Broadband Spectra of Accreting Neutron Stars

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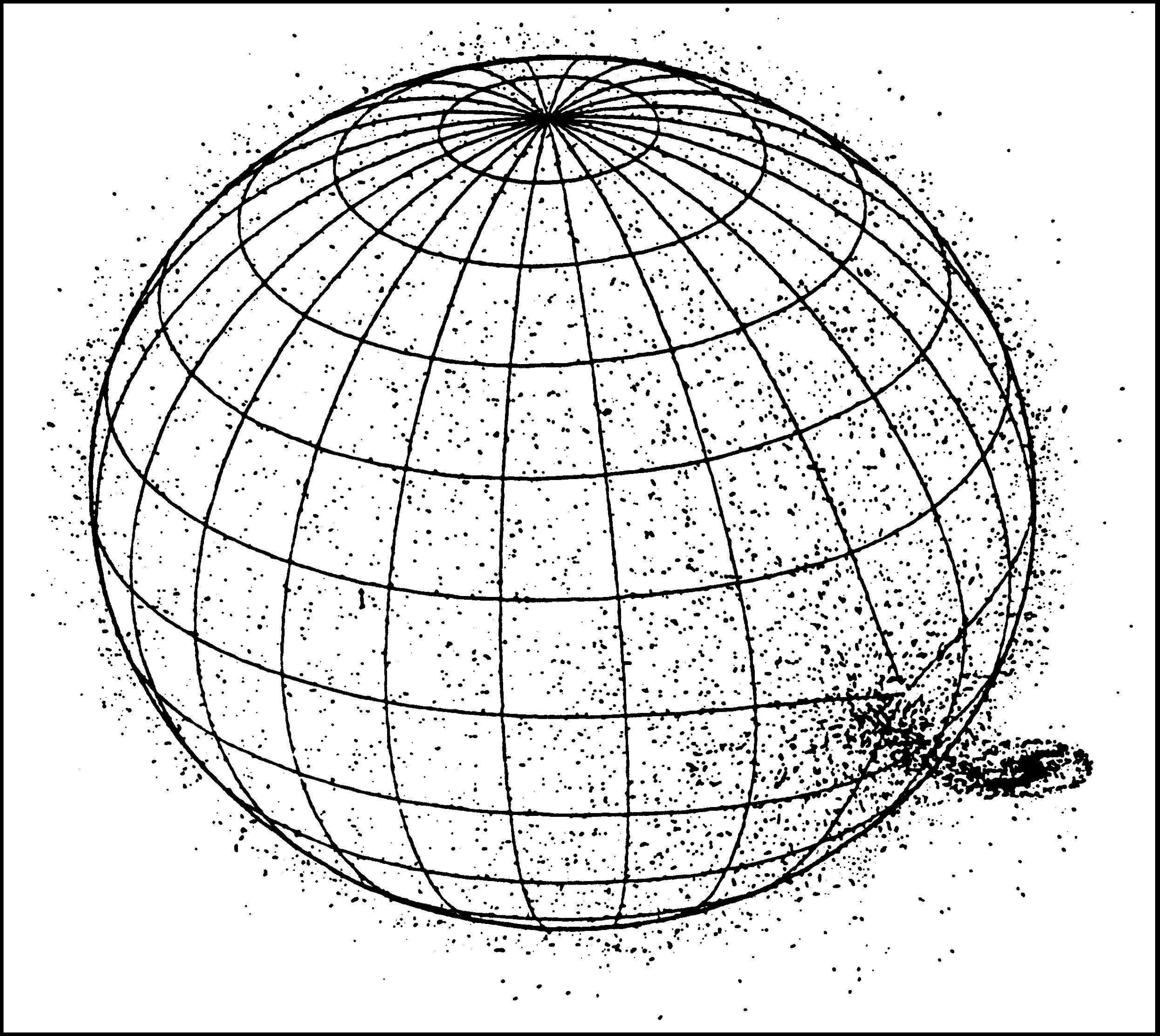
Structure of this talk:

- Accretion on Neutron Star X-Ray Binaries
  - Magnetized Neutron Stars
- Cyclotron Resonance Scattering Features (*vulgo:* Cyclotron Lines)
  - Landau Levels
  - Physics of line formation
  - Observations
- Summary

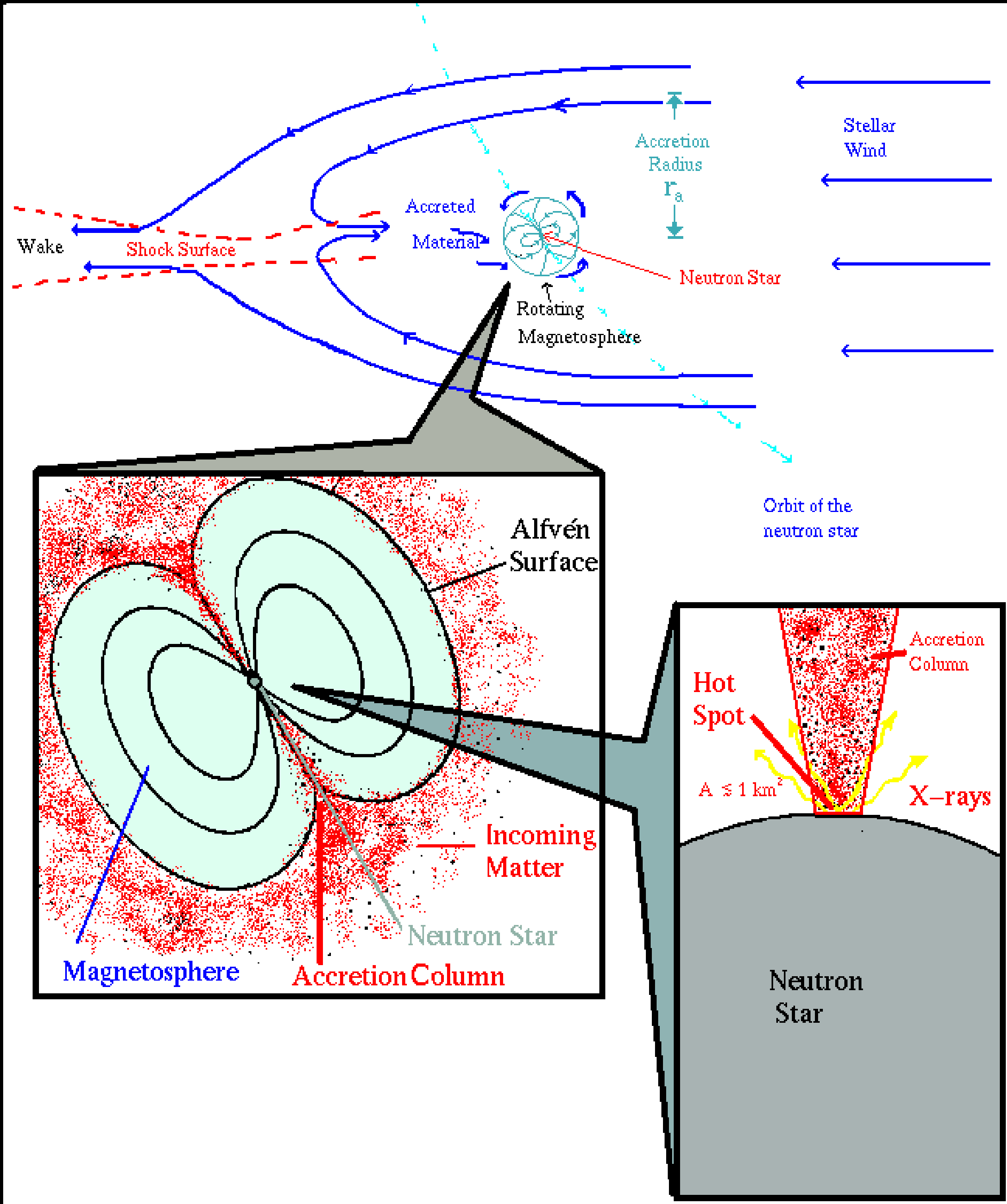


(SMC X-1; Dennerl, Dissertation MPE)

X-ray binary: neutron star accretes mass from donor star

- Low Mass X-ray Binaries (LMXB): donor late type
  $\Longrightarrow$ mainly old systems, low B
- High Mass X-ray Binaries (HMXB): donor early type
  $\Longrightarrow$ young systems, high B

I will concentrate on strongly magnetized neutron stars.



Accreting plasma couples to B-field at Alfvén radius

$$r_{\rm mag} = \left(\frac{8\pi^2}{G}\right)^{1/7} \left(\frac{R_\star^{12} B_{\rm p}^4}{M \dot{M}^2}\right)^{1/7}$$

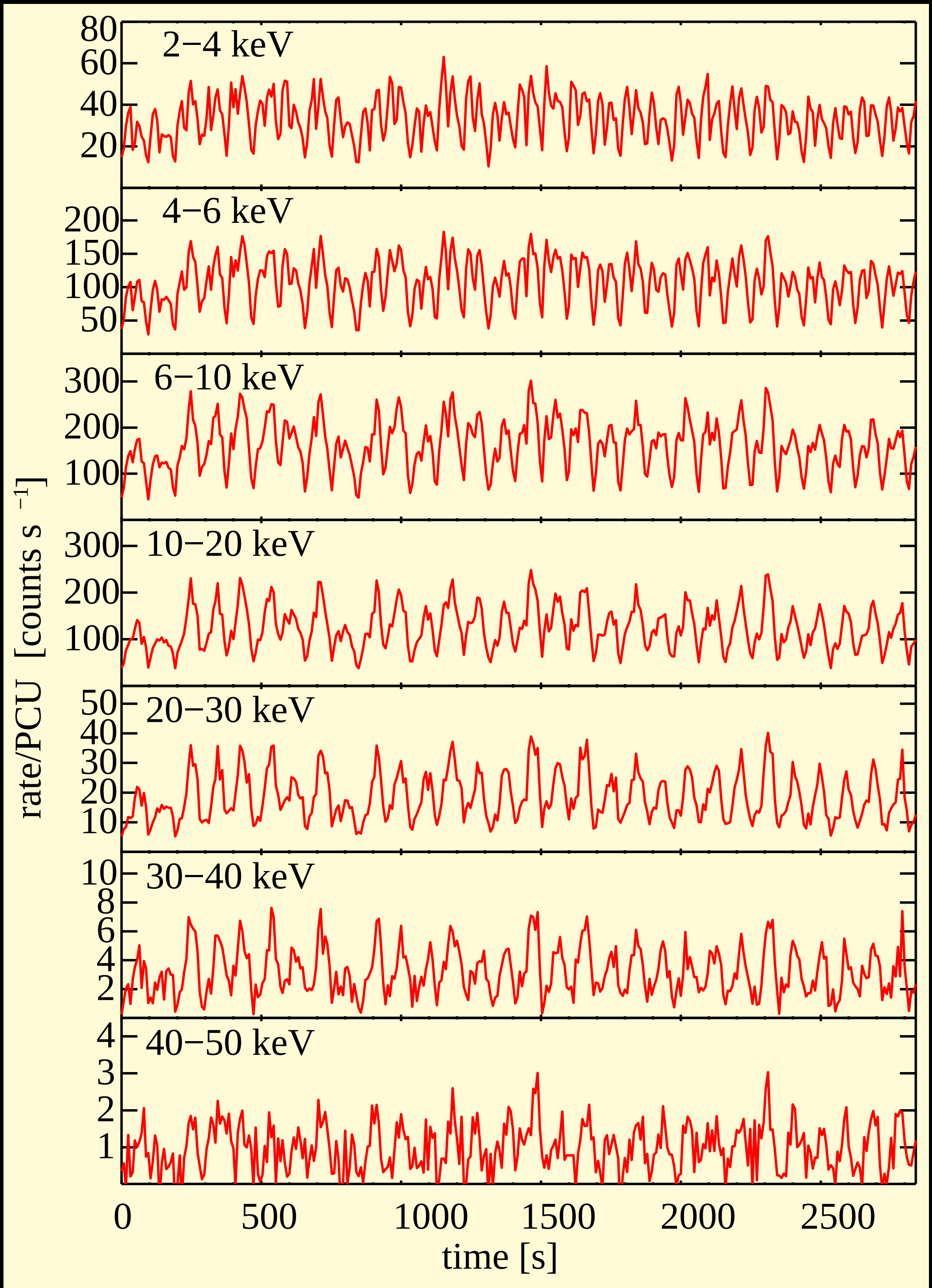
For typical neutron star parameters ($1.44\,M_\odot$, $B \sim 10^{12}$ G): $r_{\rm mag} \sim 1800$ km.

Typical parameters of accretion column:

- $\dot{M} \sim 10^{-9\ldots-11}\,{\rm M}_\odot\,{\rm yr}^{-1}$
- $v \sim 0.7\,c$

Useless number of the day: $10^{-9}\,M_\odot\,{\rm yr}^{-1} \sim 6 \times 10^{13}\,{\rm kg\,s}^{-1}$, or $\sim 2.6 \times 10^6$ flow rate of Ganges during June–Oct.

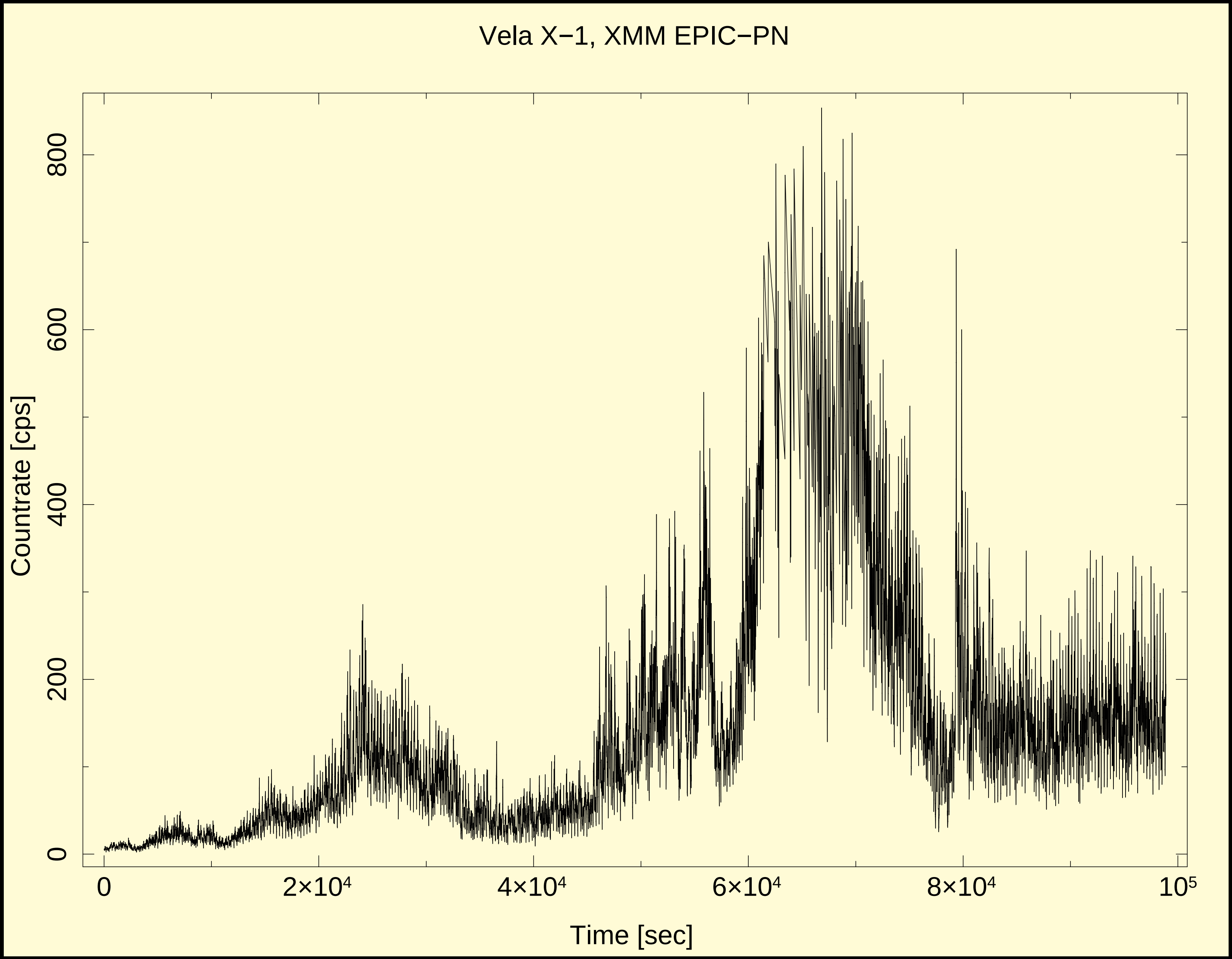
I. Negueruela
(after Davidson & Ostriker, 1973)



Lighttower effect: X-ray pulsars

Pulse period evolution allows to study coupling between B-field and accretion stream

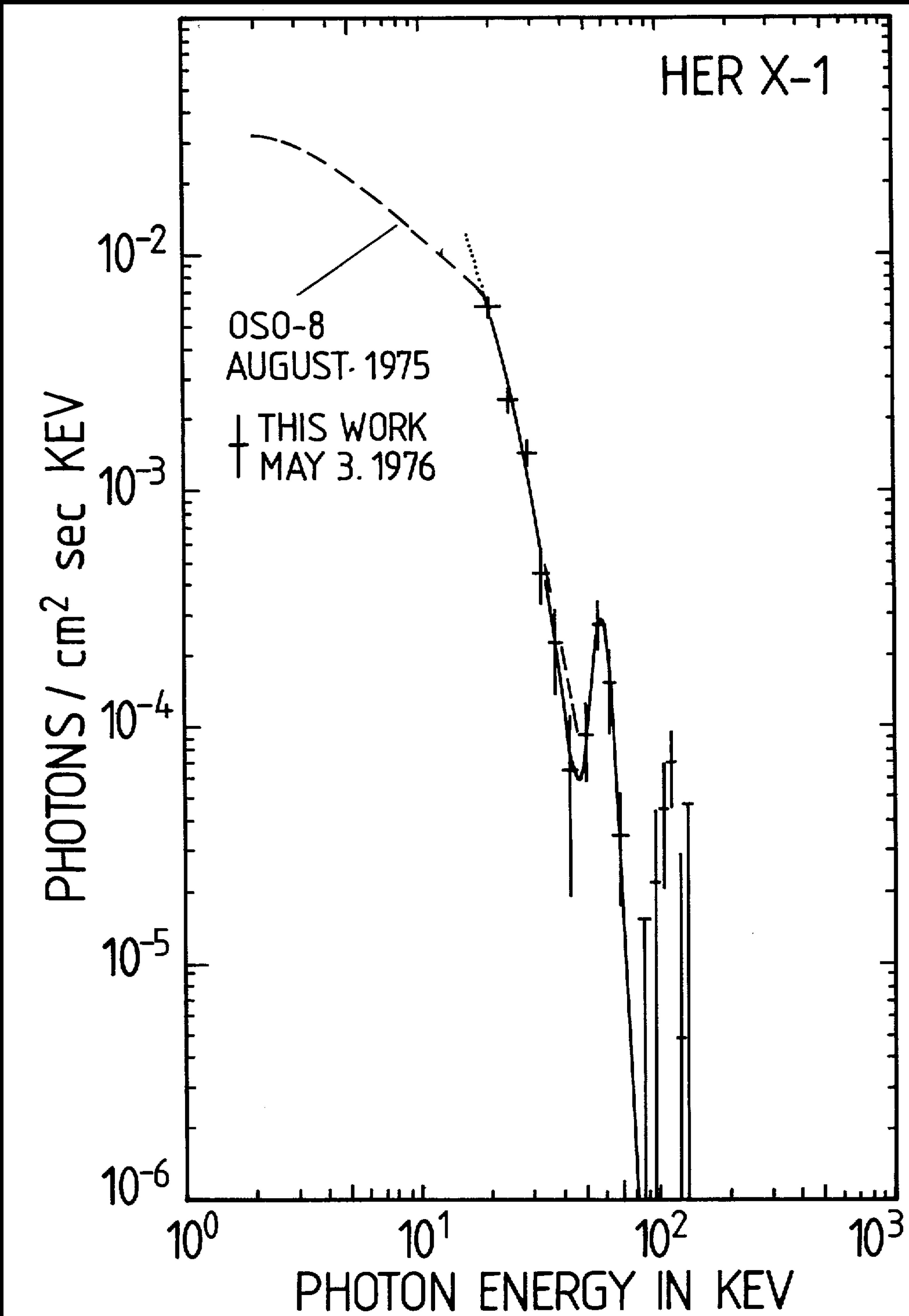
GRO J1008−57 (Kühnel, Wilms, et al., 2011, to be submitted)



Vela X-1 (Fürst et al., 2010)

Accretion process can be very violent

$\Longrightarrow$ strong short term variations of $\dot{M}$



X-ray spectral shape:

- power law continuum with exponential cutoff

  Due to Compton scattering

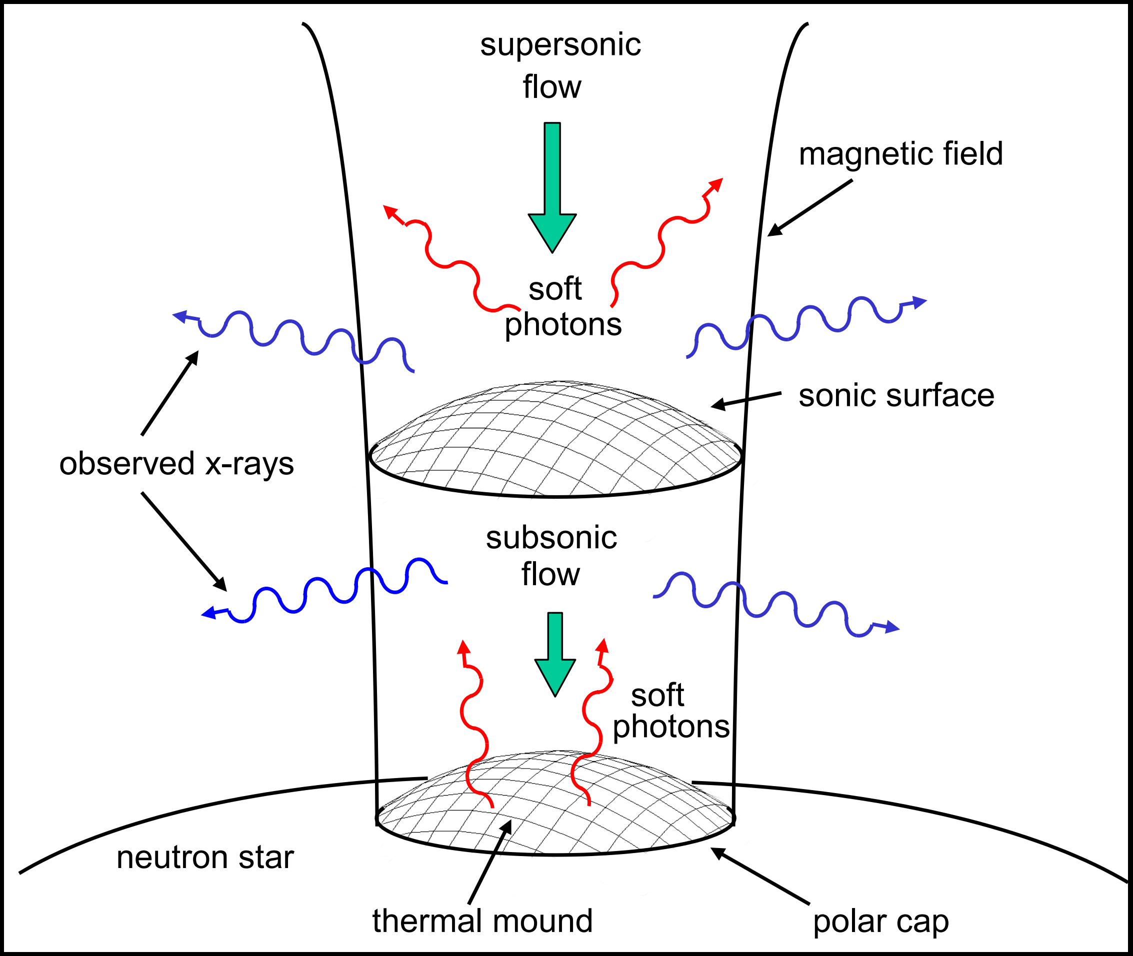
- normally strong Fe Kα line at $6.4 \ldots 6.7$ keV

  Due to fluorescence in circumstellar material.

- Cyclotron line

  Due to strong B-field

Her X-1 (Trümper et al., 1978)

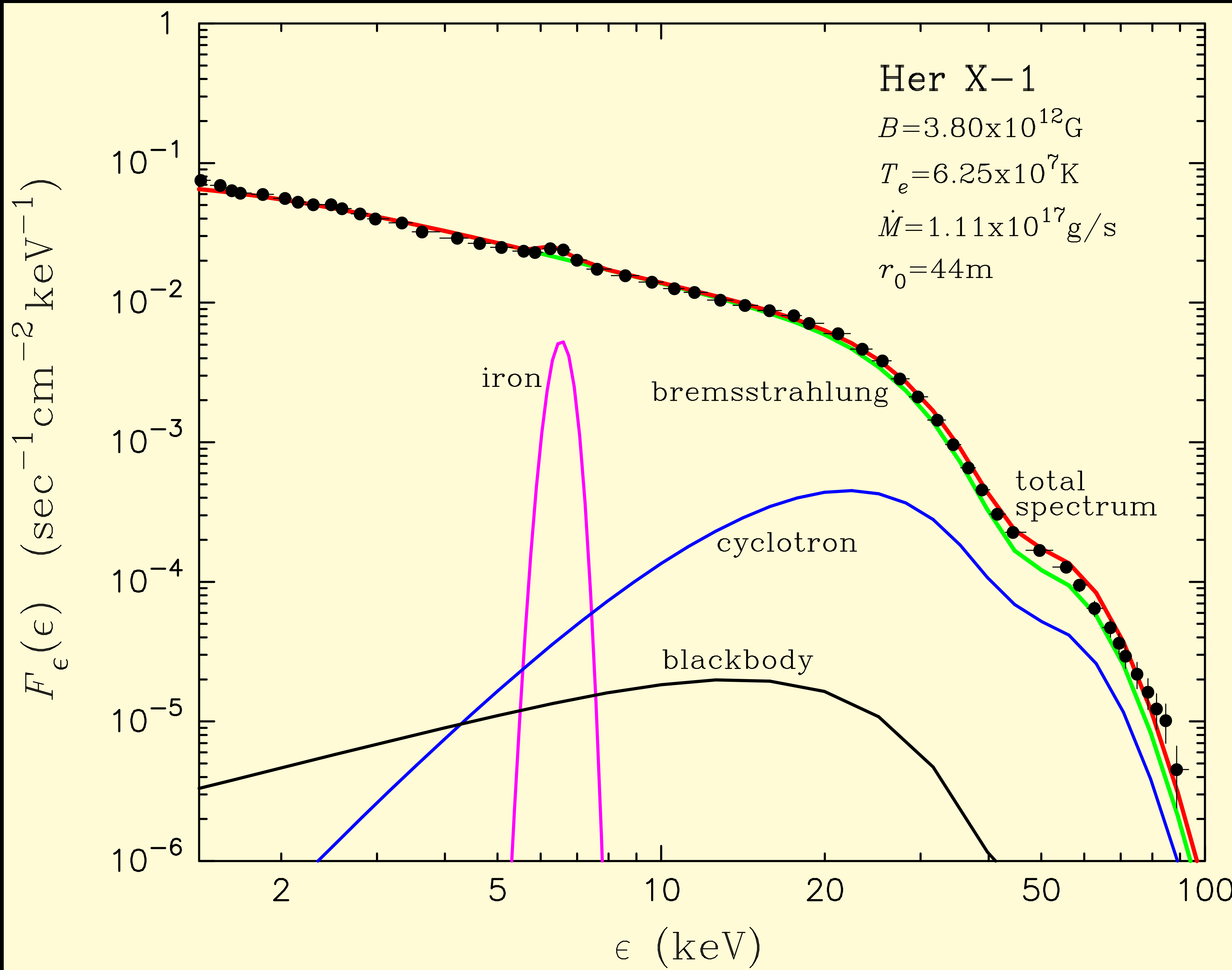


Becker & Wolff (2005a,b, 2007):
For high luminosity systems: Radiative shock dominates formation of observed continuum.

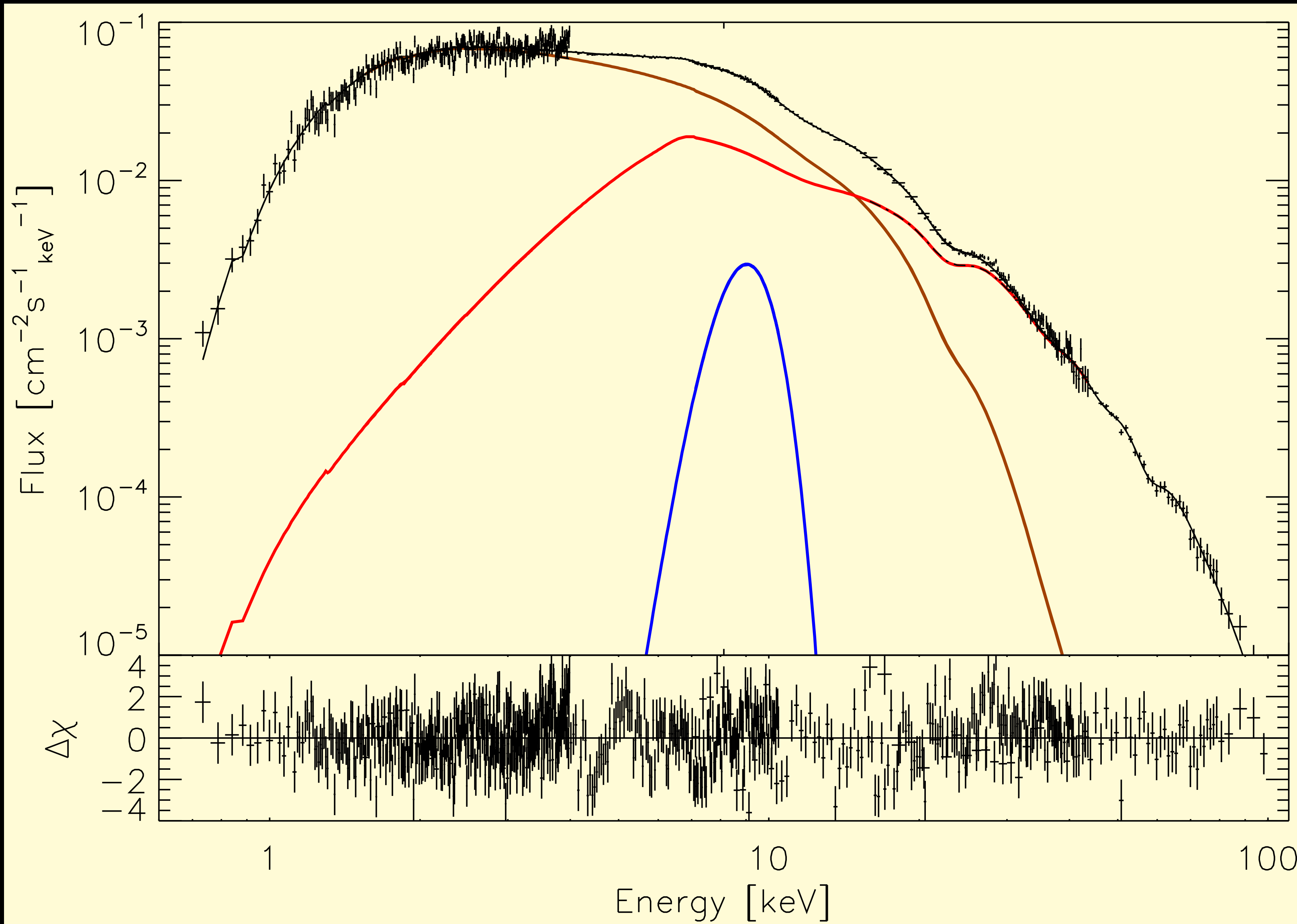
Physics:

- accretion mound produces soft X-rays (bremsstrahlung)
- X-rays are upscattered in accretion shock (bulk motion Comptonization)
- hard X-rays diffuse through walls of accretion column

Earlier work in this area, e.g., Basko & Sunyaev (1975), Nagel (1980), Mészáros & Nagel (1985a), Mészáros & Nagel (1985b), Arons et al. (1987)...



Becker & Wolff (2007, Fig. 6)



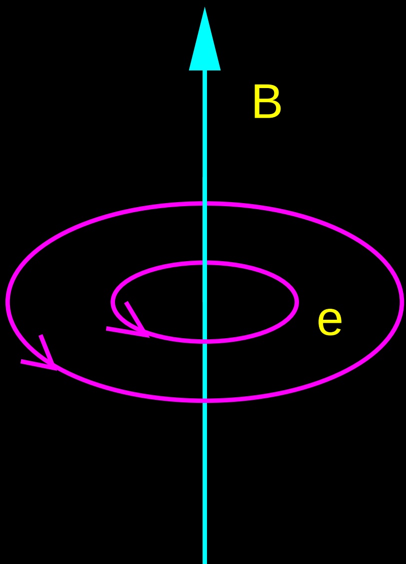
4U0115+63 (BeppoSax; Ferrigno et al., 2009)

Becker and Wolff continuum model is now available for spectral fitting (Ferrigno et al., 2009); but requires some fixes to be done in summer 2010.

Strong field at NS poles: Quantization of electron energies $\perp$ B-field lines (Landau levels):

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

$p_\parallel$: momentum of electron $\parallel$ B-field, n: major quantum number, B_crit is



$$B_\mathrm{crit} = \frac{m_\mathrm{e}^2 c^3}{\mathrm{e}\hbar} \sim 4.4 \times 10^{13}\,\mathrm{G}$$

For $B \ll B_\mathrm{crit}$, distance between Landau levels:

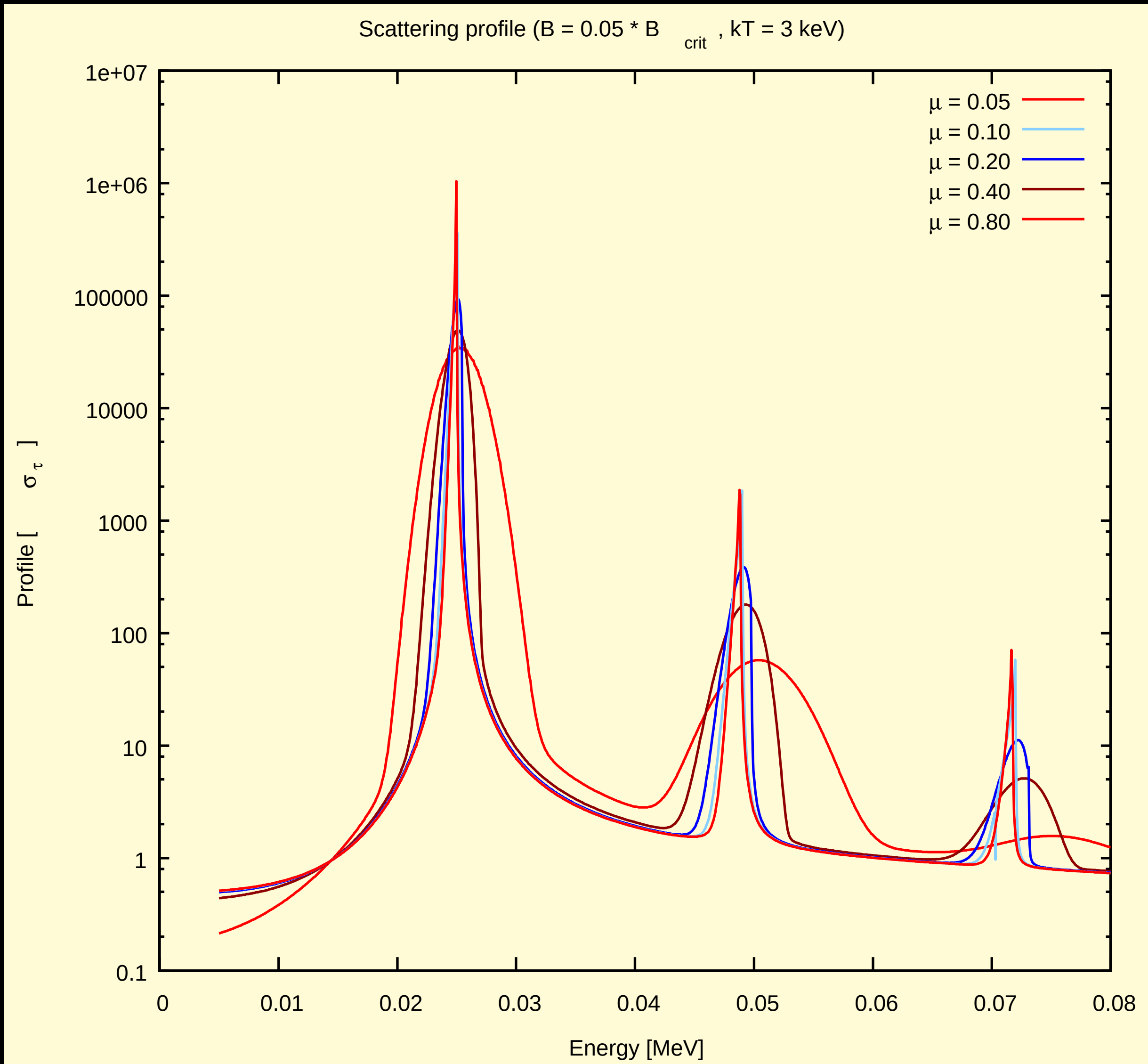
$$E_\mathrm{cyc} = \frac{\hbar e}{m_\mathrm{e} c} B = 11.6\,\mathrm{keV} \left(\frac{B}{10^{12}\,\mathrm{G}}\right)$$

($12 - B_{12}$-rule)

$\Longrightarrow$ Cyclotron Resonance Scattering Features (“Cyclotron lines”) at

$$E_n = nE_\mathrm{cyc} = (1+z)E_{n,\mathrm{obs}}$$

($1 + z \sim 1.25 \ldots 1.4$; grav. redshift!)



Radiative transfer calculation difficult because of strong dependence of cross section on energy and angle

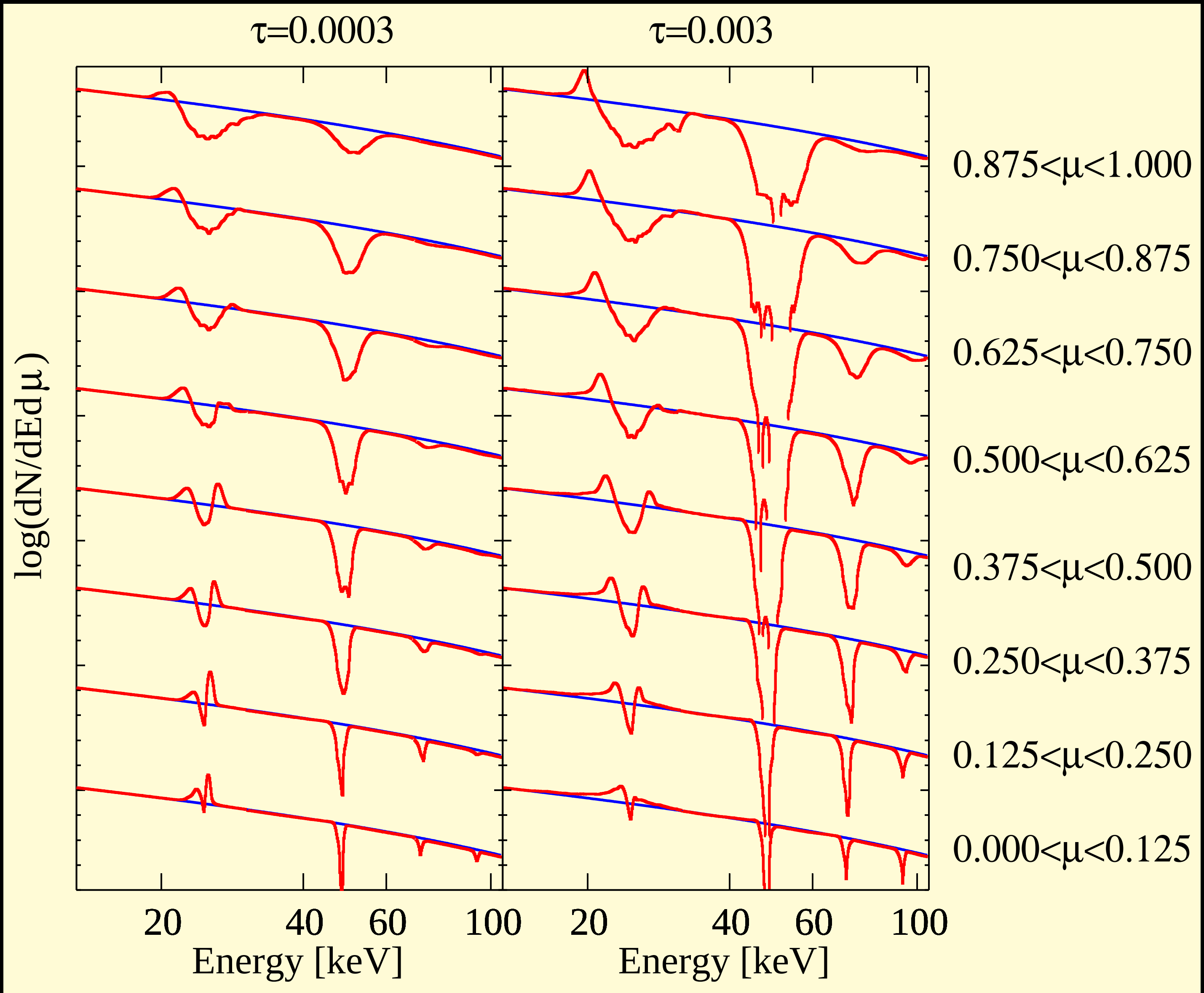
$\Longrightarrow$ Monte Carlo approach

$B = 2.2 \times 10^{12}$ G,
$\theta = \angle(\mathbf{B}, \mathbf{p}_\nu)$ Schwarm (priv. comm.)

Thermal broadening $\|$ $\mathbf{B}$: expected line width

$$\frac{\Delta E_{\mathrm{FWHM}}}{E_{\mathrm{cyc}}} \sim \sqrt{kT_{\mathrm{e}}}\,|\cos\theta| \quad (\sim 6\,\mathrm{keV\ for\ } kT_{\mathrm{e}} = 40\,\mathrm{keV})$$

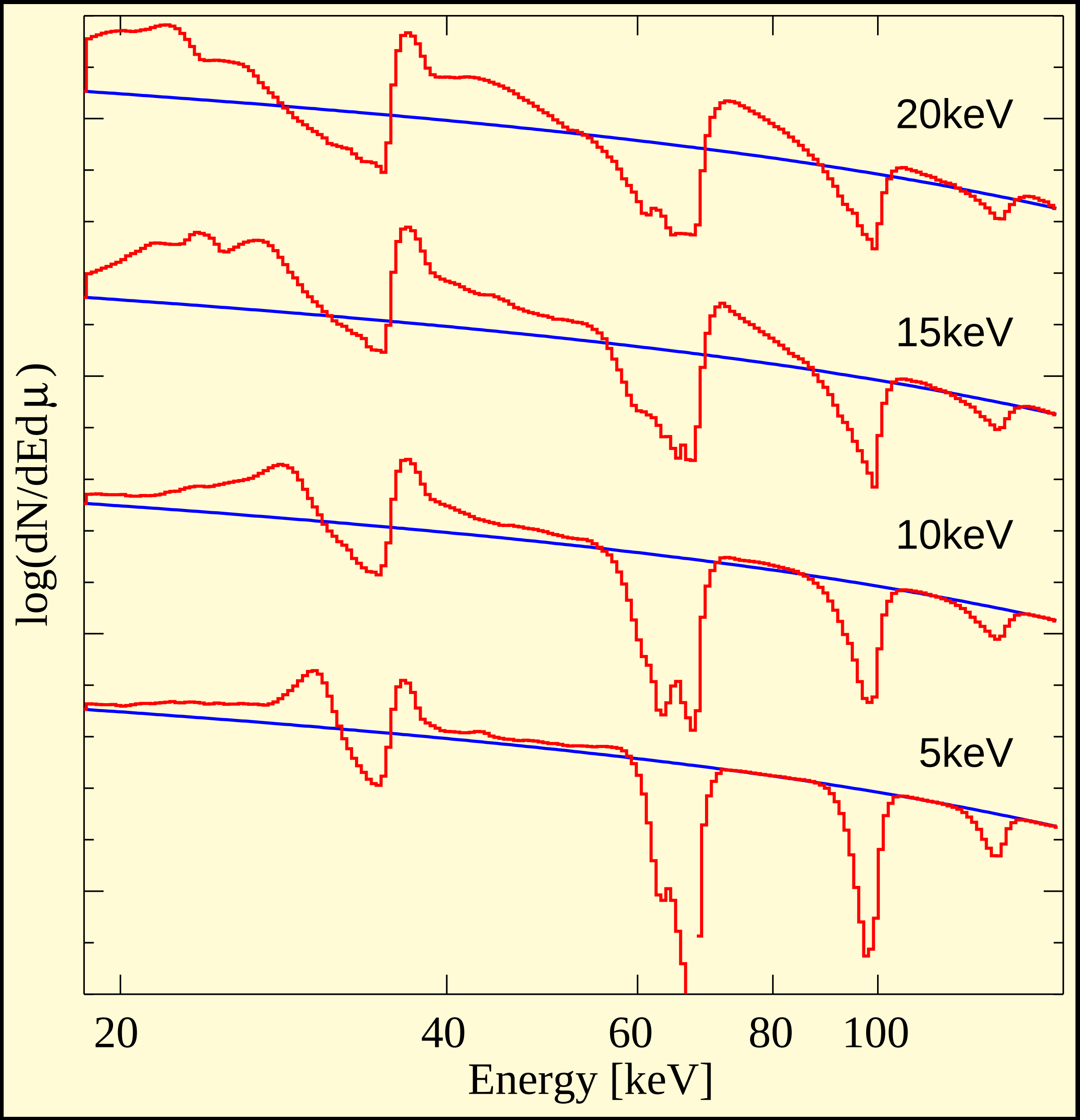
(Trümper et al., 1978; Mészáros, 1992)



Dependence of CRSF shape on optical depth and angle.

Note: resonance optical depth $\sim 10^5 \cdot \tau_{\mathrm{T}}$!

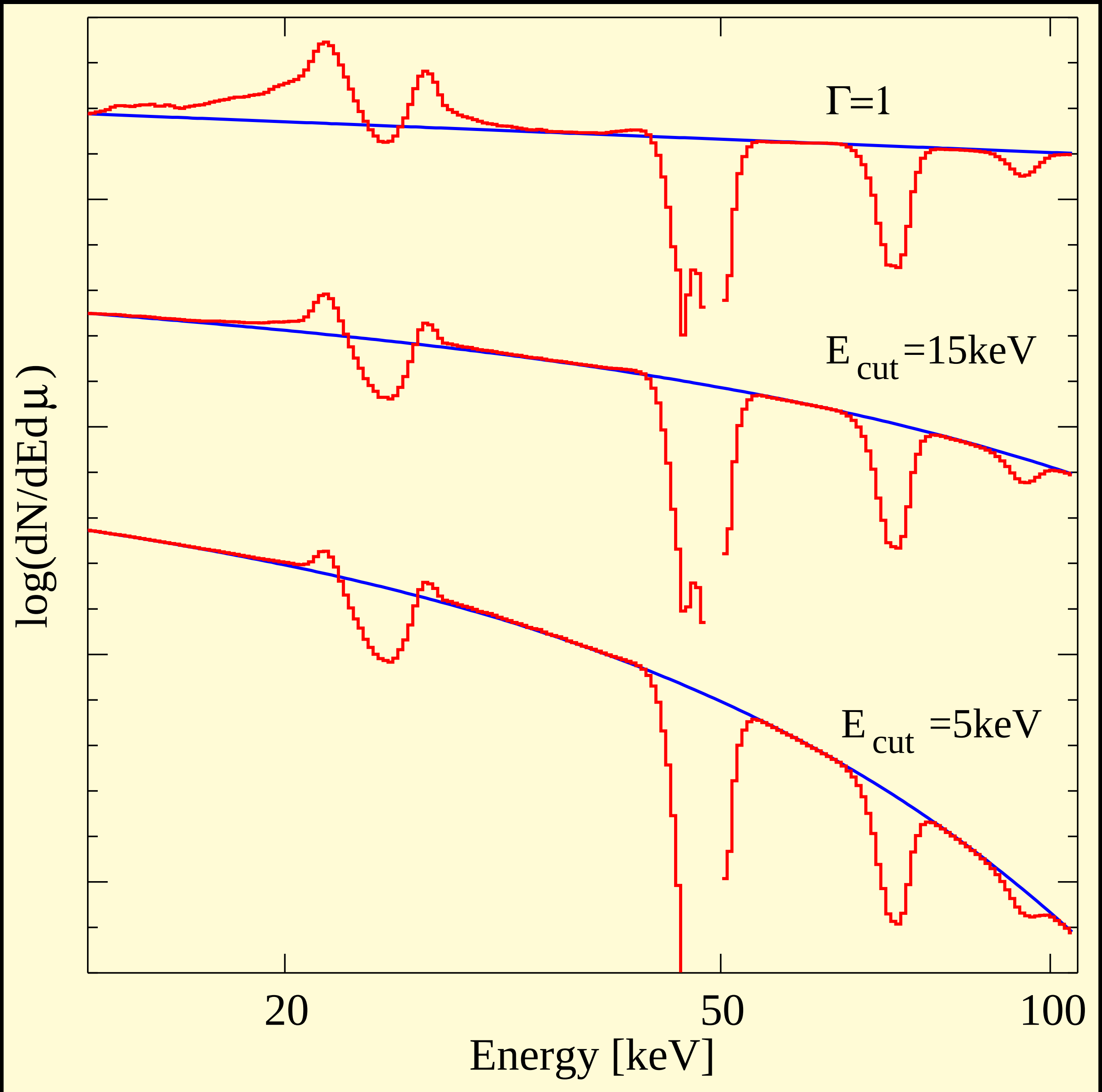
$B = 1.76 \times 10^{12}$ G,
$kT_{\mathrm{e}} = 3$ keV;
(Schönherr et al., 2007)



Dependence on electron temperature.

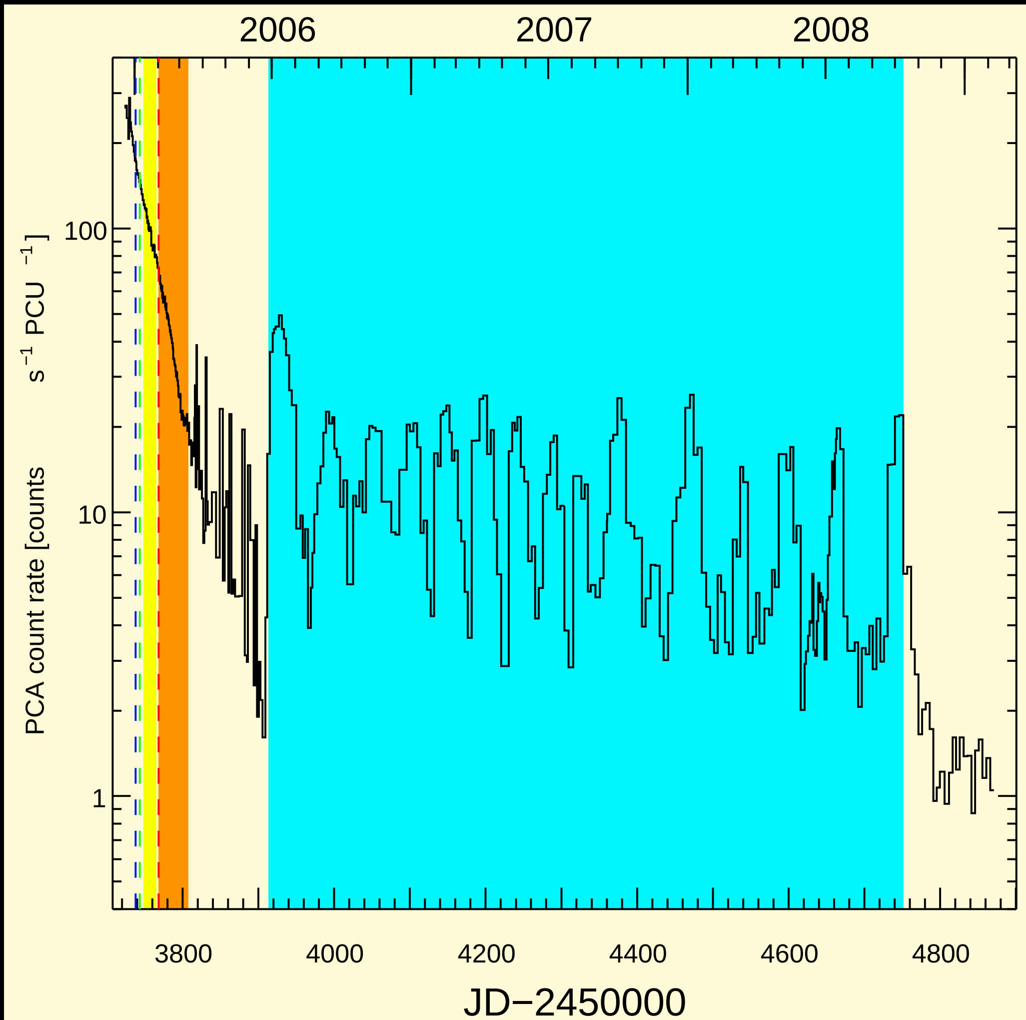
Asymmetry: relativistic Maxwellian.

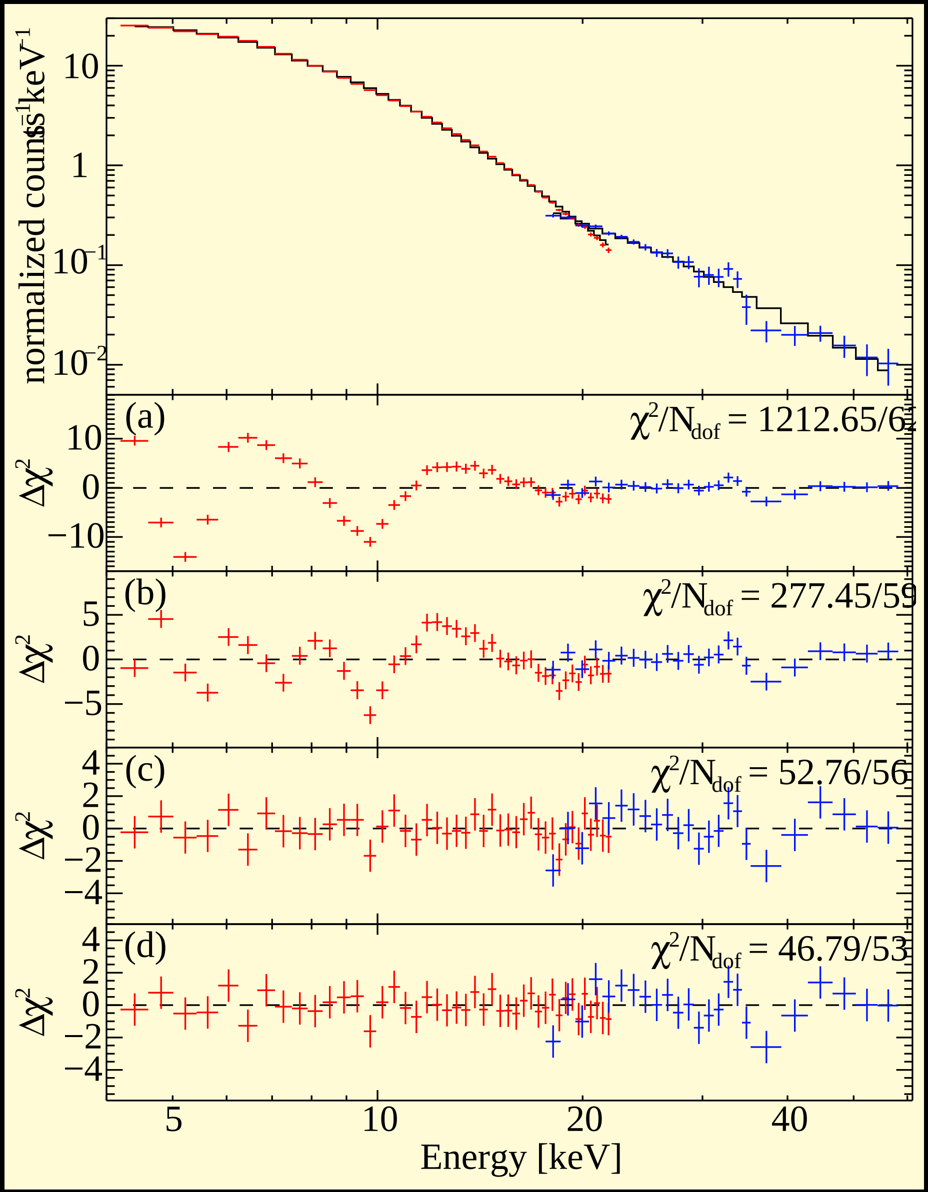
(Schönherr et al., 2007)



Dependence on continuum shape.

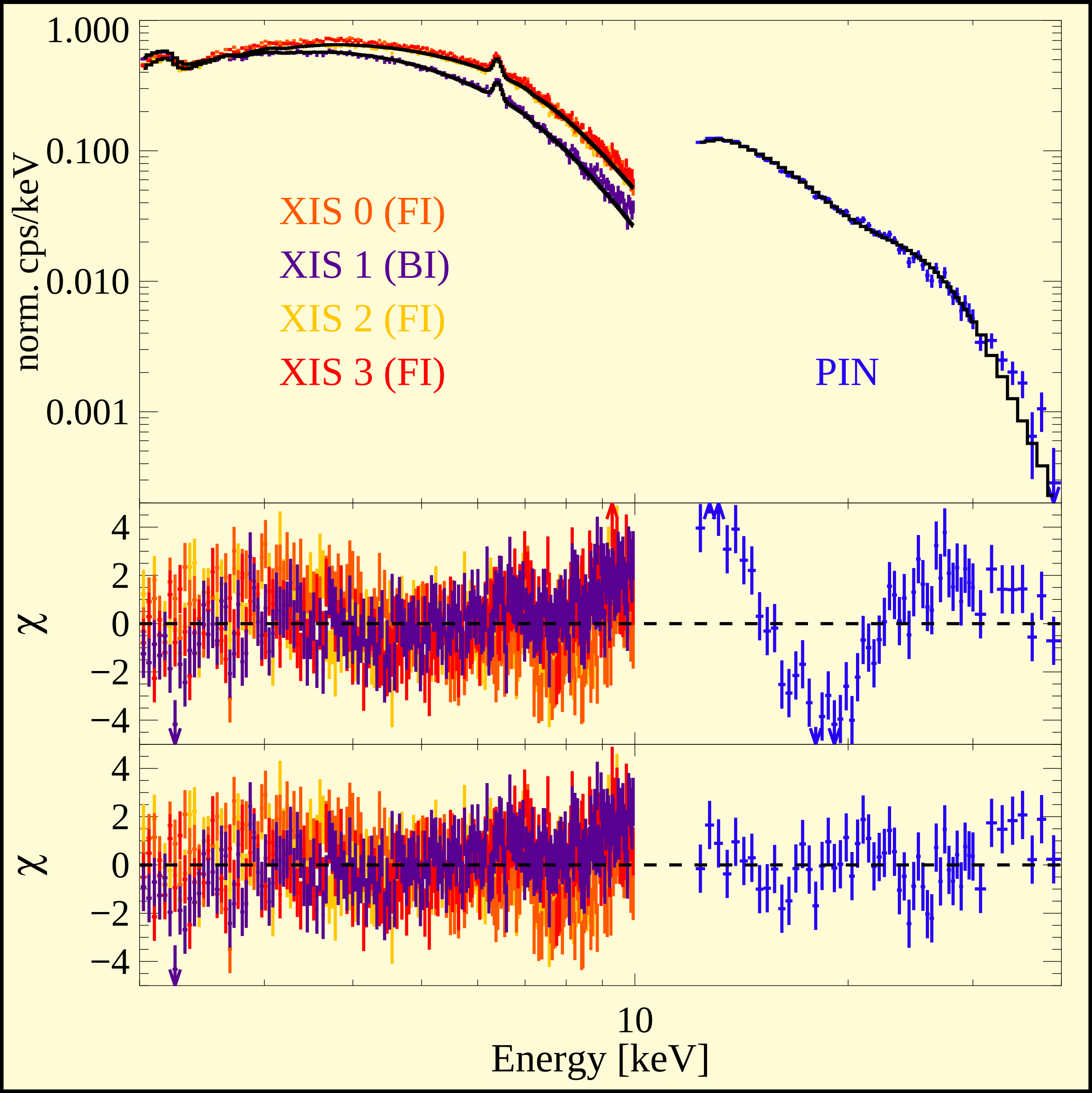
(Schönherr et al., 2007)





Swift J1626.6−5156: Discovered 2005 Dec 15 (Krimm, 2005), type II outburst, followed by several outbursts (Reig et al., 2008; Baykal et al., 2010)

Discovery of cyclotron line at ∼10 keV (deCesar et al., 2009)



4U1907+09, 2004 December:

$E_{\rm cyc} = 19.7(4)$ keV,

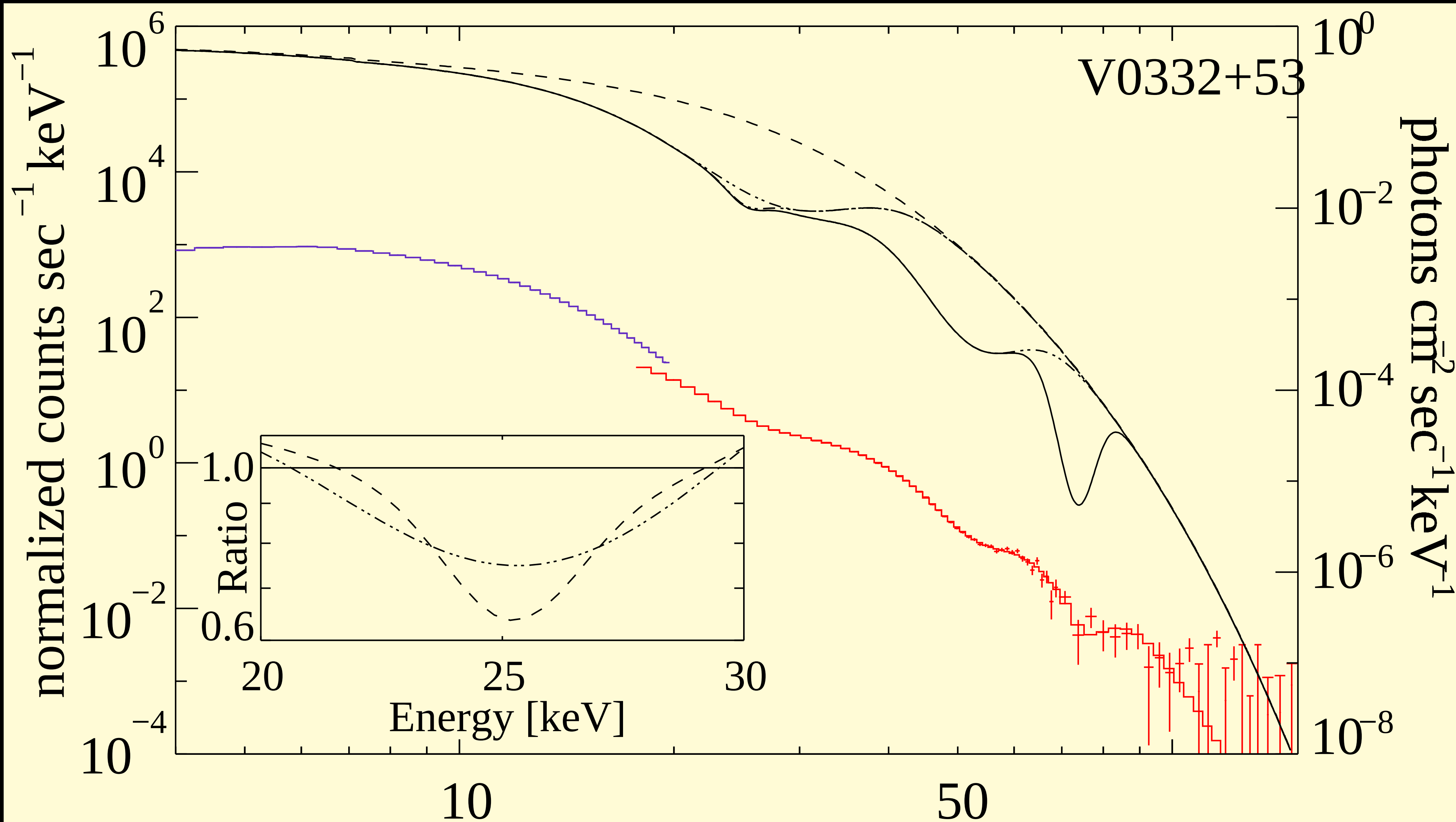
$\sigma = 3.3(3)$ keV,

in agreement with earlier results (e.g., *INTEGRAL*).

Pottschmidt et al. (2007)

Source	$E_{\rm cyc}$ (keV)	$P_{\rm puls}$ (s)	$P_{\rm orb}$ (d)	companion	discovery
Swift J1626.6−5156	10	15	132.9	Be	RXTE (deCesar, '09)
4U 0115+63	14, 24, 36, 48, 62	3.6	24.31	Be	HEAO-1 (Wheaton, '79) RXTE, SAX (Heindl '99, Sant.,'99)
4U 1907+09	18, 38	438	8.38	B2 III–IV	SAX (Cusumano, '98)
4U 1538−52	22, 47	530	3.73	B0I	Ginga (Clark,'90), RXTE (Rodes-Roca, '09)
Vela X-1	24, 52	283	8.96	B0.5Ib	Mir-HEXE (Kendziorra, '92), RXTE (Kreykenbohm, '02)
V0332+53	27, 51, 74	4.37	34.25	Be	Ginga (Makishima, '90)
Cep X-4	28	66.25	>23	B1	Ginga (Mihara, '91)
Cen X-3	29	4.8	2.09	O6.5II	SAX (Santangelo, '98) RXTE (Heindl, '98)
X Per	29	837	250.3	B0 III–Ve	RXTE (Coburn, '01)
MXB 0656−072	33	160	100?	O9.7Ve	RXTE (Heindl, '03)
XTE J1946+274	36	15.8	169.2	B0-1V-IVe	RXTE (Heindl, '01)
4U 1626−67	37	7.66	0.028	0.04 $M_\odot$	SAX (Orlandini, '98) RXTE (Heindl, '98)
GX 301−2	37	690	41.5	B1.2Ia	Ginga (Mihara, '95)
Her X-1	41	1.24	1.7	A9-B	Ballon-HEXE (Trümper, '78)
A0535+26	50, 110	105	110.58	Be	HEXE (Kendziorra, '92, '94), CGRO (Maisack, '97)
1A1118−61	55	408	400-800 d?	O9.5IV-Ve	RXTE (Doroshenko, '10)
GRO J1008−57	88?	93.5	247.8	B1–B2	CGRO (Shrader, '99)

16+1 sources

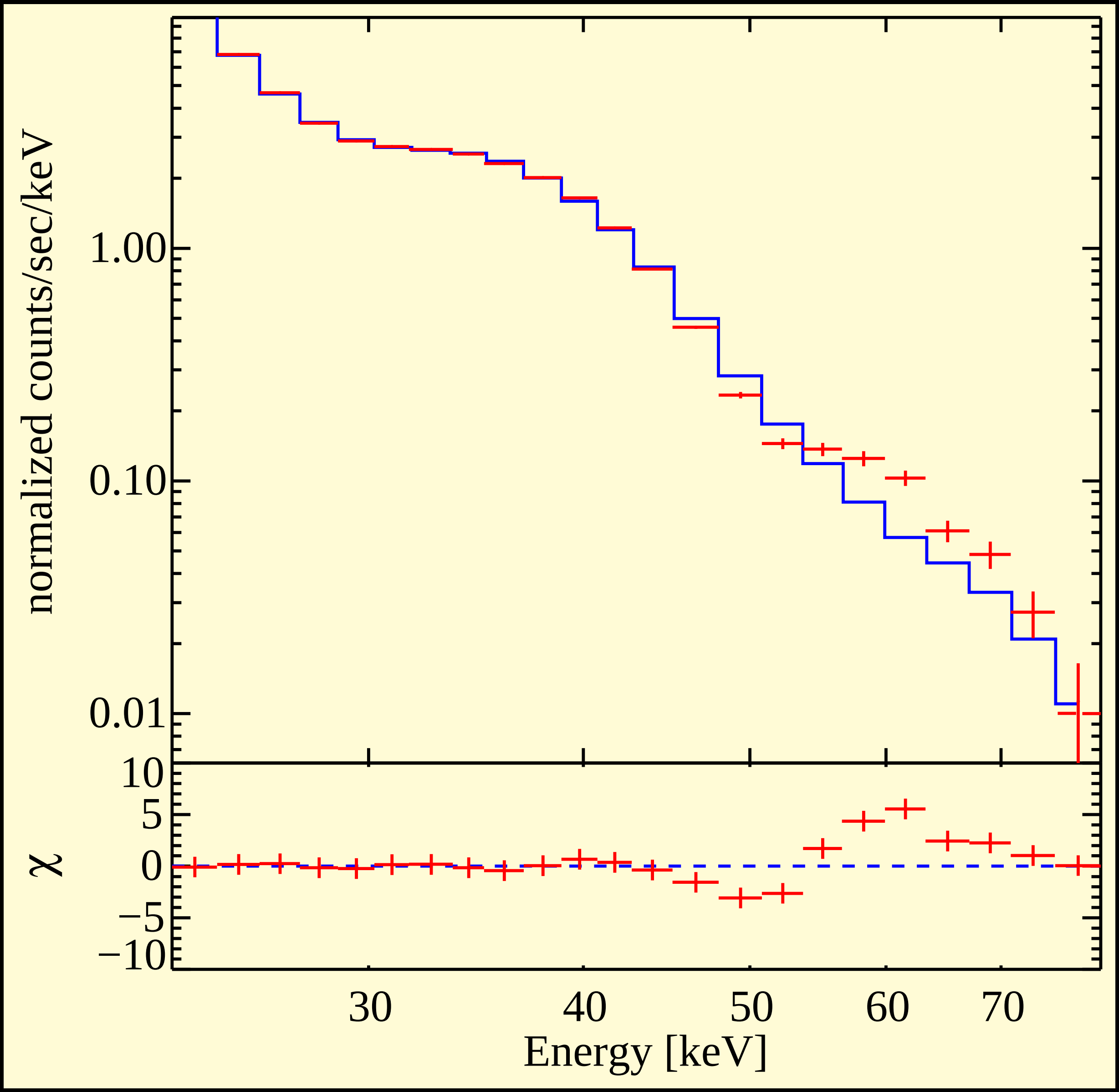


Pottschmidt et al. (2005)

V0332+53: Cyclotron lines at 27, 51, and 74 keV; complex fundamental.

2nd source after 4U 0115+63 with more than 2 lines.

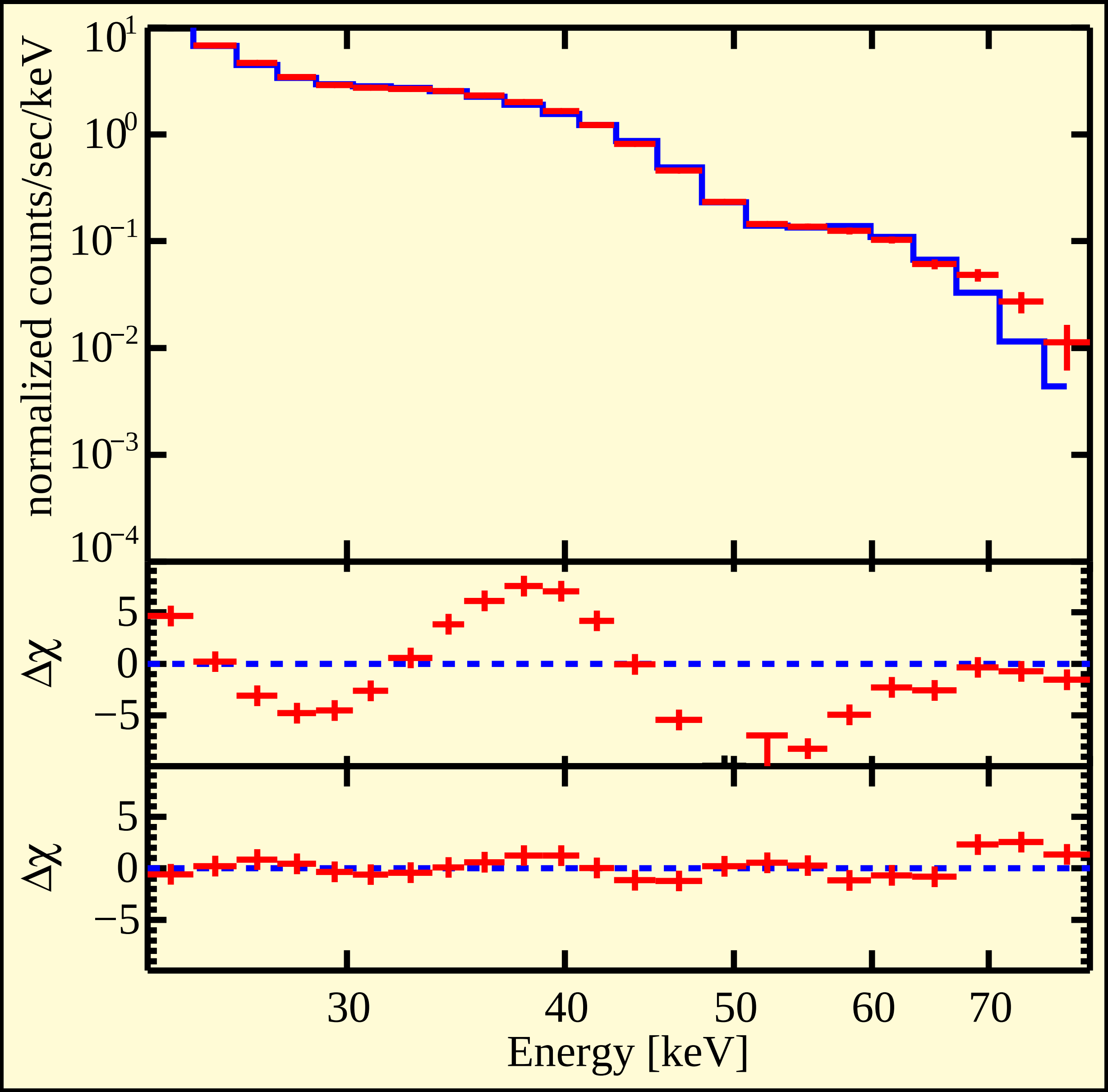
Line ratios $\neq$ 2, agrees with QED prediction; also require scattering angle of $\gtrsim$ 60°, in agreement with expectation from resonant cross-section.



Direct fits of Monte Carlo model to data are very promising and they allow to constrain the emission geometry.

accretion column: line wings too strong

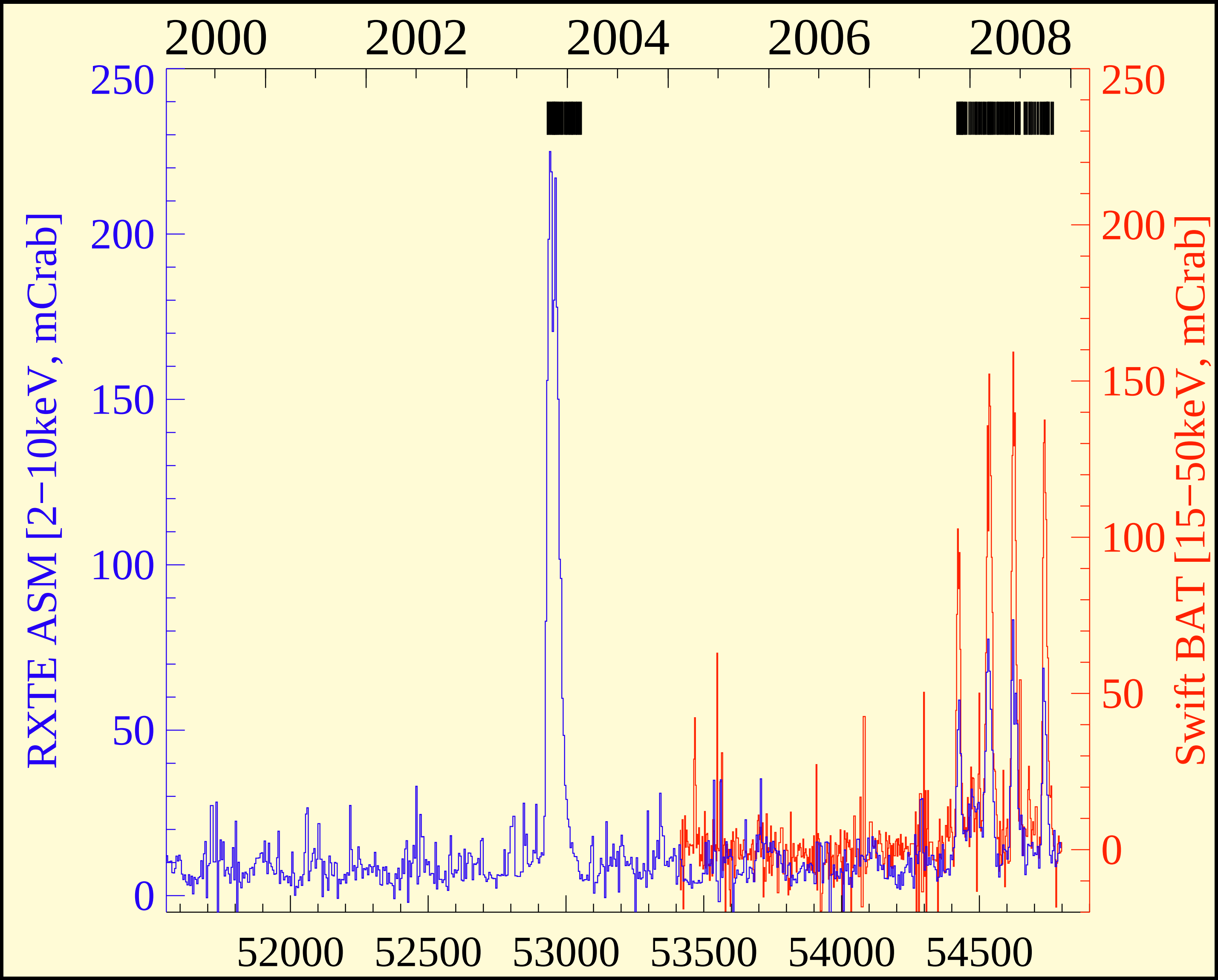
V0332+53 (Schönherr et al., 2007)



Direct fits of Monte Carlo model to data are very promising and they allow to constrain the emission geometry.

slab geometry: good fit

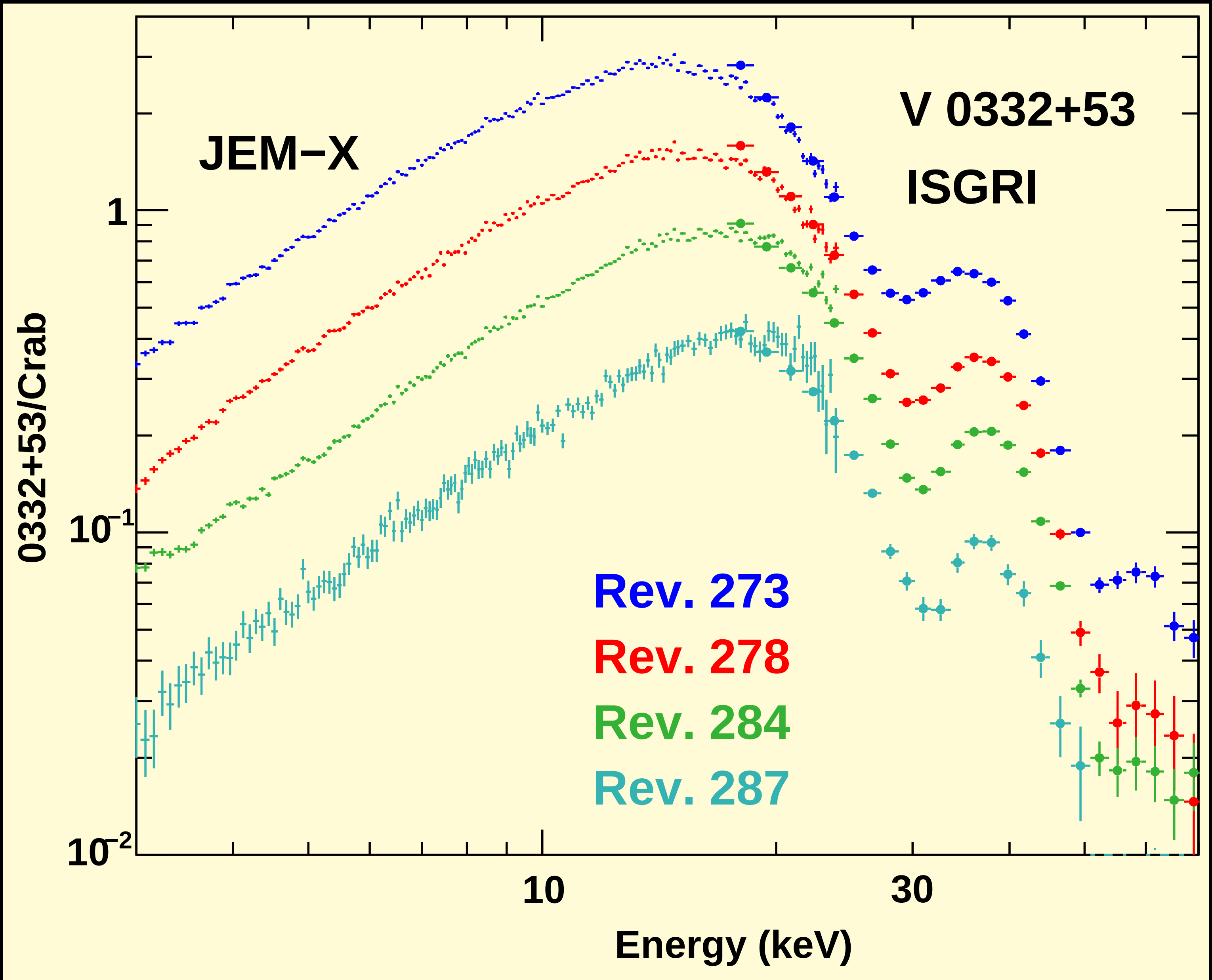
V0332+53 (Schönherr et al., 2007)



Accretion in (high mass) X-ray binaries can be strongly variable on long timescales.

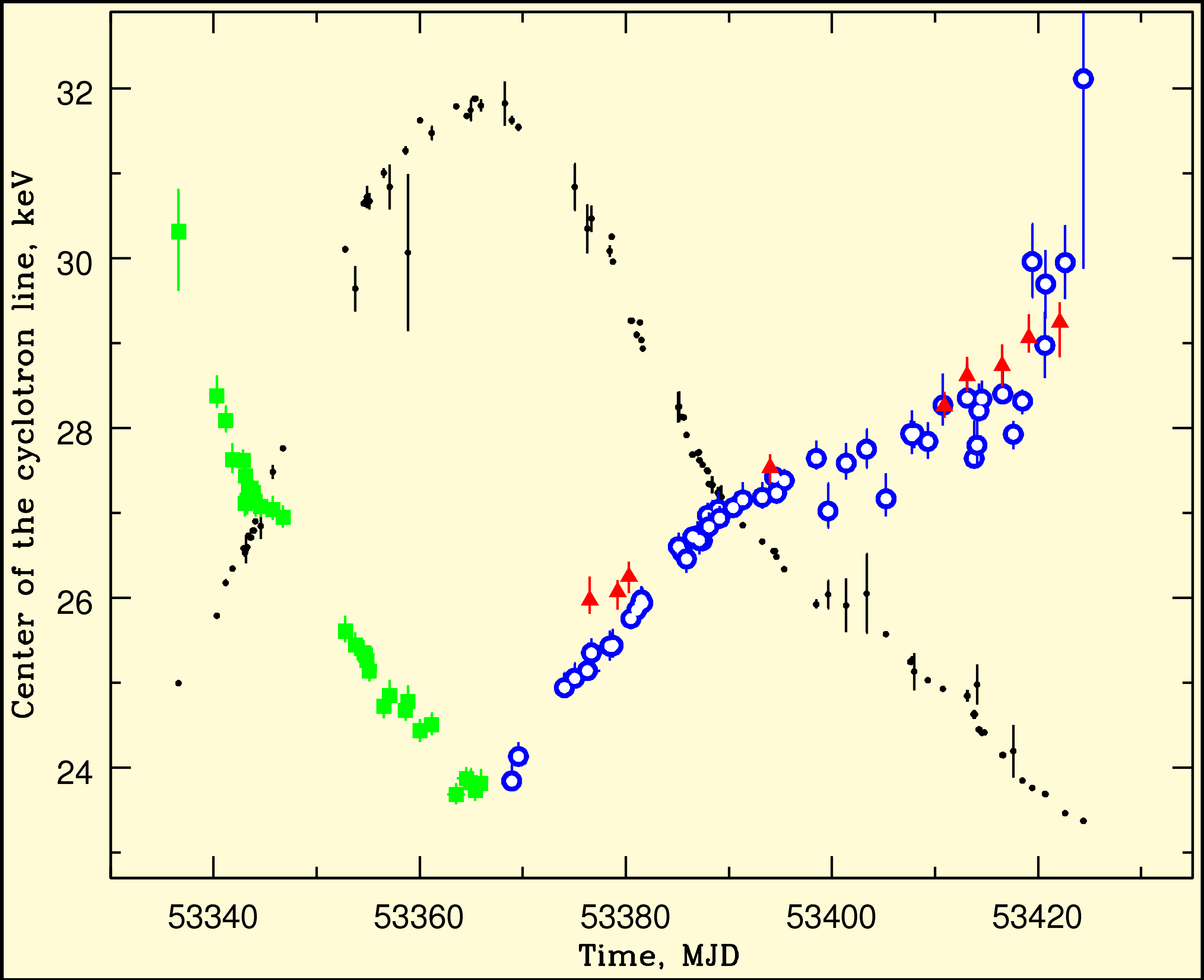
$\Longrightarrow$ Observations can cover large range of L and therefore (possibly) $\dot{M}$

(MXB 0656−072)



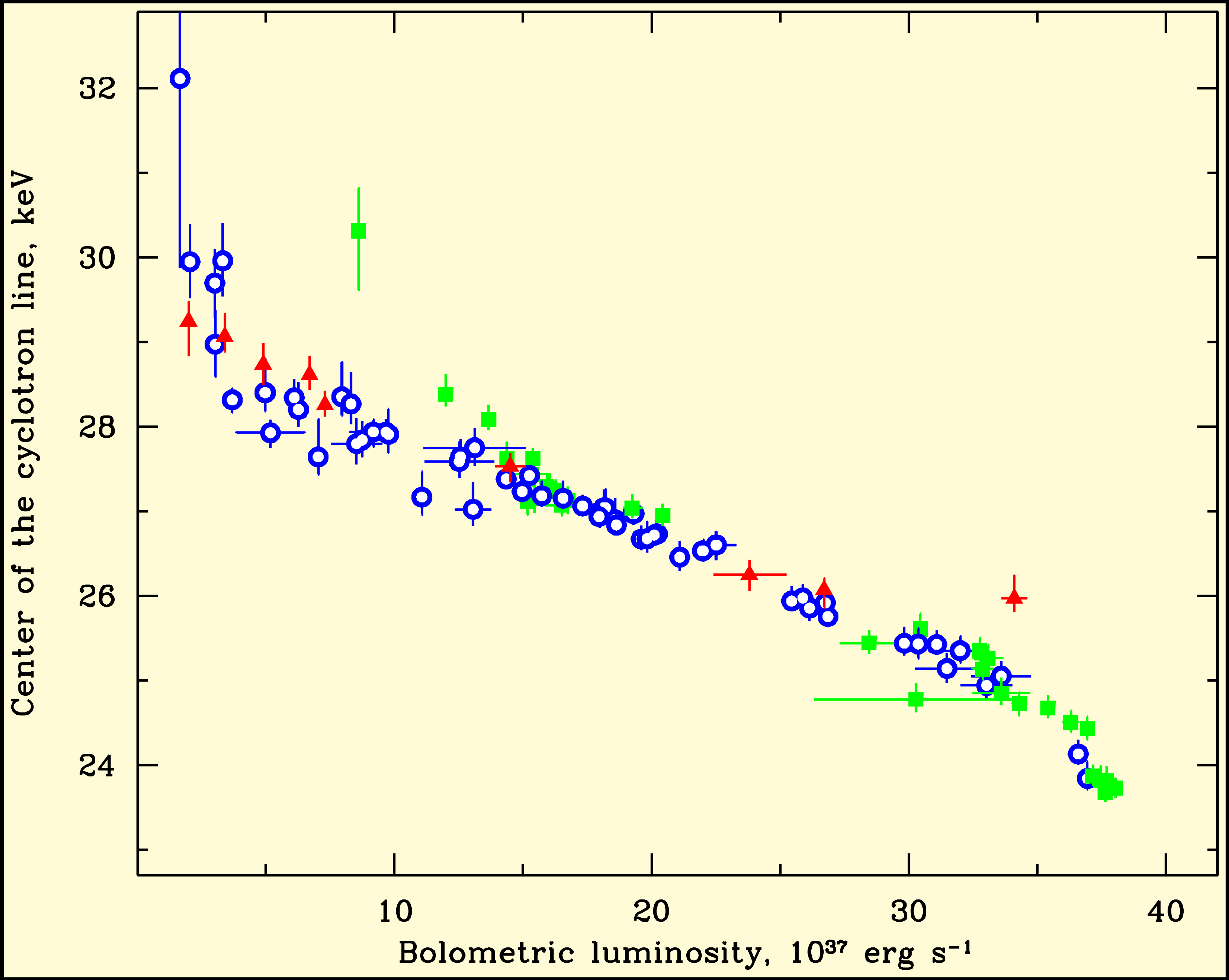
V0332+53: Energy of fundamental cyclotron line changes over outburst

(Mowlavi et al., 2006)



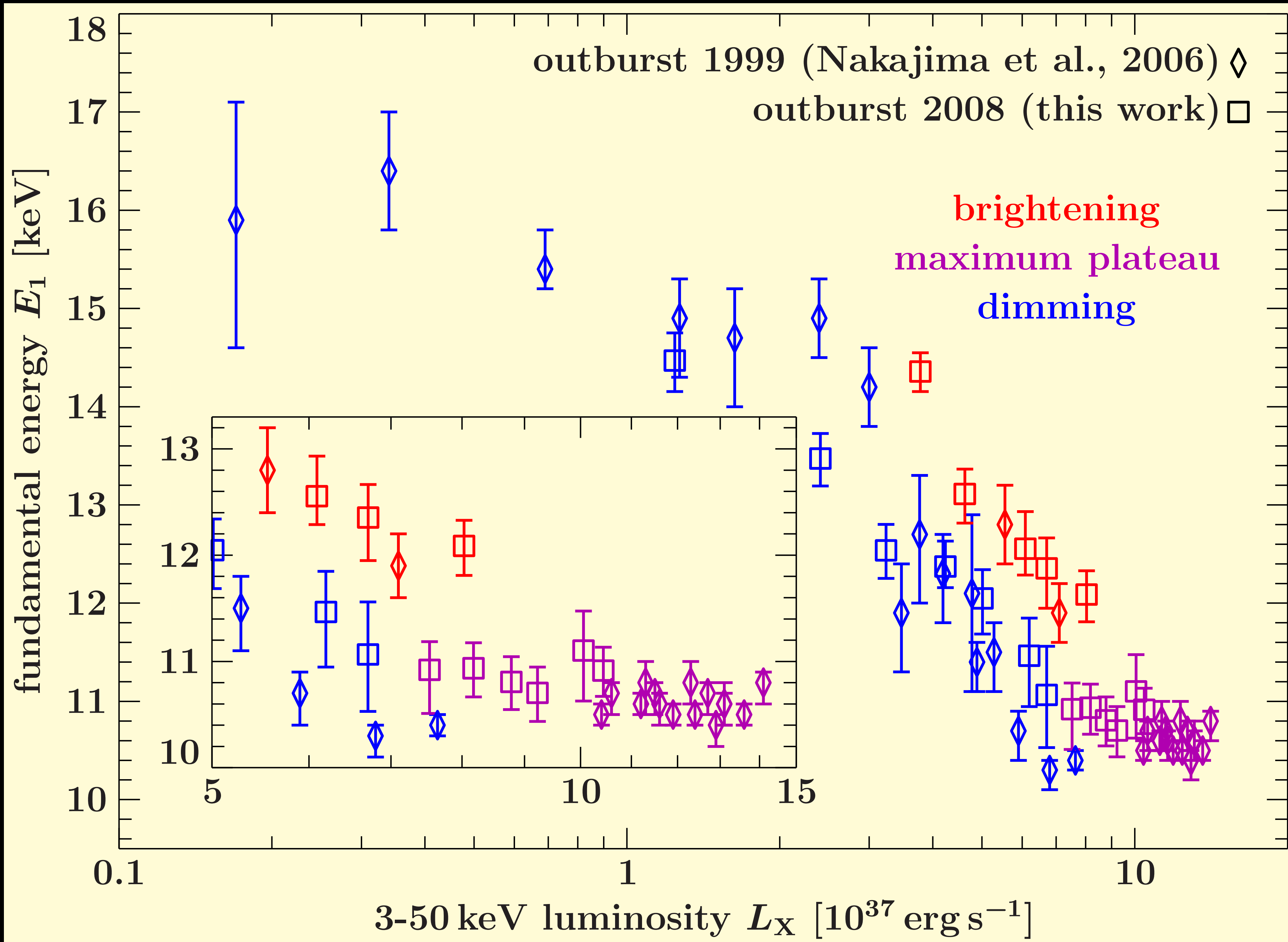
(Tsygankov et al., 2010)

V0332+53: Cyclotron line energy is time dependent



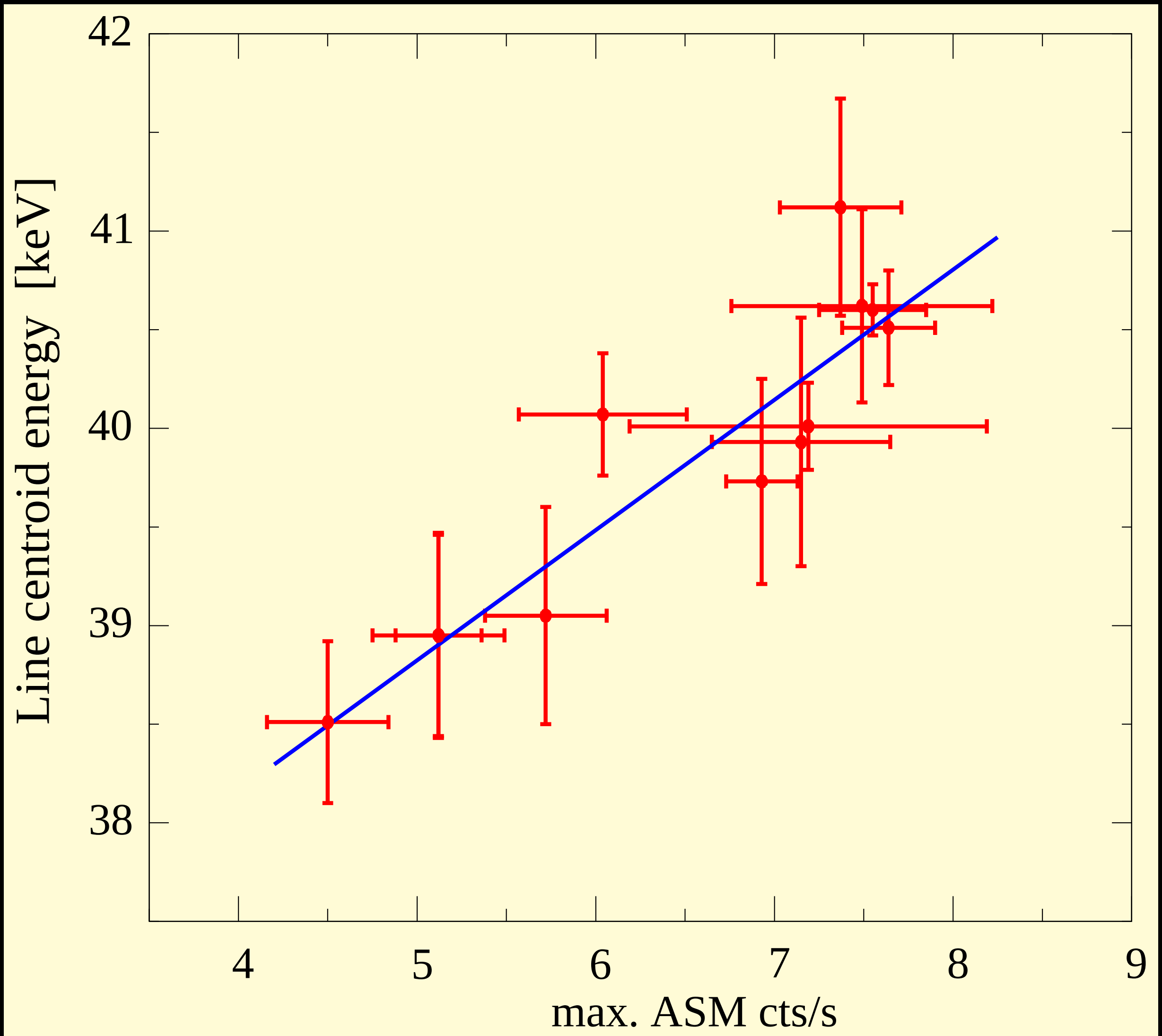
(Tsygankov et al., 2010)

V0332+53: Cyclotron line energy depends on luminosity



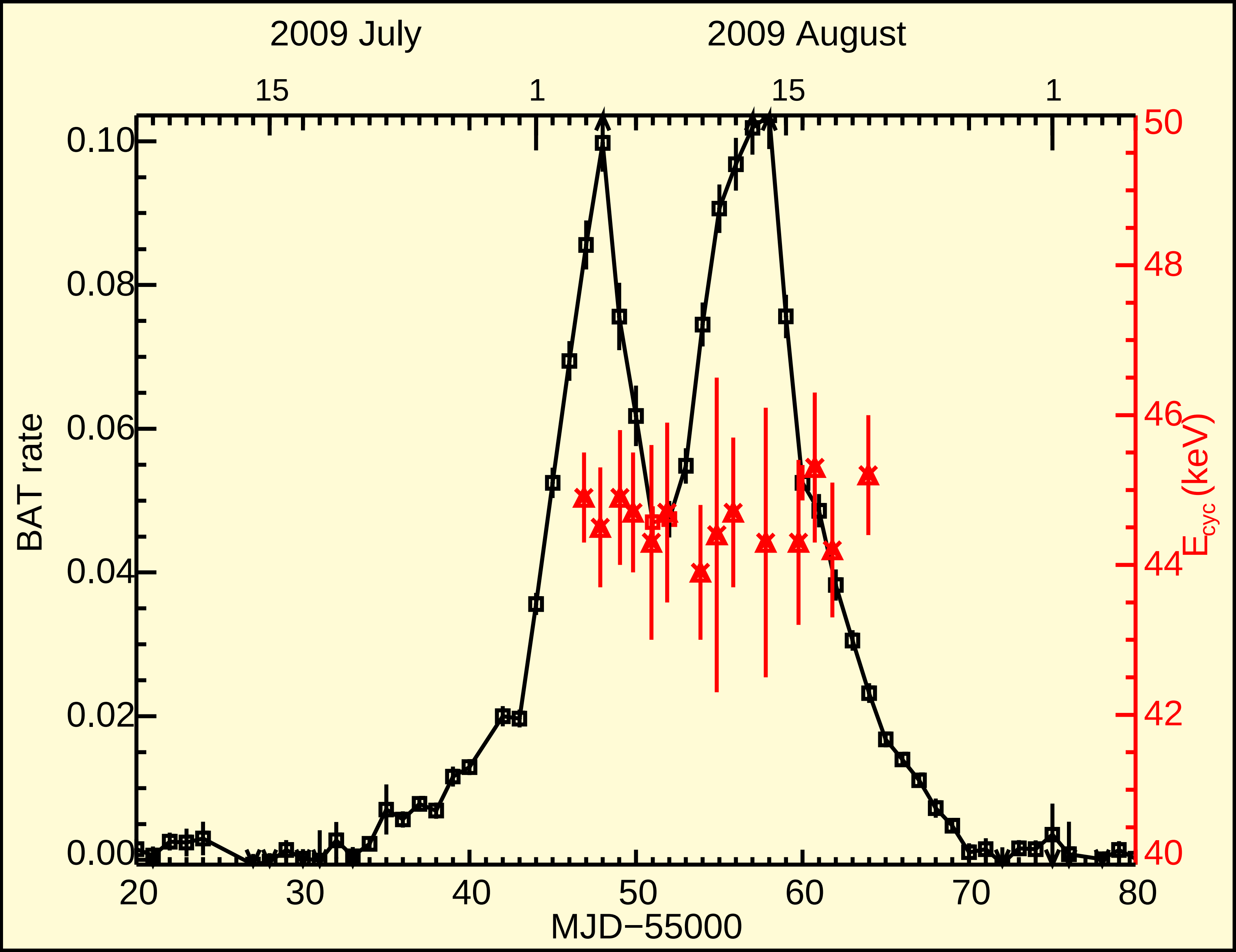
4U0115+63, Outbursts of 1999 and 2008 (Müller, JW, et al., to be submitted, Nakajima et al. 2006)

Luminosity dependent cyclotron line energies are seen in many sources



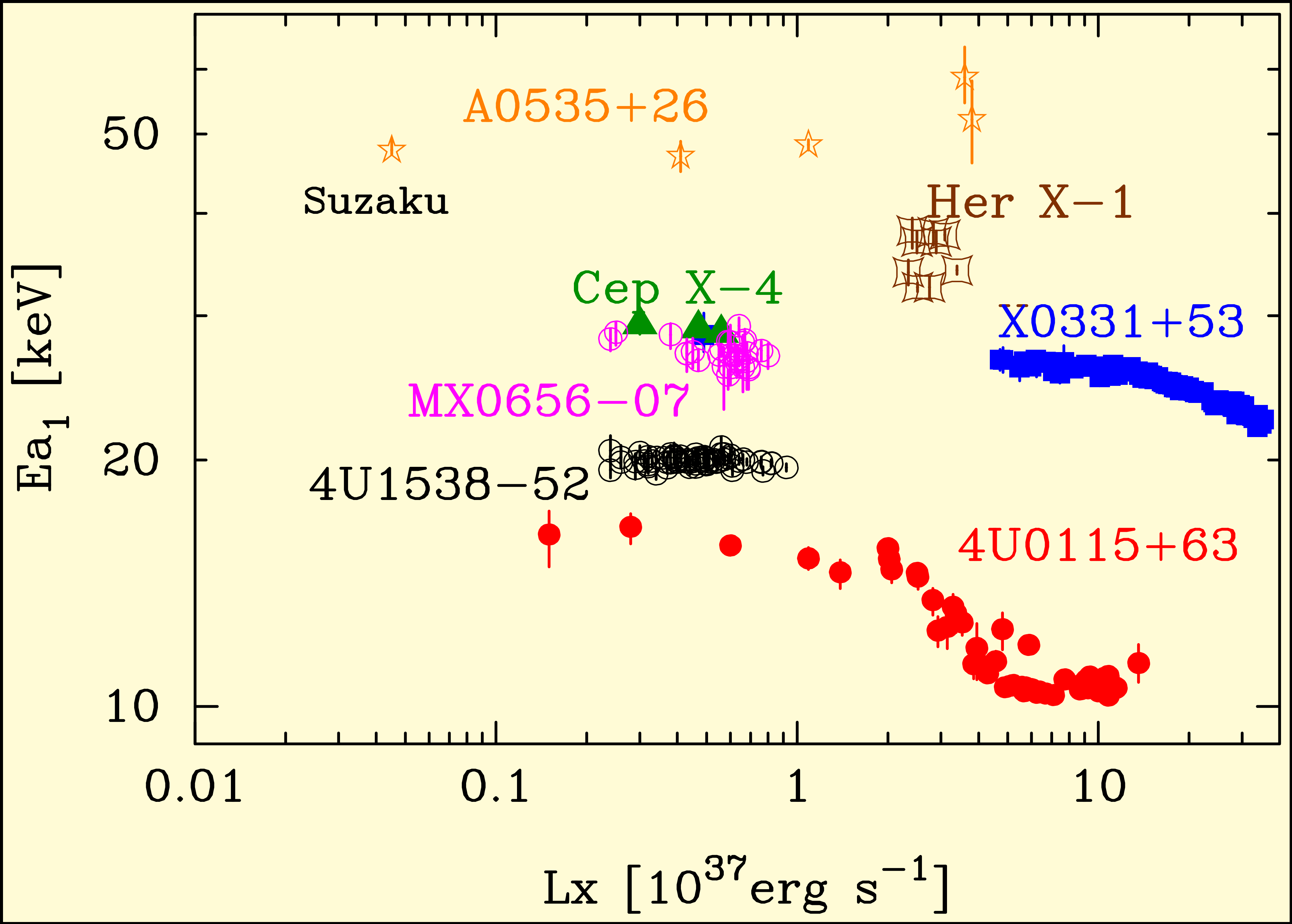
In some other sources the dependence of $E_{\rm cyc}$ on L is inverse to that seen in high luminosity sources

(Her X-1 Staubert et al., 2007)



A0535+26 (Caballero et al., 2009)

. . . and some sources such as A0535+26, Cep X-4, or 4U1538-52 do not show any significant line energy variation with L.



Mihara et al. (2007), Nakajima, PhD

Summary:

- Continuum formation now better understood than 20 years ago, but still many questions open.
- Relativistic lines show promise to determine accretion disk parameters.
- There are now 17 neutron stars with direct B-field determinations – now enough data available for both, individual studies, and study as a class.
- Line behavior with luminosity allows deeper probing of accretion column.
- Good numerical models for CRSF formation available, behavior of lines in roughly in agreement with predictions of Monte Carlo computations.

The Future:

- MAXI and Swift/BAT will discover neutron star outbursts
- ASTROSAT will allow routine measurements of broadband spectral shape and B-fields
- NuStar will start resolving CRSF shape.
- GRAVITAS or IXO will allow studies at characteristic variability timescale.

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