Constraining Neutron Star Mass and Radius without distance

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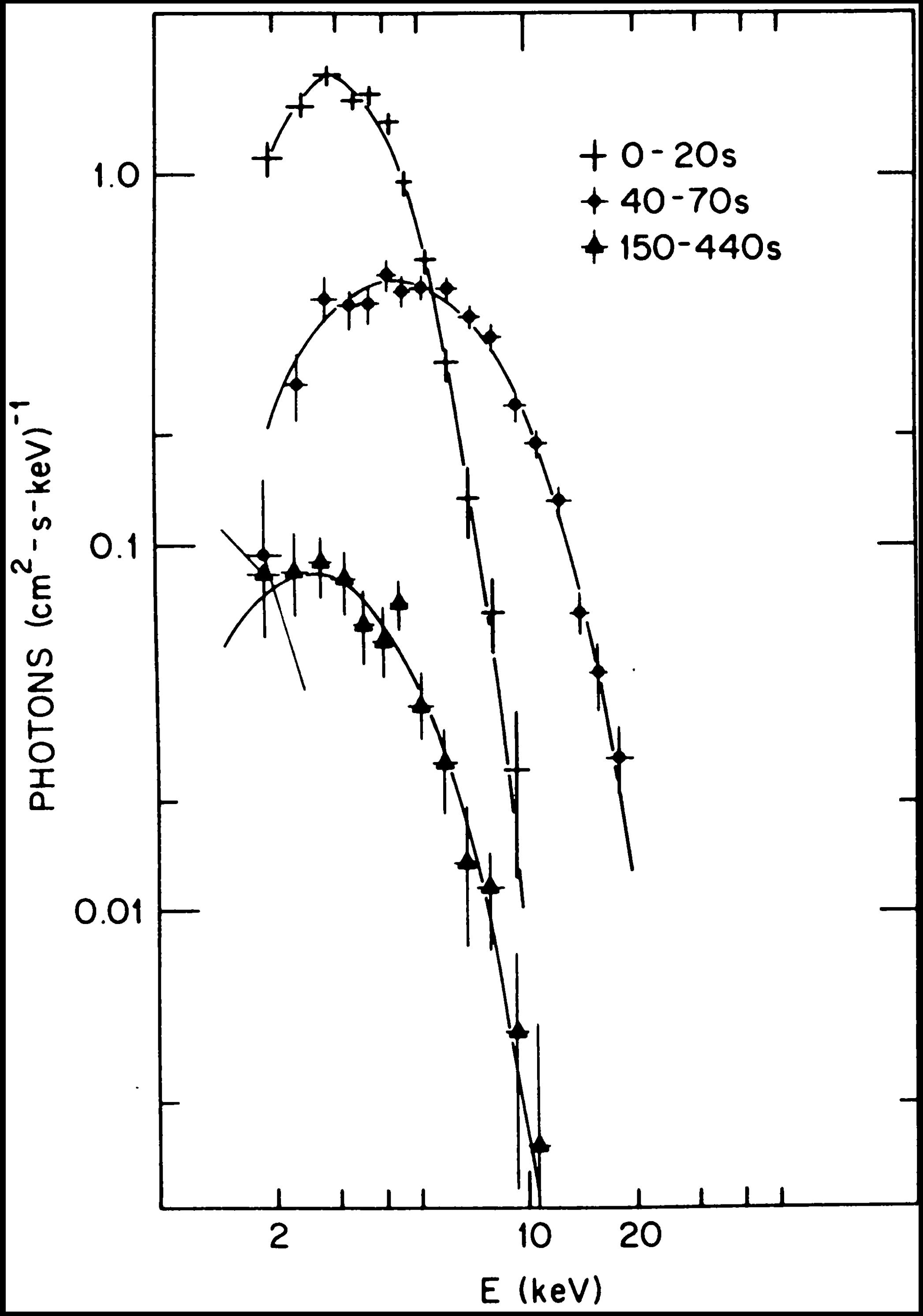
this talk

- X-ray bursts as tools for measuring M, R
  - Challenges & systematic uncertainties
- Aim is to derive constraints free of systematics
  - GS 1826-24: the “textbook burster”
- Open question about different spectral evolutions during bursts

Type I X-ray bursts to infer M,R

- They are bright
- We see the neutron star surface
- Spectra well fit by Planck curves
- We can measure ‘R_{bb}’
- Advantages: observables can be combined (e.g. F_{Edd}, R_{bb})

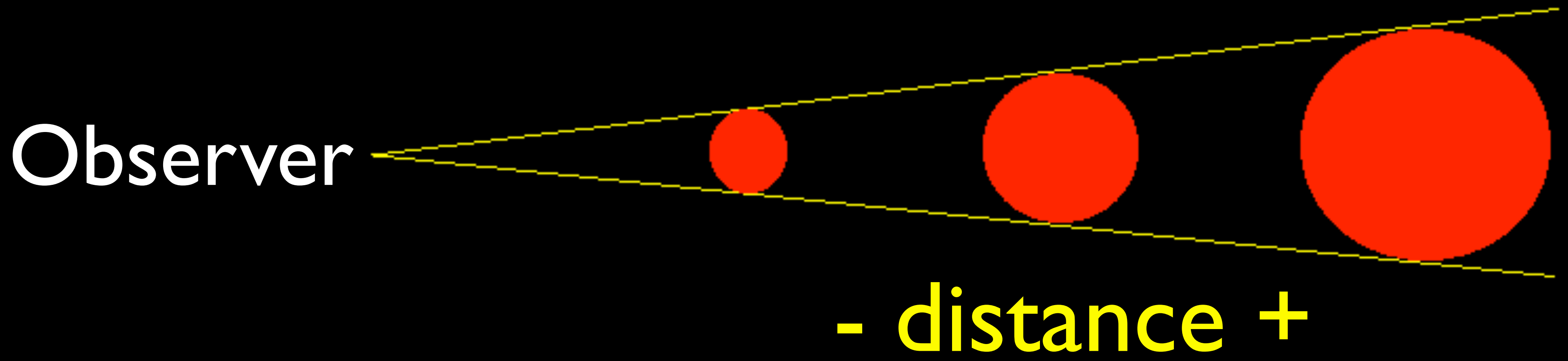


Lewin et al. (1993)

Challenges

- Either unknown or poorly constrained distance

Important because $R^2 \sim d^2 K_{bb}$


Observer

- distance +

Challenges

- Either unknown or poorly constrained distance
- Color correction in the spectrum

Neutron star spectra look like blackbody, but shifted to higher temperatures

$f_c = T_{bb}/T_{eff}$

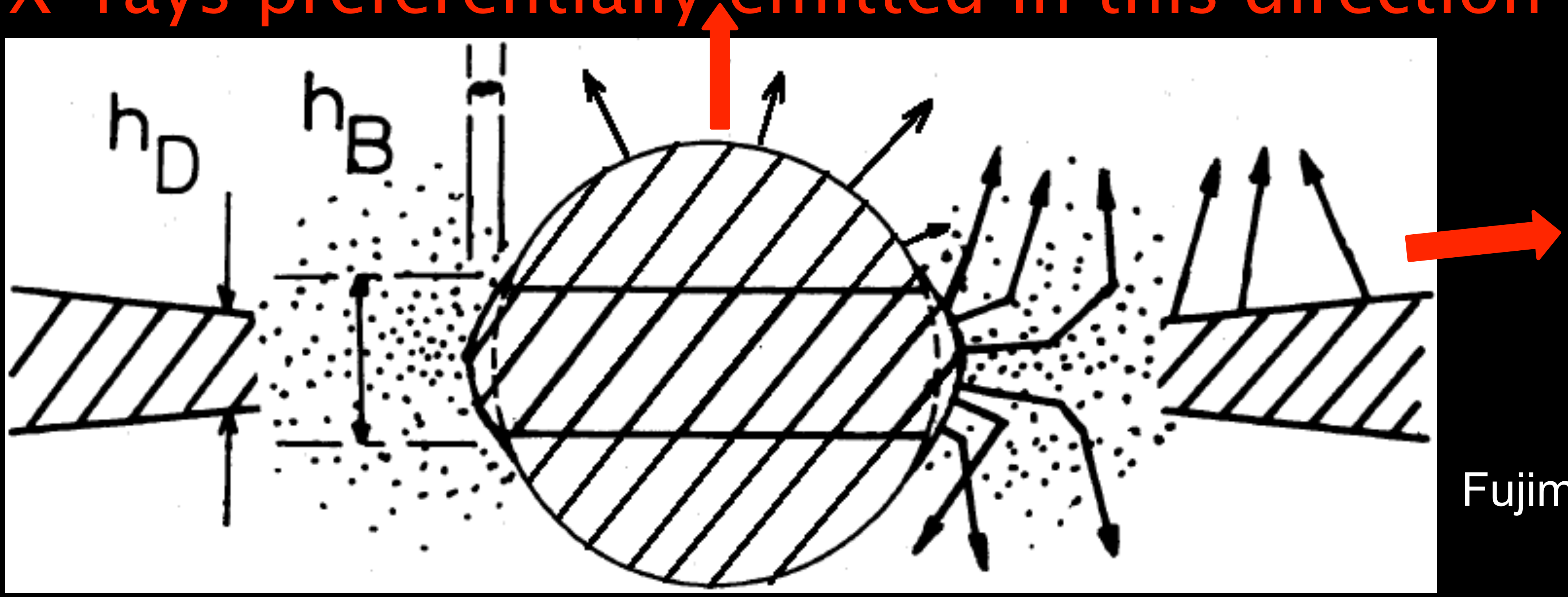
Typically by a factor $f_c = 1.3 - 1.8$

Challenges

- Either unknown or poorly constrained distance
- Color correction in the spectrum
- Emission anisotropy "ξ" (see Lapidus & Sunyaev '85, Fujimoto '88):

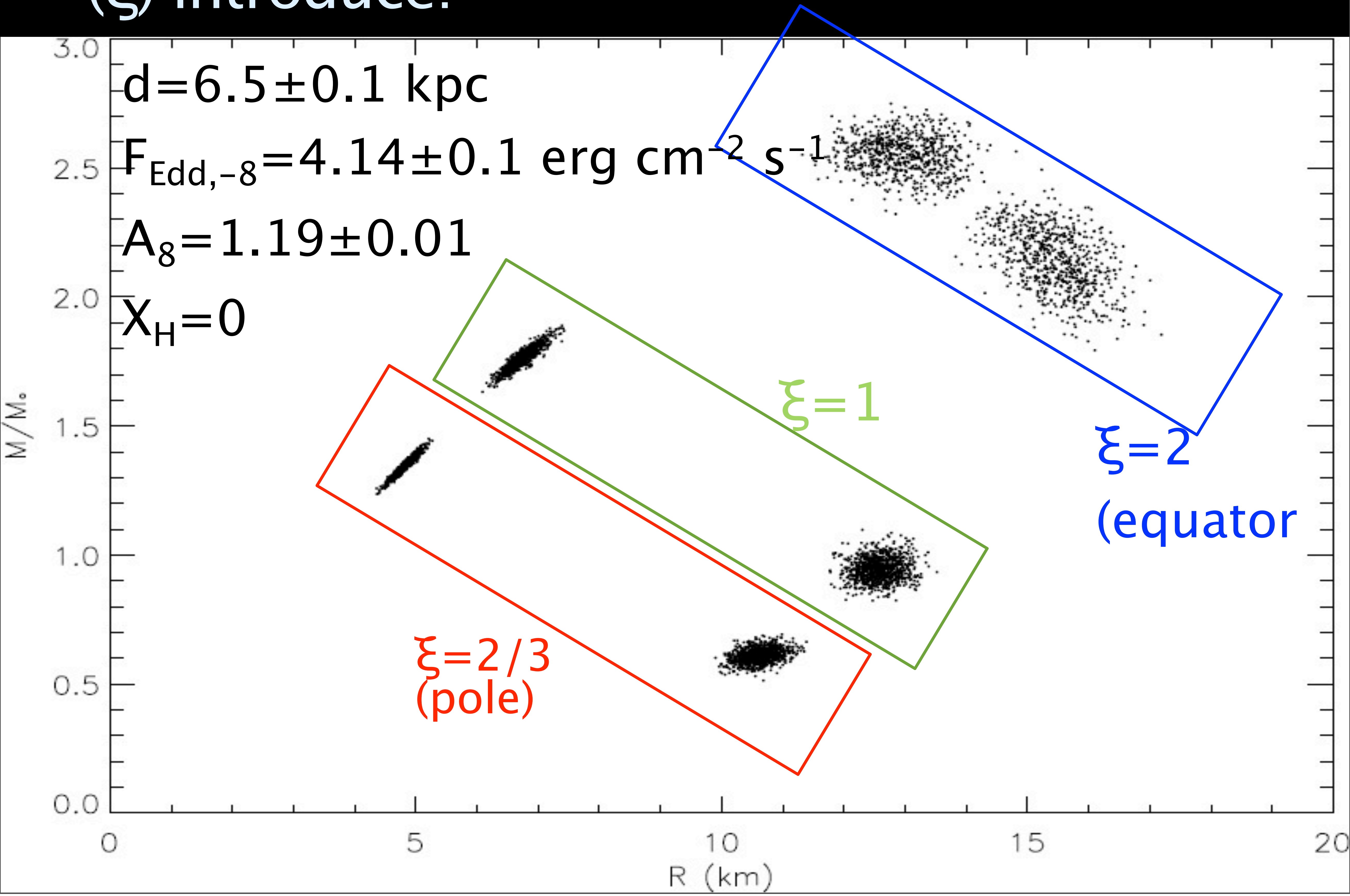
  Can change observed flux by up to a factor of 2

X–rays preferentially emitted in this direction



Fujimoto (1988)

What kind of error in M,R can anisotropy (ξ) introduce?



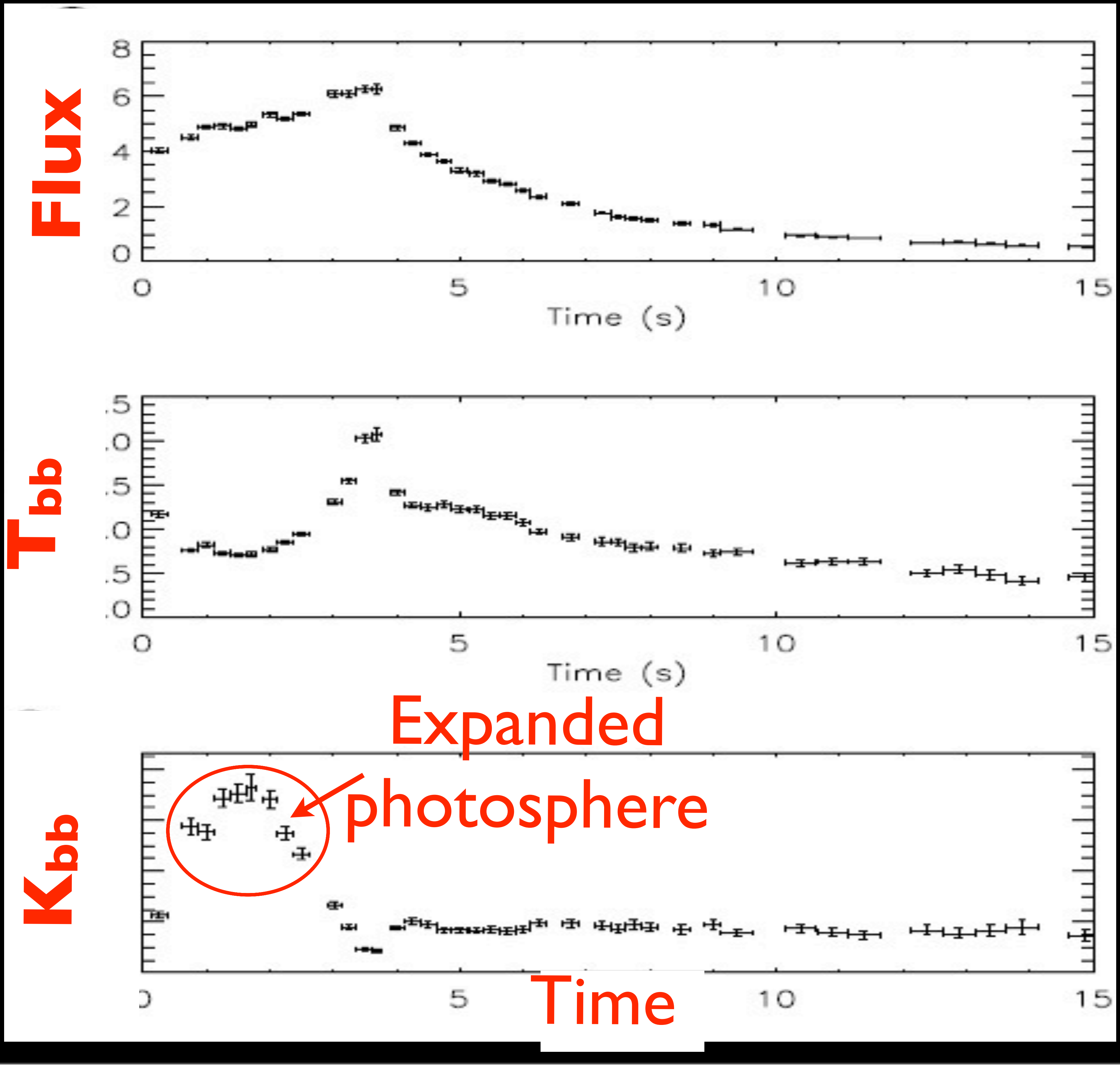
$d=6.5\pm0.1$ kpc

$F_{Edd,-8}=4.14\pm0.1$ erg cm^{-2} s^{-1}

$A_8=1.19\pm0.01$

$X_H=0$

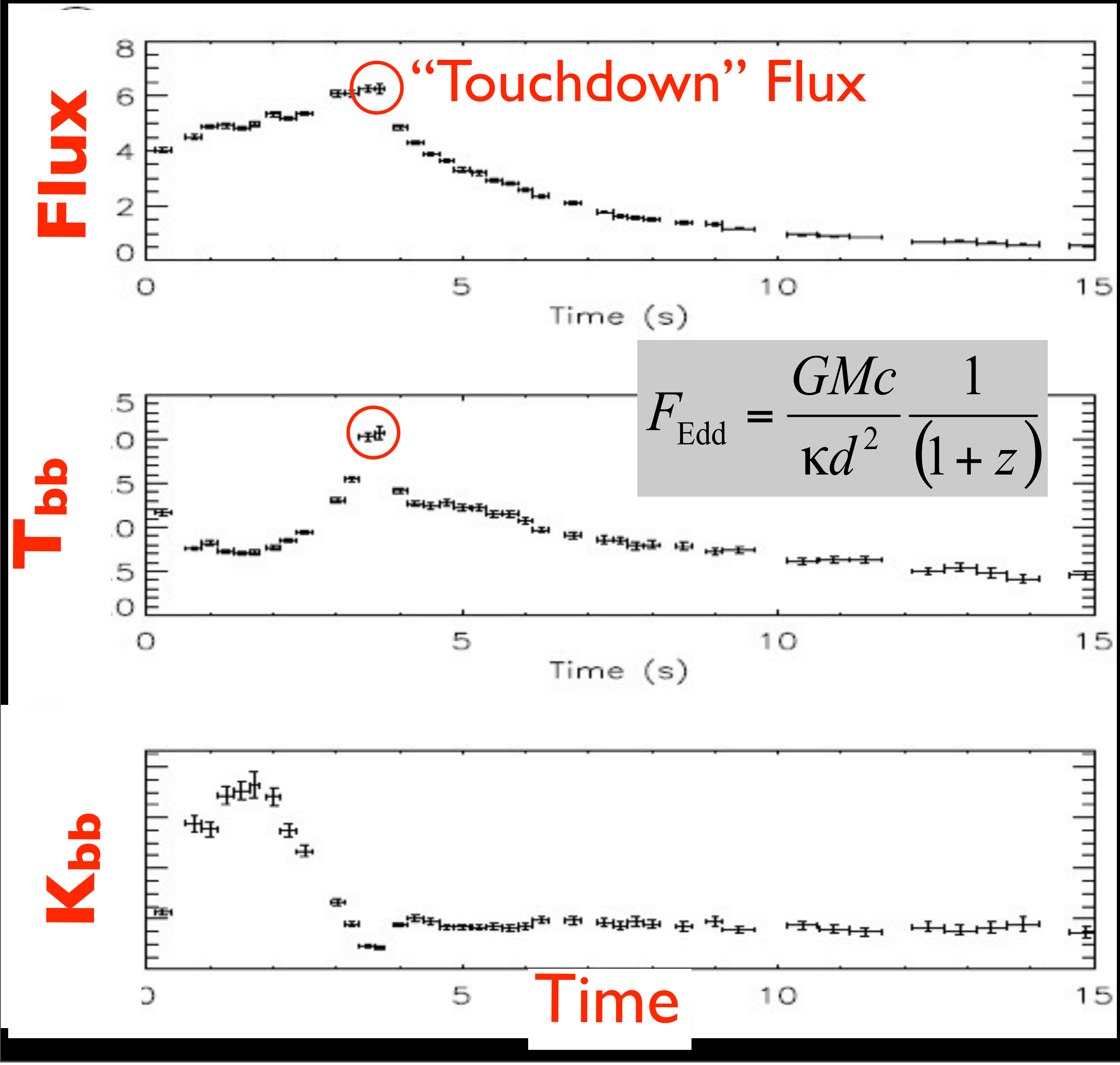
Some controversy surrounding the "touchdown method", which has been used a lot recently



(e.g Ozel 2006, Ozel, Guver Psaltis 2009, Guver et al. 2010, Sala et al. 2012)

'Photospheric Radius Expansion' (PRE) bursts are used

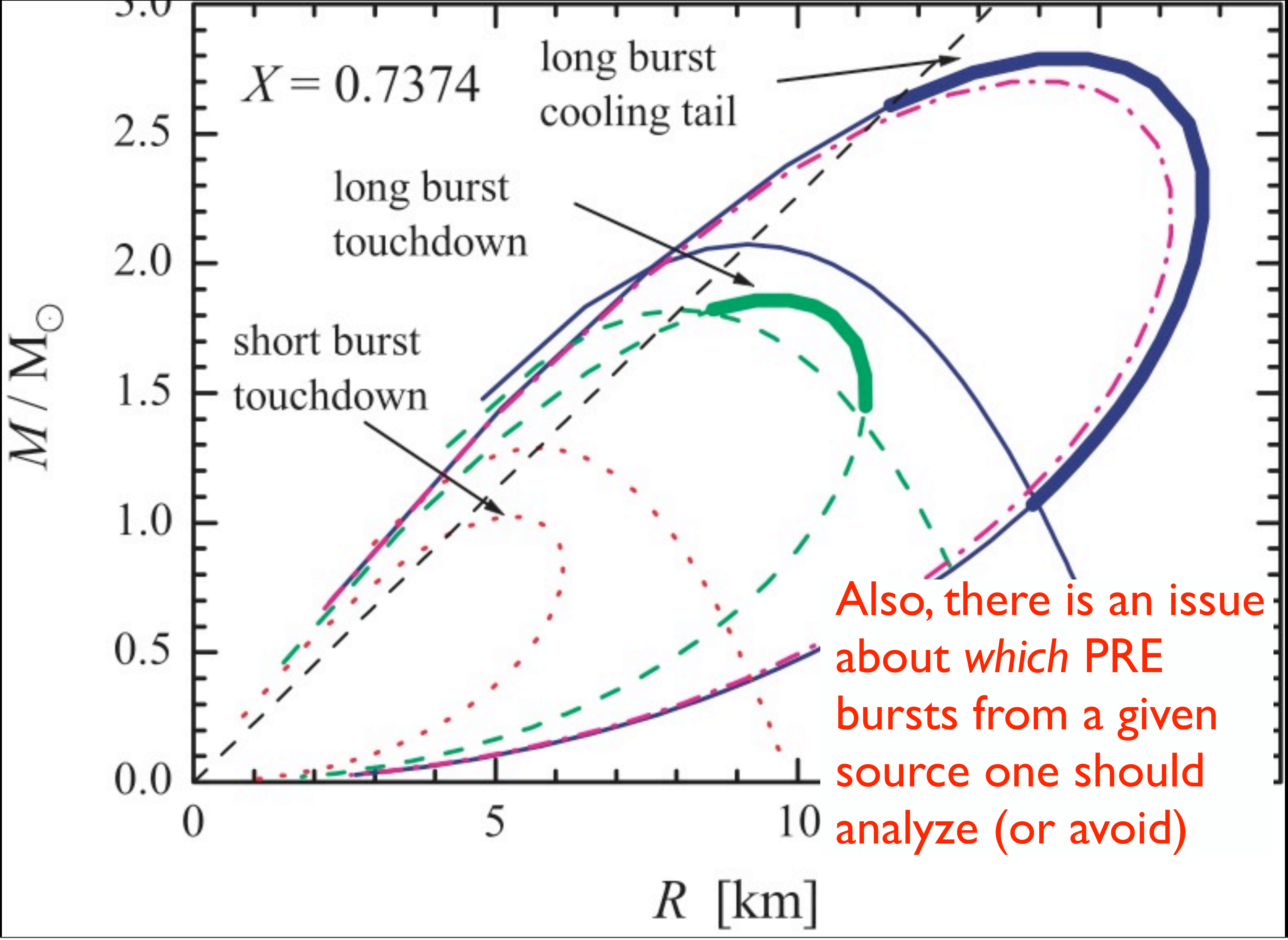
Method relies on measuring F_{Edd} at “touchdown”



$$F_{\mathrm{Edd}} = \frac{GMc}{\kappa d^2}\frac{1}{(1+z)}$$

Has the photosphere at touchdown returned to the neutron star surface? (see Steiner et al. 2010)

Also, there is an issue with *which* PRE bursts from a given source one should analyze (or avoid)



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this talk

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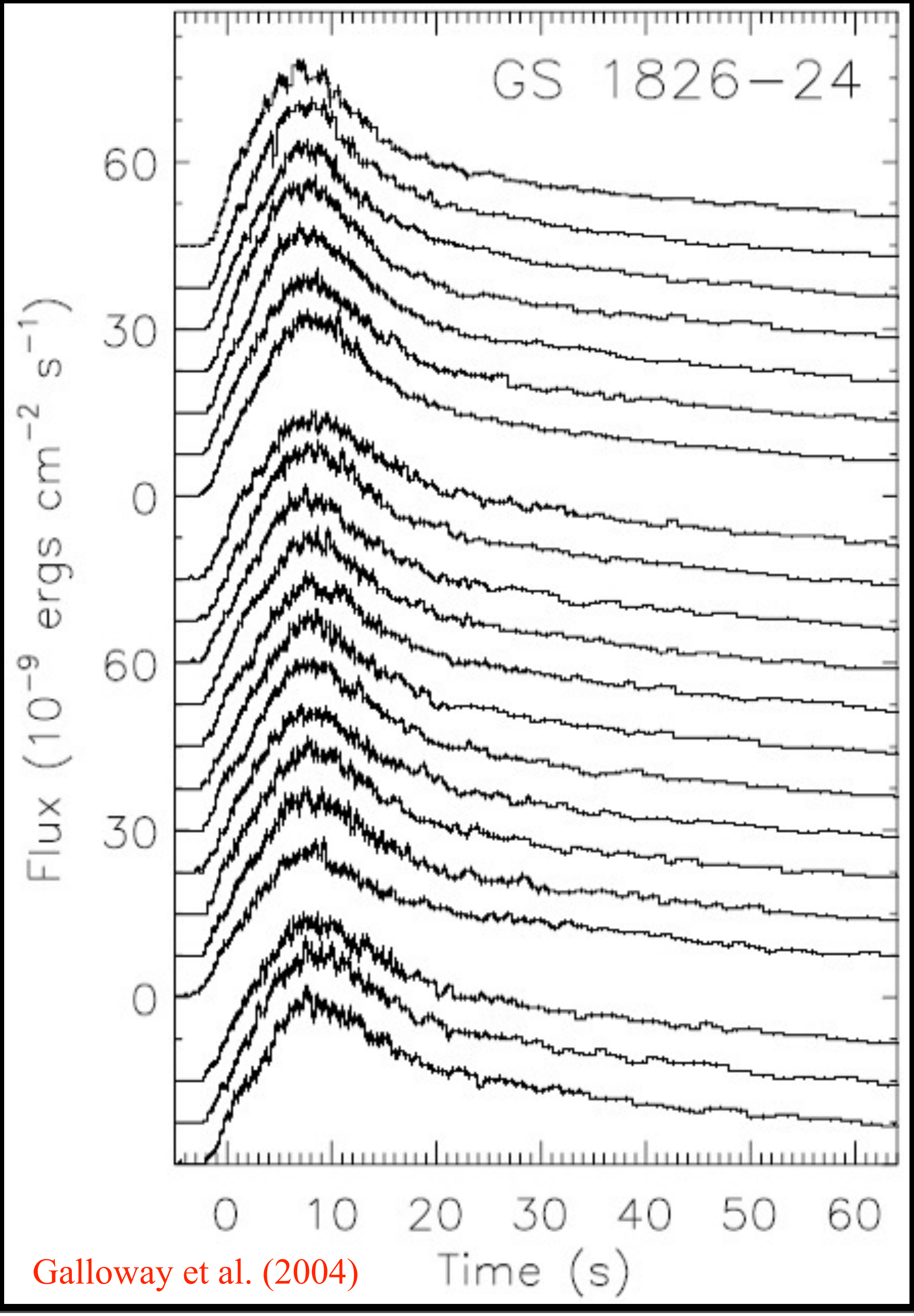
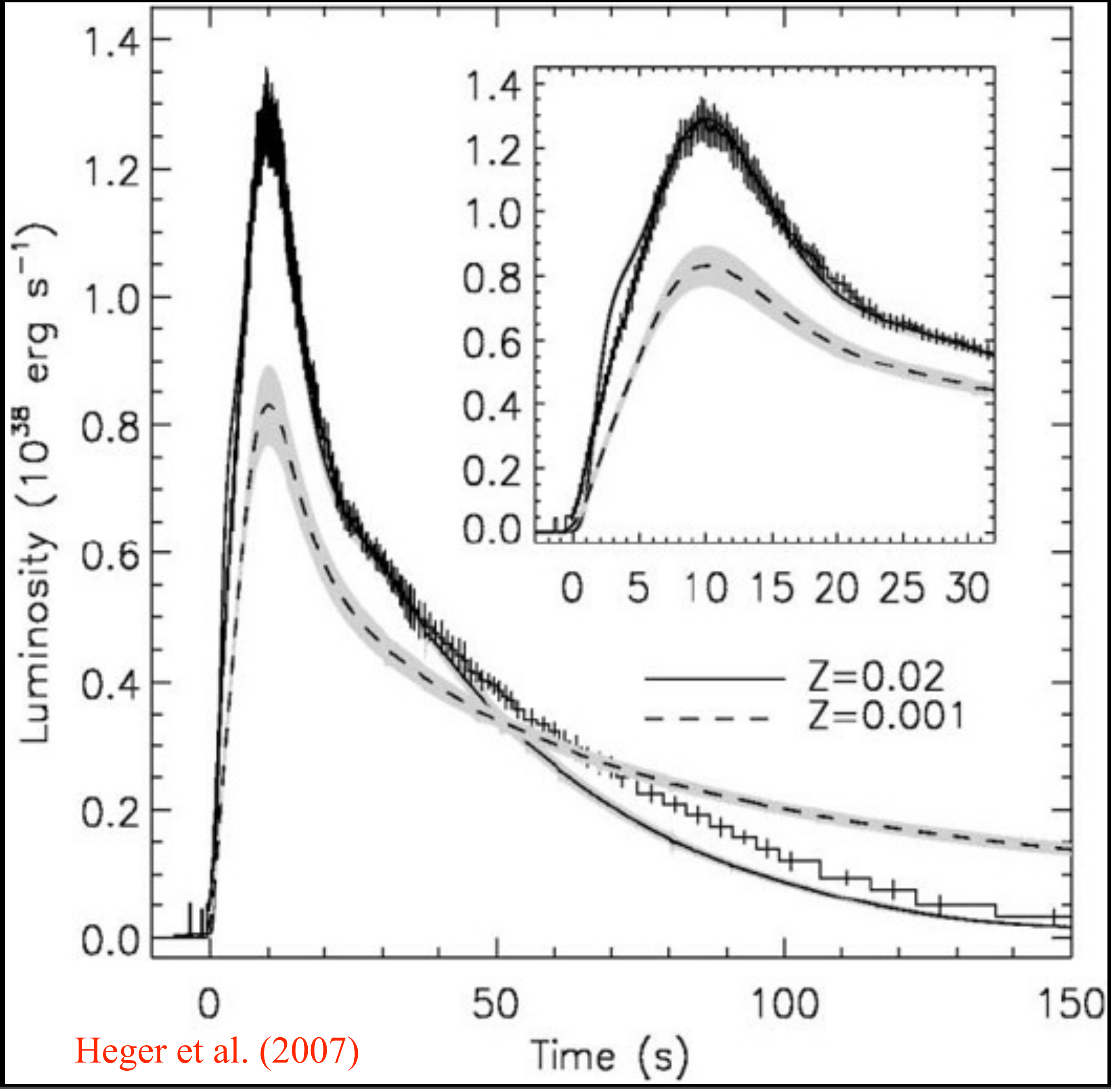
GS 1826-24: the textbook burster



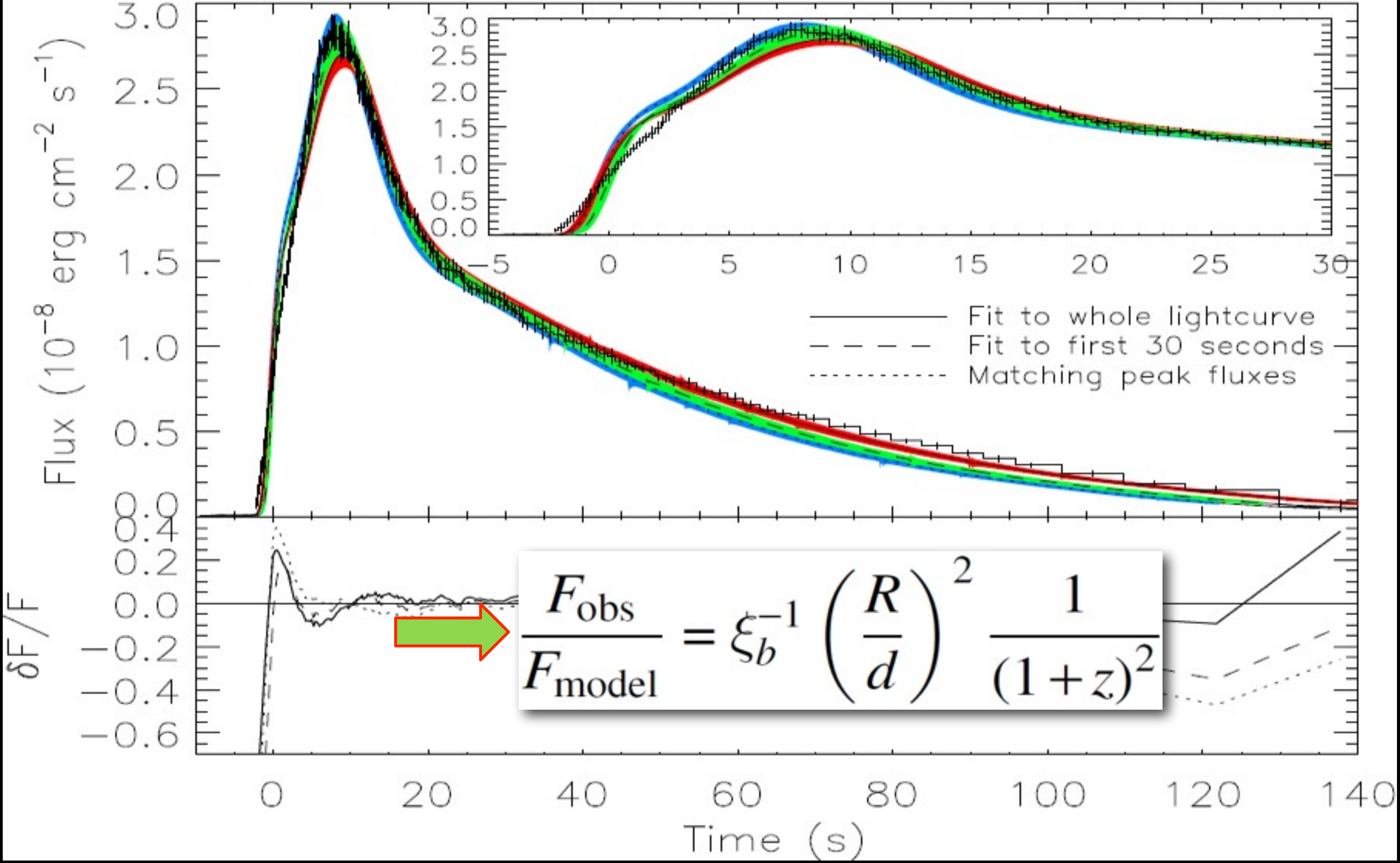
Galloway et al. (2004)

A very regular bursting source that's very well observed and understood:



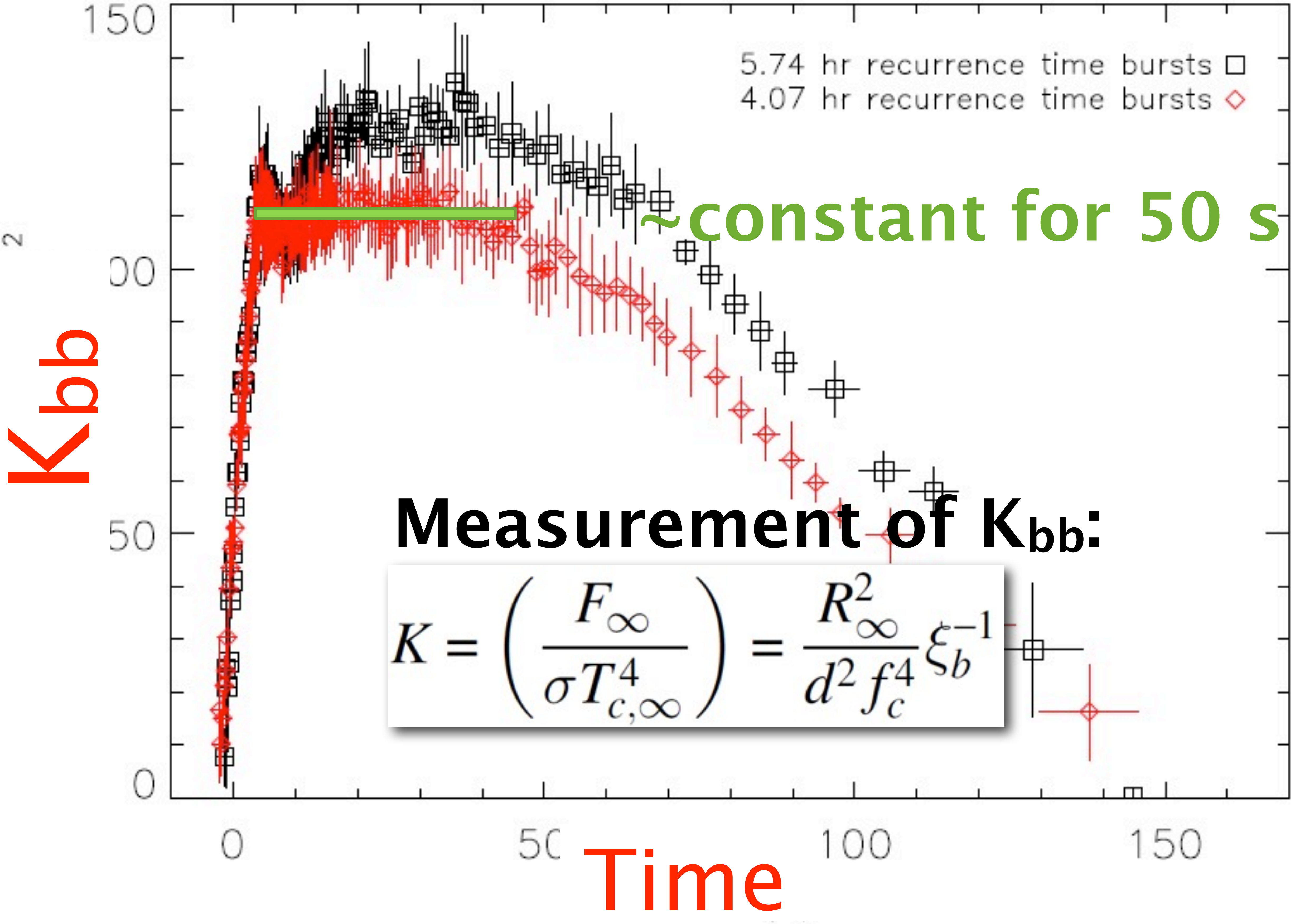
Heger et al. (2007)

lightcurve fits



$$\frac{F_{\mathrm{obs}}}{F_{\mathrm{model}}} = \xi_b^{-1} \left(\frac{R}{d}\right)^2 \frac{1}{(1+z)^2}$$

blackbody normalization (K_{bb})



~constant for 50 s

Measurement of K_{bb}:

$$K = \left(\frac{F_\infty}{\sigma T_{c,\infty}^4}\right) = \frac{R_\infty^2}{d^2 f_c^4}\xi_b^{-1}$$

Combining these two constraints, we can eliminate distance (d) and anisotropy (ξ)

$$\frac{F_{\rm obs}}{F_{\rm model}} = \enclose{circle}{\xi_b}^{-1} \left(\frac{R}{\enclose{circle}{d}}\right)^2 \frac{1}{(1+z)^2}$$

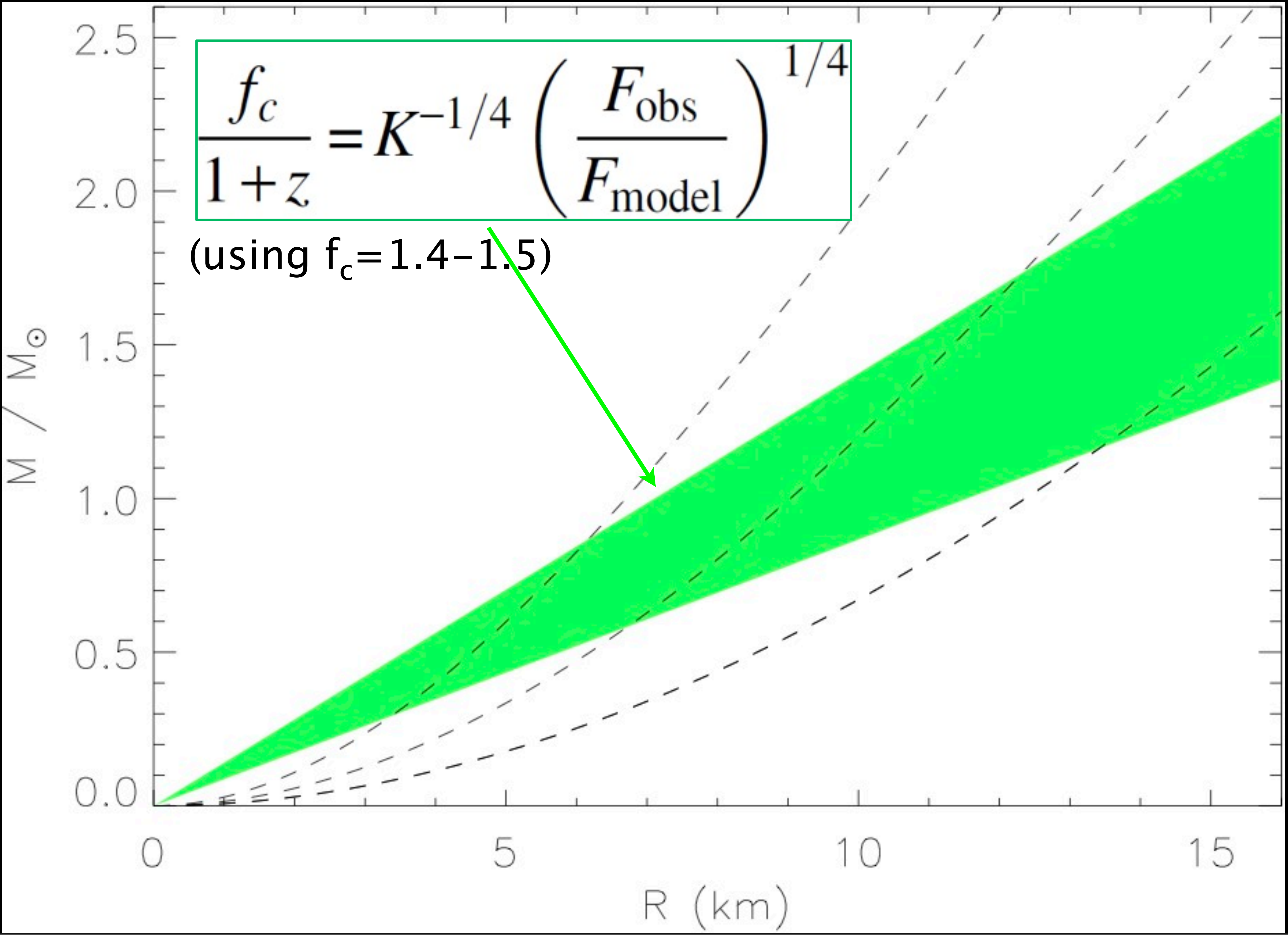
$$+$$

$$K = \left(\frac{F_\infty}{\sigma T_{c,\infty}^4}\right) = \frac{R_\infty^2}{\enclose{circle}{d}^2 f_c^4} \enclose{circle}{\xi_b}^{-1}$$

$$=$$

$$\frac{f_c}{1+z} = K^{-1/4} \left(\frac{F_{\rm obs}}{F_{\rm model}}\right)^{1/4}$$

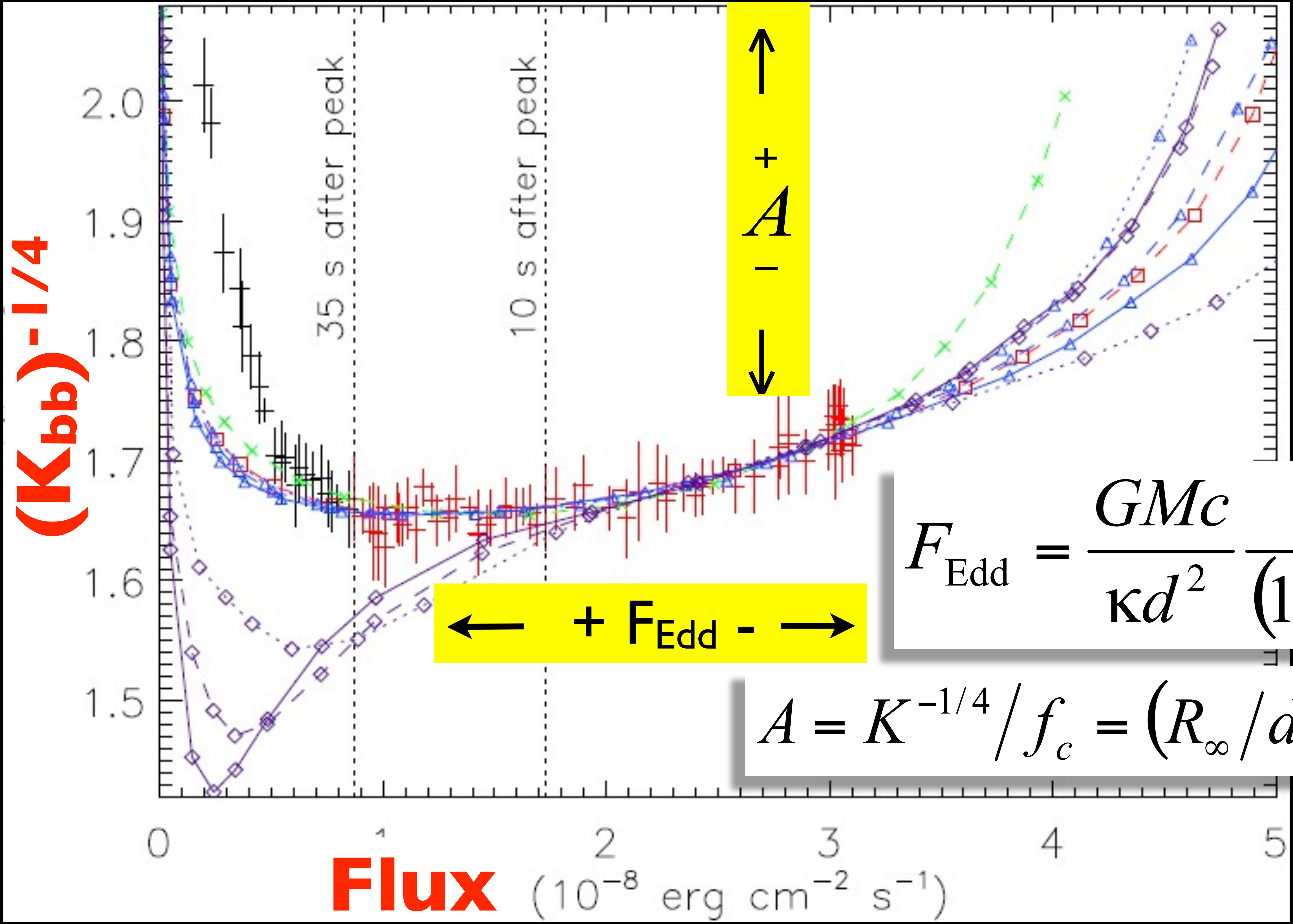
A first constraint



$$\frac{f_c}{1+z} = K^{-1/4} \left(\frac{F_{\rm obs}}{F_{\rm model}} \right)^{1/4}$$

(using f_c=1.4-1.5)

fitting to spectral models
(see Suleimanov et al. 2011)



$$F_{\mathrm{Edd}} = \frac{GMc}{\kappa d^2}\frac{1}{(1+z)}\xi_b^{-1}$$

$$A = K^{-1/4}/f_c = (R_\infty/d)^{-1/2}\xi_b^{1/4}$$

Deriving 2nd constraint

From fits the spectral models, we derive *A* and F_{Edd}

If one additionally has a distance *d* and anisotropy ξ, one can solve for R, M:

$$R^2 = \frac{d^2\xi_b}{A^2}\left[\frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 8\kappa d F_{\mathrm{Edd}} A^2 \xi_b^{1/2}/c^3}\right]$$

$$M = \frac{Rc^2}{2G}\left[\frac{1}{2} \mp \frac{1}{2}\sqrt{1 - 8\kappa d F_{\mathrm{Edd}} A^2 \xi_b^{1/2}/c^3}\right]$$

Deriving 2nd constraint

If ξ or d are unknown or poorly constrained, however..

$$R^2 = \frac{d^2\xi_b}{A^2}\left[\frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 8\kappa d F_{\mathrm{Edd}} A^2 \xi_b^{1/2}/c^3}\right]$$

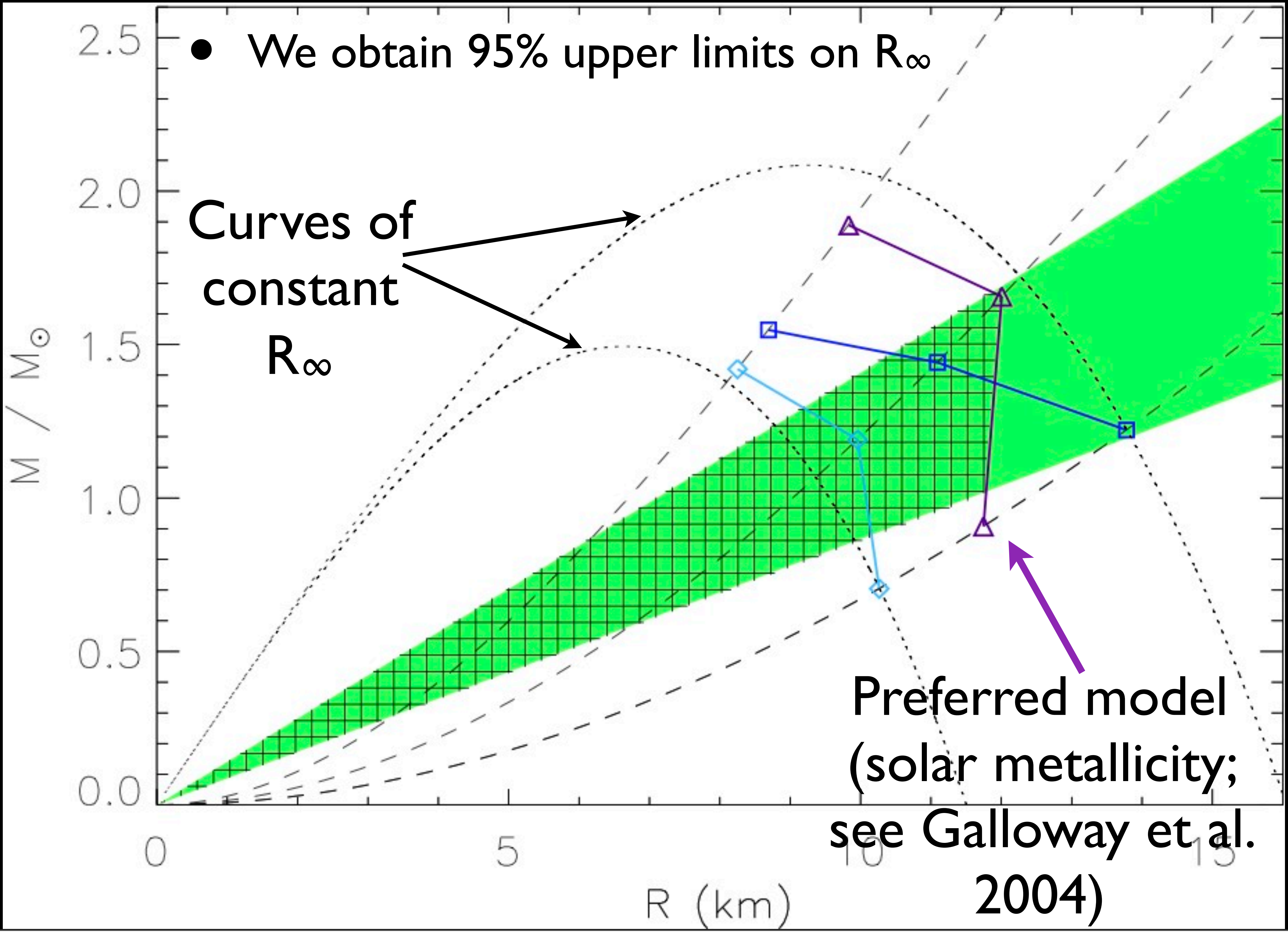
The condition that the <u>discriminant</u> must be ≥ 0 yields a condition on R∞ [R(1+z)]:

$$R_\infty \leq \frac{1}{8}\frac{c^3}{\kappa}\frac{1}{A^4 F_{\mathrm{Edd}}}$$

No dependence on distance or anisotropy ξ!

2nd constraint: Fitting spectral models

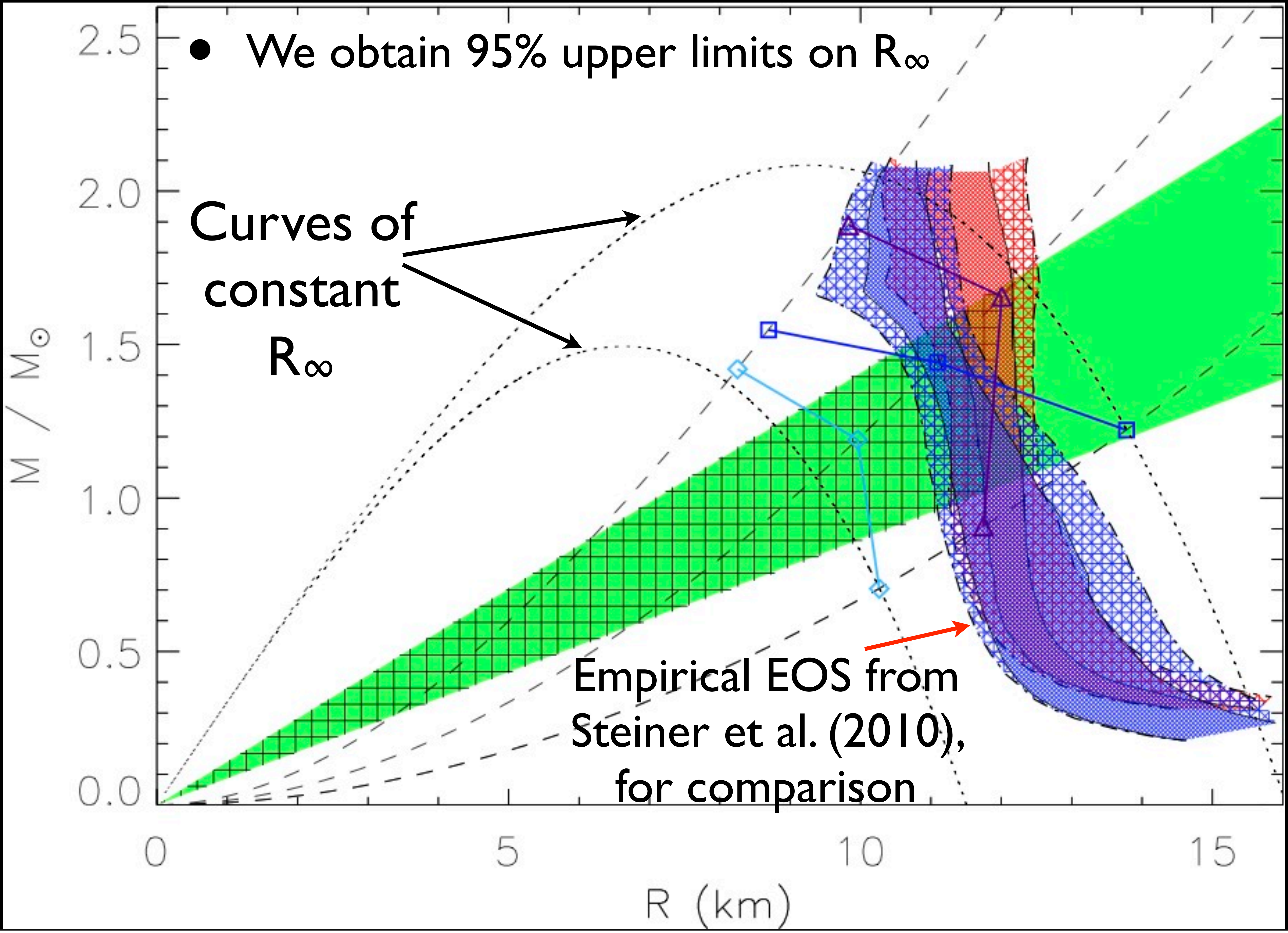
- We obtain 95% upper limits on R_∞



Curves of constant R_∞

Preferred model (solar metallicity; see Galloway et al. 2004)

2nd constraint: Fitting spectral models



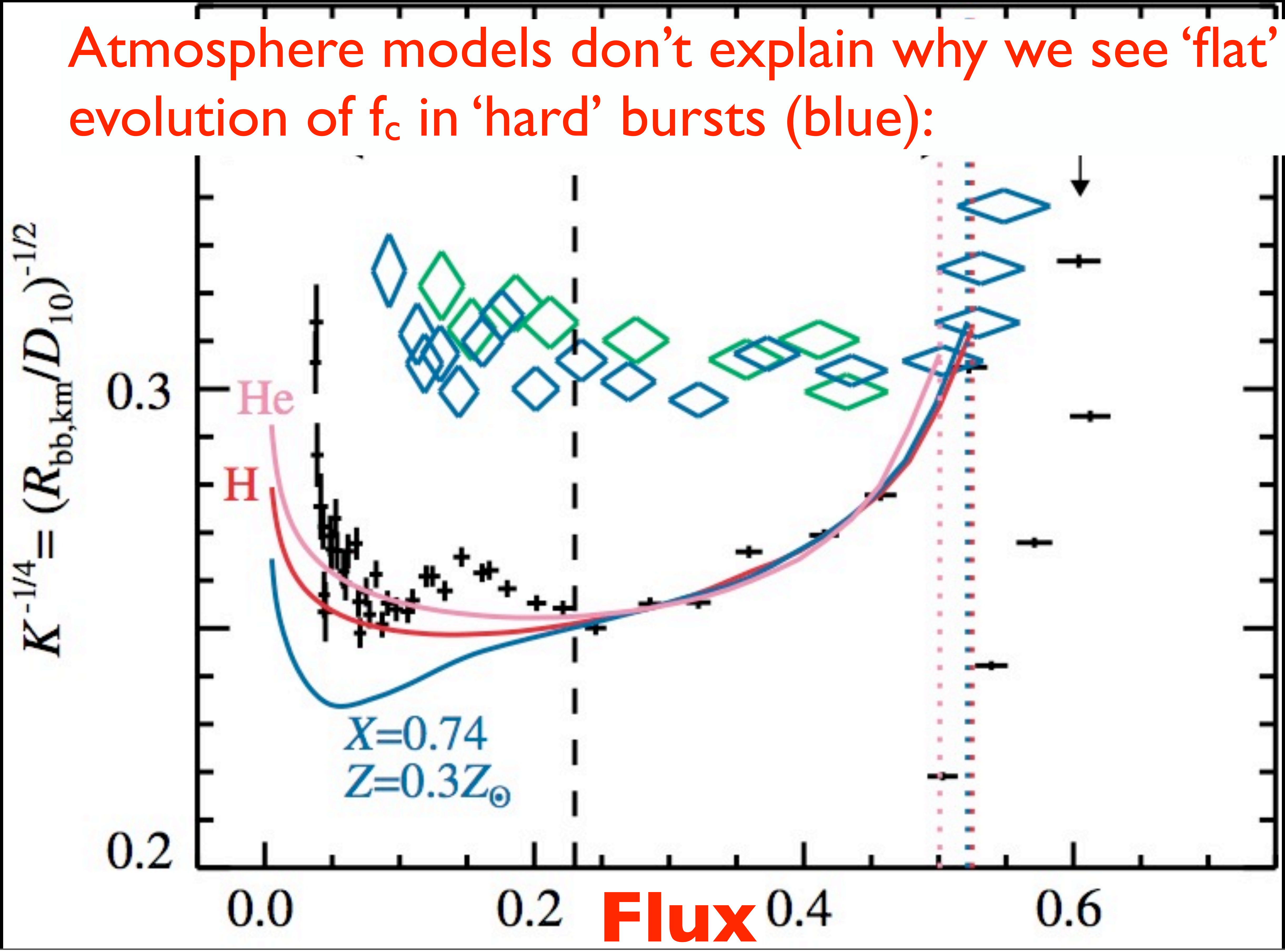
- We obtain 95% upper limits on R∞

Curves of constant R∞

Empirical EOS from Steiner et al. (2010), for comparison

Different spectral evolutions

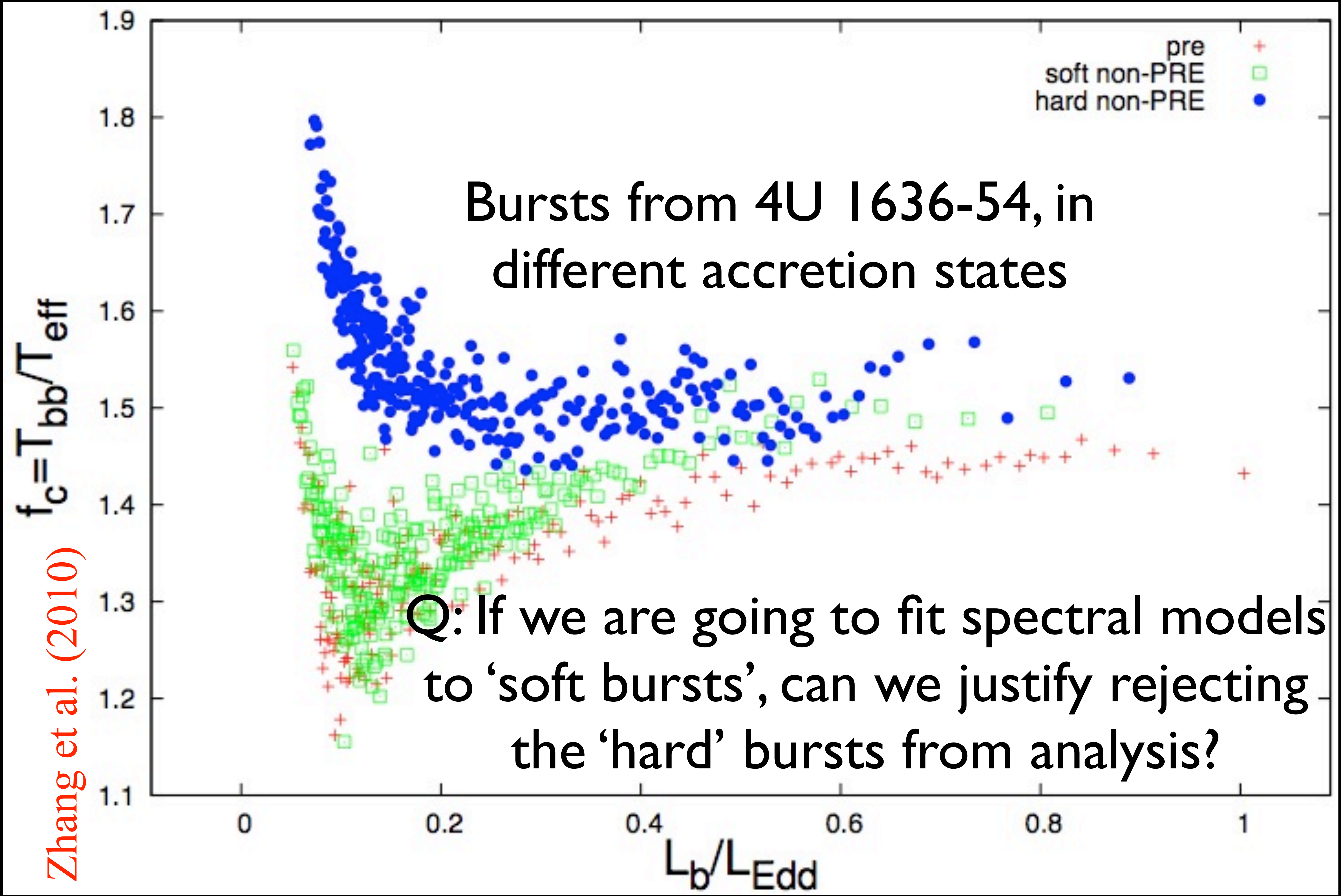
Atmosphere models don't explain why we see 'flat' evolution of f_c in 'hard' bursts (blue):



Flux

Suleimanov et al. (2011)

Different spectral evolutions



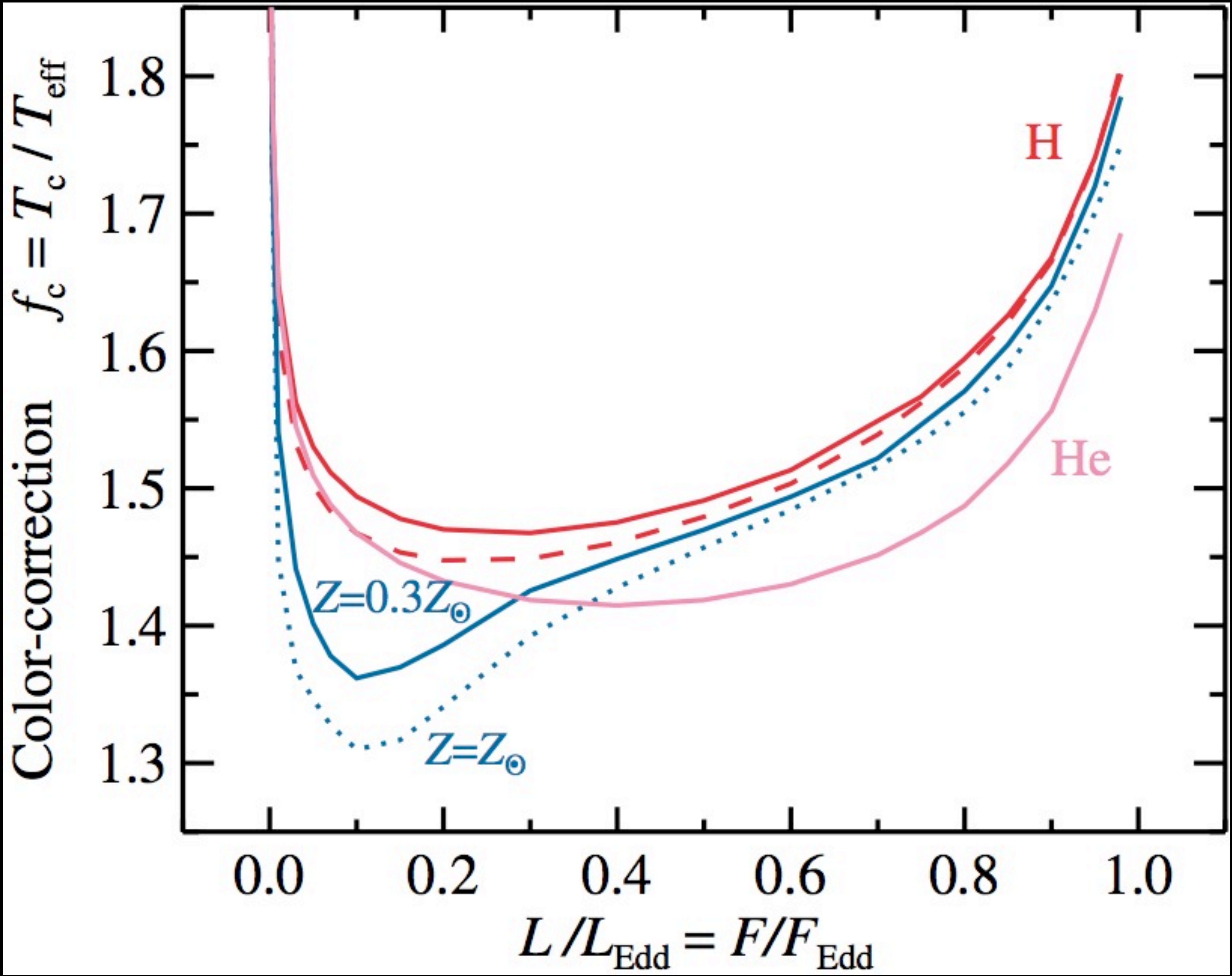
Bursts from 4U 1636-54, in different accretion states

Q: If we are going to fit spectral models to ‘soft bursts’, can we justify rejecting the ‘hard’ bursts from analysis?

Zhang et al. (2010)

Summary

- X-ray bursts useful for inferring NS M & R, but we need better handle on systematics
  - e.g. anisotropy. Even if distance is perfectly known, the unknown ξ means R could be uncertain to within a factor of 2.
- One can derive M & R constraints independent of distance and anisotropy
  - We applied this to GS 1826-24, a very well-understood source. Can be applied to other sources.
- An open physics problem in X-ray burst spectra: Flat evolution in f_c from bursts in the hard state?


Color-correction $f_c = T_c / T_{eff}$
1.8
1.7
1.6
1.5
1.4
1.3
0.0
0.2
0.4
0.6
0.8
1.0
$L/L_{Edd} = F/F_{Edd}$
H
He
$Z=0.3Z_{\odot}$
$Z=Z_{\odot}$