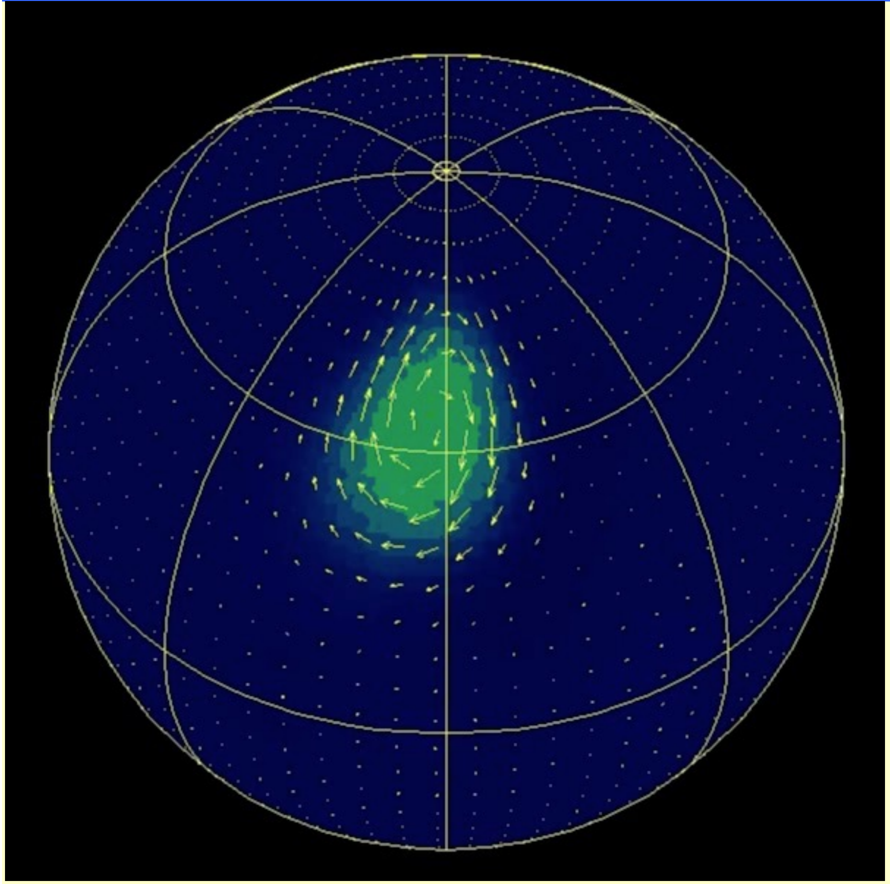
X-ray bursts and coherent millisecond oscillations

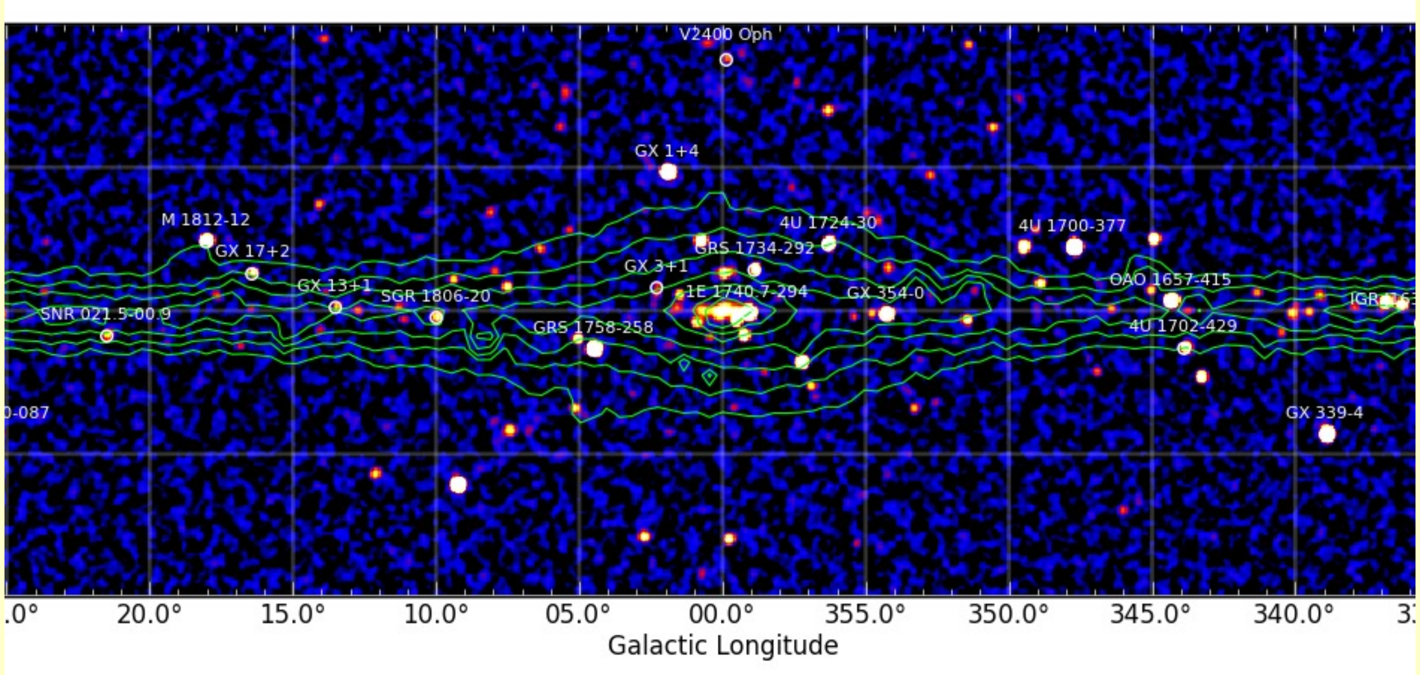
Rossi X-ray Timing Explorer
30 Dec 1995 – 5 Jan 2012



Literature:

1. Lewin W.H.G. et al., 1993, SSRv, 62, 223
2. Strohmayer T., Bildsten L., 2006, in Compact Stellar X-Ray Sources, CUP https://arxiv.org/abs/astro-ph/0301544
3. Watts A., 2012, ARAA, 50, 609 https://arxiv.org/abs/1203.2065
4. Degenar N., Suleimanov V.F. , 2018, ASSL 457, 185 https://arxiv.org/abs/1806.02833

Sources of thermonuclear bursts: LMXBs containing neutron stars

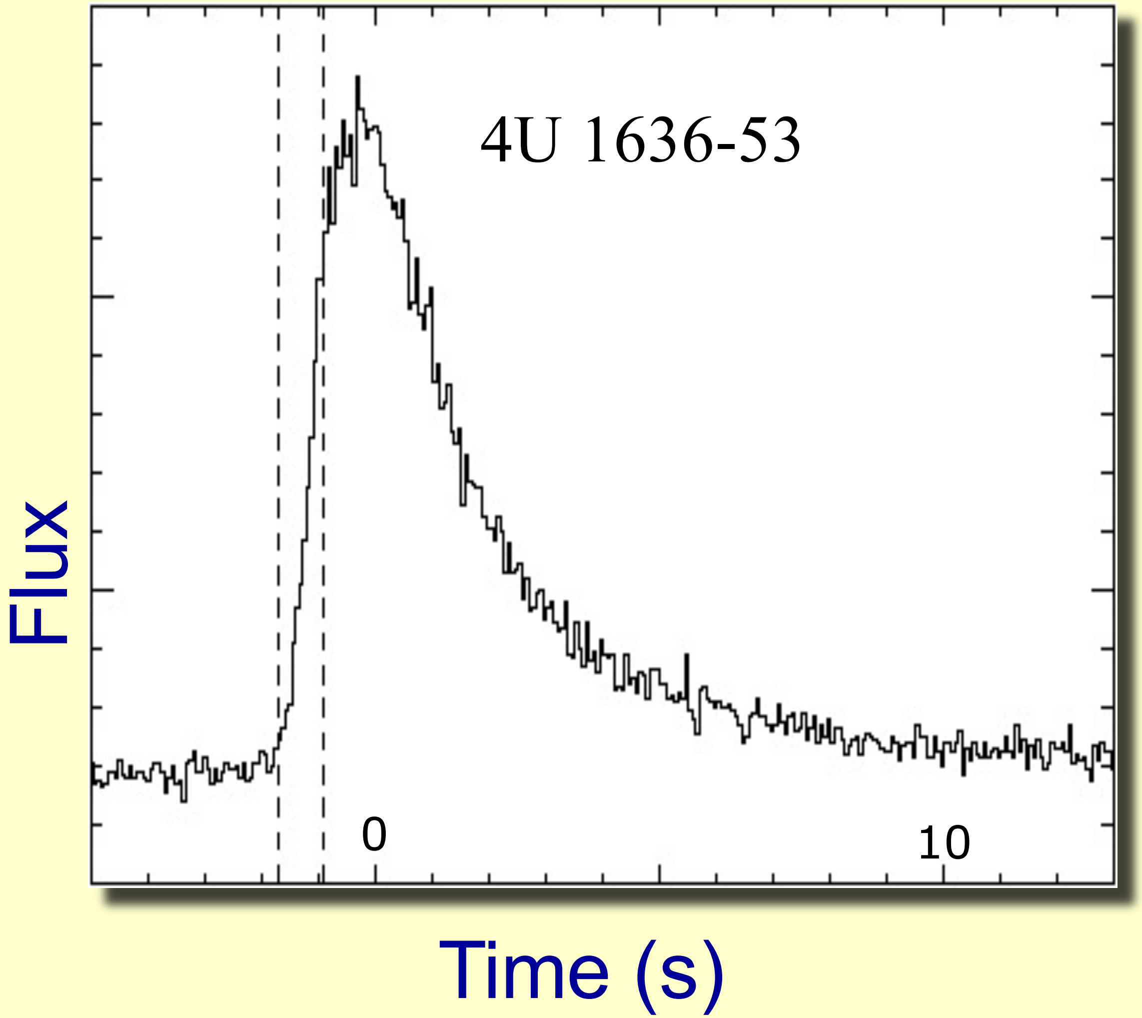


- Most sources near the Galactic center as seen here with INTEGRAL (Krivonos et al. 2012) are accreting neutron stars in low mass X-ray binaries.

- Roughly 70 bursting sources known. Concentrated in the Galactic bulge.

The X-ray burst energetics is similar to that produced by 130 15-M-ton nuclear bombs exploding over every square centimeter of the neutron star!

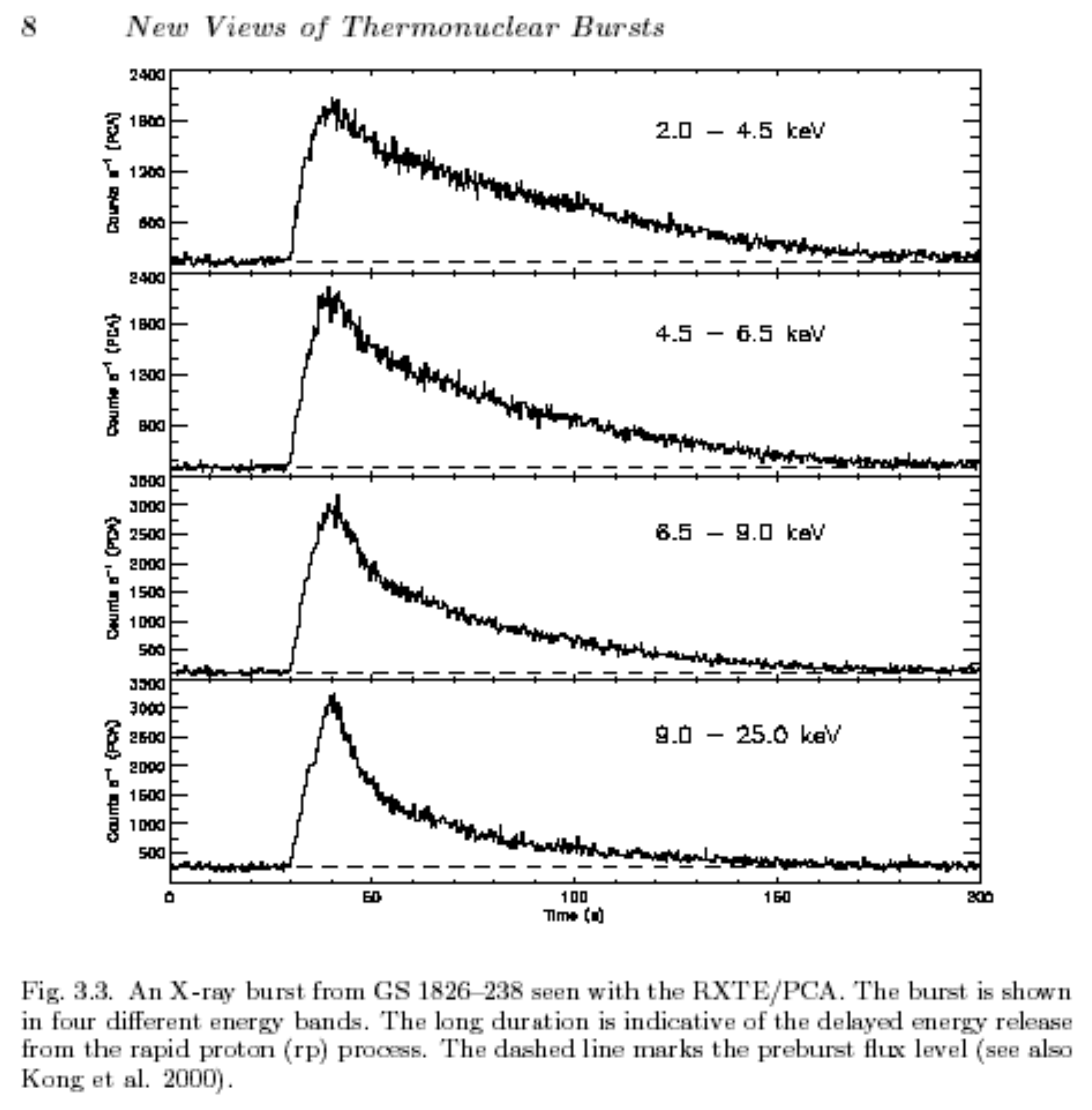
“Normal” thermonuclear bursts



- Discovered in 1974.
- 10 - 100 s flares.
- Thermal spectra which soften with time.
- 3 - 12 h recurrence times, sometimes quasi-periodic.
- Energy release ~10^{39} erg
- H and He are primary fuels

He ignition at a column depth of 2 x 10^9 g cm^{-2}

Typical profile: spectral softening

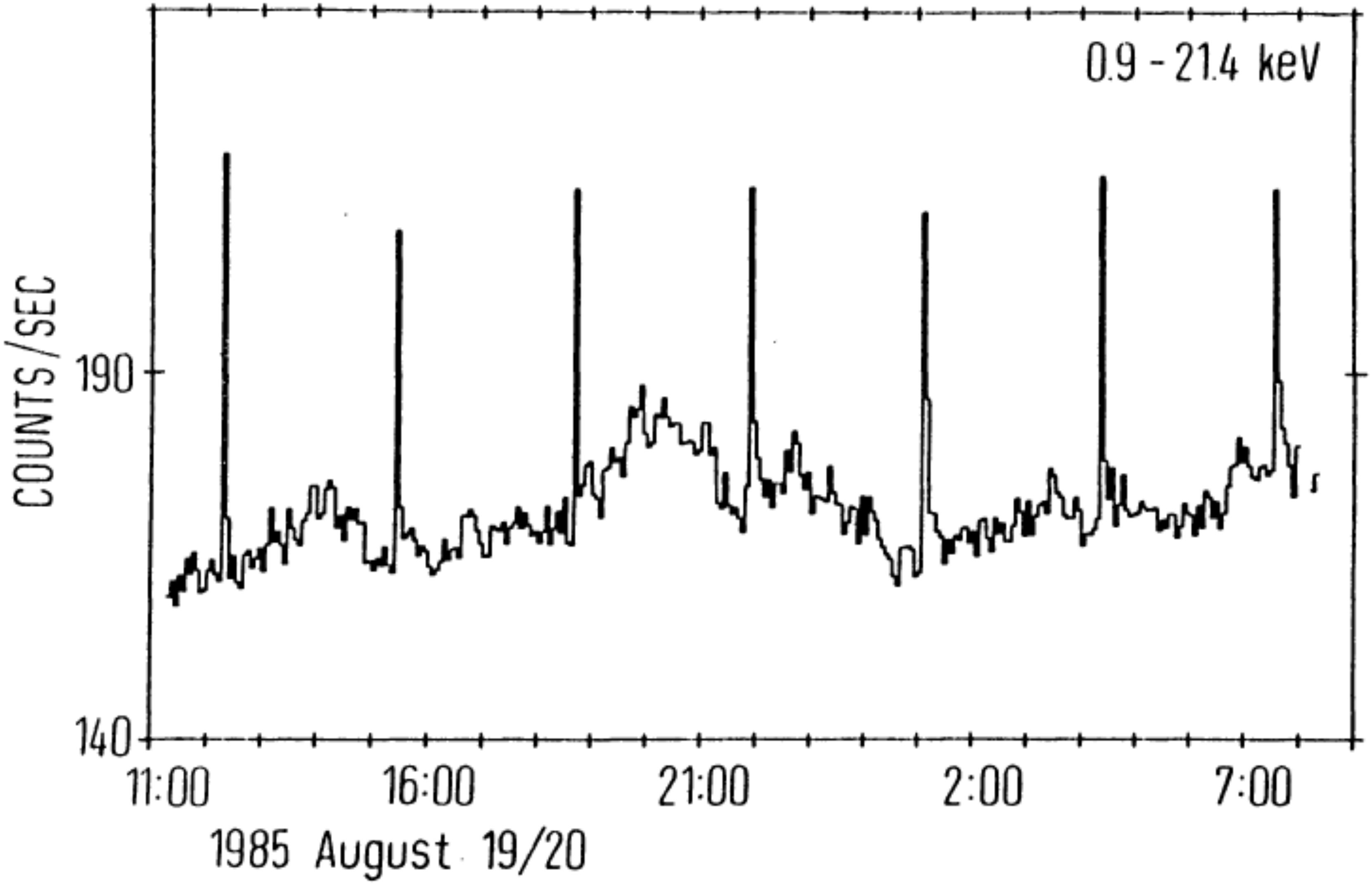


8 *New Views of Thermonuclear Bursts*

Fig. 3.3. An X-ray burst from GS 1826–238 seen with the RXTE/PCA. The burst is shown in four different energy bands. The long duration is indicative of the delayed energy release from the rapid proton (rp) process. The dashed line marks the preburst flux level (see also Kong et al. 2000).

Strohmayer & Bildsten, astro-ph/0301544

BURSTS FROM 4U/MXB 1820−30



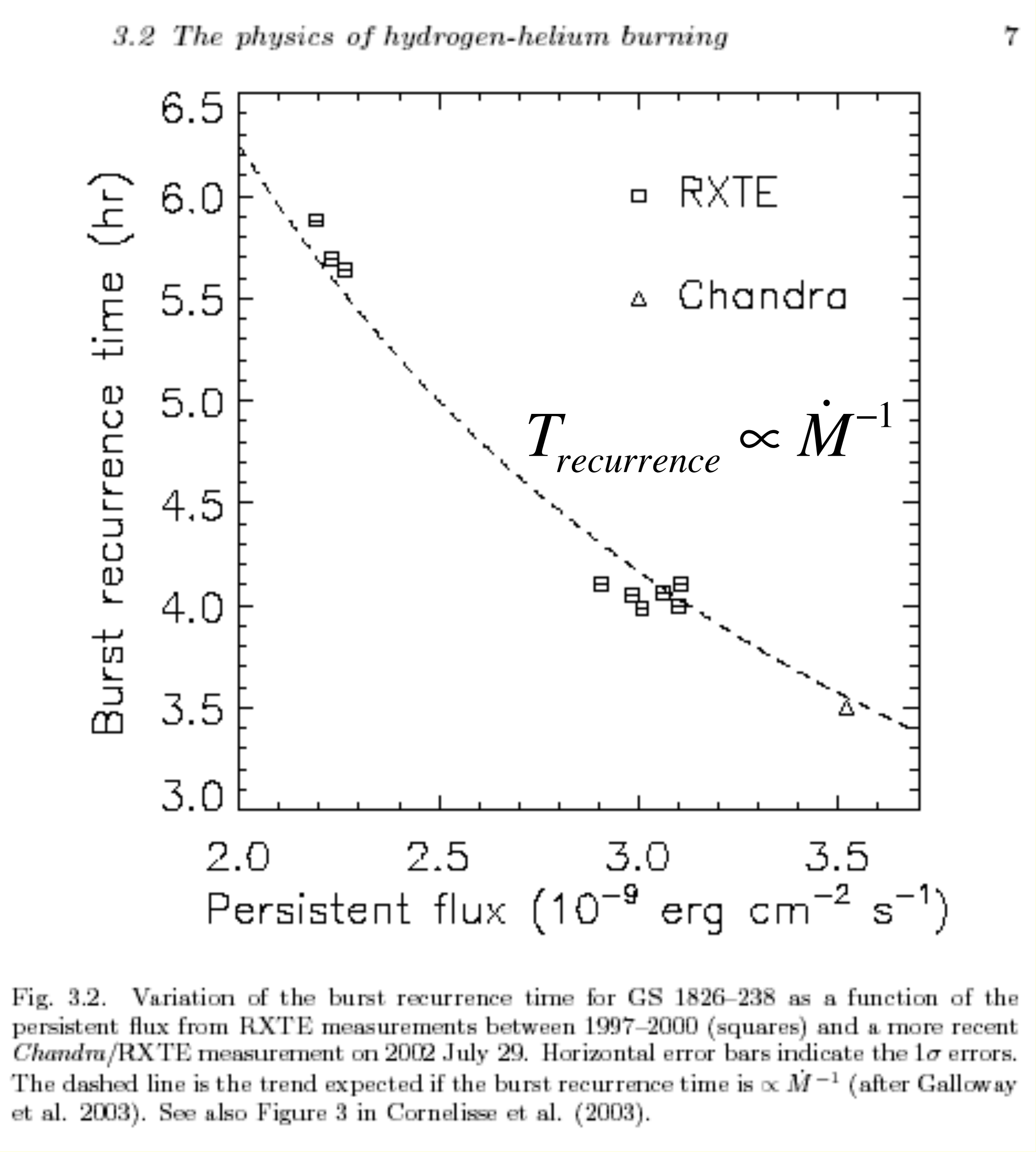
Ignition

In order to ignite hydrogen and helium a certain pressure and temperature are needed. They are achieved when sufficient amount of fuel has accreted on to the surface.

$$\Delta M = \int_0^{T_{rec}} \dot{M}(t)\,\mathrm{d}t \approx$$

$$\left\langle \dot{M} \right\rangle T_{rec} \approx \mathrm{const} \Rightarrow$$

$$T_{rec} \propto \left\langle \dot{M} \right\rangle^{-1} \propto F^{-1}$$



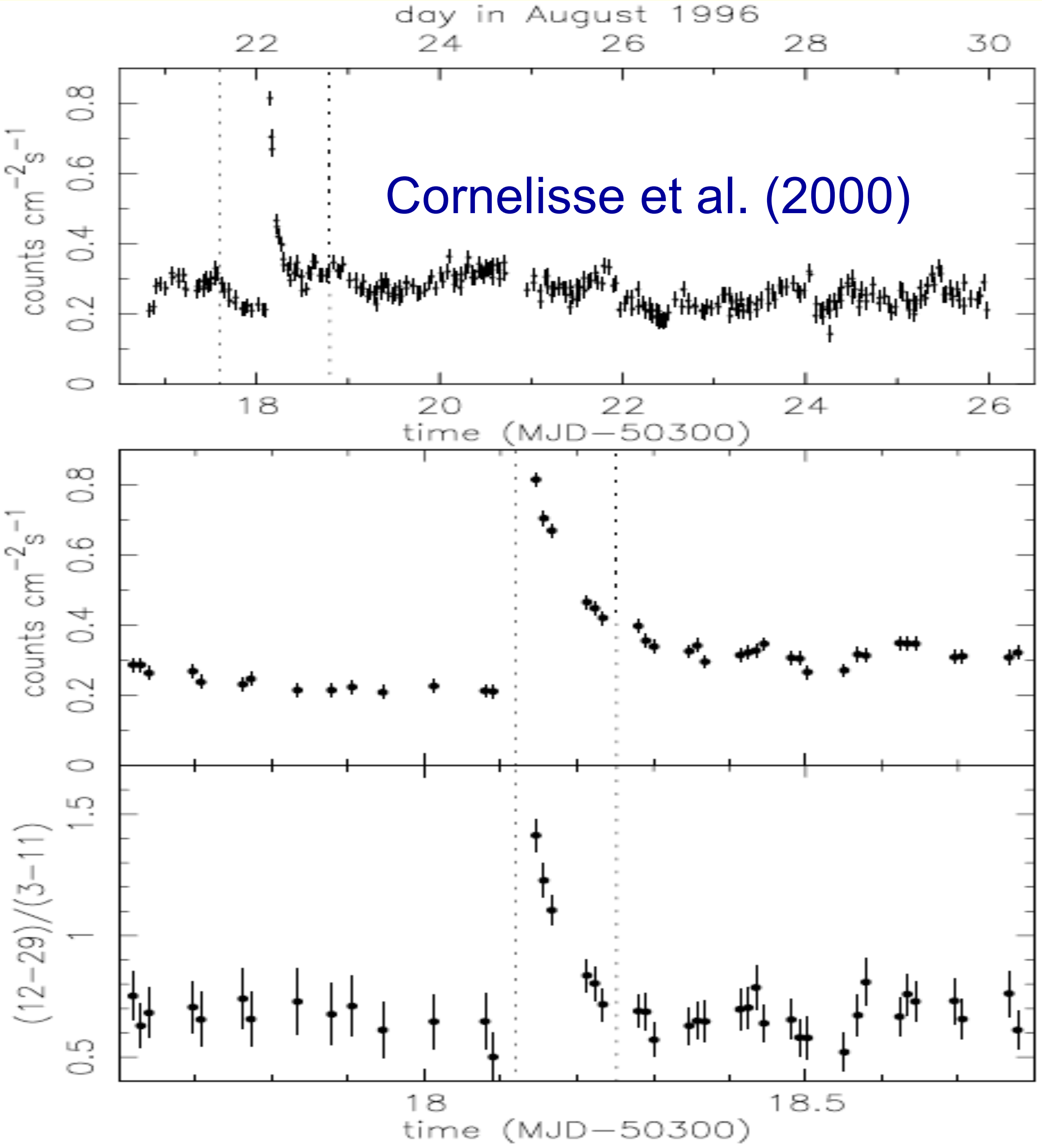
3.2 The physics of hydrogen-helium burning 7

$$T_{recurrence} \propto \dot{M}^{-1}$$

Fig. 3.2. Variation of the burst recurrence time for GS 1826–238 as a function of the persistent flux from RXTE measurements between 1997–2000 (squares) and a more recent *Chandra*/RXTE measurement on 2002 July 29. Horizontal error bars indicate the 1σ errors. The dashed line is the trend expected if the burst recurrence time is $\propto \dot{M}^{-1}$ (after Galloway et al. 2003). See also Figure 3 in Cornelisse et al. (2003).

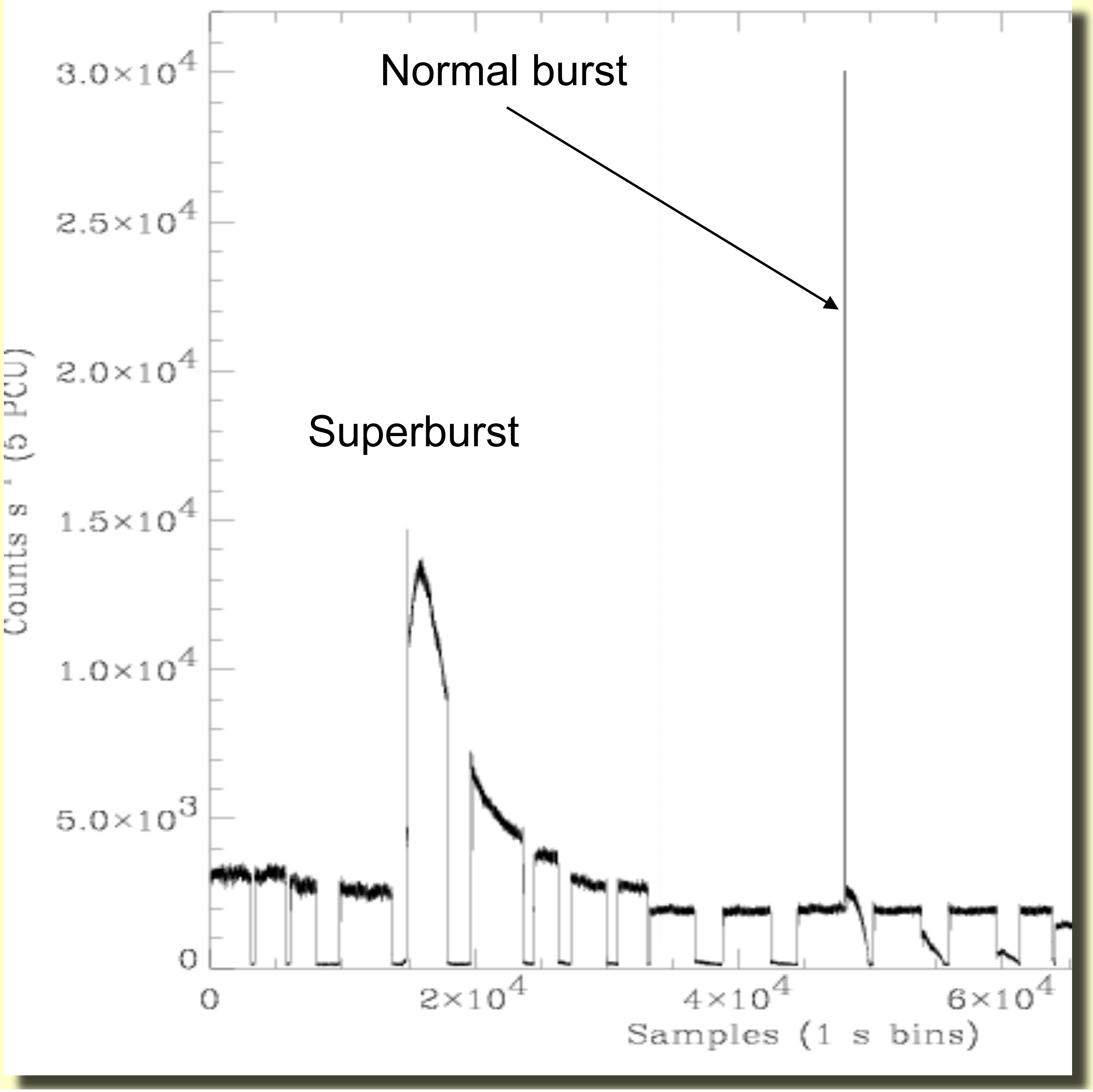
Strohmayer & Bildsten, astro-ph/0301544

Superbursts


Cornelisse et al. (2000)

- Long, 3 - 5 h flares seen to date from 6 low mass X-ray binaries (LMXB), first seen in 4U 1735-44 with *BeppoSAX*/WFC
- Spectra consistent with thermal, show softening with time.
- Two superbursts from 4U 1636-53, 4.7 yr apart.
- 1,000 times more energy than standard Type I bursts.

Recurring superbursts from 4U 1636-53



- *RXTE*/PCA observations of superburst from 4U 1636-53 (Strohmayer 2002).
- ASM detections of two superbursts spaced by ~ 5 years (Wijnands 2001). The only source with recurrence time constraint.
- Peak flux ~1/2 of the neutron star Eddington limit.
- Release of nuclear energy at greater depth than for normal bursts. ^{12}C burning is the likely energy source.

X-ray bursts (type I bursts)

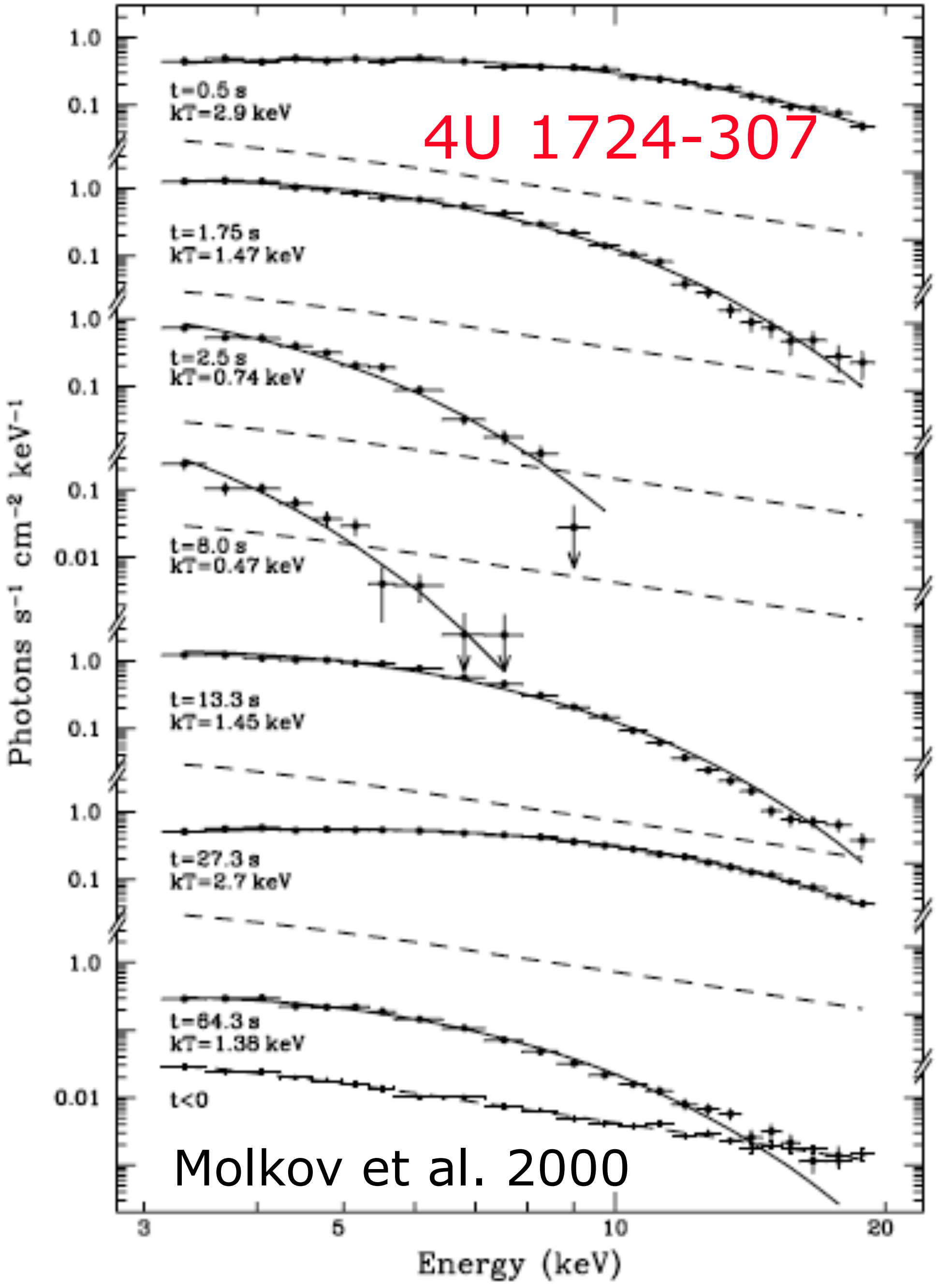
Review: Strohmayer & Bildsten, astro-ph/0301544

- These bursts are seen once every few hours to ~ 1 day in LMXRBs. 70 of the ~160 LMXRBs show bursting behaviour.
- They last for about 10-100 s; the spectrum is thermal & the area of the emission region is consistent with neutron star radius of ~10 km.
- The energy observed is produced by nuclear burning of a thin H-He layer of accreted material on the surface of neutron star.
- As nuclear burning releases energy of a few per cent of the gravitational energy ➔ steady emission is ~30 times larger than the time-average burst emission.

$$L_{acc} = \eta_{acc} \dot{M} c^2, \;\; L_{nucl} = \eta_{nucl} \left\langle \dot{M} \right\rangle c^2, \; \eta_{acc} \approx 0.2, \;\; \eta_{nucl} = 0.007$$

- Thermally unstable H/He-burning occurs when the accretion rate is less than $2\times10^{-10}\ M_\odot/\mathrm{yr}$.
- Superbursts: once in a while (perhaps once in a few years) a burst is seen with total energy release of $\sim10^{42}$ erg; these last for ~ an hour and are likely produced by unstable C-burning in deeper layers.

Spectral energy distribution of X-ray bursts



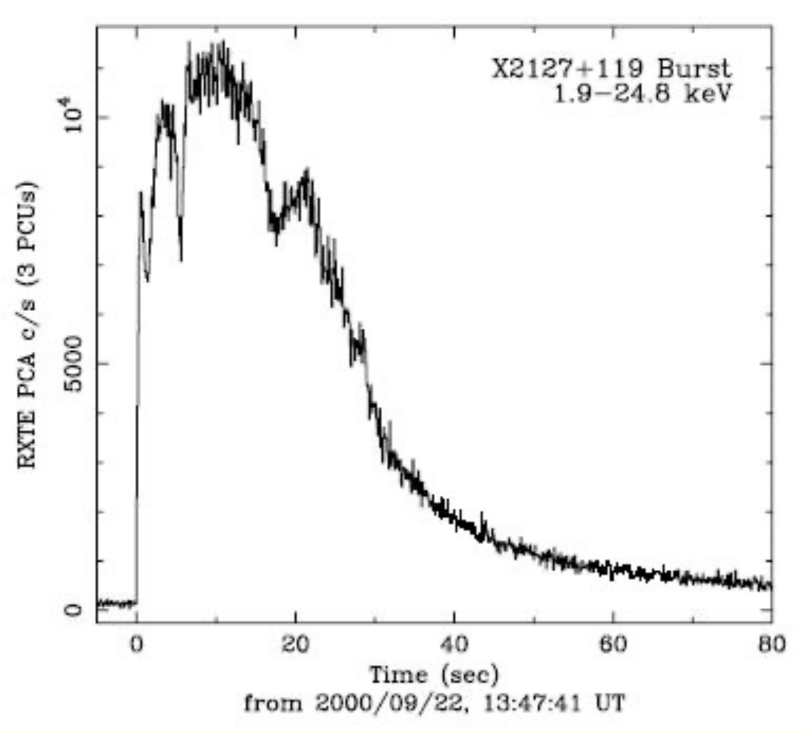
4U 1724-307

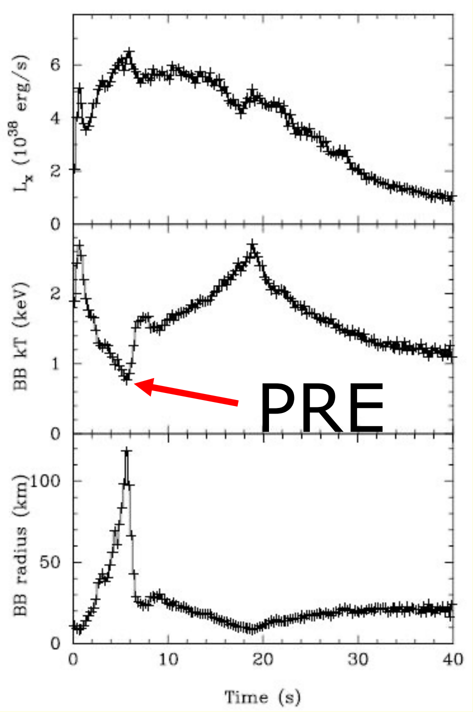
Molkov et al. 2000

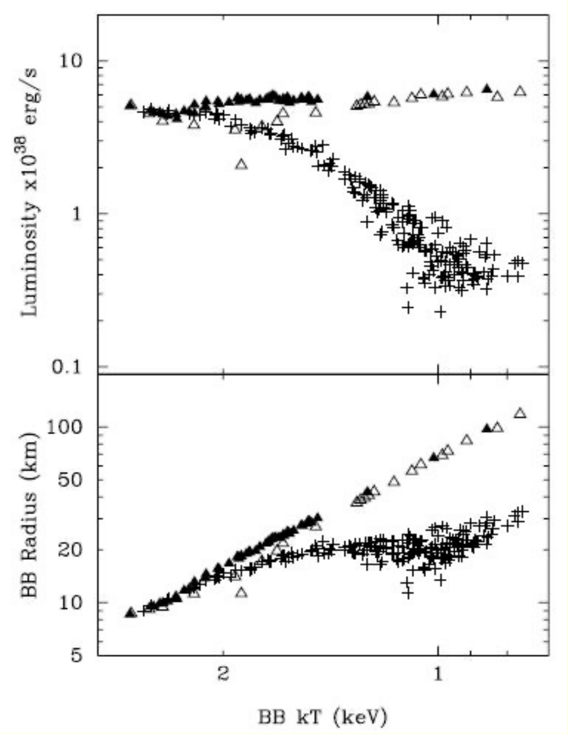
- Nearly a black body.
- Temperature varies during the burst
- Some bursts show strong decrease in temperature and large increase in apparent size during the evolution. They are called photospheric radius expansion (PRE) bursts.
- PRE are thought to exceed the Eddington limit.

Example: PRE burst in globular cluster M15

- PRE burst seen from X2127+119 by RXTE from M15 (*D*=10±0.5 kpc) by Smale (2001)







X-ray bursts as distance estimators

- The maximum luminosity during the burst is close to the Eddington luminosity $L_{\mathrm{Edd}} \sim 3\ 10^{38}$ erg/s (for a 1.4 $M_\odot$ neutron star).
- It can be used as a ”standard candle” to estimate the distance:

$$L_{\mathrm{Edd}} = L_{\mathrm{Edd},*}(1+z)^{-2} = 4\pi D^2 F_{\mathrm{bol}}$$

$$L_{\mathrm{Edd},*} = \frac{4\pi GMc}{\kappa_{\mathrm{e}}}(1+z)$$

General relativistic correction to Eddington luminosity

$$1+z = (1 - R_S / R_*)^{-1/2}$$

Redshift

$$R_{\mathrm{S}} = 2GM/c^2 = 3\ \mathrm{km}\ (M/M_{\mathrm{Sun}})$$

Schwarschild radius

- Measure bolometric flux, assume NS mass and the redshift (and composition) ⇒ distance

Neutron star mass-radius relation using blackbody radius at "infinity"

- Fitting the bursts spectra with the blackbody we get the temperature and the normalization K (dilution factor)

$$\boxed{F_{\mathrm{bol}} = \sigma_{\mathrm{SB}} T_{\mathrm{bb}}^4 K, \quad K = \frac{R_{\mathrm{bb}}^2}{D^2}}$$

- If the source lies in the globular cluster, distance to which is known, we can determine apparent radius, which is related to *R* and *M* of the neutron star.

$$\boxed{R_{\mathrm{bb}} = R_*(1+z) = R_*(1-R_{\mathrm{S}}/R_*)^{-1/2}}$$

- The problem is that the spectrum is not a blackbody…

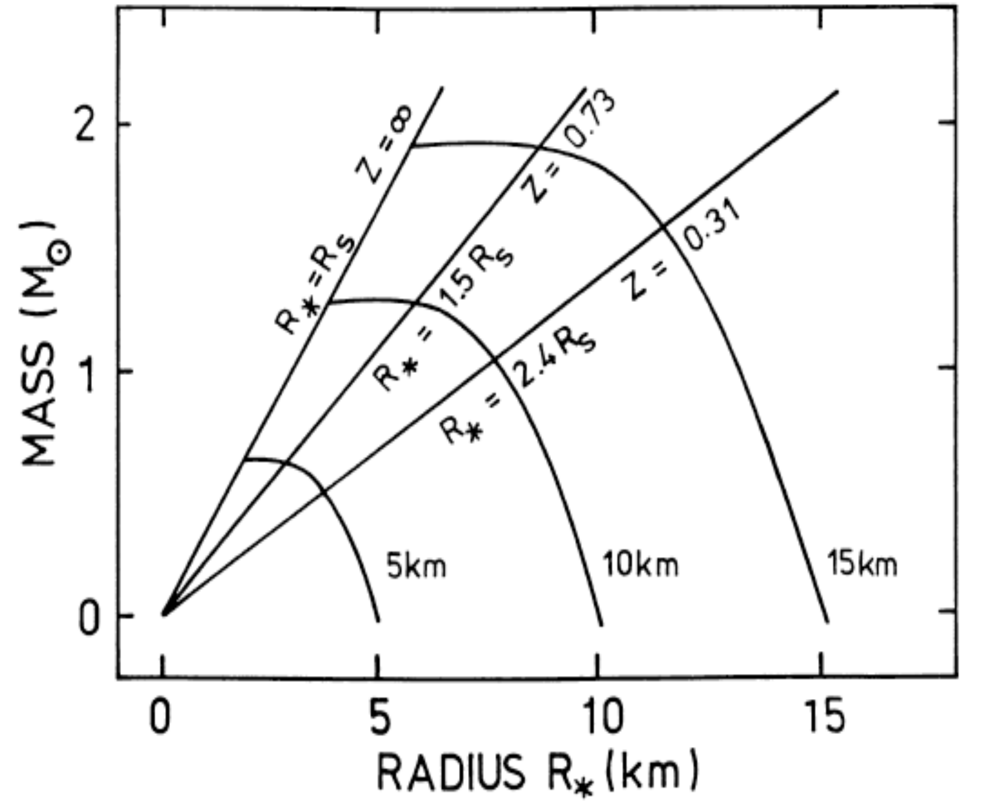
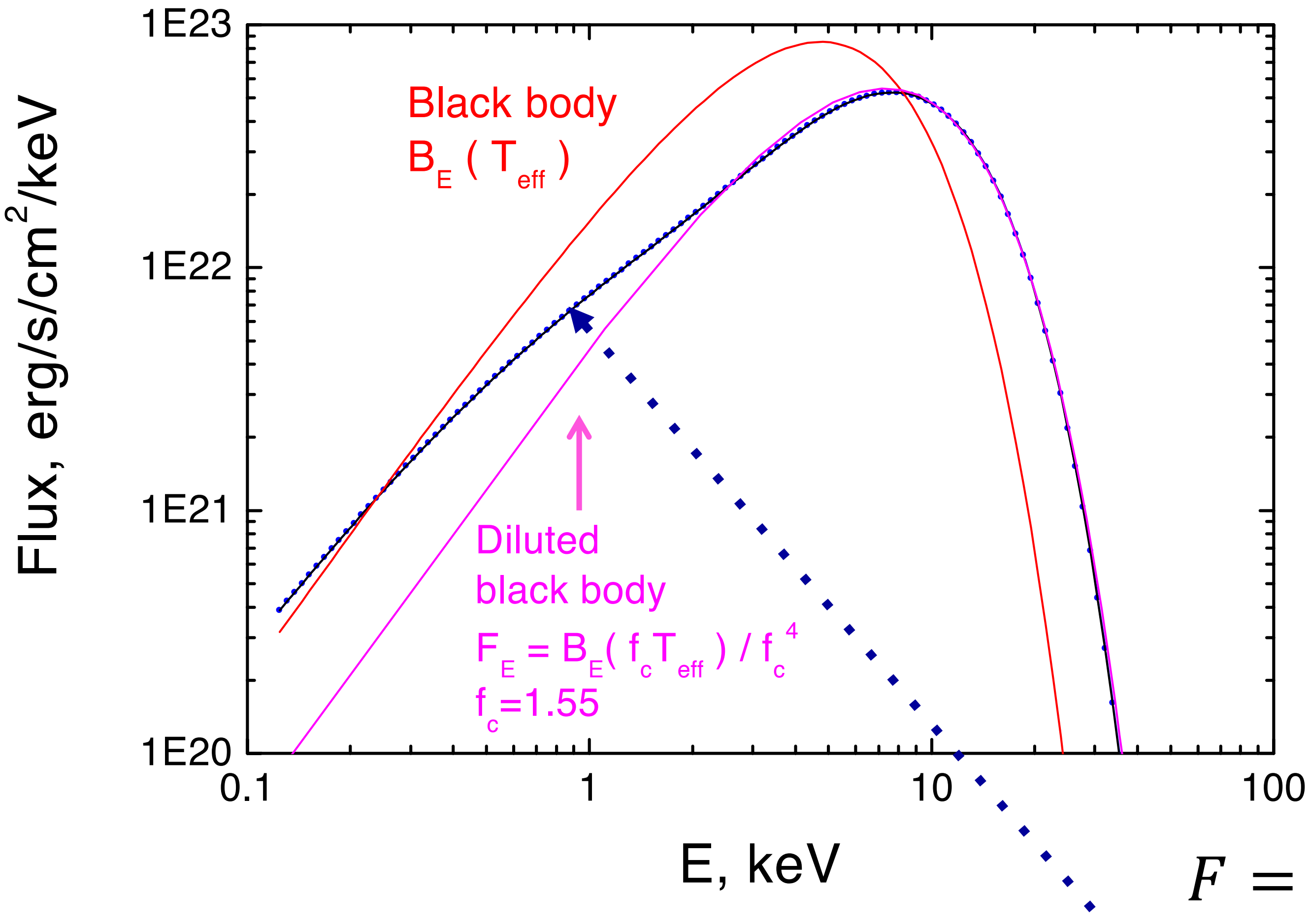


Fig. 4.3. Mass-radius relation for three hypothetical values of the blackbody radius R_∞ (5, 10, and 15 km). For clarity, we have not indicated error regions resulting from the uncertainties in the measurements. The straight lines indicate radii R_*, equal to the Schwarzschild radius R_S, 1.5 R_S, and 2.4 R_S (in the text we use R_g instead of R_S). The latter could, for example, result from an analysis of a burst with radius expansion (see text), or from the determination of the gravitational redshift of an observed spectral feature. For a given mass, the observed blackbody radius, R_∞, has a minimum value $(1.5\sqrt{3})\,R_g$; conversely, for a given blackbody radius R_∞ the mass cannot be larger than R_∞ (km)/7.7 $M_\odot$.

Spectra of bursting atmospheres



Color temperature

$T_c = f_c\, T_{eff}$

f_c - color correction factor

$$F_E \approx \frac{\pi}{f_c^4} B_E\left(f_c T_{\rm eff}\right)$$

$$F = \int F_E \, dE = \boldsymbol{\sigma_{SB}} T_{\mathbf{eff}}^{\mathbf{4}}$$

Comparison of the theoretical X-ray burst spectrum (blue curve) with the black body (red) of the same effective temperature.

Neutron star radius determination using black body radius at “infinity”

- The observed bolometric luminosity can be estimated from flux if we know the distance *D*.
- The radius at “infinity” can be determined from the observed color temperature
- Observed luminosity is related to luminosity at the surface. Both the rate of photon arrival and photon energy are decreasing by 1+z.
- Temperature decreases because photons are redshifted by 1+z.
- Stefan-Boltzmann law can be applied at the surface
- Thus we can get a relation between the apparent and the real stellar radii and mass.

$$L_{\mathrm{bol}} = 4\pi D^2 F_{\mathrm{bol}}$$

$$L_{\mathrm{bol}} = 4\pi R_{\mathrm{bb}}^2 \sigma_{\mathrm{SB}} T_{\mathrm{c}}^4$$

$$T_{\mathrm{c}} = f_{\mathrm{c}} T_{\mathrm{eff},\infty}$$

$$L_{\mathrm{bol}} = L_{\mathrm{bol},*}(1+z)^{-2}$$

$$T_{\mathrm{eff},\infty} = T_{\mathrm{eff},*}(1+z)^{-1}$$

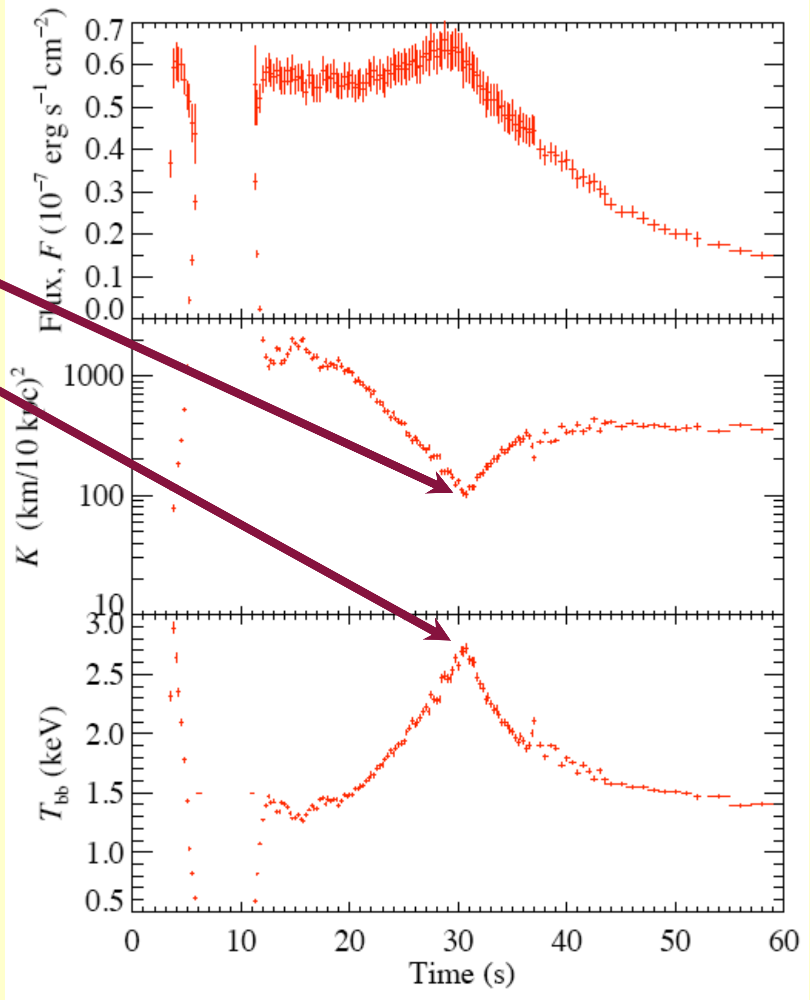
$$1+z = (1 - R_{\mathrm{S}} / R_*)^{-1/2}$$

$$L_{\mathrm{bol},*} = 4\pi R_*^2 \sigma_{\mathrm{SB}} T_{\mathrm{eff},*}^4$$

$$\boxed{R_*(1+z) = R_*(1 - R_{\mathrm{S}} / R_*)^{-1/2} = R_{\mathrm{bb}} f_{\mathrm{c}}^2}$$

NS *M* and *R* from the Eddington flux

Often it is assumed that the Eddington flux is reached during the “touchdown” (when the blackbody normalization reaches the minimum and the color temperature the maximum).



Gravity on the NS surface

$$g = \frac{GM}{R_*^2\sqrt{1-R_s/R_*}} = \frac{GM}{R_*^2}(1+z)$$

The Eddington limit at the surface

$$F_{Edd,*} = \frac{gc}{\kappa_e}, \quad \text{where } \kappa_e = \frac{\sigma}{m} = 0.2\,(1+X)\ \text{cm}^2\text{g}^{-1}$$

X – hydrogen mass fraction

For pure hydrogen, $X=1$: $\kappa_e = \frac{\sigma_T}{m_p} = 0.4\,\text{cm}^2\text{g}^{-1}$

$$L_{\text{Edd},*} = \frac{4\pi GMc}{\kappa_e}(1+z), \quad L_{\text{Edd,obs}} = L_{\text{Edd},*}(1+z)^{-2} = 4\pi D^2 F_{\text{Edd,obs}}$$

The observed Eddington flux is then

$$F_{\mathrm{Edd,obs}} = \frac{L_{\mathrm{Edd,obs}}}{4\pi D^2} = \frac{GMc}{D^2 \kappa_{\mathrm{e}} \left(1+z\right)} \Rightarrow$$

This is equivalent to

$$\boxed{R_* = 14.138\mathrm{km} \frac{(1+X) D_{10}^2 F_{-7}}{u\sqrt{1-u}}}$$

where $F_{-7} = F_{\mathrm{Edd,obs}}/10^{-7}$ erg cm^{-2} s^{-1} , $D_{10}=D/10$ kpc, $u=R_S/R$

From the blackbody fits in the burst tail

$$R_\infty = R_{\mathrm{bb}} f_{\mathrm{c}}^2 = D_{10}\sqrt{K} f_{\mathrm{c}}^2 \Rightarrow$$

$$\boxed{R_* = D_{10}\sqrt{K} f_c^2 \sqrt{1-u}}$$

Let us define the Eddington temperature as the redshift-corrected effective temperature corresponding to the surface Eddington flux

$$T_{\mathrm{Edd},\infty} = \frac{1}{1+z}\left(F_{\mathrm{Edd},*} / \sigma_{\mathrm{SB}}\right)^{1/4} \Rightarrow$$

it can be expressed through the observed K and F_{Edd} (assuming some f_{c})

$$T_{\mathrm{Edd},\infty} = \left(\frac{gc}{\sigma_{\mathrm{SB}}\kappa_{\mathrm{e}}}\right)^{1/4} \frac{1}{1+z} = \left(\frac{F_{\mathrm{Edd,obs}}}{\sigma_{\mathrm{SB}}}\right)^{1/4} \left(\frac{R_\infty}{D}\right)^{-1/2} = 9.81\, A F_{-7}^{1/4} \mathrm{keV}$$

$$A = \left(R_\infty[\mathrm{km}] / D_{10}\right)^{-1/2} = K^{-1/4} / f_{\mathrm{c}}$$

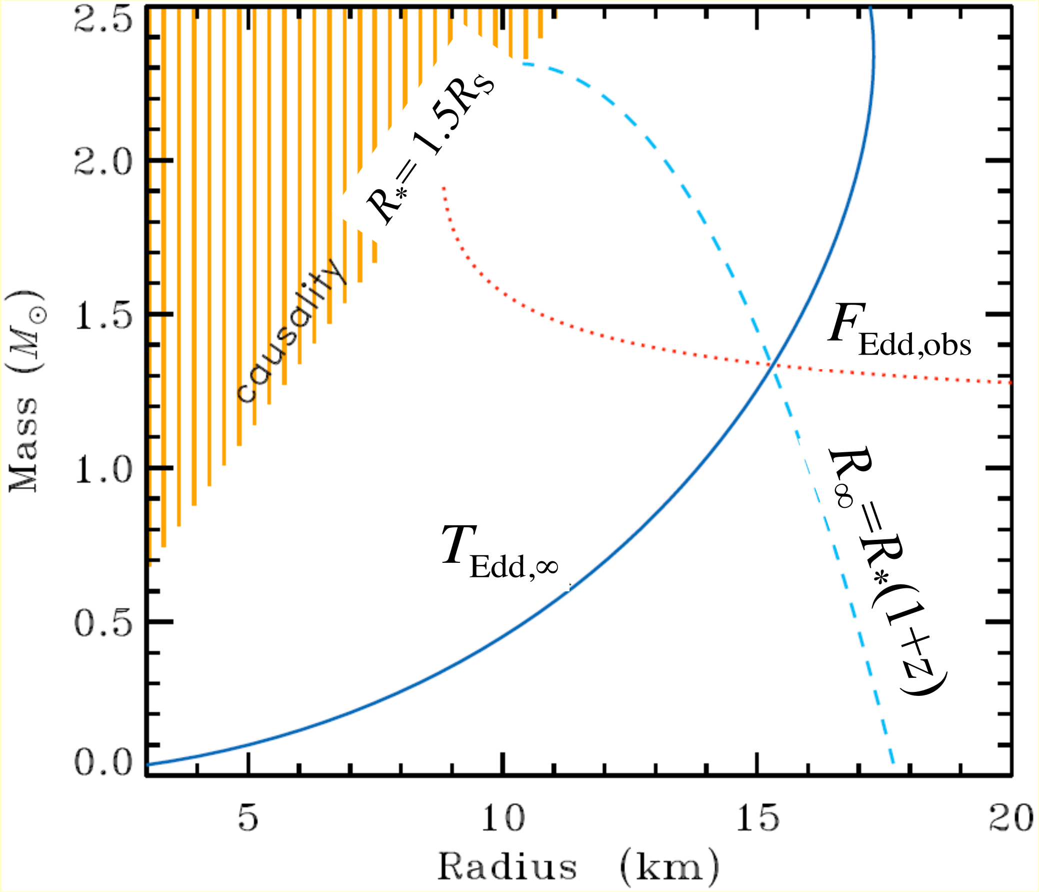
From $T_{\mathrm{edd},\infty}$ we get

$$\boxed{R_* = \frac{c^3}{2\sigma_{\mathrm{SB}} T_{\mathrm{Edd},\infty}^4 \kappa_{\mathrm{e}}} u\left(1-u\right)^{3/2}}$$

Note: this result does not depend on the distance!

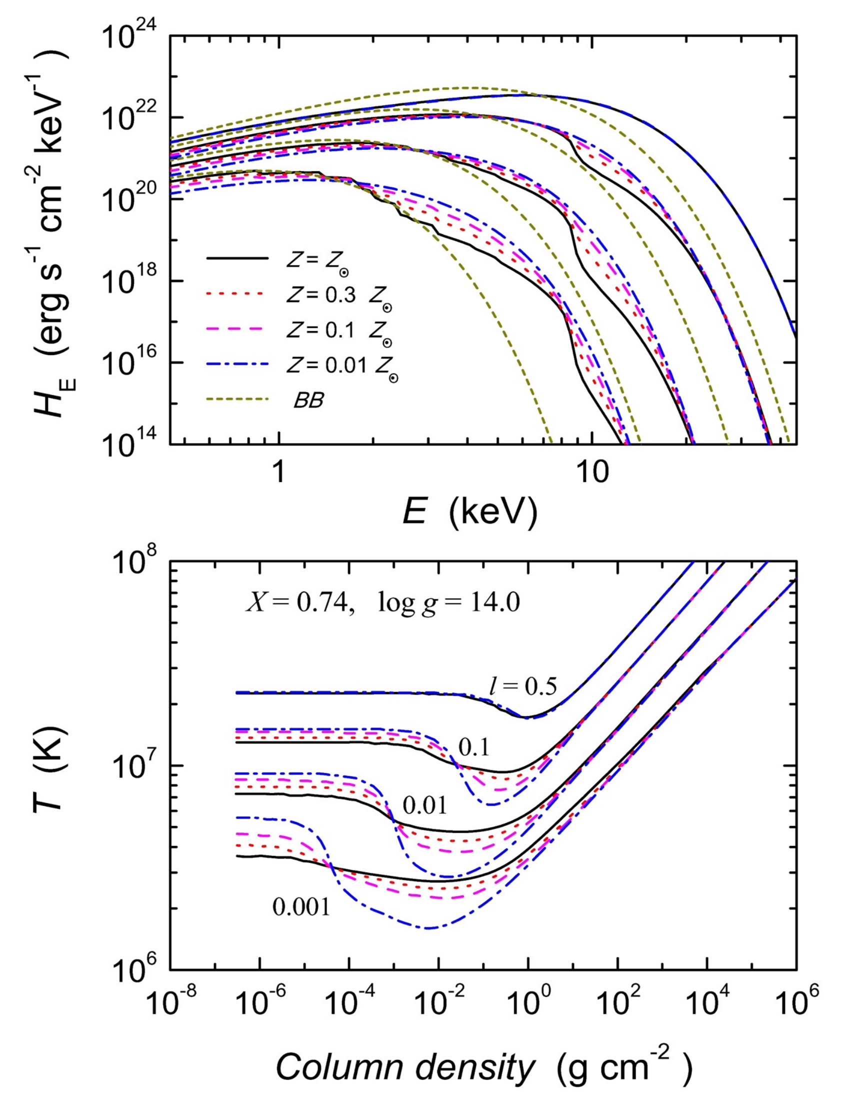
NS *M* and *R* from the Eddington flux

The solution should lie on the crossing of three lines. Constraints on *M* and *R* are then as follows

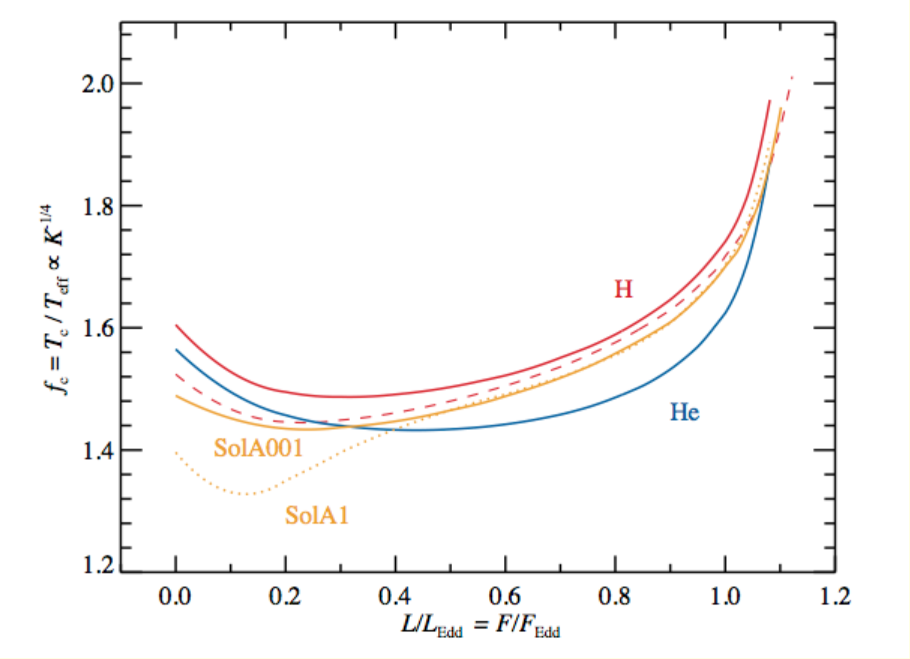


Note that the solution depends on the distance, but should lie on the curve of constant $T_{\rm Edd}$.

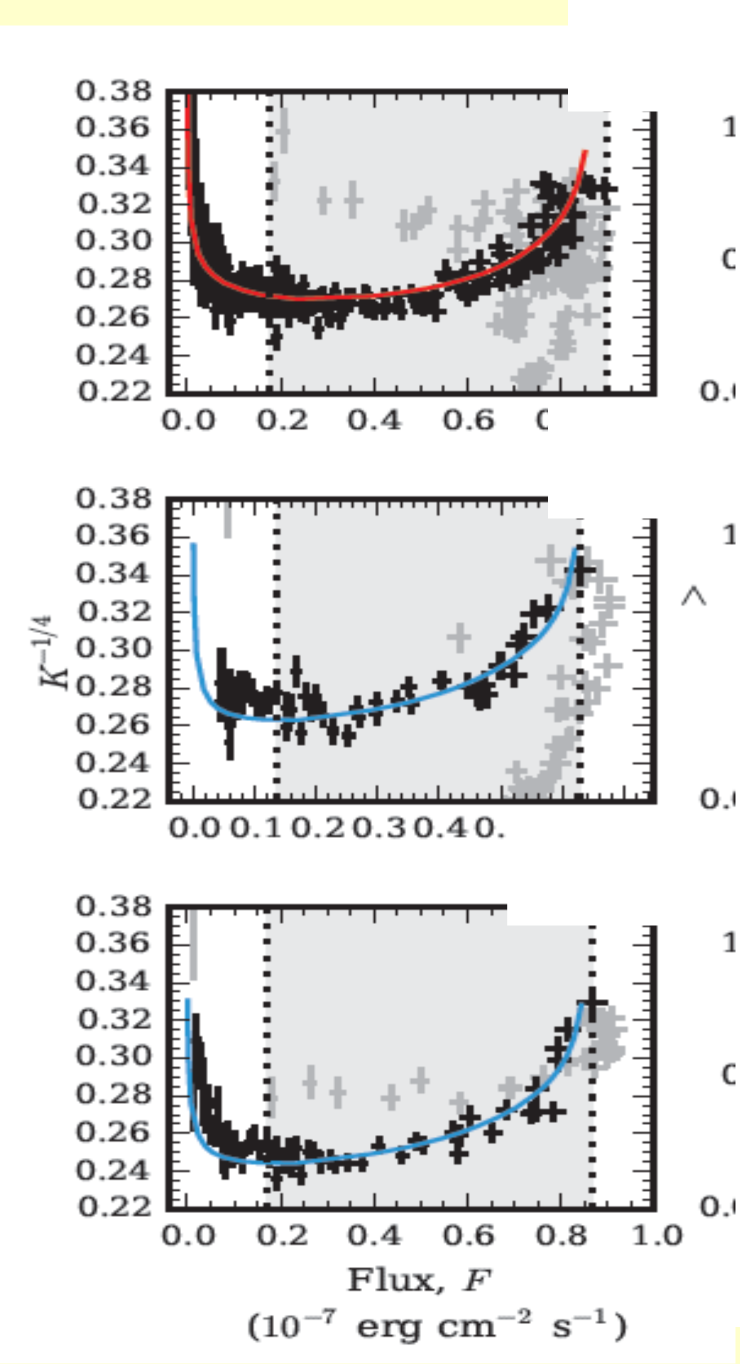
Atmosphere models and color-correction factor f_c

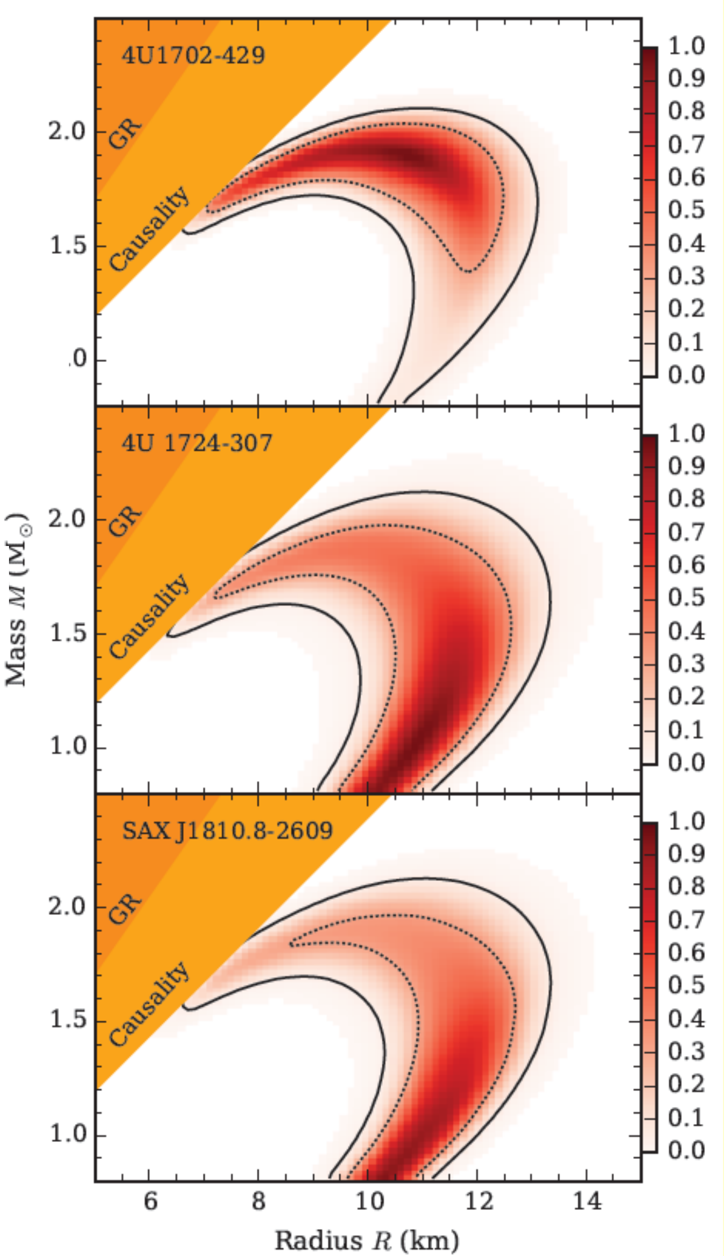


$$K^{-1/4} = A\, f_c(F / F_{\rm Edd})$$



Cooling tail method





Nättilä et al. 2016

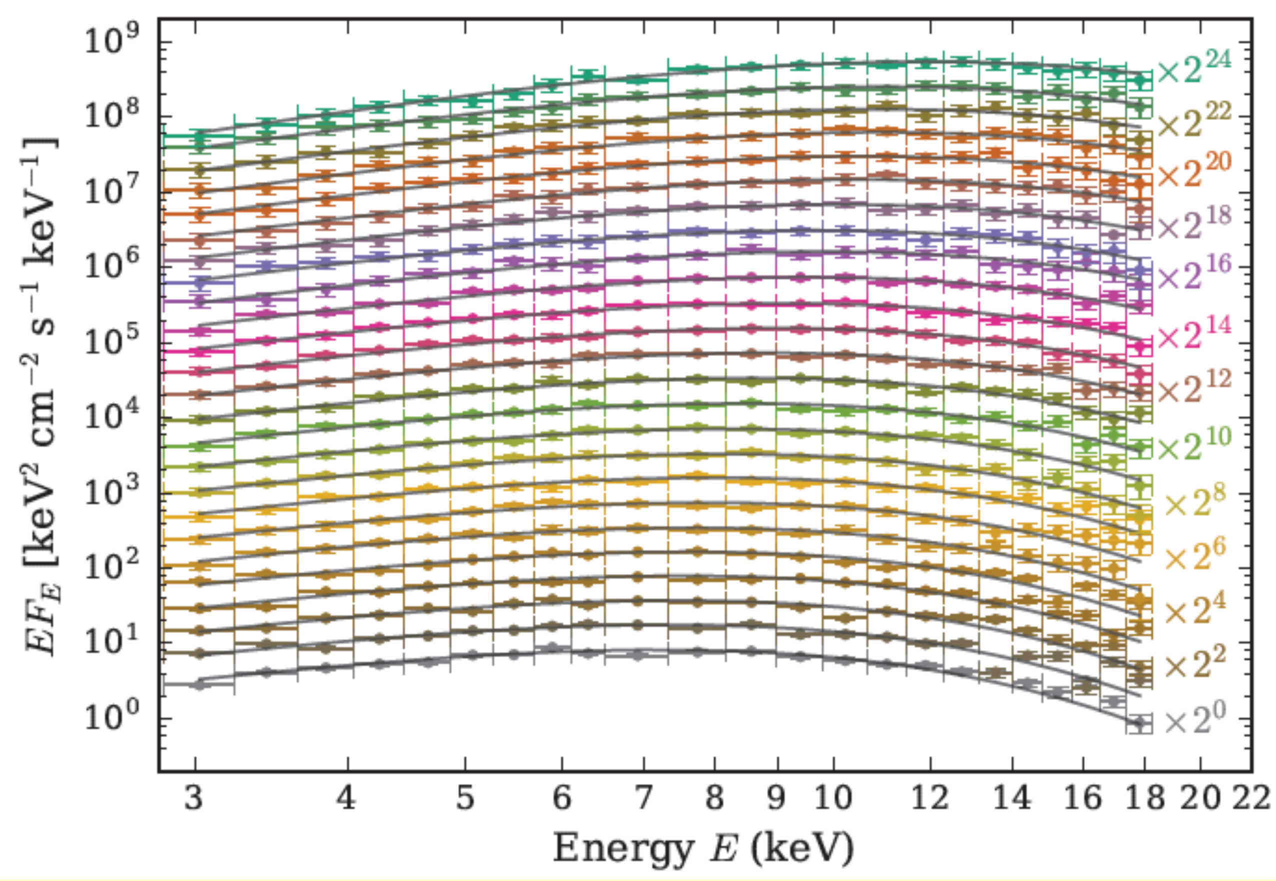
Direct spectral fitting

1. Most (all?) previous attempts to measure NS M and R from burst spectra rely on the blackbody fits. Thus plenty of information gets lost.

2. The computer power now allows to directly fit all the burst spectra from the same source simultaneously with the atmosphere models using MCMC.
Global parameters: M, R, D (+ chem. comp.)
Local: F/F_{Edd} for each spectrum

M-R constraints from 4U 1702-34

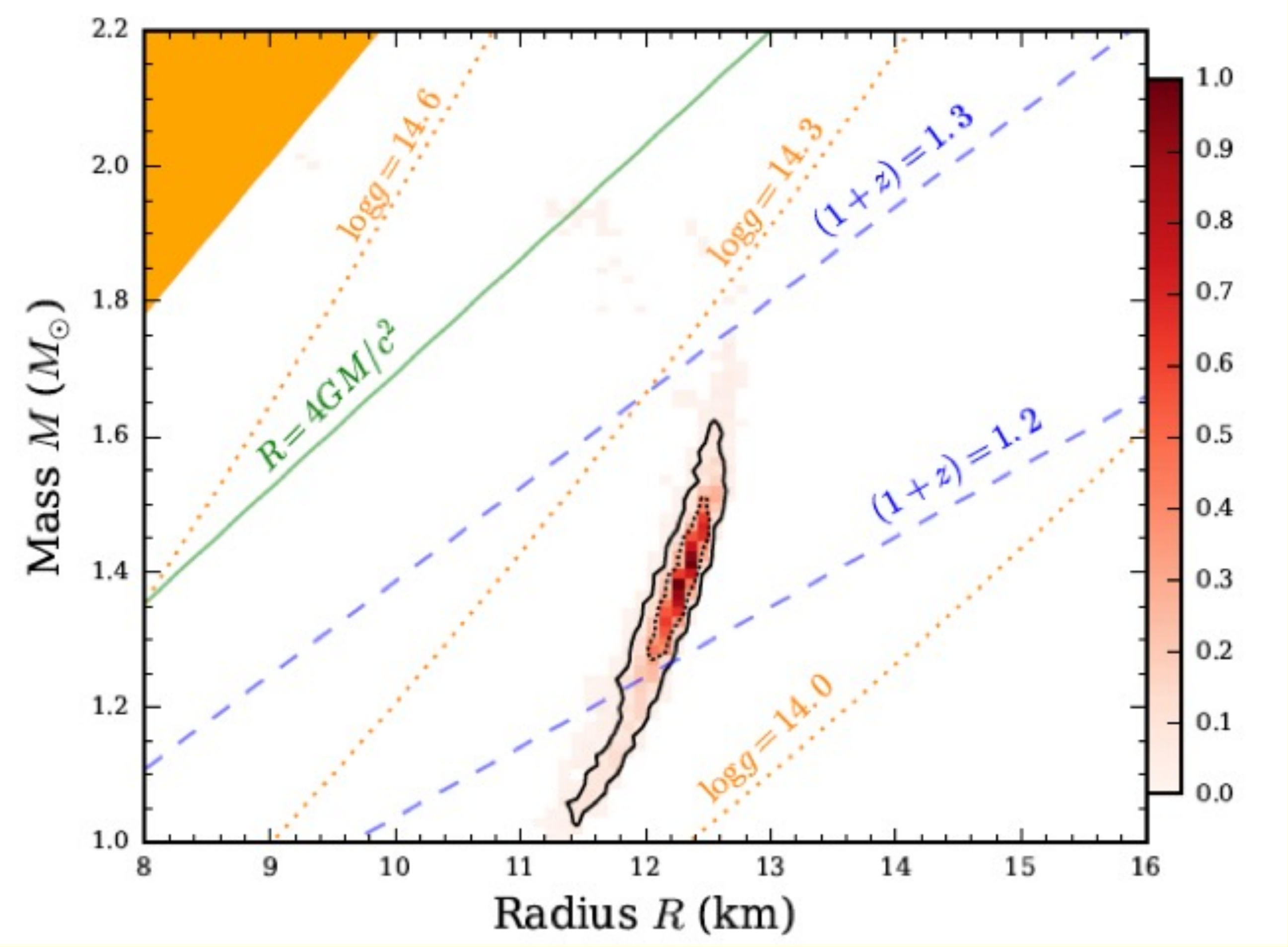
Direct fits to the X-ray burst spectra with the NS atmosphere models.



Nättilä et al. 2017

M-R constraints with atmosphere models

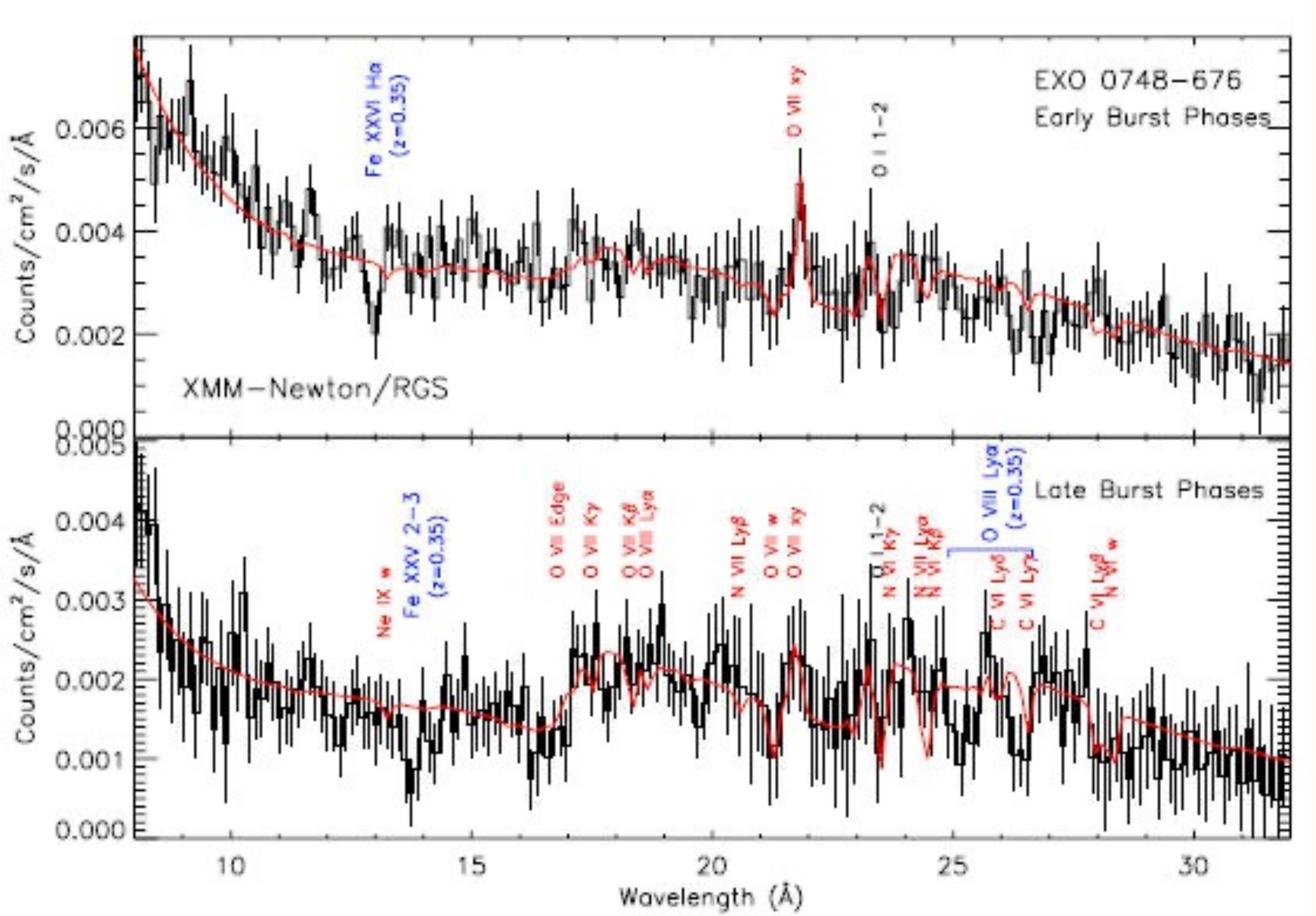
Direct fits to the X-ray burst spectra from 4U 1702-34 with the NS atmosphere models.



Nättilä et al. 2017

Atomic line shifts in X-ray burst

- Cottam et al (2002, Nature) observed and stacked 28 bursts from EXO 0748-676
- Candidate Fe XXVI lines seen at redshift z = 0.35



Atomic line shifts in X-ray bursts

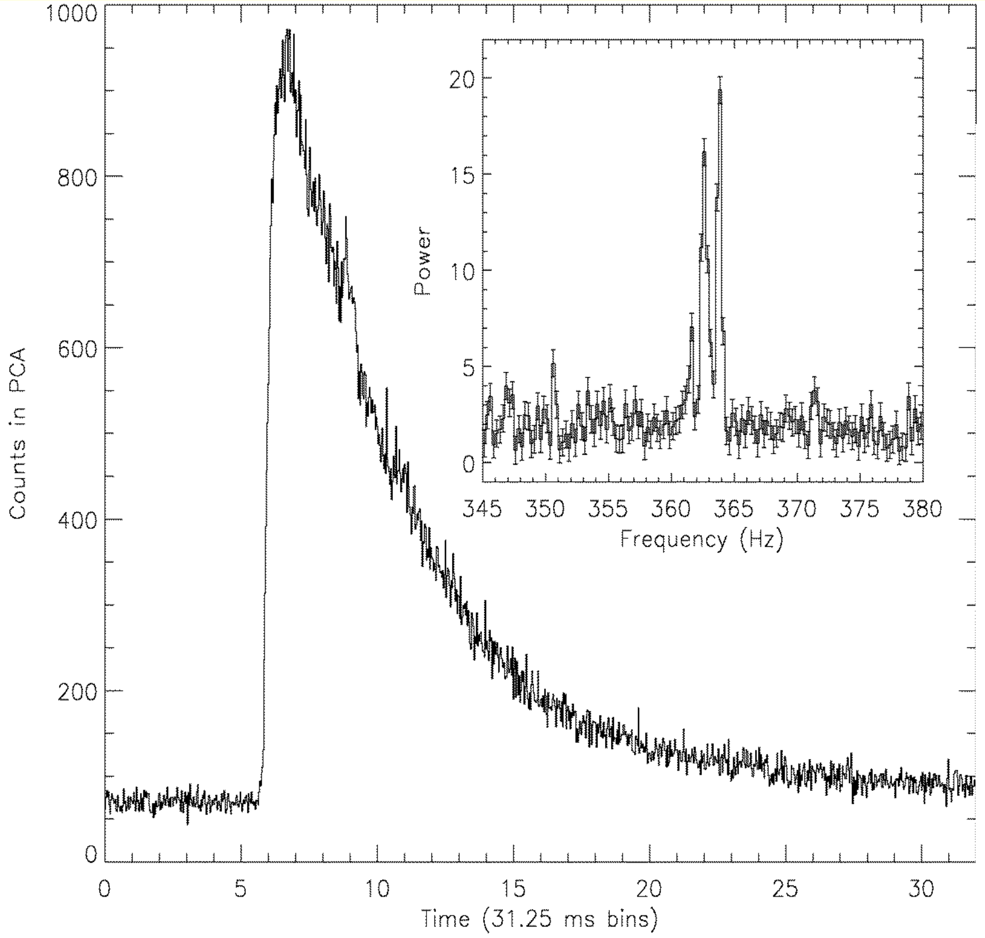
- Observed redshift would strongly constrain the *M* and *R* of the neutron star (even if the distance to the source is not known; Özel 2006).
- Unfortunately, in the existence of the lines is controversial:

1) they were not seen in other bursts (Cottam et al. 2008);
2) they are predicted to be much weaker and the lines of a different ion of Fe should be observed (Rauch et al. 2008), and finally
3) the source was later observed to pulsate at 552 Hz (Galloway et al. 2009), and such rotation would smear all the lines.

- Thus, we conclude that up to date no atomic lines have been observed from X-ray burst atmospheres.

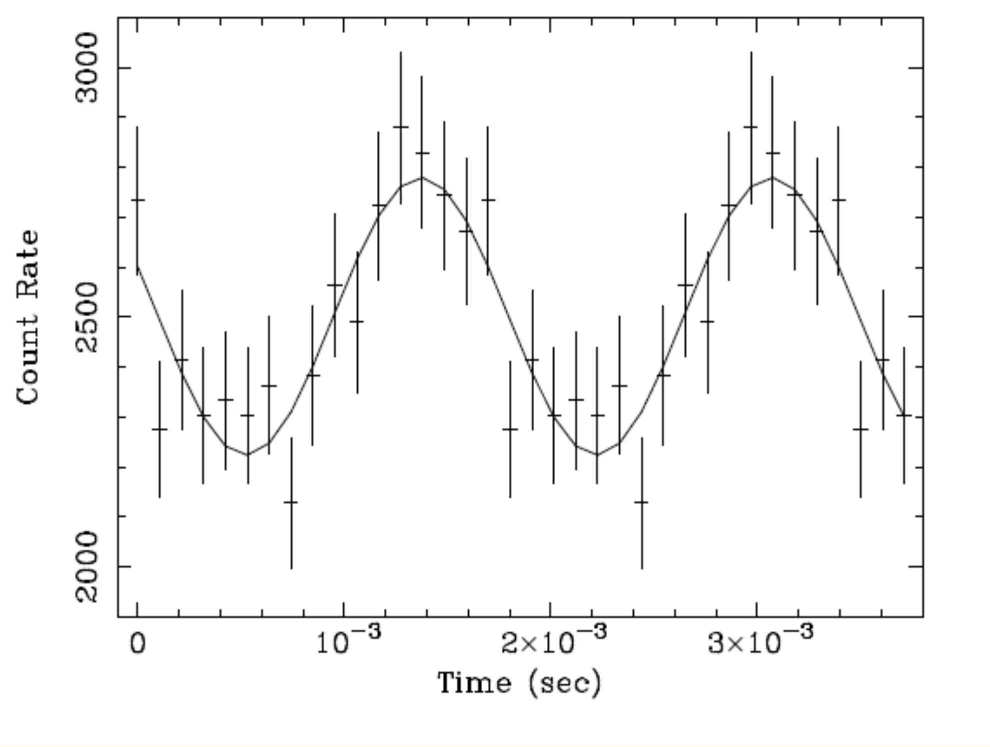
Millisecond oscillations during X-ray bursts

4U 1728-34



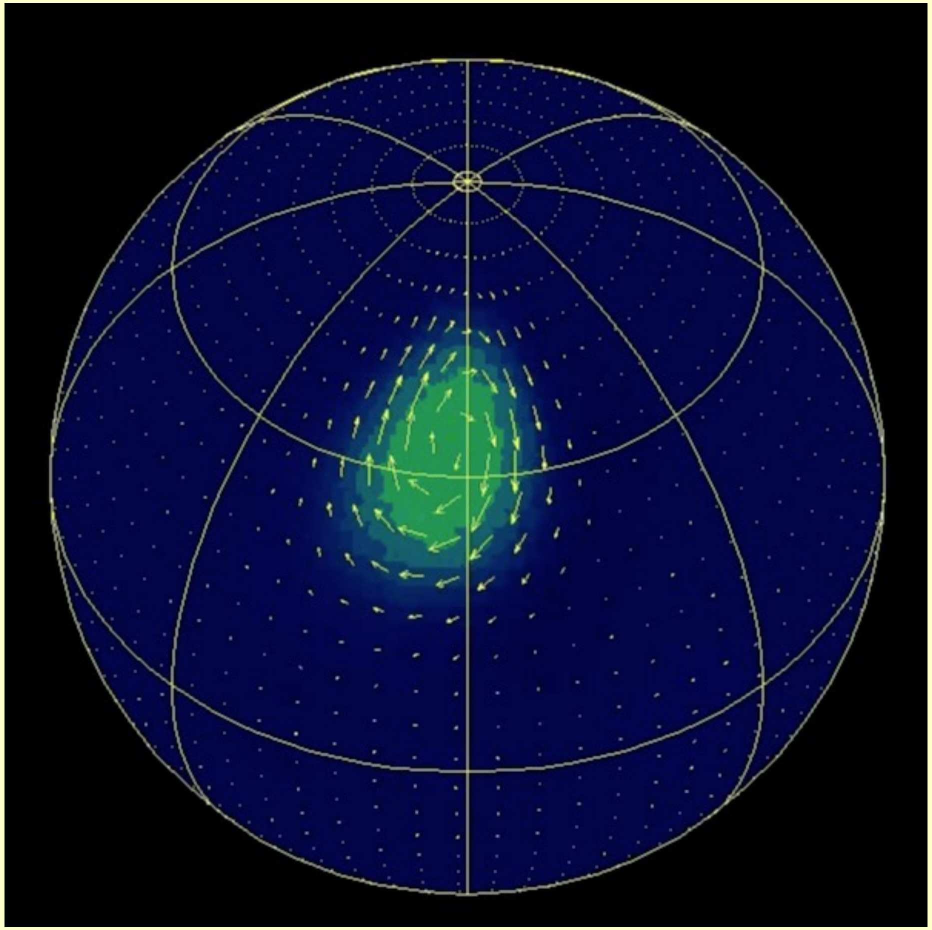
Time (s)

Light curve

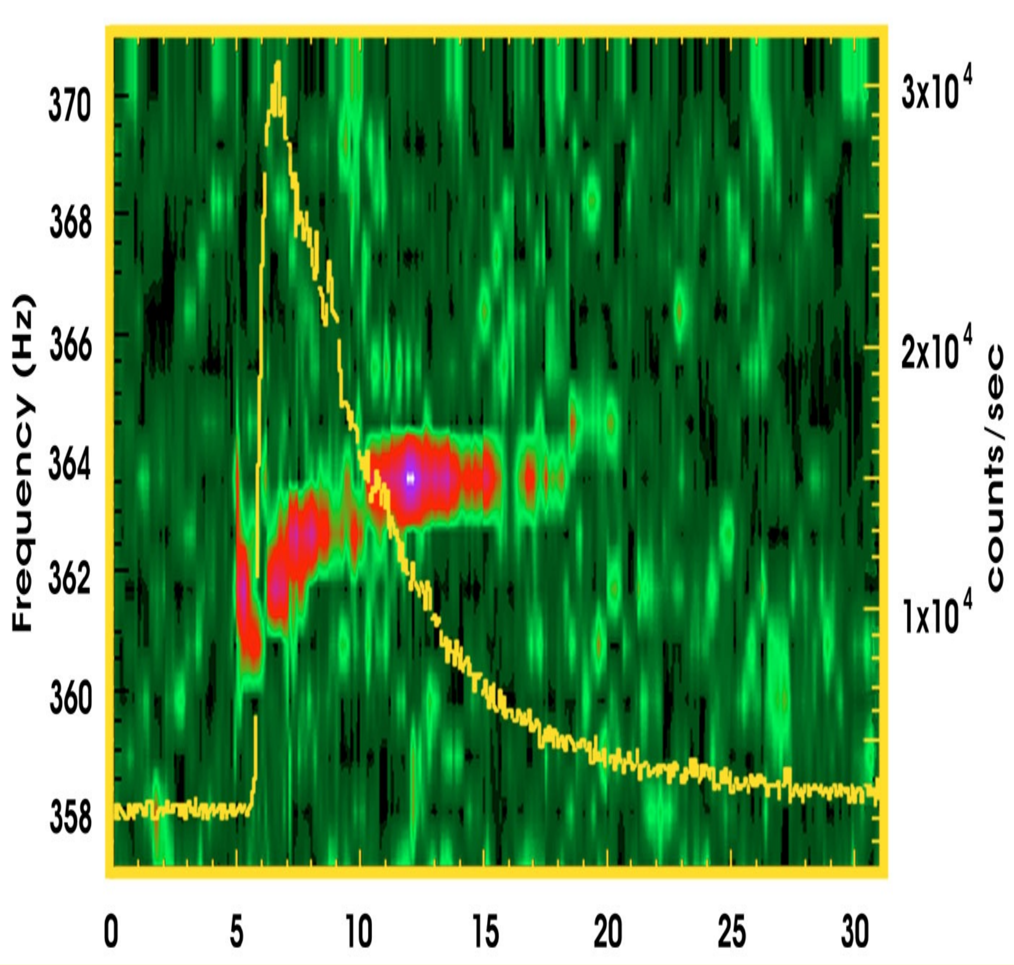


Strohmayer et al (1996, 1997)

Millisecond oscillations during X-ray bursts



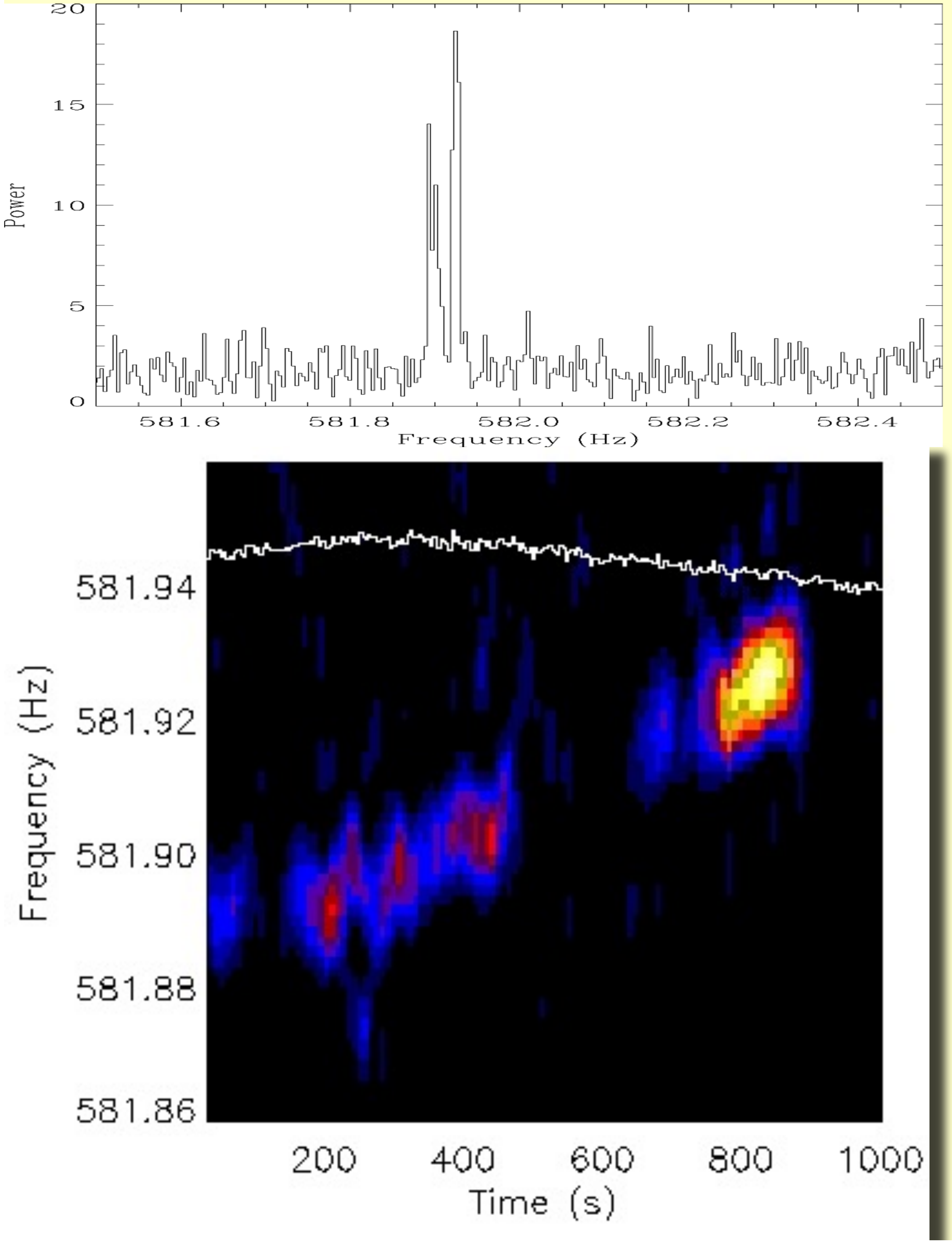
Contours:
Dynamic power-density spectra



Time (s)

simulations by A. Spitkovsky

Superburst pulsations in 4U 1636-53



- Pulse train lasts 900 seconds. Much longer than in normal (short) bursts.
- Frequency drifts by about 0.03 Hz in 800 s. Much smaller than drift in normal bursts.
- Consistent with orbital modulation of neutron star spin frequency.

Burst oscillations =
Nuclear-powered millisecond pulsars

Source	Orbital period [h]	Spin [Hz]
Sources with no persistent pulsations		
4U 1728-34	?	363
4U 1636-53	?	581
KS 1731-260	?	524
GRS 1741.9-2853	?	589
4U 1702-429	?	330
MXB 1658-298	7.1	567
4U 1916-053	0.83	267
4U 1608-52	?	619
SAX J1750.8-2900	?	601
EXO 0748-676	3.82	552
IGR J17191-2821		294
Accreting Millisecond Pulsars		
SAX J1808.4-3658	2.0	401
XTE J1814-338	4.275	314
IGR J17498-2921	3.843	401
IGR J17511-3057	3.467	245
Intermittent Accreting Millisecond Pulsars		
HETE J1900.1-2455	1.388	377
Aql X-1	19.0	549

Summary

- X-ray bursts are repeating thermonuclear explosions on the neutron star surface.
- Thermal emission during the bursts can be used to determine neutron star parameters.
- Oscillations during X-ray bursts reveal the presence of the rapidly rotating neutron star population, possible progenitors of millisecond radio pulsars.