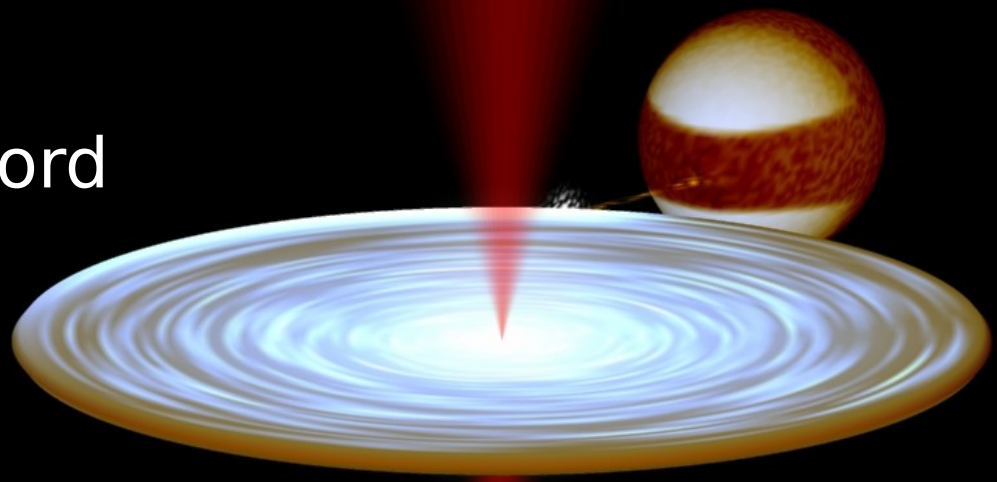
The 2015 Outburst of BHXRB V404 Cygni

Phil Charles
Southampton/UCT/Oxford



(with input from Francesco Bernardini, Jorge Casares, Poshak Gandhi, Sara Motta, Teo Muñoz-Darias, Dave Russell)

Image: Rob Hynes

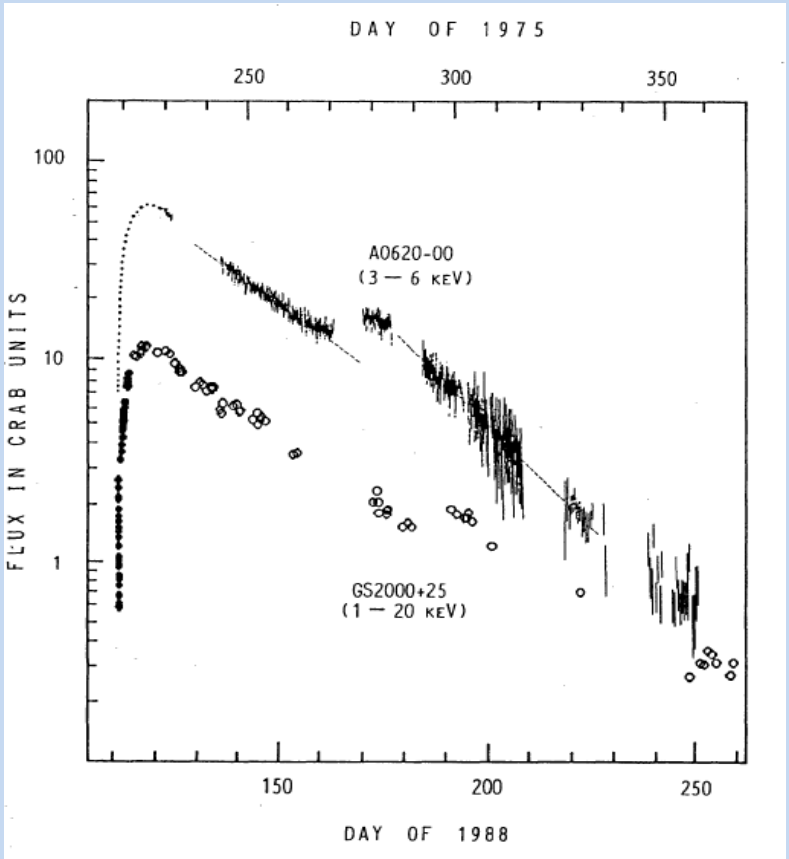
Outline

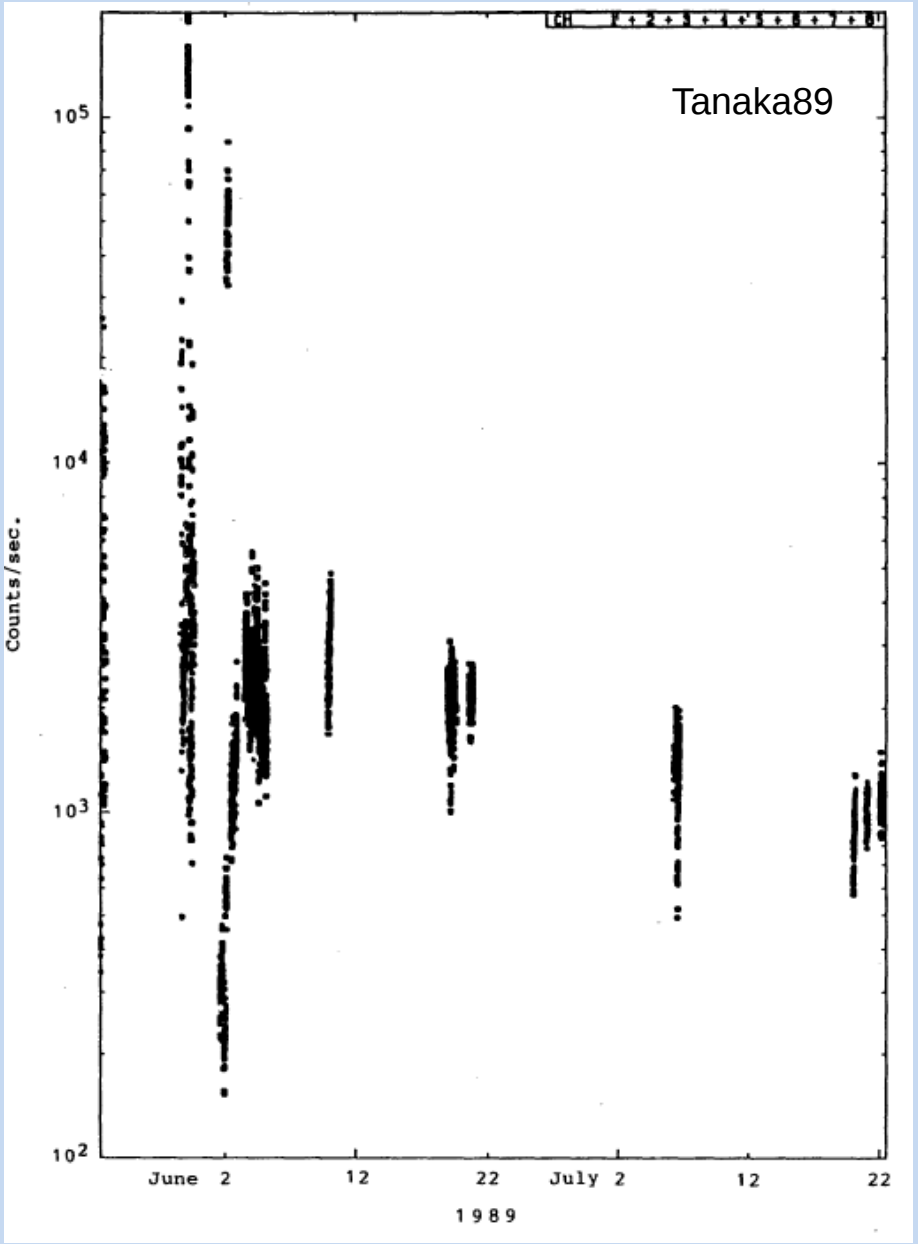
- V404 Cyg: discovered with its 1989 outburst
- What do we now know about V404 Cyg
  - and what do we not know (or are unsure of)!
- Why is it such an important object?

- The 2015 outburst:
  - a precursor to an “inside-out” outburst (Bernardini+16a)
  - very fast flickering (Gandhi+16)
  - evidence for a hot wind (King+15) and relativistic reflection (Walton+16)
  - evidence for a cold wind (Muñoz-Darias+16)
  - the optical/X-ray correlation from quiescence to outburst (Bernardini+16b)
  - Swift/INTEGRAL light-curves and spectra (Motta+17)

The 1989 Outburst

GS2023+338: peak ~20 Crab (saturation?)
cf A0620-00 ~60 Crab (1975)
GS2000+25 ~12 Crab (1988)
- but v different light curve (in first 2 weeks)
- most extreme variability yet seen
(x200 in ~1h; x20 in ~10s;
flickering to ~2ms, no QPOs)
- but all 3 with τ ~ 40d



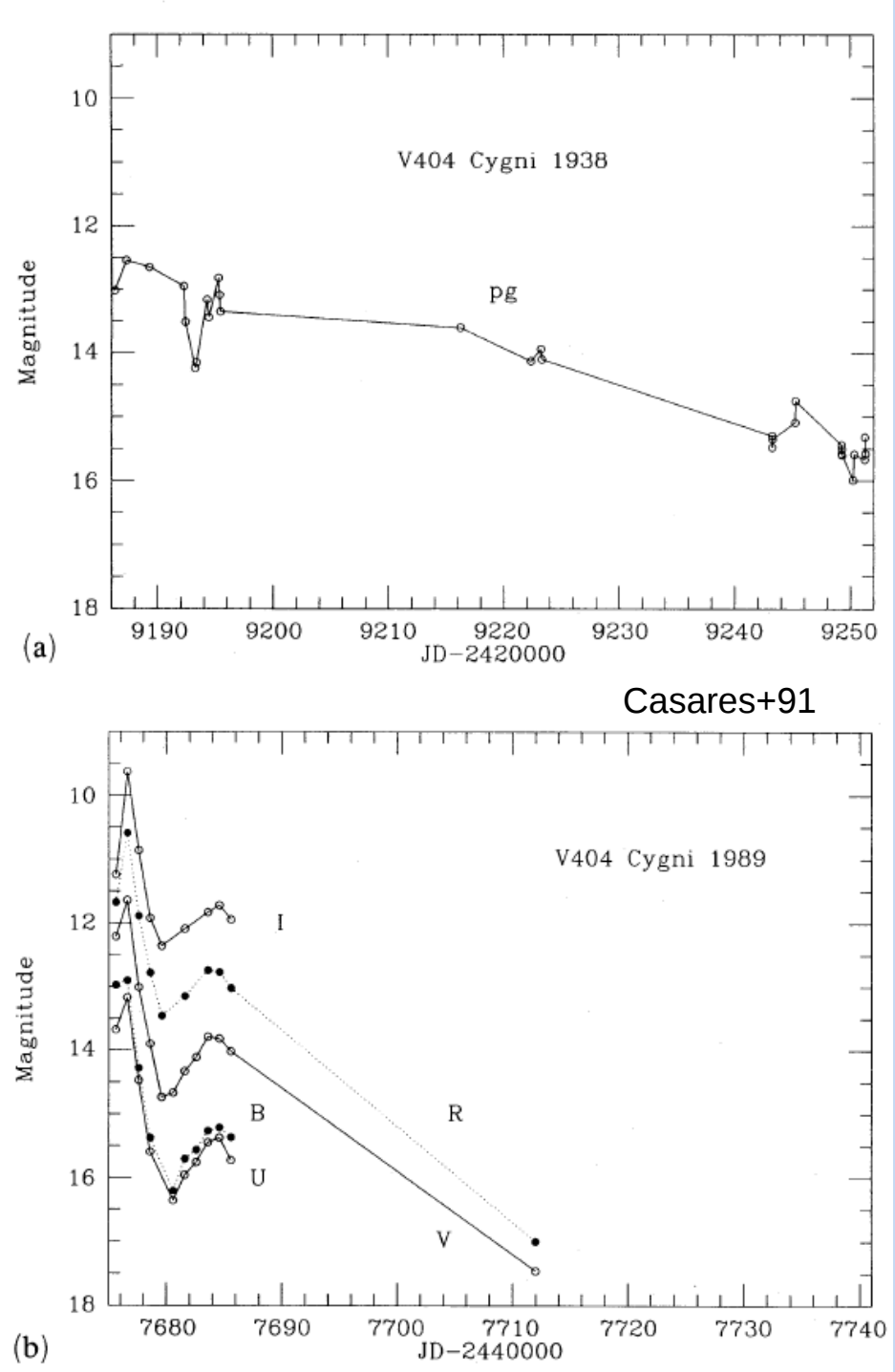


Identified as V404 Cyg by Marsden+89 → first XRT with already known optical variable (Nova Cyg 1938)

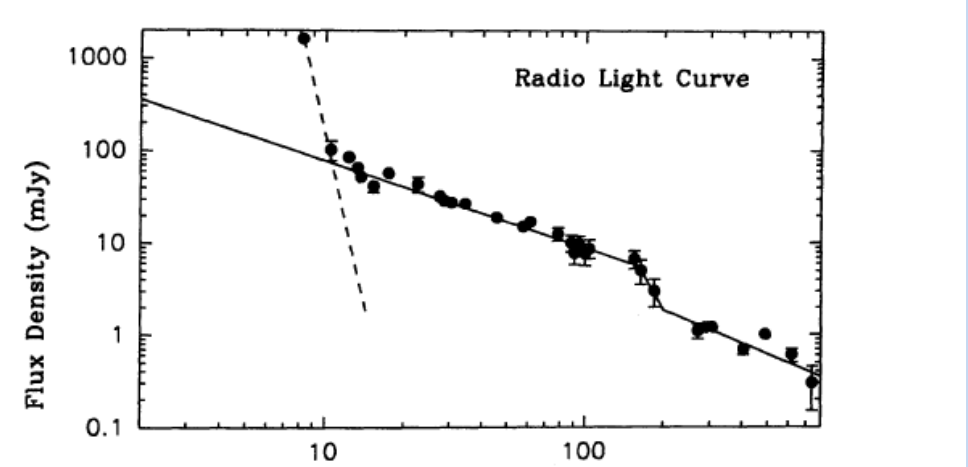
→ comparison of 1938 and 1989 light curves

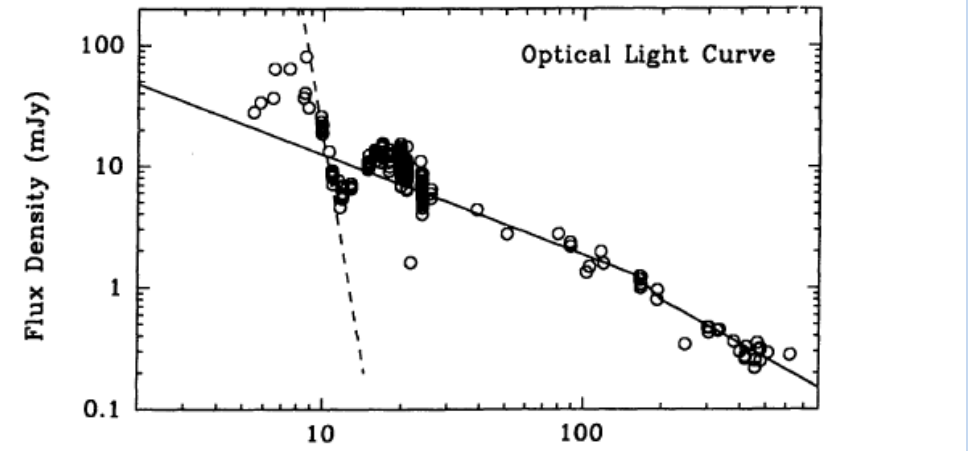
(see Duerbeck 1987 and McLaughlin 1945)

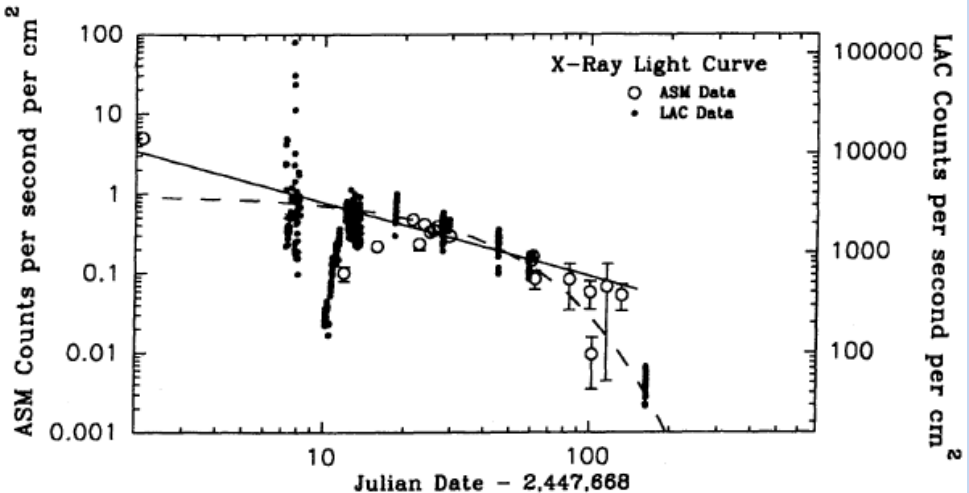
Richter 89: Sonneburg plates (1928-1989) → additional outbursts in:
1956 (bright for >9 d) – pre XRA!
1979? (single plate) – no ASM



Casares+91

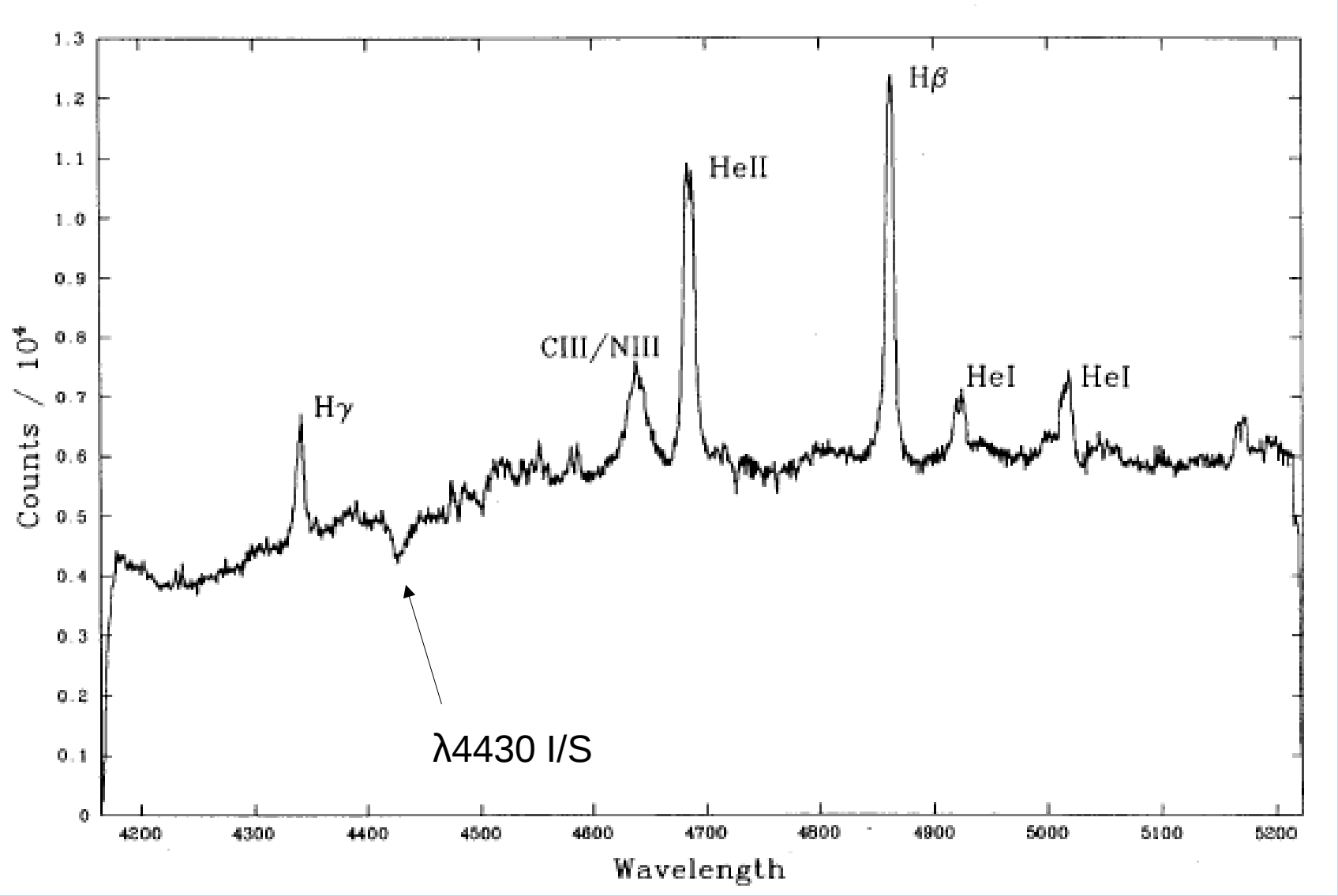






Han & Hjellming 92
Comparison of radio, optical and X-ray light curves

→ steep decay (dashed lines) due to synchrotron bubble event

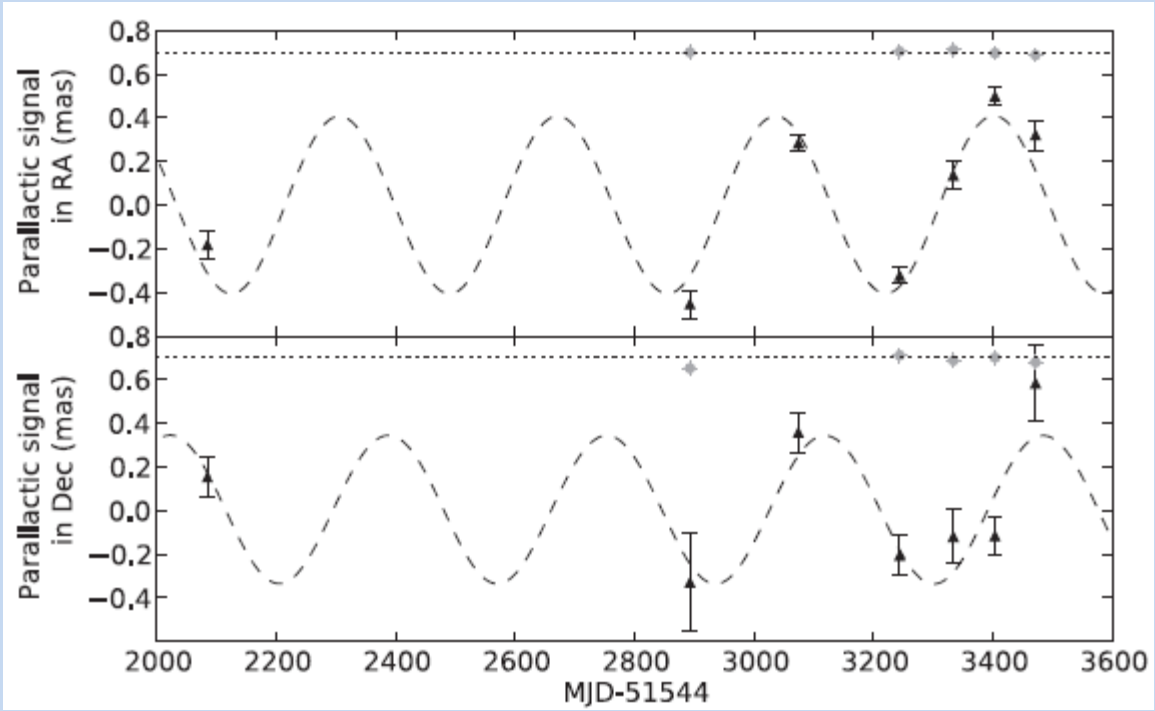


Casares+91
INT+IDS/IPCS
1989 Jun 1-11

Classic X-ray irradiated disc LMXB spectrum

Key parameter: the distance!

- VLBI (Miller-Jones+09) → PM=9.2±0.3 mas/y; and the parallax (first for a BH XRB!):



$$\mu_\alpha \cos\delta = -5.04 \pm 0.02 \,\mathrm{mas\,yr^{-1}},$$

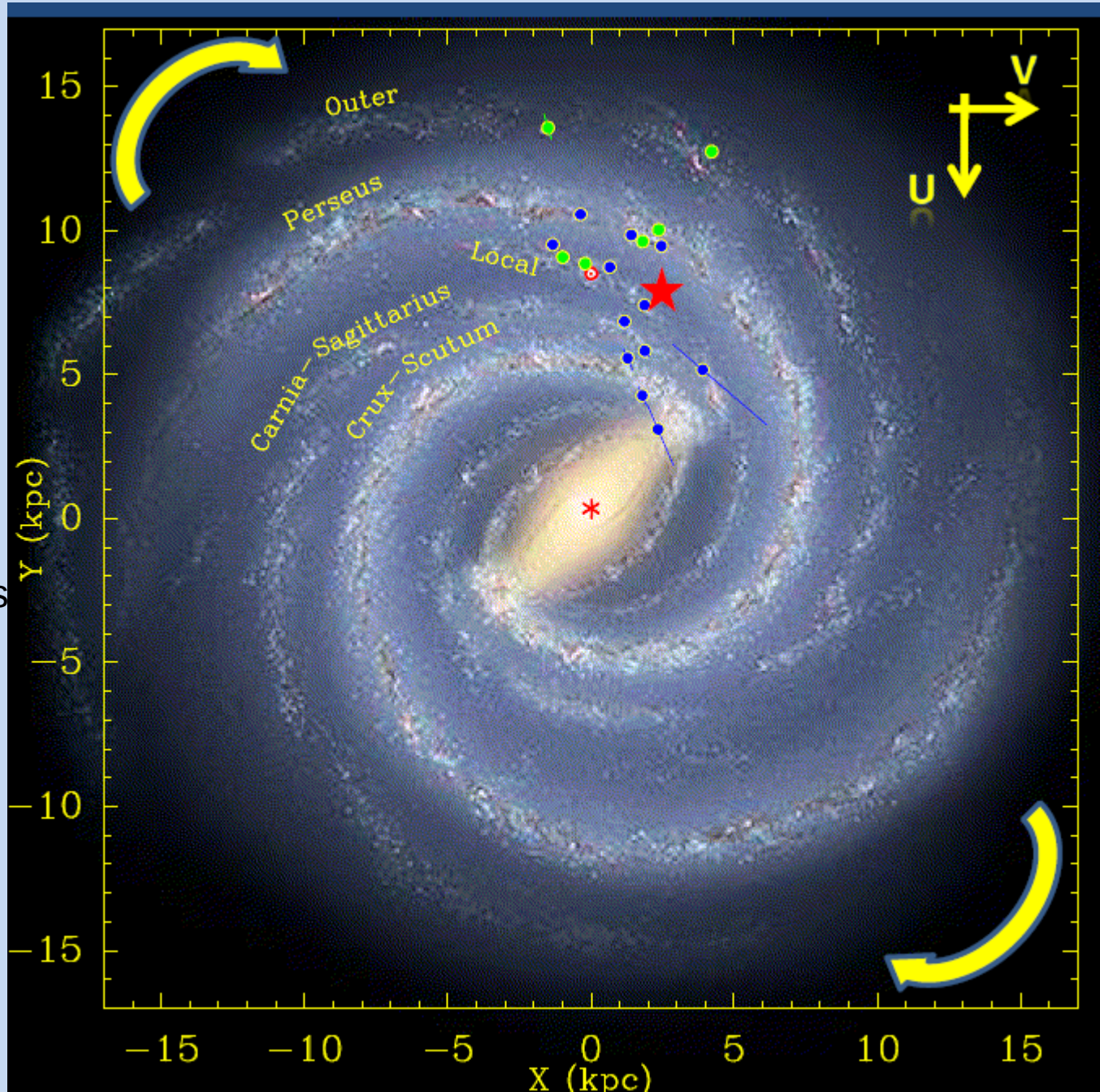
$$\mu_\delta = -7.64 \pm 0.03 \,\mathrm{mas\,yr^{-1}},$$

$$\pi = 0.418 \pm 0.024 \,\mathrm{mas}.$$

i.e. **d=2.39±0.14 kpc**

V404 Cyg Location

Miller-Jones09 on
Reid+09 image
(NASA/JPL-Caltech/SSC: R.Hurt)

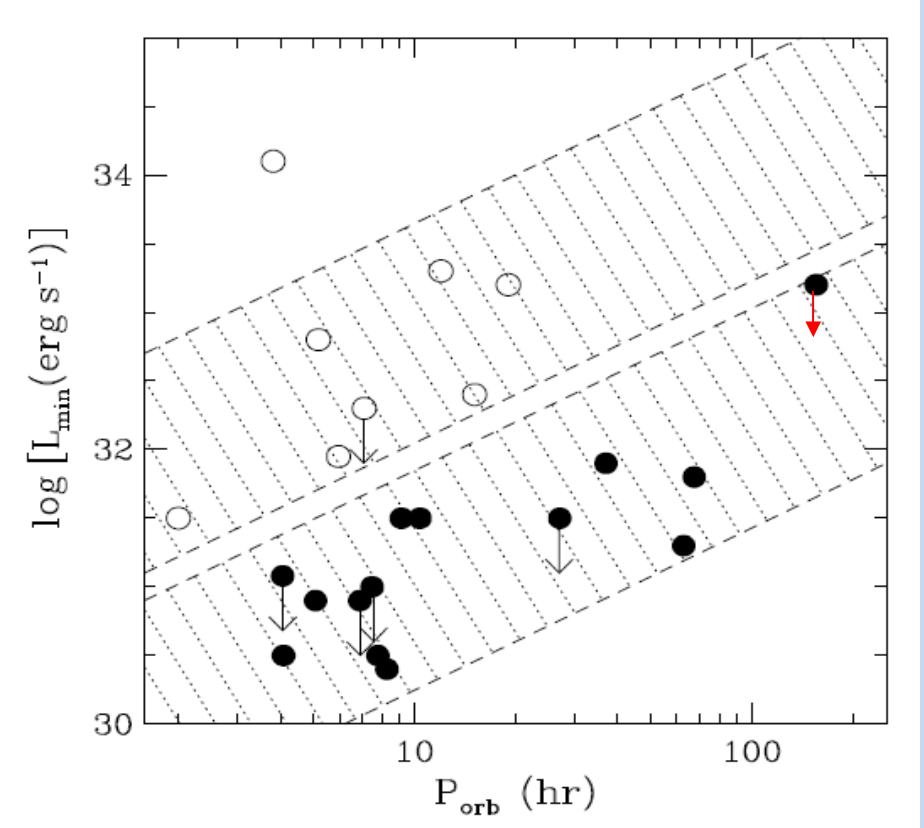


And peculiar velocity = 40±5 km/s
in Galactic Plane → consistent
with Blaauw kick in SN event

Implications:

- 1989 outburst peak of ~20 Crab (Ginga) → $L_x = 8 \times 10^{38}$ erg/s (1-70 keV)
  → ~0.5 L_{edd} for $12 M_\odot$ BH
- and new quiescent L_X of 7×10^{32} erg/s (0.3-10 keV)

Narayan & McClintock 08
- ADAFs in qXRTs
- open circles – NS systems
- filled circles – BH systems
- arrow indicates new V404 L_{min}



Importance of V404 Cyg in BHXRB work:

- in 1993 – only 5 BH candidates (see Cowley, Tutukov reviews):
  - Cyg X-1, LMC X-3 – both HMXBs, very uncertain donor mass values
  - A0620-00, V404 Cyg and Nova Mus 1991
  - of which only V404 Cyg had such a high f(M) (much $>3.2M_{\odot}$)

- it's very close (→ bright in quiescence), long P, evolved donor

• Mass function provides fundamental constraint $M_1 > f(M)$

N.B. $q = M_1/M_2 > 5$

$$f(M) = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P K_2^3}{2\pi G}$$

$$M_1 = \frac{f(M)}{\sin^3 i}(1 + 1/q)^2$$

• Rotational broadening of secondary's absorption spectrum → R_2 +

• assume that secondary fills Roche lobe (reasonable as transferring mass) →

• Measurement of K_2 and $v \sin i$ → q

$$v_{\rm rot} \sin i = \frac{2\pi R_2}{P} \sin i$$

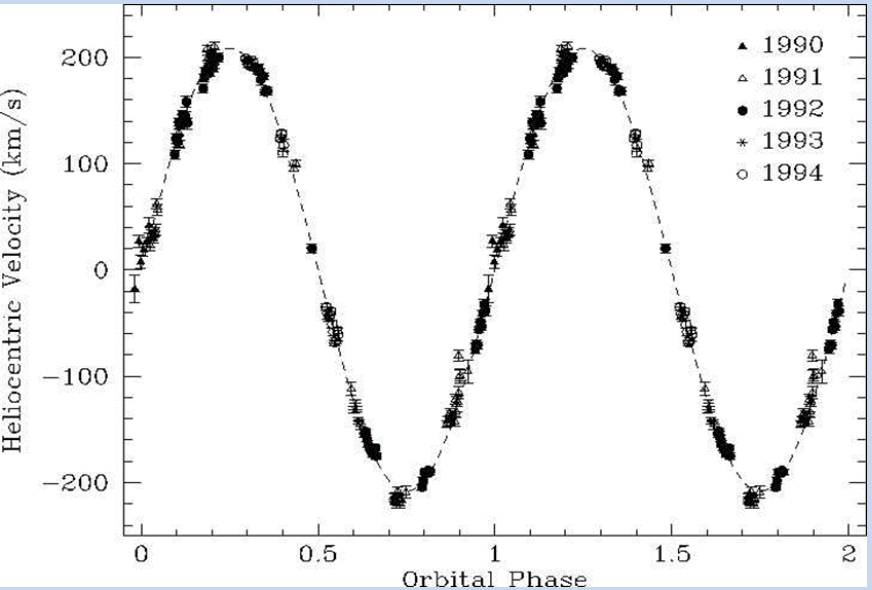
$$\frac{R_2}{a} \simeq 0.462(1 + q)^{-1/3}$$

$$v_{\rm rot} \sin i = K_2 \times 0.46 \frac{(1 + q)^{2/3}}{q}$$

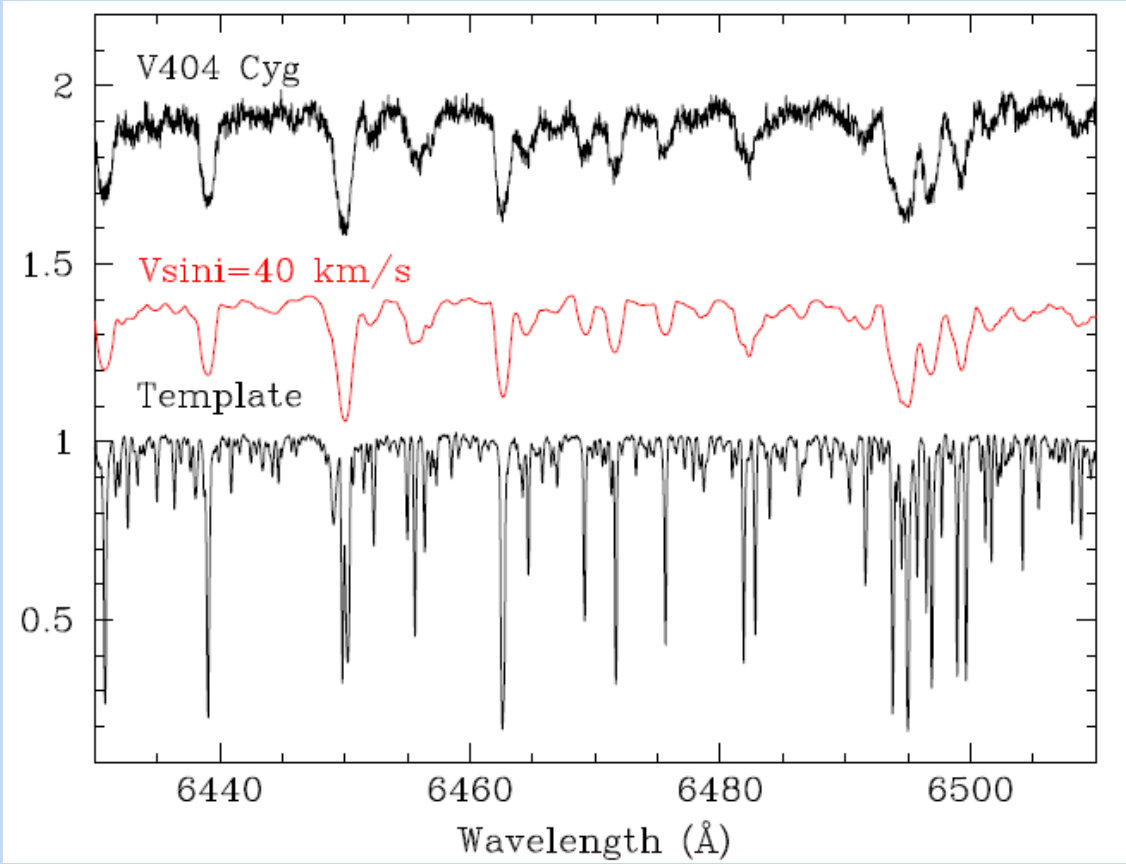
ROTATIONAL BROADENING

V404 Cyg has P=6.5d, K_2=208.5 km/s

→ f(M)=6.08±0.06 $M_\odot$



Casares & Charles 94

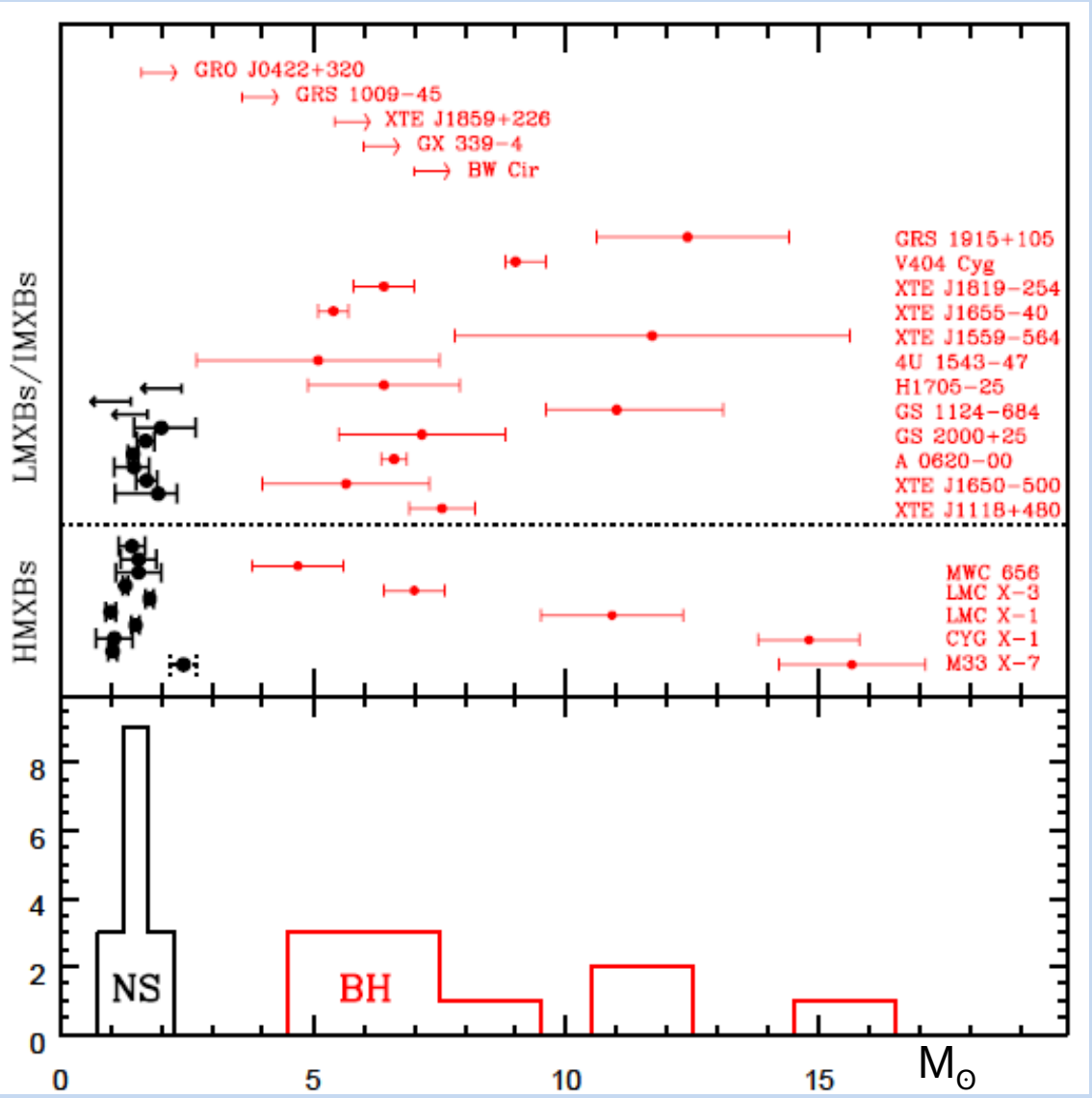


K0IV donor template

V_{rot} *sini*=40 km/s → *q*=17

NS/BH mass distribution

Charles & Coe 2006
Remillard & McClintock 2006
Casares & Jonker 2013
Casares et al 2016



21 realistic masses of BHs:
5-16 M⊙

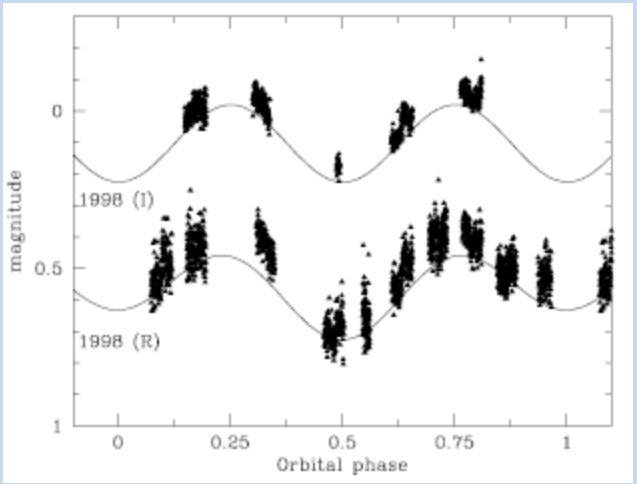
Typical errors 30%

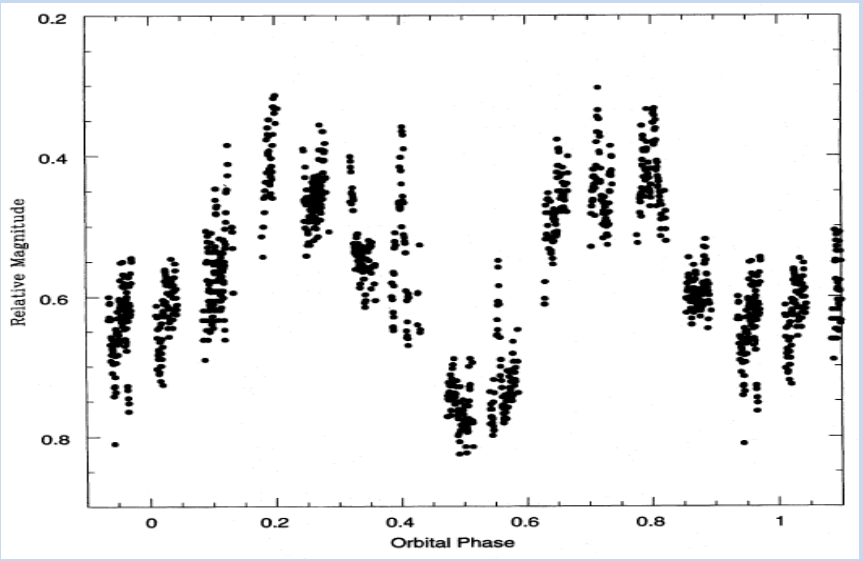
Goals:
improve statistics
reduce errors to 10%

Do BH masses cluster at a particular value? (e.g. Bailyn et al 98)
What are the edges of the BH distribution?
Is there a continuum distribution between NS & BHs, or is there a gap?

But what about V404 Cyg's quiescent light curve?

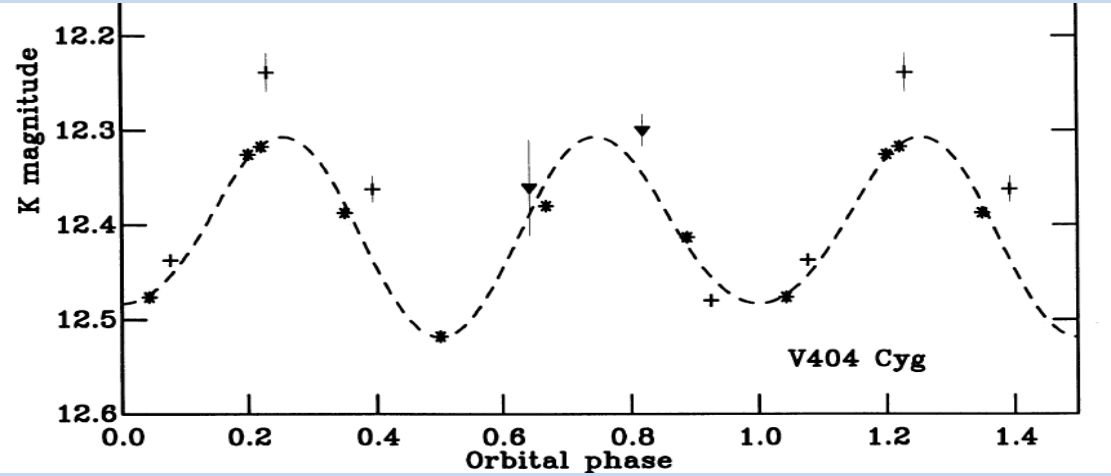
Pavlenko+96 → clear ellipsoidal modulation, but large scatter → used lower envelope (see also Zurita+04)

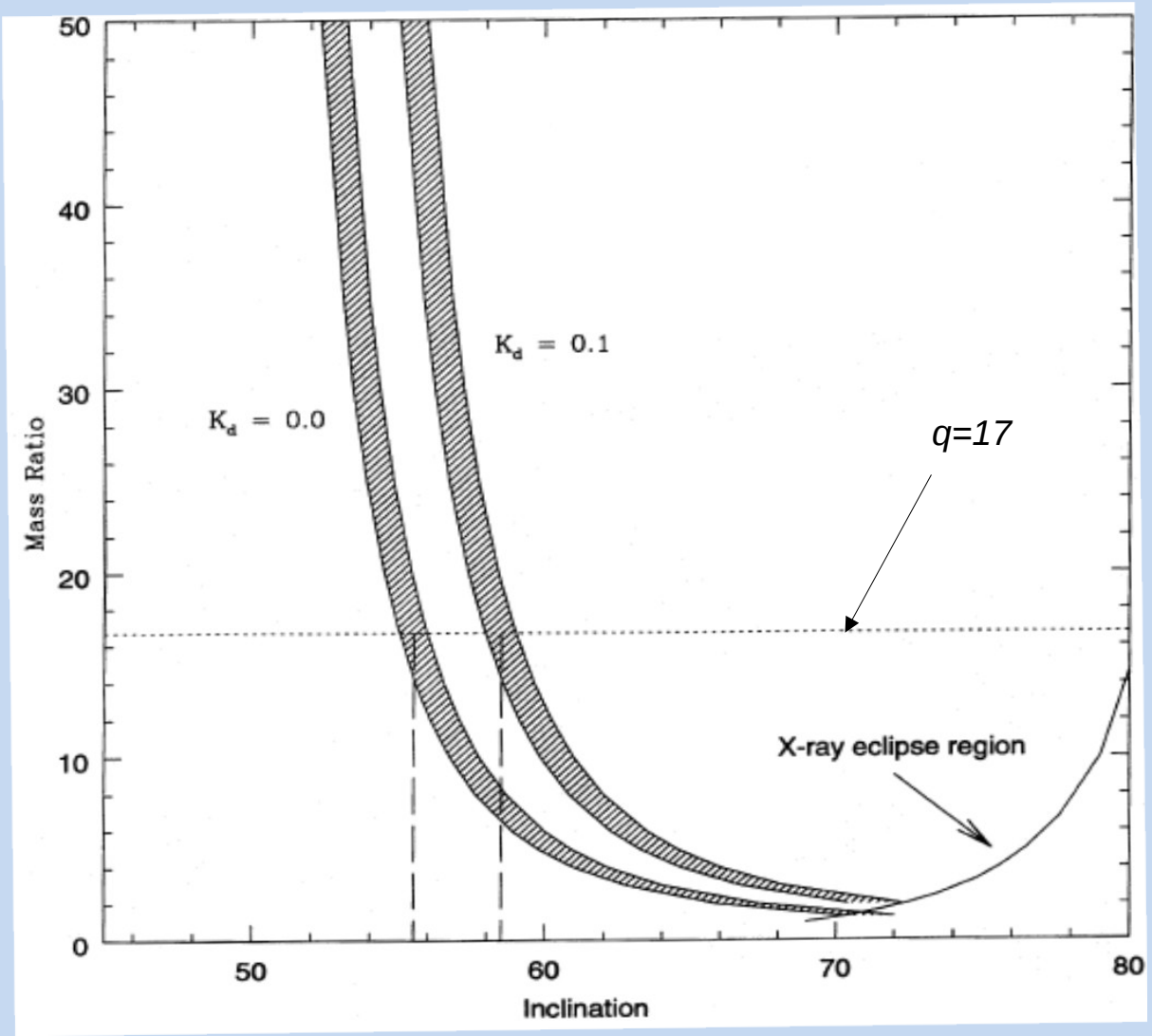




N.B. these are intrinsic variations

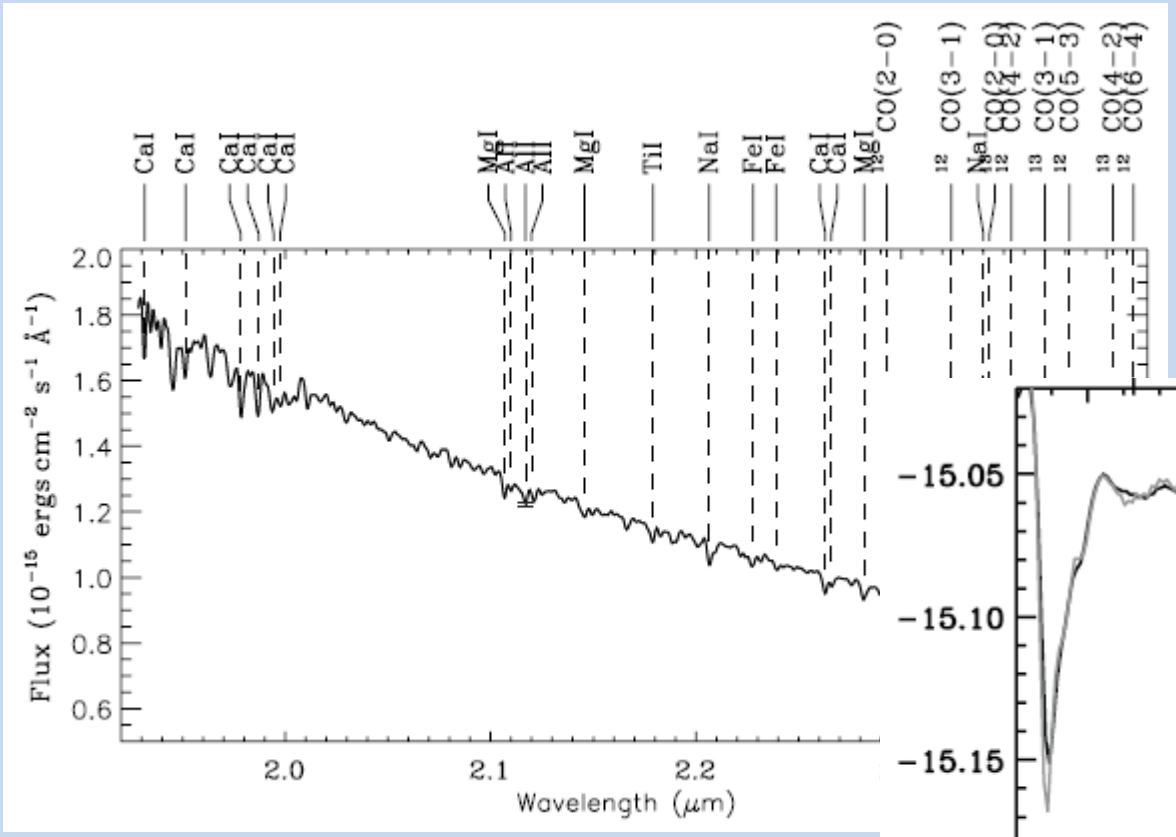
or K-band, Shahbaz+94, where disc is fainter



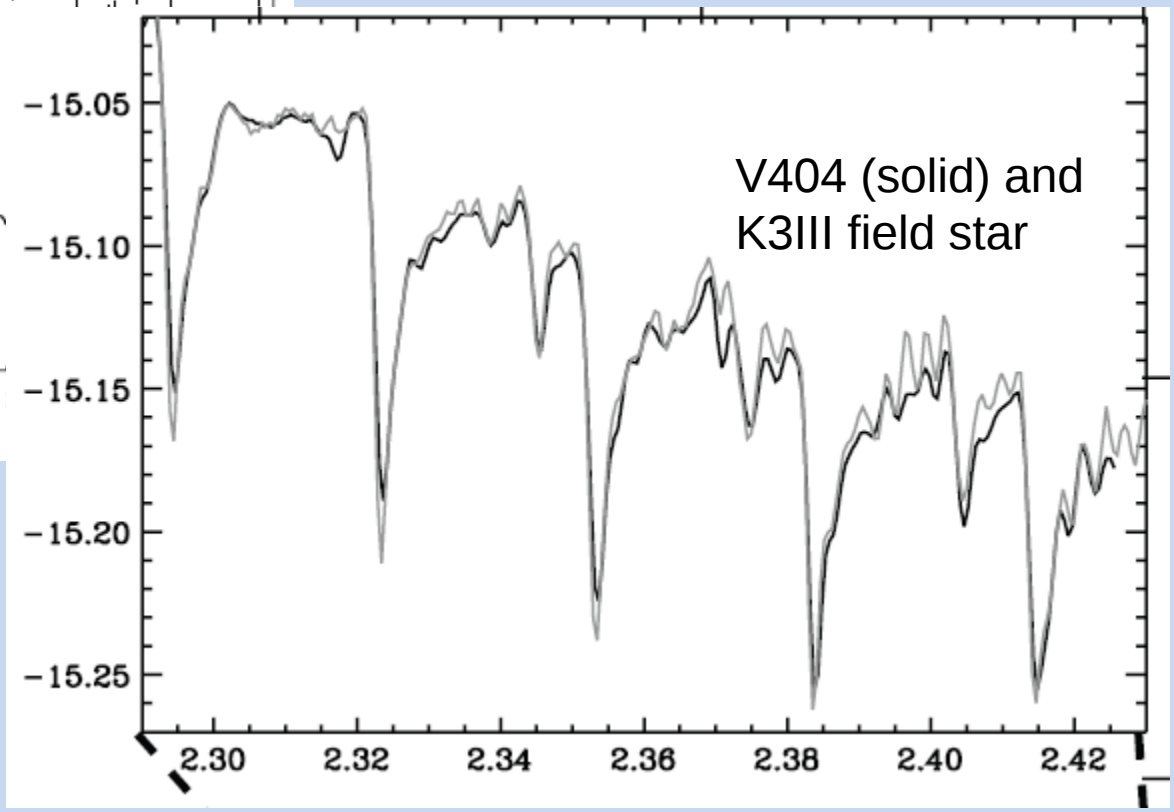


→ $i = 56° \pm 2°$ → $12 \pm 2\ M_\odot$

Recently Khargharia+10 → NIR spectroscopy of V404 Cyg → K3III

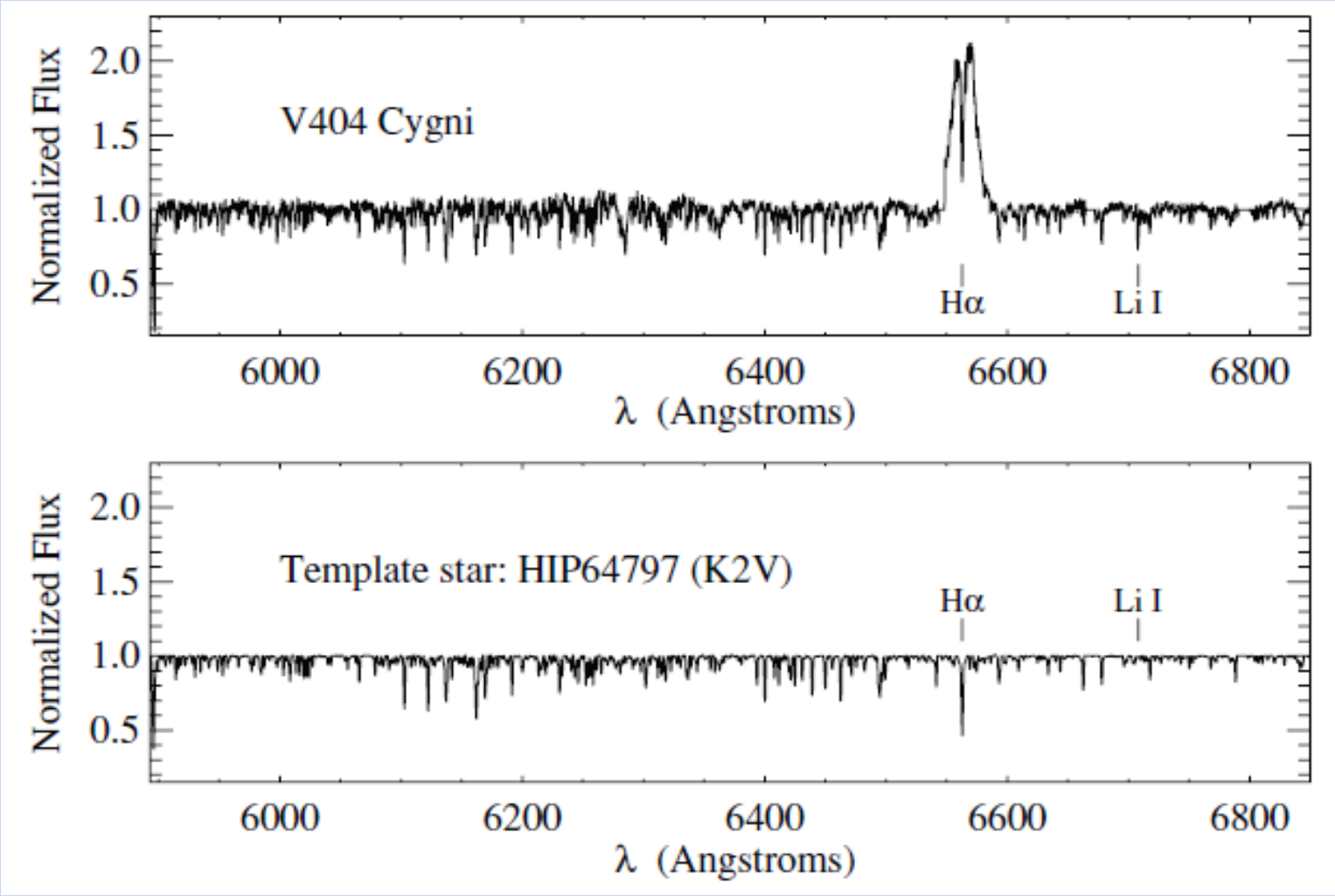


and disc contributing <3%



→ $M_{\rm BH} = 9.0^{+0.2}_{-0.6}\,M_\odot$

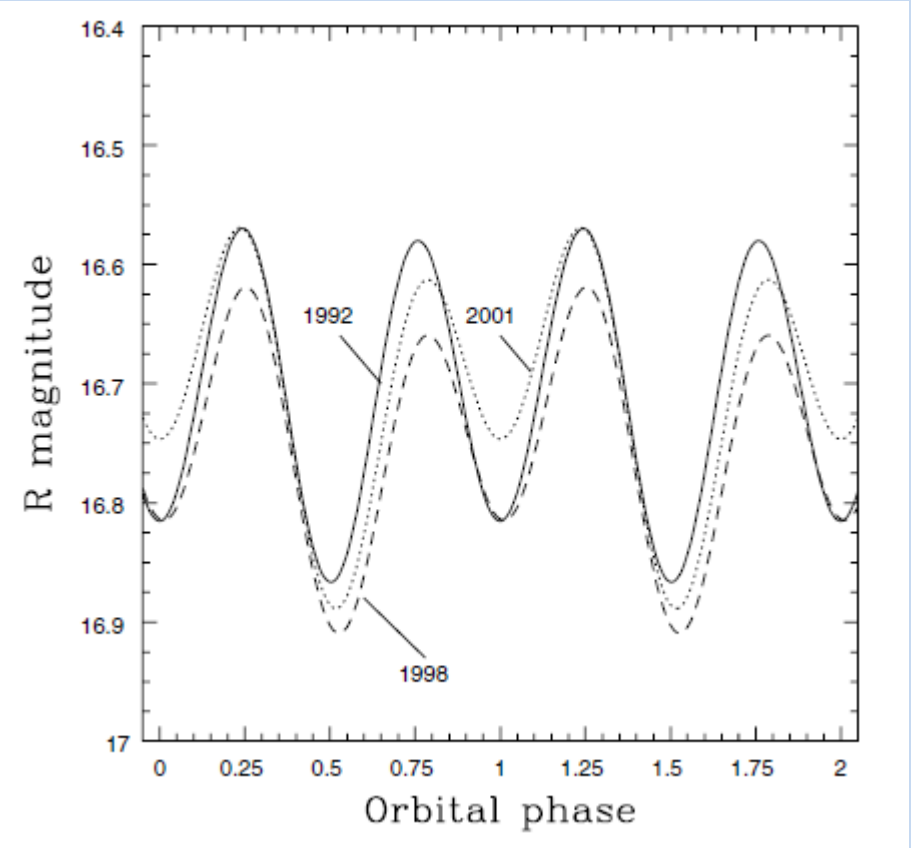
But Gonzalez-Hernandez+11 Keck HIRES spectra from 2009 → K2 sp type
(and enhanced O abundance → donor contaminated in SN/hypernova explosion?



Stellar atmosphere modelling → T_{eff}=4800±100K; log g=3.50±0.15
But we know a=31$R_{\odot}$ and using Eggleton relation → log g=2.69 ?

So, key parameter to constrain for V404 Cyg is the *inclination*

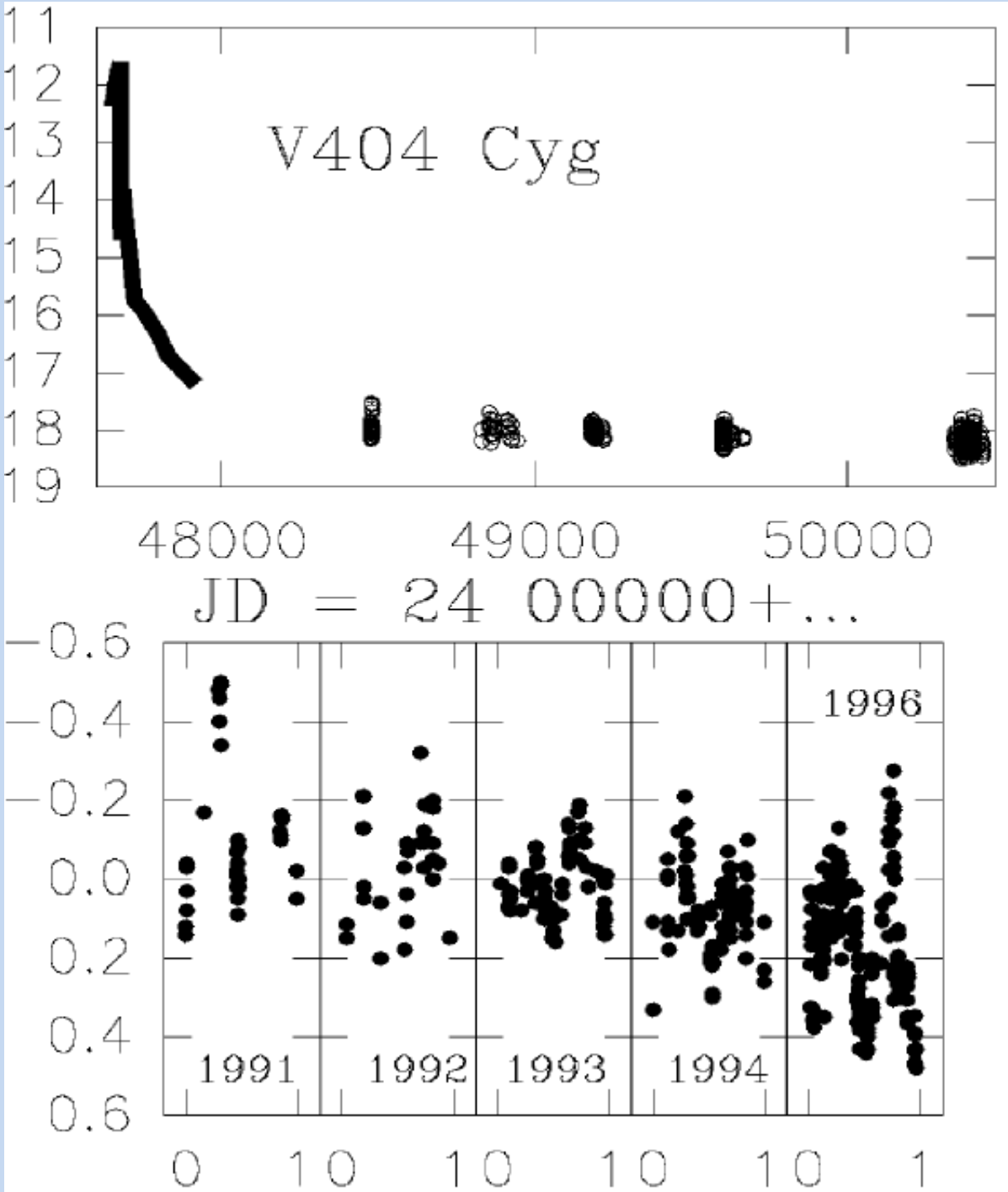
Zurita+04 → mean ellipsoidal light curves for each of 3 years (each is lower envelope)



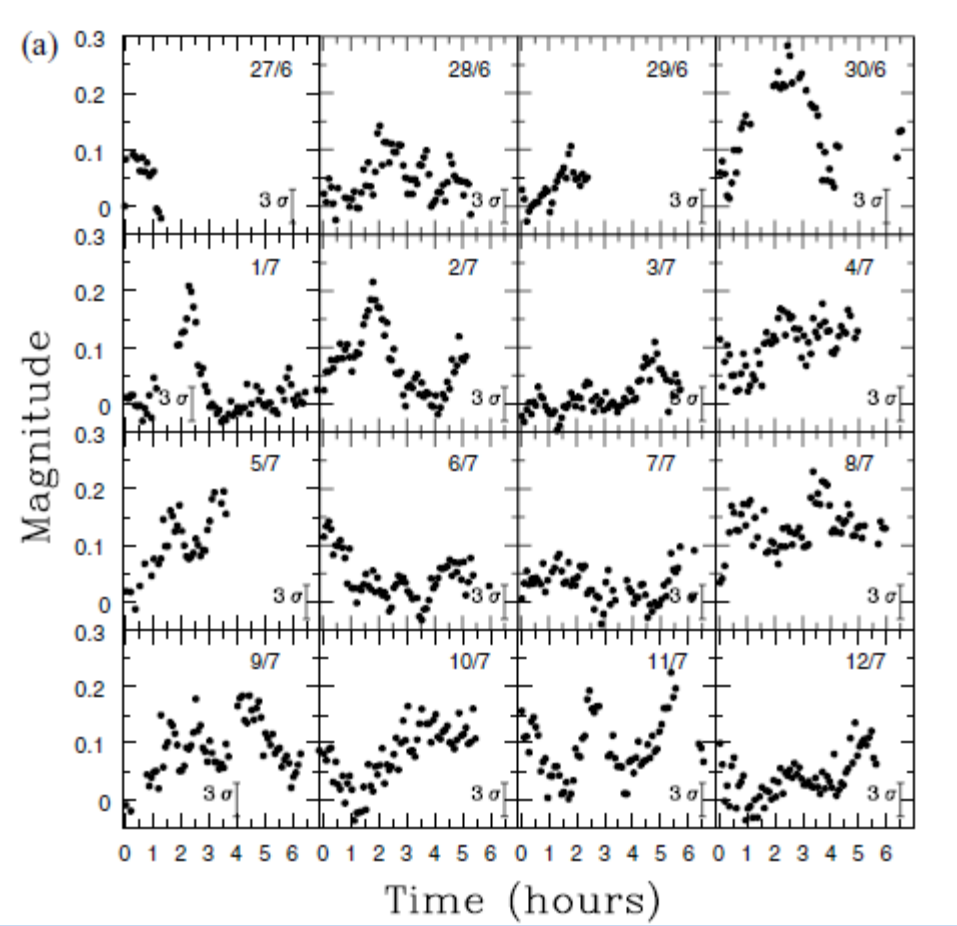
Sanwal+96 → $i = 67 \pm 2^{o}$ (based on increased disc contribution)
- controversial as NIR spec → less disc!

Pavlenko 06
Crimean Astrophys.Obs. 0.5m
B+V 1991-97

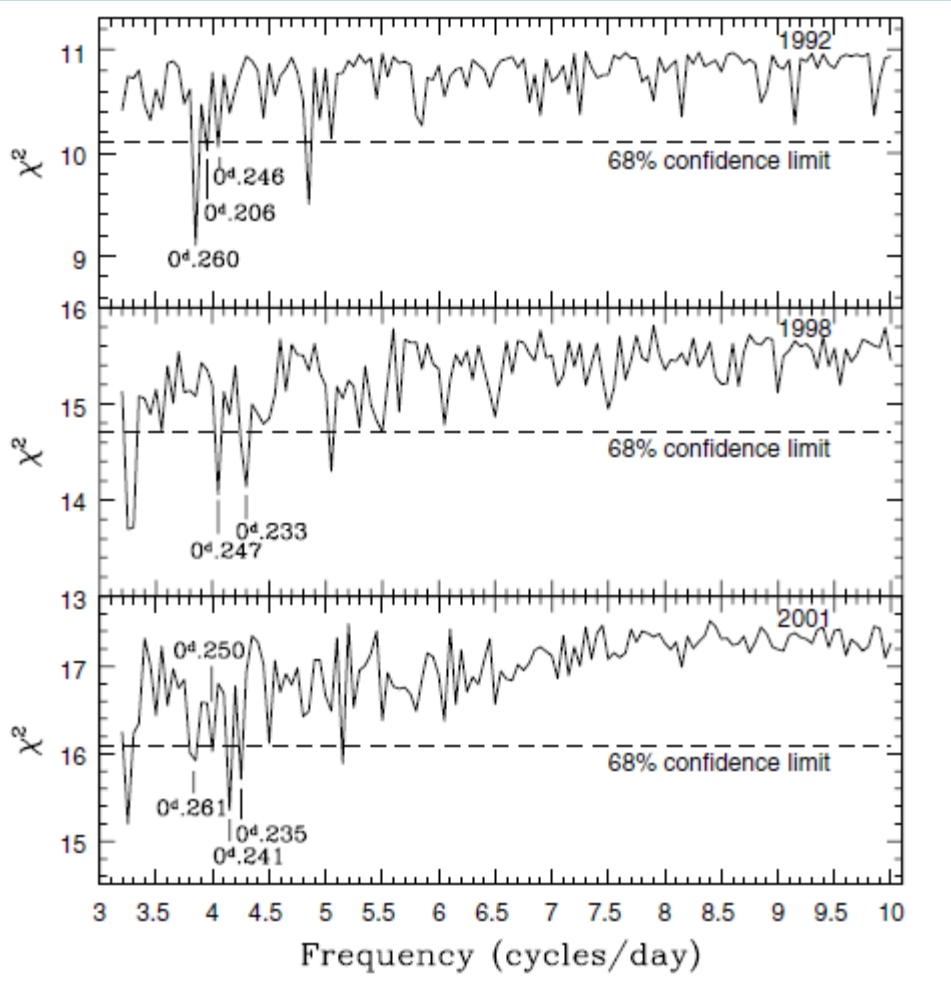
Annual mean light curve
folded on 6.5d orbital period



What is causing the “6h” variability? (Pavlenko+96; Zurita+04)

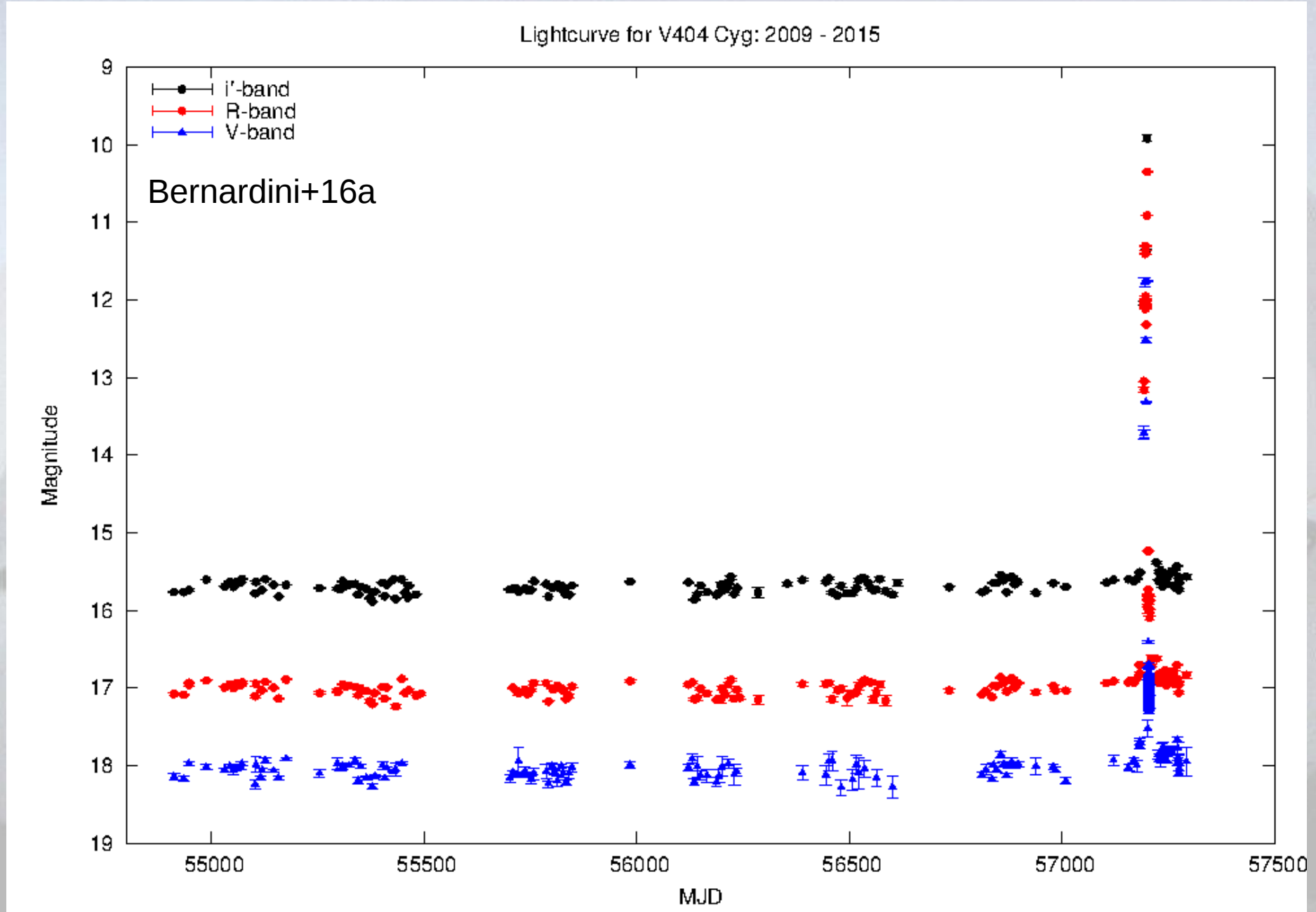


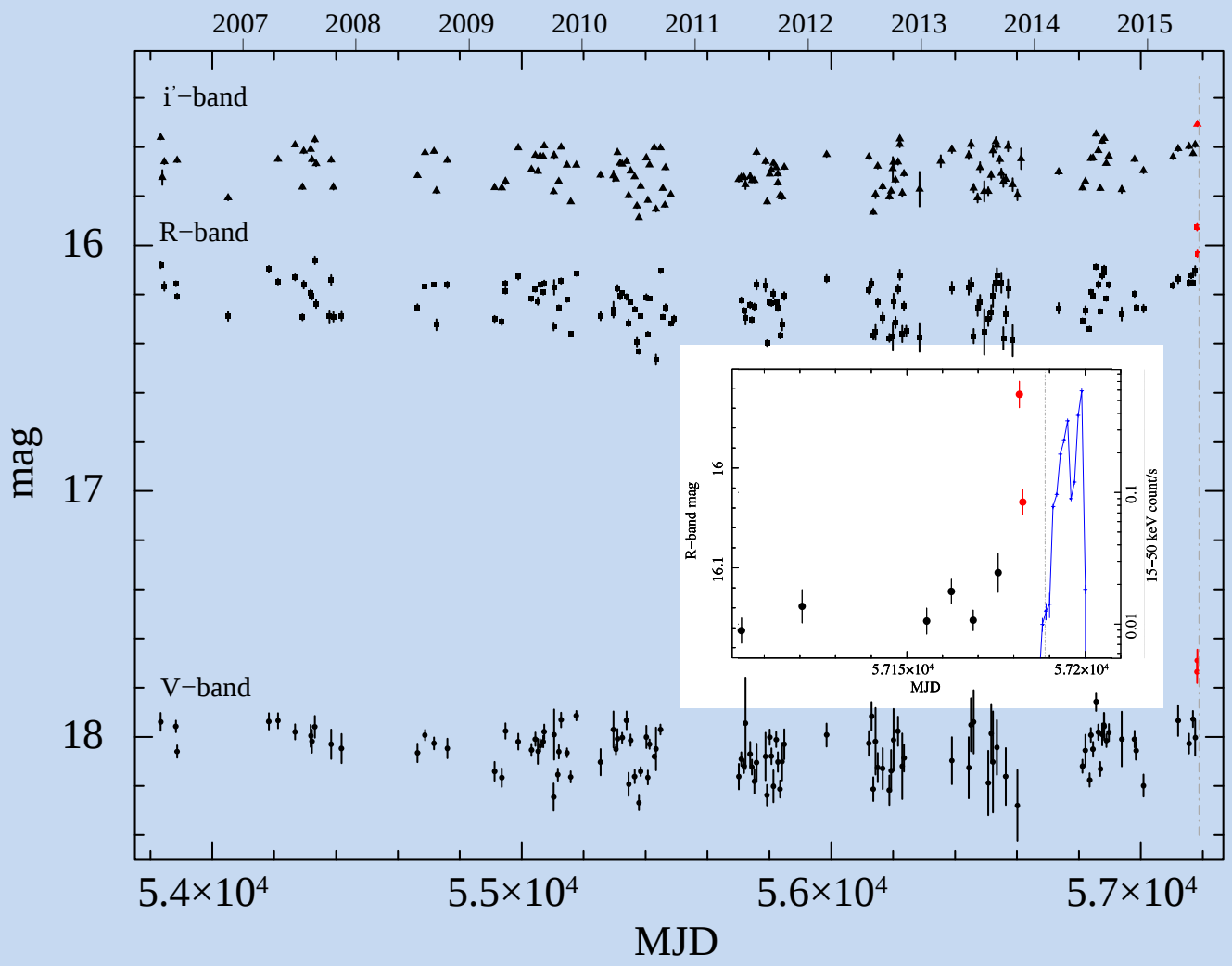
Light curves after removing ellipsoidal modulation



PDM power spectra

Robotic monitoring program with FT/LCOGT (Dave Russell, Federico Bernardini, Fraser Lewis) of ~40 LMXBs





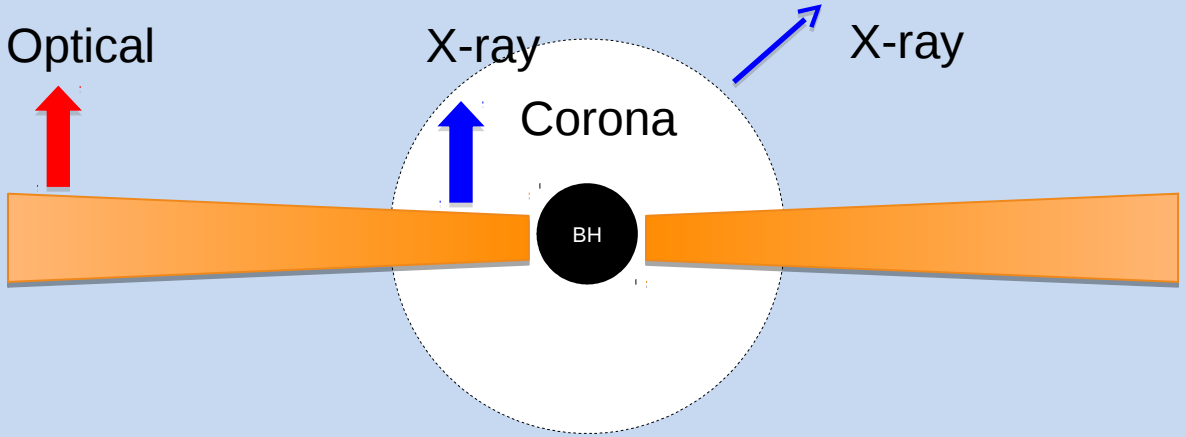
- Optical precursor

Optical rises 7 days before X-ray

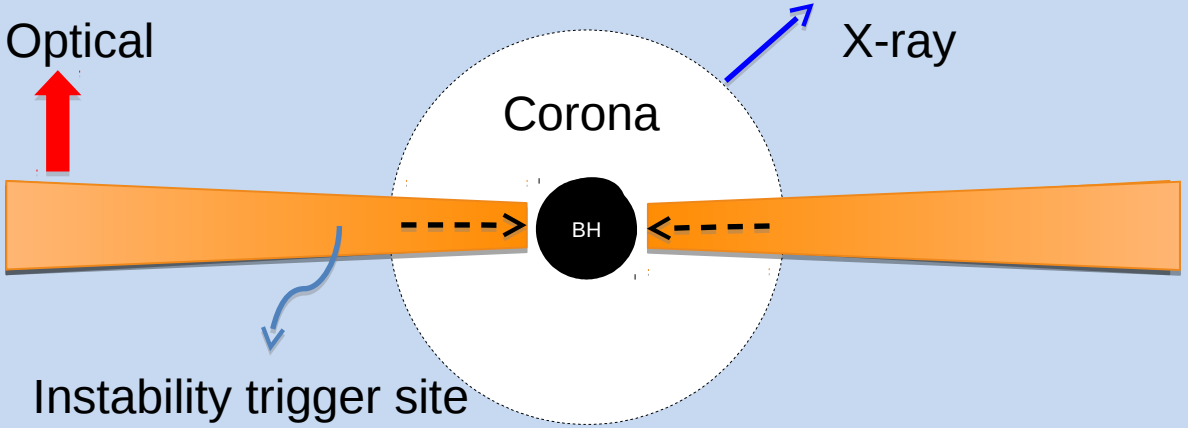
Increase is predicted by the DIM but not observed before in LMXBs

• Disk Instability Model

(Hameury+97)



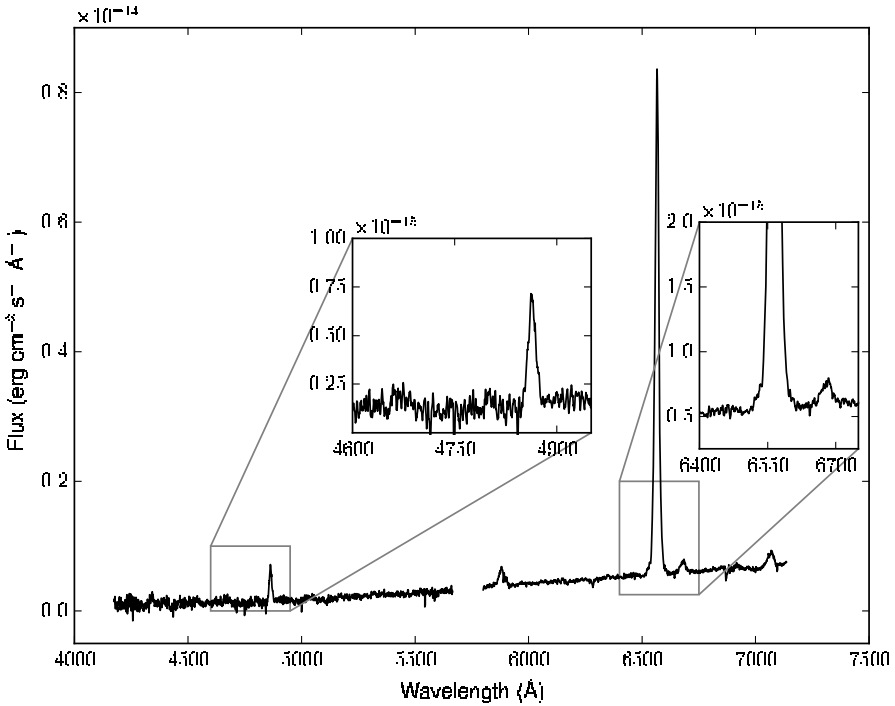
OUTBURST



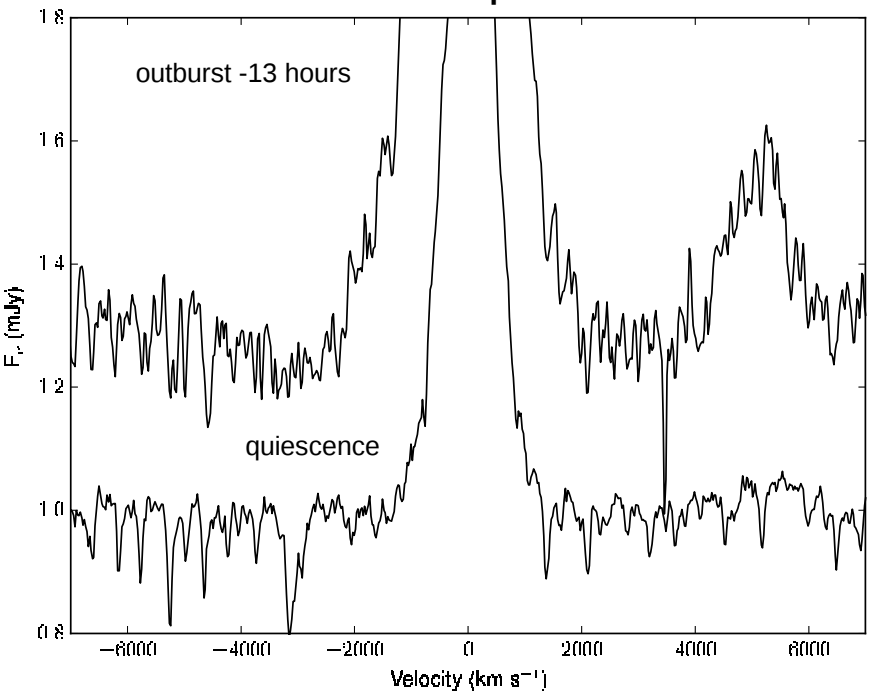
QUIESCENCE

• Optical Spectrum

Luckily V404 Cyg was observed 13 hours before its outburst



Hα is x7 quiescence

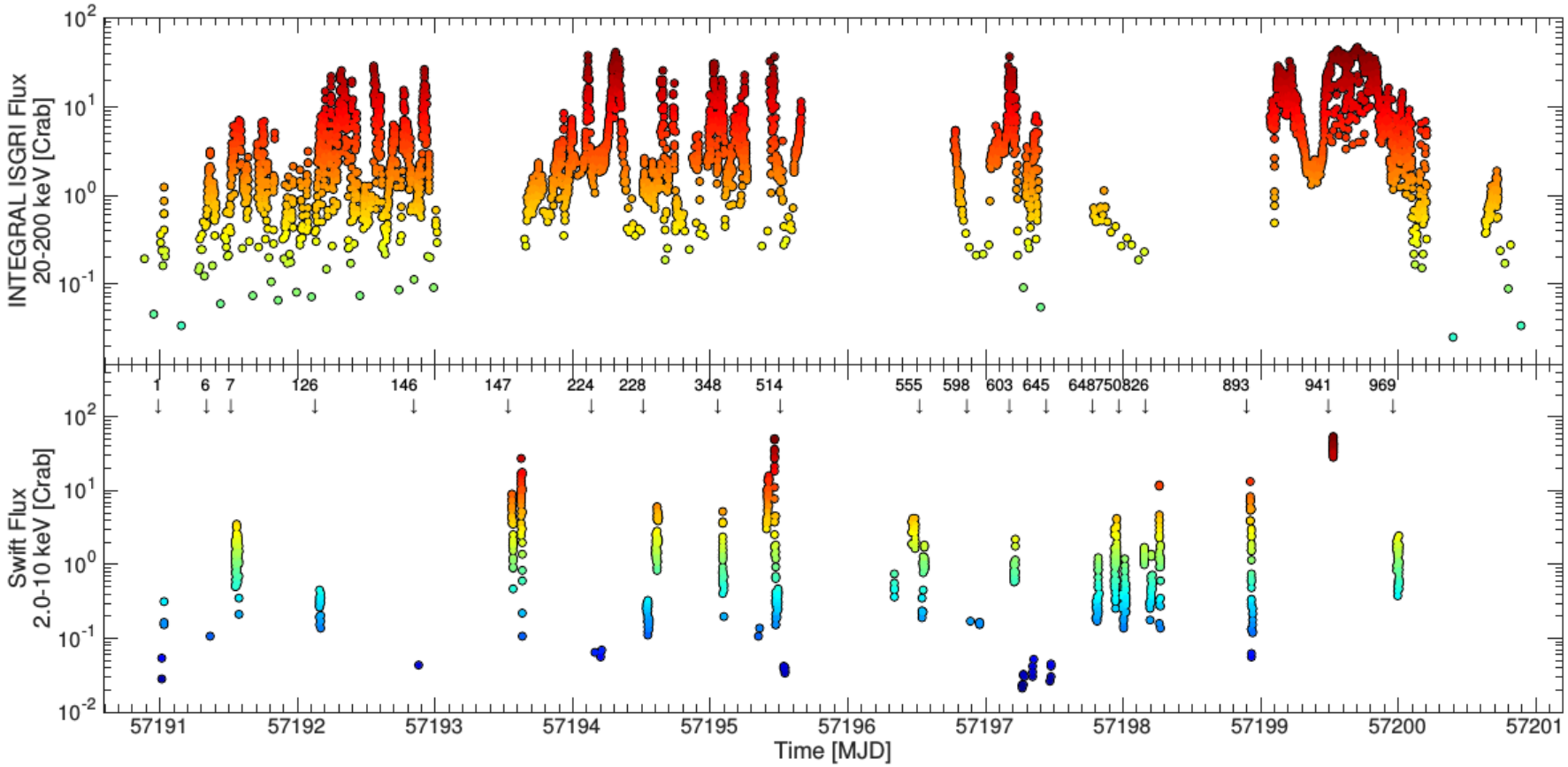


$R_{in} = 0.5(c \sin(i)/v_{in})^2$, i = 67 degrees

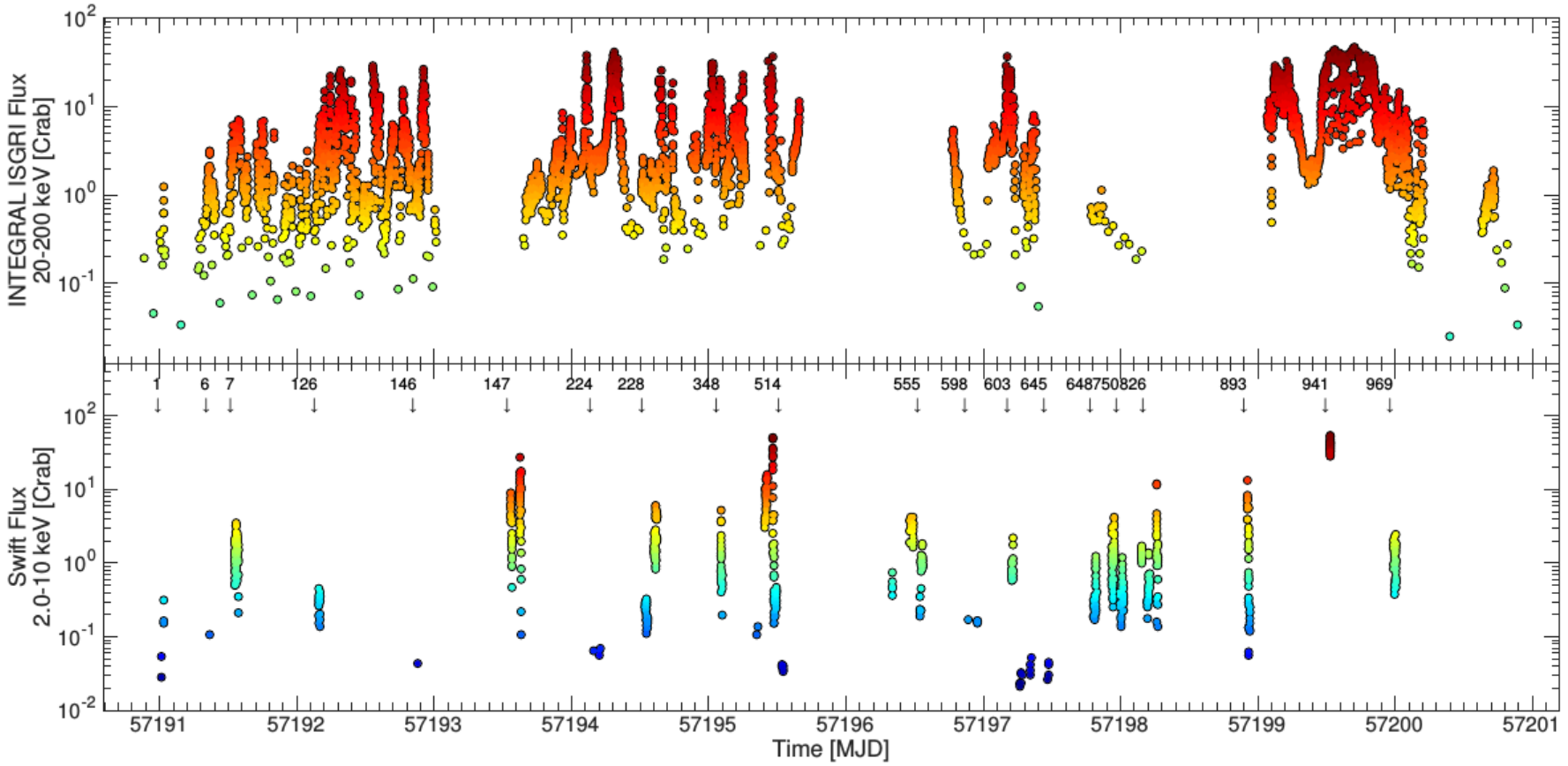
Quiescence: $v_{in} \leq 1500$ km/s → $R_{in} \geq 17000\ R_s$

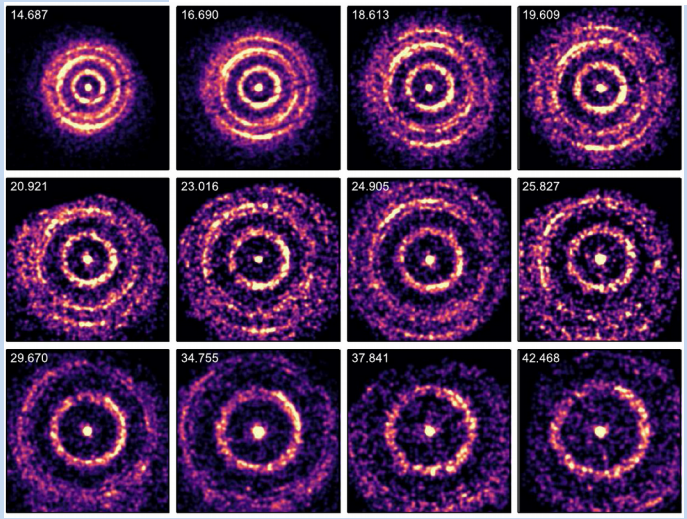
Pre-outburst: $v_{in} \geq 2468$ km/s → $R_{in} \leq 6200\ R_s$ (factor of 3 lower than quiescence)

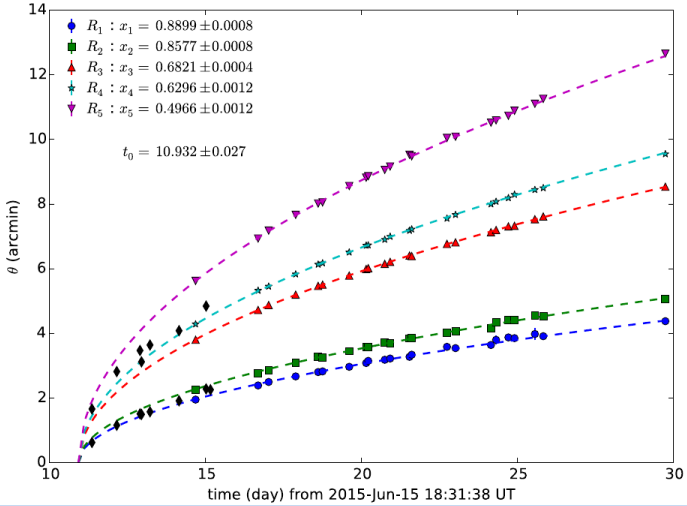
Motta+17

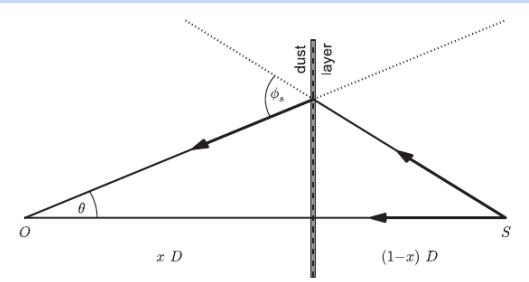

INTEGRAL ISGRI Flux
20-200 keV [Crab]
Swift Flux
2.0-10 keV [Crab]
1
6
7
126
146
147
224
228
348
514
555
598
603
645
648
750
826
893
941
969
57191
57192
57193
57194
57195
57196
57197
57198
57199
57200
57201
Time [MJD]

Motta+17

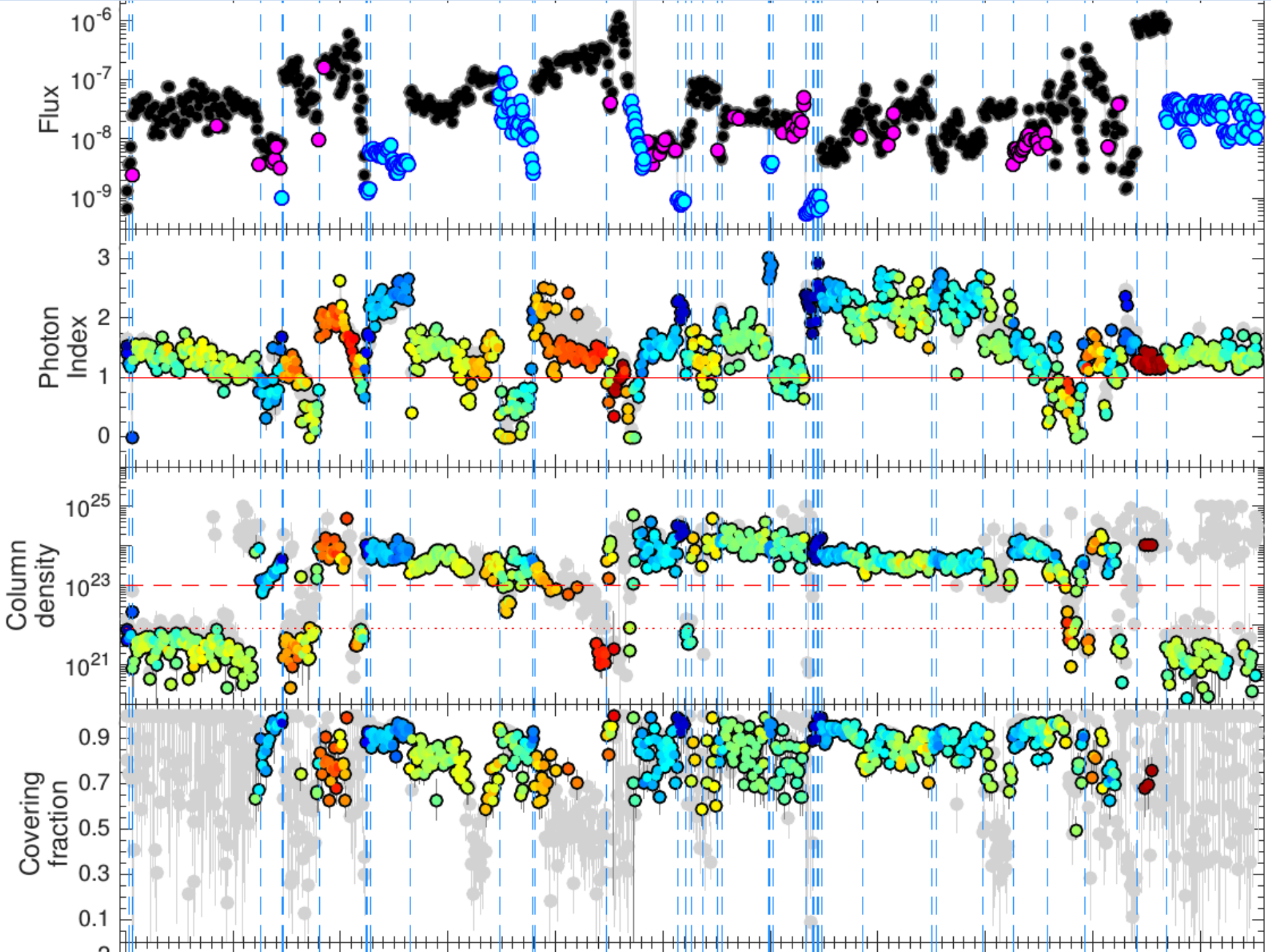




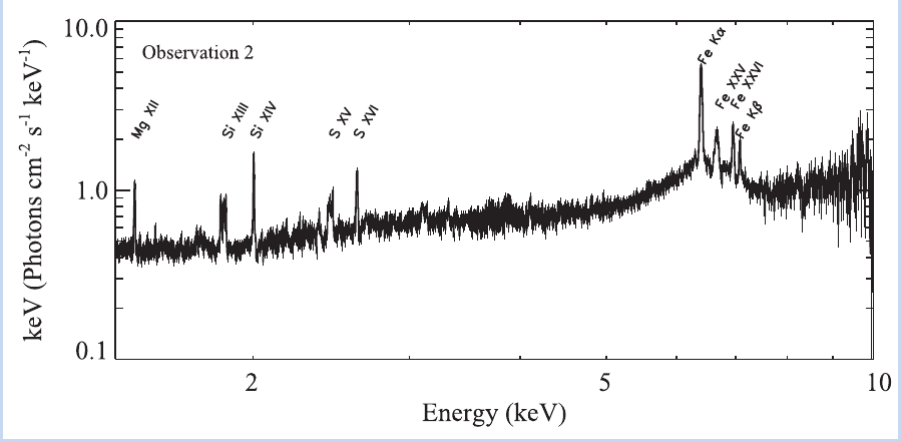




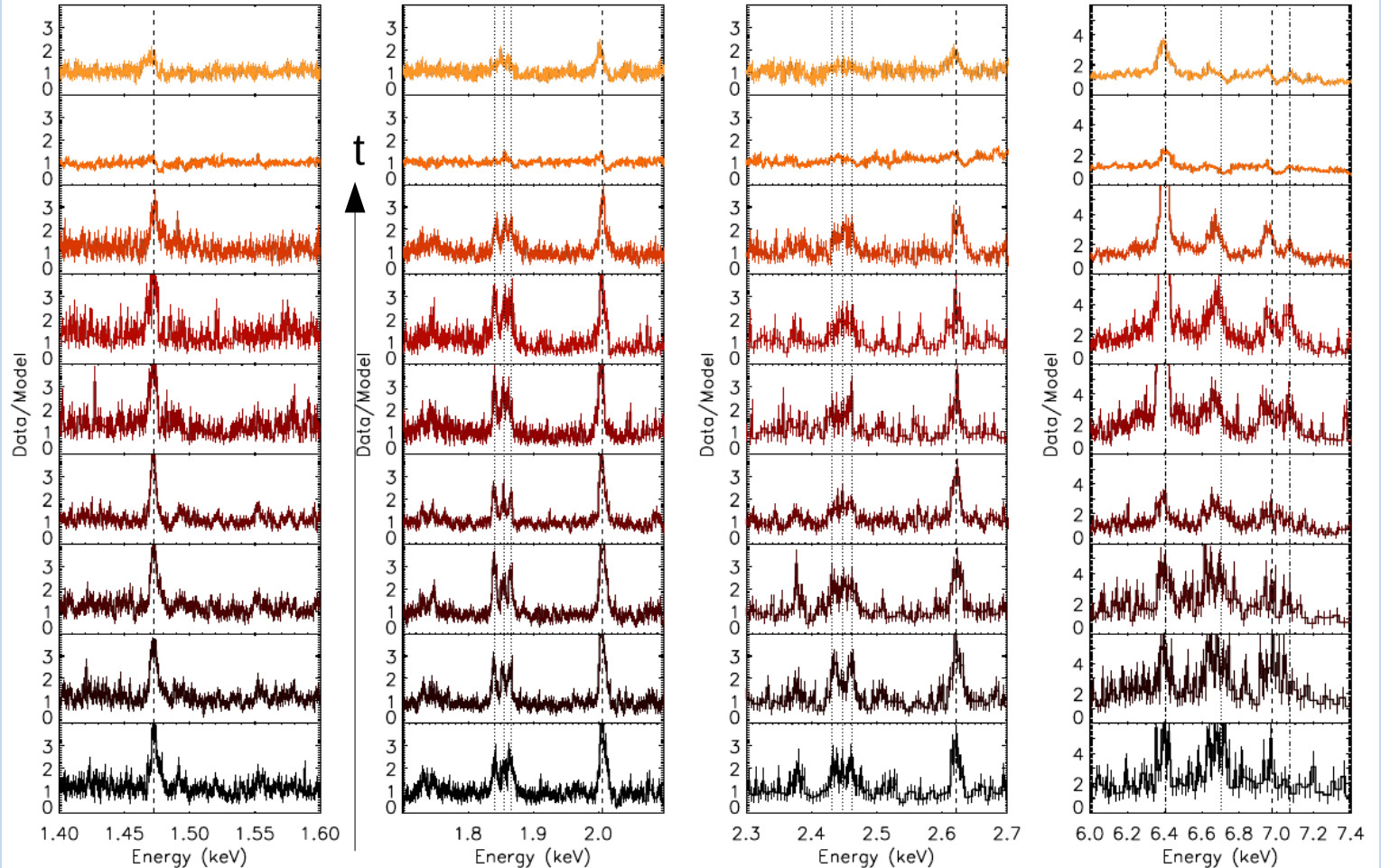
Beardmore+16

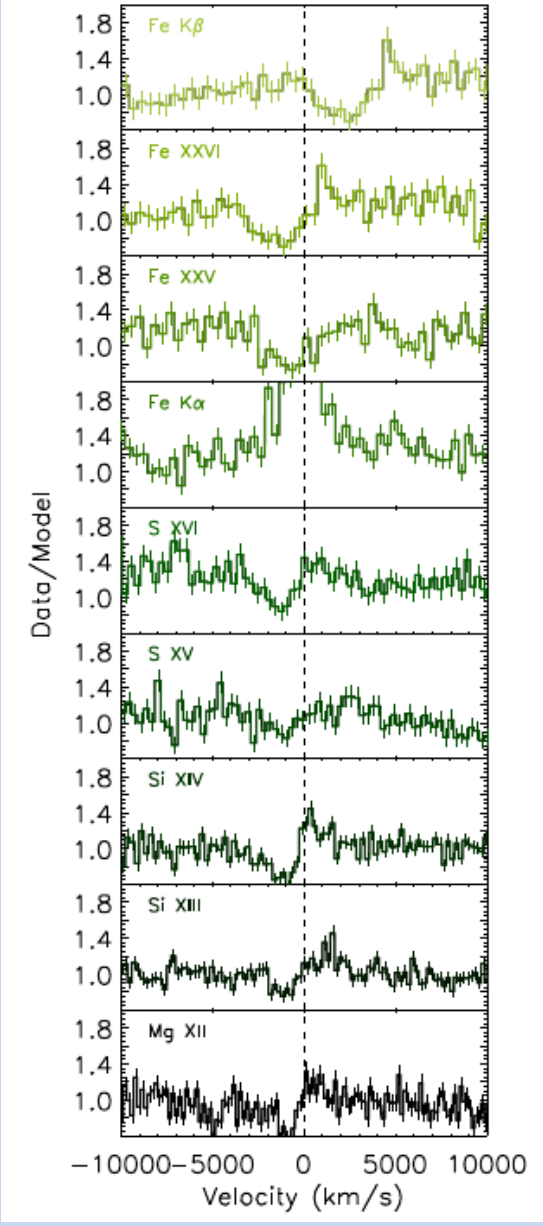

Flux
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Photon Index
3
2
1
0
Column density
10^{25}
10^{23}
10^{21}
Covering fraction
0.9
0.7
0.5
0.3
0.1

King+15: CXO spectra:
2 obs at ~10^{37} erg/s

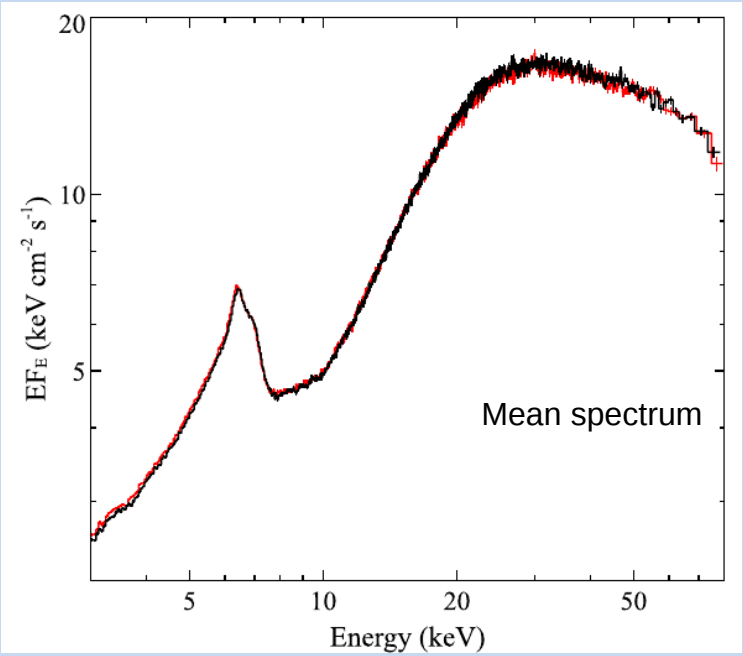


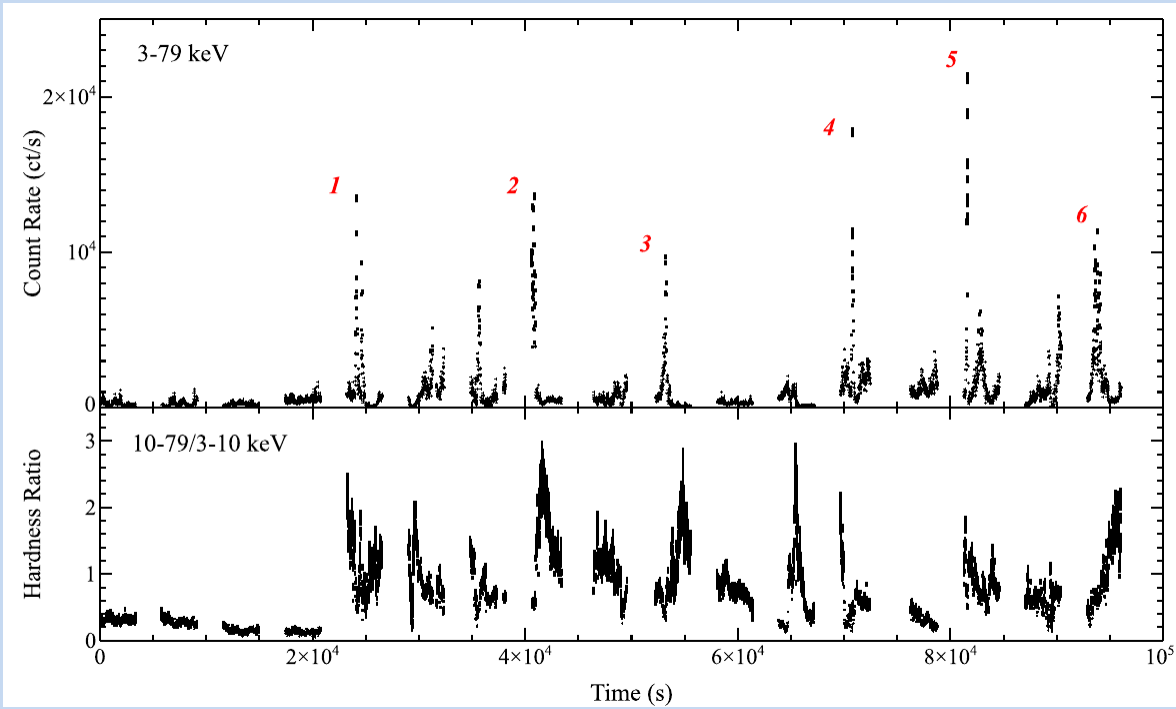
And P Cyg profiles → disc wind





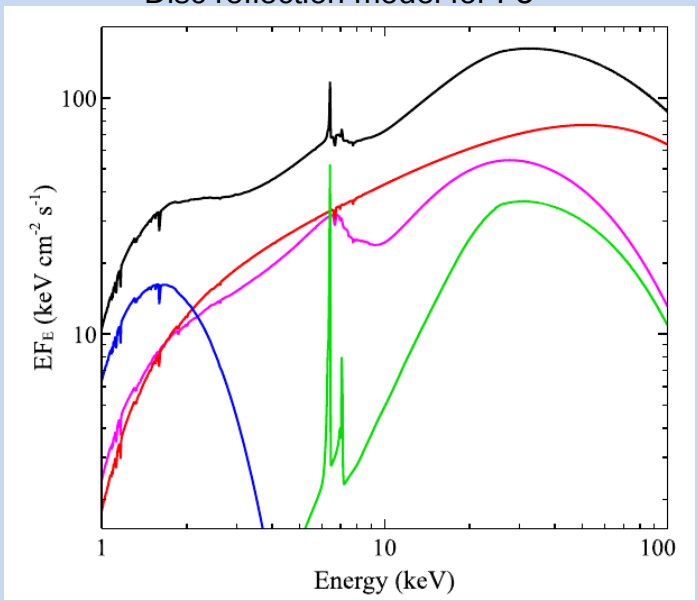
Walton+16: NuSTAR

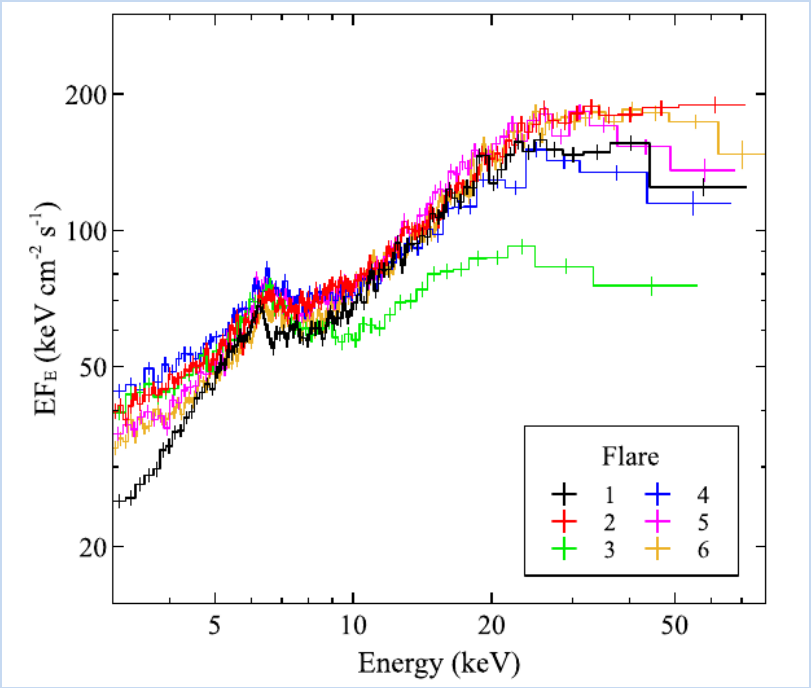


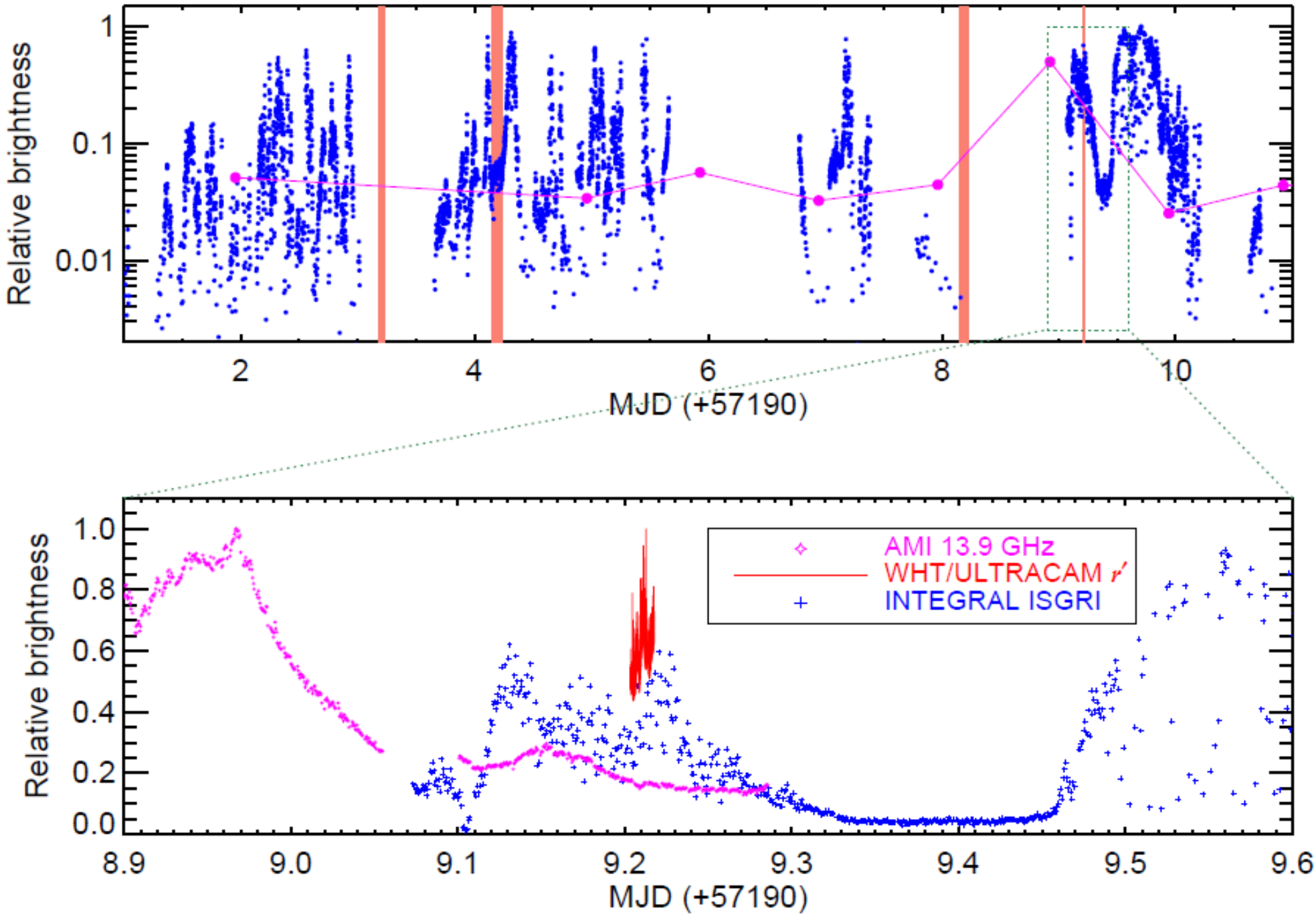


- disc
- HE PL tail
- disc reflection
- distant reflection

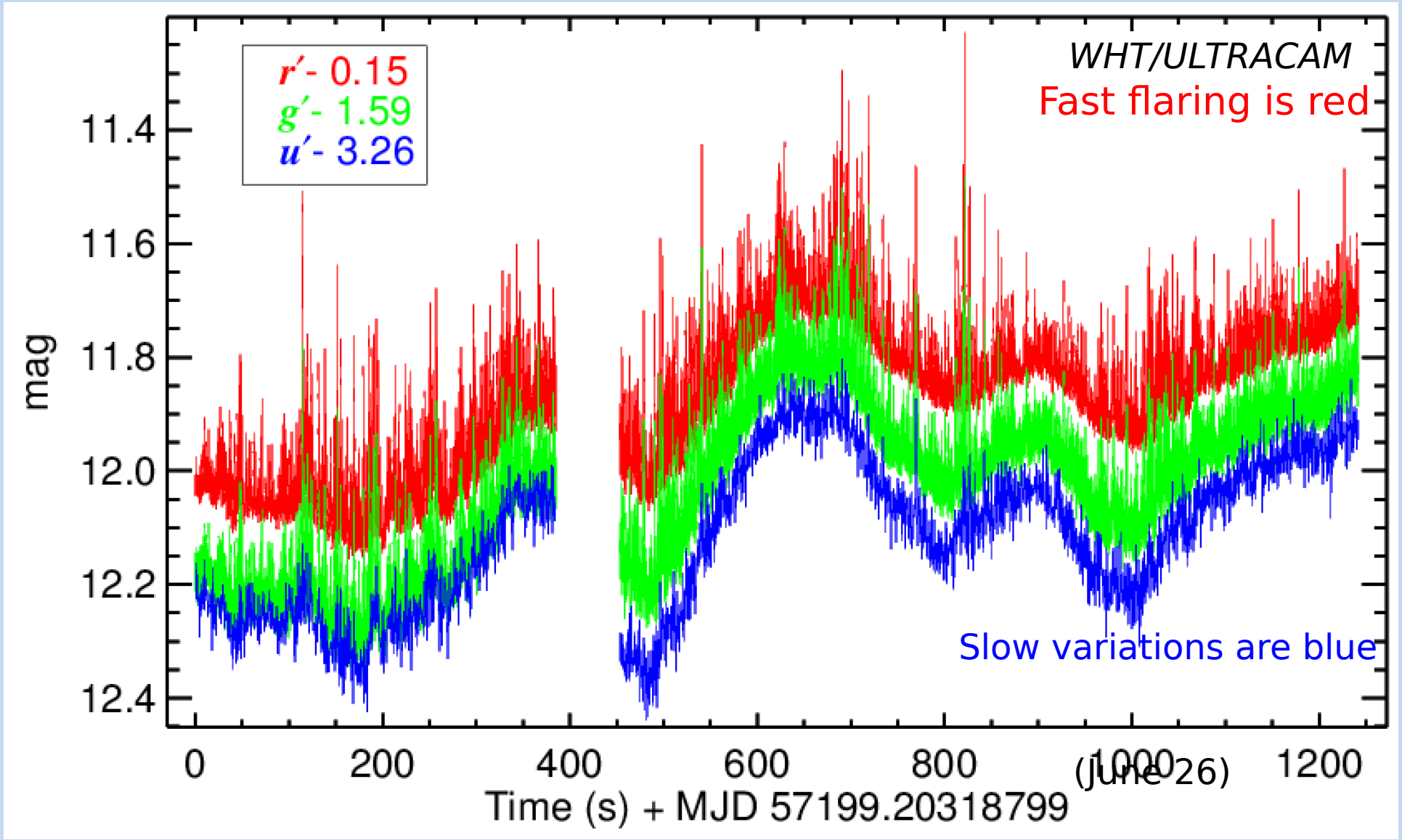
Disc reflection model for F5

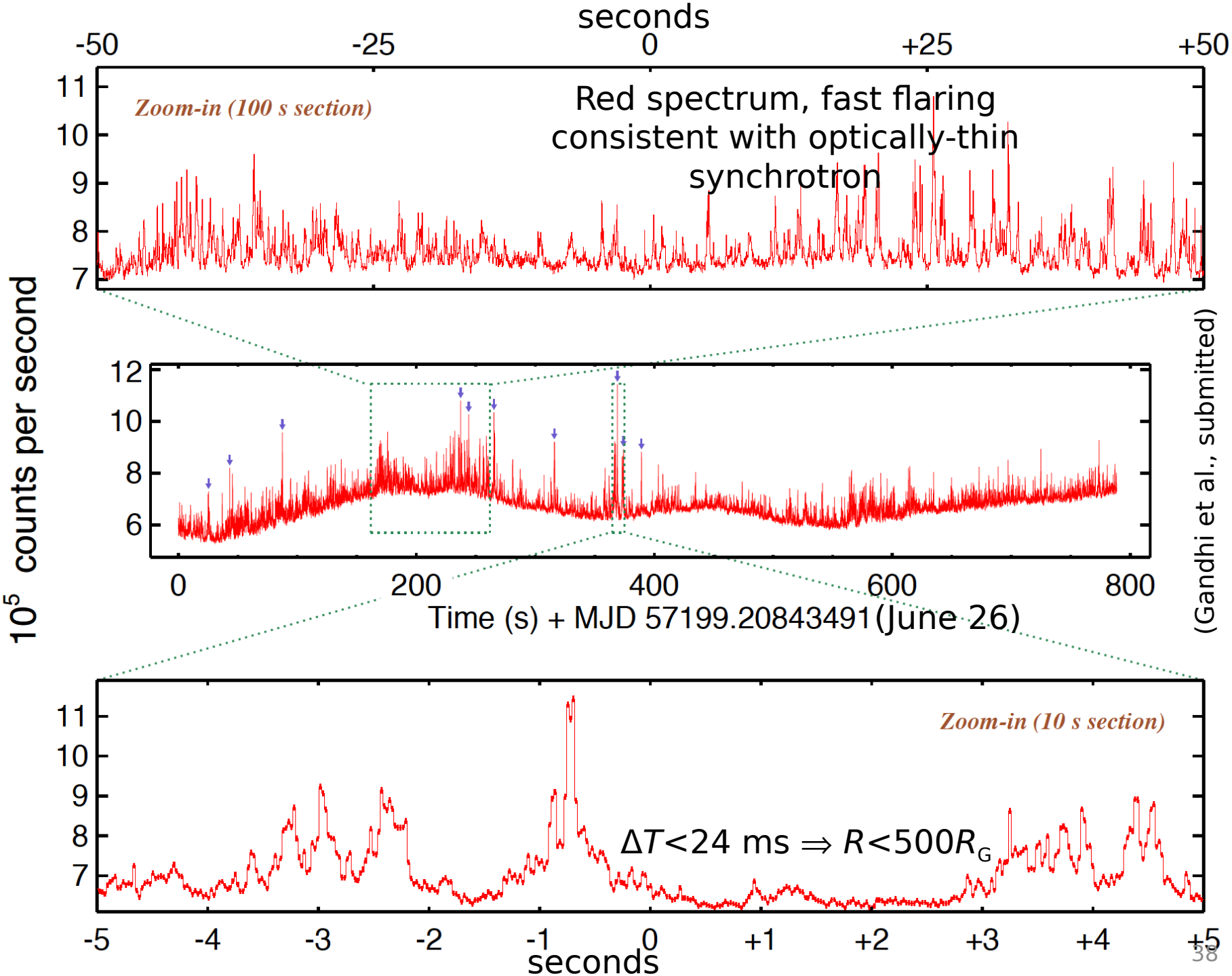




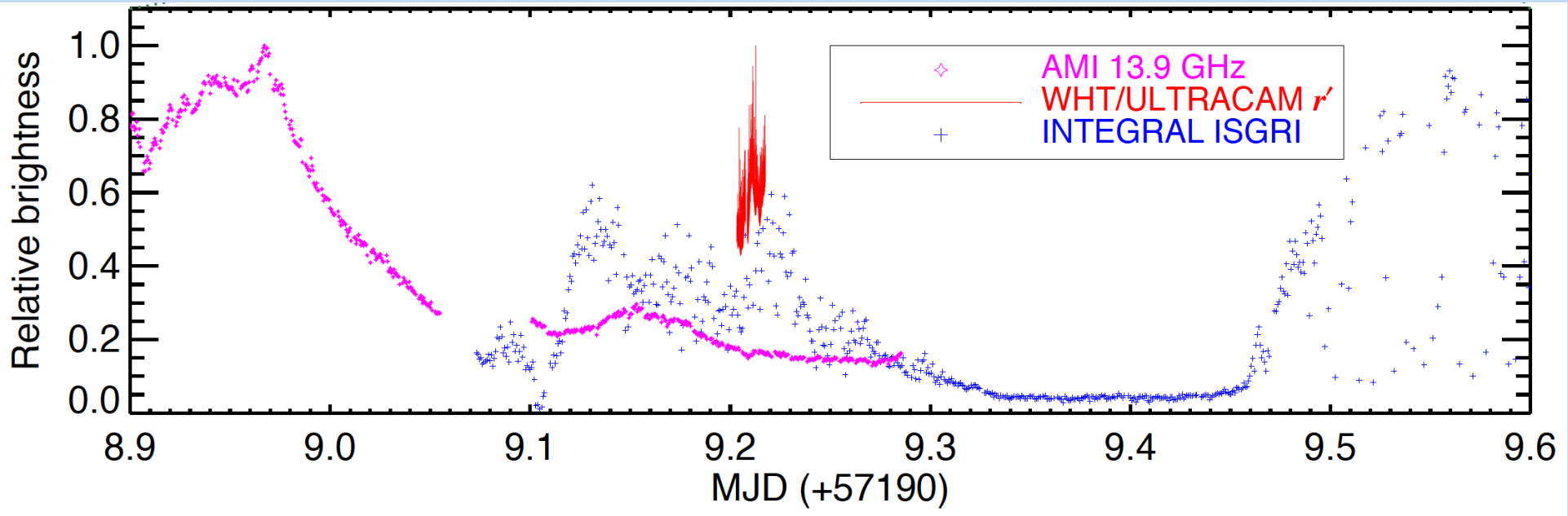

Relative brightness
1
0.1
0.01
2
4
6
8
10
MJD (+57190)
Relative brightness
1.0
0.8
0.6
0.4
0.2
0.0
AMI 13.9 GHz
WHT/ULTRACAM r′
INTEGRAL ISGRI
8.9
9.0
9.1
9.2
9.3
9.4
9.5
9.6
MJD (+57190)

Gandhi+16: Slow variations + Intense sub-second flaring (ΔT=24 ms)

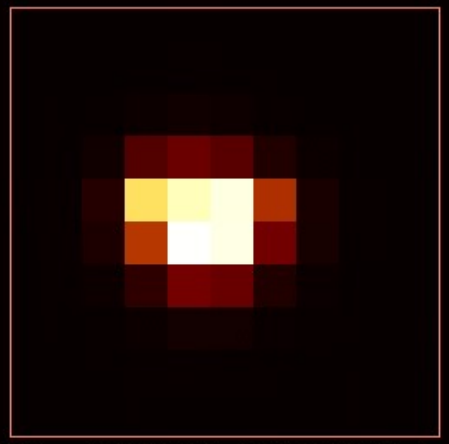



seconds
-50
-25
0
+25
+50
Zoom-in (100 s section)
Red spectrum, fast flaring
consistent with optically-thin
synchrotron
11
10
9
8
7
12
10
8
6
0
200
400
600
800
10^5 counts per second
Time (s) + MJD 57199.20843491 (June 26)
(Gandhi et al., submitted)
Zoom-in (10 s section)
ΔT<24 ms $\Rightarrow$ R<500R_G
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
+5
seconds

Sub-second flaring quasi-coincident with radio and X-ray outburst peak

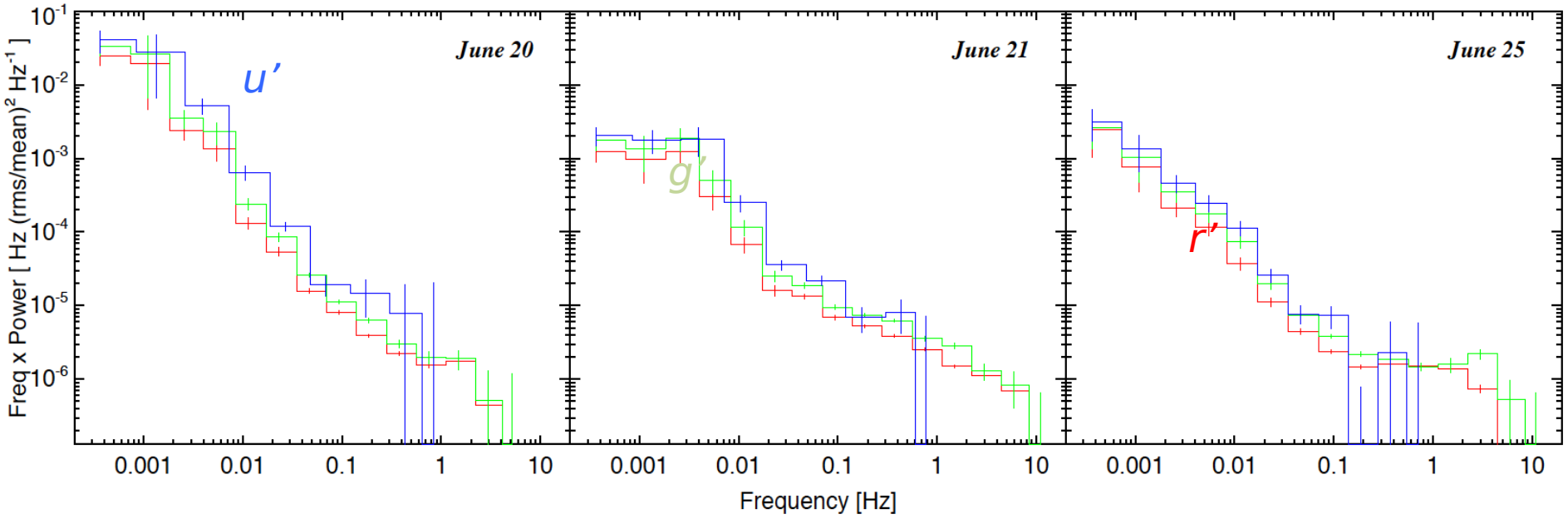


Gandhi+16 MN

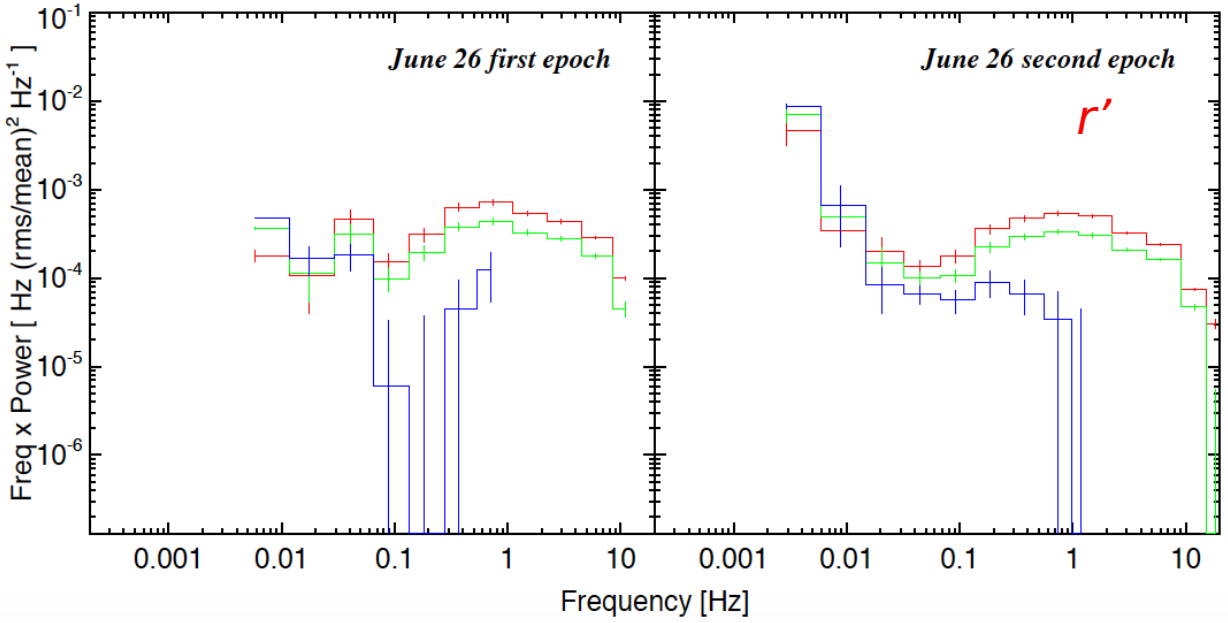


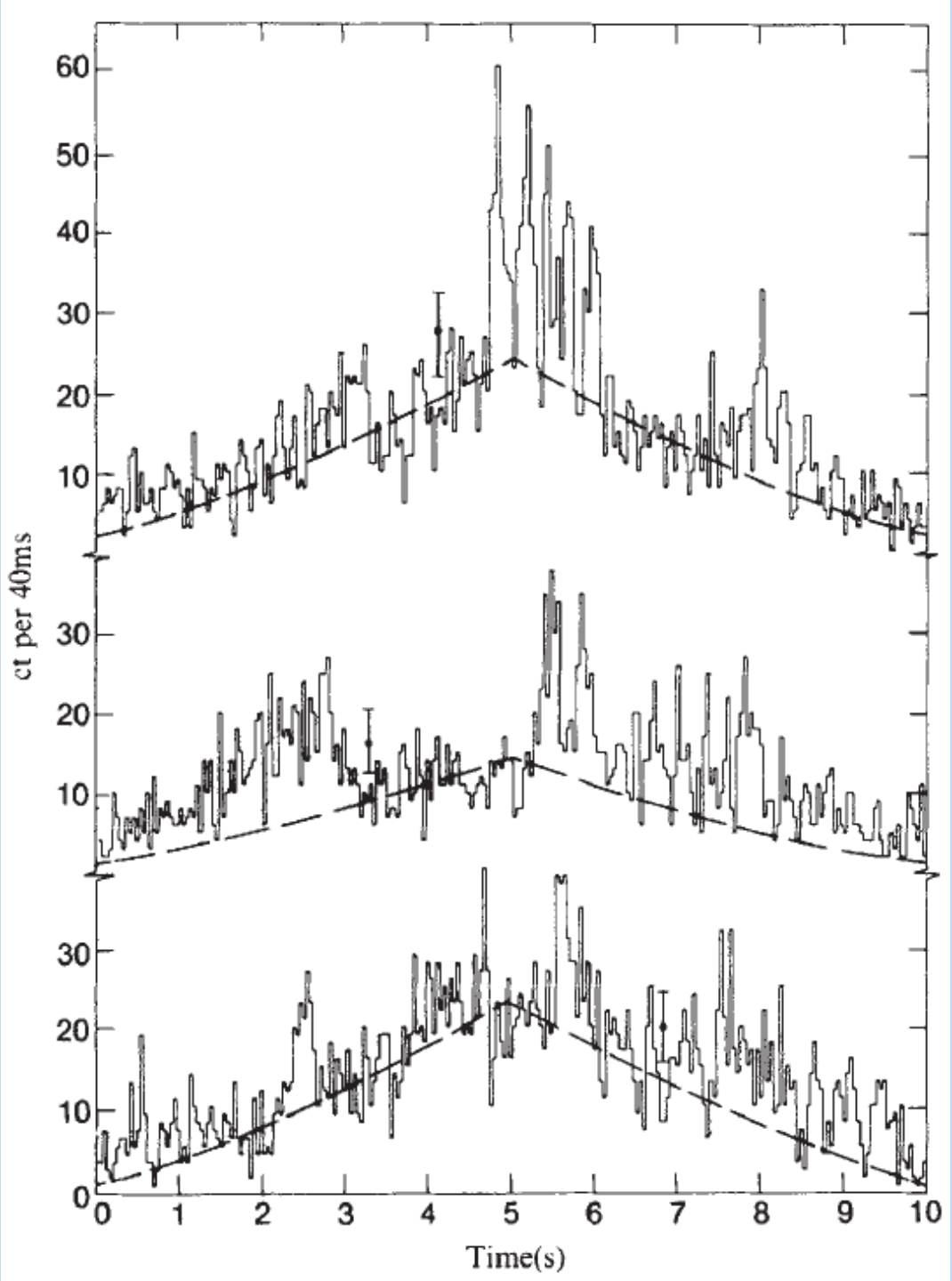
V404 Cyg / ULTRACAM / WHT (2015 Jun 26)

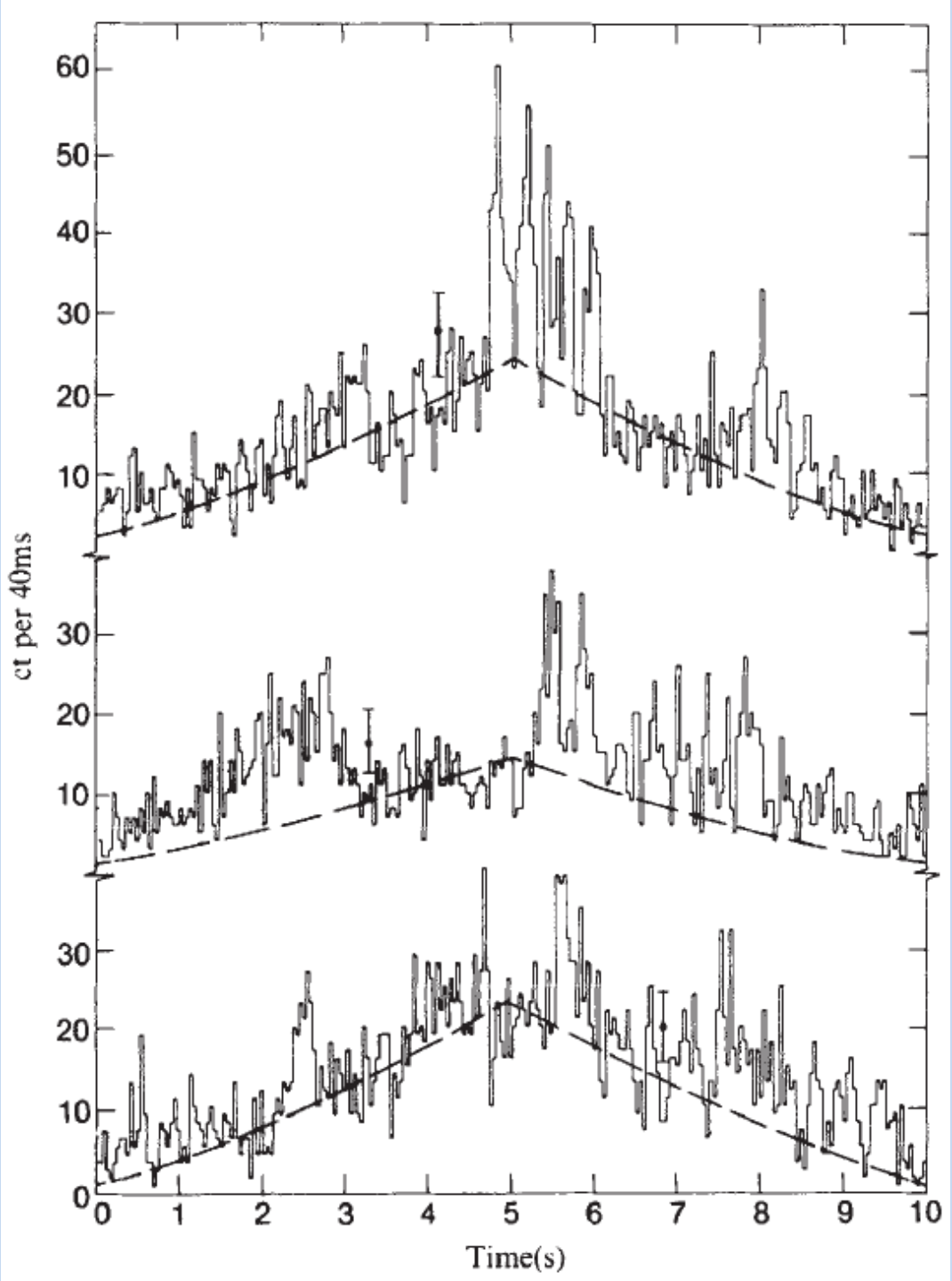
$T = 0.00\ s$



Optical PSDs



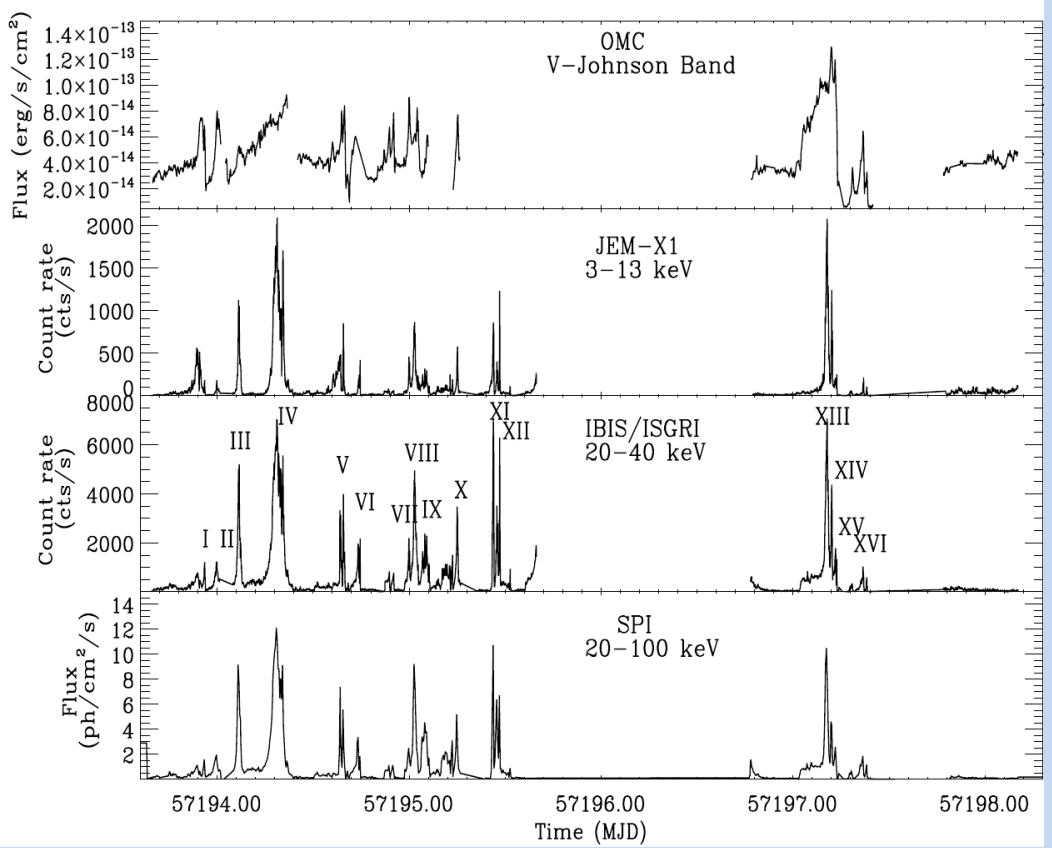

ct per 40ms
60
50
40
30
20
10
30
20
10
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
Time(s)

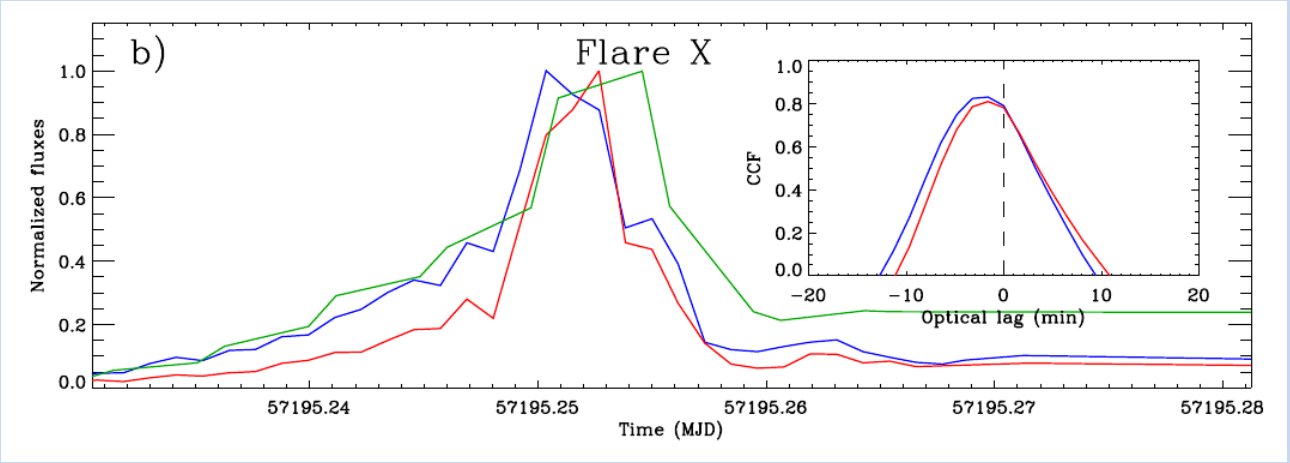


GX339-4
HEAO-1 A1 (1-20keV)
Samimi+79

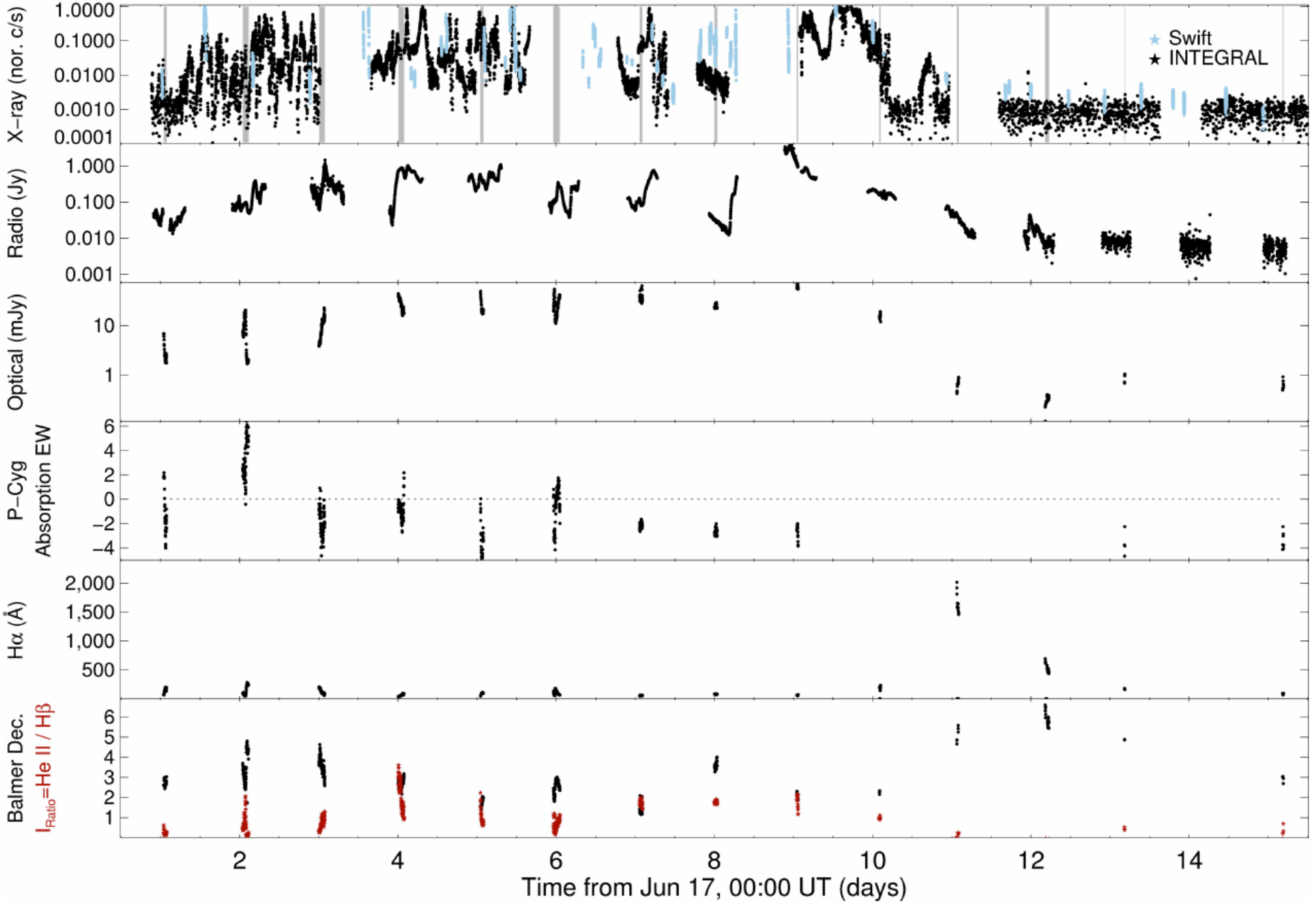
Rodriguez+15

INTEGRAL



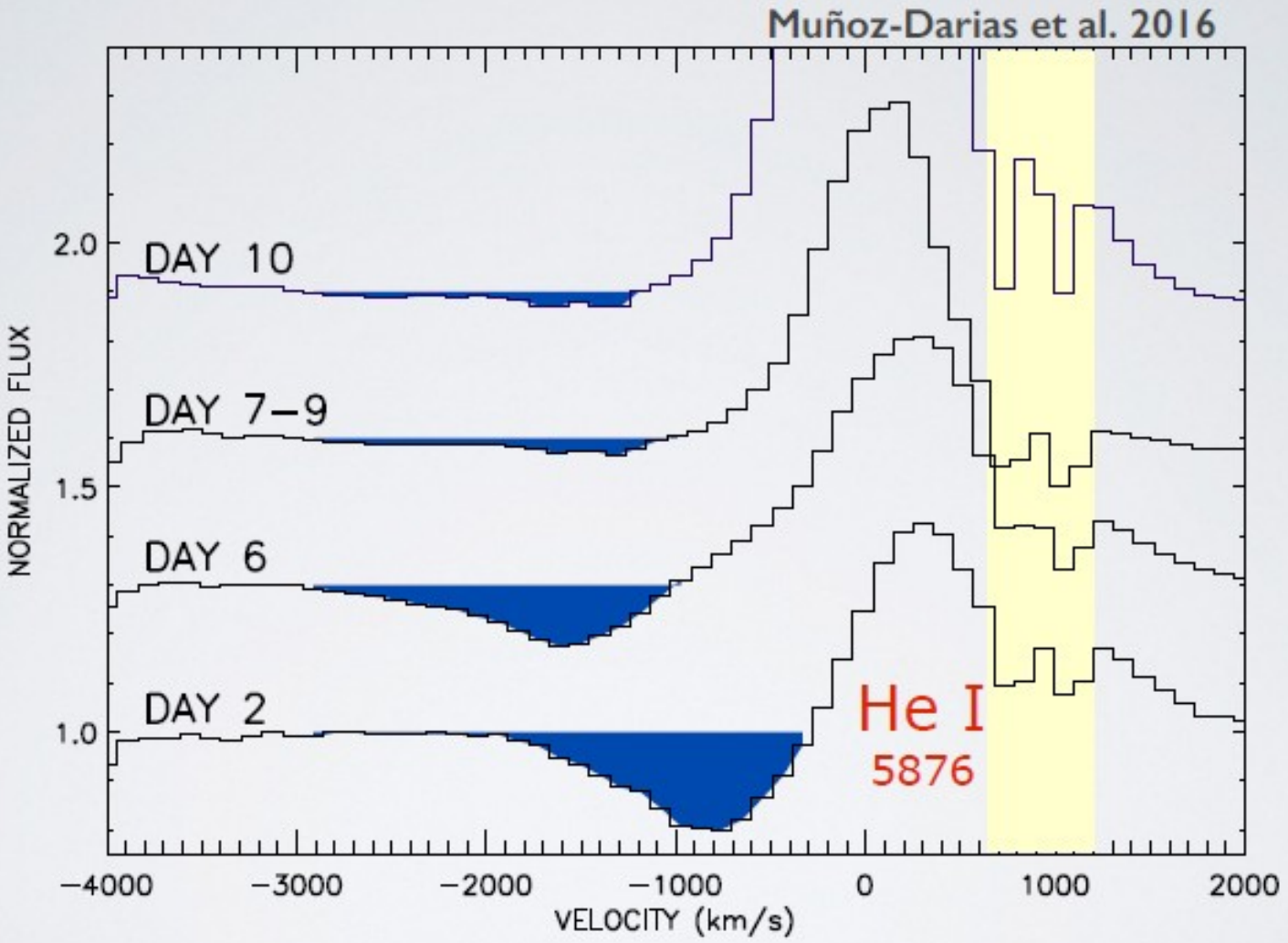


V delayed wrt X-rays by ~ minutes

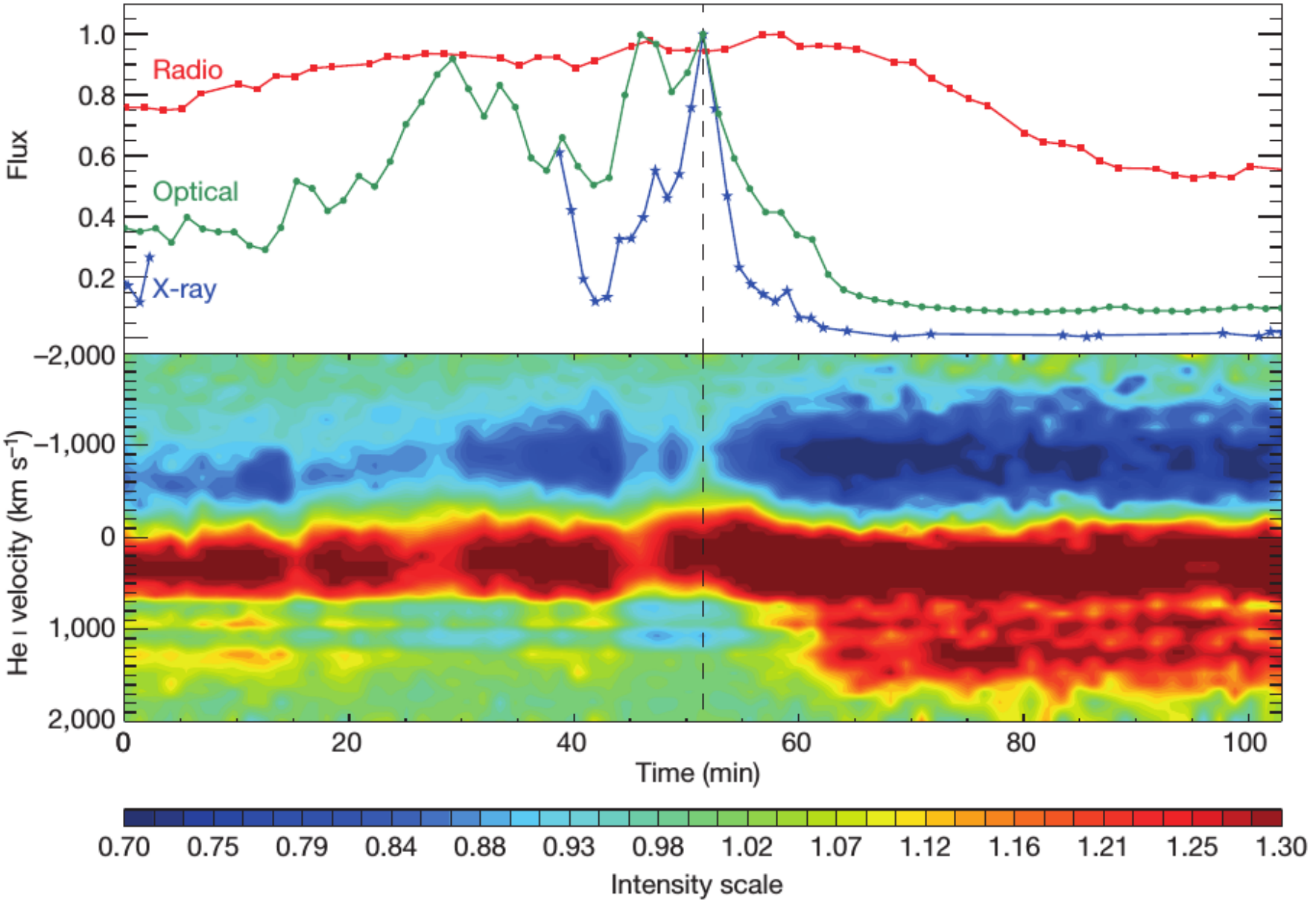


Muñoz-Darias+16

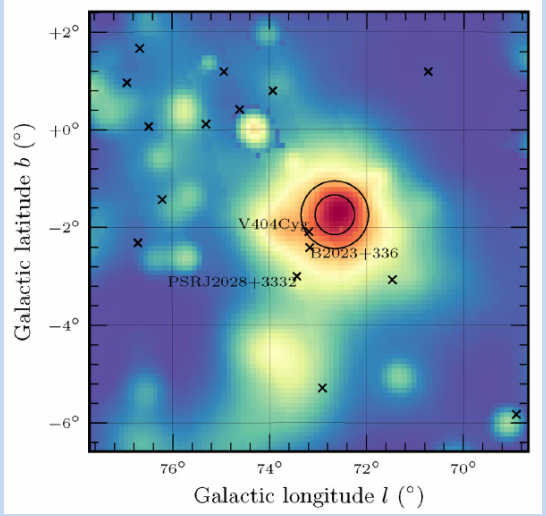
P-CYG PROFILES IN 12 LINES



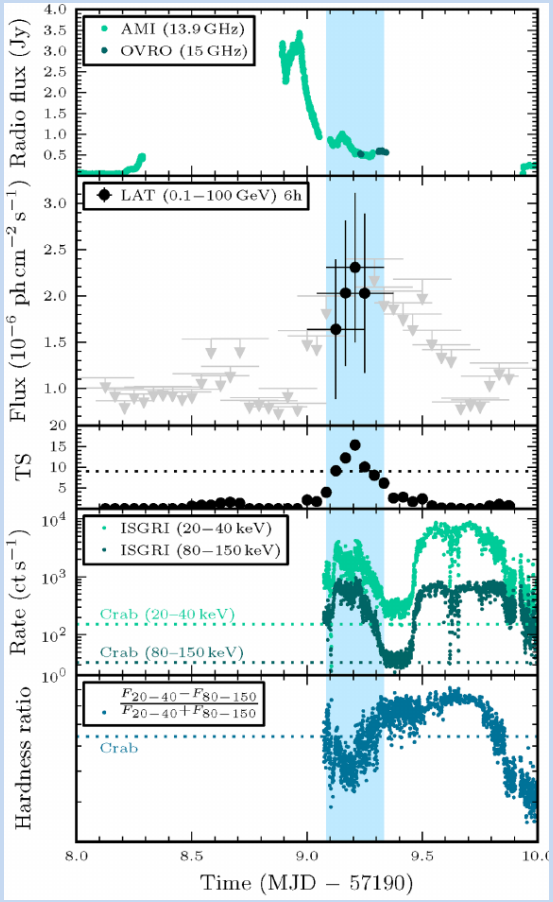
High-velocity **cold wind**. Simultaneous to the **radio-jet**



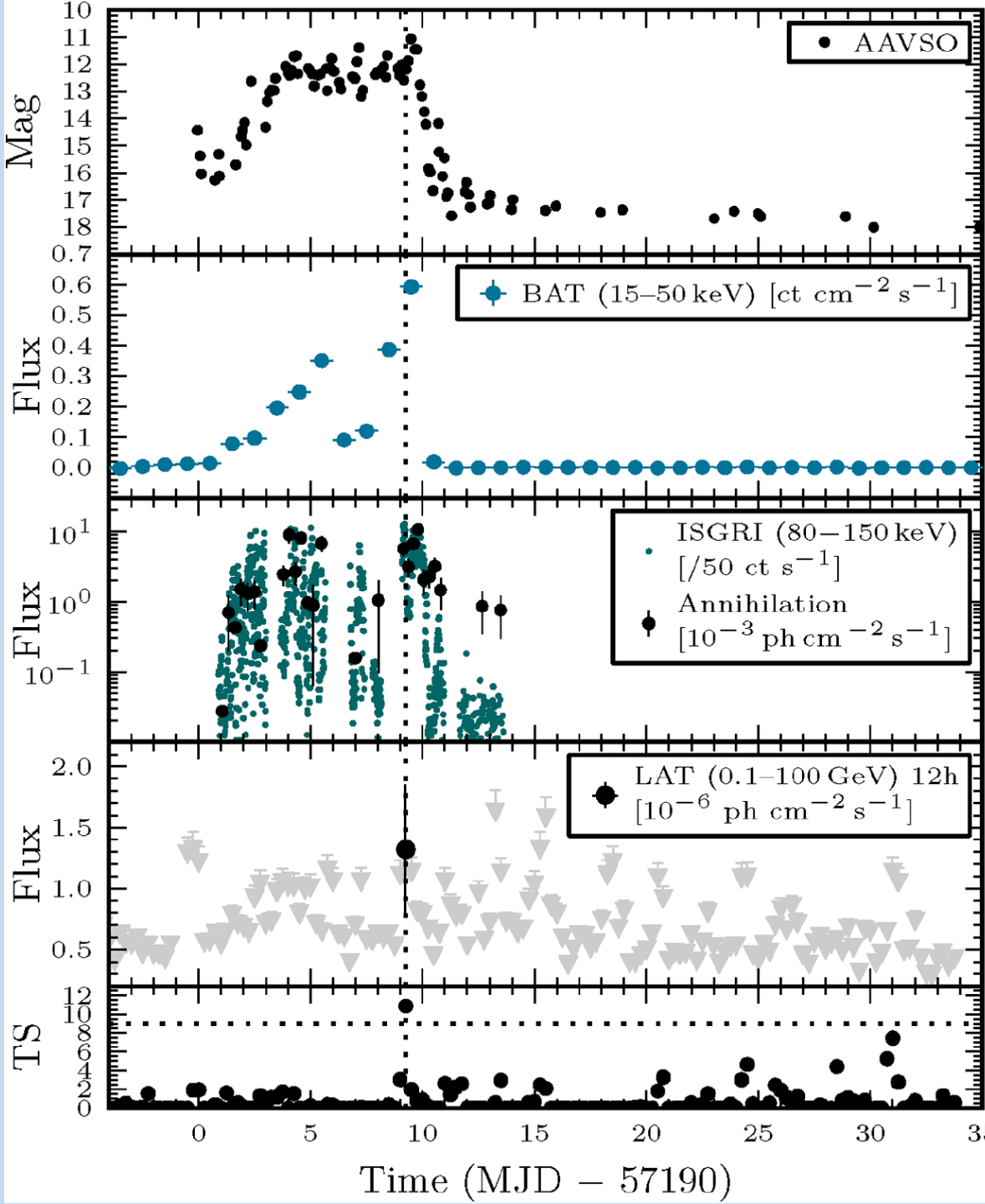
Must be launched from outer disc as need T<3x10^{4}K for HeI
→ at R~10^4R_G

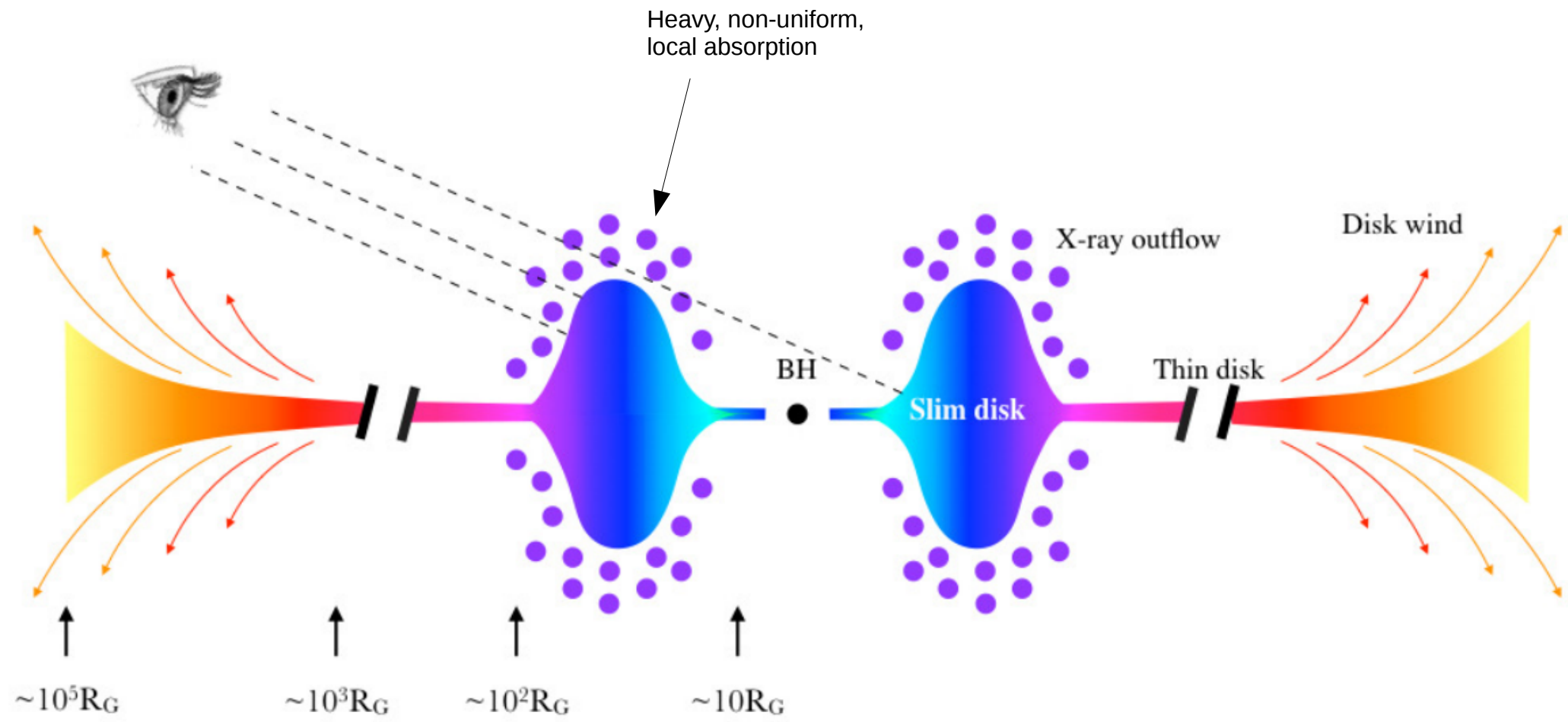


Loh+15
Fermi



γ-ray
peak




Heavy, non-uniform,
local absorption
X-ray outflow
Disk wind
BH
Slim disk
Thin disk
~10^5R_G
~10^3R_G
~10^2R_G
~10R_G

Motta+17

Summary

- Spectacular dataset from 2015 outburst & much more to come!
- Observed transition quiescence → outburst with spectroscopy in optical for first time; → confirmed DIM
- ~7d X-ray delay fits with truncated disc in disc-instability model
- Detected fast (sub-sec), red flaring → opt thin synchrotron
- Detected high velocity wind simultaneous with radio jet

Unknowns:

- origin of ~6h variations
- inclination ~56-67°
- flaring properties
- mechanisms for v fast/large amplitude XR/Nx variability