Type I X-ray burst physics and neutron star radius measurements

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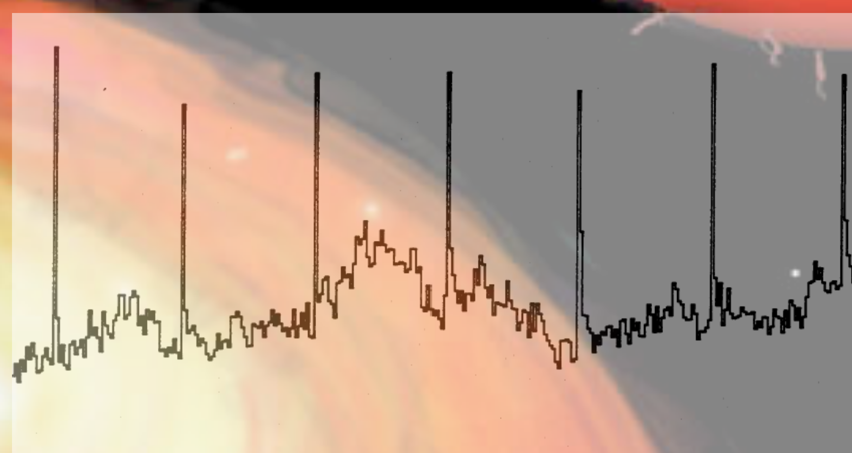
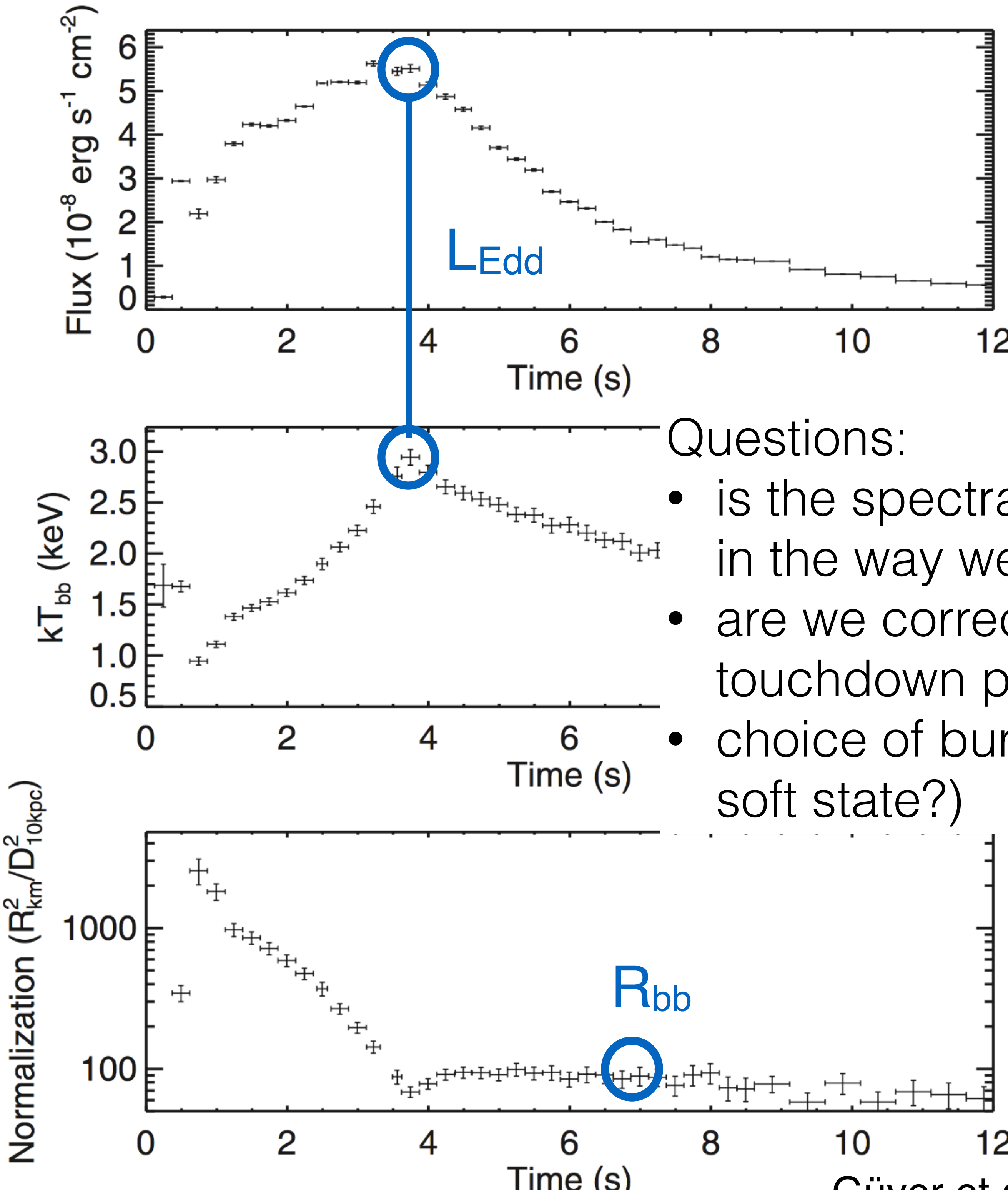


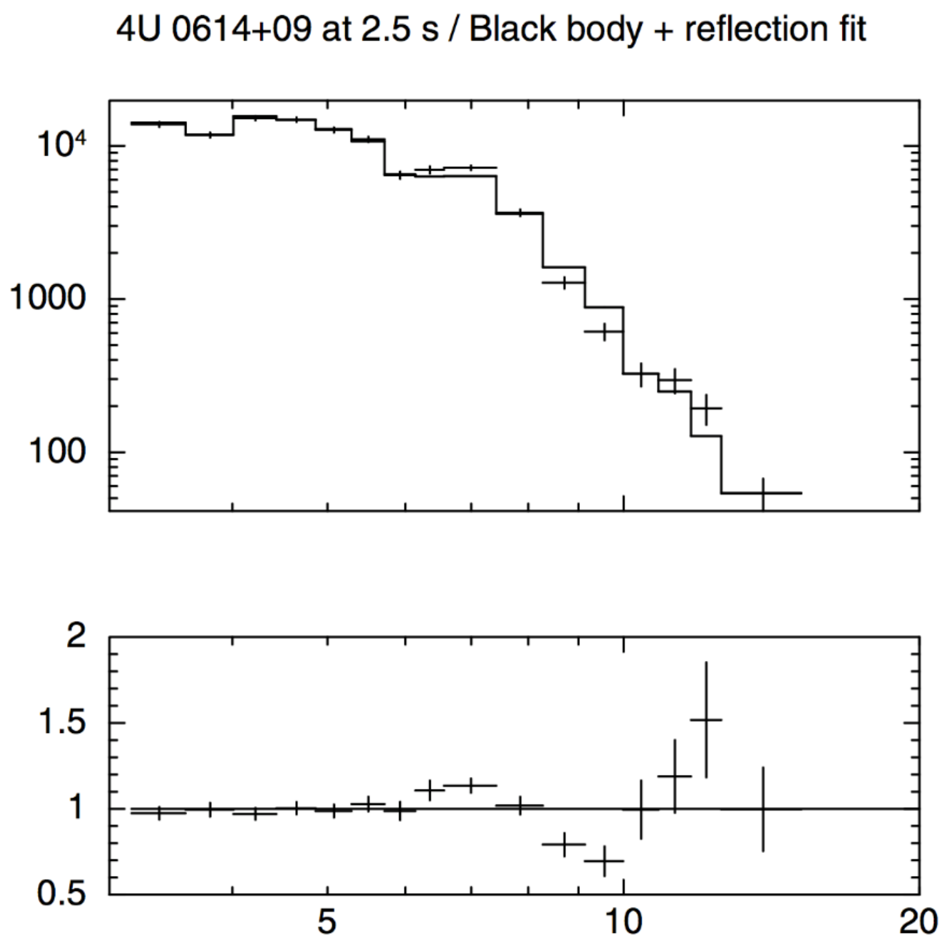


+ distance
=> [M,R]

Questions:

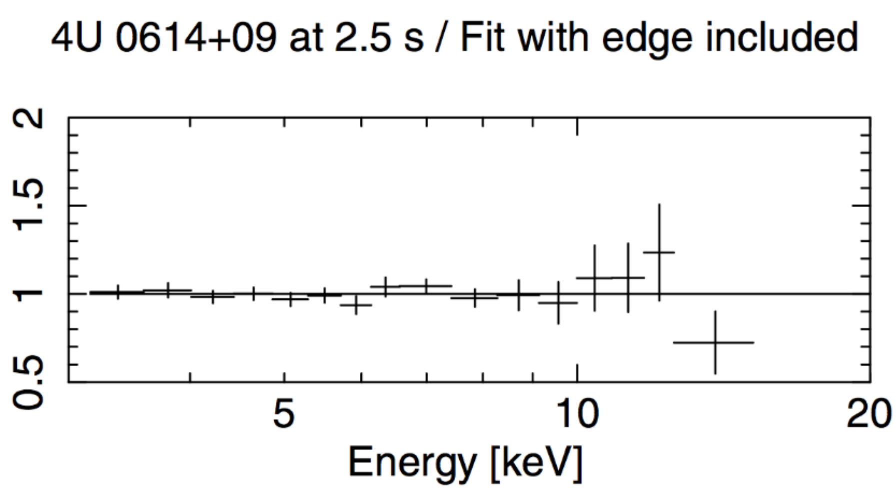
- is the spectral shape changing in the way we expect in the tail?
- are we correctly identifying the touchdown point?
- choice of bursts (hard state or soft state?)

Güver et al. (2010)



in ’t Zand & Weinberg (2010)

strong absorption
edges in two
“superexpansion”
bursts



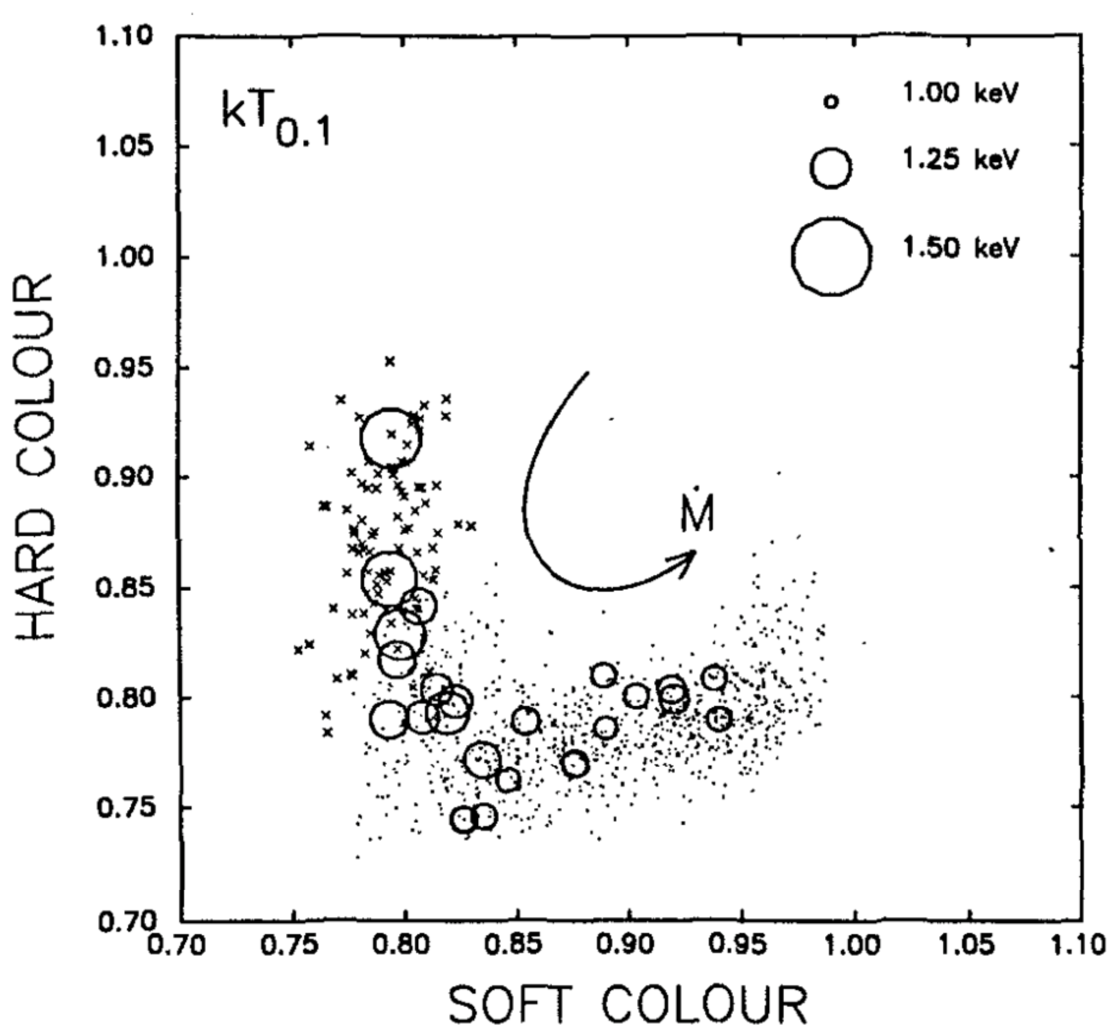
(see also Barriere et al. 2015
NUSTAR observations of GRS
1741.9-2853
5.5 keV absorption line @1.7 sigma)

This talk

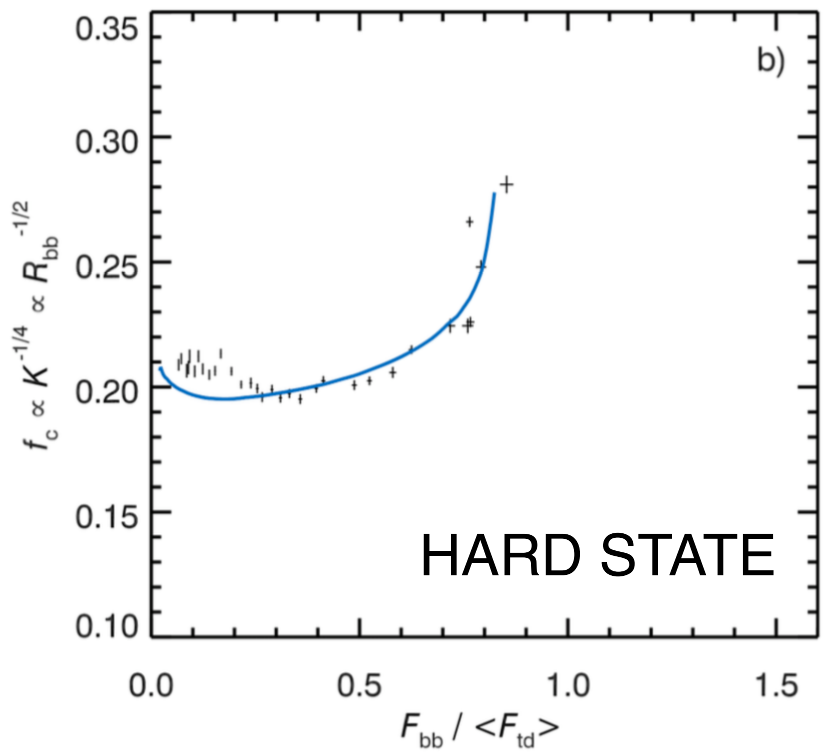
Some open issues in our understanding of Type I X-ray bursts that have been highlighted by studies of the systematic effects in radius measurements (and vice versa if we understand them better might help with understanding the systematic errors in R)

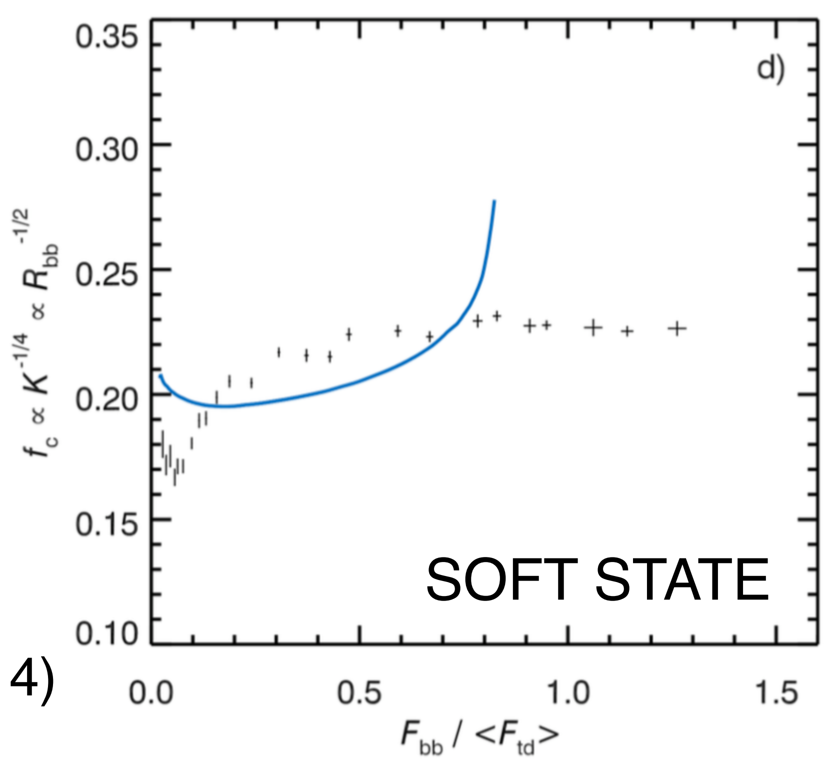
- the nuclear burning behaviour in hard and soft states
- helium flashes - winds and heavy element ejection
- anisotropic emission
- hydrogen rich bursts as standard candles

R_{BB} is systematically different between the hard and soft states



van der Klis (1990)
4U 1636-536

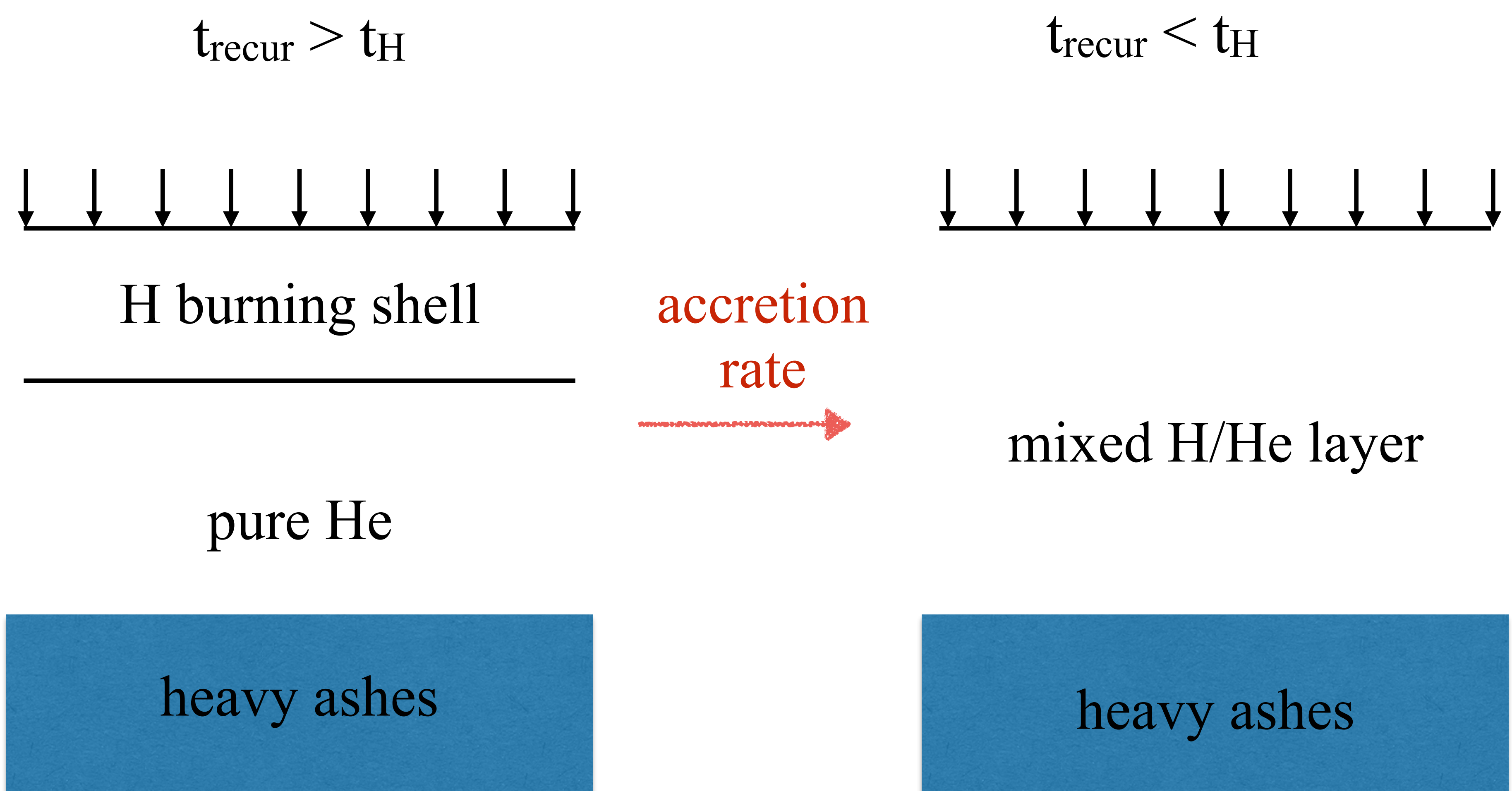


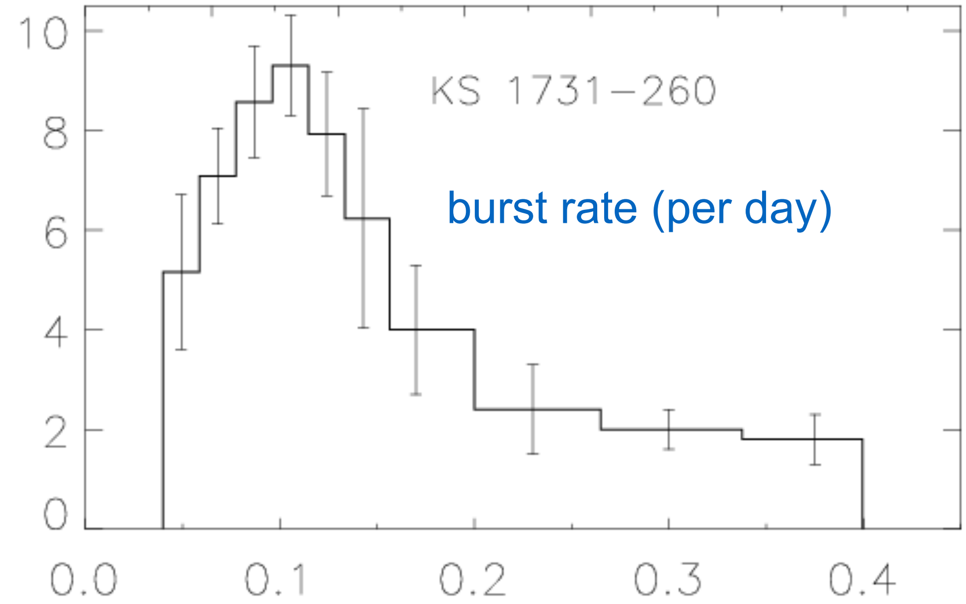


Kajava et al. (2014)
4U 1608-52

We expect a transition from helium bursts to H/He bursts as accretion rate increases

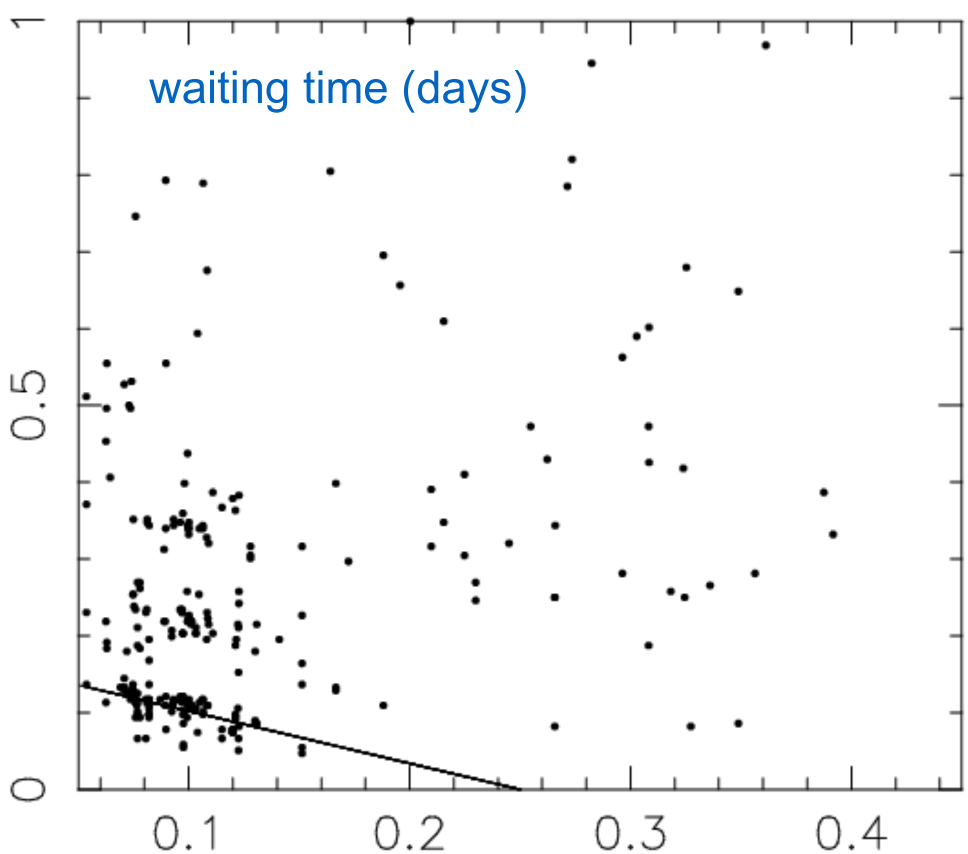
- H burns stably by the hot CNO cycle on a timescale $t_{\mathrm{H}} \approx 22\ \mathrm{hr}\left(\frac{0.01}{Z_{\mathrm{CNO}}}\right)\left(\frac{X_0}{0.71}\right)$

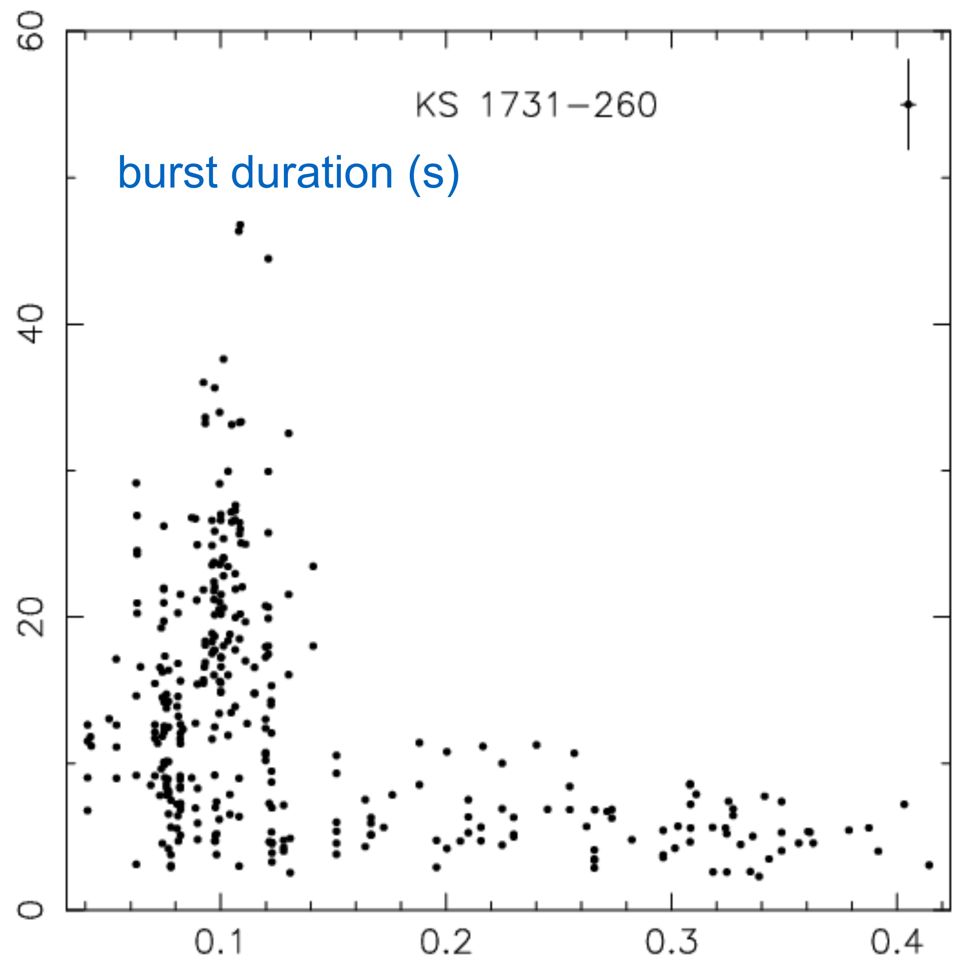




The variation of burst properties with accretion rate is opposite to that predicted!

Cornelisse et al. (2003) data for KS 1731
see also van Paradijs et al. (1989)





What happens at $L_X \sim 10^{37}$ erg/s?

regular bursts
long duration

$\alpha \approx 25 - 40$

f_c shows significant variation

burst oscillations

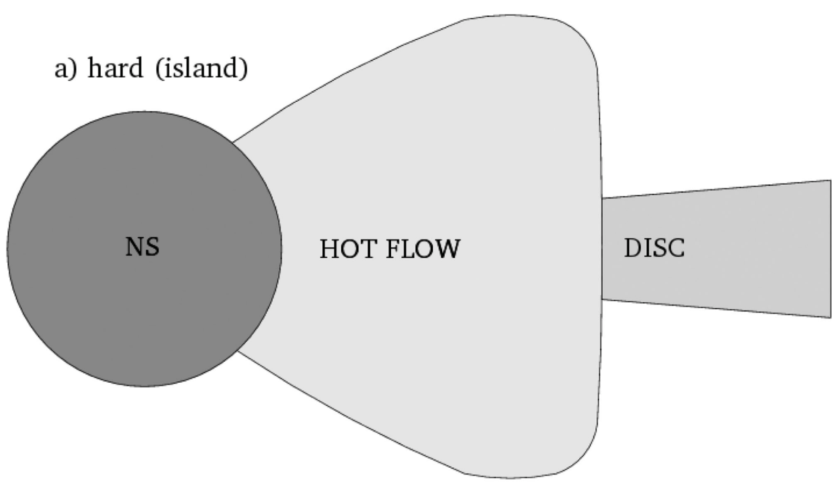
superbursts

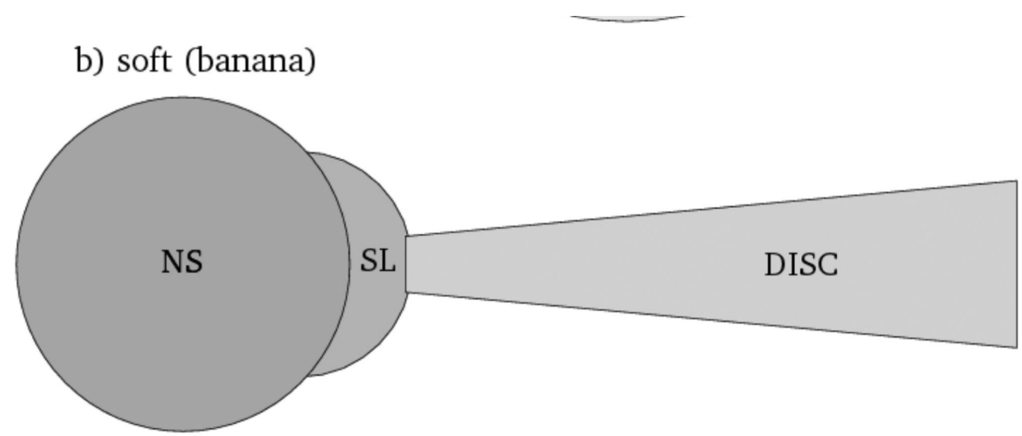
stable burning $\alpha \sim 100 - 1000$
short, irregular Type I bursts

mHz QPOs

f_c is flat!

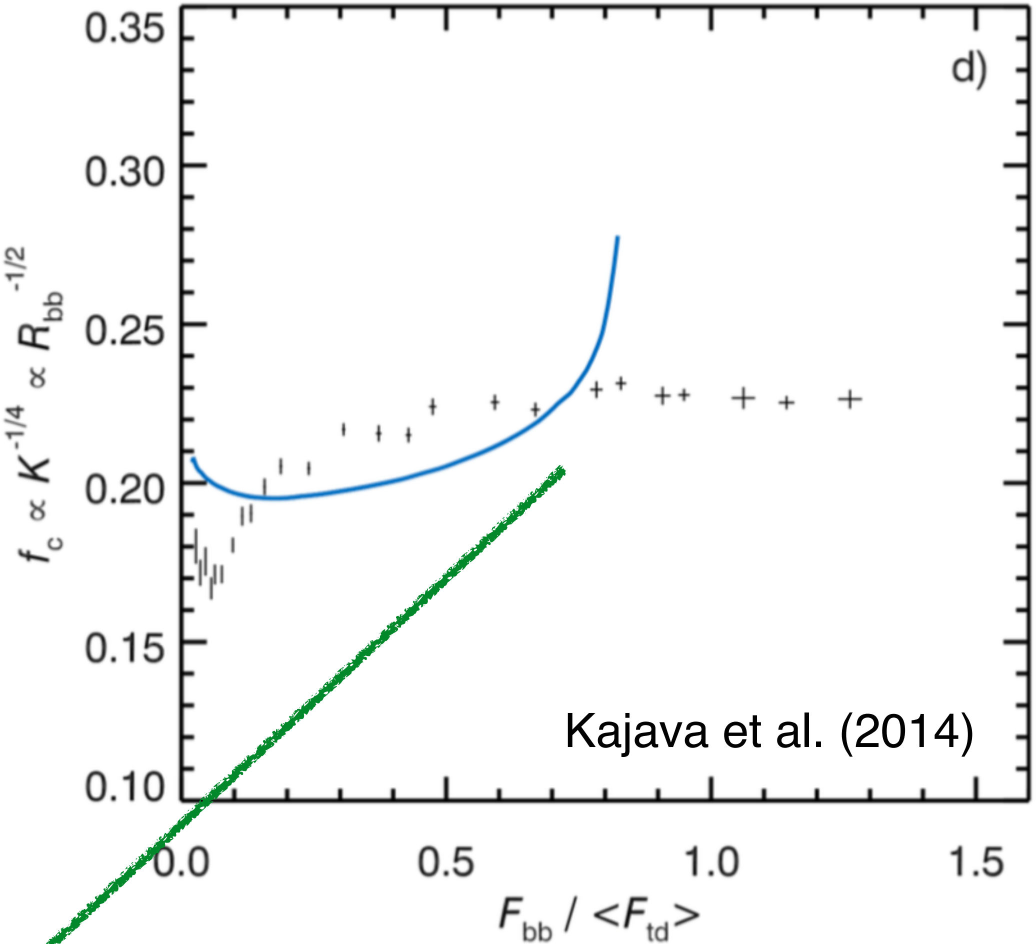
drifting mHz QPOs

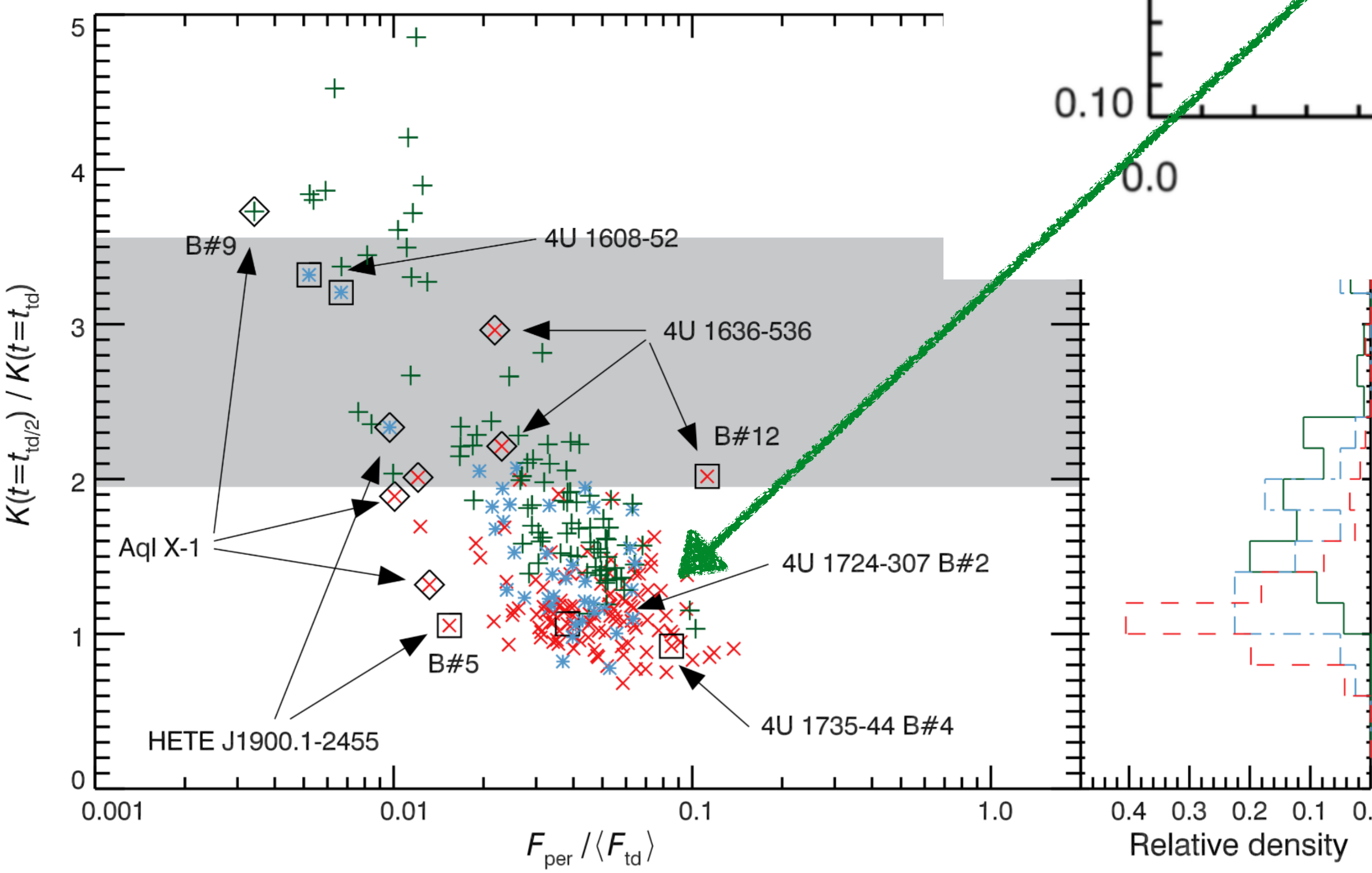




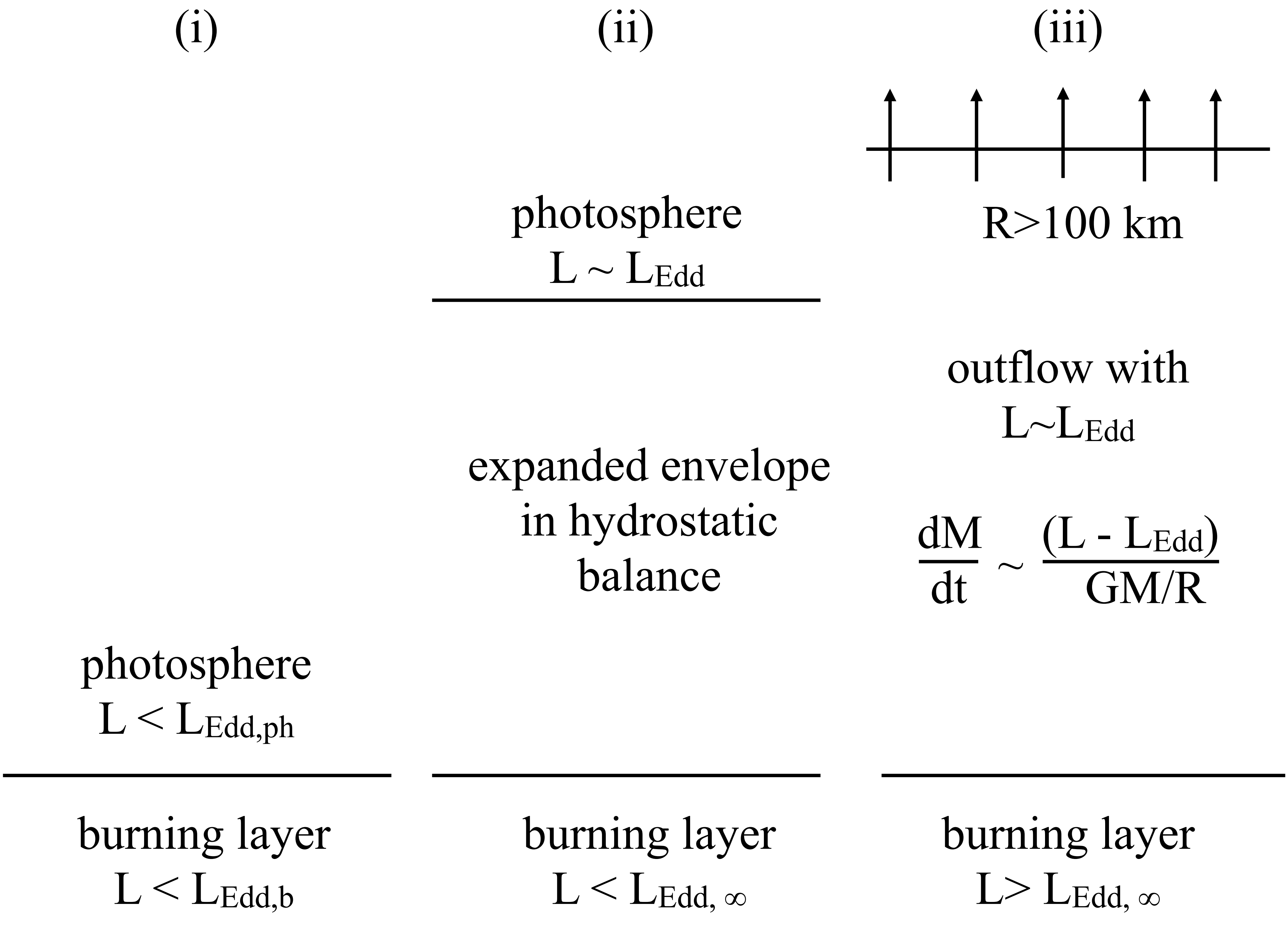
Key question: why is f_c independent of flux in many bursts?

Kajava et al. (2014) suggest that the burst spectrum is modified by the accretion disk boundary layer/spreading layer
(as in Inogamov & Sunyaev 1999,2010)

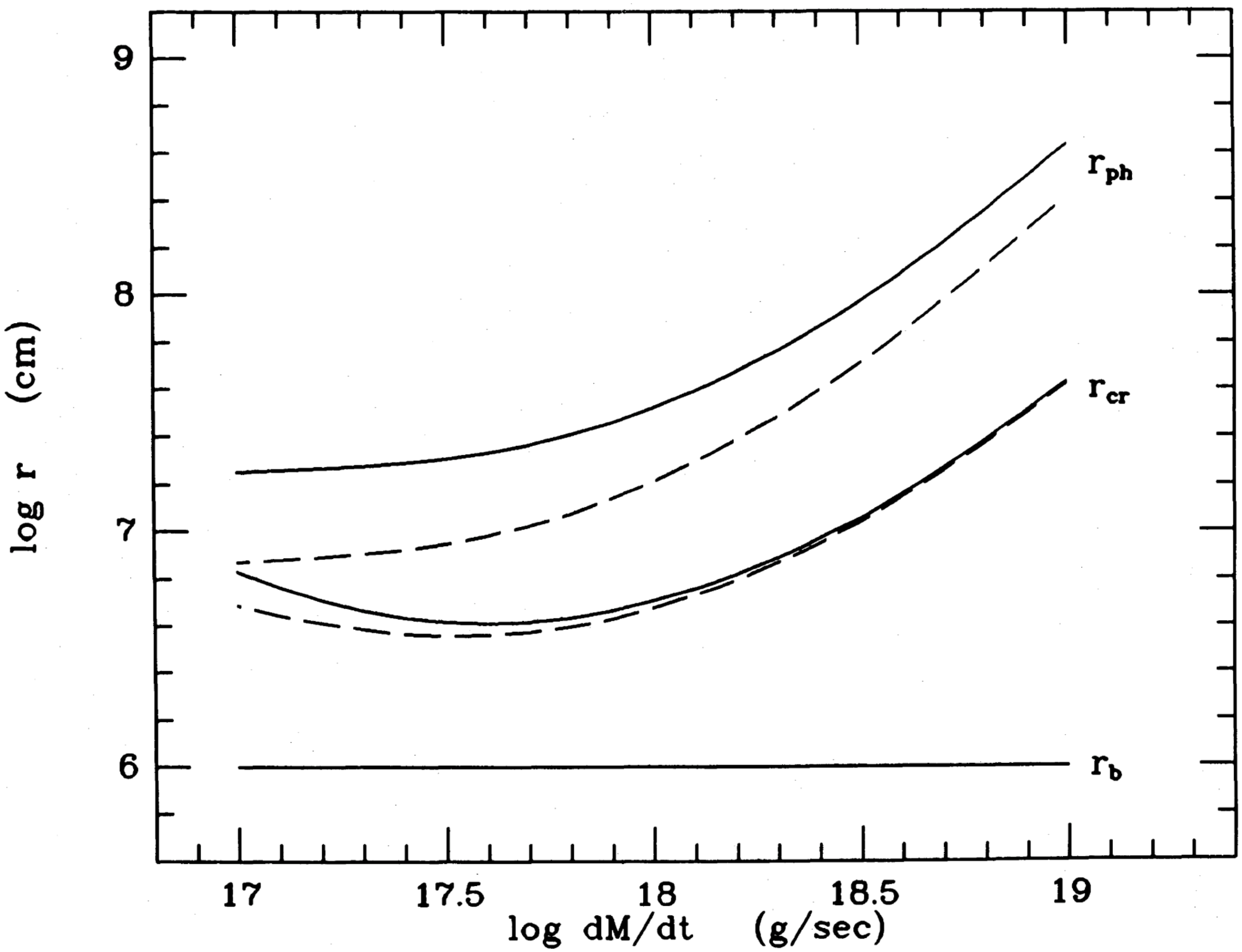




Revnivtsev et al. (2013) observationally identify a component of the spectrum in XTE J1701 that has this behaviour

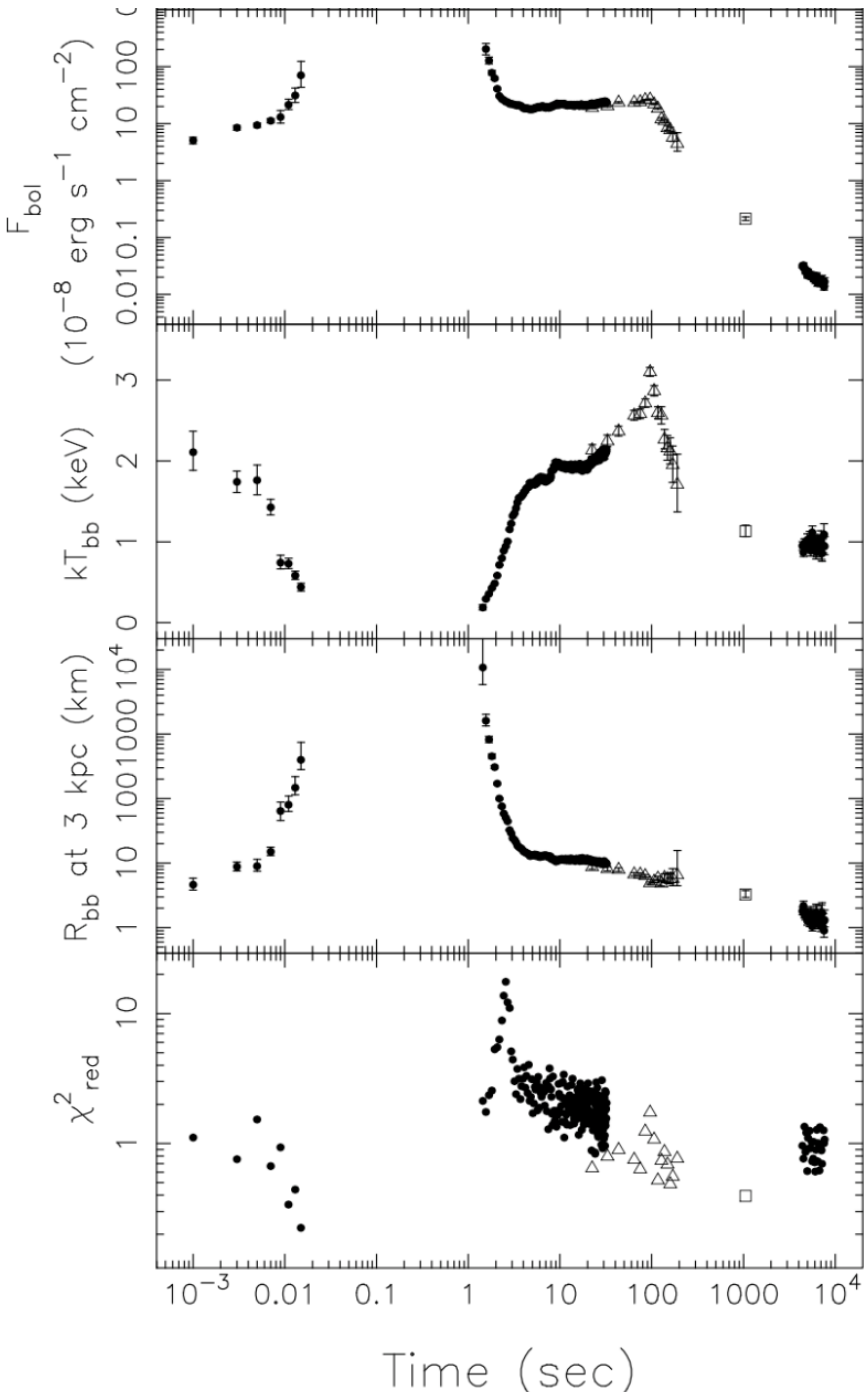


(i)
(ii)
(iii)
R>100 km
photosphere
L ~ L_Edd
outflow with
L~L_Edd
expanded envelope
in hydrostatic
balance
dM/dt ~ (L - L_Edd) / GM/R
photosphere
L < L_Edd,ph
burning layer
L < L_Edd,b
burning layer
L < L_Edd, ∞
burning layer
L> L_Edd, ∞

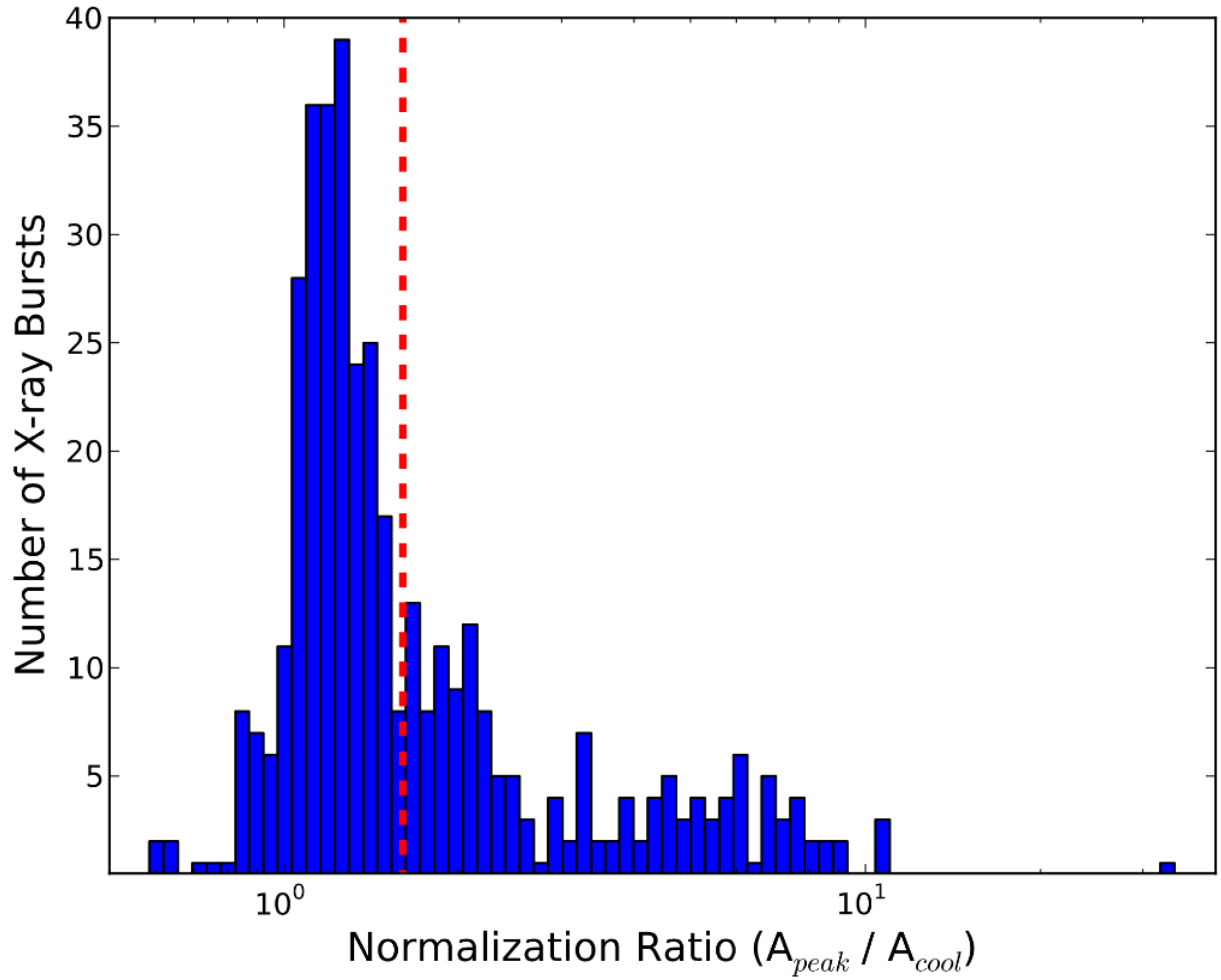


Paczynski & Proszynski (1986)
Paczynski & Anderson (1986)

(still holds for more detailed radiative transfer,
Nobili, Turolla, & Lapidus 1994, Shaposhnikov & Titarchuk 2002)



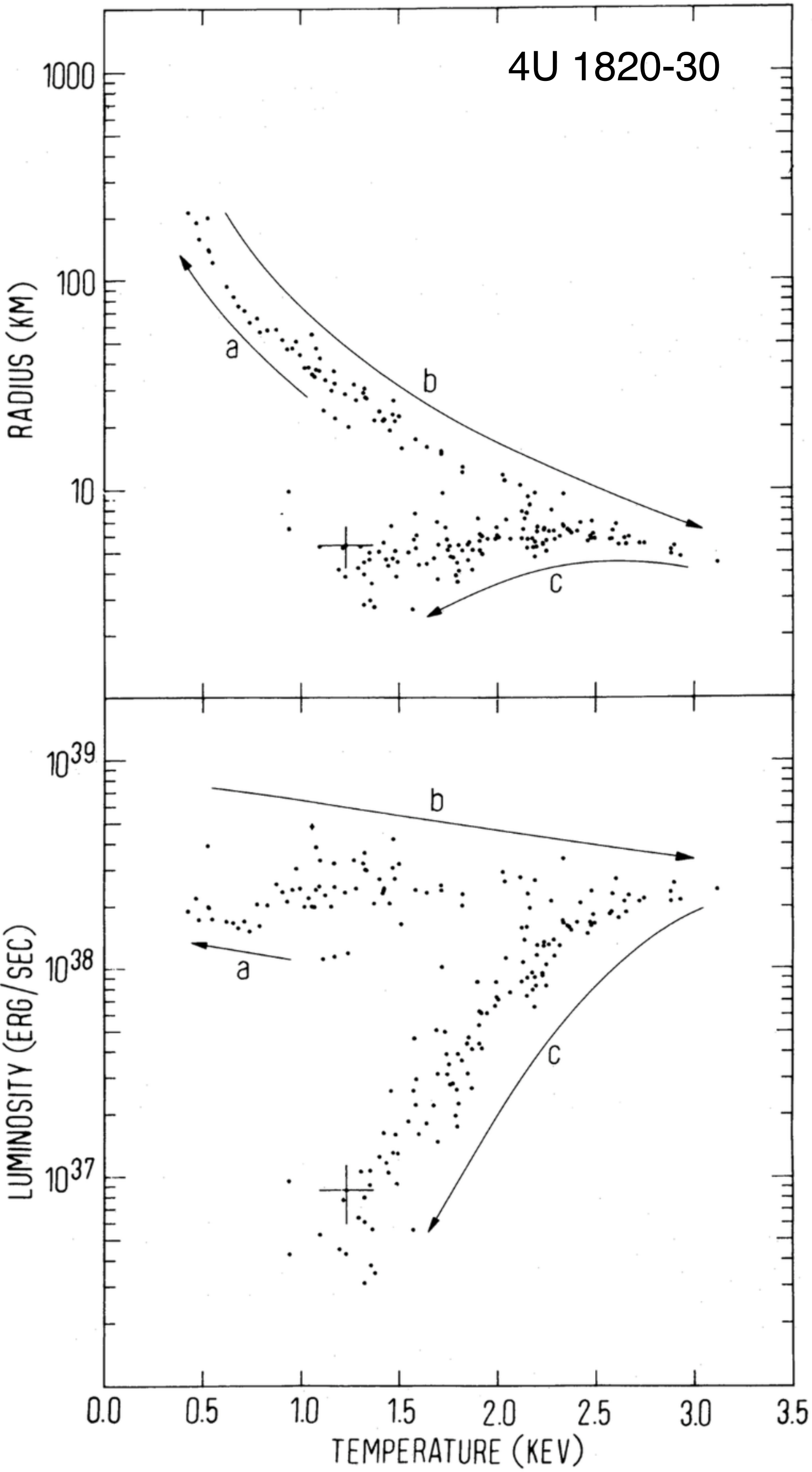
4U 0614+091 Kuulkers et al. (2010)



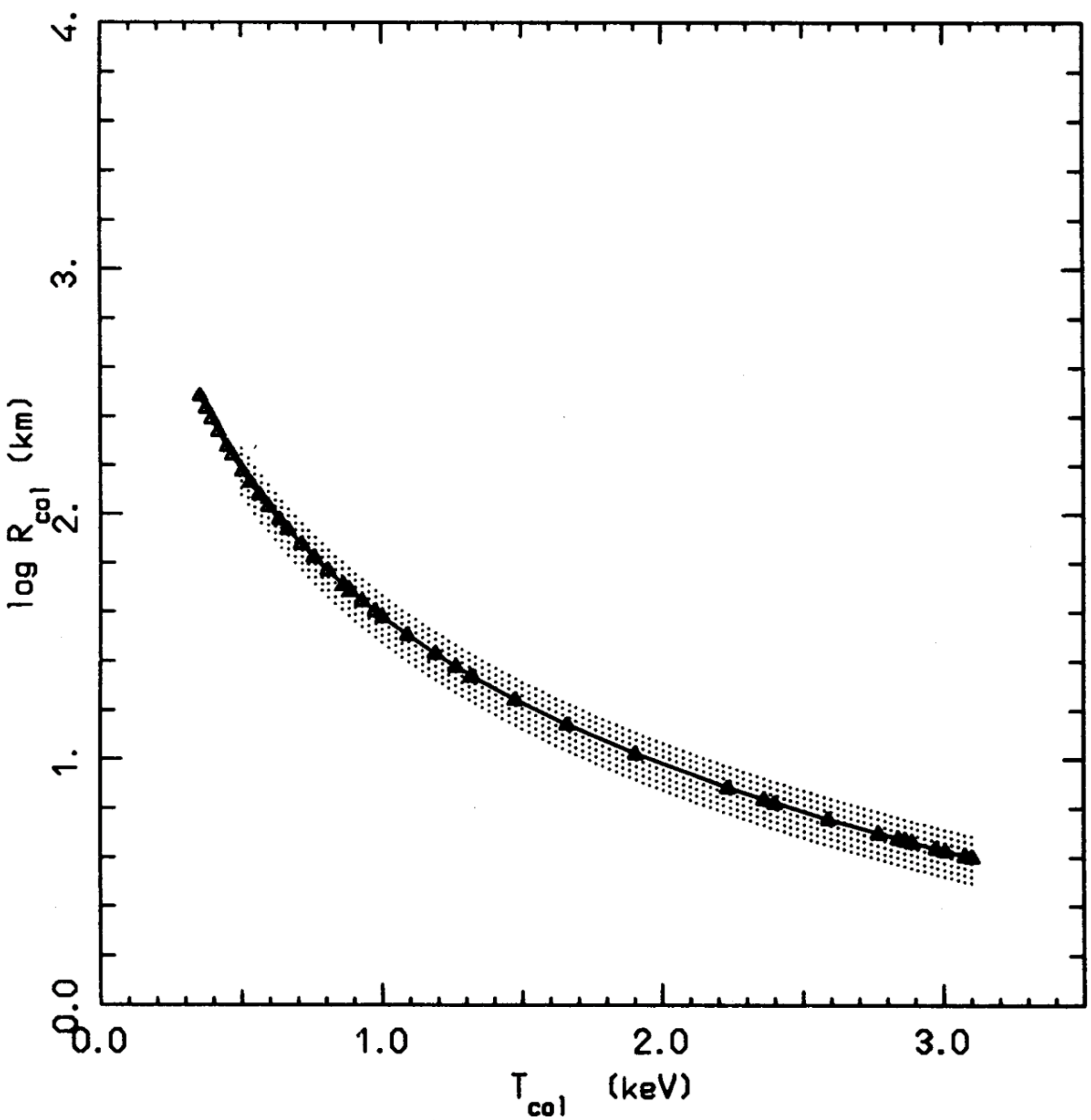
Güver, Özel, Psaltis (2012)

In most bursts, expansions are << 100km

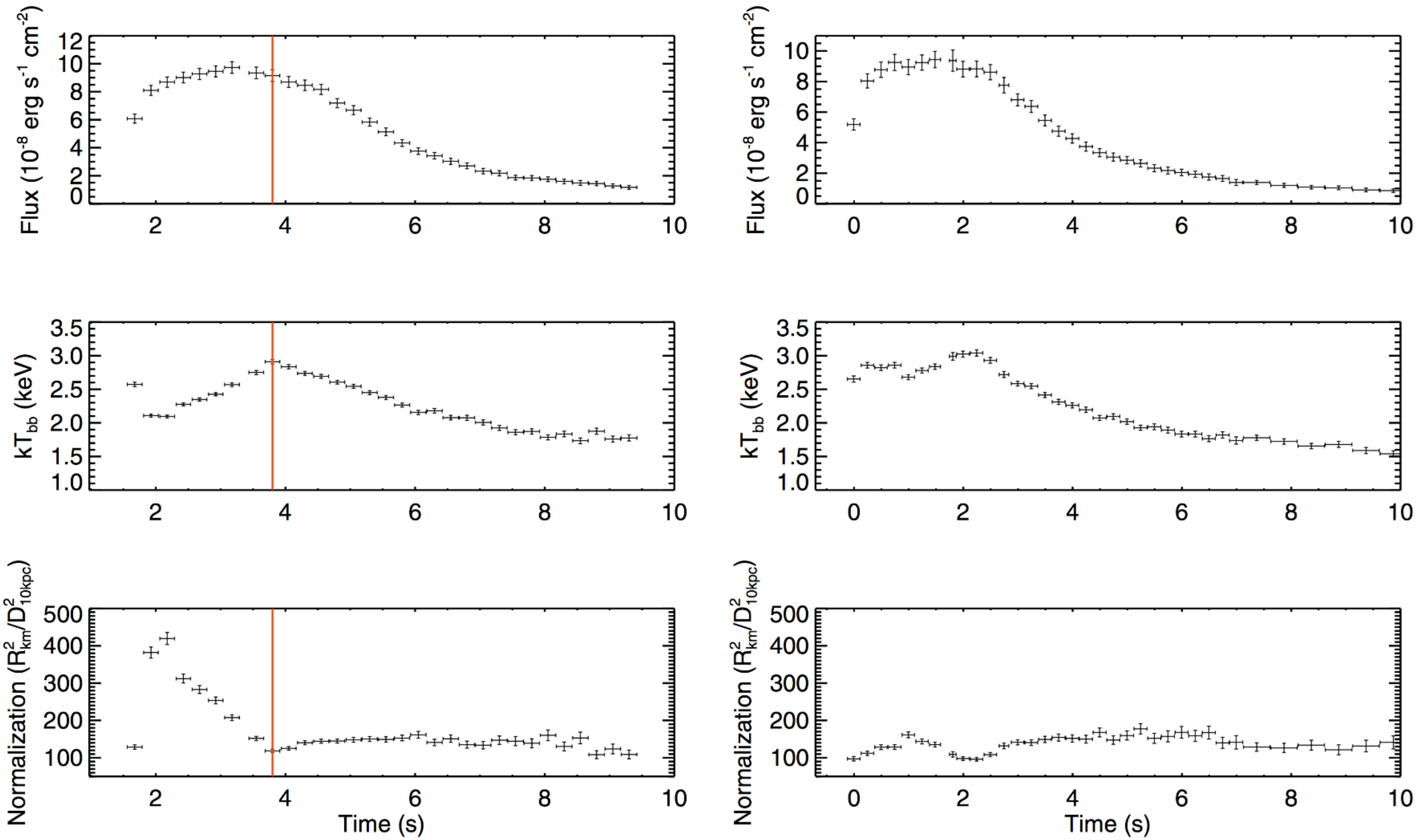
- are we seeing expanded atmospheres?
- truncation of winds by heavy elements? (in 't Zand & Weinberg 2010)
- color correction?



Haberl et al.1987

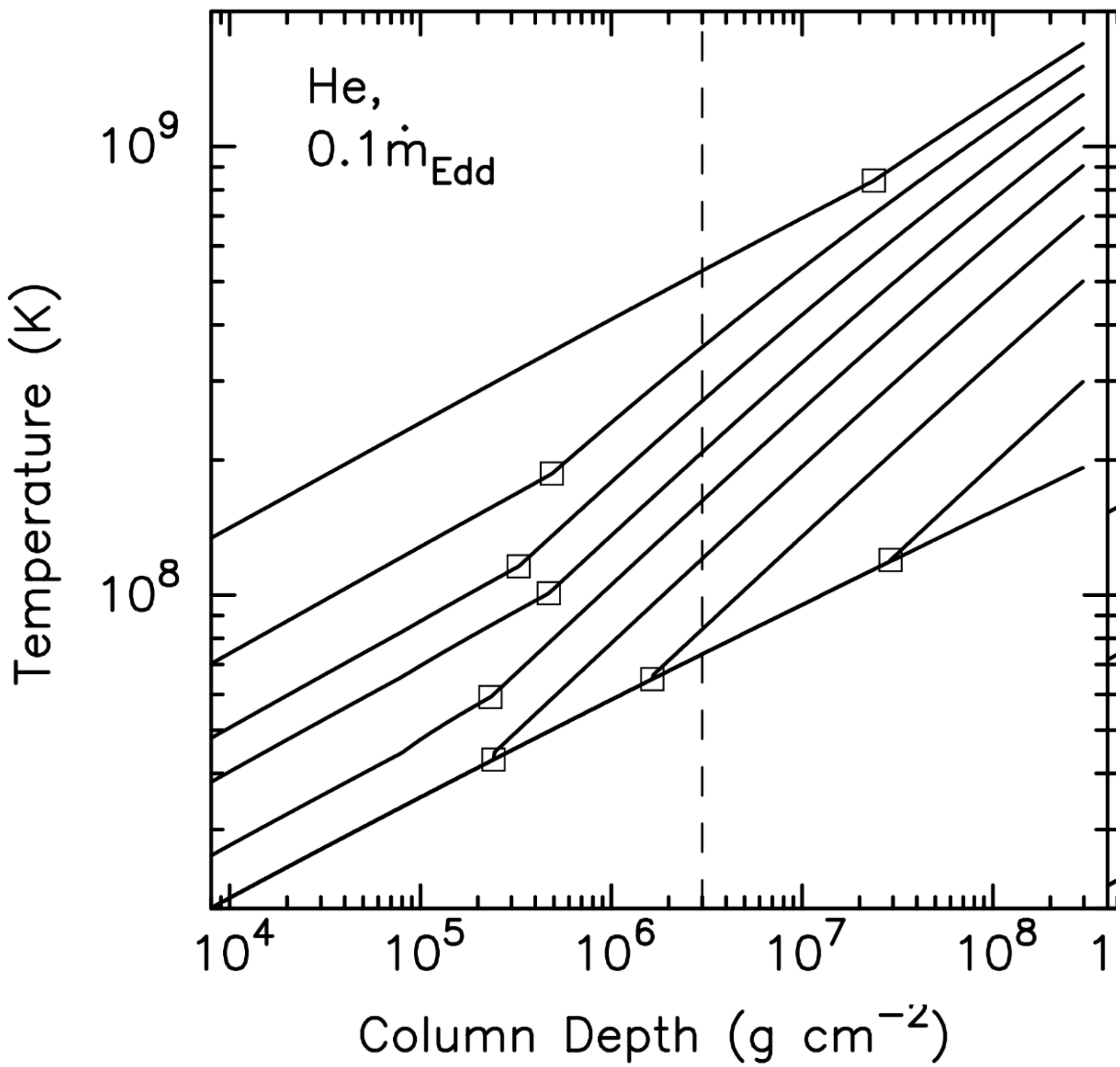


Nobili, Turolla, & Lapidus (1994)



Güver, Özel, Psaltis (2012)

Mass loss in PRE bursts



Weinberg, Bildsten & Schatz (2006)

- Joss (1976) pointed out that the convection zone cannot reach the photosphere (entropy of burned material < entropy of photosphere)

$$P_{\rm conv} \approx P_b \left(\frac{T_{\rm eff}}{T_b}\right)^{5/2} \sim 10^3 \ {\rm g\ cm^{-2}}$$

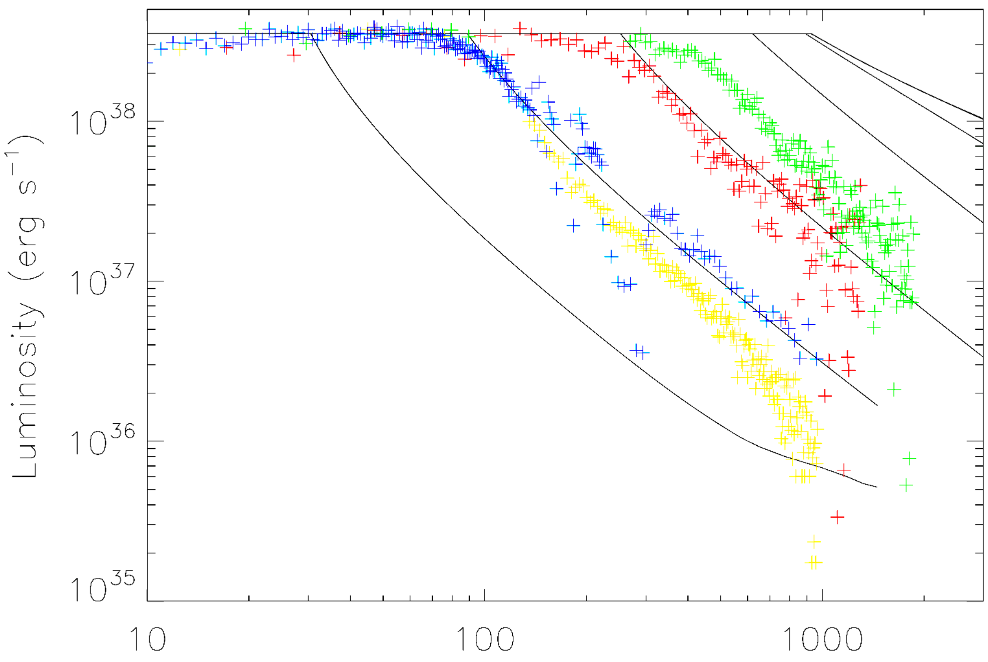
- Hanawa & Sugimoto (1982) realized that the convection zone extends until the thermal time matches the growth time

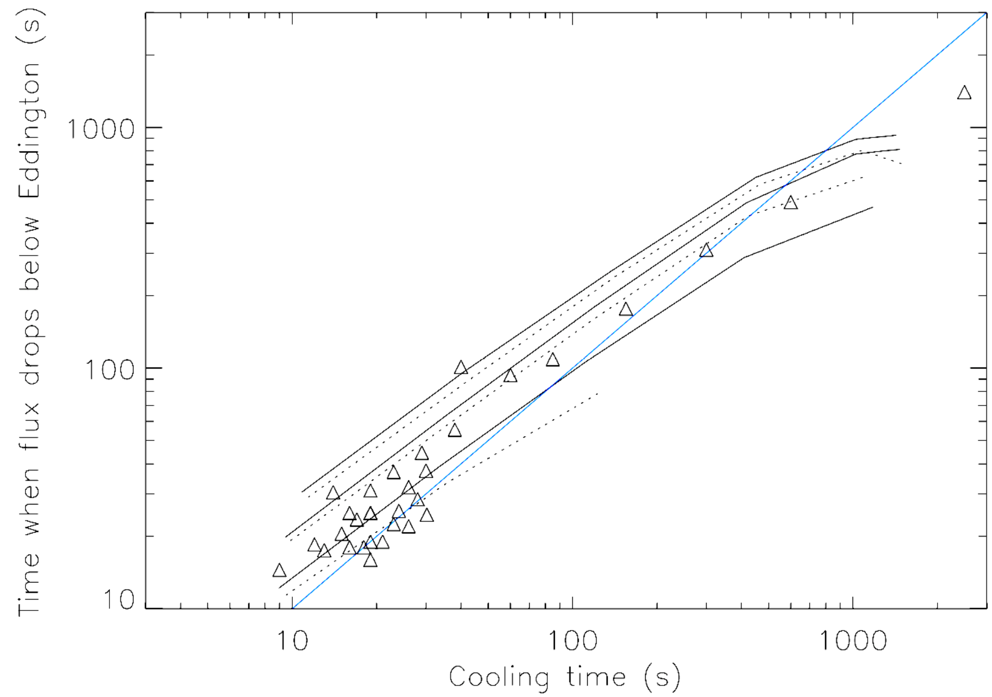
$$t_{\rm therm} = \frac{3\kappa y^2 c_P}{4acT^3} = 10^{-3}\ {\rm s}\ \frac{y_5^2}{T_8^3}\left(\frac{\kappa}{0.1}\right)$$

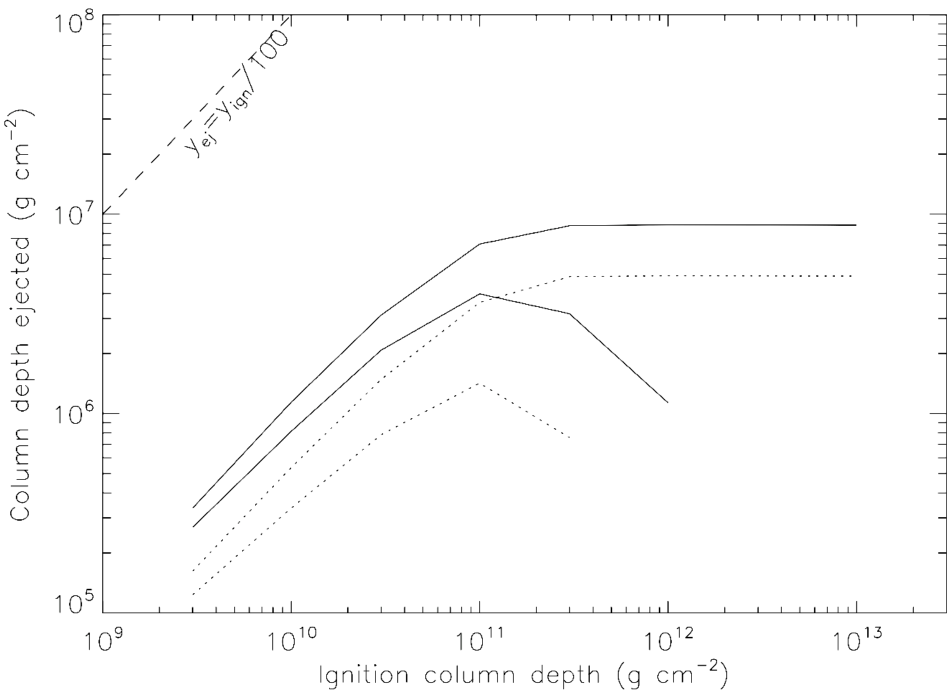
- Weinberg et al. (2006): estimate for mass loss in the wind

$$\frac{\Delta M_w}{M_{\rm acc}} \simeq \frac{\dot{M}_w \Delta t}{M_{\rm acc}} \simeq \left(1-\frac{L_{\rm Edd}}{L}\right)\frac{Q_{\rm nuc}}{v_{\rm esc}c} = 0.003\left(1-\frac{L_{\rm Edd}}{L}\right)$$

Cooling models for intermediate duration bursts



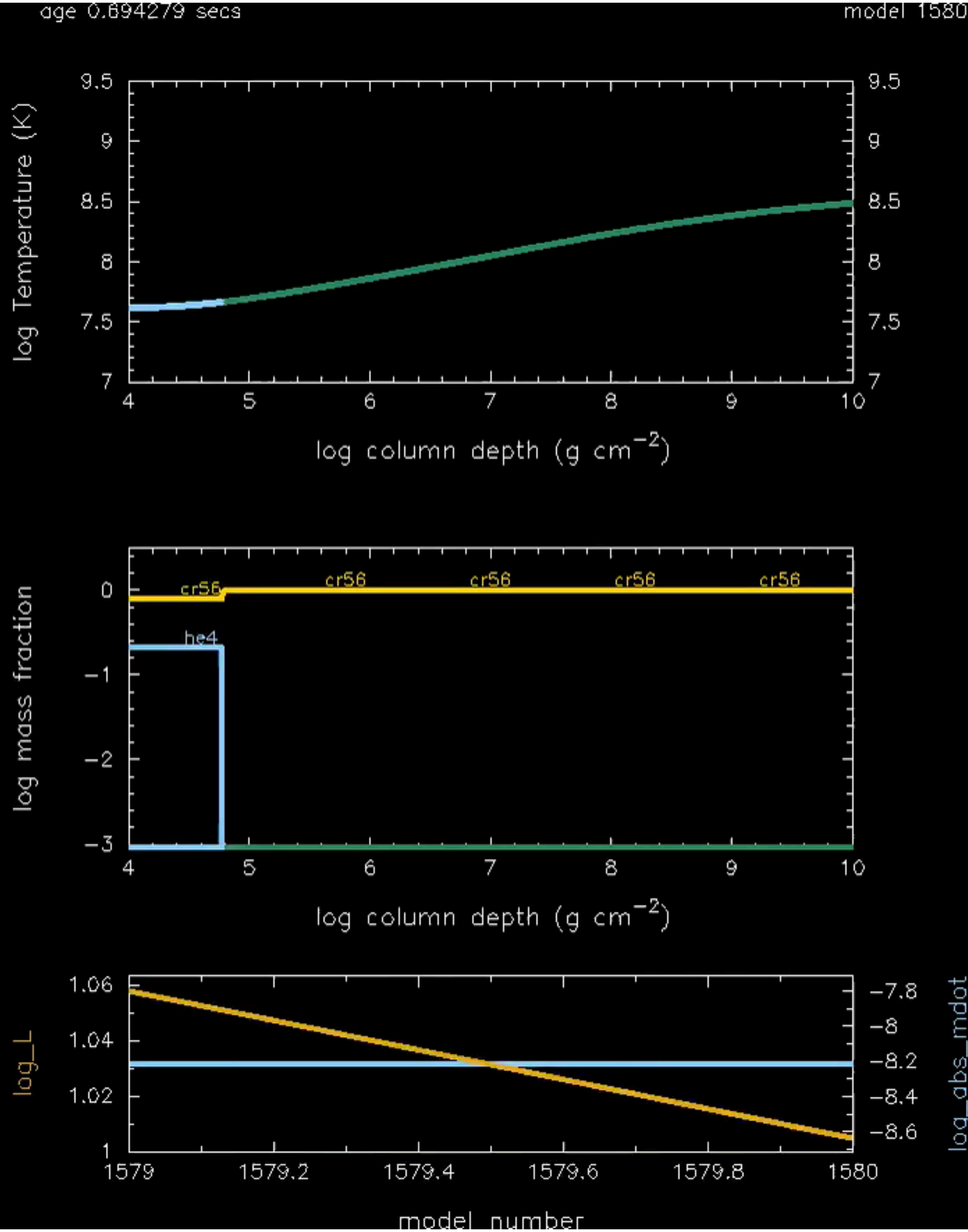




- models reproduce the lightcurves reasonably well
- reproduces the relation between the time above Eddington and the cooling time seen by in 't Zand & Weinberg (2010)
- mass loss is ~10^{-3} of the mass of the layer

Cumming, in't Zand, Falanga (in prep)

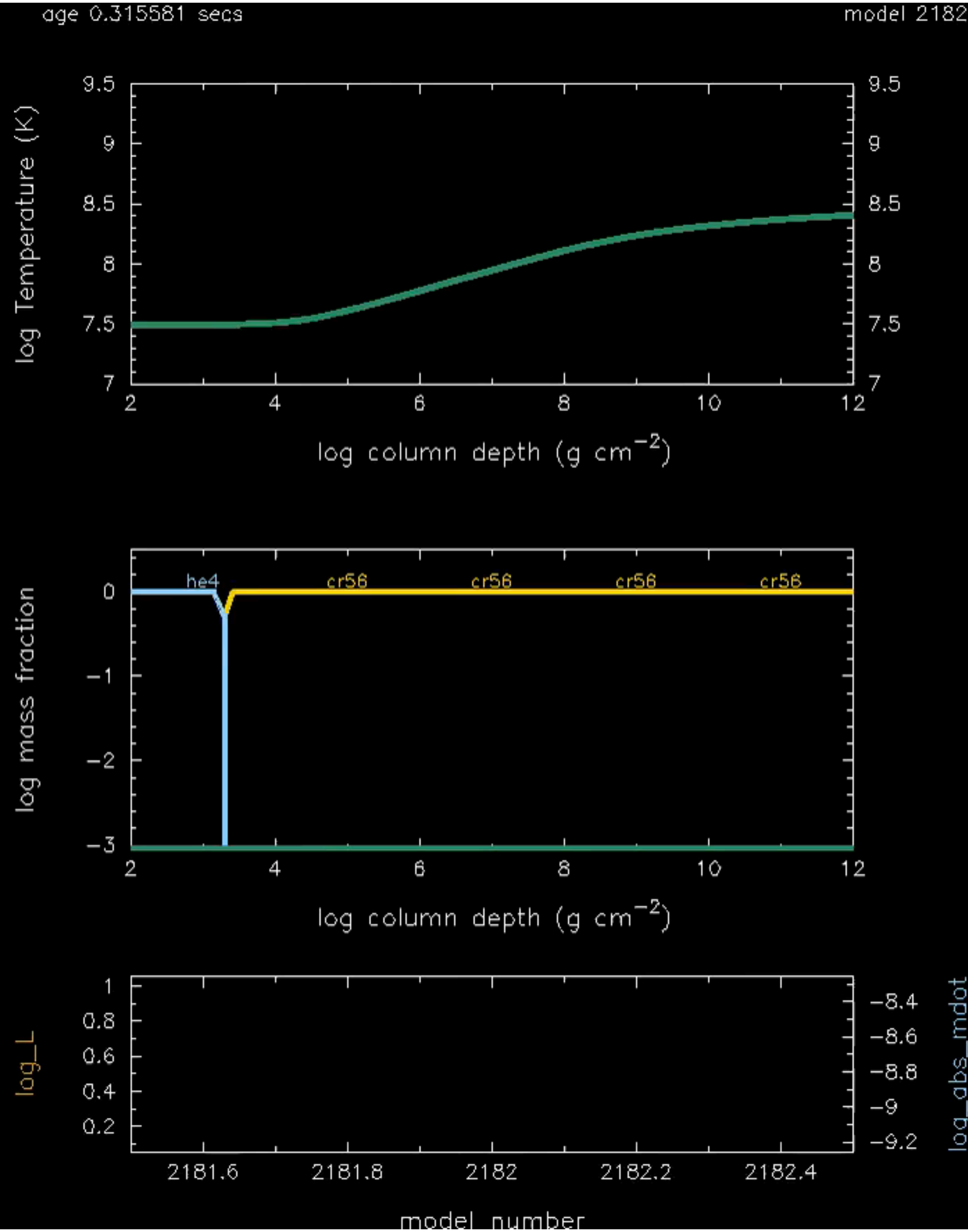
0.2 Eddington
0.4 MeV/nuc



Simulations with MESA star, including prescription for super Eddington wind

Romain Ruhlmann (McGill)

0.1 Eddington
0.1 MeV/nuc



Simulations with MESA star, including prescription for super Eddington wind

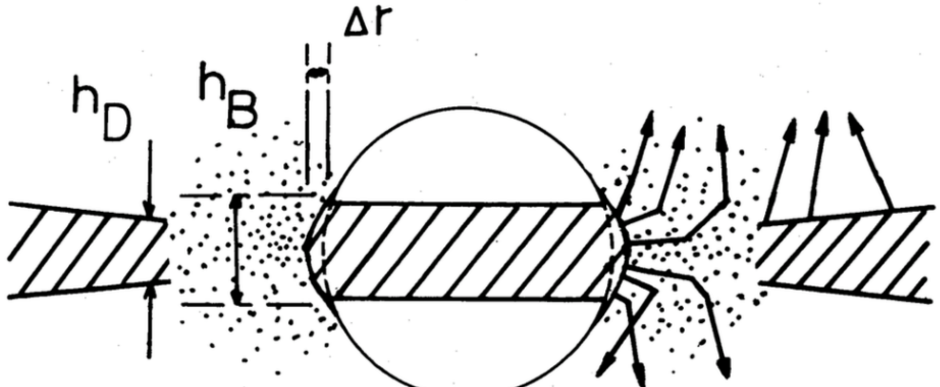
Romain Ruhlmann (McGill)

Anisotropy in burst emission

Burst flux may not be isotropic

$$4\pi d^2 F \xi = L$$

Analytic estimates based on (usually unknown or poorly constrained) inclination, e.g. Fujimoto (1988)   (see also Lapidus et al. 1985)



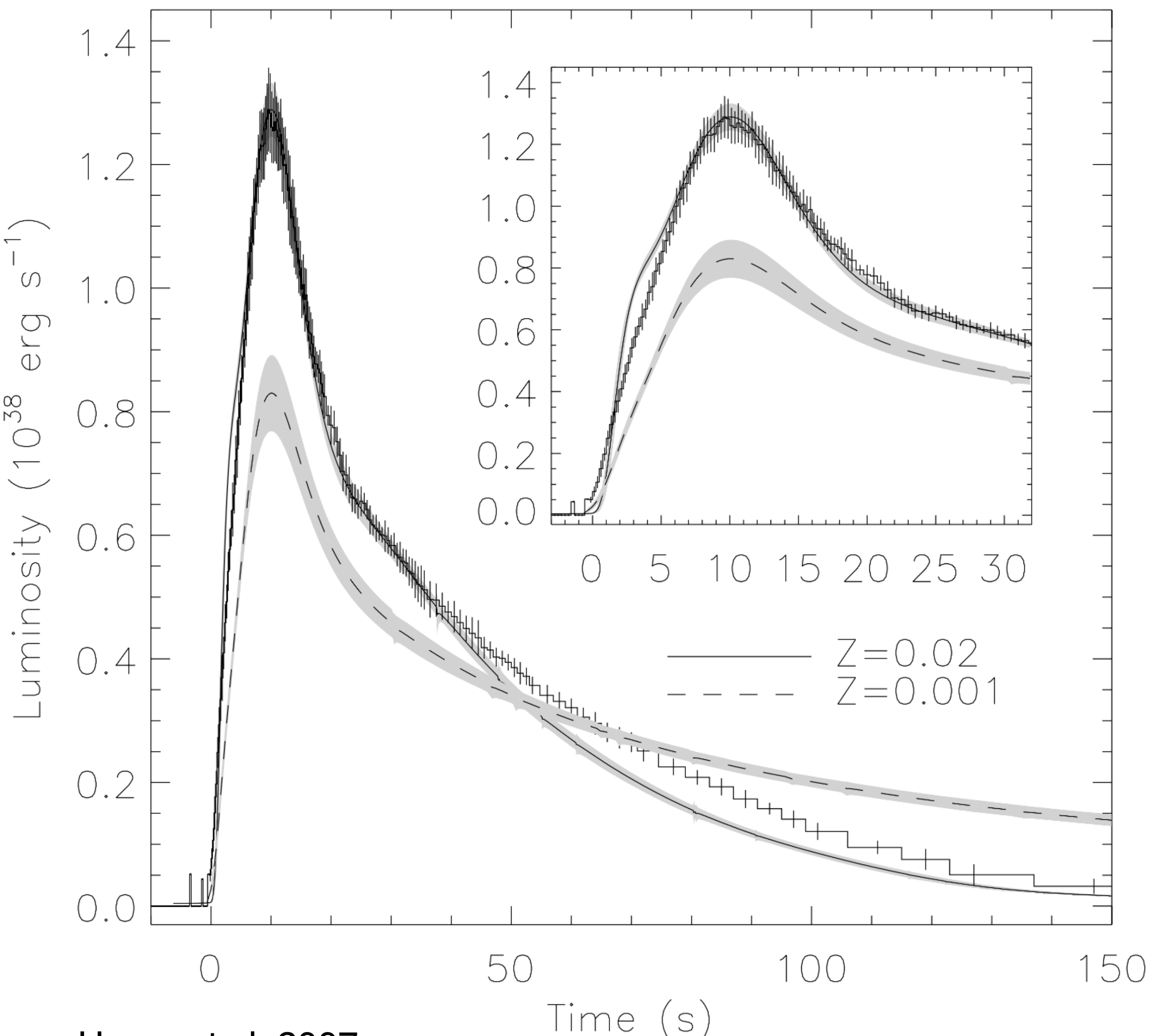
$$\xi_b^{-1} = \frac{1}{2} + |\cos\theta|$$

Anisotropy is always in combination with distance as $\xi^{1/2} d$

=> even if distance is known precisely there is an uncertainty 20-30% coming from this factor

Zamfir et al. (2012)

Mixed H/He bursts from GS 1826 as standard candles



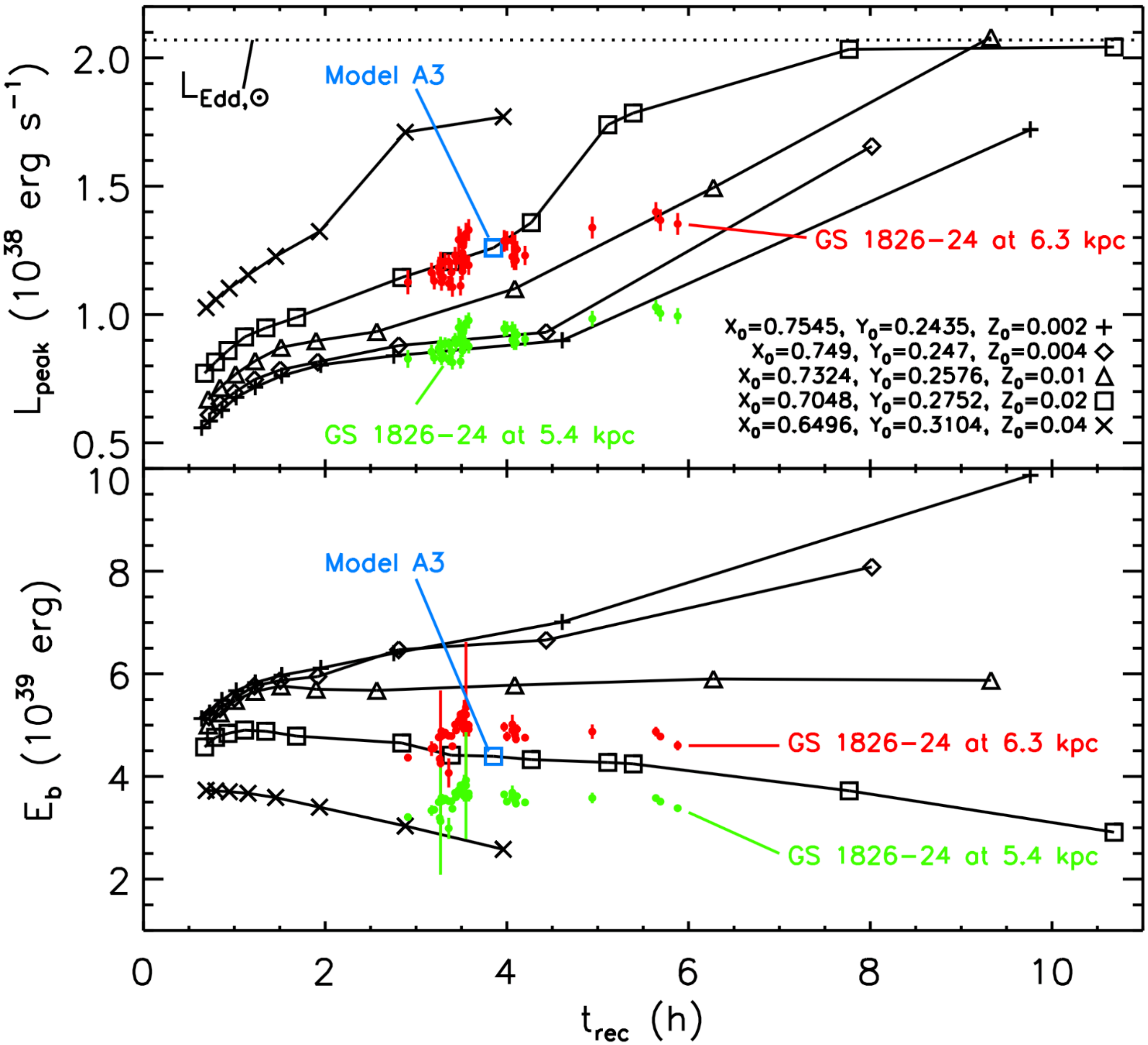
Heger et al. 2007

Model with rp-process burning agrees well with the burst lightcurve from GS 1826

Use this as an alternative to the Eddington luminosity to set the luminosity scale

Zamfir et al. (2012)

Comparison of models with GS 1826 across a range of recurrence times



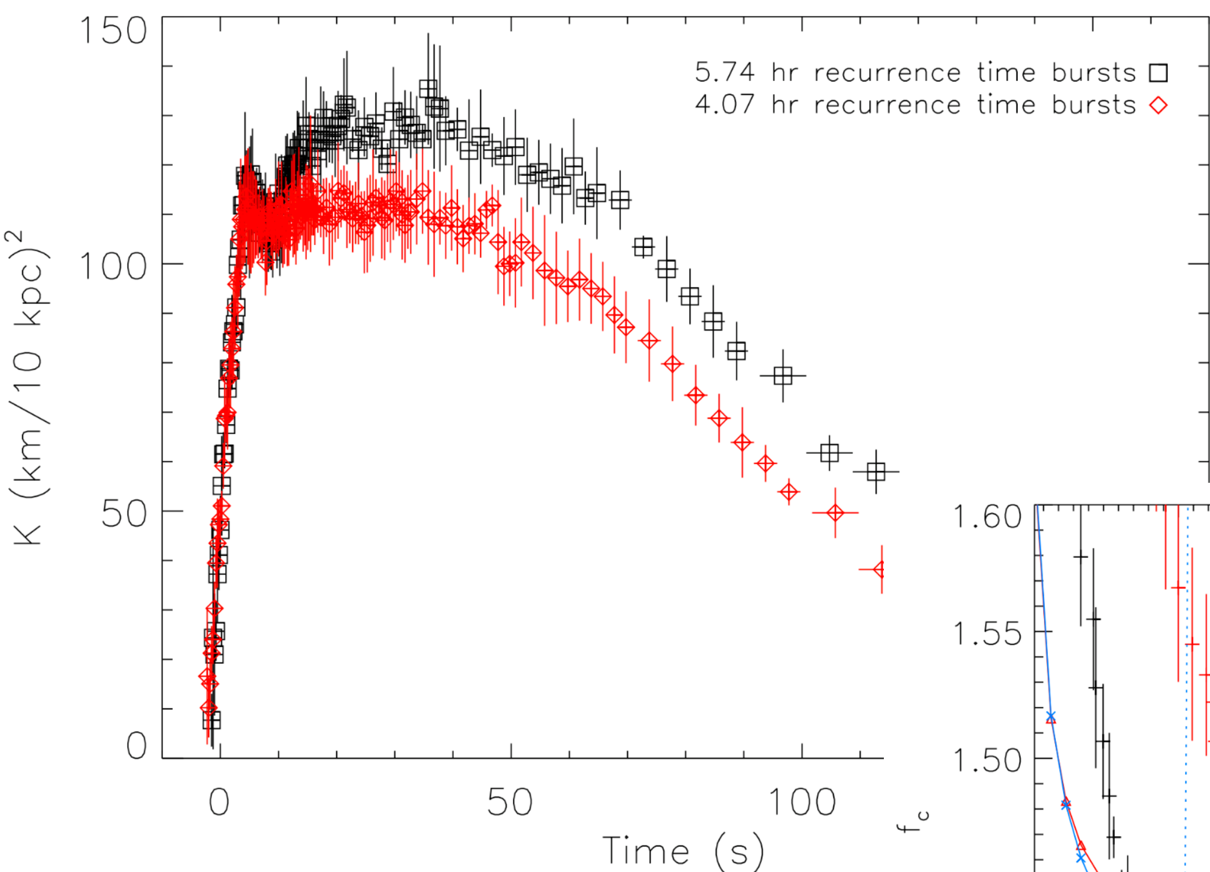
The model that worked so well at 4 hour recurrence time is too bright at 6 hours

=> need to lower metallicity, enhance helium to match the data

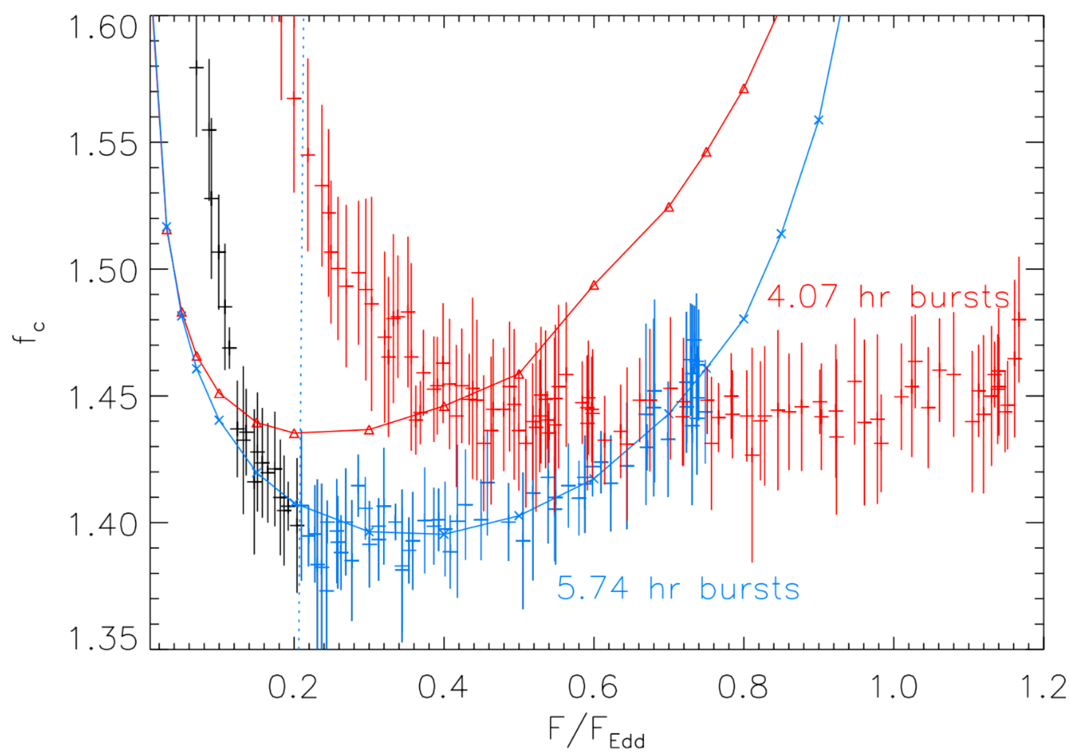
simulations in progress!

Zamfir et al. (in prep)

Change in normalization / color correction behaviour is seen in GS 1826



- 20% change in normalization with ~50% change in accretion rate
- can't explain by changing composition used for the atmospheric model



Zamfir et al. (2012); Galloway & Lampe (2012)

Summary: open issues

1. Key question: Why is $f_c(F)$ flat? What causes the offset in f_c between hard and soft states? Is this related to the change in bursting behaviour from hard to soft state?

2. Why do most PRE's (except superexpansion phases) show modest increases in R_{bb} when wind models predict large expansions R_{ph}>100 km? When do we expect heavy elements to be ejected into the wind?

3. Anisotropy adds an effective additional 20-30% uncertainty to distances for bursters. Given uncertainties in distance, look for distance-independent constraints on M,R - even limits can be constraining.

4. Bursters offer many different kinds of phenomenology - can we make consistent models

   e.g. KS 1731 has PRE bursts, "GS1826-like" bursts, superburst, crust cooling in quiescence