Clumpy stellar wind in HMXB OAO 1657-415

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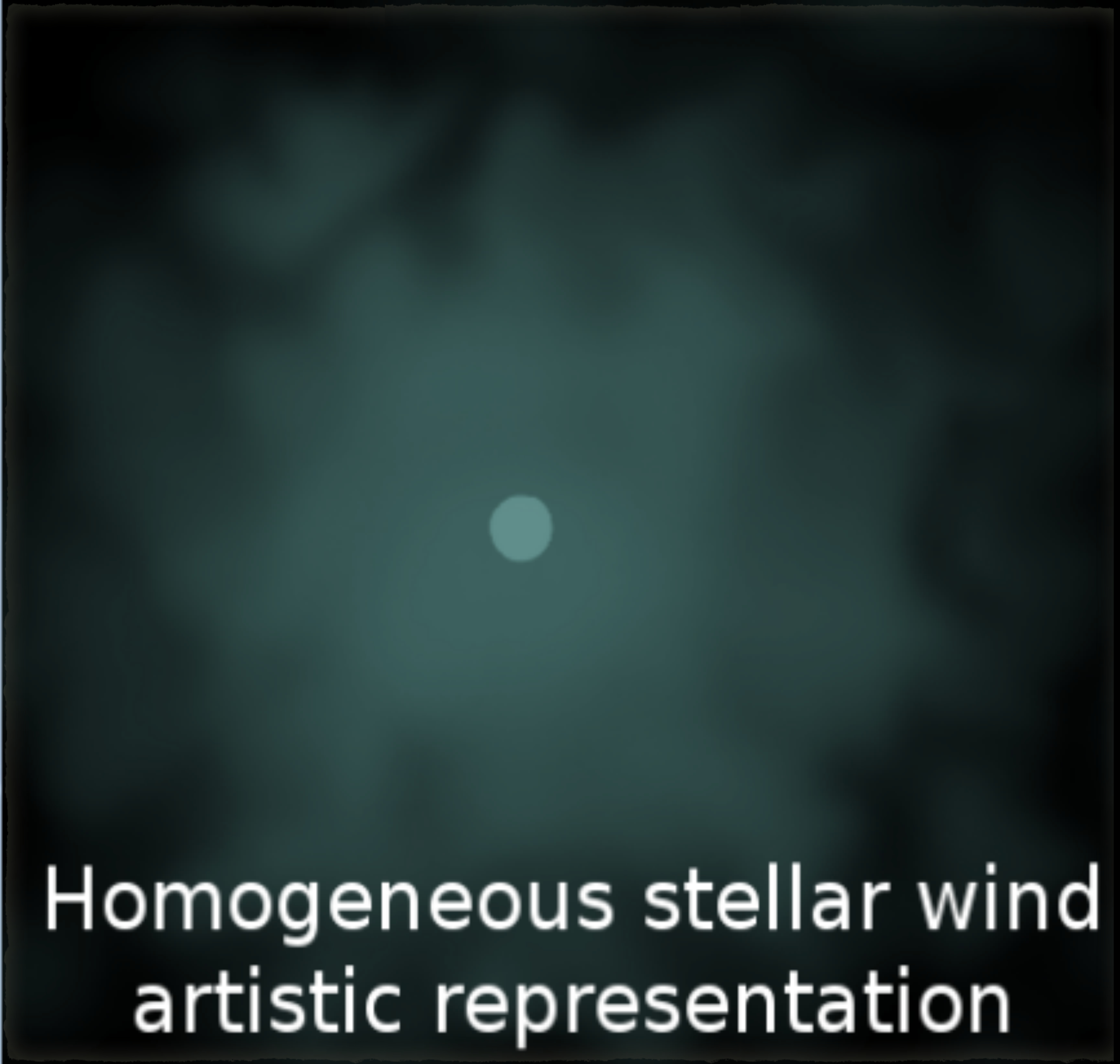
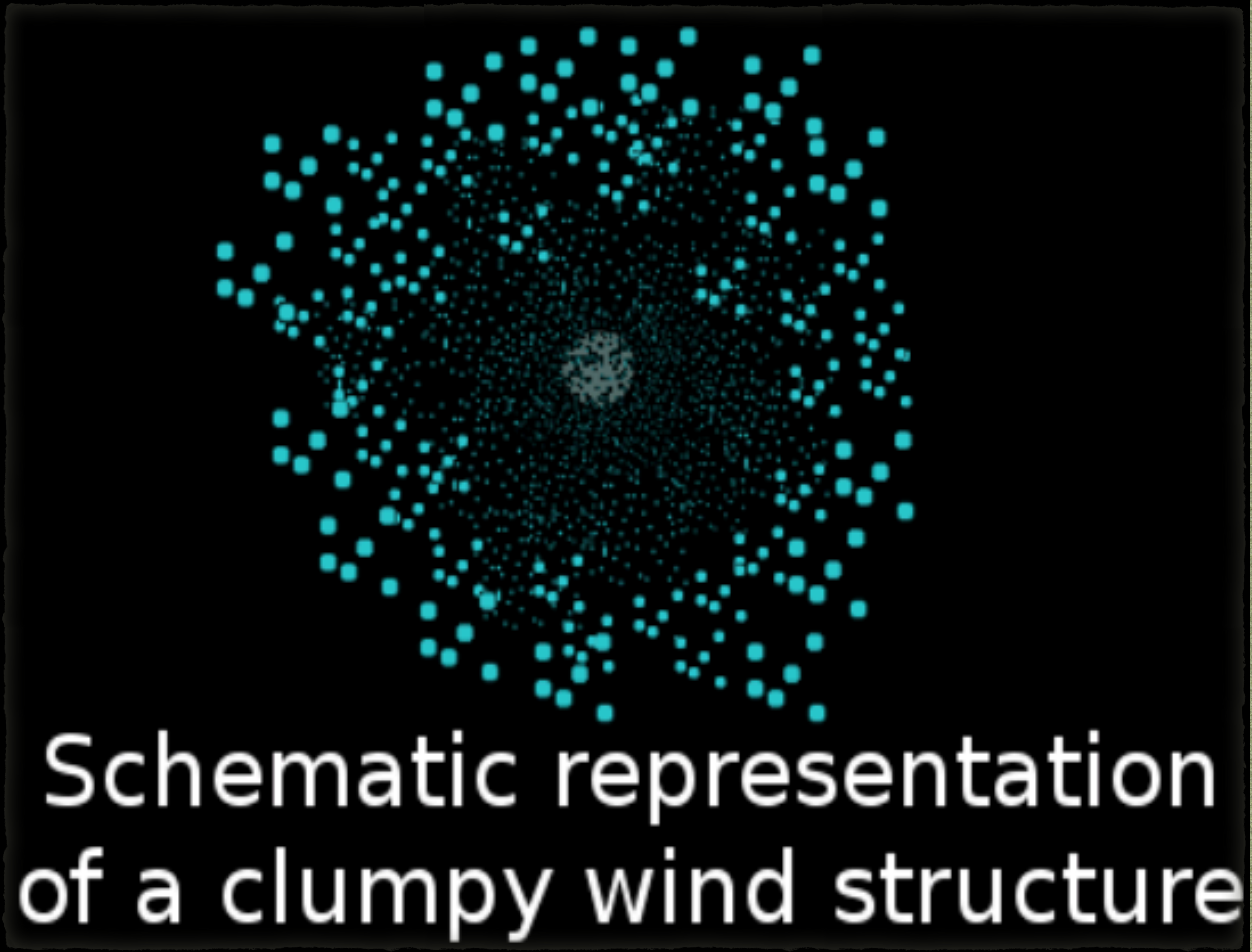
What are stellar winds?

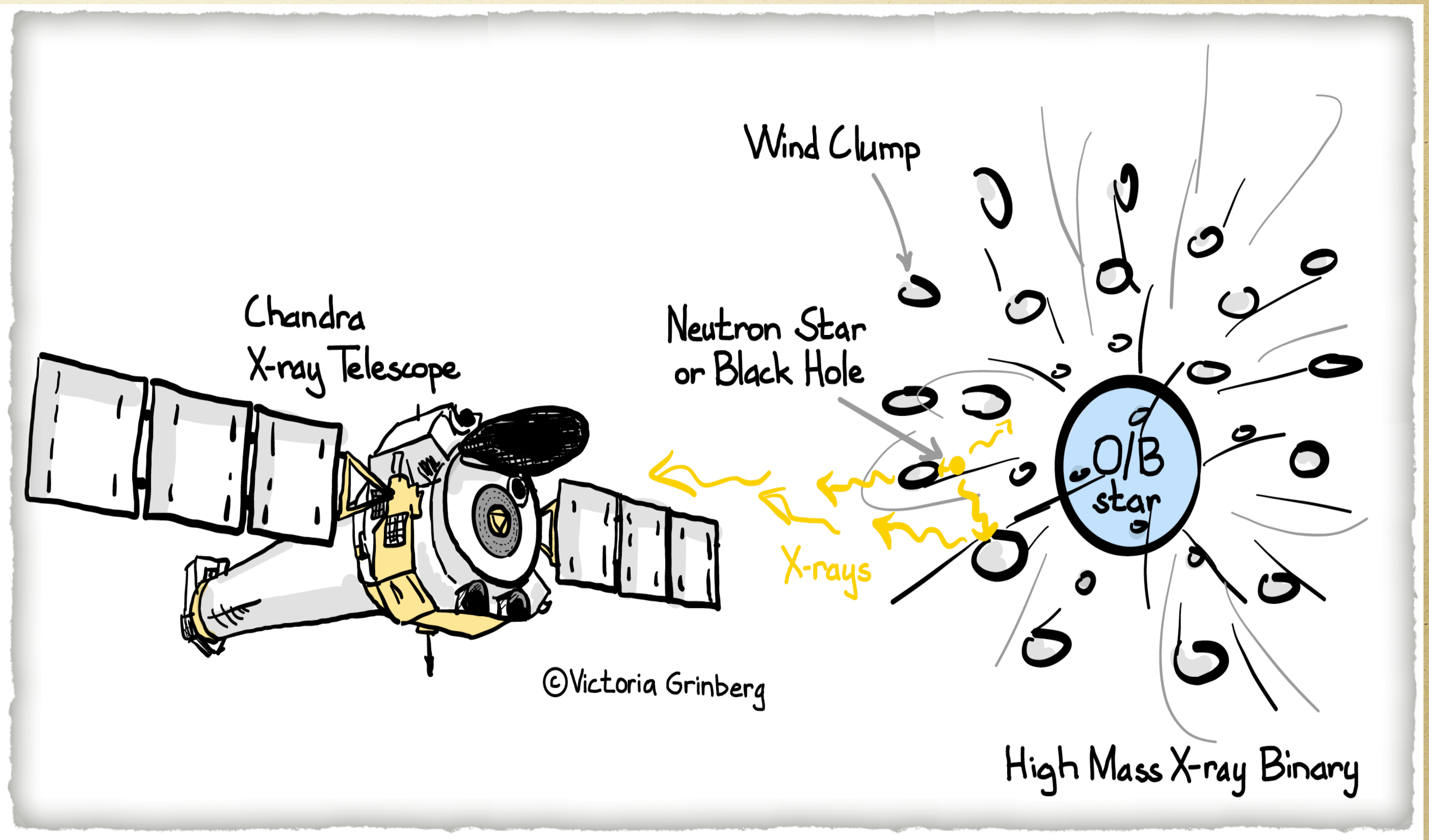
- High velocity outflows from massive stars. Shape the galaxies with radiative, mechanical and chemical feedback.
- There is an underestimation of M_dot for homogeneous winds implying stellar winds are clumpy.


Homogeneous stellar wind
artistic representation


Schematic representation
of a clumpy wind structure

Unique contributions from X-rays

- In HMXBs, the neutron star can be used as a flashlight and the X-ray variability can be used to directly measure clump sizes.
- Shape of X-ray emission lines of single stars from high-resolution spectroscopy. Stronger wind absorption makes the line becomes more skewed but there is a degeneracy in measuring M_dot and clumps sizes (porosity).
- Thermal radio excess – can give reliable M_dot measurements but is sensitive to presence of clumps
- P-Cygni profiles of UV lines to calculate M_dot – less affected by clumpiness but relies on information of elemental abundances and degree of ionization of ions producing P-Cygni profiles
- Other methods: global methods using stellar atmosphere models including the hydrodynamic effects of winds e.g., FASTWIND, PoWR. H_alpha in optical, IR for low mass-rate stars etc.



Sketch by Victoria Grinberg

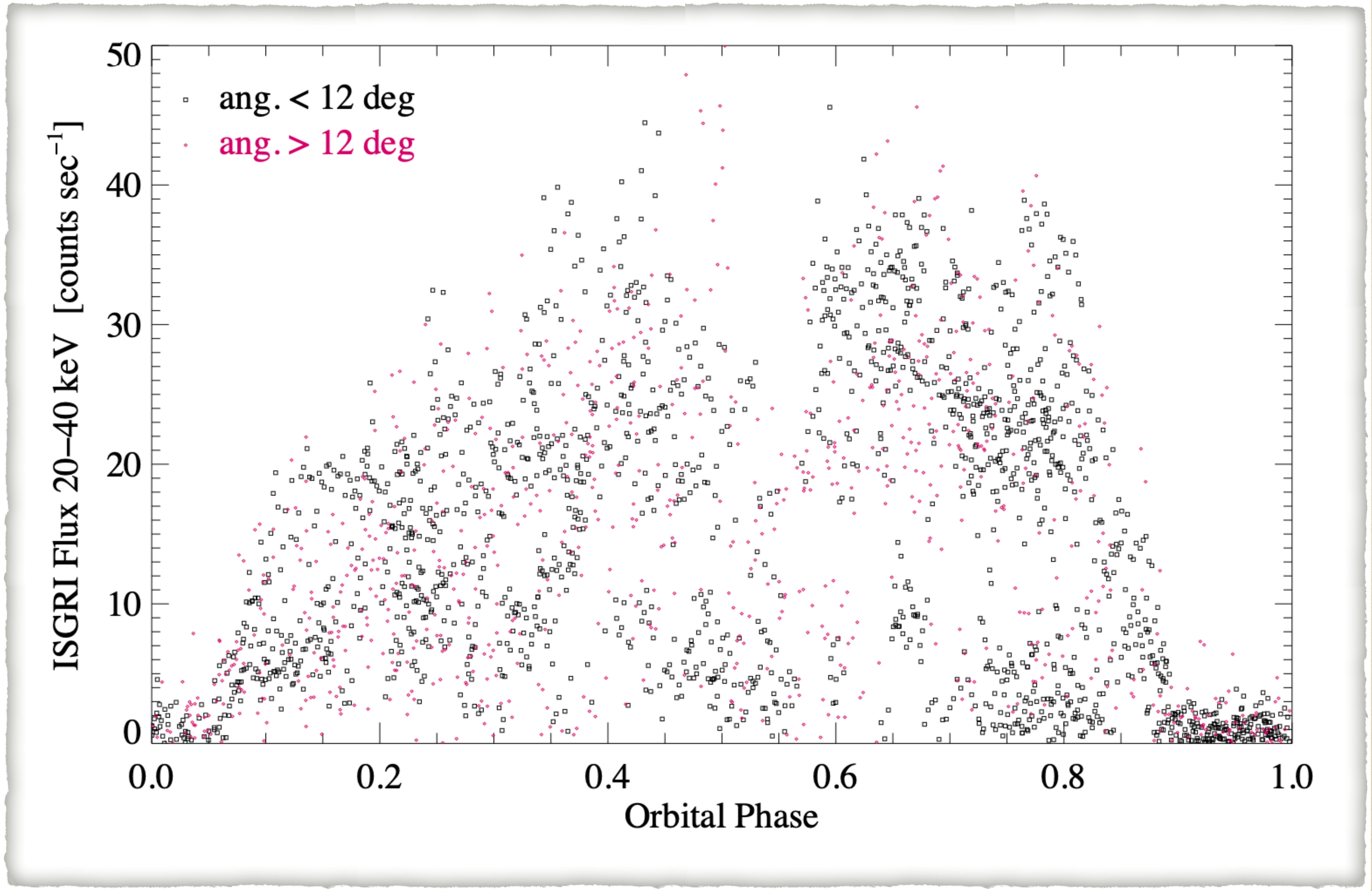
X-ray spectral fits

- NH made up of two components (NH1 and NH2)
- NH1 – global origin, possibly stellar wind
- NH2 – local absorption caused by local structures.
- Iron line emission

HMXB OAO 1657-415

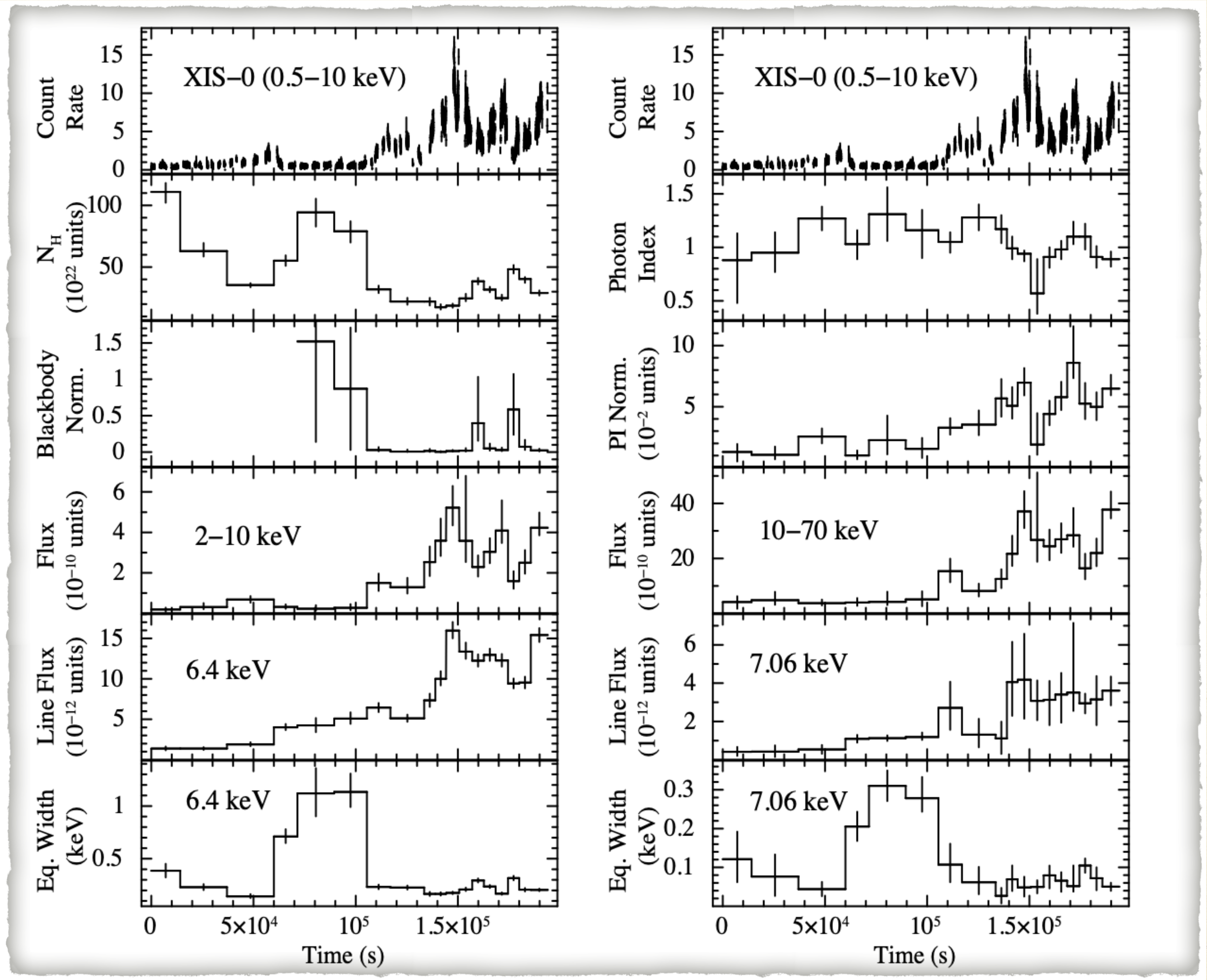
- Accreting neutron star with a WR companion.
- Pspin ~ 38 s, Porb ~ 10.5 days, e ~ 0.1, i ~ 65-70 deg (exhibits eclipses).
- Shows large variability in NH and very strong iron lines.
- Debatable cyclotron line at ~ 36 keV, ruled out now.

Long-term X-ray variability



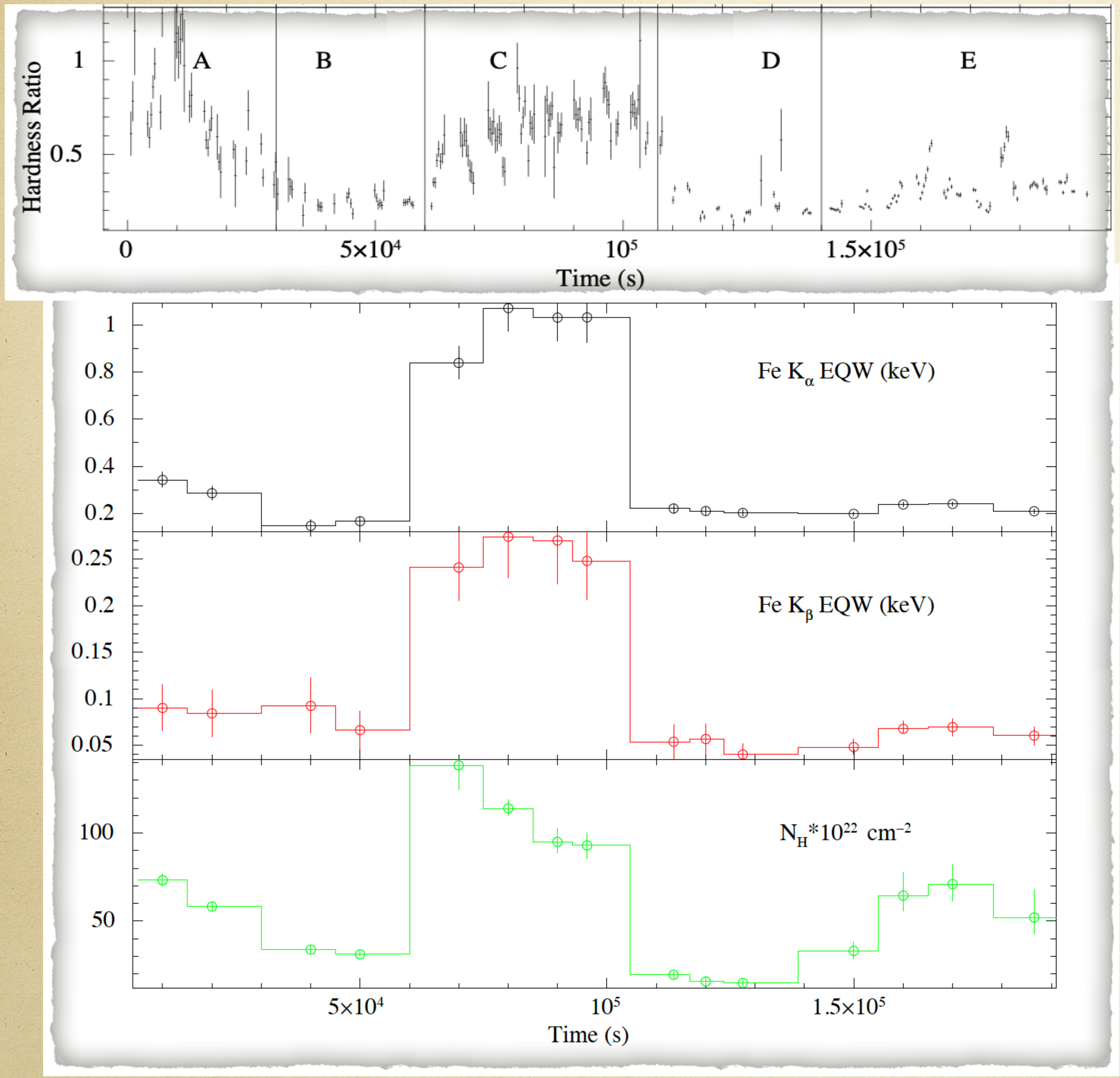
Barnstedt et al. 2008

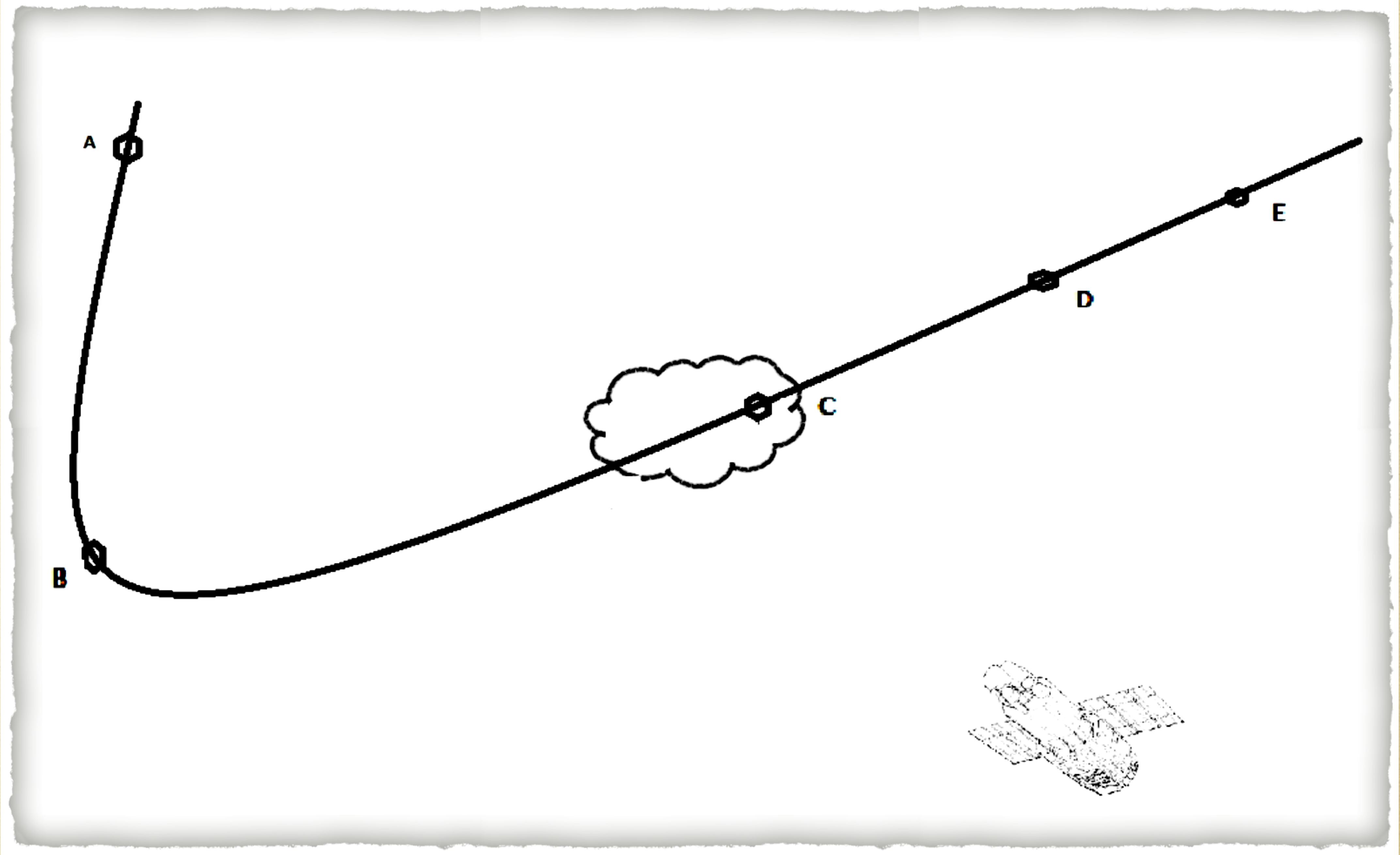
Very strong iron lines



Jaisawal et al. 2014

Very strong iron lines

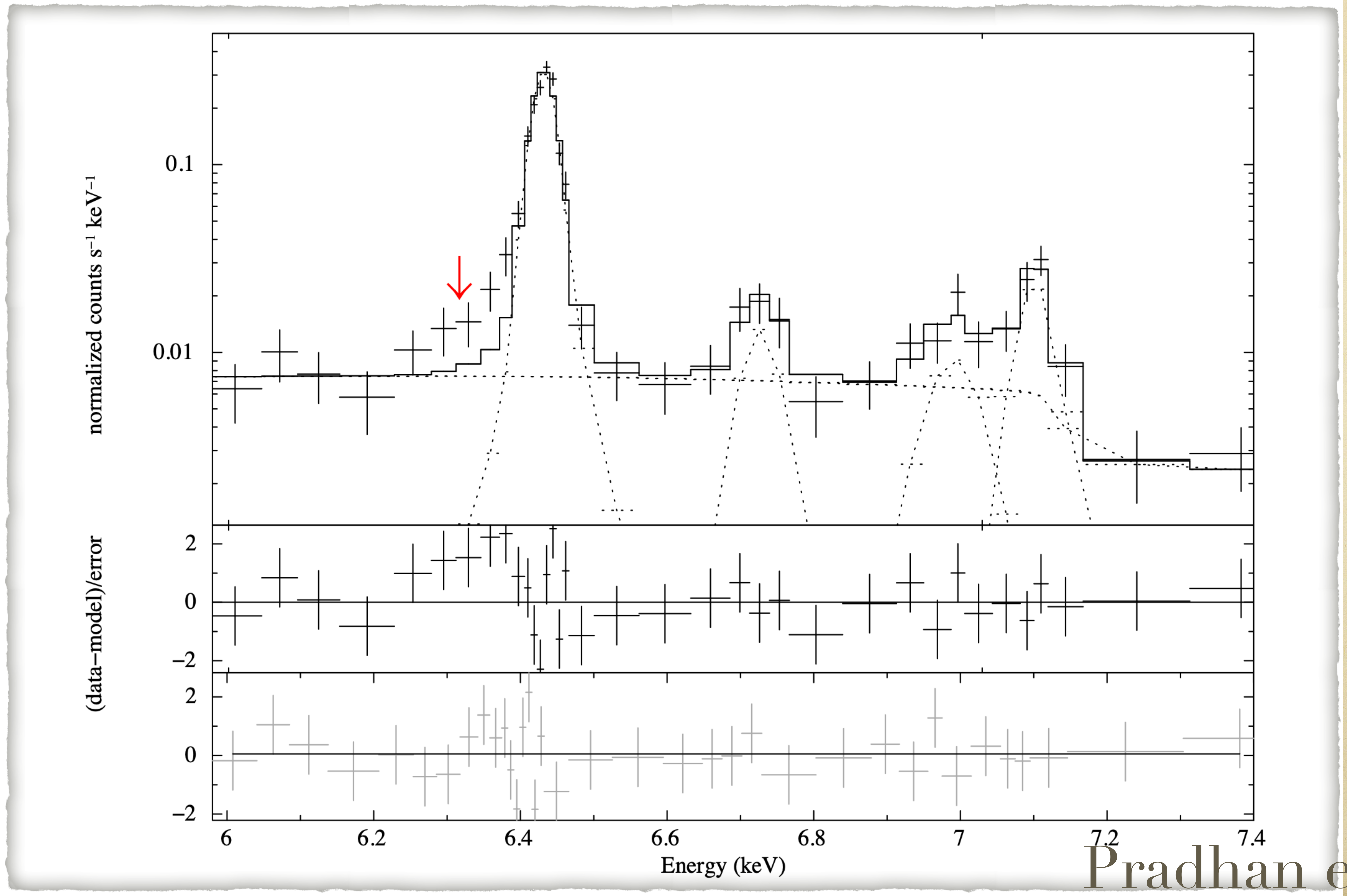




Pradhan et al. 2014

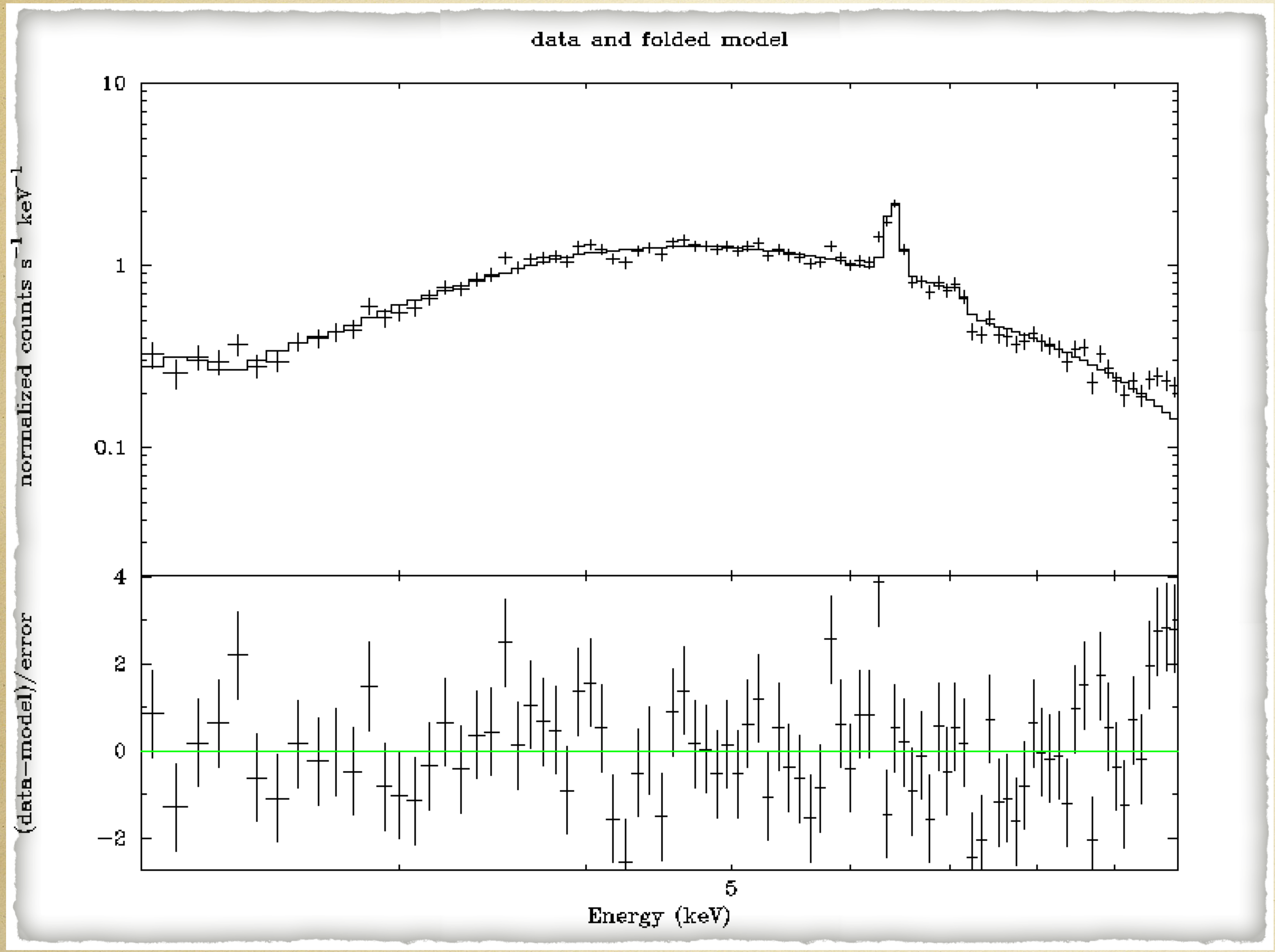
Rc ~ 4% R*   Mc ~ 3 × 10^24 g

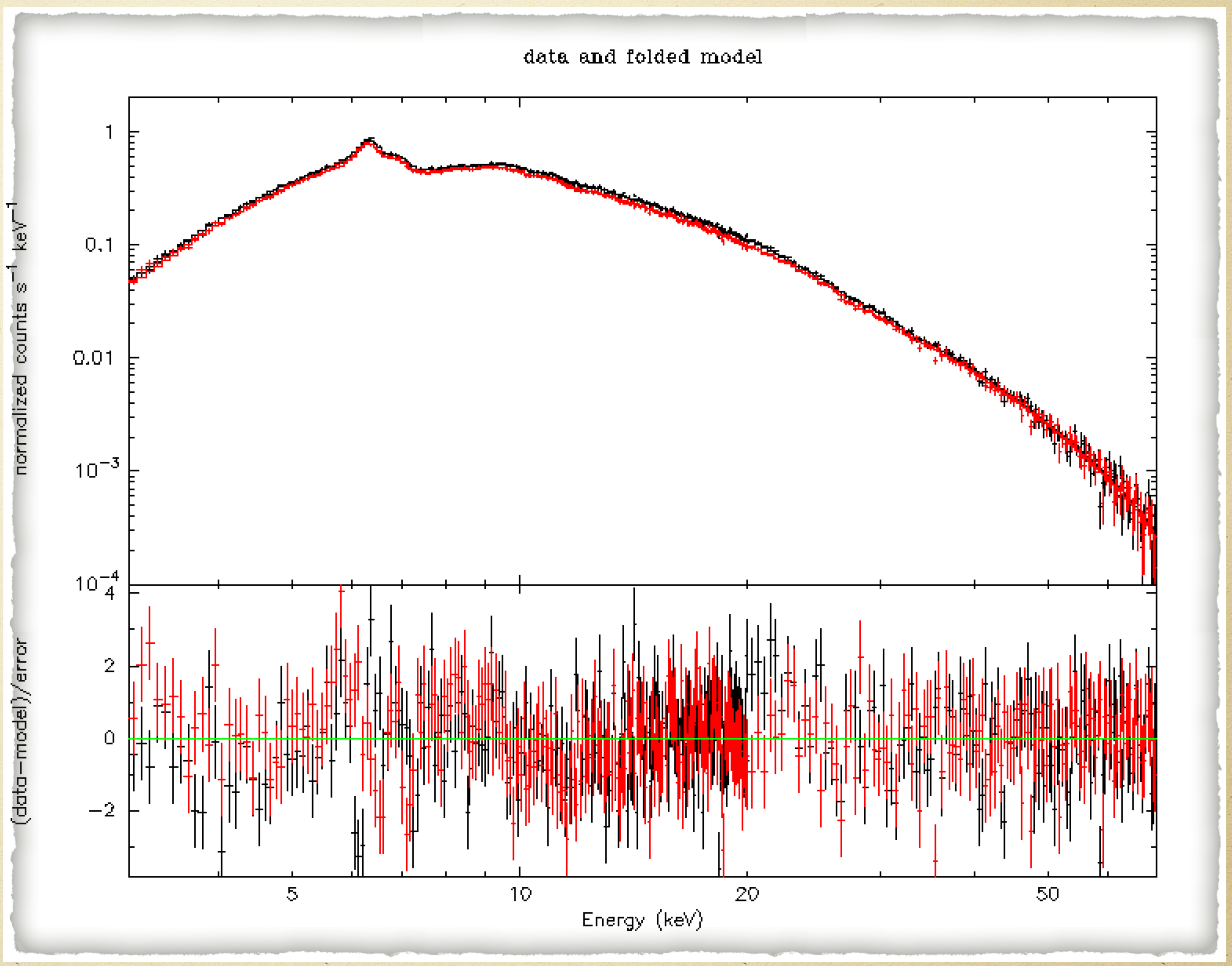
Very dense surrounding: Detection of a Compton shoulder



Pradhan et al. 2019

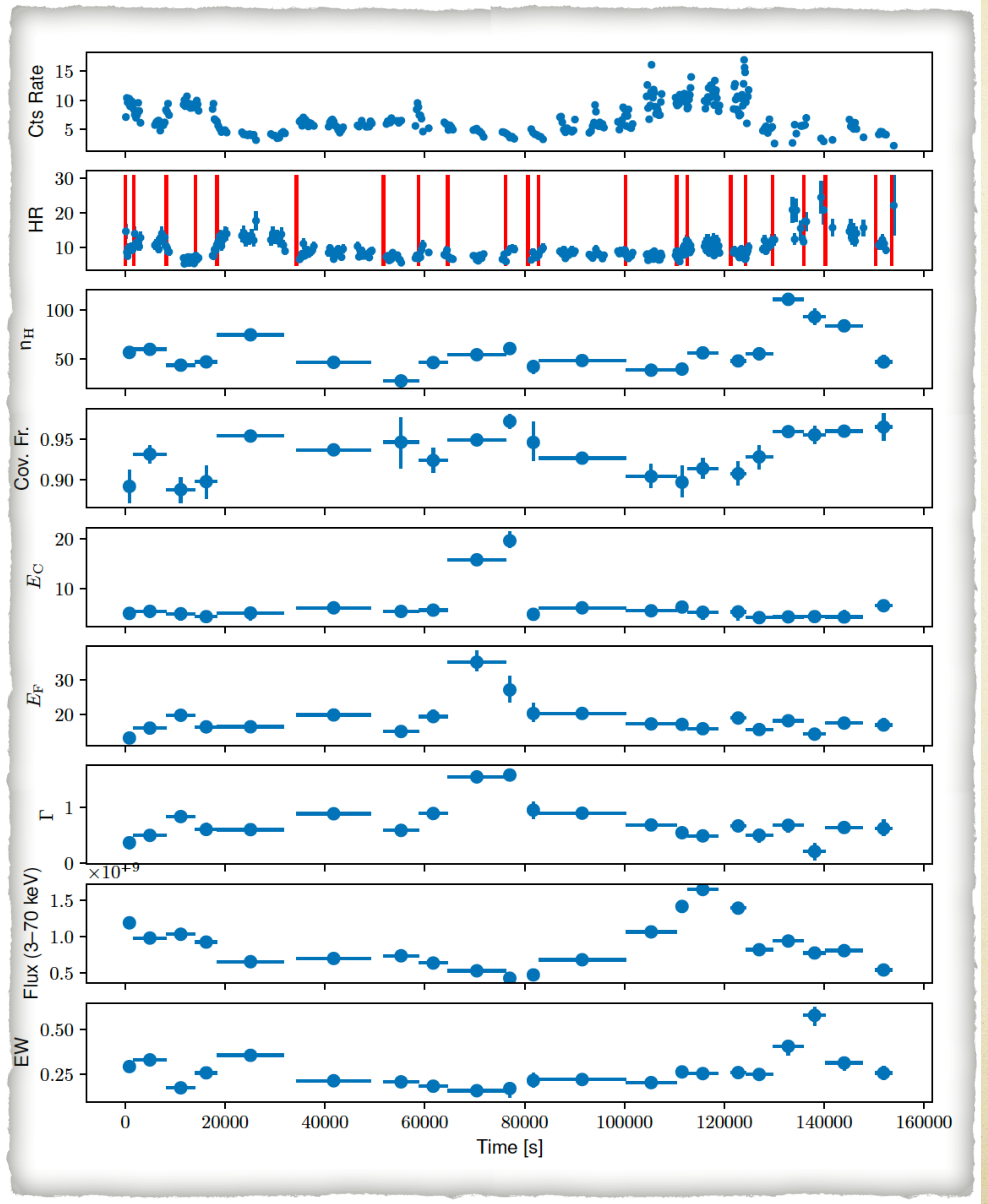
NICER + NuSTAR





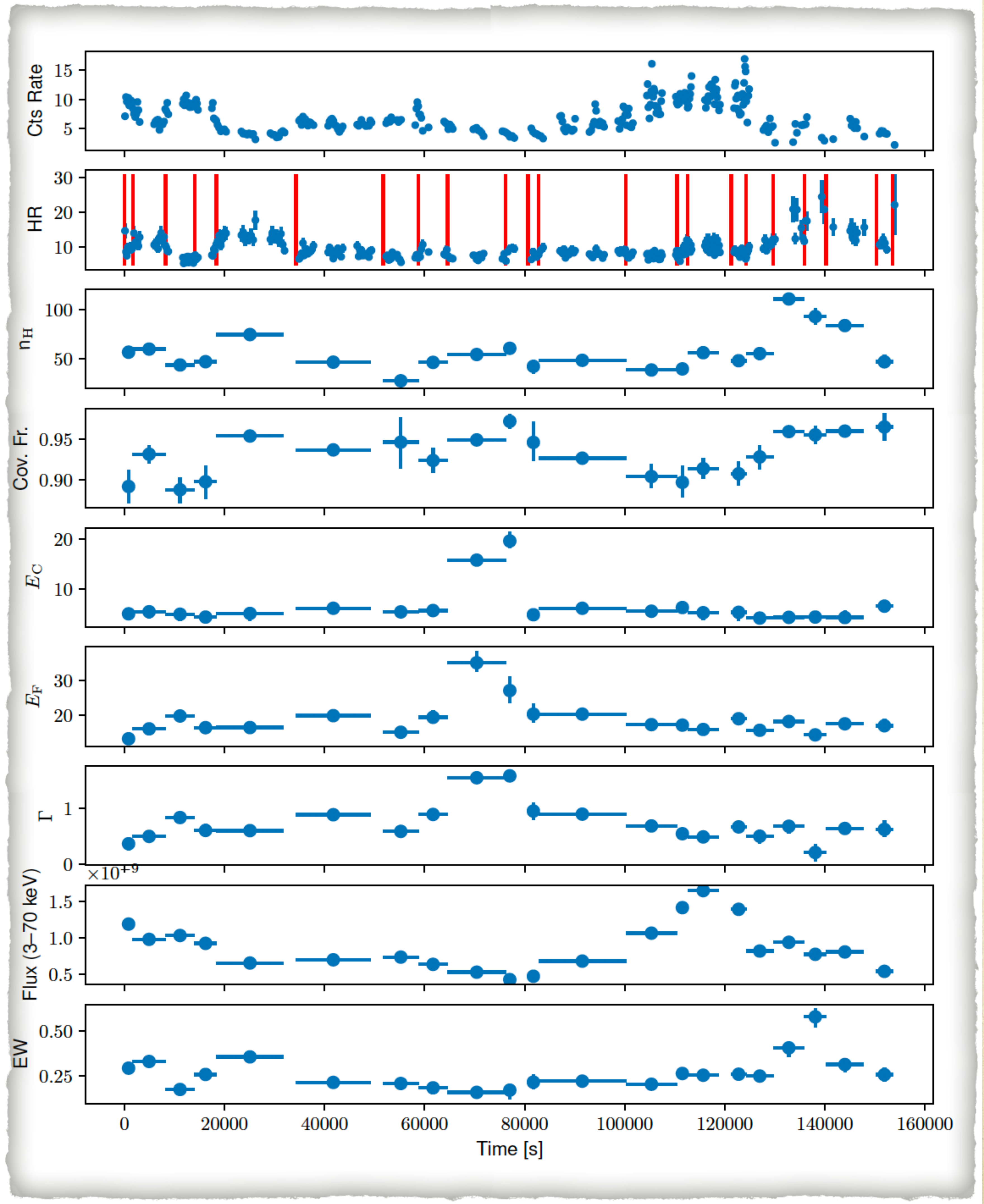
Courtesy: Jack Steiner

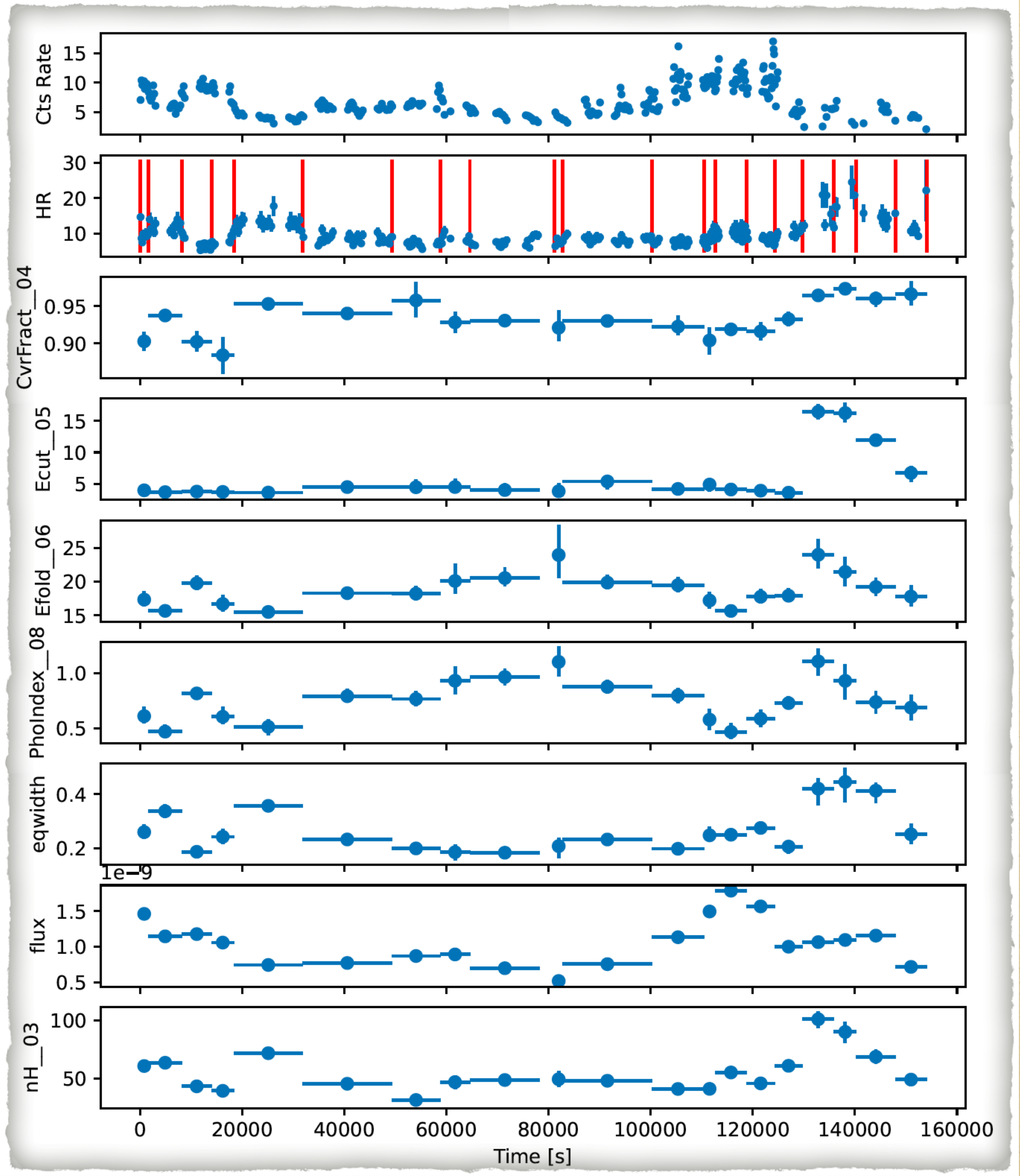
Time resolved analysis with NuSTAR



Pradhan et al. 2021

Time resolved analysis with NuSTAR





Pradhan et al. 2021

Some prominent* approaches to estimate clumps

*not a complete list

- Radiative hydrodynamical simulations of wind launching (Sundqvist 2012)
- Assume that the episodic enhancements of the intrinsic X-ray luminosity observed are due to the direct capture of a clump. (e.g., in ’t Zand 2005, Ducci 2009, Pradhan 2014)
- Takes as input (literature: stellar separation a, inclination, volume filling factor, P_orb, M_star, R_star, v_inf, M_dot + observations: median NH1, NH2 variation and time) and gives as output the clump characteristics (clump size, clump mass, porosity length), and beta (Grinberg 2015, El Mellah 2020)

$$\delta N_H = \frac{3}{32\pi}\left(m_{cl}\int_{z(\phi)}^{\infty}\frac{dz}{R_{cl}^2 r^2 v}\right)^{1/2}. \quad (12)$$

The expansion law for the clumps can then be reinjected in the formula above. For example, for linearly expanding clumps, we then have, if the velocity profile is given by the β-law (1):

$$\delta N_H = \frac{3}{8\pi}\left(\frac{m_{cl}}{R_{cl,2}^2}\int_{z(\phi)}^{\infty}\frac{dz}{r^4\,(1-1/r)^{\beta}}\right)^{1/2}. \quad (13)$$

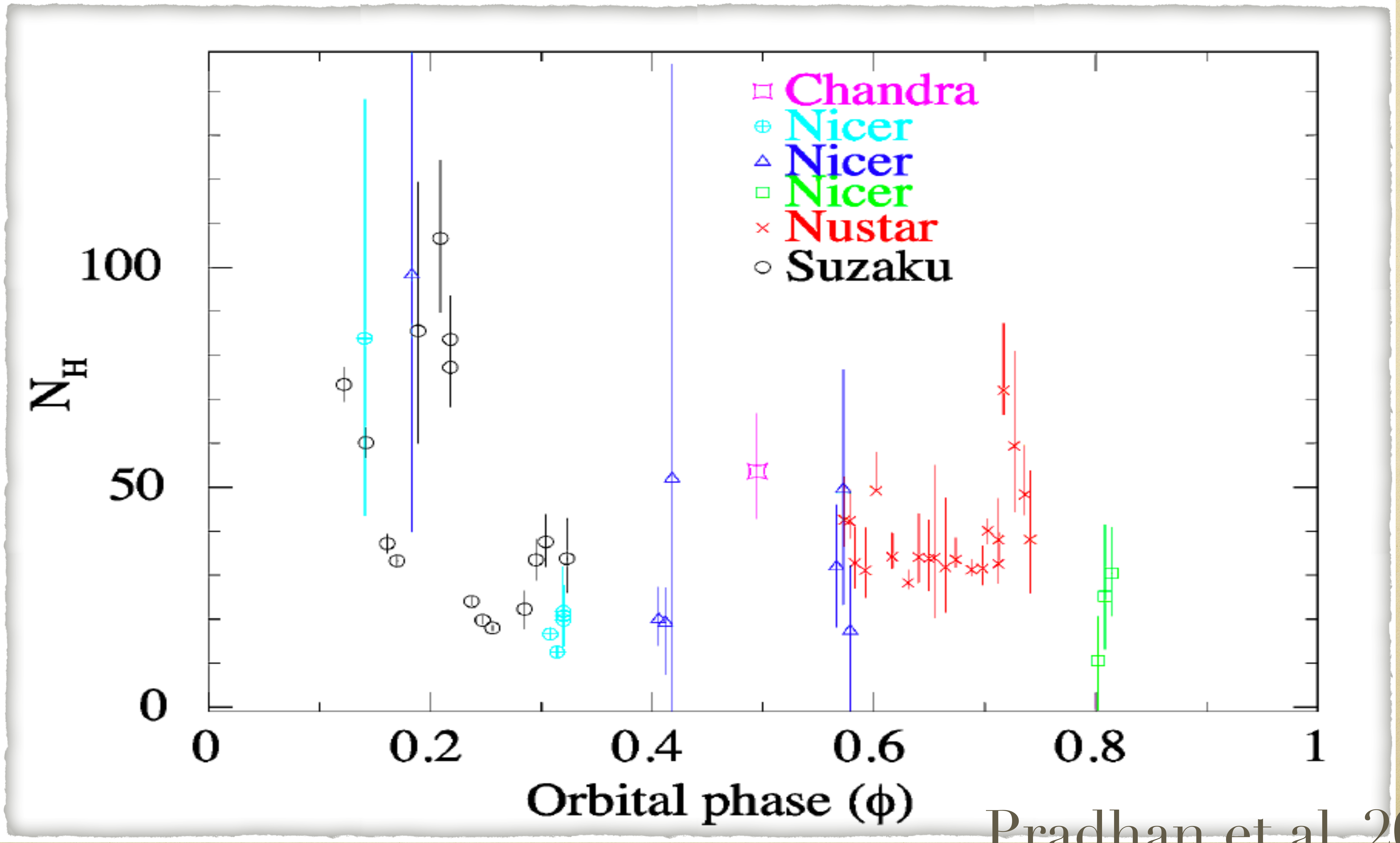
$$\begin{cases} f = \langle\rho^2\rangle/\langle\rho\rangle^2 \\ f_{\rm vol} = \rho/\rho_{cl}, \end{cases}$$

$$R_{cl} \propto r.$$

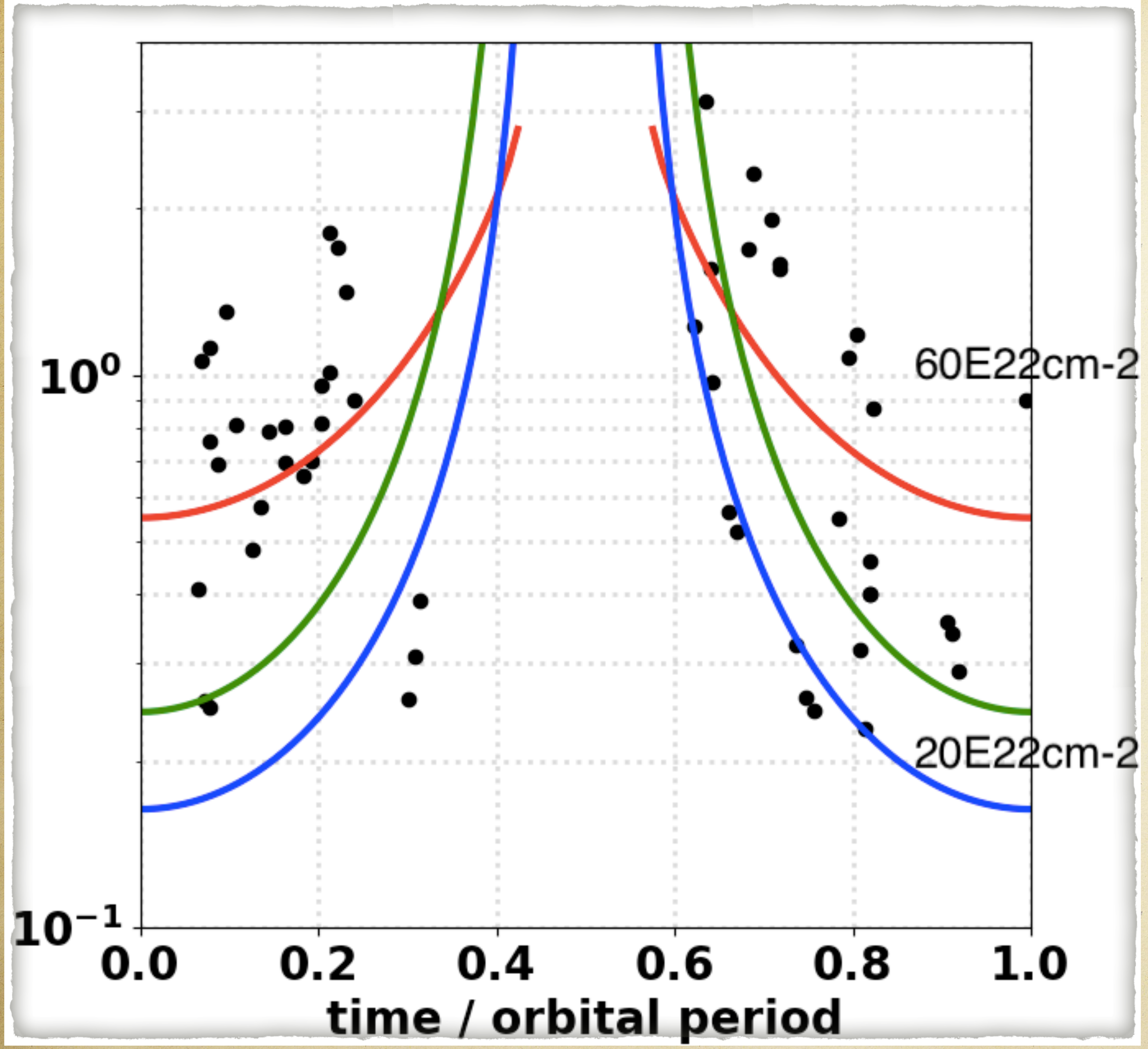
$$m_{cl} \sim 3\cdot 10^{22}\mathrm{g}\left(\frac{R_{cl,m}}{R_*}\right)^2 \times \ldots$$
$$\left(\frac{R_*}{20R_\odot}\right)^3\left(\frac{v_\infty}{1\,000\mathrm{km}\cdot\mathrm{s}^{-1}}\right)\times\ldots$$
$$\left(\frac{\dot{M}}{10^{-6}M_\odot\cdot\mathrm{yr}^{-1}}\right)^{-1}\left(\frac{\delta N_H}{5\cdot 10^{21}\mathrm{cm}^{-2}}\right)^2$$

$$h \sim 2\% R_*\left(\frac{m_{cl}}{4\cdot 10^{17}\mathrm{g}}\right)\left(\frac{R_{cl,2}}{0.01R_*}\right)^{-2}$$

Local variation in NH2



Pradhan et al. 2021

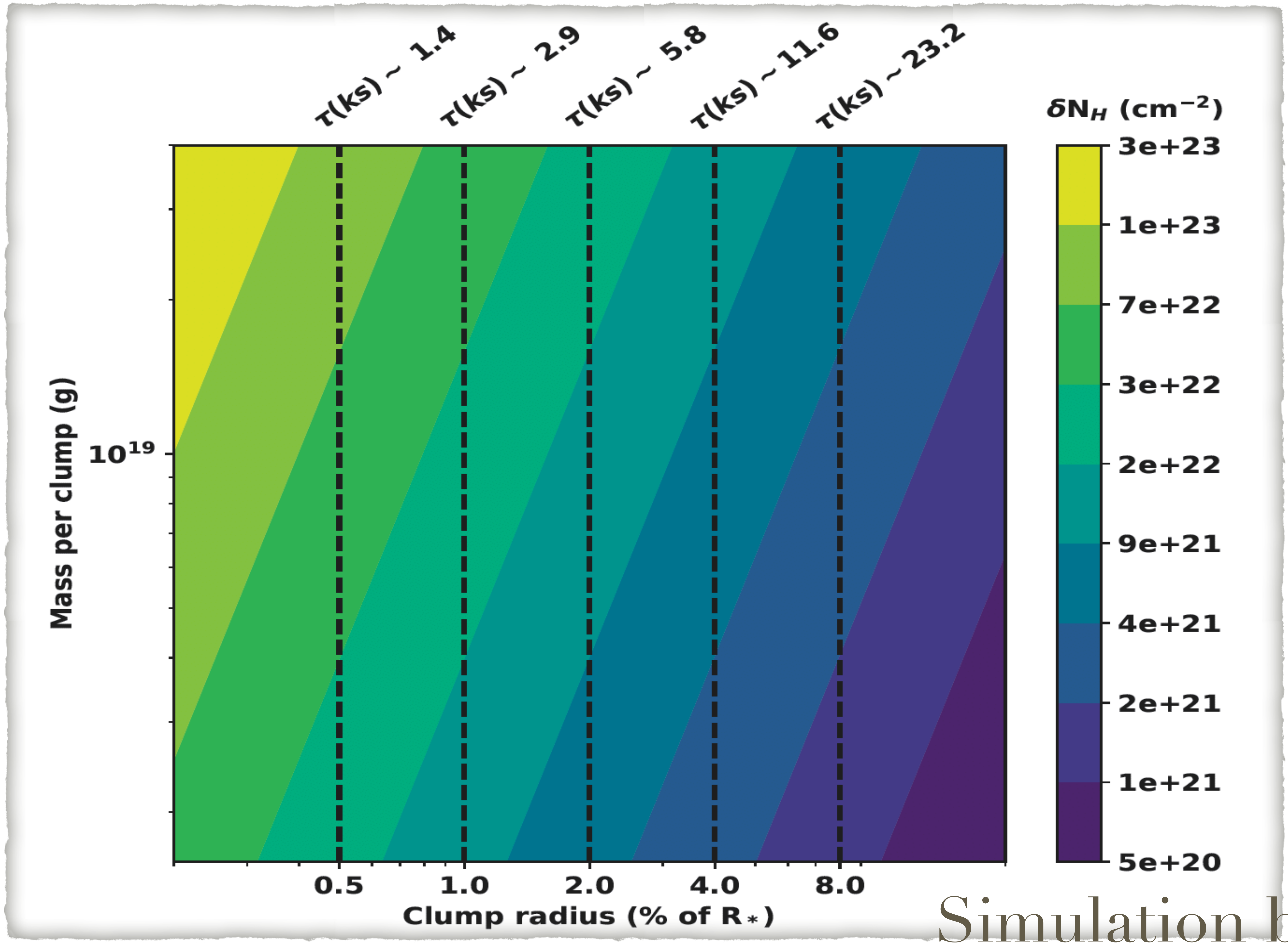


Red
- i=60 degrees
- a=1.6 stellar radius
- beta=3
- NH0=10 (though it is would correspond to a mass loss rate of almost 1e-5 solar mass per year, difficult to reconciliate with the values found in the literature)

Blue
- i=68
- a=2
- beta=2
- NH0=2

Green
- **i=65**
- **a=2**
- **beta=2**
- NH0=2

Clump size estimates



Simulation by El Mellah

Summary

- Current status of X-ray spectroscopy of HMXBs to constrain clump sizes (with certain approximations)
- XMM (and future X-ray satellites) can perform long interrupted observations with giving high quality spectra of HMXBs on coherence timescales are crucial to get accurate estimates.