X-ray Studies of Classical Novae & Super Soft Sources (SSS)

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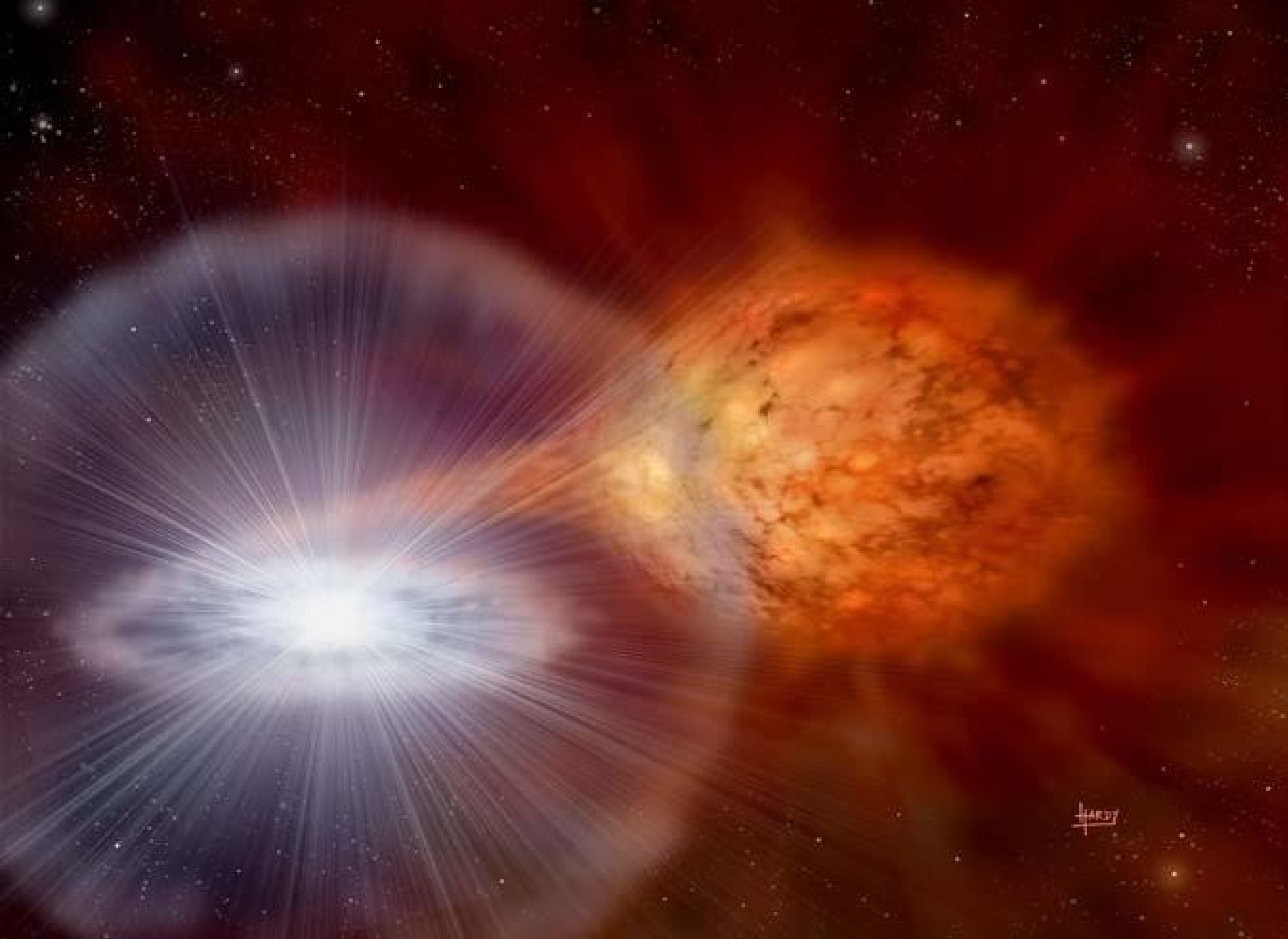
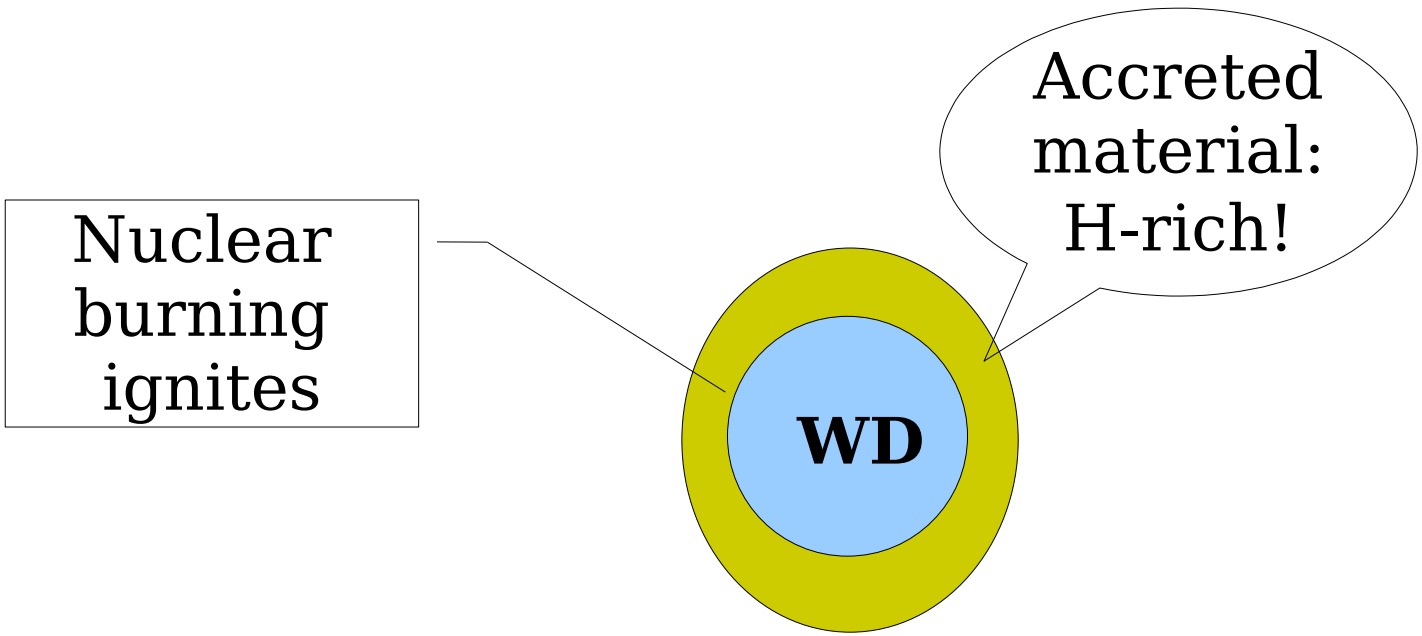
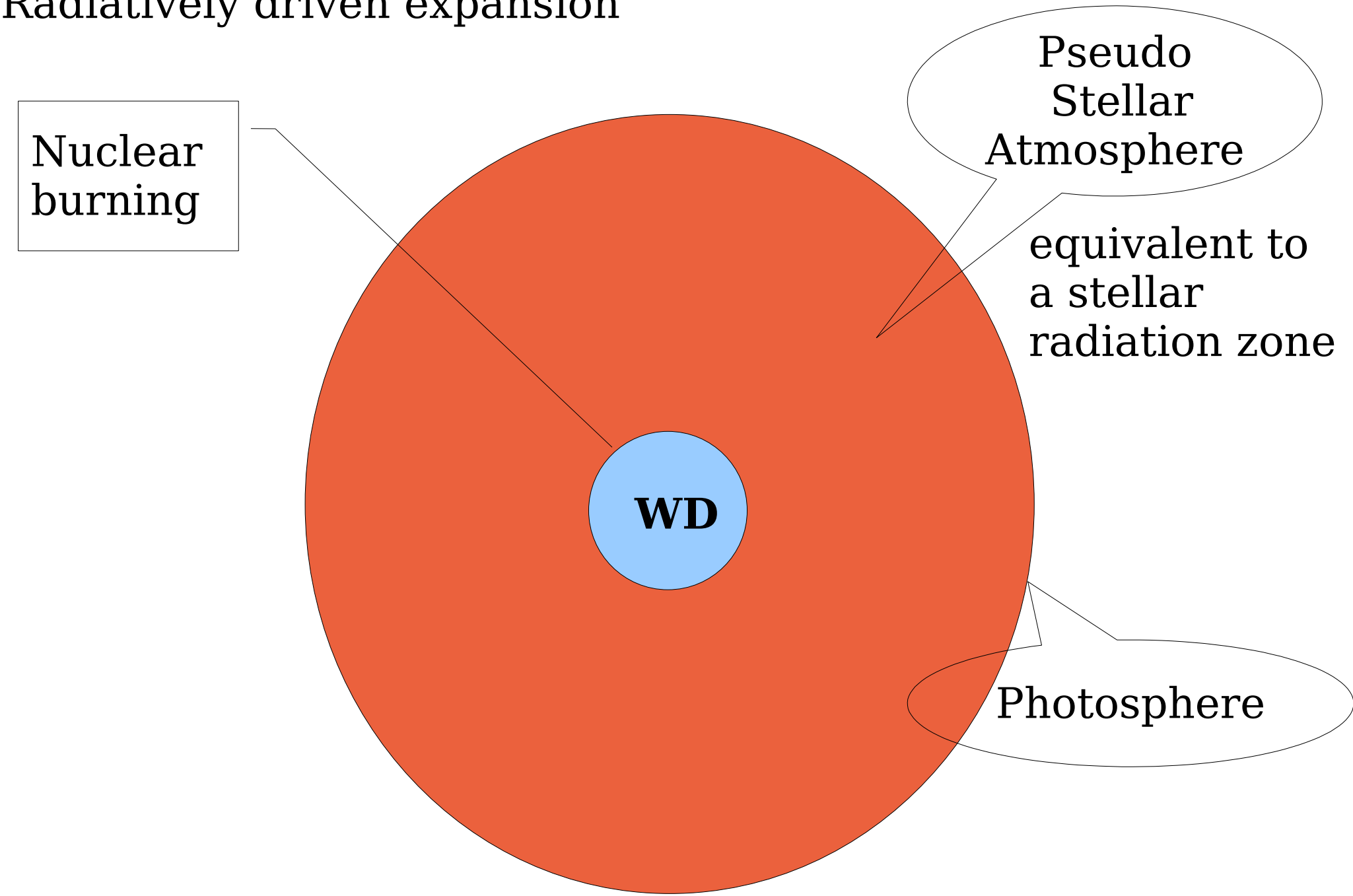
Chandra Fellow at ASU Arizona State University



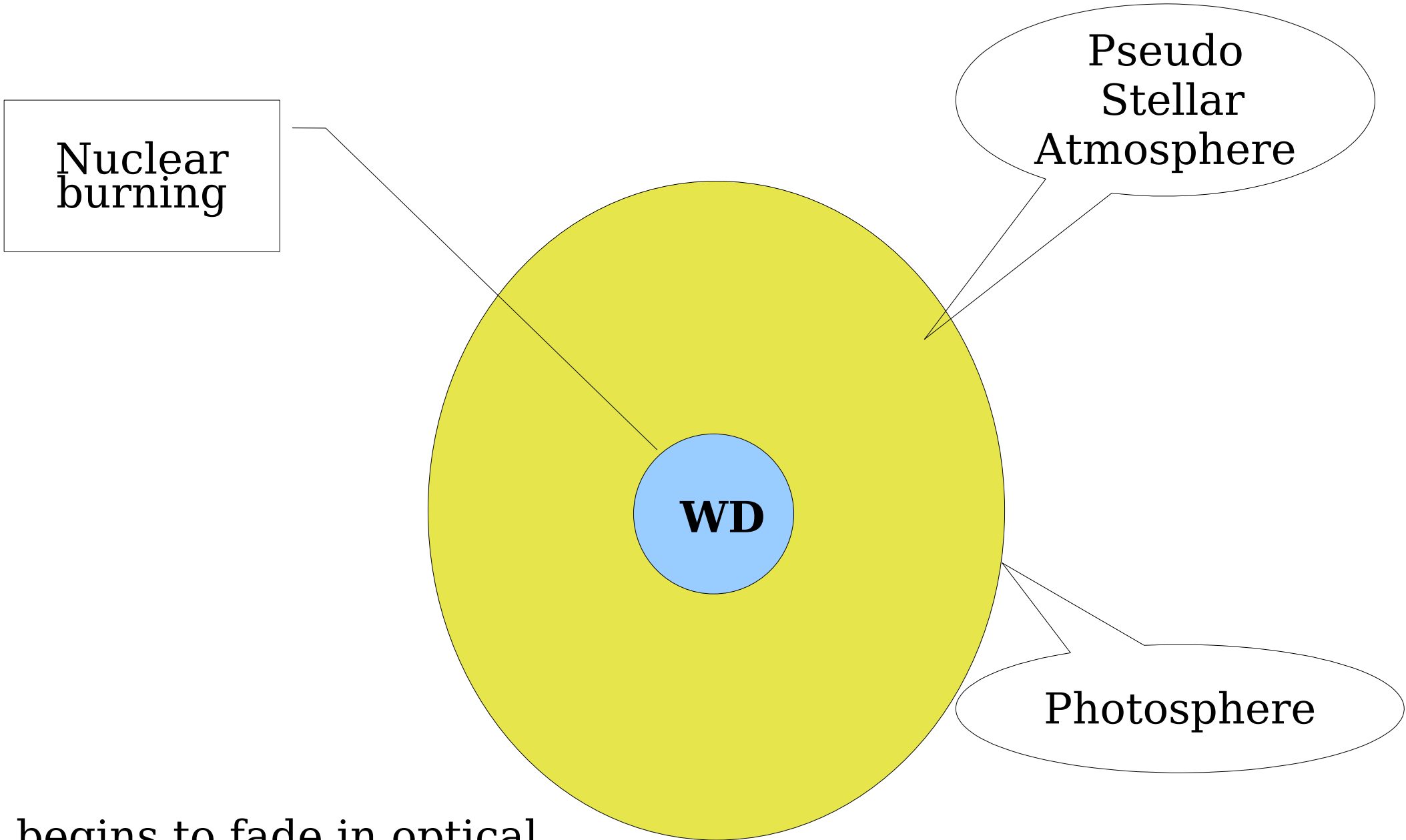
outburst



Radiatively driven expansion

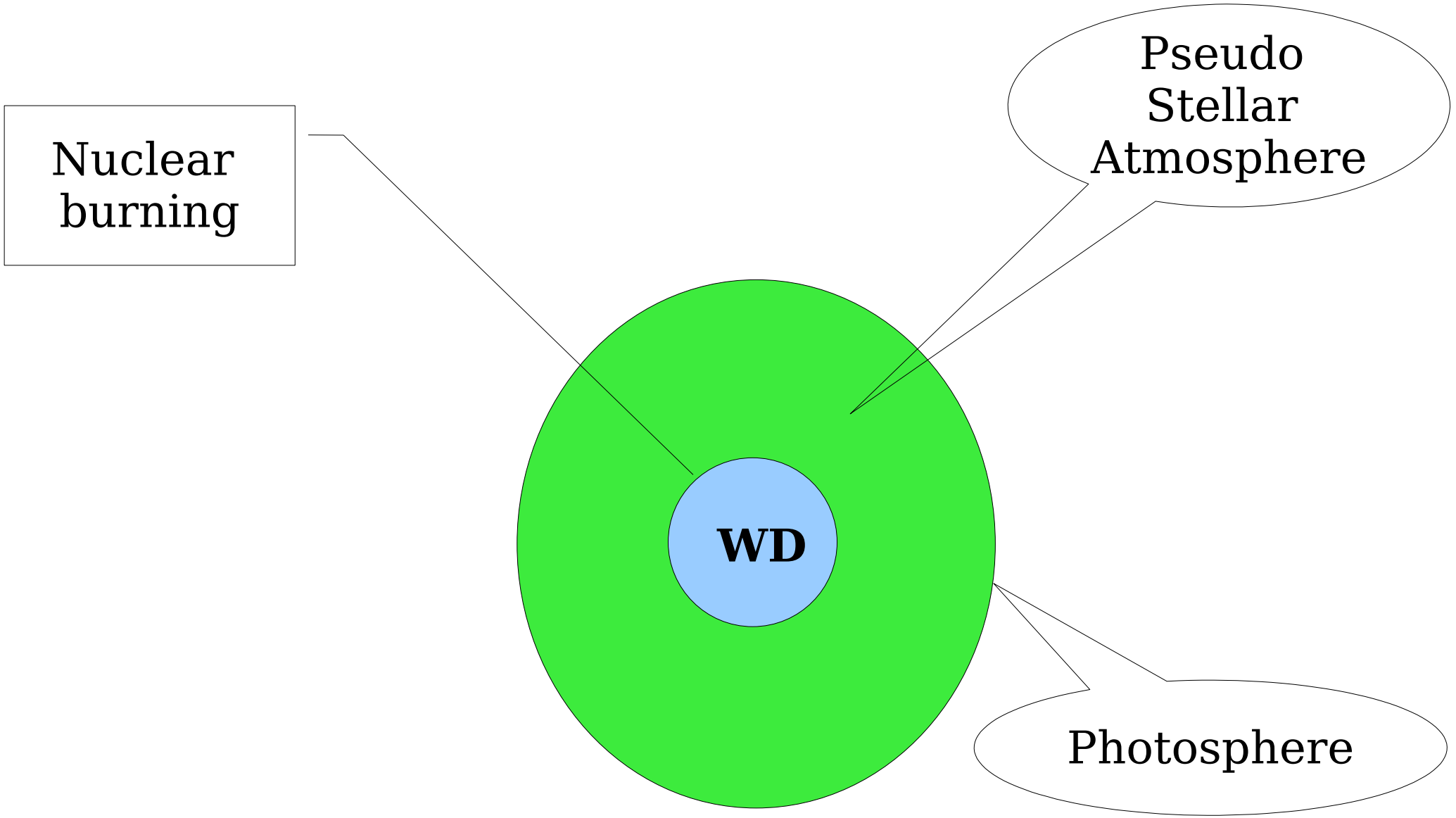


brightest in optical -> discovery



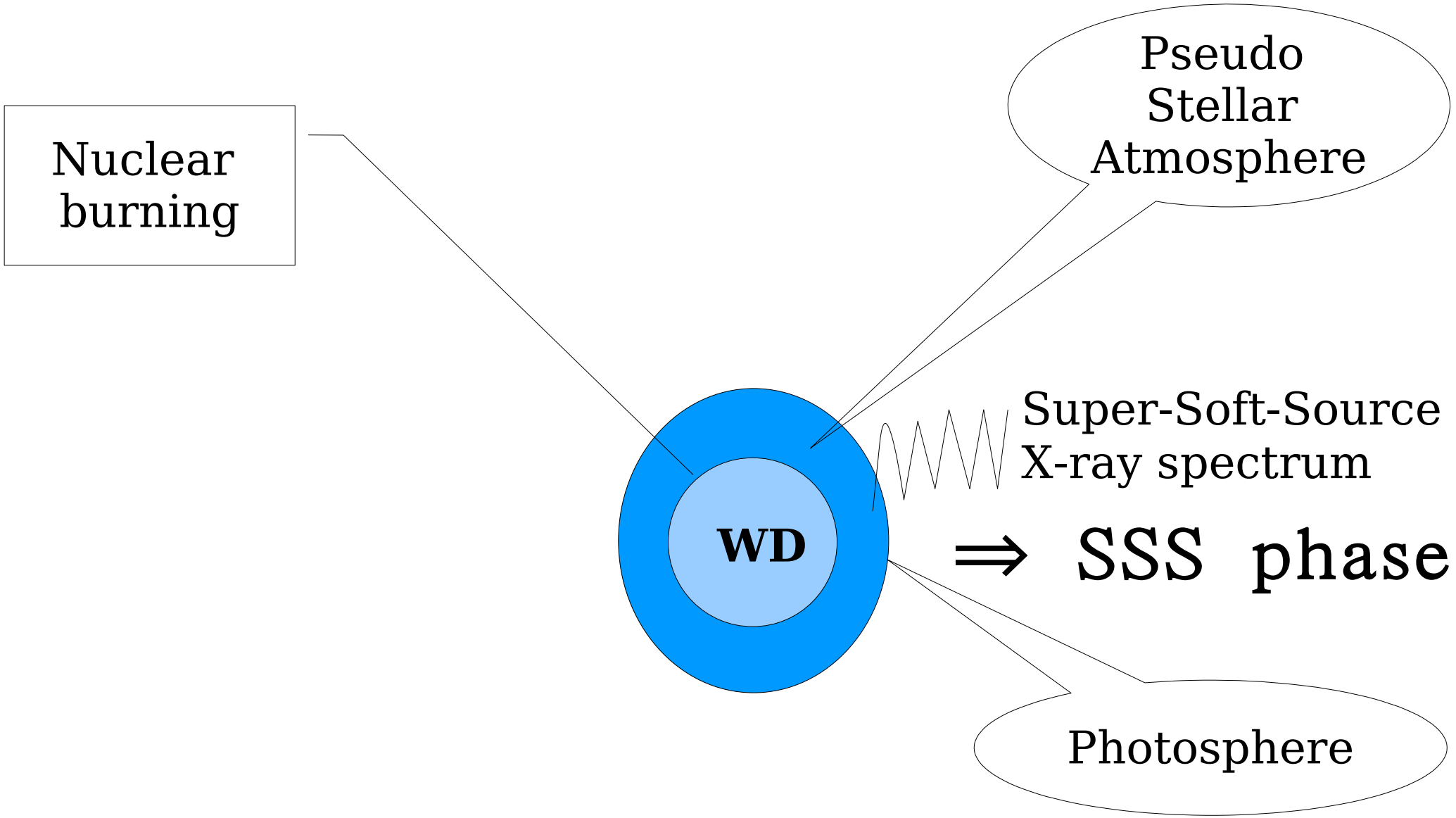
begins to fade in optical

spectrum shifts to higher energies



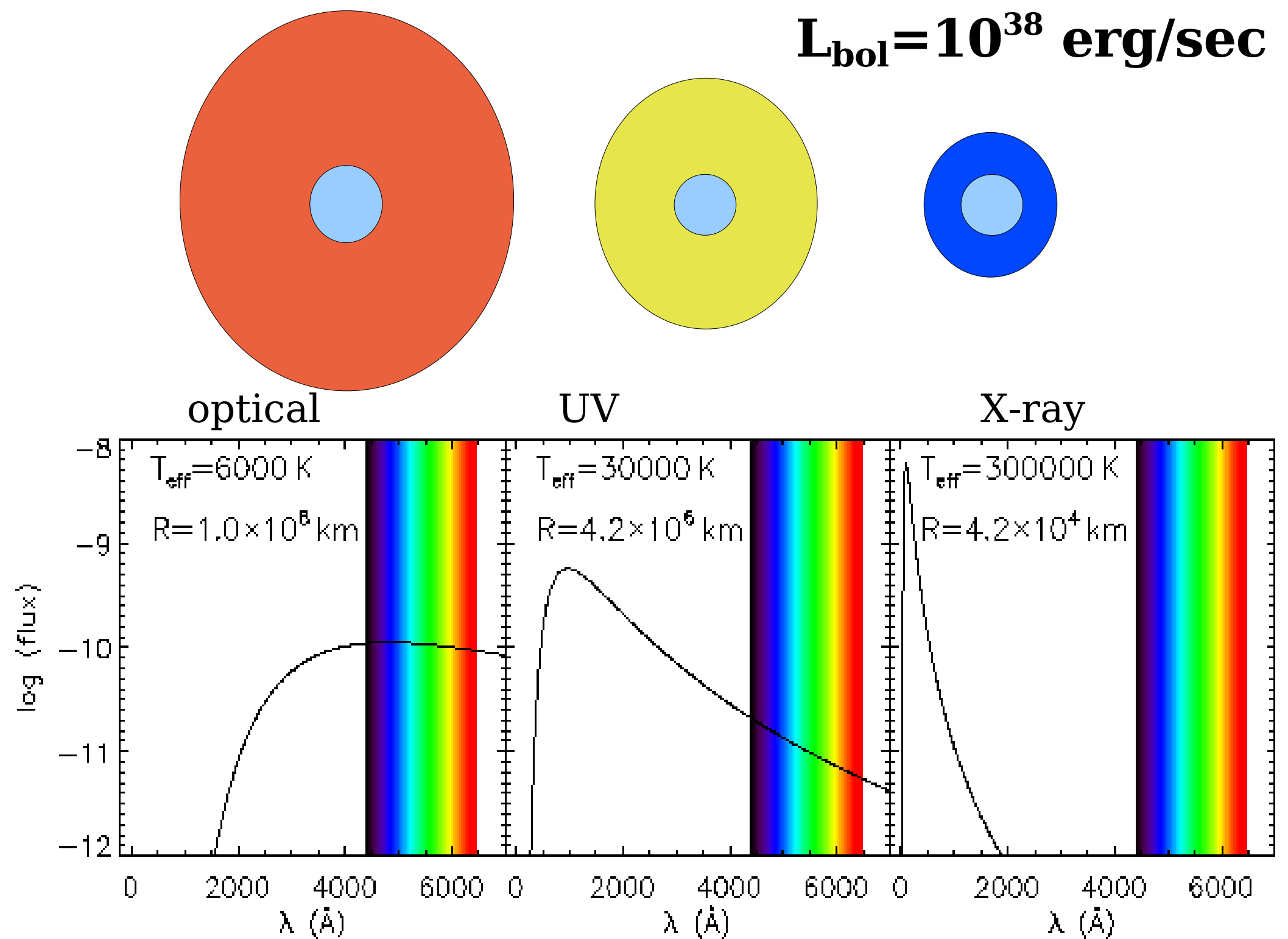
while Photosphere recedes to smaller radii

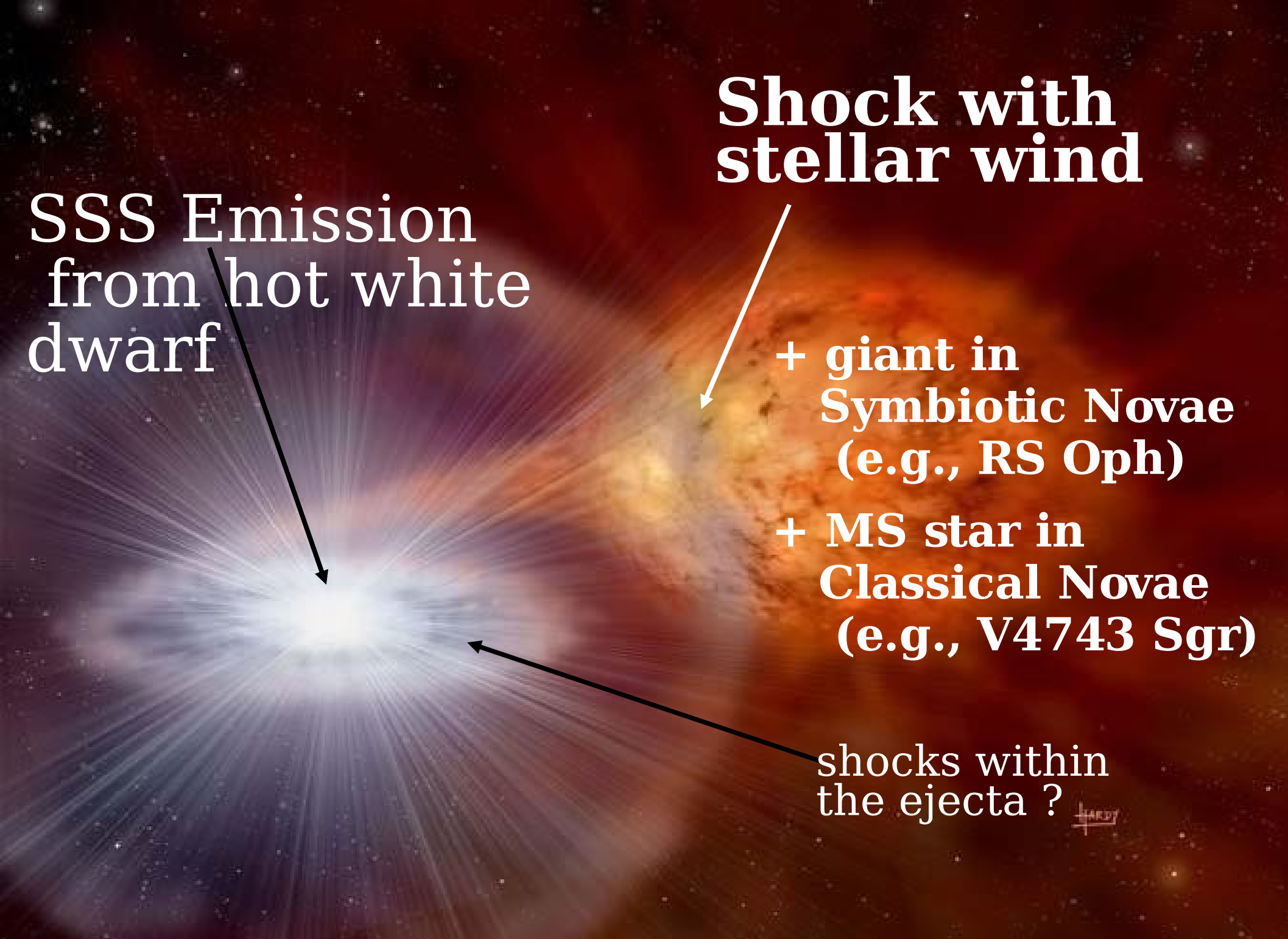
the spectrum shifts to increasingly high energies.....



.... until the peak of the spectrum reaches soft X-rays

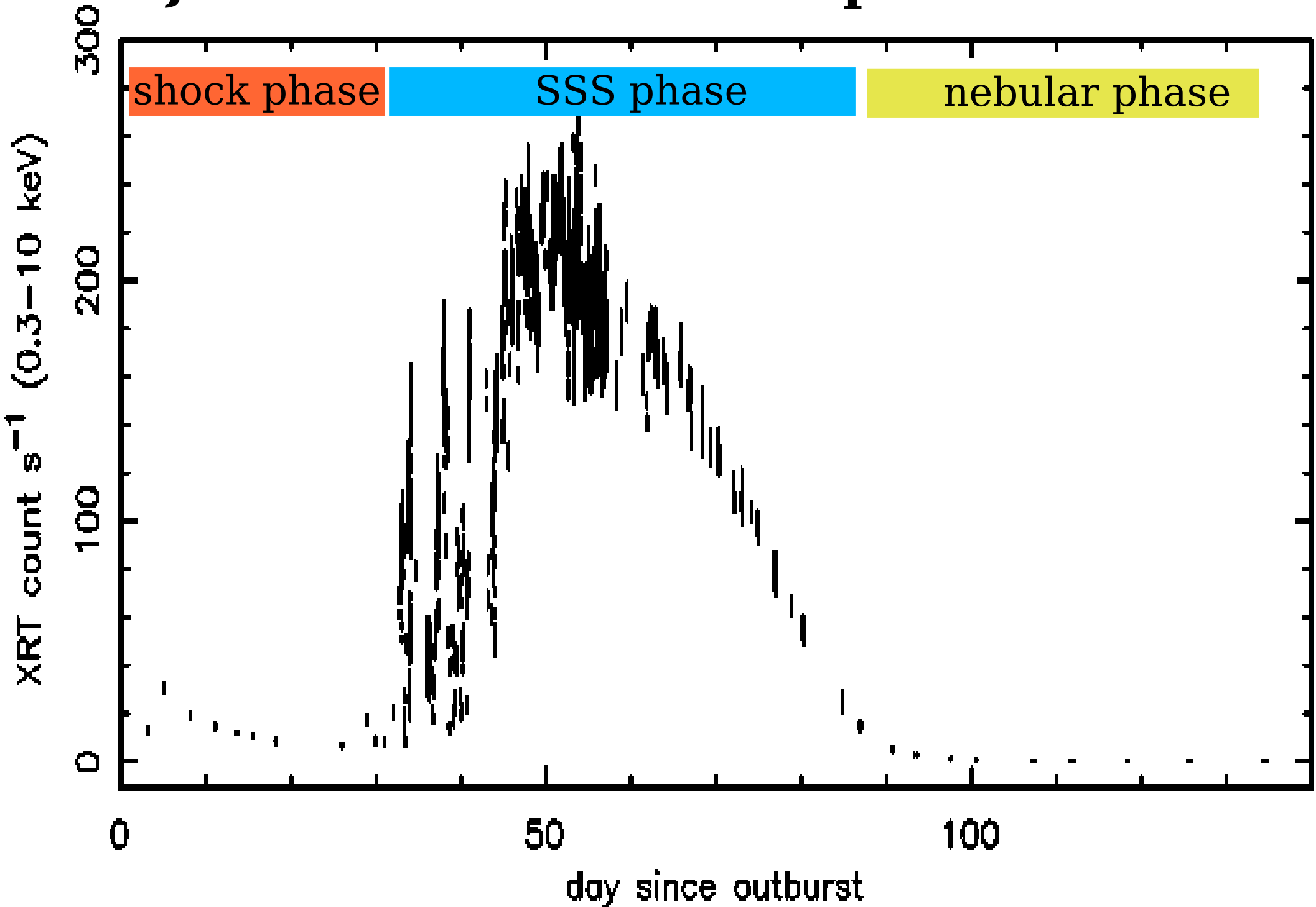
--> direct observations of nuclear burning


$L_{bol}=10^{38}$ erg/sec
optical
UV
X-ray
T_{eff}=6000 K
R=1.0×10^5 km
T_{eff}=30000 K
R=4.2×10^6 km
T_{eff}=300000 K
R=4.2×10^4 km
log (flux)
−8
−9
−10
−11
−12
0
2000
4000
6000
λ (Å)


Shock with stellar wind
SSS Emission from hot white dwarf
+ giant in Symbiotic Novae (e.g., RS Oph)
+ MS star in Classical Novae (e.g., V4743 Sgr)
shocks within the ejecta ?

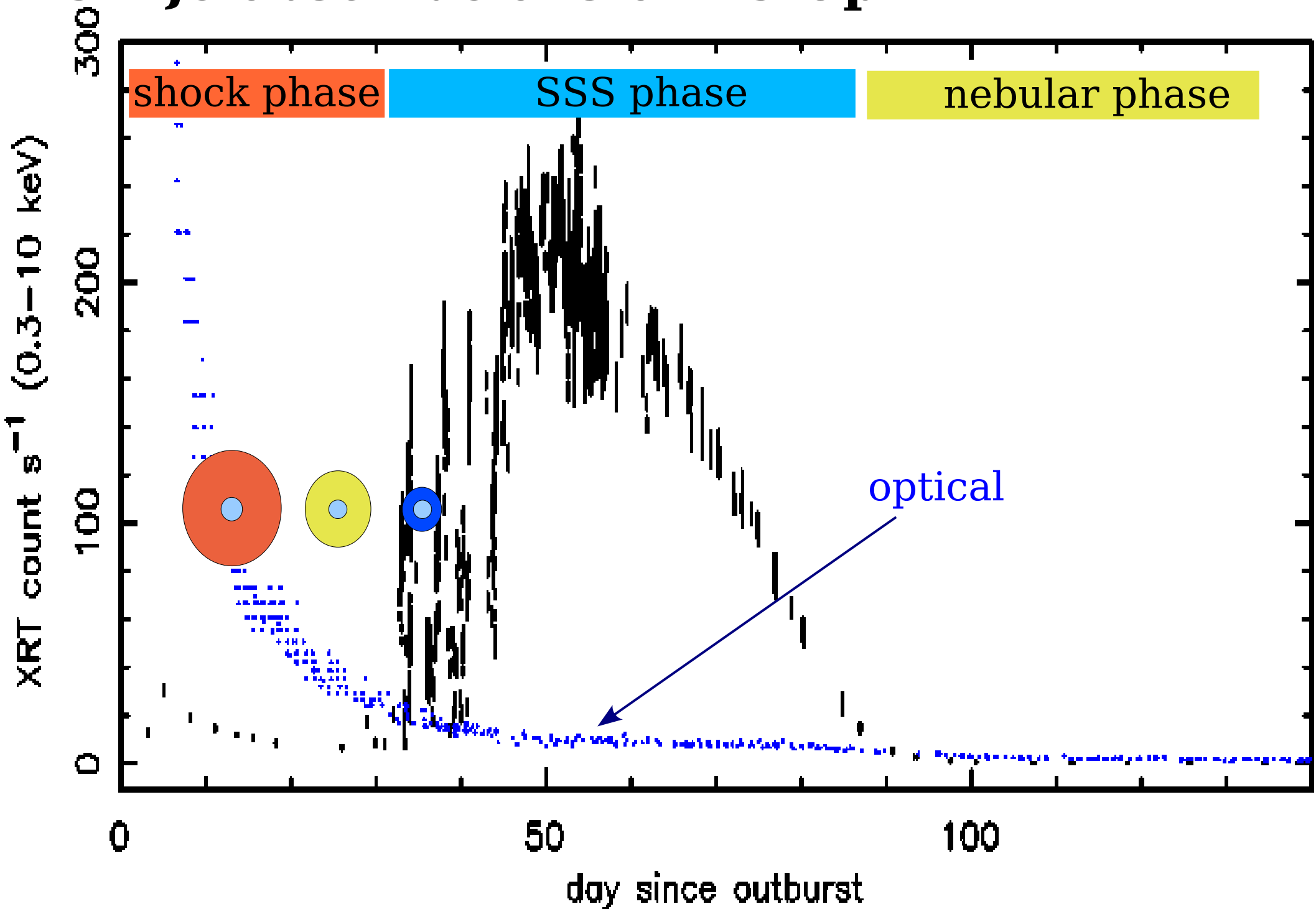
Swift observations of RS Oph

Osborne et al. (2008)



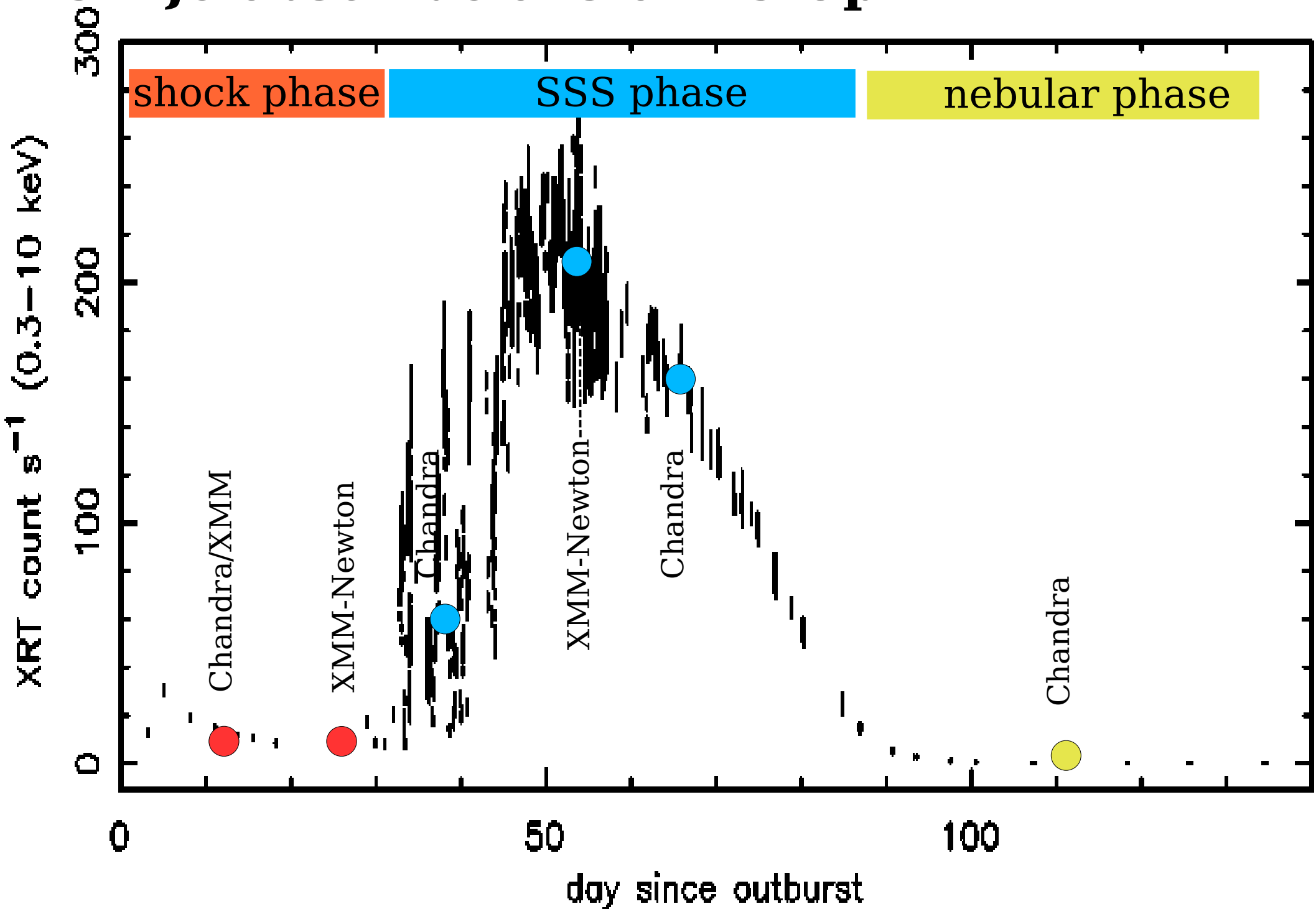
Swift observations of RS Oph

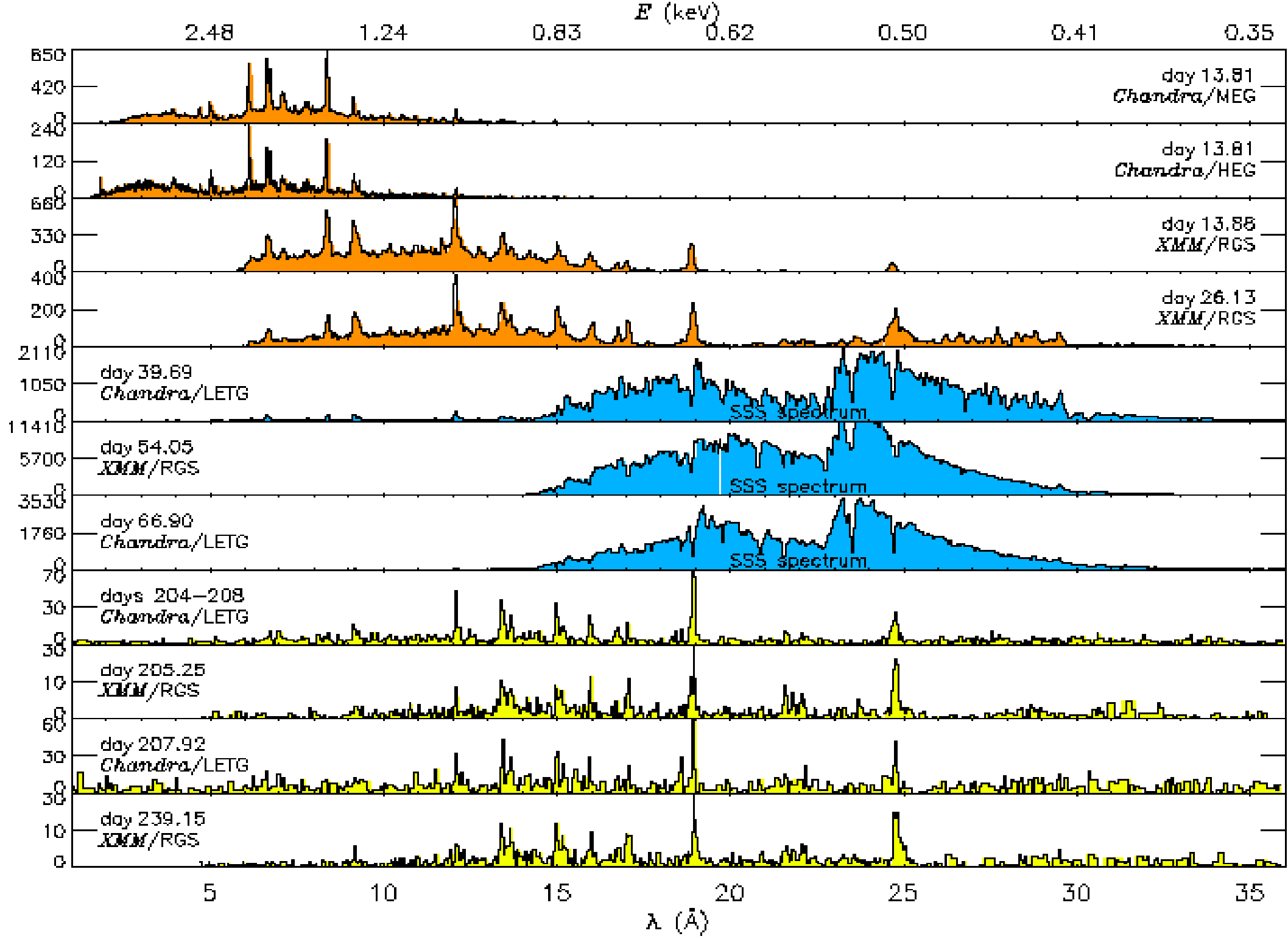
Osborne et al. (2008)

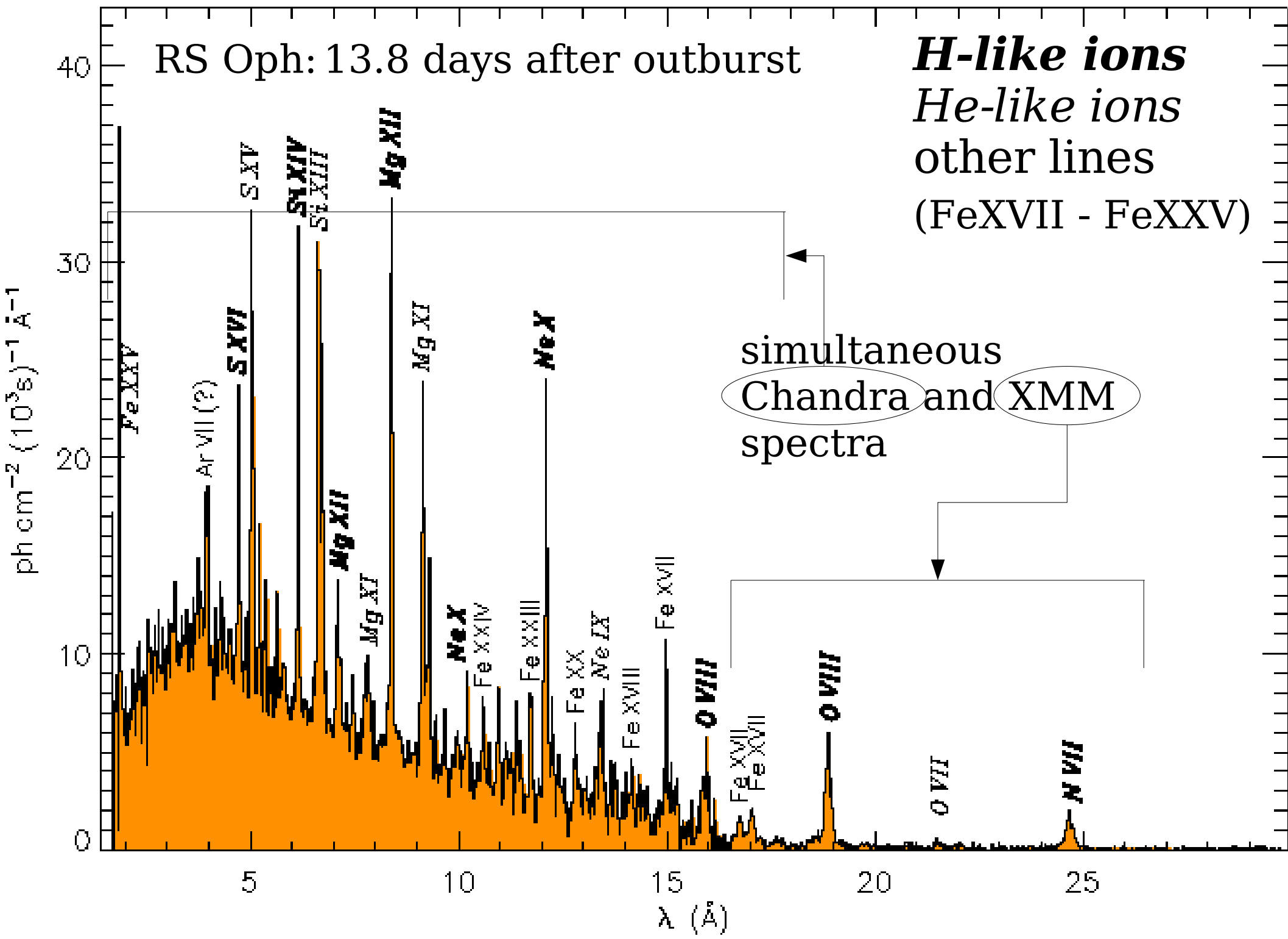


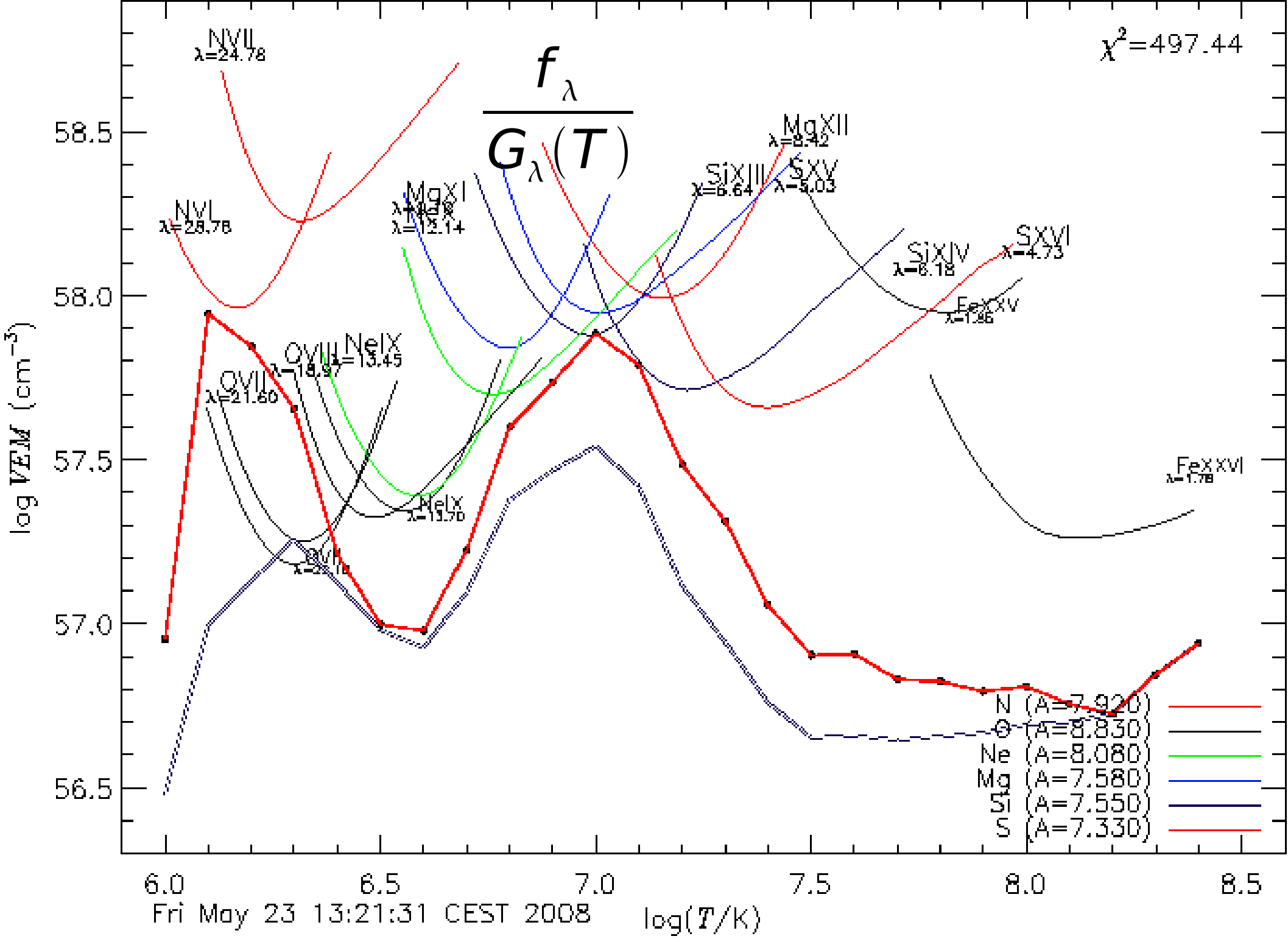
Swift observations of RS Oph

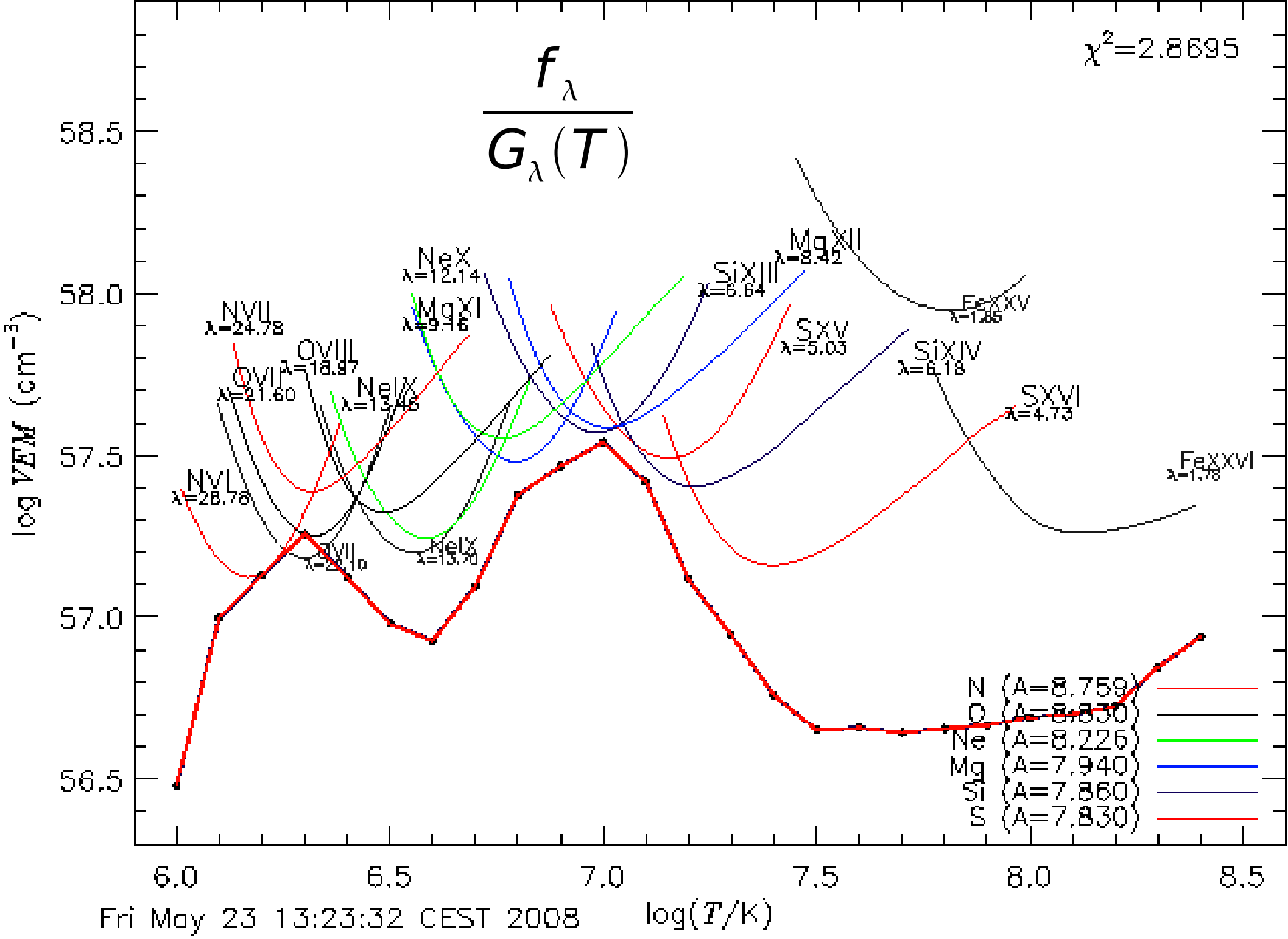
Osborne et al. (2008)

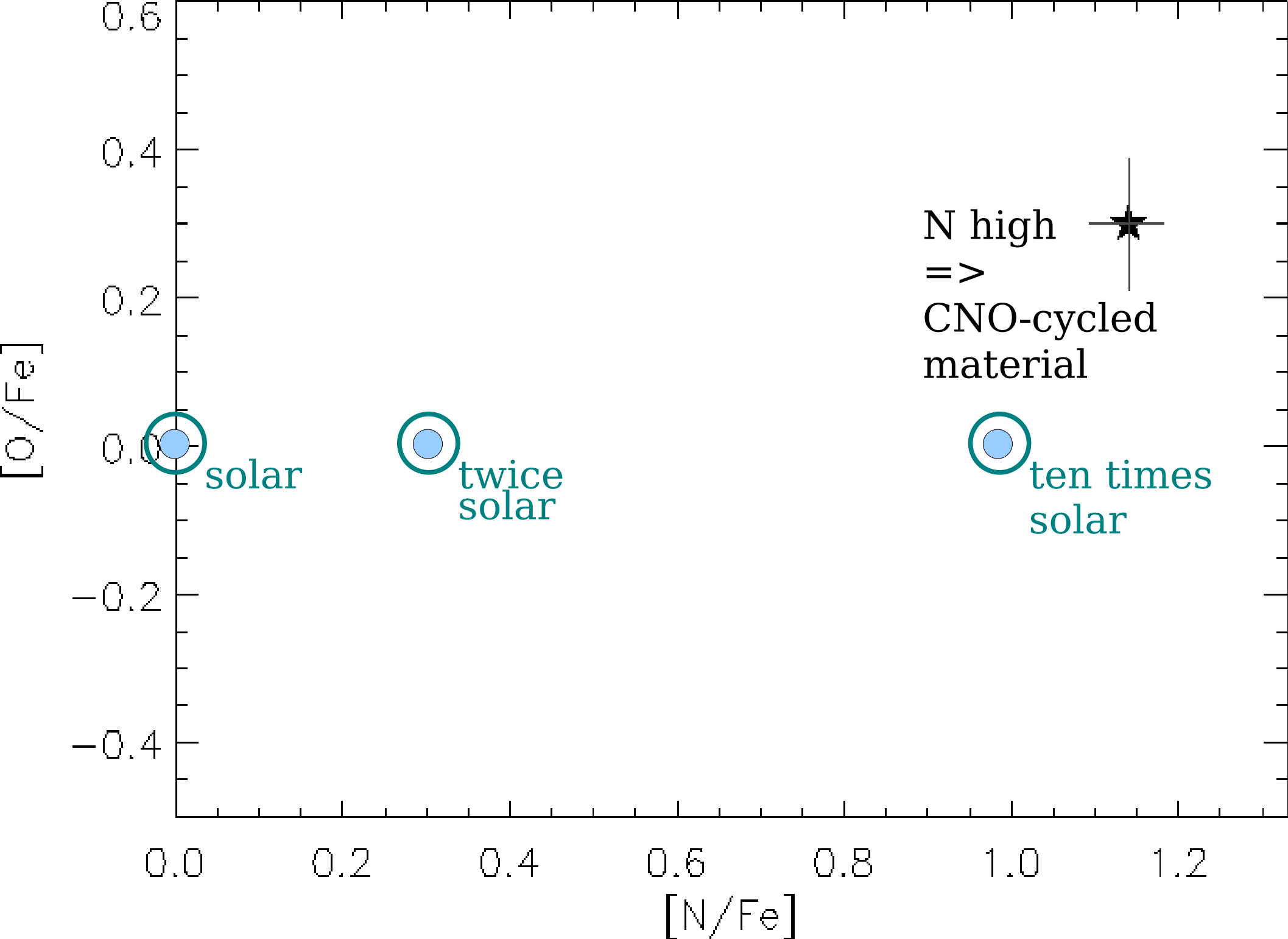


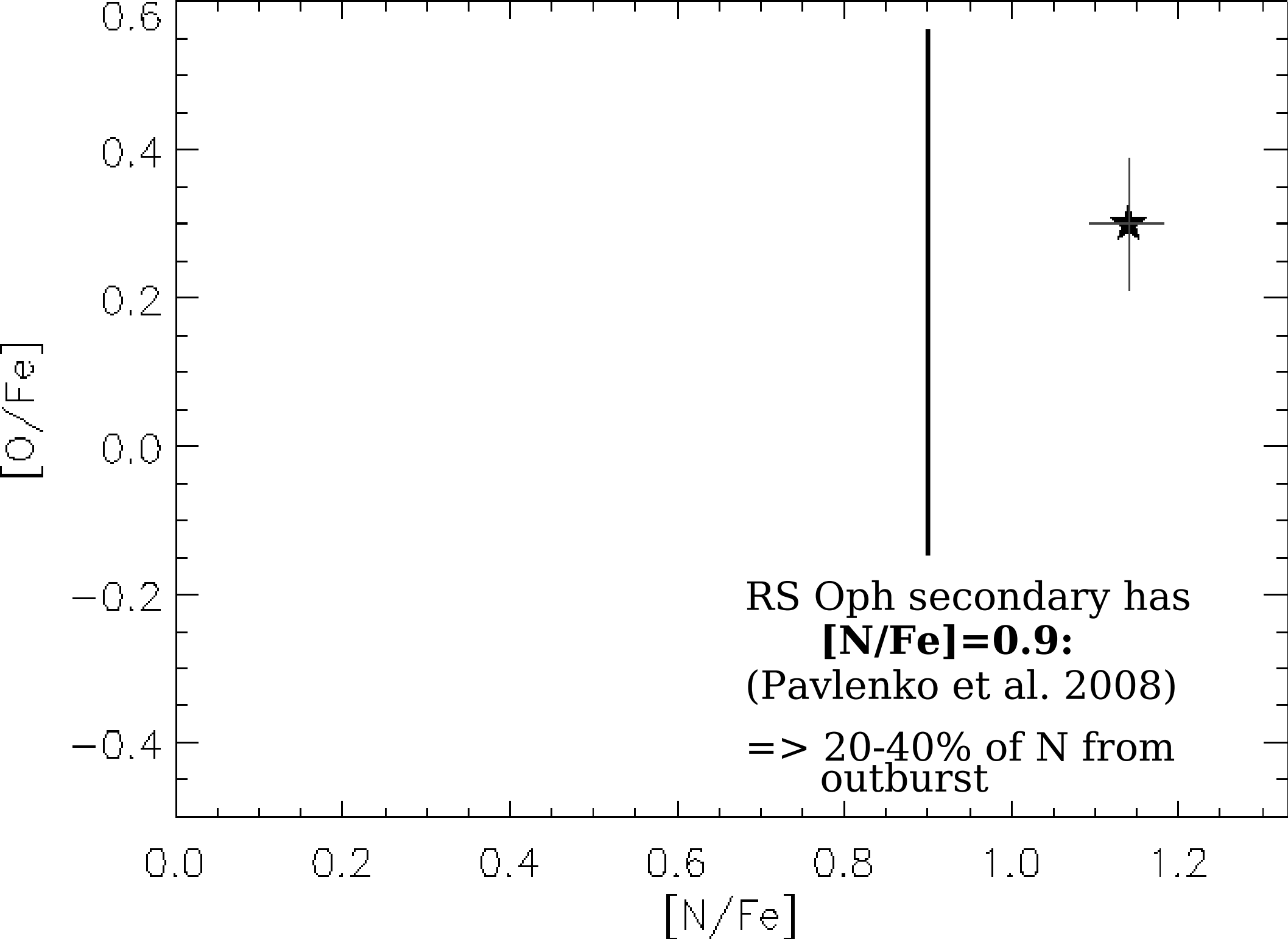

E (keV)
2.48
1.24
0.83
0.62
0.50
0.41
0.35
650
420
240
day 13.81
Chandra/MEG
120
0
day 13.81
Chandra/HEG
660
330
0
day 13.86
XMM/RGS
400
200
0
day 26.13
XMM/RGS
2110
1050
0
day 39.69
Chandra/LETG
SSS spectrum
11410
5700
0
day 54.05
XMM/RGS
SSS spectrum
3530
1760
0
day 66.90
Chandra/LETG
SSS spectrum
70
30
0
days 204–208
Chandra/LETG
38
10
0
day 205.25
XMM/RGS
60
30
0
day 207.92
Chandra/LETG
38
10
0
day 239.15
XMM/RGS
5
10
15
20
25
30
35
λ (Å)

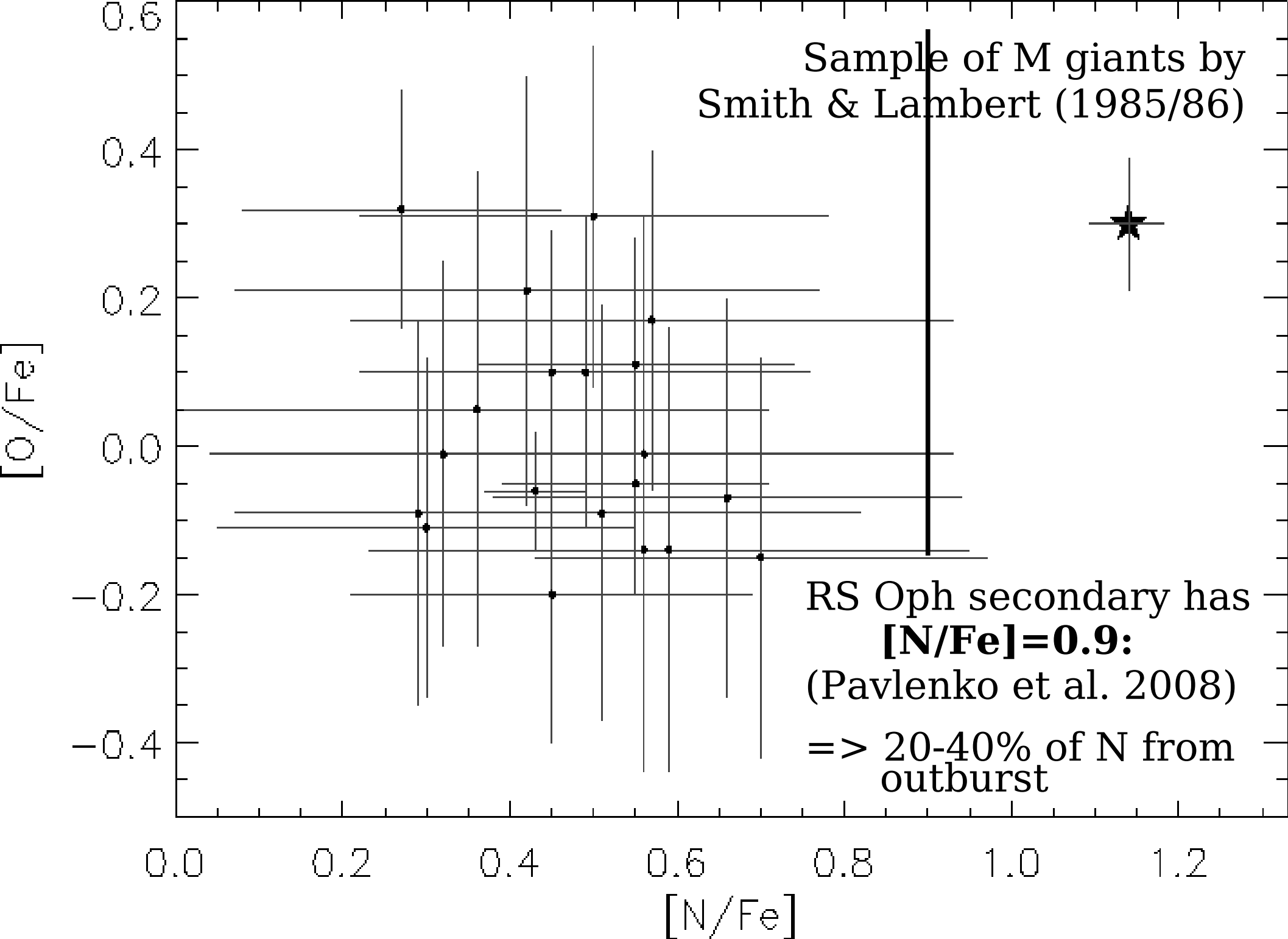

RS Oph: 13.8 days after outburst
H-like ions
He-like ions
other lines
(FeXVII - FeXXV)
simultaneous
Chandra and XMM
spectra
Fe XXV
Ar VII (?)
S XVI
S XV
Si XIV
Si XIII
Mg XII
Mg XI
Ne X
Fe XXIII
Fe XX
Ne IX
Fe XVIII
Fe XVII
O VIII
O VII
N VII
ph cm^{-2} (10^{3}s)$^{-1}$ Å^{-1}
λ (Å)

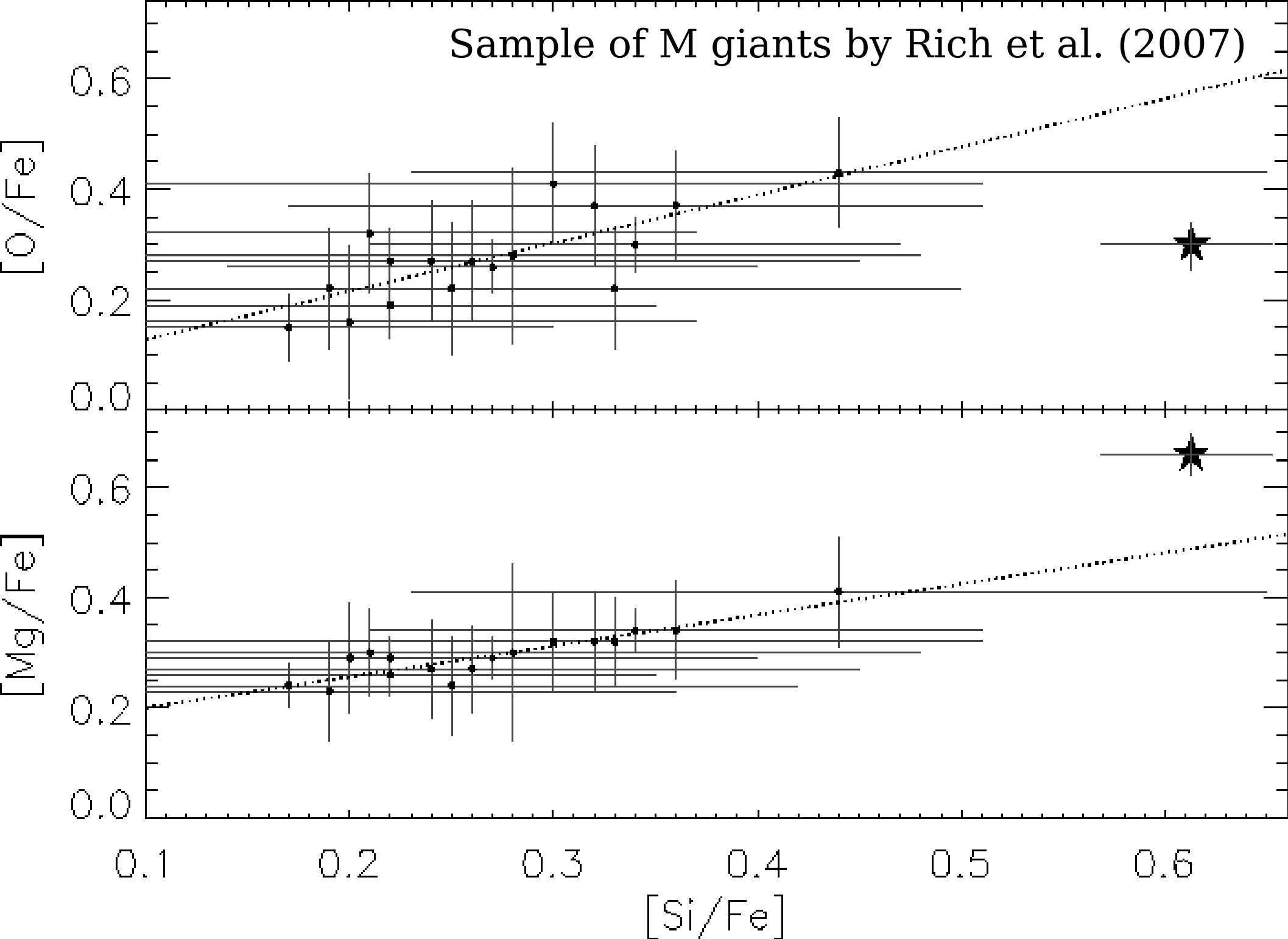

$\frac{f_\lambda}{G_\lambda(T)}$
χ^2=497.44
NVII λ=24.78
NVI λ=28.78
MgXI λ=9.23
NeIX λ=13.70
MgXI λ=12.14
OVIII λ=18.97
NeIX λ=13.45
OVII λ=21.60
OVII λ=22.10
MgXII λ=8.42
SiXIII λ=6.64
SXV λ=5.03
SiXIV λ=6.18
FeXXV λ=1.85
SXVI λ=4.73
FeXXVI λ=1.78
N (A=7.920)
O (A=8.830)
Ne (A=8.080)
Mg (A=7.580)
Si (A=7.550)
S (A=7.330)
log VEM (cm^{-3})
58.5
58.0
57.5
57.0
56.5
6.0
6.5
7.0
7.5
8.0
8.5
log(T/K)
Fri May 23 13:21:31 CEST 2008

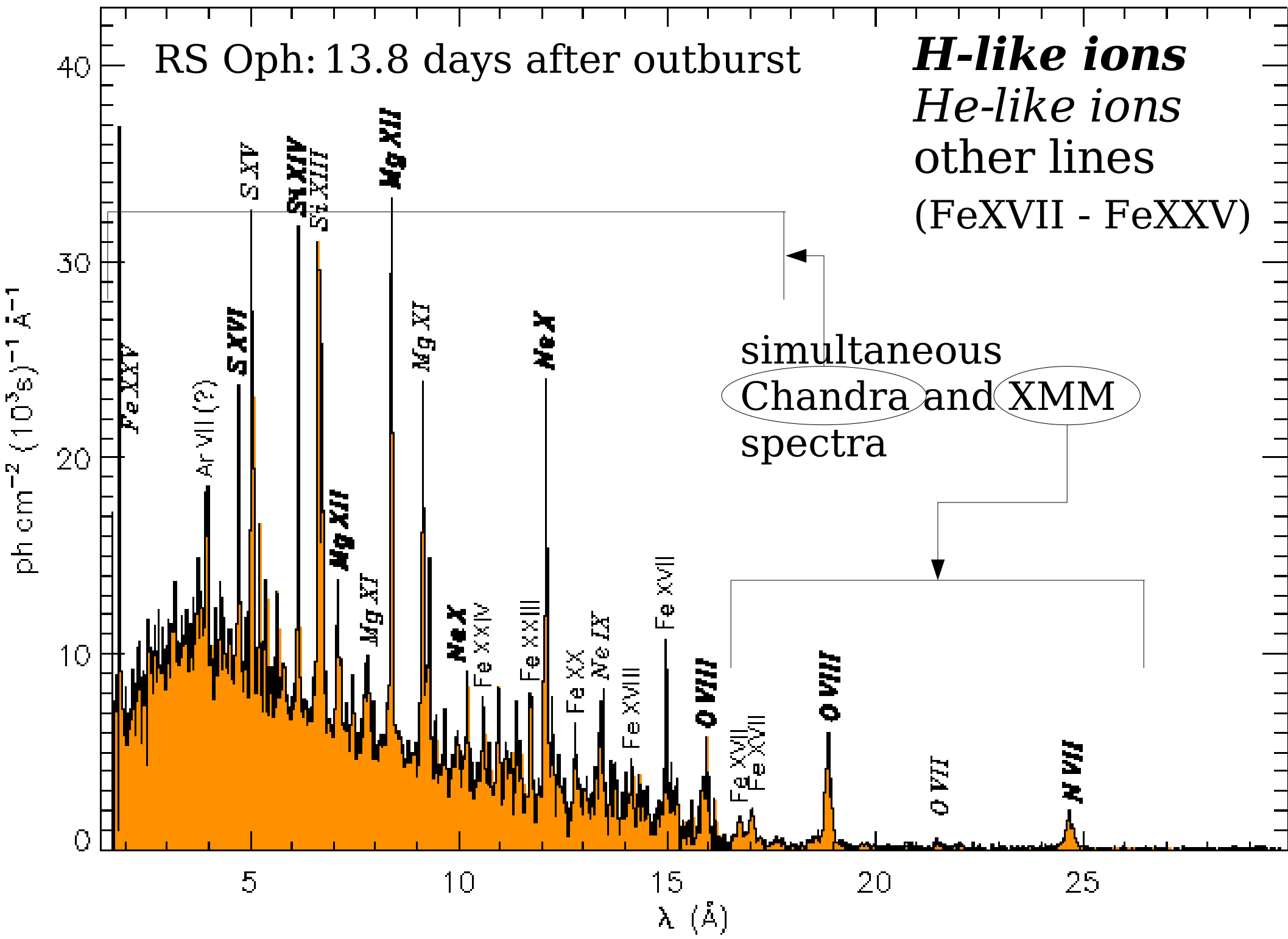

$\frac{f_\lambda}{G_\lambda(T)}$
χ^2=2.8695
log VEM (cm^{-3})
58.5
58.0
57.5
57.0
56.5
6.0
6.5
7.0
7.5
8.0
8.5
log(T/K)
Fri May 23 13:23:32 CEST 2008
NVII λ=24.78
OVIII λ=18.97
OVII λ=21.60
NeIX λ=13.45
NVI λ=28.78
NeX λ=12.14
MgXI λ=9.16
SiXIII λ=6.64
MgXII λ=8.42
SXV λ=5.03
FeXXV λ=1.85
SiXIV λ=6.18
SXVI λ=4.73
FeXXVI λ=1.78
N (A=8.759)
O (A=8.830)
Ne (A=8.226)
Mg (A=7.940)
Si (A=7.860)
S (A=7.830)


0.6
0.4
0.2
0.0
−0.2
−0.4
[O/Fe]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
[N/Fe]
N high
=>
CNO-cycled
material
solar
twice
solar
ten times
solar


0.6
0.4
0.2
0.0
−0.2
−0.4
[O/Fe]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
[N/Fe]
RS Oph secondary has
[N/Fe]=0.9:
(Pavlenko et al. 2008)
=> 20-40% of N from outburst


Sample of M giants by
Smith & Lambert (1985/86)
RS Oph secondary has
[N/Fe]=0.9:
(Pavlenko et al. 2008)
=> 20-40% of N from
outburst
[O/Fe]
[N/Fe]
0.6
0.4
0.2
0.0
−0.2
−0.4
0.0
0.2
0.4
0.6
0.8
1.0
1.2


Sample of M giants by Rich et al. (2007)
[O/Fe]
[Mg/Fe]
[Si/Fe]
0.0
0.2
0.4
0.6
0.1
0.2
0.3
0.4
0.5
0.6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Fe XXV
Ar VII (?)
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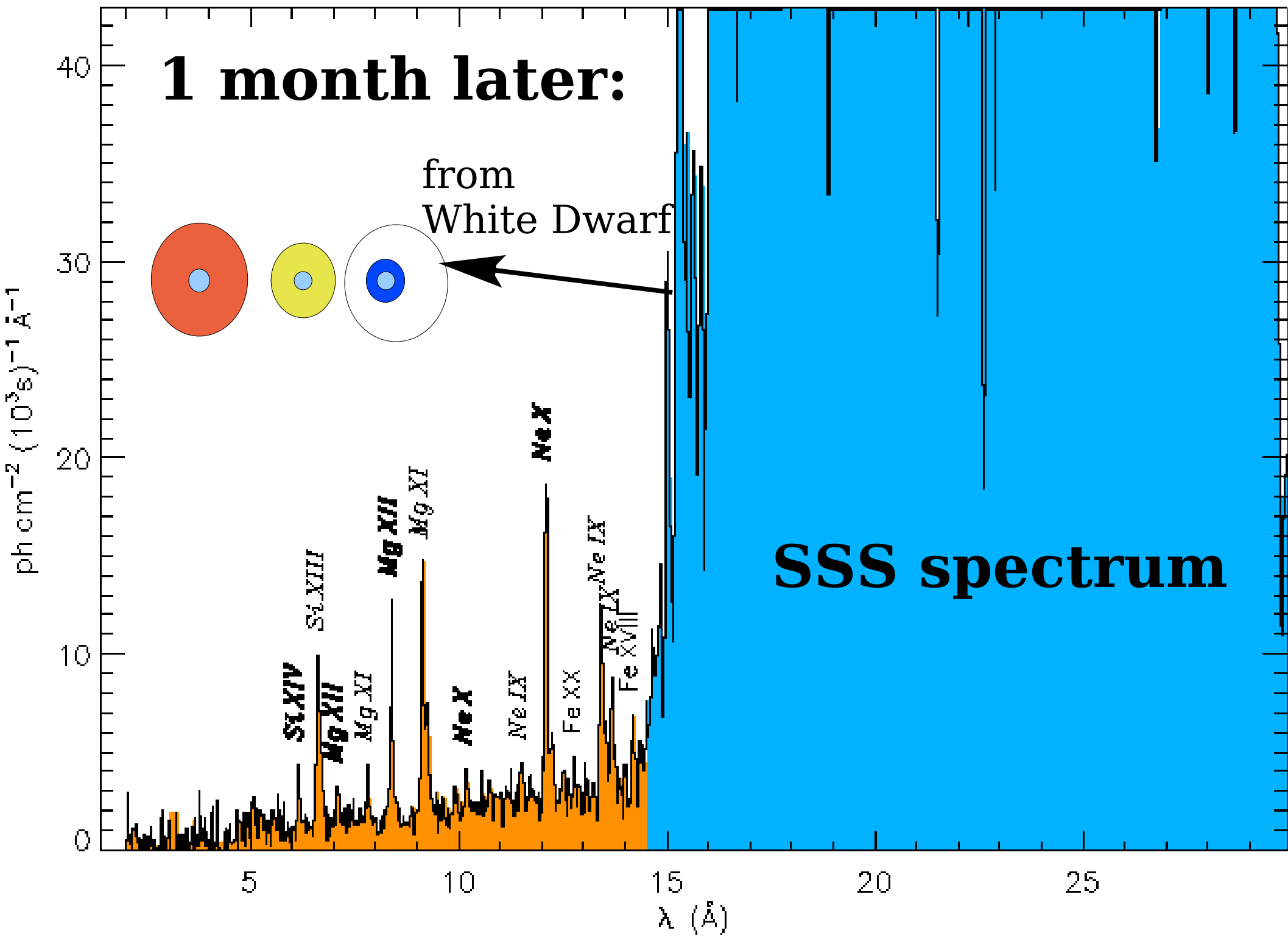
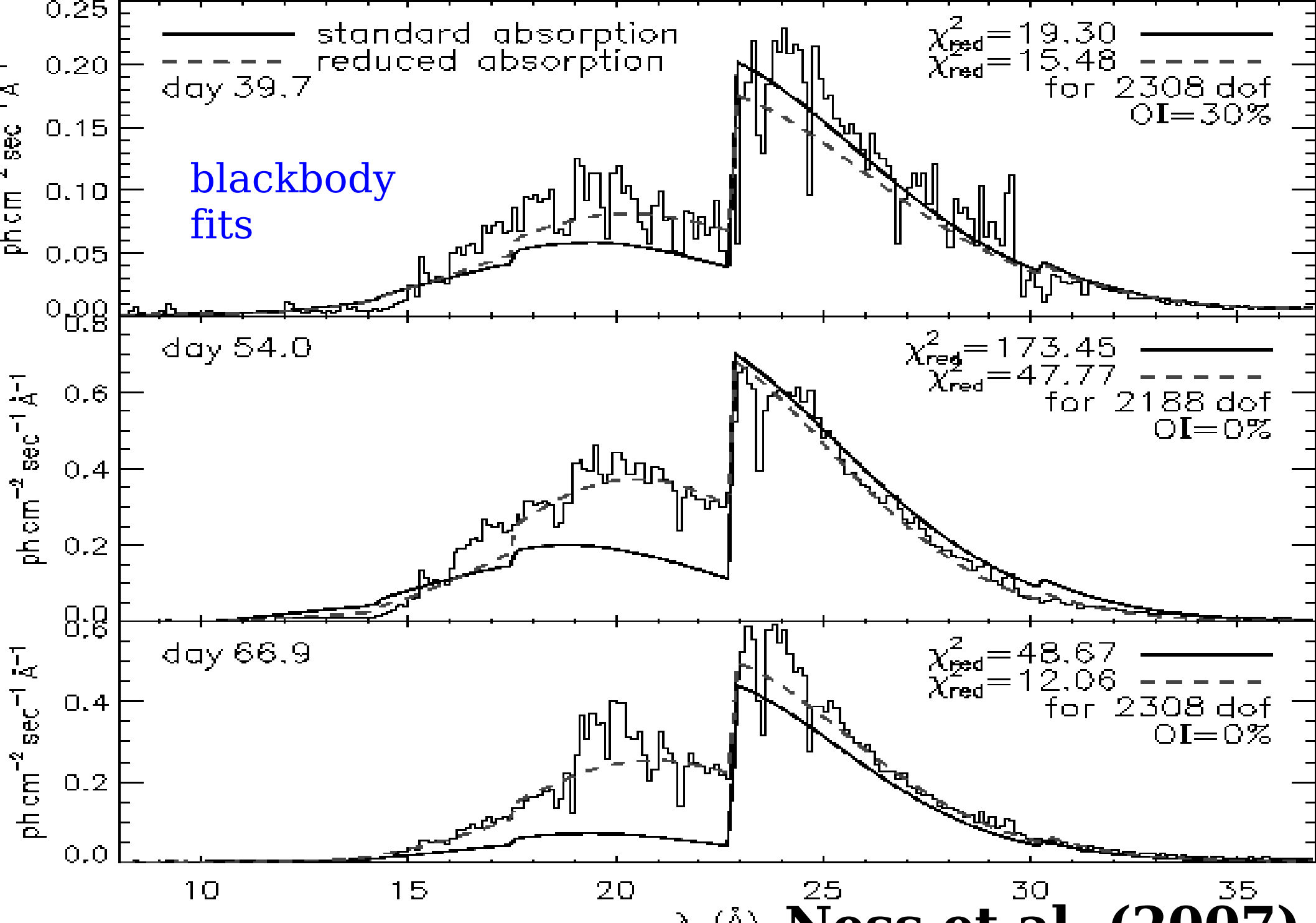
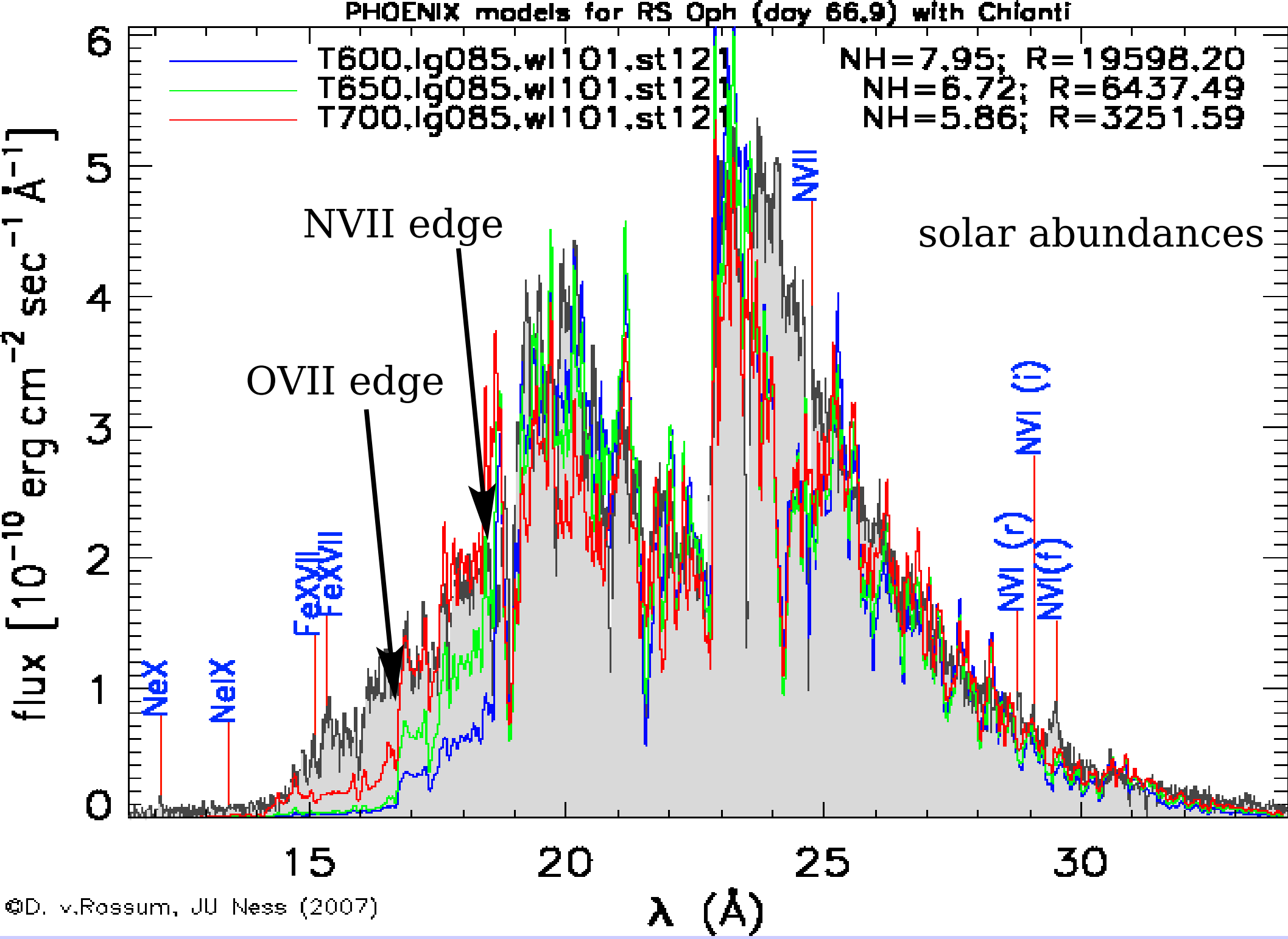
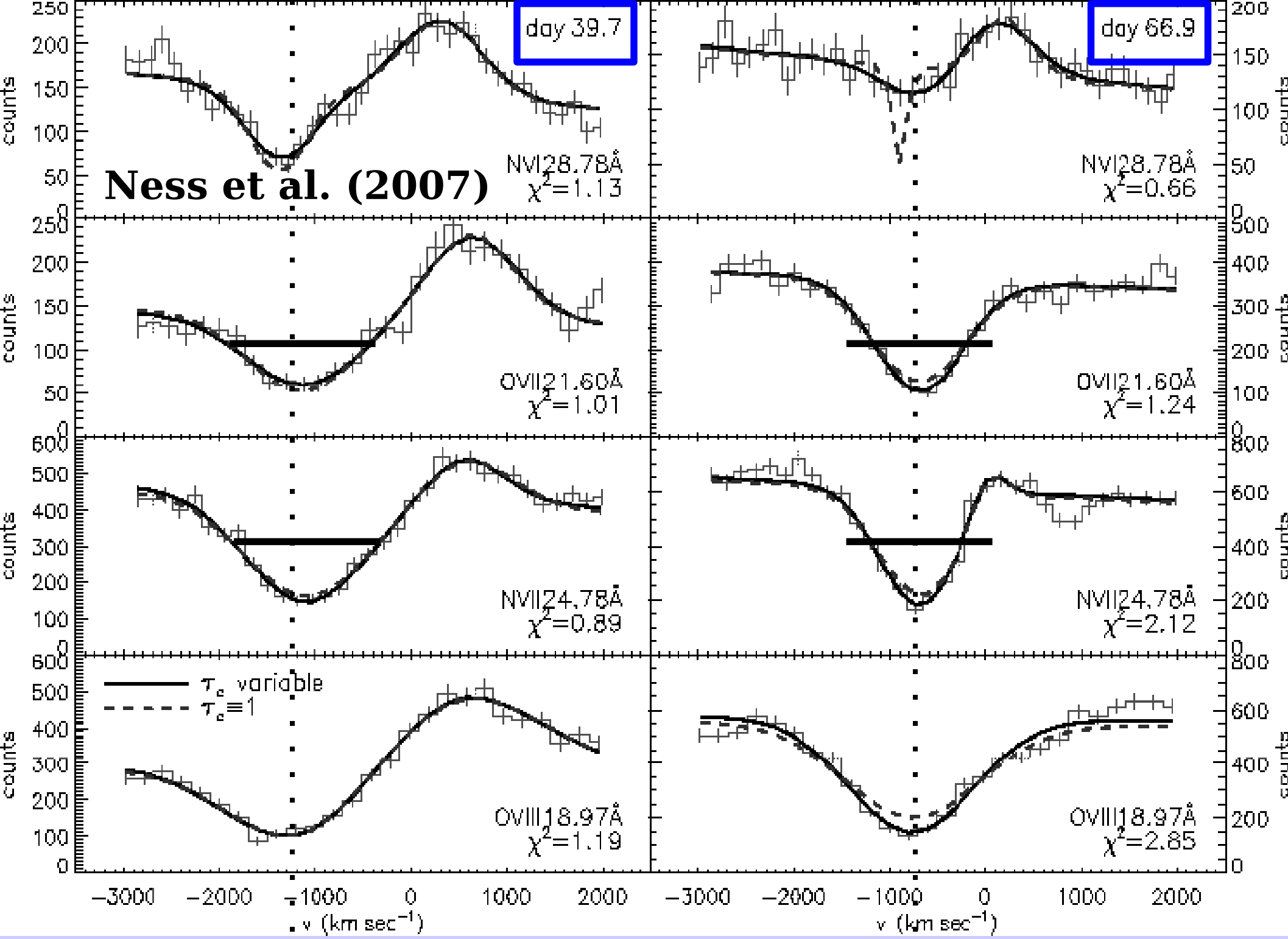
S XV
Si XIV
Si XIII
Mg XII
Mg XI
Ne X
Fe XXIII
Fe XX
Ne IX
Fe XVIII
Fe XVII
O VIII
O VII
N VII
ph cm^{-2} (10^{3}s)$^{-1}$ Å^{-1}
λ (Å)


1 month later:
from
White Dwarf
SSS spectrum
ph cm^{-2} (10^{3}s)$^{-1}$ Å^{-1}
λ (Å)
0
10
20
30
40
5
10
15
20
25
Si XIV
Si XIII
Mg XII
Mg XI
Mg XII
Mg XI
Ne X
Ne IX
Fe XX
Ne X
Ne IX
Fe XVII



Ness et al. (2007)


PHOENIX models for RS Oph (doy 66.9) with Chianti
T600.lg085.wl101.st121
T650.lg085.wl101.st121
T700.lg085.wl101.st121
NH=7.95; R=19598.20
NH=6.72; R=6437.49
NH=5.86; R=3251.59
NVII edge
OVII edge
solar abundances
NeX
NeIX
FeXVII
FeXVII
NVII
NVI (i)
NVI (r)
NVI(f)
flux [10^-10 erg cm^-2 sec^-1 Å^-1]
λ (Å)
©D. v.Rossum, JU Ness (2007)


day 39.7
day 66.9
Ness et al. (2007)
NVI 28.78Å
χ²=1.13
NVI 28.78Å
χ²=0.66
OVII 21.60Å
χ²=1.01
OVII 21.60Å
χ²=1.24
NVII 24.78Å
χ²=0.89
NVII 24.78Å
χ²=2.12
τe variable
τe≡1
OVIII 18.97Å
χ²=1.19
OVIII 18.97Å
χ²=2.85
counts
v (km sec⁻¹)

Lines are significantly shifted and broadened

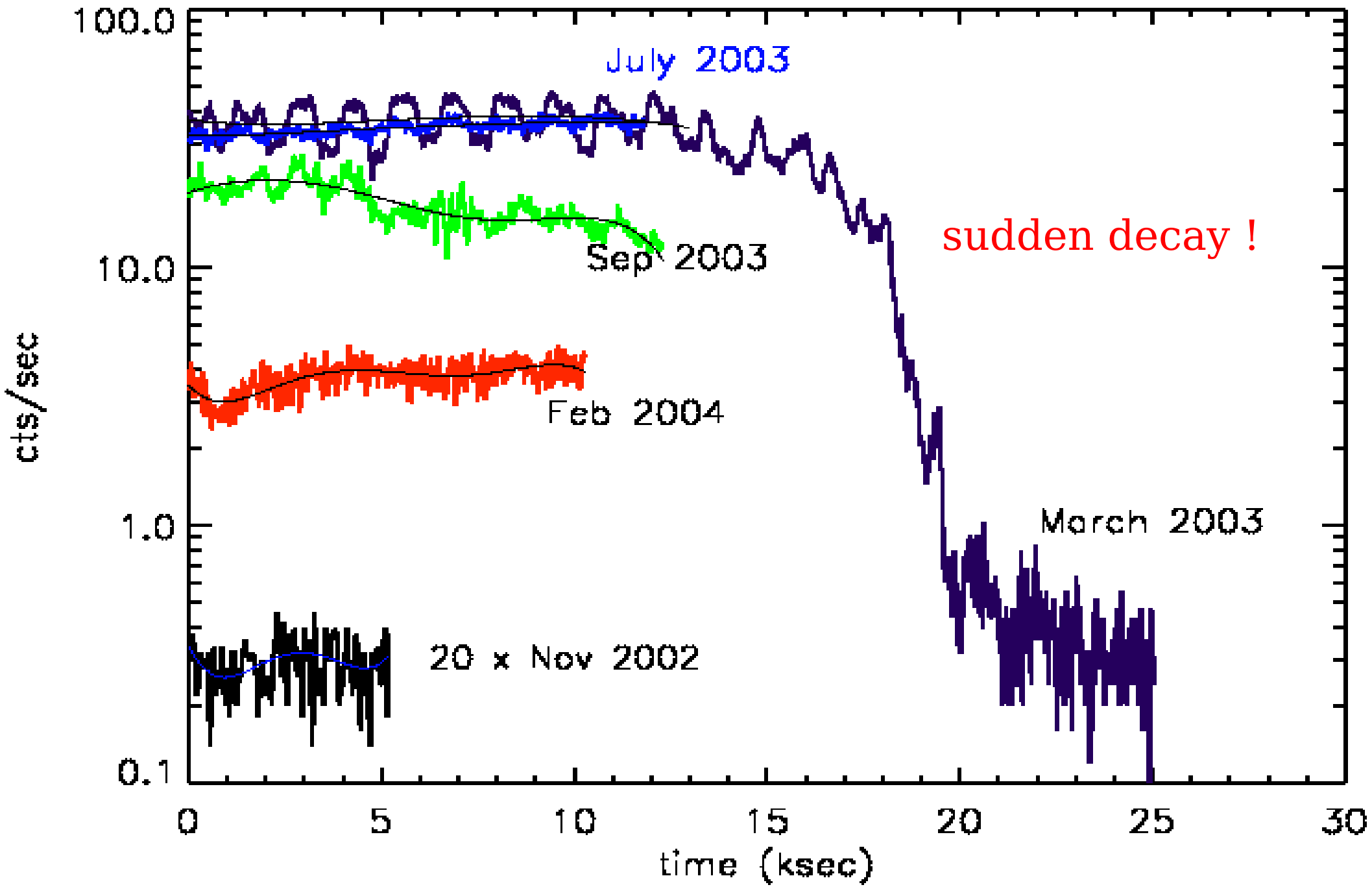
=> considerable expansion velocity of >1000 km per second

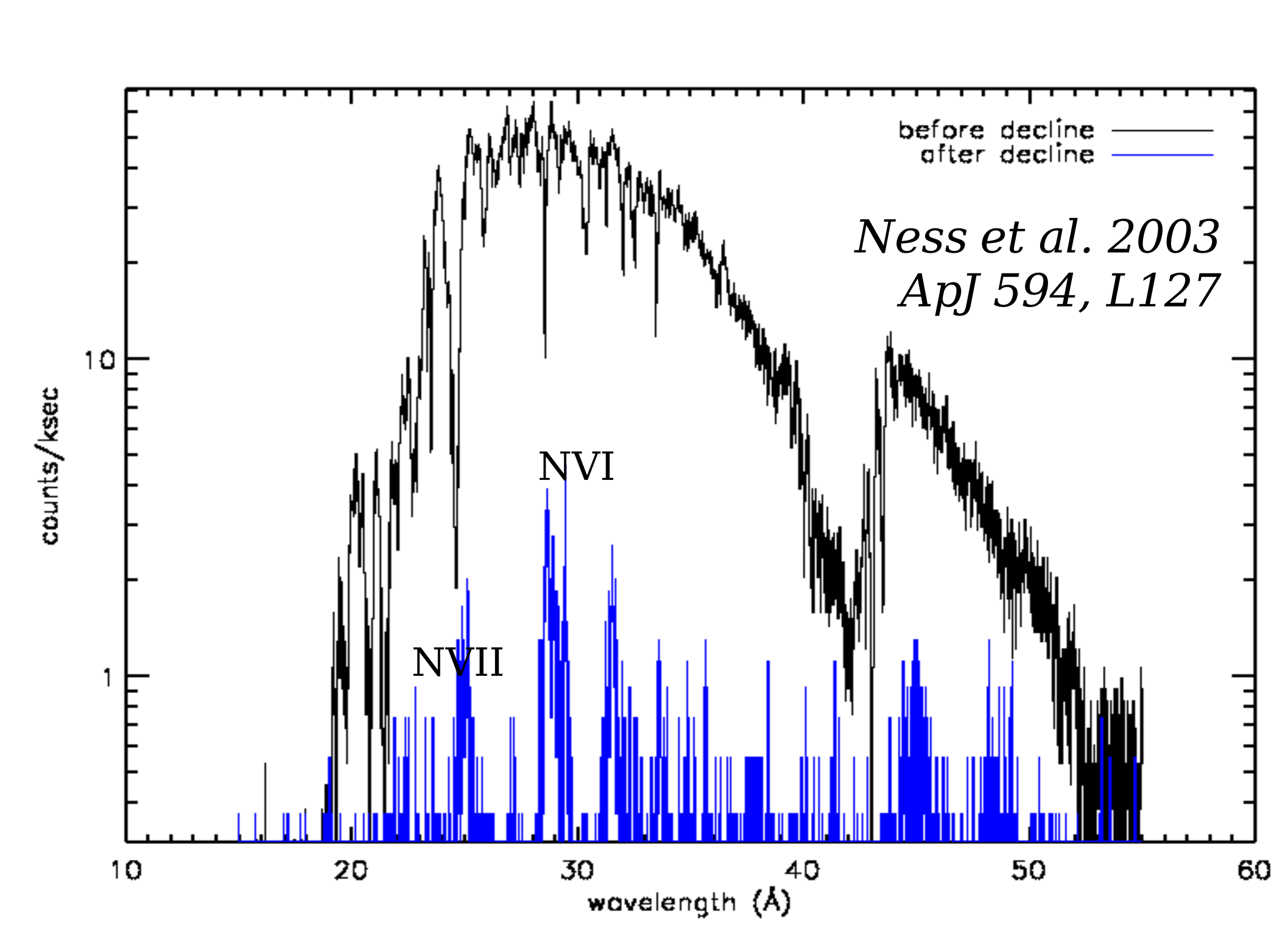
but models are static.

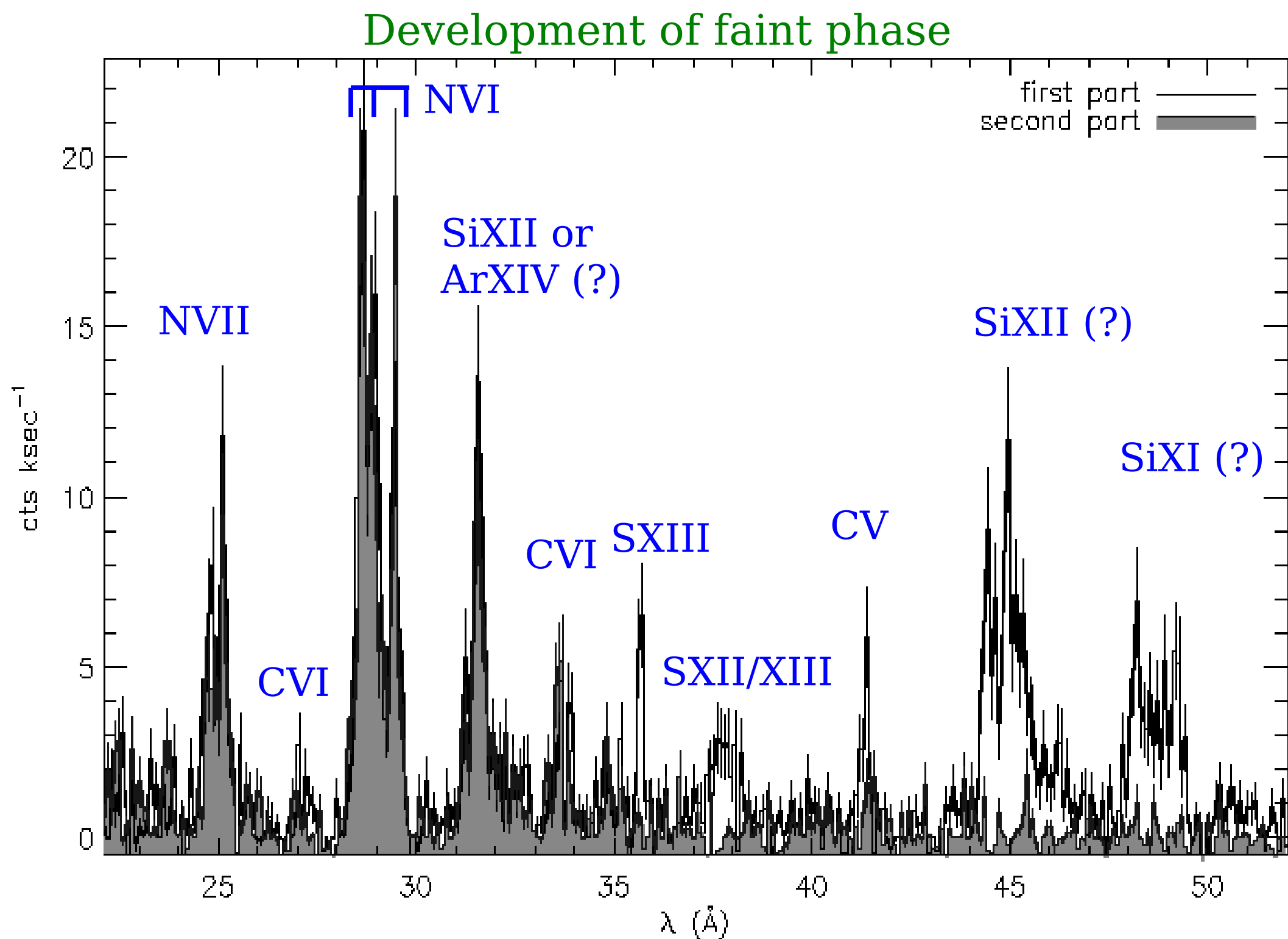
Expansion may wash out the absorption edges and needs to be taken into account.

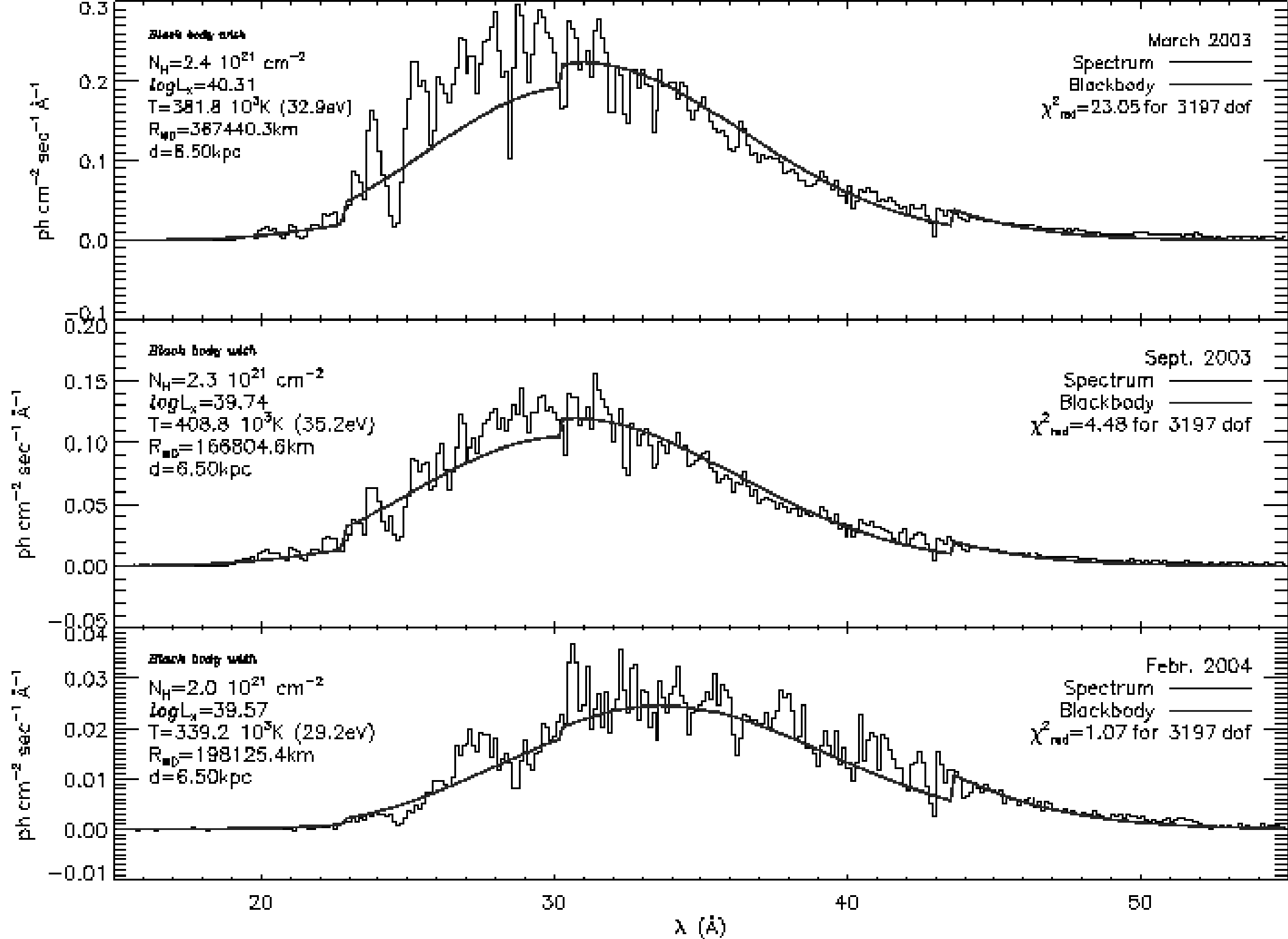
Some other novae:

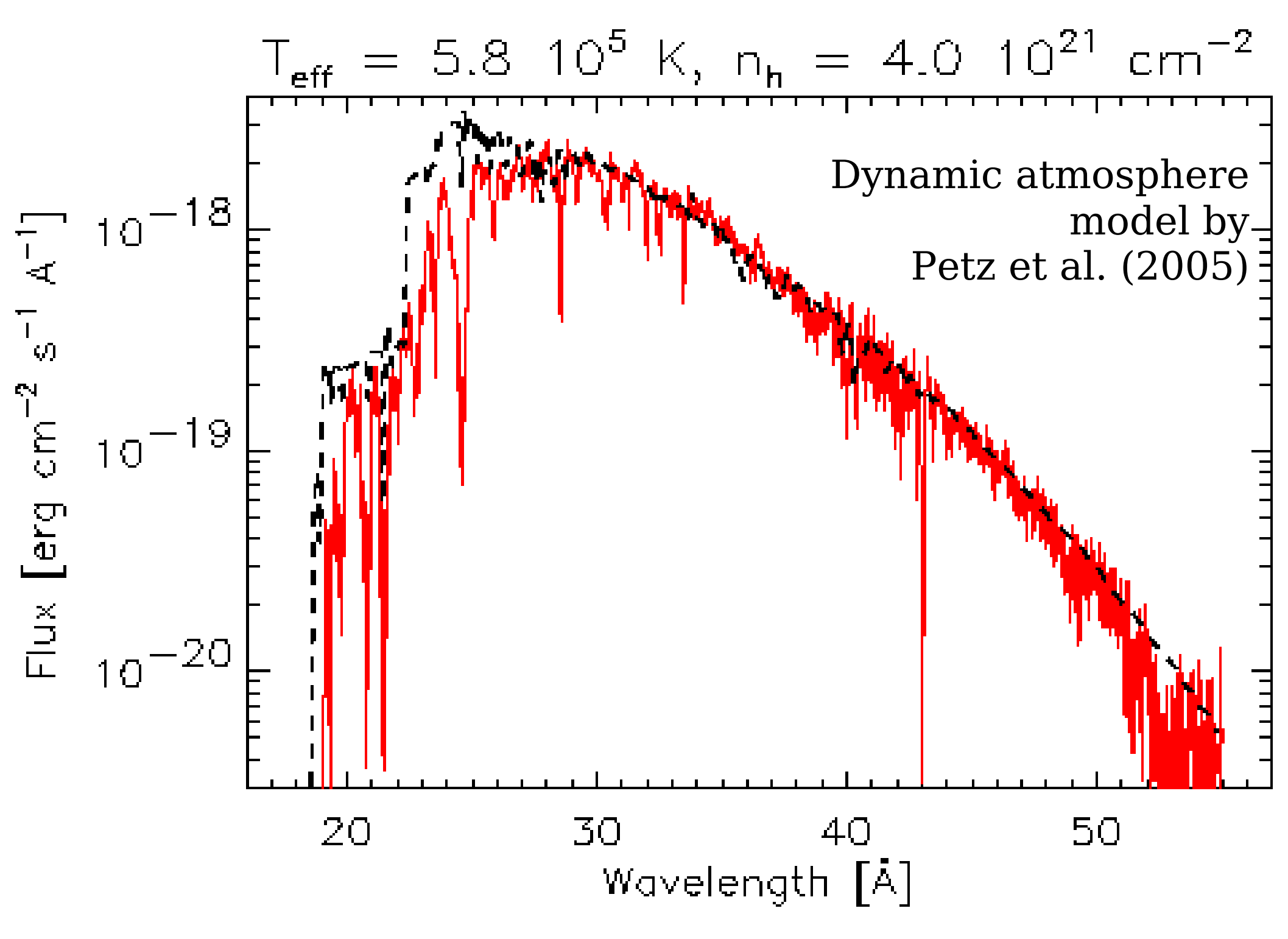
Chandra LETGS Light Curves of V4743 Sgr (Sept. 2002)

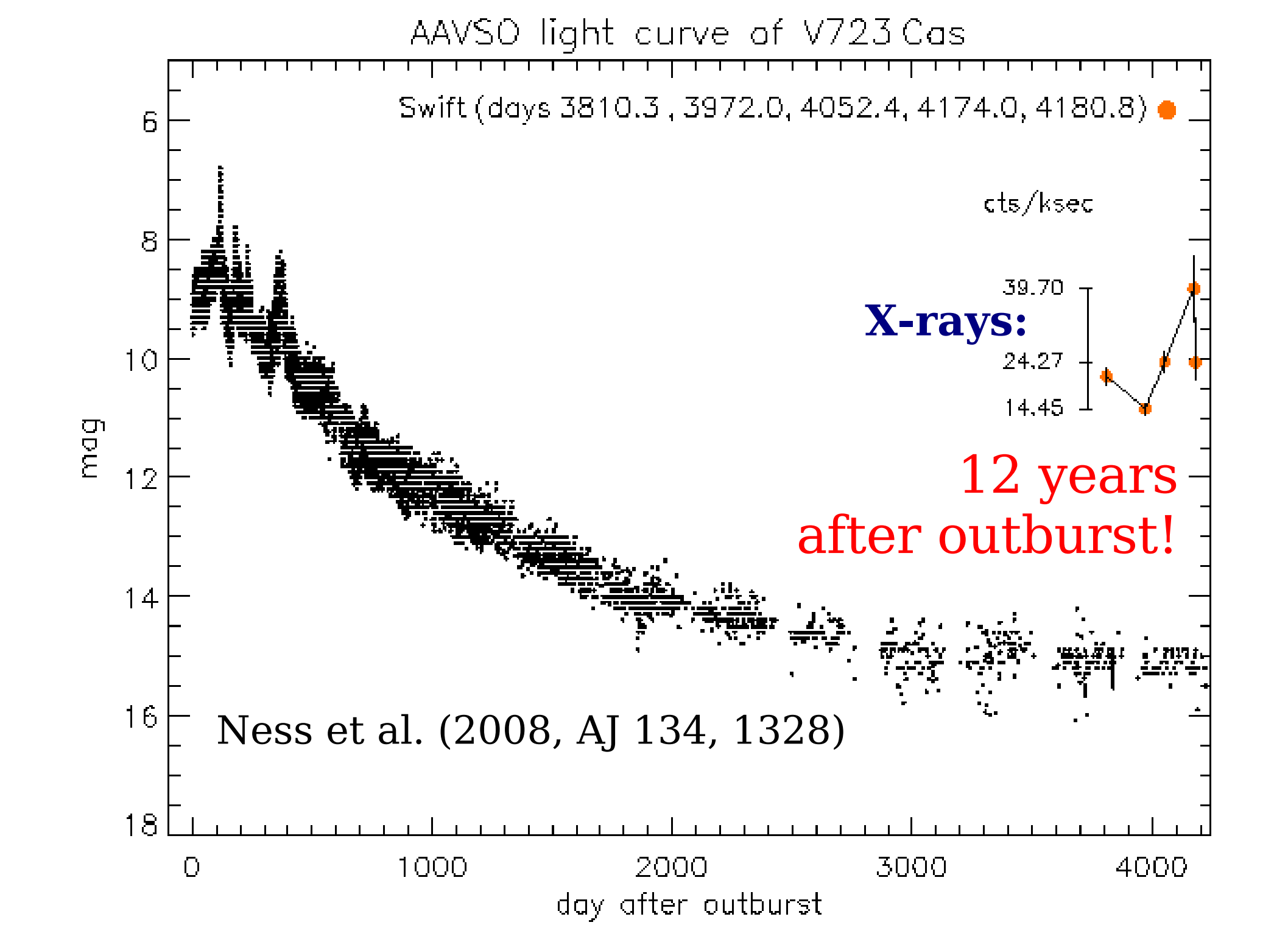



before decline
after decline
Ness et al. 2003
ApJ 594, L127
NVI
NVII
counts/ksec
10
1
10
20
30
40
50
60
wavelength (Å)

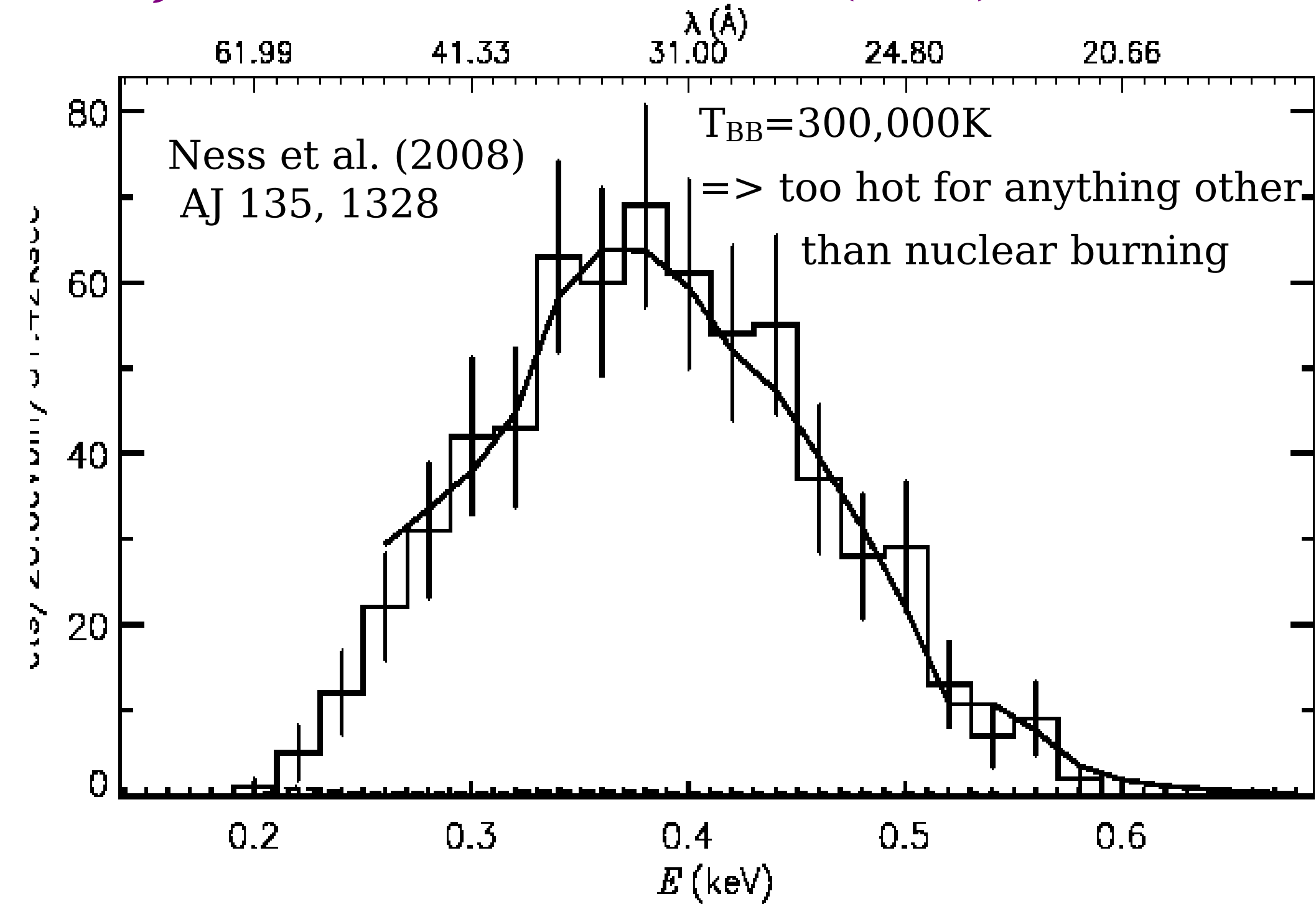

Development of faint phase
first part
second part
NVI
NVII
SiXII or
ArXIV (?)
SiXII (?)
SiXI (?)
CVI
SXIII
CV
CVI
SXII/XIII
cts ksec^{-1}
λ (Å)
0
5
10
15
20
25
30
35
40
45
50

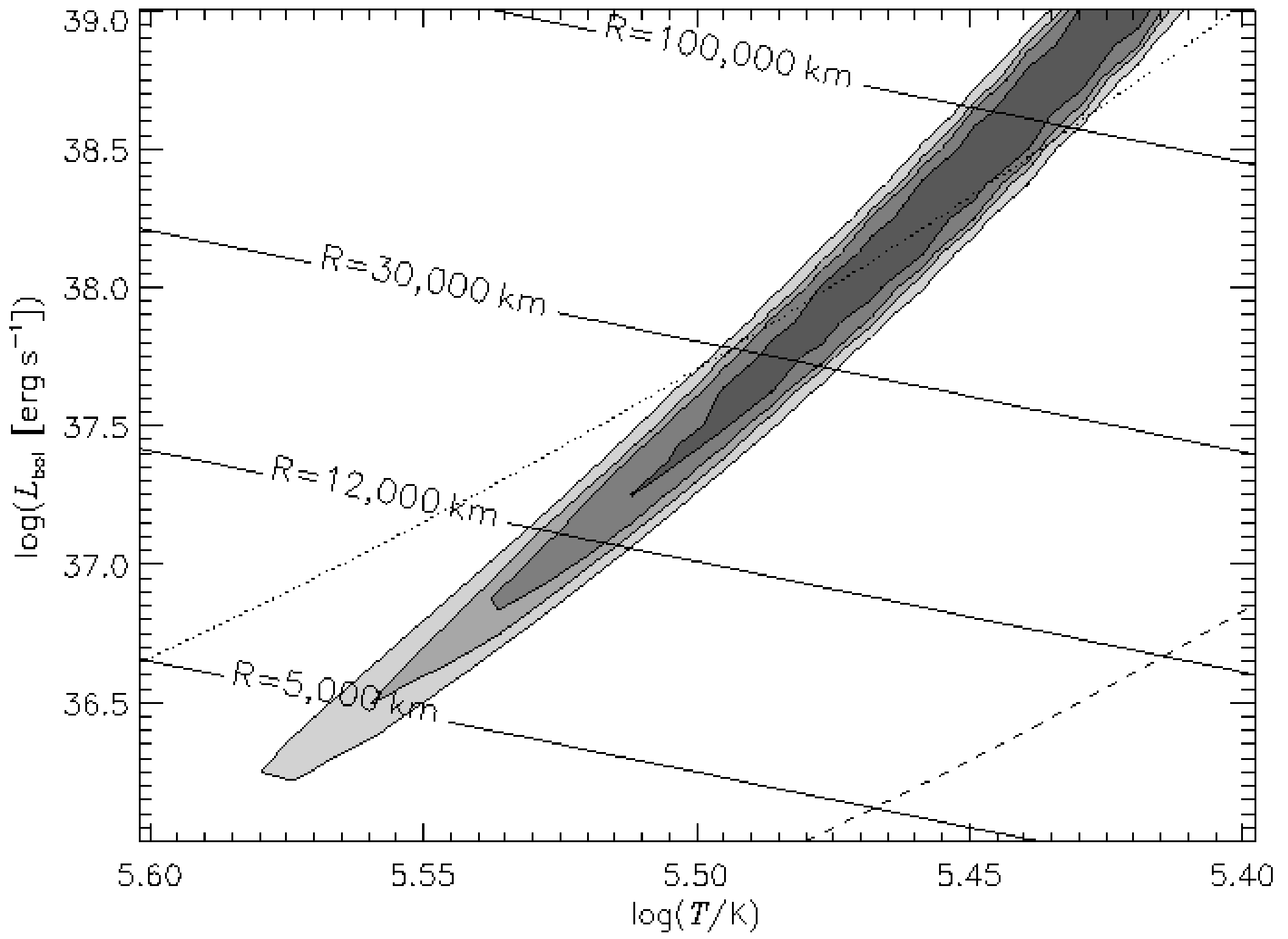

Black body with
N_H=2.4 10^21 cm^-2
logL_x=40.31
T=381.8 10^3K (32.9ev)
R_BB=367440.3km
d=6.50kpc
March 2003
Spectrum
Blackbody
χ²_red=23.05 for 3197 dof
Black body with
N_H=2.3 10^21 cm^-2
logL_x=39.74
T=408.8 10^3K (35.2eV)
R_BB=166804.6km
d=6.50kpc
Sept. 2003
Spectrum
Blackbody
χ²_red=4.48 for 3197 dof
Black body with
N_H=2.0 10^21 cm^-2
logL_x=39.57
T=339.2 10^3K (29.2eV)
R_BB=198125.4km
d=6.50kpc
Febr. 2004
Spectrum
Blackbody
χ²_red=1.07 for 3197 dof
ph cm^-2 sec^-1 Å^-1
λ (Å)

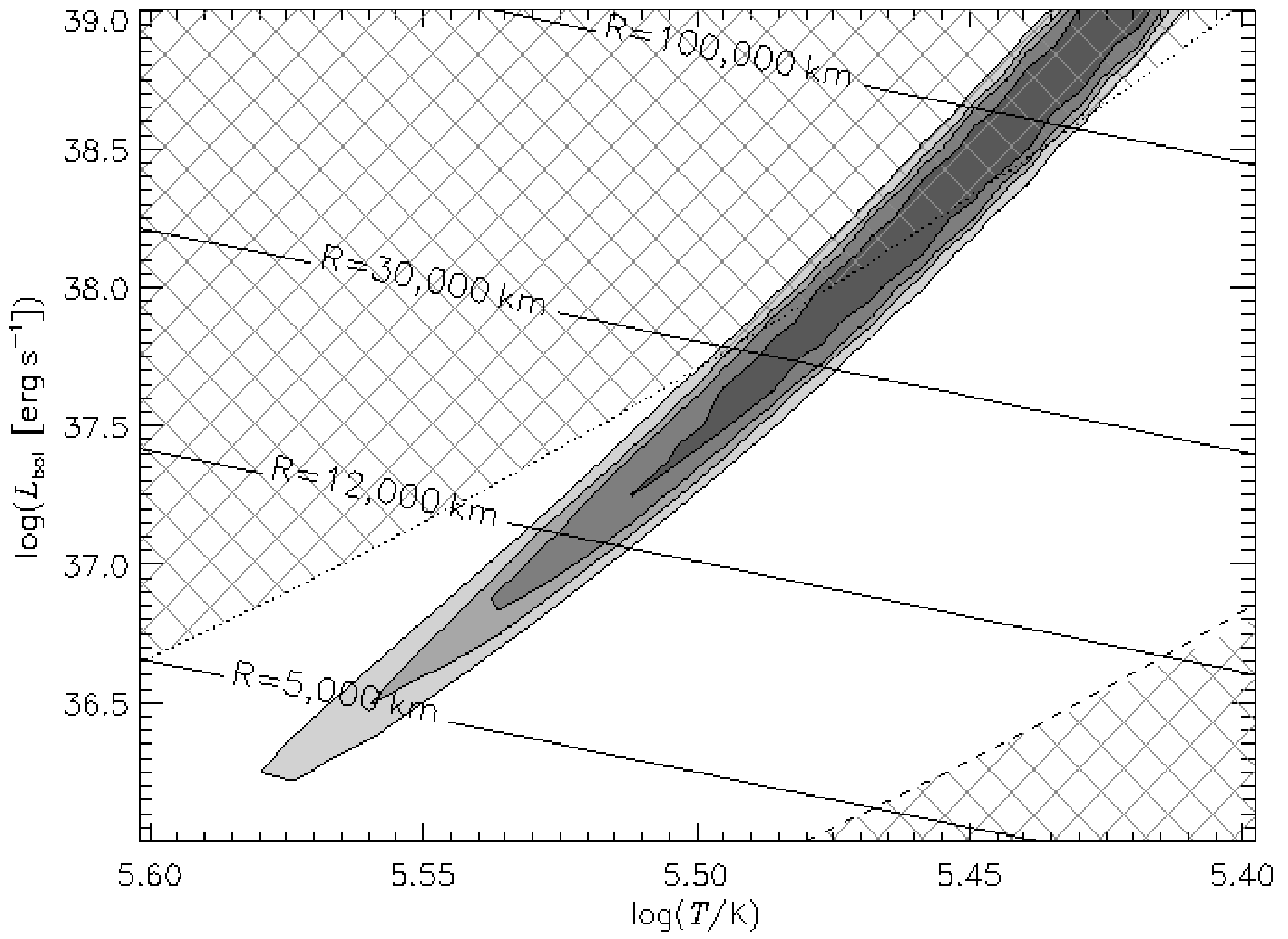

T_{eff} = 5.8 10^5 K, n_h = 4.0 10^{21} cm^{-2}
Dynamic atmosphere
model by
Petz et al. (2005)
Flux [erg cm^{-2} s^{-1} $Å^{-1}$]
10^{-18}
10^{-19}
10^{-20}
20
30
40
50
Wavelength [Å]

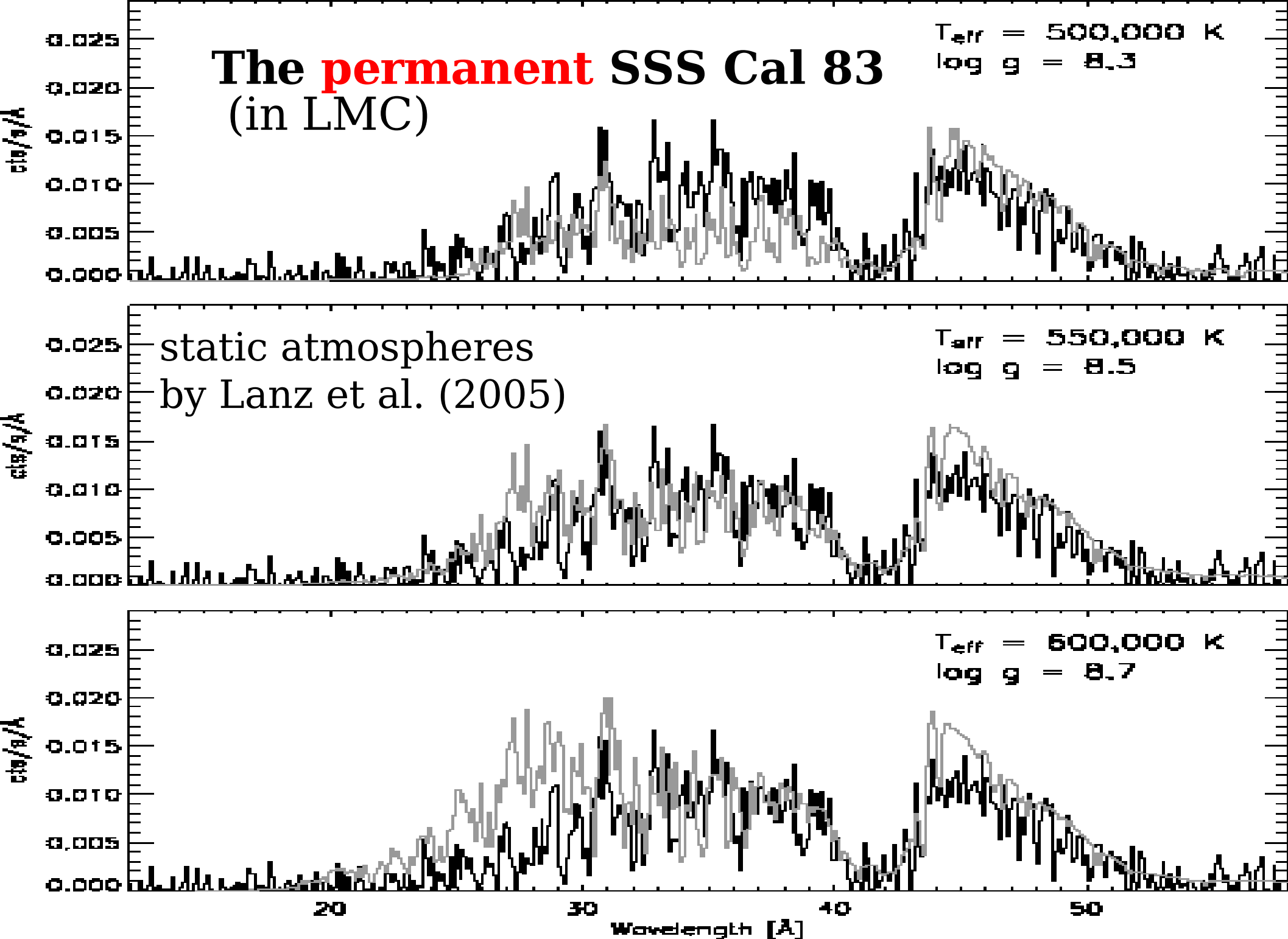

AAVSO light curve of V723 Cas
Swift (days 3810.3 , 3972.0, 4052.4, 4174.0, 4180.8)
cts/ksec
39.70
24.27
14.45
X-rays:
12 years
after outburst!
Ness et al. (2008, AJ 134, 1328)
mag
6
8
10
12
14
16
18
0
1000
2000
3000
4000
day after outburst

Swift observations of V723 Cas (1995)




R=100,000 km
R=30,000 km
R=12,000 km
R=5,000 km
39.0
38.5
38.0
37.5
37.0
36.5
log(L_bol [erg s^-1])
5.60
5.55
5.50
5.45
5.40
log(T/K)


R=100,000 km
R=30,000 km
R=12,000 km
R=5,000 km
39.0
38.5
38.0
37.5
37.0
36.5
log(L_bol [erg s^-1])
5.60
5.55
5.50
5.45
5.40
log(T/K)

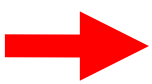

The permanent SSS Cal 83
(in LMC)
T_{eff} = 500,000 K
log g = 8.3
static atmospheres
by Lanz et al. (2005)
T_{eff} = 550,000 K
log g = 8.5
T_{eff} = 600,000 K
log g = 8.7
cts/s/Å
0.025
0.020
0.015
0.010
0.005
0.000
20
30
40
50
Wavelength [Å]

Steady burning in permanent SSS

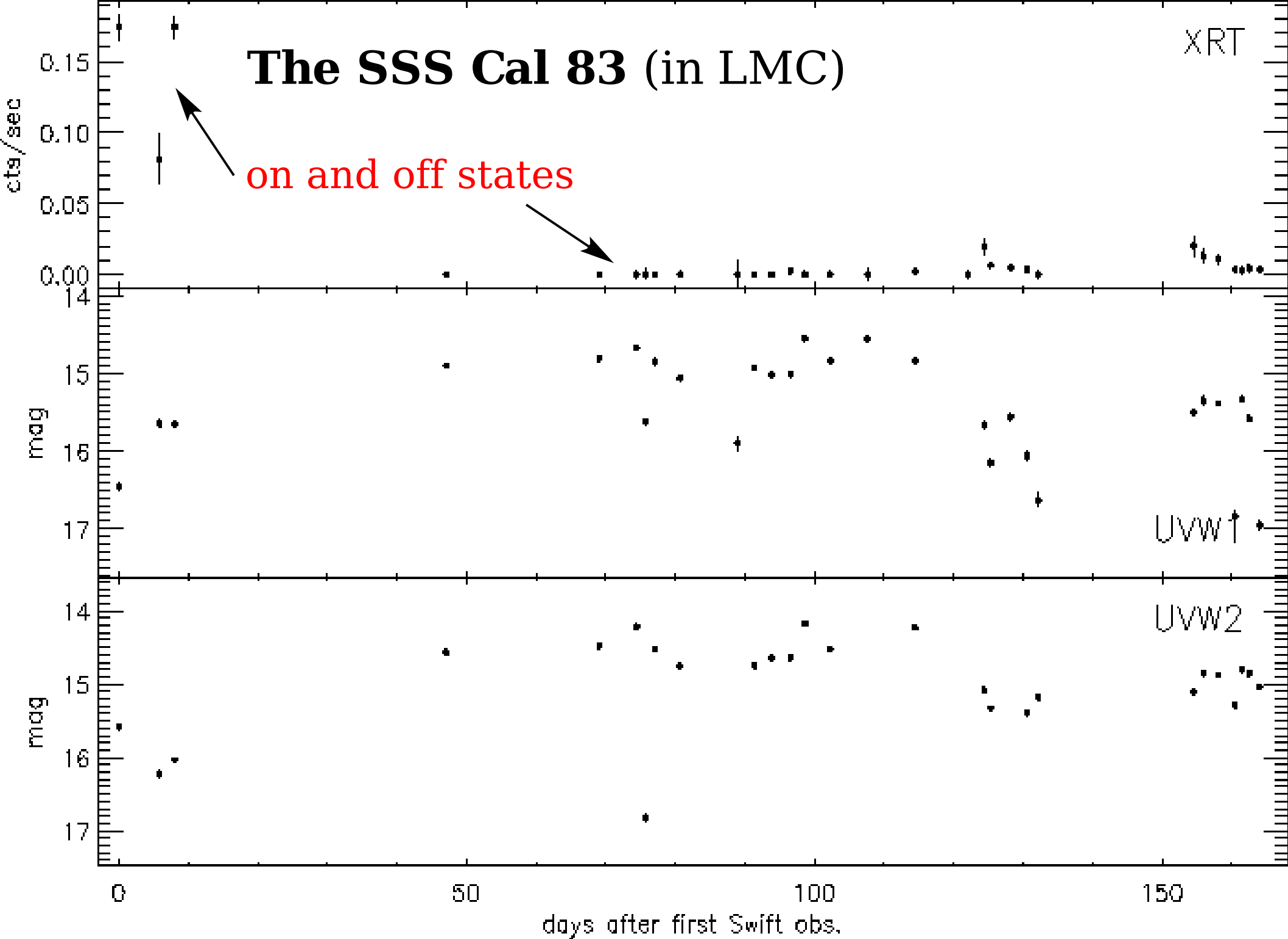
Accreted material is nuclearly processed at the accretion rate

no buildup of hydrogen -> no explosion

-> can go on for ever until Chandrasekhar mass limit is reached



Possible Supernova Ia progenitors


The SSS Cal 83 (in LMC)
on and off states
XRT
UVW1
UVW2
cts/sec
mag
mag
0.15
0.10
0.05
0.00
14
15
16
17
14
15
16
17
0
50
100
150
days after first Swift obs.

Summary

- While the concept of nova evolution is relatively simple, we have witnessed some puzzling behaviours

- The SSS phase is the brightest phase but is most difficult to model

- For novae we need expanding atmosphere models, while static models can explain SSS like Cal83

Concluding remarks

- **In order to understand the various phenomena, systematic X-ray observations have to be taken**

- **Multiwavelength studies are needed to interpret the information of each waveband in a broader context**

- **High-resolution X-ray spectra are the only way to determine abundances**

More will be covered on Friday in session C.2 with

Talks by Orio, Hernanz, Adamczak, Terada, Ishida

Other recent novae:

V5116 Sgr (Sala et al. 2008, poster C.4)

V458 Vul (Poster C.7 by D. Takei et al.)

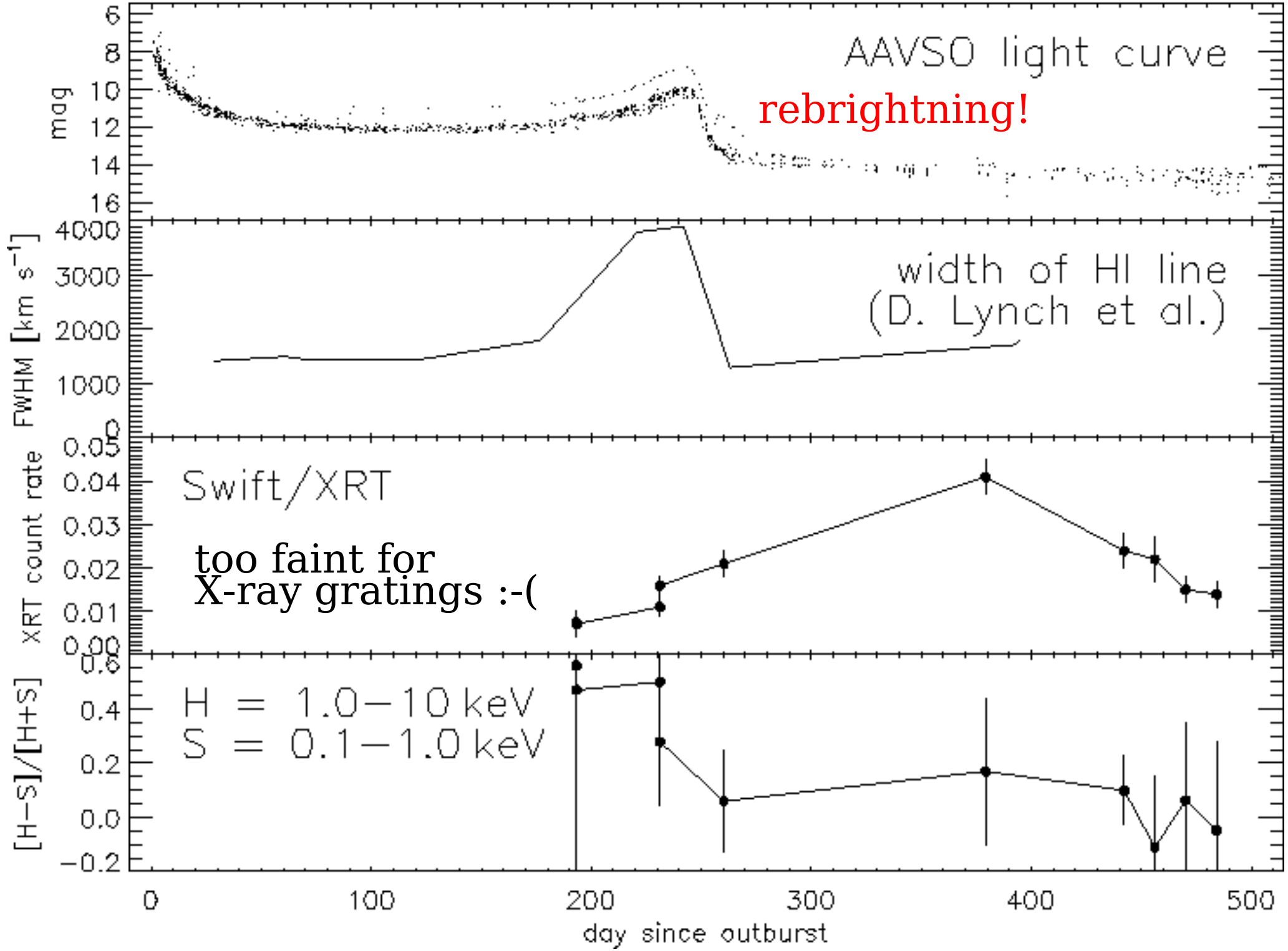
V382 Vel (Orio et al, 2001ab, Ness et al. 2005)

V2362 Cyg (Lynch et al. subm.: Rebrightning!)

V2491 Cyg (brand new XMM observation last week)

Swift is presently obtaining similar light curve as

that for RS Oph and has observed many novae
(see sample by Ness et al. 2007)


AAVSO light curve
rebrightning!
mag
width of HI line
(D. Lynch et al.)
FWHM [km s^{-1}]
Swift/XRT
too faint for
X-ray gratings :-(
XRT count rate
H = 1.0−10 keV
S = 0.1−1.0 keV
[H−S]/[H+S]
day since outburst

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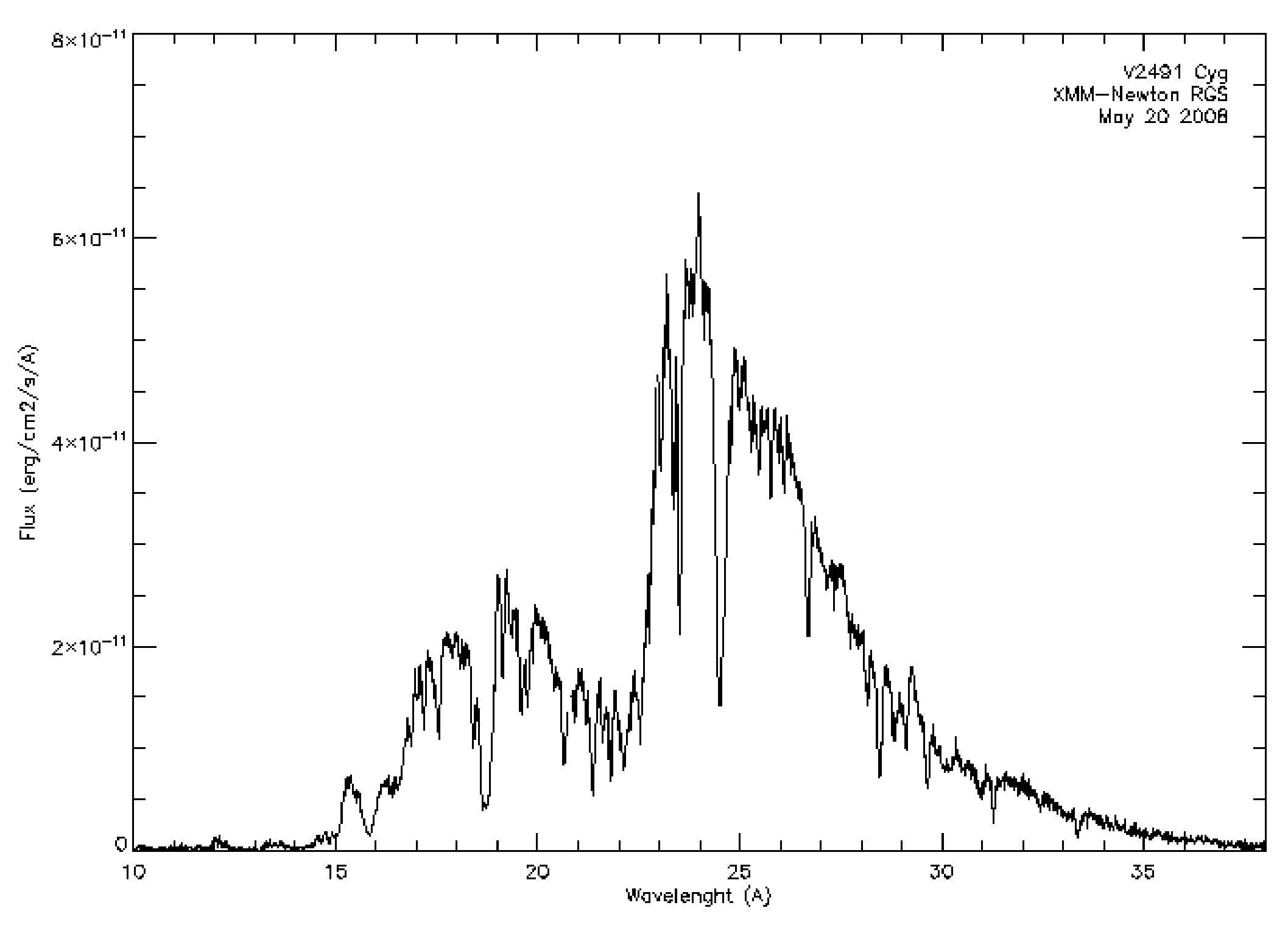
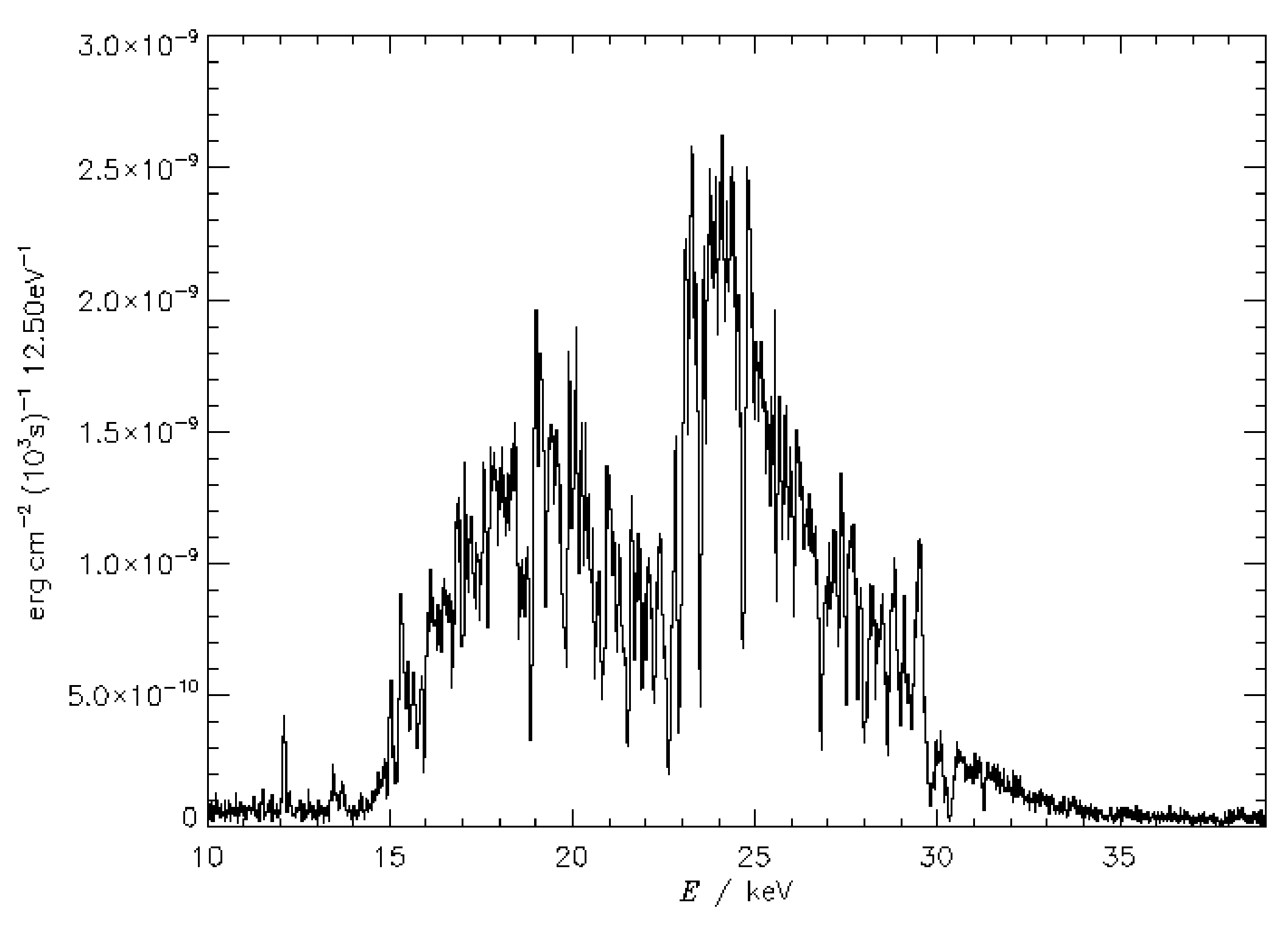
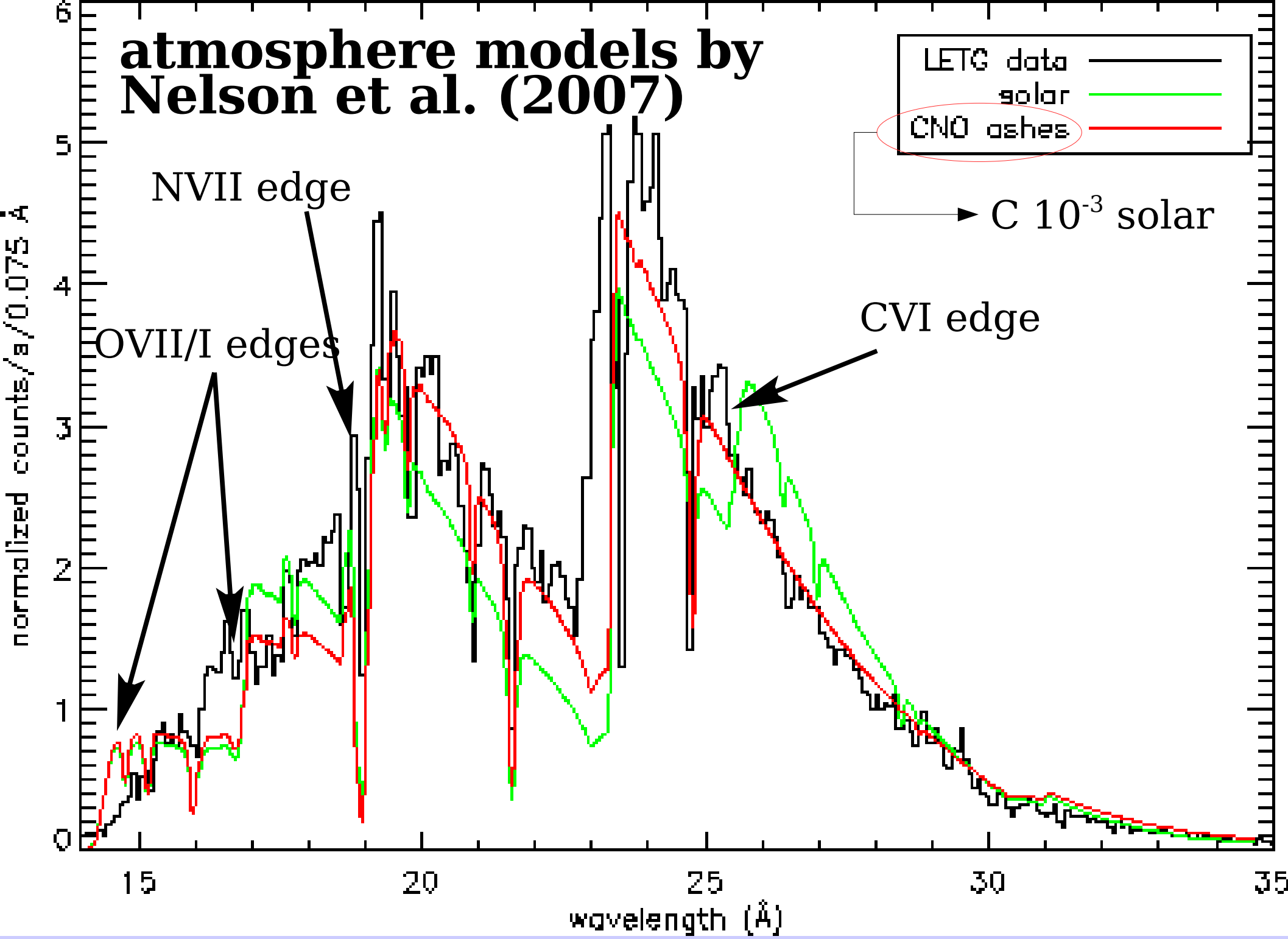
Really bright novae are rare and only three of them were observed with X-ray gratings

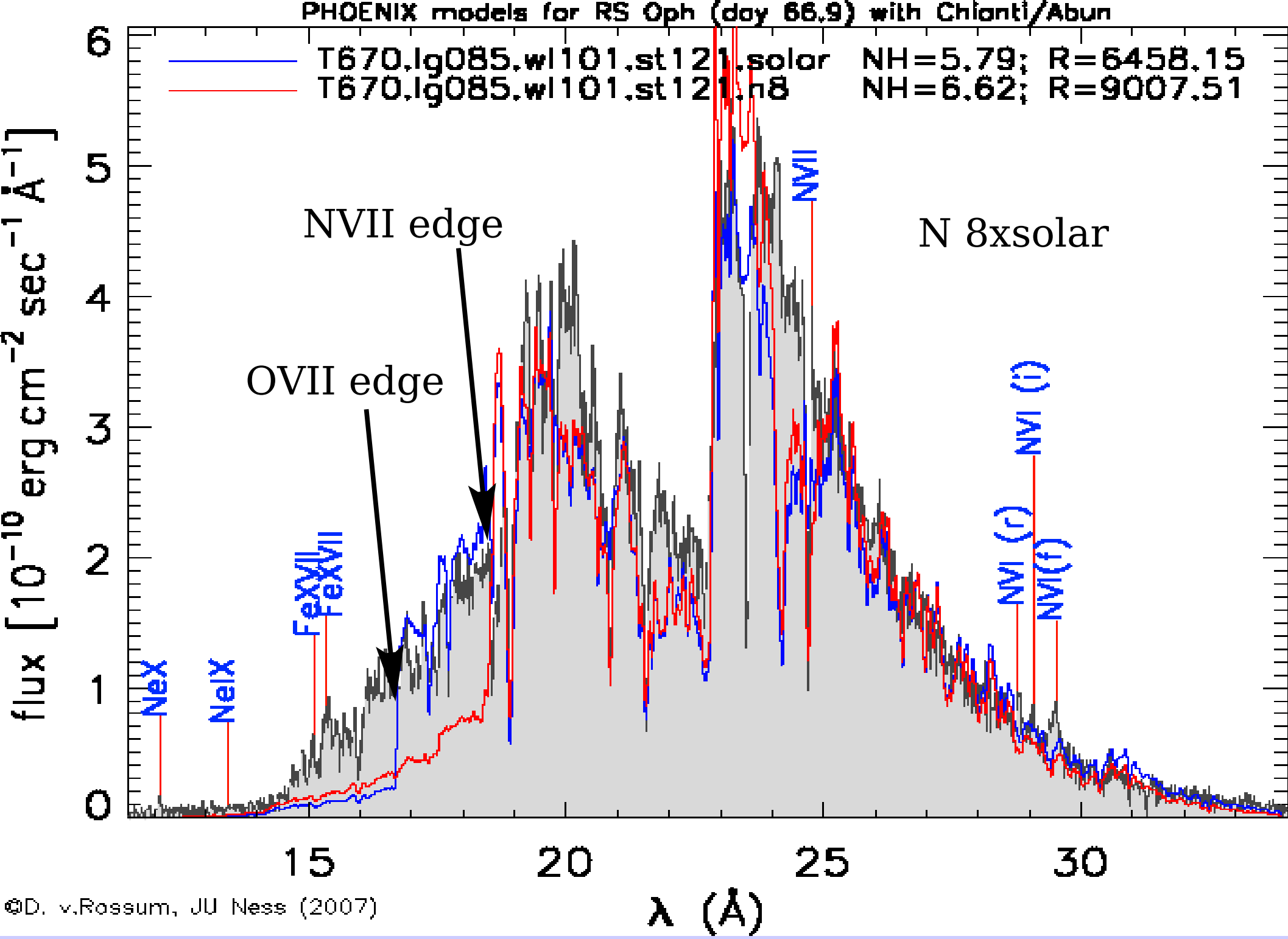
=> Our community is hoping for a long life time of XMM-Newton and Chandra!

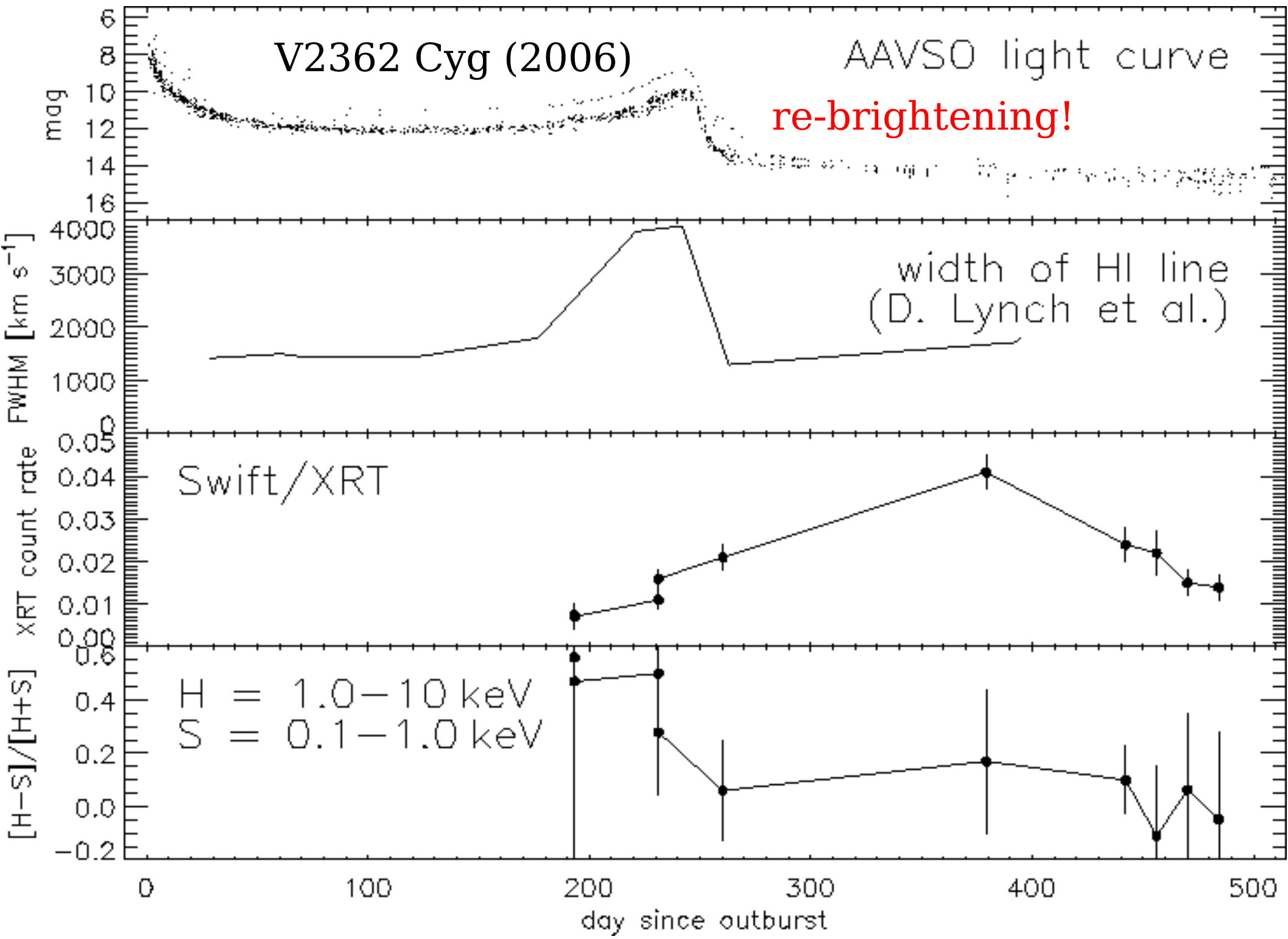
Additional information

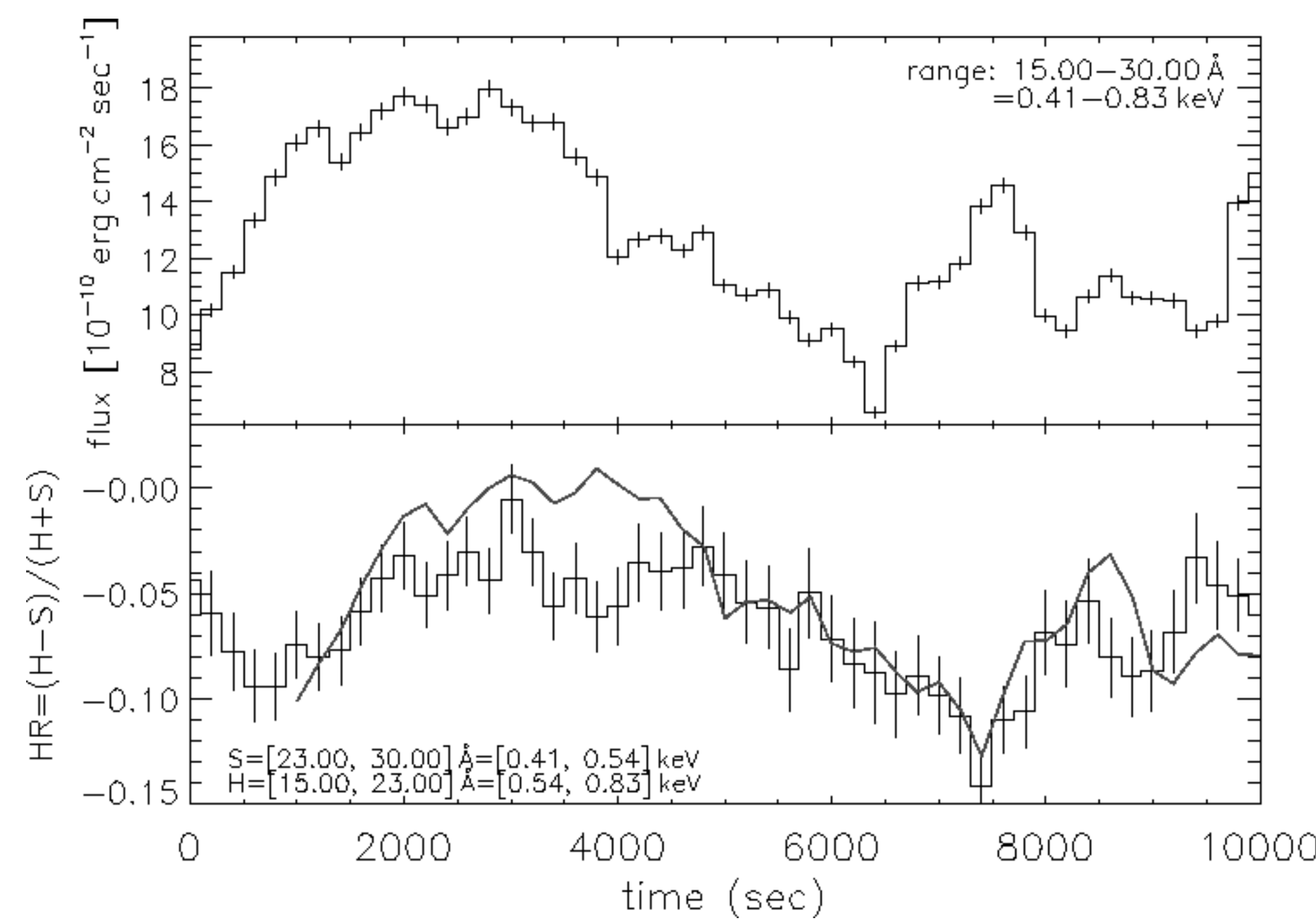

V2491 Cyg
XMM-Newton RGS
May 20 2008
8×10⁻¹¹
6×10⁻¹¹
4×10⁻¹¹
2×10⁻¹¹
0
Flux (erg/cm2/s/A)
10
15
20
25
30
35
Wavelenght (A)


3.0×10⁻⁹
2.5×10⁻⁹
2.0×10⁻⁹
1.5×10⁻⁹
1.0×10⁻⁹
5.0×10⁻¹⁰
0
erg cm⁻² (10³s)⁻¹ 12.50eV⁻¹
10
15
20
25
30
35
E / keV

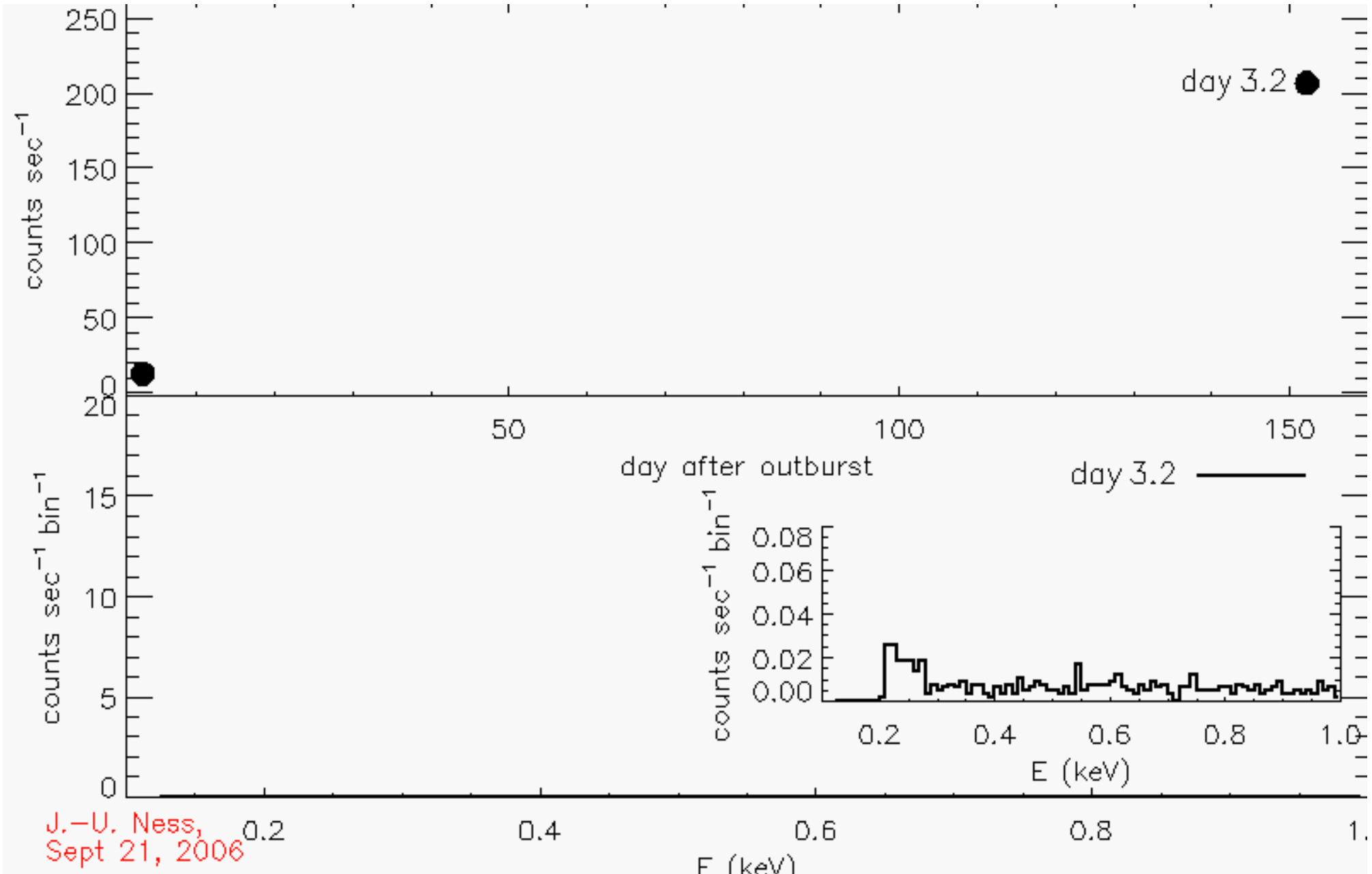

atmosphere models by
Nelson et al. (2007)
LETG data
solar
CNO ashes
C 10-3 solar
NVII edge
OVII/I edges
CVI edge
normalized counts/a/0.075 A
wavelength (A)
0
1
2
3
4
5
6
15
20
25
30
35


PHOENIX models for RS Oph (day 66.9) with Chianti/Abun
T670.lg085.wl101.st121.solor NH=5.79; R=6458.15
T670.lg085.wl101.st121.n8 NH=6.62; R=9007.51
NVII edge
OVII edge
N 8xsolar
NeX
NeIX
FeXVII
FeXVII
NVII
NVI (r)
NVI (i)
NVI(f)
flux [10^-10 erg cm^-2 sec^-1 Å^-1]
λ (Å)
©D. v.Rossum, JU Ness (2007)


V2362 Cyg (2006)
AAVSO light curve
re-brightening!
mag
width of HI line
(D. Lynch et al.)
FWHM [km s^{-1}]
Swift/XRT
XRT count rate
H = 1.0−10 keV
S = 0.1−1.0 keV
[H−S]/[H+S]
day since outburst


range: 15.00−30.00 Å
=0.41−0.83 keV
flux [10^{-10} erg cm^{-2} sec^{-1}]
8
10
12
14
16
18
HR=(H−S)/(H+S)
−0.00
−0.05
−0.10
−0.15
S=[23.00, 30.00] Å=[0.41, 0.54] keV
H=[15.00, 23.00] Å=[0.54, 0.83] keV
0
2000
4000
6000
8000
10000
time (sec)

The 6th outburst of the recurrent nova RS Oph in X-rays



Jan-Uwe Ness at ASU Arizona State University