



Inferring AGN torus morphology using X-ray spectra: A reliability study

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Abstract

Several models of the X-ray reprocessing of the AGN torus are in routine use by the community, (UXCLUMPY, CTORUS, MYTORUS etc.). They span a range of assumed torus geometries and morphologies. The degeneracies in these models can limit reliable constraints of parameters of interest, such as the intrinsic photon index and parameters determining torus morphology. To investigate these effects, we simulate synthetic data under *XMM-Newton* and *NuSTAR* response files based on six different models. We use Bayesian methods to analyze the simulated datasets with the same set of models. For exposure times and fluxes typical of nearby Compton-thick AGN, several geometrical parameters remain unconstrained. In addition, distinction between competing models or morphologies using Bayesian methods is possible only if we have a high intrinsic value of flux for a typical exposure time. Our project aims to provide guidance for the X-ray community both in terms of the accuracy in applying the correct torus model (with implications for conclusions on the torus geometry and morphology) and the robustness of estimation of model parameters (with implications for limitations on precision of those parameters).

Different Morphologies

- **CONTINUOUS**: e.g. Doughnut (MYTORUS), Biconical cut-out (BORUS) -
- **CLUMPY**: e.g. CTORUS

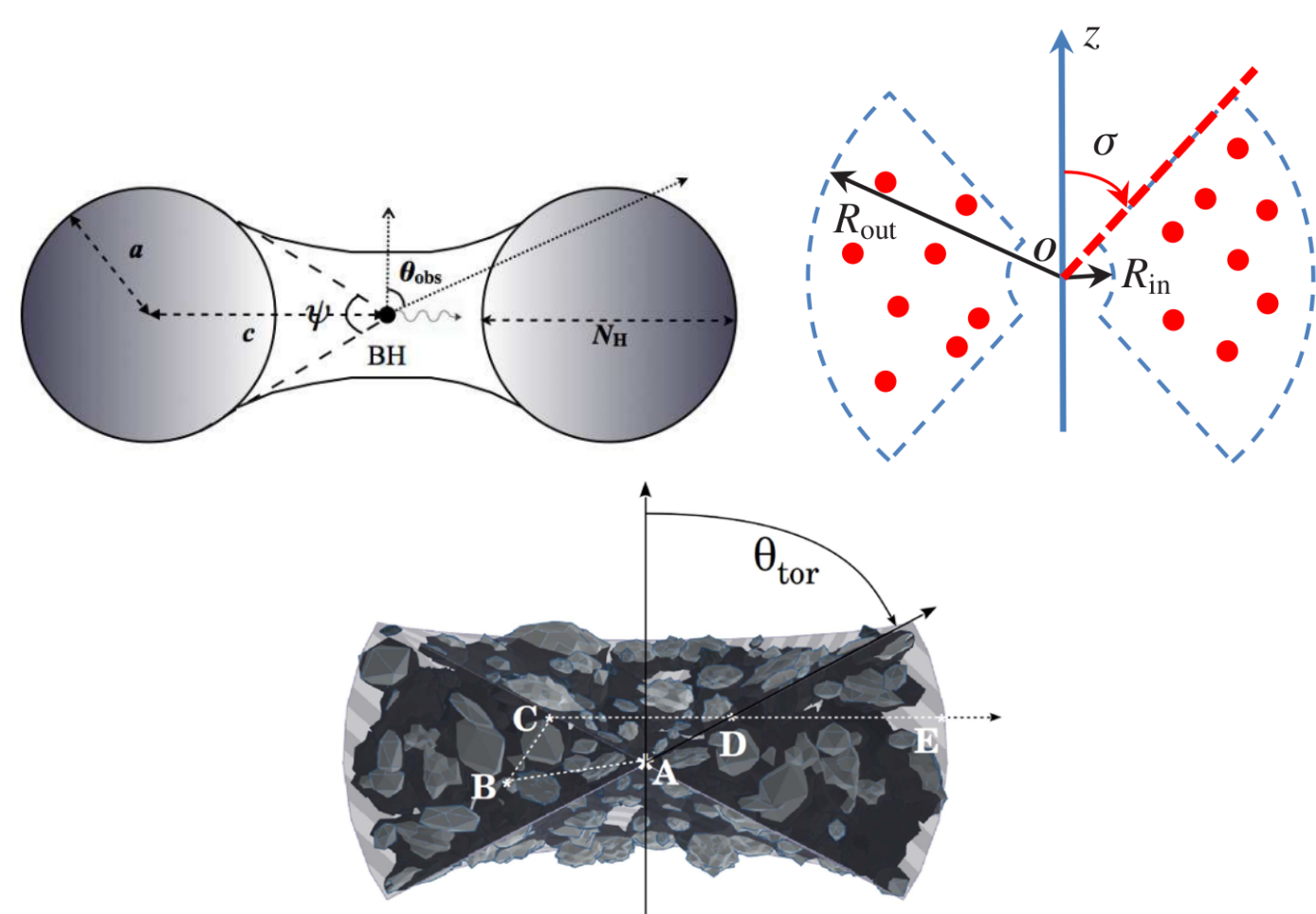


Figure 1. Left: Doughnut cross-section (MYTORUS, Murphy et al. 2009). Right side, Clumpy Torus (CTORUS, Liu et al. 2014), Bottom: BORUS from Baloković et al. (2018).

Methods

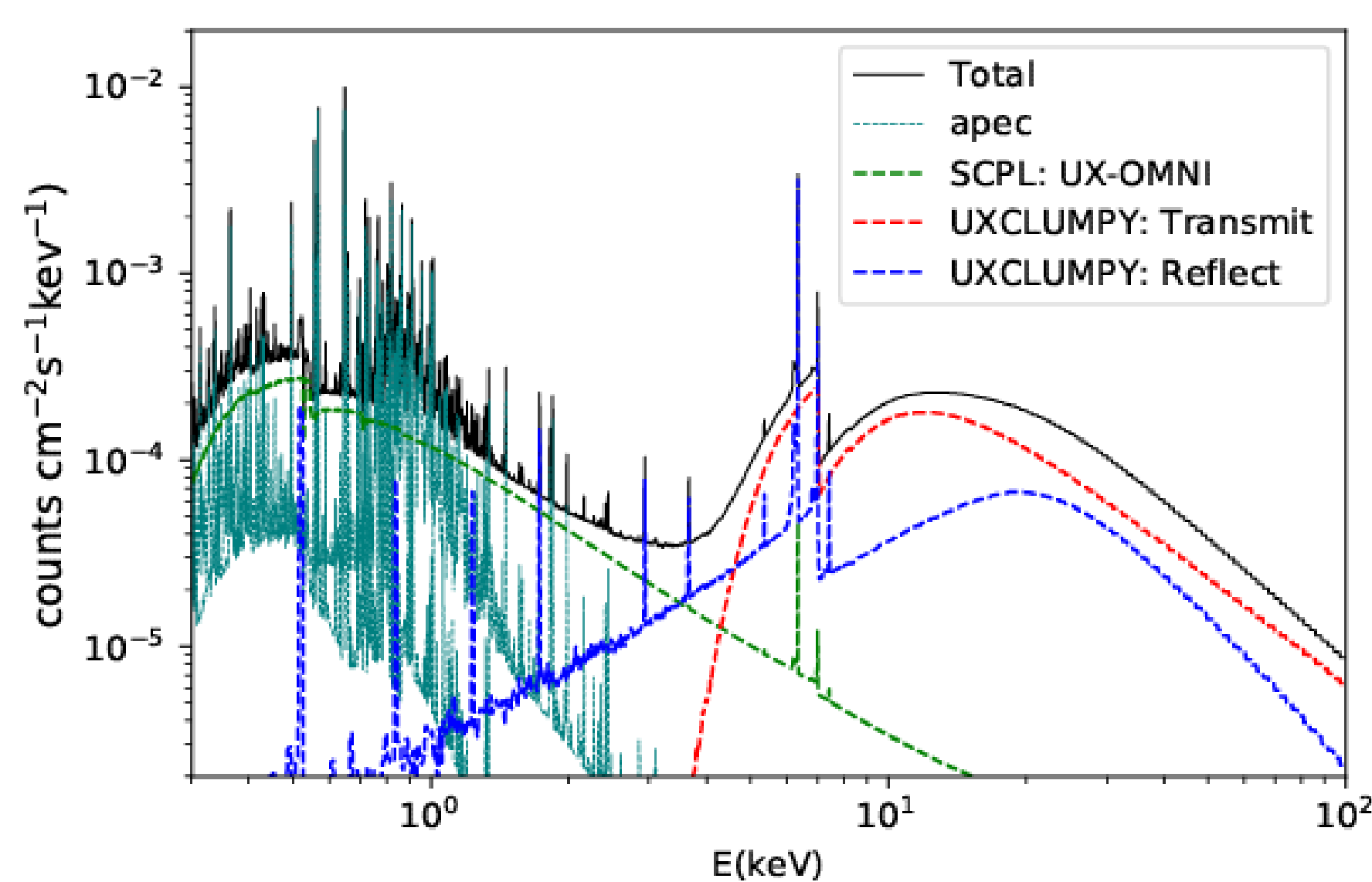


Figure 2. The spectral layout that was used for simulation. The plot illustrates the model components and the total spectrum generated under UXCLUMPY.

Synthetic data (D_i) simulated under a model (M_i) *XMM-Newton* and *NuSTAR* responses. We perform Bayesian Analysis using BXA-Multinest. Our analysis methods:

- **INTRAMODEL FITS** : Simulation and fitting model are same ($M_i \rightarrow D_i$). Are input parameters recovered?
- **CROSS-MODEL FITS** : Simulation and fitting model are different ($M_j \rightarrow D_i$). Which input parameters are recovered? What kind of irregularities are seen in parameter distributions? Are models distinguishable?

BXA-Multinest has the following advantages over conventional χ^2 -minimization and GW-MCMC:

- It does not require sequential runs with multiple burn or any assumption on number of iterations for effective convergence.
- Convergence happens around global maximum of the likelihood so the algorithm does not get stuck in any local maximum.
- BXA-Multinest allows **Evidence** ($Z = P(\text{DATASET}|\text{MODEL})$) calculation in addition to Posteriors.

Parameter Recovery

INTRAMODEL FITS

1. Most parameters are recovered successfully
 2. For a given flux, **roughly in the $N_{H,los,input} \gtrsim 2 \times 10^{24} \text{ cm}^{-2}$ regime**
 - worse constraints on $N_{H,los}$ (Fig-3 top left)
 - better constraints on morphology (Fig-3 top right) compared to when $N_{H,los,input} \lesssim 2 \times 10^{24} \text{ cm}^{-2}$
- Reason: Increased dominance of the Reflected continuum and Strong attenuation of the Transmitted continuum**
3. Parameters require both *XMM-Newton* and *NuSTAR* for constraints.

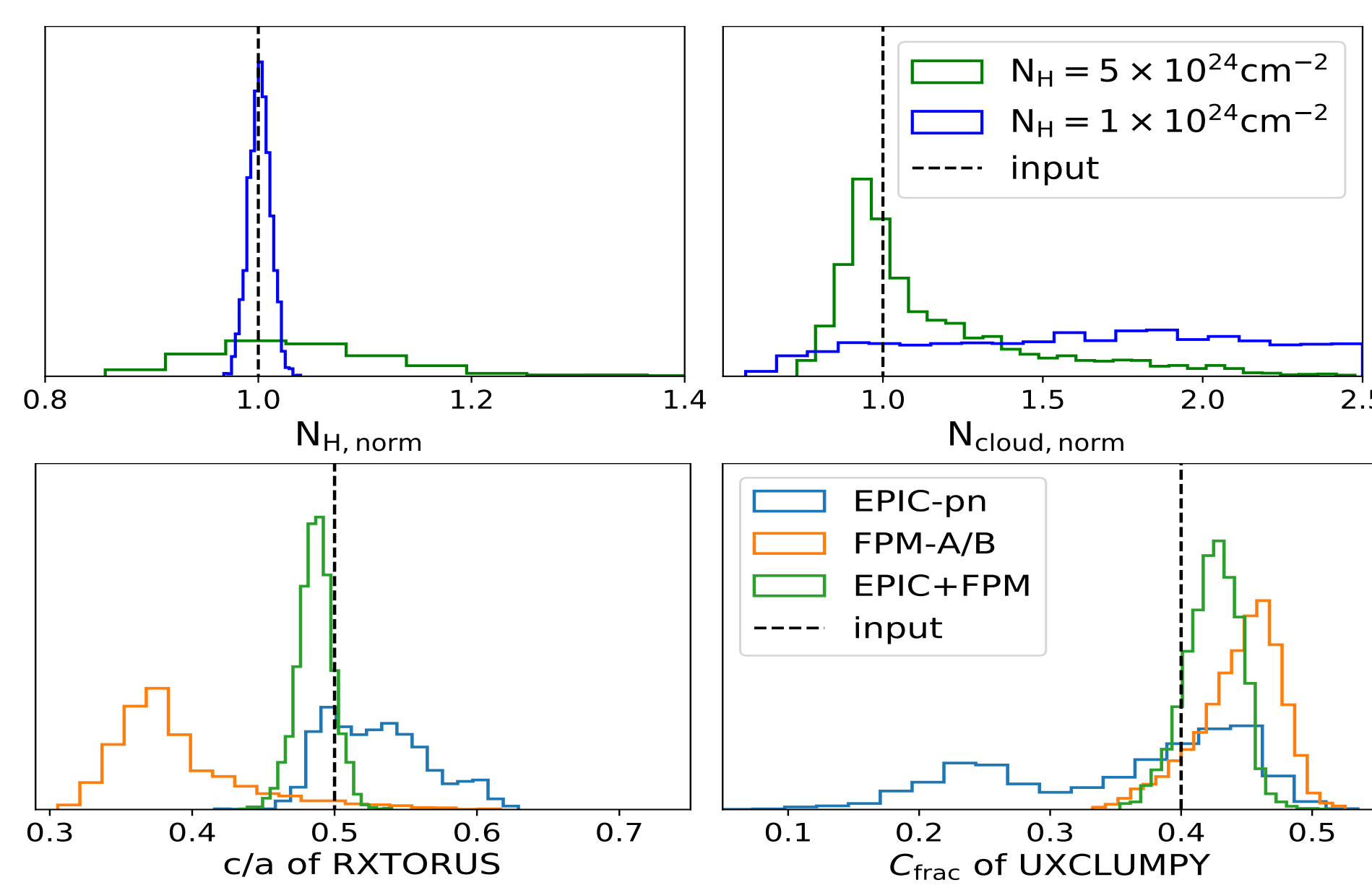


Figure 3. TOP: $X_{norm} = \frac{X_{posterior}}{X_{input}}$, left: $N_{H,los}$, right: N_{cloud} no. of clumps (in CTORUS). The relative width of the posteriors show how constraints change upon $N_{H,los}$ variation. BOTTOM: Dependence of parameters on instruments (left: c/a Doughnut thickness RXTORUS \rightarrow better constraints from *XMM-Newton*, right: C_{frac} of inner ring of UXCLUMPY \rightarrow better constraints from *NuSTAR*)

CROSS-MODEL FITS

1. Parameters are subject to systematic uncertainties when wrong models are applied (e.g. Γ and $N_{H,los}$ in Fig-4).
2. Different trends seen in the best fit model components, which can be interpreted physically might be just an artefact of model dissimilarities (e.g. Fig. 4).

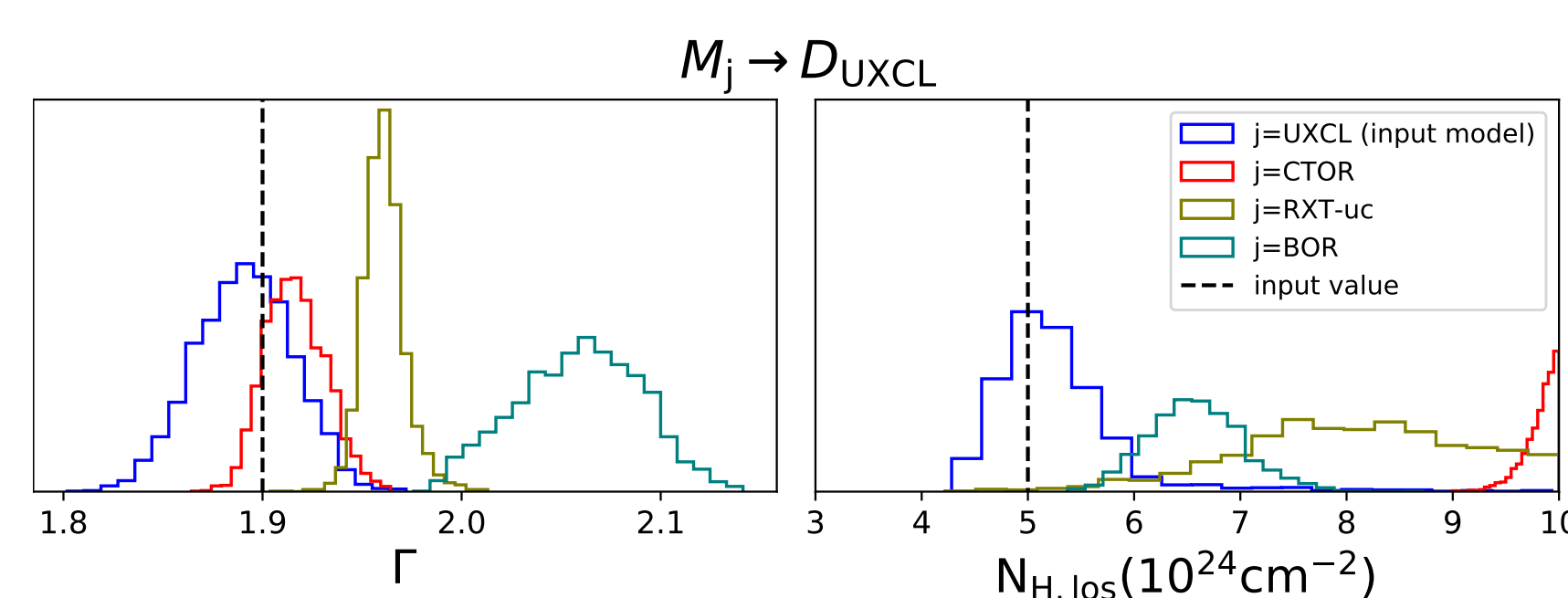


Figure 4. Left: Discrepancy in Γ Right: Discrepancy in $N_{H,los}$ all in $N_{H,los} > 2.0 \times 10^{24}$ regime.

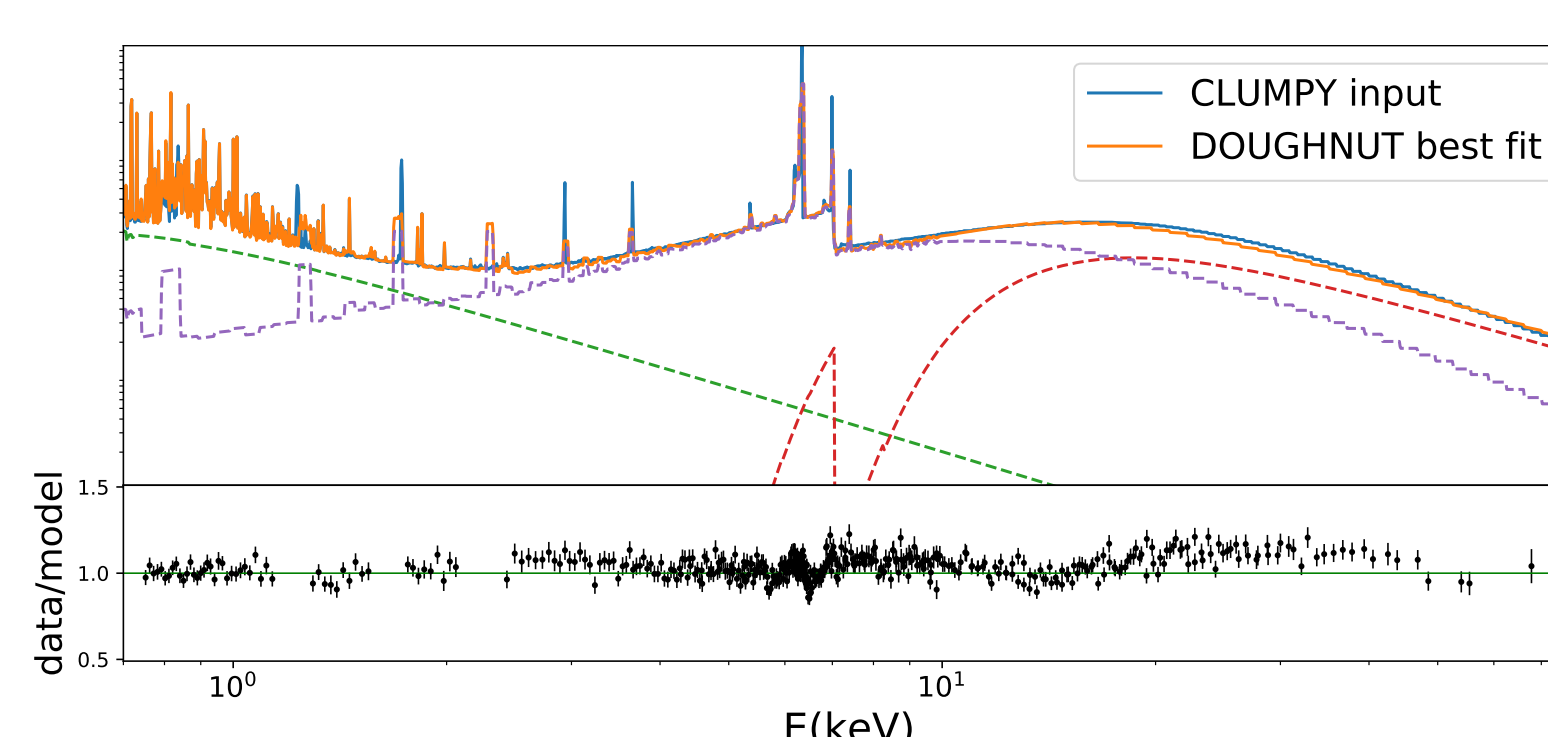


Figure 4 Doughnut best fit spectrum and its components for data simulated under clumpy model i.e. an example of **wrong model application**. Input: Transmitted component practically ABSENT; Fitting model: Transmitted component DOMINANT in the Compton hump region \Rightarrow INCONSISTENCY

Model Distinction

- For theoretical flux, $F_{2-10\text{keV},n} = \frac{0.5}{n} \text{ mCrab}$ ($n = 1-10$), we simulated spectra $D_{CTORUS,n}$.
- Model(s) Fit: $M_j \rightarrow D_{CTORUS,n}$, $j = \text{CTORUS, UXCLUMPY, BORUS}$
- \log Bayes factor (or $\log \text{BF}$) = $\log(Z_j/Z_{CTORUS})$ where Z is Bayesian evidence.

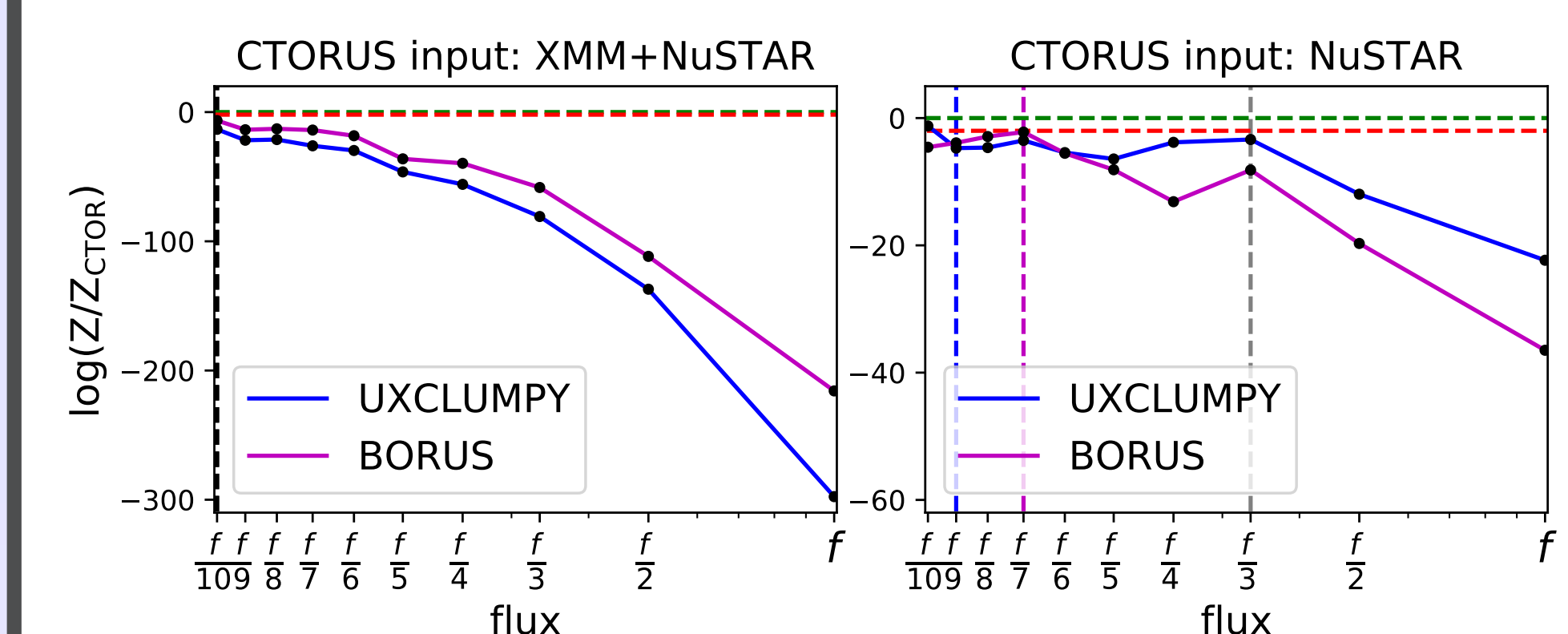


Figure 5. Variation of Bayes Factor with source flux. Left: *XMM-Newton+NuSTAR*, right: *NuSTAR* only. The blue and magenta dashed lines denote the flux level at which the relation $\log(Z_{fit}/Z_{input}) \leq -2$ holds for the wrong model. The black and green dashed lines marks the $\log \text{BF} = -2$ and $\log \text{BF} = 0$ level respectively. Random fluctuations in the *NuSTAR* only analyses increase the chance of crossing above the zone $\log \text{BF} = -2$ and hence result in a wrong model selection.

Takeaways

- **Incorrect model application can return monomodal distribution peaking at wrong values (e.g. Γ posteriors in Figure 4), implying wrong conclusion of certain parameters.**

- Using Bayes Factor values for data analysis:
 - Existence of random fluctuations implies that application in **real data analysis should be supplemented with the analysis of simulated spectrum, including Bayes Factor calculation.**

- Bayes factor threshold values are not universal and must be determined from simulations. **Conservative thresholds (far from the random fluctuation dominated zone) should be applied to reduce risks of crossing over to the Bayes factor > 1 region.**

- **Single epoch spectral analysis is limited in determining structural parameters of the circumnuclear gas, even for fluxes or exposures typical in observations of nearby Compton-thick AGN.**

References and Acknowledgements

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