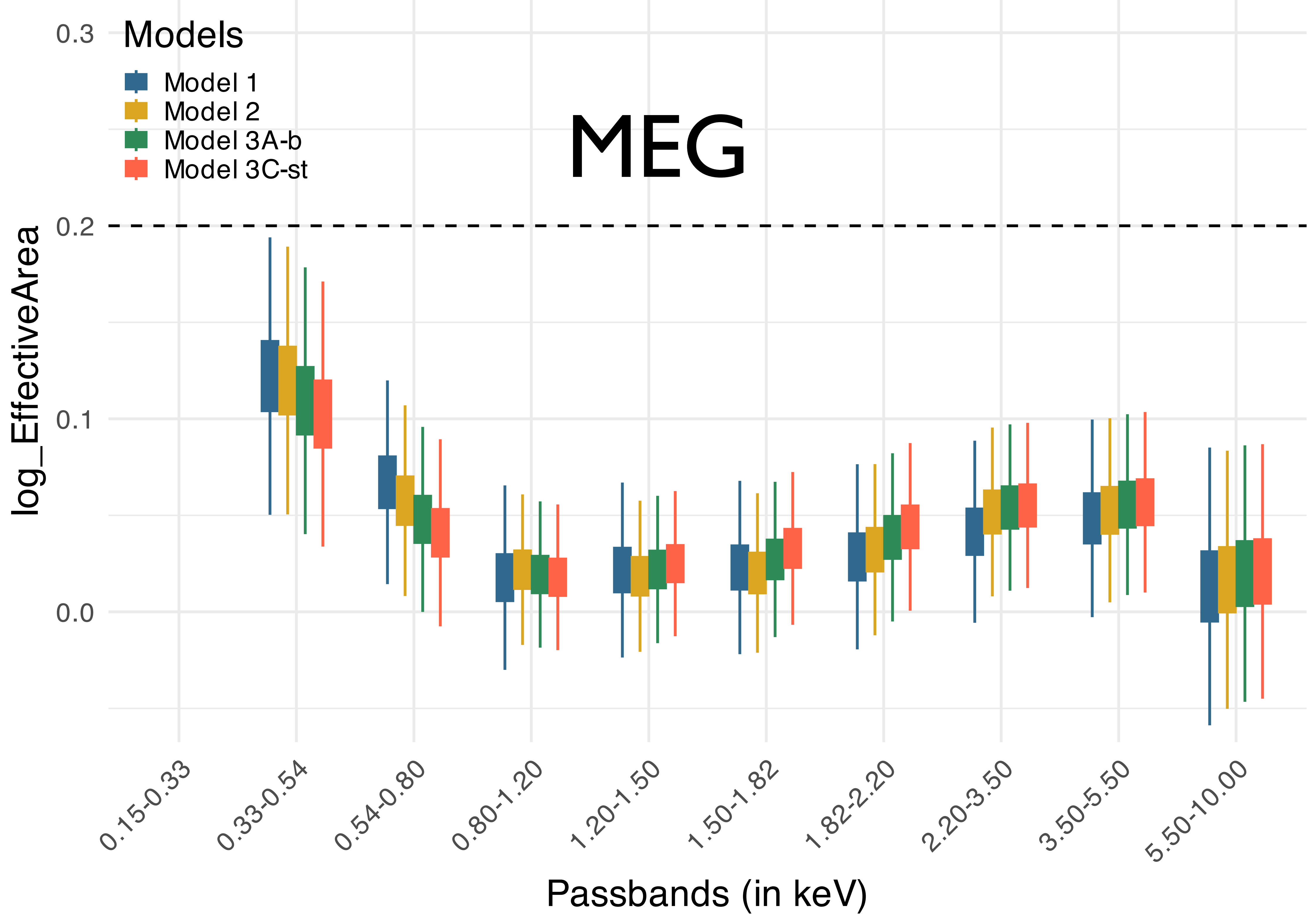


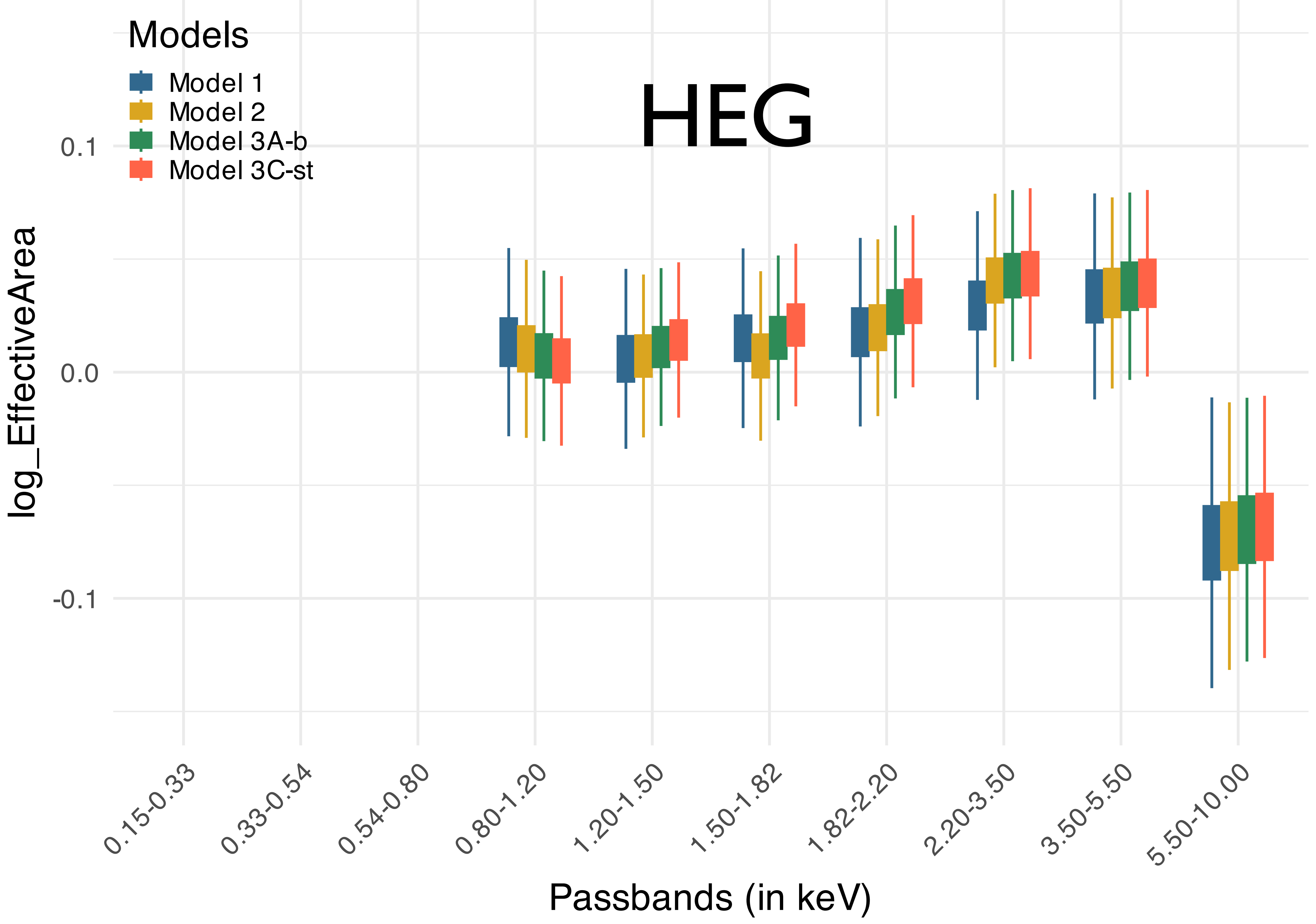


Concordance Results: EA corrections



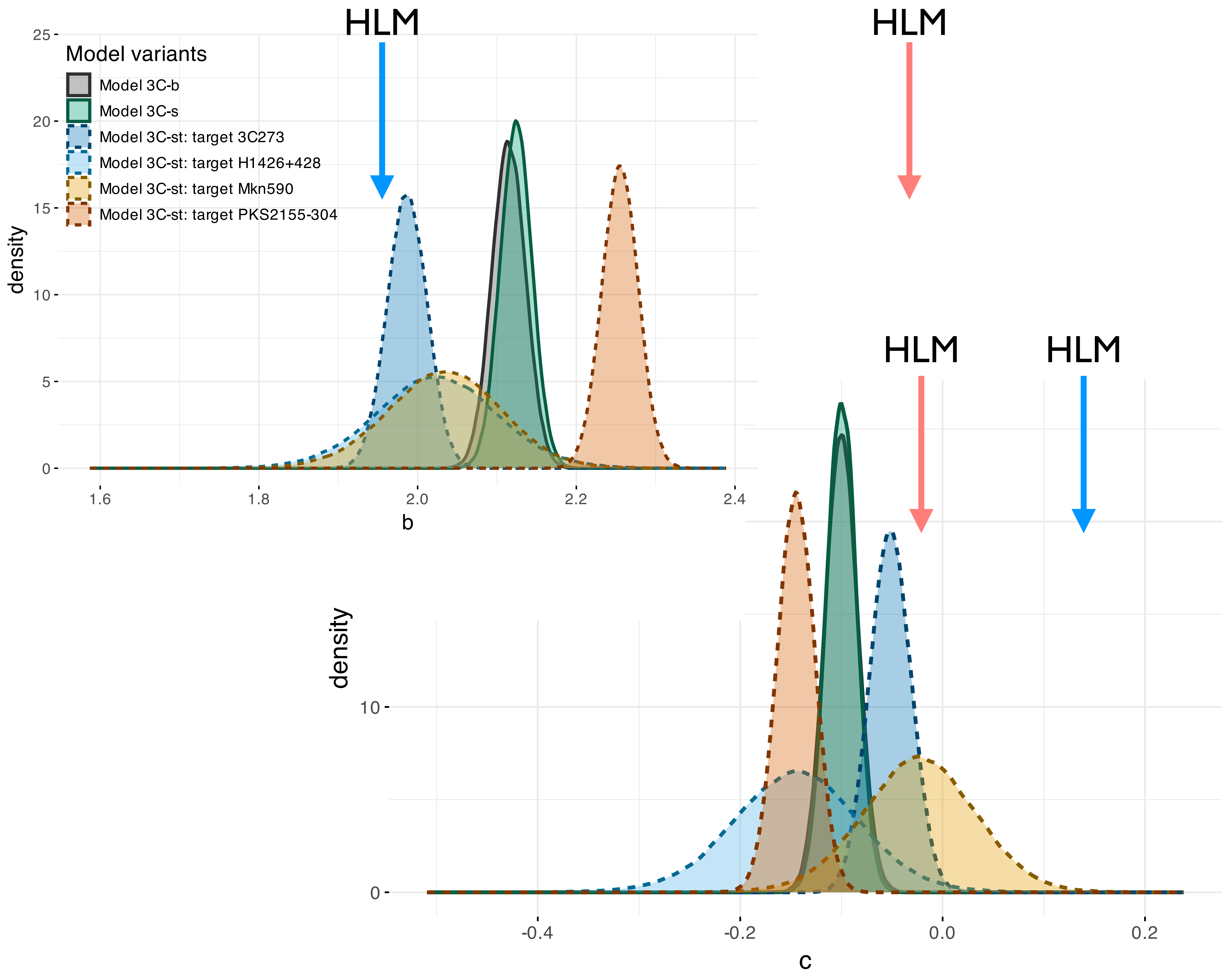
Concordance Results: EA corrections





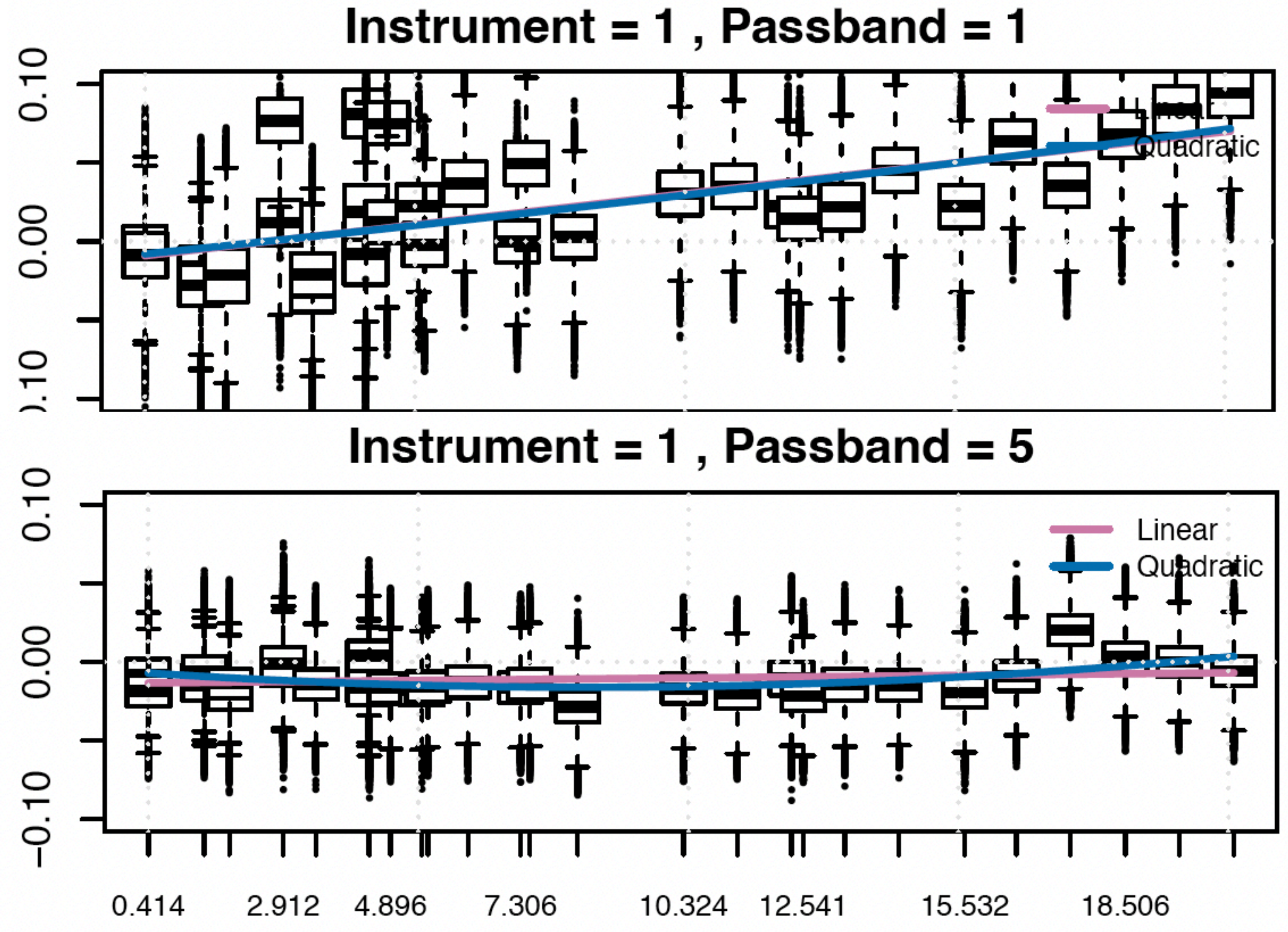
Concordance Results: Spectral Params

- Model 3C-b, 3C-s: all sources with same $\tilde{\theta} = [\Gamma, \gamma] = [b, c]$
- Model 3C-st: $\tilde{\theta}$ depends on target
- Targets: PKS 2155, 3C 273, 1H1426, Mk 590
- Simple fits (HLM):
  - PKS 2155: $[b, c] = [2.67, -0.018]$
  - 3C 273: $[b, c] = [1.96, 0.145]$
- Discrepancy is not yet resolved

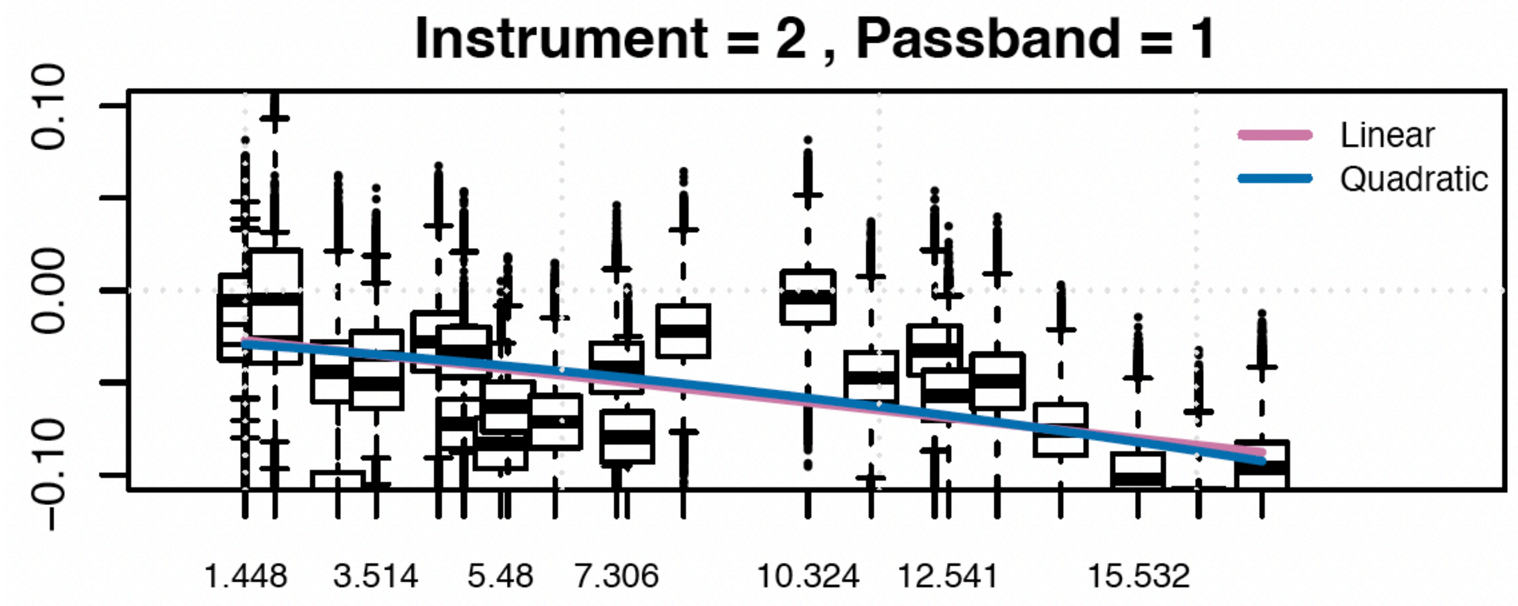


Concordance Results: Time changes

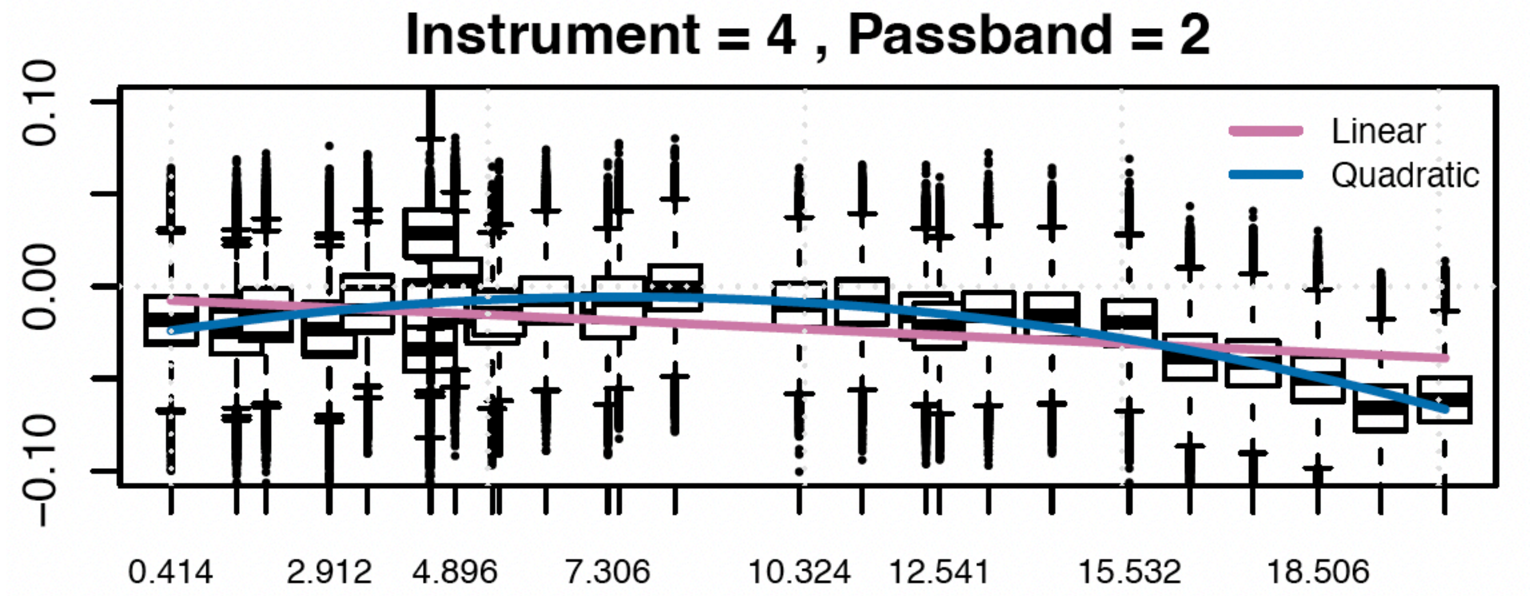
pn



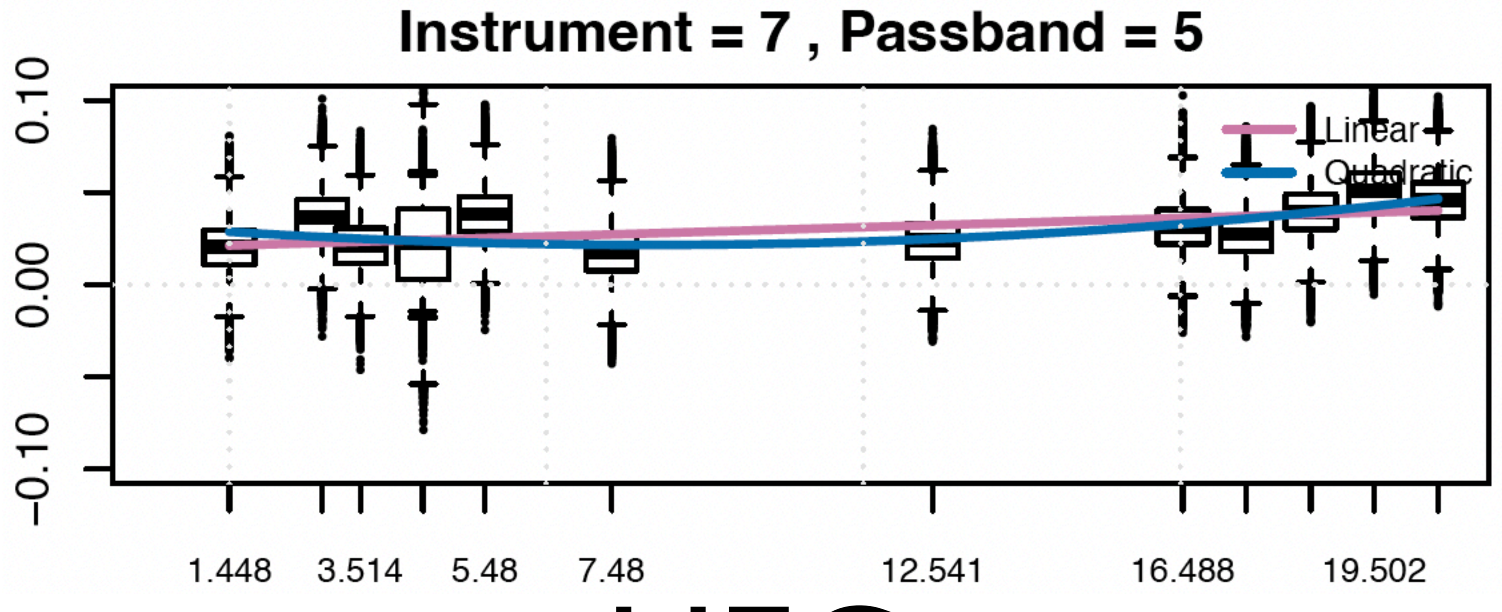
MOS1



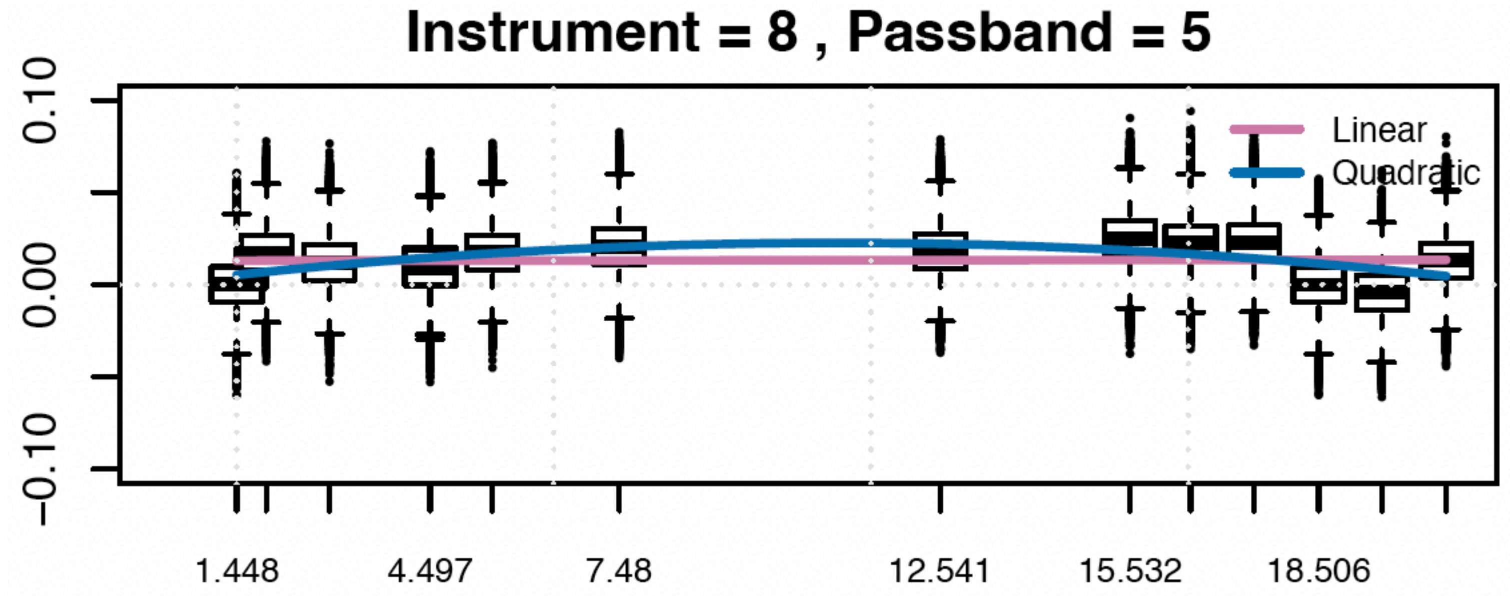
RGS1



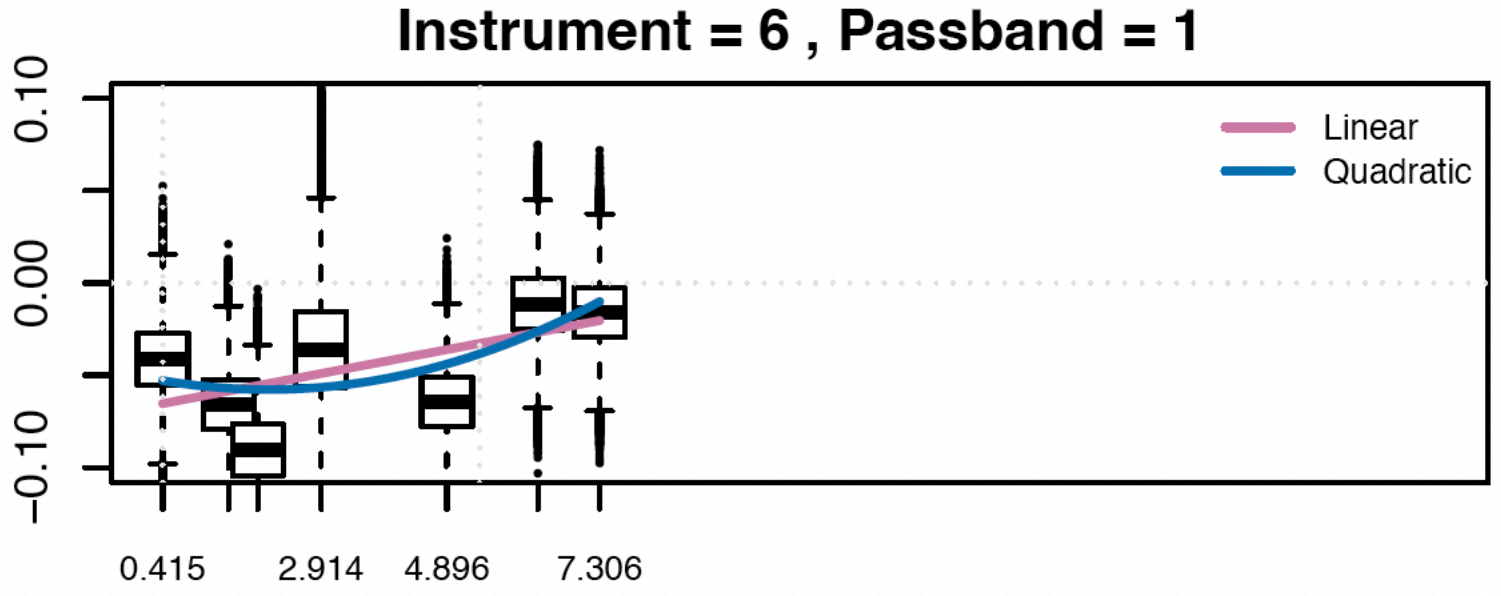
MEG



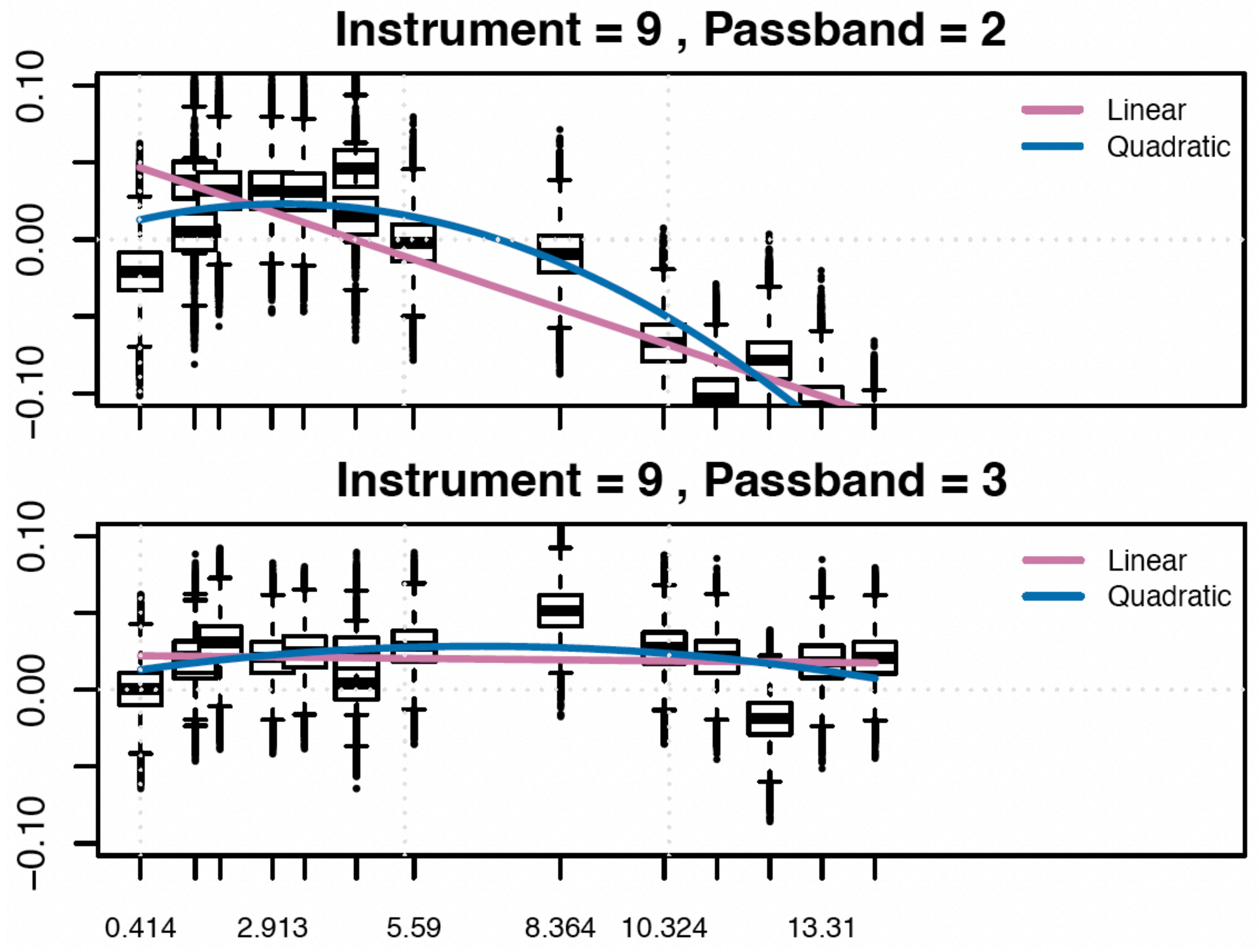
HEG



LEG/HRCS



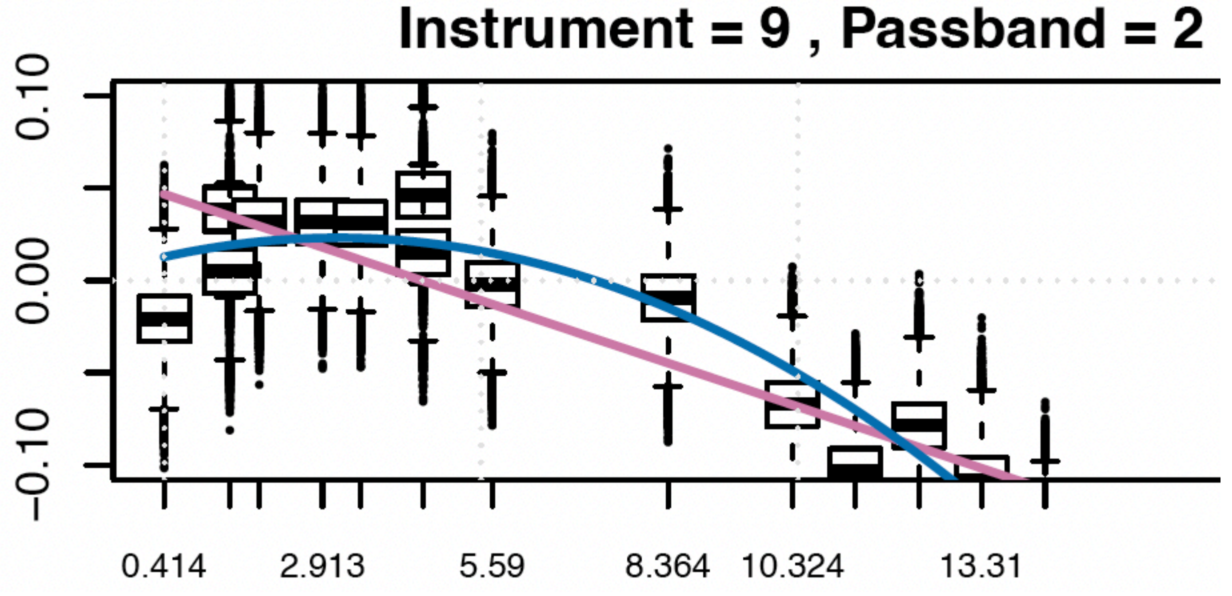
LEG/ACIS



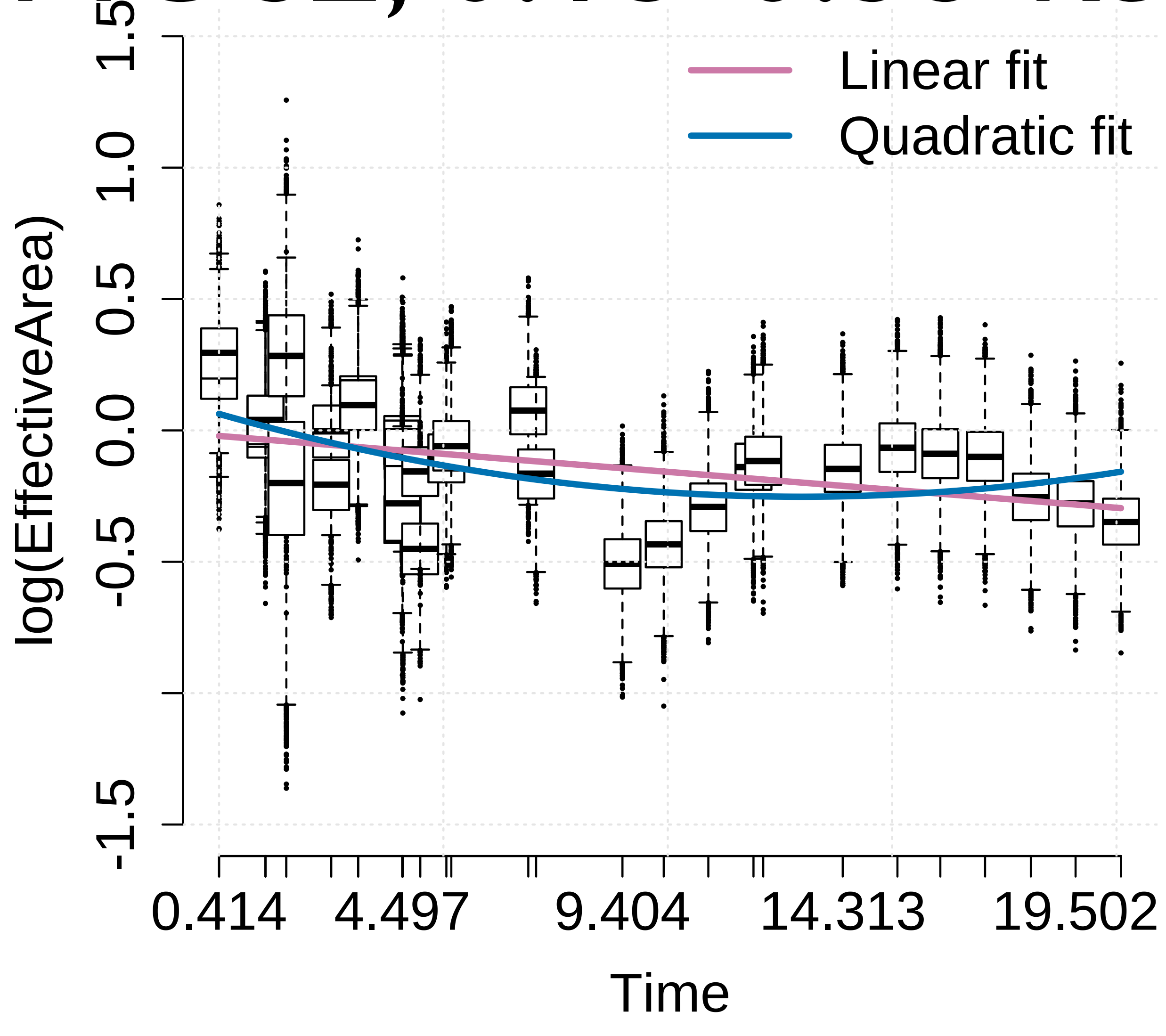
Concordance Plans

- Submit XMM/Chandra XCAL paper (next week?)
- Under consideration
  - Revisit τ values, loosen as needed
  - Refine models of time dependence
  - Collect more data:
    - Cluster fluxes (narrower bands?)
    - Include Crab fluxes to 300+ keV!
    - Use joint 3C 273 observations

LETG/ACIS, 0.33-0.54 keV



MOS2, 0.15-0.33 keV



Update Priors?

Tau_Matrix (May 5, 2024)

	.15-.33	.33-.54	.54-.8	.8-1.2	1.2-1.5	1.5-1.8	1.8-2.2	2.2-3.5	3.5-5.5	5.5-10	15-25	25-50	50-100	100-300
XMM pn	2	2	2	2	2	2	2	2	2	3				
XMM M1	20	10	6	6	6	6	6	6	6	10				
XMM M2	20	10	6	6	6	6	6	6	6	10				
XMM R1		8	5	5	5	5								
XMM R2		8	5	5	5	5								
Chandra HRCS-LEG	5	7	7	7	7	7	7	7	10	10				
Chandra ACIS-MEG		20	10	5	4	4	4	4	5	7				
Chandra ACIS-HEG				5	4	4	4	4	5	7				
Chandra ACIS-LEG	10	10	7	5	4	4	4	4	5	7				
Chandra HRCI-LEG	5	7	7	7	7	7	7	7	10	10