Application of the physical accretion model by Becker & Wolff (2007) to Cen X-3

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in collaboration with

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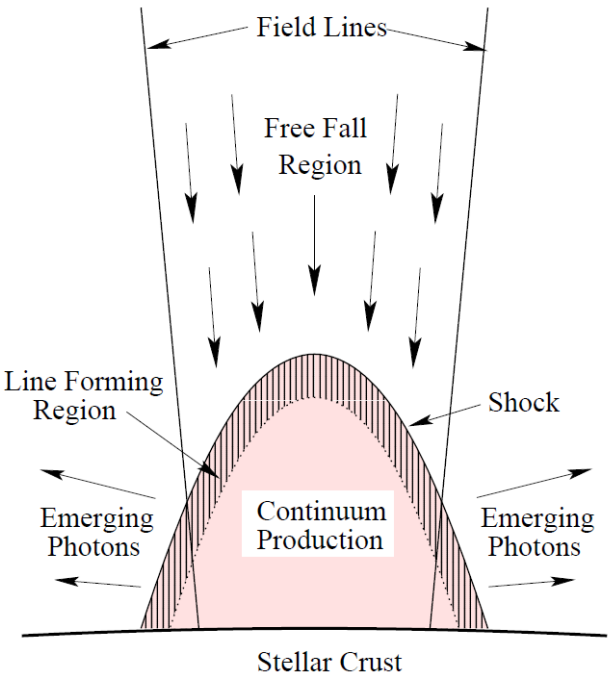
General Problem for modeling X-ray binary spectra



Heindl et al. (2004)

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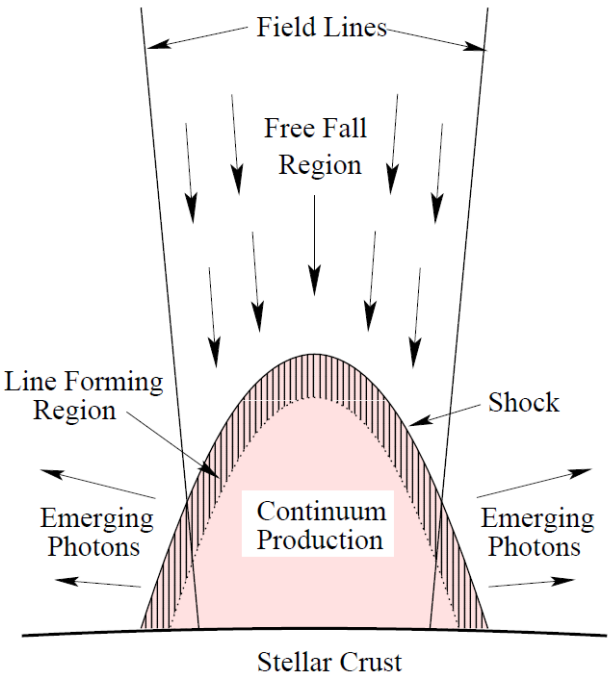
Very complex environment governed by magnetohydrodynamics, GR, light-bending, EoS of the NS, ...



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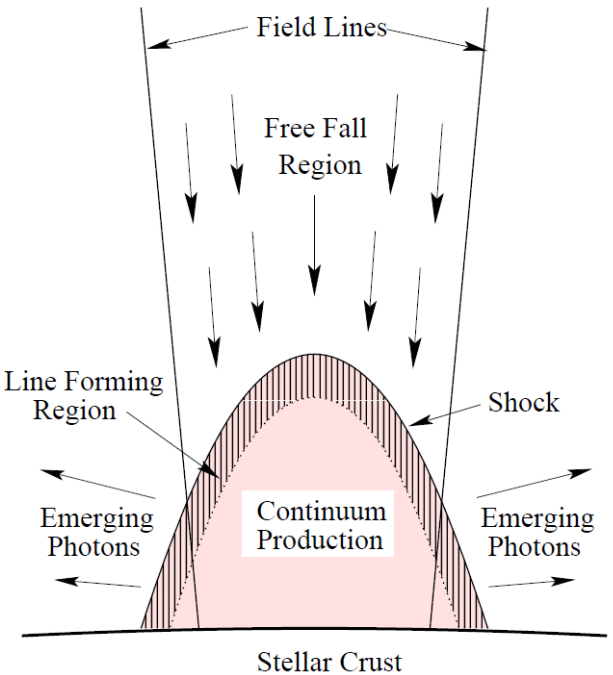

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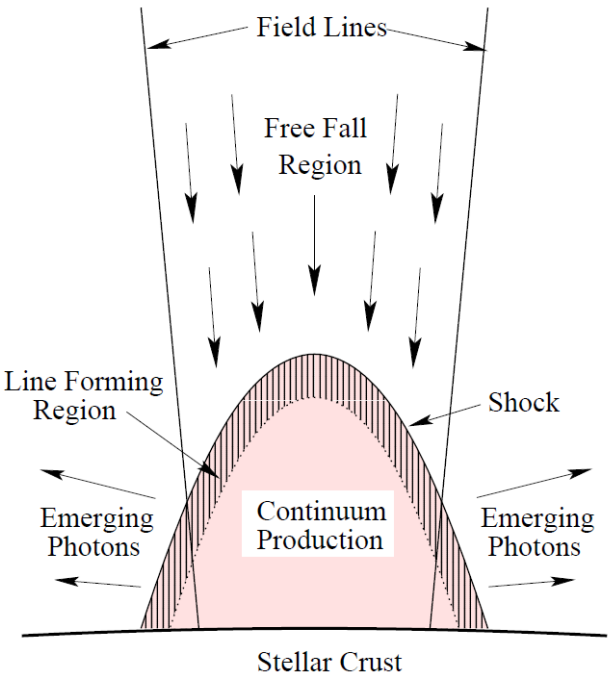

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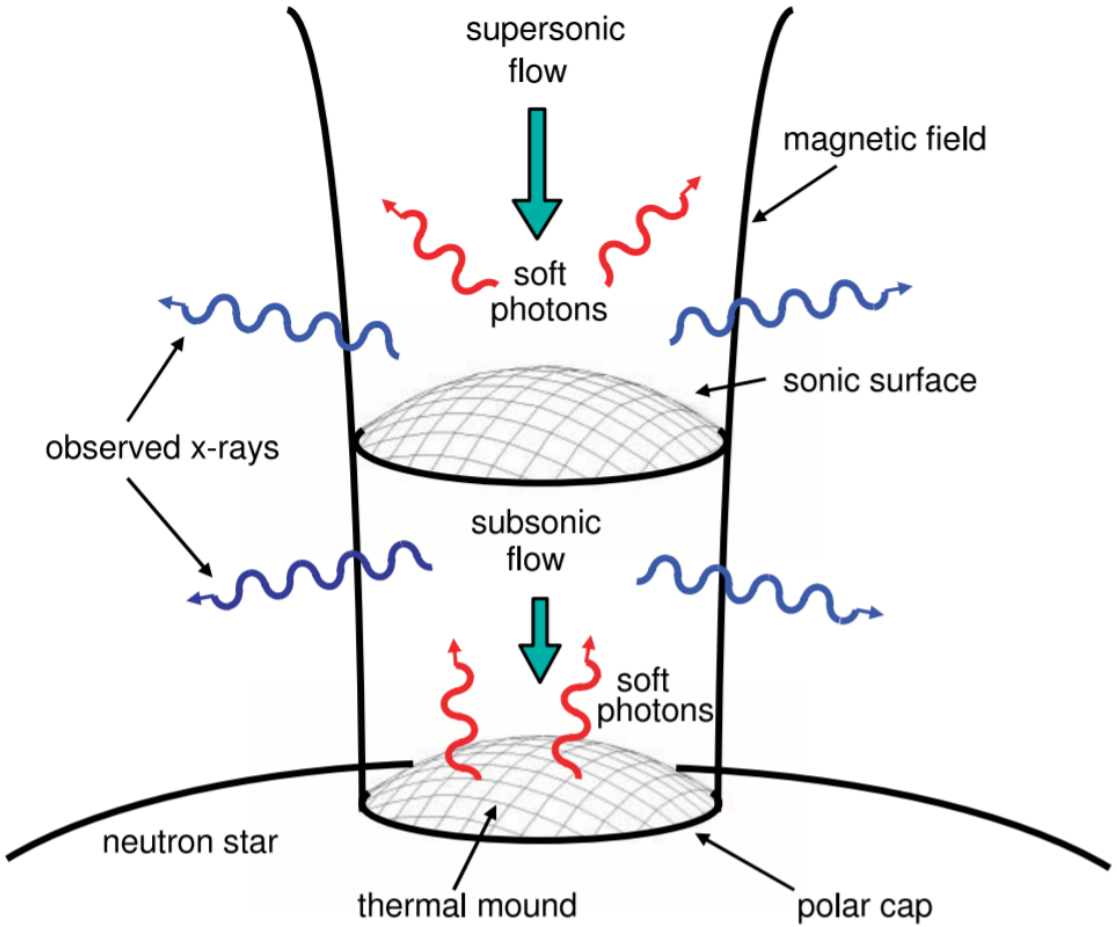
⇒ Just fit a power-law
X-ray binary spectra are generally only described by empirical models! (i.e., Absorbed cutoff power-low + ”patches”)
⇒ Deduction of physical conditions limited!

Accretion Model by Becker & Wolff (BW07)



Becker & Wolff (2007)

BW07: More Precisely

Radiative Transfer Equation:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial z} =$$
$$\frac{dv}{dz}\frac{\epsilon}{3}\frac{\partial f}{\partial \epsilon} + \frac{\partial}{\partial z}\left(\frac{c}{3n_e\sigma_{\|}}\frac{\partial f}{\partial z}\right) - \frac{f}{t_{\rm esc}} + \frac{n_e\bar{\sigma}c}{m_ec^2}\frac{1}{\epsilon^2}\frac{\partial}{\partial \epsilon}\left[\epsilon^4\left(f + kT_e\frac{\partial f}{\partial \epsilon}\right)\right] + \frac{Q(z,e)}{\pi r_0^2}$$

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Source terms $Q(z, \epsilon)$:

- Bremsstrahlung
- Black-body
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Assumptions:

- Velocity profile $\propto$ optical depth
- Cylindrical accretion column
- Constant B-Field
- Phase-averaged by Integration
- Simplified scattering cross sections

Parameter for BW07

Parameter	Comment
D	Distance
B_0	Magnetic Field
$\dot{M}$	Accretion rate
r_0	Column Radius
T_e	Electron Temperature
ξ	Depends on cross-sections and geometry
δ	Relative strength of bulk & thermal comptonization

Problem: Energy conservation

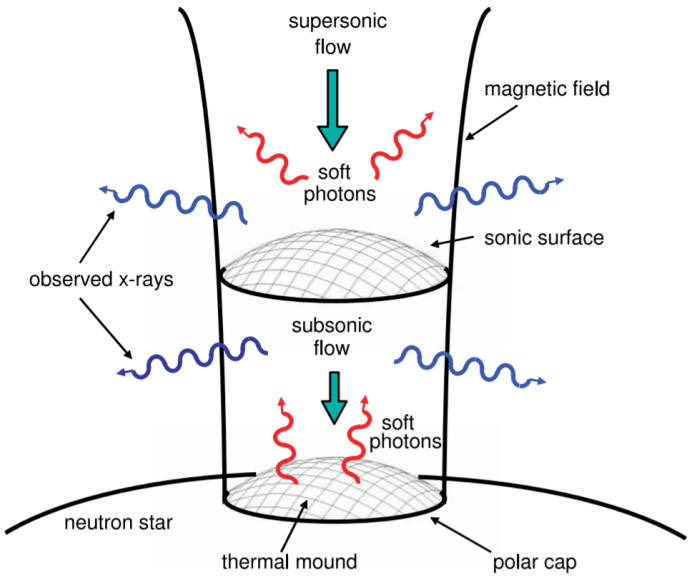
- Incoming gravitational energy:

$$L_{\mathrm{acc}} = \frac{\dot{M} M_{\mathrm{NS}} G}{R_{\mathrm{NS}}}$$

- Released X-Ray energy:

$$L_{\mathrm{X}} = 4\pi D^2 \int F_E(E)\, dE$$

- Both given by model
  $\Rightarrow$ NOT internally ensured to be equal!
  $\Rightarrow$ Has to be taken care of manually



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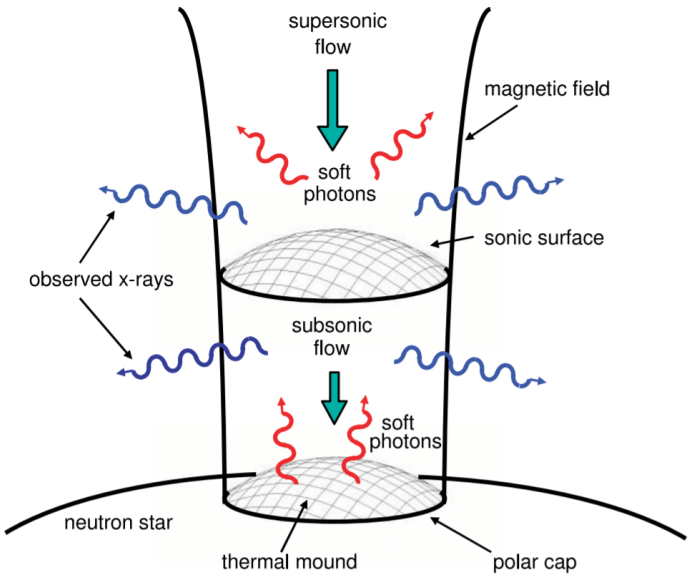

Current Approach

Initial Fit $\rightarrow L_X \rightarrow$ Adjust/Fix $\dot{M} \rightarrow$ Re-Fit $\rightarrow L_X \rightarrow$ Adjust/Fix $\dot{M} \rightarrow$ ...

Our solution: Let the fit ensure that $\dot{M}$ fits L_X

$$\chi^2 = \sum_i^n \frac{(x_i - \mu_i)^2}{\sigma_i^2}$$

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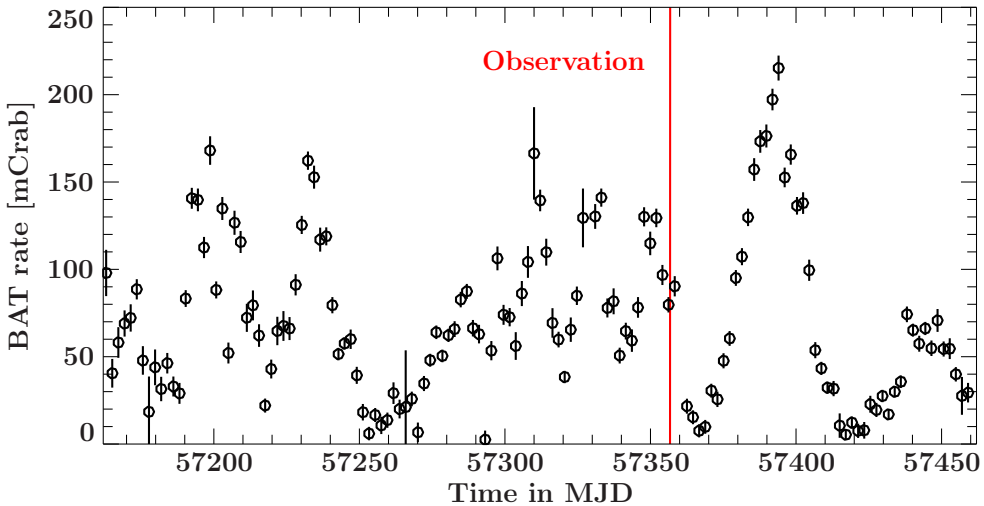
$$\Downarrow$$

$$\chi^2_{\mathrm{new}} = \chi^2 \cdot \left(1 + C \left(\frac{L_{\mathrm{acc}} - L_{\mathrm{X}}}{\Delta L_{\mathrm{X}}}\right)^2\right)$$

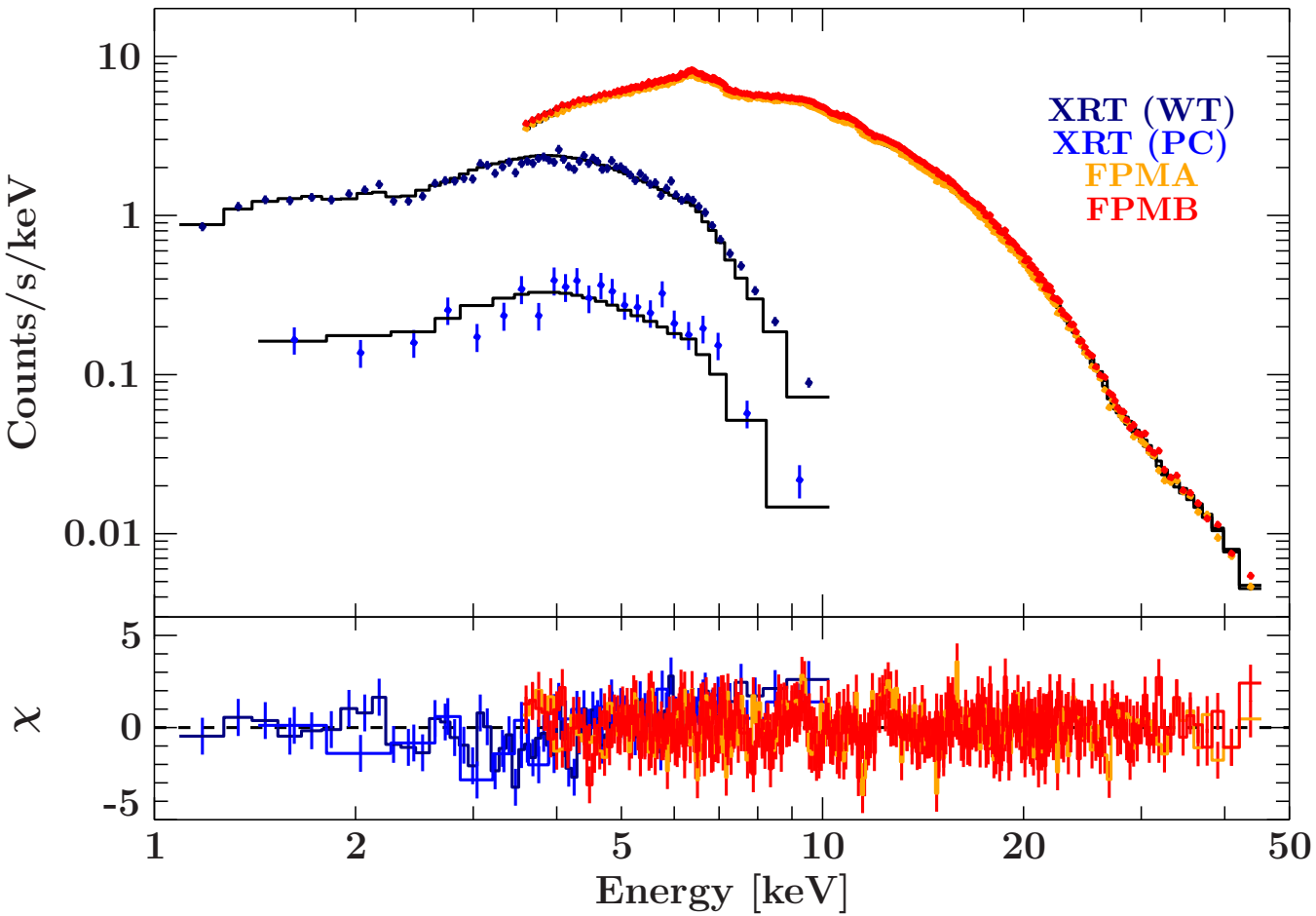
Familiar Test-Source: Cen X-3

- Luminosity $3.29 \cdot 10^{37}$ erg s^{-1}
- Distance: 5.7 ± 1.5 kpc
- Cyclotron line at $\sim$30 keV $\Rightarrow$ Constrain B-Field
- O-Type Optical Companion

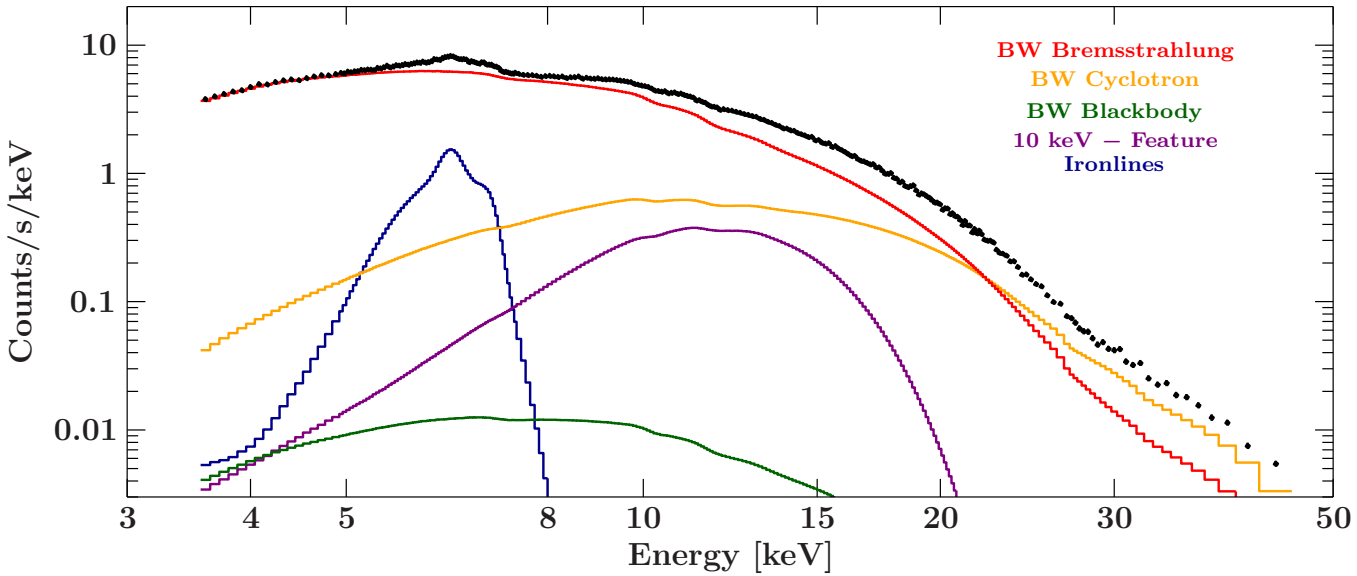


$\Rightarrow$ Observed in 2015 November 30 with Swift (0.2-10 keV) & NuStar (3-75 keV)

Final spectrum:

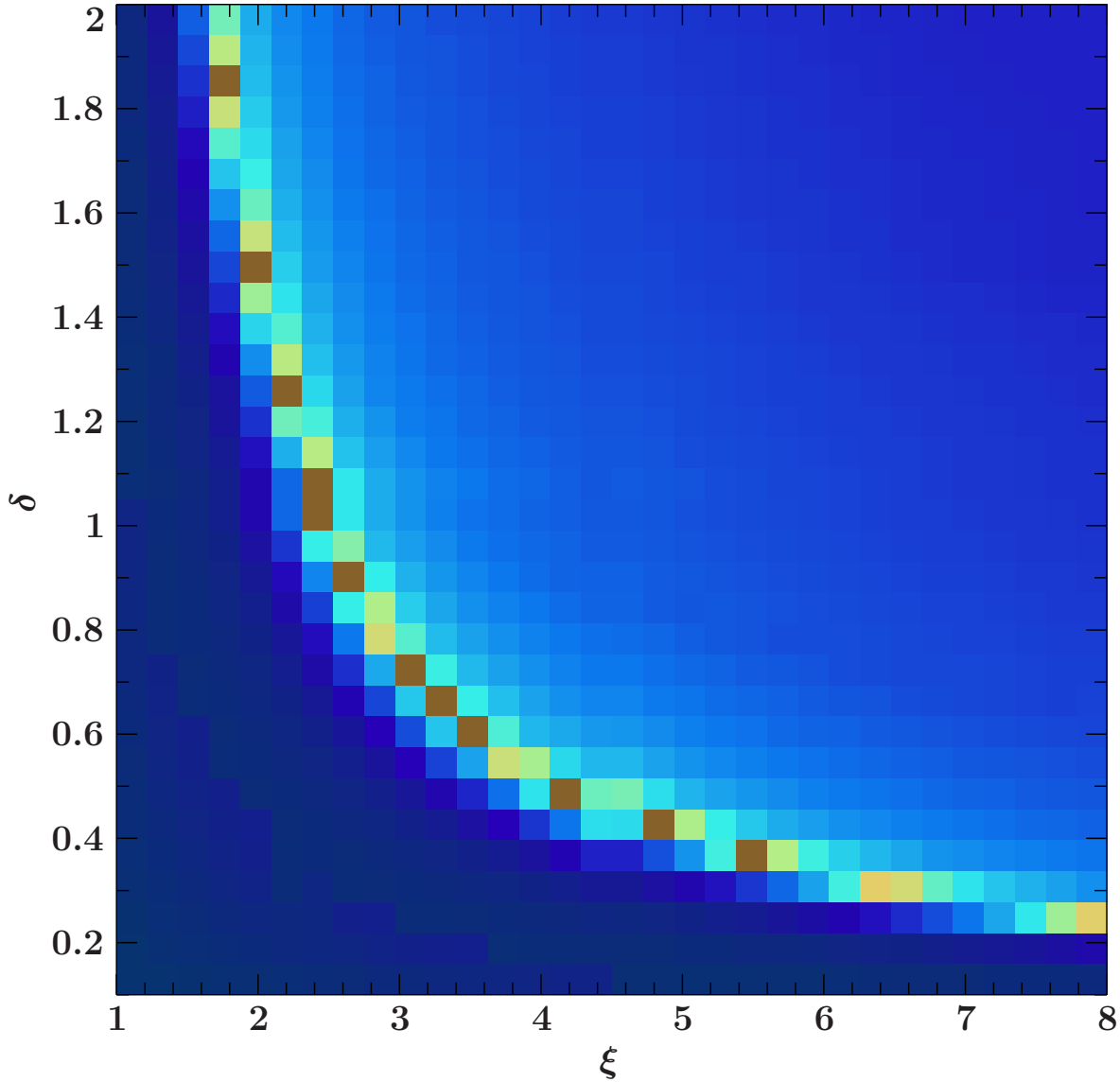


Cen X-3: Best Fit parameters

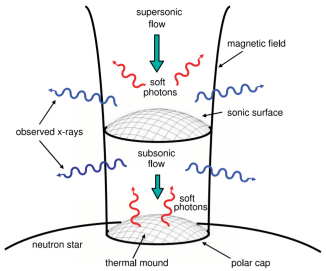


- $\dot{M} = 1.8 \times 10^{17}$ g s^{-1}
- Column Radius: 67 m
- $\delta = 2.10 \Rightarrow$ thermal Comptonization slightly more important
- B-Field: 3.32 $\times 10^{12}$ G
- 10 keV Feature at 12.7 keV: Width: 3.3 keV
- CRSF at 29.3 keV: Width: 6.6 keV $\Rightarrow$ Broad Cyclotron line

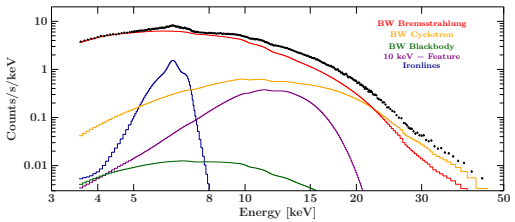
Still problematic: Parameter correlations



Summary and outlook:



$\Leftrightarrow$



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- Can describe high luminosity sources as Cen X-3 well

- Still have to be careful about degeneracies
- Future models hopefully internally ensure energy conservation.

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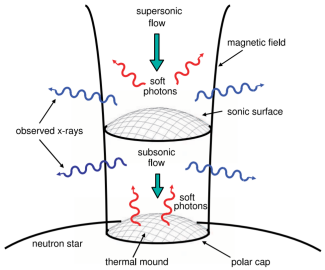

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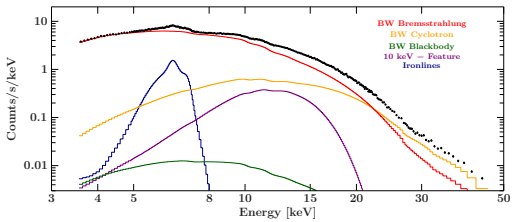

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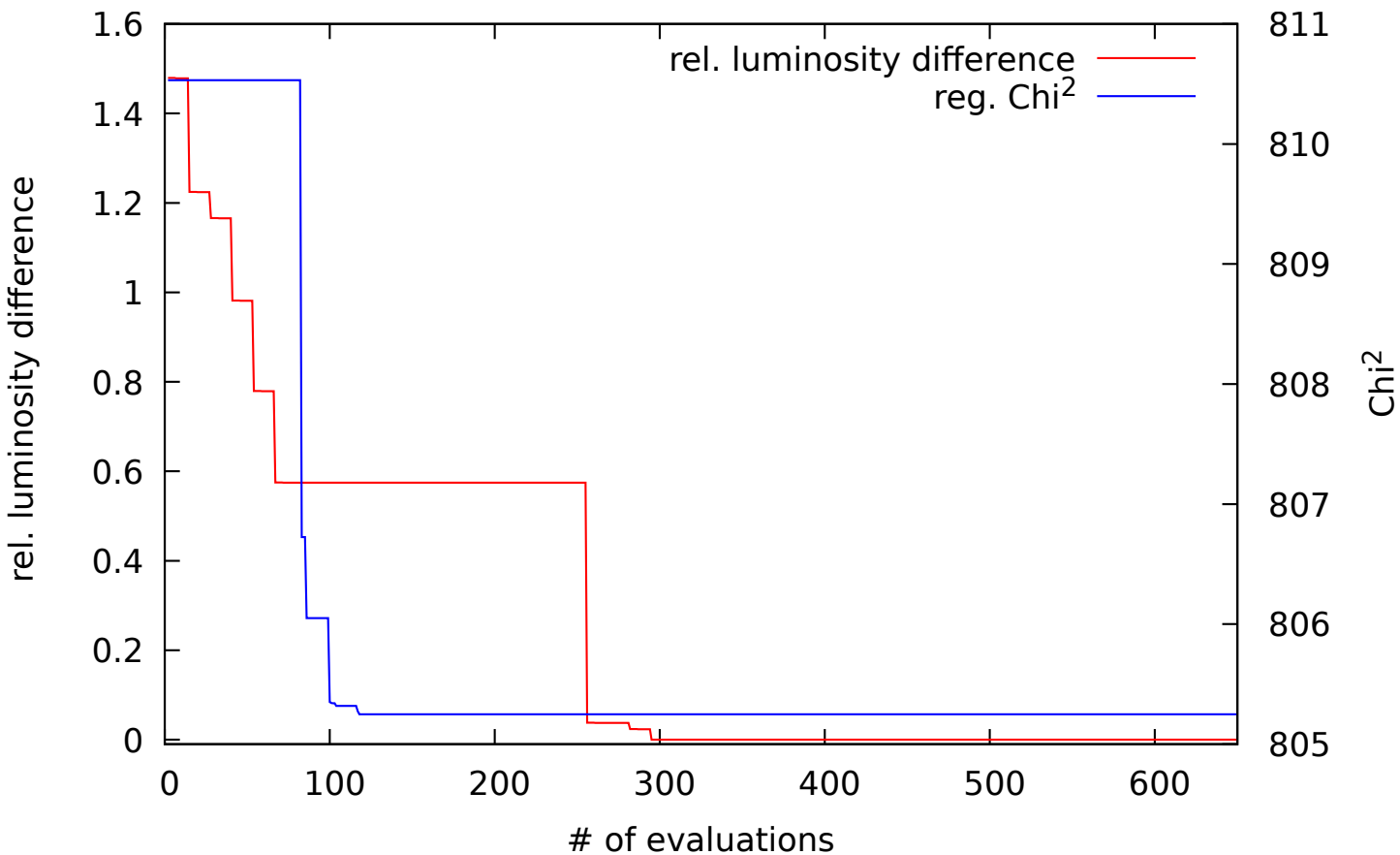
Thank you
for your attention!

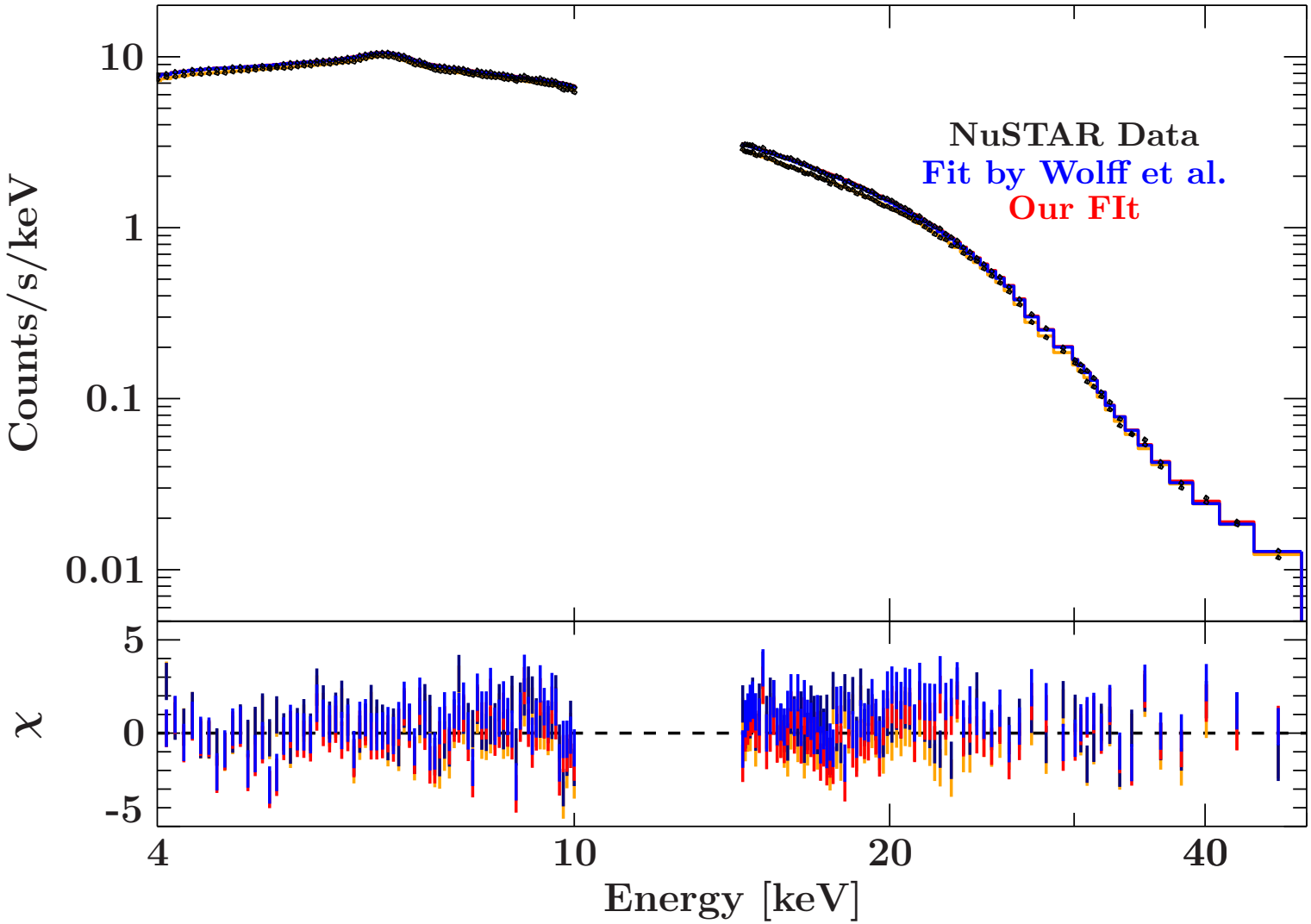
Convergence behaviour:



Phenomenological fit to Cen X-3

Parameter	Highcut	FDcut
N_H (cm^{-2})	1.71 ± 0.28	1.62 ± 0.28
$N_{\mathrm{H/pcf}}$ (cm^{-2})	$10.8^{+1.1}_{-1.0}$	10.3 ± 1.0
pcf	$0.798^{+0.030}_{-0.033}$	0.78 ± 0.04
$\mathrm{Norm_{PL}}$	$0.205^{+0.033}_{-0.022}$	$0.178^{+0.019}_{-0.015}$
Γ	$1.17^{+0.10}_{-0.07}$	1.05 ± 0.07
E_{cutoff} (keV)	$12.67^{+0.17}_{-0.15}$	22^{+6}_{-5}
E_{Fold} (keV)	$9.6^{+0.7}_{-0.4}$	$6.1^{+0.9}_{-1.3}$
σ_{gabs} (keV)	$1.63^{+0.35}_{-0.27}$	—
$\mathrm{A_{gabs}}$	$0.29^{+0.15}_{-0.10}$	—
$\mathrm{A_{6.4\,keV}}$	$\left(1.22^{+0.17}_{-0.18}\right) \times 10^{-3}$	$\left(1.24^{+0.18}_{-0.19}\right) \times 10^{-3}$
$\mathrm{A_{6.7\,keV}}$	$(2.4 \pm 1.4) \times 10^{-4}$	$\left(2.9^{+1.6}_{-1.5}\right) \times 10^{-4}$
$\mathrm{A_{6.97\,keV}}$	$(5.3 \pm 1.5) \times 10^{-4}$	$\left(5.9^{+1.6}_{-1.5}\right) \times 10^{-4}$
$\mathrm{A_{broad}}$	$(4.3 \pm 0.6) \times 10^{-3}$	$\left(3.9^{+0.6}_{-0.7}\right) \times 10^{-3}$
$\mathrm{E_{broad}}$ (keV)	6.23 ± 0.08	$6.21^{+0.08}_{-0.09}$
σ_{broad} (keV)	0.55 ± 0.06	0.51 ± 0.06
$\mathrm{A_{10\,keV}}$	$0.018^{+0.013}_{-0.007}$	$\left(9.7^{+3.7}_{-2.7}\right) \times 10^{-3}$
$\mathrm{E_{10\,keV}}$ (keV)	$13.5^{+1.0}_{-1.2}$	12.6 ± 0.4
$\sigma_{\mathrm{10\,keV}}$ (keV)	4.1 ± 0.6	$2.9^{+0.5}_{-0.4}$
$\mathrm{E_{CRSF}}$ (keV)	$29.6^{+0.5}_{-0.4}$	$28.90^{+0.36}_{-0.29}$
σ_{CRSF} (keV)	3.8 ± 0.5	$6.3^{+0.9}_{-1.1}$
$\mathrm{A_{CRSF}}$	2.7 ± 0.7	13^{+10}_{-6}
$\mathrm{C_{FPMB}}$	1.0256 ± 0.0022	1.0255 ± 0.0022
$\mathrm{C_{PC}}$	0.76 ± 0.06	0.76 ± 0.06
$\mathrm{C_{WT}}$	1.076 ± 0.017	1.075 ± 0.017

BW07 fit to Her X-1



Cen X-3: Best Fit parameters

Parameters:	
$N_{\rm H}$ ($\rm cm^2$)	$1.51^{+0.26}_{-0.06}$
$N_{\rm H/pcf}$ ($\rm cm^2$)	$10.35^{+0.30}_{-0.88}$
pcf	$0.780^{+0.020}_{-0.035}$
$\dot{M}$ (10^{17} g $\rm s^{-1}$)	$1.769^{+0.031}_{-0.030}$
$kT_{\rm c}$ (keV)	$5.28^{+0.06}_{-0.08}$
r_0 (m)	$\left(1.456^{+0.007}_{-0.005}\right) \times 10^2$
B (10^{12}G) (tied to $\rm E_{CRSF}$)	3.32
ξ	$5.655^{+0.024}_{-0.056}$
δ	$0.341^{+0.004}_{-0.009}$
$A_{10\,\rm keV}$	$0.0129^{+0.0006}_{-0.0015}$
$E_{10\,\rm keV}$	$16.42^{+0.24}_{-0.20}$
$\sigma_{10\,\rm keV}$	$3.77^{+0.27}_{-0.37}$
$E_{\rm CRSF}$ (keV)	$38.46^{+0.17}_{-0.37}$
$\sigma_{\rm CRSF}$ (keV)	$7.84^{+0.26}_{-0.31}$
$\rm A_{CRSF}$	$18.4^{+0.6}_{-1.3}$

Sources

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