# Application of a Physical Continuum Model to Recent X-ray Observations of Accreting Pulsars


Diana M. Marcu-Cheatham

University of Maryland Baltimore County
CRESST/GSFC

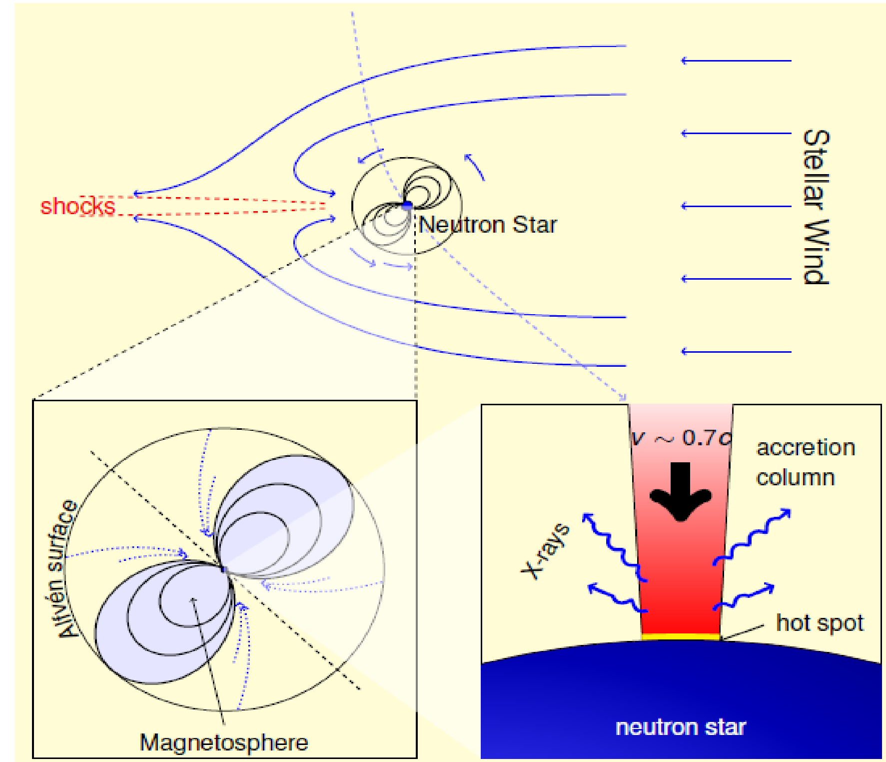
K. Pottschmidt, M.T. Wolff, P.A. Becker, K.S. Wood, J. Wilms, P.B. Hemphill, A.M. Gottlieb, F. Fuerst, F.-W. Schwarm, R. Ballhausen

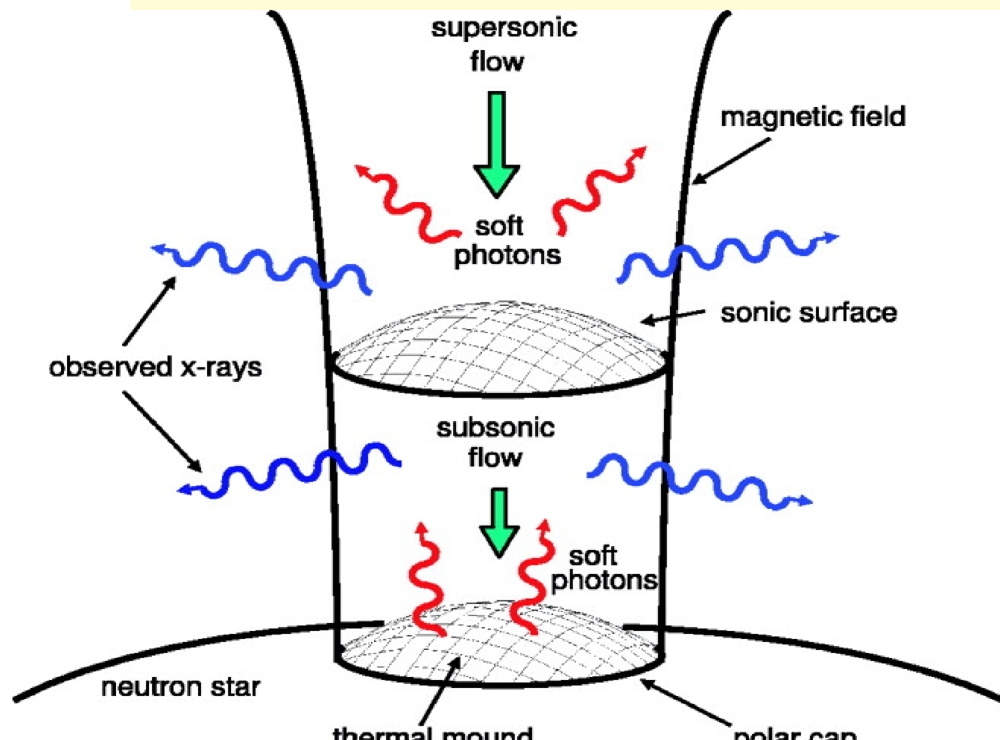
# Accretion onto NS Surface

- **X-ray seed photons** emission in the **accretion column**:
  - **Bremsstrahlung emission**
  - **Cyclotron emission**
  - **Blackbody emission**

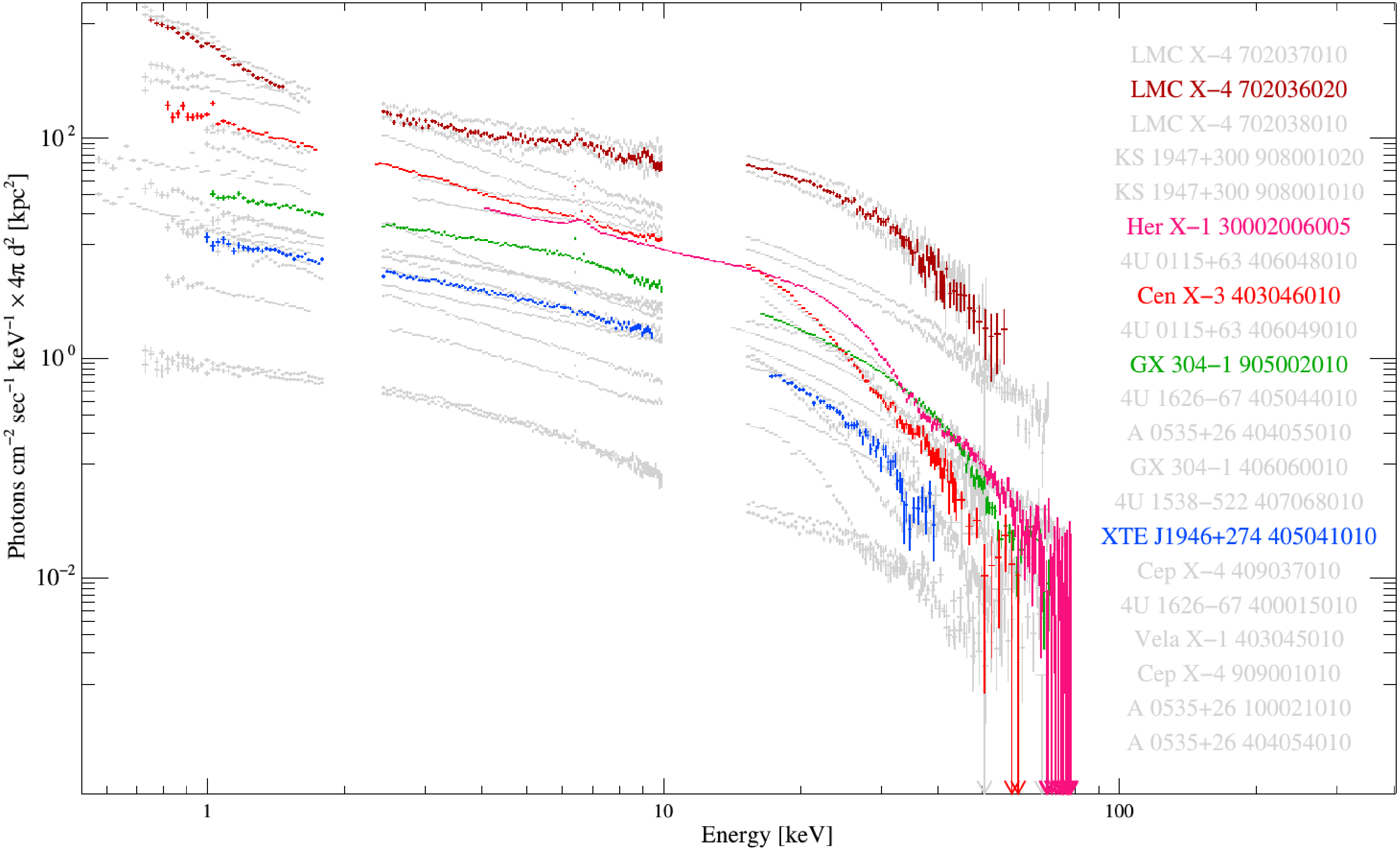
- Seed photons are **up-scattered by electron scattering** in the accretion column:
  - **Bulk Comptonization** due to the bulk motion of infalling electrons
  - **Thermal Comptonization** due to stochastic electron motion
  - Solution to **Radiative Transfer Equation** using **Analytical Formalism by Becker & Wolff 2007**

- Empirical models are used to described cutoff power law shape of the continuum (e.g. Cutoff Power Law, Fermi Dirac Cutoff, etc.)



# Sources and Properties

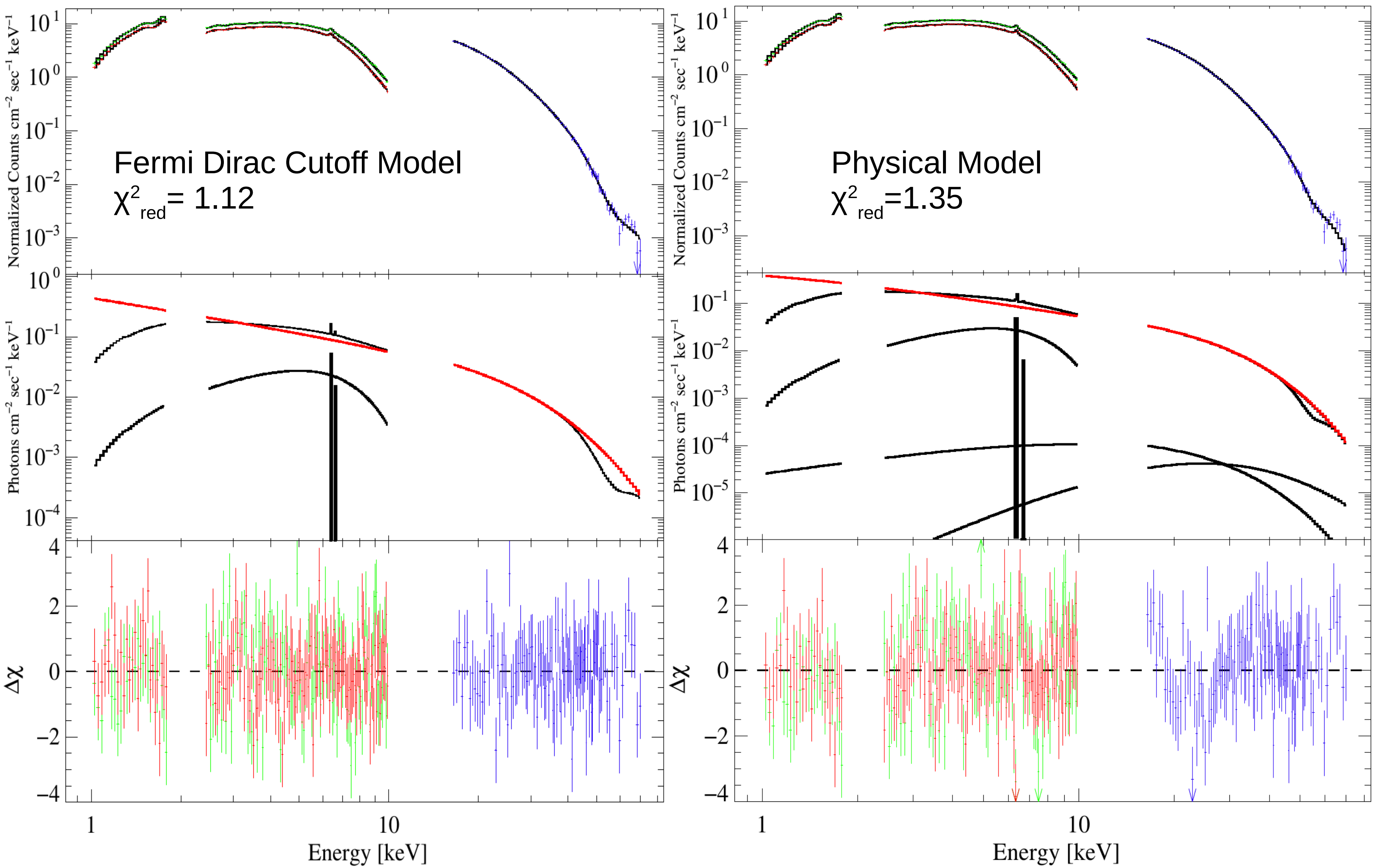



- GX 304-1
- XTE J1946+274

- Cen X-3 (Gottlieb et al. 2016 in prep.) Poster #120.09
- Her X-1 (Wolff et al. 2016 Submitted) Poster #120.24

- All sources have measured cyclotron lines
  - except LMC X-4

# Spectral Fitting GX 304-1



# Fit results

# Physical & Fermi Dirac Cutoff Models

| Source $L_{X\ 1-80keV}$ | $kT_e$ [keV] | $r_0$ [m] | $\sigma_{\parallel}$ [$\times 10^{-5}\sigma_T$] | $\bar{\sigma}$ [$\times 10^{-4}\sigma_T$] | $E_{fold}$ [keV] | $E_{cut}$ [keV] | $\Gamma$ |
|---|---|---|---|---|---|---|---|
| LMC X-4 $25.4 \times 10^{37}$ erg s$^{-1}$ | $6.53^{+0.08}_{-0.15}$ | $1912^{+759}_{-604}$ | $1.14^{+1.12}_{-0.52}$ | 106.06 | $8.0^{+0.8}_{-0.7}$ | $26.2^{+2.0}_{-2.7}$ | 0.65(4) |
| 1 Her X-1[a,b] $4.9 \times 10^{37}$ erg s$^{-1}$ | 4.58(7)[a] | $170.4^{+1.7}_{-1.8}$ [a] | 5.2(1)[a] | 3.5(2)[a] | $6.0^{+0.5}_{-0.8}$ [b] | $35.9^{+3.0}_{-0.3}$ [b] | $0.888^{+0.008}_{-0.009}$ [b] |
| Cen X-3 [c] $4.0 \times 10^{37}$ erg s$^{-1}$ | $3.1^{+0.4}_{-0.1}$ [c] | $65^{+12}_{-4}$ [c] | 0.28(2)[c] | $1.6^{+0.6}_{-0.3}$ [c] | $7.0^{+0.7}_{-0.6}$ [c] | 18(3)[c] | $1.1^{+0.2}_{-0.1}$ [c] |
| GX 304−1 $2.0 \times 10^{37}$ erg s$^{-1}$ | 6.28 | 69.4 | 2.7 | 8.5 | $9.3^{+0.8}_{-0.7}$ | $29.2^{+2.4}_{-2.7}$ | 1.47(3) |
| XTE J1946+274 $0.5 \times 10^{37}$ erg s$^{-1}$ | 4.45(3) | 14.0(2) | 1.07(2) | $7.0^{+0.5}_{-0.4}$ | 9.1(4)[d] | 0.0[d] | 0.59(2)[d] |

**Note**. — (a) Wolff et al. 2016 submitted, Poster #120.24; (b) Fuerst et al. (2013); (c) Gottlieb et al. 2016 in prep, Poster #120.09; (d) Marcu-Cheatham et al. (2015).

# Conclusions

- Results:
  - All sources have statistically good fits **1.04 < $\chi^2_{red}$ < 1.35**
  - Regardless of the diversity of the sources, there are **no strong variations in $T_e$**: ~3 – 6 keV – similarly to **$E_{fold}$**: ~6 – 9 keV
  - Possible correlation: **$r_0 \sim L_X$**
  - Physical fits reproduce the empirical (FDCO) fits → features that strongly influence the continuum were found in both, i.e., BBODY (GX 304-1), "10 keV bump" (Cen X-3), strong Fe line (Her X-1)

- Revolutionizing spectral modeling of neutron star accretion
  - Large improvement in modeling the X-ray continuum by successfully **statistically fitting a physical model**
  - Estimates for accretion column parameters: $T_e$, $r_0$, cross sections

- Next: Physics of Cyclotron Lines

# Her X-1, Cen X-3, LMC X-4

- Comparison with BW 2007:
  - $T_e$ approximately the same in both cases, even though luminosities are different
  - Largest differences are in $r_0$, especially in LMC X-4, other two show smaller differences probably due to different luminosities
  - Cen X-3 data was taken at a much higher luminosity in BW 2007

# Comparison with Farinelli et al. 2015 (F15)

- F15 states that their velocity profile is more generalized rather than the free fall velocity used by BW

- F15 calculates the second order (vs. first order in BW) bulk-Comptonization → Te slightly lower in F15

- F15 claims a high cyclotron emission that described the "10 keV bump", however, we don't see a comparably strong cyclotron emission

- F15 finds much higher $r_0$ values (on the order of 1 – 3 km)

# Empirical Continuum Models

$$\mathrm{CUTOFFPL}(E) = AE^{-\Gamma} \times e^{-E/E_{\mathrm{fold}}}$$

$$\mathrm{FDCO}(E) = AE^{-\Gamma} \frac{1}{1 + e^{(E - E_{\mathrm{cut}})/E_{\mathrm{fold}}}}$$

$$\mathrm{PLCUT}(E) = AE^{-\Gamma} \times \begin{cases} 1 & (E \leq E_{\mathrm{cut}}) \\ e^{-(E - E_{\mathrm{cut}})/E_{\mathrm{fold}}} & (E > E_{\mathrm{cut}}) \end{cases}$$

$$\mathrm{NPEX}(E) = (A_1 E^{-\alpha_1} + A_2 E^{+\alpha_2}) e^{-E/E_{\mathrm{fold}}}$$

# Empirical CRSF Models

$$M(E) = \begin{cases} \mathrm{GABS}(E) = \tau_{\mathrm{c}} e^{-(E - E_{\mathrm{c}})^2/(2\sigma_c^2)} \\ \mathrm{CYCLABS}(E) = D_{\mathrm{c}} \frac{(W_{\mathrm{c}} E/E_{\mathrm{c}})^2}{(E - E_{\mathrm{c}})^2 + W_{\mathrm{c}}^2} \end{cases}$$

$$I_0(E) \rightarrow I_0(E) e^{-M(E)}$$

# Becker and Wolff Physical Model for Accreting Pulsars

- Green's function distribution $f_G$ satisfies the generalized Kompaneets (1957) transport equation

$$v \frac{\partial f_{\rm G}}{\partial z} = \frac{dv}{dz}\frac{\epsilon}{3}\frac{\partial f_{\rm G}}{\partial \epsilon} + \frac{\partial}{\partial z}\left(\frac{c}{3 n_e \sigma_{_\parallel}}\frac{\partial f_{\rm G}}{\partial z}\right) - \frac{f_{\rm G}}{t_{\rm esc}}$$

$$+ \frac{n_e \overline{\sigma} c}{m_e c^2}\frac{1}{\epsilon^2}\frac{\partial}{\partial \epsilon}\left[\epsilon^4\left(f_{\rm G} + kT_e\frac{\partial f_{\rm G}}{\partial \epsilon}\right)\right] + \frac{\dot{N}_0\,\delta(\epsilon-\epsilon_0)\,\delta(z-z_0)}{\pi r_0^2 \epsilon_0^2}$$

- $f_G$ convolved with a source distribution function for each type of emission provides the final spectral model

# Becker and Wolff Physical Model for Accreting Pulsars

- Green's function distribution $f_G$ satisfies the generalized Kompaneets (1957) transport equation

Advection

First order Fermi energization "bulk" Comptonization

Spacial diffusion along column axis

Photon escape

$$v\,\frac{\partial f_G}{\partial z} = \frac{dv}{dz}\,\frac{\epsilon}{3}\,\frac{\partial f_G}{\partial \epsilon} + \frac{\partial}{\partial z}\left(\frac{c}{3 n_e \sigma_{\parallel}}\,\frac{\partial f_G}{\partial z}\right) - \frac{f_G}{t_{\rm esc}} + \frac{n_e \overline{\sigma} c}{m_e c^2}\,\frac{1}{\epsilon^2}\,\frac{\partial}{\partial \epsilon}\left[\epsilon^4\left(f_G + kT_e\,\frac{\partial f_G}{\partial \epsilon}\right)\right] + \frac{\dot{N}_0\,\delta(\epsilon-\epsilon_0)\,\delta(z-z_0)}{\pi r_0^2 \epsilon_0^2}$$

Thermal Comptonization

Photon injection

NOTE! Final model is LINEAR: $F_\epsilon(\epsilon) \equiv \frac{\left[\Phi_\epsilon^{\rm cyc}(\epsilon) + \Phi_\epsilon^{\rm bb}(\epsilon) + \Phi_\epsilon^{\rm ff}(\epsilon)\right] A_c(\epsilon)}{4\pi D^2}$