The magnetic spectrum of X-ray binary pulsars

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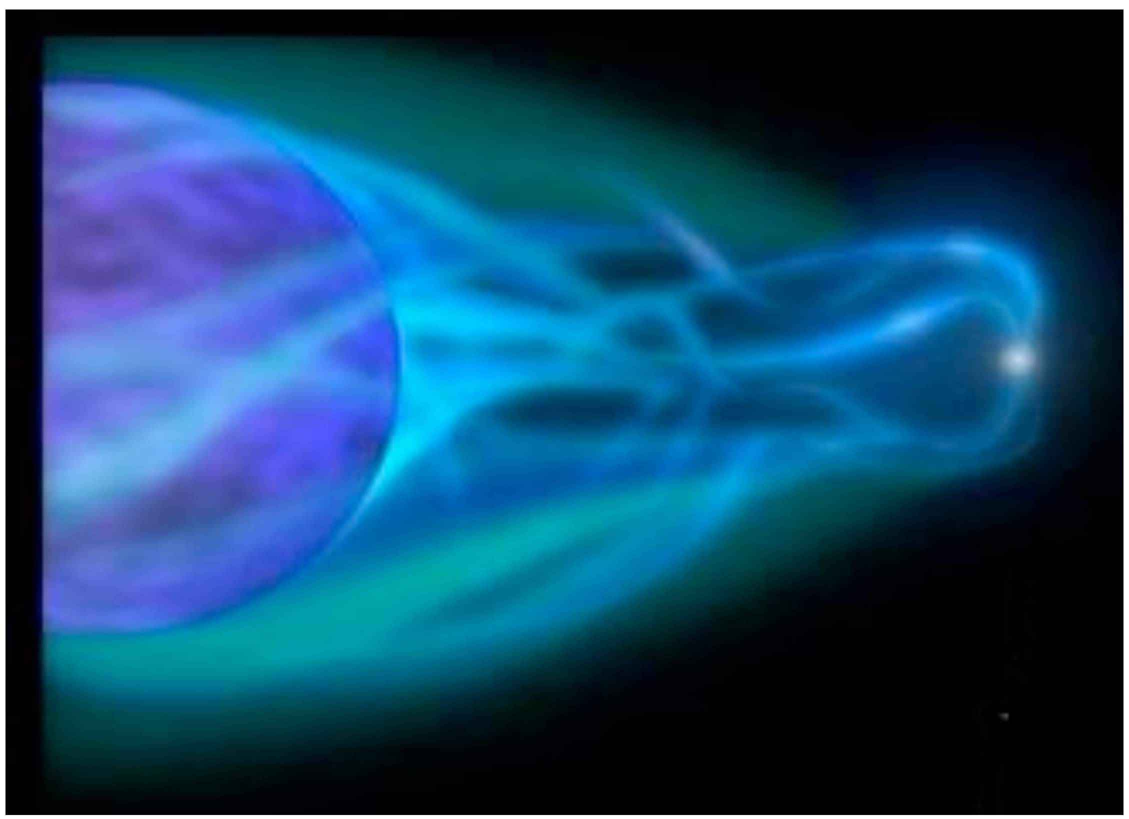
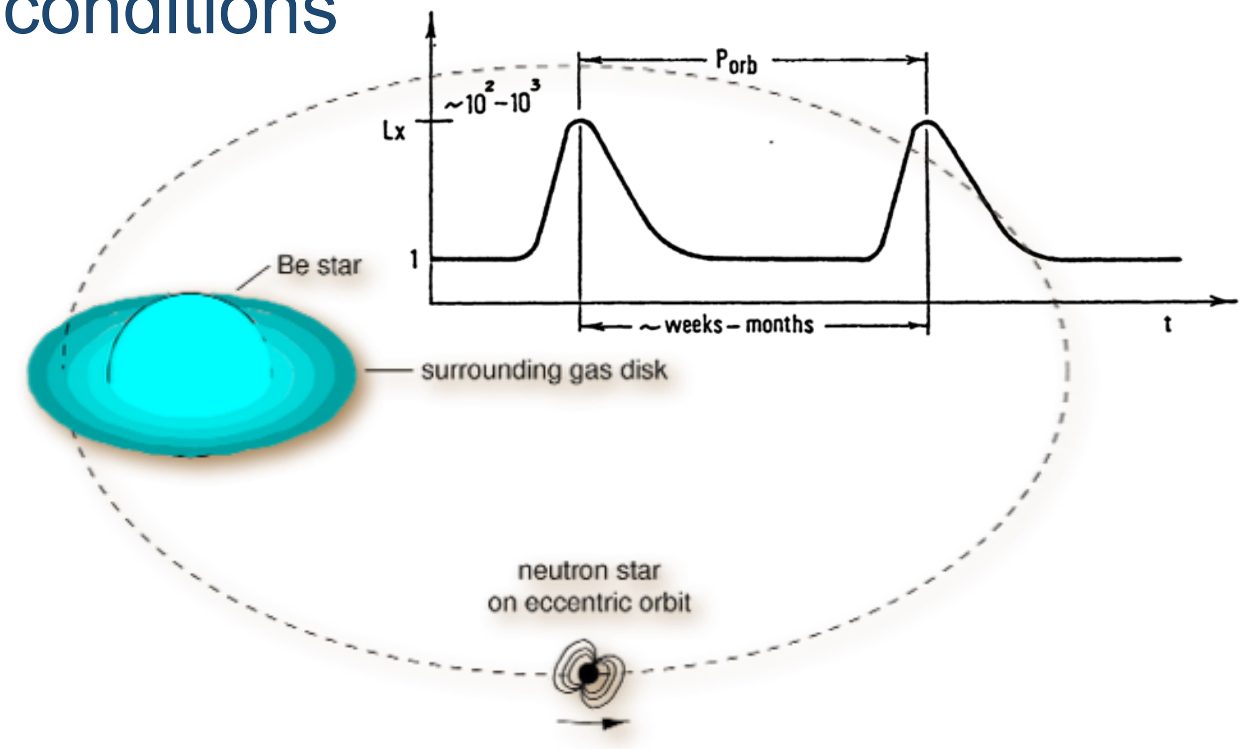
High B-field: an ubiquitous property

- High mass X-ray binaries are normally young systems, where NS has a high B-field (10^{12-13} G)



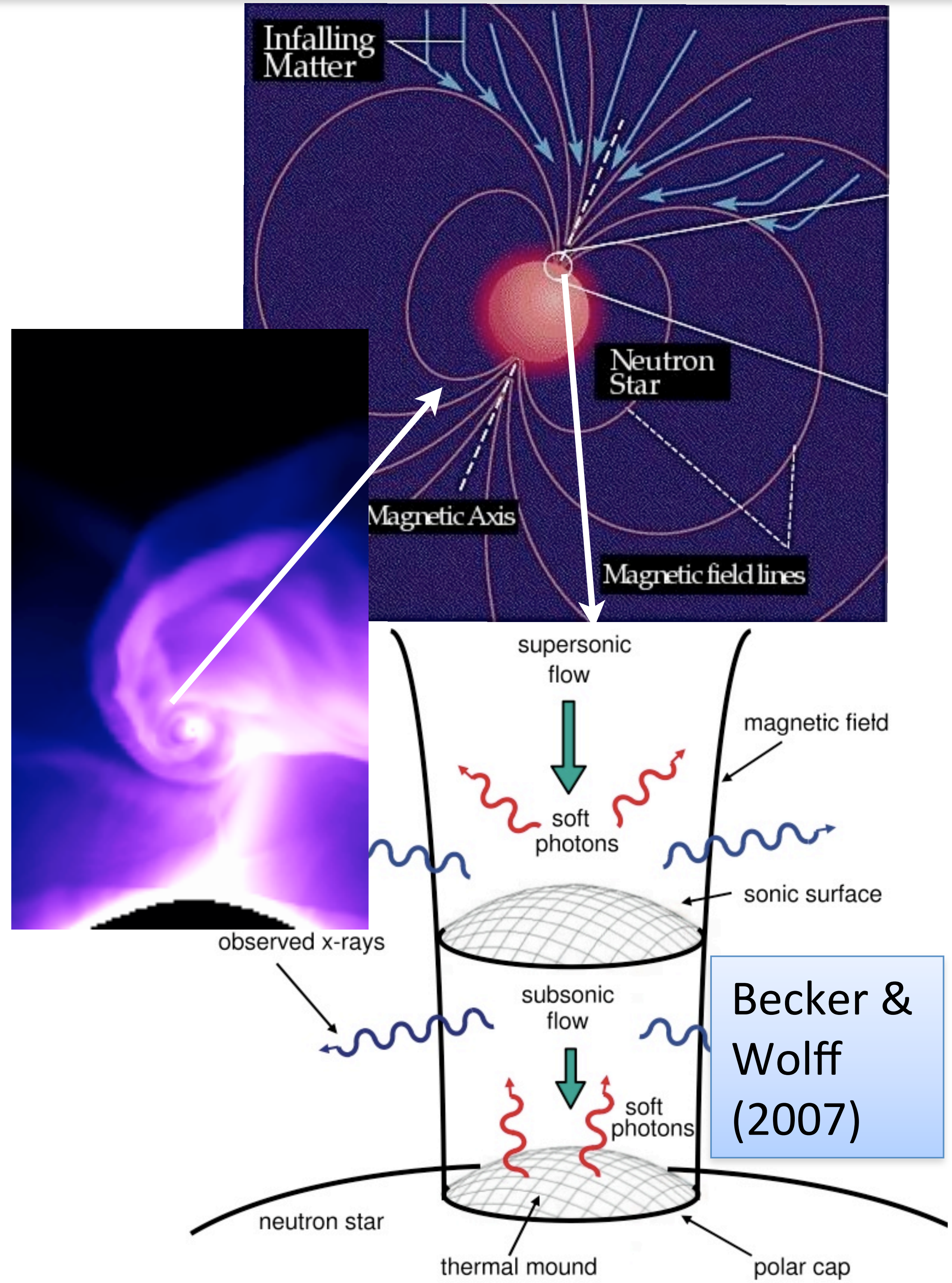
- Be/X-ray binaries become very bright during giant outbursts: an ideal laboratory for studying matter and radiation at extreme conditions



$$\frac{L_X^{outburst}}{L_X^{quiescence}} \sim 10^3$$

Introduction

- Accreting matter acquires a high kinetic energy v~c/2 which is eventually dissipated close to the compact object surface and emitted in the form of X and Gamma-rays.
- If the neutron star has a considerable magnetic field, accreting matter is trapped along the field lines and channeled to the magnetic poles
- For low accretion rates a hot spot is formed on the surface, for high accretion rates, radiation pressure dominates and a bright accretion column is formed.
- Photons originating in the thermal mound at the base and magnetic breemstrahlung in the column are Compton scattered and emitted from the column's surface.



Becker & Wolff (2007)

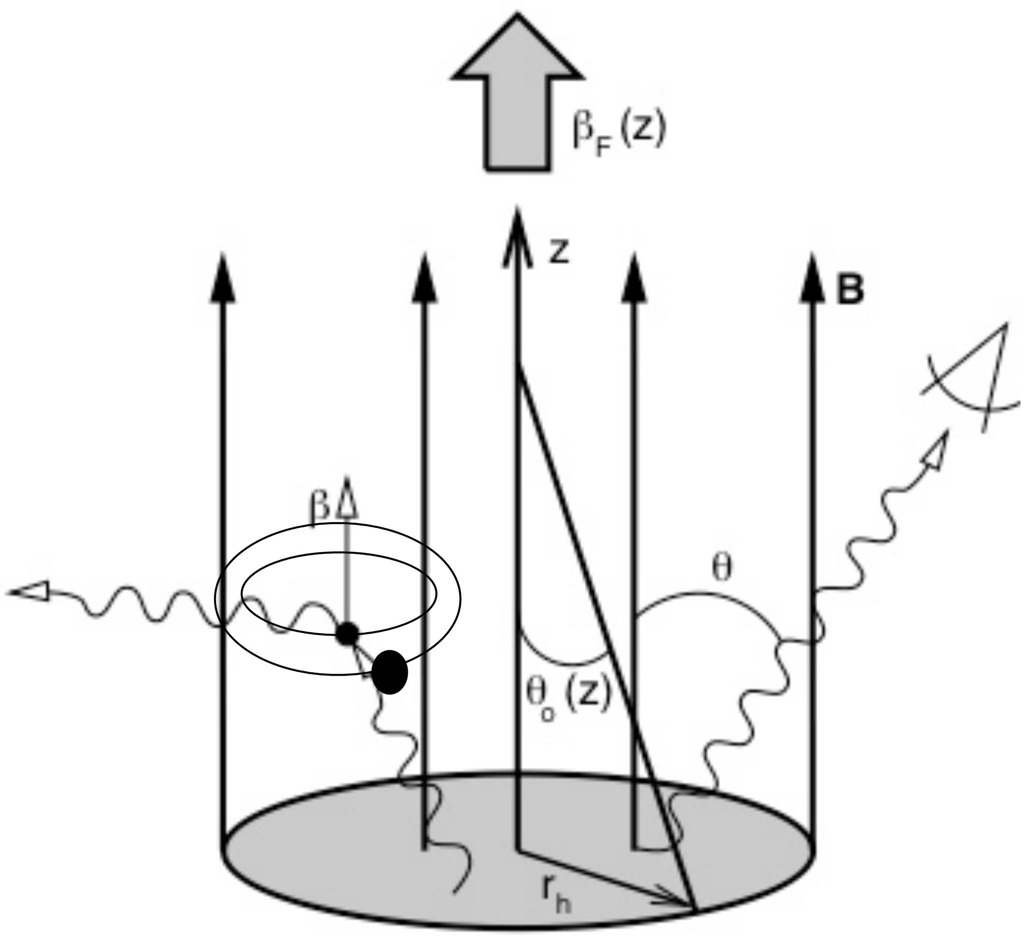
Cyclotron scattering absorption features

- Photon excite electrons to the first Landau level: broad absorption lines.
- B-field of $10^{12\text{-}13}$ G to be observed in the X-ray domain

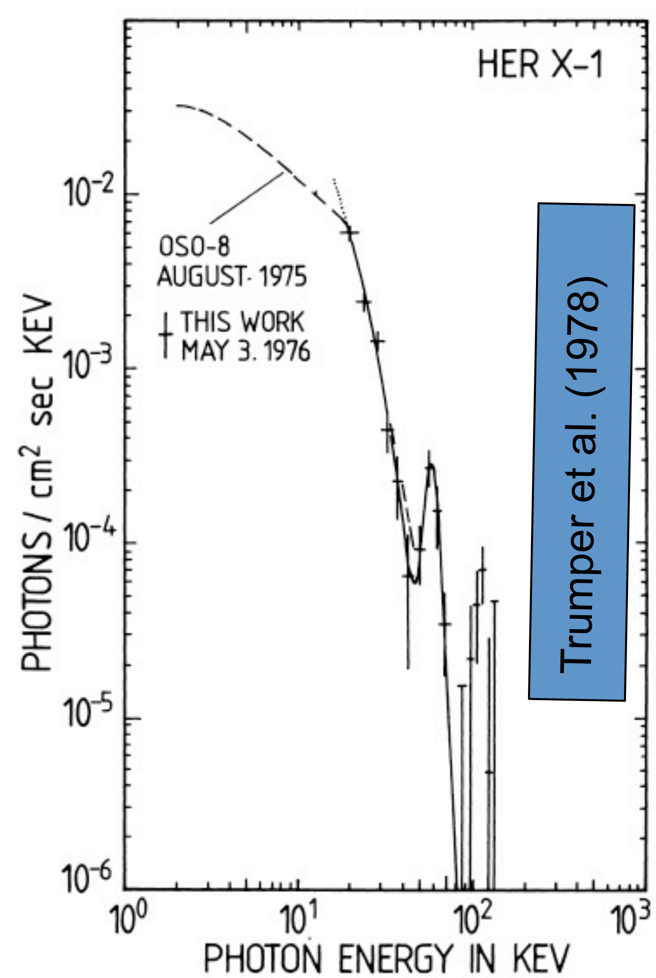
$$E_n = m_e c^2 \frac{\sqrt{1 + 2n(B/B_{\mathrm{crit}}) \sin^2\theta} - 1}{\sin^2\theta} \frac{1}{1+z},$$

B_{crit} → 4.4×10^{13}G

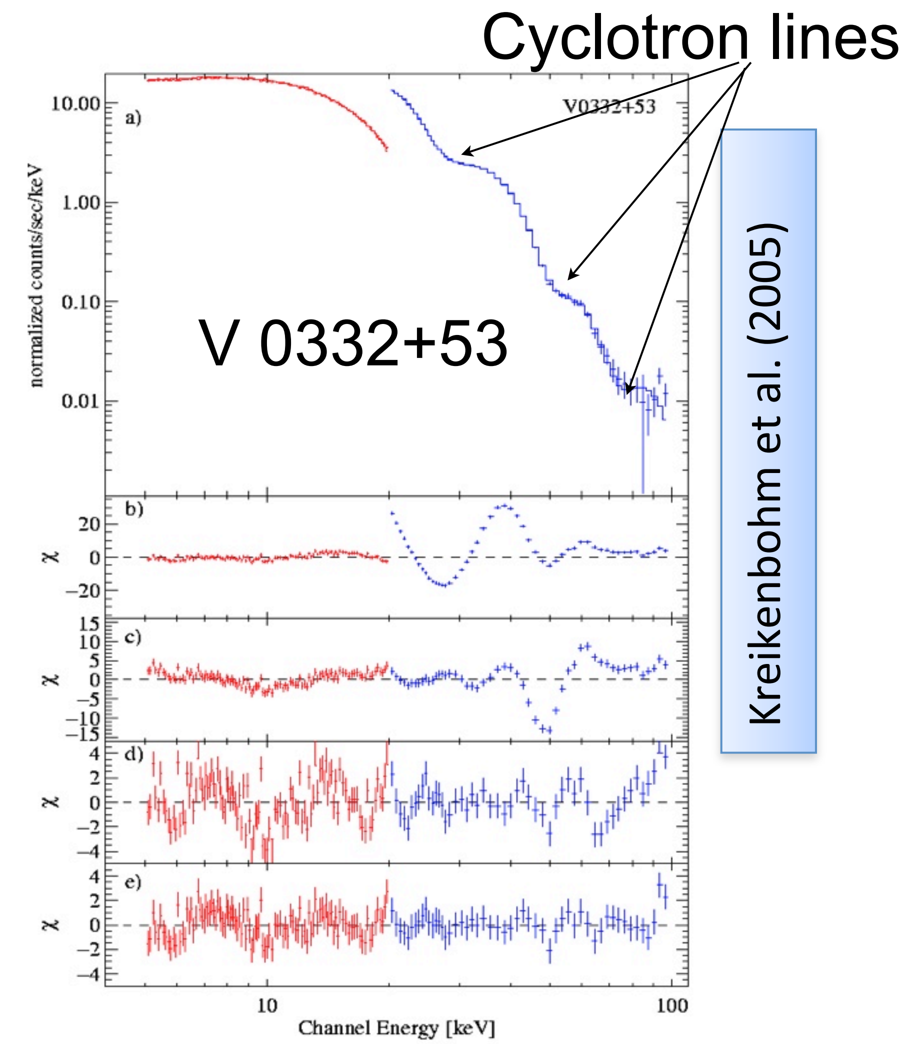
- Discovered in the spectrum of Her X-1 (Trumper 1977, 1978) and then in other 25 objects



Isenberg et al. (1998)



Trumper et al. (1978)

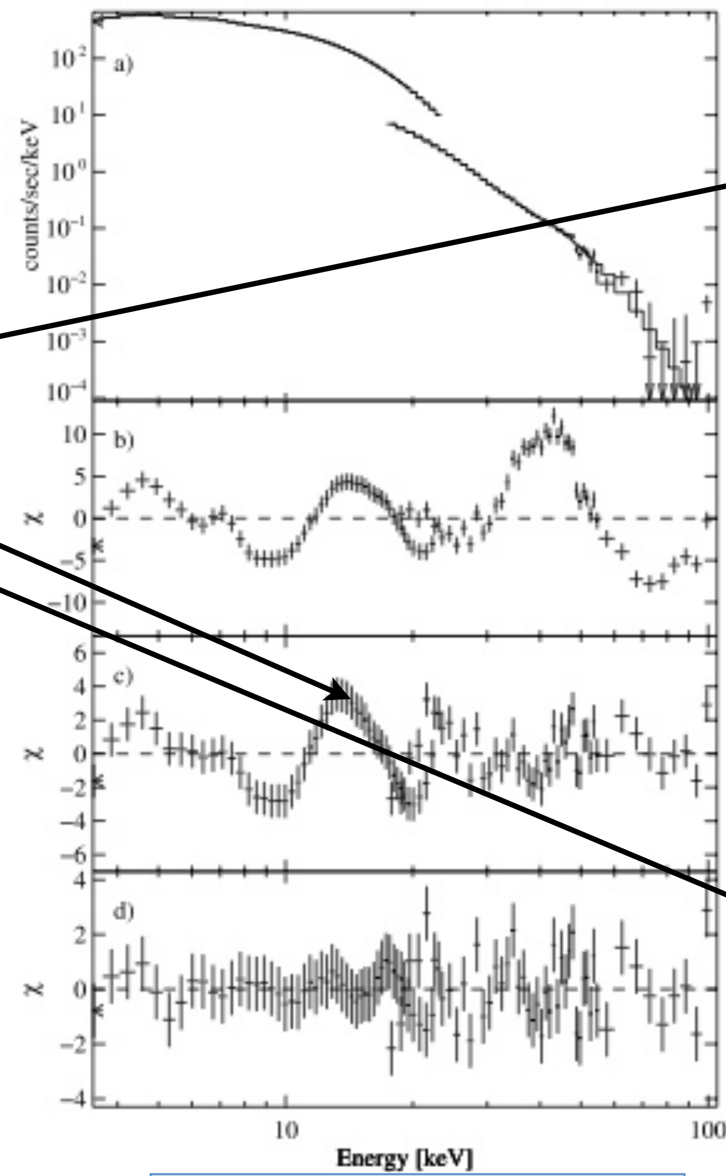


Kreikenbohm et al. (2005)

Rationale: what is the "10 keV bump"?

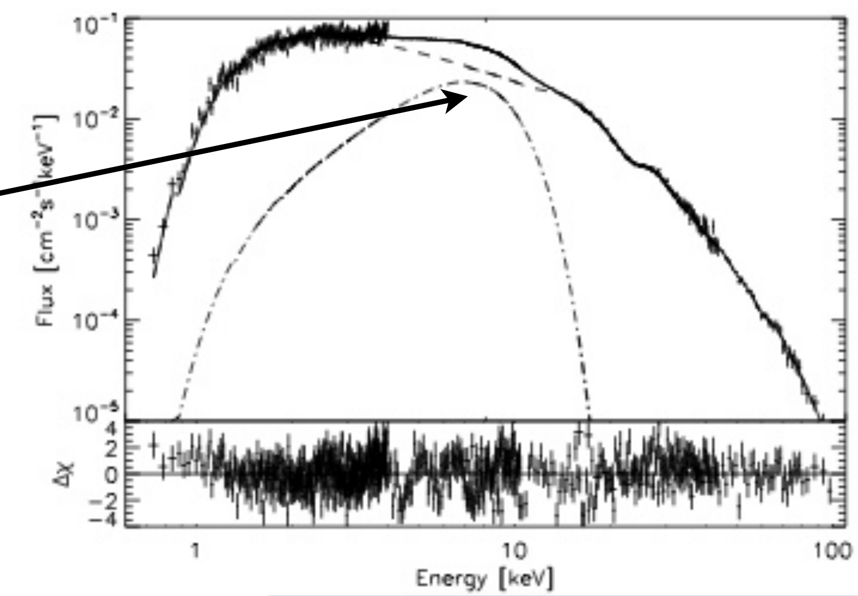
- Phenomenological power-law with many fashions of a high-energy cut-off and a puzzling "10-keV bump".

Cen X-3

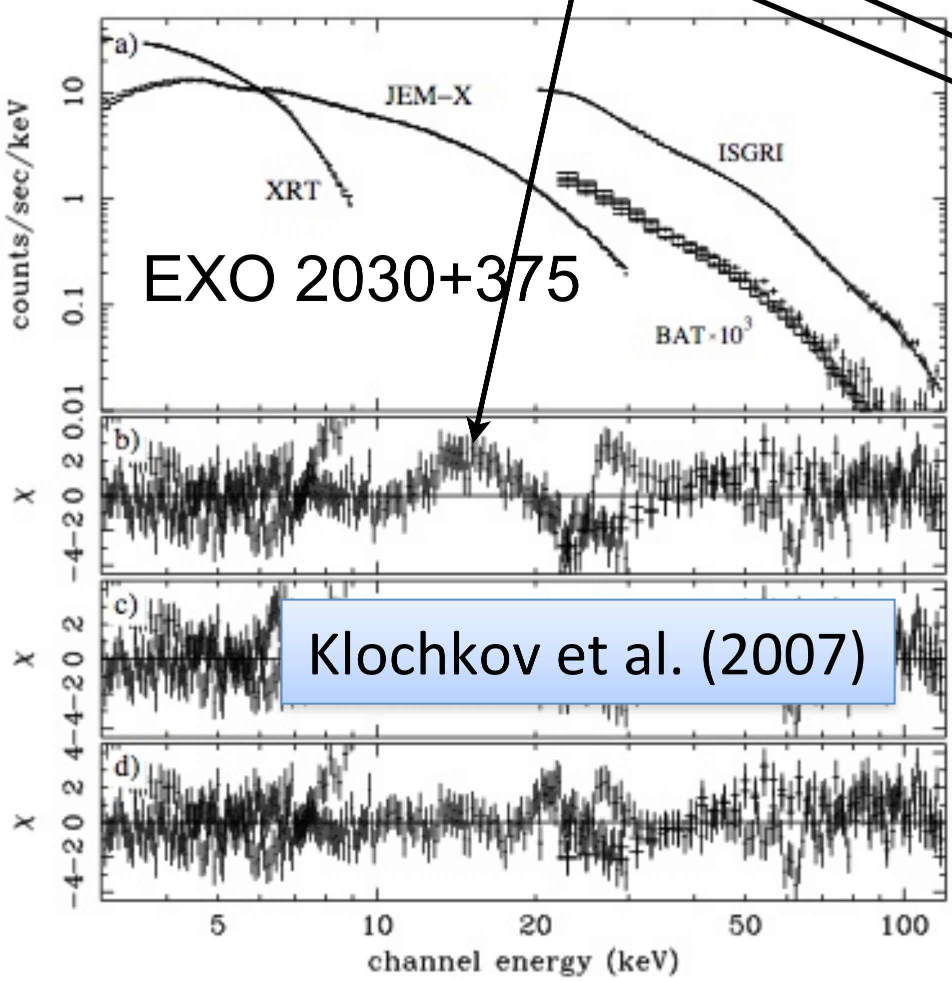


Suchy et al. (2008)

4U 0115+63

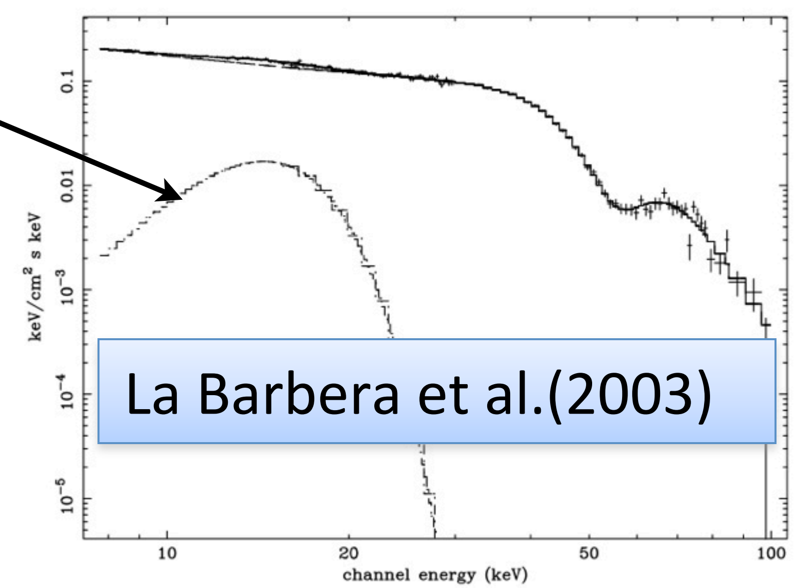


Ferrigno et al.(2009)



Klochkov et al. (2007)

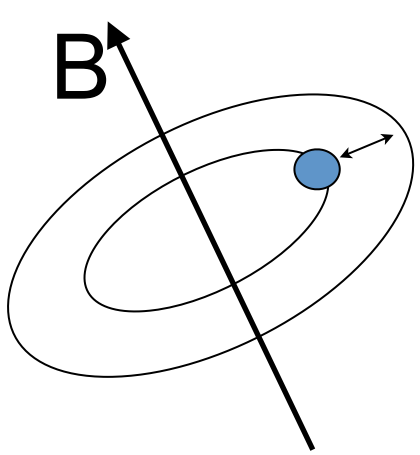
Vela X-1



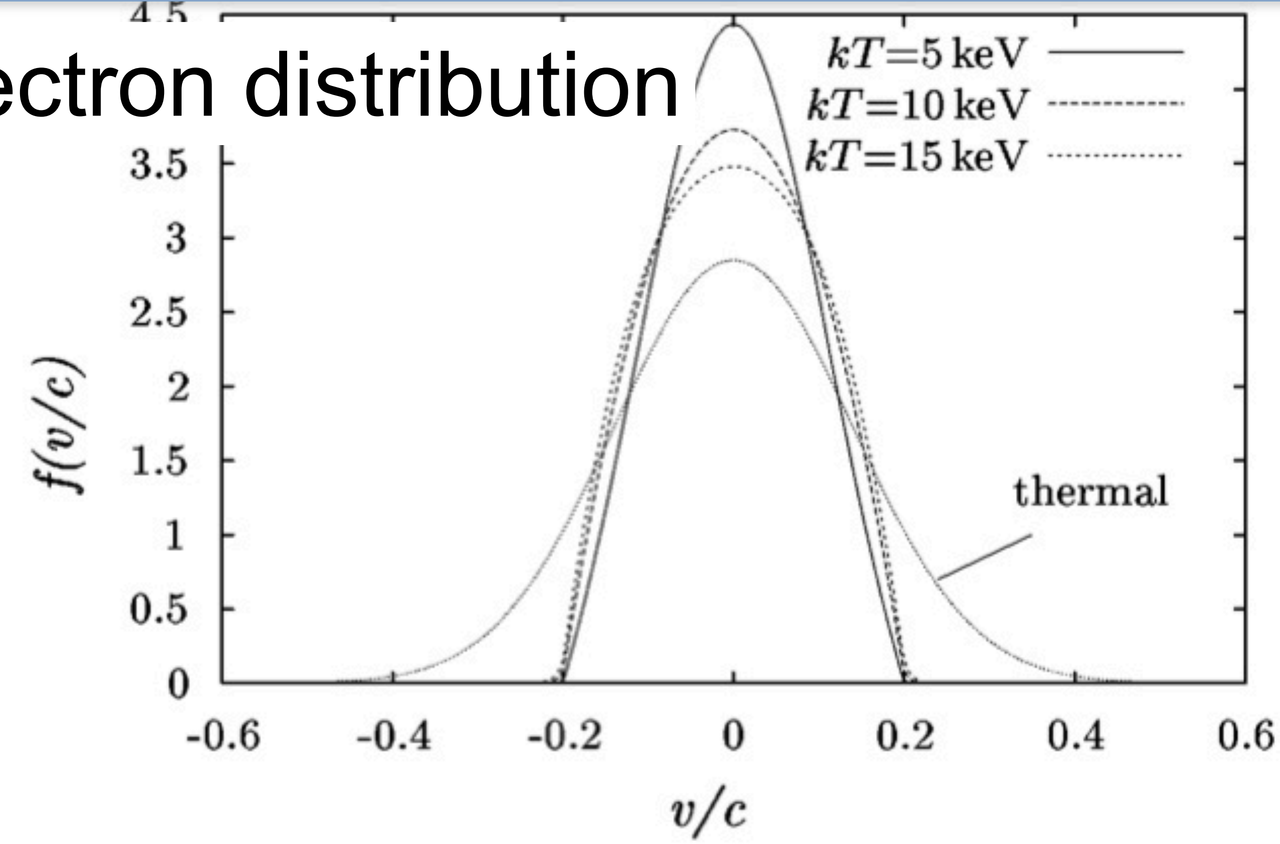
La Barbera et al.(2003)

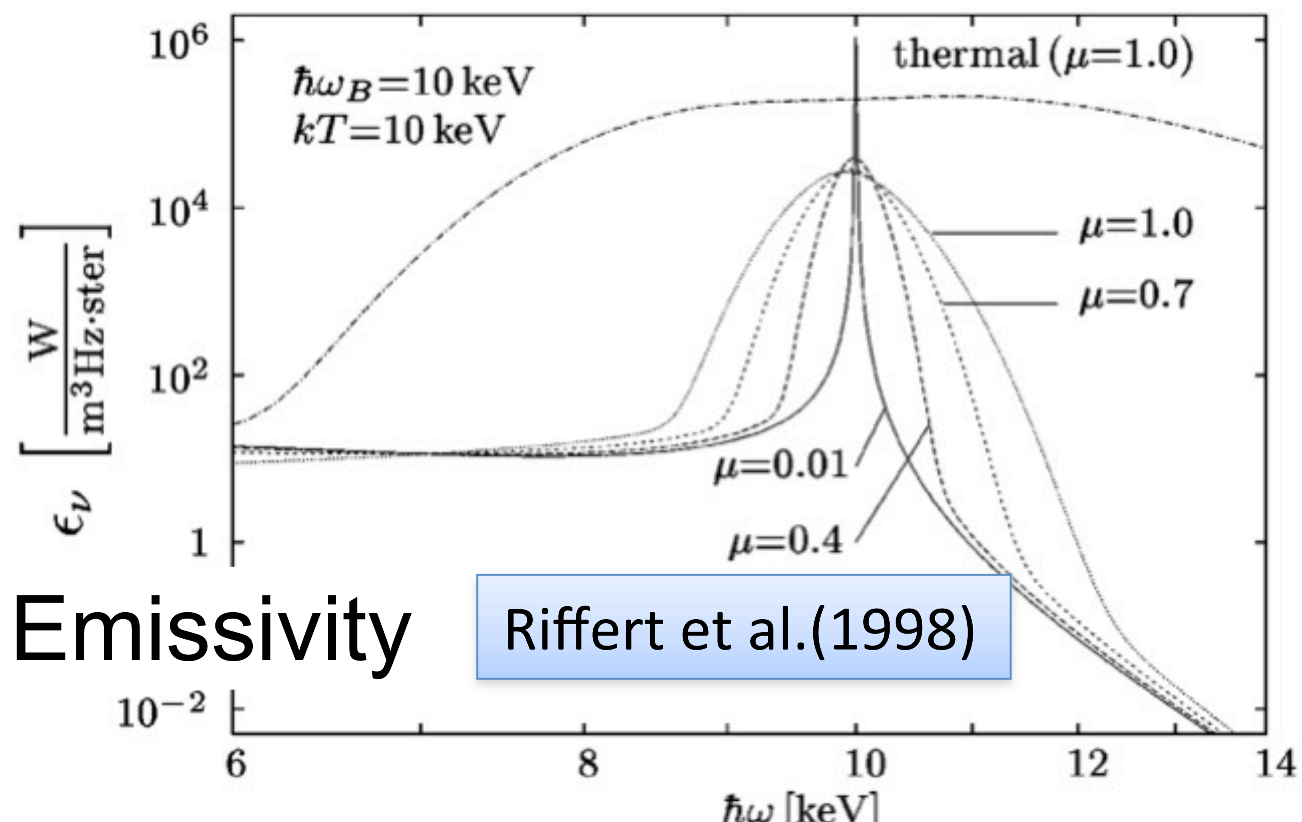
Electron emissivity in a strong magnetic field

- In a high B-field, thermal electrons do not have a Maxwellian distribution.
- High-energy depletion due to collisional excitation of the plasma's Landau levels.
- For an optically thin plasma, an angle dependent plasma emissivity can be derived.



Electron distribution





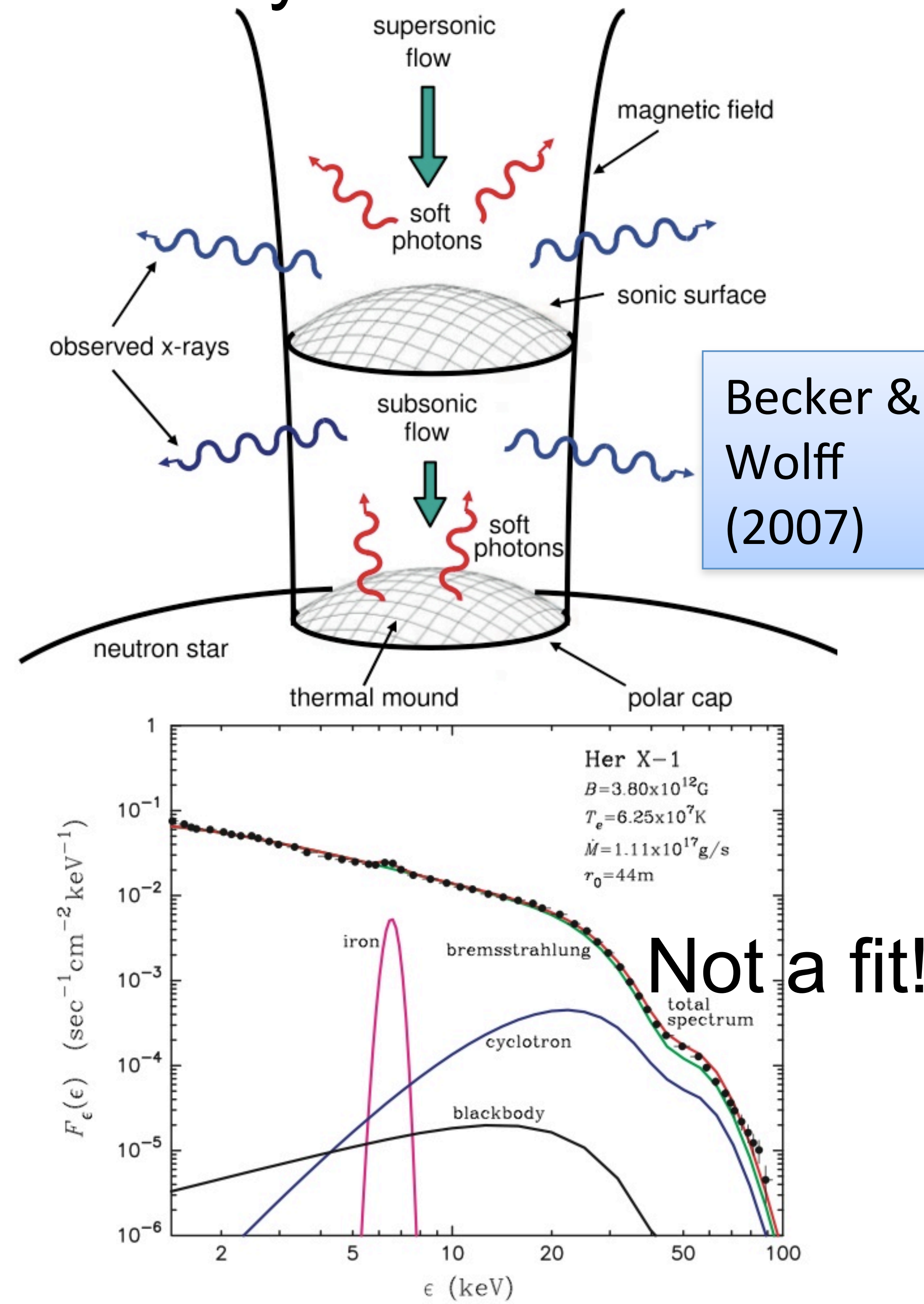
Emissivity

Riffert et al.(1998)

Continuum model: linearizing to simplify

- Correct solution would treat photons coupled to in-falling matter using angle and energy dependent cross sections.
- Problem can be factorized:
  – use an approximate velocity profile of in-falling matter
  – compute Green's functions of Compton up-scattering for isothermal plasma in cylindrical symmetry with simplified cross sections
  – model seed photons in dipolar magnetic field
- We compute a numerical solution to the radiation transfer equation.

An analytical solution



Becker & Wolff (2007)

Not a fit!

The new compMag model

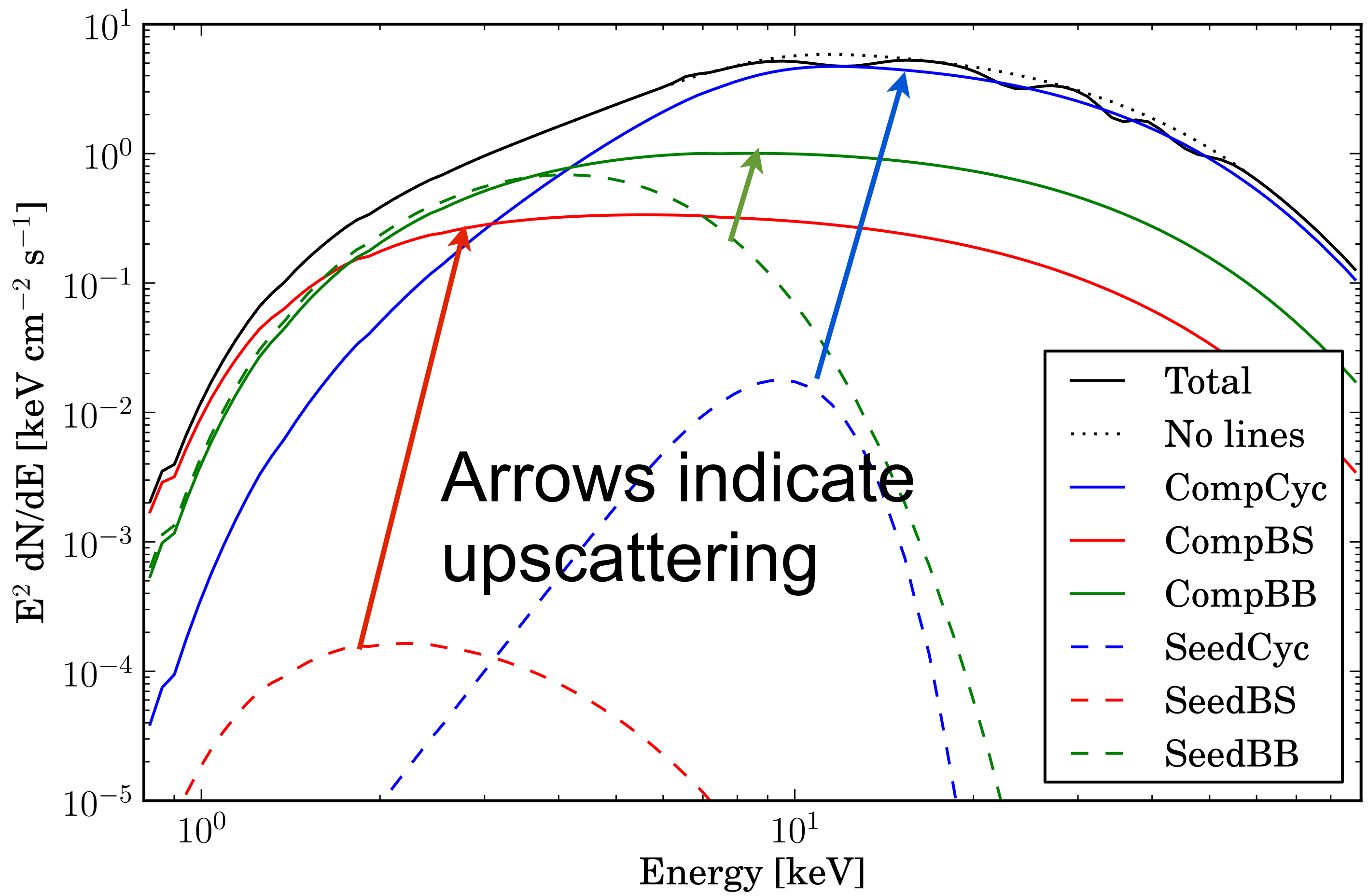
- Evolution of the compMag model available in Xspec (Farinelli et al. 2012)
- Seed photons: blackbody at the base; thermal breemstrahlung and Gaussian shaped line at *local* cyclotron energy to approximate plasma's emissivity in the column.
- Choose emission in fan beam (lateral surface) or pencil beam (top surface).
- Choose accelerated or decelerated velocity profiles

$$\beta(Z) = -\mathscr{A}(Z_s/Z)^{-\eta} \qquad \mathscr{A} = \beta_0(Z_0/Z_s)^{\eta}$$

- Very simplified cross section: parallel to B-field = 0.001 perpendicular to B-field

$$\frac{1}{c}\frac{\partial n}{\partial t} - j_{\rm bb}(x) - j_{\rm ff}(x) - j_{\rm cyc}(x) = -\frac{v}{c}\frac{\partial n}{\partial Z} + \frac{dv}{dZ}\frac{x}{3c}\frac{\partial n}{\partial x} + \frac{\partial}{\partial Z}\left(\frac{1}{3n_{\rm e}\sigma_{\parallel}}\frac{\partial n}{\partial Z}\right) - \frac{n}{t_{\rm esc}} + \frac{n_{\rm e}\overline{\sigma}\Theta}{x^2}\frac{\partial}{\partial x}\left[x^4\left(n + f_{\rm b}\frac{\partial n}{\partial x}\right)\right] + \frac{K_{\rm ff}(x)}{x^3}(e^{-x}-1)n, \qquad (1)$$

where $x = E/kT_{\rm e}c^2$, $\Theta = kT_{\rm e}/m_{\rm e}c^2$, $f_{\rm b} = 1 + m_{\rm e}v^2/3kT_{\rm e}$, $\sigma_{\parallel} = 10^{-3}\sigma_{\rm T}$, $\overline{\sigma} = 10^{-1}\sigma_{\rm T}$.

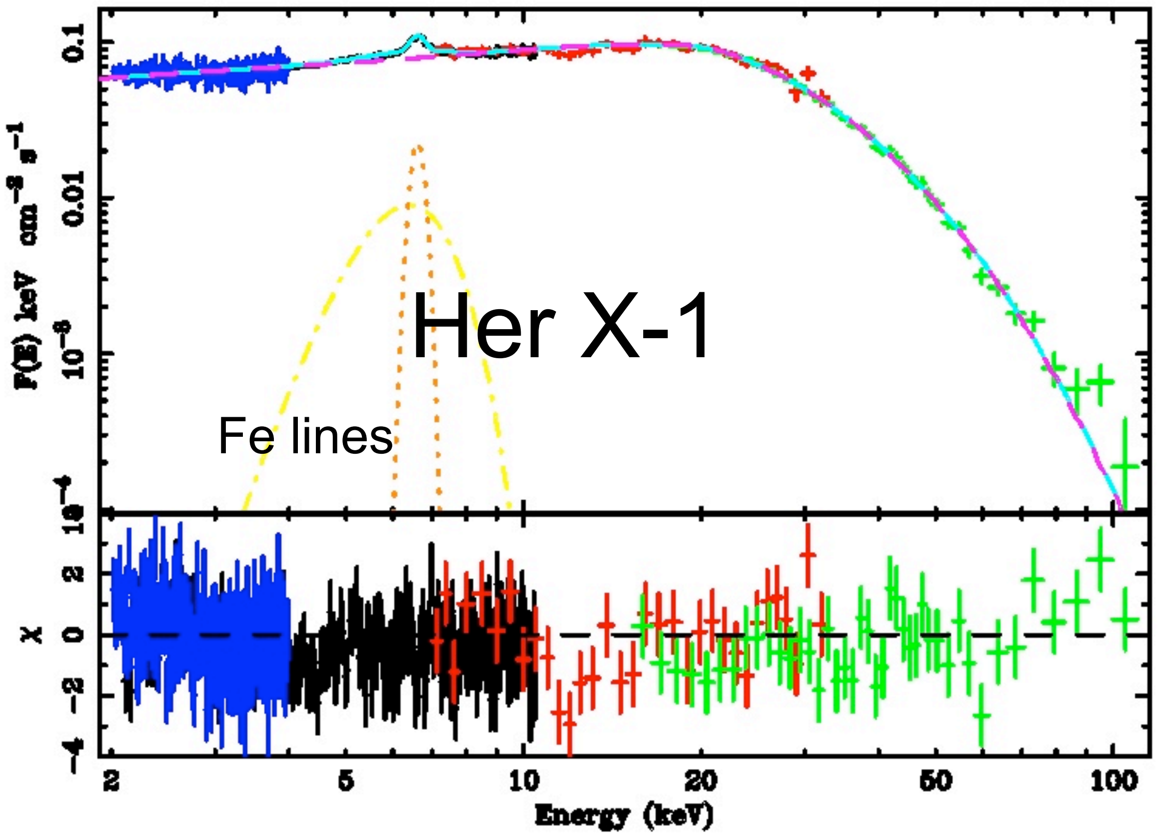


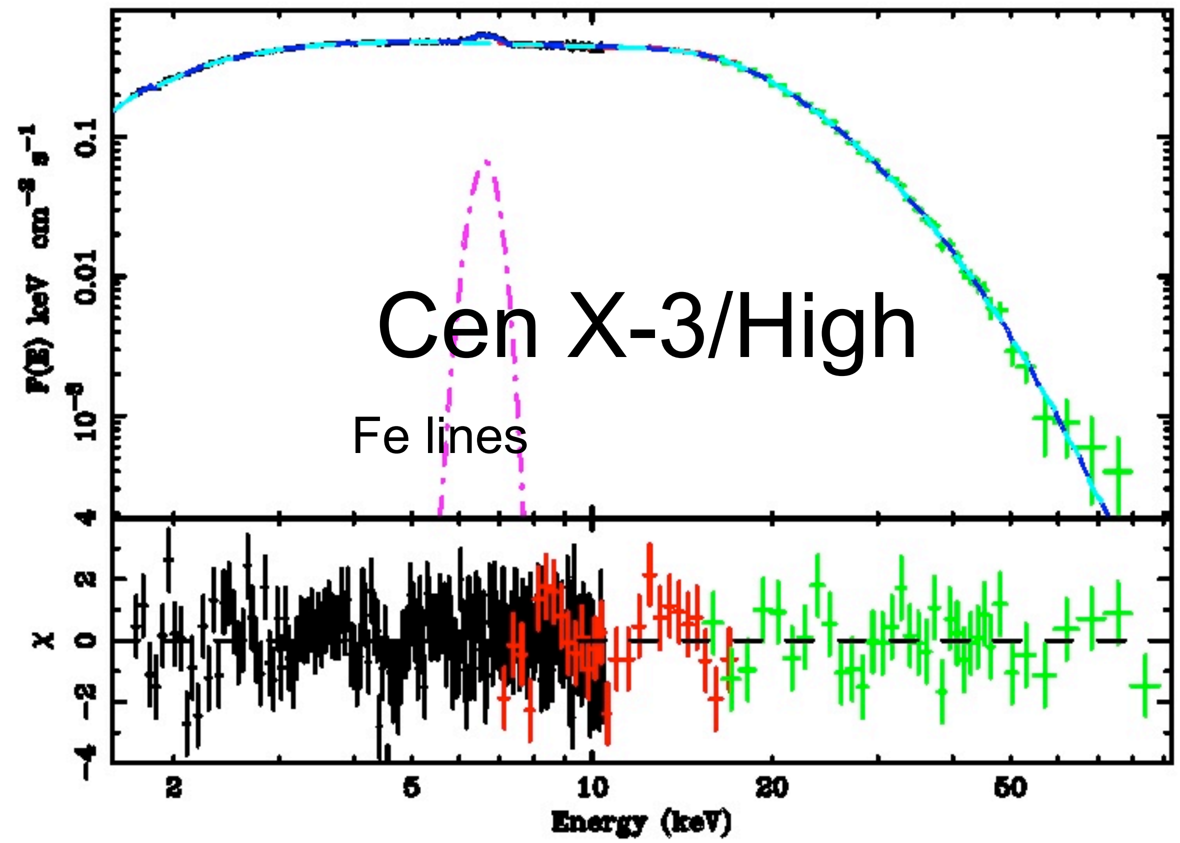
Model parameters (in this work)

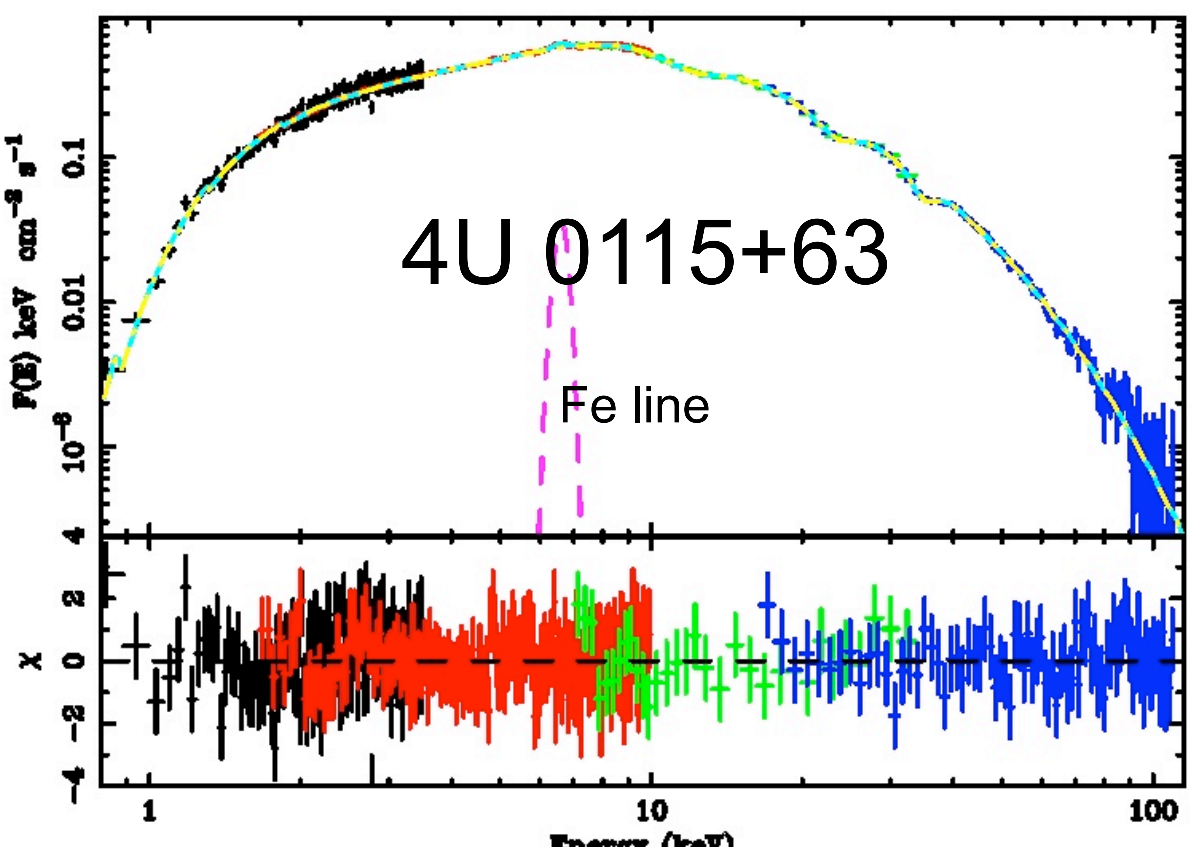
	Parameter	Units	Description
✔	$kT_{\rm bb}$	keV	Seed photon blackbody temperature
	BB flag		Blackbody seed emission present (=1) or absent (=0)
✔	$kT_{\rm e}$	keV	Electron temperature
✔	τ		Optical depth of the accretion column ⟶ $\dot{M}$
	η =0.5		Index of the velocity profile
✔	$\beta_{\rm max}$		Terminal velocity at the NS surface
✔	r_0	km	Radius of the accretion column
✔	$z_{\rm max}$	$R_{\rm S}$	Height of the accretion column
	Velocity flag		Accelerating (=1) or decelerating (=2) velocity profile
✔ (linked)	B_{12}	10^{12} G	Magnetic field at the NS surface
✔	$\sigma_{\rm cyc}$	keV	Width of the cyclotron gaussian emission feature
	Cyclotron flag		Cyclotron seed emission present (=1) or absent (=0)
	bremsstrahlung flag		bremsstrahlung seed emission present (=1) or absent (=0)
	A = 1		Albedo at the NS surface
	N		Normalization ($D_{10\,\rm kpc}^{-2}\times$beaming)

- ✔ Fitted
- ✔ Linked

Application to famous sources

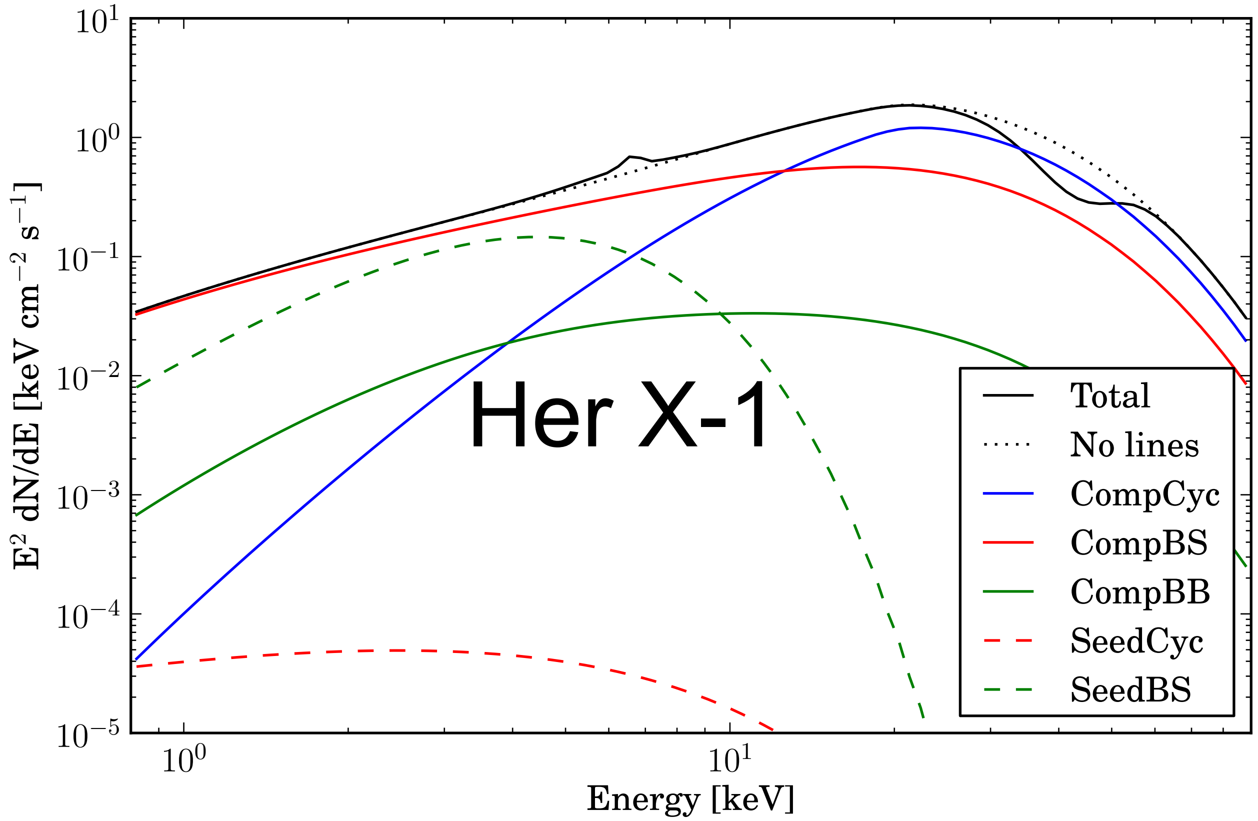


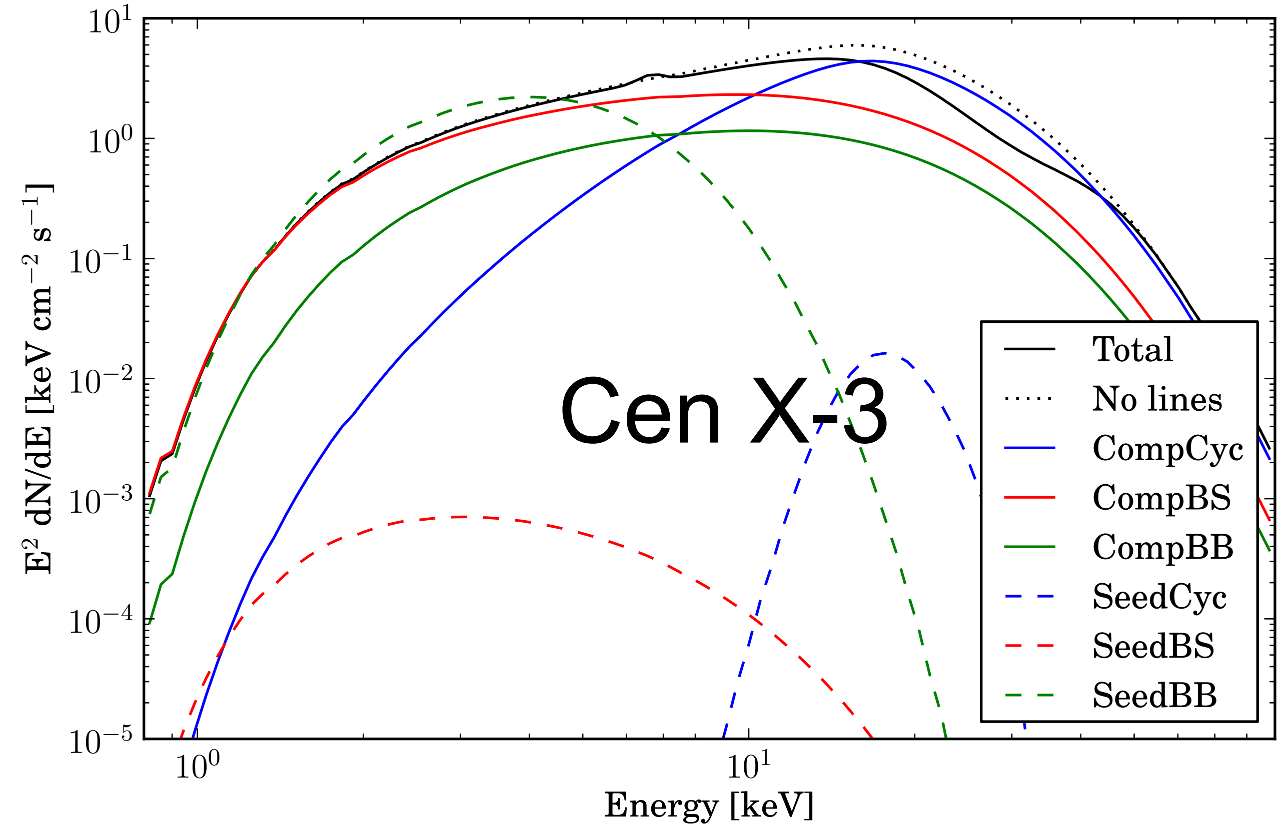


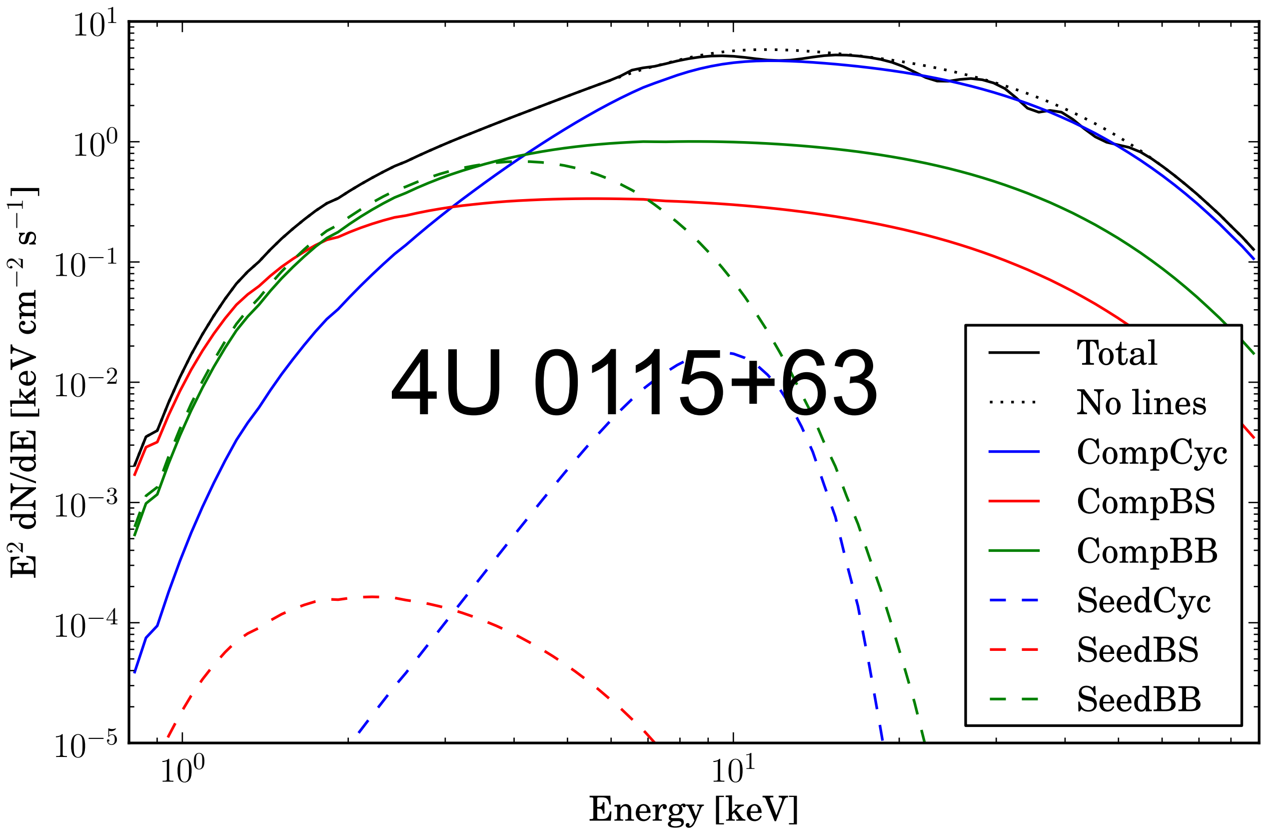


- Accelerated profile
- Fan beam
- Model derived accretion rate is kept similar to the one computed from bolometric flux
- Cyclotron absorption features produced near the NS surface

The decomposition







- Absorption lines are local
- Comptonized cyclotron emission dominates at high energy and explains the "10-keV bump"
- BS important in Her X-1 and Cen X-3, BB in 4U 0115

Some parameters

Her X-1

E_{cyc} = 42.5 ± 0.4 keV

kT_{bb} = 1.1 ± 0.1 keV
kT_e = 3.8 ± 0.1 keV
τ = $2.2018^{+0.27}_{-0.05}$
β_{max} = $0.1312^{+0.0034}_{-0.0014}$
r_0 = $0.0519^{+0.0004}_{-0.0062}$ km
H = $2.72^{+0.03}_{-0.12}$ km
$\dot{M}$ = 0.032 ± 0.008
χ^2 / d.o.f. = 1.061/426

Cen X-3

E_{cyc} = 28.5 ± 0.3 keV

kT_{bb} = 0.95 ± 0.03 keV
kT_e = $2.51^{+0.18}_{-0.03}$ keV
τ = $1.38^{+1.08}_{-0.05}$
β_{max} = $0.097^{+0.0025}_{-0.0042}$
r_0 = 0.25 ± 0.01 km
H = $2.20^{+0.08}_{-0.04}$ km
$\dot{M}$ = $0.43^{+0.40}_{-0.09}$
σ_B = 0.7 ± 0.1 keV
χ^2 / d.o.f. 1.212/237

4U 0115+63

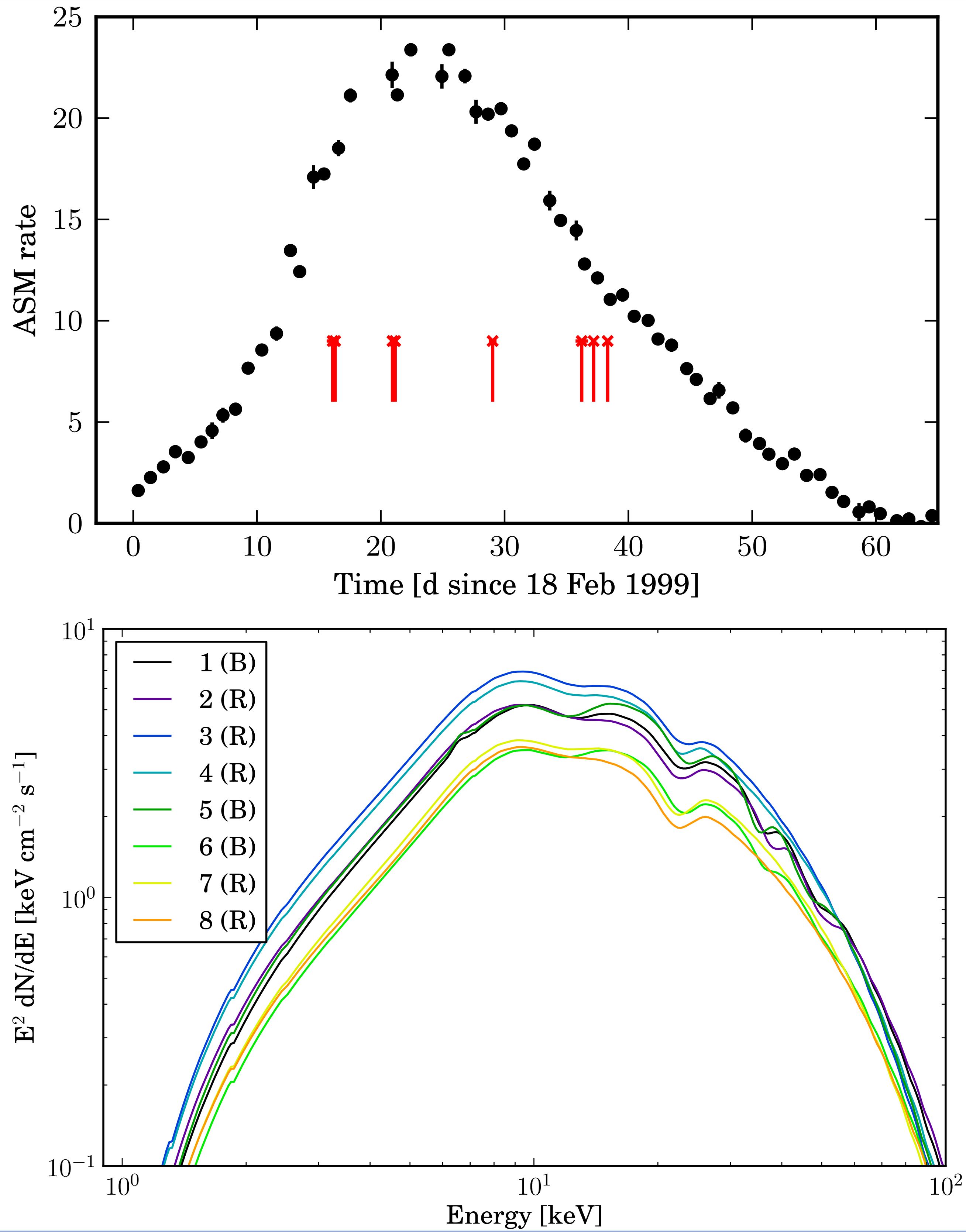
$E1_{cyc}$ = 11.98 ± 0.13 keV
$E2_{cyc}$ = 23.3 ± 0.2 keV
$E3_{cyc}$ = 34.9 ± 0.4 keV
$E4_{cyc}$ = 46.0 ± 0.9 keV

kT_{bb} = 0.99 ± 0.08 keV
kT_e = 1.30 ± 0.06
τ = 0.41 ± 0.04
β_{max} = $0.220^{+0.006}_{-0.003}$
r_0 = 0.30 ± 0.03 km
H = 1.6 ± 0.1 km
$\dot{M}$ = 0.6 ± 0.3
σ_B = 1.6 ± 0.2 keV
χ^2 / d.o.f. = 0.797/434

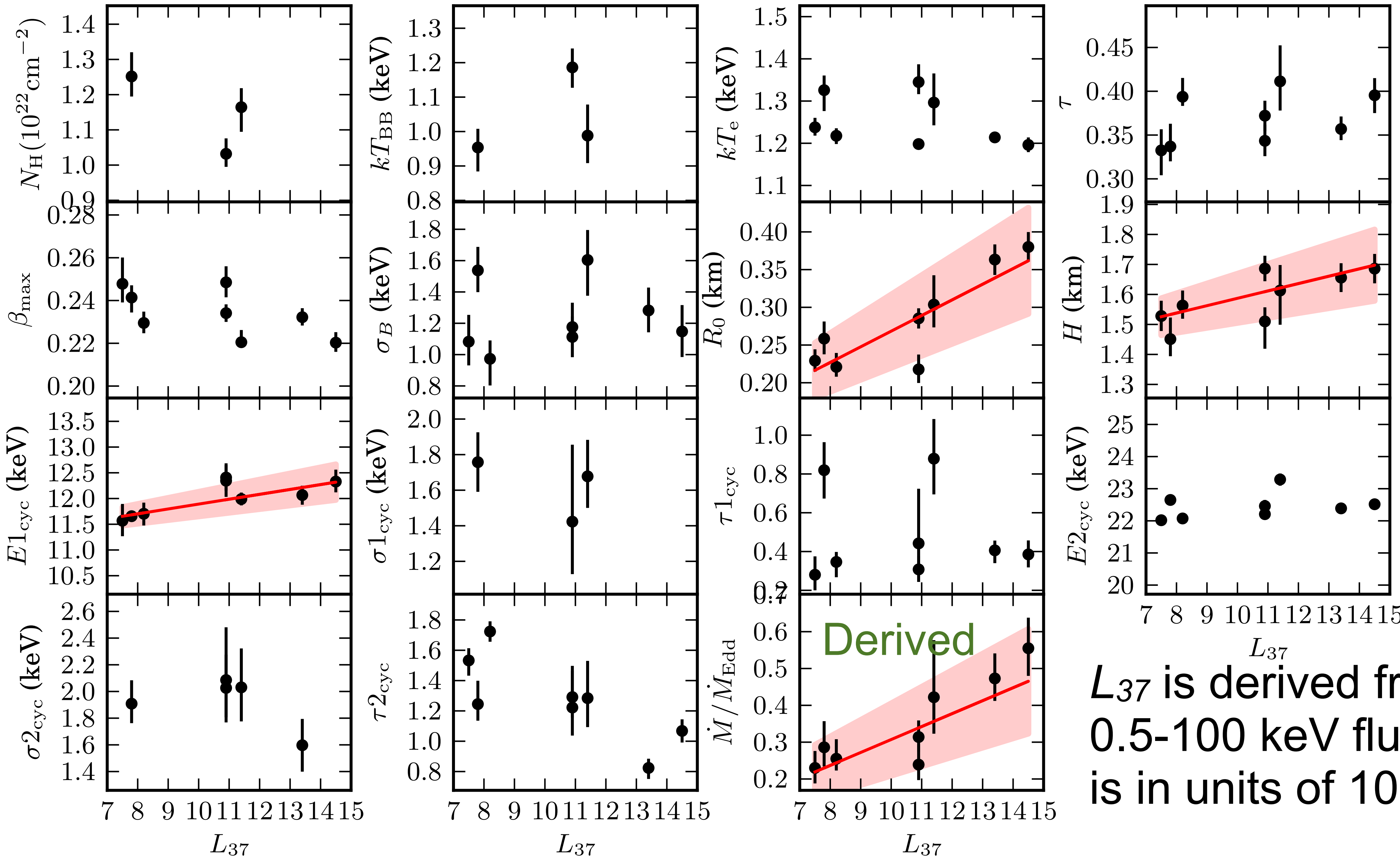
- B and T_e correlate because cyclotron emission cools the plasma
- Radius scales with Luminosity
- H scales with the the 'bump' energy and luminosity
- Relatively Slow flow

During the outburst

- Temporal sequence of different observations of 4U0115+63.
- Search of long and broad-band observations with good outburst coverage (B=BeppoSAX, R=RXTE)
- $B_{12} = E2_{cyc}/23.14$



Parameters (preliminary)



L_{37} is derived from 0.5-100 keV flux and is in units of 10^{37} erg/s

- Only significant linear trends are shown

Conclusions

- Self consistent model for column's emission which describes the emission from X-ray binary pulsars with high magnetic fields using physical quantities.
- Successfully applied to different objects and to different states of one source ... so far.
- Computationally intensive, need to have good S/N spectra with broad energy coverage to constrain parameters.
- Number of parameters is similar to the most complex phenomenological models, so it is not over-fitting.

- Test more extensively different configurations (beaming/profile)
- To apply this model to other datasets including nuSTAR and ASTRO-H.
- This model will go into the Xspec distribution.

The Compmag normalization

Adimensional flux in the Eddington approximation (Blandford & Payne 1981)

$$F(x,\tau) = -\frac{x^3}{3}\left(\frac{\partial N}{\partial \tau} + \beta_\tau \frac{\partial N}{\partial x}\right)$$

where N(x, τ) is the zero-moment occupation number of the photon field

The conversion factor to physical units for the average intensity

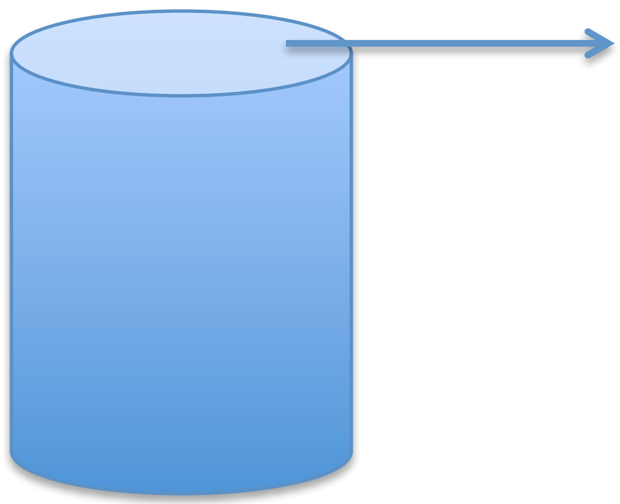
$$J(E,\tau) \approx \pi 10^{31} kTe^3 x^3 N(x,\tau) \text{ keV cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \text{ ster}^{-1}$$

$$N_{\text{model}} = \frac{\int F(E,\tau)\, dS}{4\pi D^2}$$

with integration extended over the emitting surface

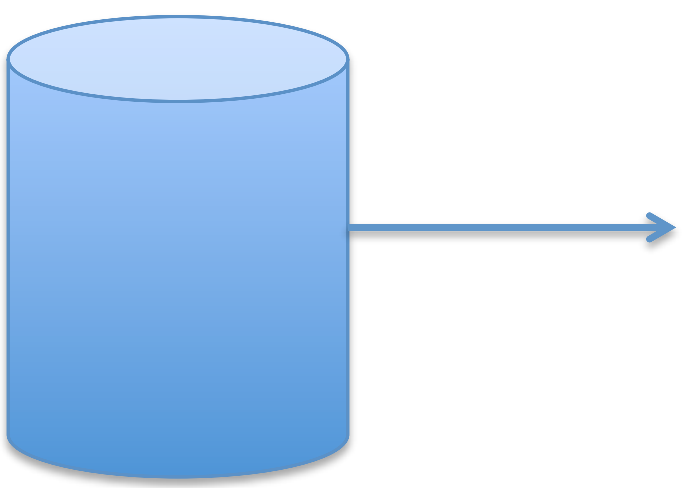
Geometry

Pencil beam



$$F_{tot}(E) = \pi R_0^2 F(E,\tau_0)$$

Fan beam



$$F_{tot}(E) = 2\pi R_0 \int_0^{\tau_0} \pi J(E,\tau) \frac{dz}{d\tau}\, d\tau$$

Because the model does not compute radial gradient, the uniform brightness approximation for the flux through the columns walls is used (Ribycki & Lightman 1979)

$$F(E,\tau) = \pi J(E,\tau) \ \ \mathrm{keV\ cm^{-2}\ s^{-1}\ keV^{-1}}$$