X-ray Observations of Dwarf Novae in Quiescence and Outburst

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X-ray Emission from Nonmagnetic CVs

Boundary Layer (BL)

$L_{BL} \approx L_{disk} = GM_{wd}\dot{M}_{acc}/2R_{wd} = L_{acc}/2$

matter decelerates from Keplerian velocities to the slowly rotating WD $L_{BL} \approx L_x$

(Patterson & Raymond 1985; Narayan Popham 1993, Popham &Narayan 1995, Godon et al. 1995)

Optically thick BL

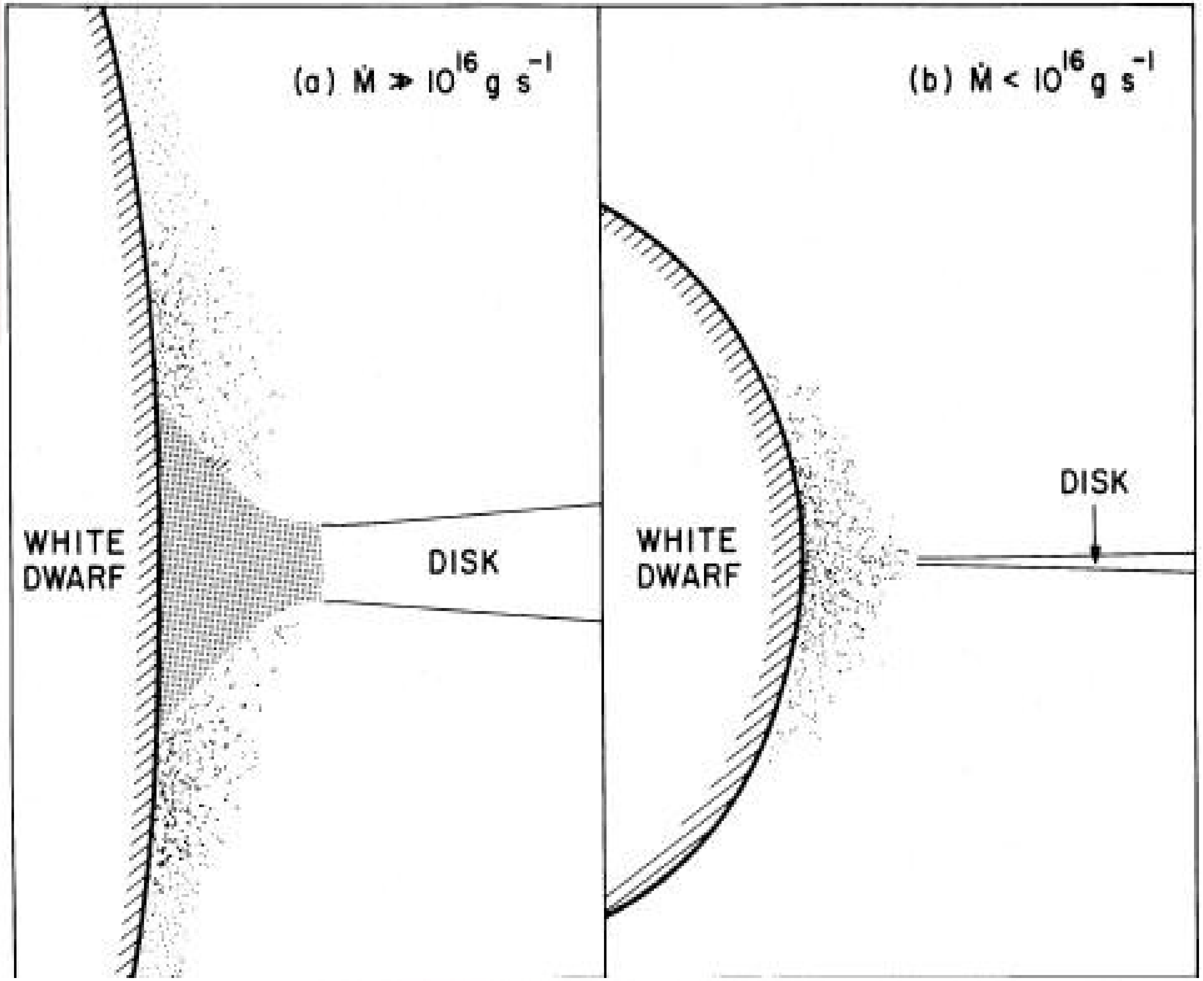
→ Soft X-rays ~10^5 K

$\dot{M} > 10^{-9}\ M_\odot$ /yr

Optically thin BL

→ Hard X-rays ~10^8 K

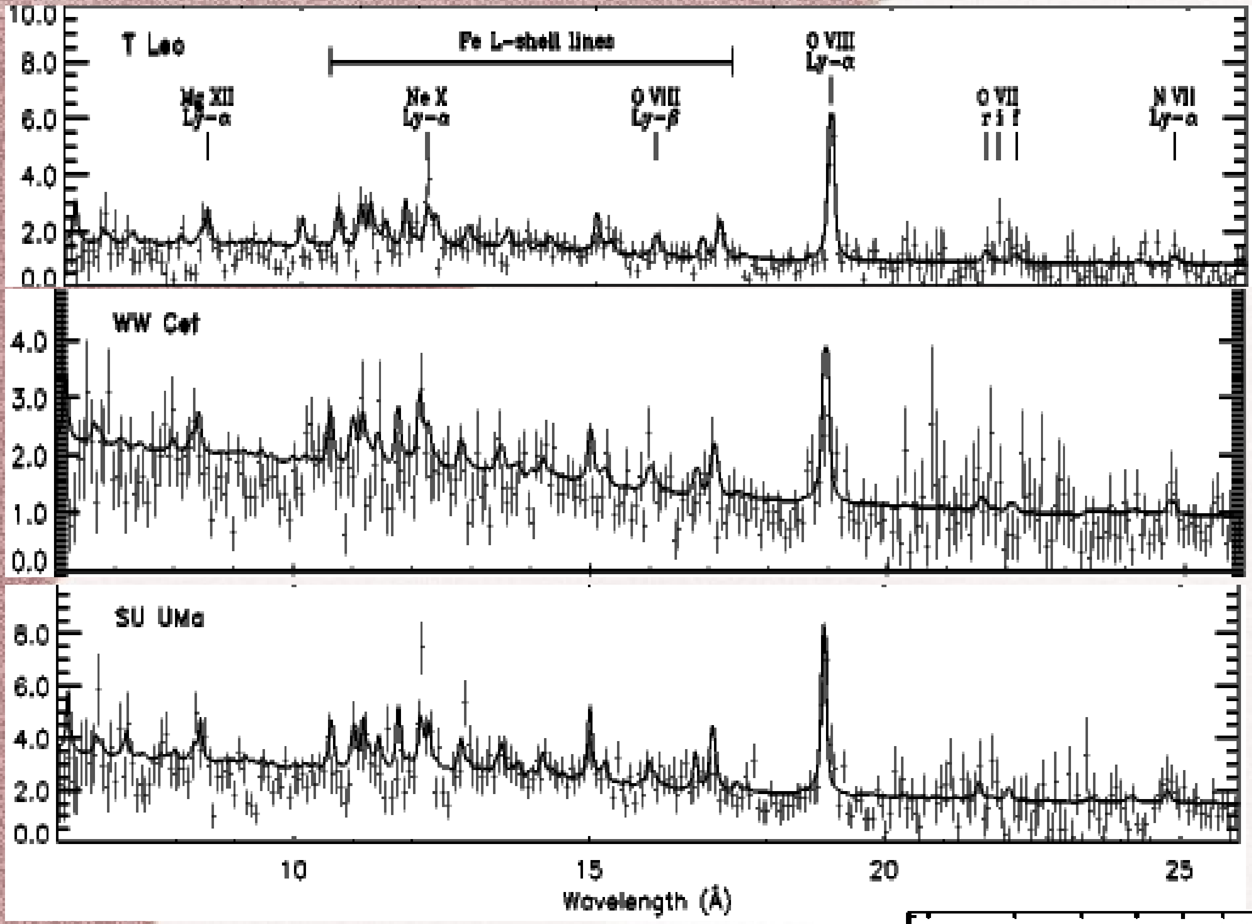
$\dot{M} < 10^{-9} M_\odot$ /yr



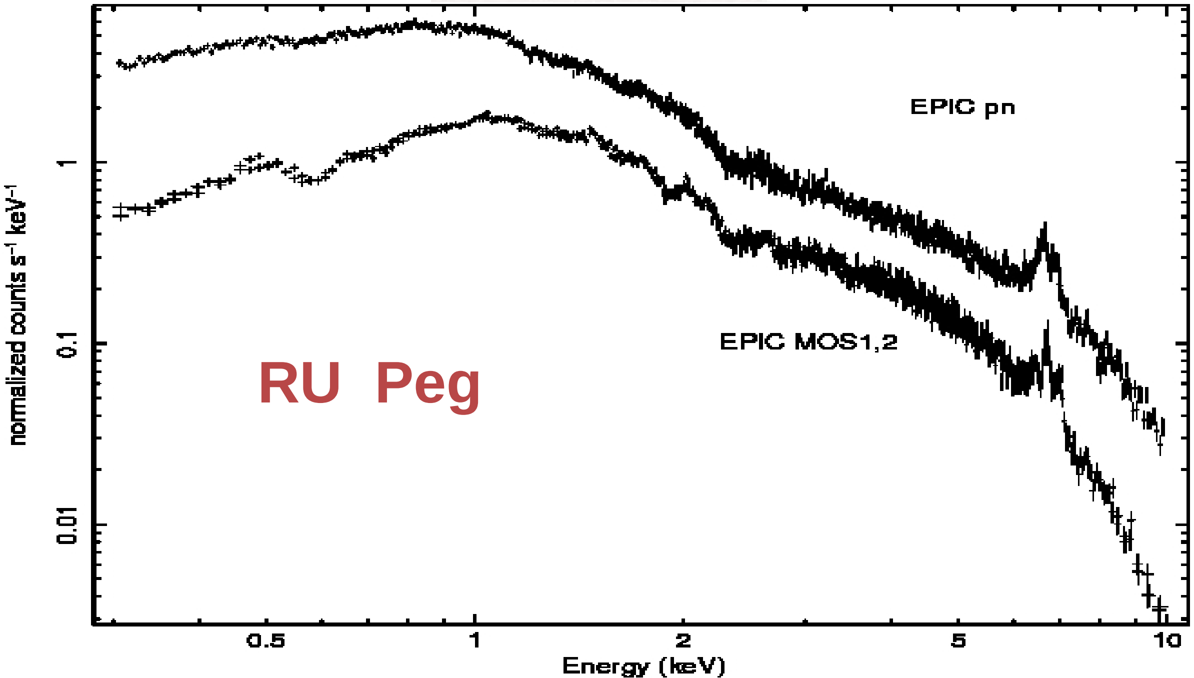
X-ray Emission in Quiescence (DN)

- Low-mass accretion, $\dot{M}_{acc}=10^{-12}-10^{-10}\, M_{\odot}$ /yr, BL → optically thin ➤ hard X-ray emission (Narayan&Popham 1993; Popham 1999).
- Narrow emission lines (strongest OVIII Kα), nearly solar abundances, reflection off of WD (6.4 keV emission line),
- Multi-temperature isobaric cooling flow model plasma emission with T_{max} = 9-55 keV ,
- Doppler broadening in lines <750 km/s; electron densities > 10^{12} cm^{-3}

  (see Baskill et al. 2005, Kuulkers et al. 2006 ; Pandel et al. 2005, Rana et al. 2006, Singh et al. 2006, Balman et al. 2011)
- Missing BL in the X-rays (low L_x/L_{disk} ratio) --> BL emits significant fraction of its luminosity in the EUV/FUV
  BL --> star, temperature very high --> X-rays
  BL --> disk, T~60.000 K --> FUV (e.g., fast rotating hot ring)



Pandel et al. 2005

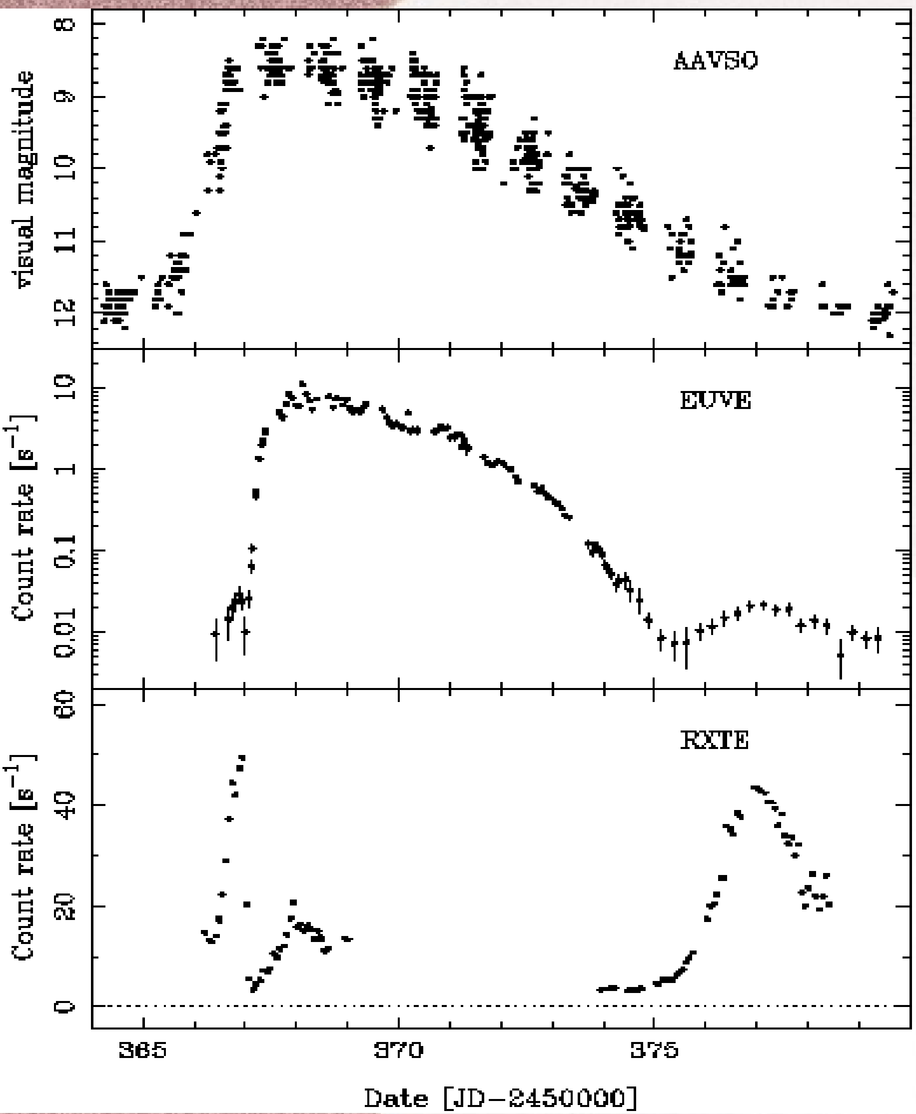


Balman et al. 2011

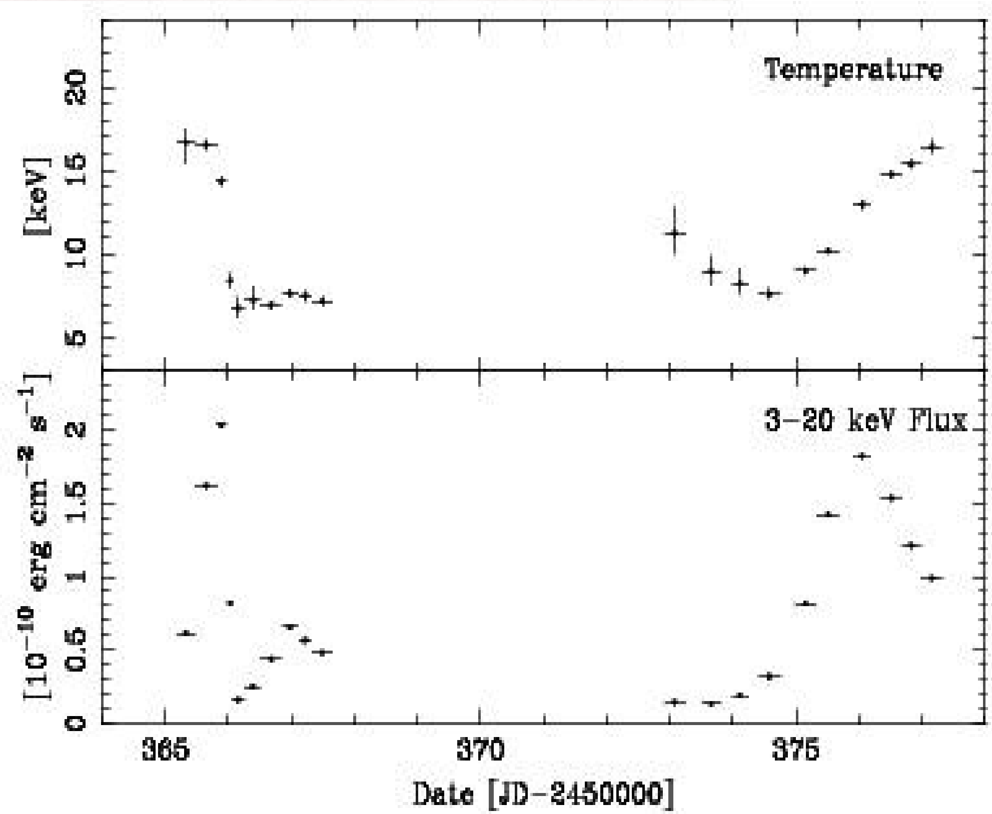
X-ray Emission During DNe Outbursts

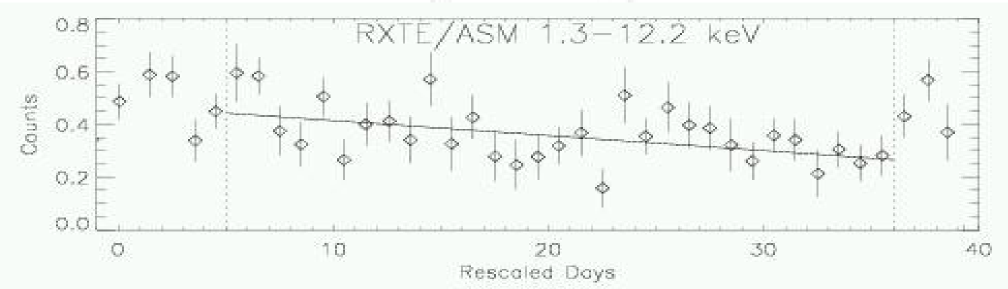
- Optically thick BL with 10^5-10^6 K emitting in the soft X-ray to EUV band. (observed T ~ 5-30 eV , Mauche et al. 1995; Mauche & Raymond 2000 Byckling et a. 2009)
- Suppressed (low F) hard X-ray emission during optical bright phases (peak) – at lower temperatures w.r.t. Quiescence and low neutral hydrogen column density (MacGowen et al. 2004, Wheatley et al. 2003, Collins & Wheatley 2010, Fertig et al. 2011)
- Some systems U Gem (Güver et al. 2006) GW Lib (Byckling et al. 2009) show increased X-ray emission.
- UV and X-ray delays in rise to outburst (w.r.t. optical)
- During outburst -- no eclipses in the eclipsing systems or much orbital variations.
- $L_x \sim 10^{30\text{-}33}$ erg/s in outburst.
- Grating spectroscopy indicate large widths for lines with velocities in excess of 1000 km/s (Mauche 2004, Rana et al. 2006)

SS Cyg

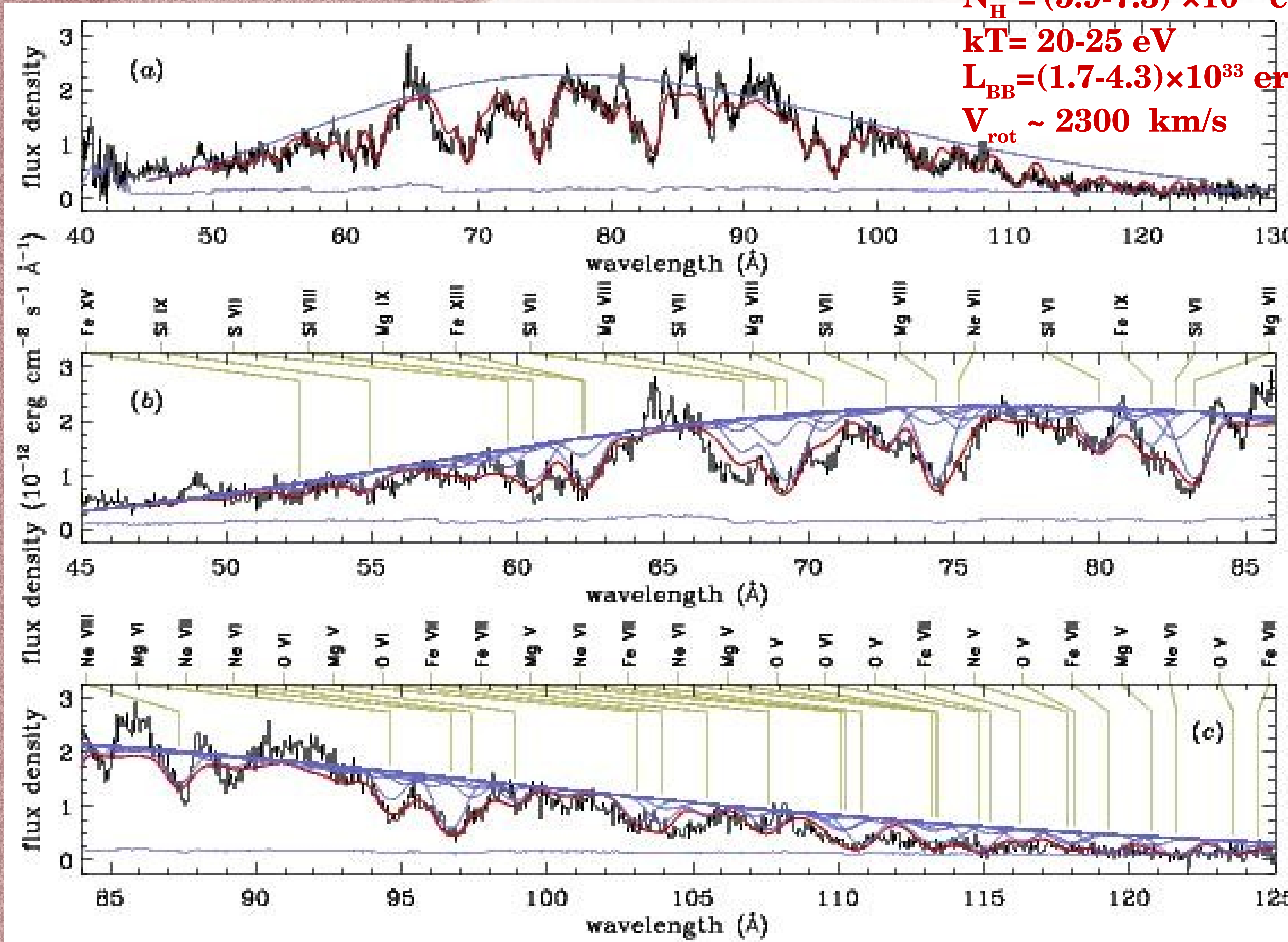


Wheatley et al. 2003





McGowan et al. 2004



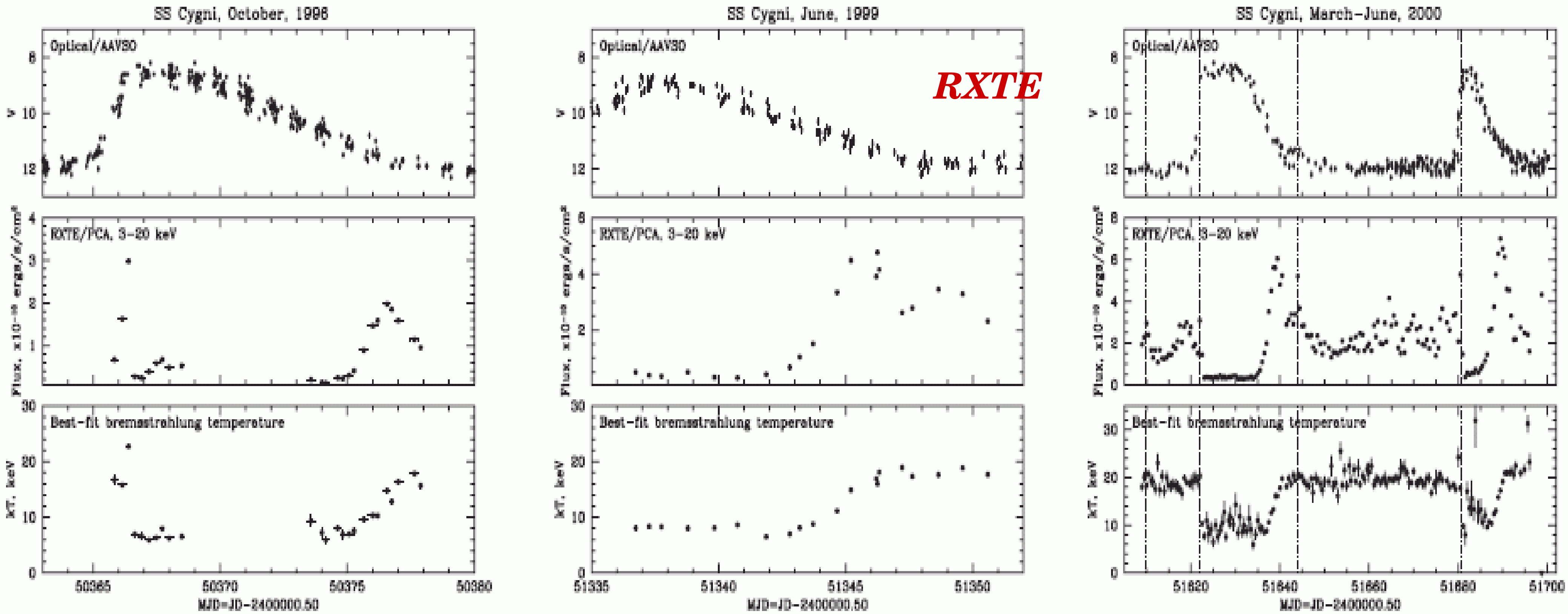
N_H = (5.9-7.3) ×10^{19} cm^{-2}

kT= 20-25 eV

L_{BB}=(1.7-4.3)×10^{33} erg/s

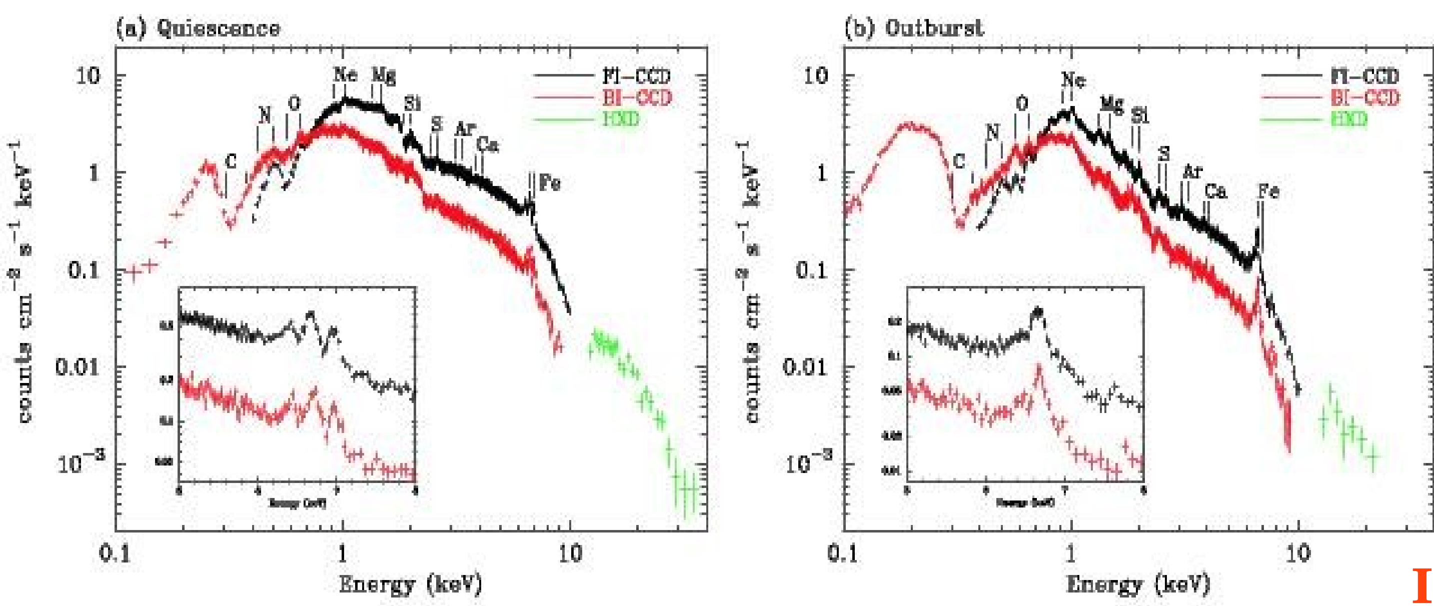
V_{rot} ~ 2300 km/s

Mauche 2004



RXTE

McGowan et al. 2004

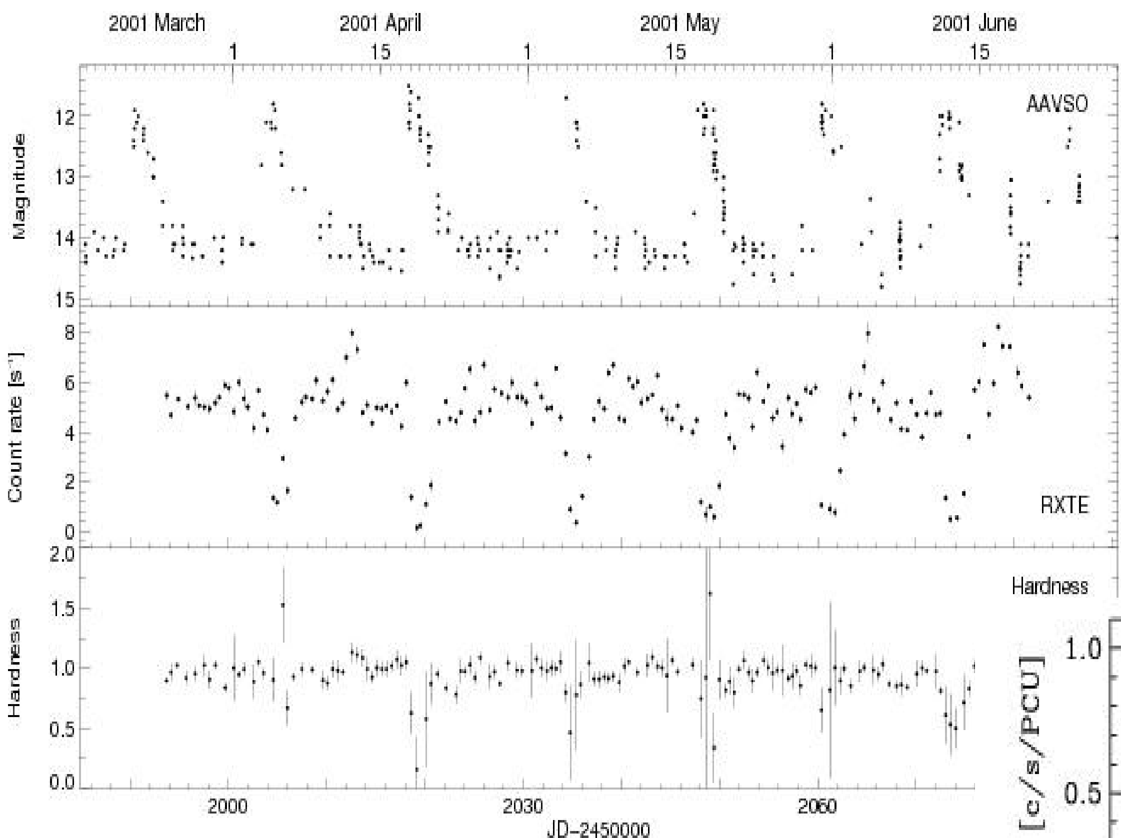


SUZAKU

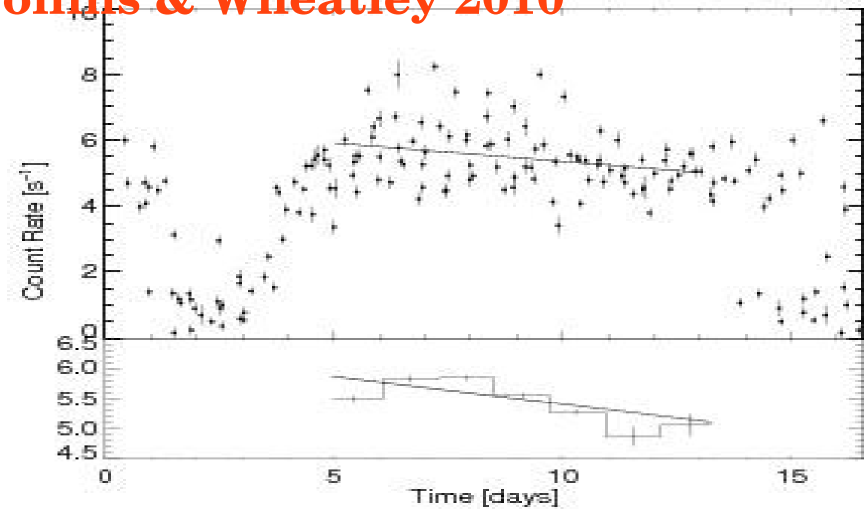
Reflector size $<7\times10^9$cm
In outburst

Ishida et al. 2009

SU UMa



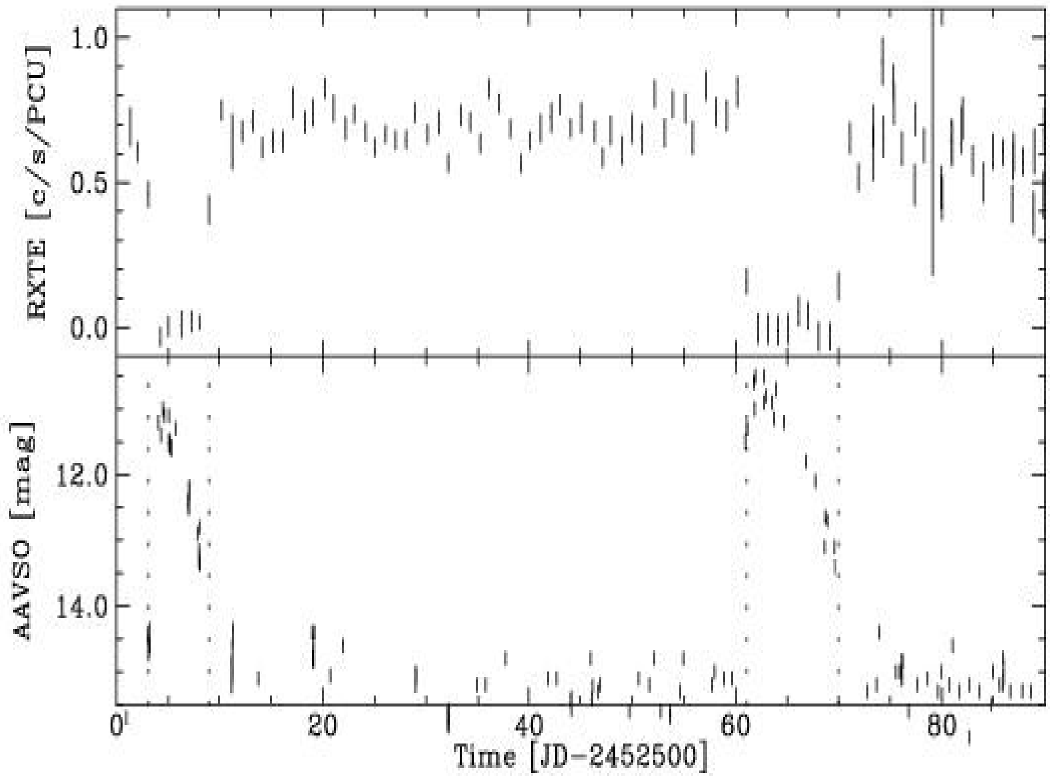
Collins & Wheatley 2010



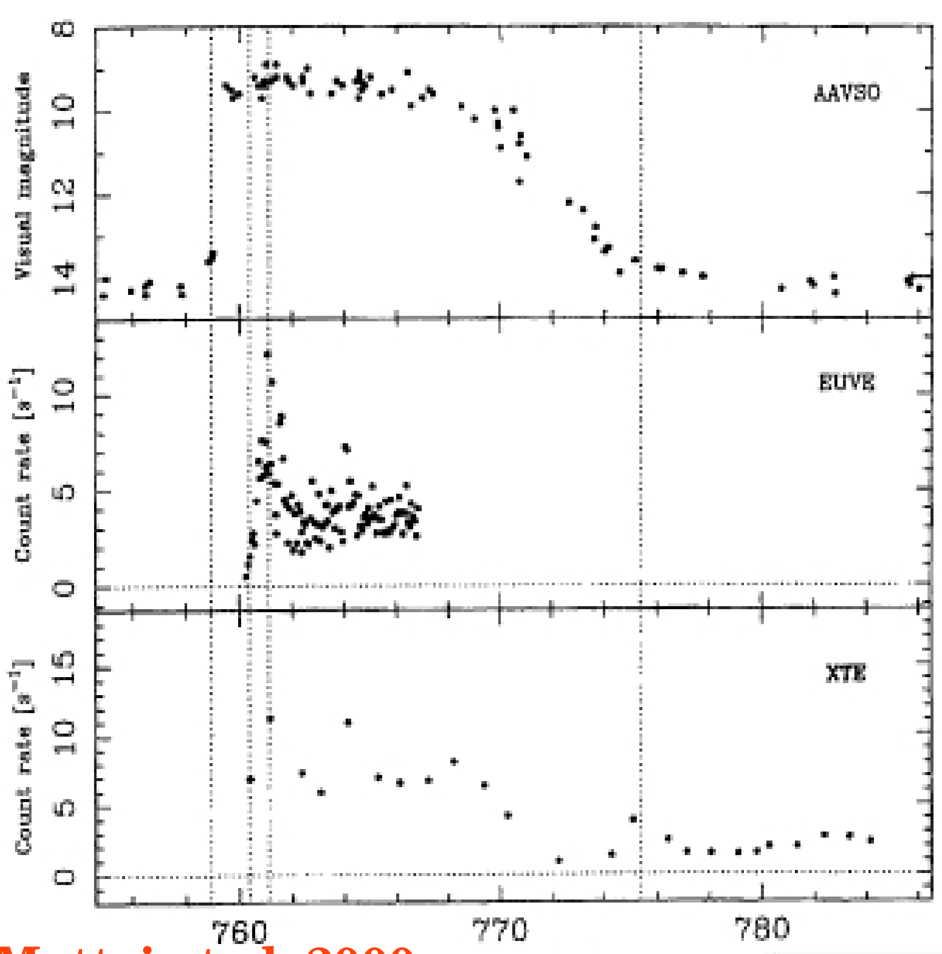
$L_{x(max)}$=2.6×10^{32} erg/s
kT ~ 4 keV
Quiescent kT ~ 12-19 keV

WW Cet

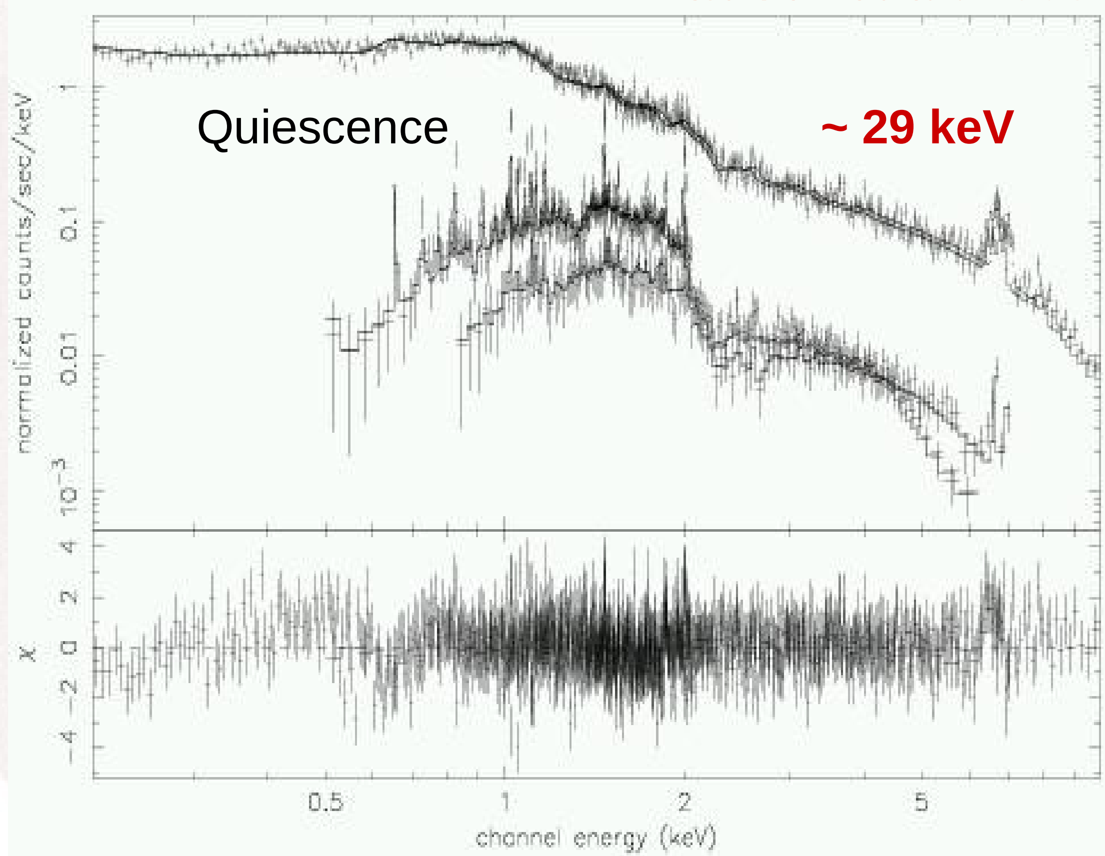
Fertig et al. 2011



U Gem

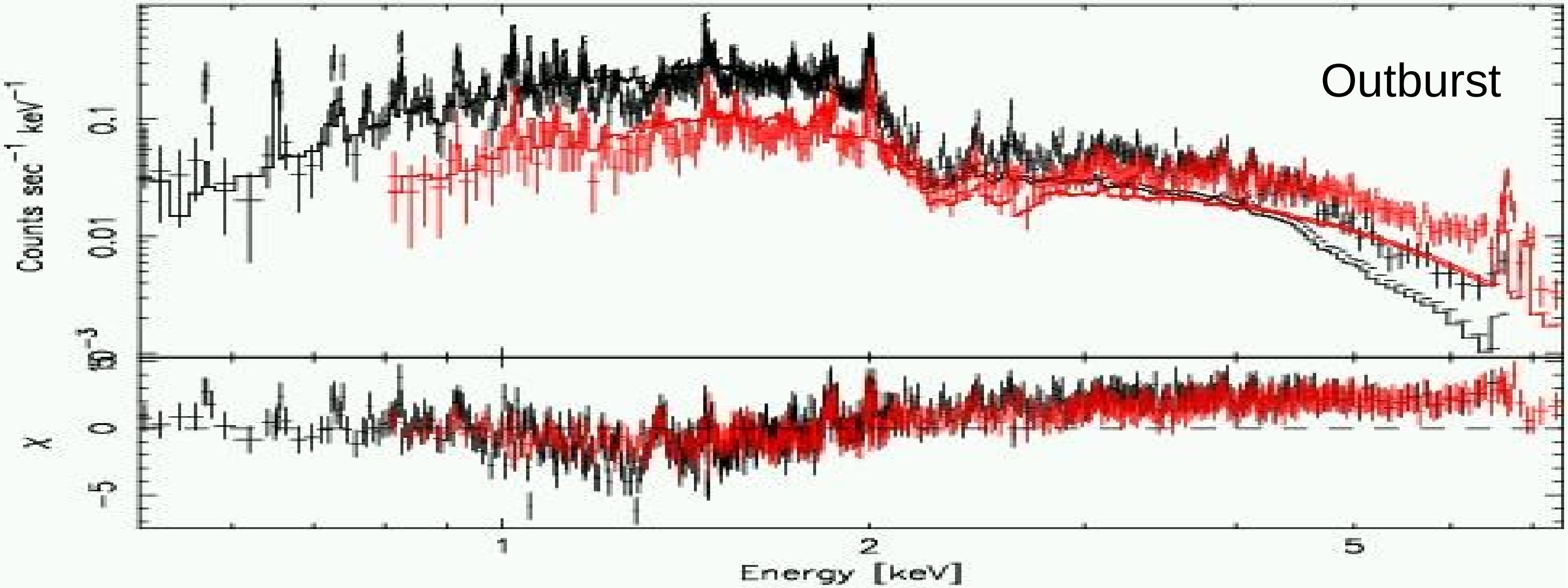


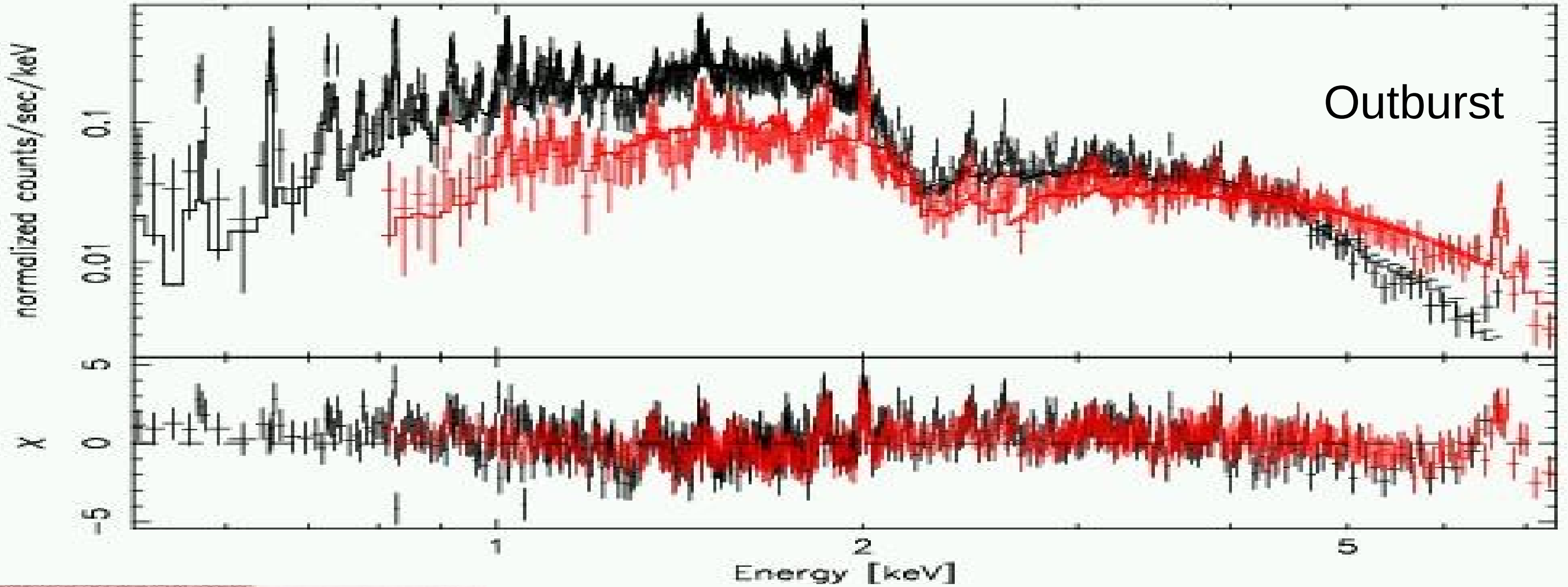
Mattei et al. 2000



Güver et al. 2006

Line	Wavelength Å	Quiescence Flux 10^{-5}Photons/cm^2/s	Outburst Flux 10^{-5}Photons/cm^2/s	Quiescence Velocity km/s	Outburst Velocity km/s
S XV	5.0665	0.94±0.52	4.16±1.47	1350	4180±2000
Si XIV	6.1804	2.17±0.33	6.91±0.80	1120	3080±460
Mg XII	8.4192	1.86±0.27	2.59±0.49	820	2200±690
Mg XI	9.1687	0.70±0.26	1.26±0.62	552±277	2000±900
Fe XXIV	10.6190	2.14±0.43	4.89±0.96	1340±440	4450±1000
Ne X	12.1321	3.46±0.65	11.2±1.85	1000±290	3450±550
Fe XVII	15.0140	3.17±0.89	12.3±2.49	740±350	2470±760
O VIII	16.0055	1.14±0.70	3.98±1.87	430	1400±1200
Fe XVII	17.0510	2.97±1.10	17.9±3.96	400	2830±913

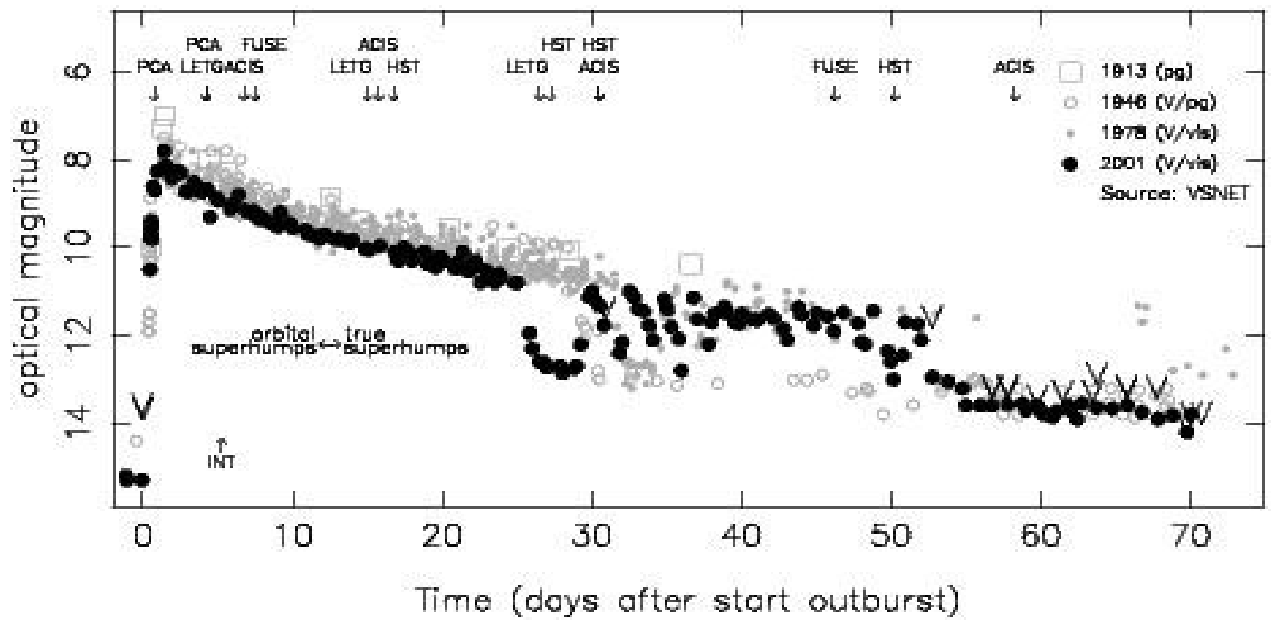


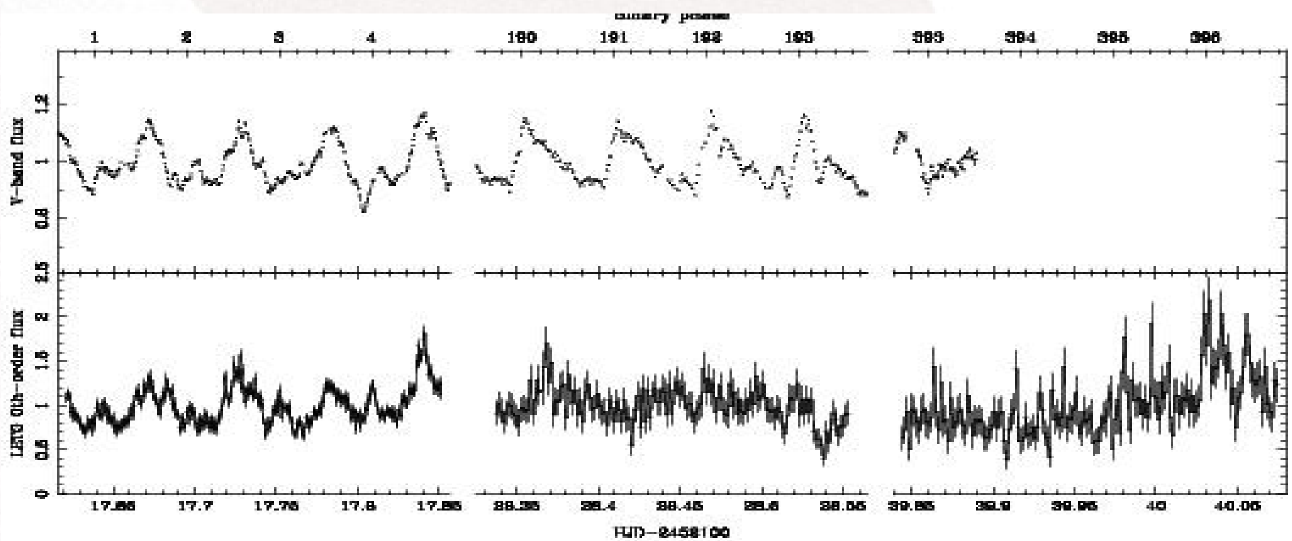


Dataset	Model Name	NH 10^{21}atoms/cm^2	T_{Max} kT (keV)	Power-Law index of cemekl α	Photon Index Γ	T keV	Flux 10^{-11}ergs/cm^2/s	χ^2_ν
MEG	cemekl	0.37±0.004	100±3.4	0.52±0.04	-	-	3.00	1.877
HEG	cemekl	0.37±0.004	100±13.2	0.69±8.23	-	-	3.40	1.877
HEG	cemekl+pow	0.45±0.45	9.49±4.1	1.35±0.49	0.54±0.16	-	3.31±1.38	1.297
MEG	cemekl+pow	0.45±0.45	18.44±10.5	0.26±0.11	0.64±0.06	-	3.39±0.53	1.297
HEG	cemekl+bremss	3.43±0.38	94.17	0.07	-	199.3	-	-
MEG	cemekl+bremss	3.43±0.38	1.73	0.01	-	199.3	-	-

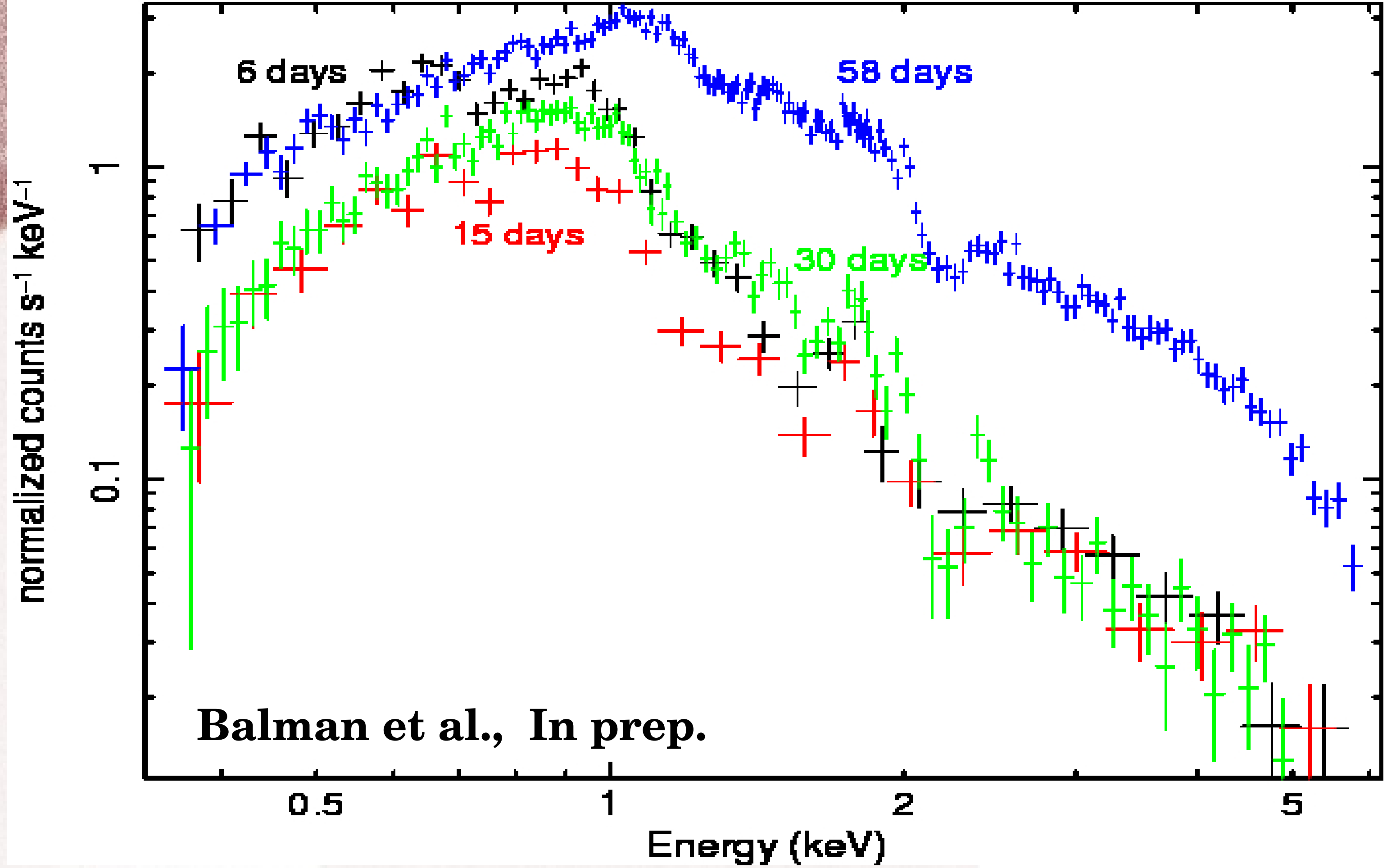
WZ Sge

July-August 2001
Superoutburst

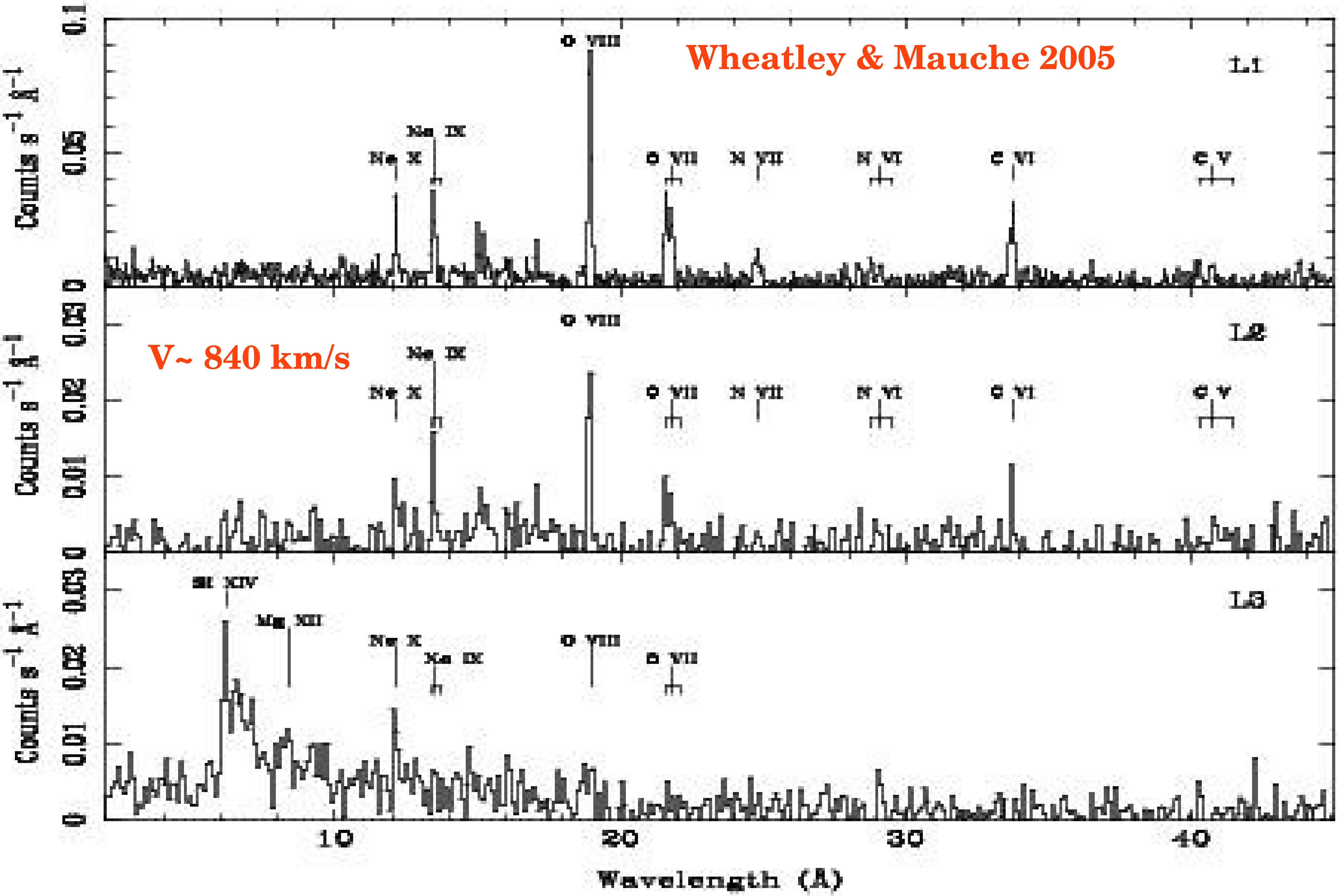




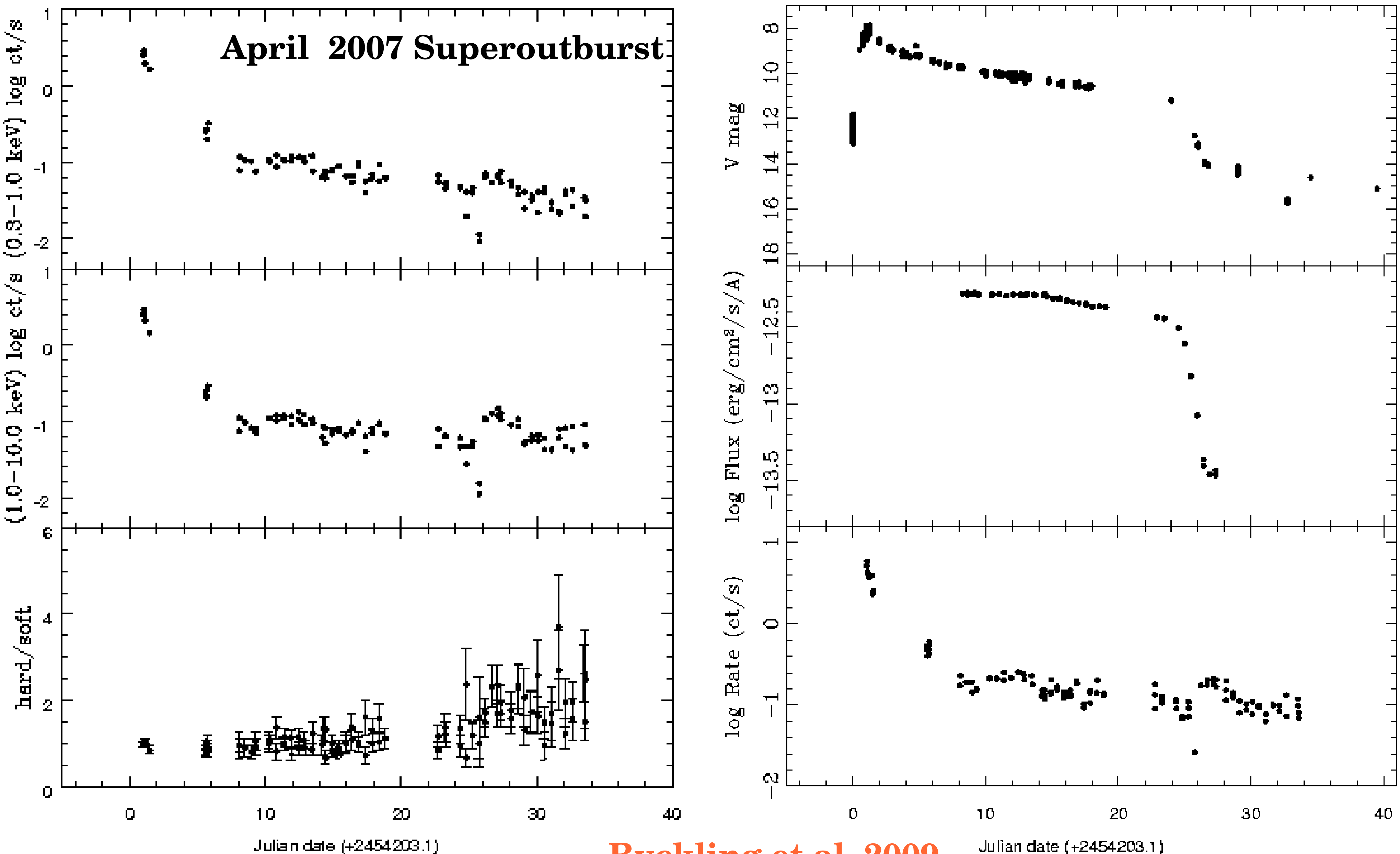
WZ Sge



- 6 days kT_{max} ~ 1.1 keV ; low N_H, Γ=1.3
- 15 days kT_{max} ~1.04 keV; 10^{21} cm^{-2}, Γ=0.82
- 30 days k_{max} ~ 1.92 keV; 10^{21} cm^{-2}, Γ=1.29 **L_x ~ 2.1×10 ^{30} erg/s**
- 58 days kT_{max} ~ 21 keV ; 10^{21} cm^{-2} **L_x ~ 9.4×10 ^{30} erg/s**


Wheatley & Mauche 2005
V~ 840 km/s
L1
L2
L3
O VIII
Ne IX
Ne X
O VII
N VII
N VI
C VI
C V
Si XIV
Mg XII
Counts s^{-1} Å^{-1}
Wavelength (Å)

GW Lib

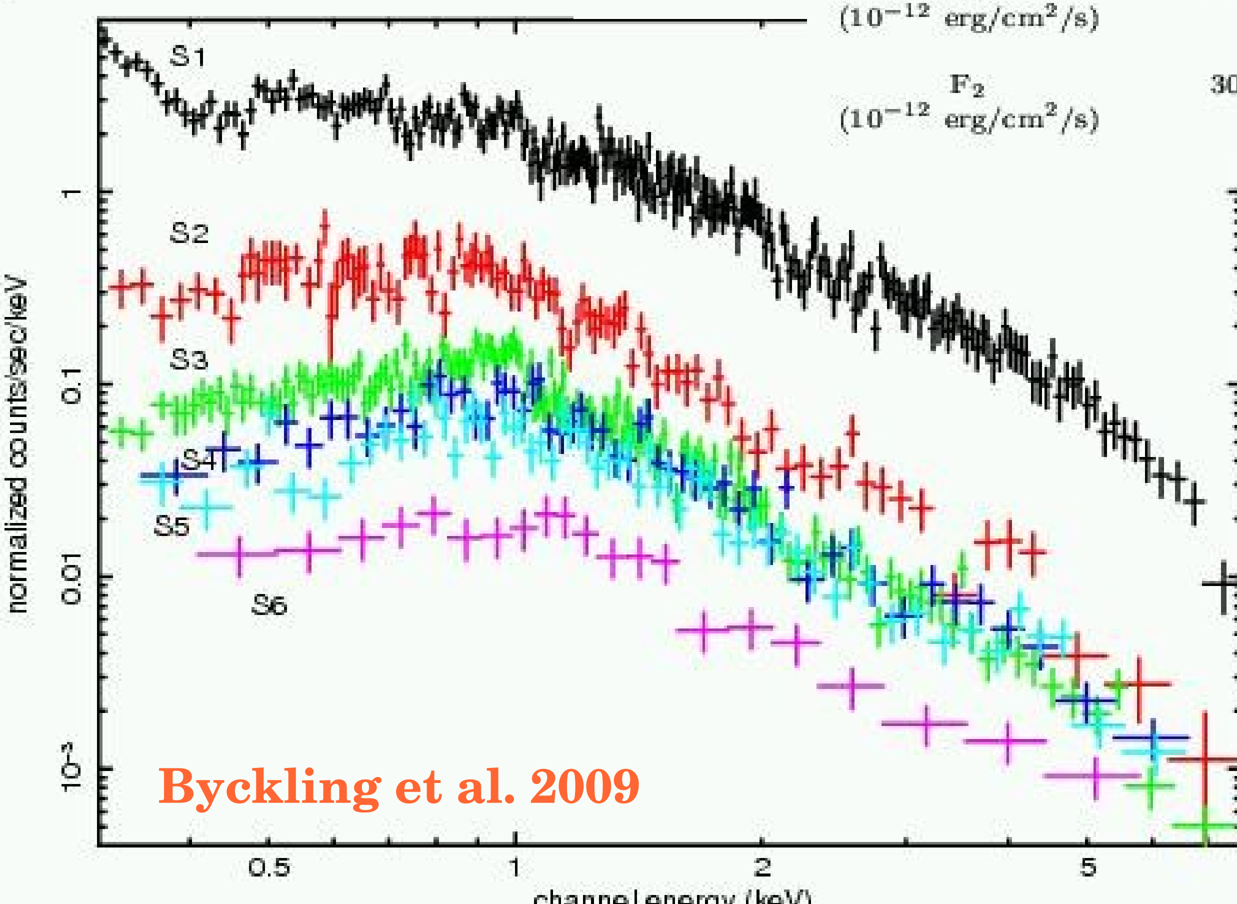


Byckling et al. 2009

Spec	Epoch (d)
S1	1–2
S2	6
S3	8–19
S4	23–28
S5	28–34
S6	(2008 & 2009 data)

2008+2009
$0.11^{+4.45}_{-0.11}$
$3.51^{+1.46}_{-1.16}$
1.1×10^{-12}
1.4×10^{30}
1.2×10^{13}

Spectrum	S1	S2	S3	S4	S5
Model	wa(bb+3me)	wa(3me)	wa(2me)	wa(2me)	wa(2me)
n_H (10^{20} cm^{-2})	$23.83^{+0.05}_{-0.04}$	$8.61^{+5.38}_{-3.99}$	$8.15^{+1.23}_{-1.17}$	$13.25^{+7.28}_{-3.38}$	$14.63^{+6.86}_{-4.36}$
kT_{bb} (keV)	$0.013^{+0.001}_{-0.001}$	–	–	–	–
kT_1 (keV)	$5.46^{+1.26}_{-0.86}$	$4.80^{+6.07}_{-1.66}$	$5.79^{+2.73}_{-1.51}$	$5.19^{+5.13}_{-1.88}$	$4.92^{+3.82}_{-1.36}$
kT_2 (keV)	$0.71^{+0.23}_{-0.13}$	$0.64^{+0.21}_{-0.14}$	$0.66^{+0.06}_{-0.07}$	$0.57^{+0.23}_{-0.24}$	$0.48^{+0.20}_{-0.16}$
kT_3 (keV)	$0.17^{+0.01}_{-0.01}$	$0.17^{+0.10}_{-0.05}$	–	–	–
F_1 (10^{-12} erg/cm^2/s)	120.	6.72	3.05	3.88	3.62
F_2 (10^{-12} erg/cm^2/s)	30.5	8.44	3.94	2.38	1.67



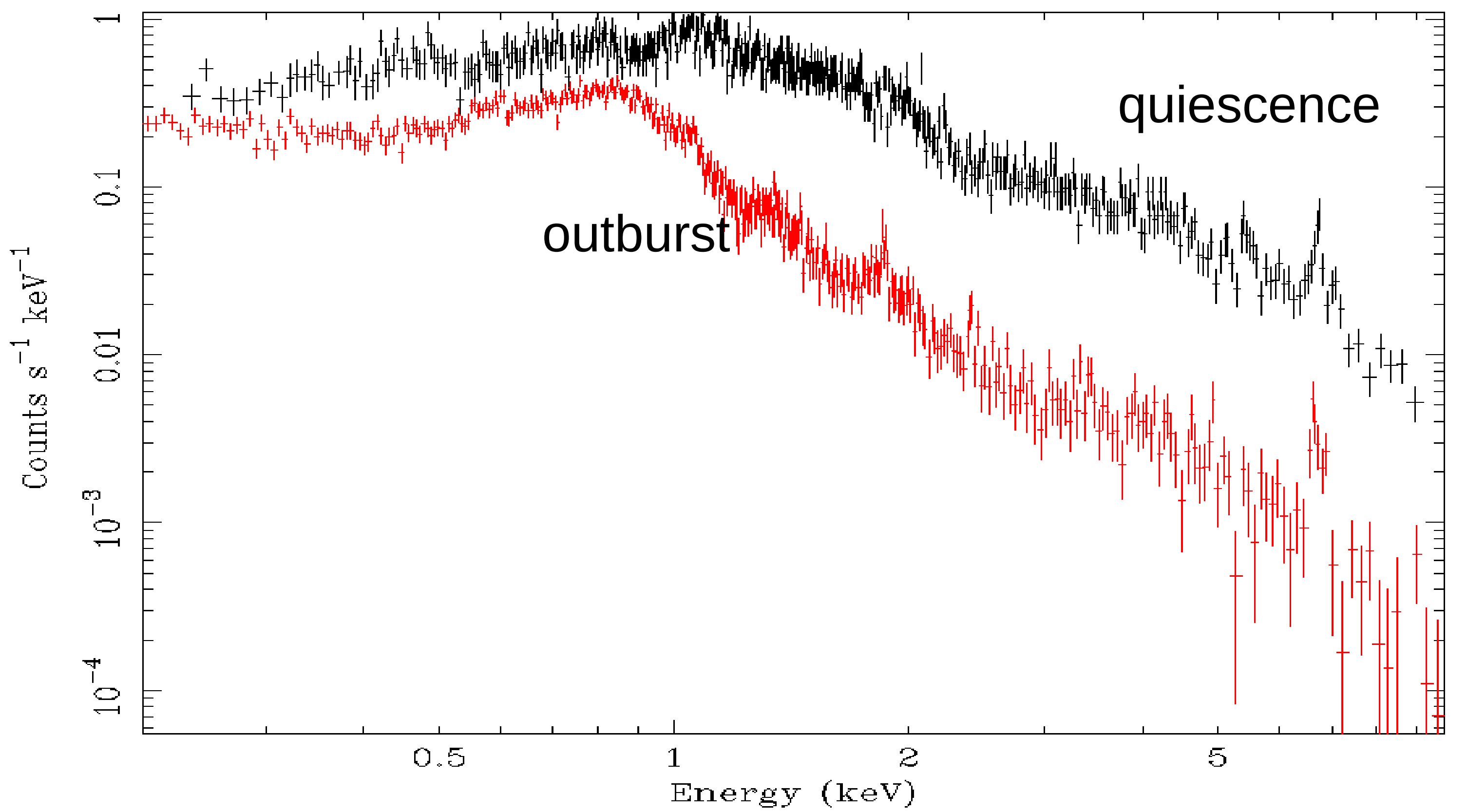
The black body luminosity not well-constrained

In 0.3-10 keV peak luminosity
L = 2.1 x 10^{32} erg/s
($\dot{M}$ = 1.7 x 10^{15} g/s)

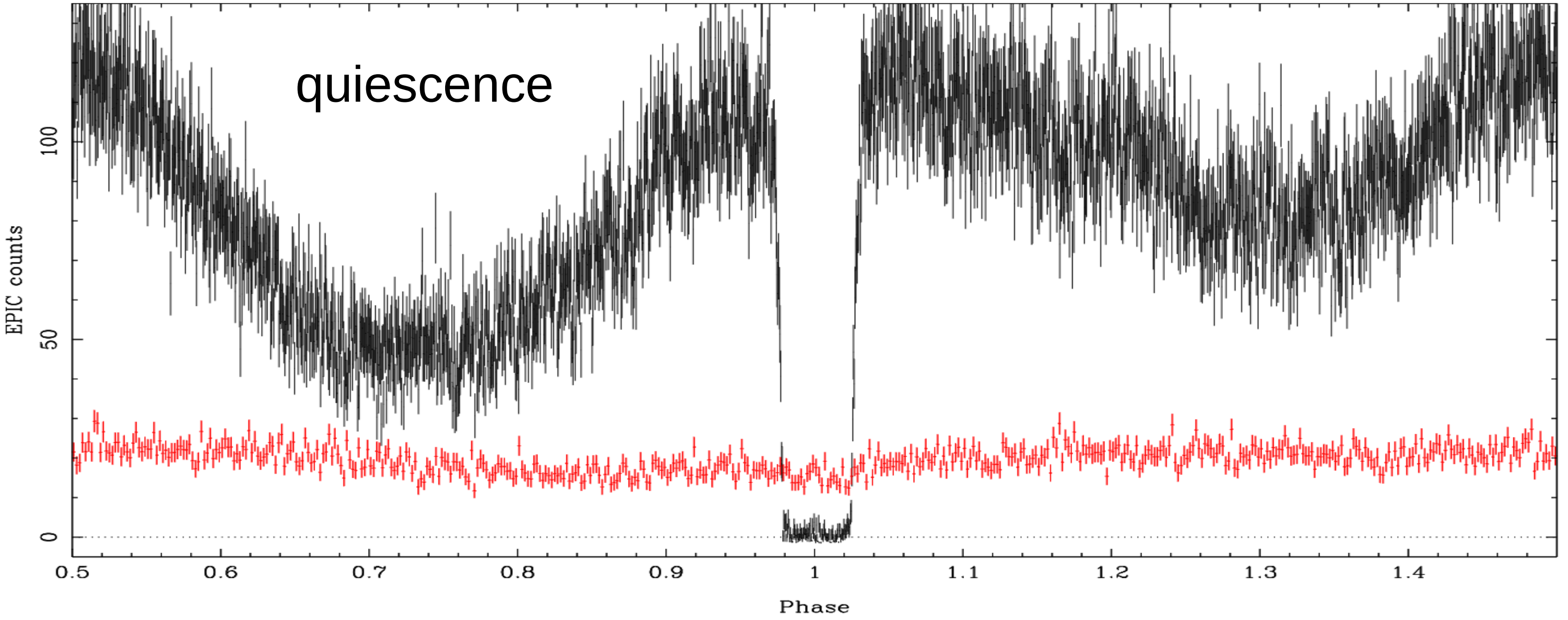
At the end of the Outburst
L = 4.7 x 10^{30} erg/s
($\dot{M}$ = 3.9 x 10^{13} g/s)

No periods seen in the X-ray light curves

Z Cha

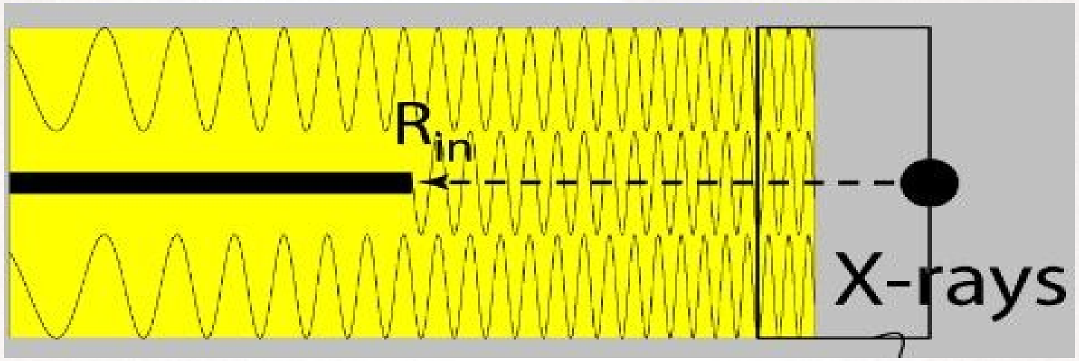


Wheatley 2009

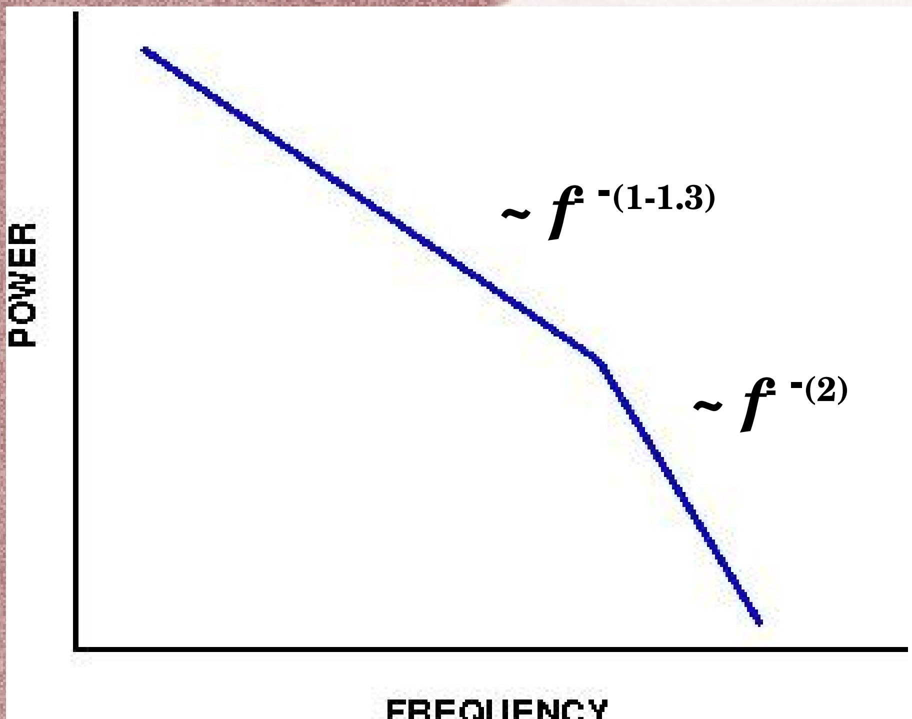


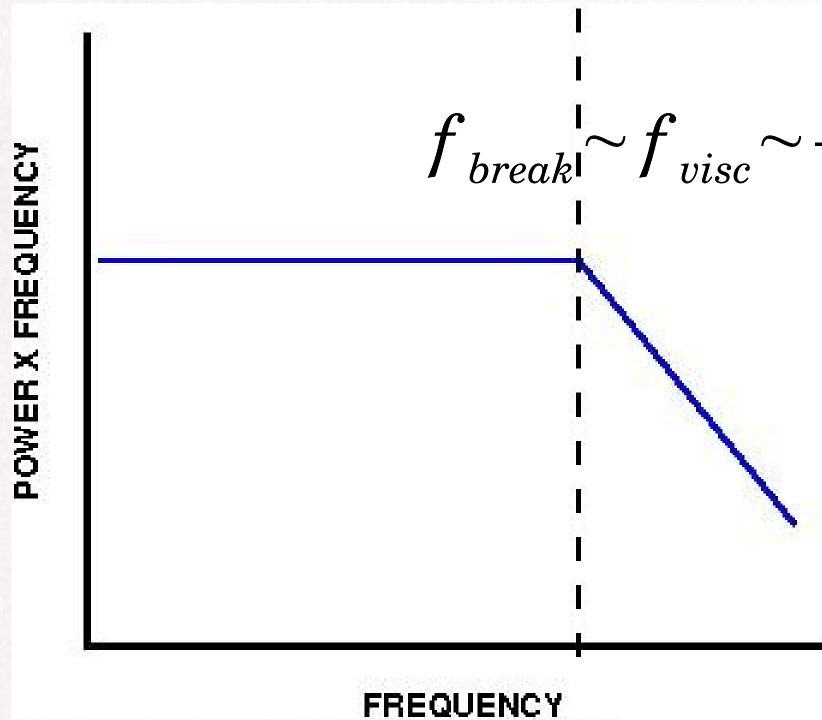
Accretion Flows-Matter Fluctuations and Broadband Noise

- Self-similar variability of accretion rate in the disks → **flicker noise** (Lyubarskii 1997, for CVs see : Warner & Nather 1971, Bruch 1992, 2000, Baptista&Bortoletto 2004)
- Variable instant mass accretion rate in the region of energy release→ variable flux from the disk → inserted at all radii due to the nature of its viscosity (Churazov et al. 2001, Revnivtsev et al. 2009, 2010, Uttley & McHardy 2001, Uttley et al. 2011, Scaringi et al. 2012)
- **Propagating fluctuations** of low frequency in the outer disk → the inner disk and finally to the X-ray emitting region.



$$t_{visc} = \alpha^{-1} \left(\frac{H}{R} \right)^{-2} \Omega_K^{-1}$$





$$f_{break} \sim f_{visc} \sim \frac{1}{t_{visc}}$$

$$P(f) \propto f^{-1} \left(1 + \left(\frac{f}{f_0} \right)^4 \right)^{-1/4}$$

$$\Omega_K(r) = \left(\frac{G M_{wd}}{r^3} \right)^{1/2} = 2\pi f(r)$$

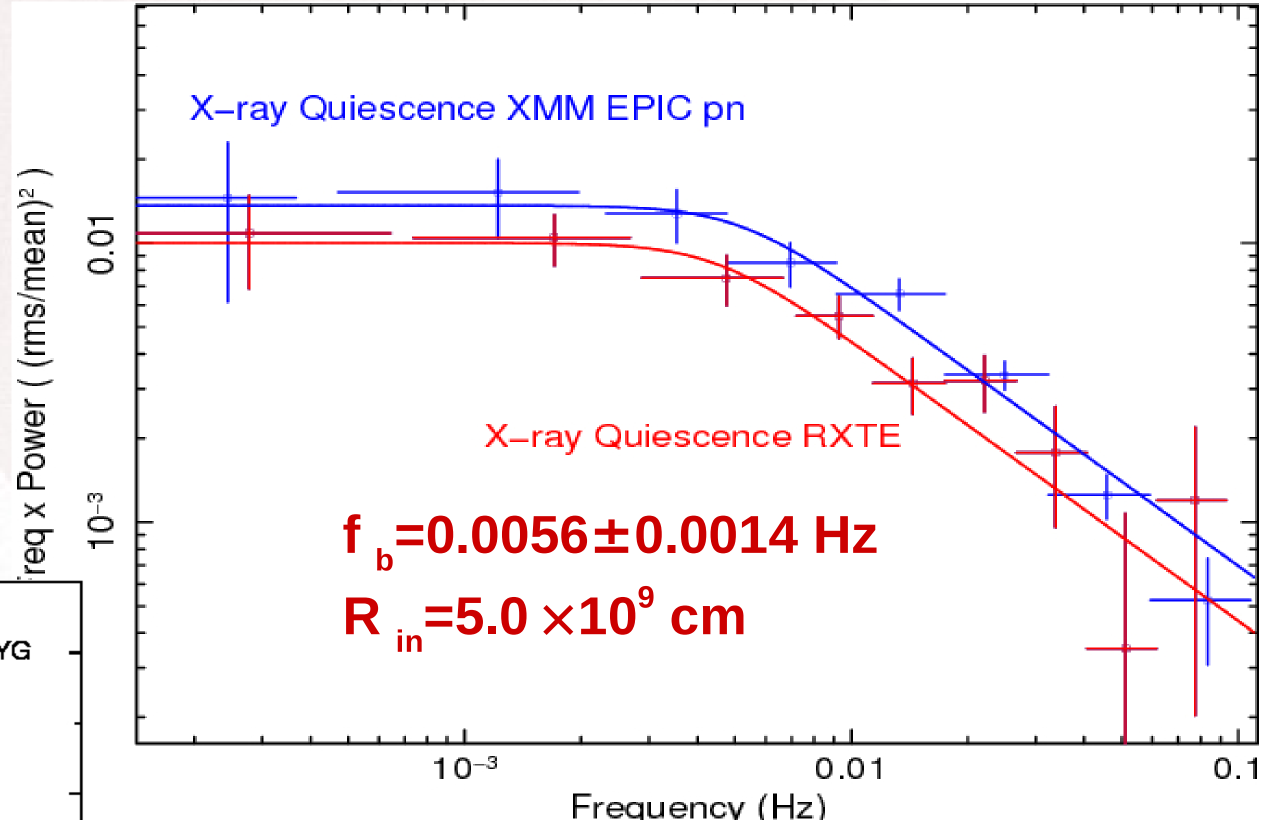
Investigating DNe Inner Disk Structure with Broadband Noise

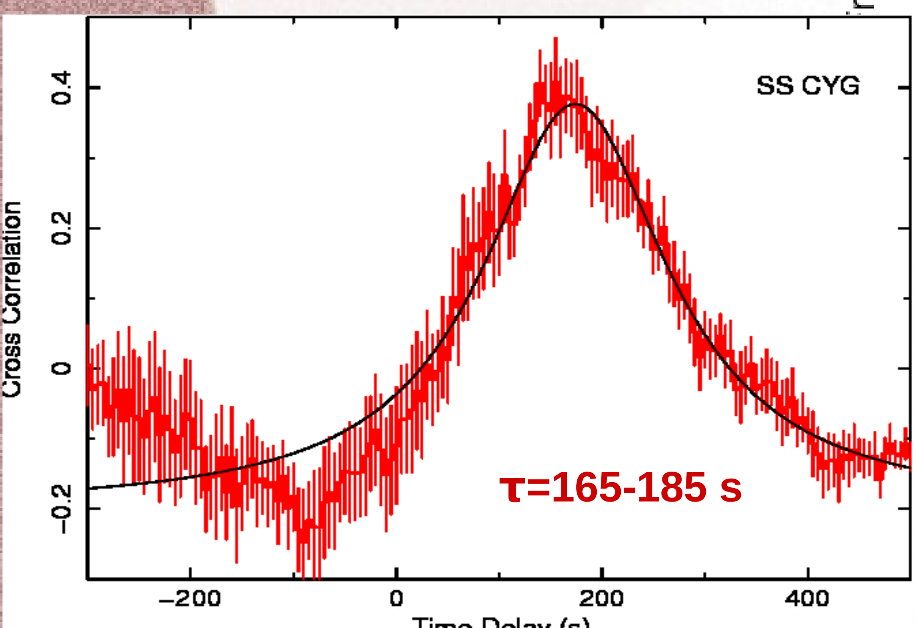
SS Cyg

40 d, 15-20 d

6.6 hrs

~20 keV

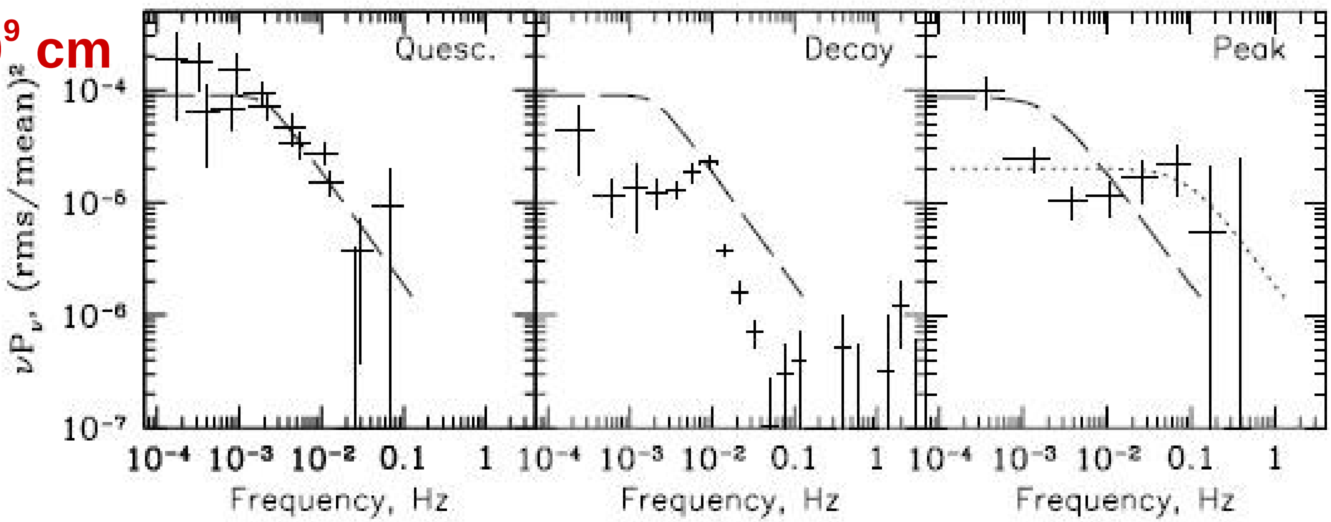


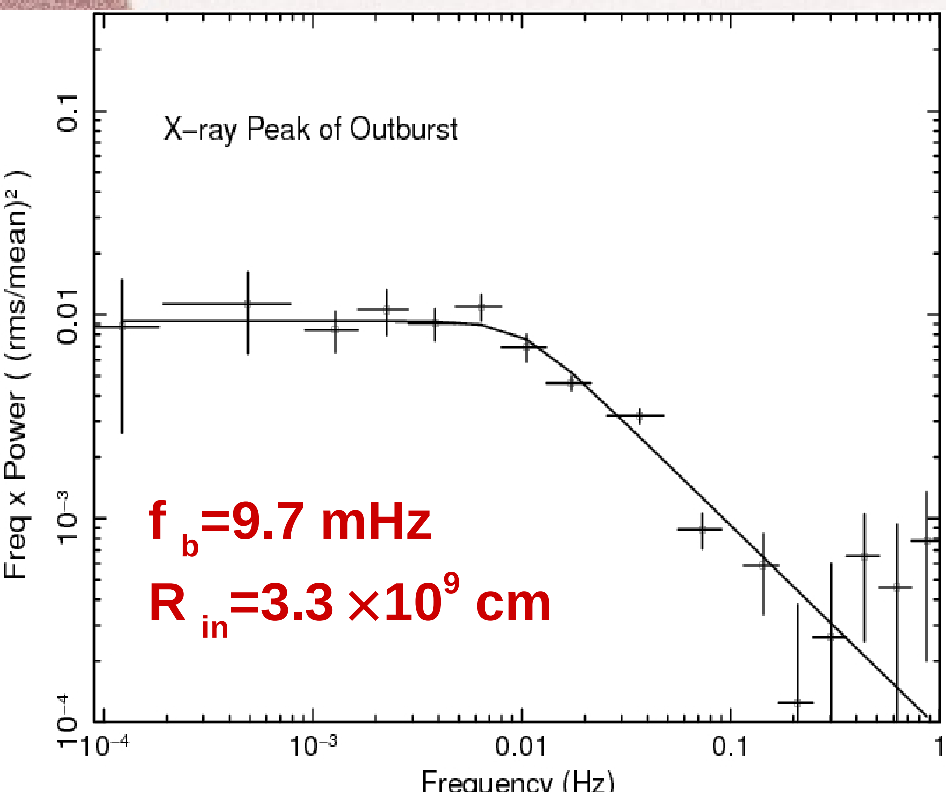


f_b=2.1m Hz

R_{in}=8.5 ×10^9 cm

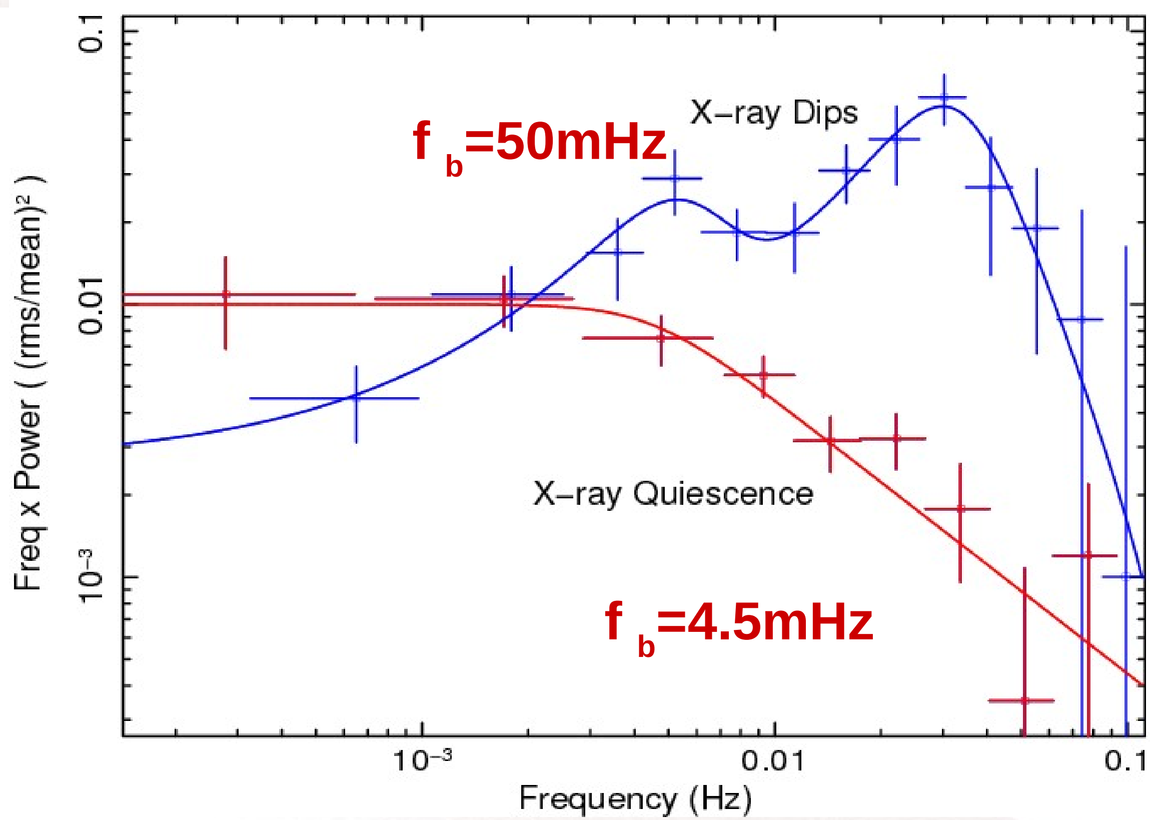
Revnivtsev et al. 2012





f_b=9.7 mHz

R_{in}=3.3 ×10^9 cm



f_b=50mHz

f_b=4.5mHz

Balman & Revnivtsev 2012

R_{in}=1.1 ×10^9 cm ➡ 5.5 ×10^9 cm

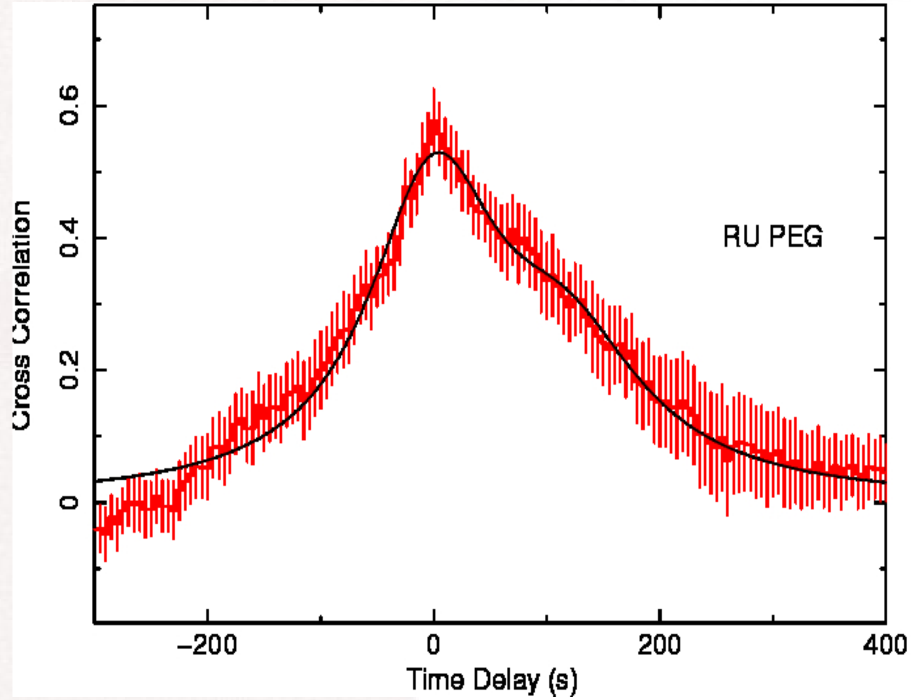
RU Peg

50 d, 20 d

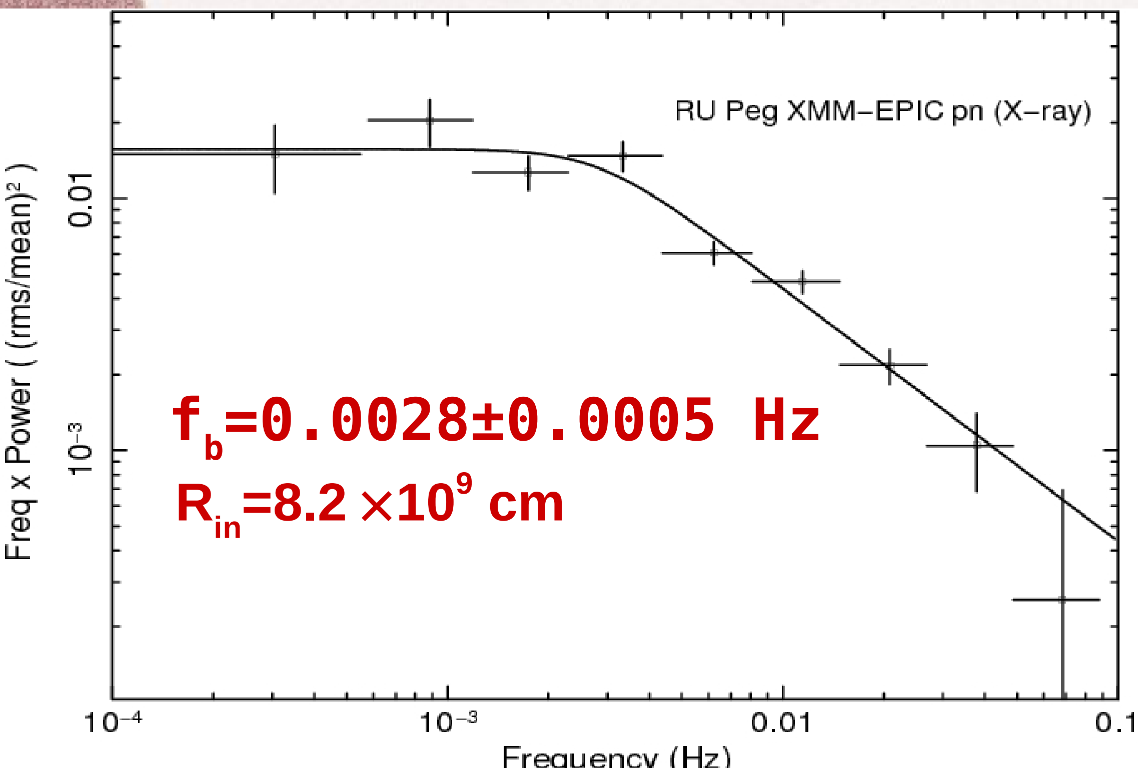
8.99 hr

~31 keV

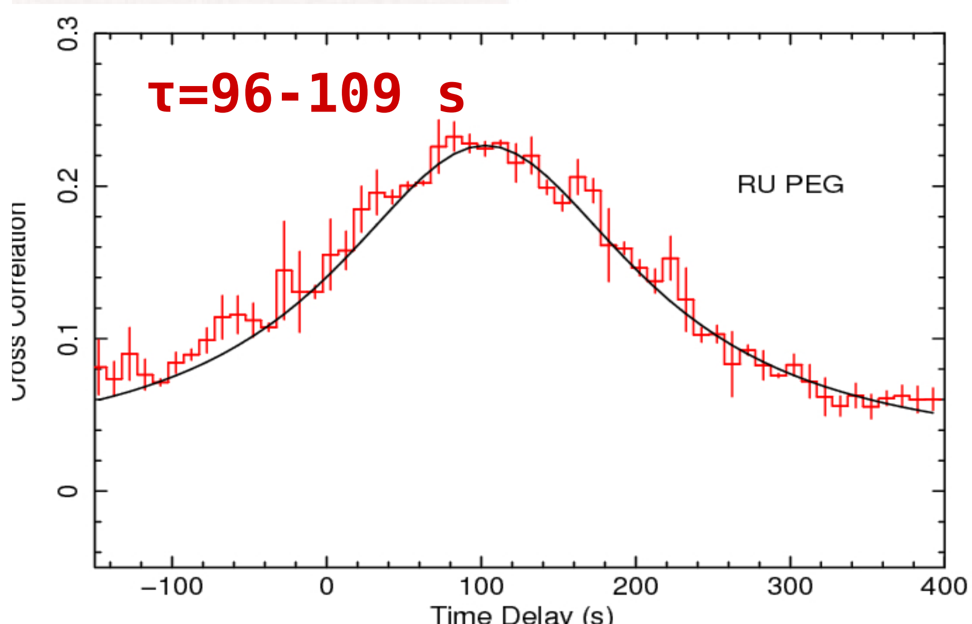
τ=100-130 s



Balman et al. 2011



Balman & Revnivtsev 2012

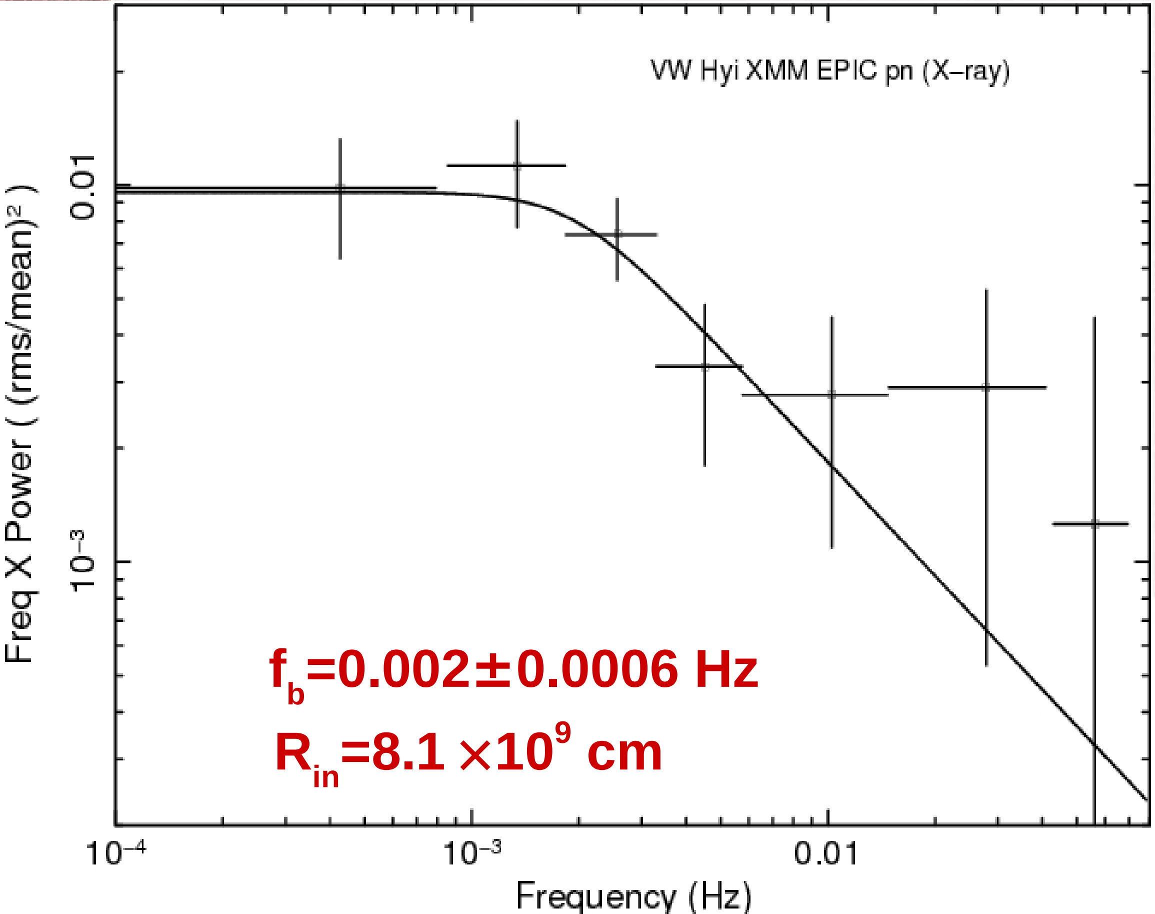


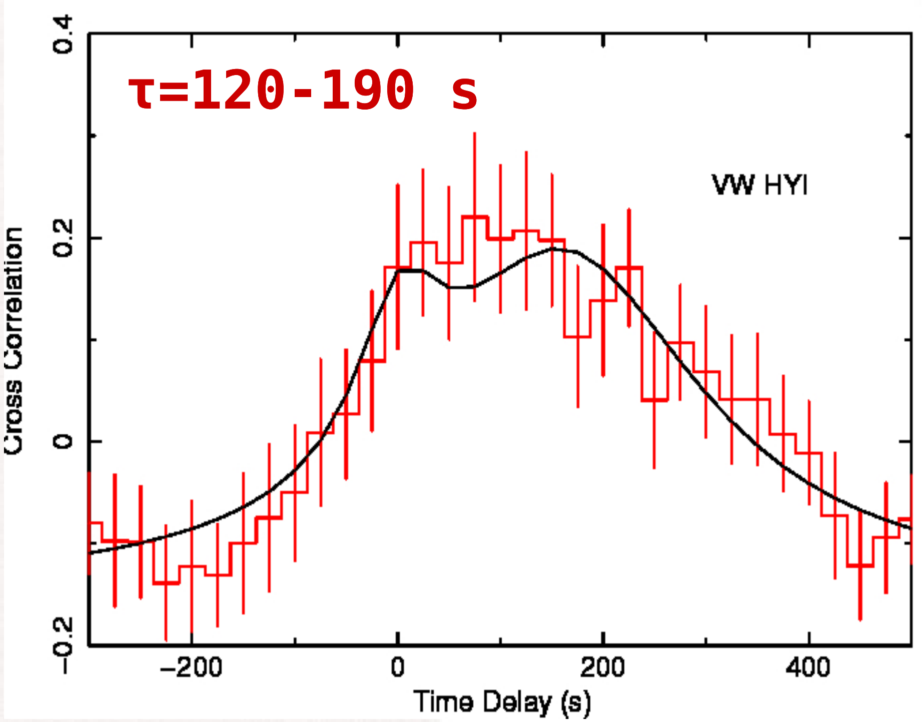
VW Hyi

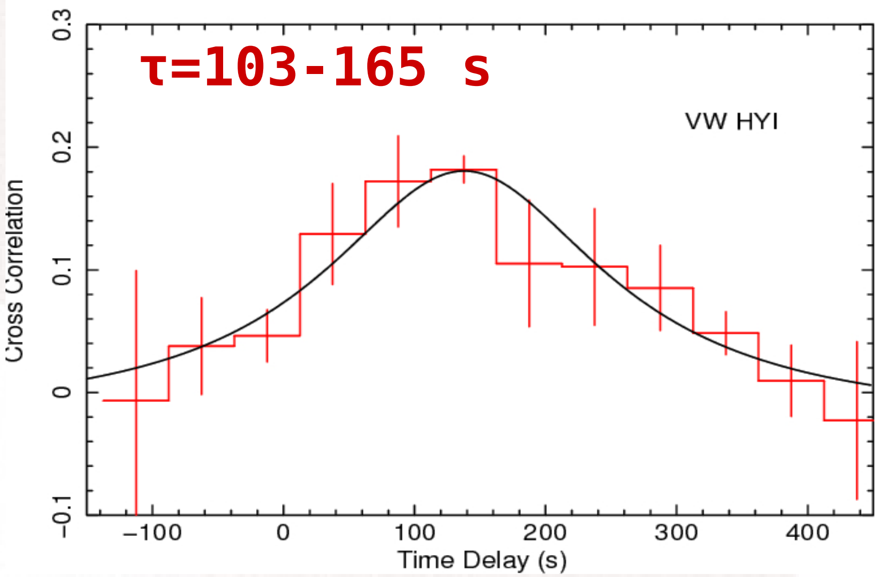
28 d, 179 d

107 min

~9 keV







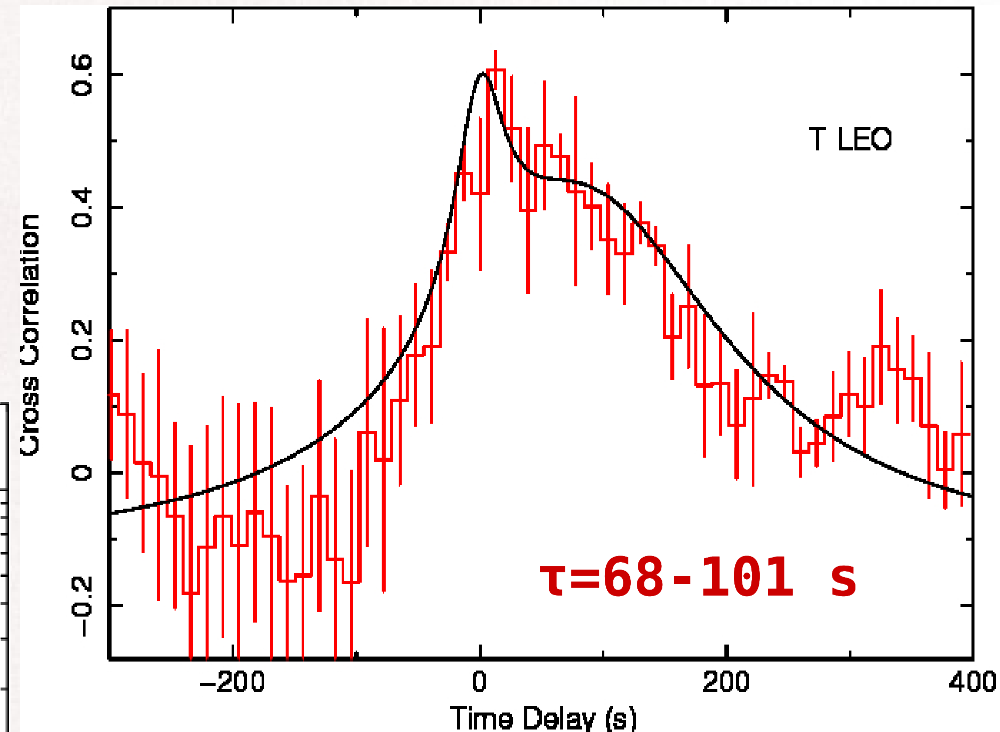
Balman & Revnivtsev 2012

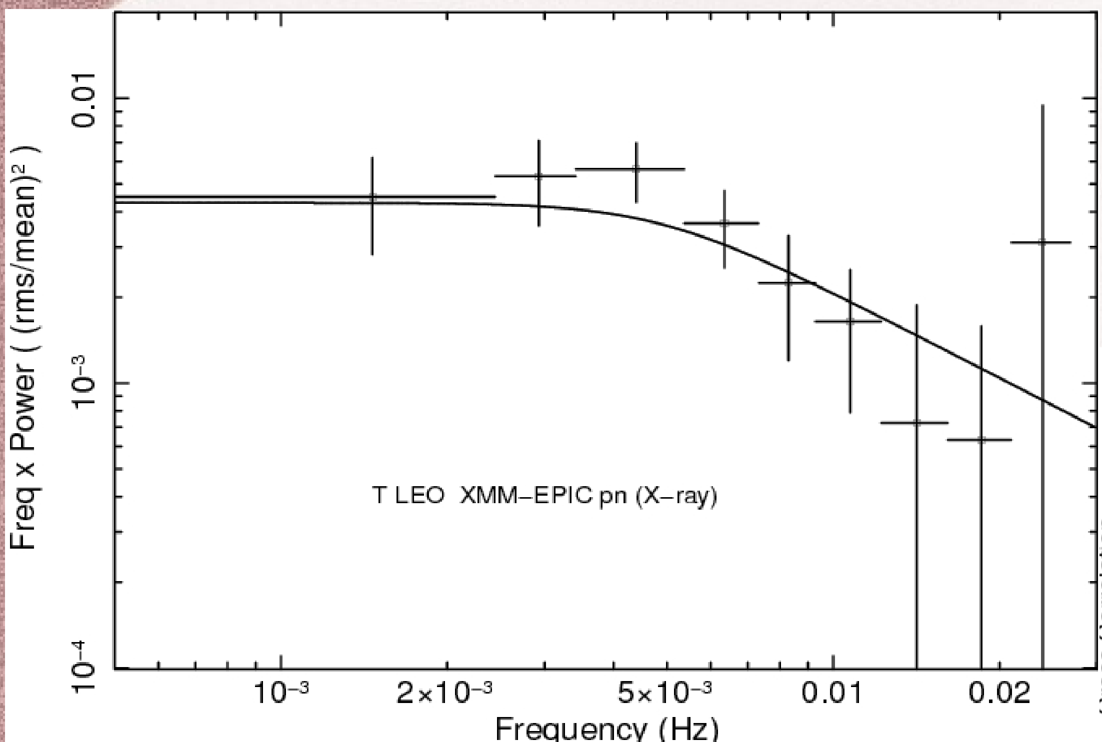
T Leo

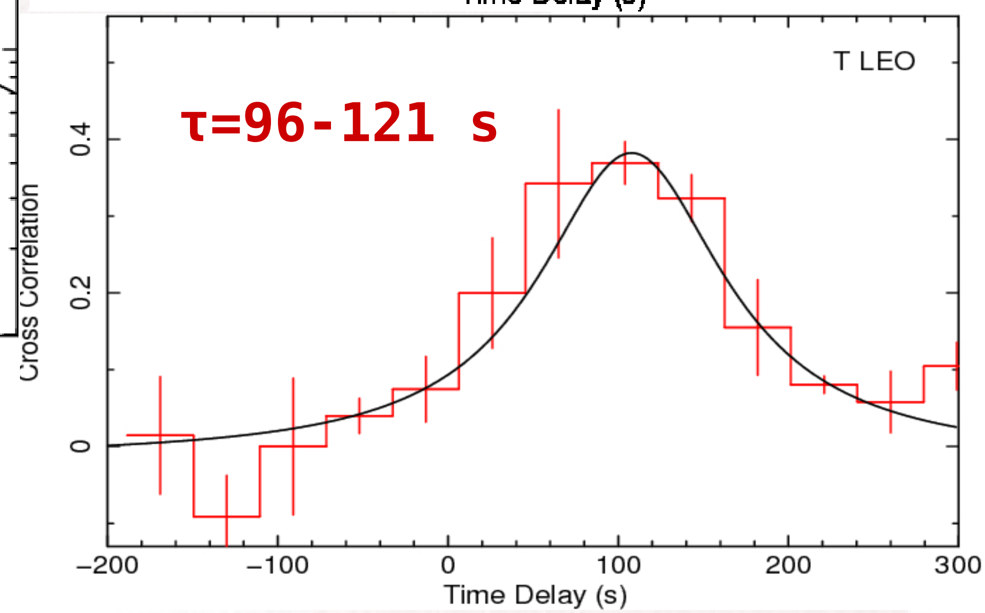
?? , 420 d

84.7 min

~11 keV







f_b=0.0045±0.0015 Hz

R_{in}=4.0 ×10^9 cm

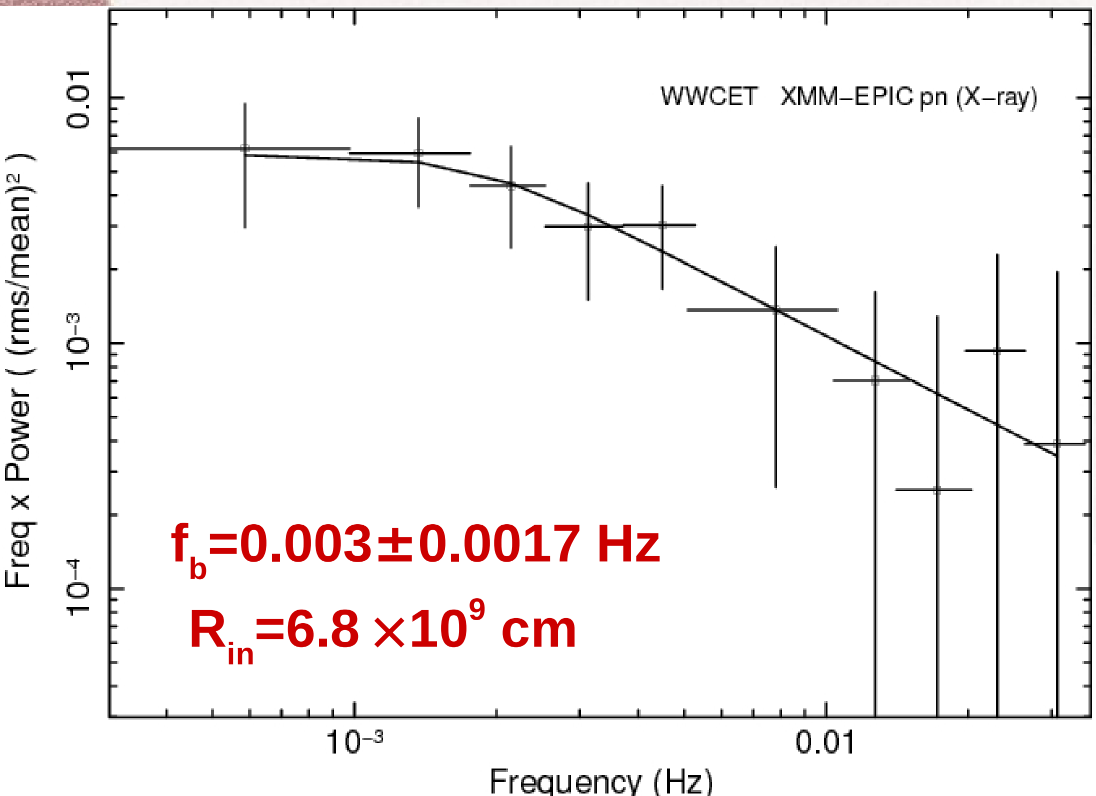
Balman & Revnivtsev 2012

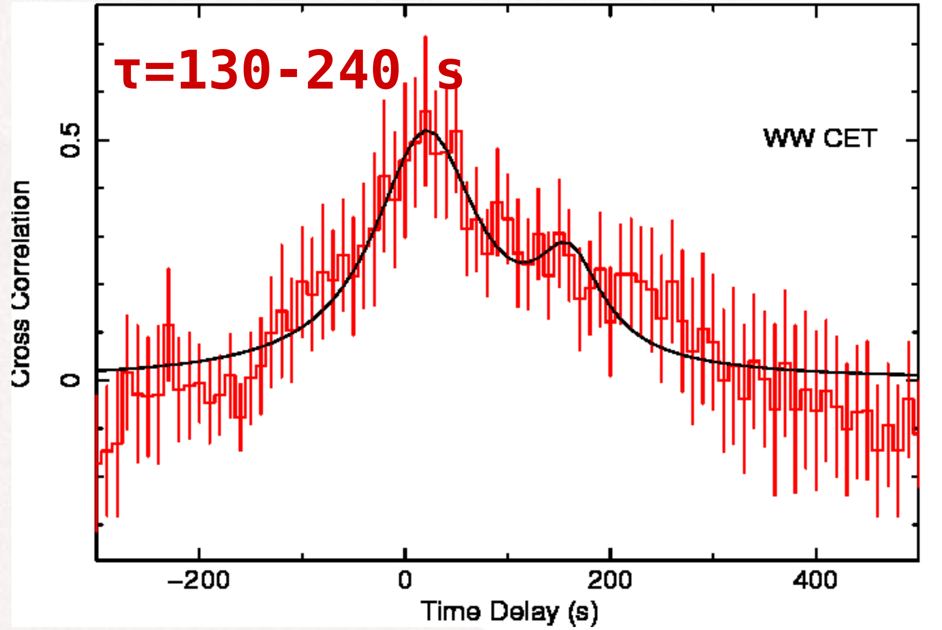
WW Cet

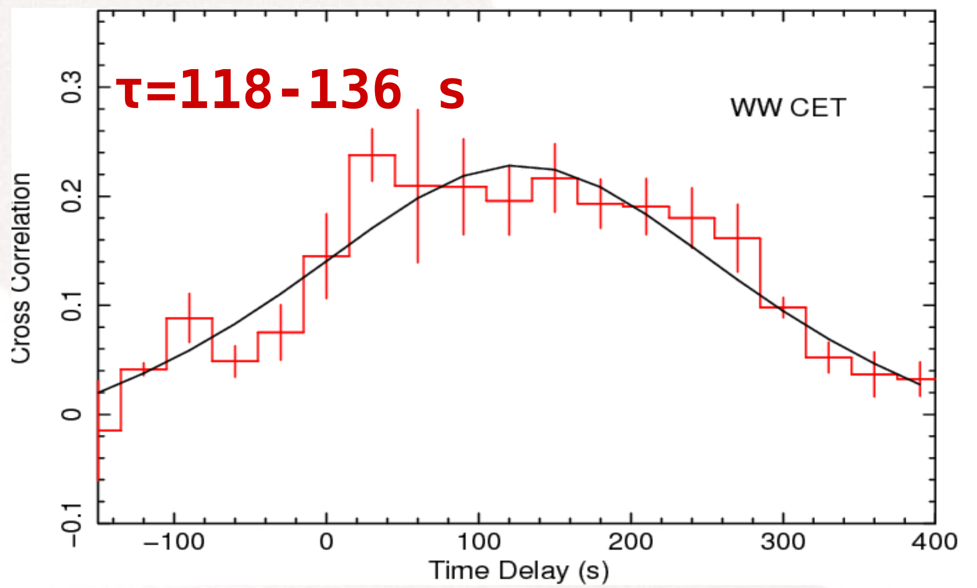
45 d

253 min

~15 keV



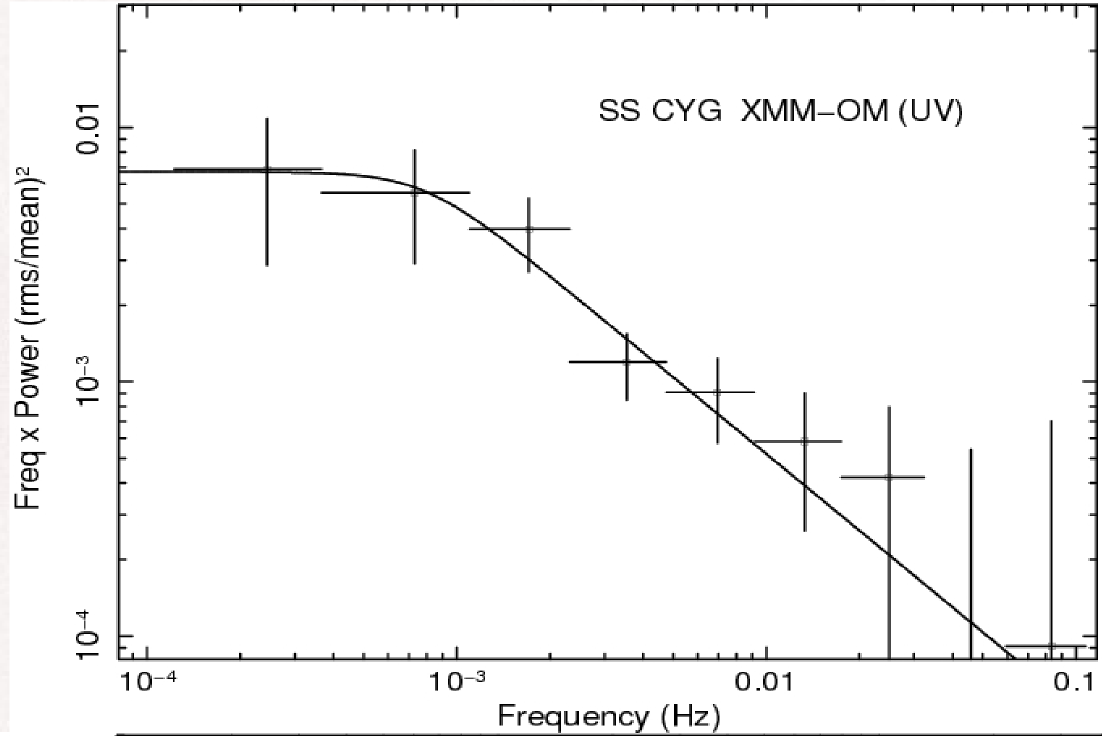


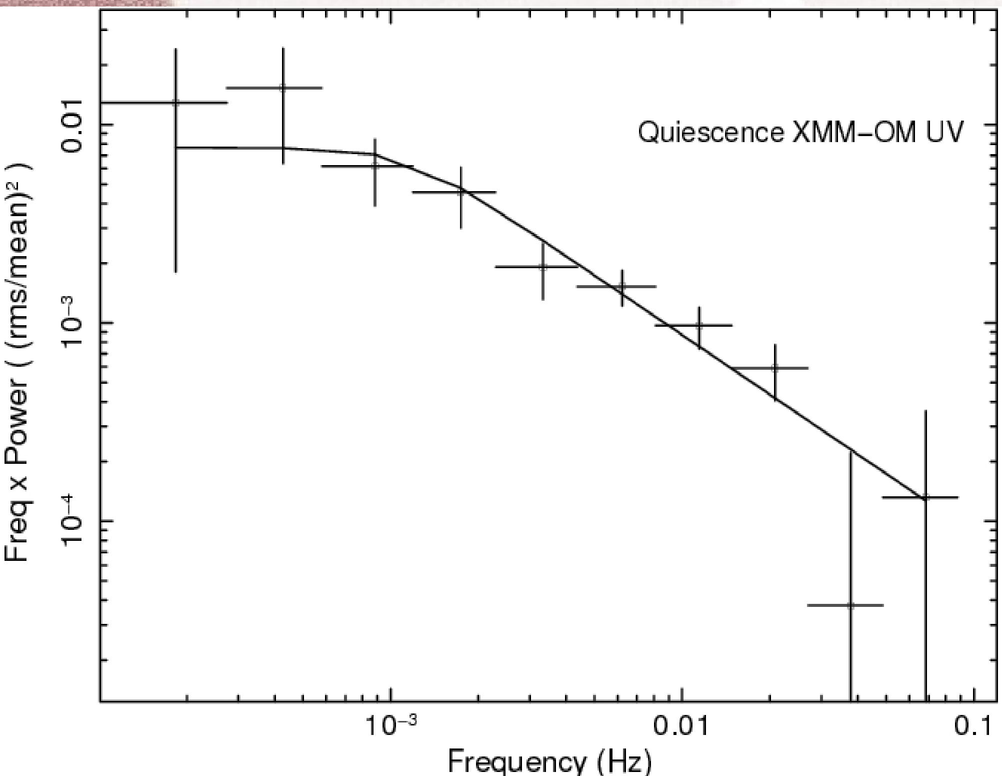


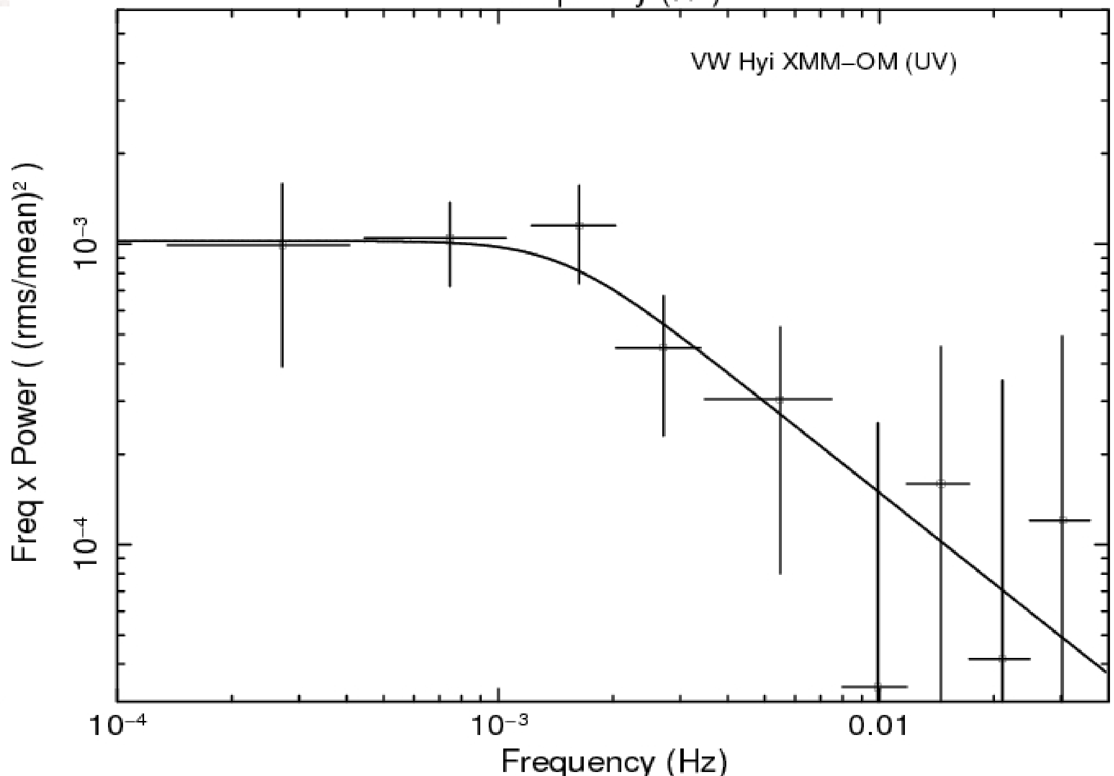
Balman & Revnivtsev 2012

UV Power Spectra

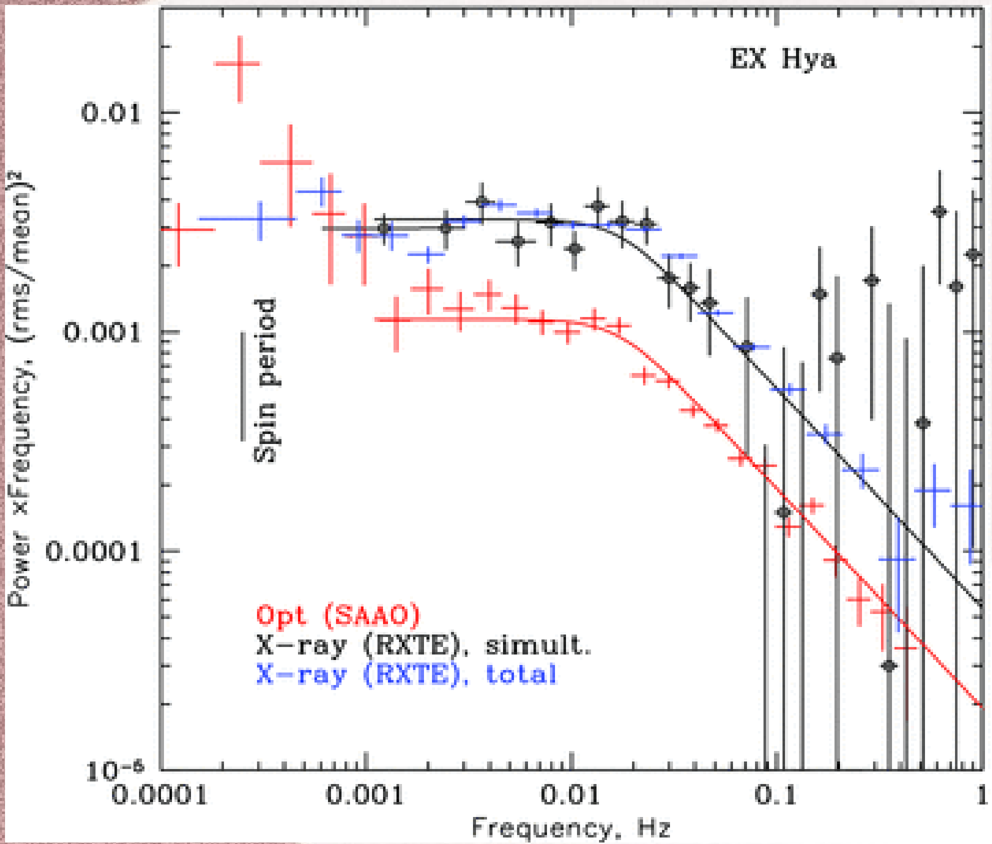
XMM-Newton OM
UVW1 filter 240-340 nm

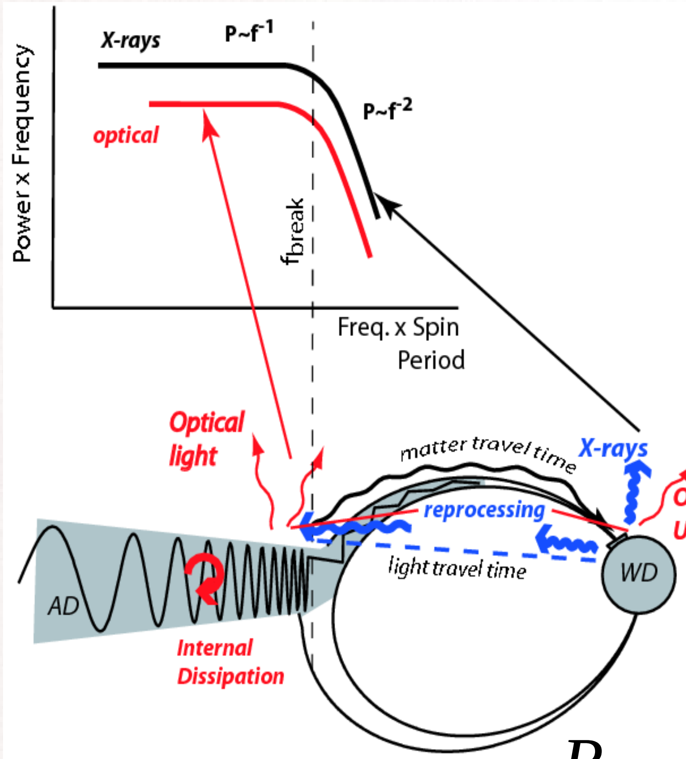




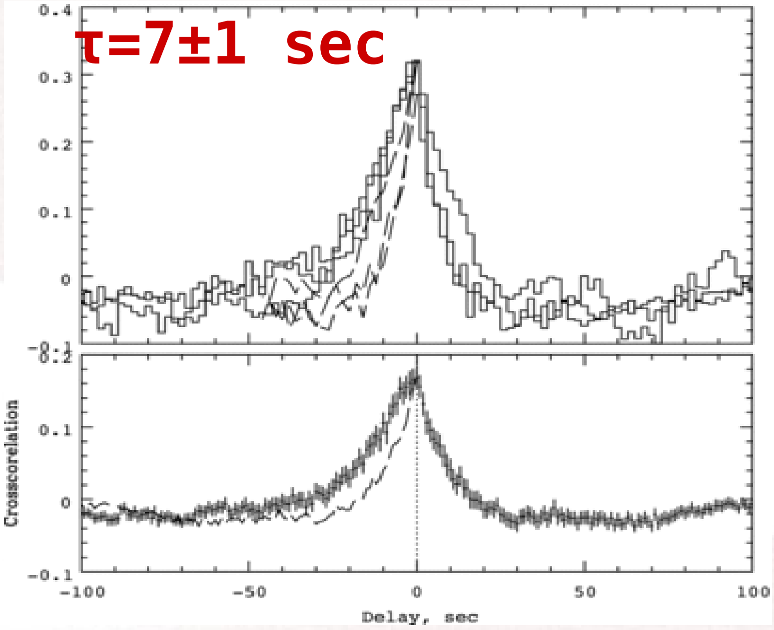


Intermediate Polars and Disk Truncation radii





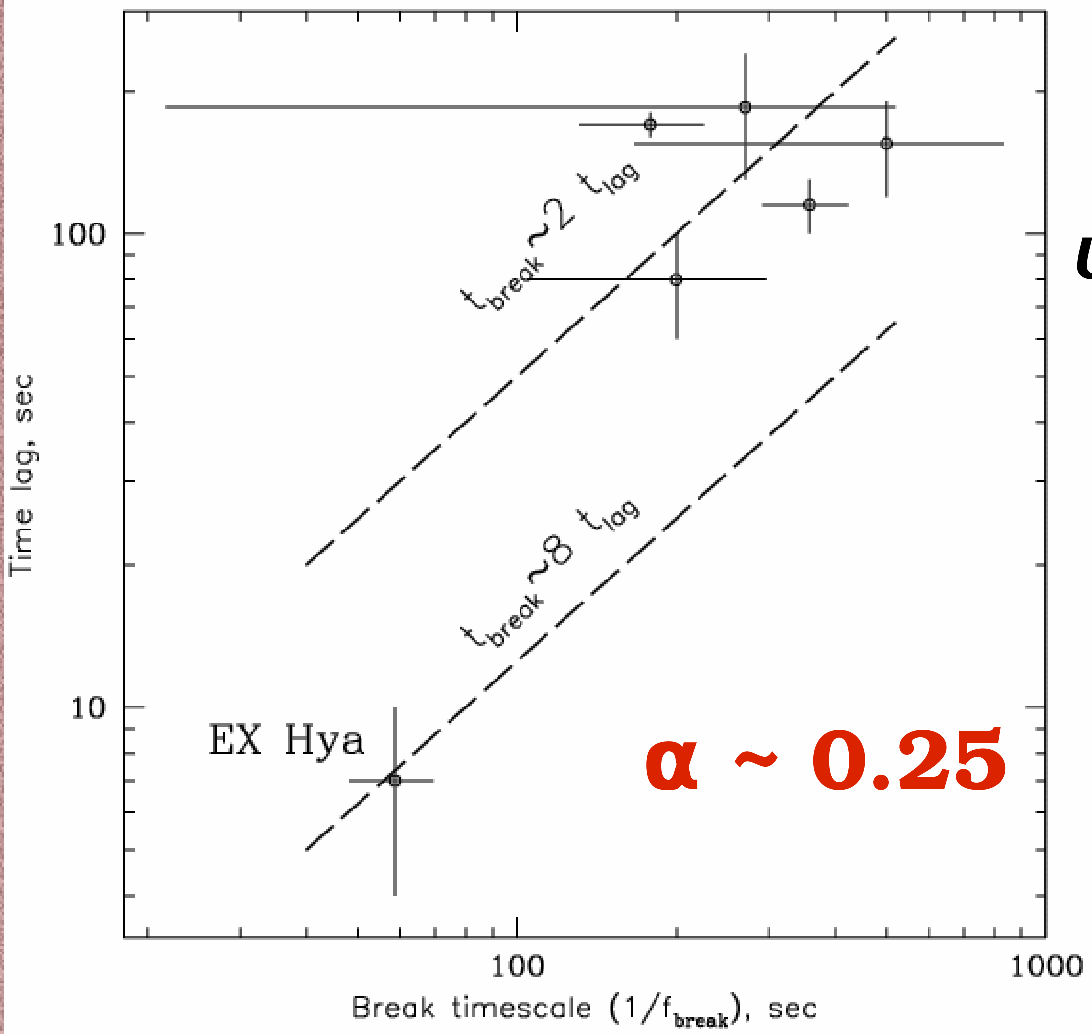
$$\Delta t \sim \frac{R_{in} - R_{wd}}{(GM_{wd}/R)^{1/2}}$$



$R_{in}=1.9\times10^9$ cm

$f_b=2.1\pm0.1\times10^{-2}$ Hz

Revnivtsev et al. 2011



$\upsilon_r \propto \alpha \nu_K$ **Non-magnetic CV**

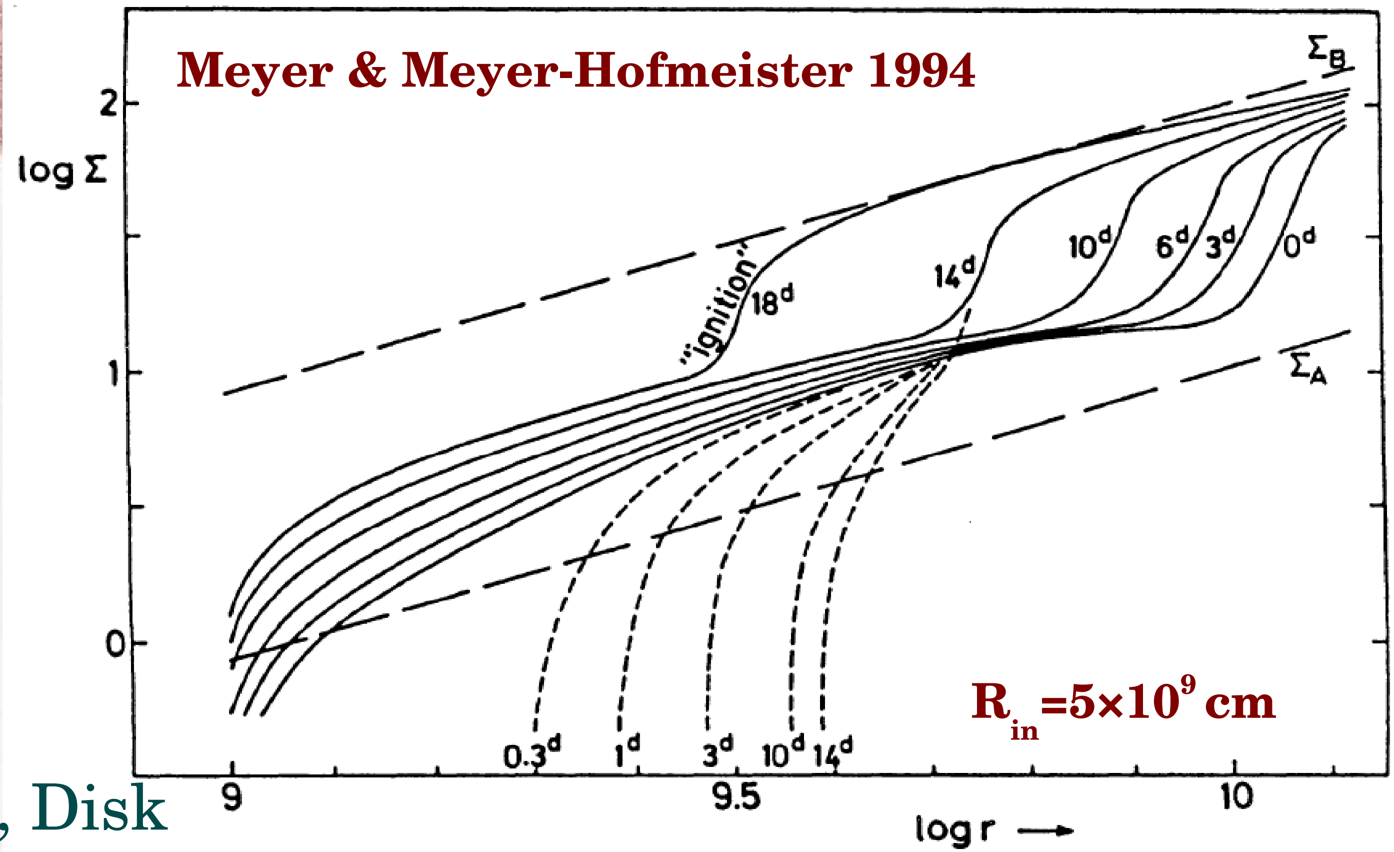
$\upsilon_r \propto \nu_K$ **Magnetic CV**

Standard Disk & Boundary Layer

(Kippenhahn & Thomas 1978, Patterson & Raymond 1985, Narayan & Popham 1993)

Optically thick cold outer disk and optically thin inner corona

(Esin, McClintock & Narayan 1997)



➔Coronal siphon-flow, Disk evaporation (Meyer & Meyer-Hofmeister 1994(2001), Liu et al. 1995 1997, Meyer et al. 2000) (see also de Kool & Wickramansinghe 1999, Mineshige et al. 1998)

--- **$2\text{-}6\times10^9$ cm**

➔ WD Irradiation (King 1997)

$(1\text{-}5)R_{WD}$

$T_{cor} < T_{vir}$ (10-30 keV--M_{wd})

$10^{-13}\ M_\odot$/yr → $10^{-11}\ M_\odot$/yr

Frictional and Thermal Boundary Layers

Conclusions

- Large scale truncation in the Disks of Dwarf Novae (DN) in at least 5 systems with radii in a range $R_{tr} \simeq 0.3\text{-}1.0\times10^{10}$ cm. The Magnetic CVs (MCVs) show rather smaller truncation radii ~$0.9\text{-}1.9\times10^{9}$ cm.
- Time delays in X-rays of the order of 96-181 sec in all of our sample (5 objects) . This value is about 6-8 sec for the Intermediate Polar EX Hya.
- Suggest .... most these systems (DN) have truncated disks with coronal flows dominating in the inner disks as in e.g. Meyer & Meyer-Hofmeister 1994-- (ie. ADAF/ rotating disk coronae)
- There is evidence that the disk truncation varies with accretion rate changes in quiescence and outburst.
- Existence of ADAF/Coronae will help to explain quiescence and outburst spectra and light curve variations.