Physics of 1 keV feature in X-ray Binaries-part II

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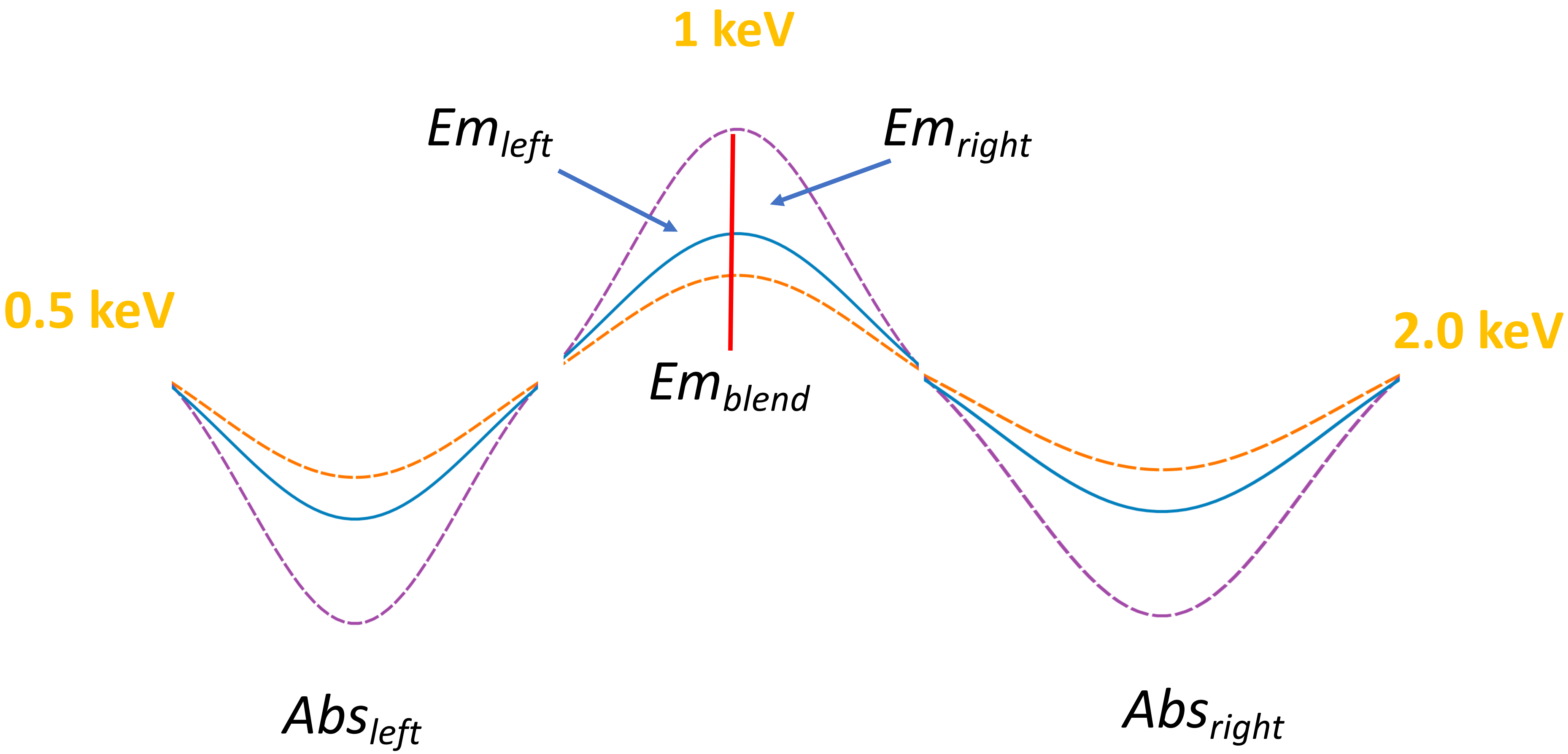
The Mysterious 1 keV Feature in X-Ray Binaries: An Unsolved Puzzle

•Observed in various types of X-ray binaries:

- **ULXs**: *Pinto et al.* (2020,2021)
  - NGC 1313 X-1
  - NGC 247 ULX-1
- **X-ray Pulsars**: *Kosec et al. (2022)*
  - Hercules X-1
- **Typical LMXBs**: *Ludlam et al.* (2018,2022)
  - Cygnus X-2
  - Serpens X-1

https://www.sciencephoto.com/media/449438/view/x-ray-binary-star



$$Em_{left} + Em_{right} = Em_{blend}$$

$$Abs_{left} + Abs_{right} = Abs_{blend}$$

How to create an XSPEC model?

A CLOUDY/XSPEC Interface

R. L. Porter[1], G. J. Ferland[1], S. B. Kraemer[2], B. K. Armentrout[2], K. A. Arnaud[3], & T. J. Turner[4]

ABSTRACT

We discuss new functionality of the spectral simulation code CLOUDY which allows the user to calculate grids with one or more initial parameters varied and formats the predicted spectra in the standard FITS format. These files can then be imported into the x-ray spectral analysis software XSPEC and used as theoretical models for observations. We present and verify a test case. Finally, we consider a few observations and discuss our results.

Subject headings: methods: data analysis — methods: statistical — X-rays: general

How to create an XSPEC model?

```
table power law
hden 10
xi 1 vary
grid 0 4 1
stop column density 20 vary
grid 21 23 1
punch last xspec atable spectrum "spectrum.fits"
punch last xspec atable reflected spectrum "reflection.fits"
```

mtable

Porter et al,. (2006)

https://ui.adsabs.harvard.edu/abs/2006PASP..118..920P/abstract

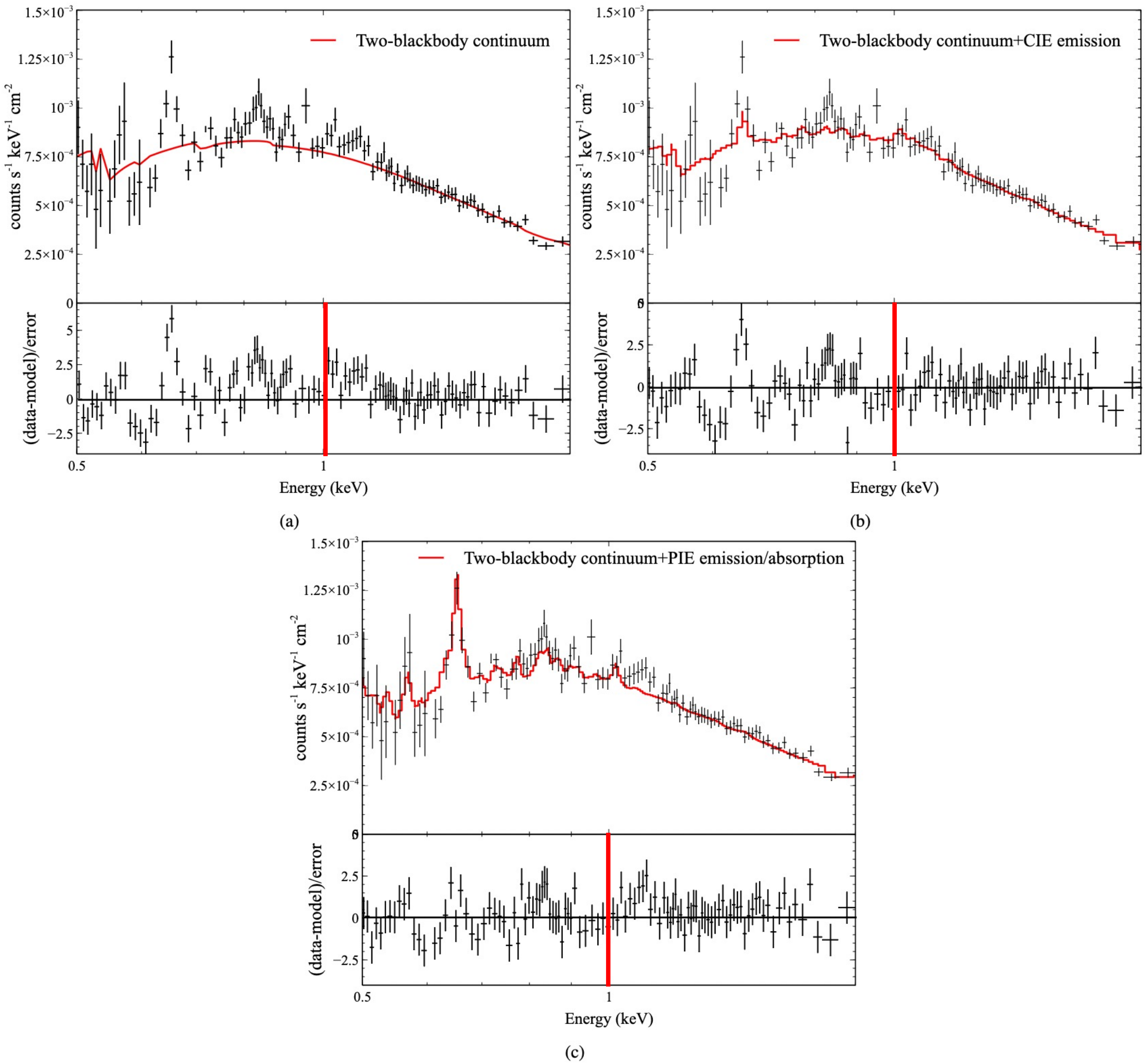
New Cloudy Command added

Database Chianti mixed

In the next Cloudy release, there will be an option to incorporate theoretical energy values for instances where experimental data are absent.

Table 2. List of spectral lines in the 1 keV blend. Line intensities vary depending on the shape of the SED, ξ, N_{H}, and T.

Ion	λ (Å)	Ion	λ (Å)	Ion	λ (Å)	Ion	λ (Å)	Ion	λ (Å)	Ion	λ (Å)
Mg XII	6.58008	Al XII	6.63476	Si XIII	6.64803	Si XIII	6.68827	Si XIII	6.74039	Mg XII	7.10615
Al XIII	7.17271	Mg XI	7.31028	Mg XI	7.47313	Al XII	7.75730	Mg XI	7.85052	Fe XX	8.20998
Fe XX	8.27000	Fe XX	8.31000	Mg XII	8.42100	Fe XX	8.44003	Fe XX	8.46002	Fe XX	8.50000
Fe XX	8.69996	Fe XXII	8.71500	Fe XXII	8.72200	Fe XX	8.74004	Fe XX	8.77001	Fe XIX	8.81003
Fe XXI	8.84000	Fe XXI	8.85500	Fe XXI	8.89800	Fe XX	8.89996	Fe XX	8.91997	Fe XX	8.93001
Fe XIX	8.96001	Fe XXII	8.97700	Fe XIX	9.03000	Fe XX	9.06500	Fe XIX	9.06997	Fe XXII	9.07300
Fe XX	9.11000	Fe XXII	9.12200	Fe XXI	9.14000	Fe XXII	9.14800	Fe XX	9.16300	Mg XI	9.16875
Fe XX	9.18400	Fe XIX	9.18999	Fe XIX	9.19997	Fe XX	9.21600	Fe XIX	9.21999	Fe XX	9.22000
Fe XIX	9.23003	MgXI	9.23121	Fe XX	9.25800	Fe XX	9.28100	Mg XI	9.31434	Fe XIX	9.32001
Fe XX	9.32500	Ni XXV	9.33000	Fe XIX	9.33001	Ne X	9.36162	Ni XX	9.37700	Ni XX	9.38500
Fe XIX	9.45001	Ni XX	9.45500	Fe XXI	9.47500	Ne X	9.48075	Fe XXI	9.48200	Fe XXI	9.54200
Fe XXI	9.54800	Ni XX	9.55800	Ni XX	9.55900	Fe XXI	9.58200	Fe XXI	9.58700	Fe XIX	9.63900
Fe XXI	9.69000	Fe XIX	9.69100	Fe XXI	9.70000	Fe XXI	9.70500	Ne X	9.70818	Fe XIX	9.72600
Fe XXI	9.82100	Fe XIX	9.84800	Fe XIX	9.85200	Fe XIX	9.88800	Na XI	10.02500	Fe XVIII	10.08000
Ni XIX	10.11000	Ne X	10.23890	Fe XVIII	10.41000	Fe XXIII	10.50600	Fe XVIII	10.52600	Fe XXIV	10.61900
Fe XIX	10.63200	Fe XIX	10.63300	Fe XIX	10.65500	Fe XIX	10.65700	Fe XXIV	10.66300	Fe XIX	10.68400
Fe XIX	10.70200	Cr XX	10.71200	Fe XIX	10.74400	Fe XIX	10.75800	Fe XIX	10.76000	Ni XX	10.77200
Fe XIX	10.80500	Fe XIX	10.81600	Fe XIX	10.82700	Fe XIX	10.88000	Fe XIX	10.91600	Fe XIX	10.93300
Fe XXIII	10.98000	Na X	11.00260	Fe XXIII	11.01800	Ni XX	11.13800	Ni XX	11.15800	Ni XX	11.22600
Ni XXI	11.22700	Ni XXI	11.24100	Ni XXI	11.24200	Ni XXI	11.27200	Ni XX	11.28200	Ni XXI	11.30200
Ni XXI	11.31900	Fe XVIII	11.32600	Ni XXI	11.38000	Fe XVIII	11.42000	Fe XXII	11.44200	Fe XXII	11.45900
Ni XXI	11.46800	Fe XXIII	11.48500	Fe XX	11.51000	Ni XXI	11.51600	Ni XXI	11.51700	Fe XVIII	11.52500
Ni XXI	11.53900	Ne IX	11.54660	Mn XXIII	11.57660	Ni XXI	11.59700	Fe XXII	11.59900	Fe XXII	11.66900
Fe XXIII	11.71800	Fe XXIII	11.73700	Fe XX	11.73900	Fe XXII	11.76800	Ni XX	11.78700	Ni XX	11.83200
Fe XXIII	11.84600	Ni XX	11.86500	Ni XX	11.87400	Fe XXII	11.92100	FeXX	11.93300	Fe XXII	11.93400
Fe XXI	11.93800	Ni XX	11.96100	Mn XXII	11.97000	Fe XXI	11.97500	Ni XX	11.97800	Fe XX	11.98700
Ca XVIII	11.98900	Ni XX	11.99100	Mn XXII	11.99800	Ni XX	12.00600	Ti XIX	12.01000	Fe XXIII	12.02700
Fe XXI	12.04400	Ni XX	12.04700	Ni XX	12.08100	Fe XXI	12.08200	Fe XXI	12.10700	Ni XX	12.11200
Ni XX	12.13000	Ne X	12.13390	Fe XXI	12.14600	Ni XX	12.15700	Fe XXIII	12.16100	Ni XXI	12.16500
Fe XXII	12.19300	Ni XXI	12.20900	Fe XXI	12.26100	Ni XXI	12.27600	Fe XXI	12.28200	Fe XXI	12.29700
Fe XXI	12.32700	Fe XXIII	12.35100	Fe XXI	12.39500	Fe XXI	12.42200	Fe XX	12.42600	Ni XIX	12.43500
Fe XXIII	12.44400	Ni XXI	12.44600	Fe XXI	12.46200	Ni XXI	12.47200	Fe XXI	12.49000	Fe XXI	12.49200
Fe XXIII	12.49300	Fe XXI	12.49900	Fe XXI	12.50000	Fe XXI	12.52300	Ni XXI	12.53300	Fe XX	12.56600
Fe XXI	12.56800	Fe XX	12.58100	Ni XXI	12.59100	Cr XXII	12.61300	Fe XXI	12.62300	Ca XVIII	12.63600
Ni XXI	12.64800	Fe XXIII	12.65300	Cr XXII	12.65500	Ni XIX	12.65600	Fe XXI	12.66300	Fe XXI	12.69100
Fe XXI	12.70100	Fe XXIII	12.70300	Fe XXII	12.74300	Fe XX	12.75300	Fe XXI	12.77200	Fe XX	12.80400
Fe XX	12.81200	Fe XVIII	12.81800	Fe XXI	12.82200	Fe XX	12.82400	Fe XX	12.82700	Fe XX	12.84500
Fe XXI	12.87000	Fe XX	12.90500	Fe XIX	12.92400	Ni XX	12.92700	Fe XXII	12.93600	Fe XX	12.95100
Fe XX	12.96600	Fe XX	12.98200	Fe XX	12.99100	Fe XIX	13.01800	Ni XX	13.03200	Fe XIX	13.03900
Fe XX	13.04400	Fe XX	13.04600	Fe XIX	13.05100	Fe XX	13.05200	Fe XXI	13.05200	Fe XX	13.05900
Fe XIX	13.07500	Ni XX	13.07500	Fe XX	13.07800	Fe XX	13.09100	Fe XIX	13.09100	Fe XX	13.09100
Fe XX	13.11400	Fe XX	13.12300	Cr XXI	13.12300	Fe XX	13.14000	Fe XX	13.14300	Fe XXI	13.17900
Fe XX	13.18800	Fe XX	13.20300	Fe XX	13.20600	Fe XIX	13.21200	Fe XIX	13.21200	Fe XX	13.25300
Fe XX	13.25400	Fe XIX	13.25400	Fe XXI	13.25500	Ni XX	13.25600	Fe XX	13.26700	Fe XX	13.26900
Fe XX	13.27000	Ni XX	13.28200	Fe XX	13.29200	Fe XX	13.30100	Fe XIX	13.31100	Fe XVIII	13.31900

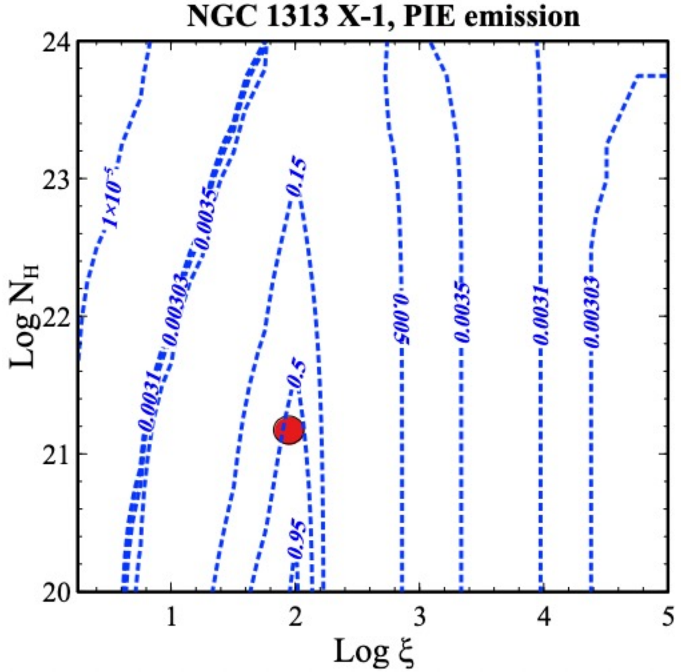


NGC 1313 X-1

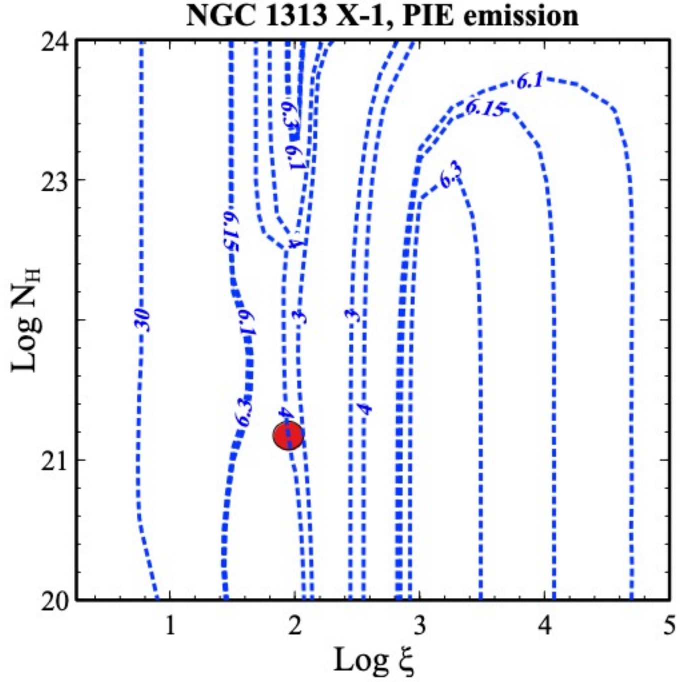
Figure 8. a) Combined first-order spectra of NGC 1313 X-1, overplotted with best-fitting two blackbody continuum model, the 1 keV residual is visible within 0.6 and 1.25 keV. b) Spectra of NGC 1313 X-1 overlaid with the continuum model + line emission from CIE plasma, with the 1 keV emission/absorption residuals persisting. c) The same spectra overlaid with continuum model+ PIE line emission, effectively resolving the 1 keV emission/absorption residuals.

NGC 1313 ULX-1

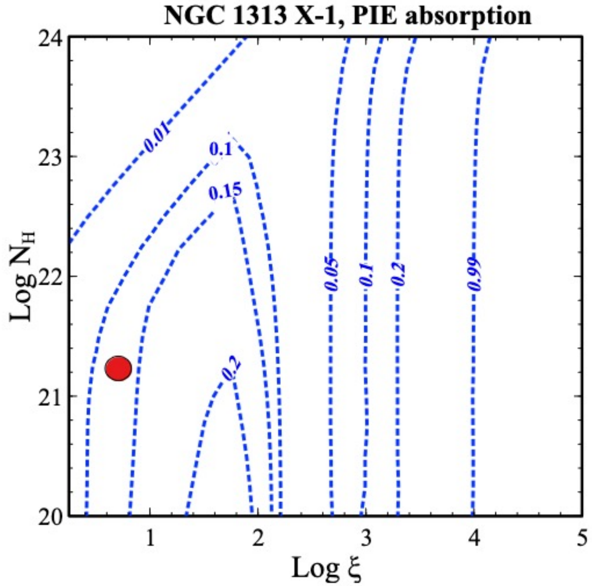
Em_{blend}



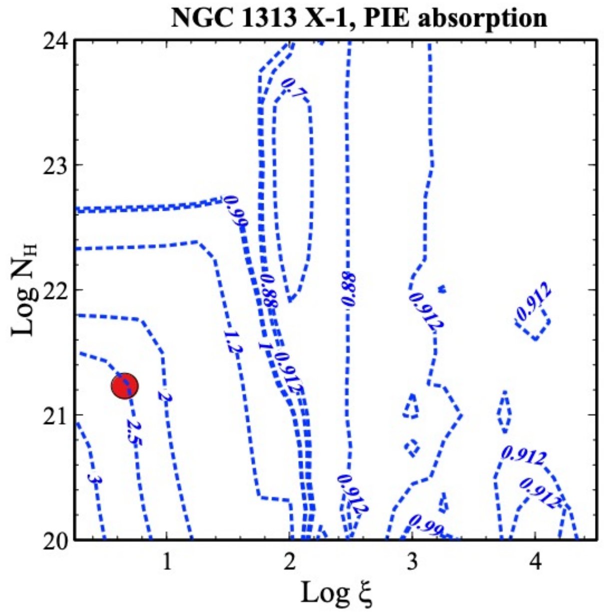
Em_{left}/Em_{right}



Abs_{blend}



Abs_{left}/Abs_{right}



Hercules X-1

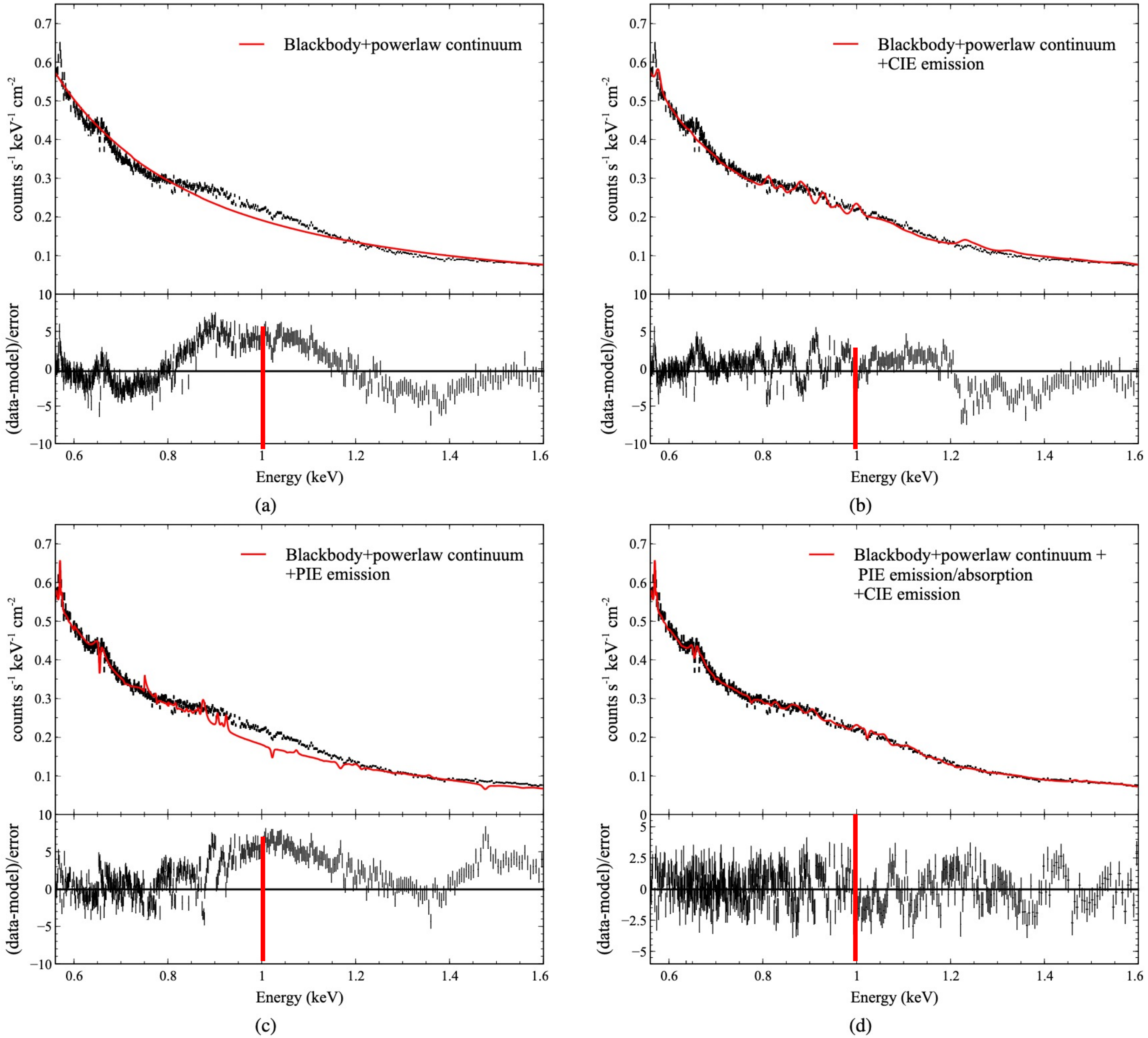
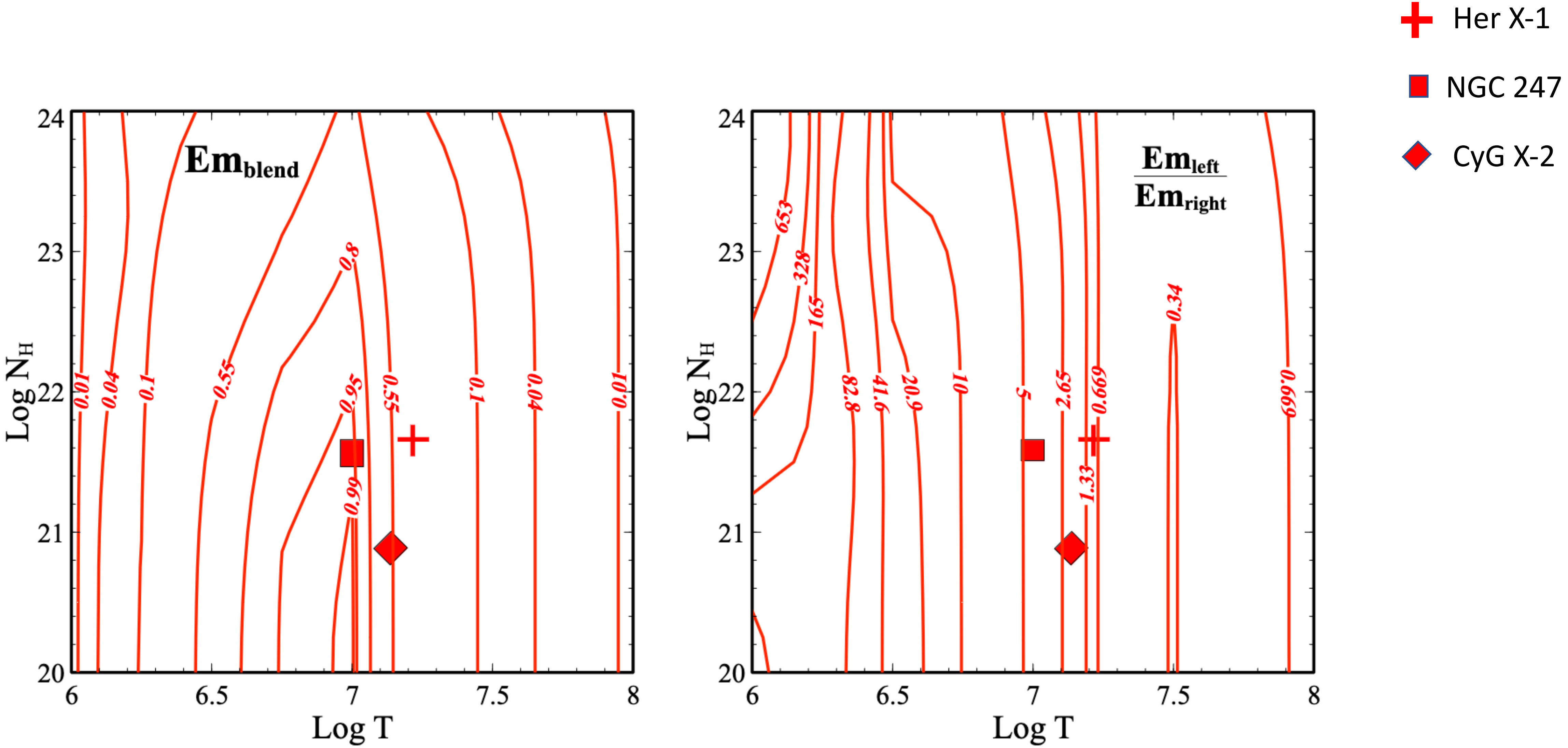


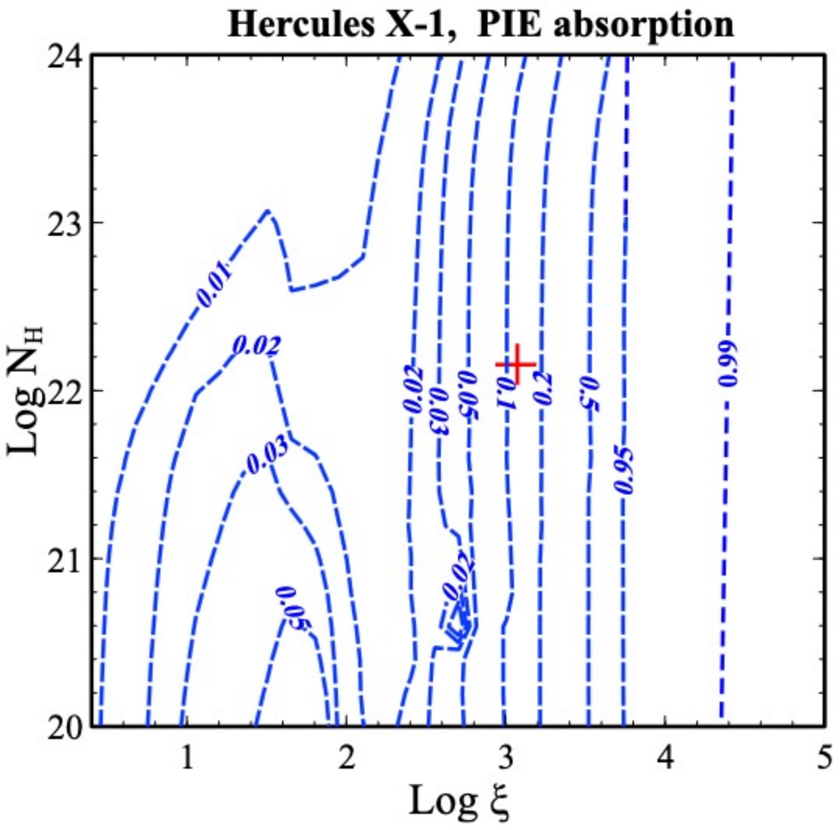
Figure 10. a) Combined first-order spectrum of Hercules X-1, overlaid with best-fitting blackbody+powerlaw continuum model, the 1 keV residual is visible. b) Adding CIE emission to the continuum model significantly improves the emission residuals between 0.8-1.2 keV, while the absorption residual remains. c) The continuum model along with line emission/absorption produced by a PIE model improves the fit below 0.8 keV, but significant emission/absorption residuals persist for energies > 0.8 keV. d) The combination of the continuum, CIE emission, and PIE emission/absorption models successfully eliminated most of the residuals across all energies between 0.56 and 1.6 keV.

CIE emission

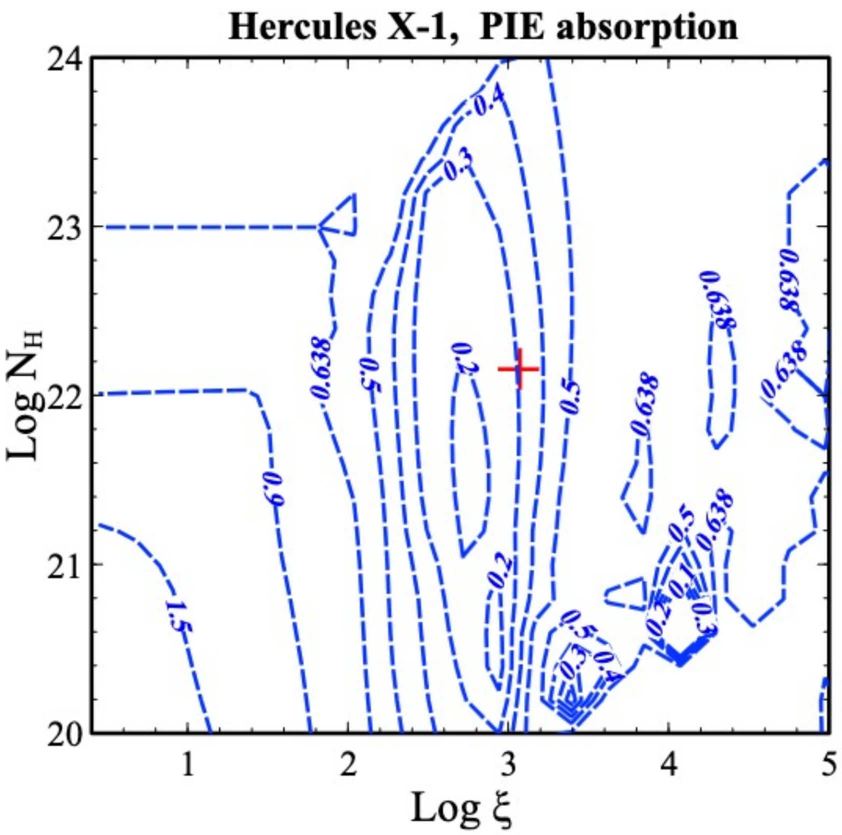


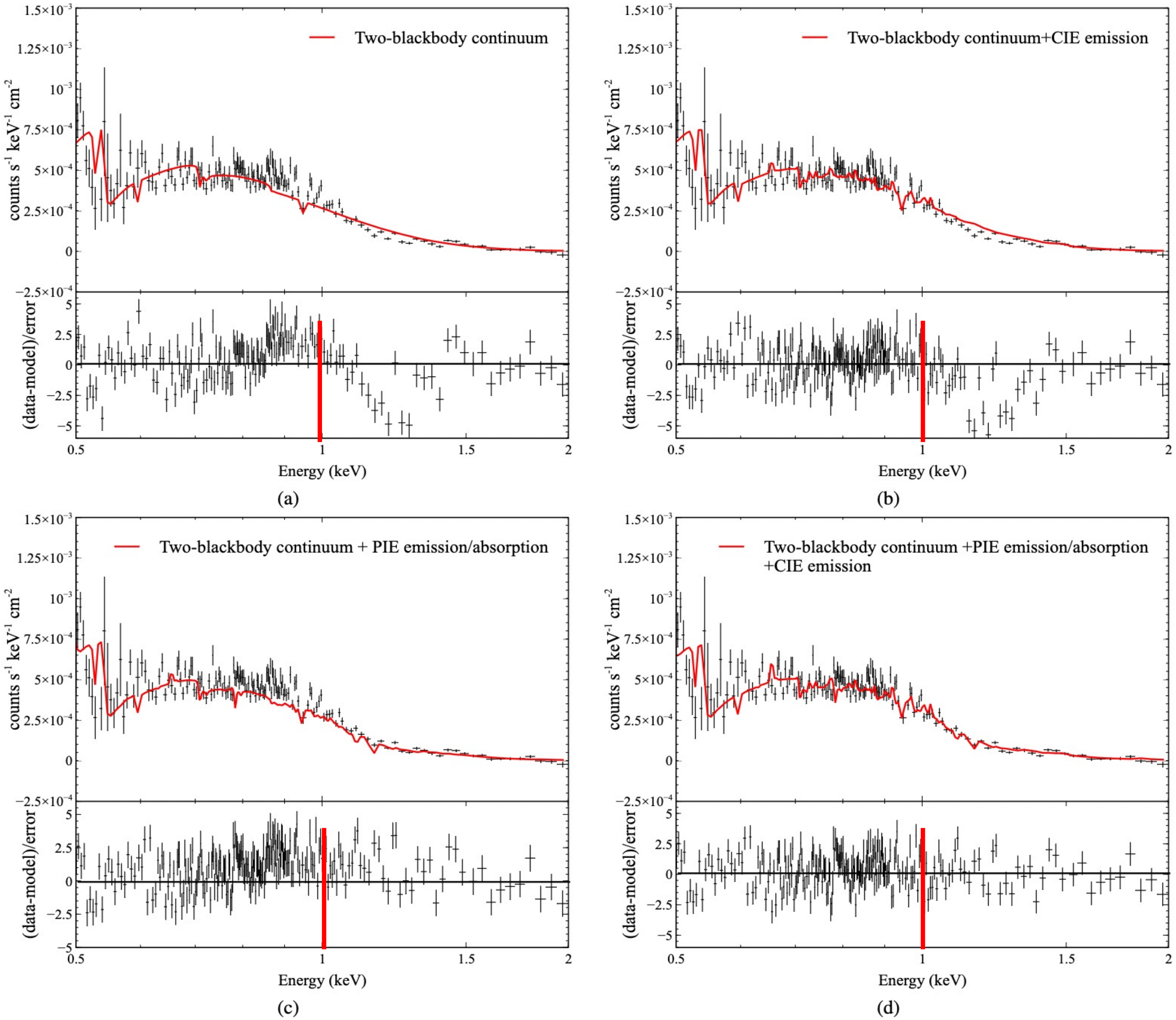
Hercules X-1

Abs_{blend}



Abs_{left}/Abs_{right}





NGC 247 ULX-1

Figure 9. a) Combined first-order spectra of NGC 247 ULX-1, overlaid with best-fitting two blackbody continuum model, the 1 keV residual is visible. b) NGC 247 ULX-1 spectra, featuring the continuum model with line emission derived from a CIE model, successfully accounting for the 1 keV emission residual, while the 1 keV absorption residual remains. c) Same spectra of NGC 247 ULX-1, overlaid with the continuum model along with line emission/absorption produced by a PIE model, effectively addressing the 1 keV absorption residual while the 1 keV emission residual persists. d) Spectra of NGC 247 ULX-1 overlaid with combined PIE and CIE emission/absorption models along with the continuum model, comprehensively accounting for the 1 keV emission/absorption feature.

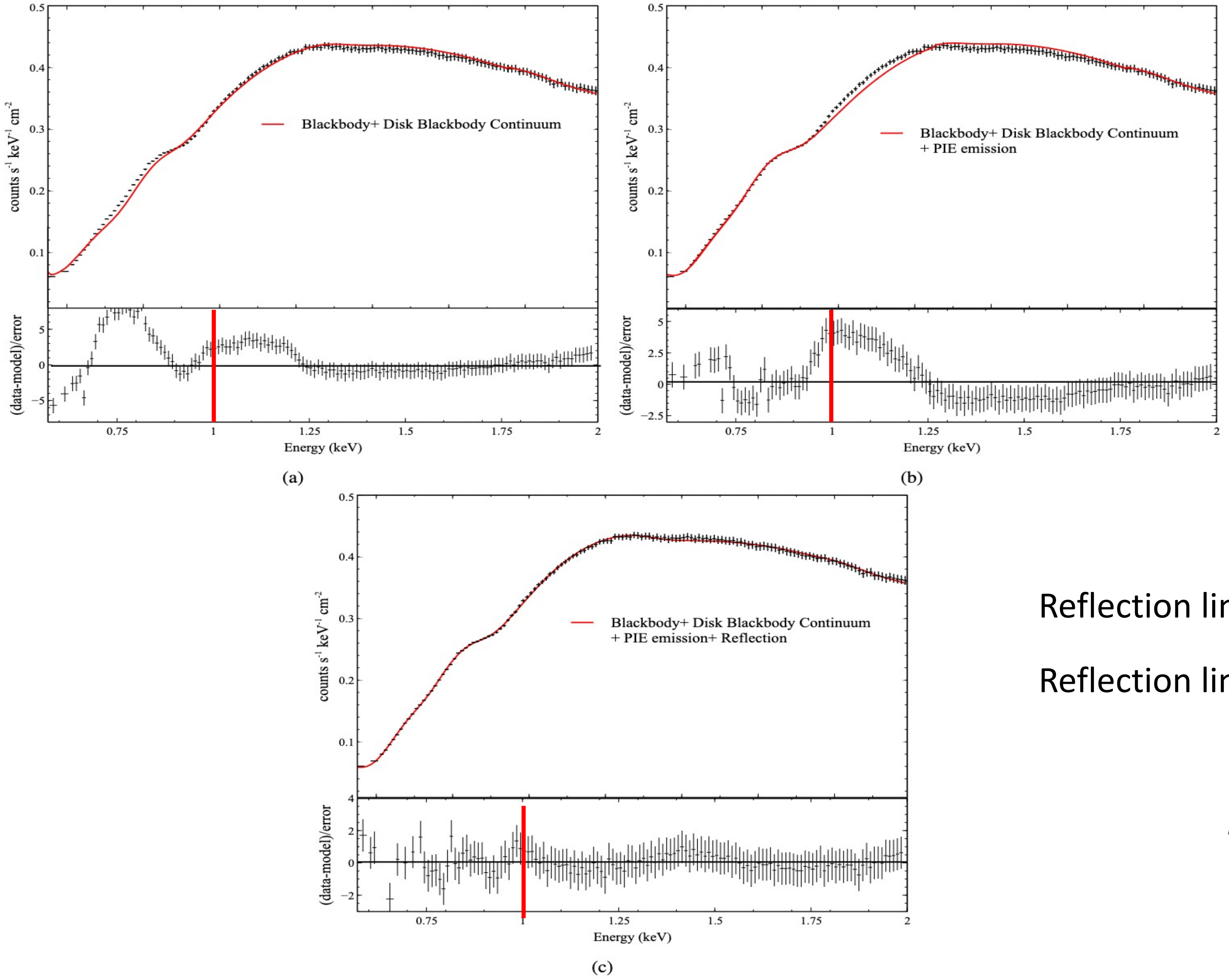


Figure 11. a) *NICER* spectrum of Ser X-1, overlaid with best-fitting continuum model, a more pronounced emission residual is found (0.5-0.9 keV) with a less pronounced emission residual (0.9-1.3 keV). b) The same spectrum overlaid with the continuum model + line emission from PIE plasma. The residual between 0.5-0.9 keV have largely diminished, while the residual between 0.9-1.3 keV persists. c) The same spectrum overlaid with continuum model+ PIE line emission+ reflection emission effectively resolving both emission residuals

Serpens X-1

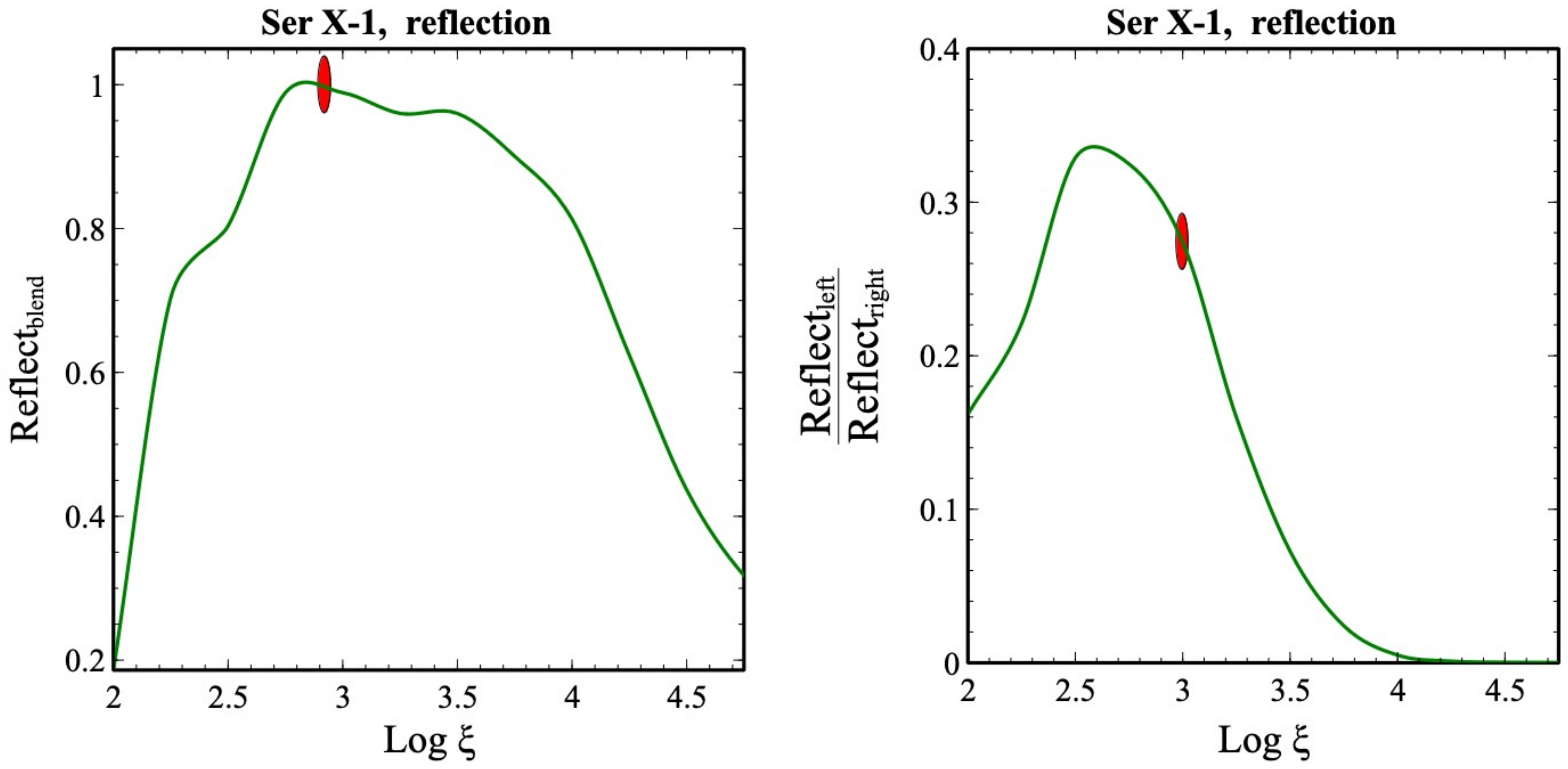
Reflection features present

Reflection line below with energies < 1keV, $Reflect_{left}$

Reflection line above with energies > 1keV, $Reflect_{right}$

$$Reflect_{left} + Reflect_{right} = Reflect_{blend}$$

Serpens X-1


Ser X-1, reflection
Reflect$_{blend}$
Log ξ
Ser X-1, reflection
Reflect$_{left}$ / Reflect$_{right}$
Log ξ

Cygnus X-2

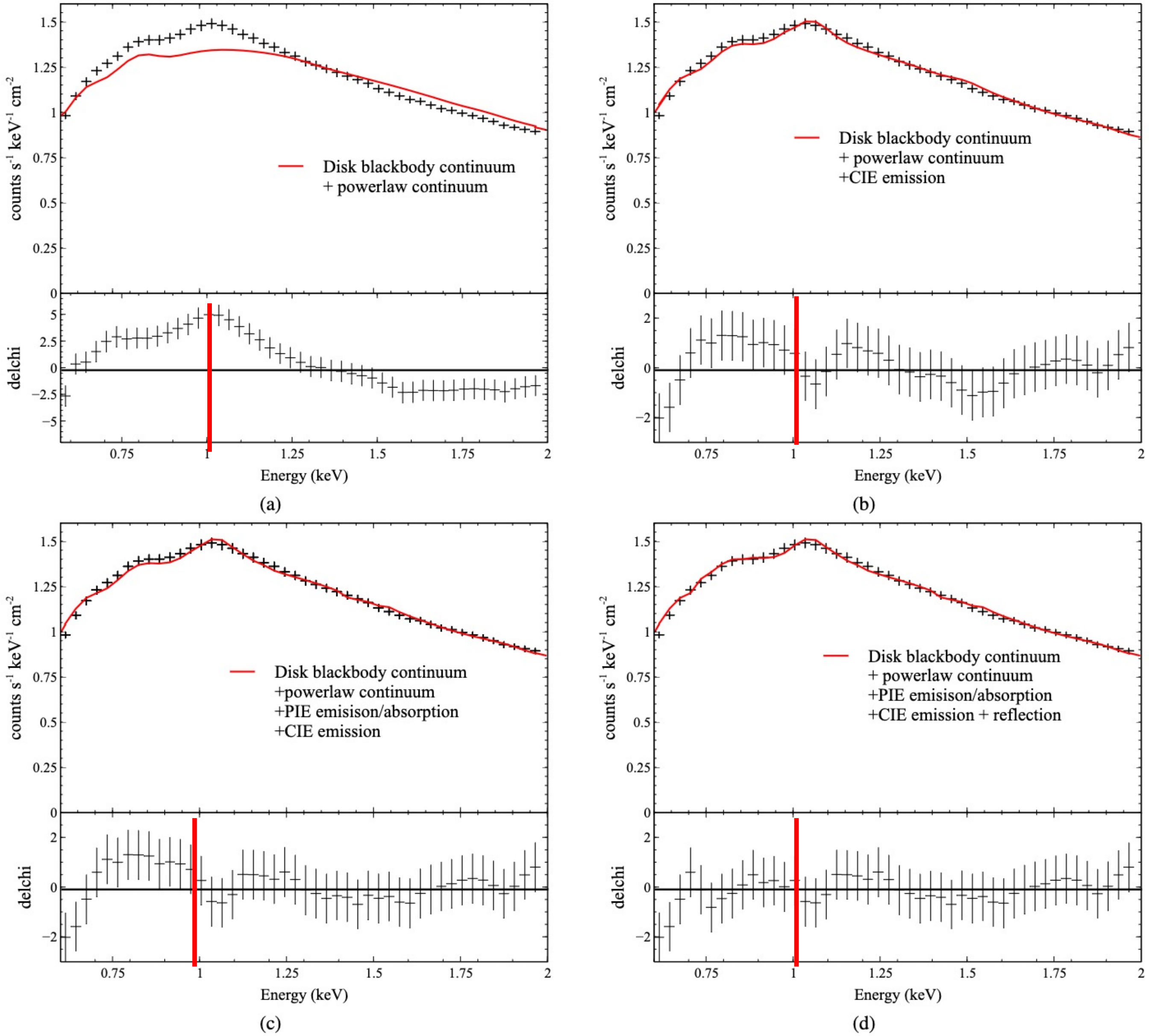
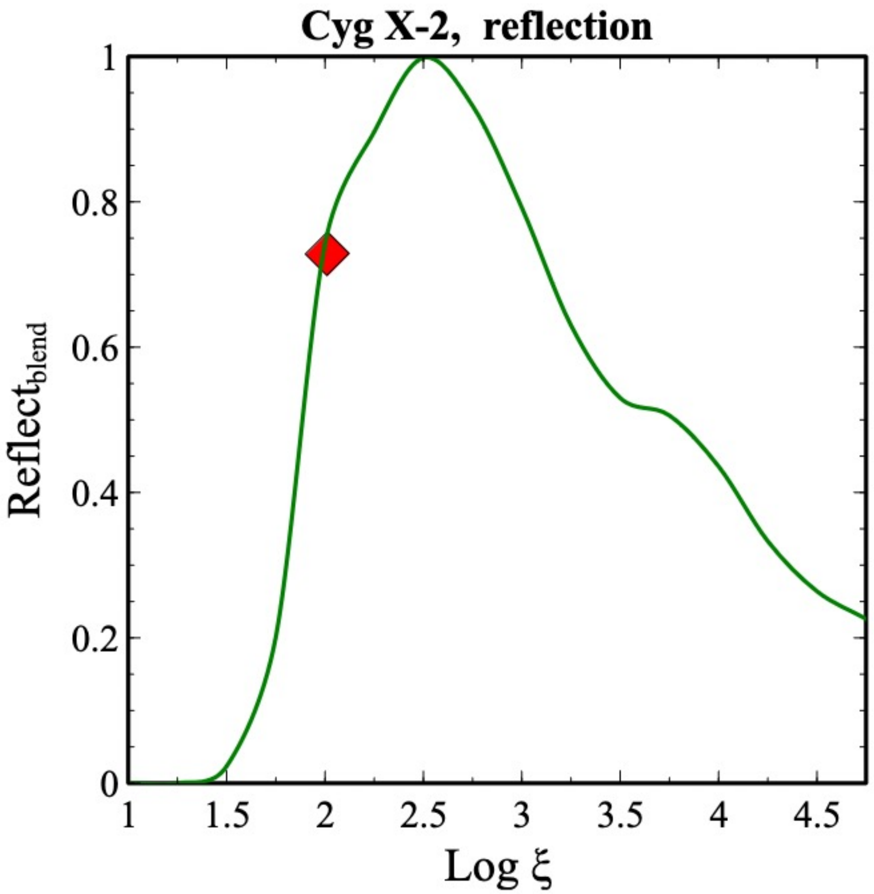
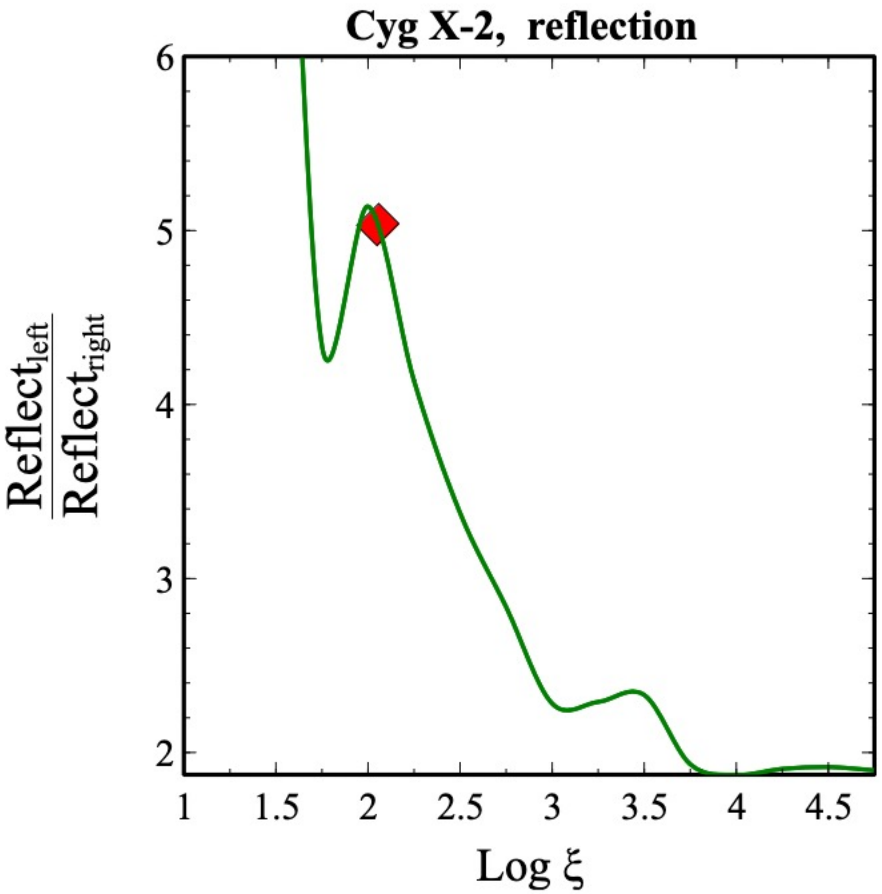


Figure 12. a) *NICER* spectrum of Cyg X-2, overlaid with best-fitting continuum model, the 1 keV residual is more prominent in emission, less noticeable in absorption. b) Adding CIE emission to the continuum model significantly improves the residuals, although some emission residuals persist in specific energy ranges (0.65-1 keV and 1.1-1.2 keV), with minor absorption residuals in the 1.4-1.6 keV range. c) The continuum + CIE emission + PIE emission/absorption effectively eliminates all the absorption residuals, small emission residual remains between 0.65-1.0 keV. d) The continuum + CIE emission + PIE emission/absorption+ reflection model eliminates all the emission and absorption residuals.


Cyg X-2, reflection
Reflect$_{blend}$
Log ξ
1
0.8
0.6
0.4
0.2
0
1
1.5
2
2.5
3
3.5
4
4.5


Cyg X-2, reflection
Reflect$_{left}$ / Reflect$_{right}$
Log ξ
6
5
4
3
2
1
1.5
2
2.5
3
3.5
4
4.5

Summary

We presented a comprehensive theoretical framework for the origin of the 1 keV feature, both in terms of its centroid and intensity

We studied 5 XRBs- NGC 1313 ULX1, NGC 247 ULX-1, Hercules X-1, Cyg X-2, and Serpens X-1 with spectrum obtained from XMM-Newton RGS and NICER

We created line blends for emission, absorption, and reflection, and study the variation of the line blends with Cloudy grids on ionization parameter and column density for PIE, temperature and column density for CIE, and ionization parameter for reflection line blends

We compared the best-fit physical parameters with from the observed spectrum with the Cloudy line blends to explain the origin and variability of the 1 keV feature