中国科学院国家天文台
NAOC

Accretion in Stellar Systems
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ylqiu@bao.ac.cn

CG X-1

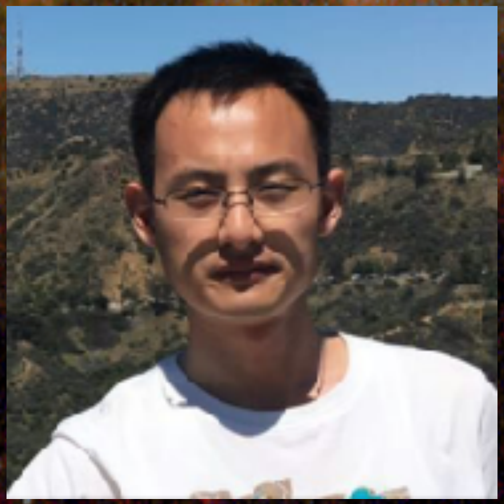
An Eclipsing Wolf-Rayet ULX in the Circinus Galaxy

Yanli Qiu

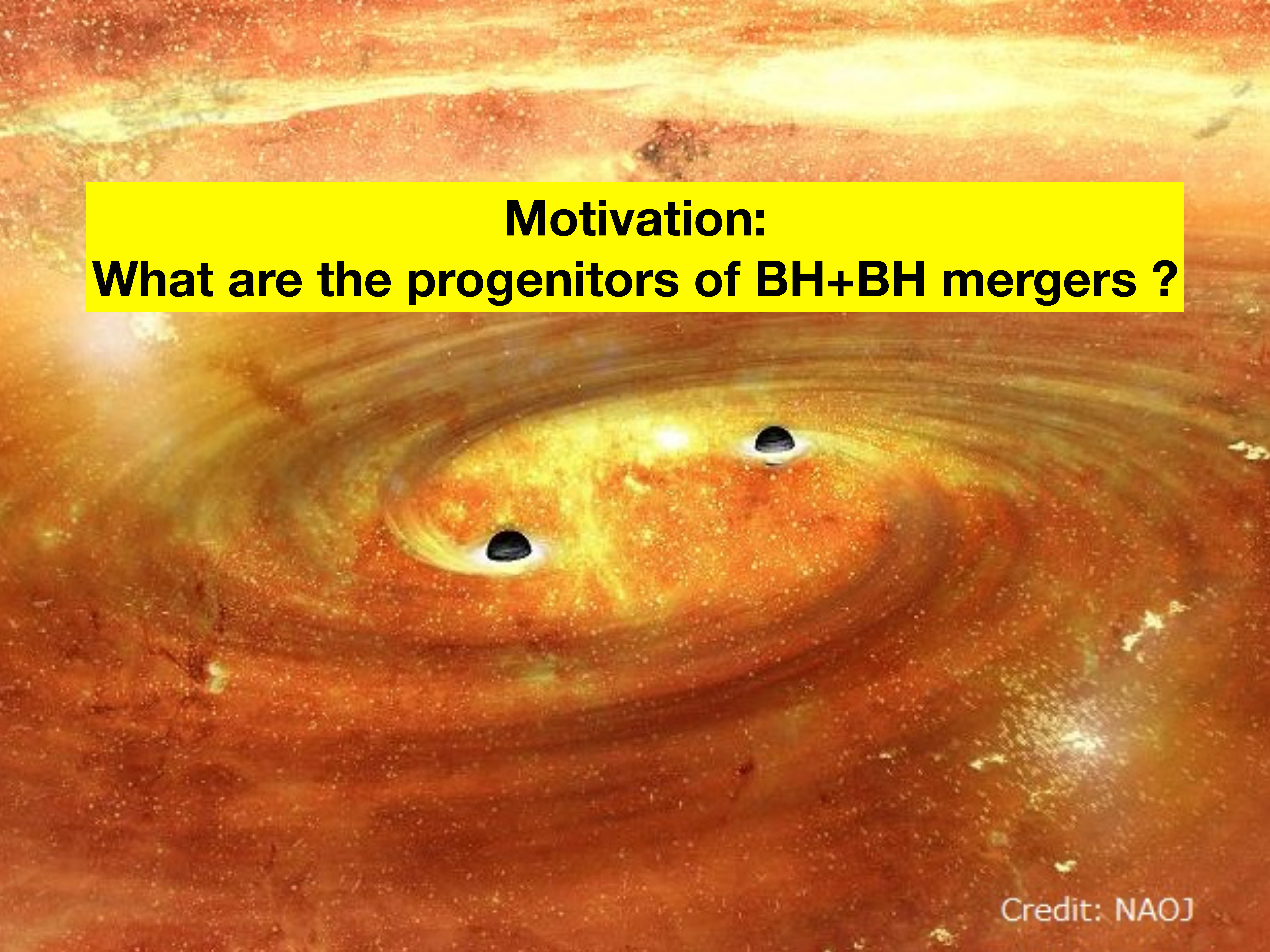
Prof. Roberto Soria

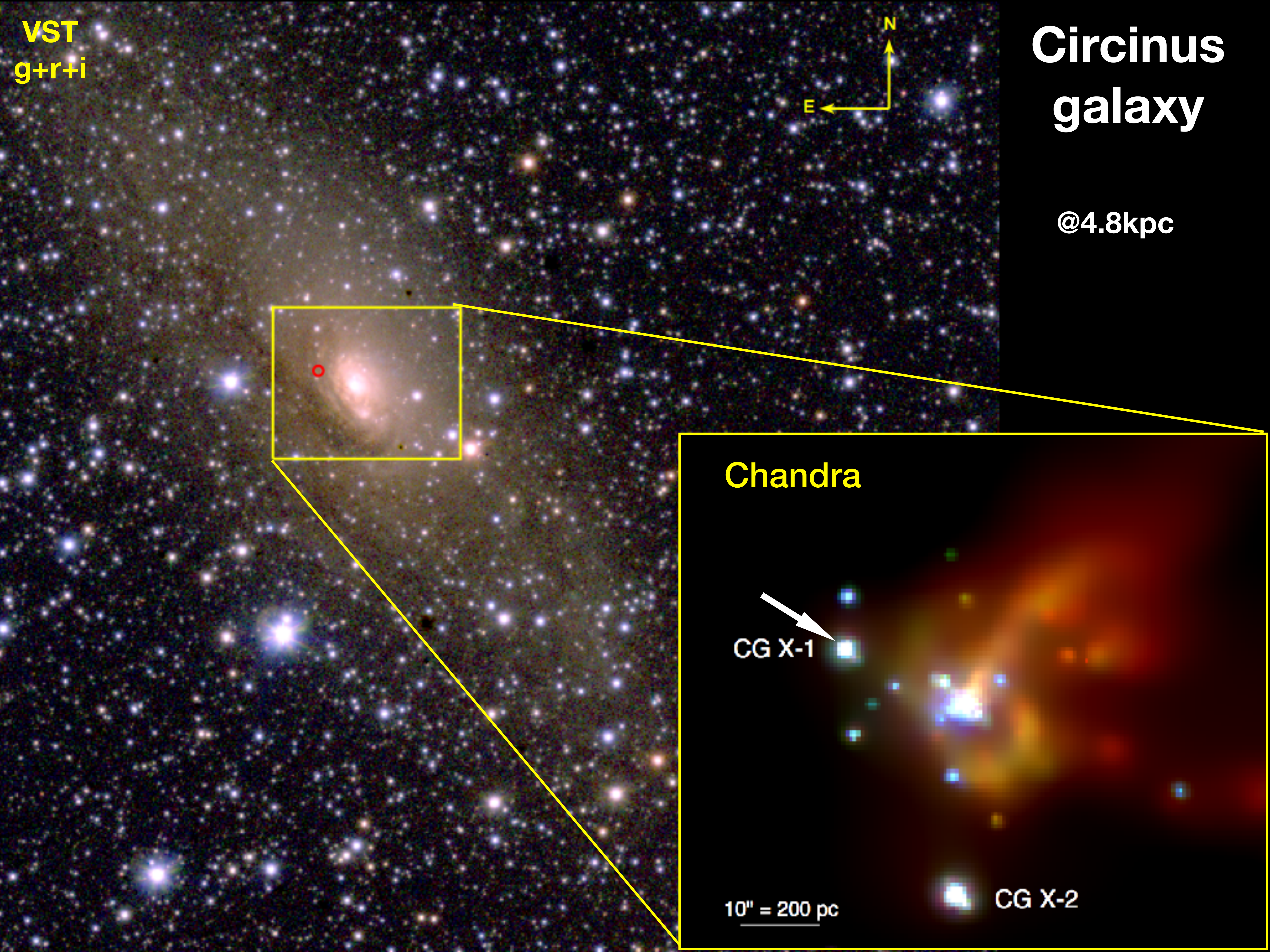
Prof. Jifeng Liu

Dr. Song Wang



Motivation:
What are the progenitors of BH+BH mergers ?



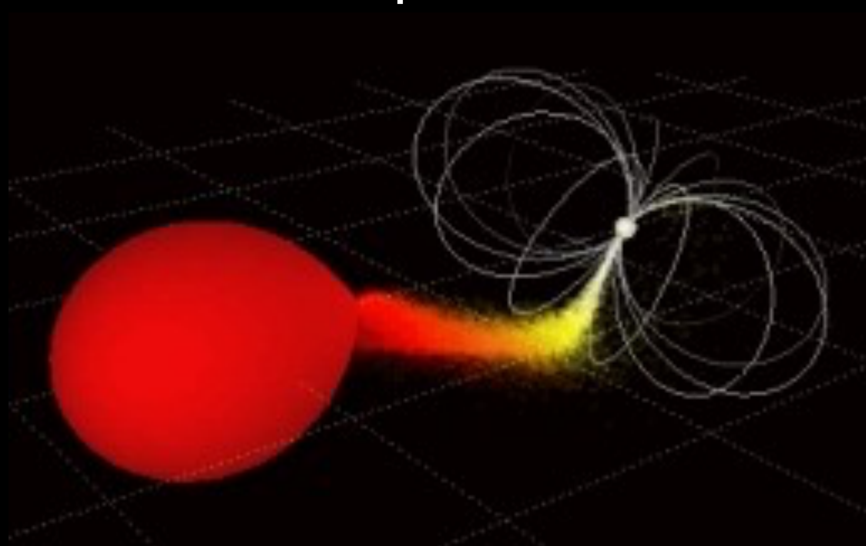

VST
g+r+i
N
E
Circinus
galaxy
@4.8kpc
Chandra
CG X-1
CG X-2
10" = 200 pc

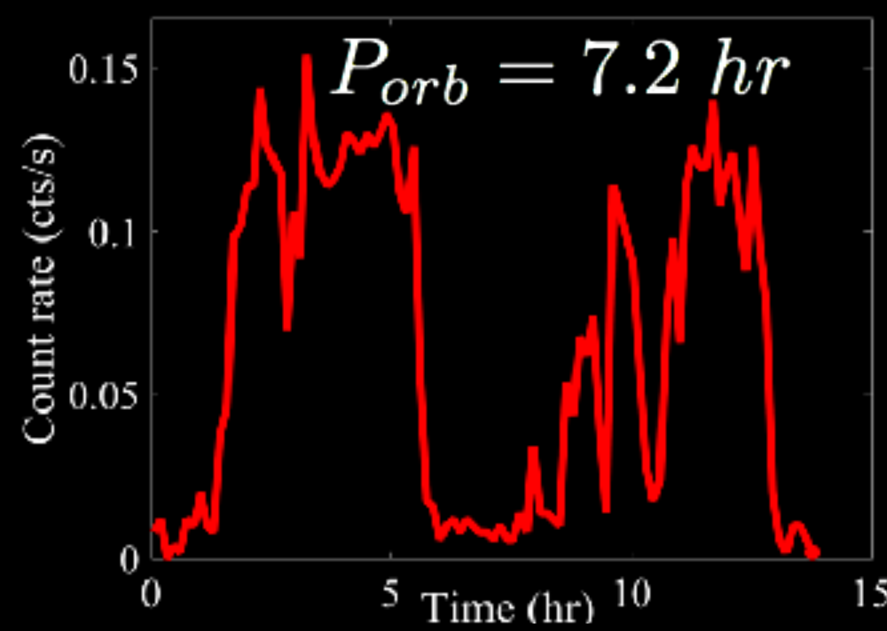
mCV (polar) in Milky Way

or

ULX (WR+BH) in Circinus

Weisskopf et al. 2004





$lon. = 311.33,\ lat. = -3.81$

Esposito et al. 2015

mWD + late type dwarf star

- strong magnetic field
  - B ~ tens of MG
- no accretion disk
- P_spin=P_orb
- Lx<1e32 erg/s
- with Fe lines

- Lx ~ 1e34 erg/s @ 5 kpc
- Lx ~ 2e40 erg/s @ 4.8 Mpc
- No Fe lines

Our goal:

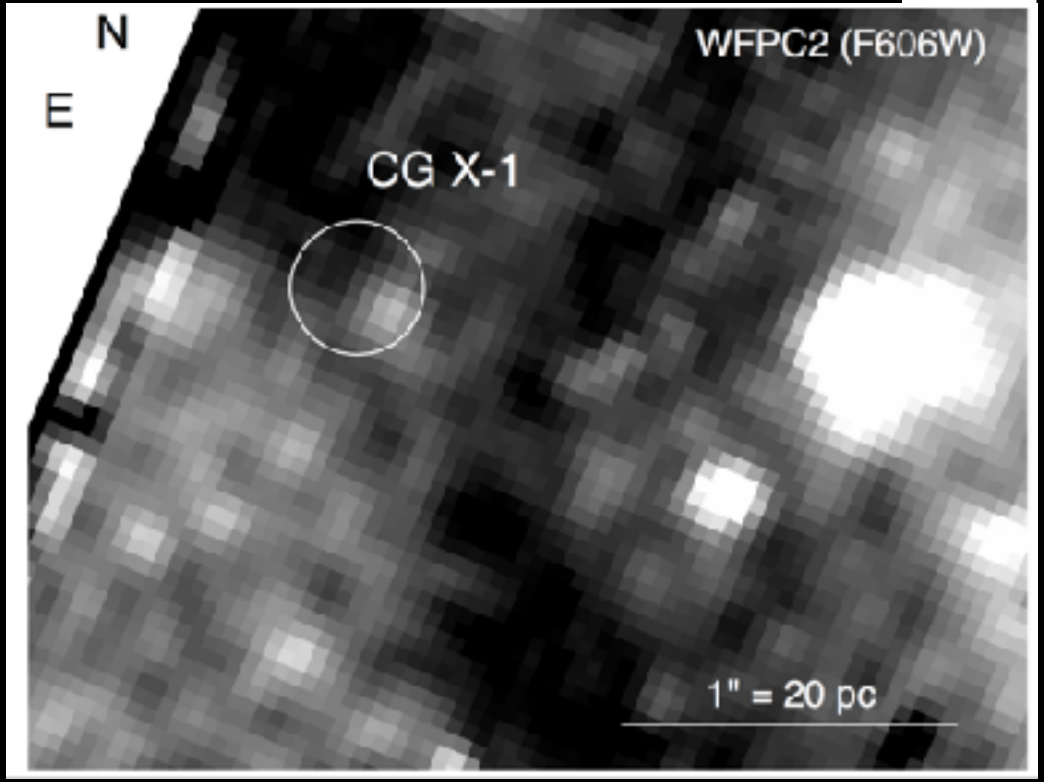
1. **Galactic CV or BH ULX?**
2. **Any reasonable explanations for observational features?**

Rule out a WD binary

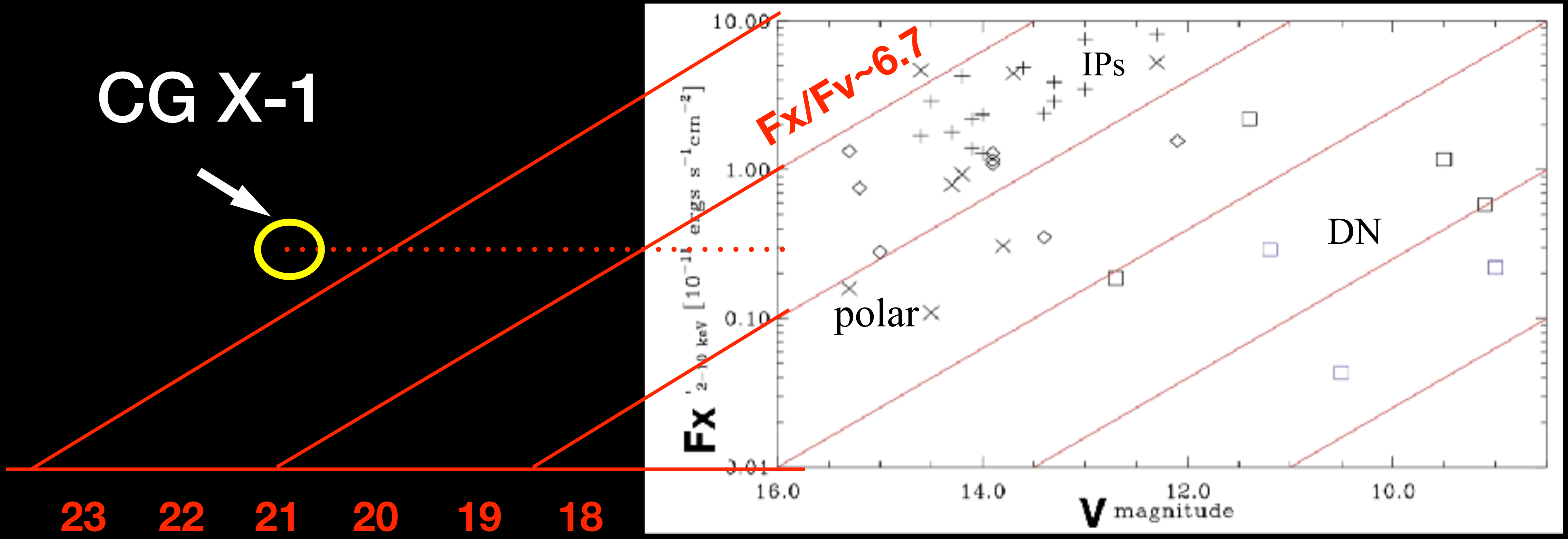
mv ~ 24.3 mag
Av ~ 3+/-1 mag
Mv ~ -7 mag @ 4.2 Mpc
Mv ~ 7.8 mag @ 5 kpc
Fx (2-10 keV) = 1.93e-12 erg/s/cm^2
Fv ~ 1.49e-14 erg/s/cm^2

high Fx/Fv ~ 130 !!!

HST

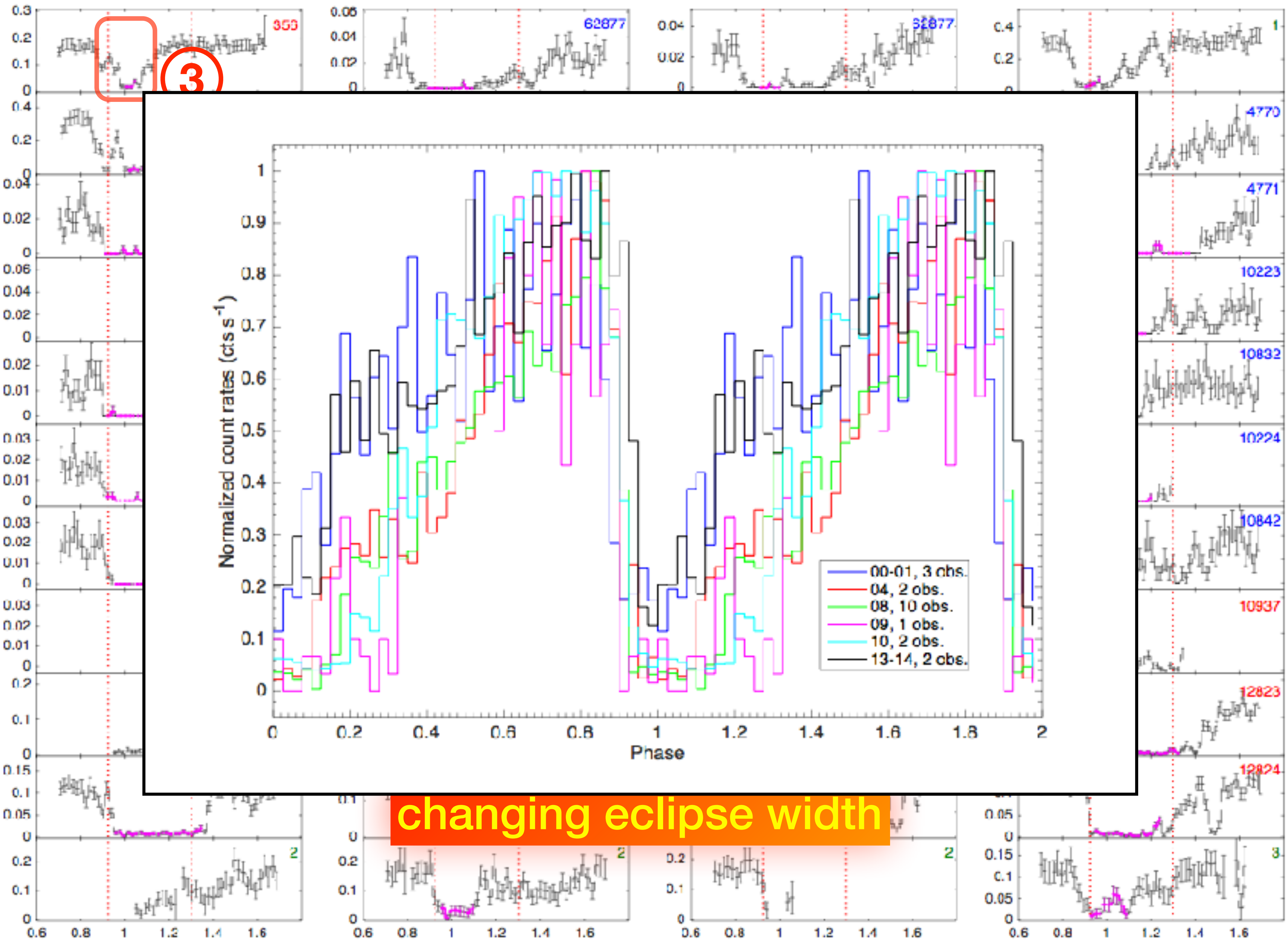


CG X-1



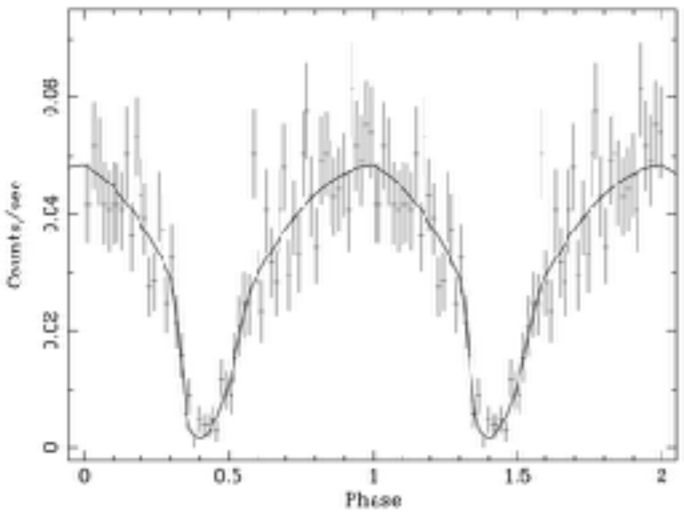
Mukai 2017

light curves over 20 years



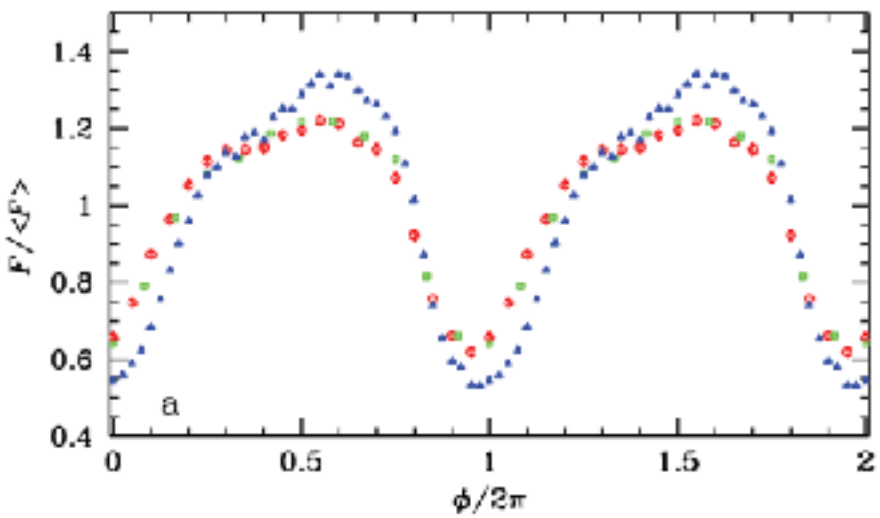
Close WR + BH/NS

NGC 4214 X-1
P=3.6 hr



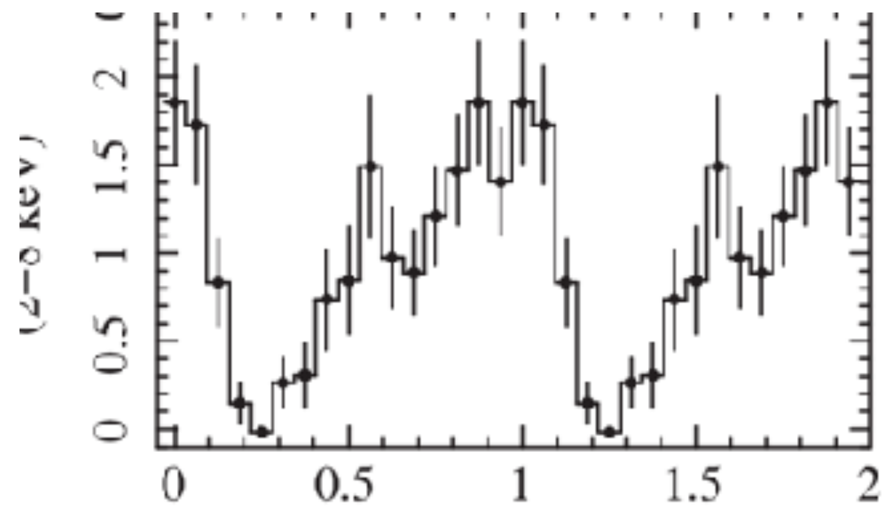
Ghosh et al. 2006

Cyg X-3
P=4.8 hr



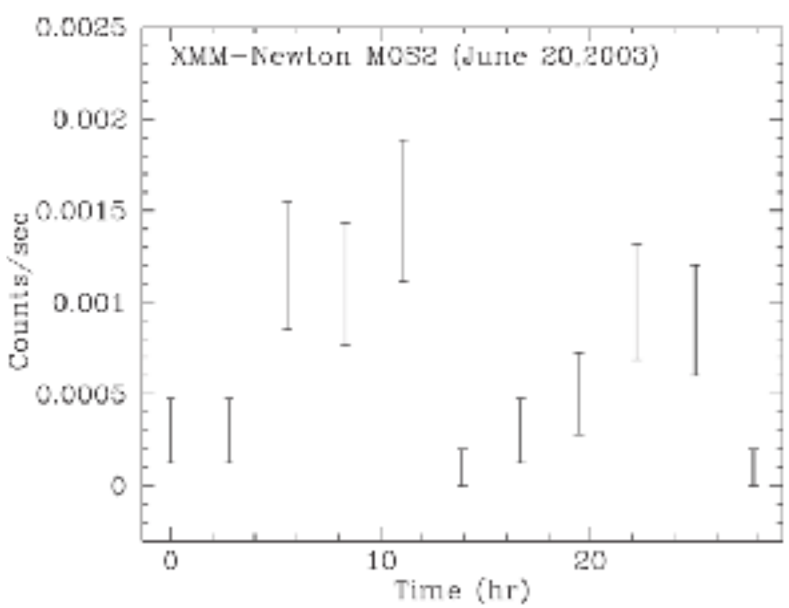
Zdziarski et al. 2012

NGC 4490 J123030.3
P=6.4 hr



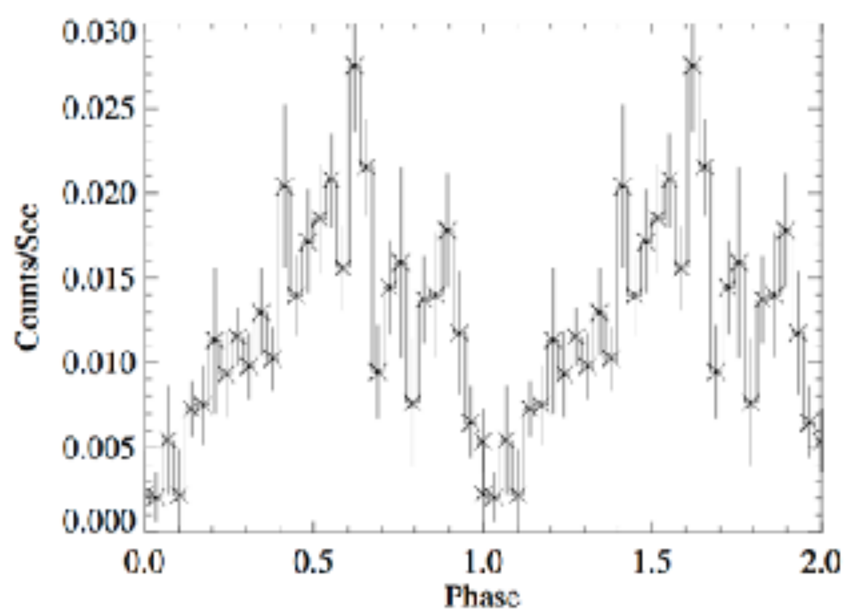
Esposito et al. (2013)

NGC 253 X-1
P=14.5 hr



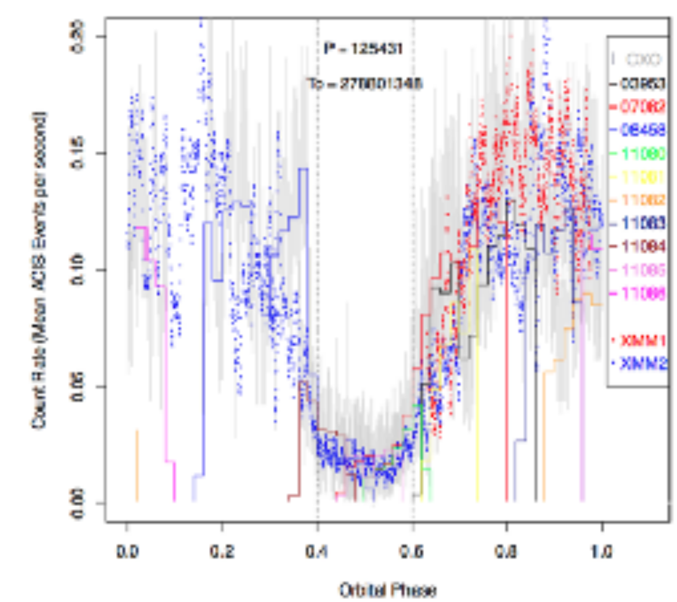
Maccarone et al. 2014

NGC 300 X-1
P=32.8 hr



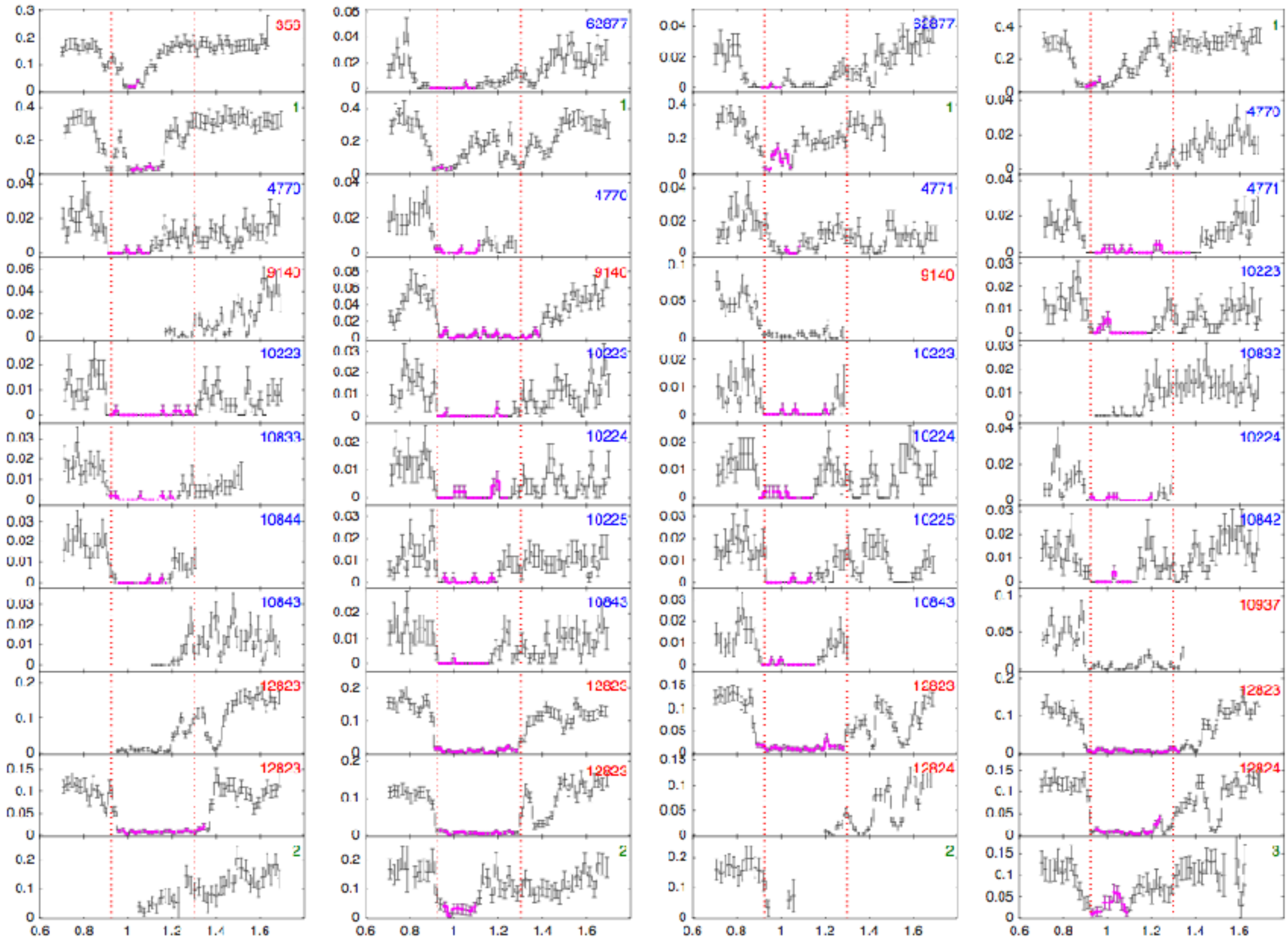
Carpano et al. 2007

IC 10 X-1
P=34.8 hr

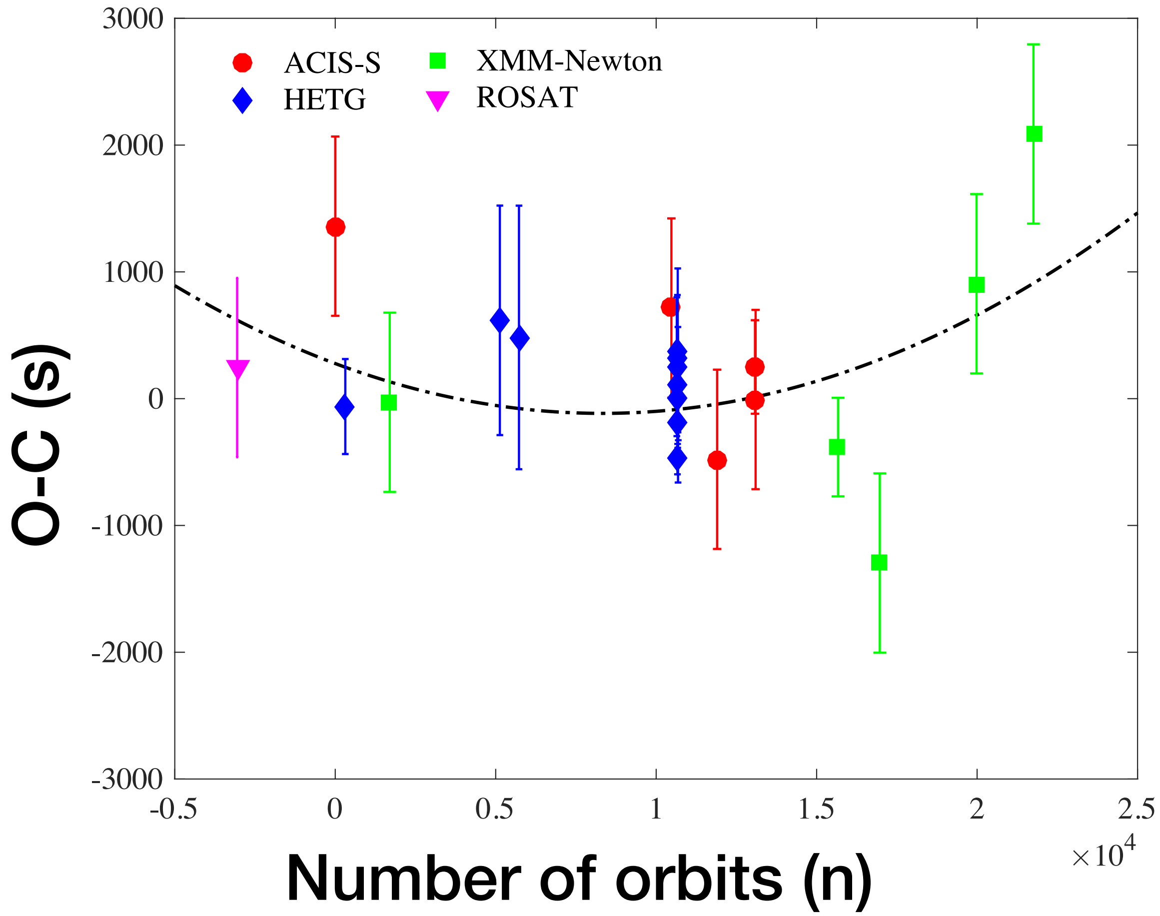


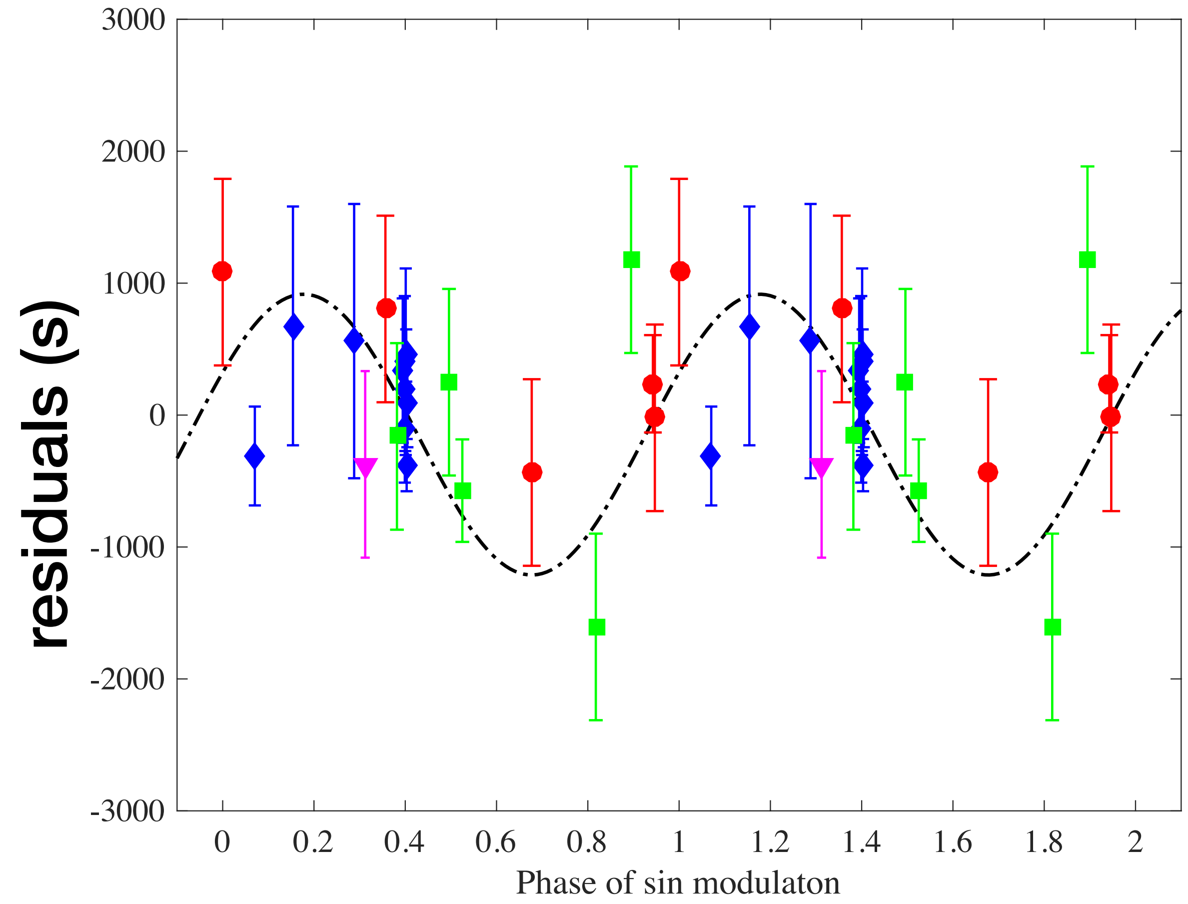
Laycock et al. 2015

light curves over 20 years



Orbital ephemeris





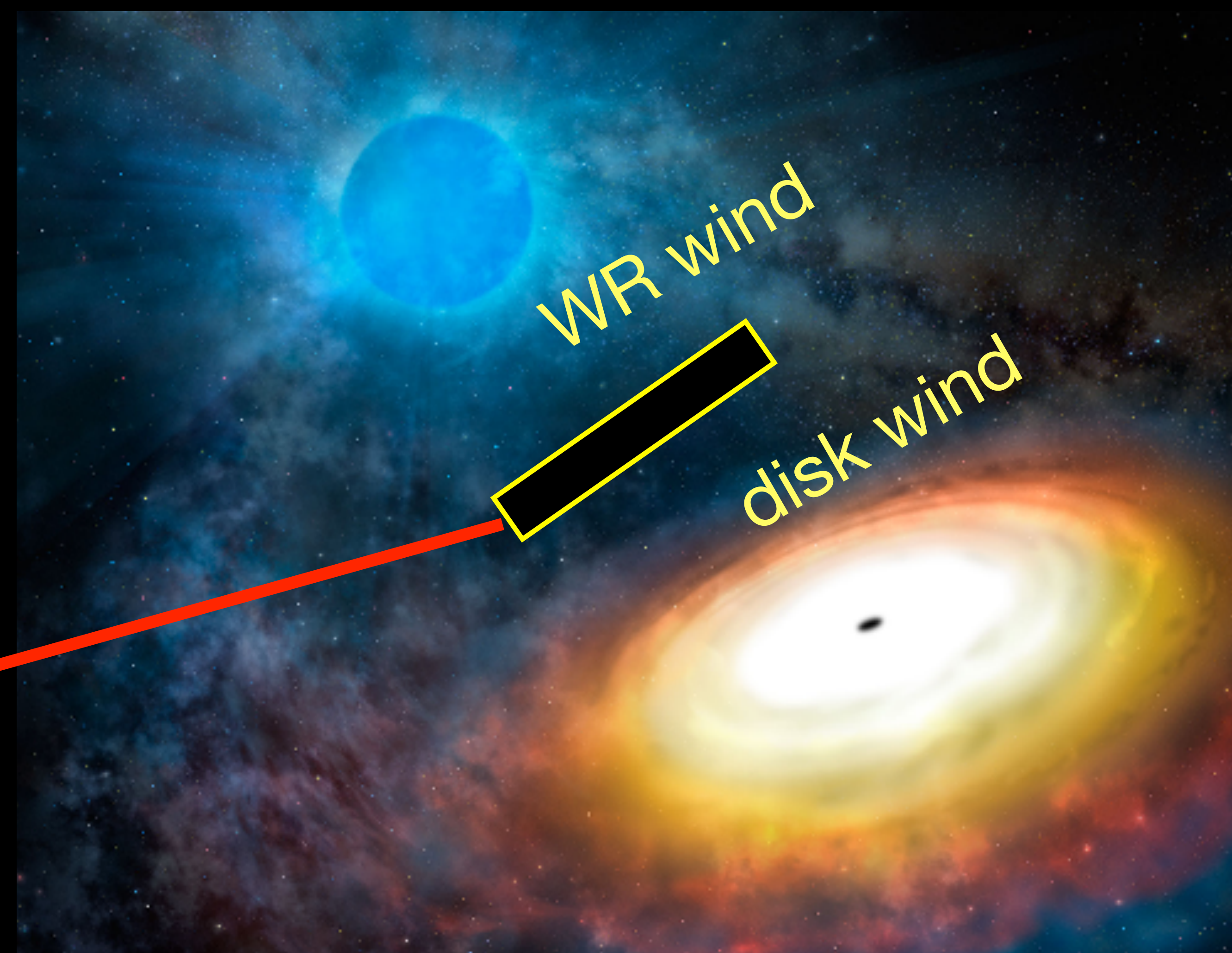
Porb = 7.2 hr

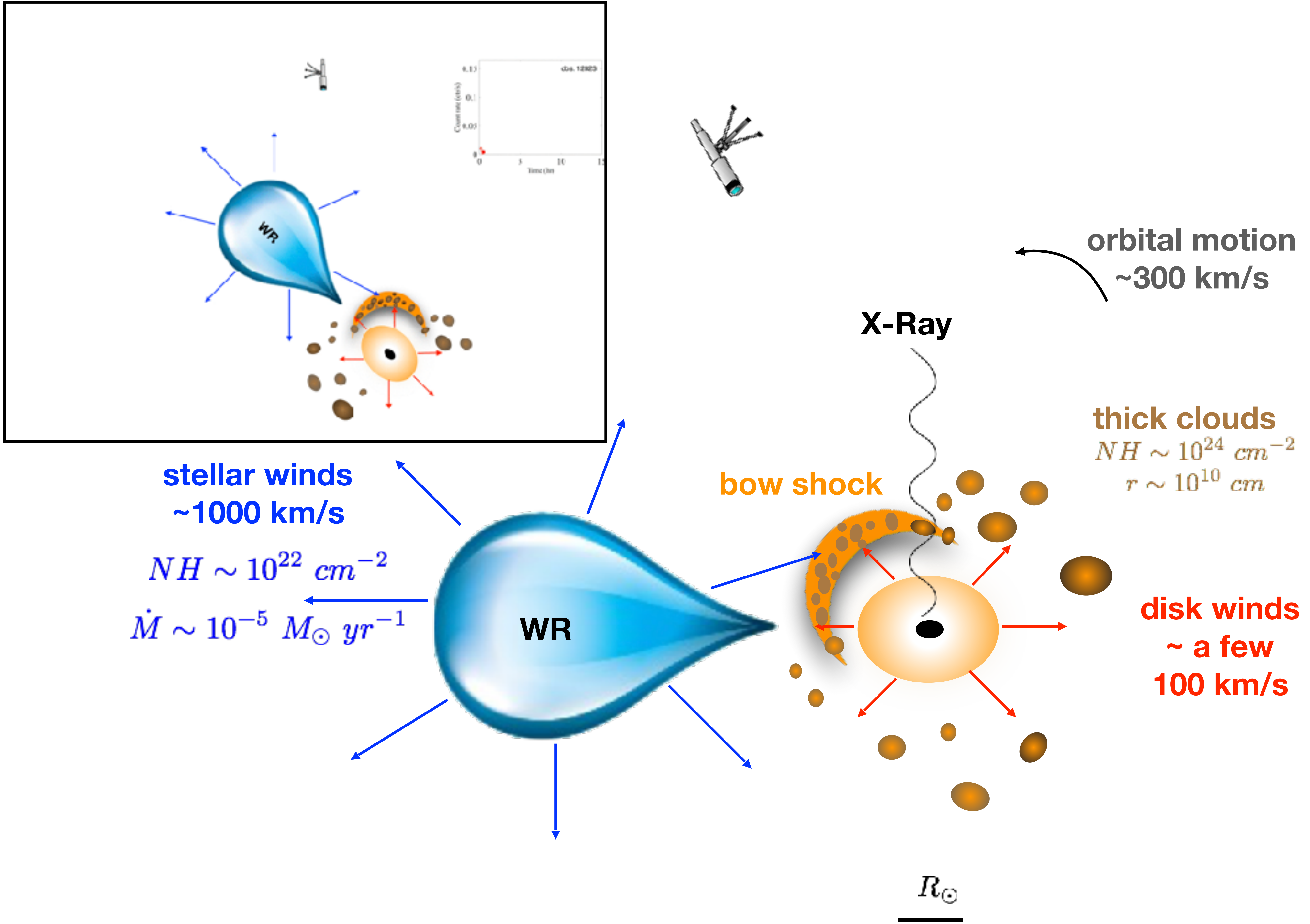
folded by 3.67 yr

- caused by light-travel time effect ?
- indicating a third body with ~ 10 solar mass ?

WR+BH

bow shock





WR
orbital motion
~300 km/s
X-Ray
thick clouds
$NH \sim 10^{24}\ cm^{-2}$
$r \sim 10^{10}\ cm$
bow shock
stellar winds
~1000 km/s
$NH \sim 10^{22}\ cm^{-2}$
$\dot{M} \sim 10^{-5}\ M_{\odot}\ yr^{-1}$
WR
disk winds
~ a few
100 km/s
$R_{\odot}$

Chandra spectra:
eclipse + egress + bright

dominate in faint phase
Lx ~ 1e38 erg/s

tbabs * mekal

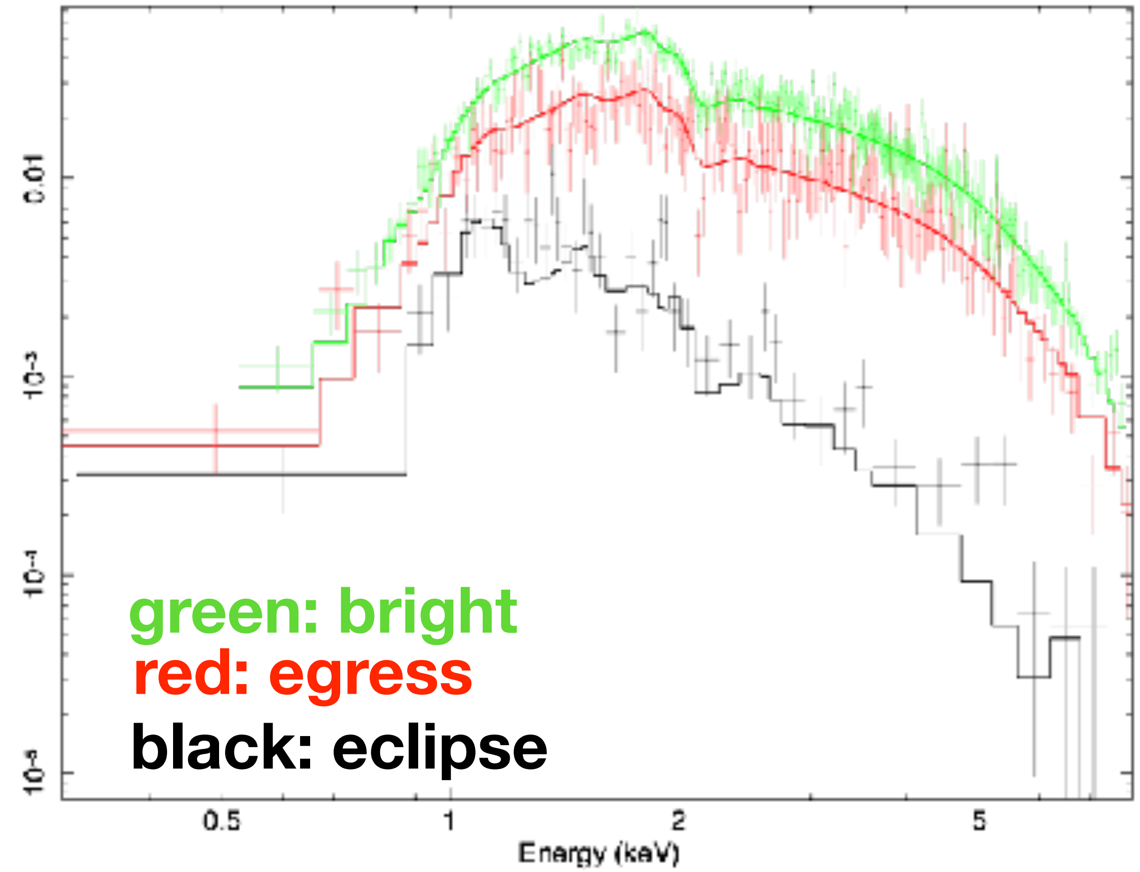
scattering emission by corona

+

dominate in bright phase
Lx ~ 2e40 erg/s

partially covering by clouds

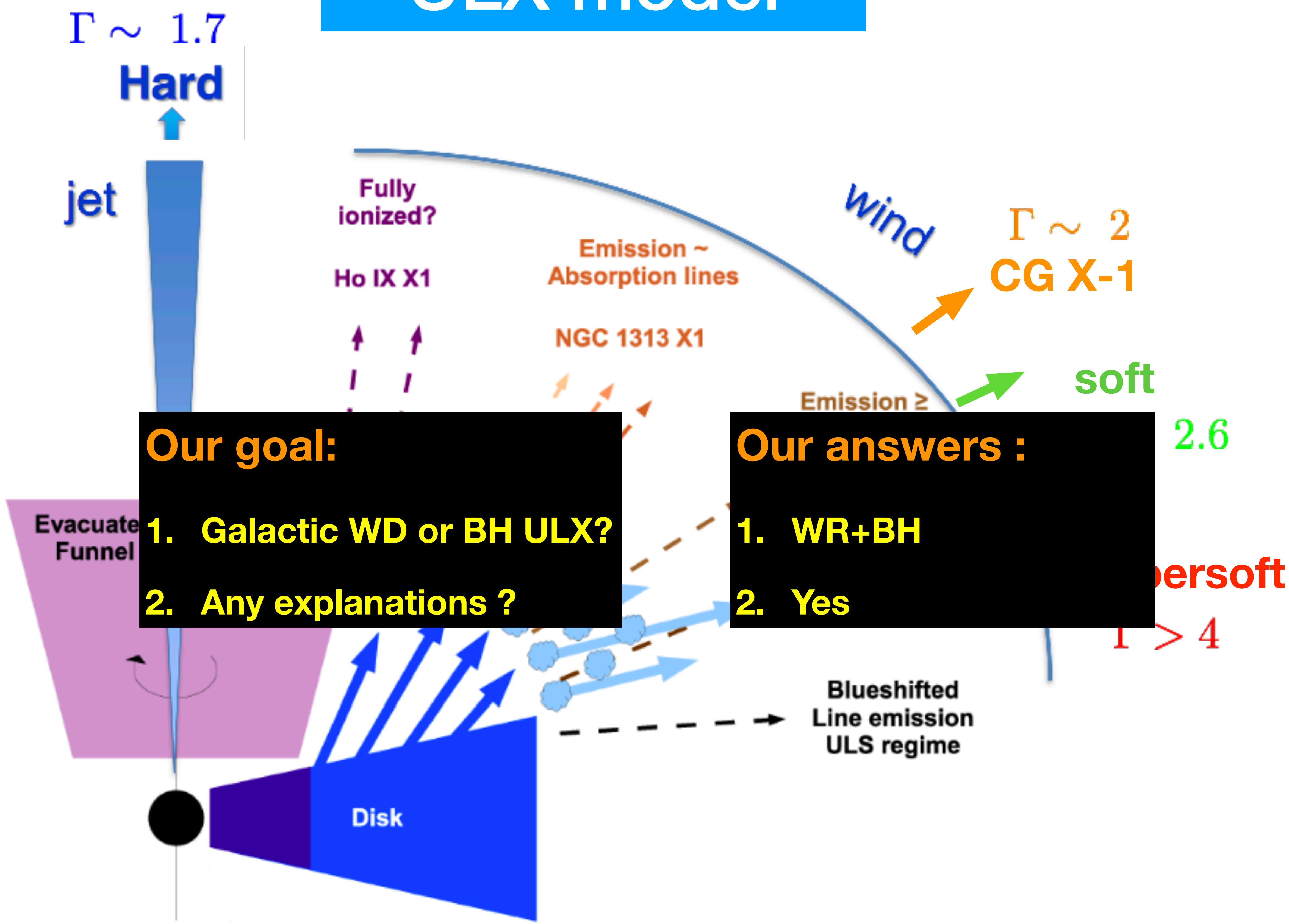
acis12823



tbabs * absori * tbabs * pcfabs * po

- **X-ray emission is partially covered by clouds during egress phase.**
- Covering fraction is set to 0 during the bright phase, and 1 during eclipse.
- Adding “absori” can improve the fitting which is a simple power-law.

ULX model



Our goal:

1. **Galactic WD or BH ULX?**
2. **Any explanations ?**

Our answers :

1. **WR+BH**
2. **Yes**

adapted from Pinto et al. 2017 & Soria

WR+BH formation rate or BH+BH merging rate

- So far, 4 - 6 WR+BH has been found with in 6 Mpc, the typical life time of WR stage is 1-4 e5 yr, so the WR + BH birth rate is:

$$R_{birth} \sim 100 \frac{(4-6)\ in\ 6\ Mpc}{(1-4) \times 10^5\ yr} \sim 100\ Gpc^{-3} yr^{-1}$$

- The LIGO events give the BH+BH merging rate:

$$R_{merge} \sim 100\ Gpc^{-3} yr^{-1}$$

- Thus, the WR+BH rate is highly consistent with the BH+BH merging rate.

Take-home message

- CG X-1, a rare WR+BH ULX binary, is the most promising progenitor of BH+BH mergers.
- CG X-1 can constrain the model of evolution of massive close binaries.

Thank you !

Backup slides

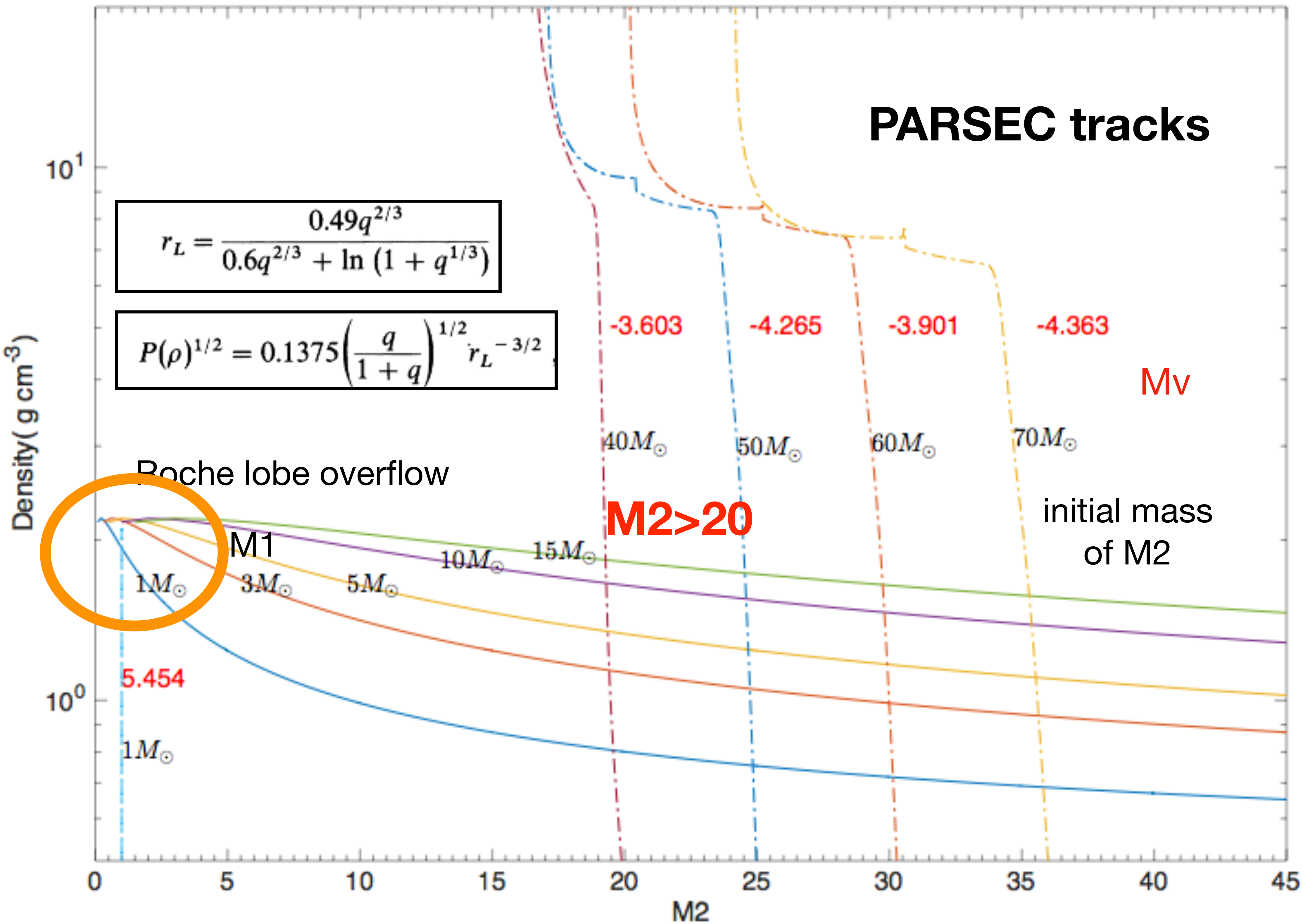
24+5+2 observations

Table 1. X-ray observations.

Obsid	Instrument	Start date	Exp. T (ks)	off-axis angle (acrmin)	counts
rh702058a02	ROSAT-HRI	1997-03-03 21:50:52	26.38	0.30	75
rh702058a03	ROSAT-HRI	1997-08-17 10:44:29	45.89	0.30	169
355	ACIS-S	2000-01-16 10:18:17	1.32	1.56	43
365*	ACIS-S	2000-03-14 06:01:26	4.97	1.09	1639
356	ACIS-S	2000-03-14 07:46:18	24.72	1.09	3579
374	HETG	2000-06-15 22:01:09	7.12	1.06	85
62877	HETG	2000-06-16 00:38:28	60.22	1.06	923
2454*	ACIS-S	2001-05-02 16:02:48	4.40	0.73	301
0111240101*	MOS+PN	2001-08-06 08:54:51	109.85	0.27	15791
4770	HETG	2004-06-02 12:40:42	55.03	1.32	591
4771	HETG	2004-11-28 18:26:32	58.97	1.11	603
9140	ACIS-S	2008-10-26 10:24:46	48.76	4.28	1176
10226	HETG	2008-12-08 17:57:06	19.67	1.35	201
10223	HETG	2008-12-15 15:46:15	102.93	1.34	642
10832	HETG	2008-12-19 18:15:08	20.61	1.34	187
10833	HETG	2008-12-22 07:29:35	28.36	1.34	211
10224	HETG	2008-12-23 11:25:12	77.10	1.33	483
10844	HETG	2008-12-24 23:17:37	27.17	1.33	290
10225	HETG	2008-12-26 04:02:06	67.89	1.33	651
10842	HETG	2008-12-27 12:03:26	36.74	1.33	332
10843	HETG	2008-12-29 10:10:49	57.01	1.32	448
10873	HETG	2009-03-01 23:28:35	18.10	1.12	151
10850	HETG	2009-03-03 00:43:18	13.85	1.12	77
10872	HETG	2009-03-04 15:29:52	16.53	1.12	83
10937*	ACIS-S	2009-12-28 21:10:27	18.31	2.96	464
12823*	ACIS-S	2010-12-17 18:10:27	152.36	1.52	10464
12824*	ACIS-S	2010-12-24 03:38:54	38.89	1.52	2368
0701981001*	MOS+PN	2013-02-03 07:24:11	58.91	4.80	3177
0656580601*	MOS+PN	2014-03-01 09:55:41	45.90	0.27	1833
0792382701*	MOS+PN	2016-08-23 16:53:33	37.00	4.70	5939
0780950201	MOS+PN	2018-02-07 12:11:49	44.36	4.70	4302

Observations with asterisks are used to extract spectra.

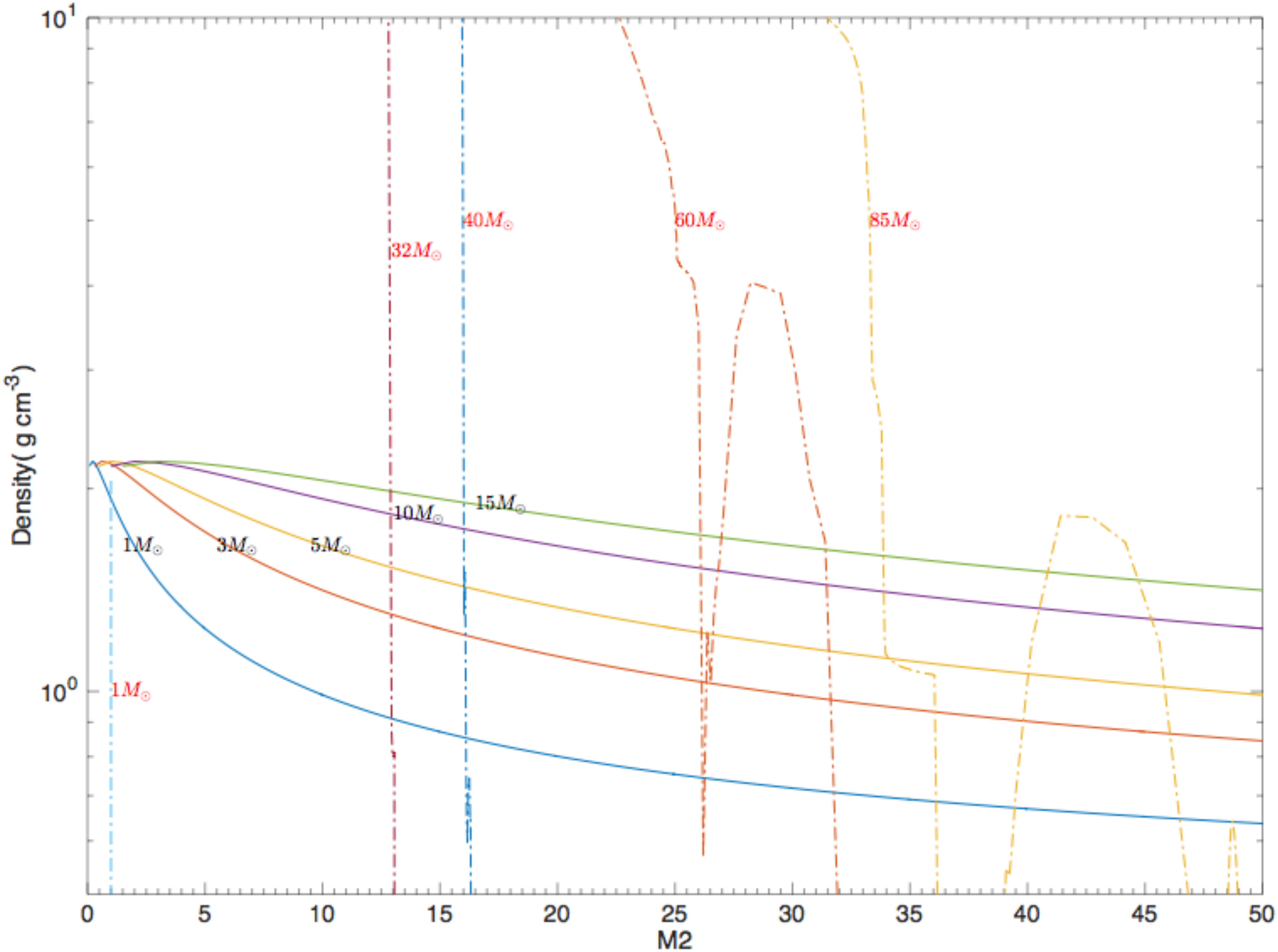
Eggleton lines & stellar evolution tracks



Eggleton 1983

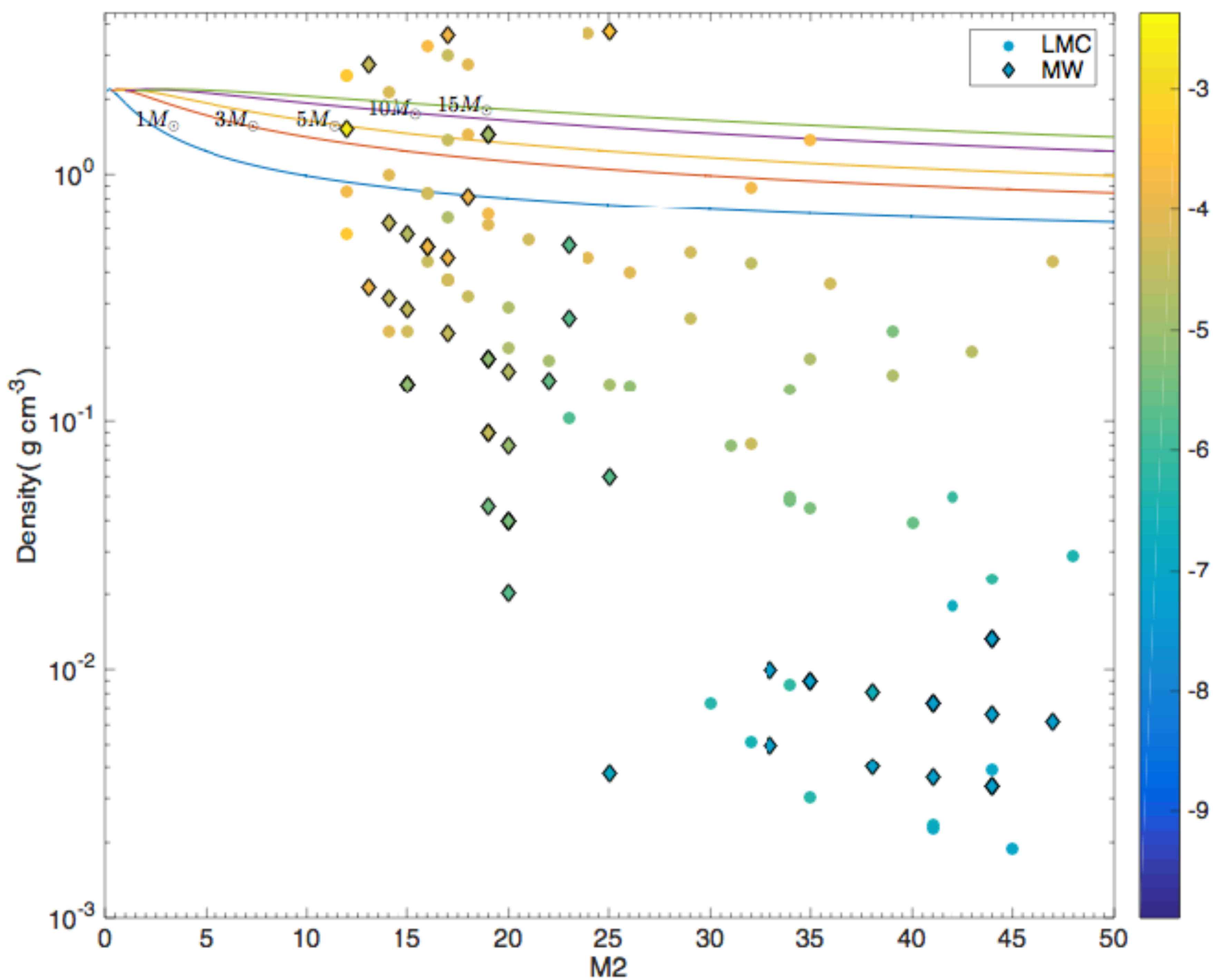
WR Geneva tracks,v4,Z=0.014

Georgy et al. 2012

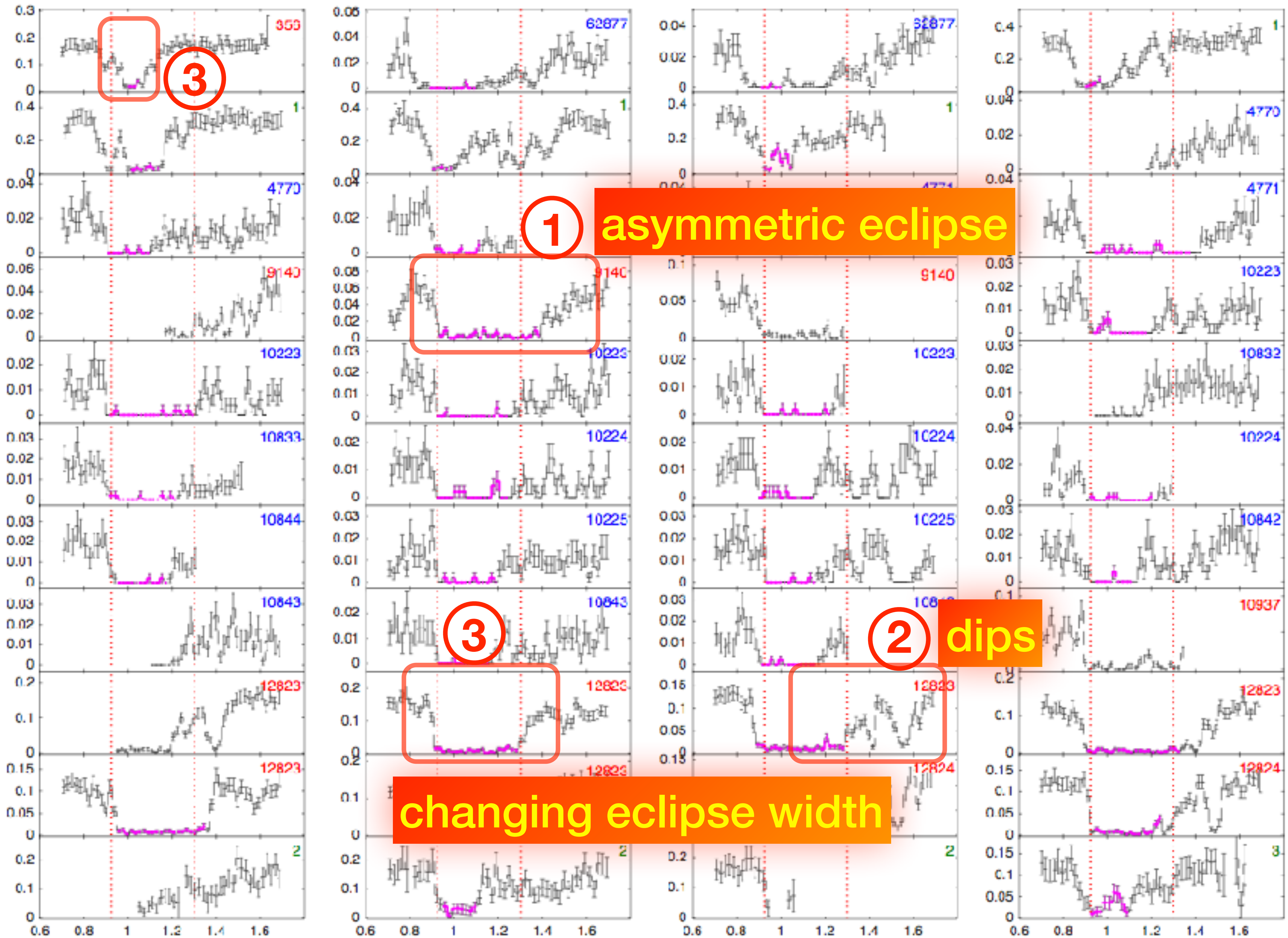


M2>13

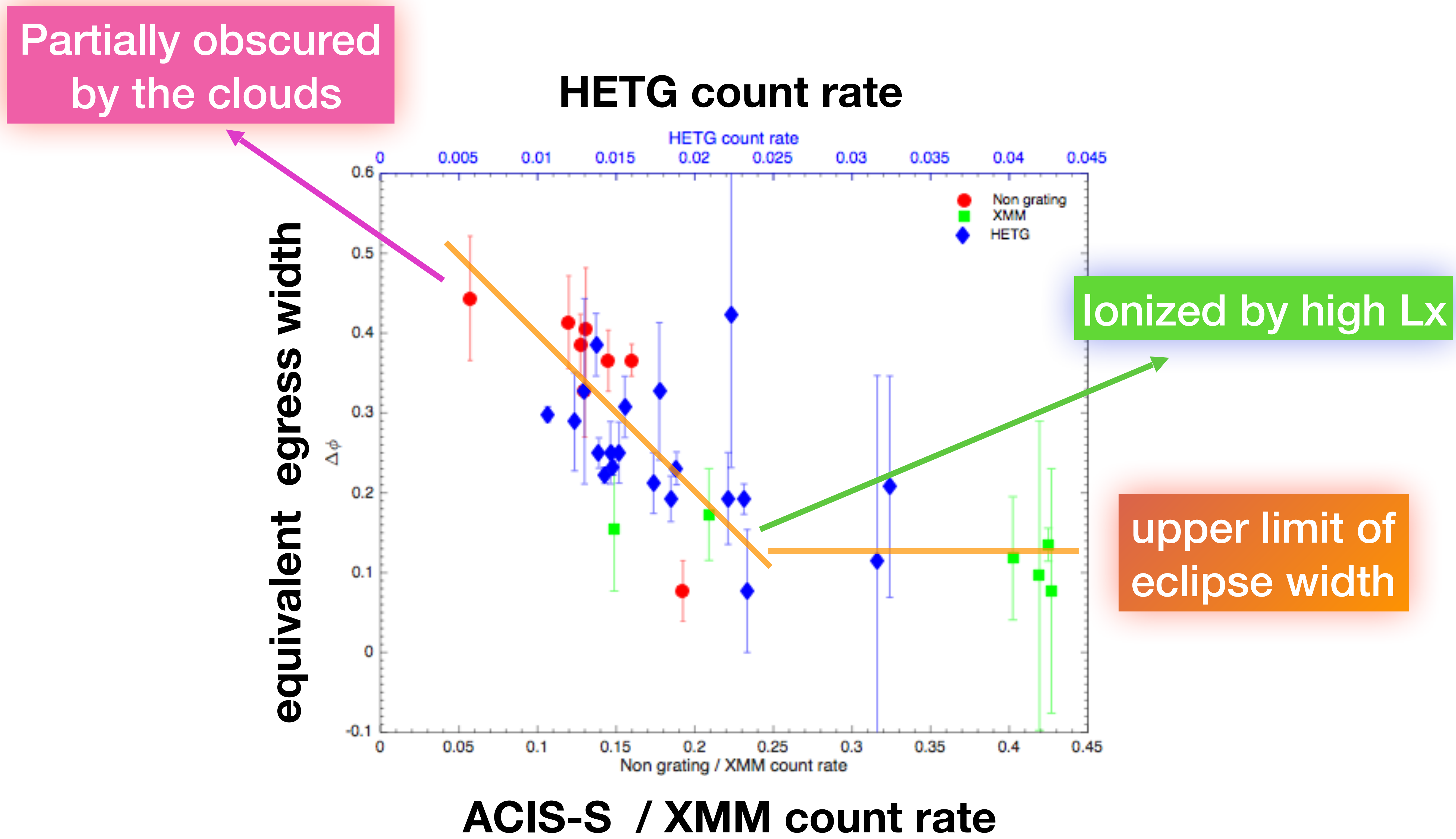
WRs in LMC and MW



light curves over 15 years



egress variability

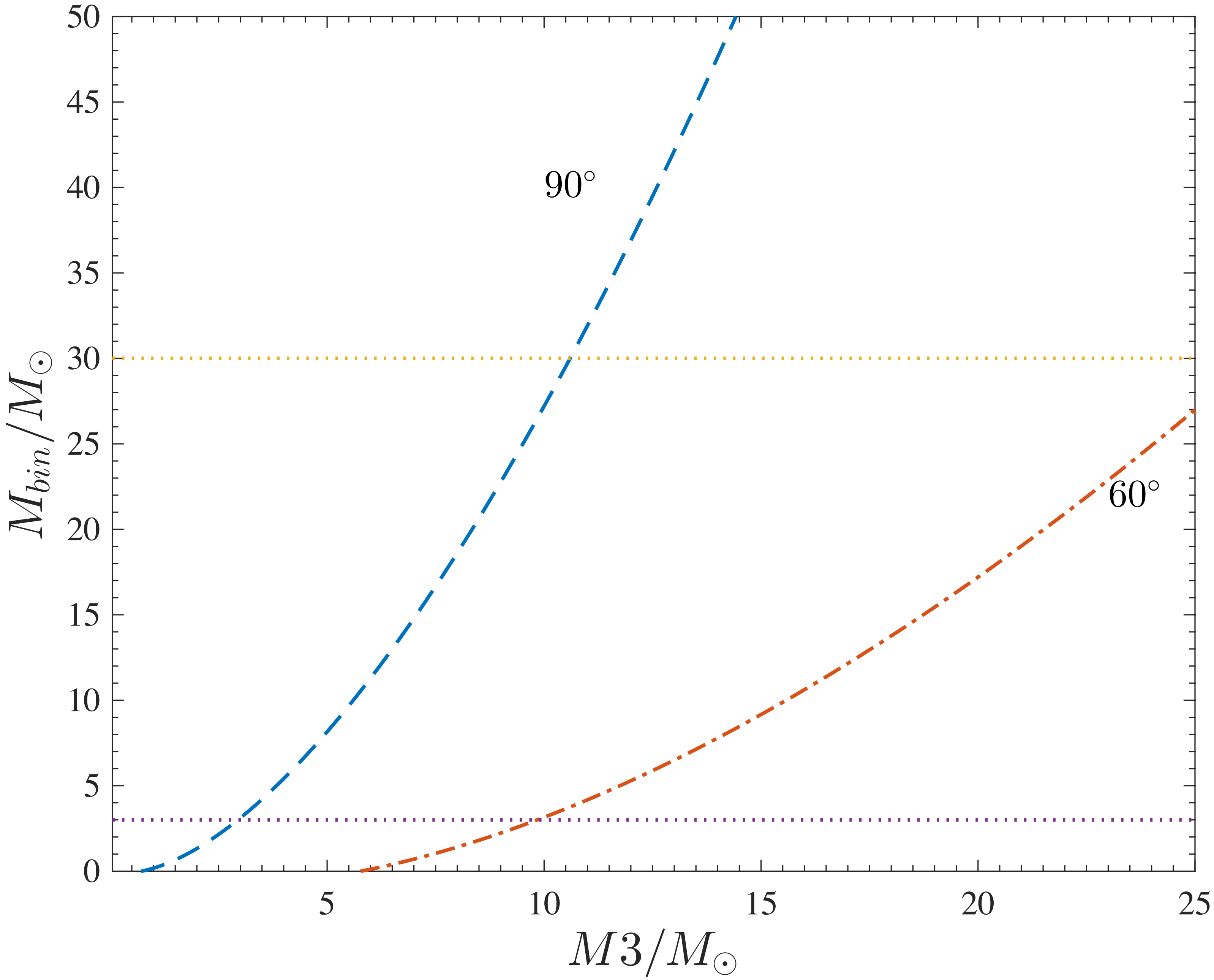


WR + BH/NS

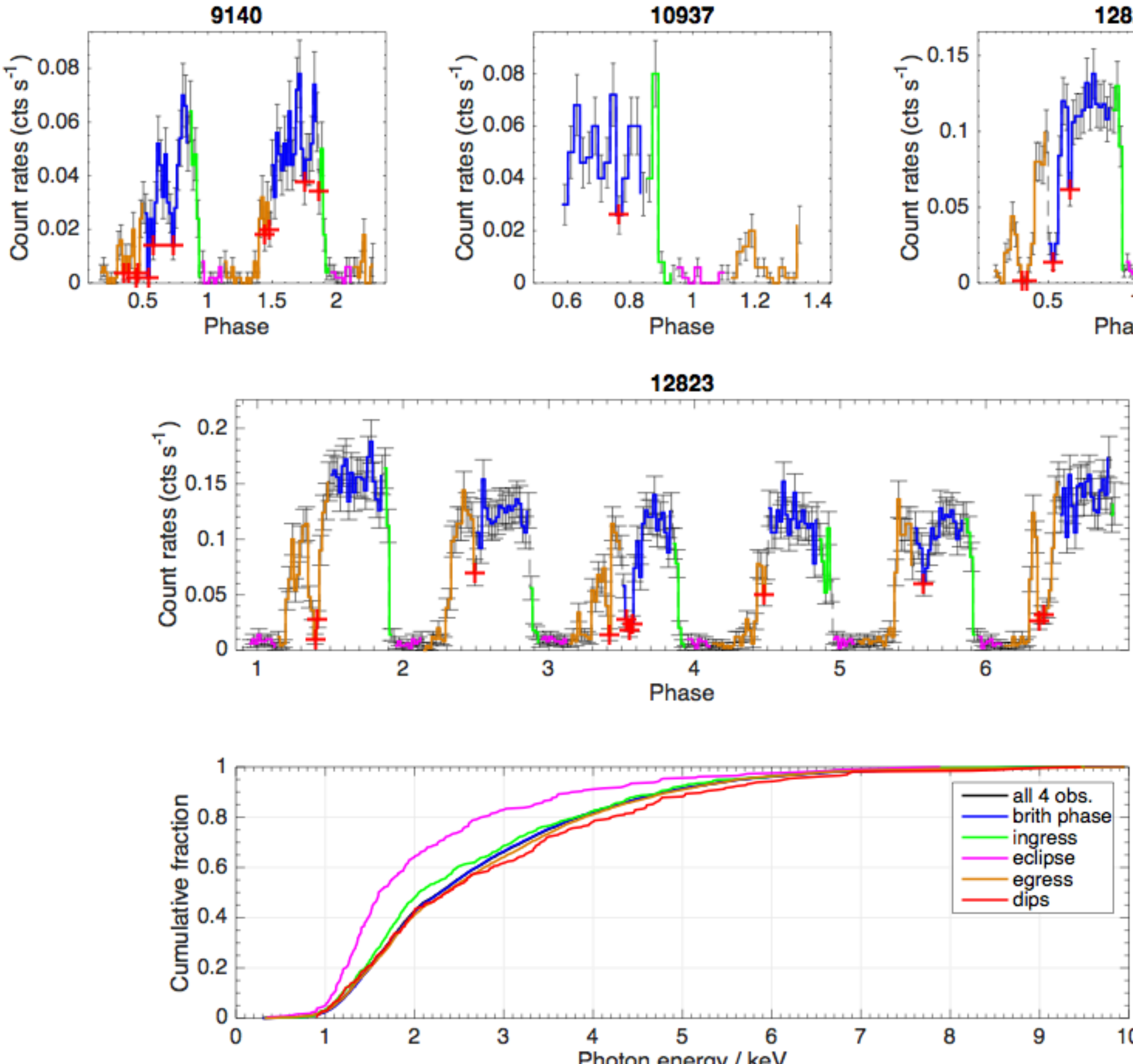
	Name	Lx (erg/s)	Porb hr	Dis. Mpc	M1 Msolar	M2 Msolar	opt. Mag	ra dec	NH Tau	SFR Msolar/yr	ref
1	NGC 4214 X-1	7E+38	3.6	3.5	NS?	He core 2-3	22.6	121538.2 +361921	1.8e21 1.8		Ghosh et al. 2006 2006ApJ...650..872G
2	Cyg X-3	1E+38	4.8	(7-9)e-3	NS?						Zdziarski et al. 2012 2012MNRAS. 426.1031Z
3	CG X-1	2.3E+40	7.2	4.2	BH? >10?	He core 13-50?	24.3			3-8	Esposito et al. 2015
4	NGC 4490 X-1	1.1E+39	6.4	7-10	BH?						Esposito et al. 2013 2013MNRAS.436.3380E
5	NGC 253 X-1	1E+38	14.5	11	BH? 10?	WR 8?	No	004732.0 −251722.1	1e22 1.37		Maccarone et al. 2014 2014MNRAS. 439.3064M
6	NGC 300 X-1	1E+39	32.8	1.88	BH						arpano et al 2007 2007A&A...466L..17C
7	IC 10 X-1	1.2E+38	34.8	0.66	BH						Laycock et al. 2015 2015MNRAS. 446.1399L
8	M33 X-7		82.8 3.45d	0.8	BH						Pietsch, 2006 2006ApJ...646..420P
9	M101 ULX-1	1.6E+39	196.8 8.2 d	6.4	BH 20	WR 19					Liu et al. 2013 Soria & Kong 2016

Table 2. Fitting of O-C.

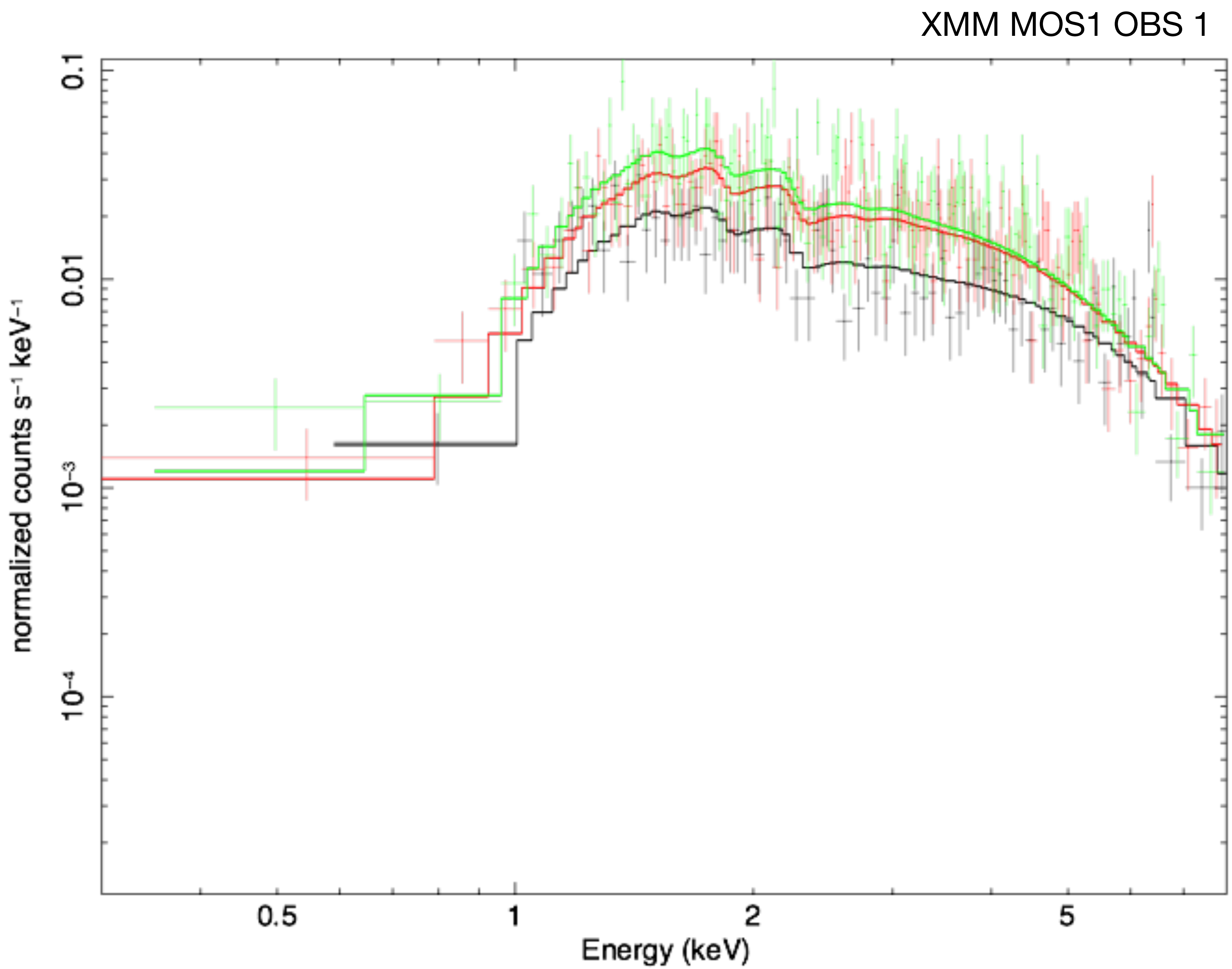
Model	Reduced χ^2	dof.	χ^2	ftest line	ftest quadratic+sin
line	1.292	19	31.716	-	0.079
quadratic	1.216	18	26.616	0.080	0.143
sin	1.236	17	25.971	0.183	0.169
quadratic+sin	1.118	15	20.604	0.079	-



50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
$M_{bin}/M_\odot$
$M3/M_\odot$
90°
60°


9140
10937
12824
12823
Count rates (cts s^{-1})
Phase
Cumulative fraction
Photon energy / keV
all 4 obs.
brith phase
ingress
eclipse
egress
dips

XMM: 2 egress phase + 1 bright phase



- no pileup
- more counts
- but more contaminations

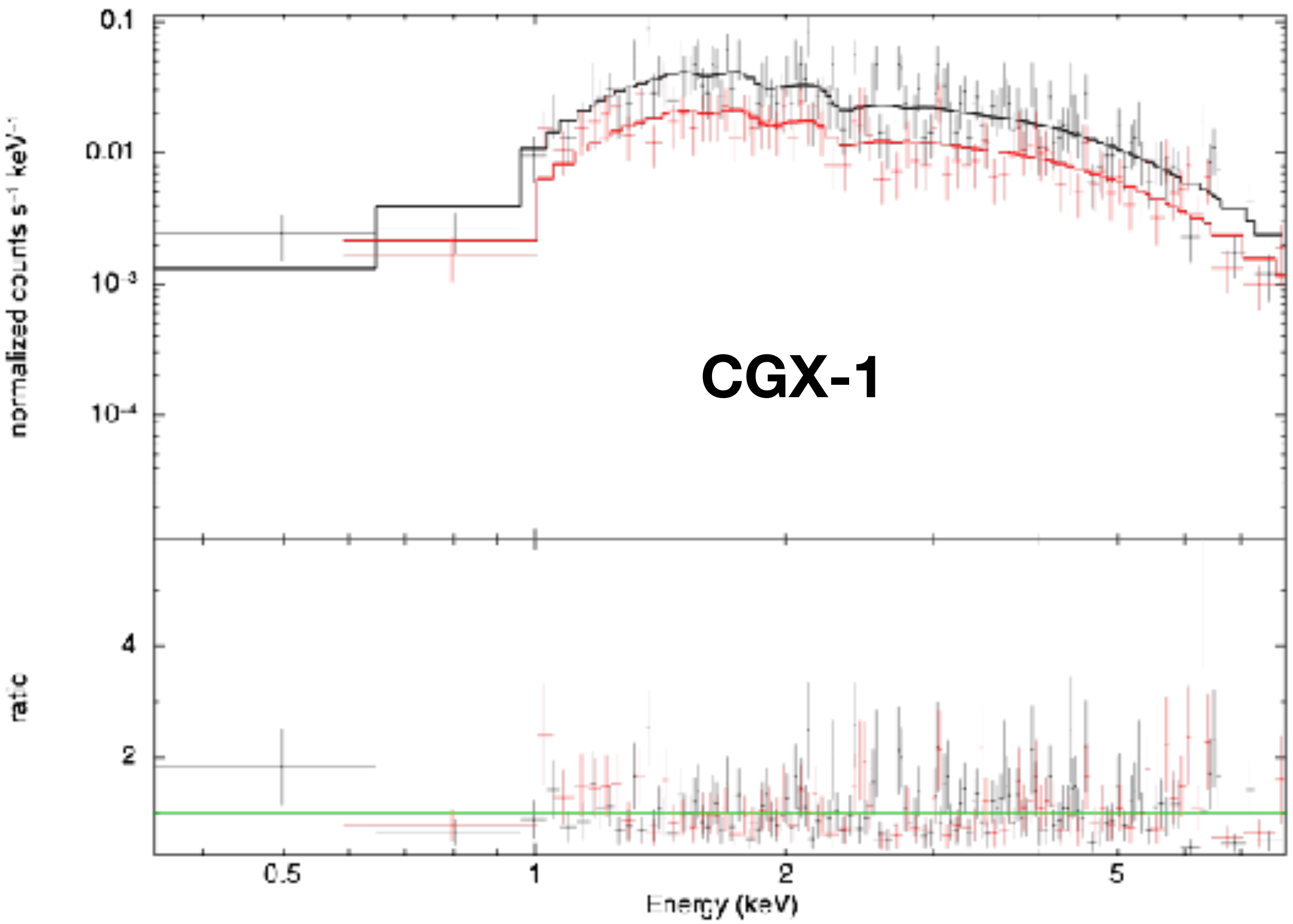
green: bright phase 8

red: egress phase 4

black: egress phase 2

pcfabs*tbabs*po

Comparison: AN OPTICALLY THICK DISK WIND IN GRO J1655–40?



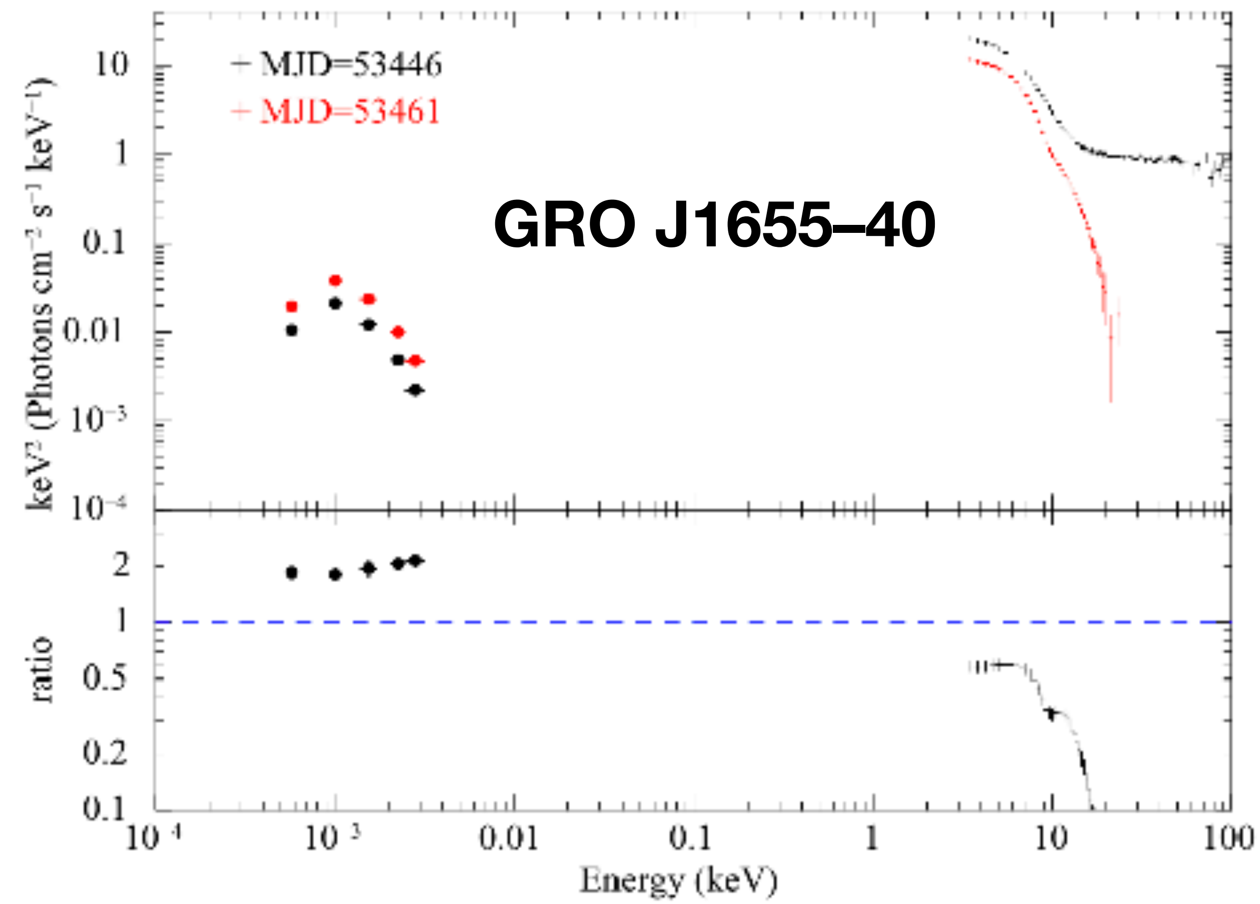


Figure 2. Top: multi-wavelength SEDs in the normal high/soft state (MJD 53446, black) and at the *Chandra* epoch in the hypersoft state (MJD 53461, red). For the HEXTE data (above 20 keV), the Cluster A spectra are not plotted for illustrative purposes. Bottom: the ratio of the two SEDs. The latter data are divided by the former.

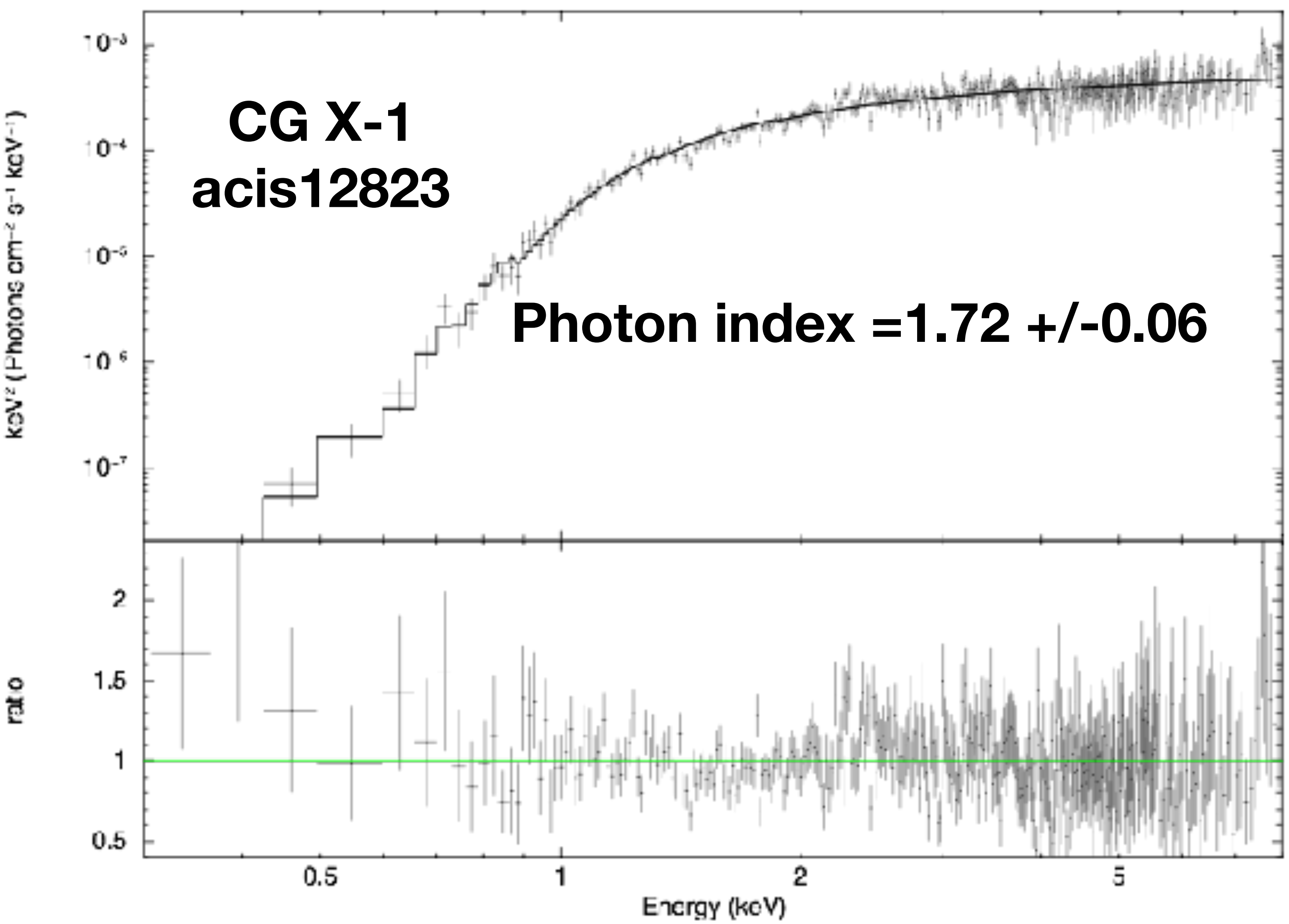
XMM MOS1
tbabs*tbabs*cabs*po
black: phase 8
red: phase 2

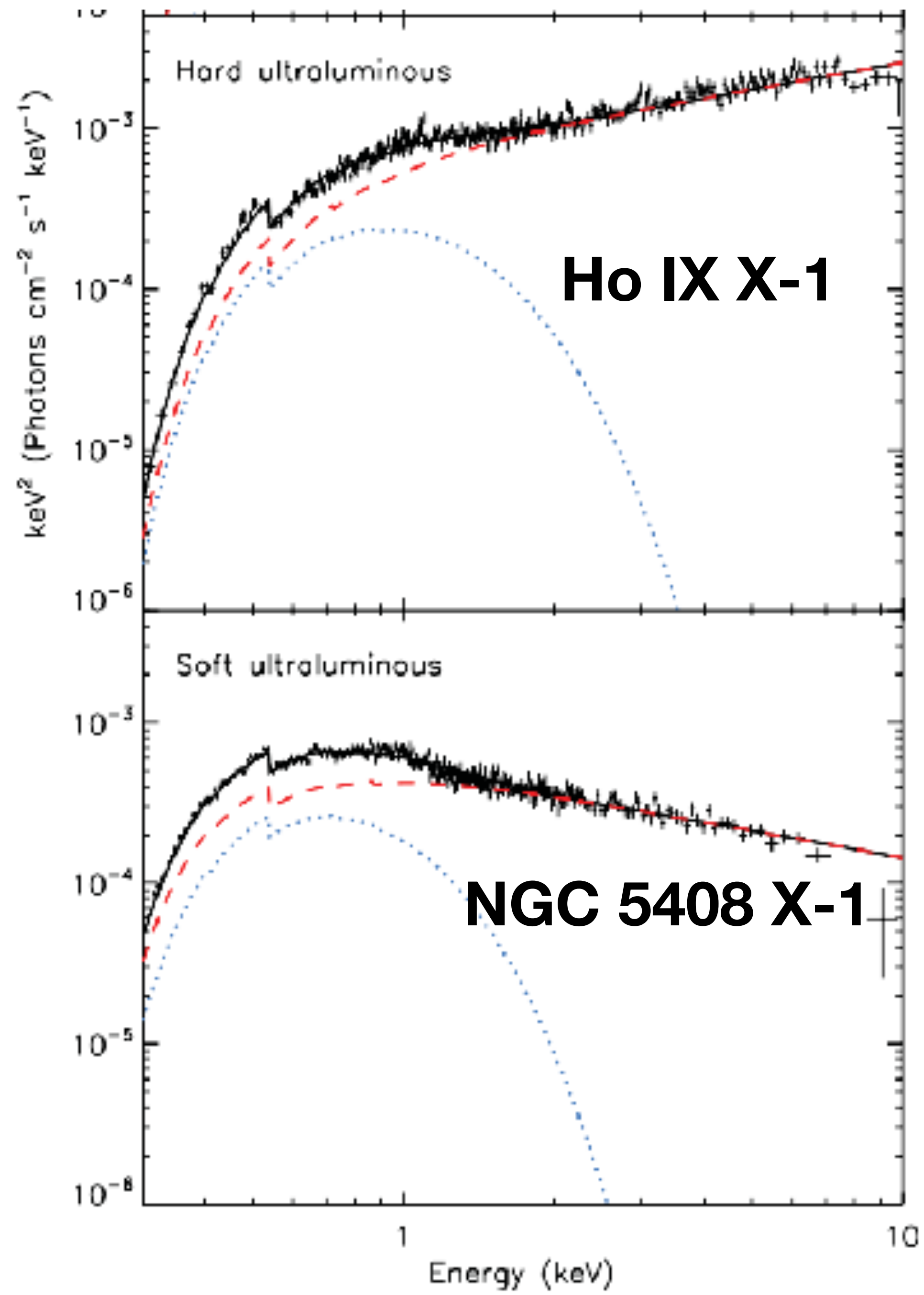
wind on/off can not cause the sharp dips in the bright phase

outburst
ionized wind on/off

Shidatsu et al. 2016

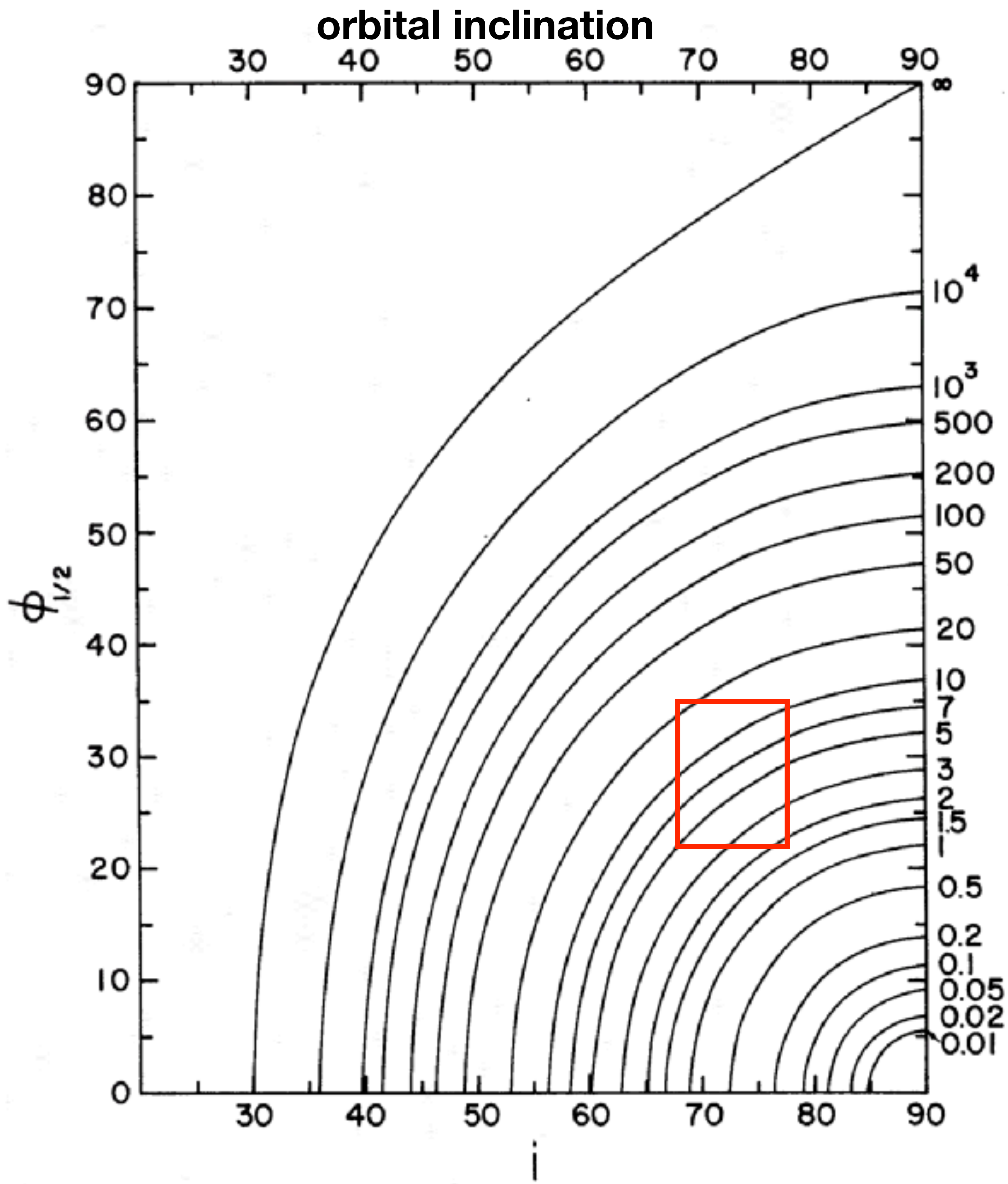
Hard spectrum





- no bending above 1.7
- no line features around 1keV

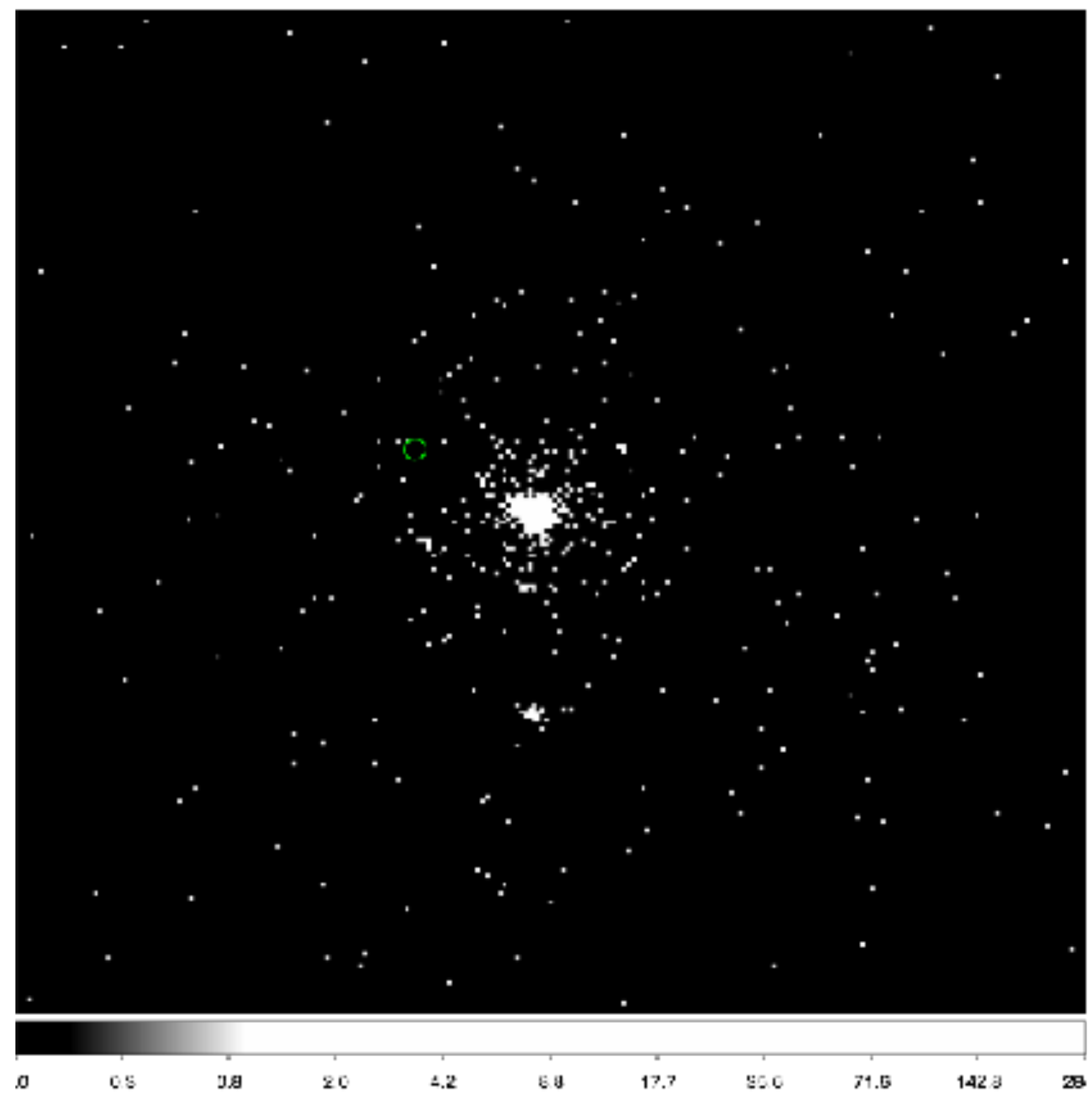
Sutton et al. 2013



Chanan et al. 1976

acis12823 eclipse Fe

- energy from 6.3-6.7 keV



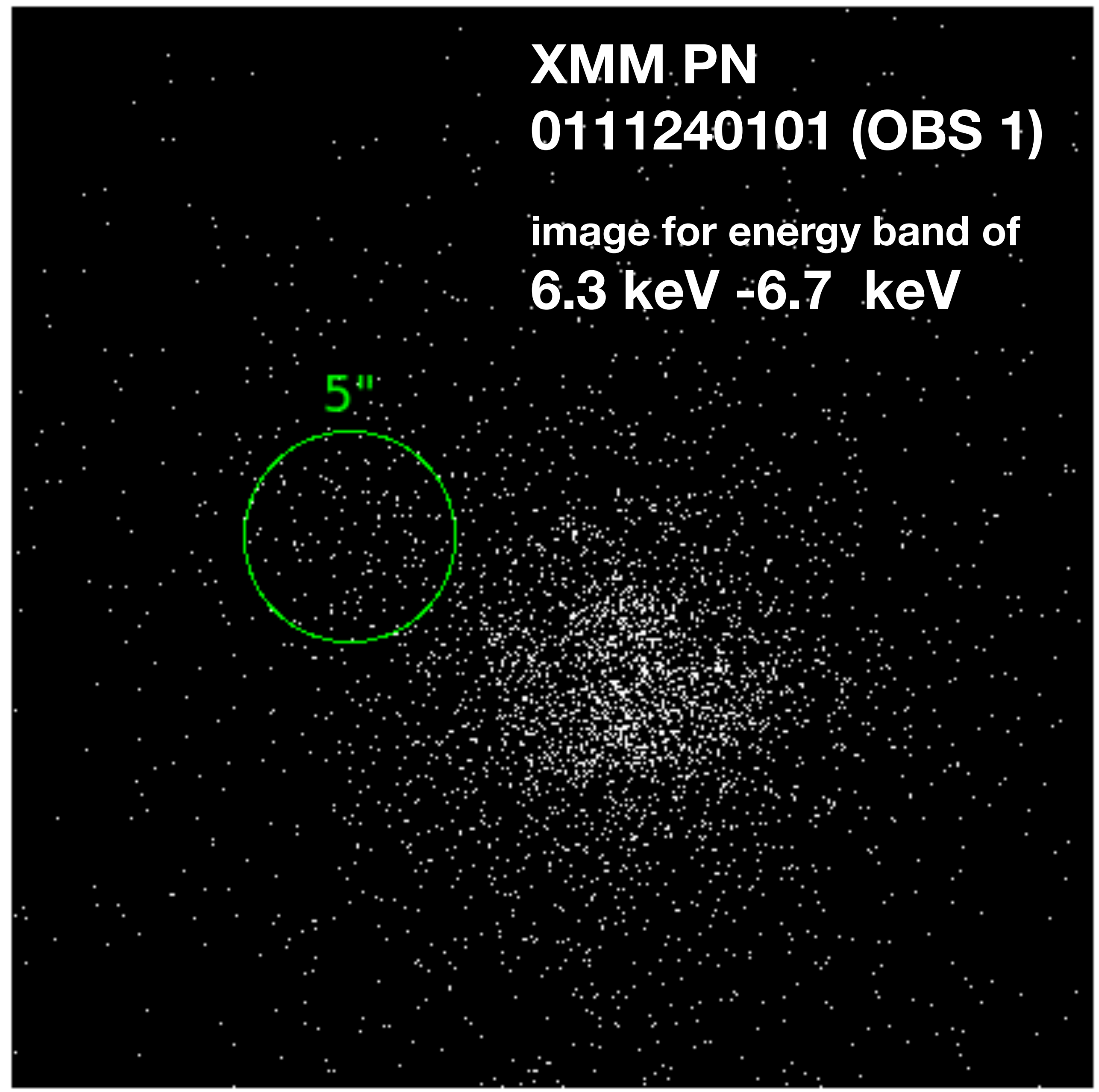
No Fe line

spectrum of eclipse has no Fe line
but in bright phase yes

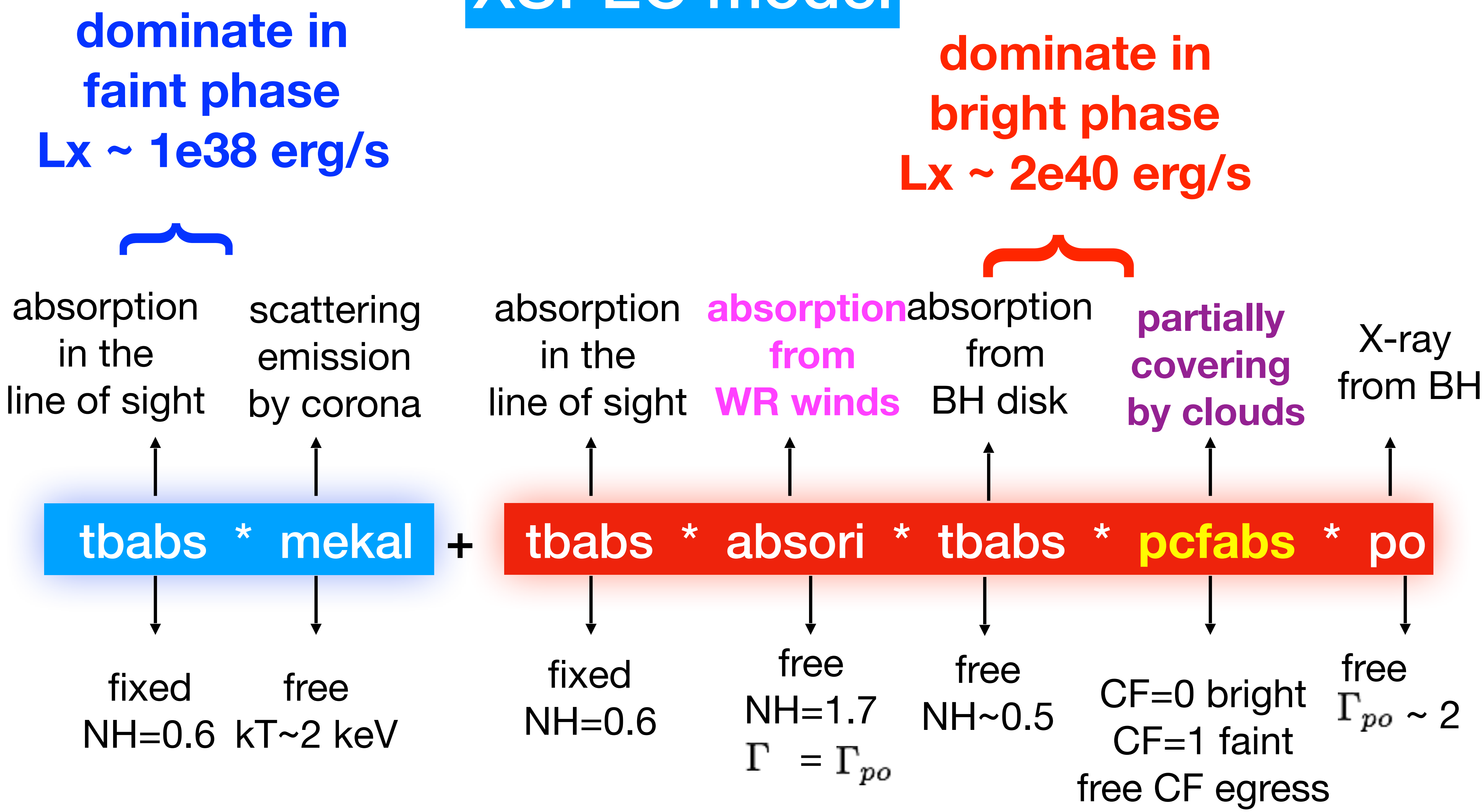
check the spectra with grp1, and about 5-8 counts in the Fe lines band 6.35-6.9 keV in both eclipse and bright phase, so there indeed are Fe lines in all the phase but they are contaminations from the center of Circinus galaxy.

Evidence for no Fe lines

1. no lines in Chandra spectra
2. in XMM Fe image, no compact source concentrates in the position of CG X-1



XSPEC model



- **X-ray emission is partially covered by clouds during egress phase.**
- **Covering fraction is set to 0 during the bright phase, and 1 during eclipse.**
- **Adding “absori” can improve the fitting which is a simple power-law.**