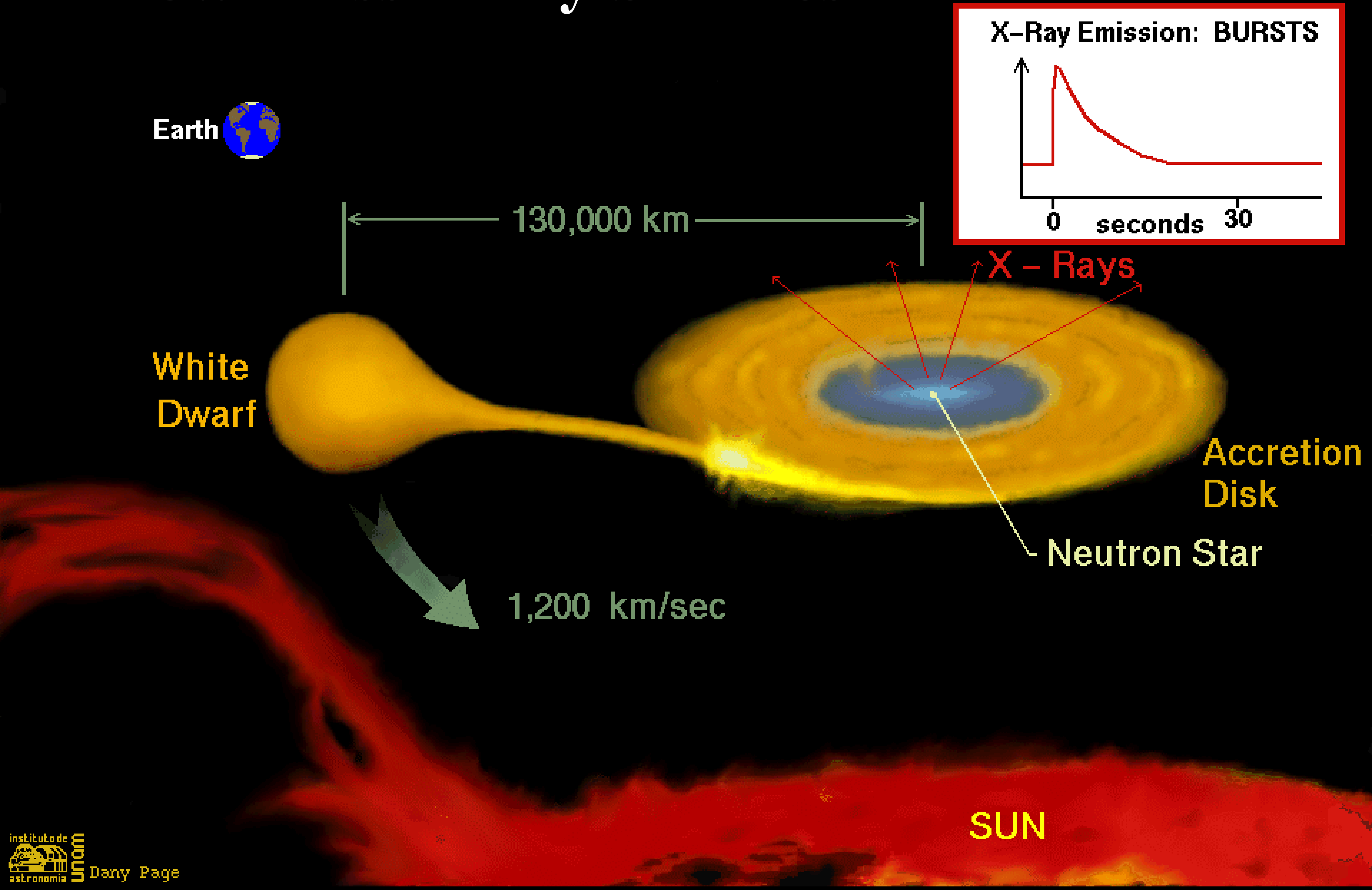
Low-mass X-ray binaries



instituto de astronomia unam Dany Page

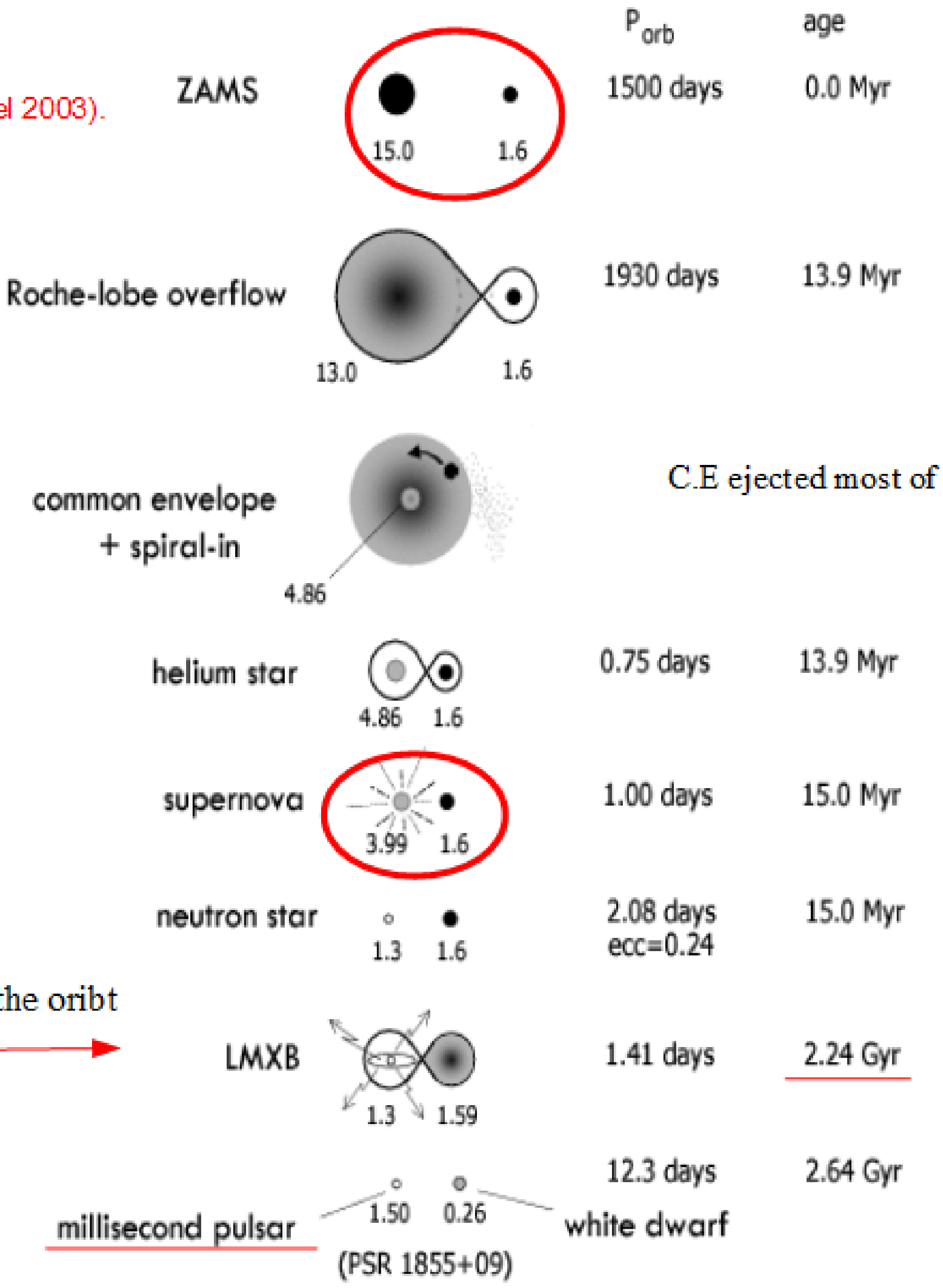
X-ray binaries: LMXB

- Mass donor of *late spectral type* (G or later); orbital periods of minutes to hours (typically)
- M < 1-2 $M_\odot$
- Mass transfer via *Roche lobe overflow* (RLO)
- Accretion via disk
- *Old* systems, with characteristically low magnetic fields (~$10^{8\text{-}9}$ G)
- Diversity of mass donors, compact object etc.

Example: Ultra-Compact X-Binary (UCXB) P< 1hr
Example: Accretion-powered neutron stars → AMXP

LMXB

(Tauris and van den Heuvel 2003).



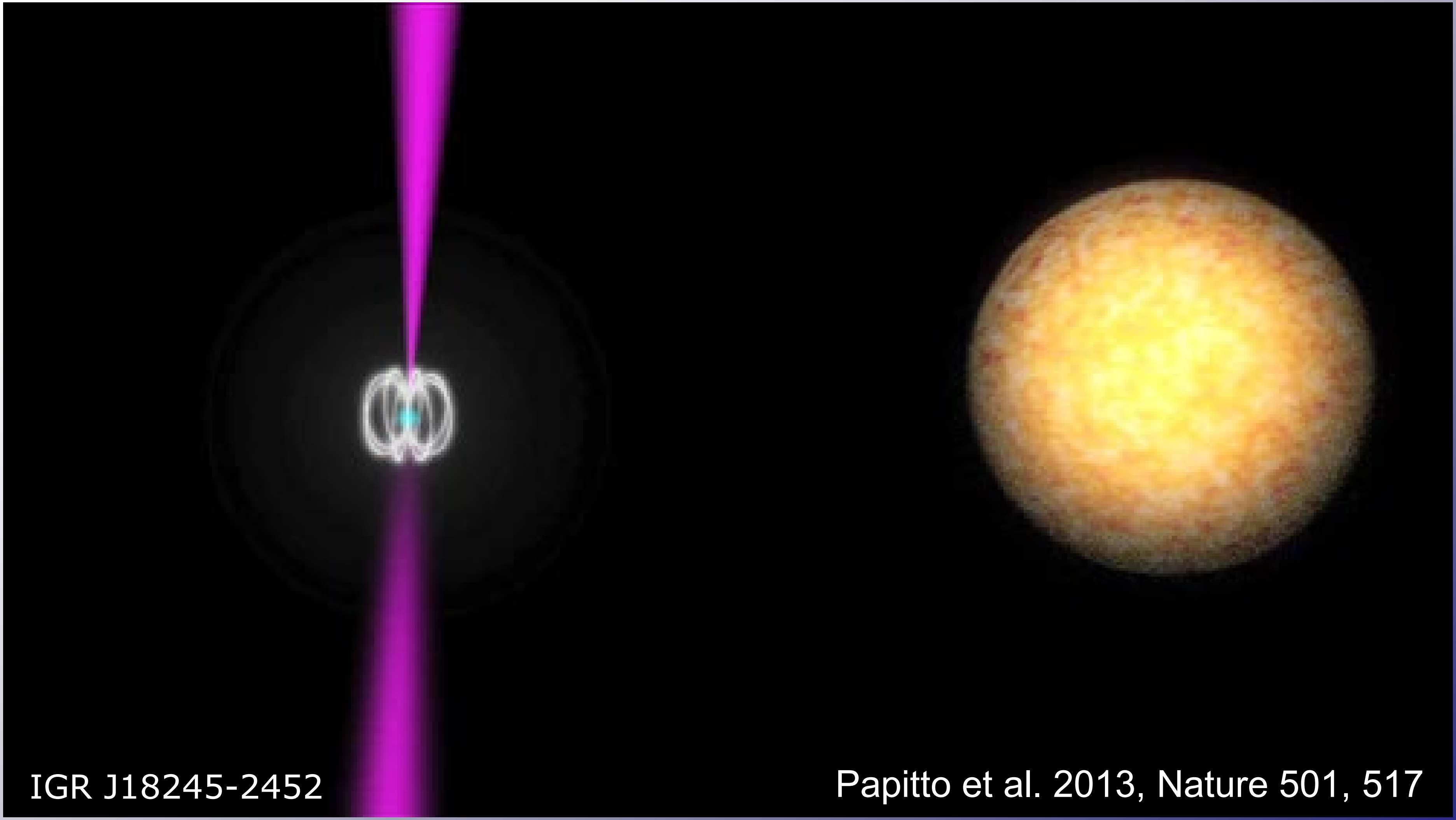
C.E ejected most of times

More massive explodes

Accretion circularises the oribt

(not the only way...
but ok to have an idea)

Millisecond-pulsar

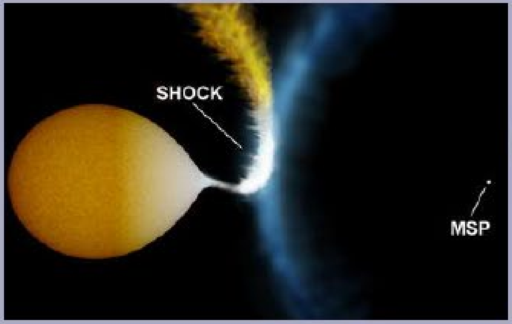


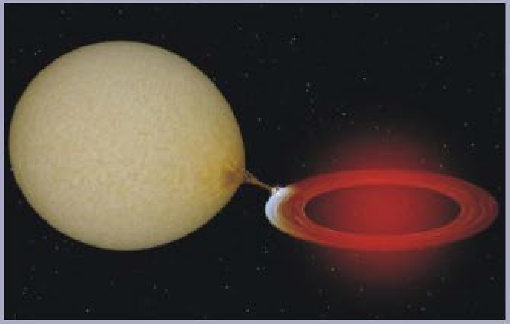
Papitto et al. 2013, Nature 501, 517

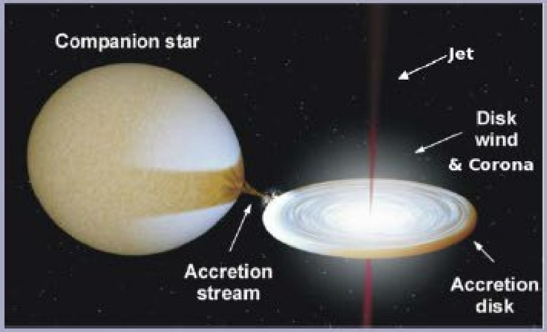
Recent discovery of a transition between rotation and accretion power
Accretion: X-ray pulsar (LMXB) ↔ **Rotation**: (magnetic) radio pulsar

INCREASING X-RAY LUMINOSITY

Log(Lx;erg/s):	31-32	33-34	35-37

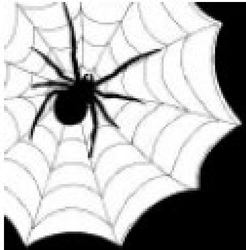






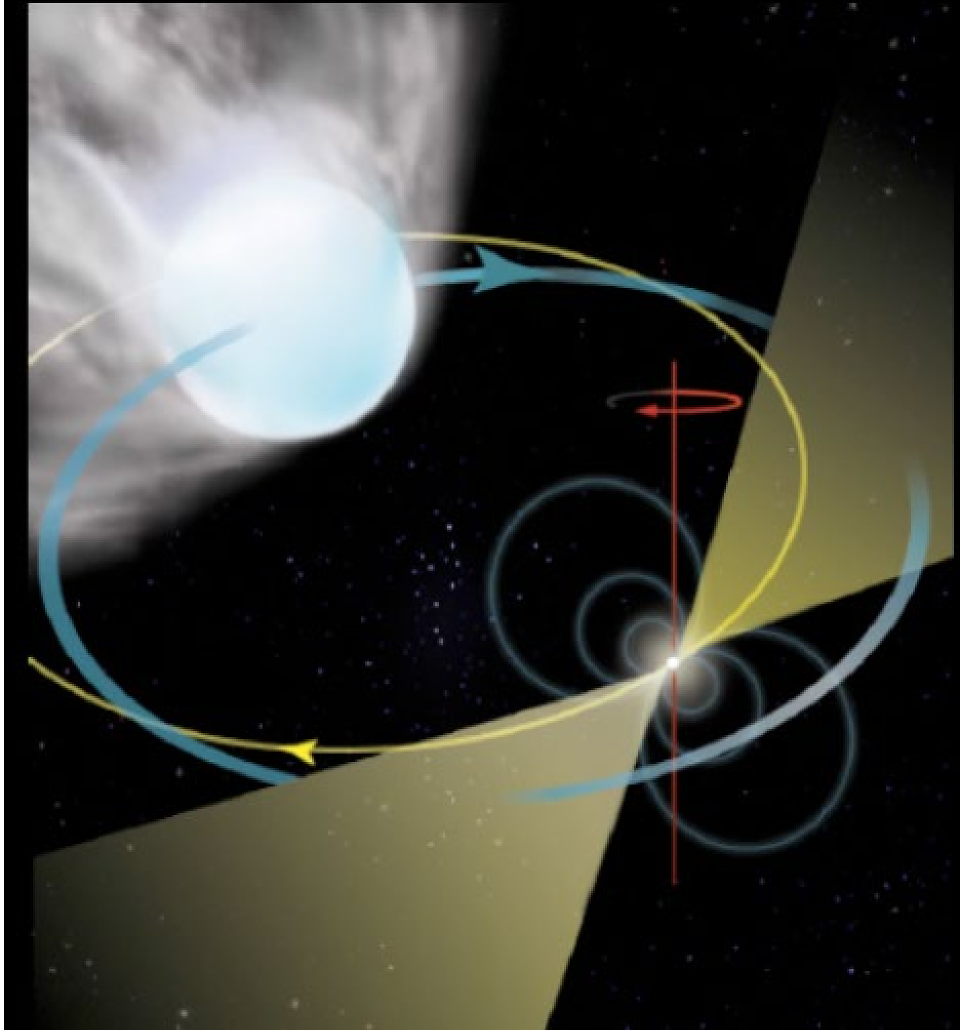
PULSAR WIND SHOCK	ACCRETION vs. ROTATION	LMXB
(Rotation-powered) **PULSAR STATE**	(Rotation?/Accretion) **DISK STATE**	(Accretion-powered) **OUTBURST STATE**

Courtesy: Manu Linares



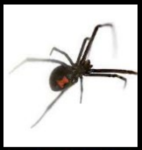
MSP “Spiders”

‘Black Widow’ and ‘Redback’ Pulsar Binaries



So named because these pulsars are ‘devouring’ (ablating) their companions

Black widows:



<< $0.1M_{Sun}$ (semi) degenerate companion

Redbacks:

~ $0.2M_{Sun}$ non-degenerate companion

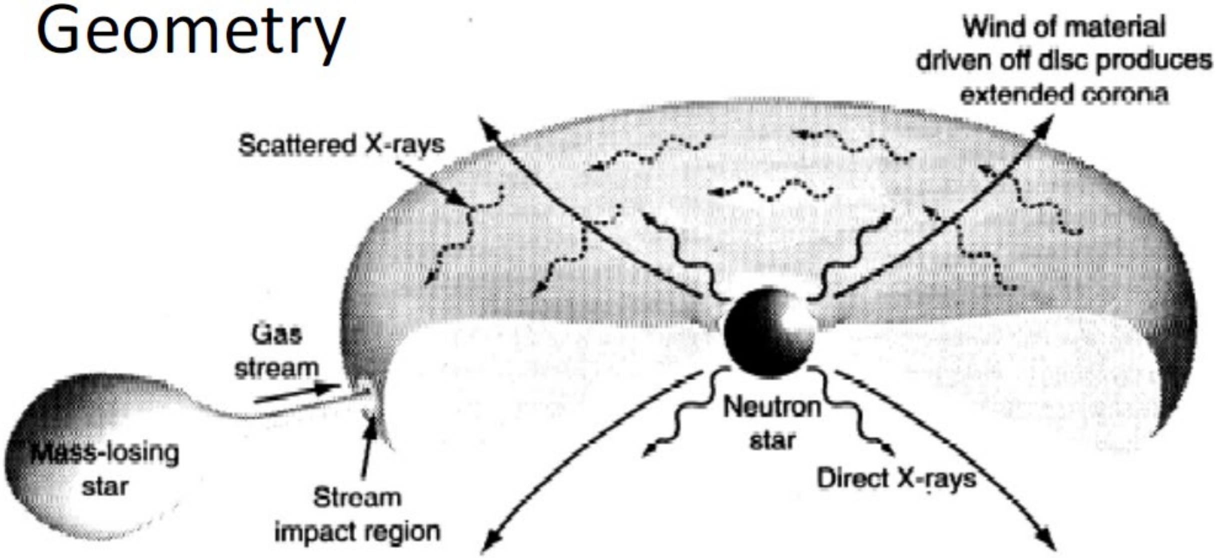
X-ray binary observational properties

- Varying spectral states during *outbursts* correspond to changes in the accretion flow.

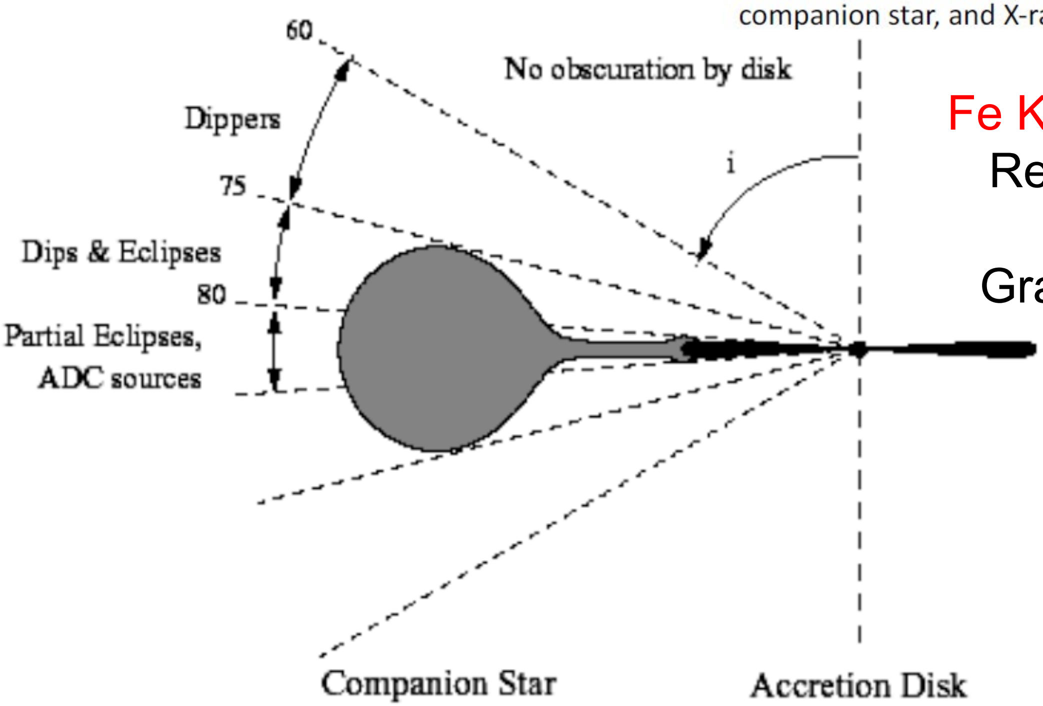
- Diagnostic tools:
  - Spectral analysis (energy)
  - Timing analysis (QPO)
  - Color-Color Diagram (CCD)
  - Hardness-Intensity Diagram (HID)

Geometry

Observed phenomenology depends on viewing angle



For BH, X-ray emission is from disk. For NS, there is also emission from boundary layer where disk meets NS and surface of NS. Optical emission arises from outer disk, companion star, and X-rays reprocessed by disk or companion.

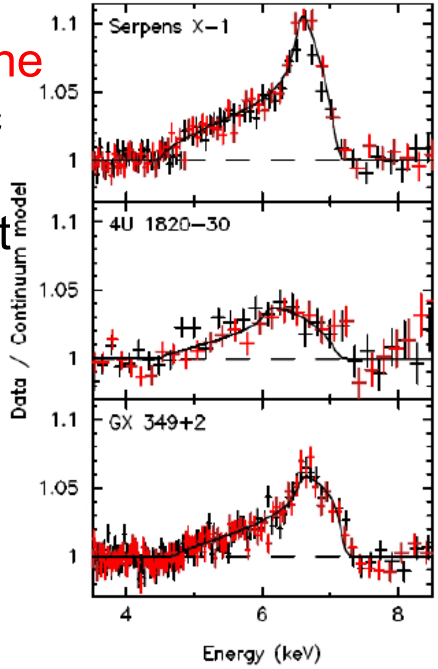


Fe Kα fluorescence line

Reflection from disc

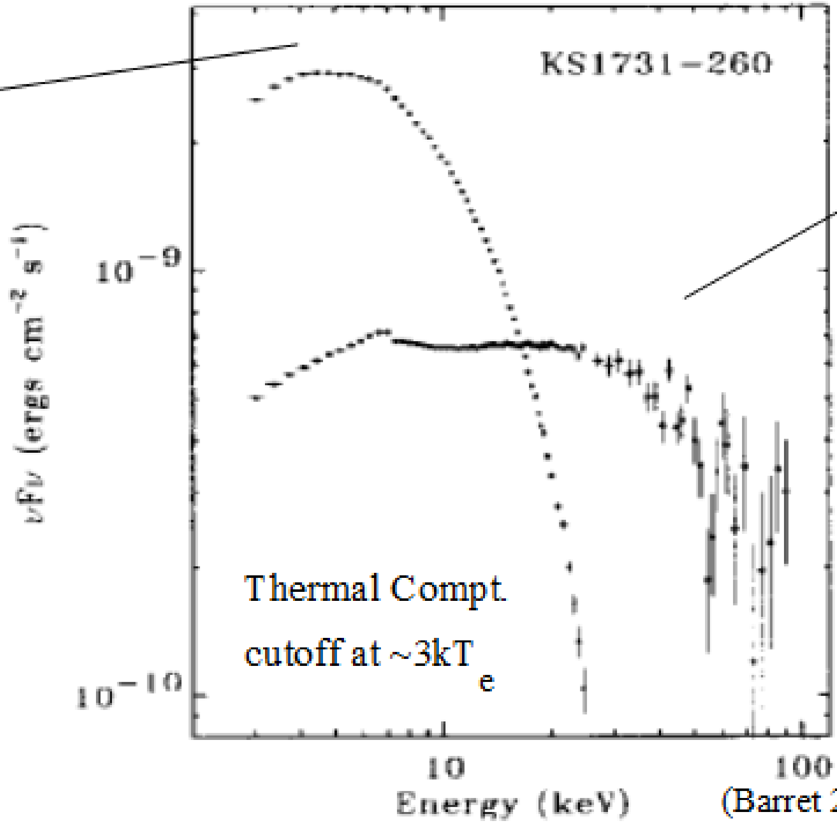
Doppler effect

Gravitational redshift



LMXB spectral states

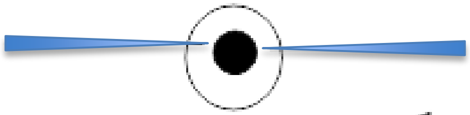
High soft state
Disc/NS: ~1keV
Plasma: kT$_e$~3keV
τ~5-15



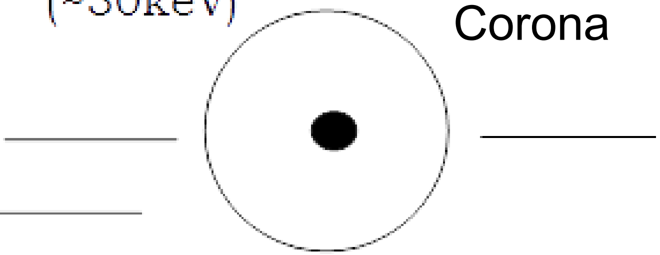
(Barret 2001)

Low Hard State
Disc/NS: ~1keV
Plasma: ~30keV
τ~2-3

Efficient cooling (~3keV)

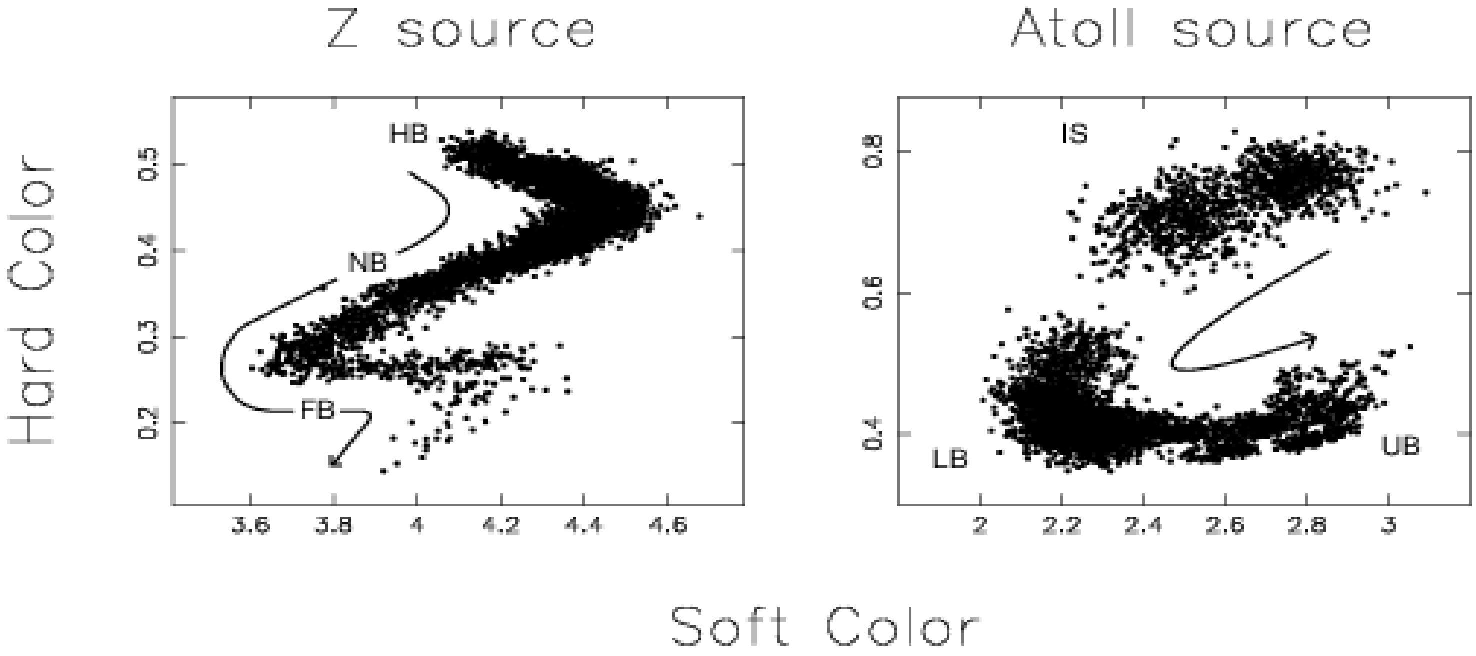


Inefficient cooling (~30keV)



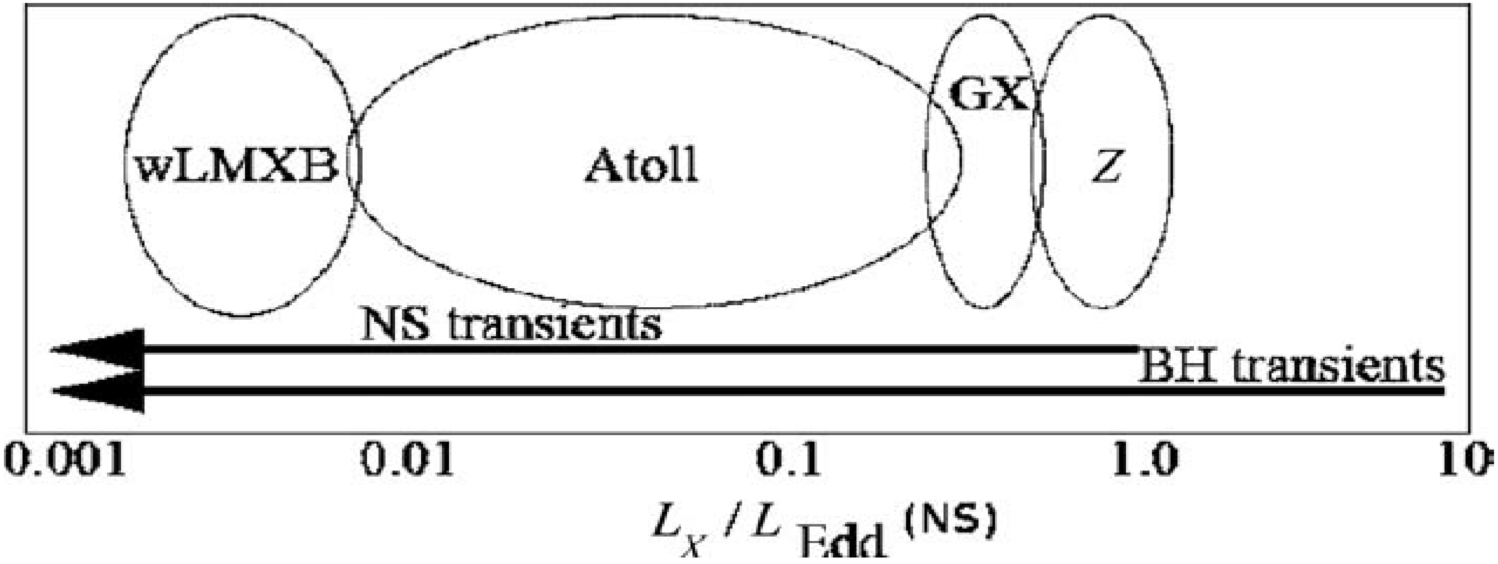
Mdot

Always dim?


Z source
Atoll source
Hard Color
Soft Color
HB
NB
FB
IS
LB
UB
0.5
0.4
0.3
0.2
0.8
0.6
0.4
3.6
3.8
4
4.2
4.4
4.6
2
2.2
2.4
2.6
2.8
3

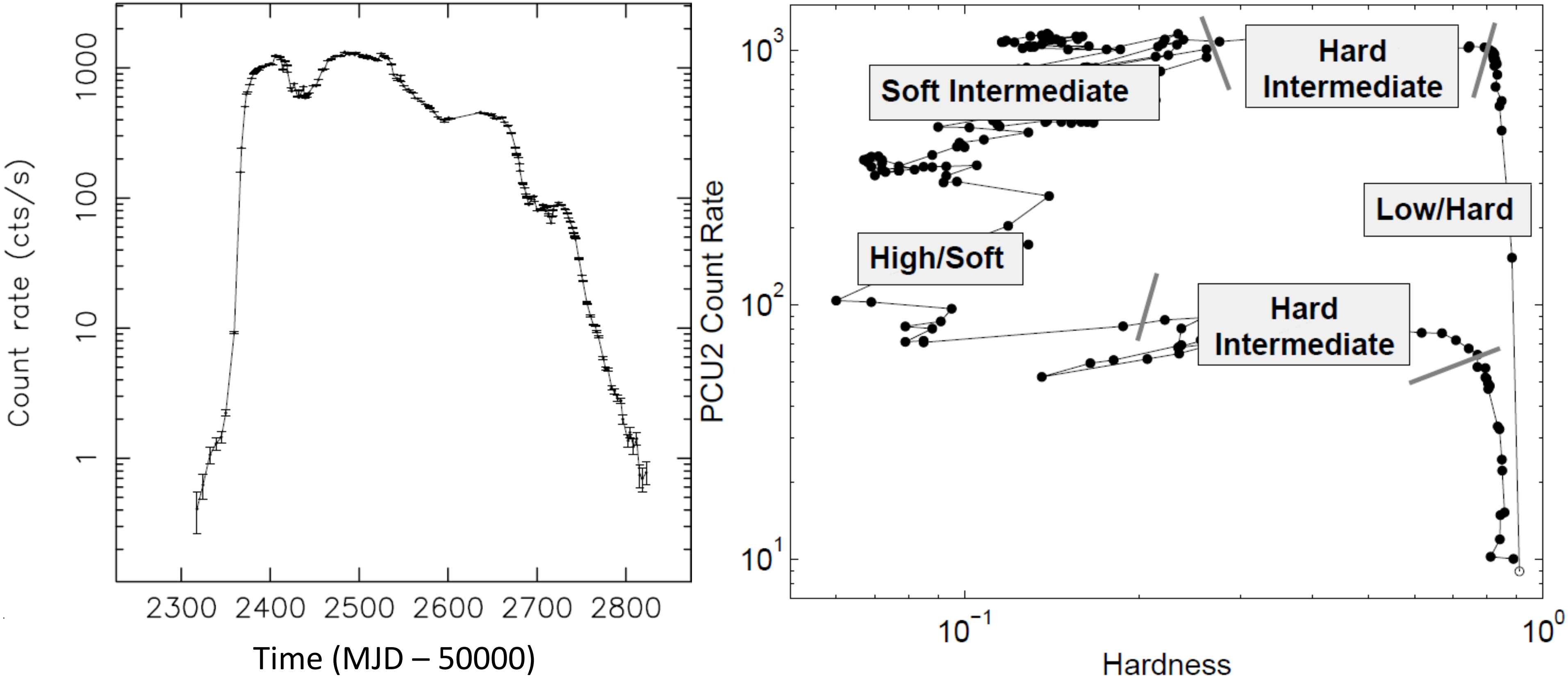
CCD

NS-LMXBs


wLMXB
Atoll
GX
Z
NS transients
BH transients
0.001
0.01
0.1
1.0
10
L_X / L_{Edd} (NS)

(Black hole X-ray binaries)

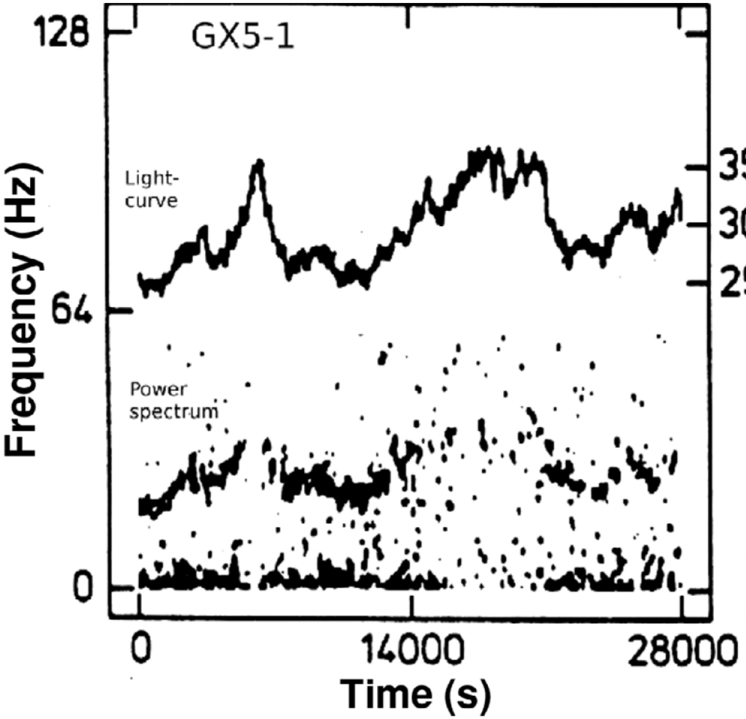
GX 339-4 2002/2003 outburst



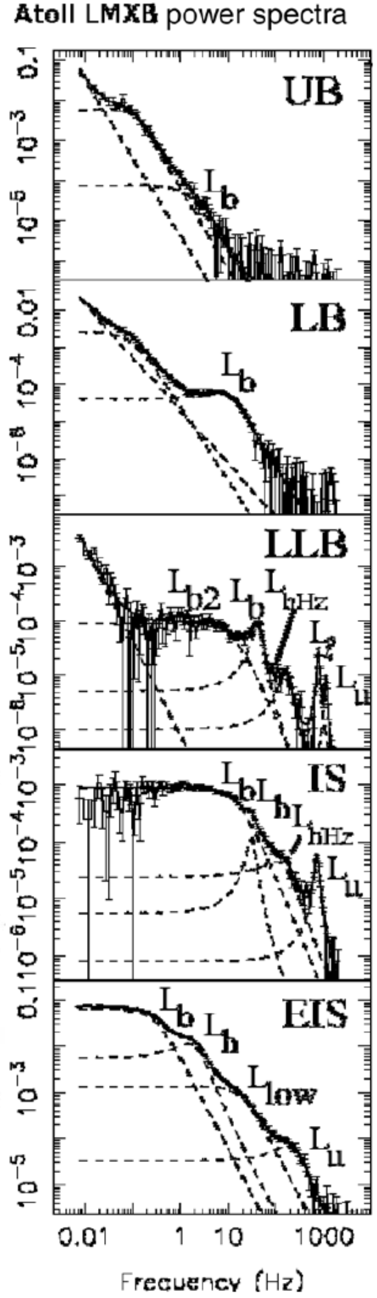
Homan & Belloni 2005

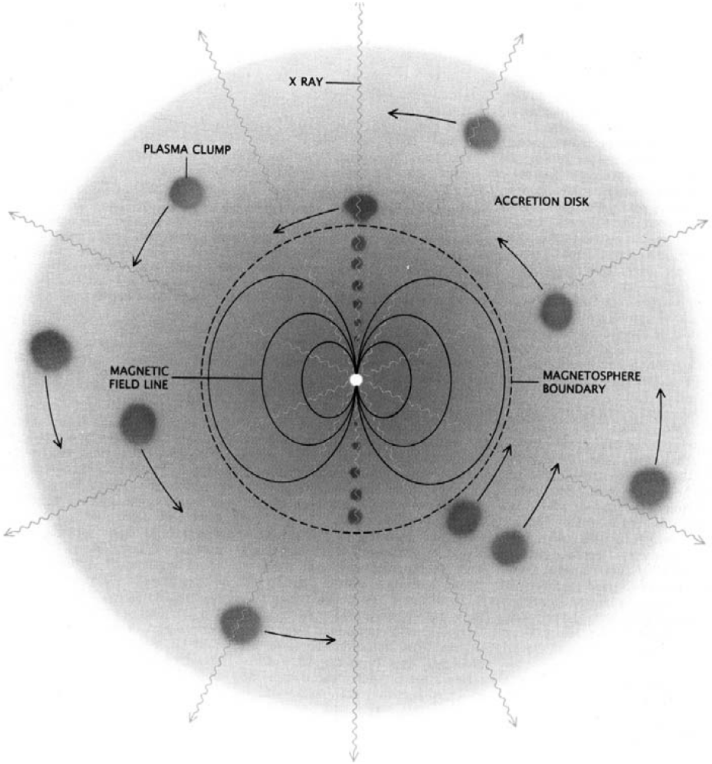
See lecture on black holes

TIMING



QPOs



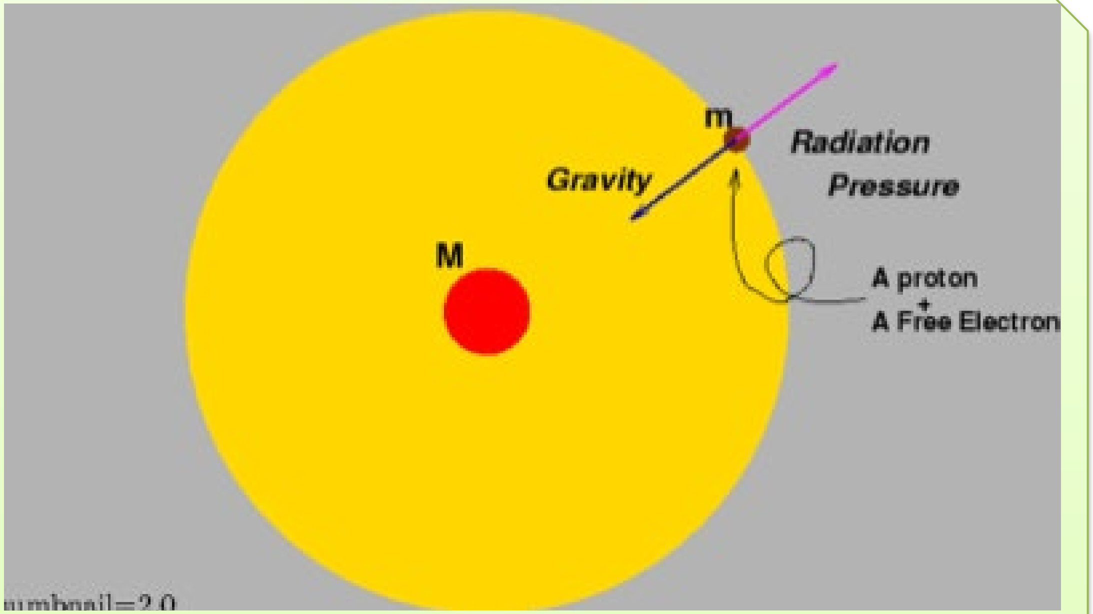


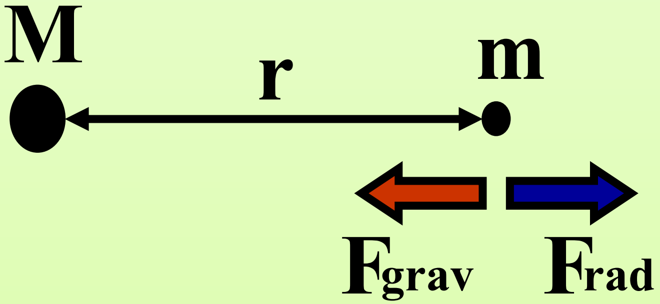
ISCO: $r = 6\frac{GM}{c^2}$

$P_{orb} \Rightarrow r_{ISCO} \Rightarrow M_{NS} \Rightarrow$ NS-EOS

The Eddington limit

- There is a limit to the luminosity that can be produced by a given object, known as the *Eddington luminosity*.



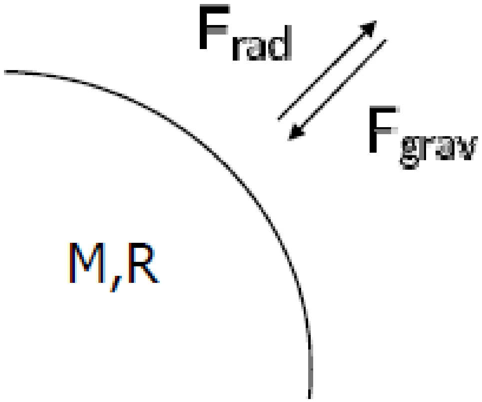


At this limit the inward gravitational force on the accreting matter is balanced by the outward transfer of momentum by the accretion luminosity

The Eddington luminosity

Fully ionised plasma: only Thomson scattering

Radiation exerts force on electrons via Thomson scattering
Cross-section of protons is a factor $(m_e/m_p)^2 \sim 2.5\text{x}10^{-7}$ smaller



Radiation force: $F_{rad} = \frac{\sigma_T F_{lux}}{c}$

Gravitation: $F_{grav} = \frac{GMm}{R^2}$

Thomsom cross-section:

$$\sigma_T = 6.65 \times 10^{-29} \text{m}^2$$

$$\sigma_T = \frac{2}{3}\left(\frac{e^2}{mc^2}\right)^2$$

$$L = 4\pi R^2 F_{lux} \Longrightarrow F_{rad} = \frac{\sigma_T L}{4\pi R^2 c}$$

$$m_p = 1830 m_e \Longrightarrow F_{grav} = \frac{GMm_p}{R^2}$$

$m_p = 1.67 \text{ x } 10\text{-}^{27}\text{kg}$

At the limit (Eddington):

$$F_{rad} = F_{grav} \Longrightarrow \boxed{L_E = \frac{4\pi GMm_p c}{\sigma_T}}$$

$$M = 1M_\odot \Longrightarrow L_E = 1.3 \times 10^{31} \text{Js}^{-1}$$

$$L_E \simeq 1.3 \text{ x } 10^{38} \left(\frac{M}{M_\odot}\right) \text{erg s}^{-1}$$

Eddington limit application 1

- Some thermonuclear bursts are bright enough to exceed the Eddington limit at the peak
- The atmosphere is (temporarily) unbound and will expand, sometimes to very large radii
- Provided the mass range of the neutron stars are small, these events serve as a *standard candle* for distance estimation

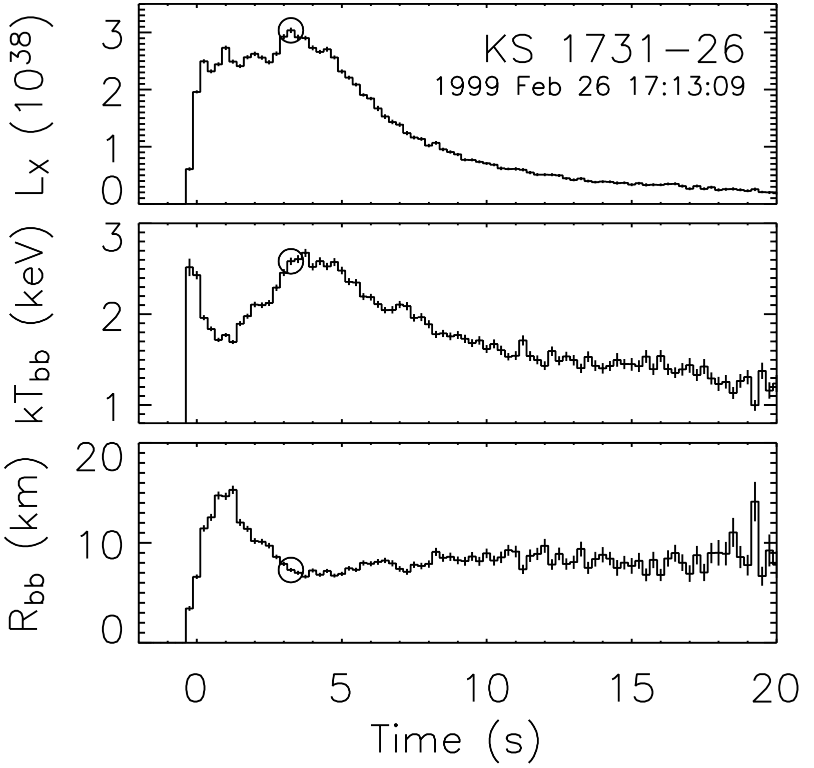


FIG. 2.—Spectral evolution in a thermonuclear burst exhibiting photospheric radius expansion, from KS 1731−26. *Top*: Burst luminosity L_X, in units of ergs s^{-1}; *middle*: blackbody (color) temperature kT_{bb}; *bottom*: blackbody radius R_{bb}. The L_X and R_{Bbb} are calculated at an assumed distance of 7.2 kpc (Table 9). Note the anti-correlation between kT_{bb} and R_{bb} in the first few seconds, indicative of the expanding photosphere, and the approximately constant flux throughout the expansion. The time at which the flux reaches a maximum is indicated by the open circle; by then the radius has declined to the asymptotic value in the burst tail, suggesting that the photosphere has settled ("touched down") on the NS surface.

via the triple-α process, which is moderated by the strong nuclear

Eddington limit application 2

- The Eddington flux, combined with other measurements from bursts, can be used to infer the mass and radius of the neutron star
- This can in turn provide constraints on the neutron star *equation of state*

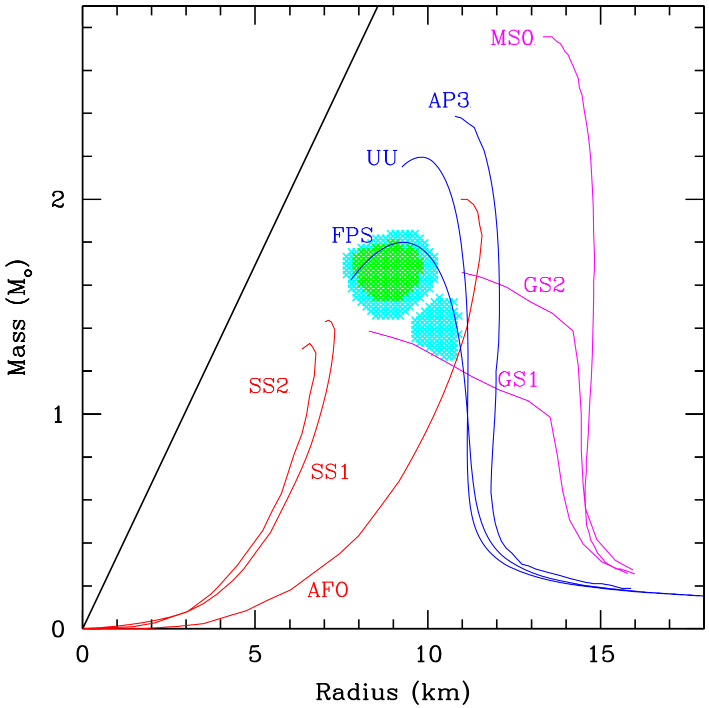


Figure 5. Plot of 1σ and 2σ contours for the mass and radius of the neutron star in EXO 1745−248, for a hydrogen mass fraction of $X = 0$, based on the spectroscopic data during thermonuclear bursts combined with a distance measurement to the globular cluster. Neutron star radii larger than ~ 13 km are inconsistent with the data. The descriptions of the various equations of state and the corresponding labels can be found in Lattimer & Prakash (2001).

(A color version of this figure is available in the online journal.)

Özel, Guver &c, 2006–; see also Steiner et al. 2010

Eddington limit application 3

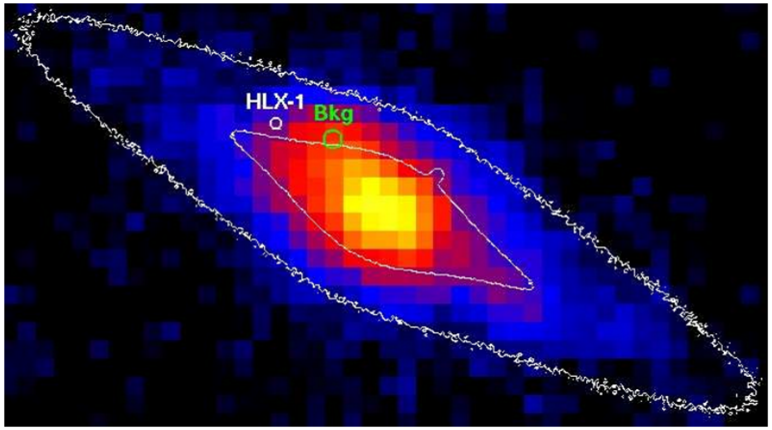


Fig. 3 *Uvw2* image from 150 ks of *Swift* UVOT data. The white contours show the orientation of the galaxy, and the white circle indicates the *Chandra* position of HLX-1. The green circle indicates the position of the background emission-line source (see Figure 5).

Farrell et al. 2009, 2011 etc.

- The growth history of supermassive black holes is basically a mystery
- We know of no intermediates more massive than the stellar-mass black holes in XRBs
- Eddington-limit arguments offer evidence for intermediate-mass BH via ultra- (and even *hyper*-) luminous X-ray sources in other galaxies

X-ray bursters

RXTE PUFFED ACCRETION DISK
VERSION 2 WITH NO WOBBLE

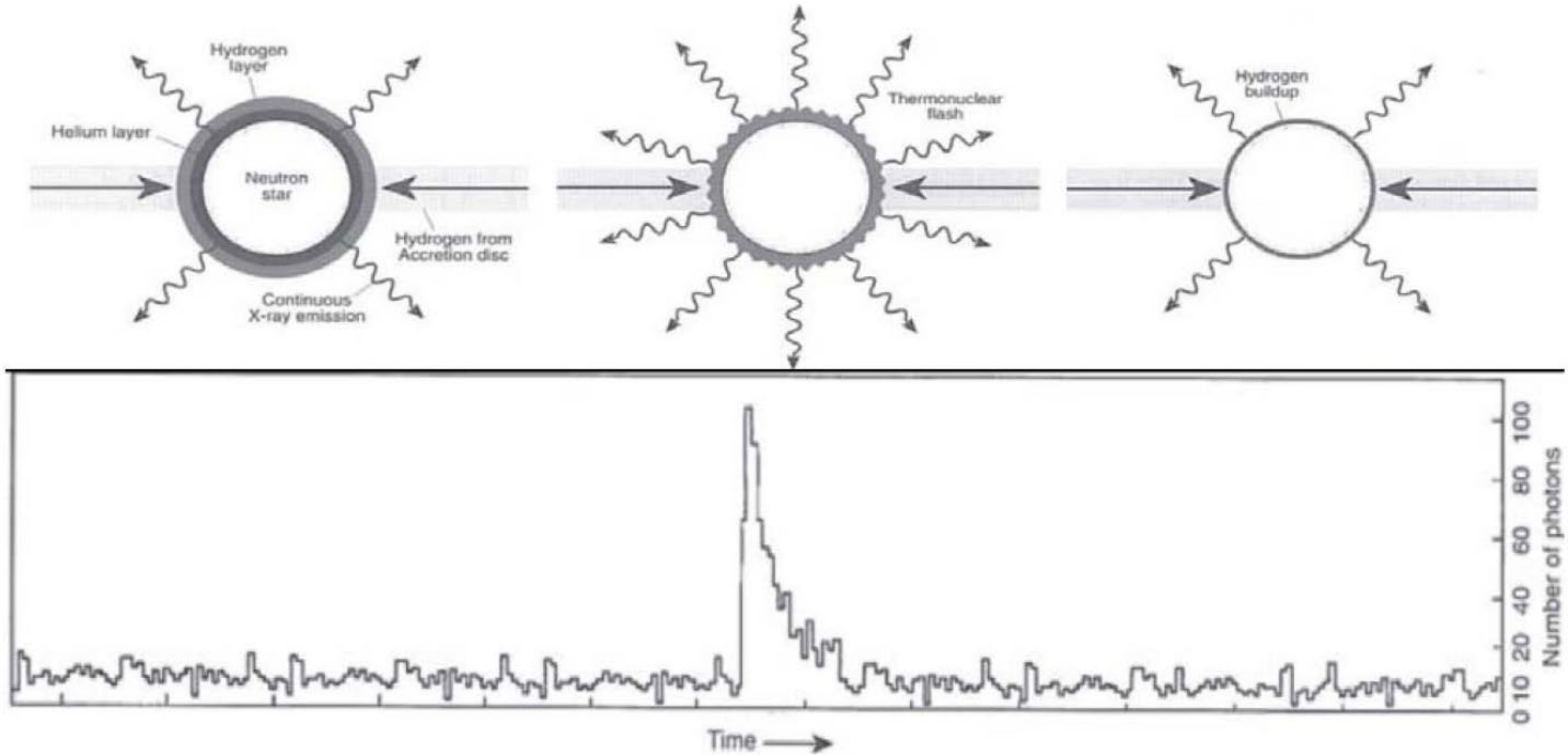
ANIMATION BY

DANA BERRY

SKYWORKS DIGITAL ANIMATION
310-441-1735

X-ray bursts

A recurrent process



Type-I X-ray bursts are thermonuclear explosions in the surface layers of a neutron star accreting H and/or He from a low-mass companion star. Their emission can be described by blackbody radiation with peak temperature ~2 keV and X-ray softening during the (exponential) decay.

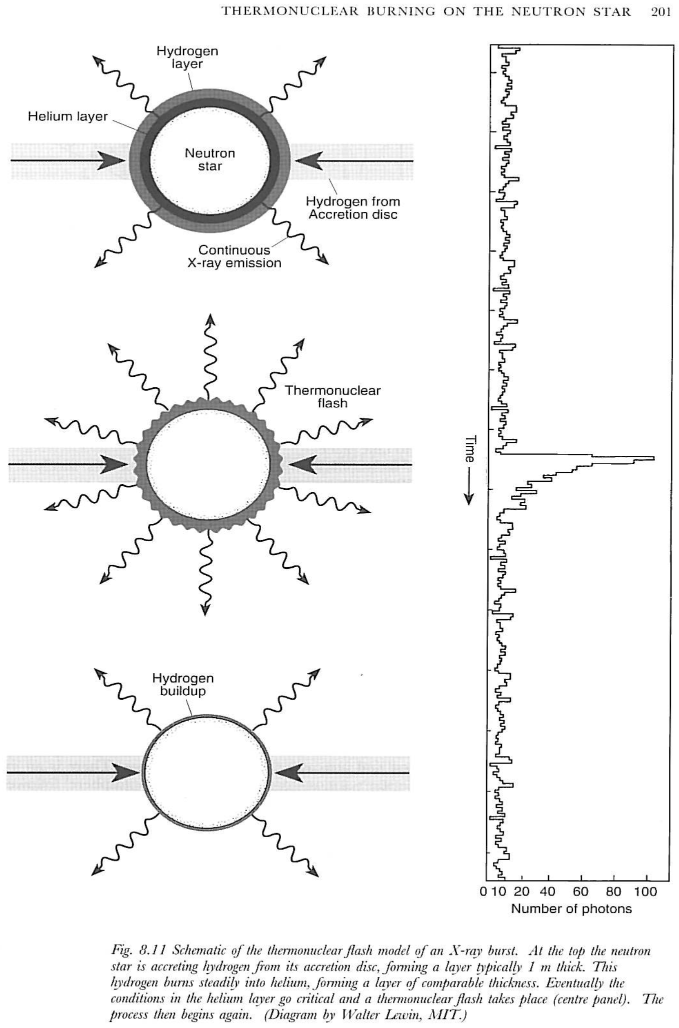


Fig. 8.11 Schematic of the thermonuclear flash model of an X-ray burst. At the top the neutron star is accreting hydrogen from its accretion disc, forming a layer typically 1 m thick. This hydrogen burns steadily into helium, forming a layer of comparable thickness. Eventually the conditions in the helium layer go critical and a thermonuclear flash takes place (centre panel). The process then begins again. (Diagram by Walter Lewin, MIT.)

TYPE I

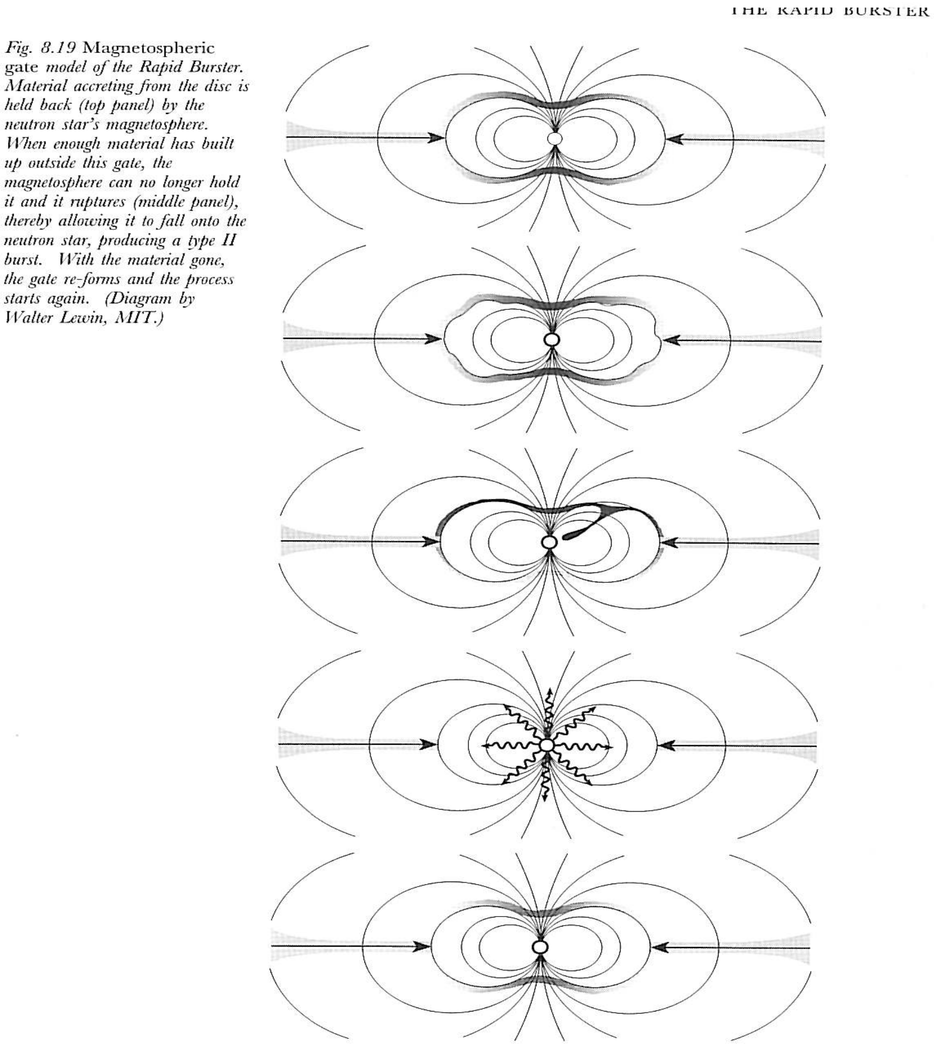


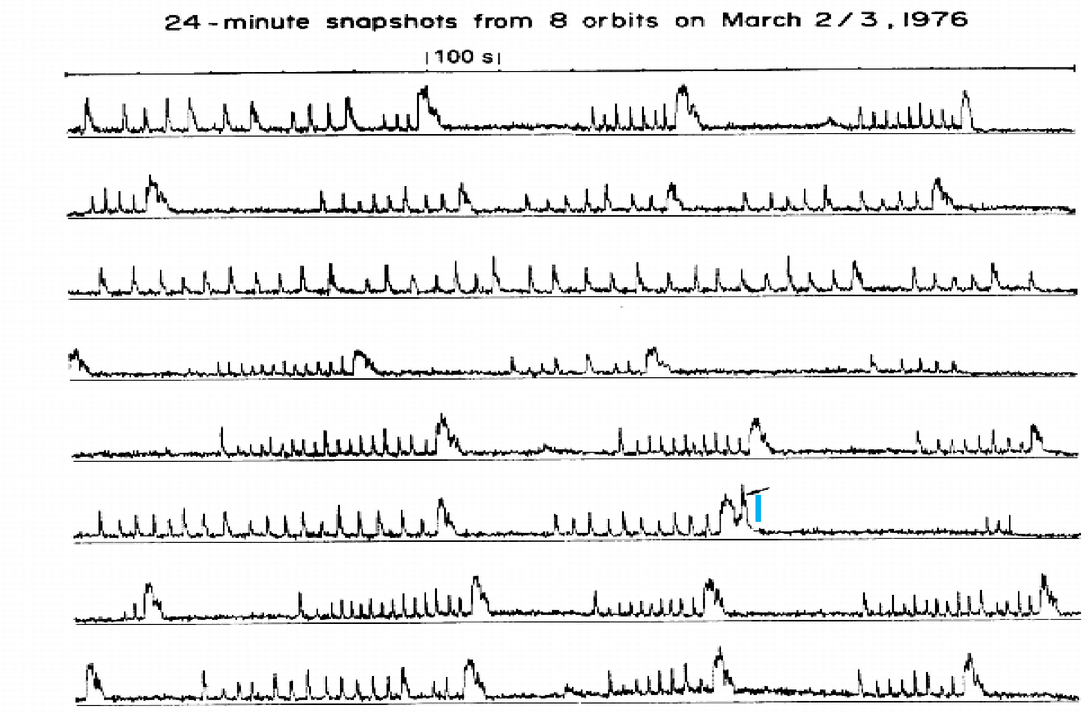
Fig. 8.19 Magnetospheric gate *model of the Rapid Burster. Material accreting from the disc is held back (top panel) by the neutron star's magnetosphere. When enough material has built up outside this gate, the magnetosphere can no longer hold it and it ruptures (middle panel), thereby allowing it to fall onto the neutron star, producing a type II burst. With the material gone, the gate re-forms and the process starts again. (Diagram by Walter Lewin, MIT.)*

TYPE II

Type-II X-ray bursts: not thermonuclear

Only 2 Type-II X-ray bursters known so far:
MXB 1730-335 (Rapid Burster) and the Bursting Pulsar GRO J1744-28 (no type I).

Rapid Burster

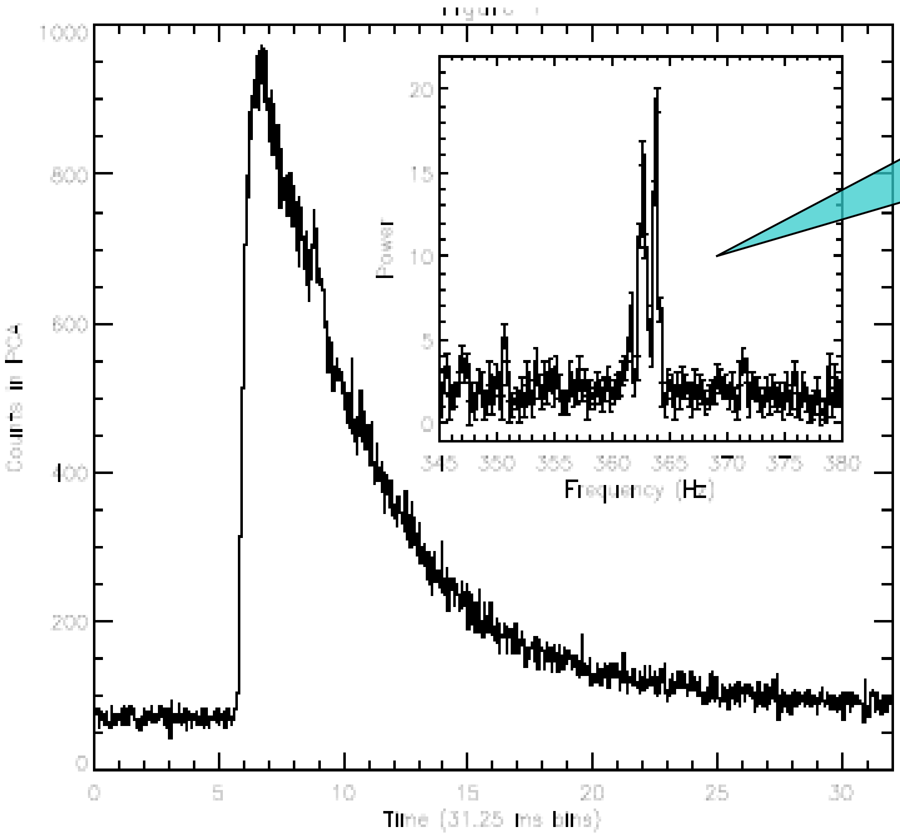


(Lewin et al., 1995, Fig. 4.19)
Bursting of the "Rapid Burster" 1730—-335: Type I and Type II bursts.

Type II bursts: magnetospheric gate model: B-field blocks accretion until gas pressure $>$ magnetic pressure $\Longrightarrow$ BOOM.

Black Holes have no surface $\Rightarrow$ no X-ray bursts!

X-ray burst oscillations

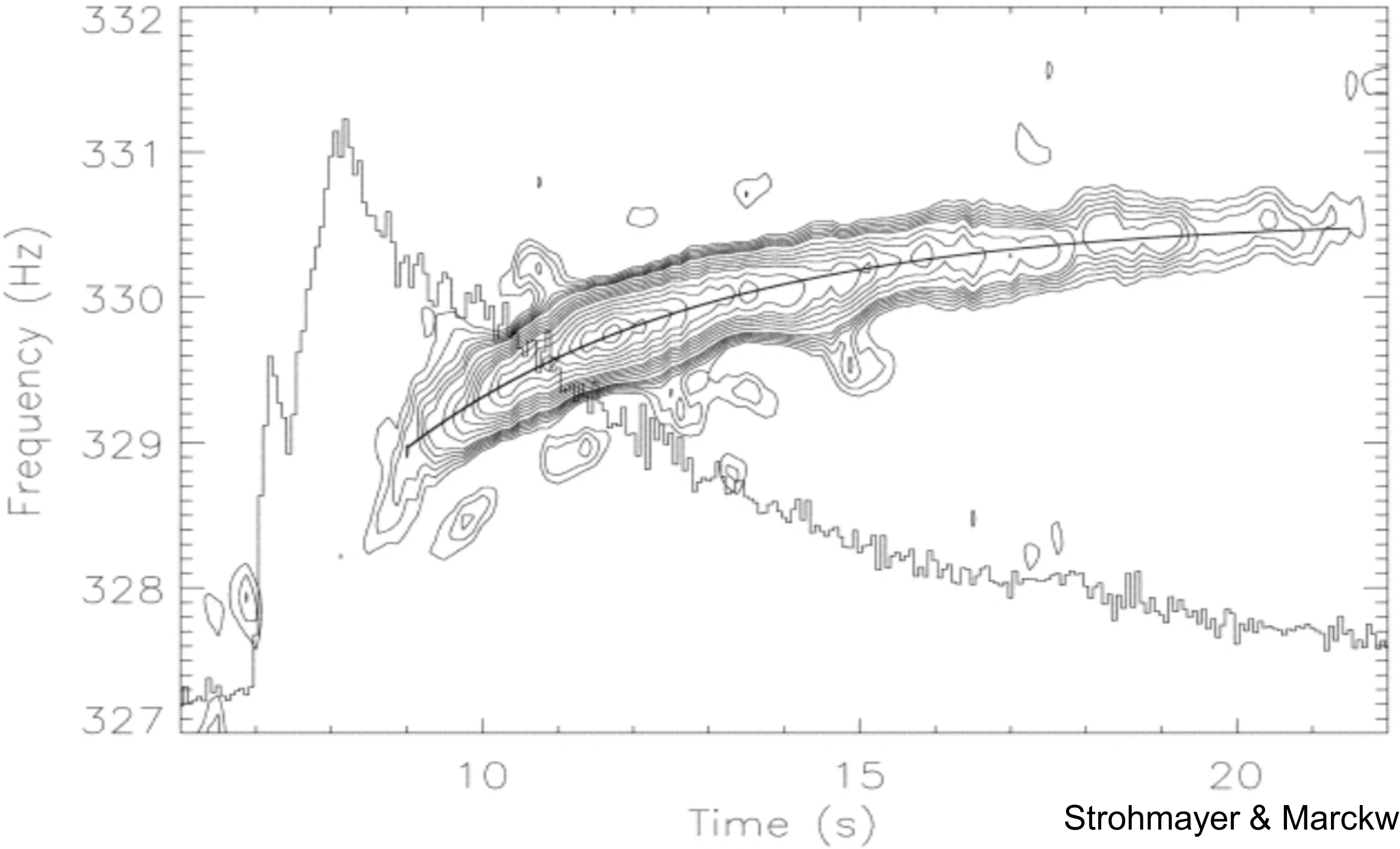


Power spectrum showing millisecond variability during X-ray bursts

Fig. 3.6. An X-ray burst from 4U 1728–34 observed with the PCA onboard RXTE. The main panel shows the X-ray counts observed by the PCA in (1/32) s bins. The inset panel shows the power spectrum in the vicinity of 363 Hz (after Strohmayer et al. 1996).

X-ray burst power spectra sometimes show millisecond variability corresponding to the neutron star spin frequency, thus indicating a local asymmetry on the surface of the neutron star during the burst.

X-ray burst oscillations

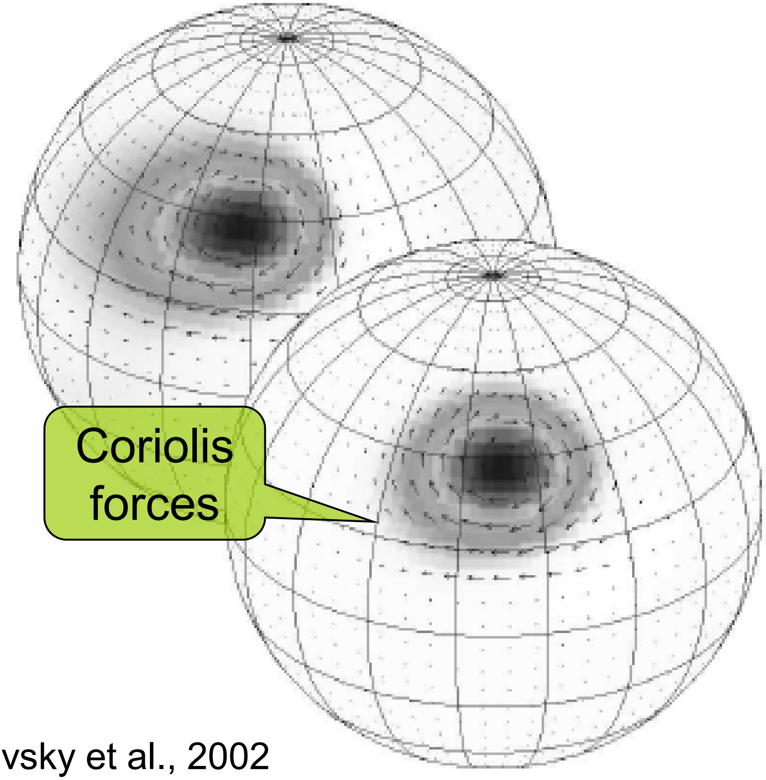


Strohmayer & Marckwardt, 1999)

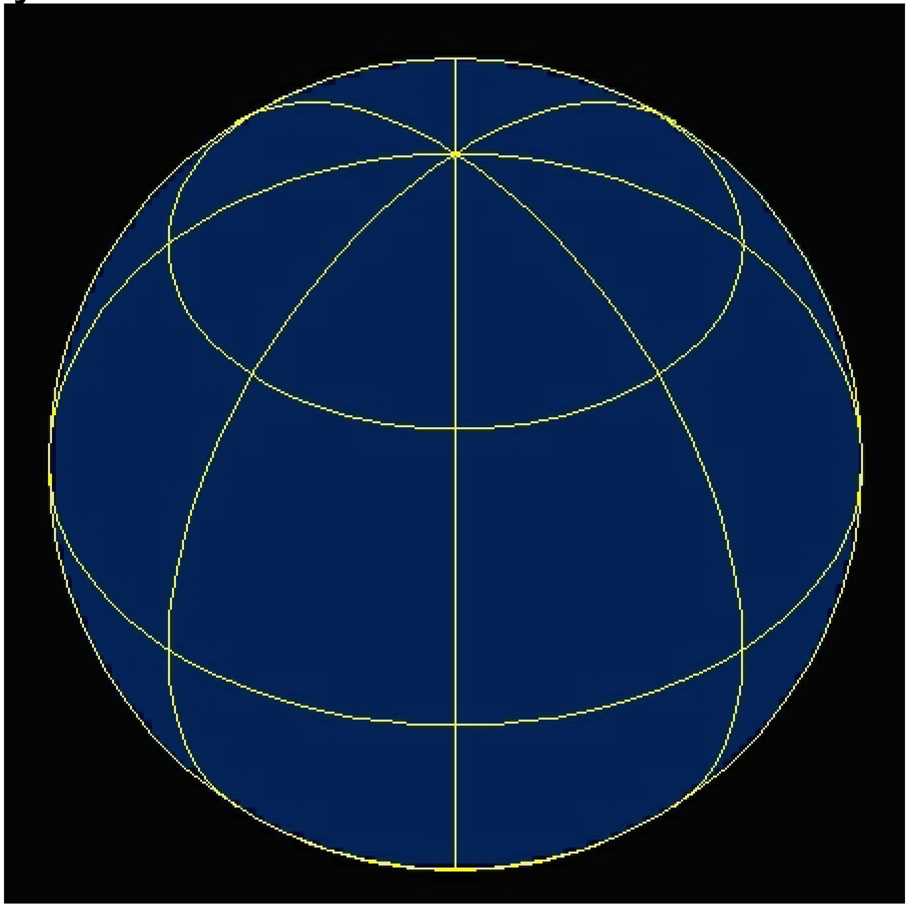
Slight variations in burst oscillation frequency during the tail may be related to atmospheric motion and/or spreading on the neutron star surface, but not all burst oscillations show a consistent picture.

Spin modulation

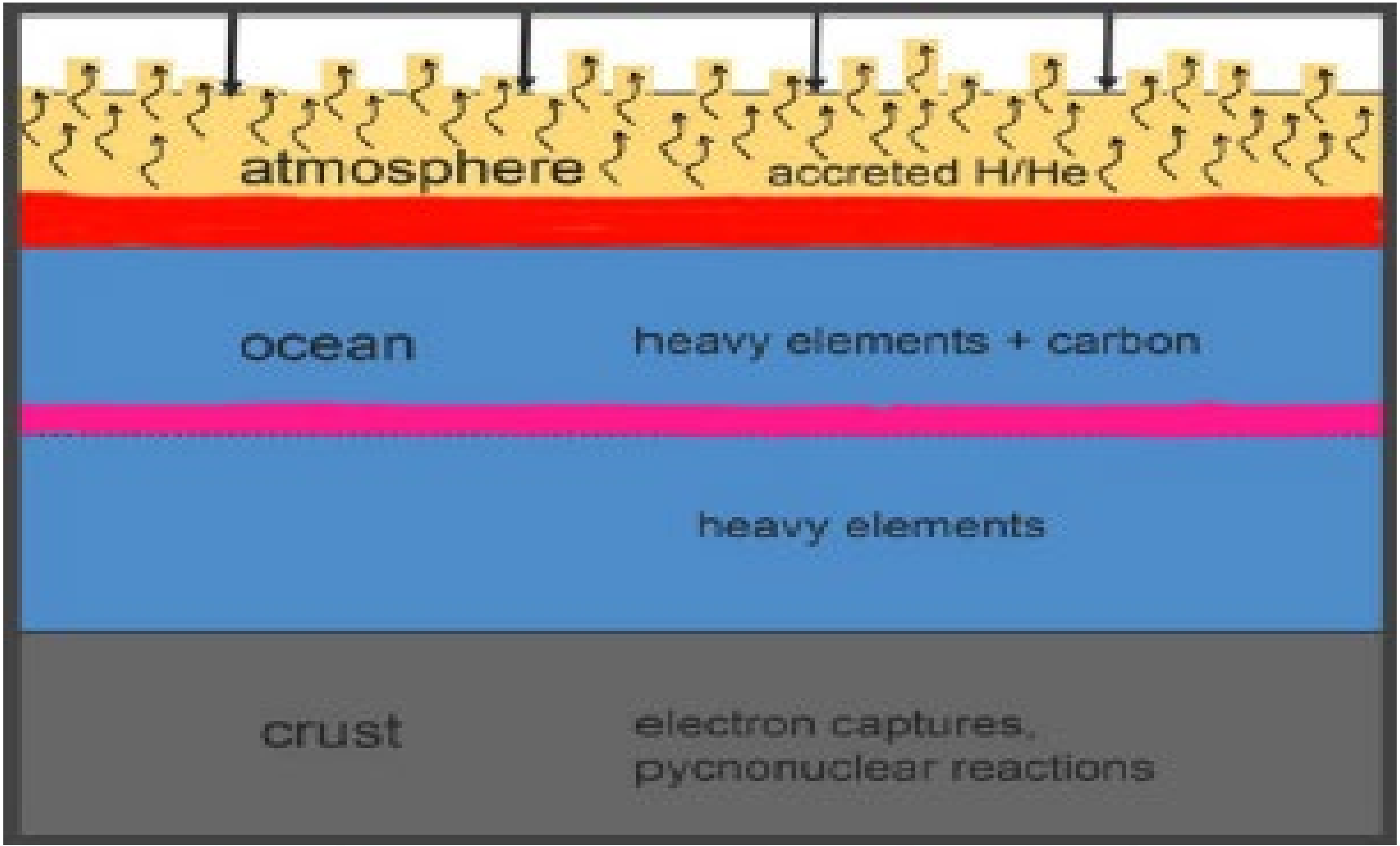
Burst oscillations are associated with a hot spot expanding on the NS surface like a deflagration flame and modulated by the NS rotation. The modulation drops as spot grows. The frequency drift seems associated to the burning layer elevation.



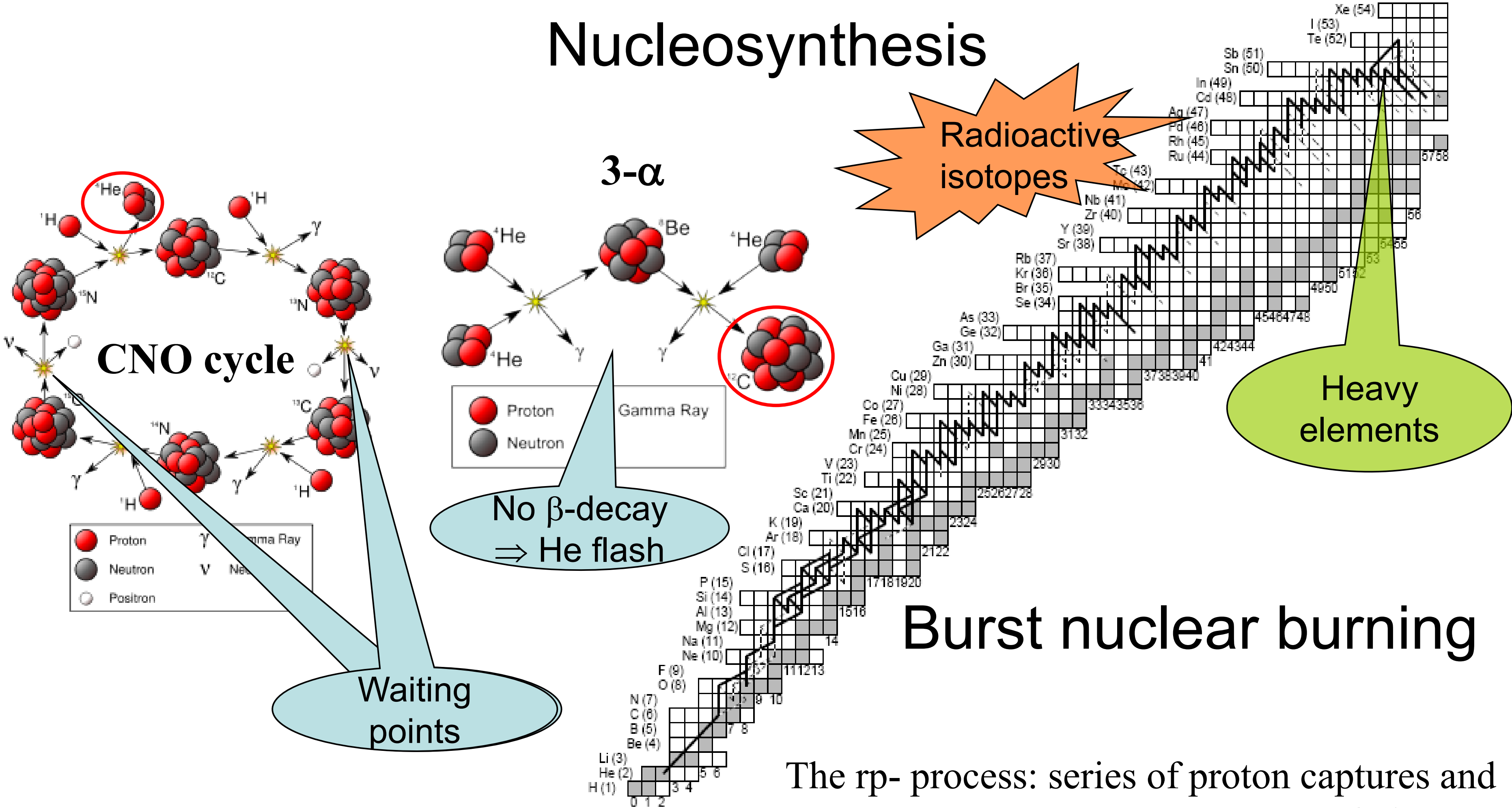
Spitovsky et al., 2002



History of an accreted fluid element



Nucleosynthesis



CNO cycle

3-α

Radioactive isotopes

Heavy elements

Waiting points

No β-decay
⇒ He flash

Burst nuclear burning

The rp- process: series of proton captures and β decays.

Fig. 3.1. Schematic showing the dominant pathways of the nuclear reaction flows during the rp process. Elements far beyond ^{56}Fe can easily be reached. Filled squares denote stable nuclides (after Schatz et al. 2001).

Burst energetics

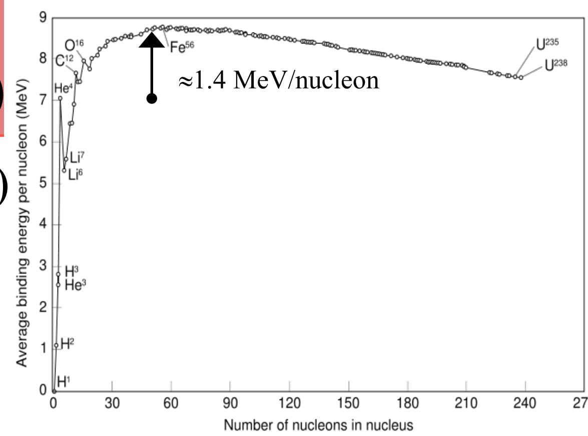
Nuclear energy vs. gravitational energy

⇓

Relationship between accretion and thermonuclear burning processes

Energy of accretion: $E_{grav} = \dfrac{GM_{NS}m_p}{R_{NS}} \approx 200\mathrm{Me}$` nucleon

Energy release of nuclear burning to heavy elements is
≈ 1.4 MeV/nucleon for pure He (X≈0) and
≈ 5.6 MeV/nucleon for solar composition (X≈0.7)



$E_{nuc} \approx 1.35 + 6.05X$ MeV/nuc (Goodwin, Heger, Galloway, 2019)

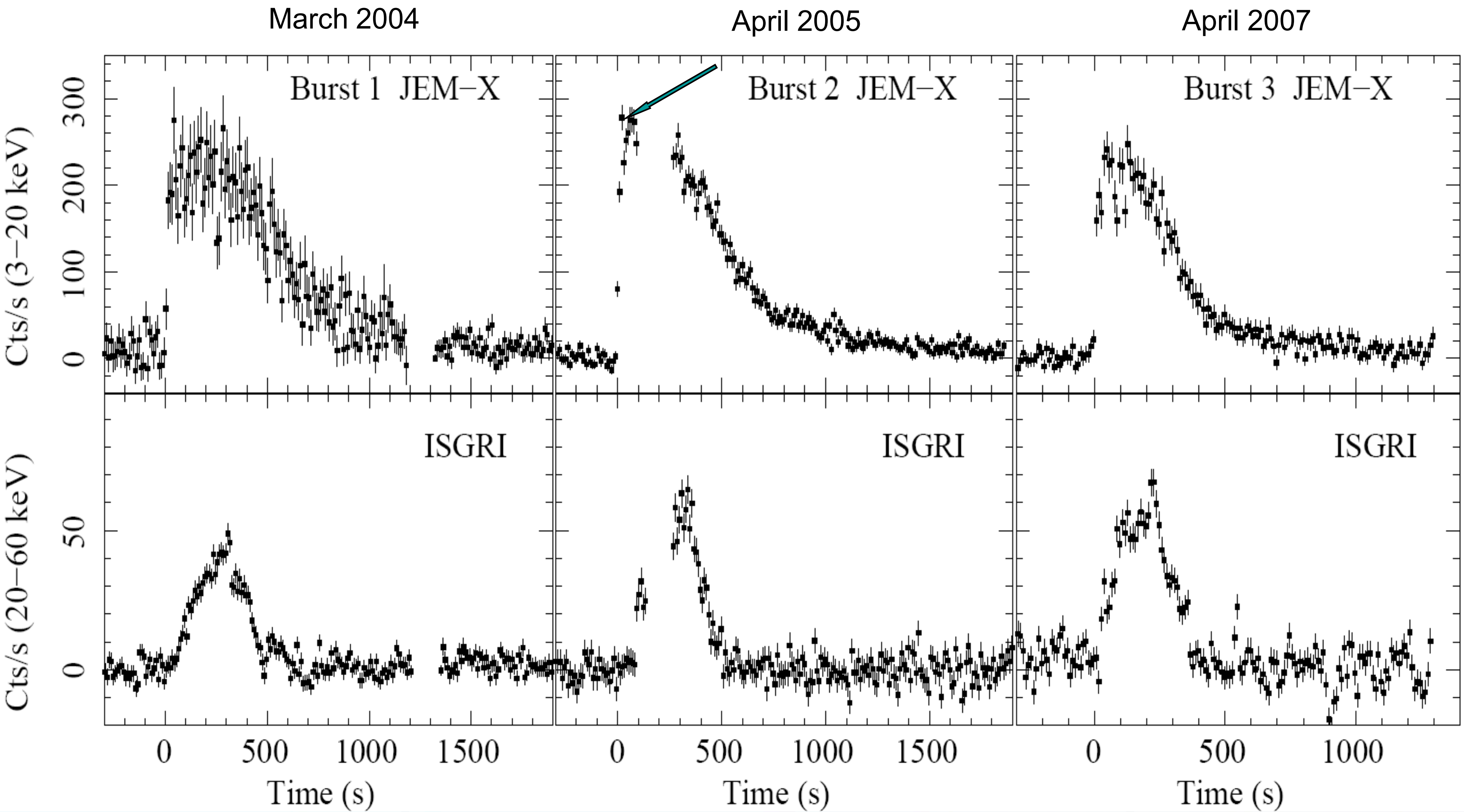
$$\alpha = \frac{E_{grav}}{E_{nuc}} = \frac{F_{pers}}{\mathbf{F}_b}\Delta t \approx 30 \sim 200$$

<50 : mostly H
>50 : mostly He

⇒ Ineffective process compensated by accumulation

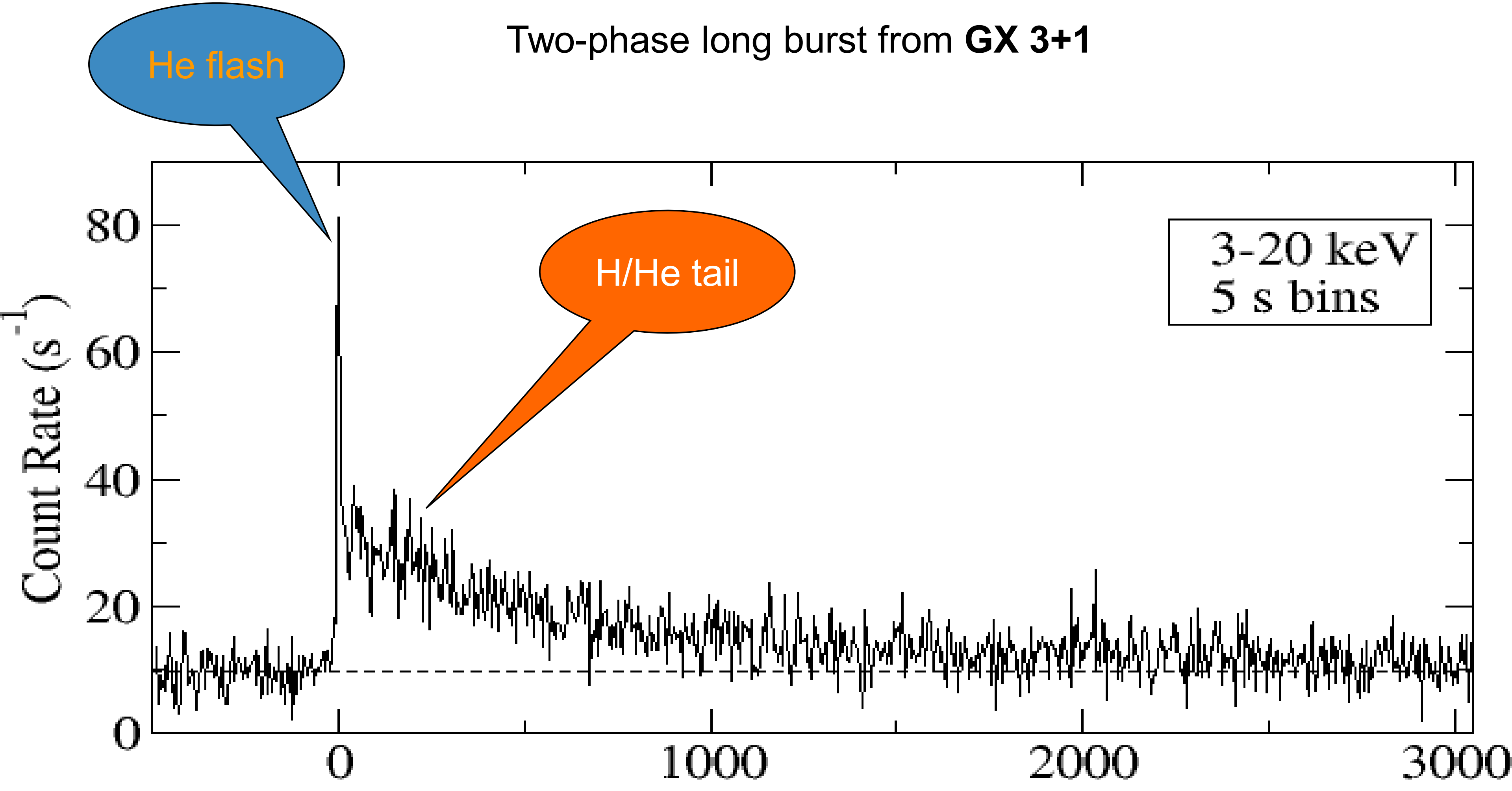
Relationship between accreted material and burning regimes

Intermediate long bursts from SLX 1737-282 (Falanga, Chenevez et al., 2008)



Intermediate burst

Two-phase long burst from **GX 3+1**



Chenevez et al., 2006

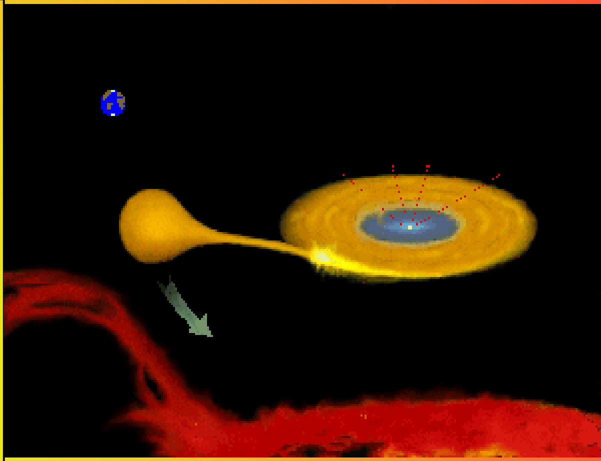
Intermediate long bursts

Only ≈70 bursts have shown a duration of a few tens of minutes

Most intermediate bursts are observed from low luminosity sources and are interpreted as long pure He bursts. If no H is accreted, they are consistent with the burning of a slowly accreted, thick He layer, in **Ultra Compact X-ray Binaries (UCXB)** where the donor star is probably a degenerated helium white dwarf.

Unusually long bursts seem generally to be associated with mixed H/He burning at low accretion rate. Depending on the actual accretion rate, either the burning of a large amount of H is triggered by an He flash, or a large column of "sedimented" He is triggered by H ignition.

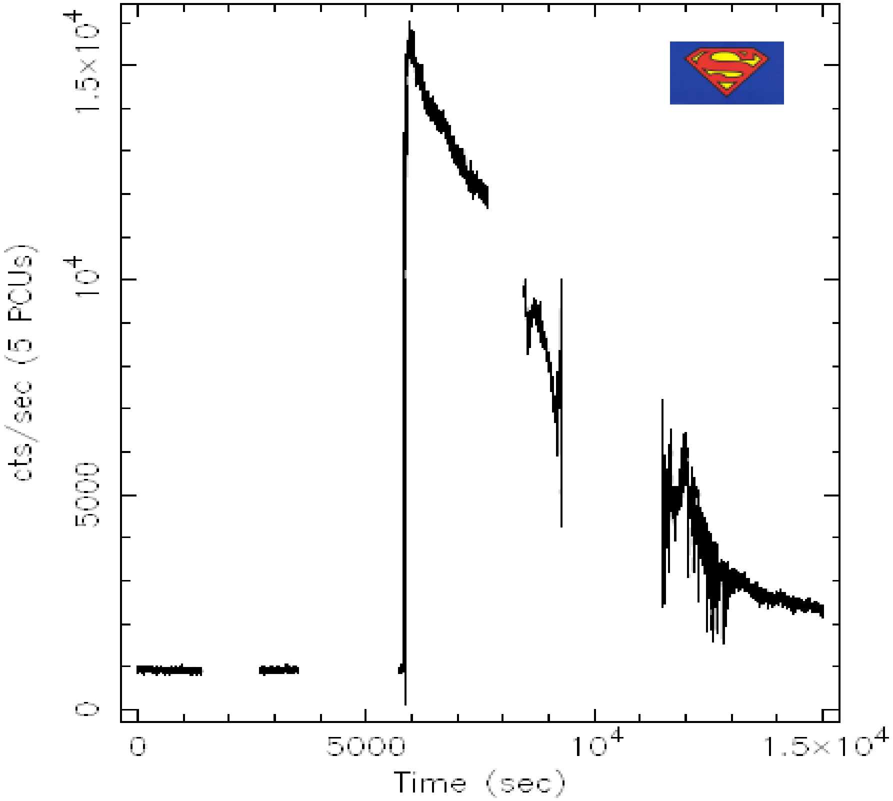
(Two phase burst from GX3+1: aborted superburst due to the premature ignition of a carbon layer triggered by an He detonation may also be considered.)



Superbursts

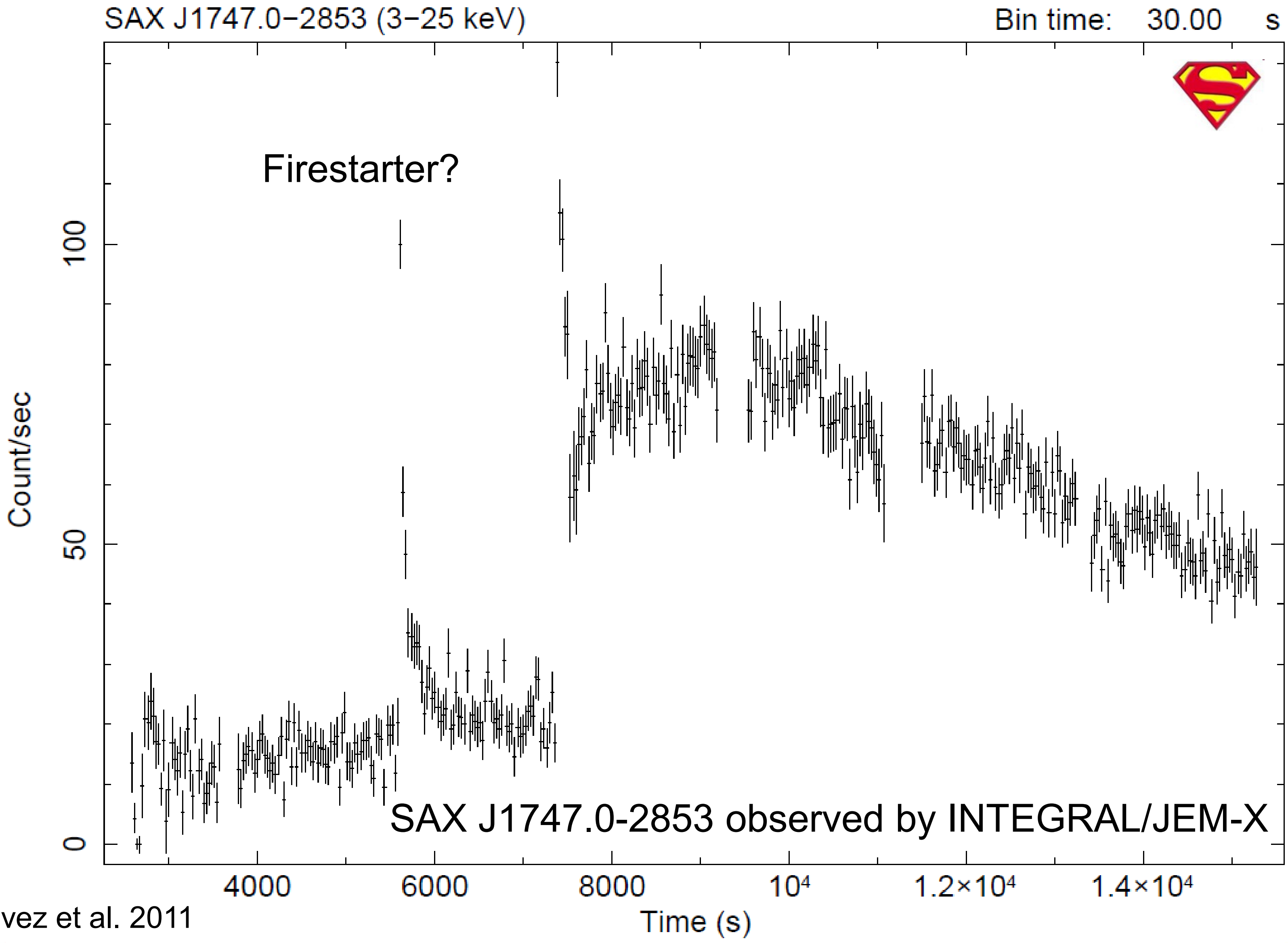
Compared to normal type I X-ray bursts, superbursts are ~1000 times more energetic ($E_b \approx 10^{42}$ ergs), ~1000 times longer (from hours to half a day), and have recurrence times of the order of years. They are very rare, only 25 such events having been found from 10 sources.

Superbursts display the same properties as usual X-ray bursts.
They are thought to arise from Carbon shell flashes in the sub-layers where heavy elements have previously been produced through the occurrence of H/He bursts. Their long duration is explained by their depth below the surface.



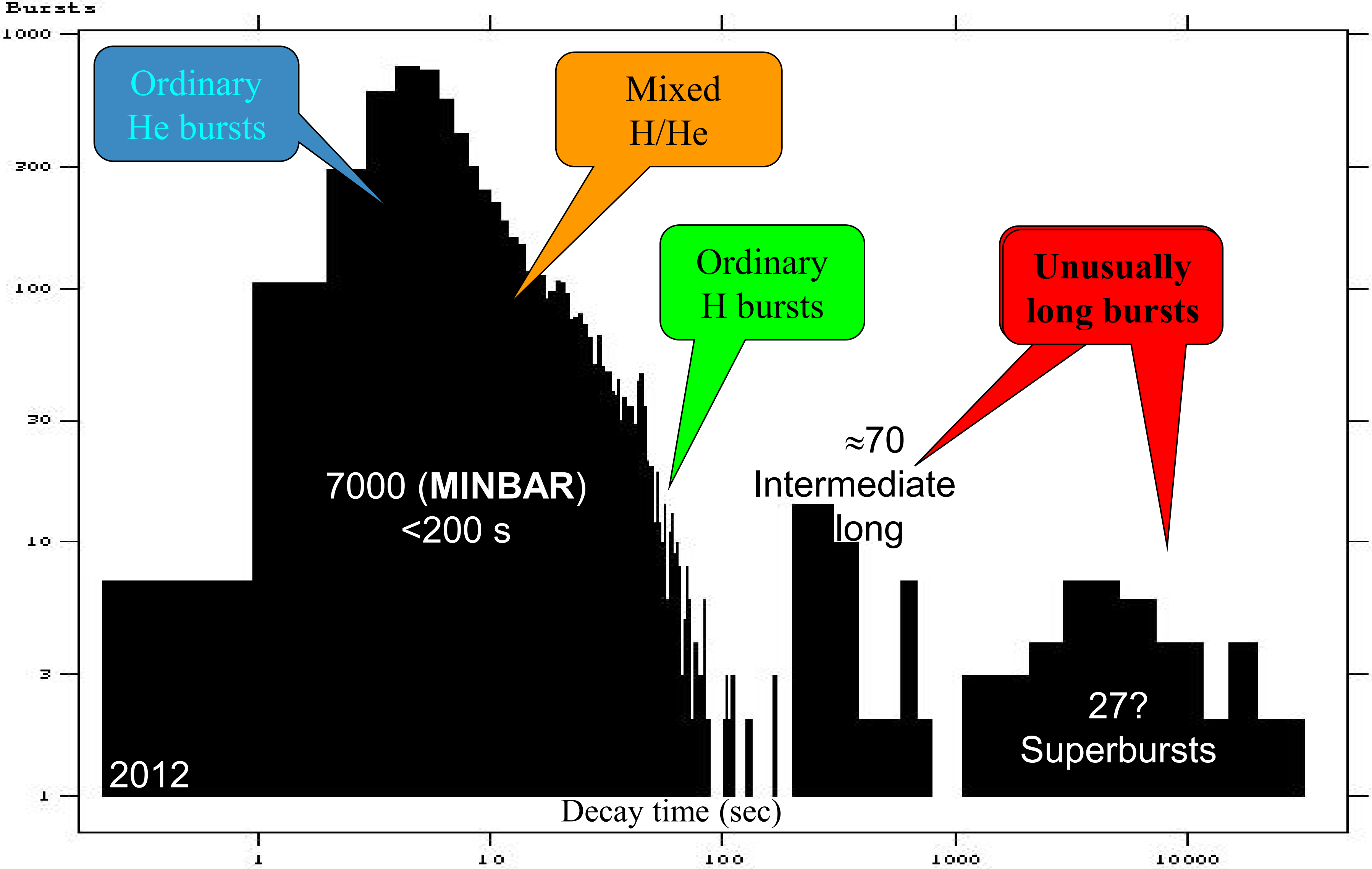
Superburst from 4U 1820-30 on 9/9/1999 (Kuulkers, 2003)

Superburst on 13 February 2011



Chenevez et al. 2011

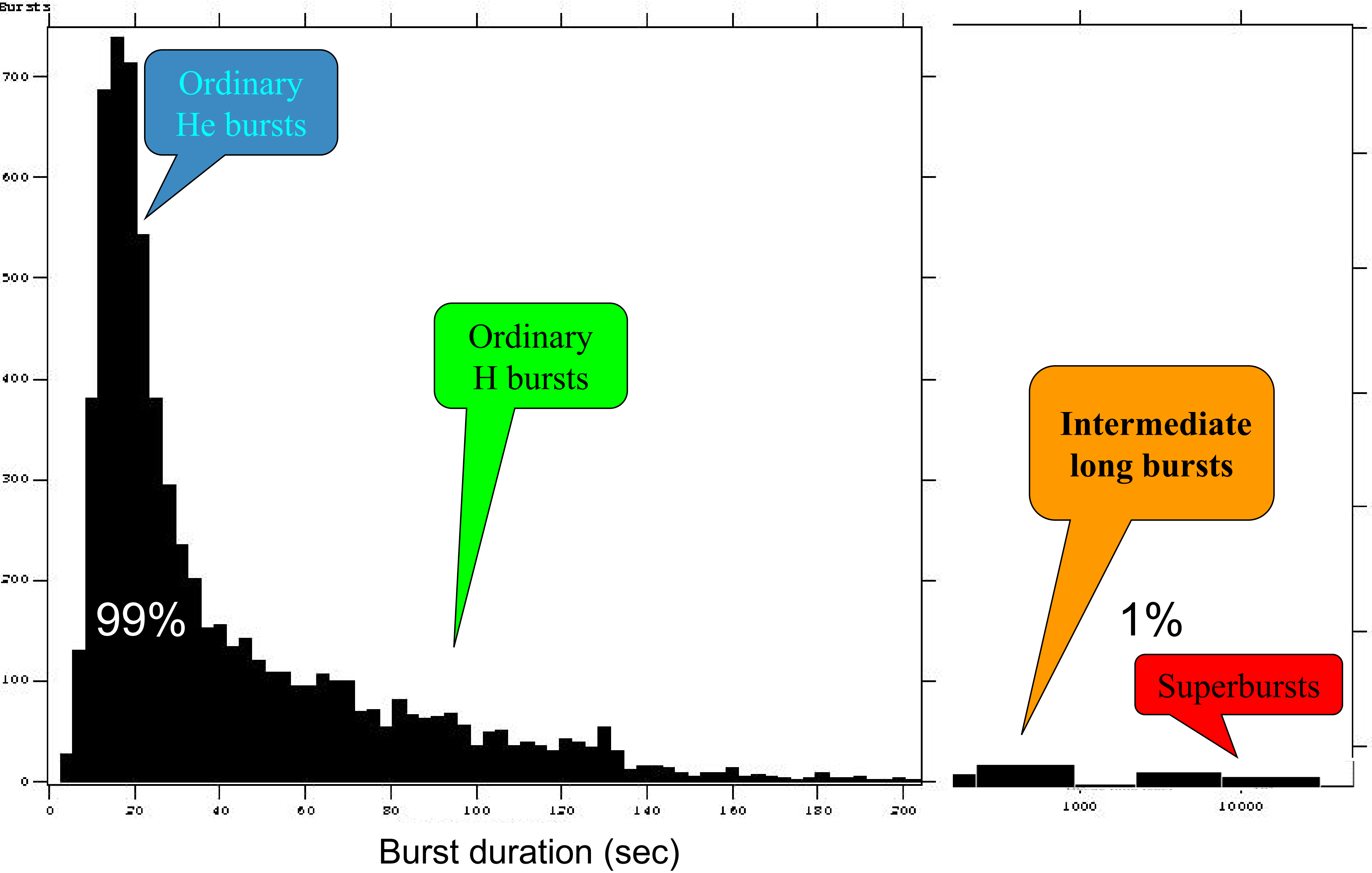
More or less long bursts



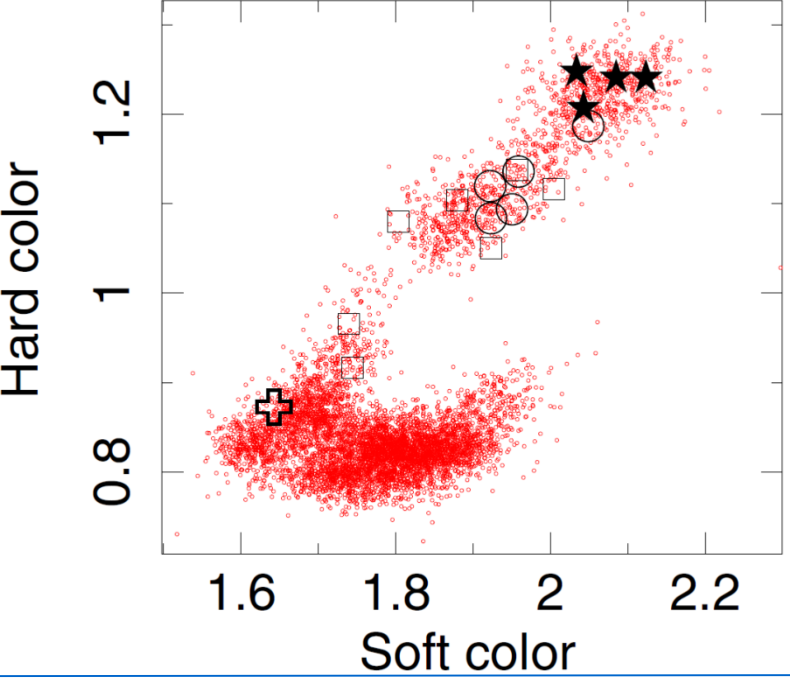
Distribution of the X-ray bursts as a function of their exponential decay time

Toward a continuous spectrum?

Histogram of MINBAR 7000 short *duration* bursts

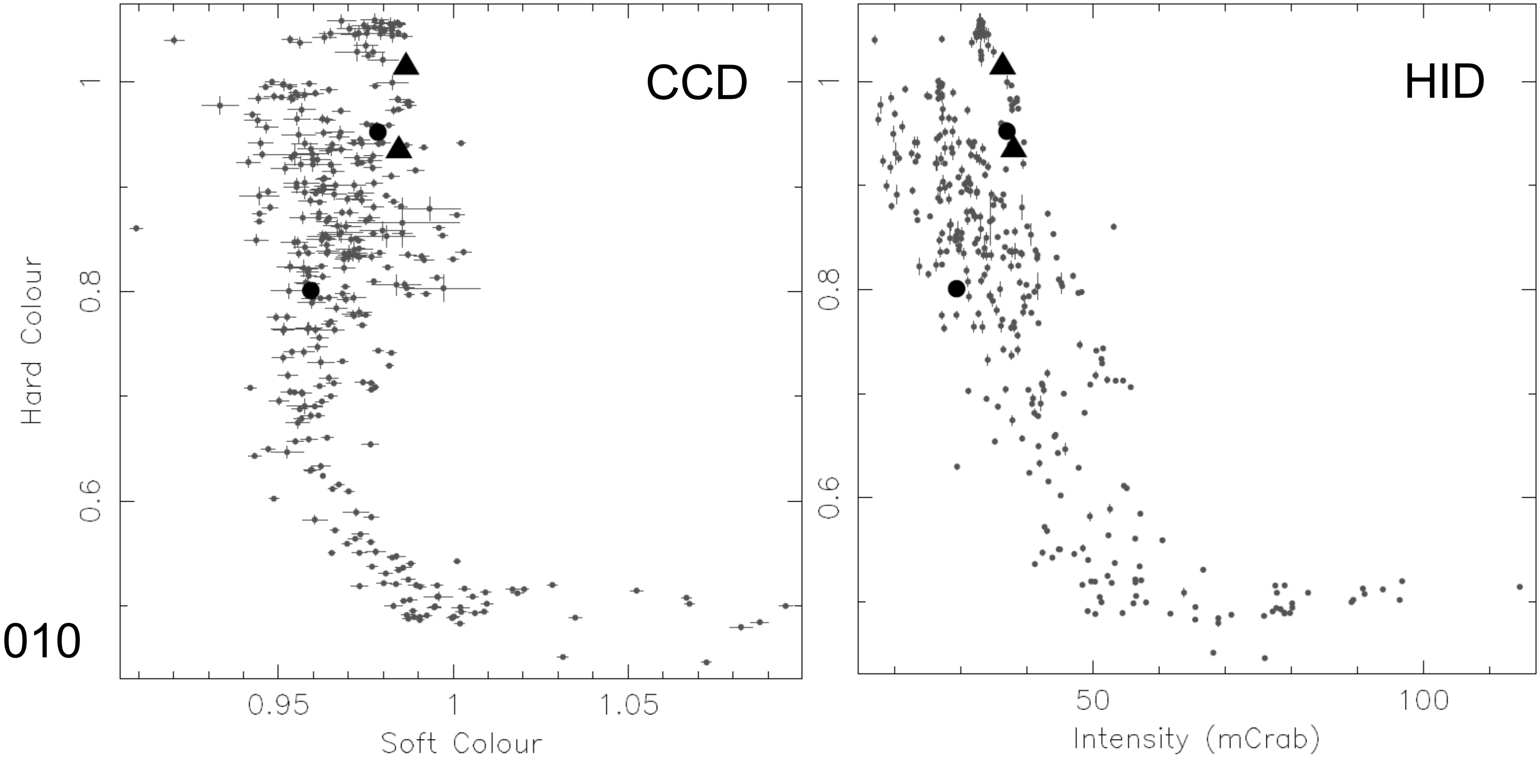


Bursts spectral state dependency



★ PRE
✙ Superburst

4U 1820-30: in ‘t Zand et al. 2012

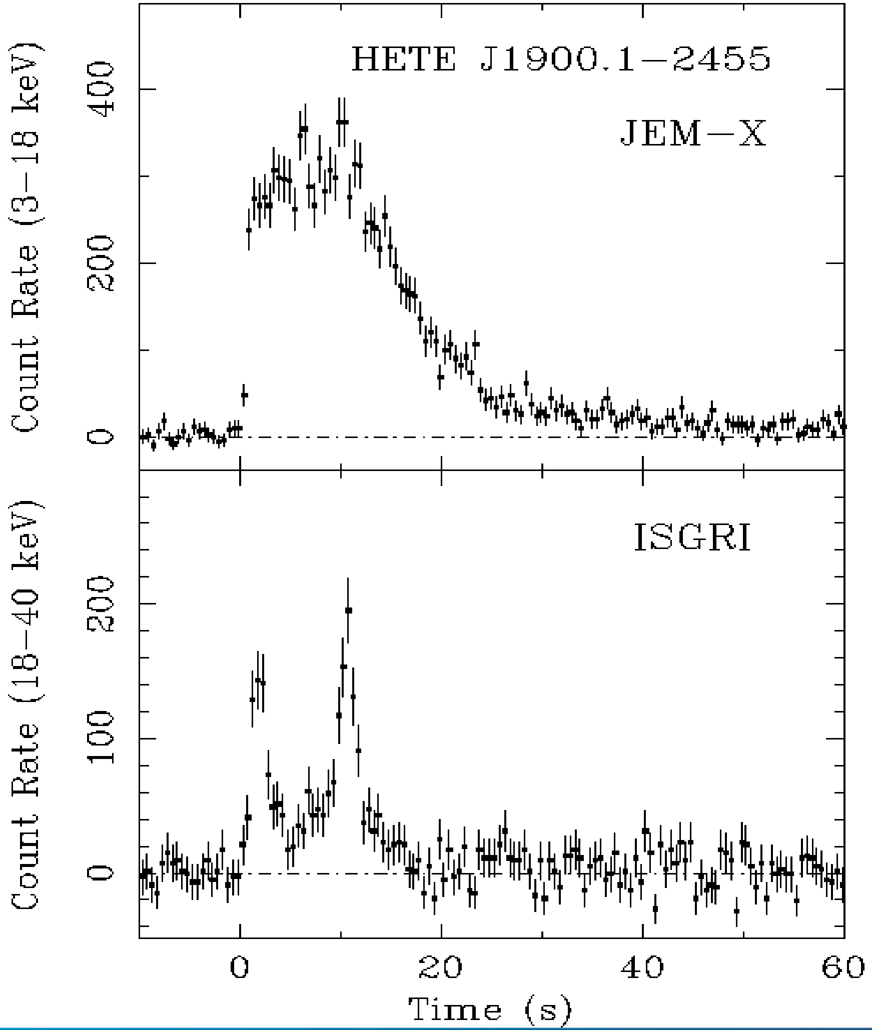


4U 0614+09:
Kuulkers et al. 2010

Photospheric Radius Expansion

PRE

PRE burst from INTEGRAL light-curves (Falanga et al., 2006)



Recall: the Eddington Limit

For any luminous object, there is a maximum luminosity beyond which radiation pressure will overcome gravity, and material outside the object will be forced away from it rather than falling inwards.

- Eddington luminosity

$$L_{Edd} = \frac{4\pi c G M m_p}{\sigma_e} = 1.3\times 10^{38}\left(\frac{M}{M_{sun}}\right) erg\cdot s^{-1}$$

- Eddington temperature

Stefan-Boltzmann: $T_{Edd} = \left(\frac{L_{Edd}}{4\pi R_{NS}^2 \sigma}\right)^{1/4}$ Peak Temperature (at “touchdown”):

- Eddington accretion rate

$\dot{M}_{Edd} =$ $M_\odot\ \mathrm{yr}^{-1}$

Per unit area: $\dot{m}_{Edd} =$ $\mathrm{g\ cm^{-2}\ s^{-1}}$

Eddington Luminosities

For pure H : $L_{Edd} = 1.3 \cdot 10^{38} \times \frac{M}{M_\odot} \, \mathrm{erg/s}$

For Solar composition: $L_{Edd} = 1.7 \cdot 10^{38} \times \frac{M}{M_\odot} \, \mathrm{erg/s}$

For pure He: $L_{Edd} = 2.7 \cdot 10^{38} \times \frac{M}{M_\odot} \, \mathrm{erg/s}$

Observationally (bursts in globular clusters) : $L_{Edd} \approx 3.8 \times 10^{38}$ erg/s (Kuulkers et al. 2003)

Application

- X-ray bursts as standard candles: if $L = L_{Edd} \Rightarrow d$ thanks to flux conservation

$$L \leq L_{Edd} \Leftrightarrow 4\,\pi\, d^2\; F \leq L_{Edd}$$

$$\Leftrightarrow d \leq \sqrt{\frac{L_{Edd}}{4\pi\, F}}$$

: upper limit to distance

Investigation method

Time-resolved spectral analysis

- Standard method: modelling of the *net* burst emission by blackbody (BB)
- 2-component method: modelling of the total burst emission by BB+PL
  (PL is fixed by pre-burst “persistent” emission)
- New method: impact of the burst on the accretion flow is accounted for
  by a variable factor (f_a): BB + $f_a \times$PL

Blackbody emission from a neutron star

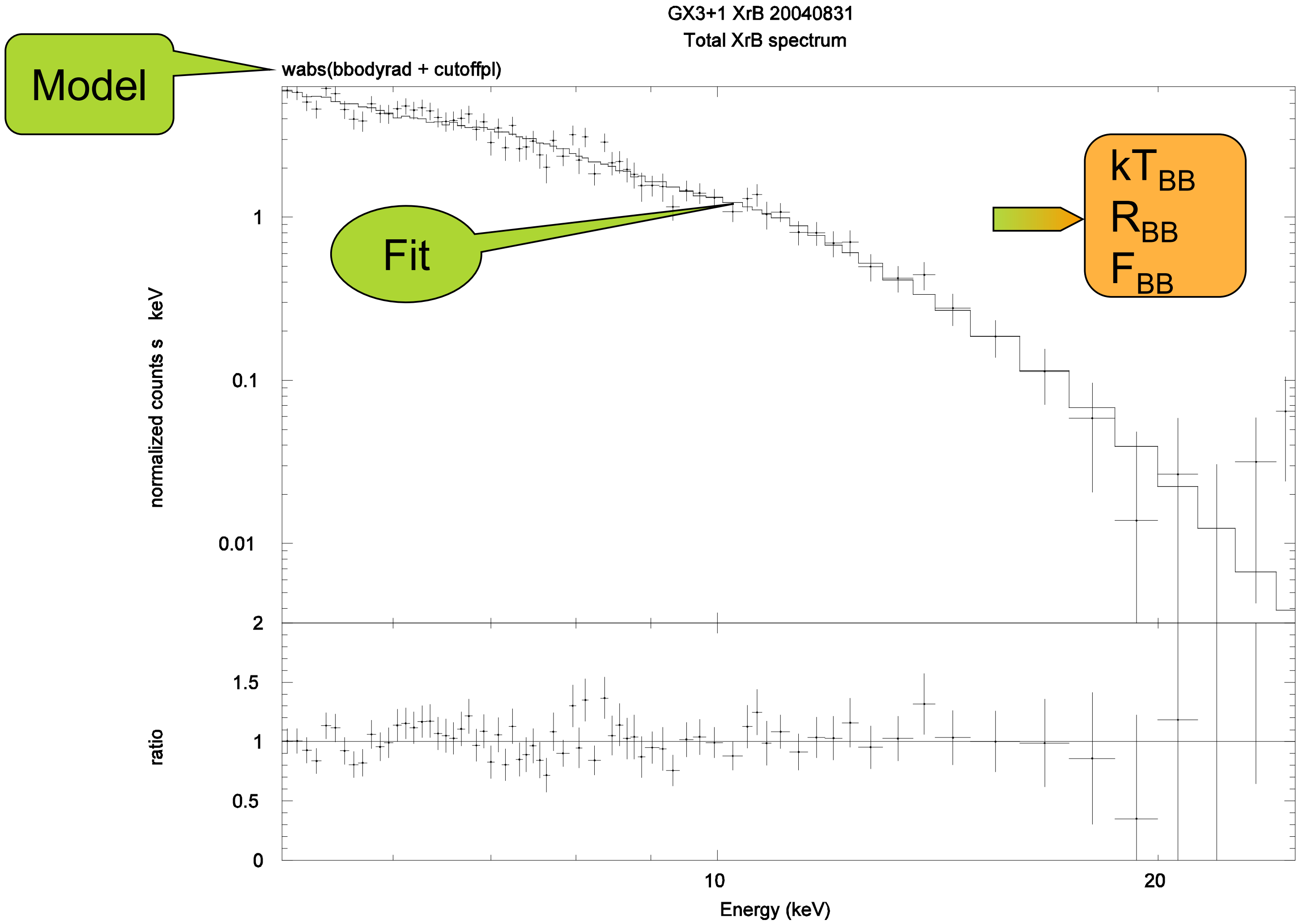
Flux conservation: $L_{emi} = \Phi_{obs}$

$$\Leftrightarrow 4\pi R_{BB}^{2} \sigma T_{eff}^{4} = 4\pi d^{2} F_{BB}$$ (Stefan-Boltzman's law)

$$\Leftrightarrow R_{BB} = \frac{d}{T_{eff}^{2}} \sqrt{\frac{F_{BB}}{\sigma}}$$

Caveats:

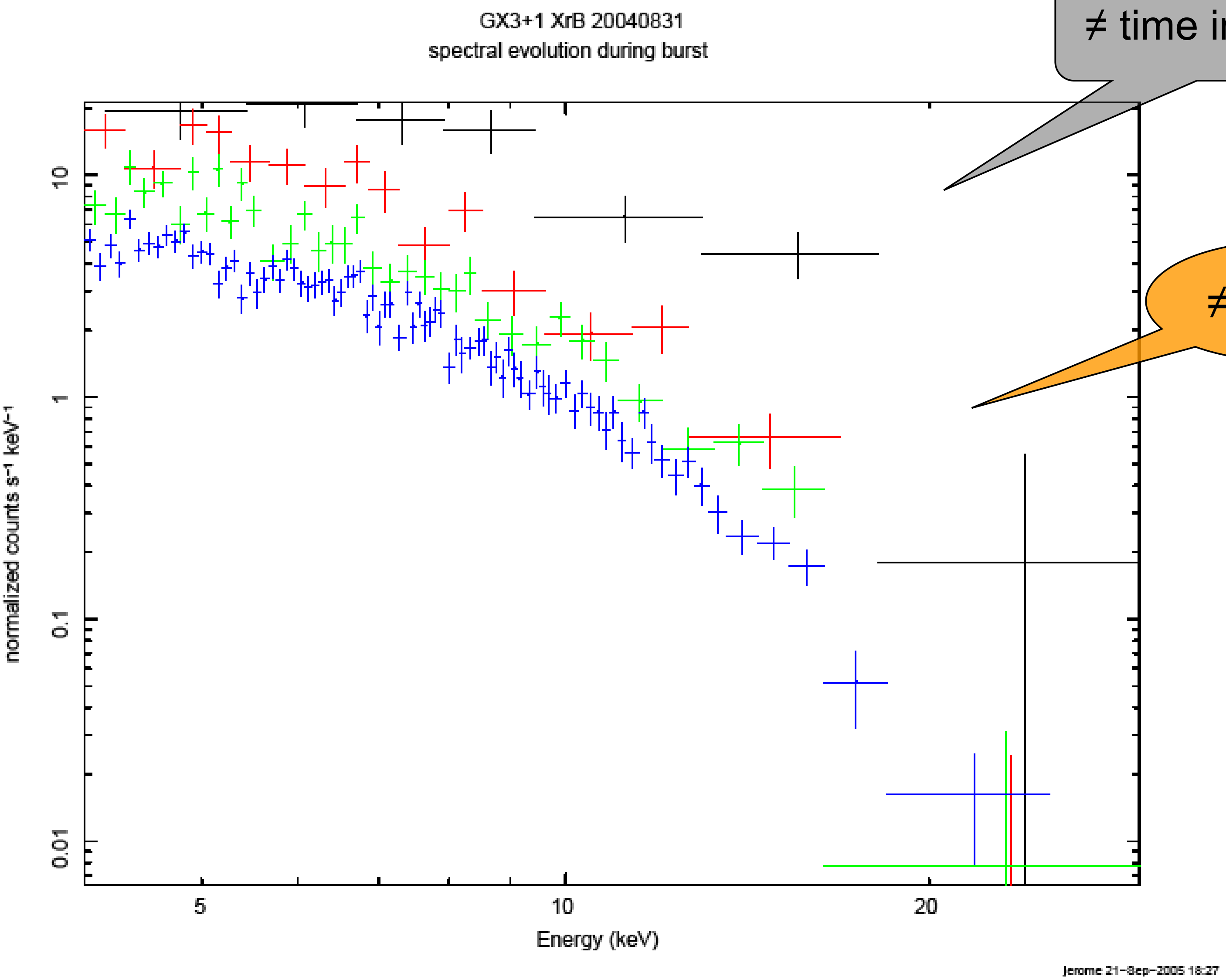
- Burst emission is assumed isotropic (ξ=1)
- Gravitational redshift effects $\begin{cases} L = L_{\infty}(1+z)^{2} \\ T = T_{\infty}(1+z) \\ R = R_{\infty}(1+z)^{-1} \end{cases}$
- What is actually observed is a "colour temperature"…



Model

Fit

kT_{BB}
R_{BB}
F_{BB}

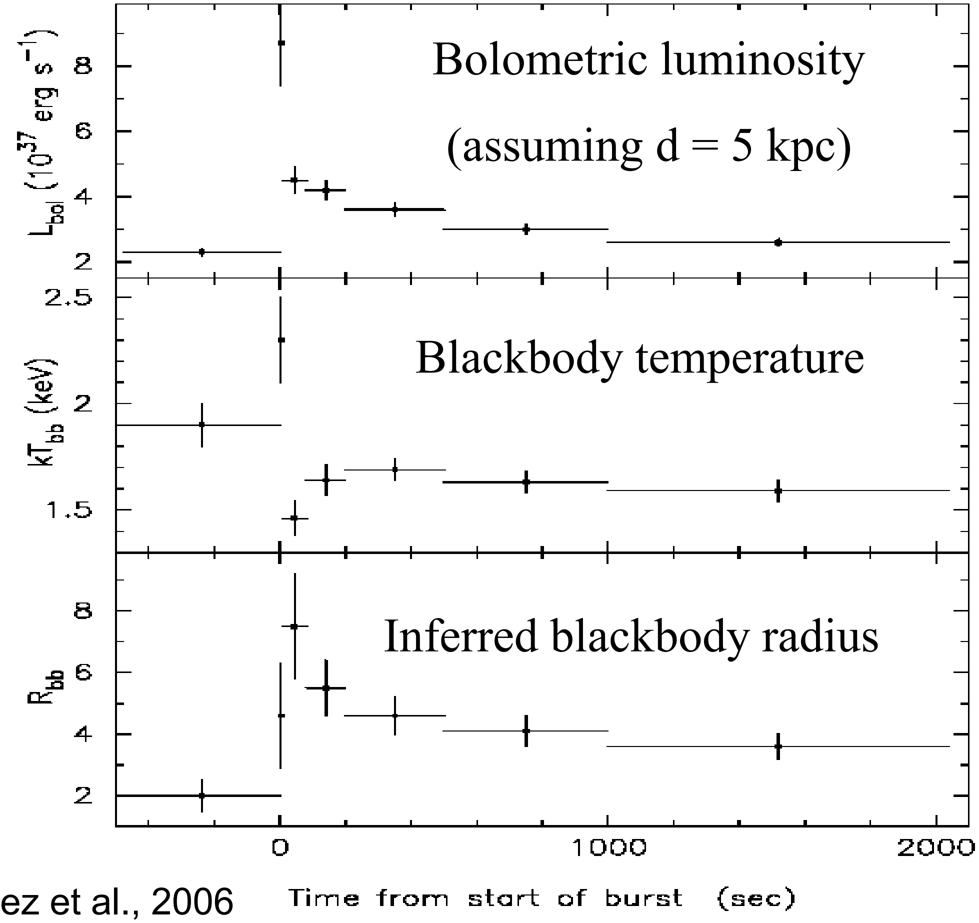


≠ time intervals

≠ kT_{BB}…

Example of **Results**

The time-resolved spectral analysis of GX 3+1 long X-ray burst reveals variations in the temperature and inferred blackbody radius which indicate expansion and contraction of the emission region.



Chenevez et al., 2006