Accretion in Ultracompact X-ray Binaries: A Unified Picture of 4U 1626-67

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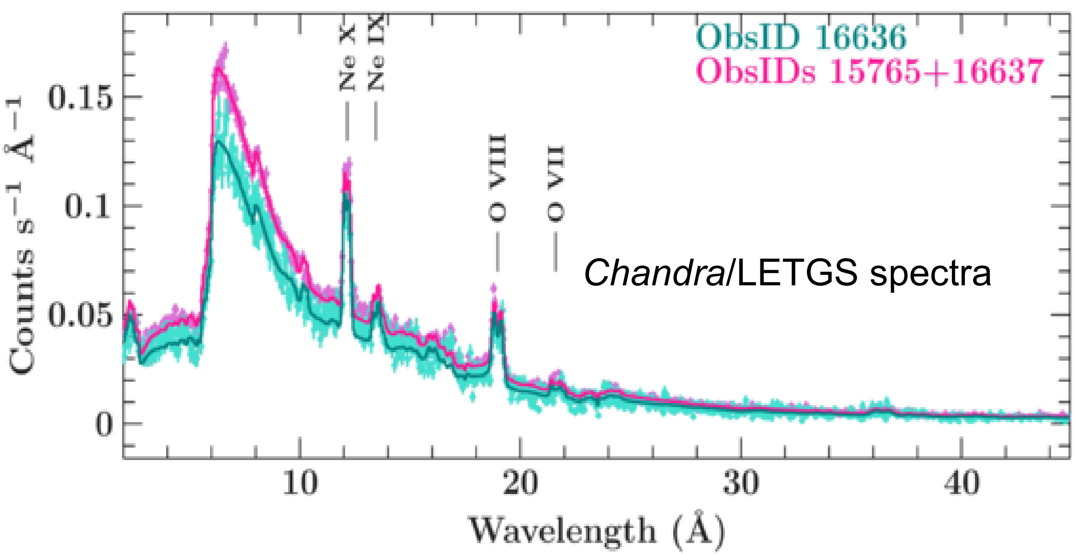
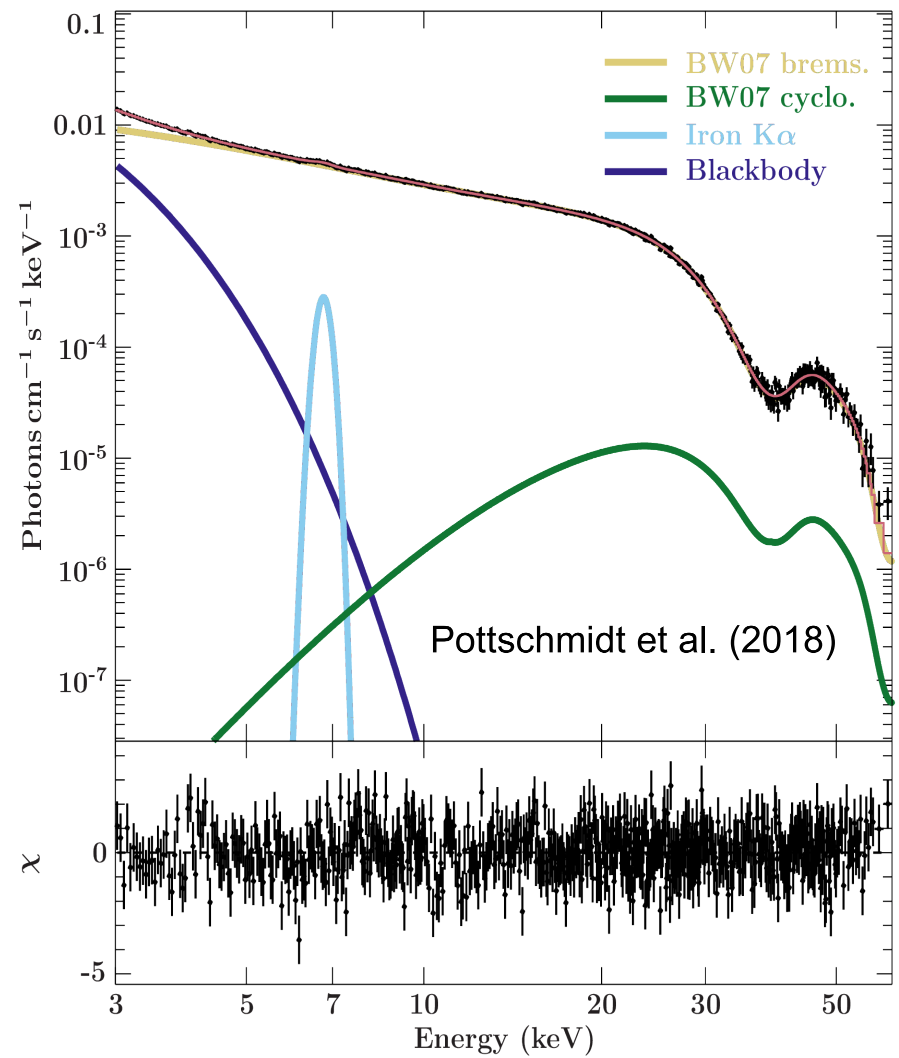
4U 1626-67: A unique UCXB

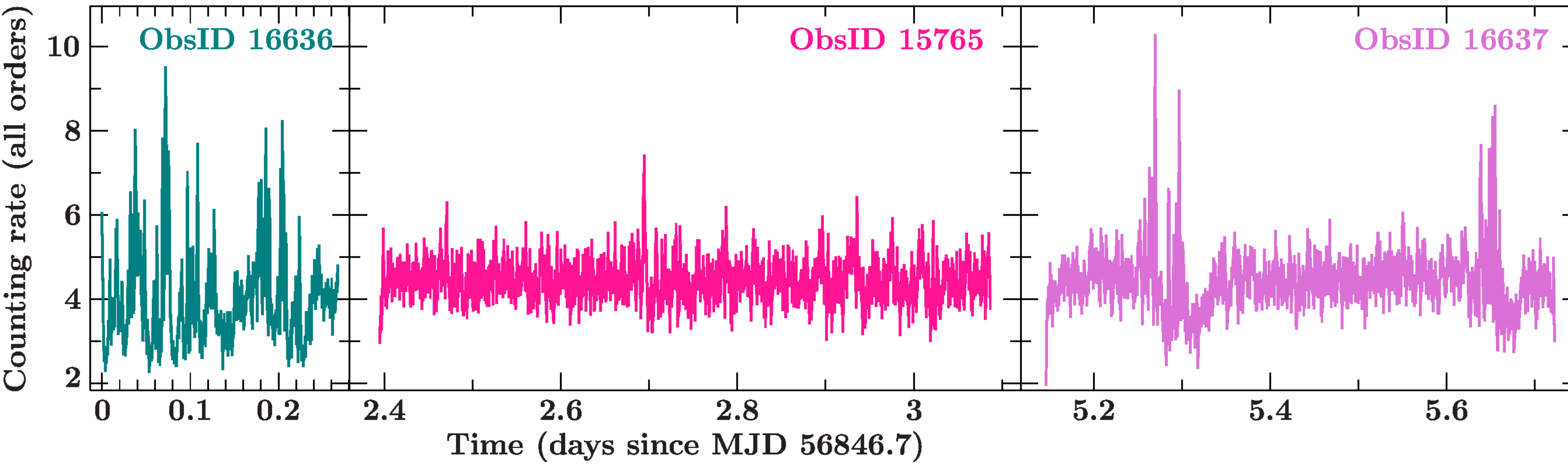
- Ultracompact XRB – 42 min orbit
- X-ray pulsar (7.7 s, 4e12 G field)
- Bright (10^{36}-10^{37} erg/s, persistent)
- Currently spinning up
- No H/He detected in visible/UV



Very strong neon and oxygen lines



Cyclotron line in hard X-rays: 4×10^{12} G magnetic field

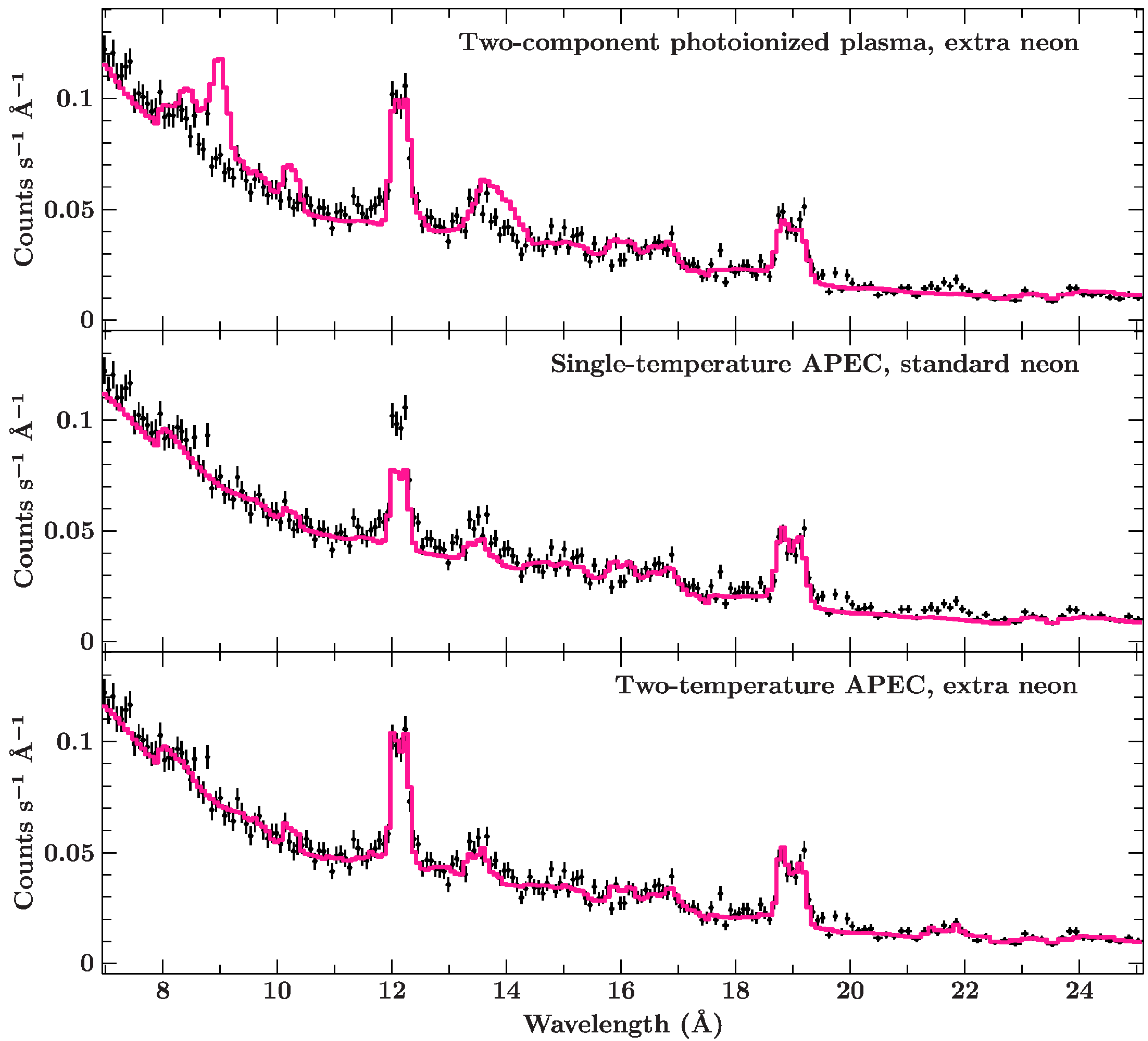

ObsID 16636
ObsID 15765
ObsID 16637
Counting rate (all orders)
Time (days since MJD 56846.7)
10
8
6
4
2
0
0.1
0.2
2.4
2.6
2.8
3
5.2
5.4
5.6

Model comparison

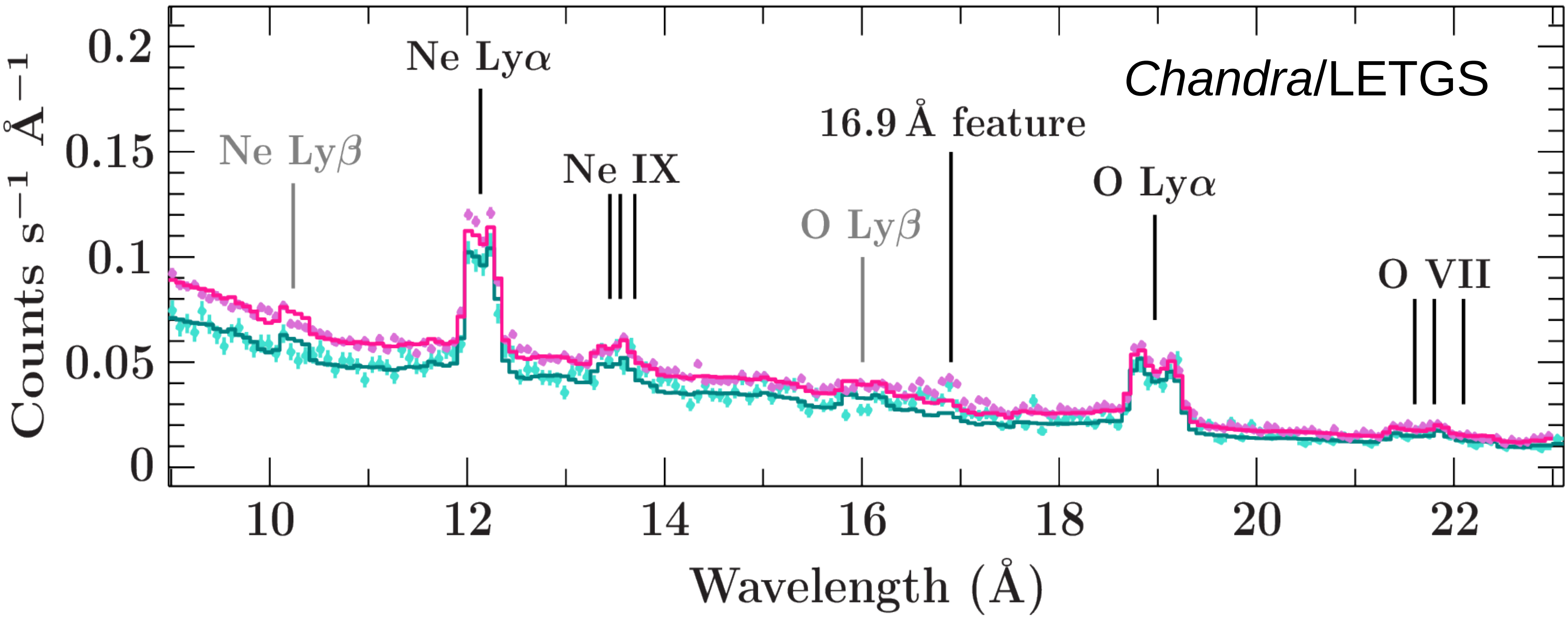
Photoionized plasma (photemis/XSTAR):
Drastically overproduced Ne IX RRC

Single-temperature APEC:
Underpredicts Ne X and O VII.

Two-temperature APEC, enhanced Ne abundance:
Works best, despite slightly overpredicted Ne X Kbeta, unexplained 17 Å feature.



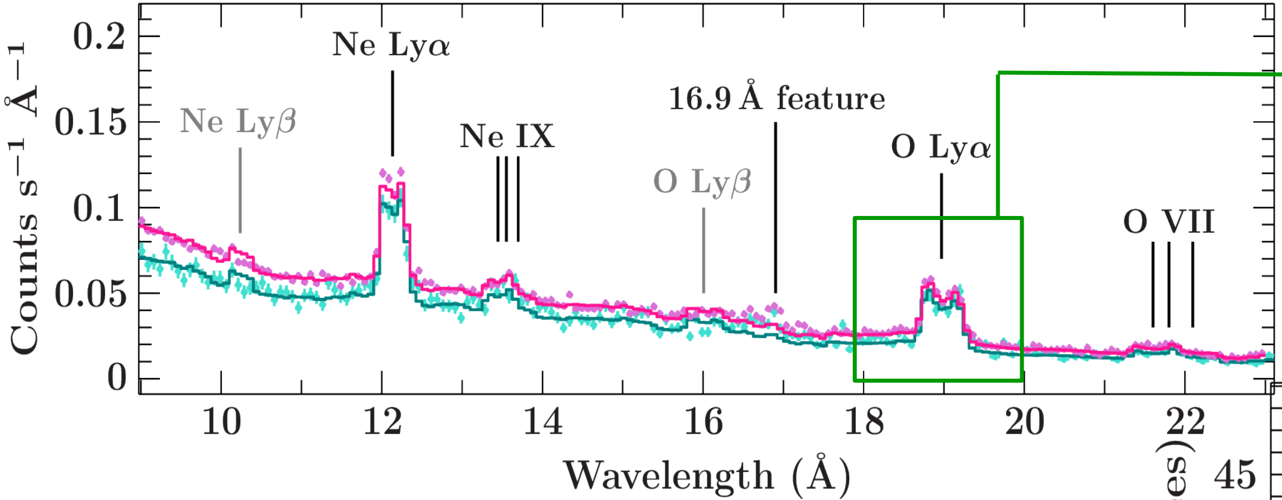
Fitting the *Chandra* gratings spectra: disk-blurred two-temperature APEC

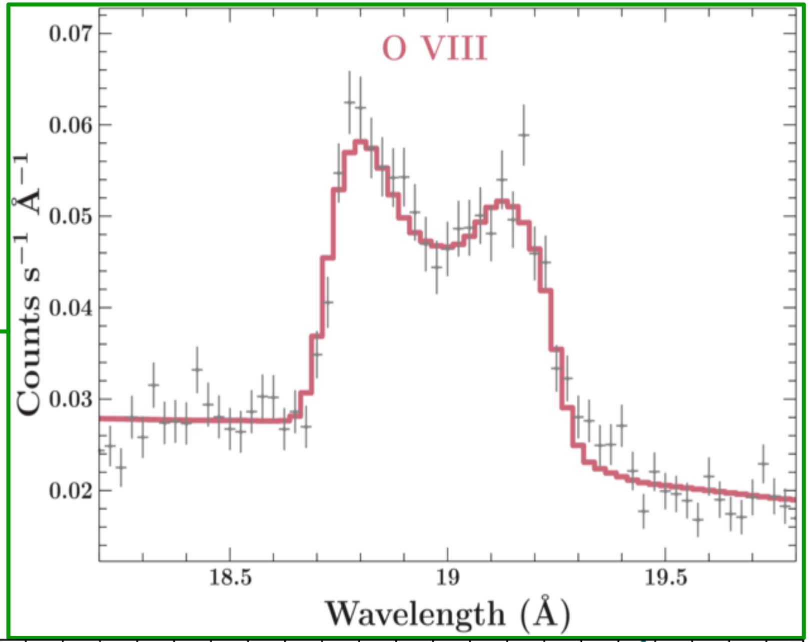


`rdblur(apec)` fit in ISIS – similar params for LETGS and HETGS:

- Temperatures: **~13 MK and ~2.3 MK**
- **~3.5x higher Ne abundance, ~10x lower Fe & Mg**, relative to solar oxygen abundance
- However: APEC undermodels 16.9 Å feature

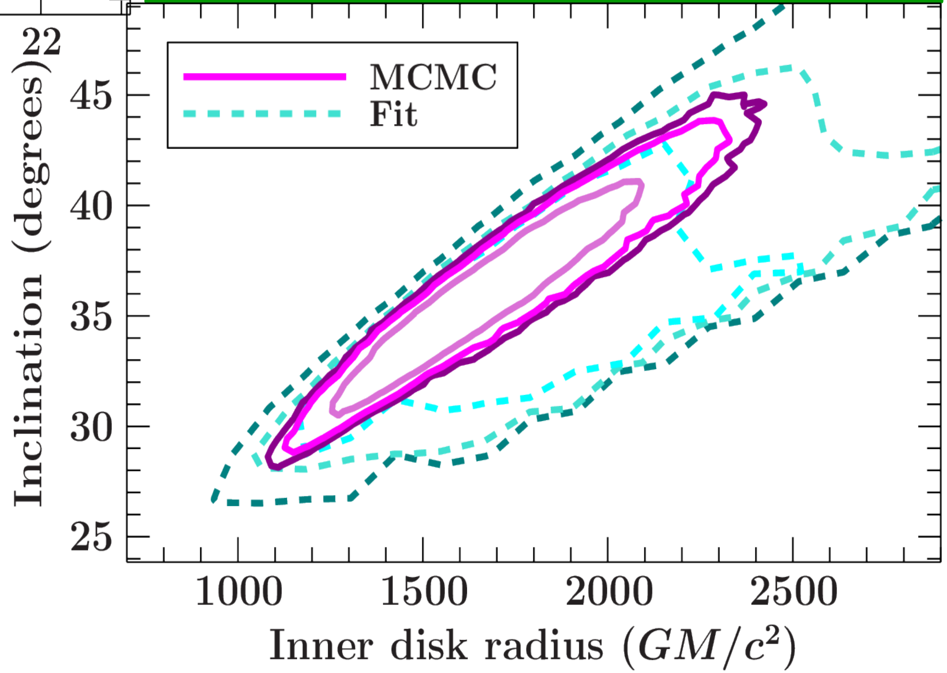
Spectral fitting: disk-blurred two-temperature APEC





Accretion disk parameters from line profiles, modeled with `rdblur` convolution model:

- **Inner disk radius:**
  1500 R_G ≃ 3E8 cm ≃ 3000 km
  - *cf.* Alfvén radius 4000 km, corotation radius 6500 km – not unreasonable and consistent w/ spin-up!
- **Inclination > 25°**

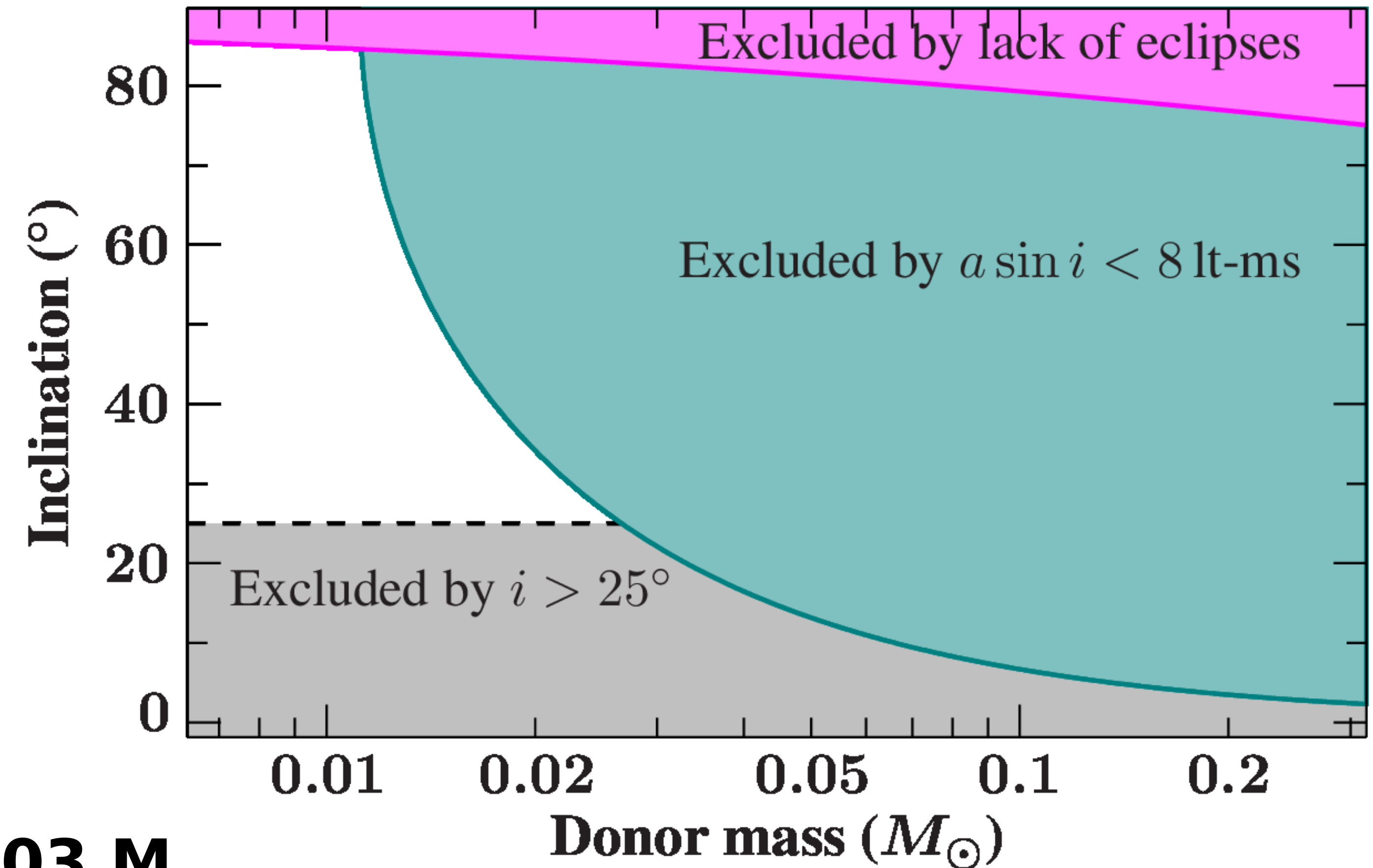


Donor mass

From this work:
i > 25°

Shinoda+ (1990):
$a_x$sin*i* < 8 lt-ms

Assume **donor fills Roche lobe** and **lines track system inclination.**



Result: $\mathbf{M_{donor} \lesssim 0.03\ M_\odot}$

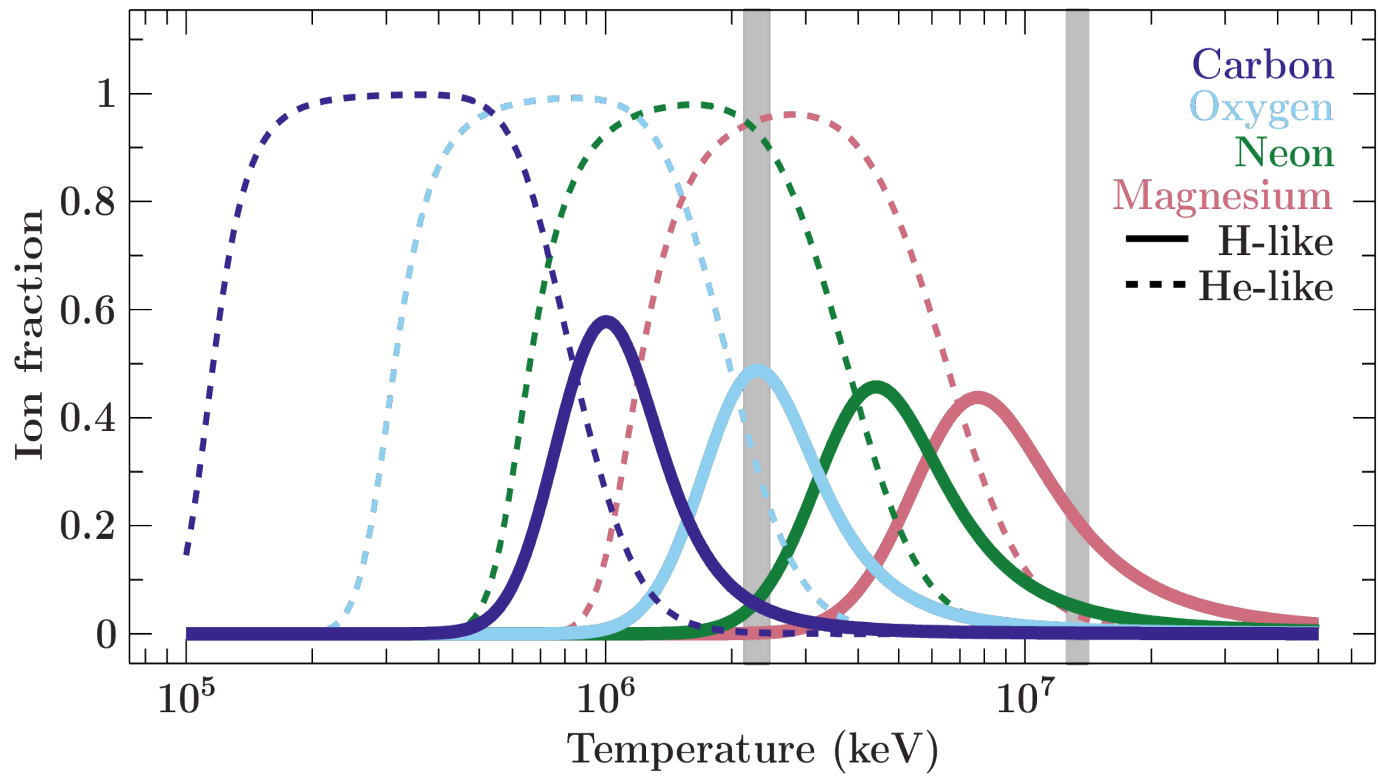
Donor composition

"Abundance" is somewhat misleading – no hydrogen! So we look at ratios relative to oxygen.

Relative to oxygen, by number:

- **Ne/O ≃ 50%**
- **Mg/O ≃ Fe/O ≲ 0.4%**

Again: that's ~3.5x higher Ne, ~10x lower Mg & Fe, compared to solar



Can't constrain carbon in X-rays – too hot! (but carbon is *maybe* seen in UV – see Homer+ 2002).

Possible donor stars

Helium star (see, e.g., Nelemans+ 2010): Accretion starts *during* He-burning phase.

Note that He burning is not happening right *now* – otherwise source would be much brighter!

Pros:
- Can reach high persistent accretion rate (see, e.g., Heinke+ 2013)
- Overall larger → easier to fill Roche lobe

Cons:
- Stars with high Ne/O ratio and accretion rate tend to have lots of He – why don't we see it?

White dwarf (Schulz+ 2001, Yungelson+ 2002): Accretion starts *after* He burning completed.

Need to have completed enough He burning to produce significant Ne, so likely C/O or O/Ne WD.

Pros:
- C/O WD: Heavier ^{22}Ne sinks to core, so can get enhanced Ne w/o helium
- O/Ne WD: naturally high Ne abundance

But:
- Timescale issues: magnetic field decay?
- Low Mg difficult to reconcile w/ O/Ne WD
- Disk can't store enough mass to explain long-term flux (Heinke+ 2013) – but irradiation may help - see Lü+ (2017).

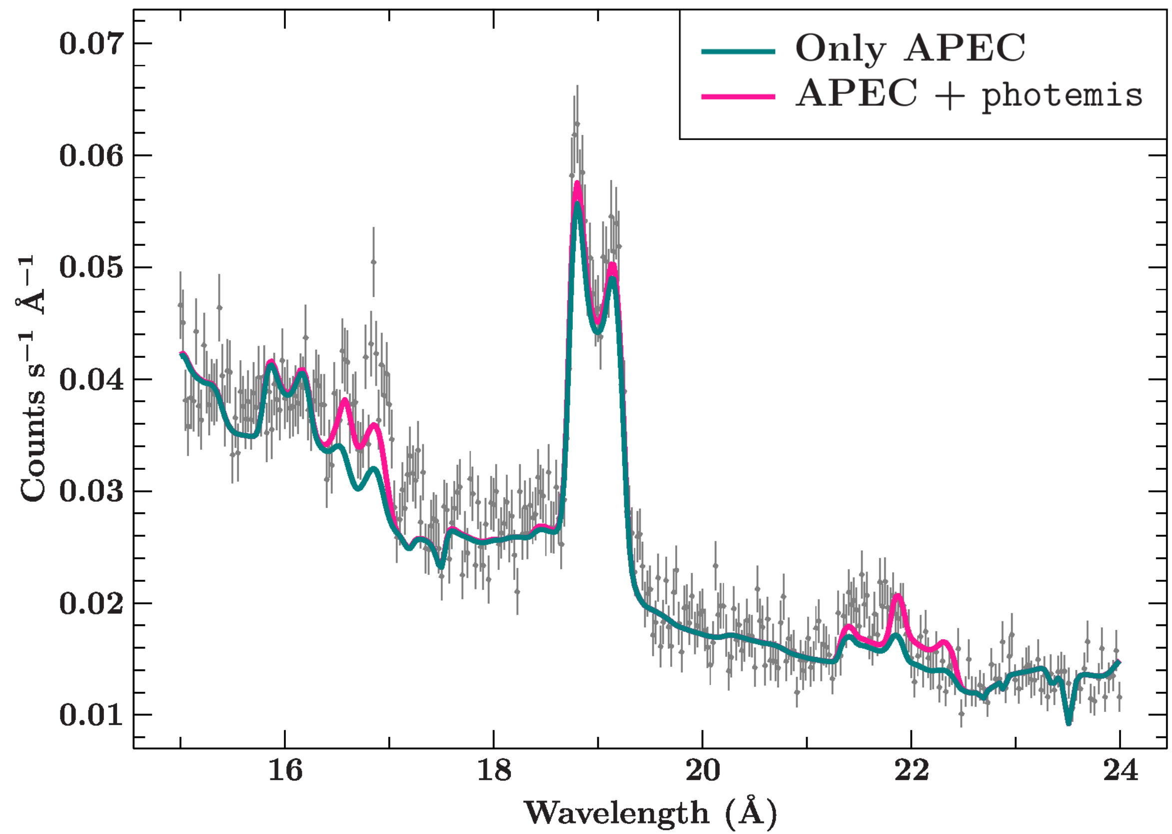
Plasma modeling

Two-temperature APEC works *best*, but isn't perfect.

16.9 Å feature: probably **O VII recombination** (16.775 Å, but split by the accretion disk). Note: also seen in XMM RGS!

Right: adding a photemis component to the model. logξ ~ 1, emission measure is ~10% of the APEC EM.

But this is simplistic – photemis and APEC aren't talking to each other, photemis assumes too low temperature & density, UV depopulation of He-like lines is clearly off, etc.



LETGS spectra with disk-blurred APEC+photemis model

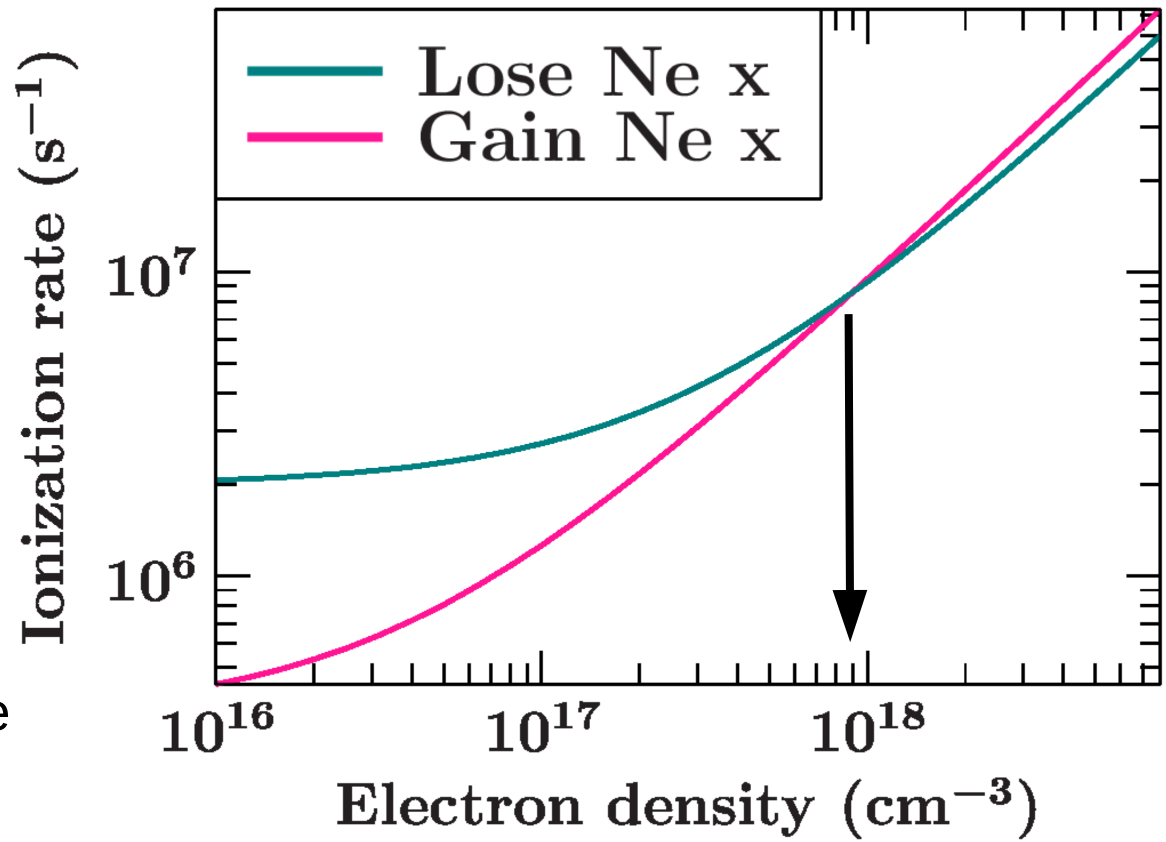
Plasma modeling – Ionization balance and density

$$n_{Z,i}(\beta_{Z,i}+n_e\alpha_{Z,i}+n_eC_{Z,i})=n_{Z,i+1}n_e\alpha_{Z,i+1}+n_{Z,i-1}(\beta_{Z,i-1}+n_eC_{Z,i-1})$$

Rough numbers for Ne X:
$\beta \sim 10^6$ s^{-1} (photoionization)
$\alpha \sim 10^{-12}$ cm^3 s^{-1} (recombination)
C ~ 10^{-12} cm^3 s^{-1} (collisional)

Ionization balance thus gives us an estimate of the density:
$n_e \sim 10^{18}$ cm^{-3}

Implications:
- Photo- and collisional ionization rates are comparable
- With APEC emission measure, emitting region must be *small*



Summary and conclusions

Gratings observations of 4U 1626-67 allow us to *simultaneously* constrain its accretion disk geometry and plasma parameters

- Inner disk radius consistent with observed spin-up and magnetic field strength
- Inclination implies donor mass $< 0.03\ M_\odot$
- Emission lines suggest highly enhanced Ne and depleted Mg & Fe, relative to oxygen
- Mostly-collisional, high-density plasma with $n_e \sim 10^{18}\ \mathrm{cm}^{-3}$

Remaining questions:

What, exactly, is the donor? And what produces the X-rays in the disk?

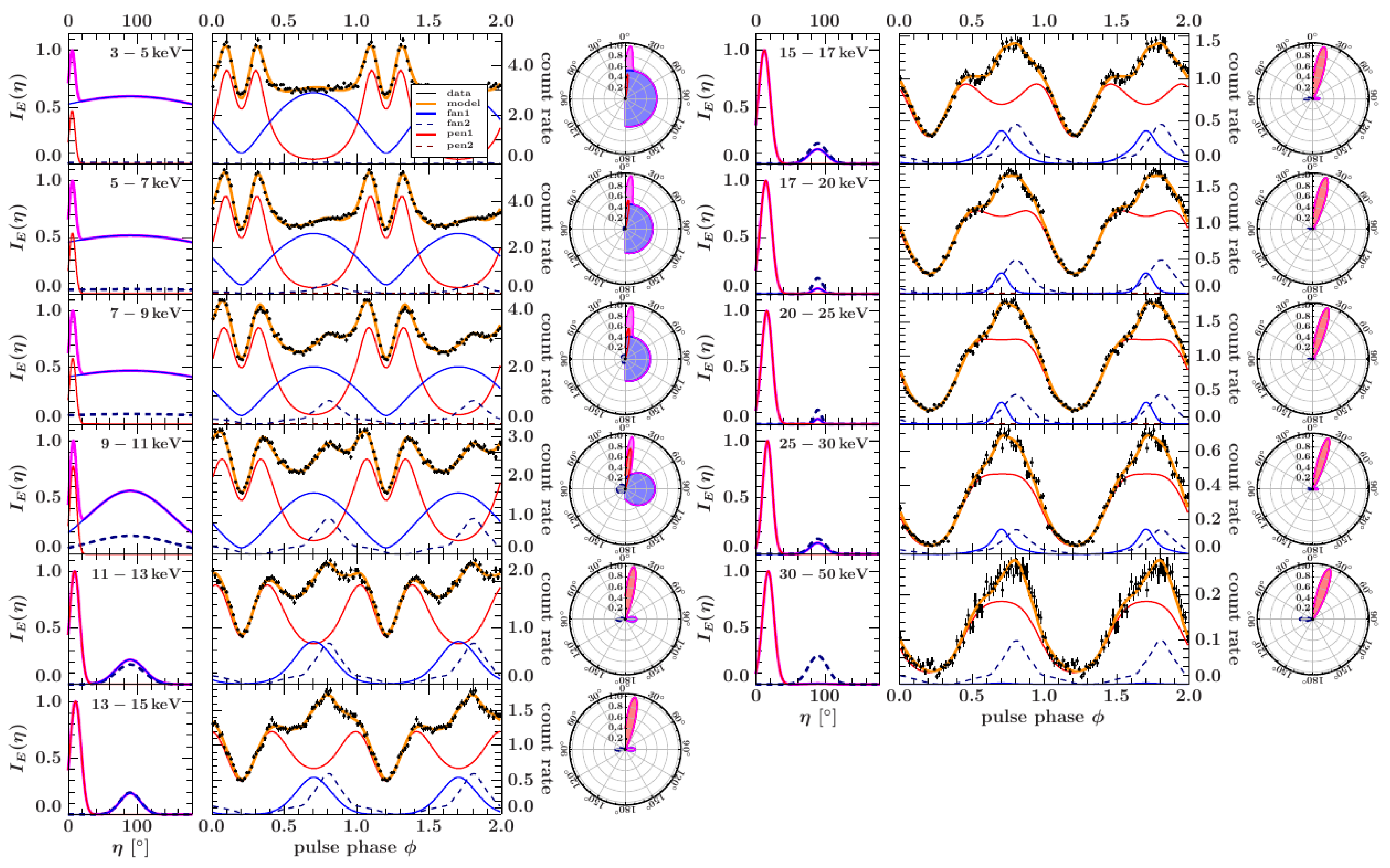
Donor:

- No H lines in optical/UV, so can't be main sequence
- High Ne abundance could be produced in both He star and WD
- No He lines – either it's not there, or the disk is too hot

Disk:

- How to interpret, e.g., APEC emission measure in H-depleted plasma?
- Photo- and collisional ionization comparable – why does it *look* collisional? Why *doesn't* it look photoionized?
- Variability, torque reversals, pulse profile modeling suggest a *warped disk* – how does this affect things?

Spare parts



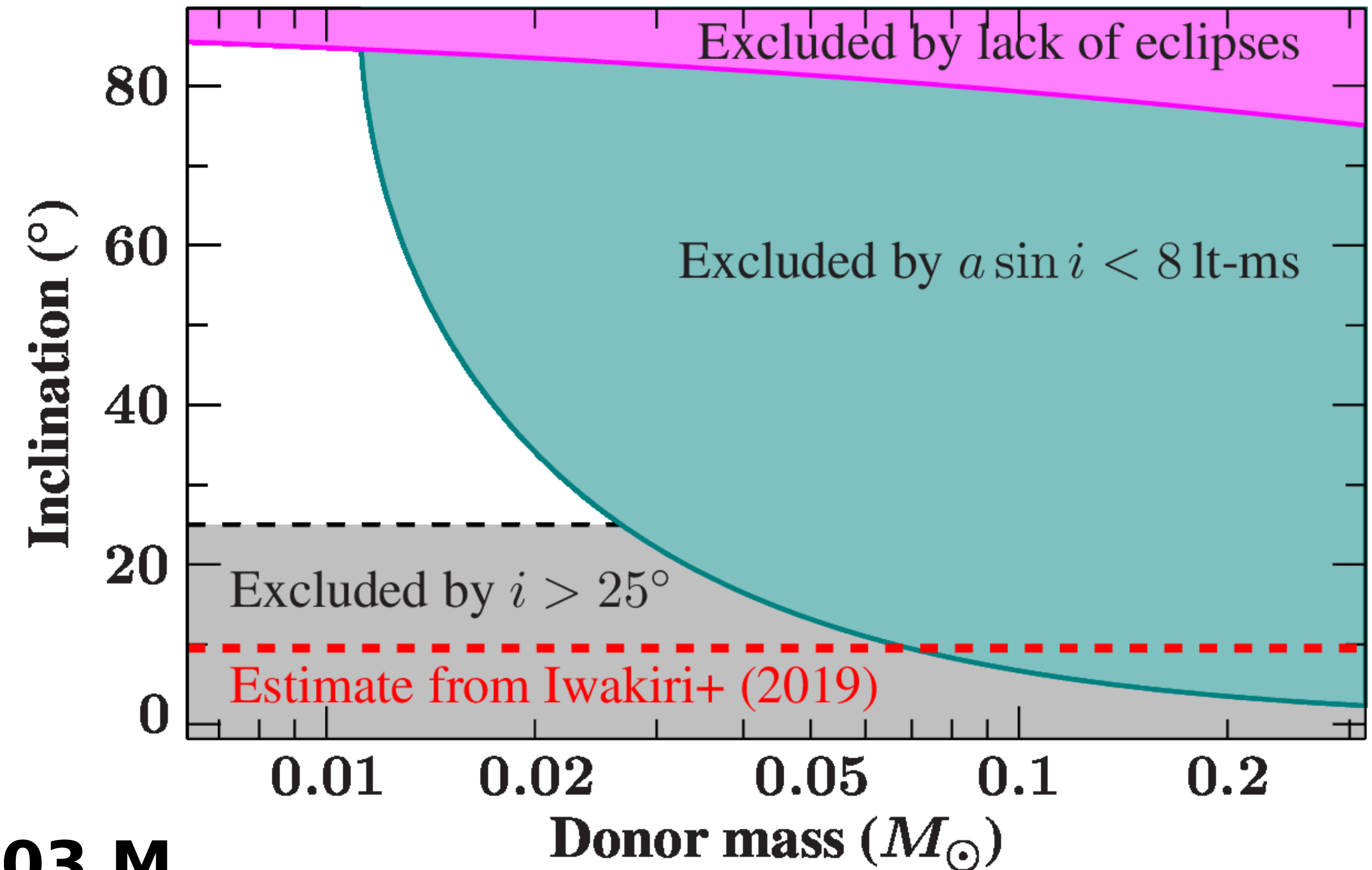
3 − 5 keV
5 − 7 keV
7 − 9 keV
9 − 11 keV
11 − 13 keV
13 − 15 keV
15 − 17 keV
17 − 20 keV
20 − 25 keV
25 − 30 keV
30 − 50 keV
$I_E(\eta)$
η [°]
pulse phase ϕ
count rate
data
model
fan1
fan2
pen1
pen2

Donor mass

From this work:
i > 25°

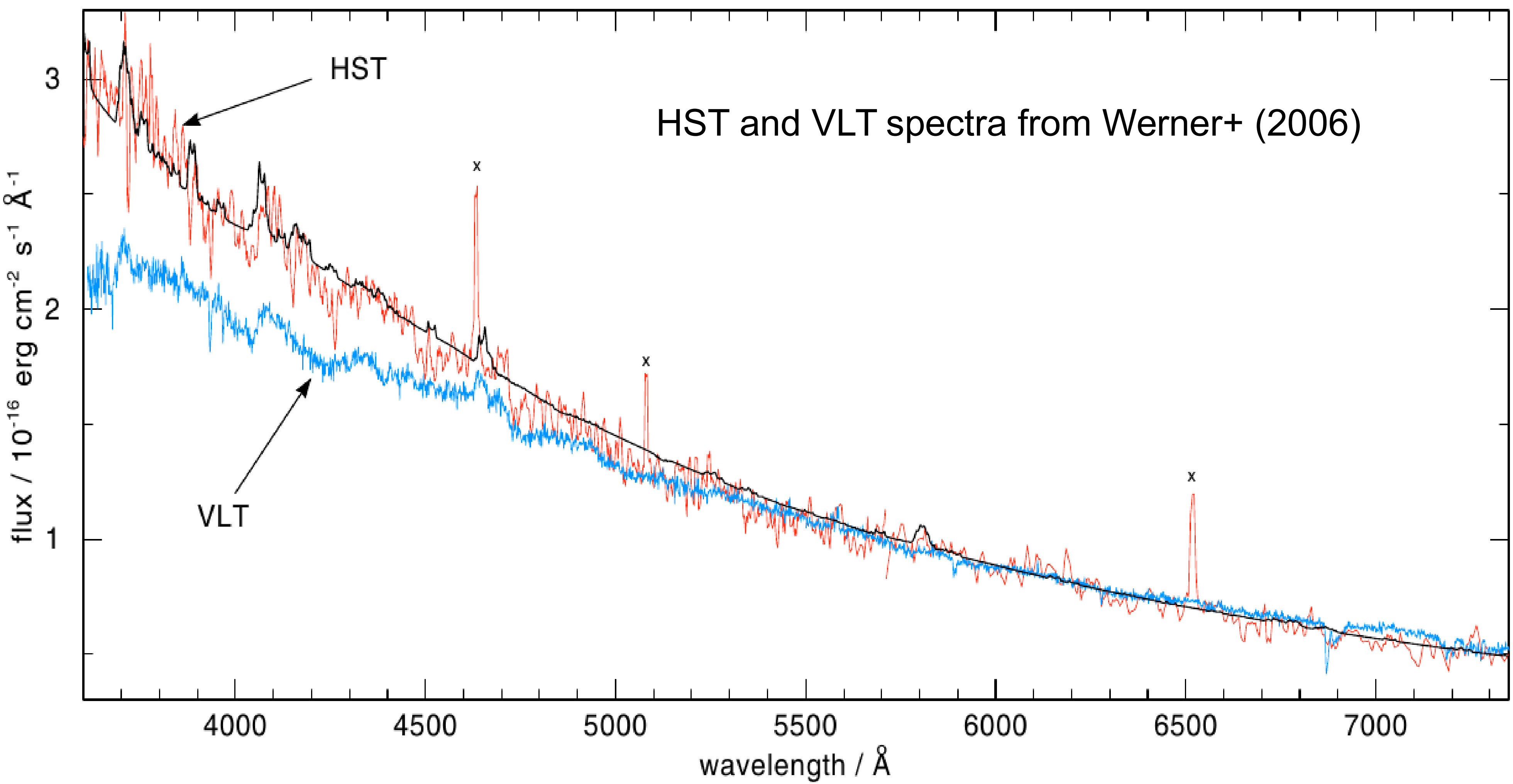
Shinoda+ (1990):
$a_x \sin i$ < 8 lt-ms

Assume **donor fills Roche lobe** and **lines track system inclination.**

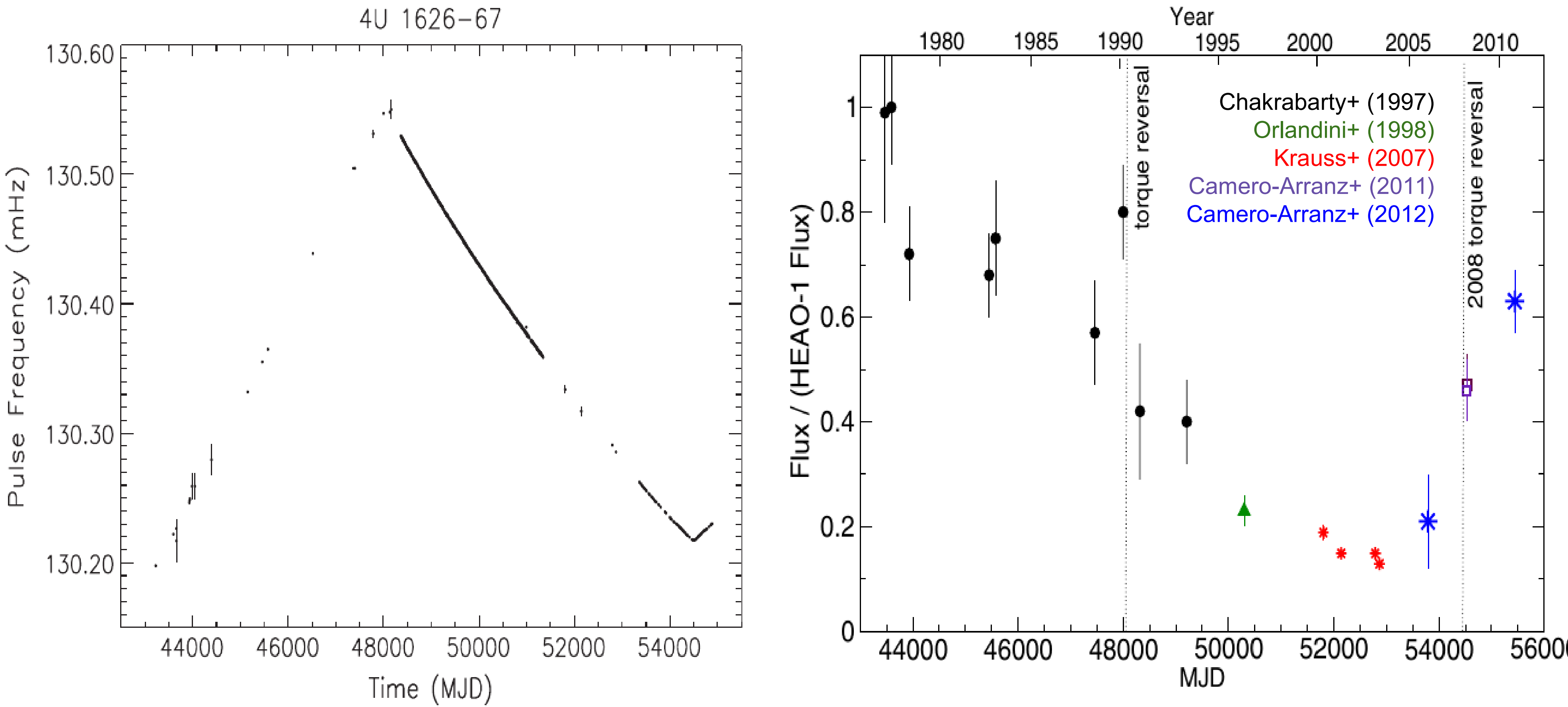


Result: $\mathbf{M_{donor} \lesssim 0.03\ M_\odot}$

Or maybe: $\mathbf{M_{donor} \lesssim 0.08\ M_\odot}$?



Optical and UV (HST, VLT): no hydrogen or helium lines
(see Homer et al. 2002, Werner et al. 2006)



4U 1626-67: Pulse period and flux history (Camero-Arranz et al. 2010, 2012).

Plasma diagnostics: He-like triplets

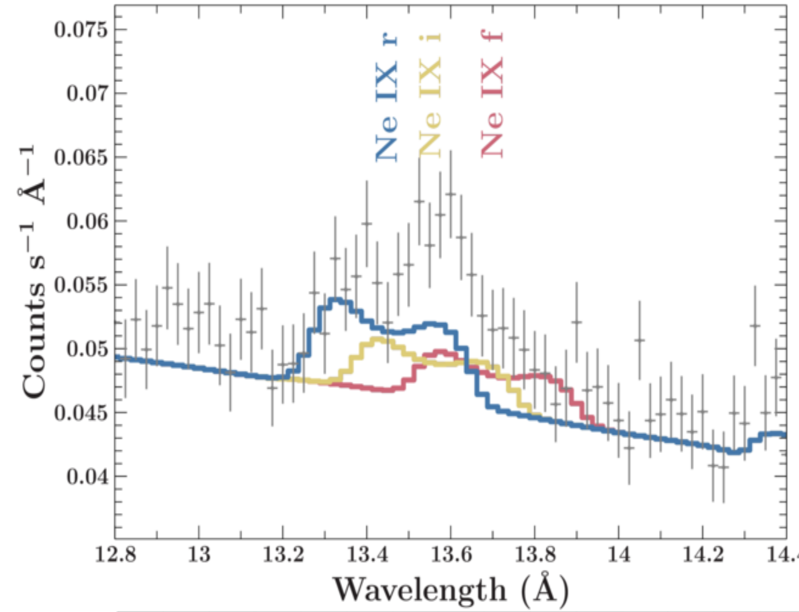
If we model the He-like lines as disk lines, the *resonance* line is dominant

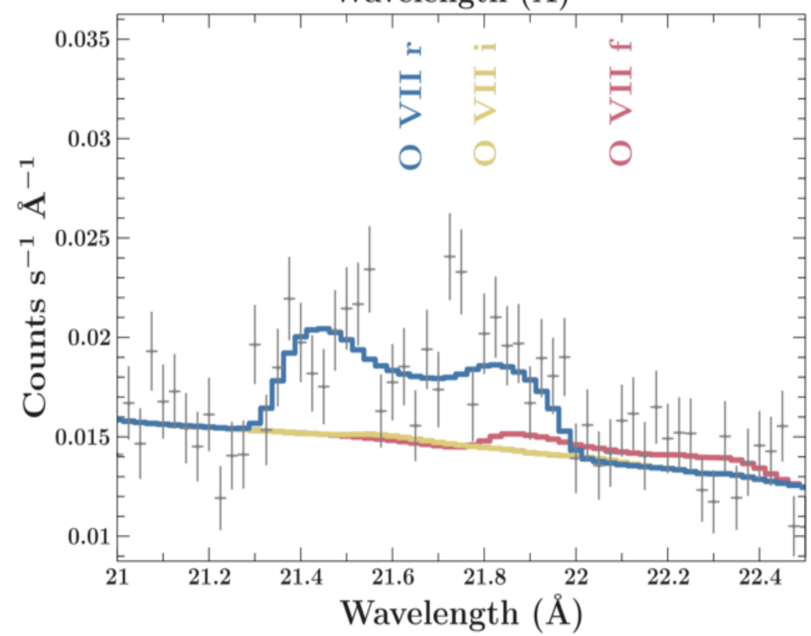
Compare: Schulz+ (2001), who found $r < i$ during spin-down epoch.

Can’t constrain *i* or *f* lines very well generally: Ne R-ratio is 1.0 ± 0.7, oxygen is unconstrained

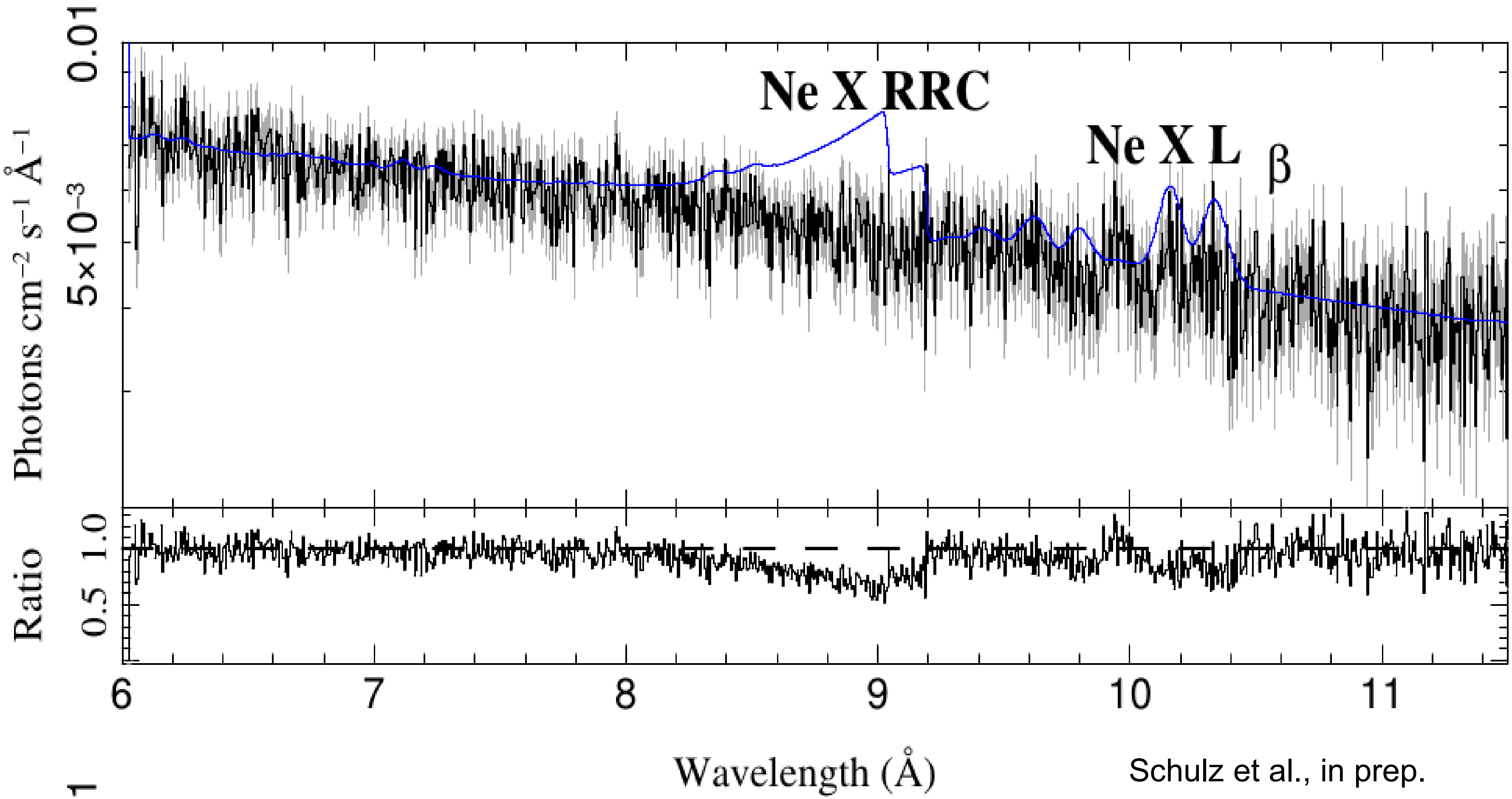
However, UV continuum probably makes this dubious in any case

G-ratio + He-like/H-like ratio combined are consistent with high (~10 MK) plasma temperatures

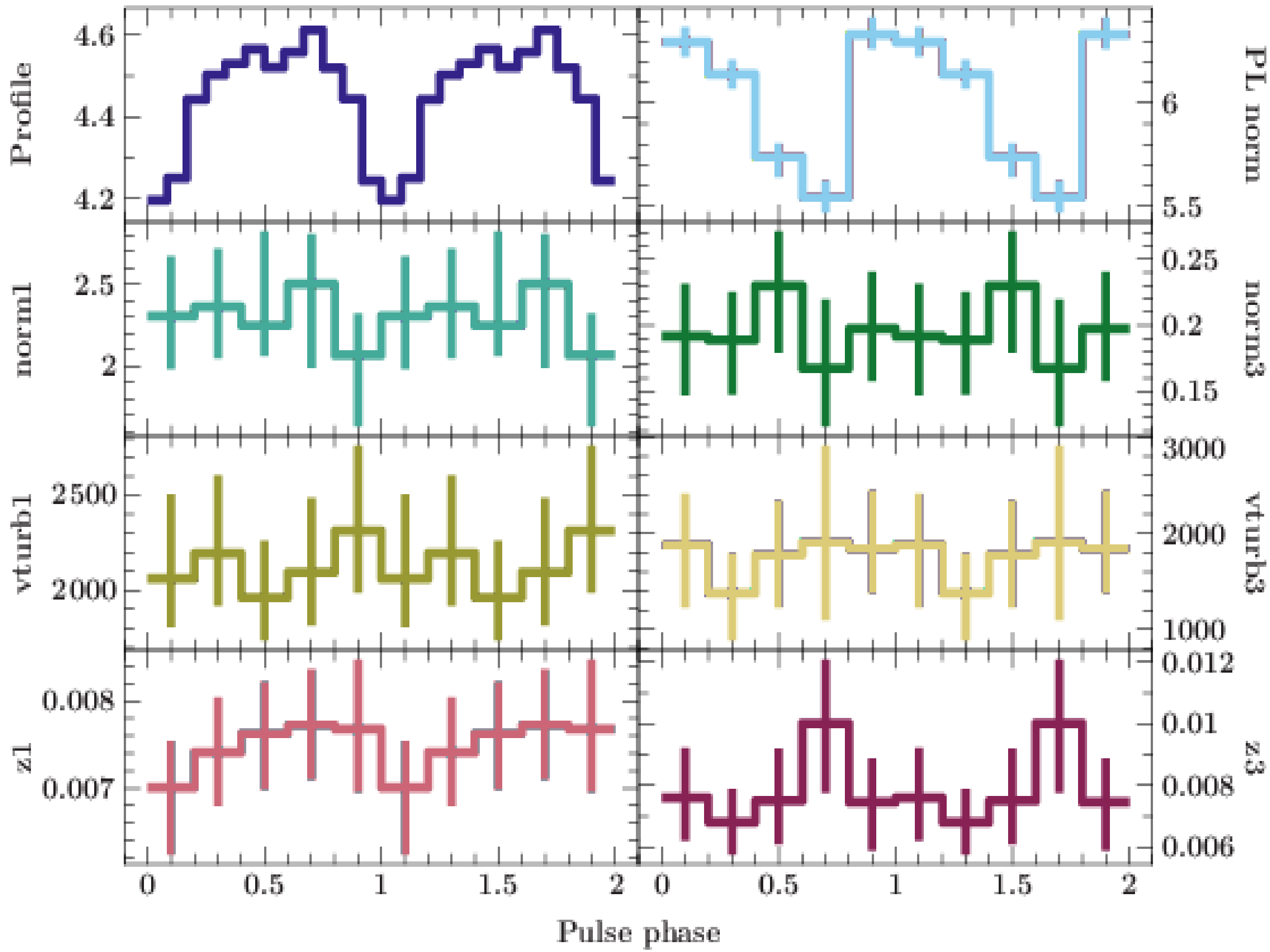




Photoionized plasma



Schulz et al., in prep.



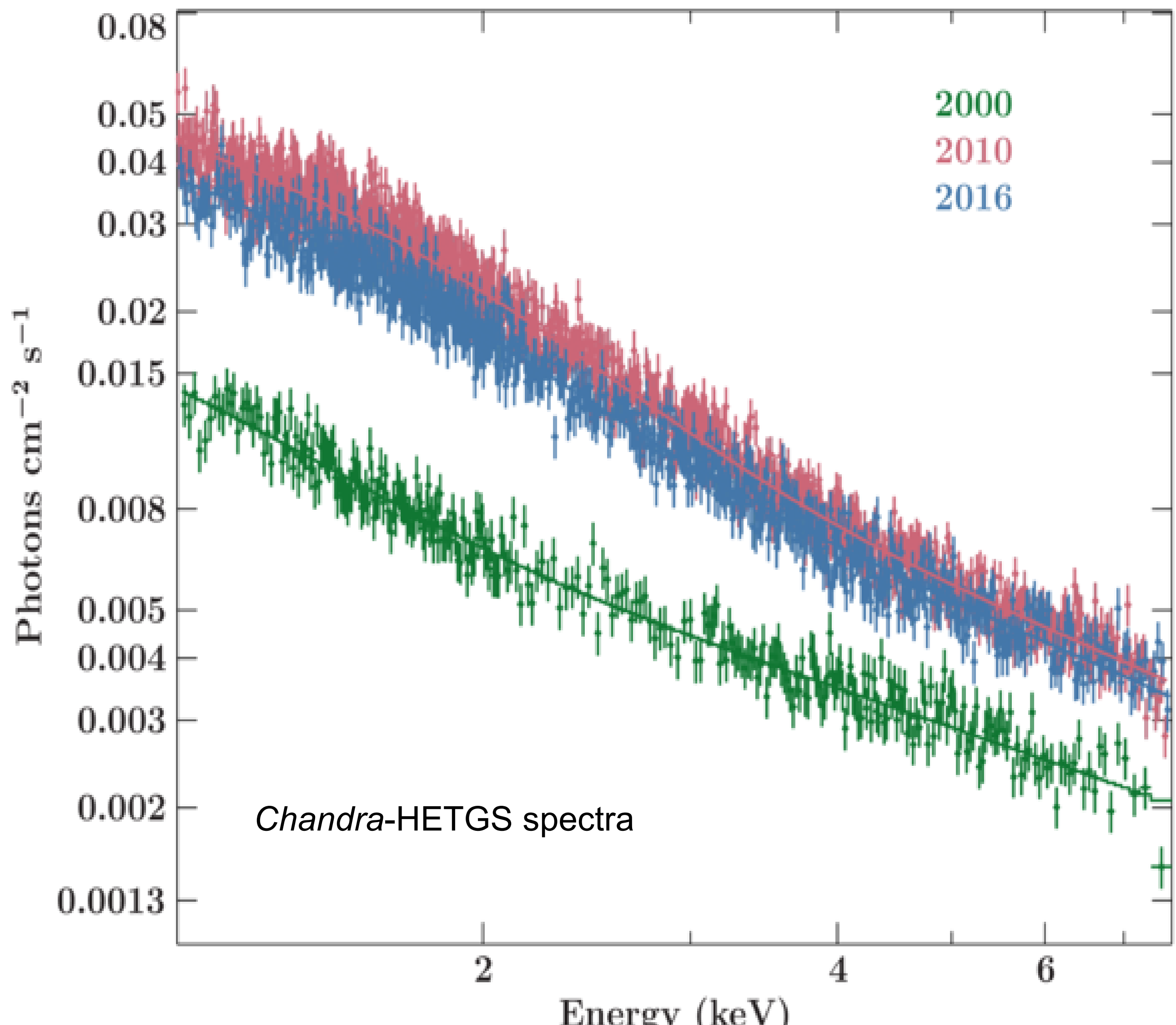
4U 1626-67: Phase-resolved APEC fits

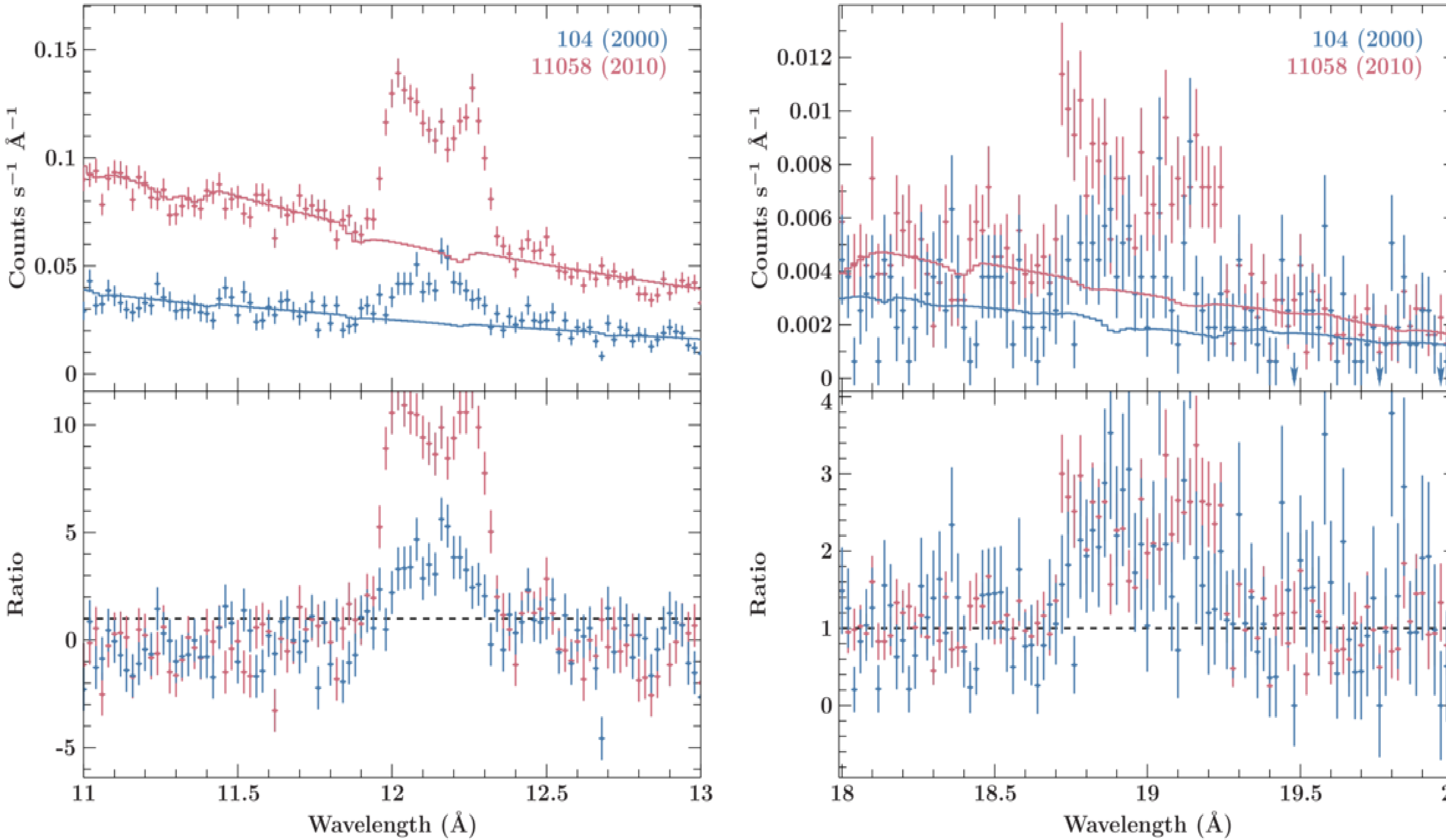
Torque reversals

Torque reversal in 2008 came with an **increase in flux** and a change in spectral parameters:

PL got *softer* - photon index changed from ~0.8 to ~1.0

BB got *hotter* (from ~0.25 keV to 0.5 keV) **and *smaller*** (R^2/D_{10} 200 → 100)





Ne X (left) and O VIII (right) pre-reversal (2000, blue) and post-reversal (2010, red)

Carbon line region