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

Structure of the X-ray emitting region in accreting pulsars

Dmitry Klochkov

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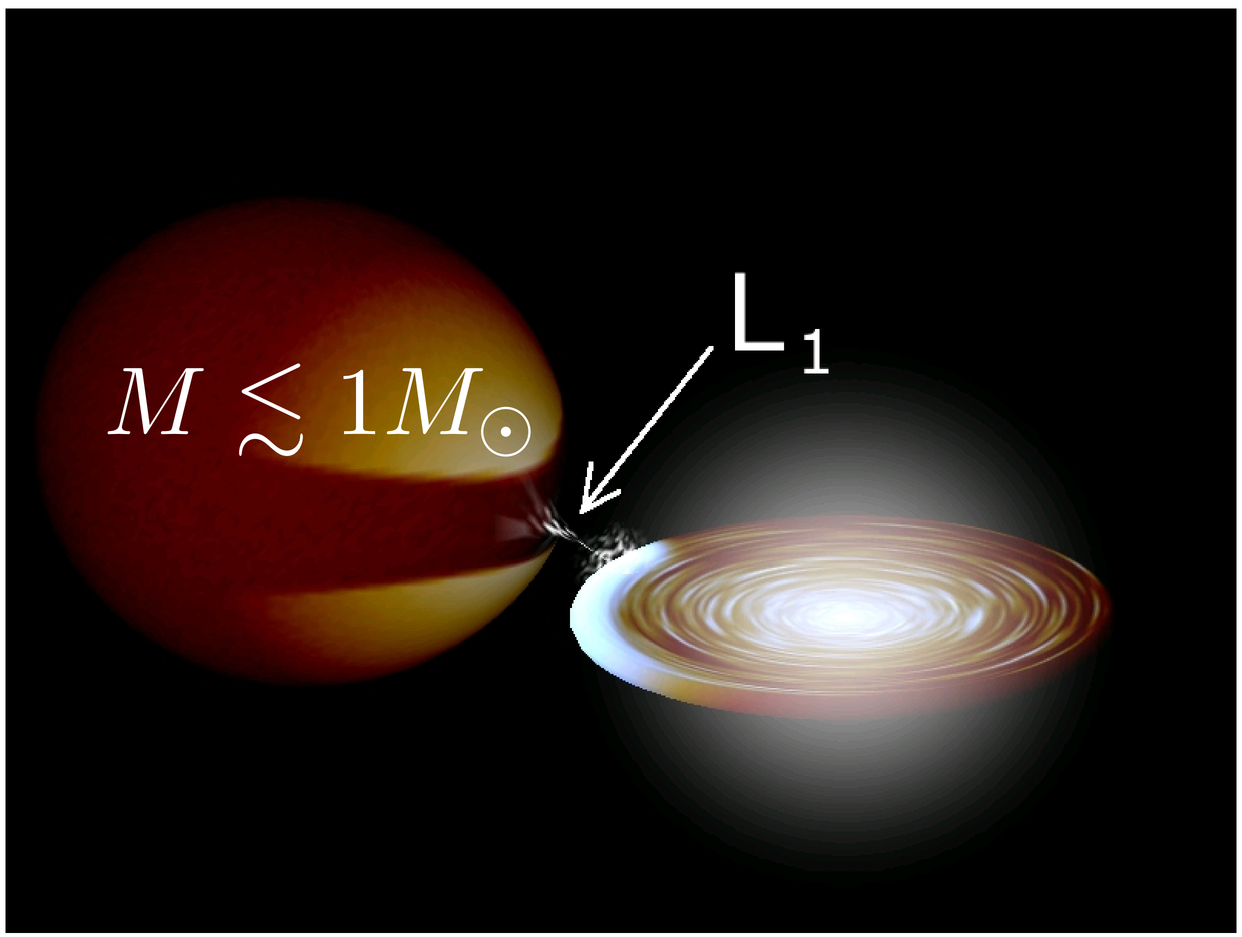
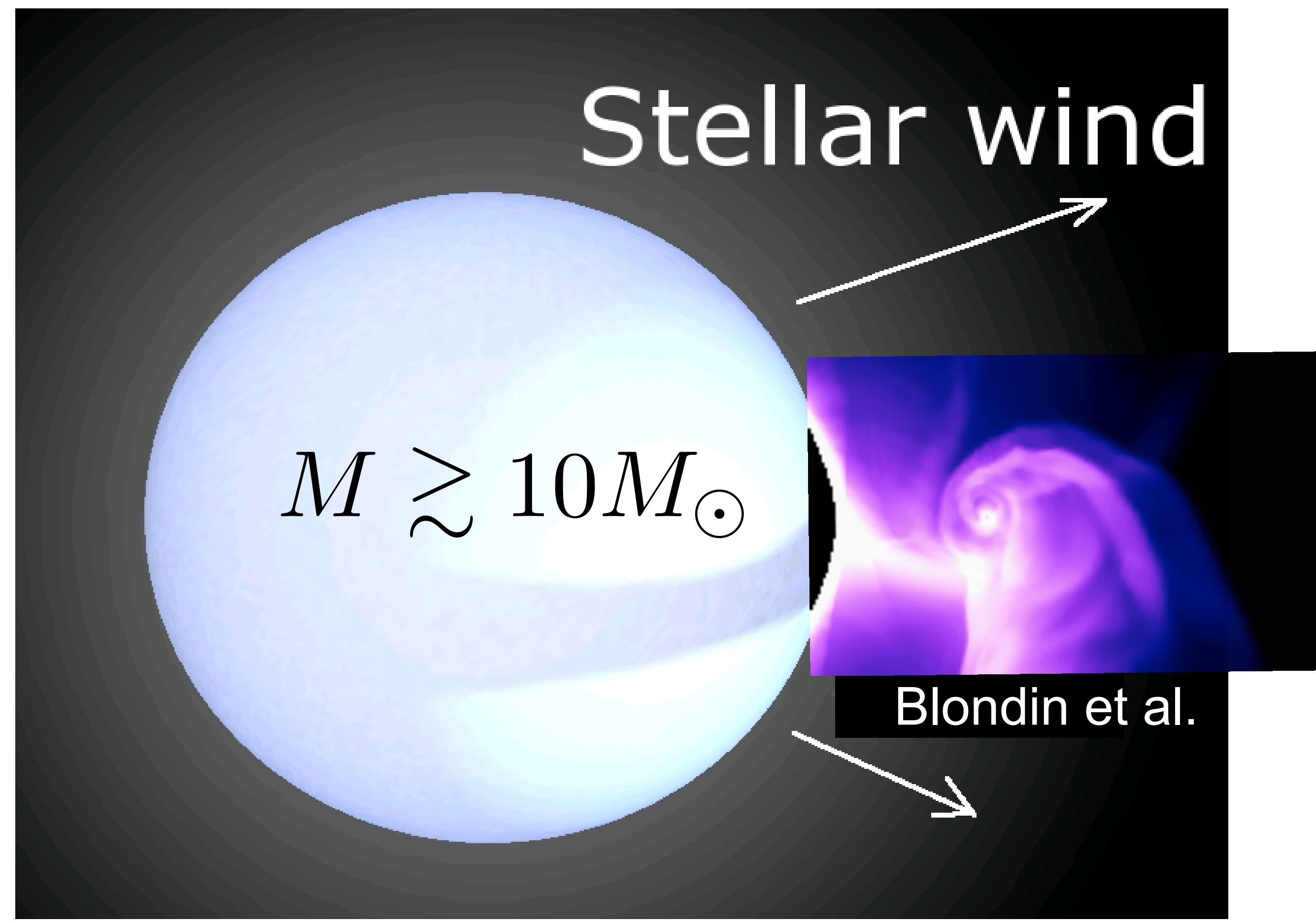
X-ray binaries

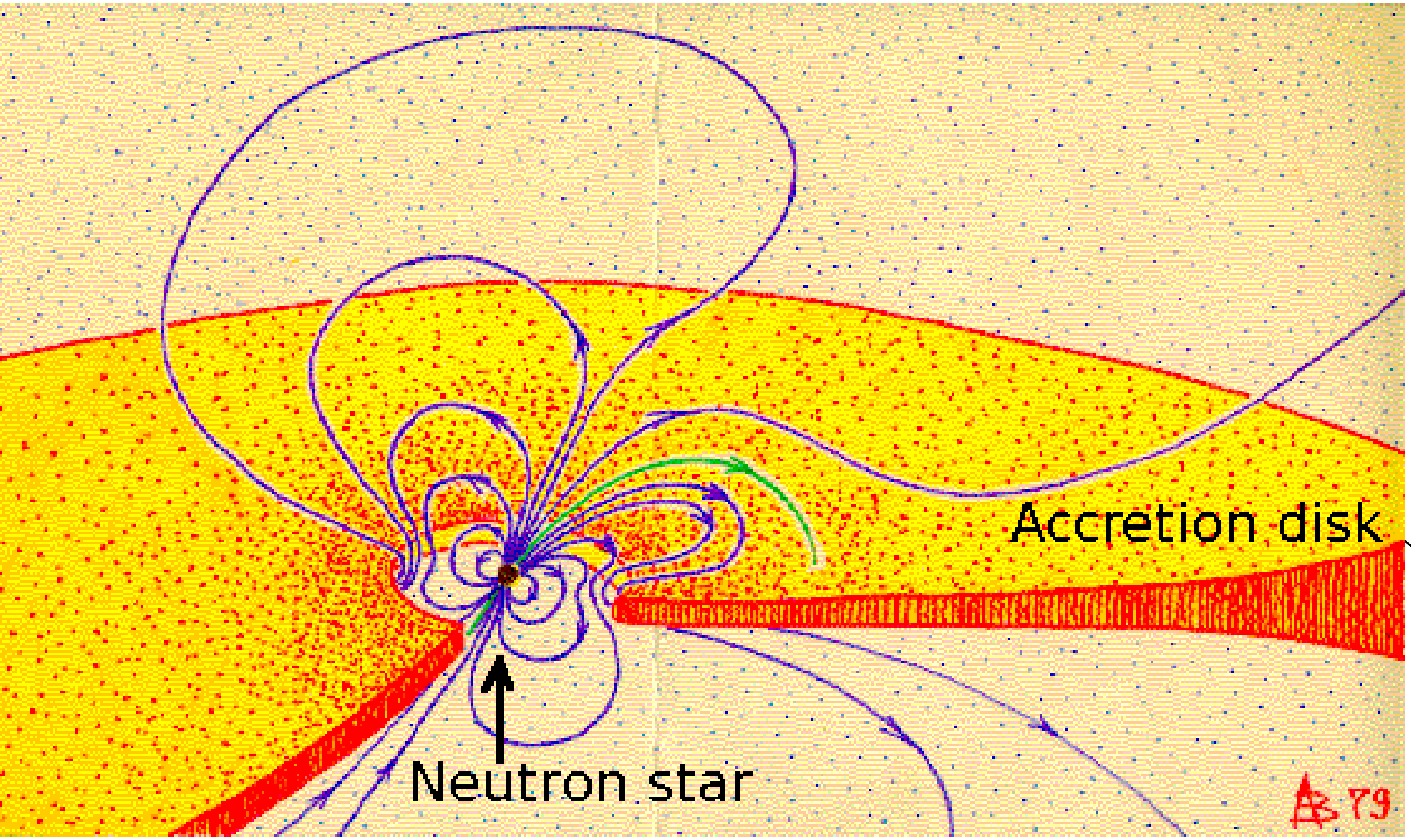
LMXB

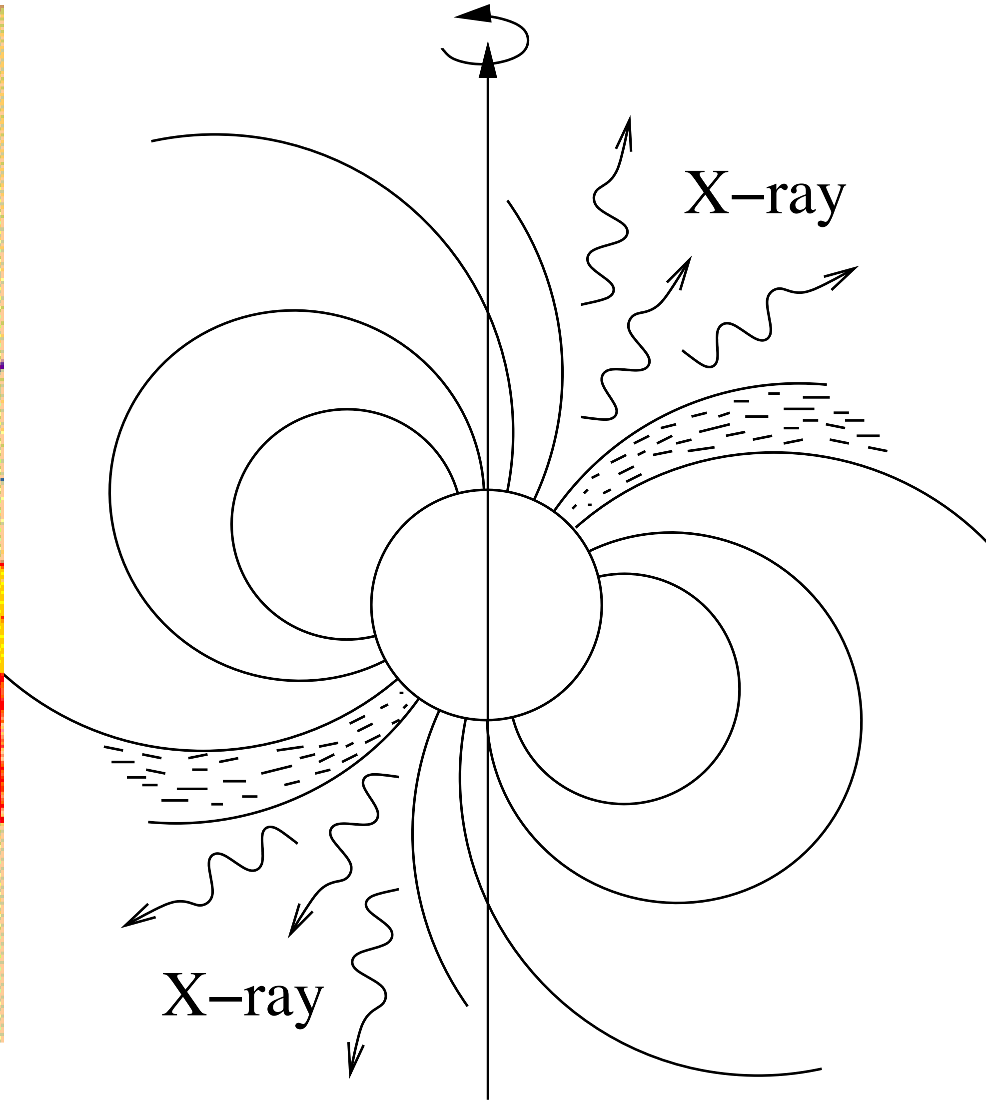


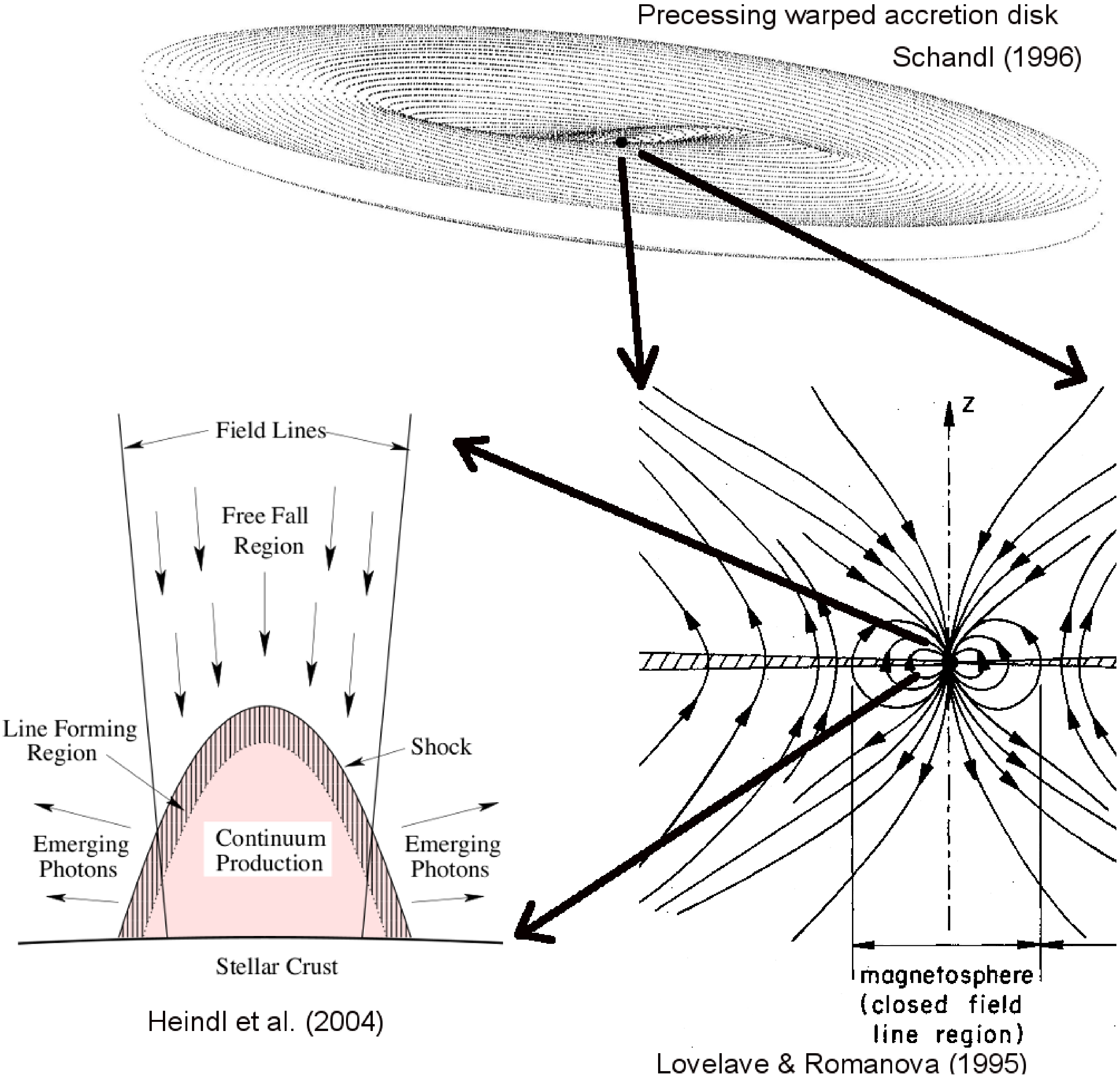
HMXB



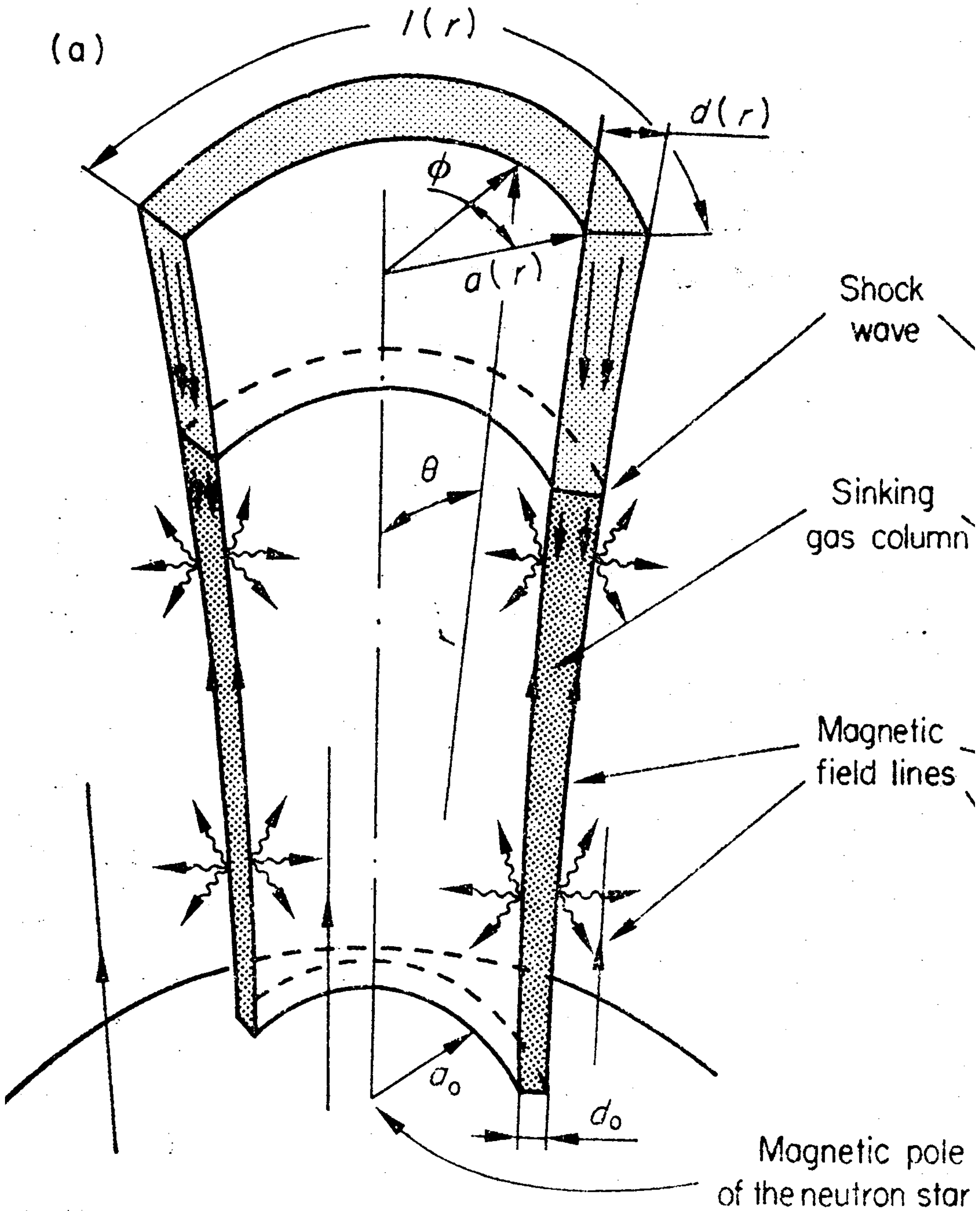
Accreting pulsars



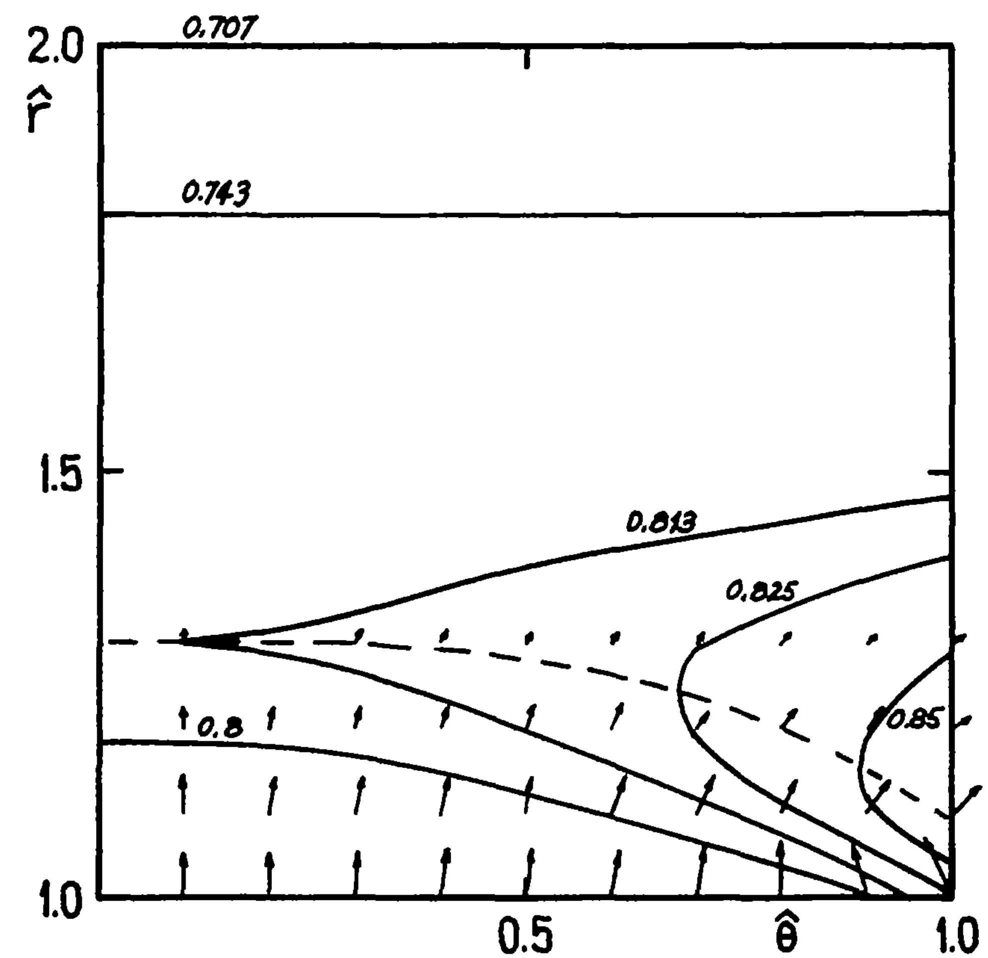



Precessing warped accretion disk
Schandl (1996)
Field Lines
Free Fall Region
Line Forming Region
Shock
Emerging Photons
Continuum Production
Emerging Photons
Stellar Crust
Heindl et al. (2004)
z
magnetosphere
(closed field
line region)
Lovelave & Romanova (1995)

X-ray emitting region



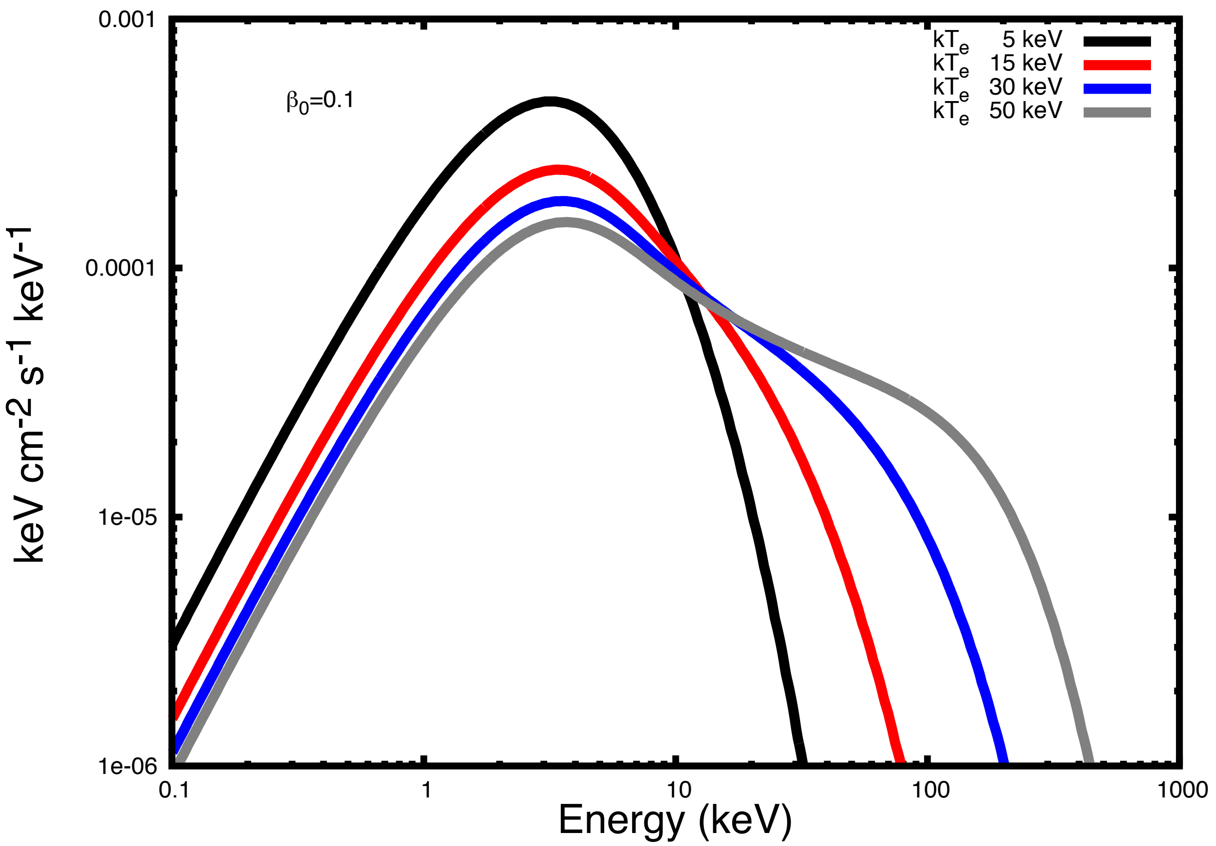
Basko&Sunyaev (1976)



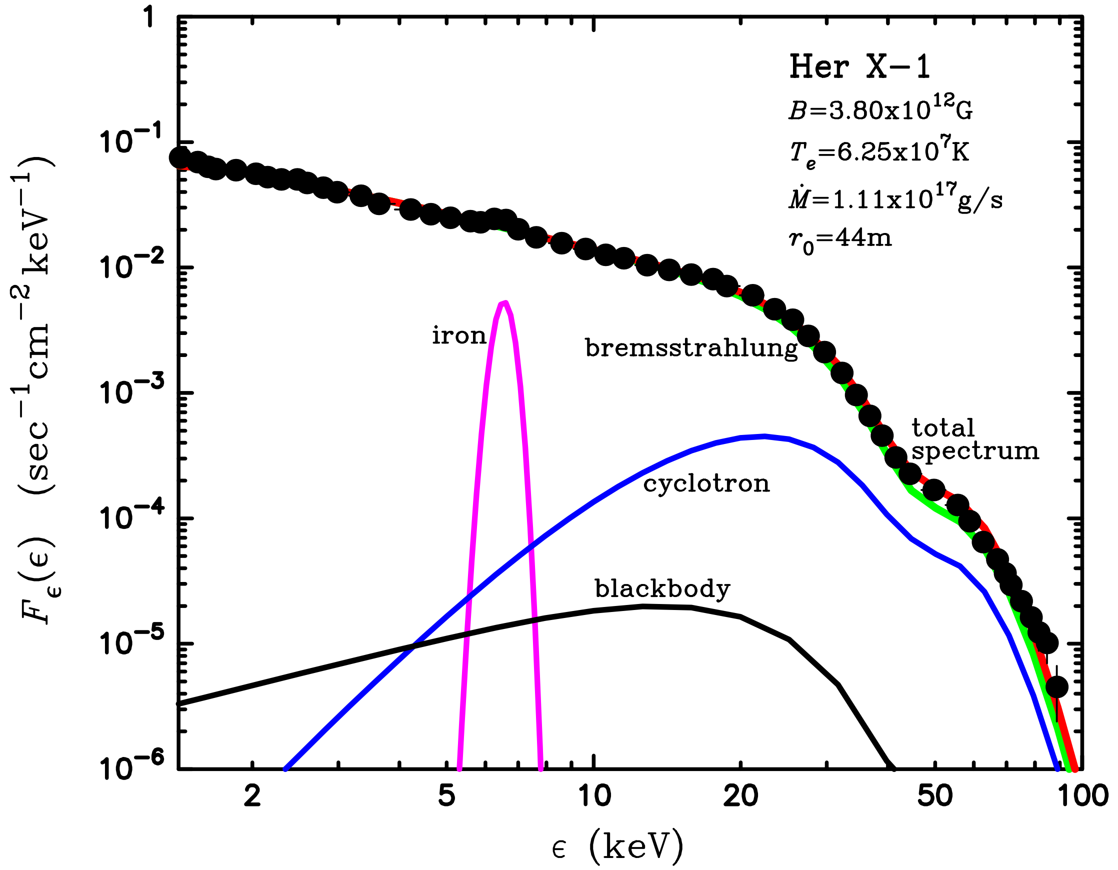
Wang&Frank (1981)

Theoretical modeling of pulsars' X-ray spectra

Farinelli et al. (2012)

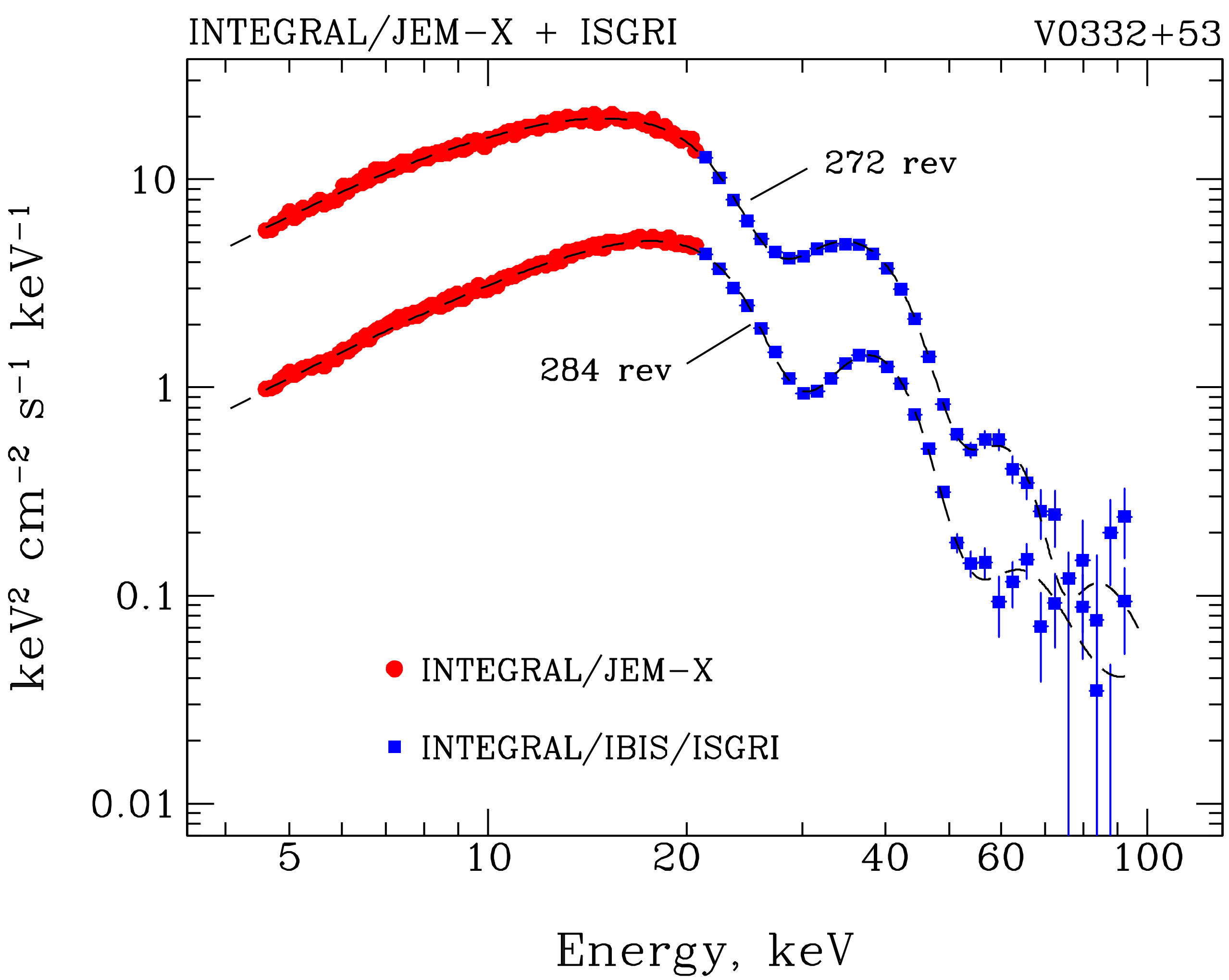


Becker&Wolff (2007)



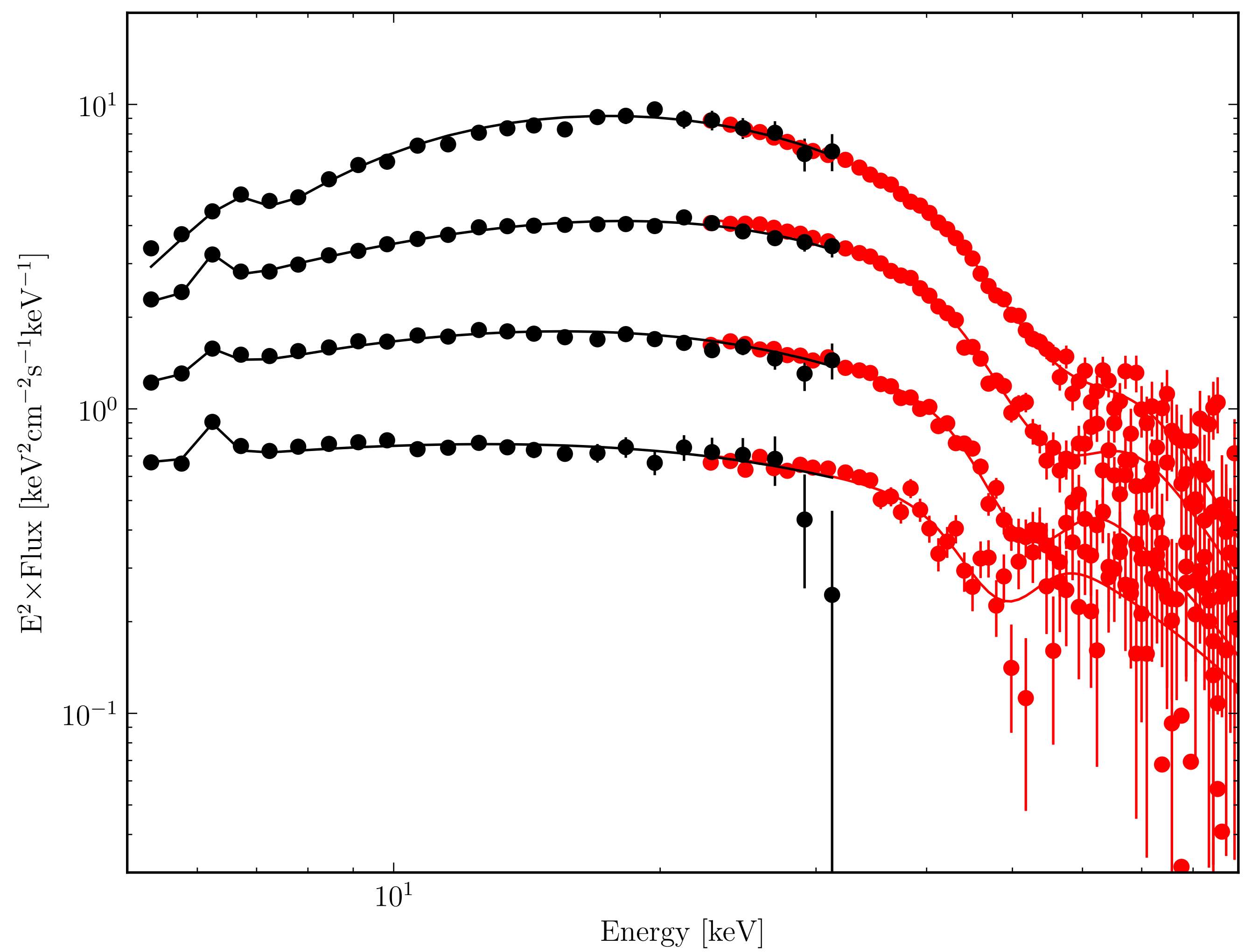
Spectrum-Luminosity dependence

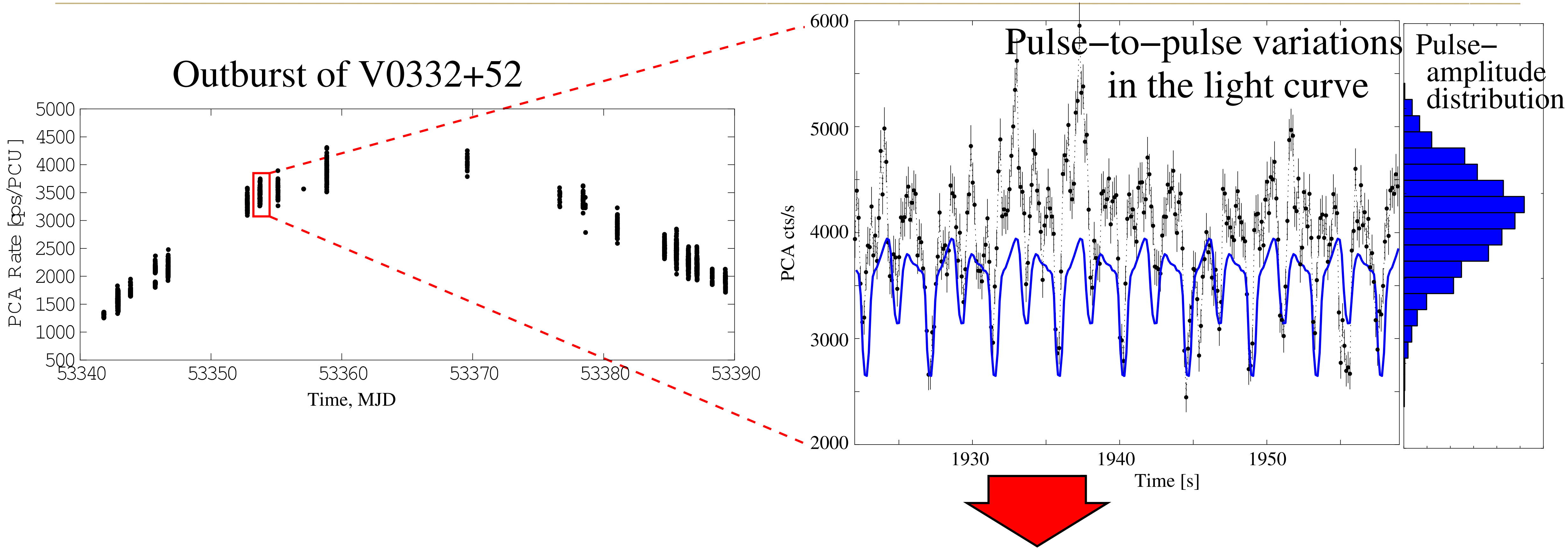
Tsygankov et al. (2006)

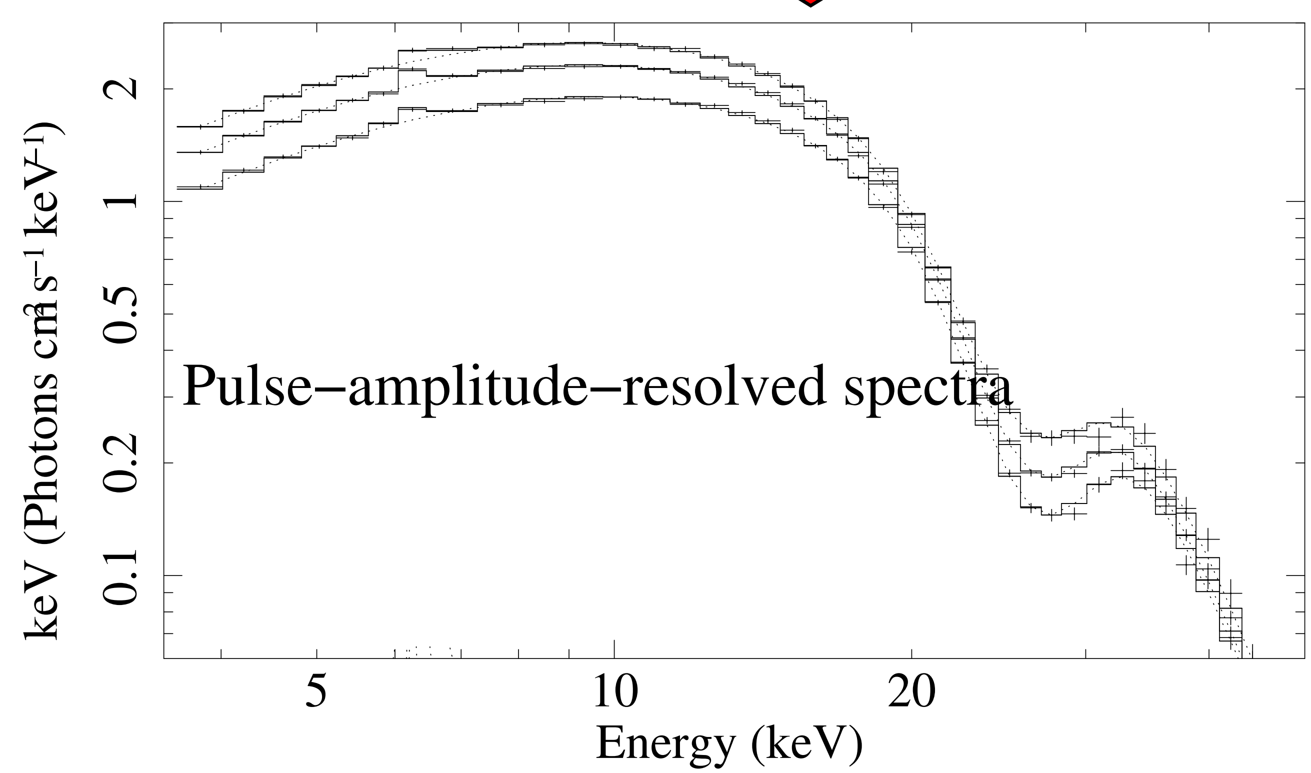


Klochkov et al. (2012)

GX 304-1

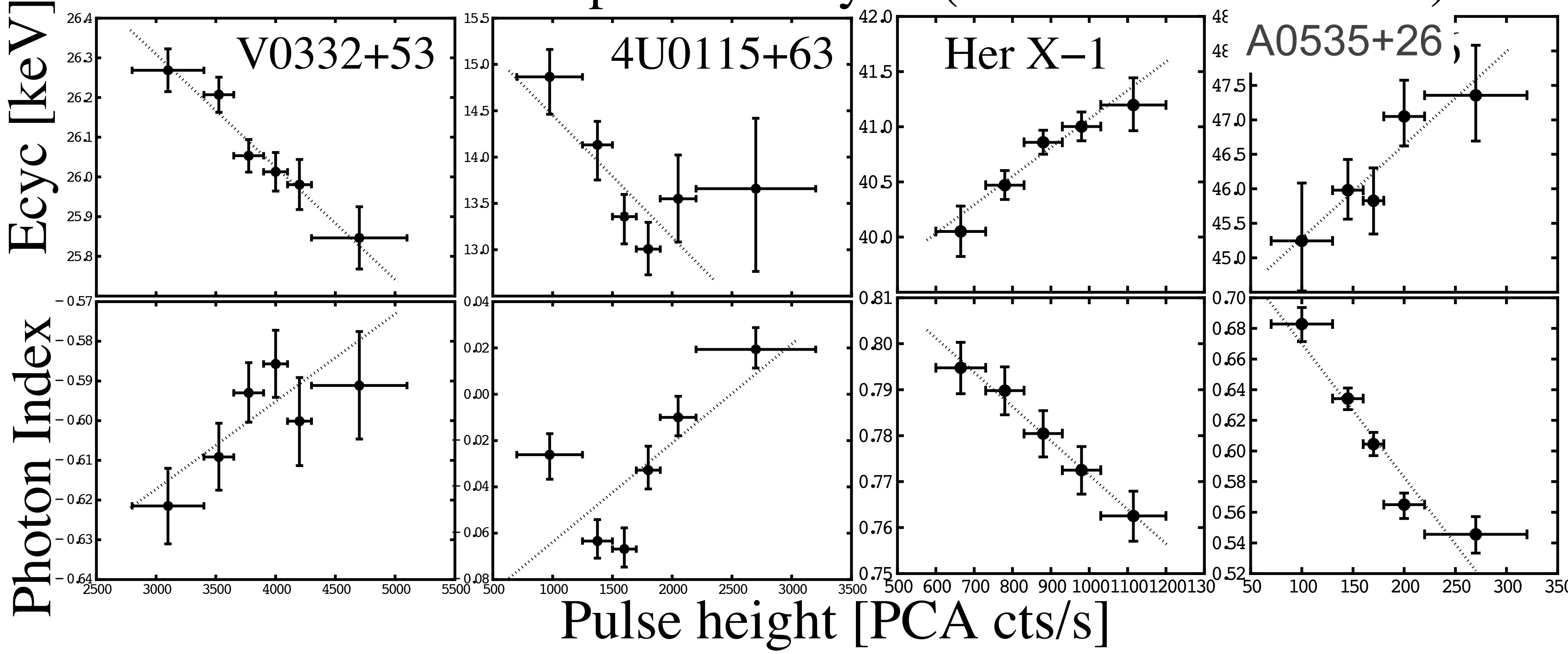




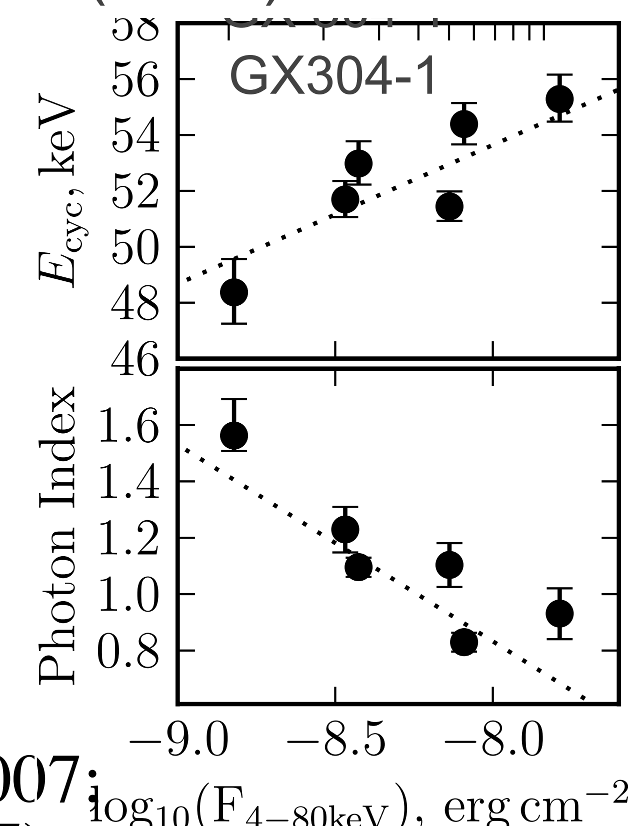


Klochkov et al. (2011)

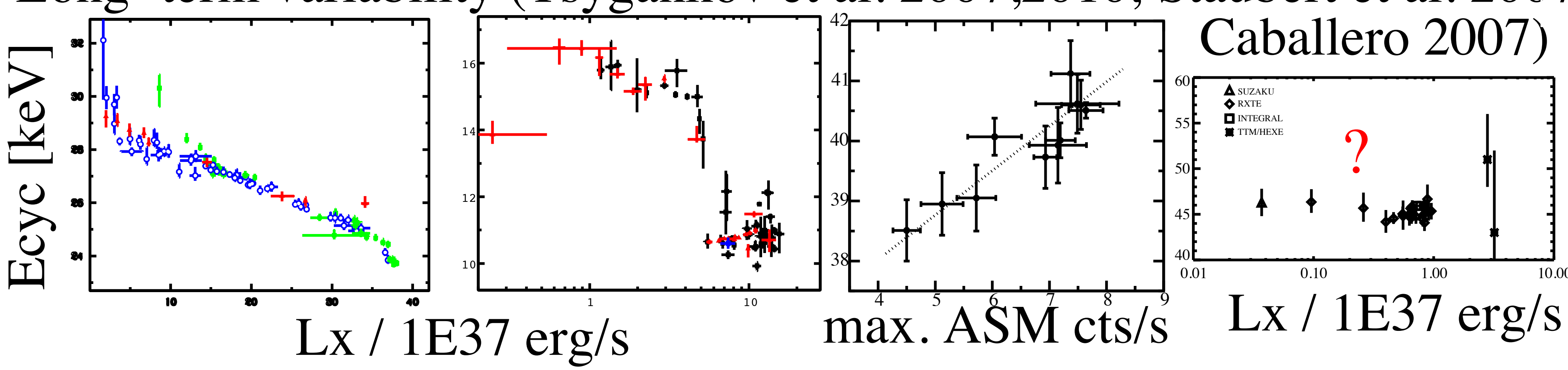
"Pulse–to–pulse" analysis (Klochkov et al. 2011)



Klochkov et al. (2012)



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



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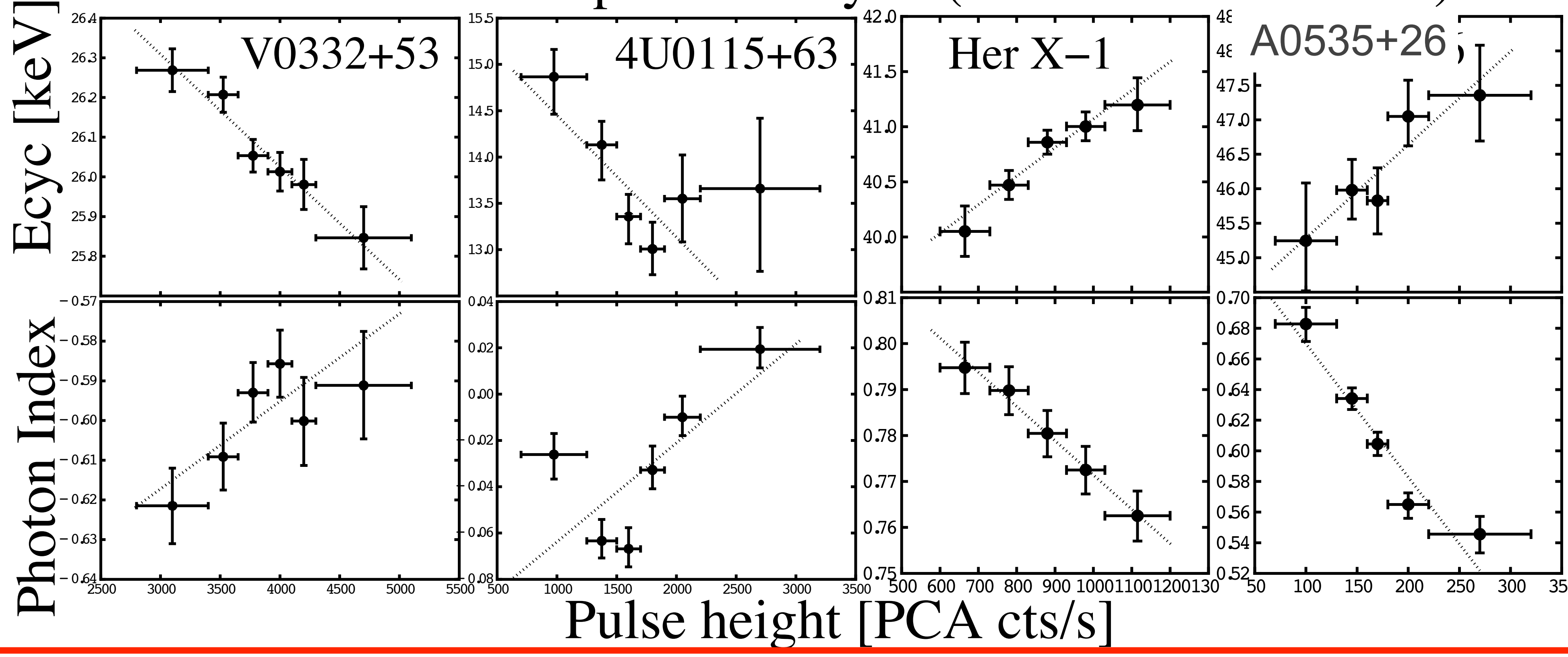
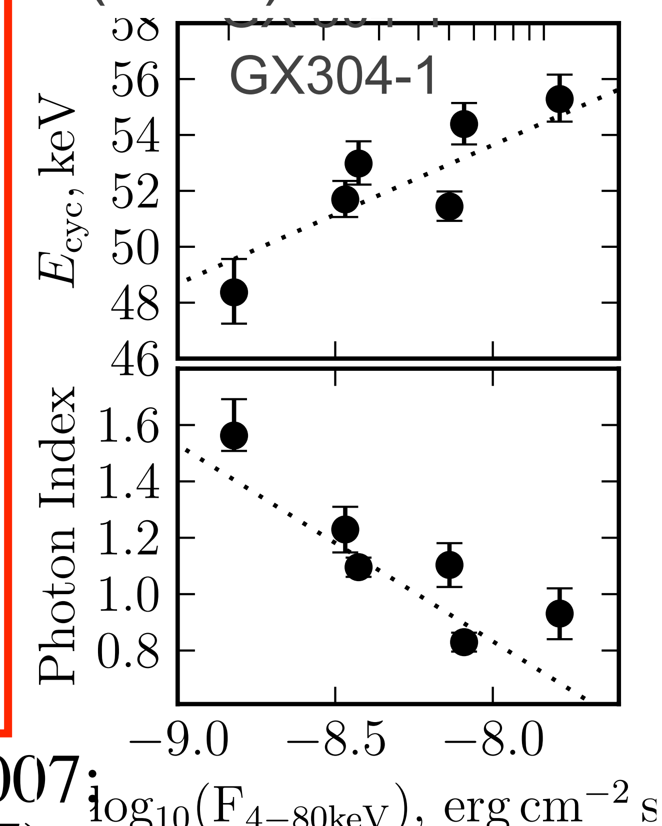


Klochkov et al. (2012)



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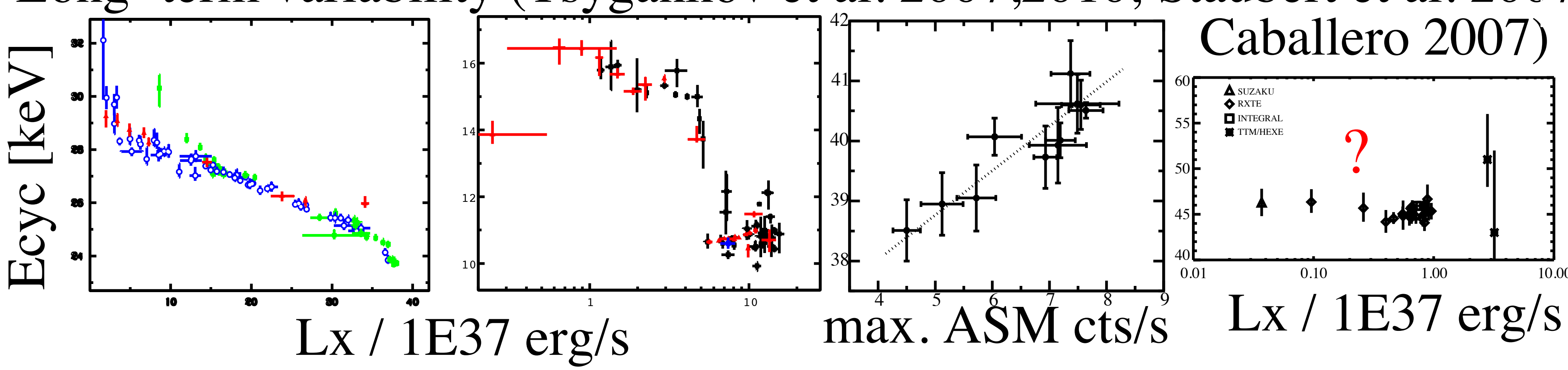

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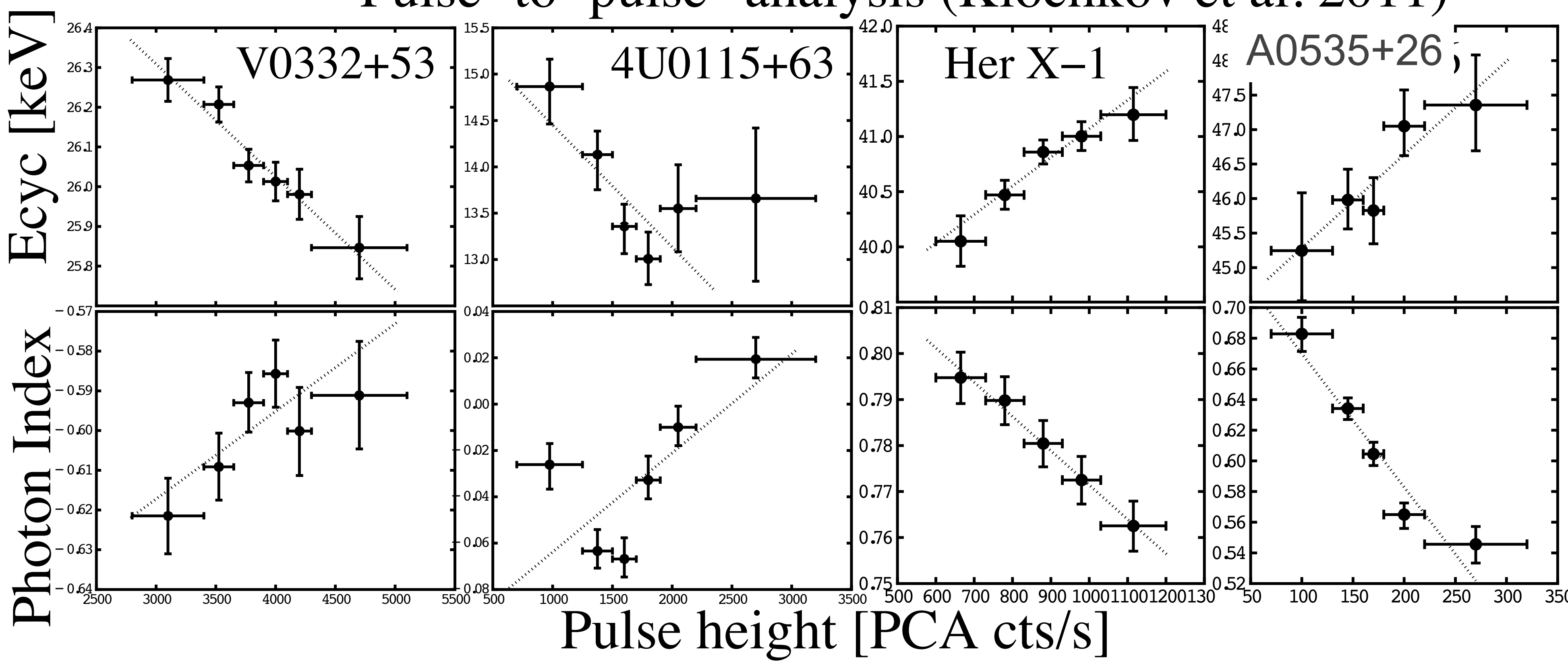
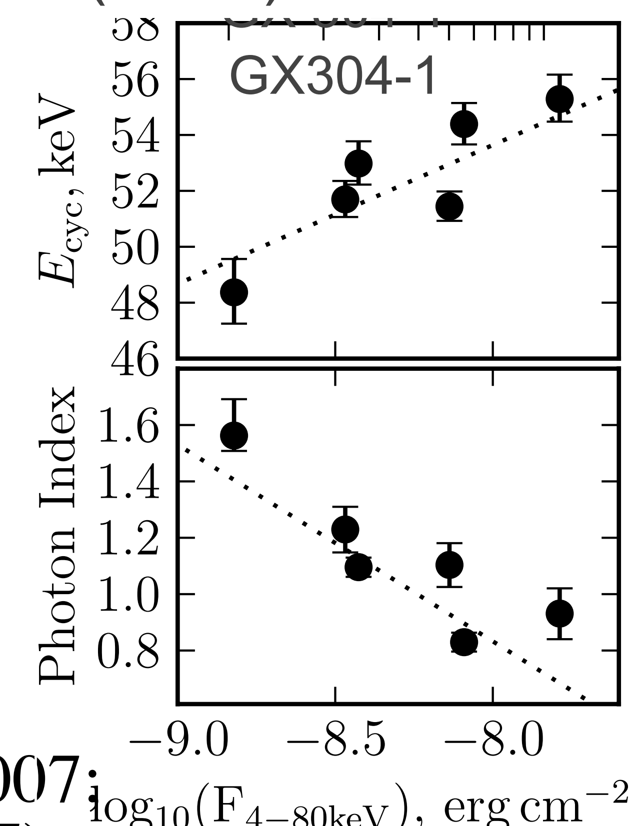


Klochkov et al. (2012)



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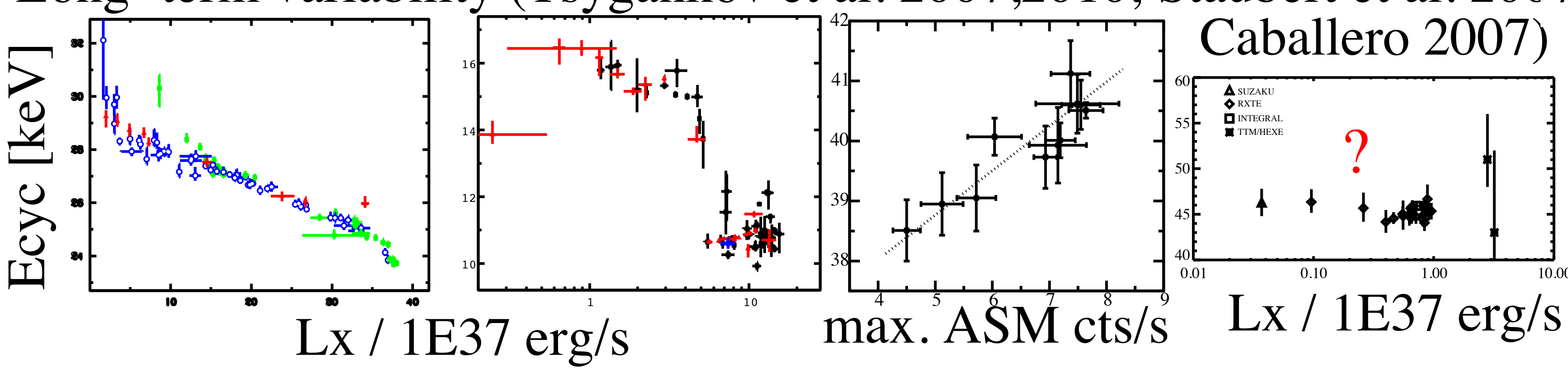
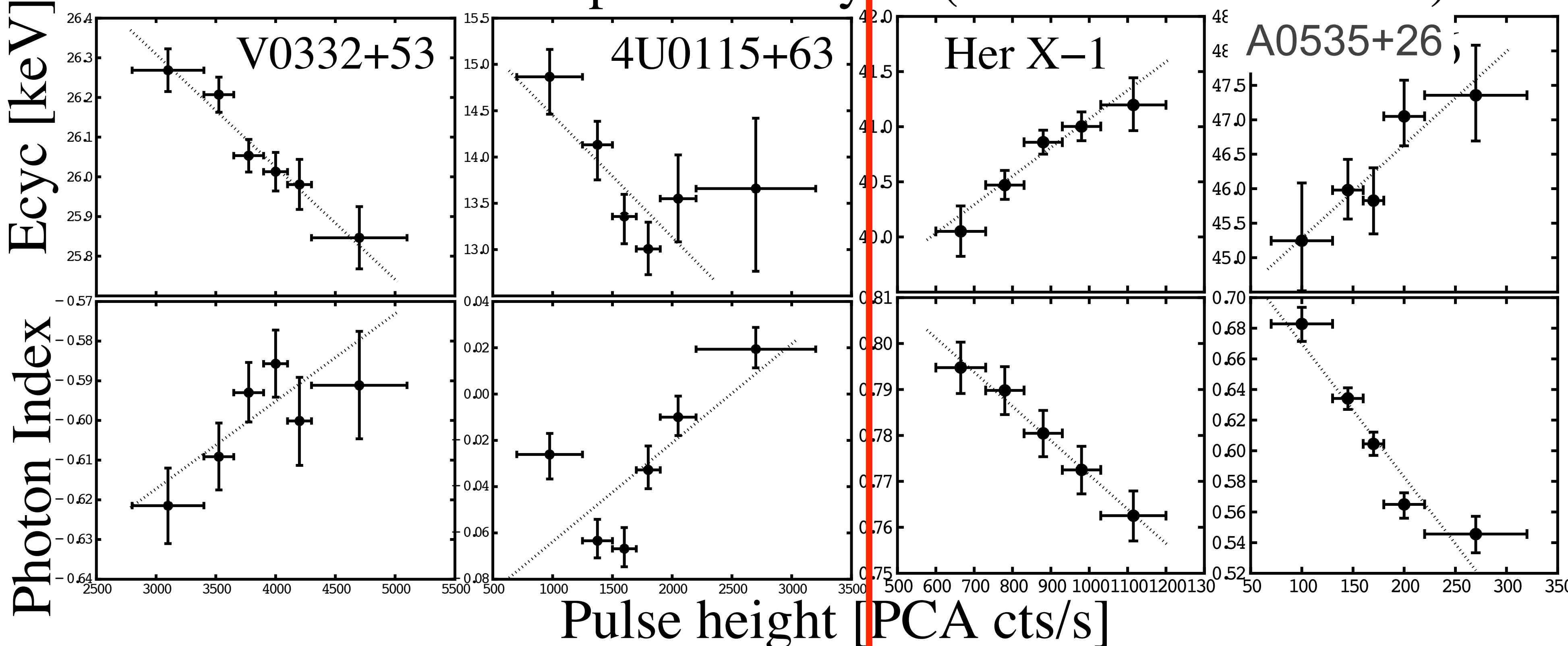
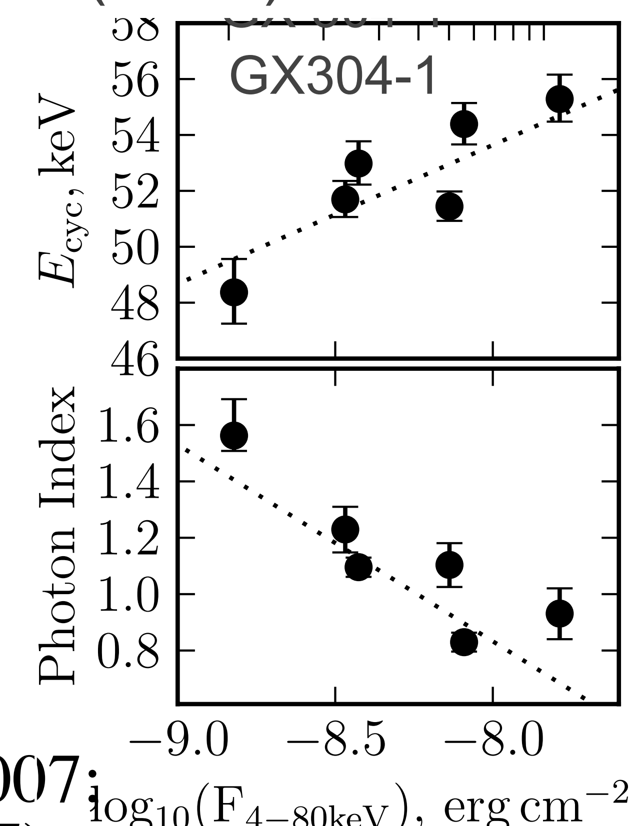


“Supercritical” “Subcritical”

"Pulse–to–pulse" analysis (Klochkov et al. 2011)



Klochkov et al. (2012)



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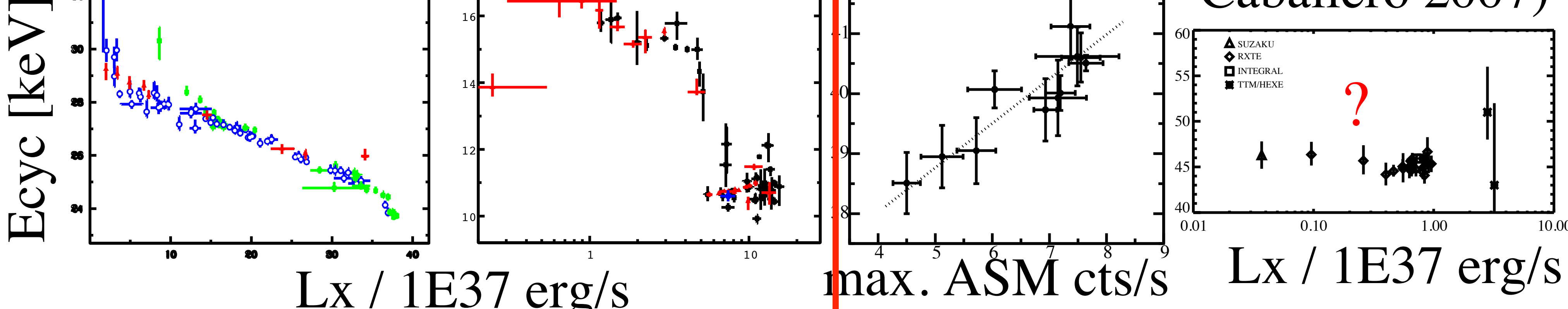
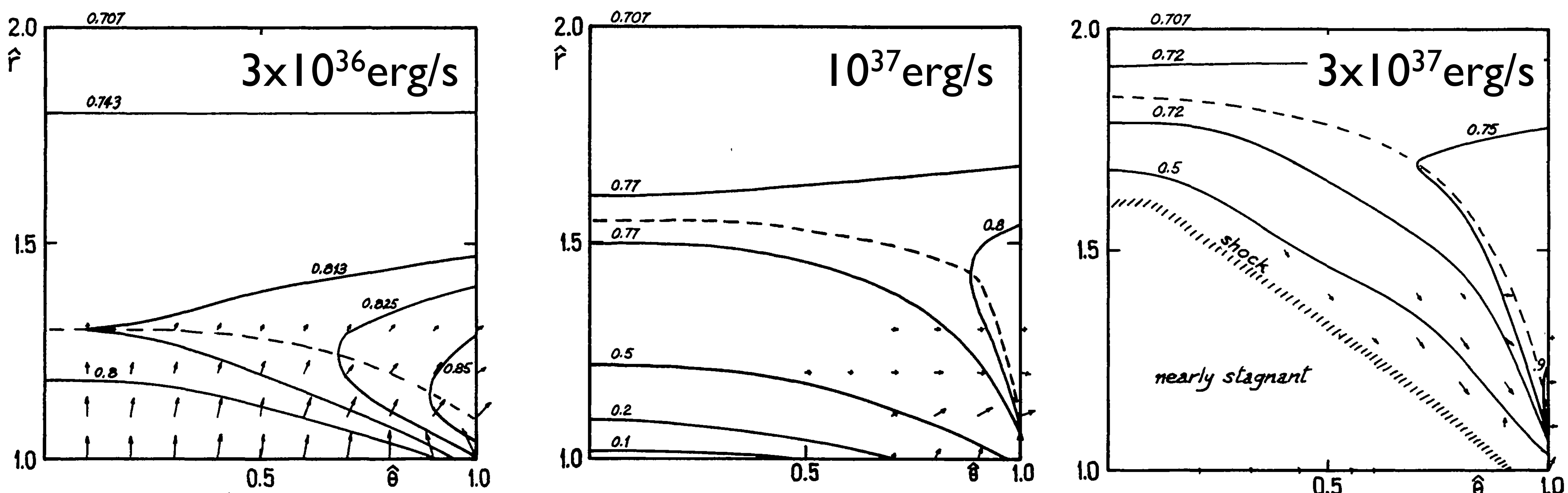
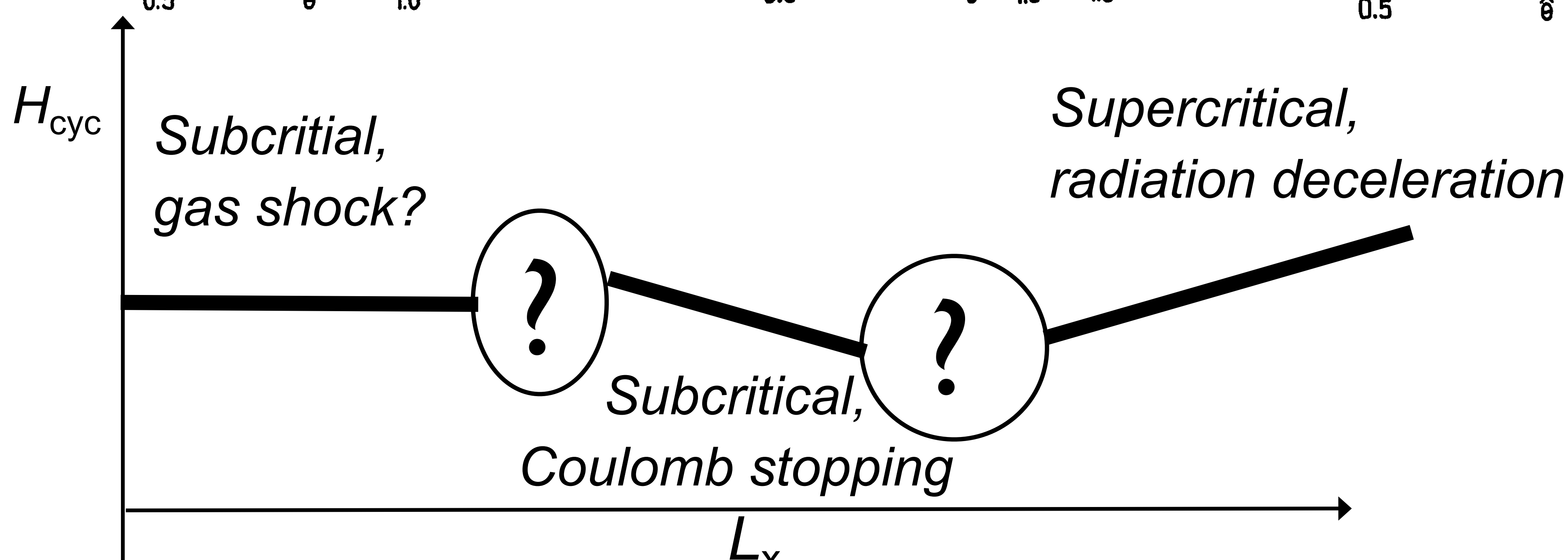


Height of the emitting region above the NS surface

Wang&Frank (1981)





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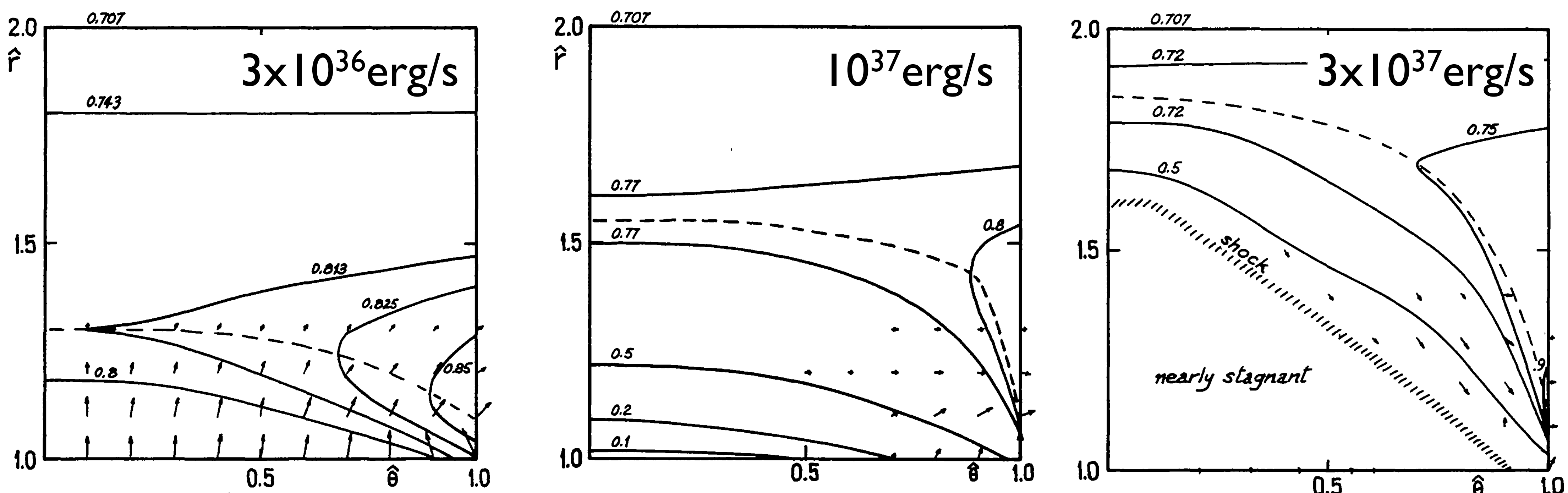

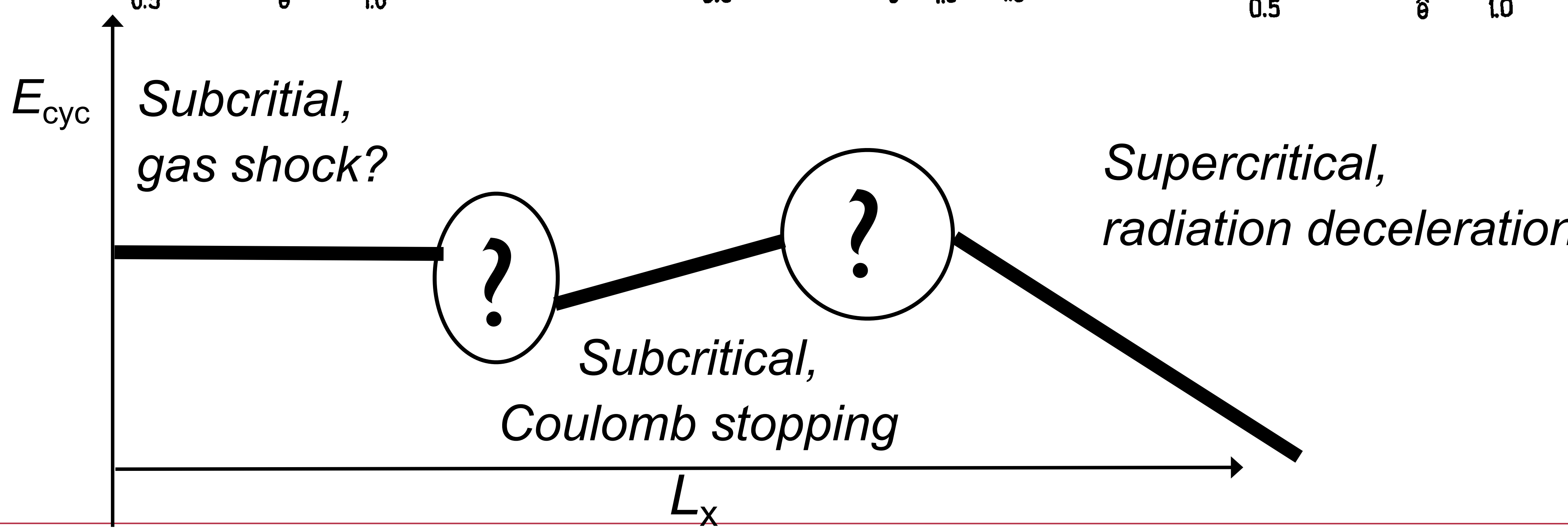

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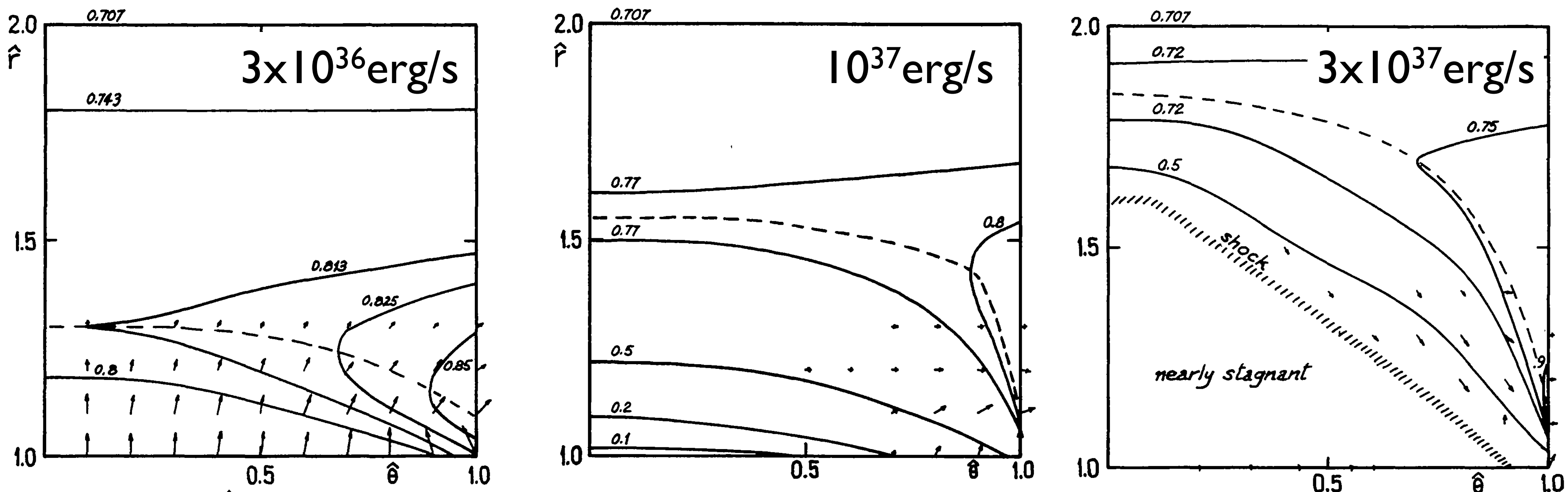
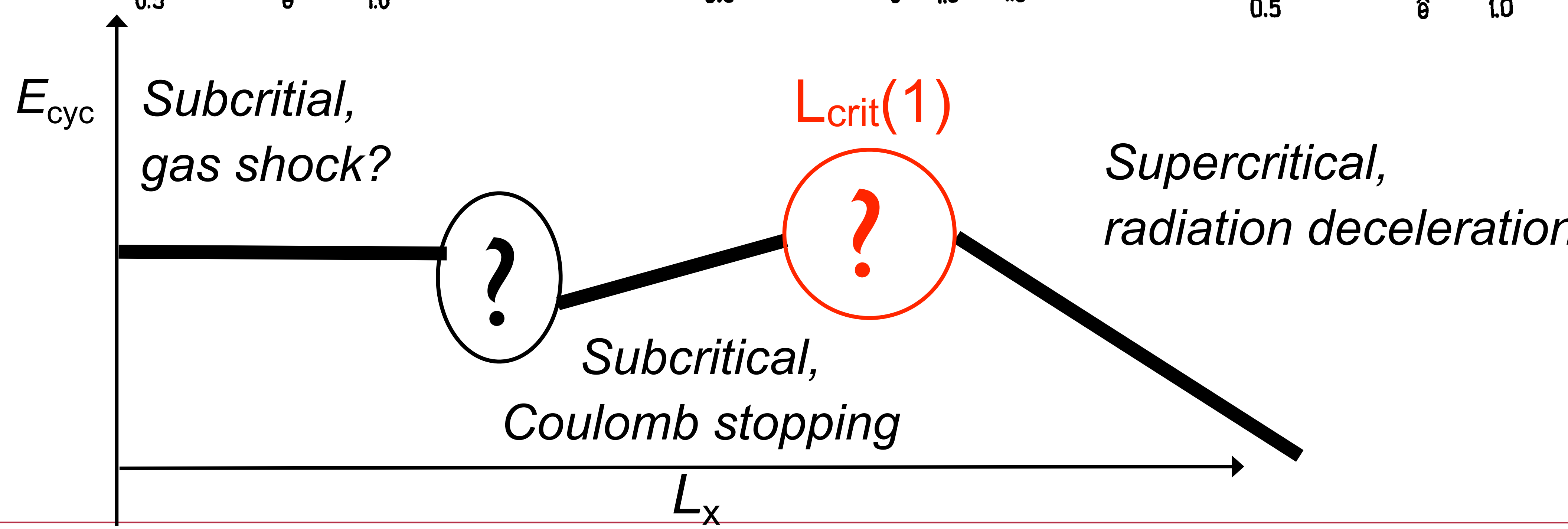
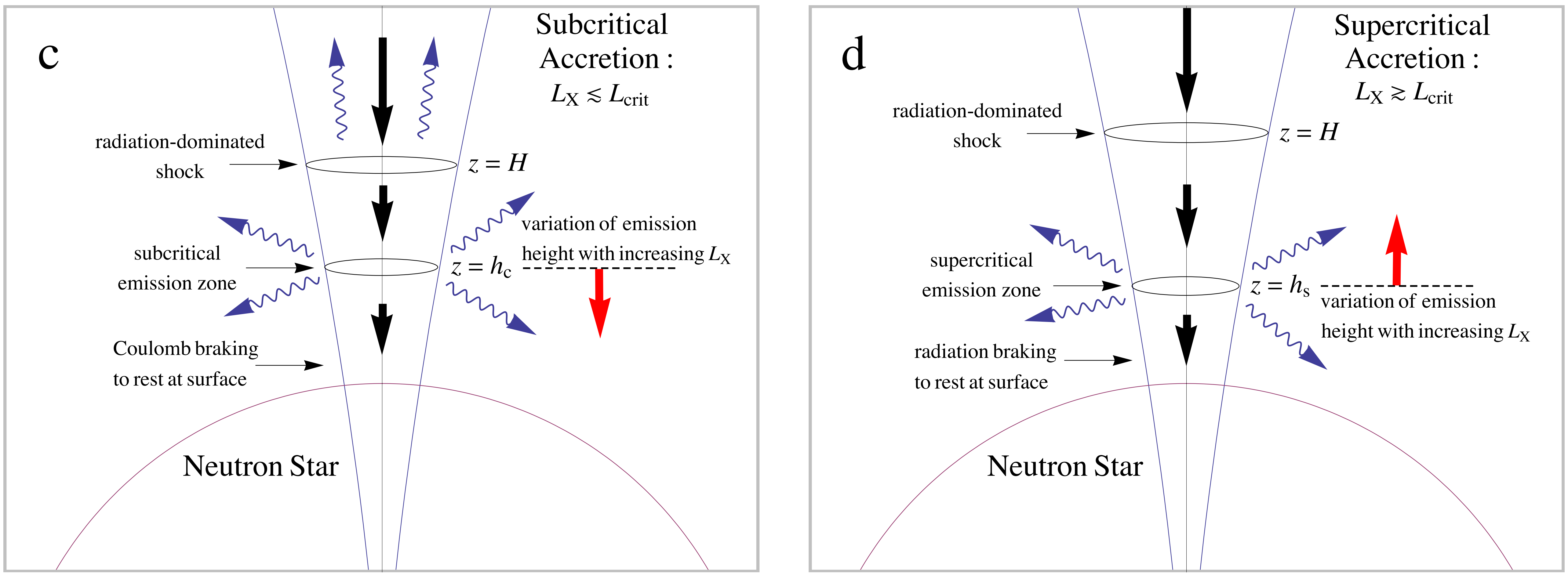


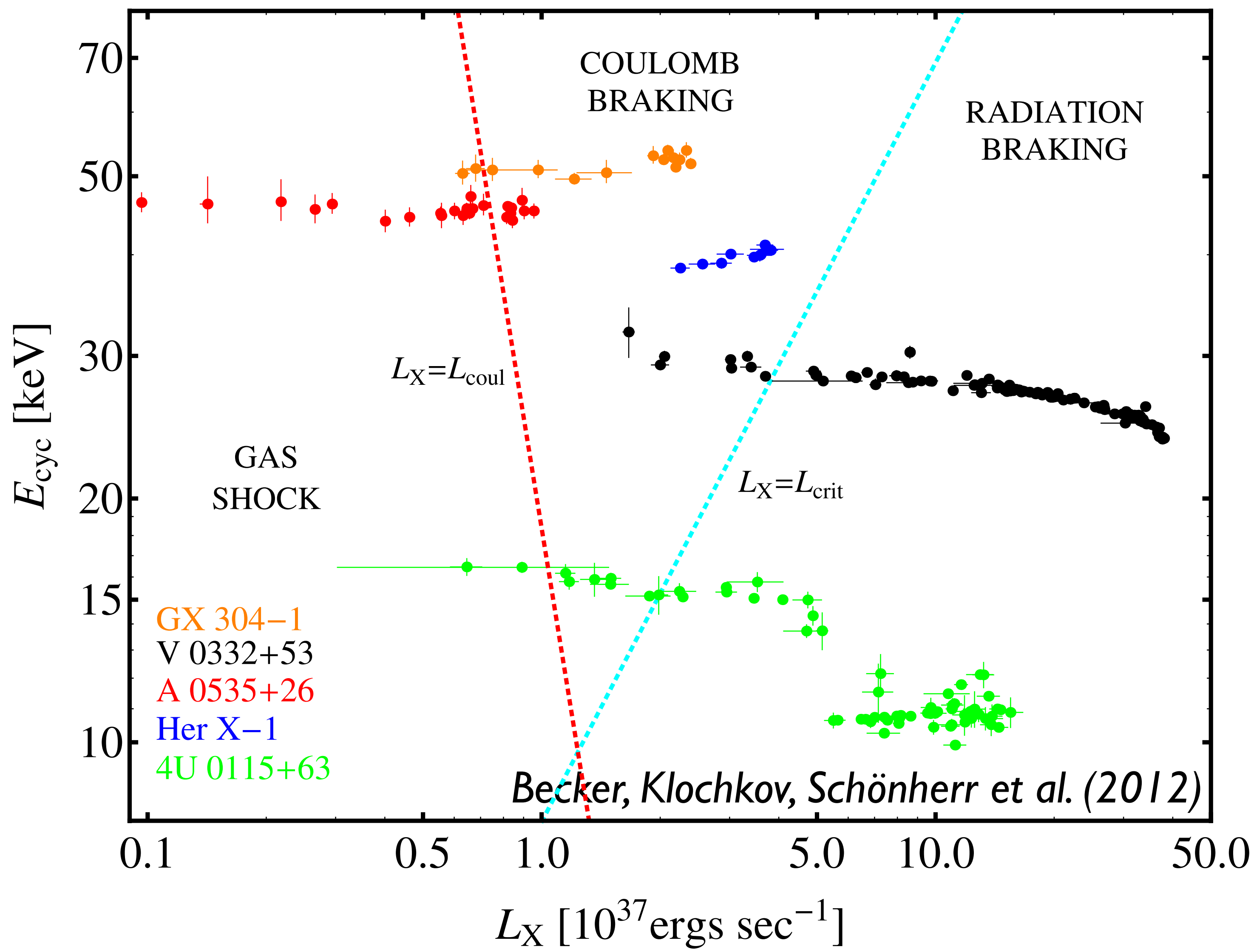


Variations of the emitting region with changing $\dot{M}$



Becker, Klochkov, Schönherr et al. (2012)

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



$$L_{crit} = 1.28 \times 10^{37} \text{ erg s}^{-1} \left(\frac{\Lambda}{0.1}\right)^{-7/5} w^{-28/15}$$

$$\times \left(\frac{M_*}{1.4\, M_\odot}\right)^{29/30} \left(\frac{R_*}{10 \text{ km}}\right)^{1/10} \left(\frac{E_*}{10 \text{ keV}}\right)^{16/15}$$

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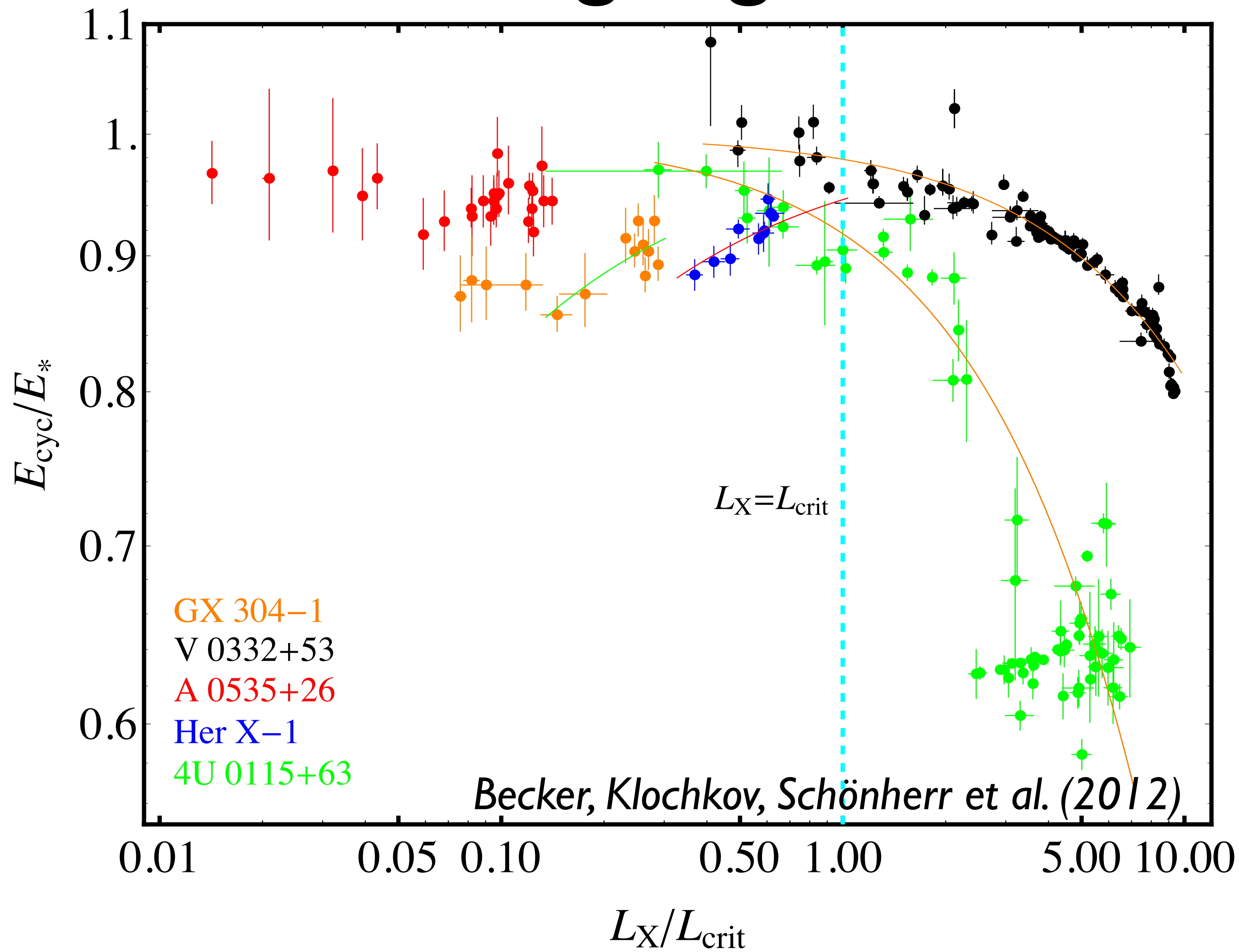

$$h_s = 2.28 \times 10^3 \text{ cm} \left(\frac{\xi}{0.01}\right)\left(\frac{M_*}{1.4\ M_\odot}\right)^{-1} \times \left(\frac{R_*}{10\text{ km}}\right)\left(\frac{L_X}{10^{37}\text{ erg s}^{-1}}\right).$$

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

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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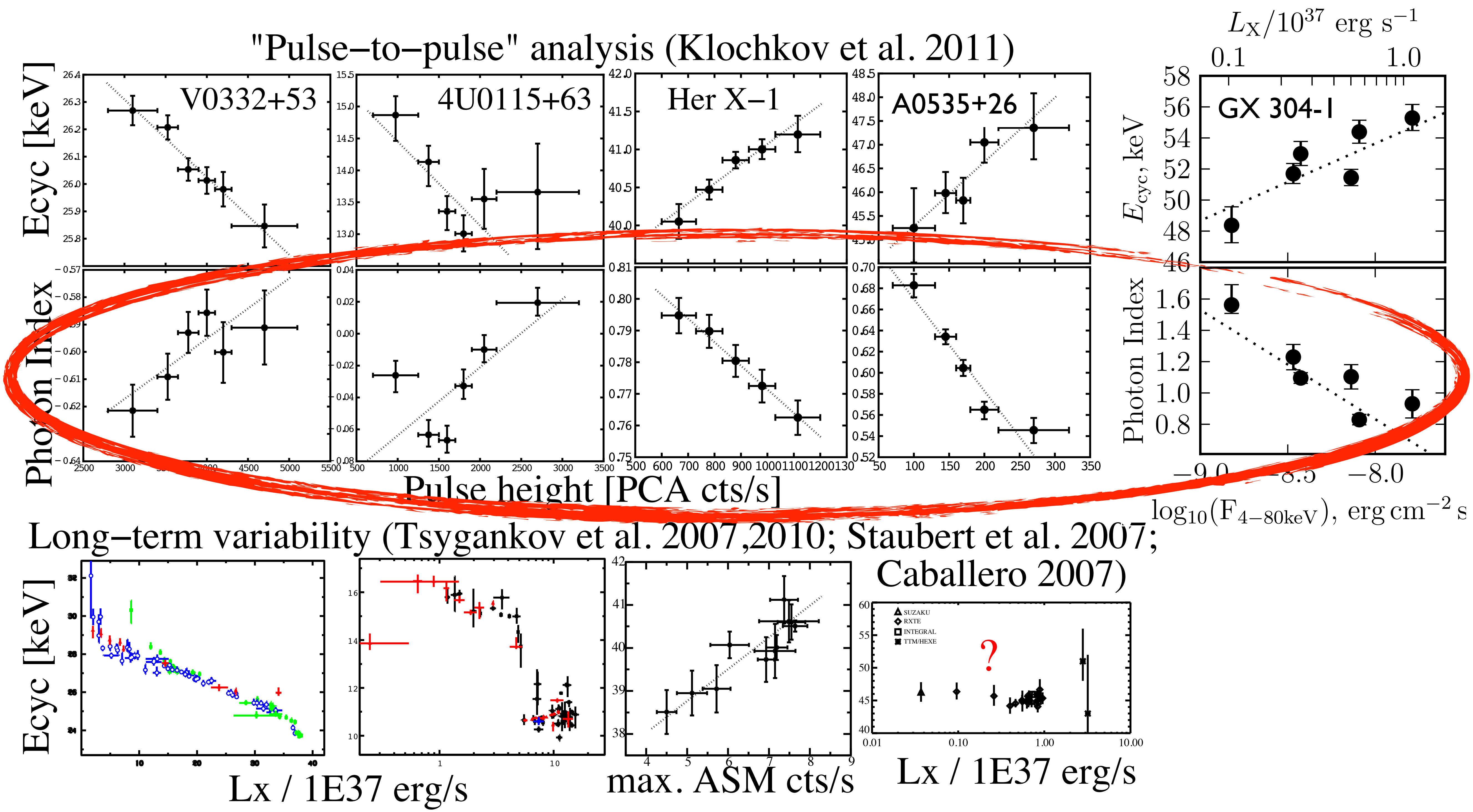
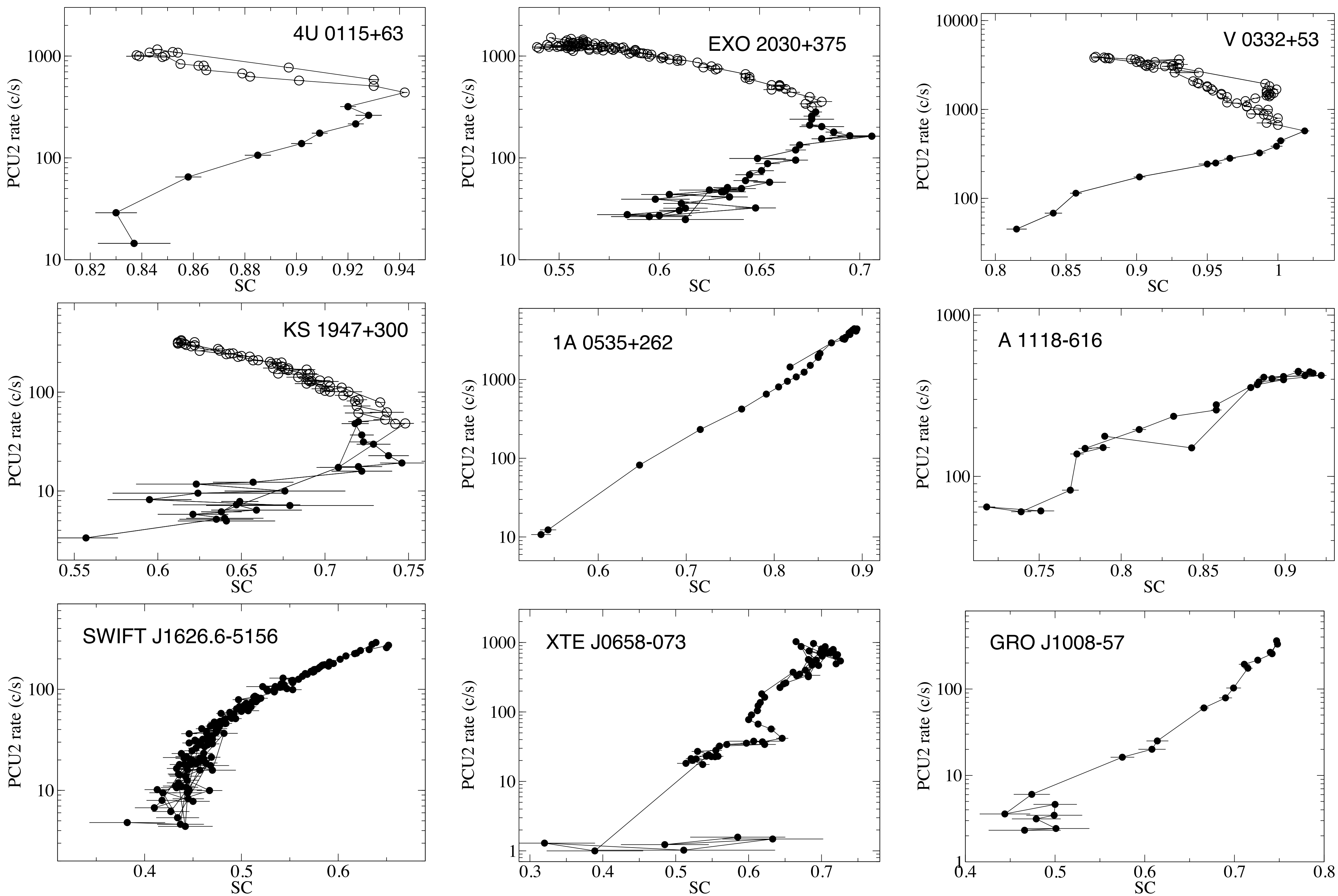
MAGNET Collaboration (based on Caballero&Wilms 2012)

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

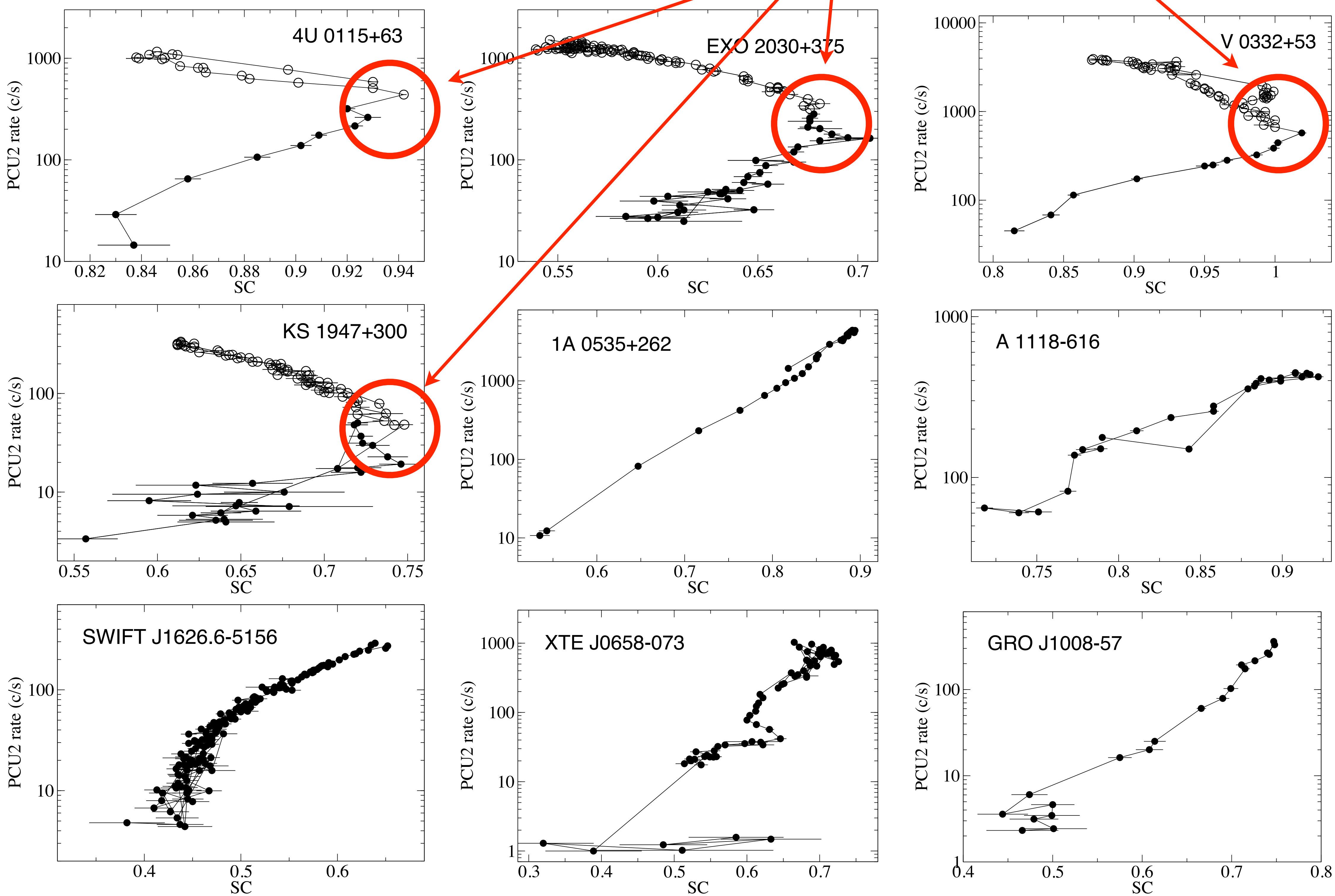


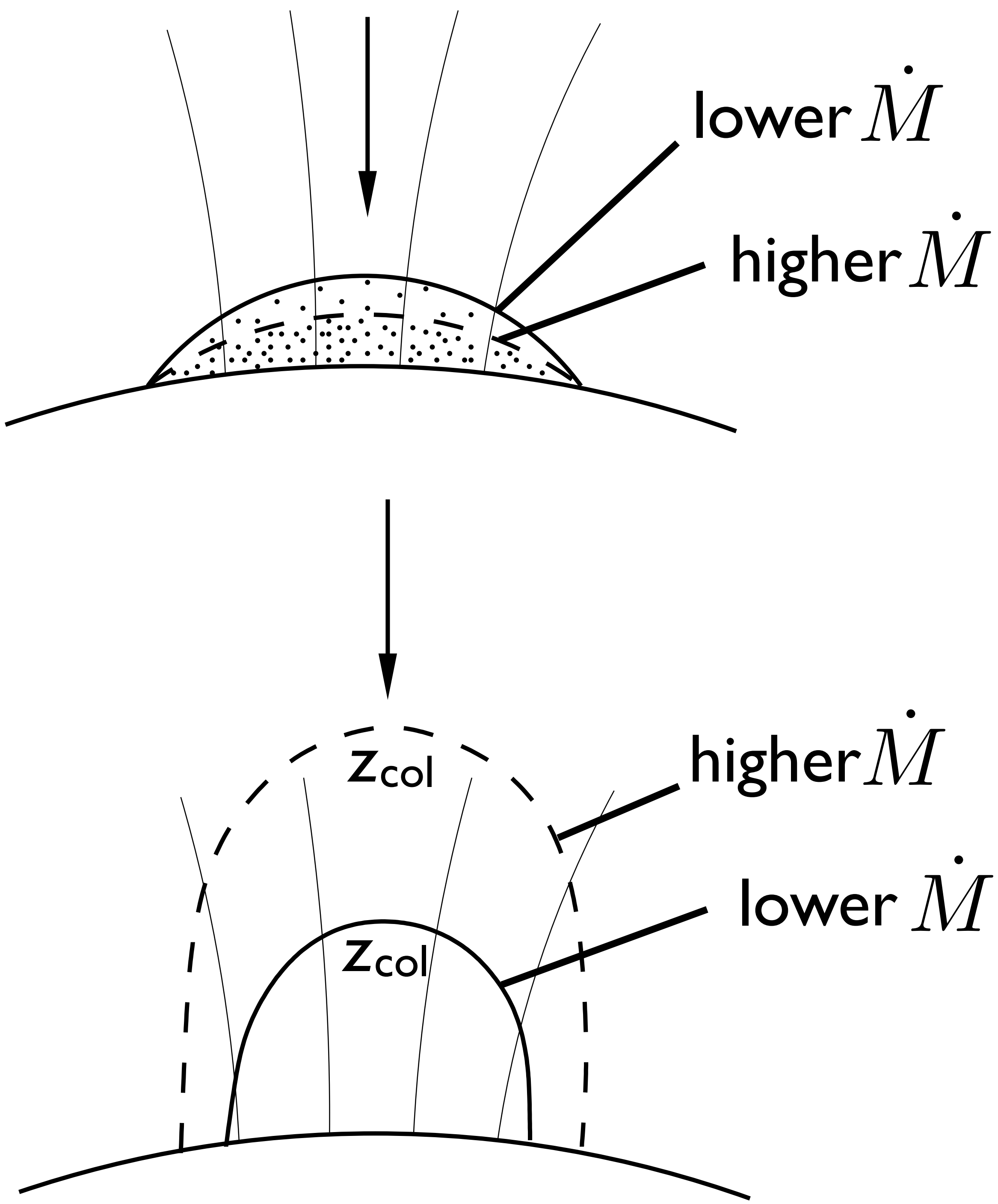
Reig&Nespoli (2012)



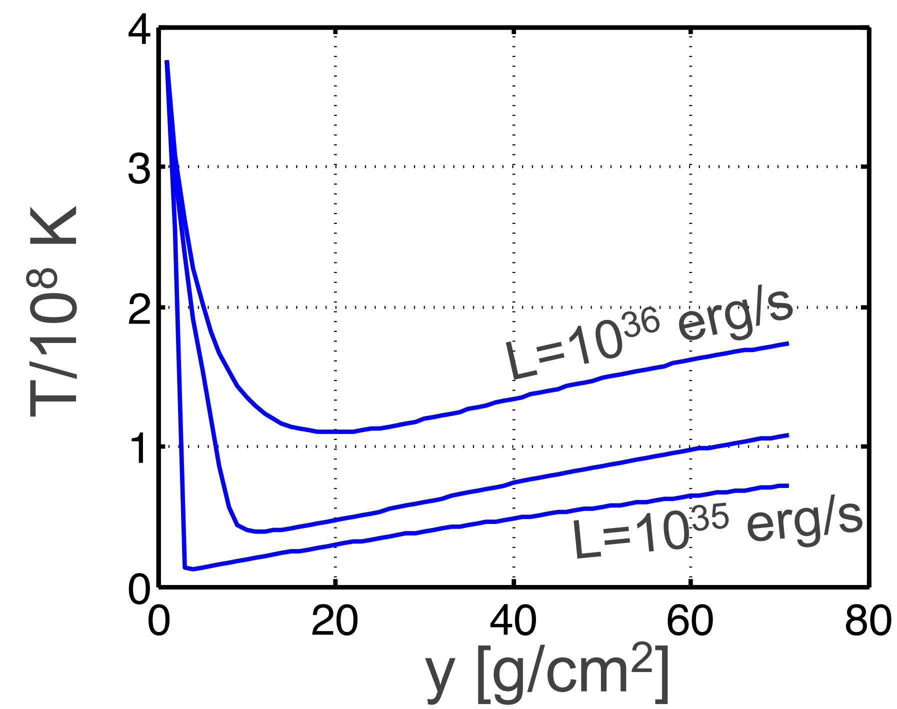
Reig&Nespoli (2012)

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

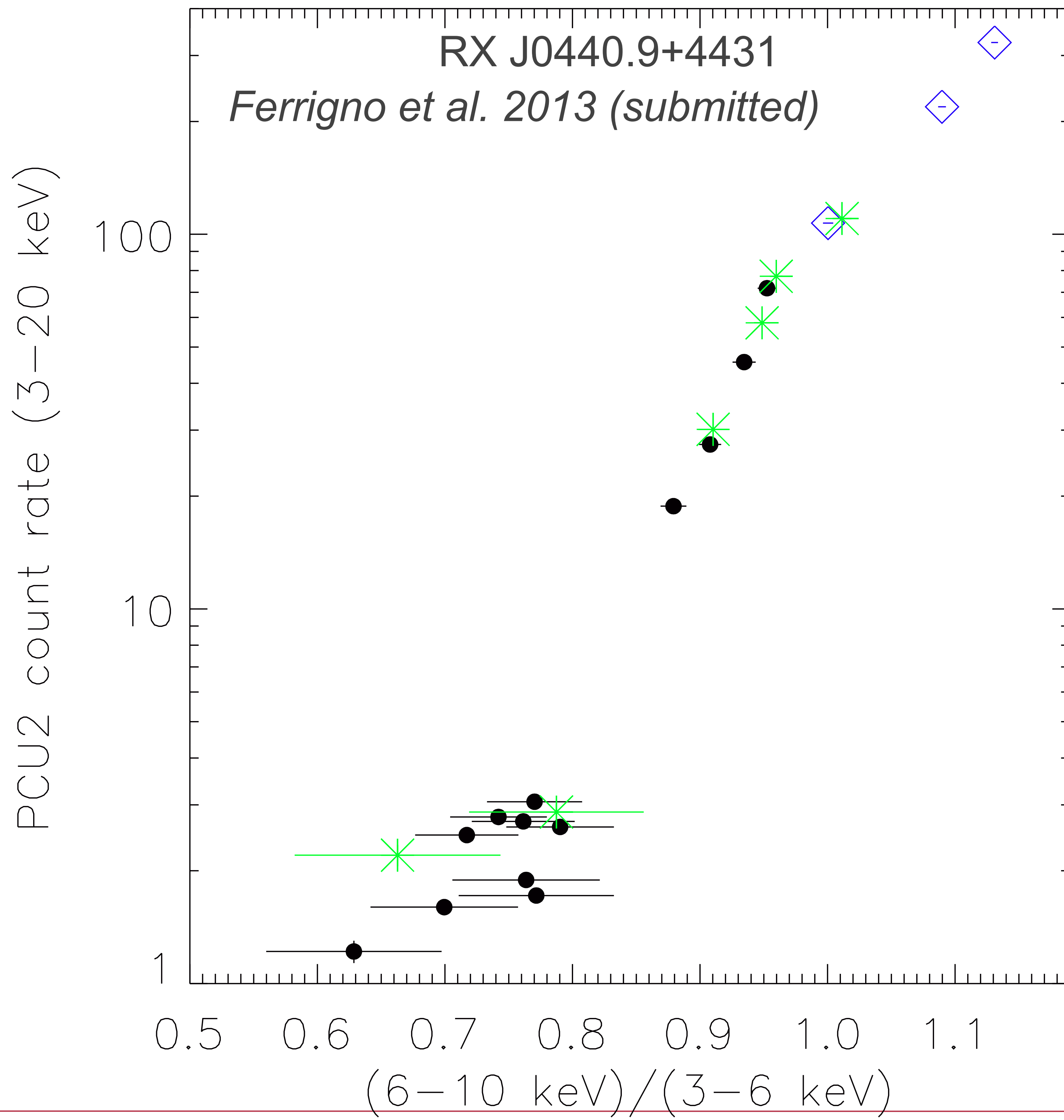




$L<L_c$: An increase of $\dot{M}$ leads to an increase of n_e, T_e и τ_{Compt} $\rightarrow$ a **harder** continuum



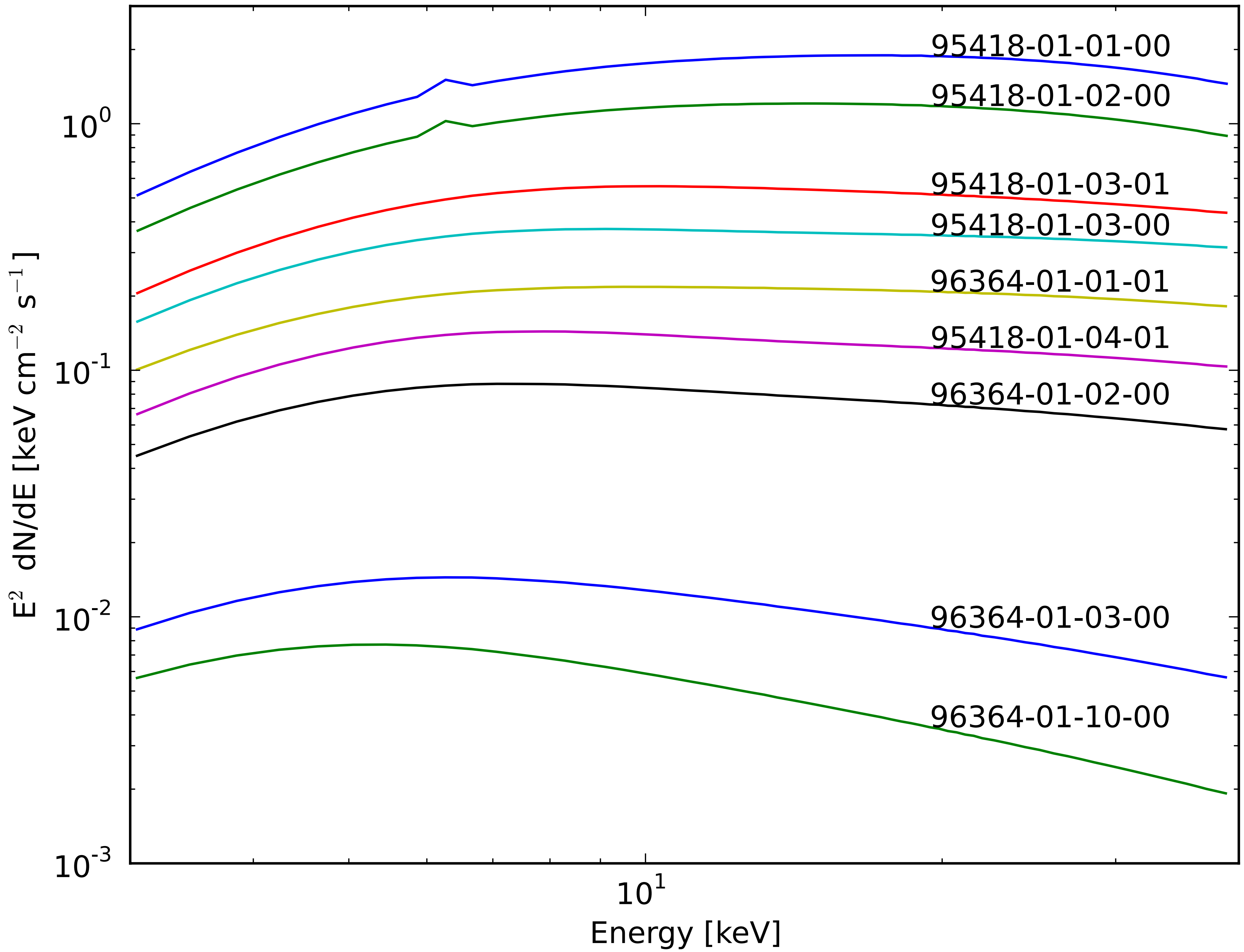
$L>L_c$: A more complicated case: horizontal energy transfer is important $\rightarrow$ 1-dimensional approach does not work



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

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

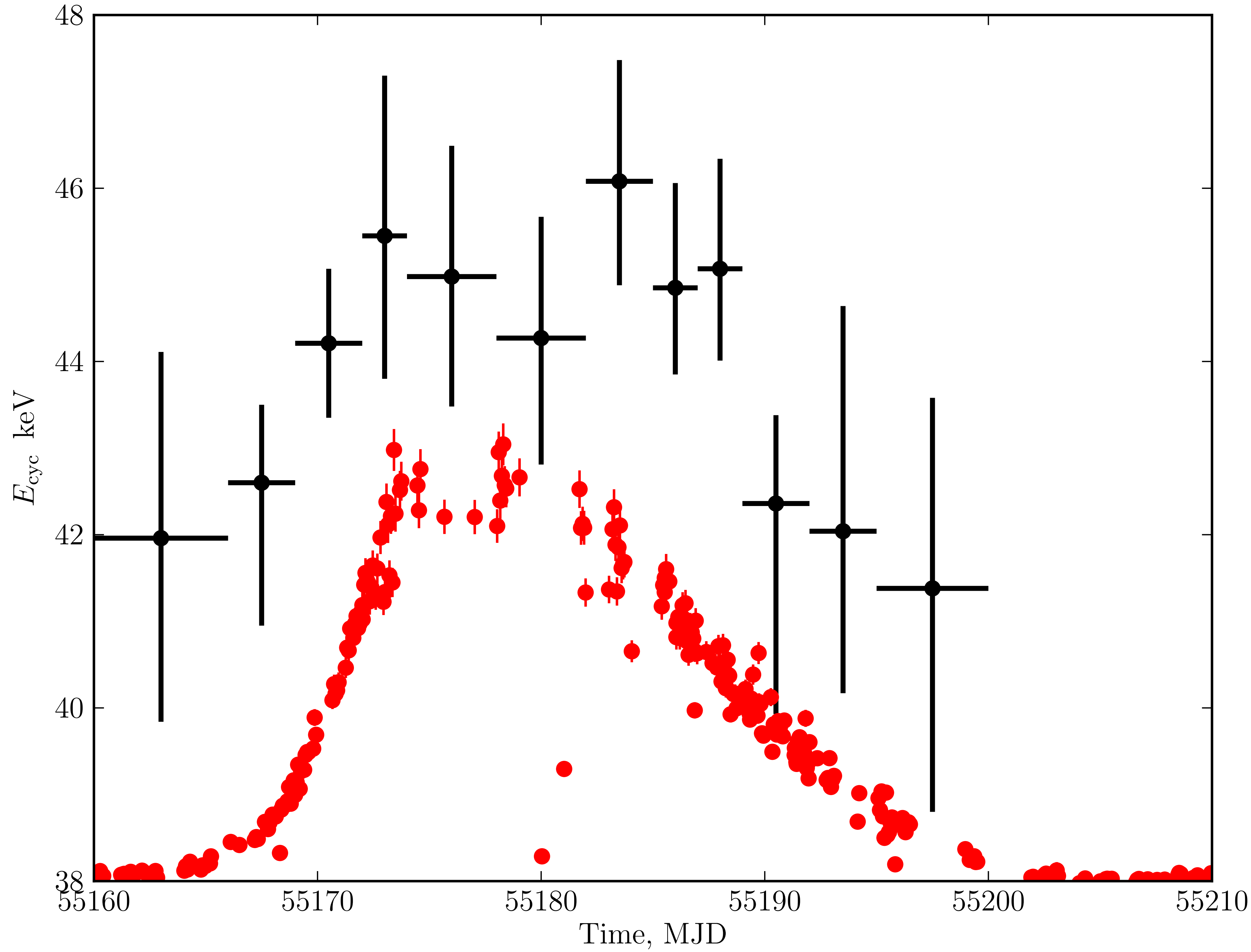
RX J0440.9+4431

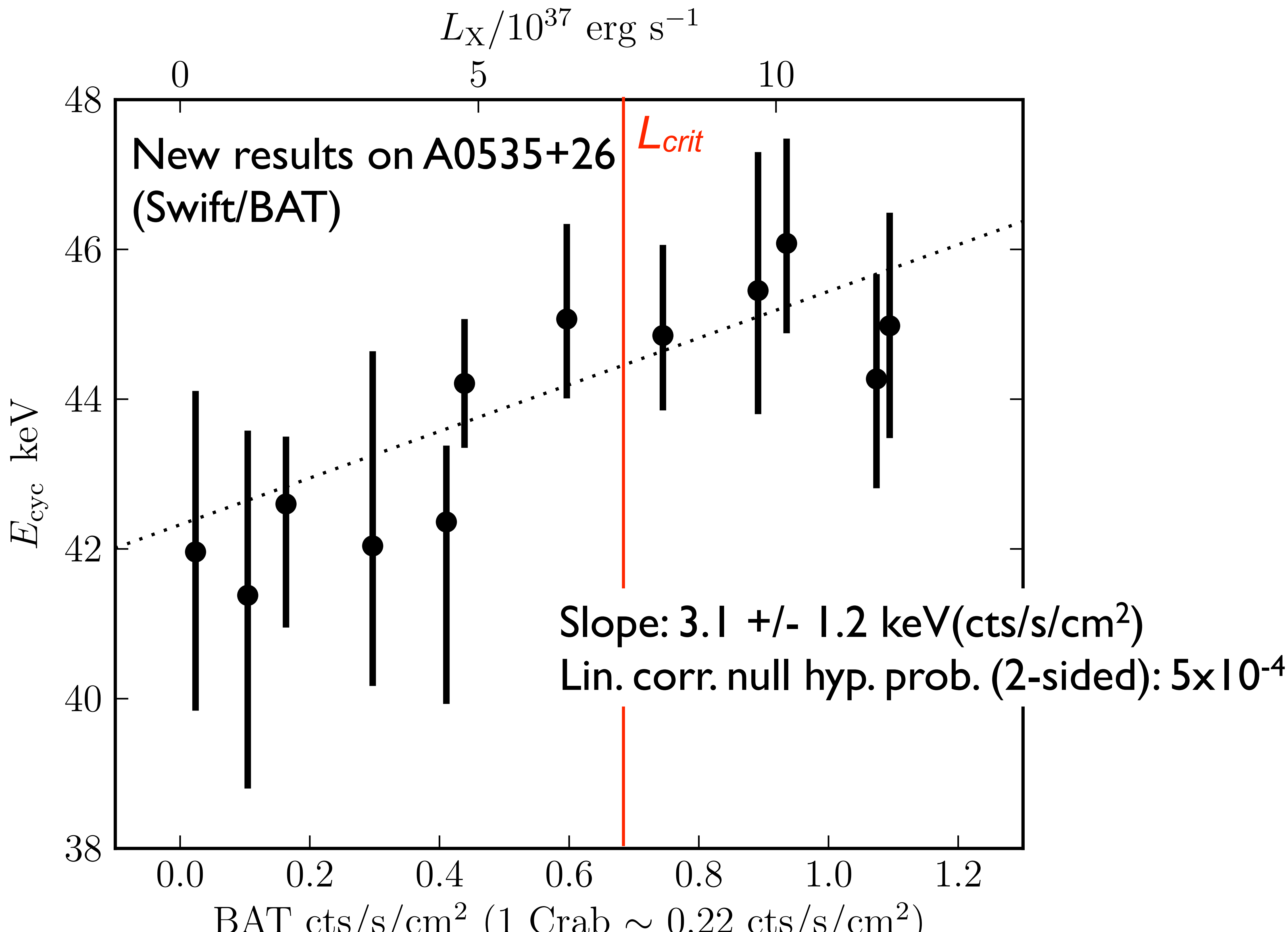


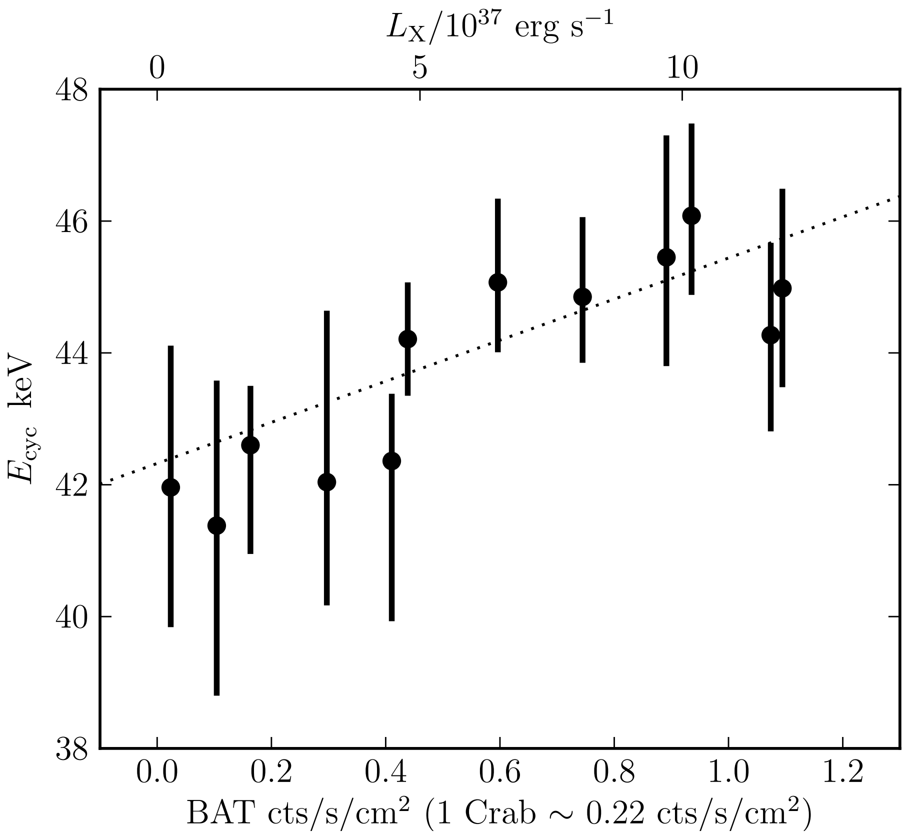
$L_X < 10^{37}$ erg/s

Ferrigno et al. 2013 (submitted)

New results on A0535+26 (Swift/BAT)




$L_X/10^{37}$ erg s^{-1}
0
5
10
48
46
44
42
40
38
E_{cyc} keV
L_{crit}
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}
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)


$L_X/10^{37}$ 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
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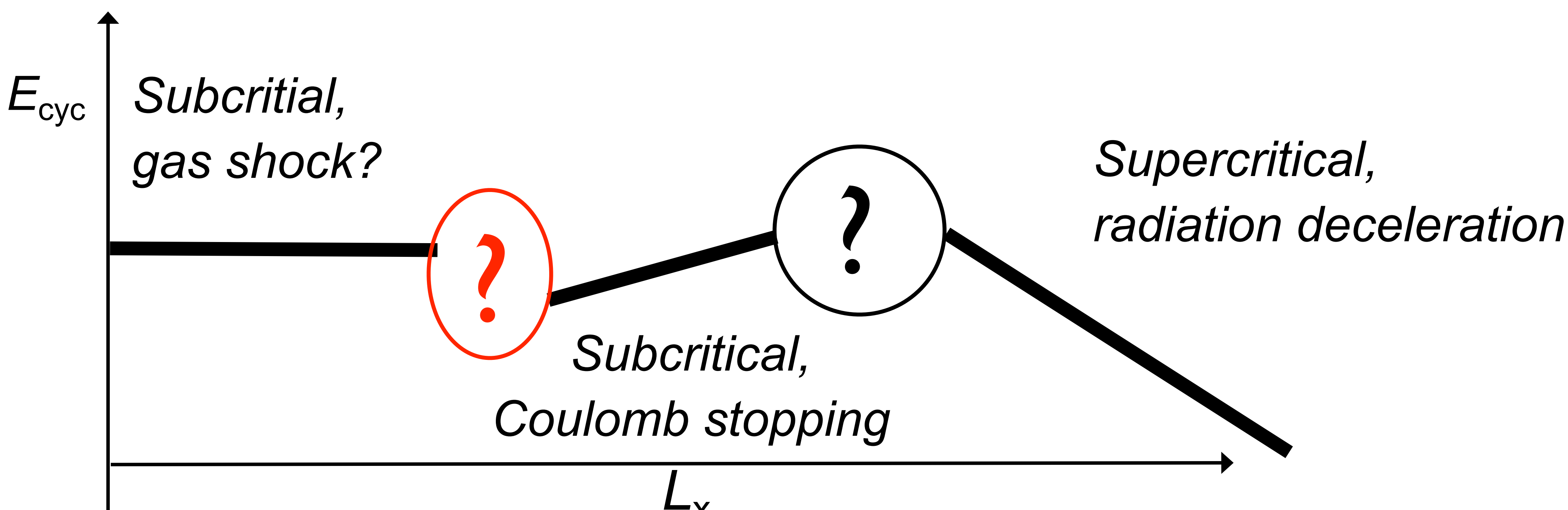
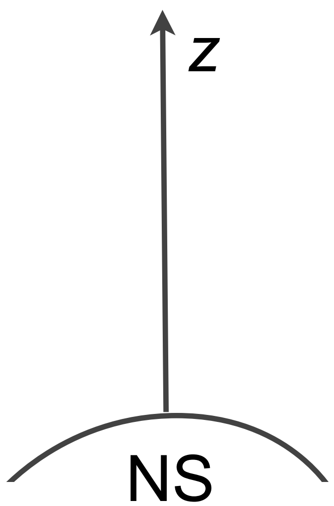

E_{cyc}
Subcritial,
gas shock?
?
?
Supercritical,
radiation deceleration
Subcritical,
Coulomb stopping
L_X

“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*.

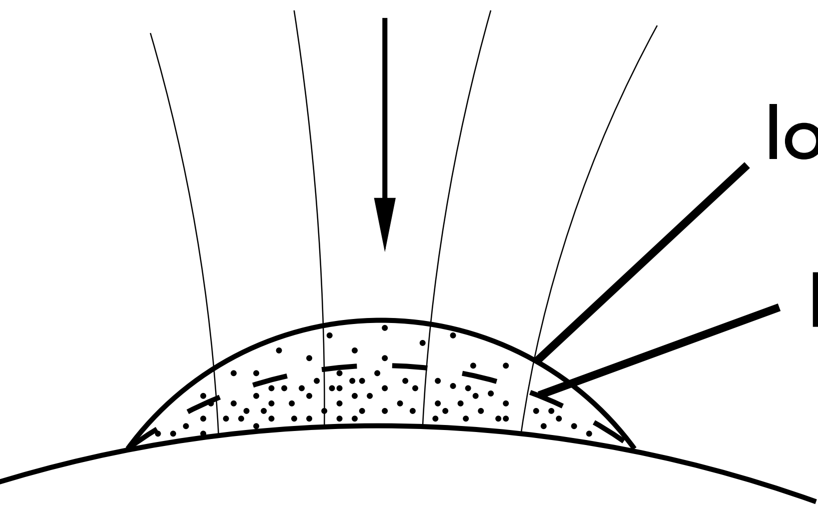
$$-\frac{dp}{dy} = \rho v\frac{dv}{dy} - g$$

$\rho(z)v(z)=\rho_0 v_0$=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 $\tau = \tau_\star$:

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

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