EBERHARD KARLS UNIVERSITÄT TÜBINGEN
FACULTY OF SCIENCE
Institute of Astronomy and Astrophysics

Probing the configuration of the emitting region in accreting magnetized neutron stars

Dmitry Klochkov

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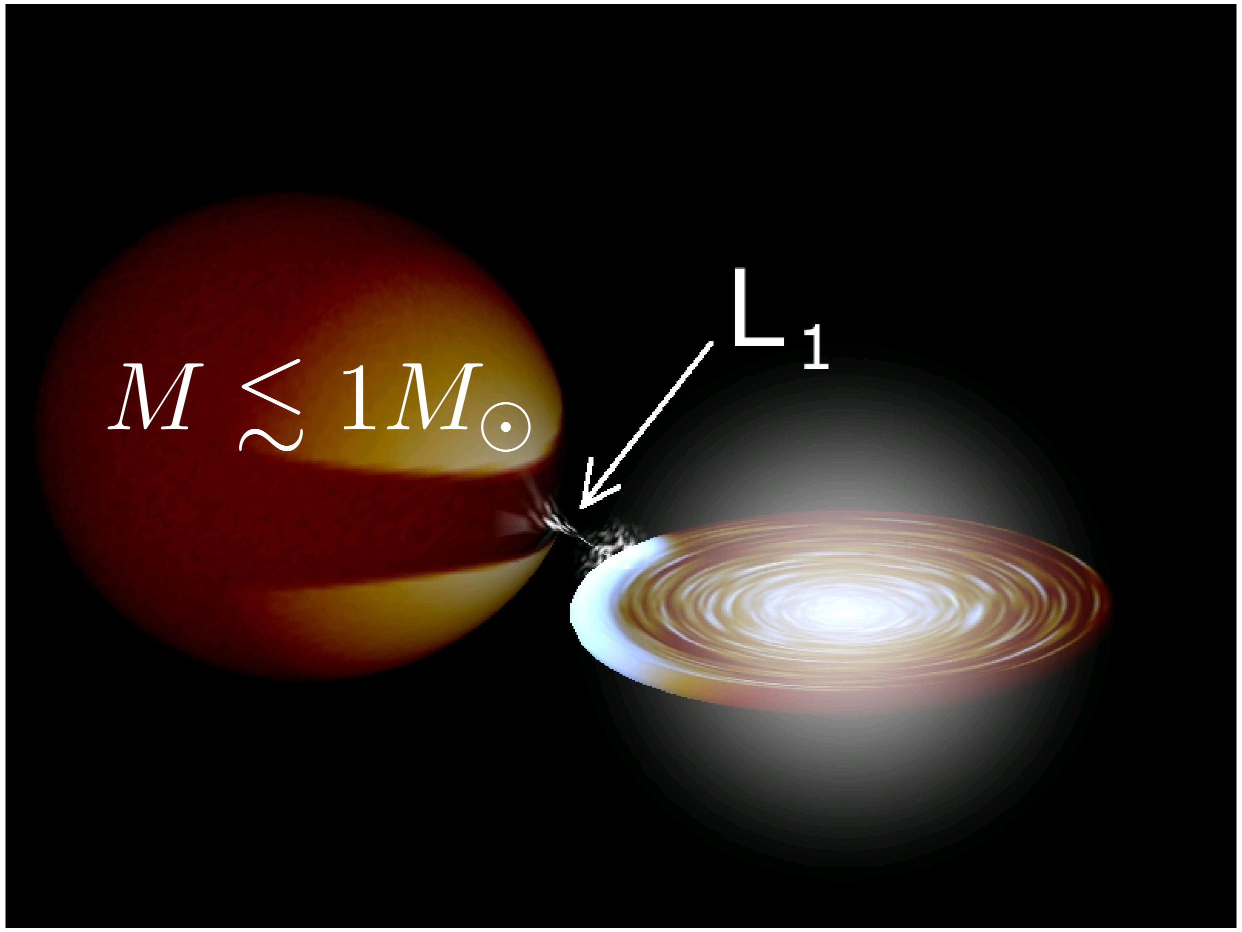
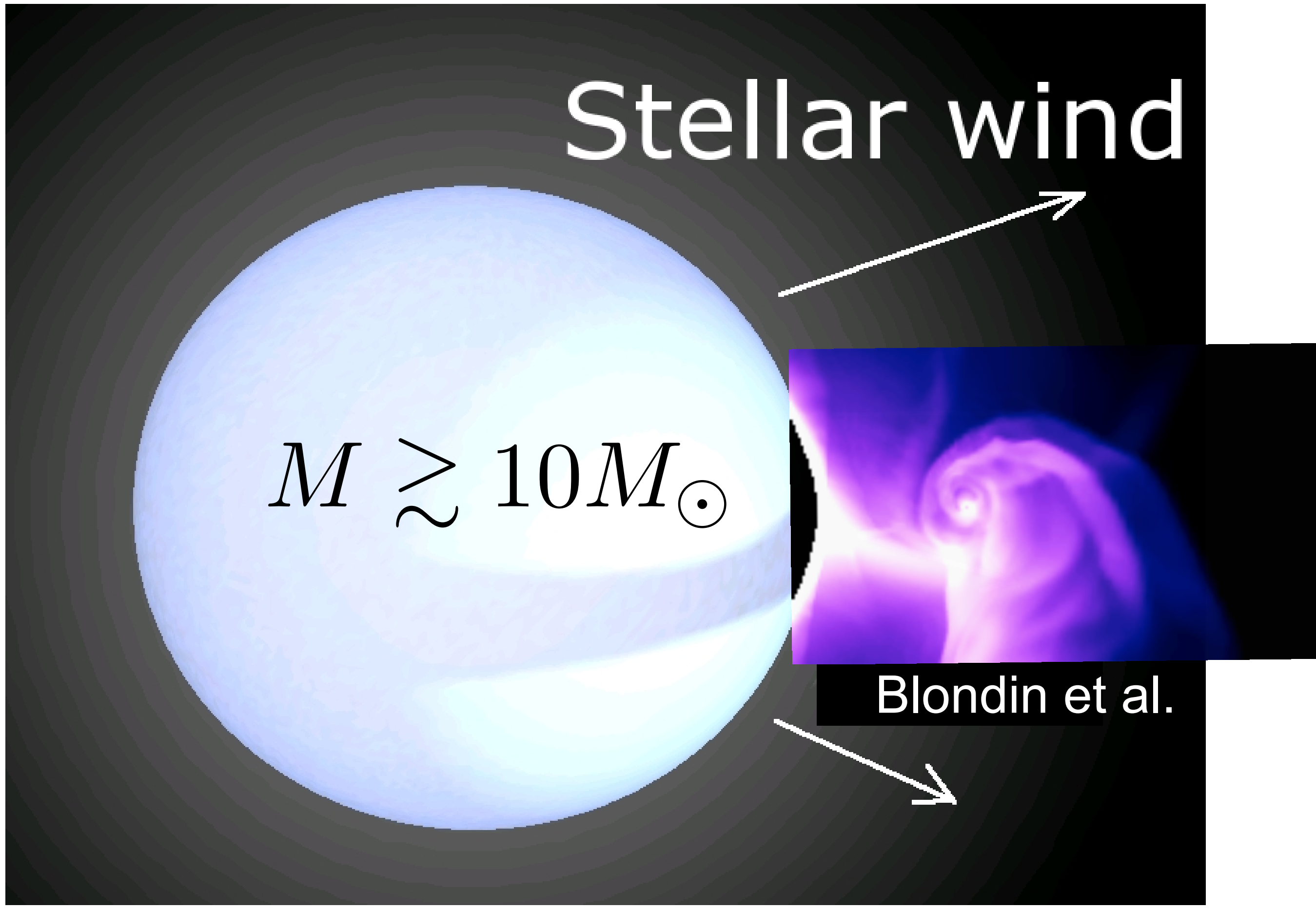
X-ray binaries

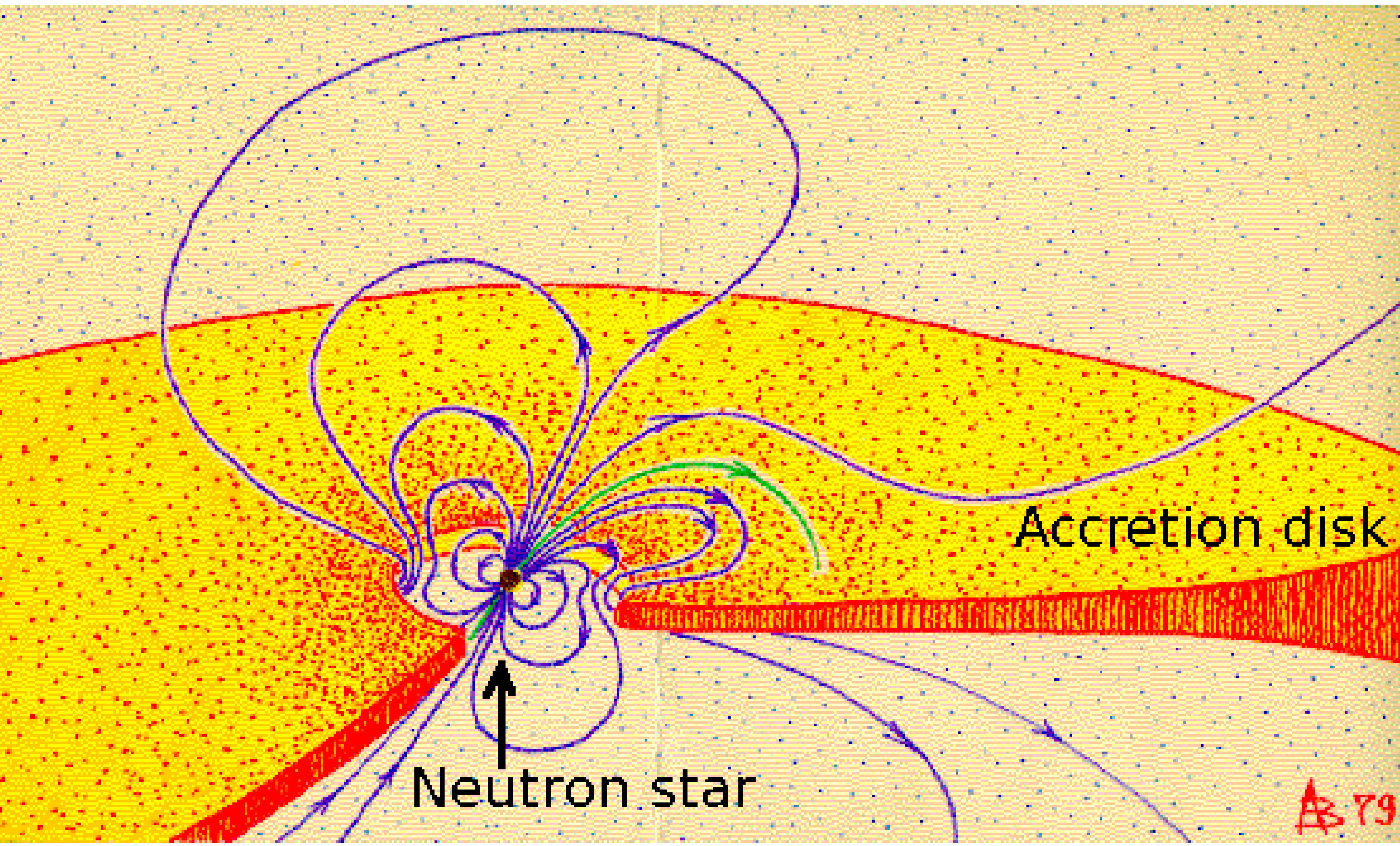
LMXB

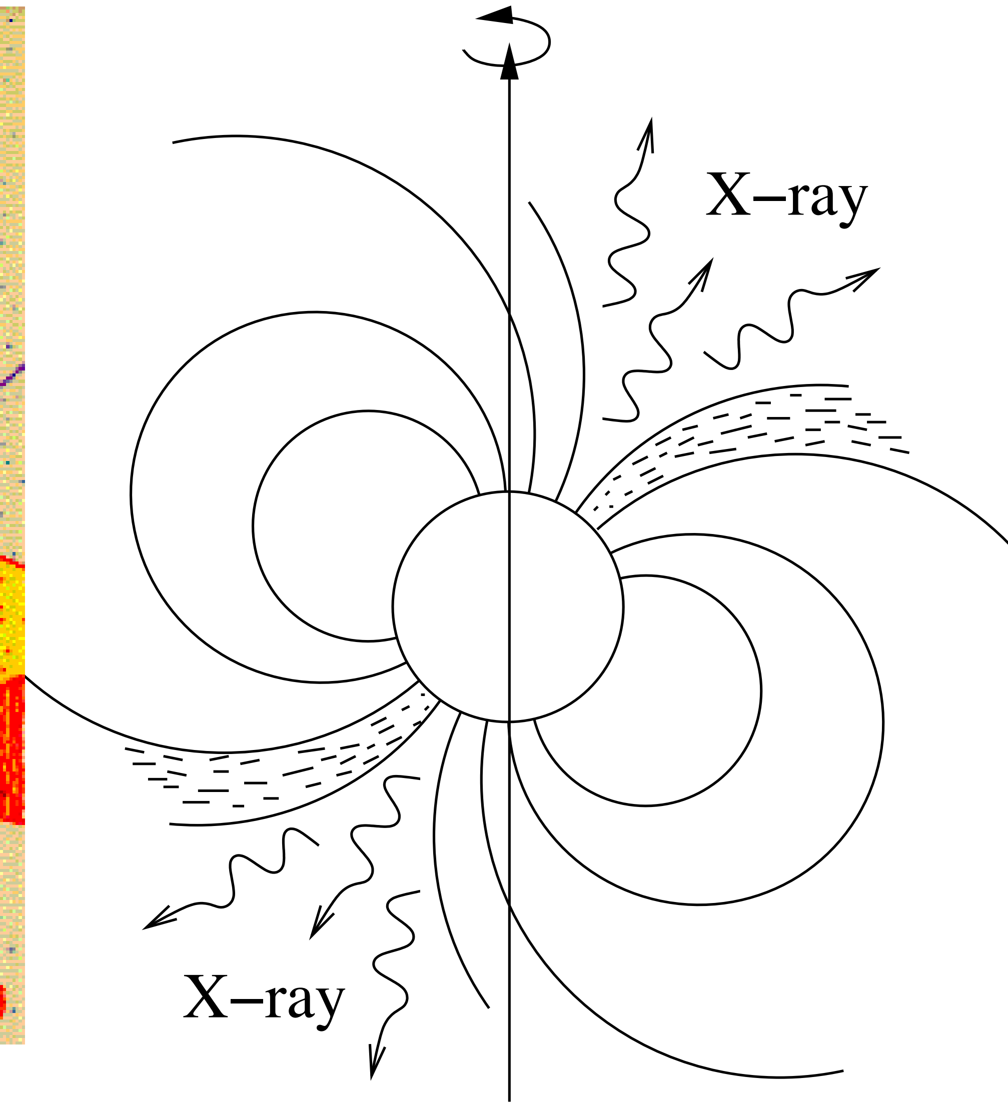


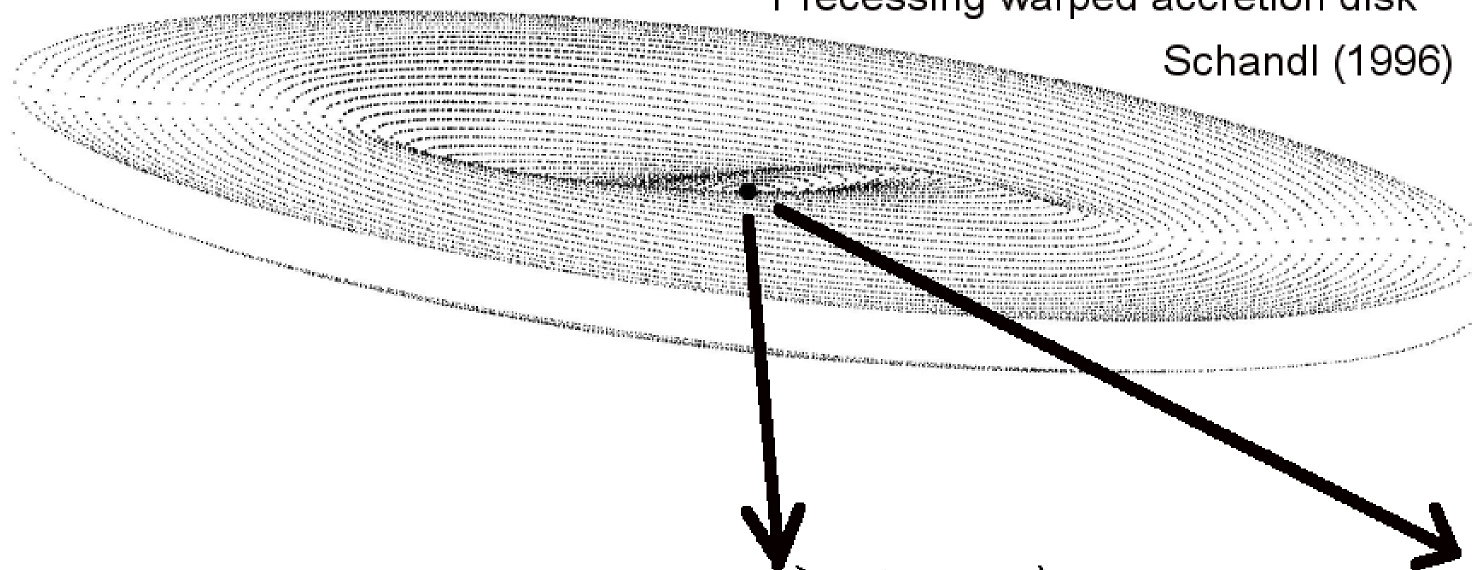
HMXB



Accreting pulsars

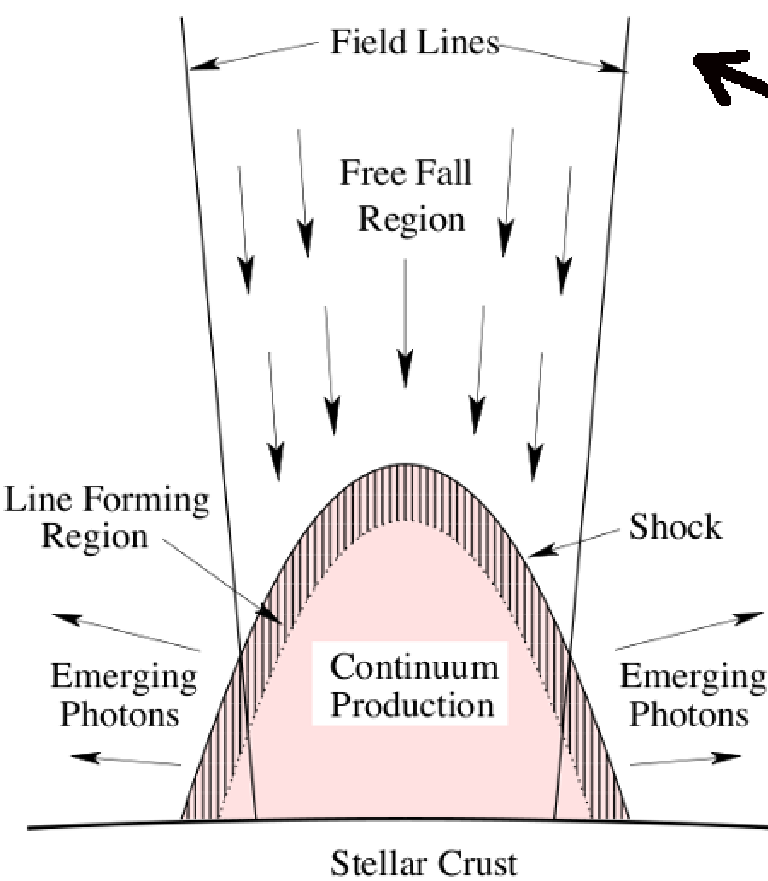




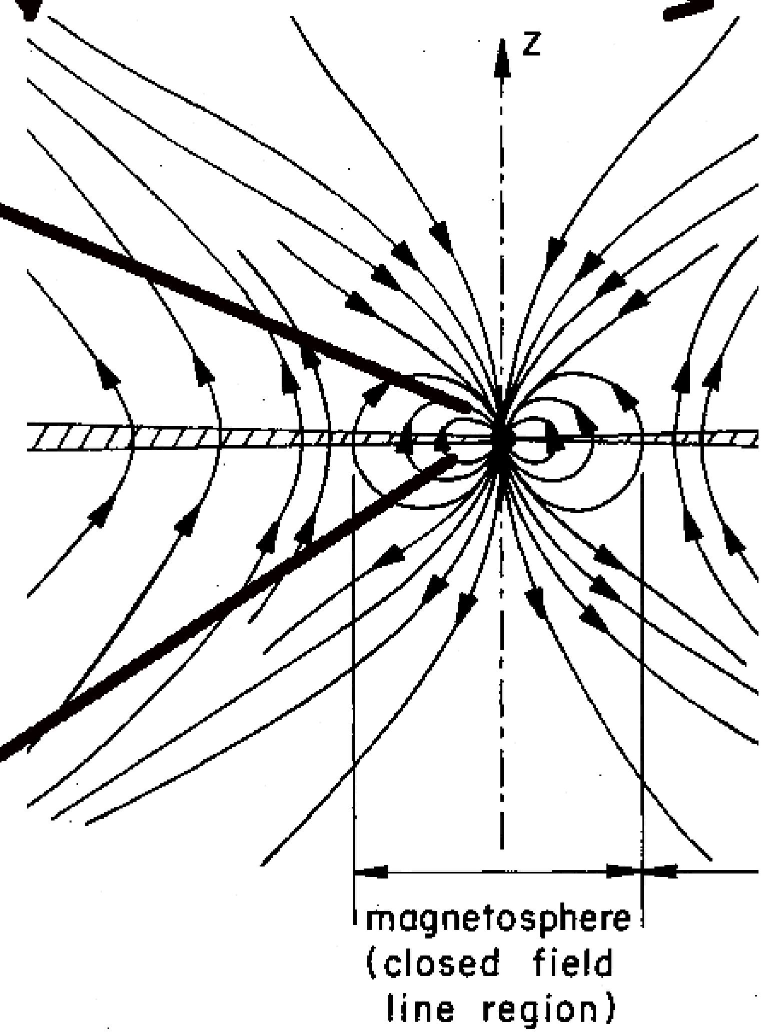


Precessing warped accretion disk

Schandl (1996)

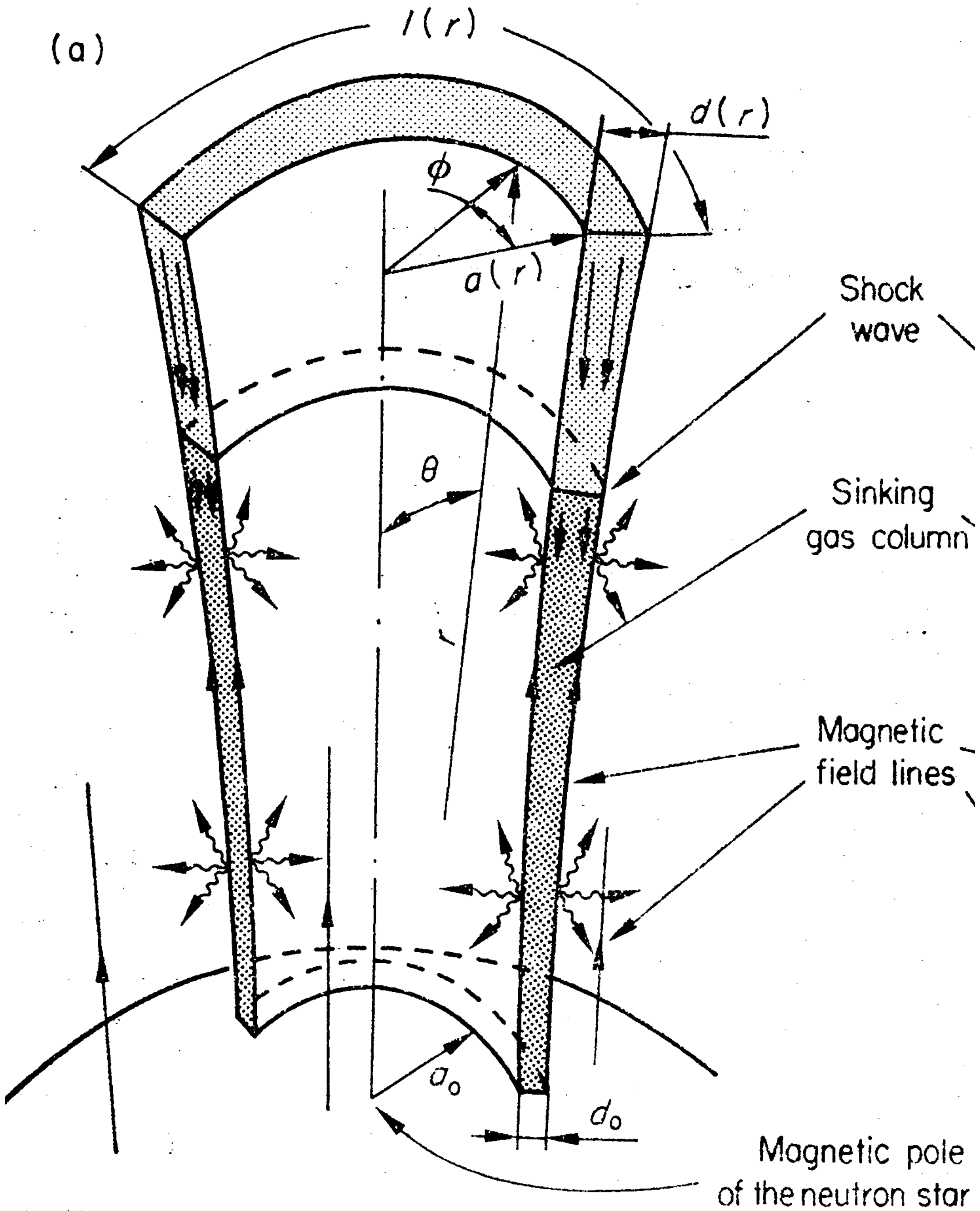


Heindl et al. (2004)

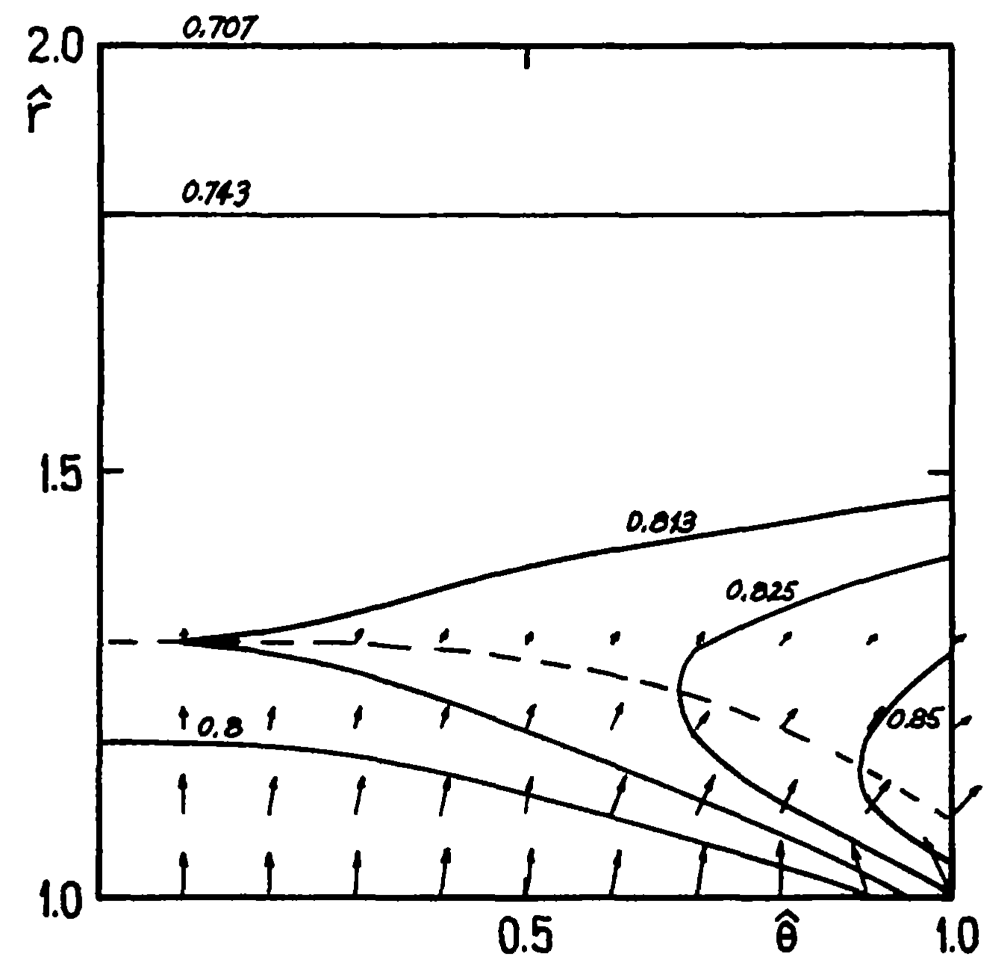


Lovelave & Romanova (1995)

X-ray emitting region



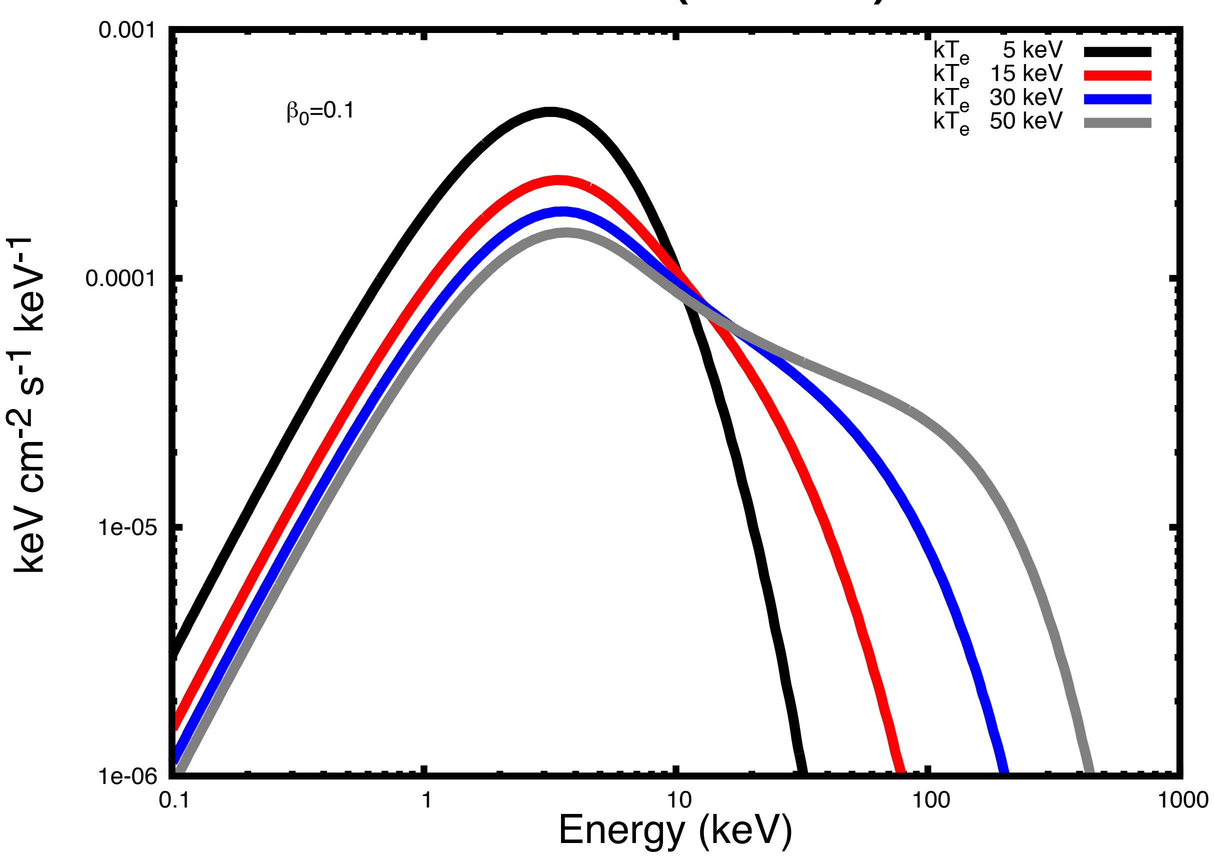
Basko&Sunyaev (1976)



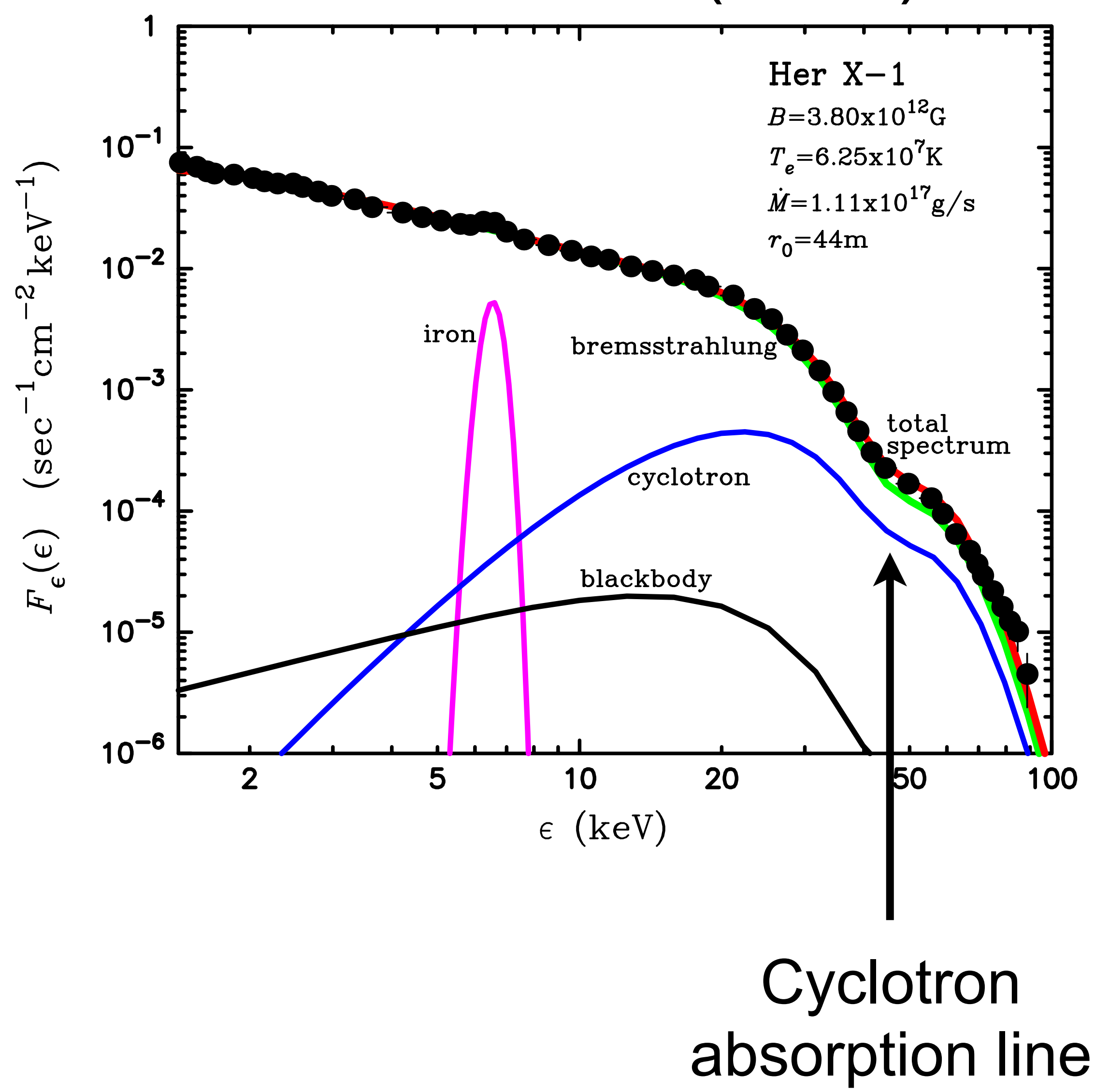
Wang&Frank (1981)

Theoretical modeling of pulsars' X-ray spectra

Farinelli et al. (2012)

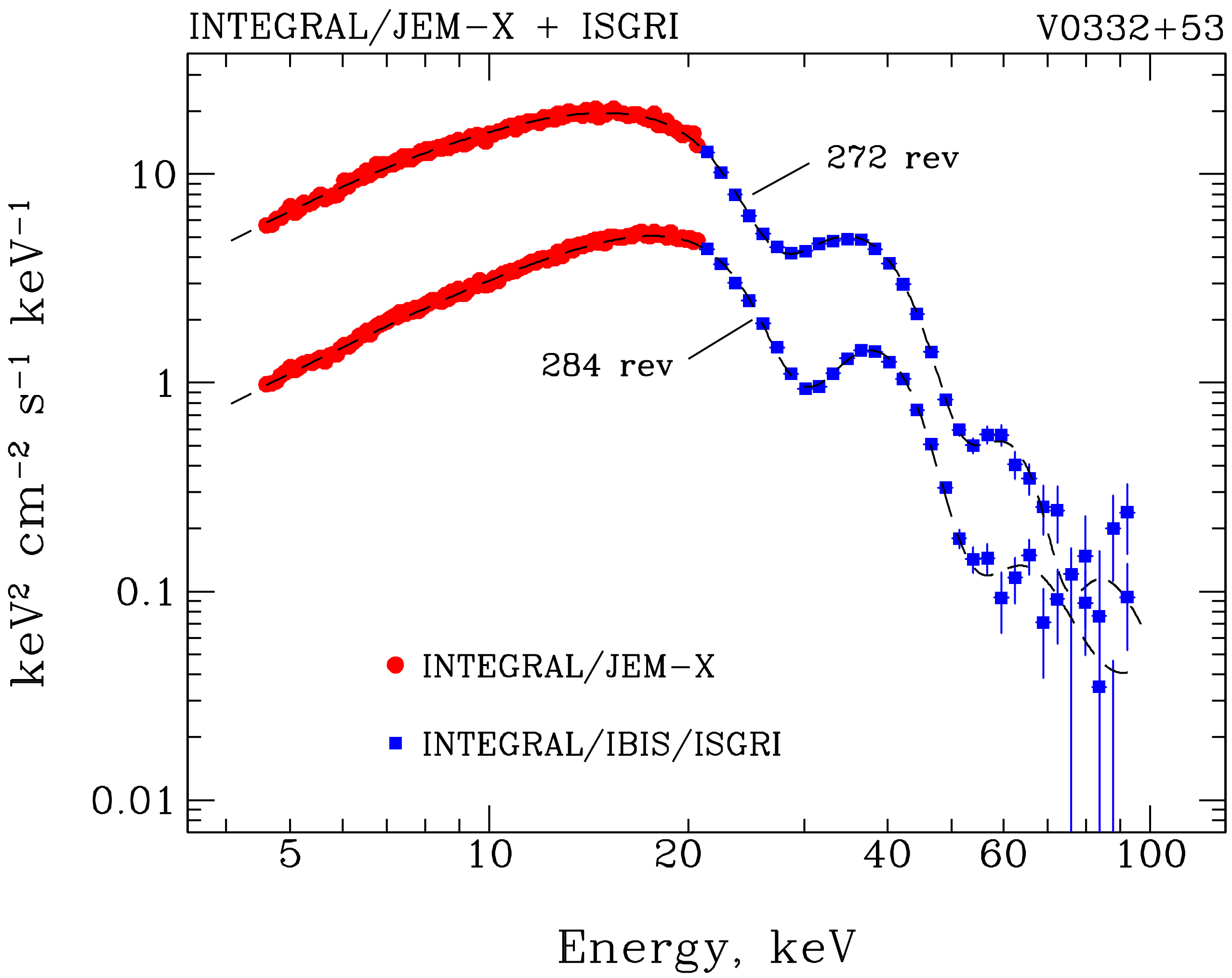


Becker&Wolff (2007)



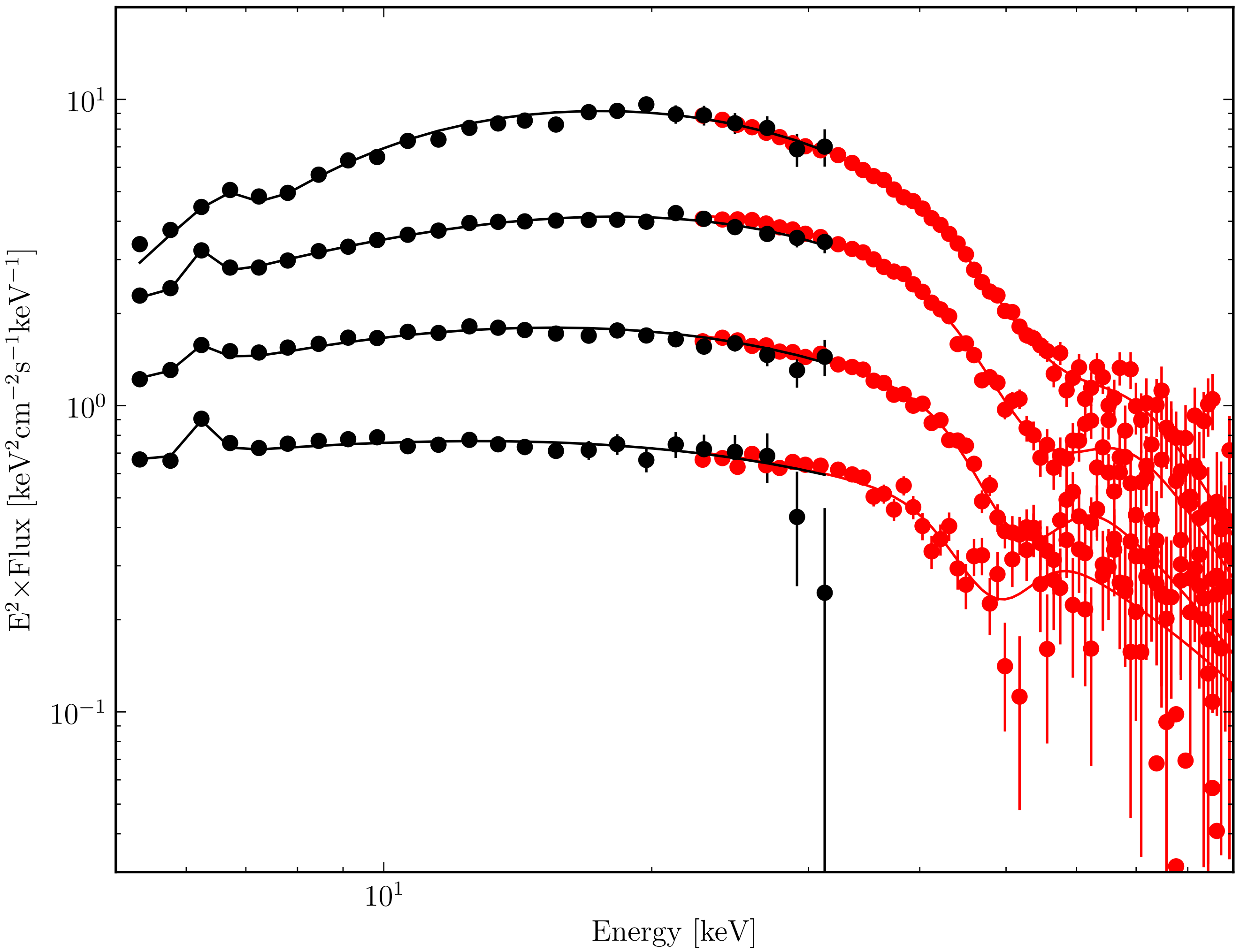
Spectrum-Luminosity dependence

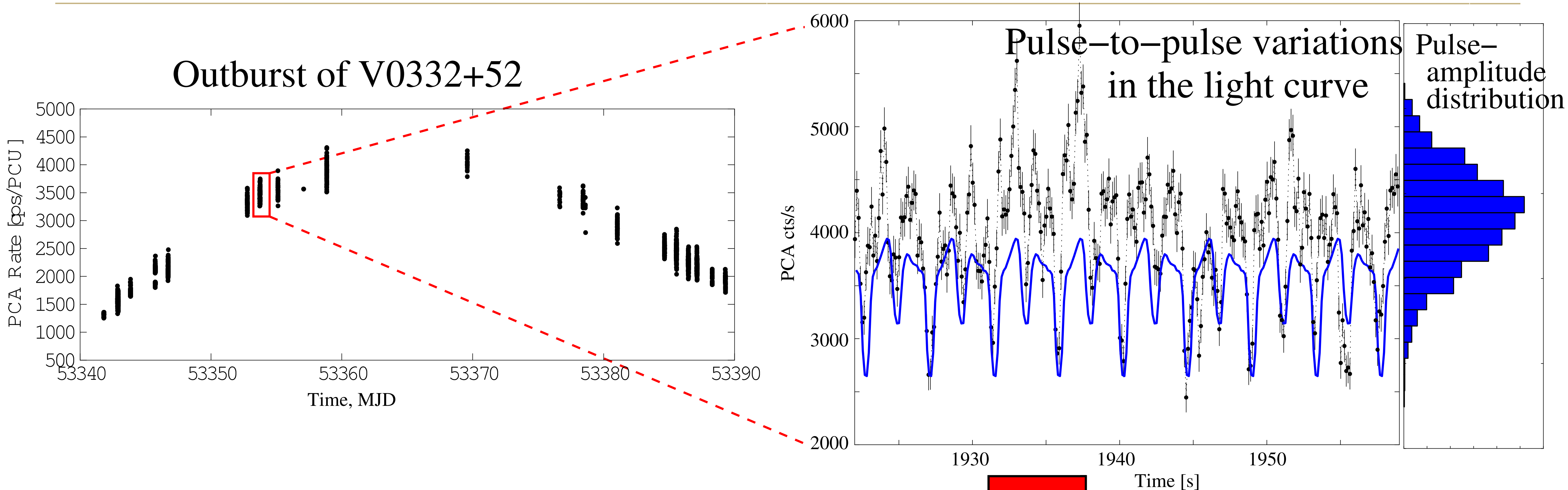
Tsygankov et al. (2006)

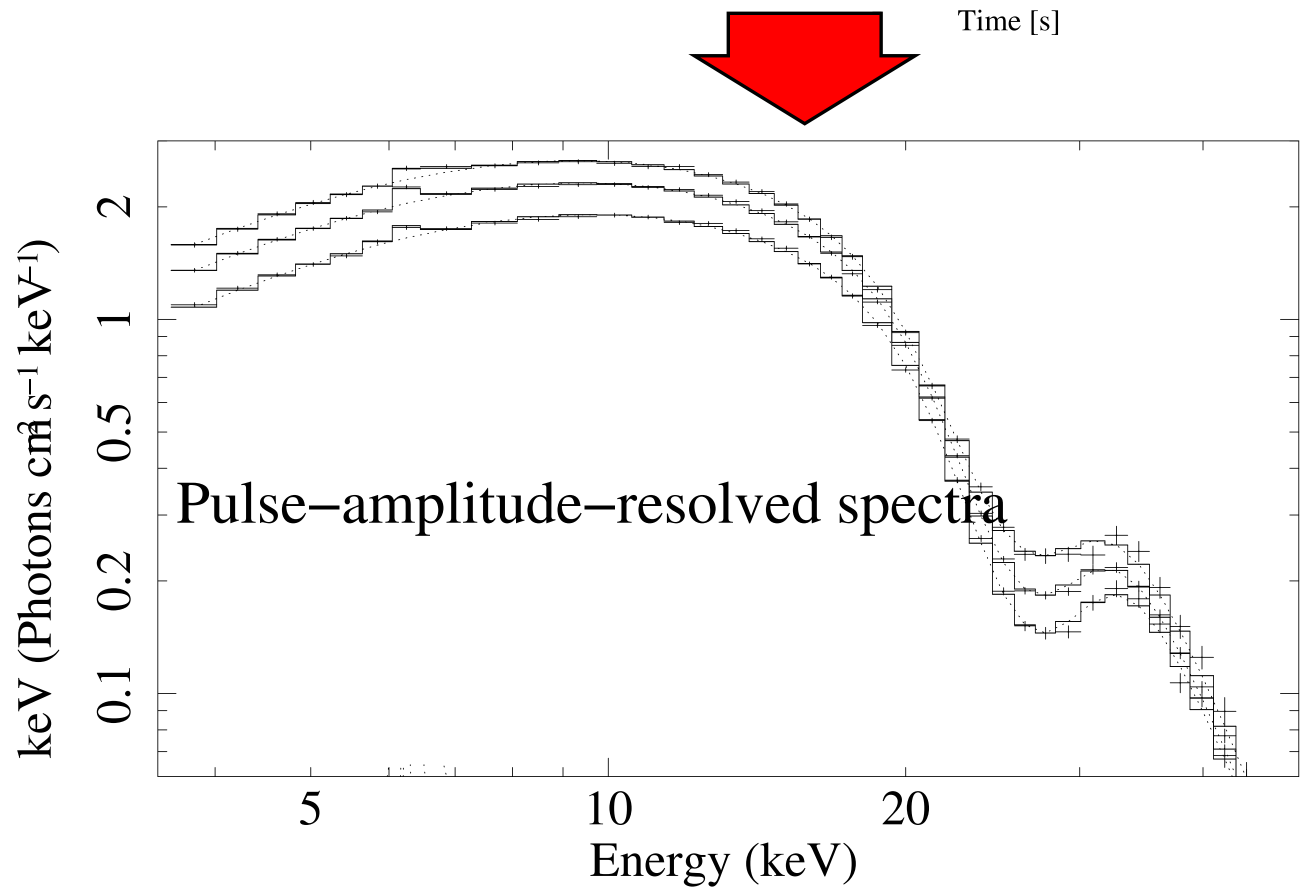


Klochkov et al. (2012)

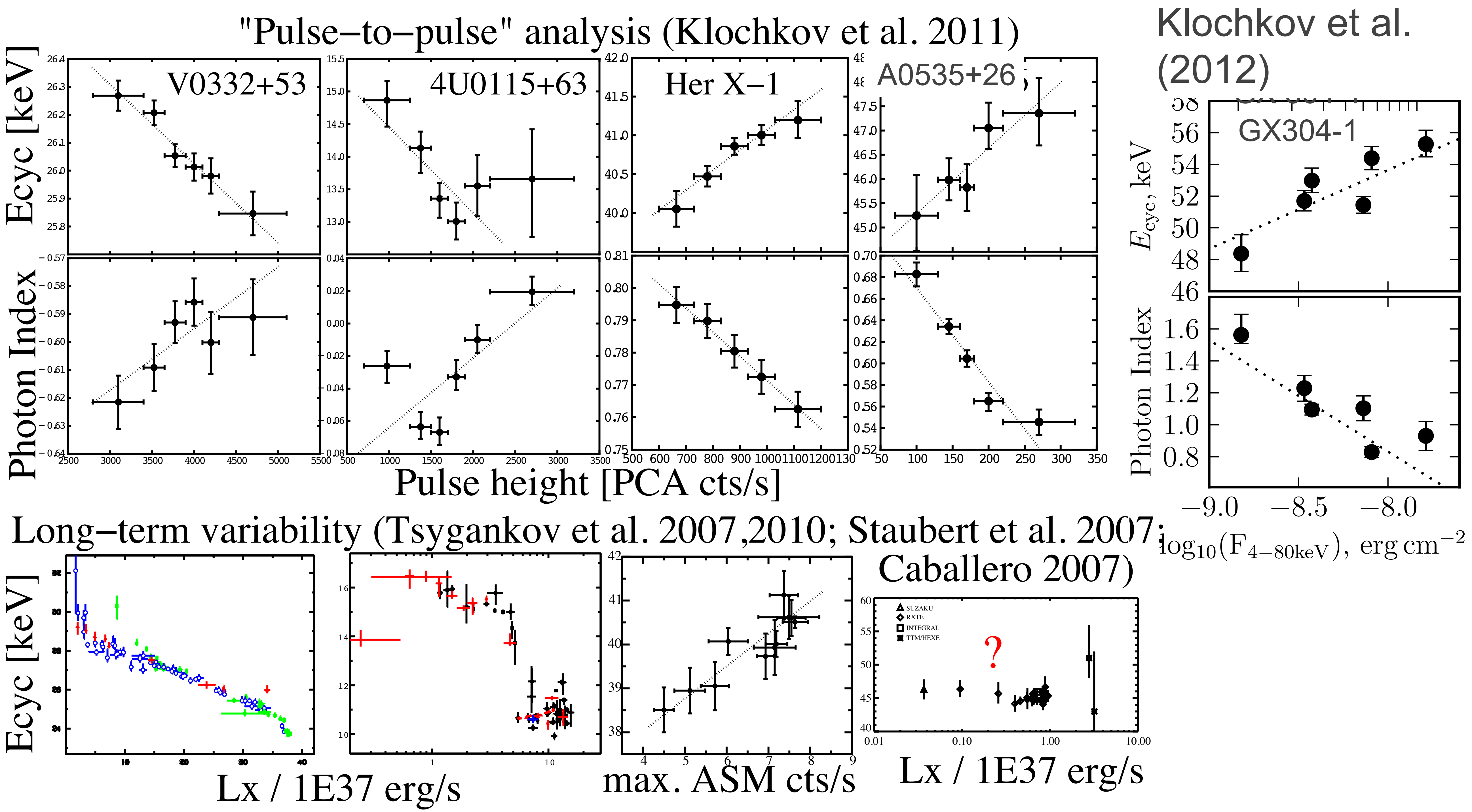
GX 304-1



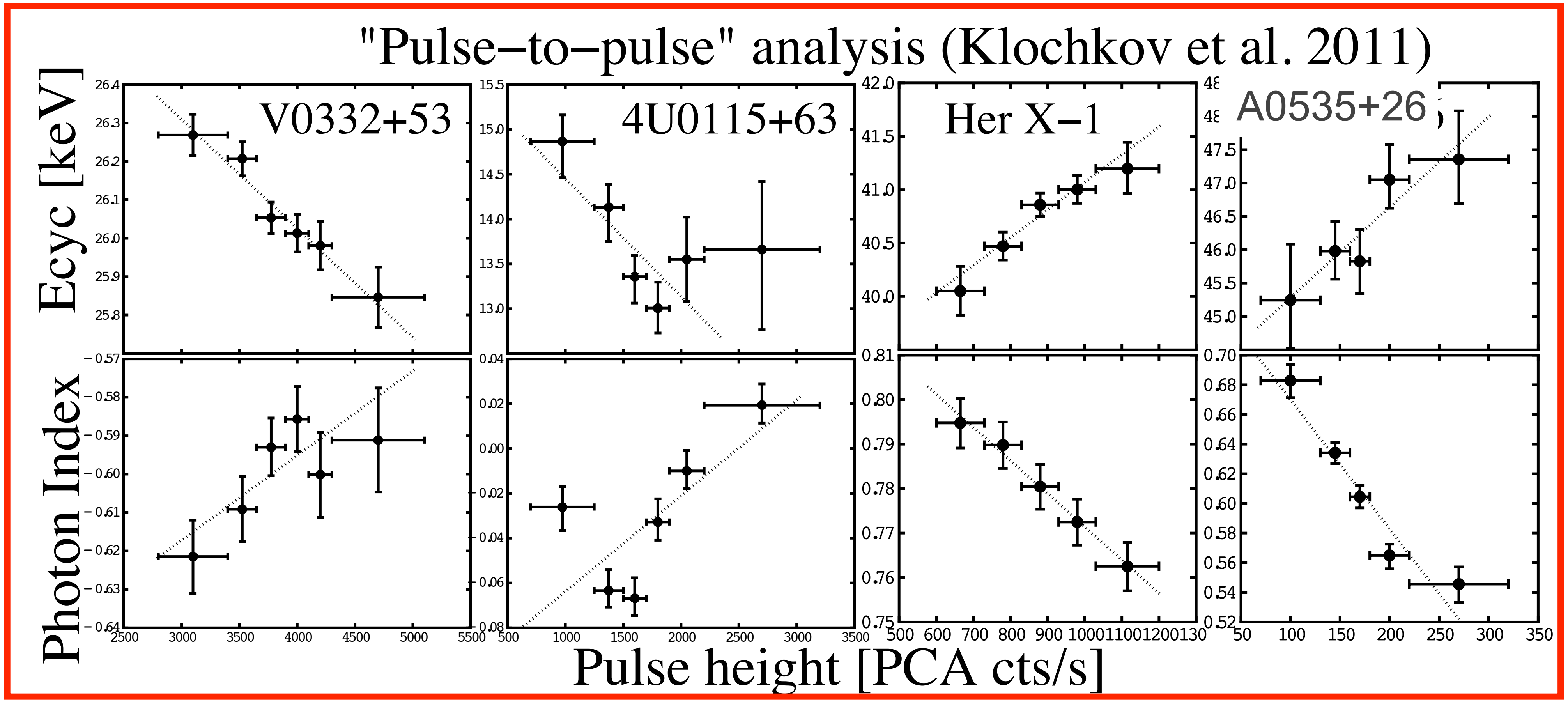


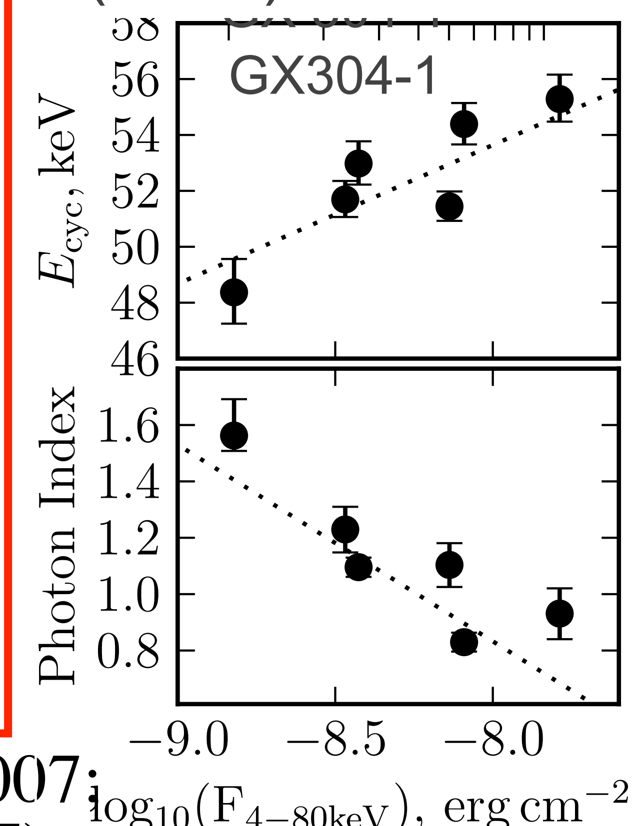


Klochkov et al. (2011)

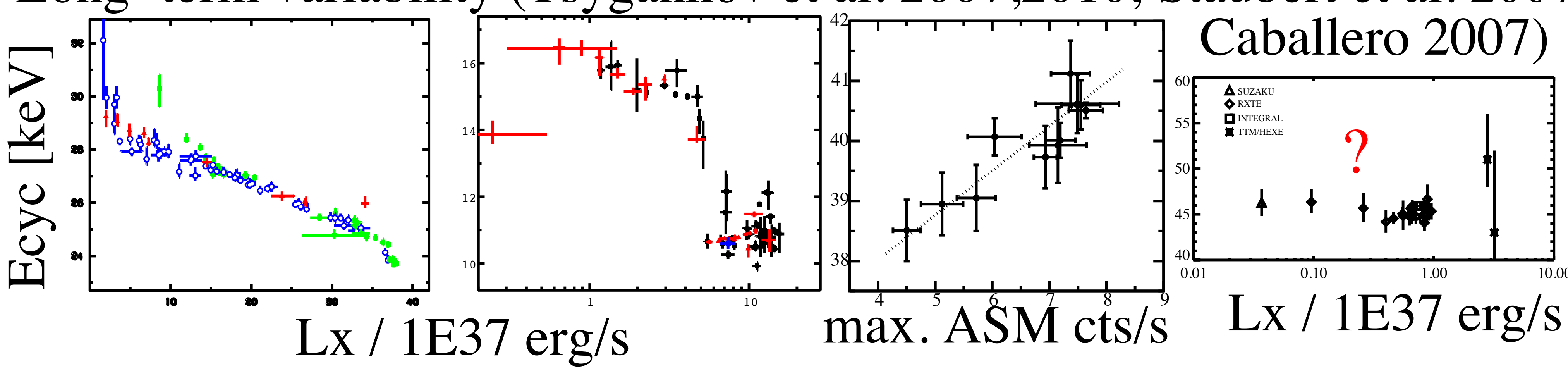

"Pulse–to–pulse" analysis (Klochkov et al. 2011)
Klochkov et al. (2012)
V0332+53
4U0115+63
Her X–1
A0535+26
GX304-1
Ecyc [keV]
Photon Index
Pulse height [PCA cts/s]
E_{cyc}, keV
$\log_{10}(F_{4-80keV})$, erg cm^{-2} s
Long–term variability (Tsygankov et al. 2007,2010; Staubert et al. 2007; Caballero 2007)
Ecyc [keV]
Lx / 1E37 erg/s
max. ASM cts/s
Lx / 1E37 erg/s
SUZAKU
RXTE
INTEGRAL
TTM/HEXE
?

Klochkov et al. (2012)





Long–term variability (Tsygankov et al. 2007,2010; Staubert et al. 2007; Caballero 2007)



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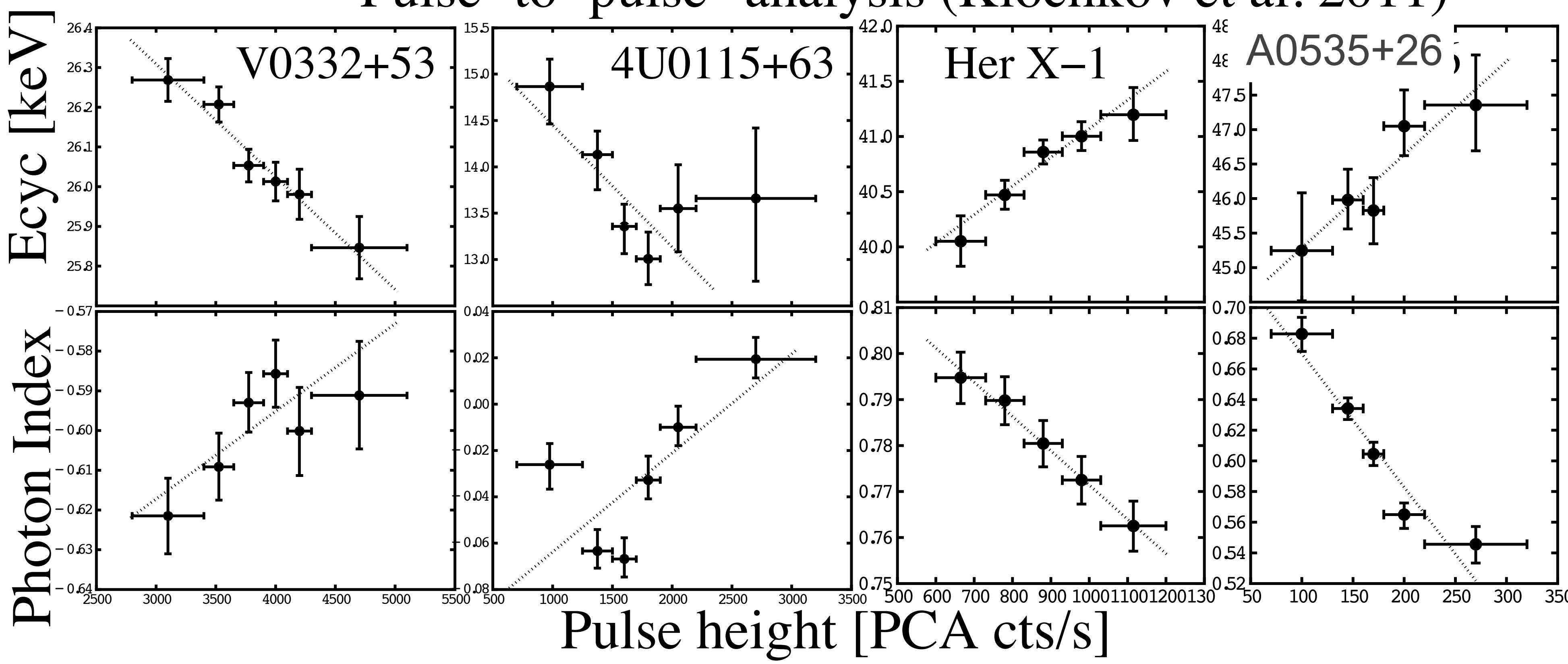
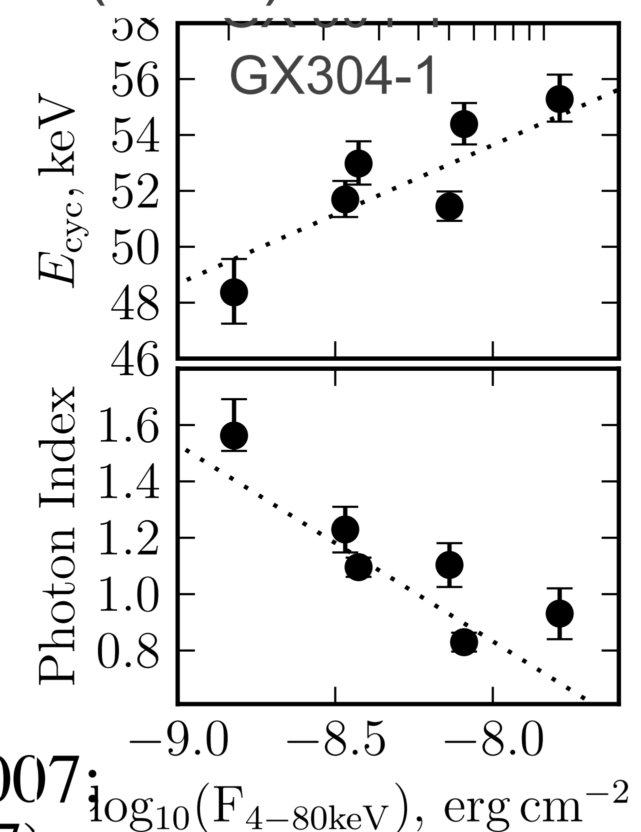


Klochkov et al. (2012)



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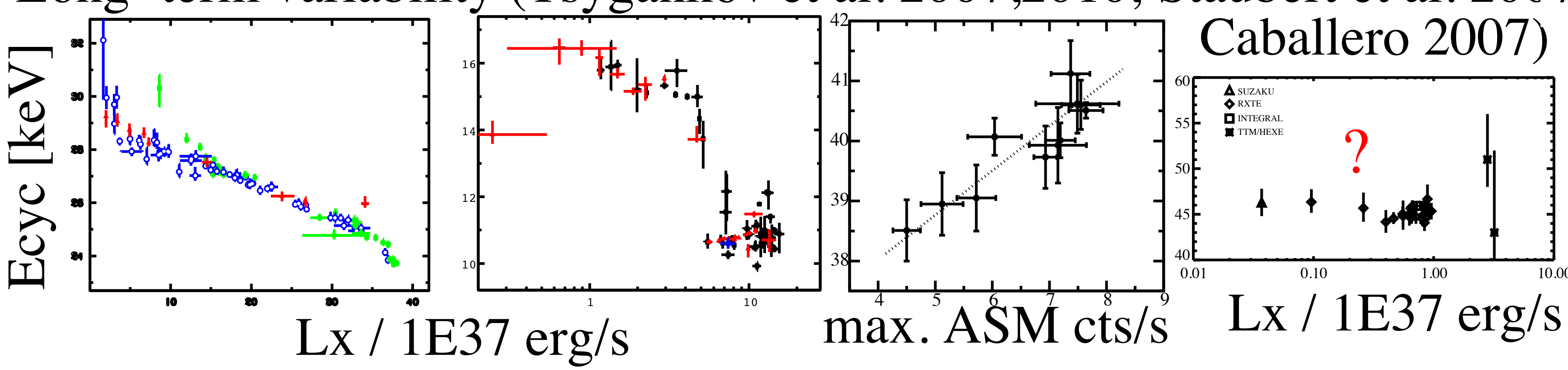

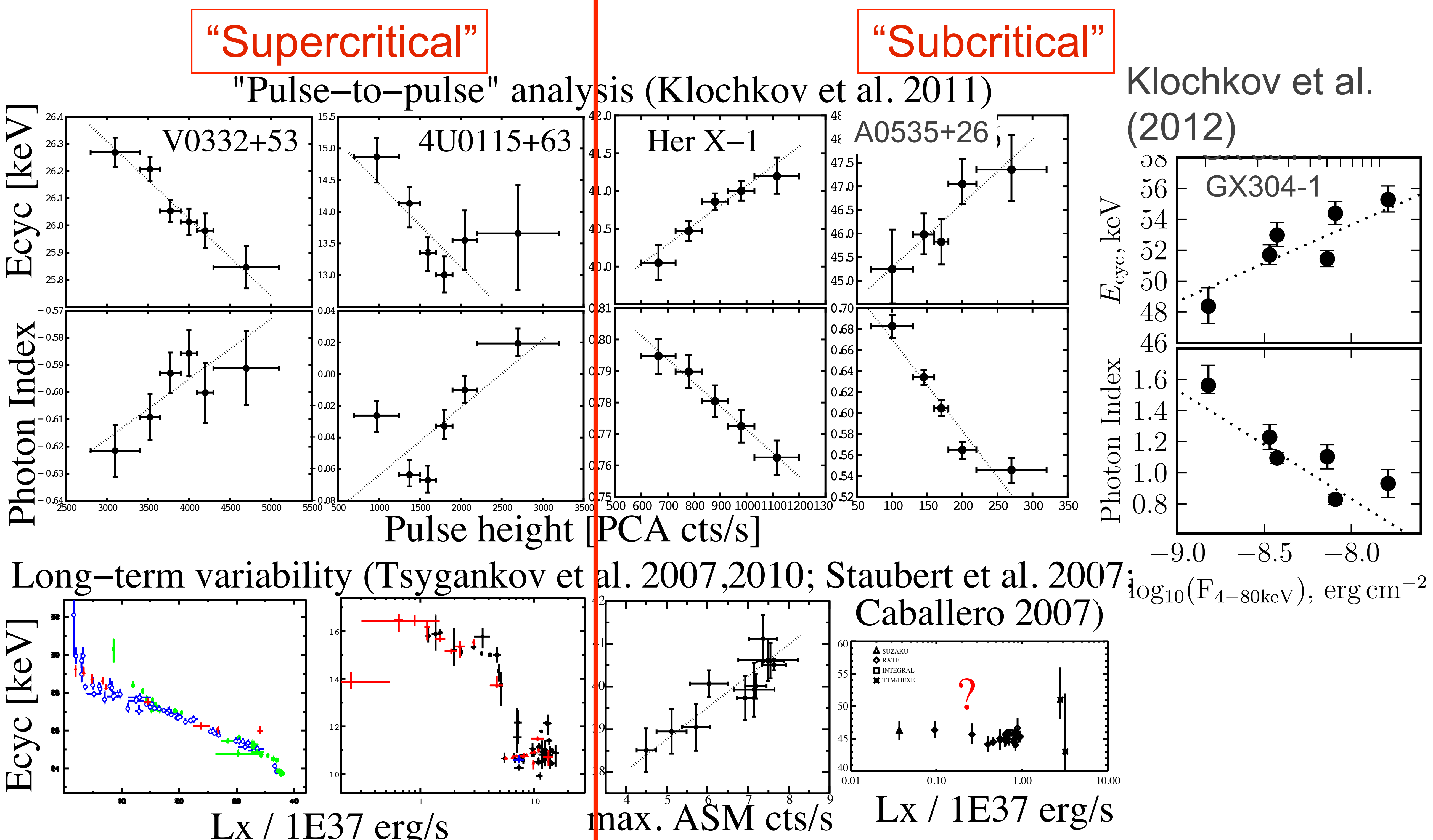
"Supercritical"
"Subcritical"
"Pulse–to–pulse" analysis (Klochkov et al. 2011)
Klochkov et al. (2012)
V0332+53
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Her X–1
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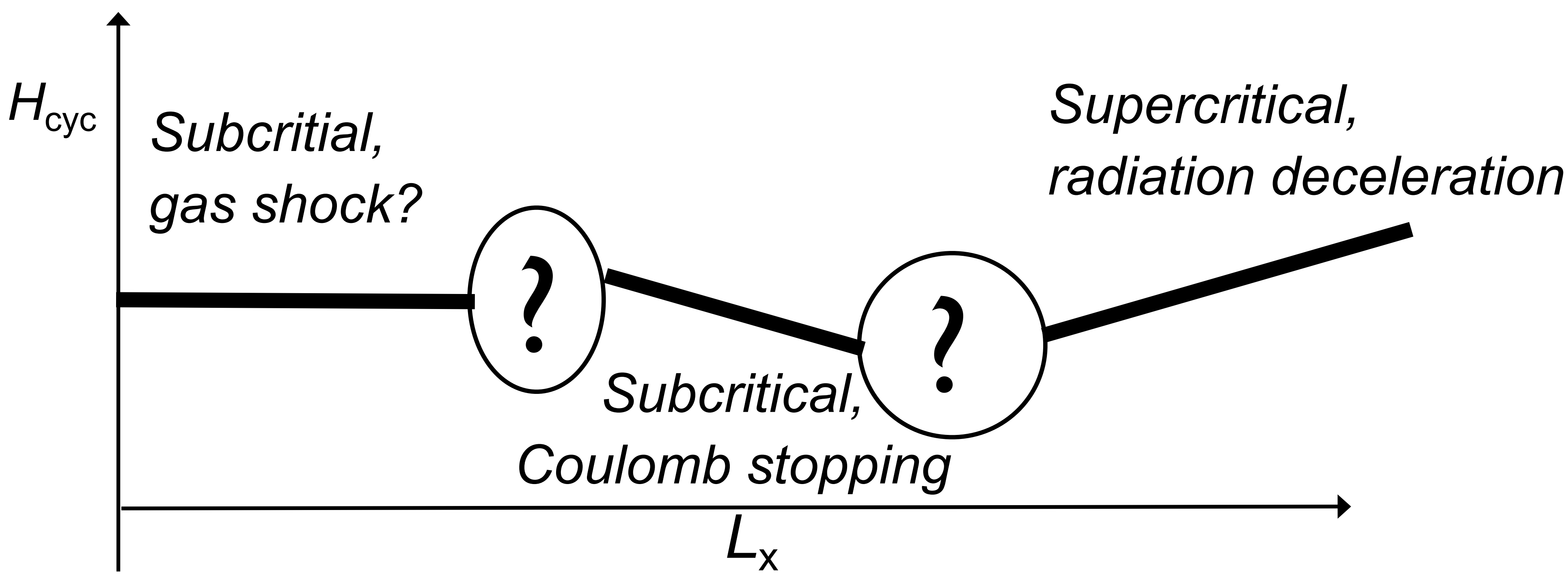
max. ASM cts/s
SUZAKU
RXTE
INTEGRAL
TTM/HEXE
?

Height of the emitting region above the NS surface



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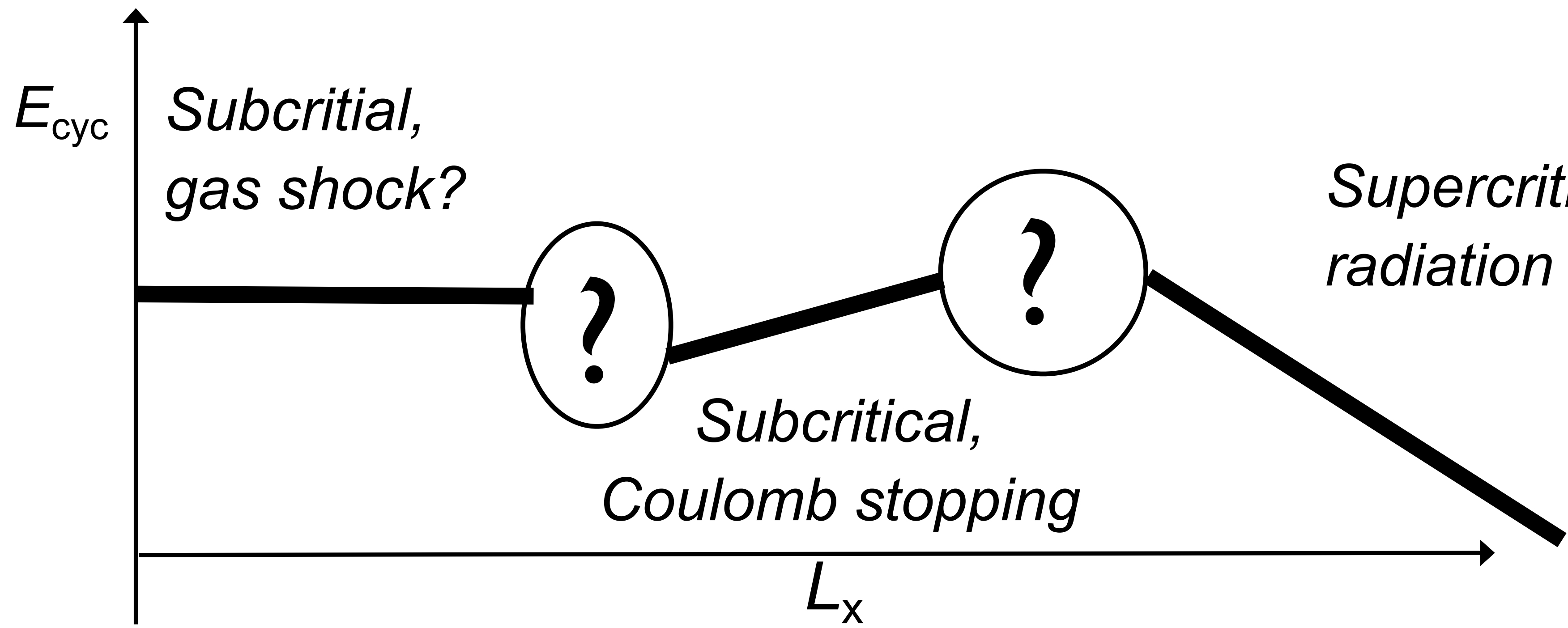

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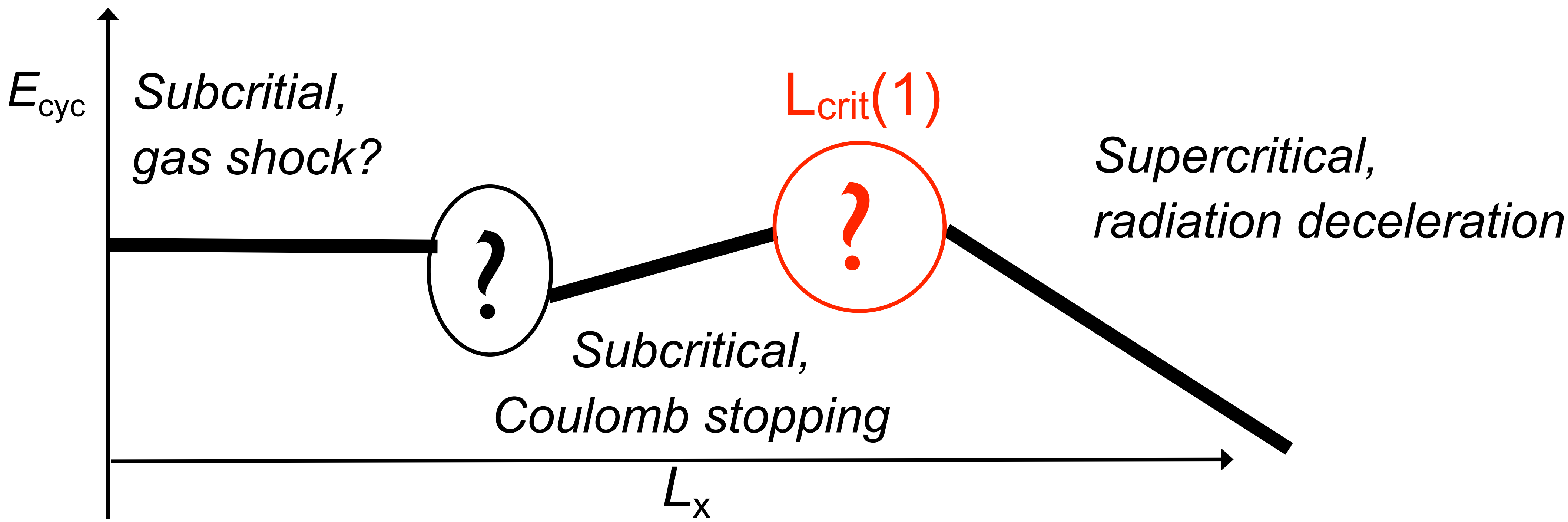
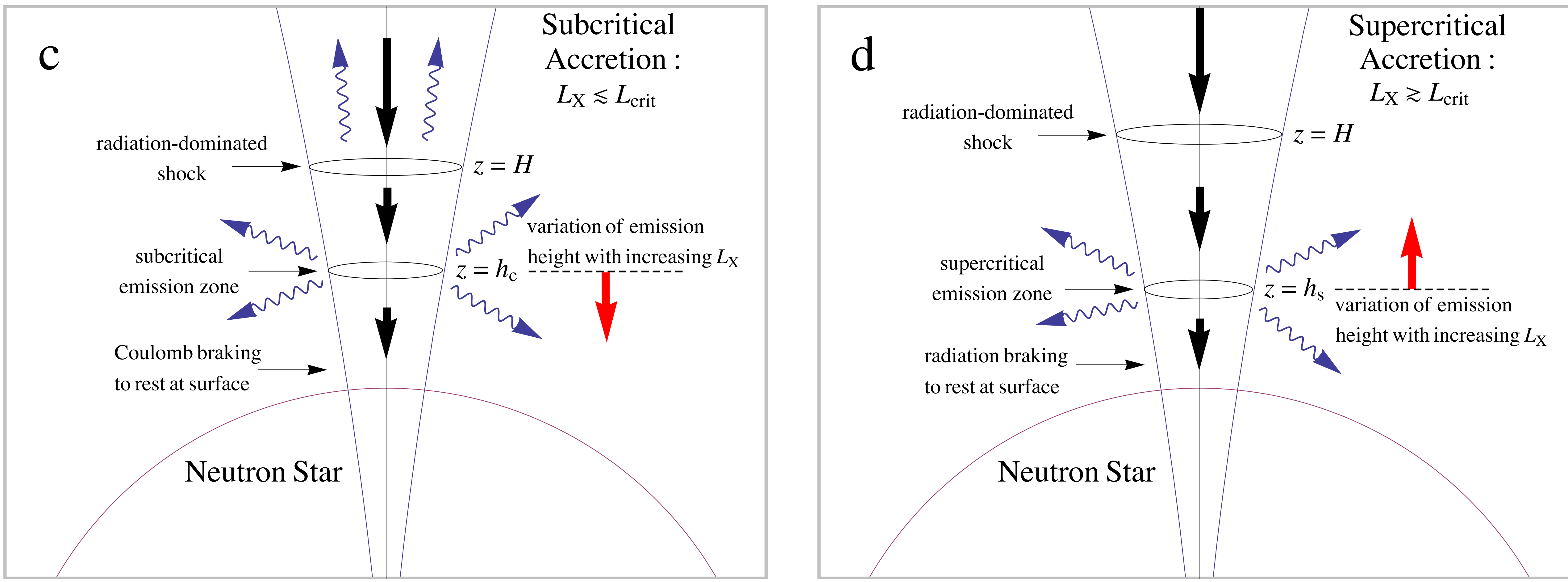
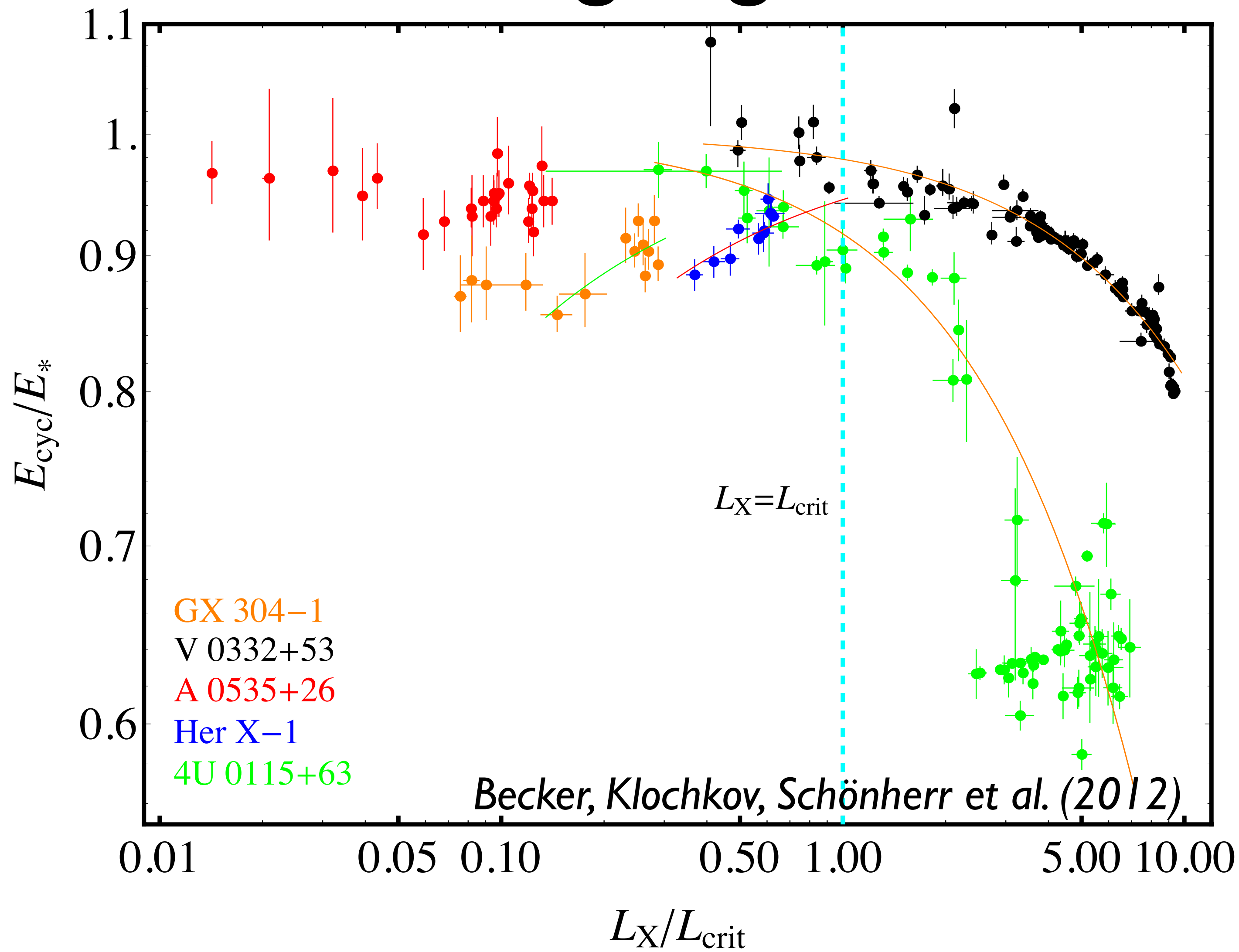


Variations of the emitting region with changing $\dot{M}$



Becker, Klochkov, Schönherr et al. (2012)

Variations of the emitting region with changing $\dot{M}$



$$h_s = 2.28 \times 10^3 \text{ cm} \left(\frac{\xi}{0.01}\right)\left(\frac{M_*}{1.4\ M_\odot}\right)^{-1} \times \left(\frac{R_*}{10\text{ km}}\right)\left(\frac{L_X}{10^{37}\text{ erg s}^{-1}}\right).$$

$$h_c = 1.48 \times 10^5 \text{ cm} \left(\frac{\Lambda}{0.1}\right)^{-1}\left(\frac{\tau_*}{20}\right)\left(\frac{M_*}{1.4\ M_\odot}\right)^{19/14}\left(\frac{R_*}{10\text{ km}}\right)^{1/14} \times \left(\frac{B_*}{10^{12}\text{ G}}\right)^{-4/7}\left(\frac{L_X}{10^{37}\text{ erg s}^{-1}}\right)^{-5/7}. \quad (5$$

http://www.sternwarte.uni-erlangen.de/wiki/doku.php?id=cyclo:start

Source	E_{cyc} [keV]	P_{spin} [s]	$P_{orbital}$ [d]	Companion	T/P
Swift J1626.6-5156	10	15.4	132.9	Be	P
4U 0115+634	14, 24, 36, 48, 62	3.6	24.3	Be	T
4U 1907+09	18, 38	441	8.37	B2 III-IV	P
4U 1538-52	22, 47	530	3.7	B0I	P
Vela X-1	24, 52	283	8.96	B0.5Ib	P
V 0332+53	27, 51, 74	4.37	34.25	Be	T
Cep X-4	28	66.25	>23	B1	T
Cen X-3	29	4.8	2.09	O6.5II	P
X Per	29?	837	250.3	B0 III-Ve	P
RX J0440.9+4431	32	203	155	B0.2 Ve	T
MXB 0656-072	33	160	100?	O9.7Ve	T
XTE J1946+274	36	15.8	169.2	B0-1V-IVe	T
4U 1626-67	37	7.66	0.028	WD?	P
GX 301-2	37	690	41.5	B1.2Ia	P
Her X-1	41	1.24	1.7	A9-B	P
A0535+26	45, 100+	104	110.6	Be	T
1A1118-616	55, 110?	408	400-800?	O9.5IV-Ve	T
GRO J1008-57	88?	93.7	249.46	B1-B2	T
GX 304-1	54	272	132.5	B2 Vne	P

MAGNET Collaboration (based on Caballero&Wilms 2012)

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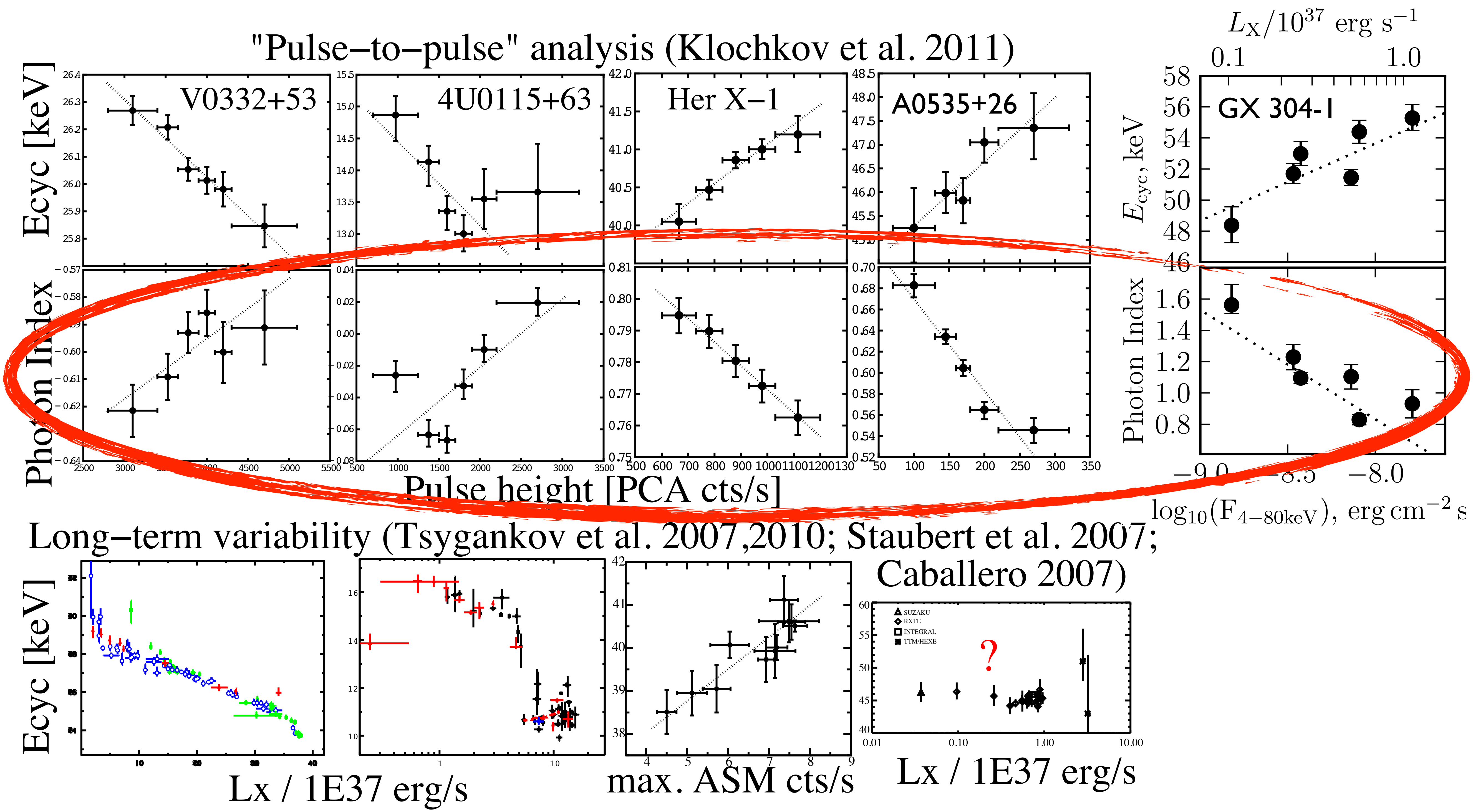
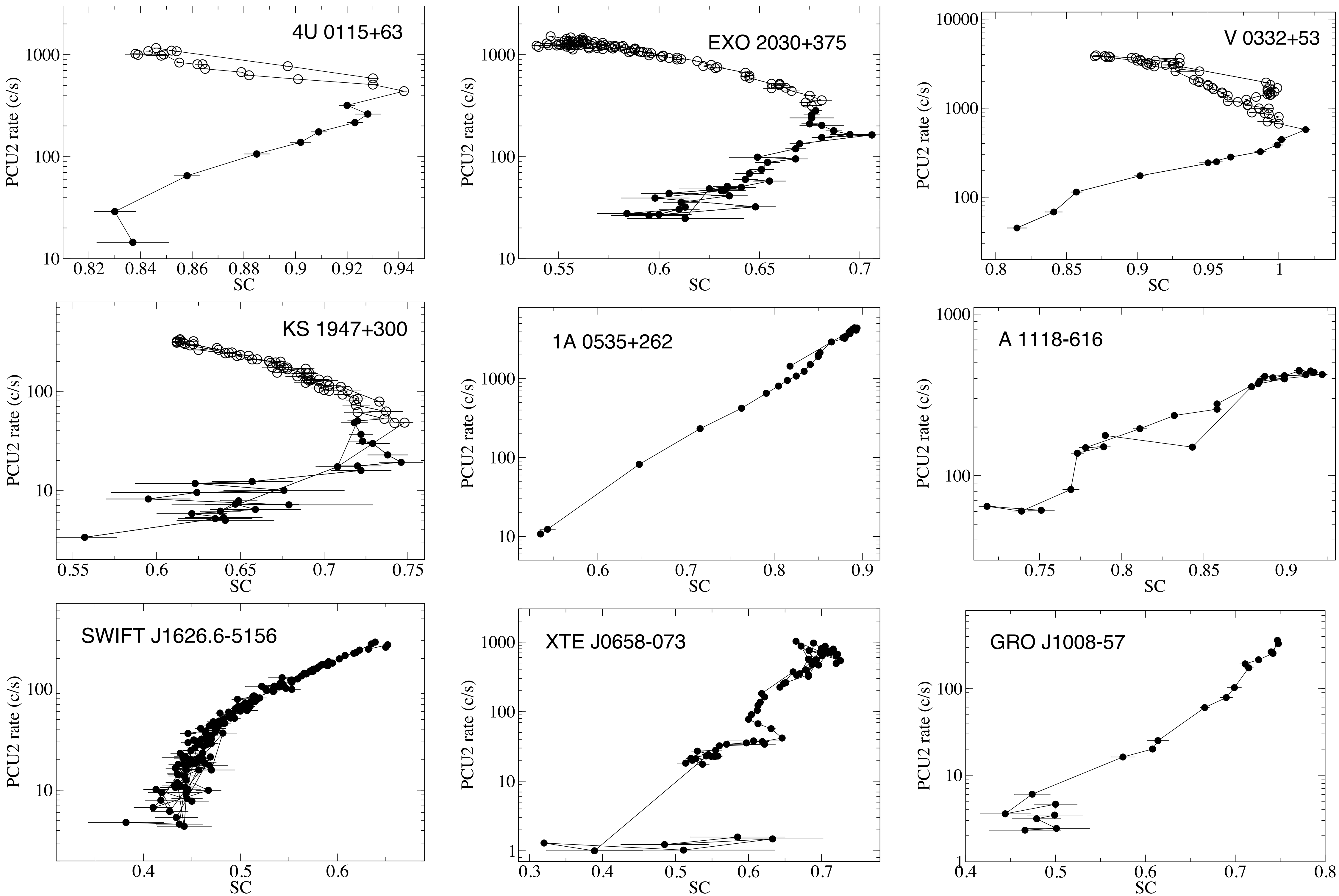
MAGNET Collaboration (based on Caballero&Wilms 2012)

Variations of continuum is an alternative indicator of the accretion regime, not requiring measurements of CRSF

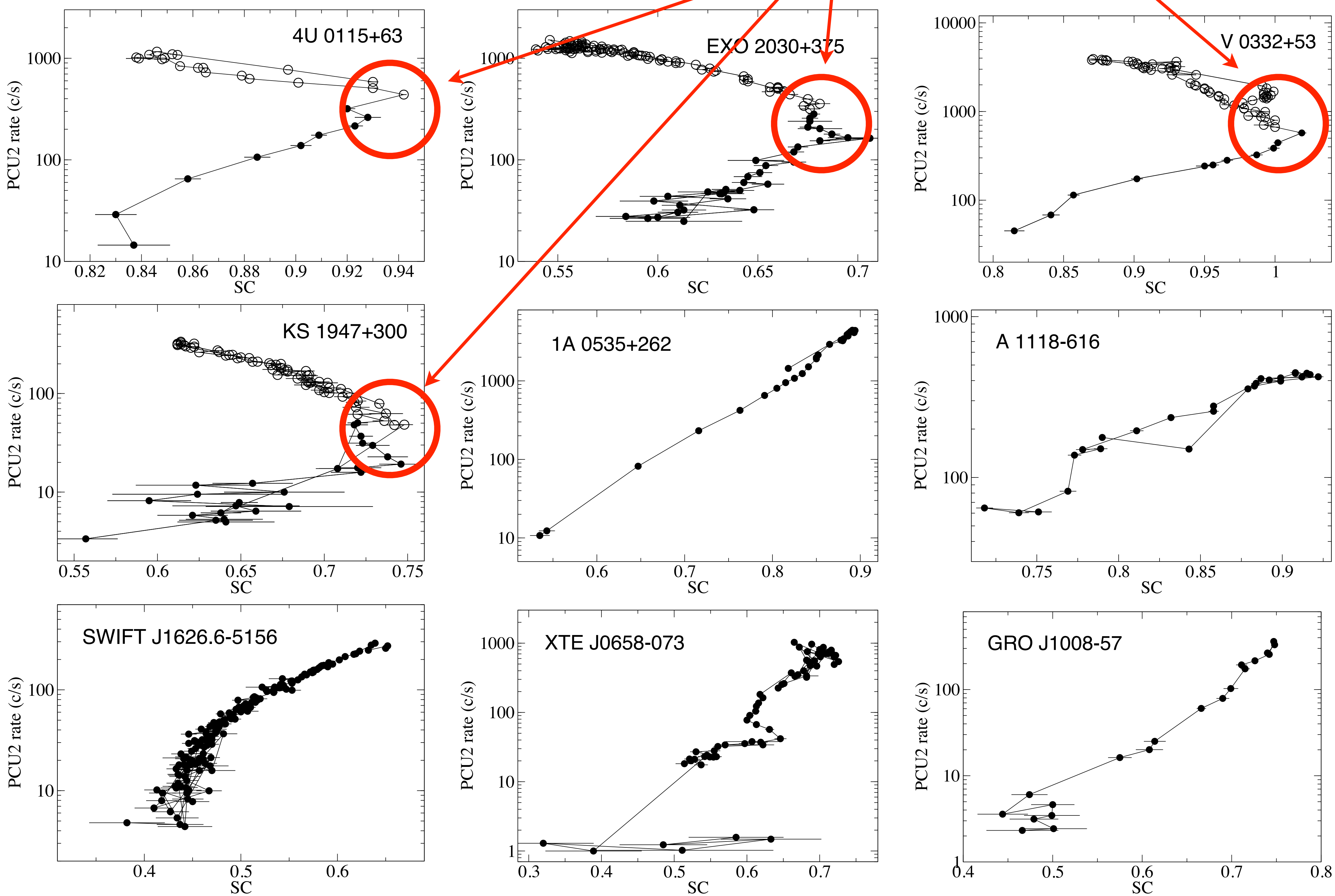


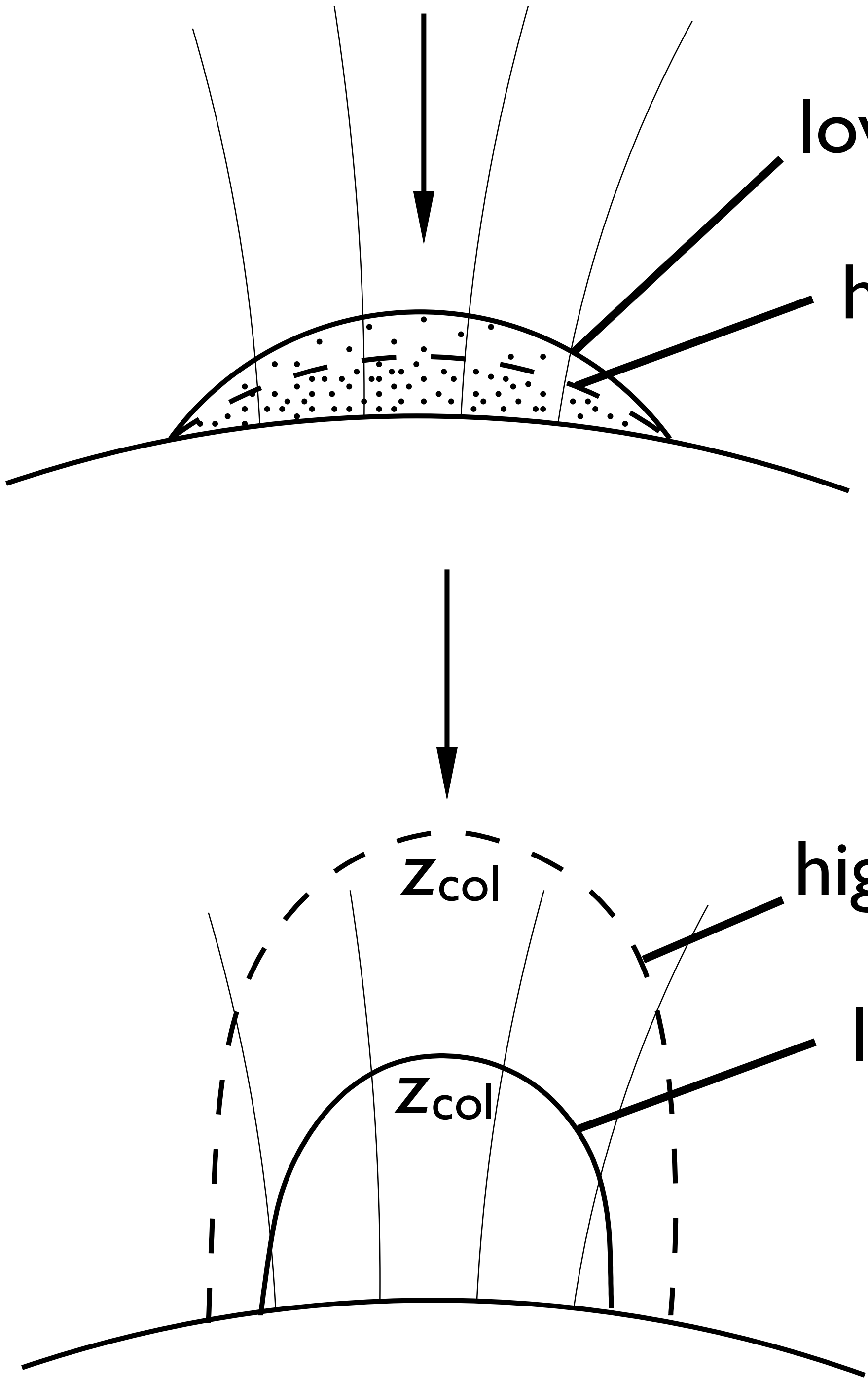
Reig&Nespoli (2012)



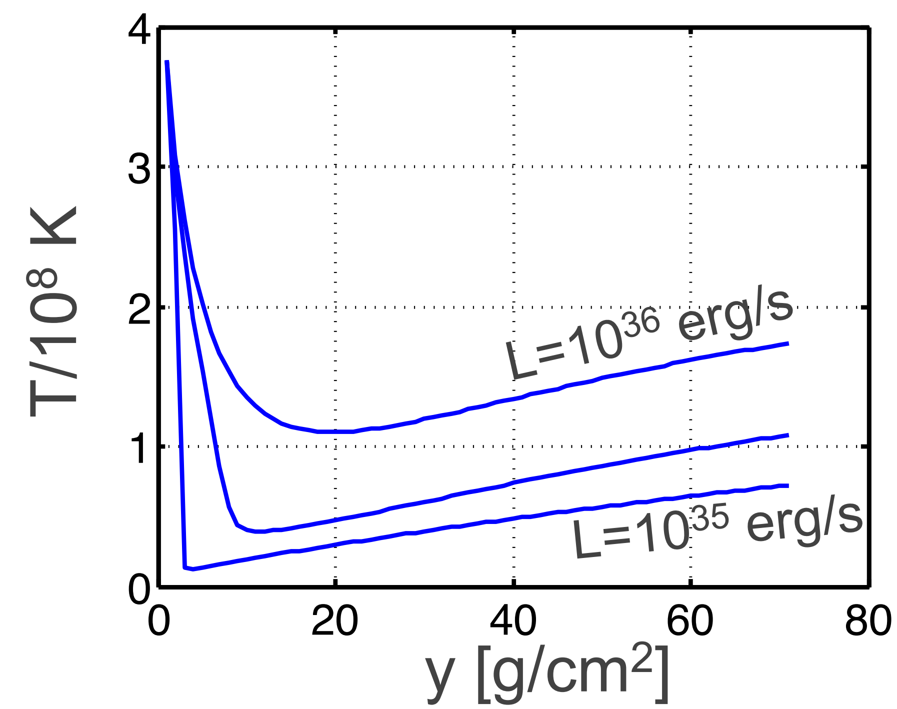
Reig&Nespoli (2012)

L ~ (a few)x10^{37} erg/s

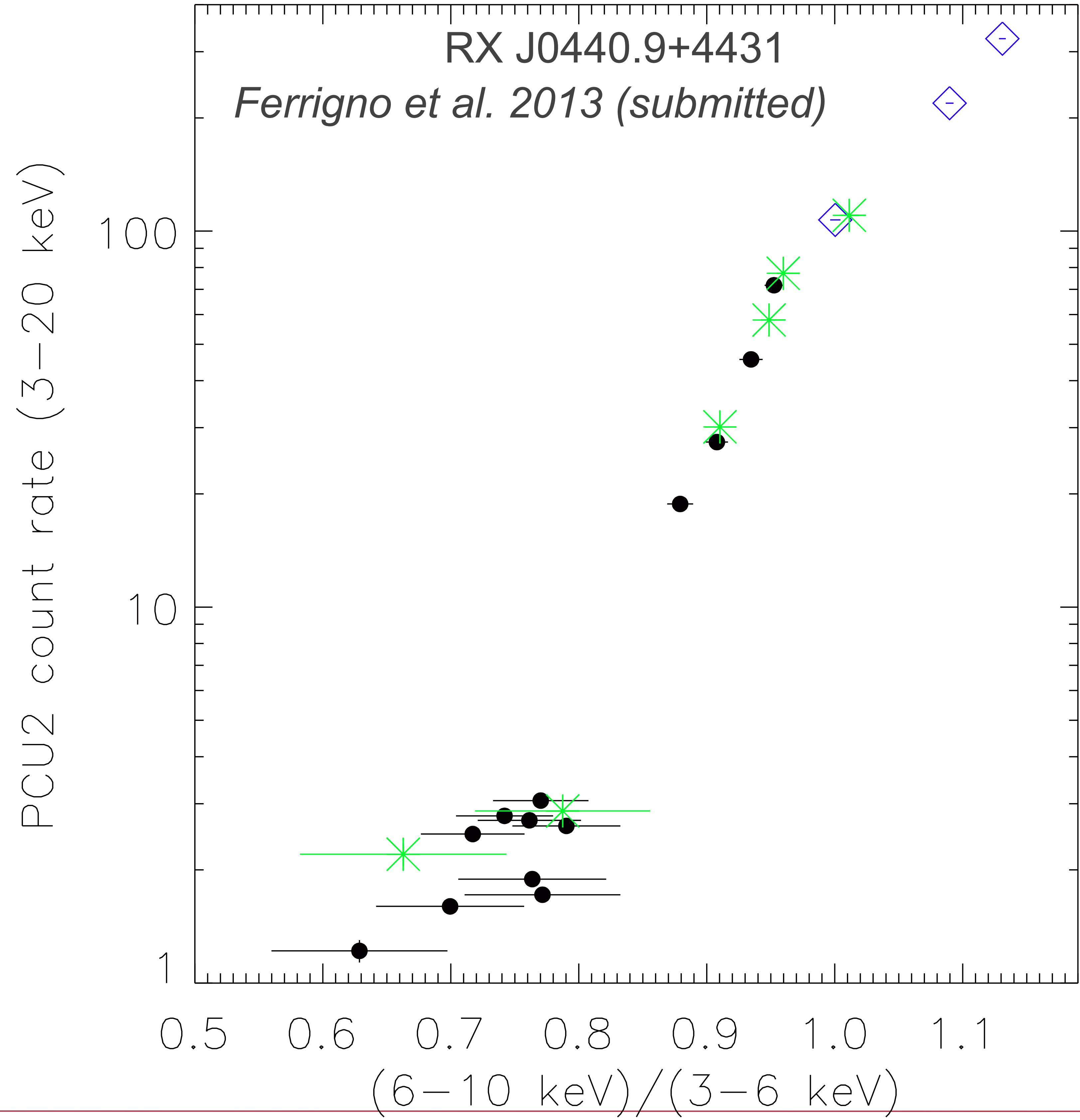




L<L$_c$: An increase of $\dot{M}$ leads to an increase of n_e, T_e и τ_{Compt} → a **harder** continuum

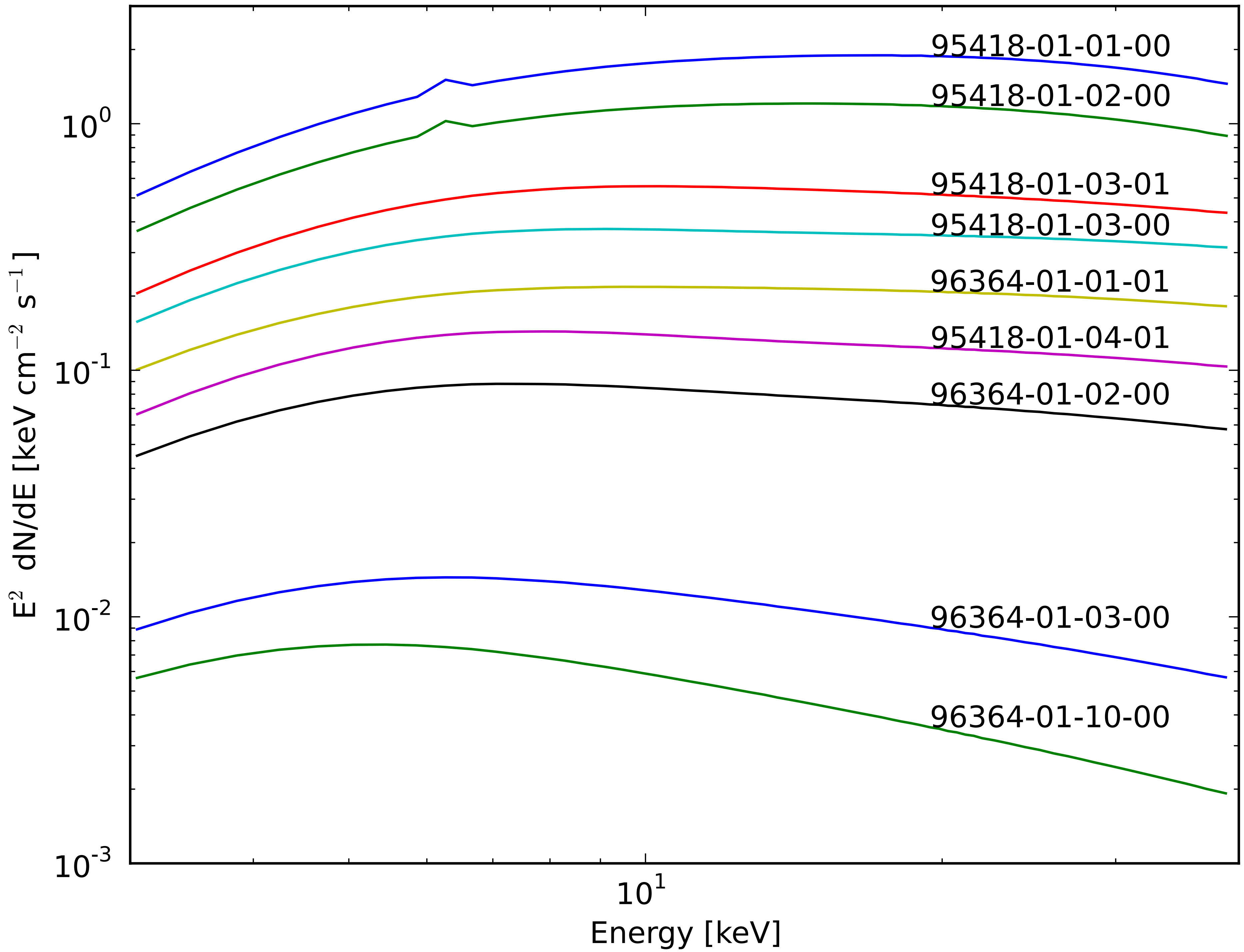


L>L$_c$: A more complicated case: horizontal energy transfer is important → one-dimensional approach does not work


RX J0440.9+4431
Ferrigno et al. 2013 (submitted)
PCU2 count rate (3−20 keV)
100
10
1
0.5
0.6
0.7
0.8
0.9
1.0
1.1
(6−10 keV)/(3−6 keV)

$L_X < 10^{37}$ erg/s

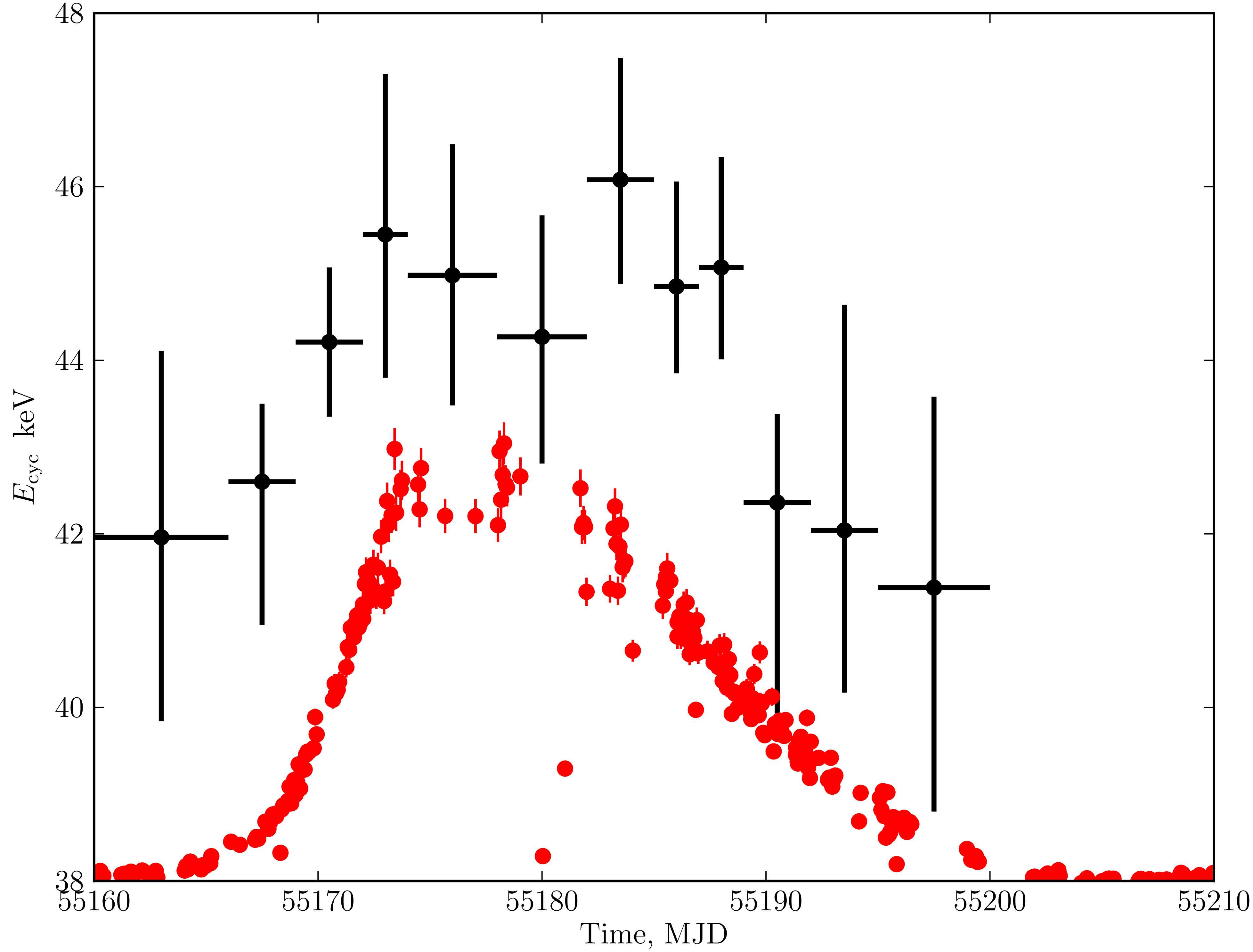
RX J0440.9+4431



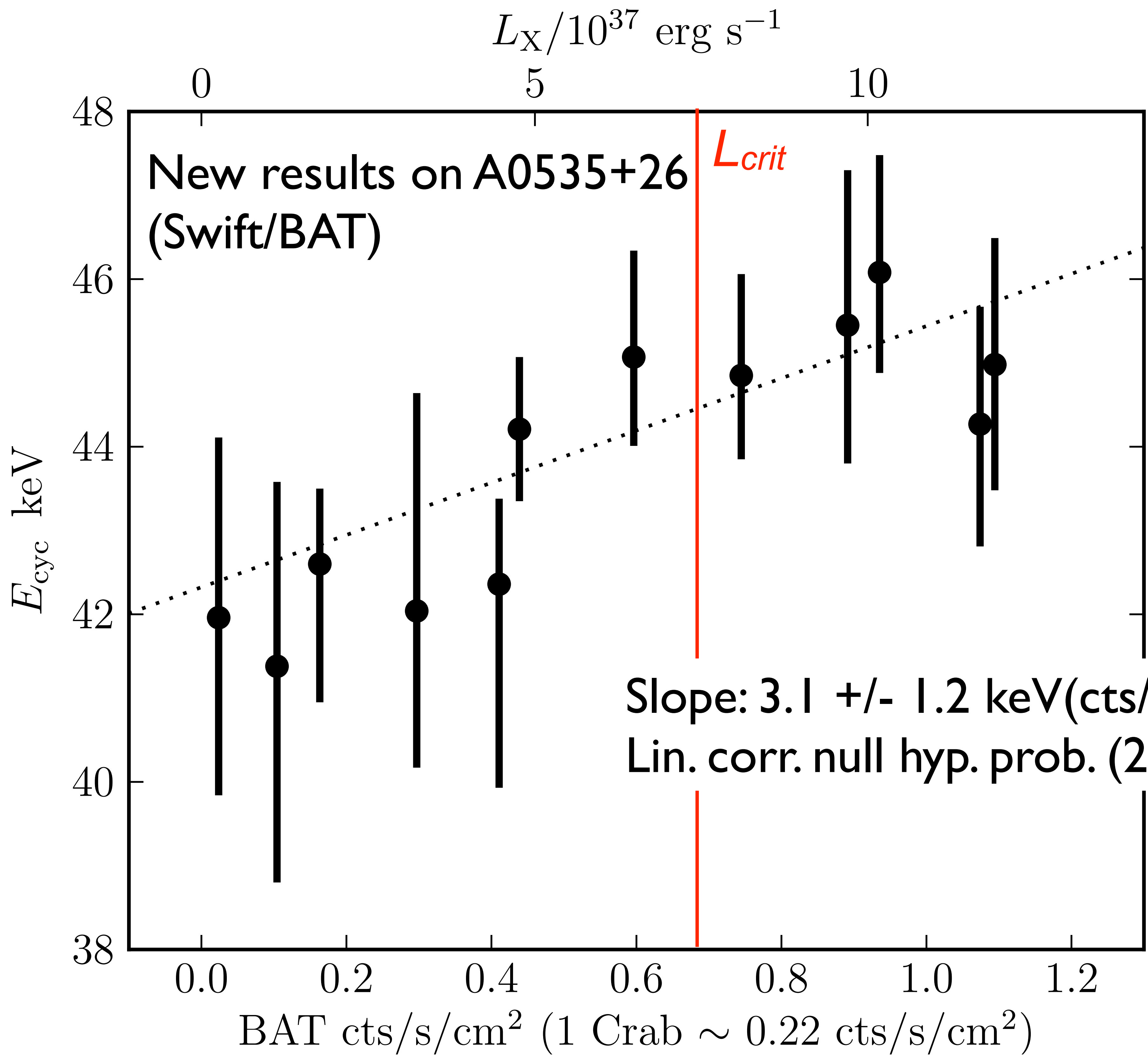
$L_X < 10^{37}$ erg/s

Ferrigno et al. 2013 (submitted)

New results on A0535+26 (Swift/BAT)

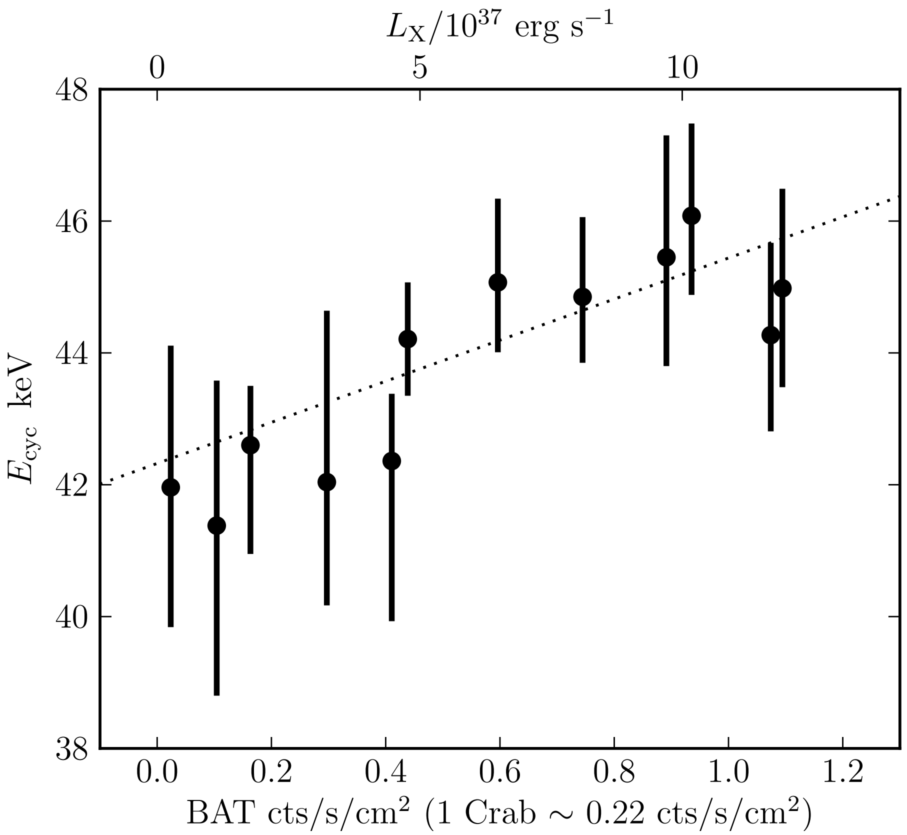


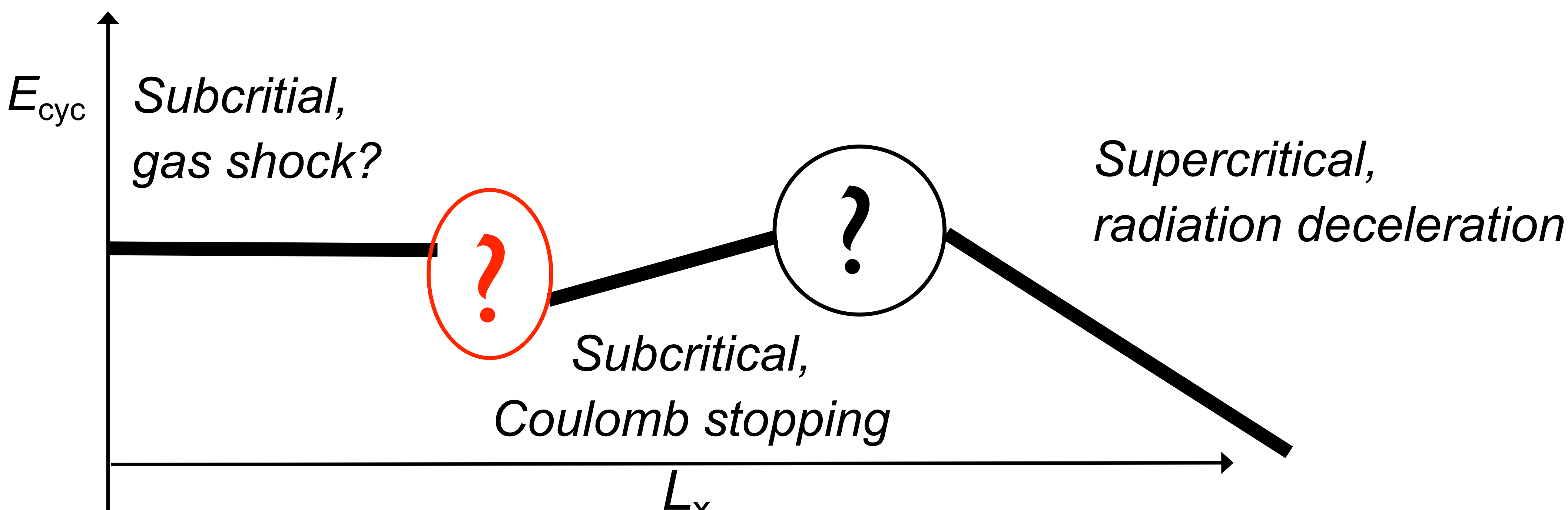
New results on A0535+26 (Swift/BAT)



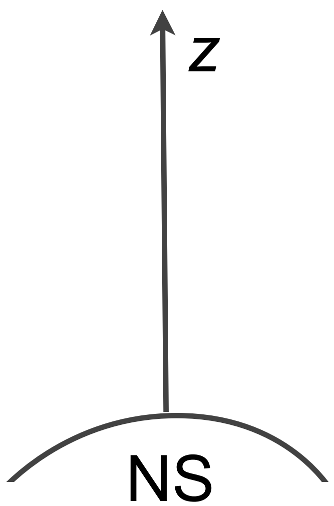
Slope: 3.1 +/- 1.2 keV(cts/s/cm^2)

Lin. corr. null hyp. prob. (2-sided): 5x10^{-4}


$L_X/10^{37}$ erg s^{-1}
0
5
10
48
46
44
42
40
38
E_{cyc} keV
0.0
0.2
0.4
0.6
0.8
1.0
1.2
BAT cts/s/cm^2 (1 Crab ~ 0.22 cts/s/cm^2)


E_{cyc}
Subcritial,
gas shock?
?
?
Supercritical,
radiation deceleration
Subcritical,
Coulomb stopping
L_x

"Second" critical luminosity



Navier-Stokes equation in a stationary case:

$$0 = -\boldsymbol{v}\nabla\boldsymbol{v} - \frac{1}{\rho}\nabla p + \boldsymbol{g}$$

Along *z*-axis:

$$\frac{1}{\rho}\frac{dp}{dz} = -v\frac{dv}{dz} - g$$

Let us introduce a column density variable *y*: d*y* = -ρd*z*.

$$-\frac{dp}{dy} = \rho v\frac{dv}{dy} - g$$

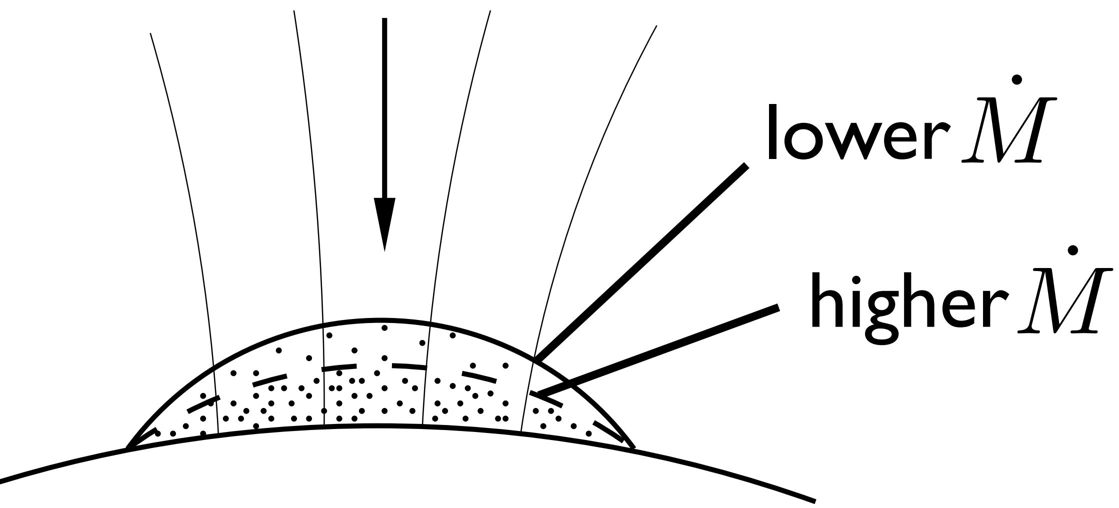
$\rho(z)v(z)=\rho_0 v_0$=const. The equation above can thus be trivially integrated:

$$p(y) = gy + v_0\rho_0(v_0 - v)$$

(see also Staubert et al. 2007)

“Second” critical luminosity

$$p(y) = \underbrace{gy}_{\text{hydrostatic term}} + \underbrace{v_0\rho_0(v_0 - v)}_{\text{dynamic term}}$$



The accretion mound starts to “respond” to the varying $\dot{M}$ when hydrostatic term starts to be comparable to the dynamic one.

Using continuity equation $\rho v = \dot{M}/A$ and velocity profile from *Nelson et al. (1993)*:

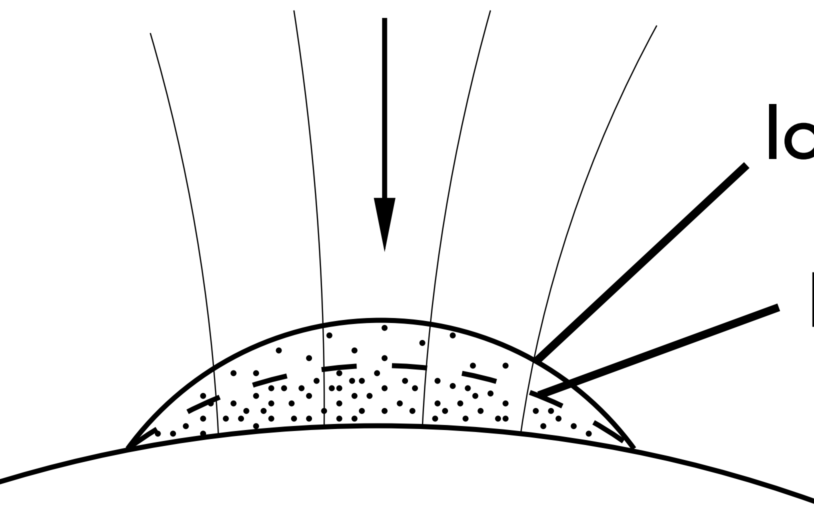
$$v_0\rho_0(v_0 - v) = \frac{\dot{M}v_0}{A}\left[1 - \left(\frac{v}{v_0}\right)^2\right] = \frac{\dot{M}v_0}{A}\left[1 - \left(1 - \frac{\tau}{\tau_\star}\right)^{1/4}\right]$$

Equating static and dynamic terms at $\tau = \tau_\star$:

$$gy = \frac{\dot{M}v_0}{A} \quad \rightarrow \quad L_X \sim 10^{36} \text{ erg/s}$$

“Second” critical luminosity

This is only a toy model!

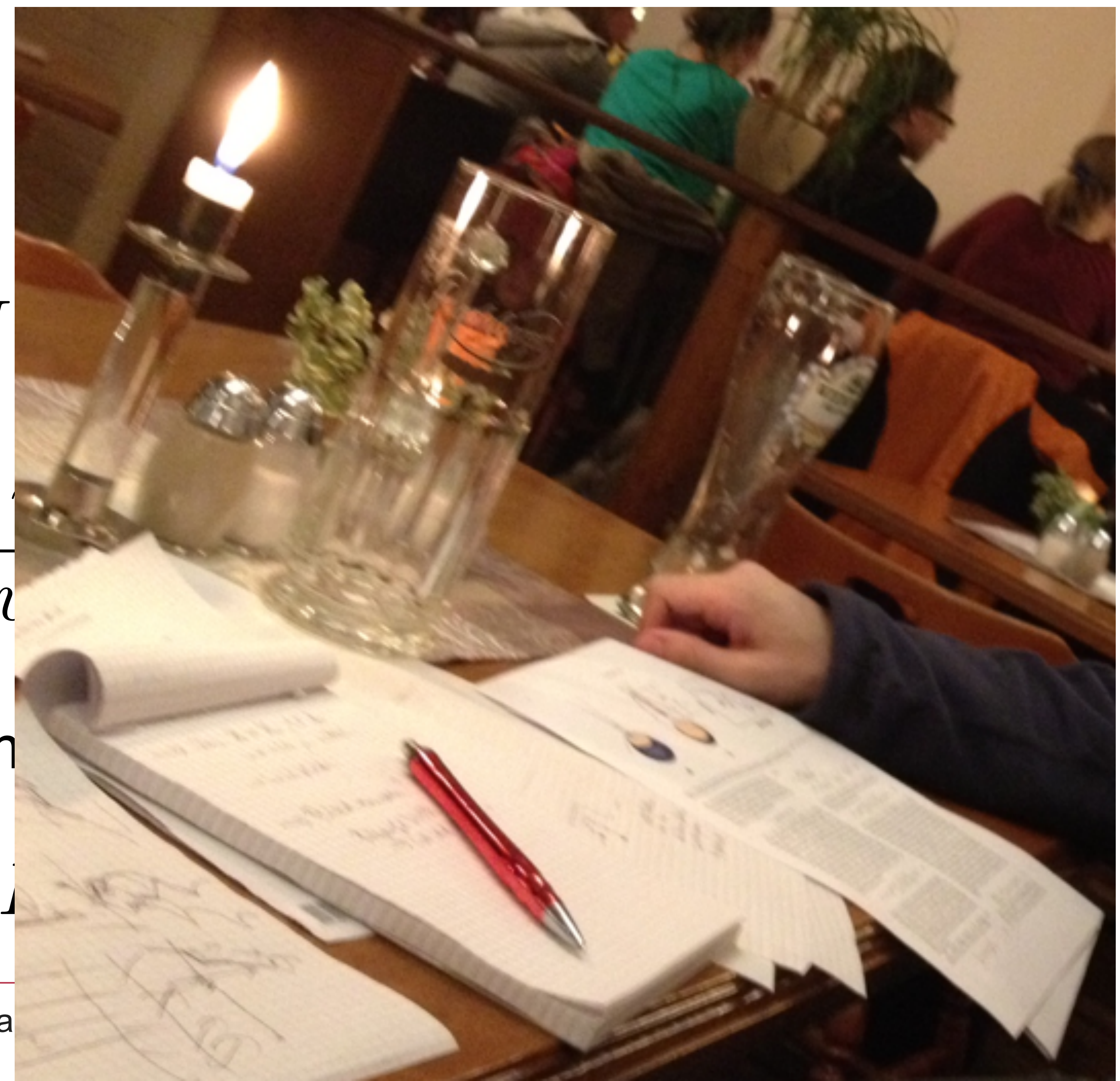


Using continuity equation $\rho v = \dot{M}$
Nelson et al. (1993):

$$v_0 \rho_0 (v_0 - v) = \frac{\dot{M} v_0}{A} \Big[1 - \Big($$

Equating static and dynamic tern

$$gy = \frac{\dot{M} v_0}{A} \quad \rightarrow$$



Summary

• Luminosity-dependence of the X-ray spectrum of accreting pulsars (reaction on the changing $\dot{M}$) is a key source of information about the configuration of the emitting region
• Spectrum-luminosity dependence can be studied on very short pulse-to-pulse time scale
• Accreting pulsars show at least two types of spectrum-luminosity correlations which we interprete as manifestations of different emitting region configurations
• Transition between different accretion modes occur at certain “critical” luminosity(-ies), L_{crit}, which depend on individual pulsars’ properties
• Our theoretical estimates of L_{crit} are consistent with the observed transitions between different regimes