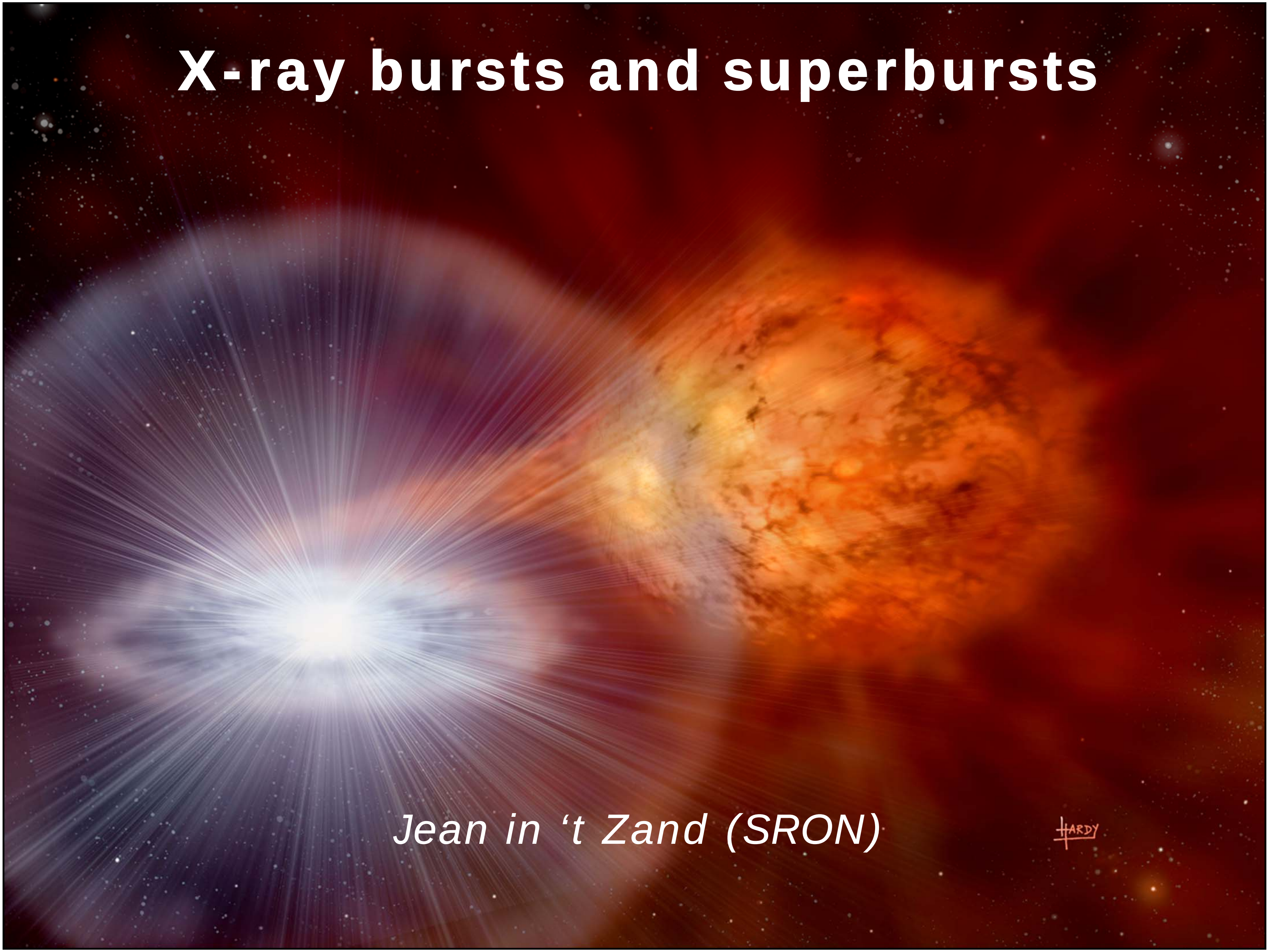
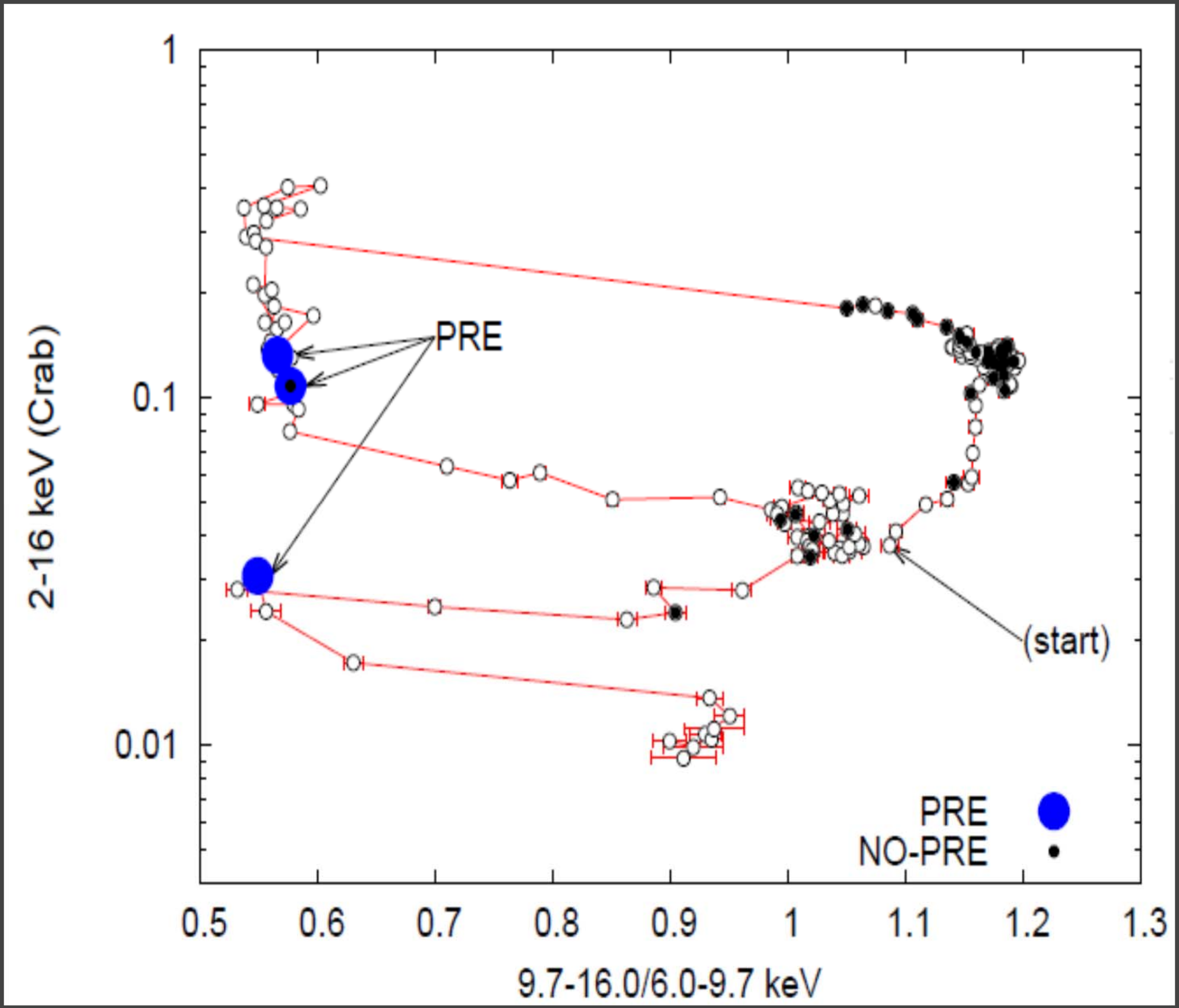
X-ray bursts and superbursts



Jean in ‘t Zand (SRON)

Plea for neutron stars..

e.g., IGR J17473-2721 in 2008 (Chenevez et al., MNRAS, 2010)



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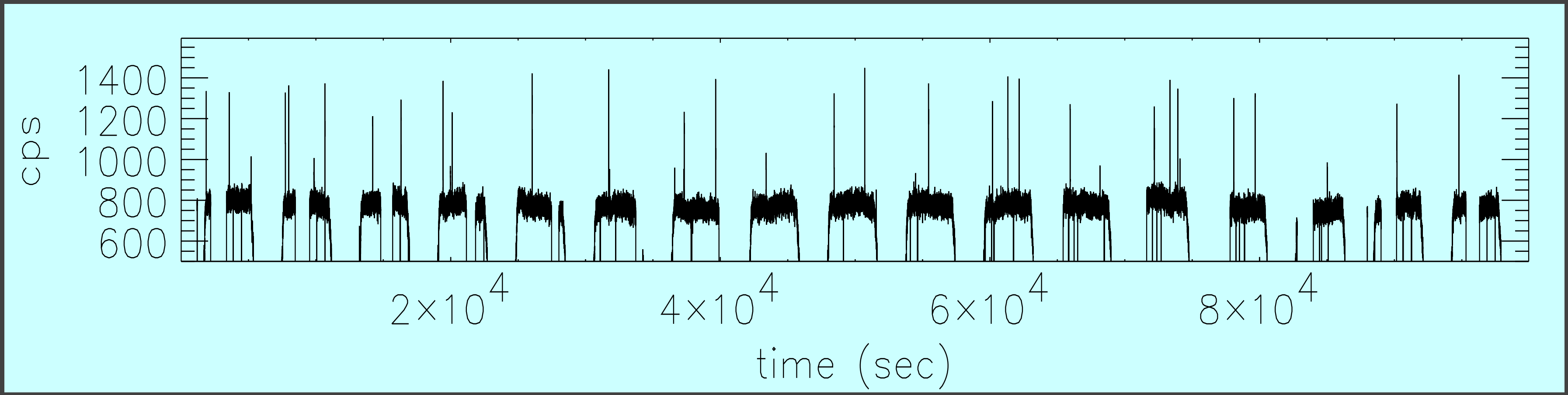
The X-ray burst phenomenon is omnipresent !



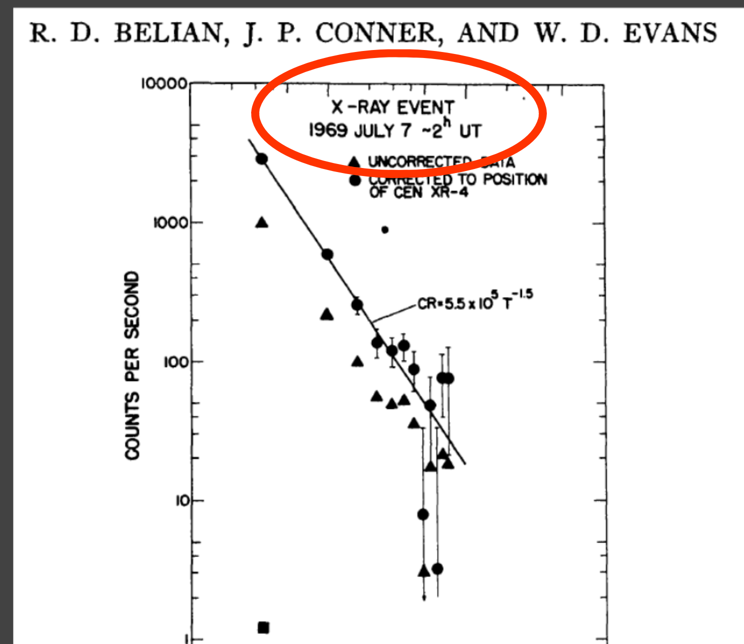
X-ray bursts and superbursts
a brief review

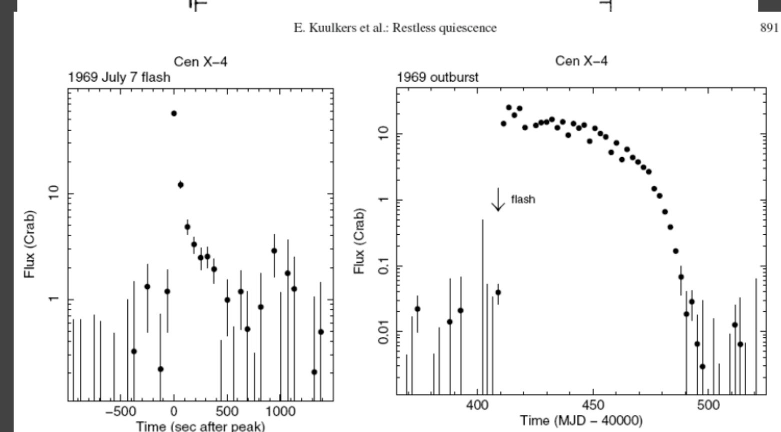
Talk outline

- **Past:** Discovery, nature
- **Recent:** Superbursts, intermediate-duration bursts
- **Future:** with current & future instrumentation

Brief history: the ‘first’ X-ray burst (in hindsight)

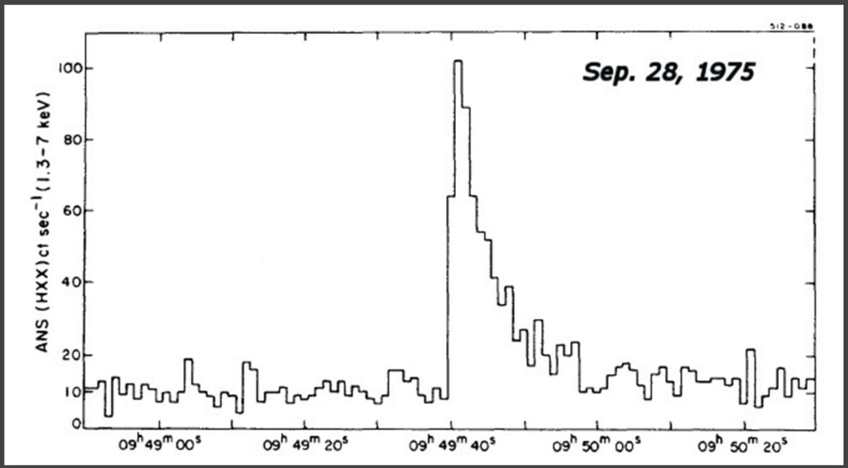
- Detected in 1969 with Vela 5b
- Published by Belian et al. (1972)
- First cited in 1976
- Still the brightest X-ray burst ever: 1.4 x 10^{-6} erg s^{-1} cm^{-2} (50 x Crab !). Bright enough to disturb earth’s ionosphere.
- Re-investigated by Kuulkers et al. (2009). Happened few days prior to accretion outburst





Brief history: the discovery X-ray burst

- Detected in 1975 with first pointed X-ray satellite ANS (Grindlay & Heise 1975)
- Prompted a spur of subsequent burst discoveries, particularly with SAS-C (Lewin, Hoffman et al.)
- Explained as thermonuclear shell flash on NS by Maraschi & Cavaliere (1977), Woosley & Taam (1977), based on theoretical work by Hansen & van Horn (1975)



Grindlay & Heise, IAUC, dec 1975
Grindlay et al., ApJ, 1976

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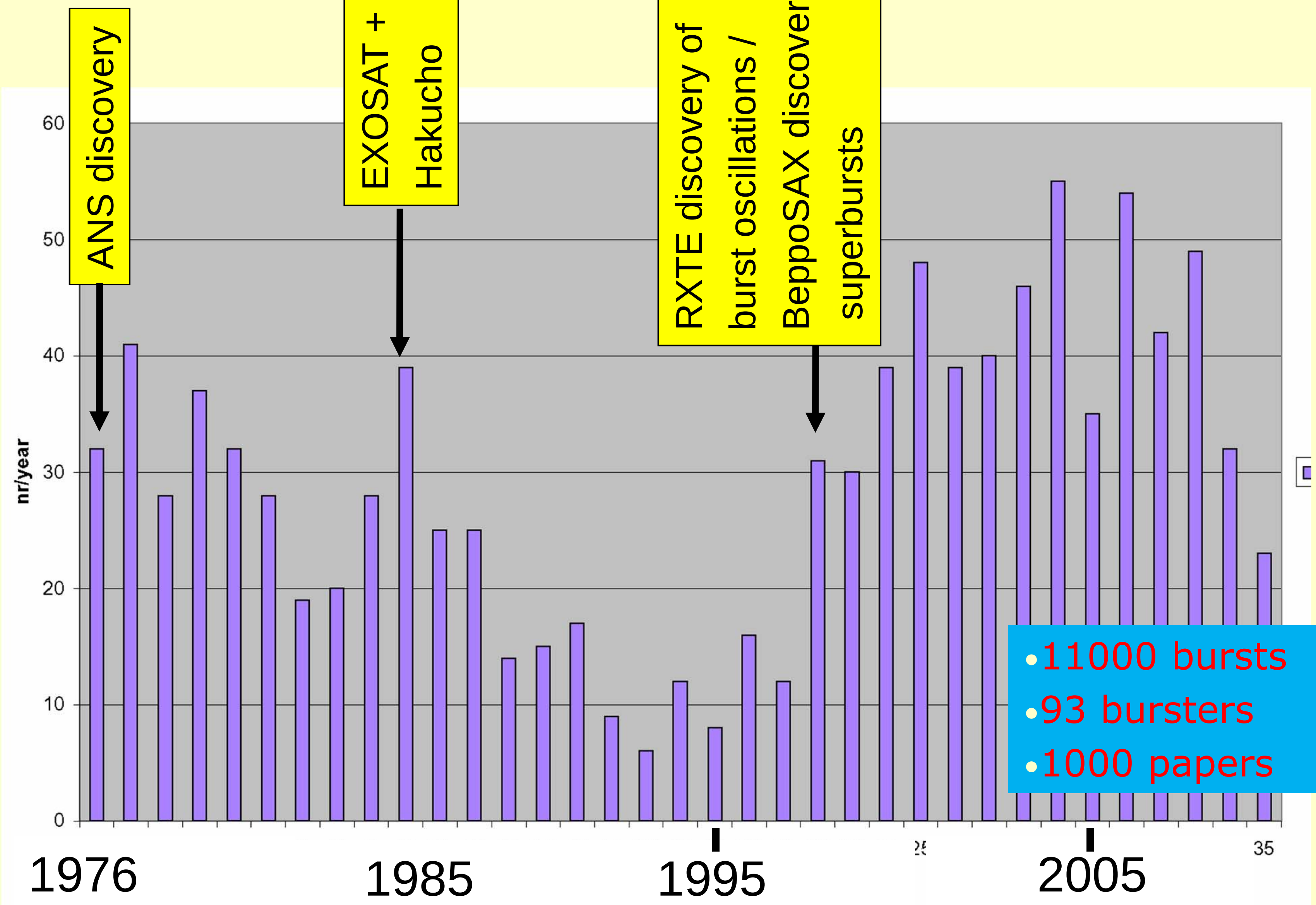
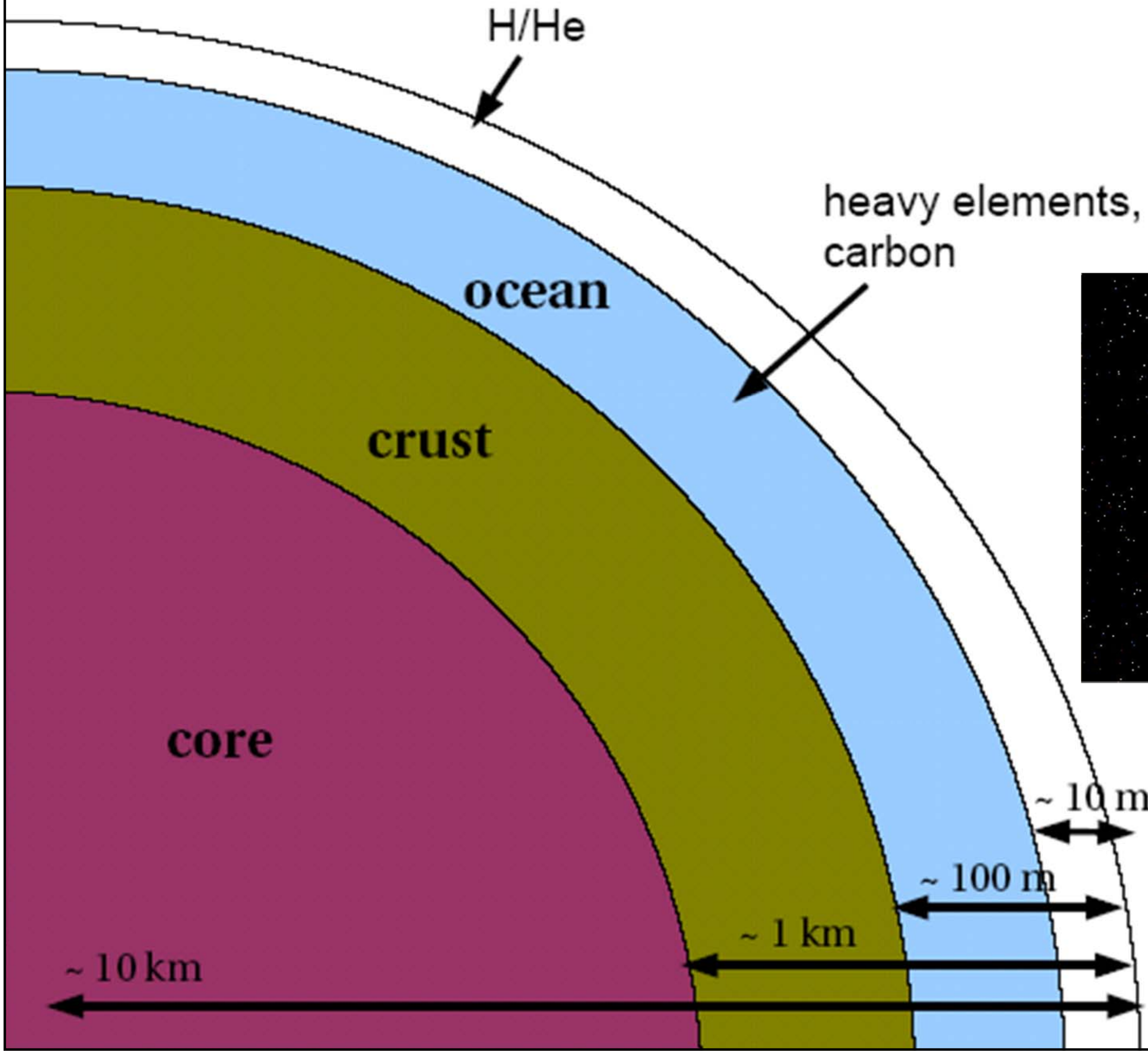
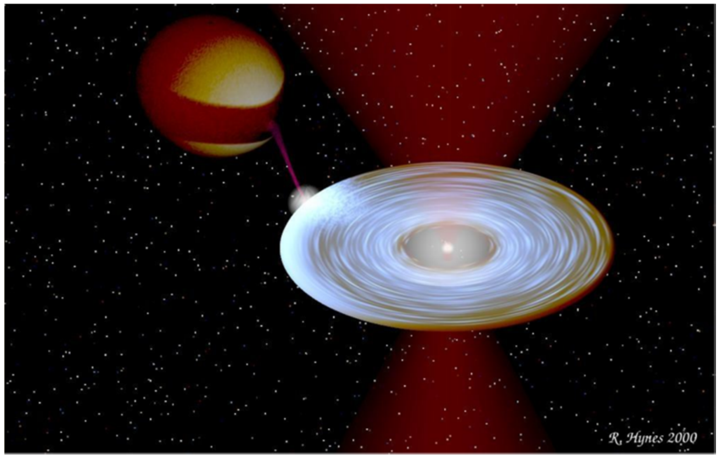
X-ray burst publications per year



- 11000 bursts
- 93 bursters
- 1000 papers

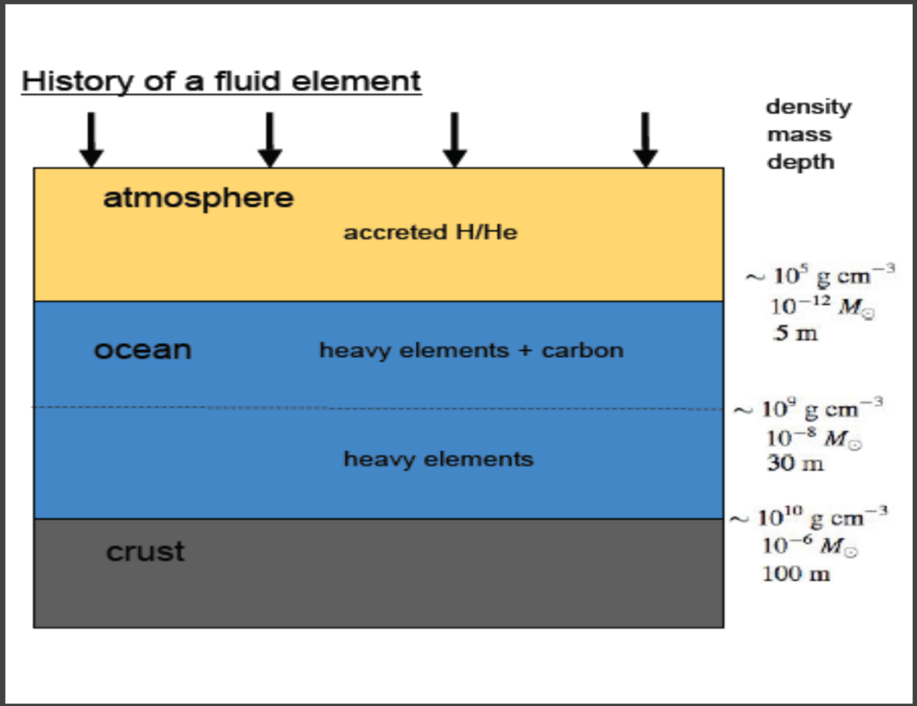
Structure of an Accreting Neutron Star





Fuel accumulation and ignition

- Local accretion rate in low-B NSs is 10 to 10^5 gr s^{-1} cm^{-2}
- For M-dot>10% Edd, H burns through hot CNO cycle, producing pure He layer
- After hours to days, accumulate columns of $y=10^{6-8}$ gr cm^{-2} (cf, 10^3 for earth atmosphere) or 10^{21} g
- Pressure (y*g) builds up to ignition condition for explosive triple-alpha, CNO cycle and rp-capture processes, 1 m deep
- heating (:) T^{17}, cooling (:) T^4 → thermonuclear shell flash
- Layer heats up to 10^9 K within milliseconds and then cools radiatively over tens of seconds→ X-ray burst



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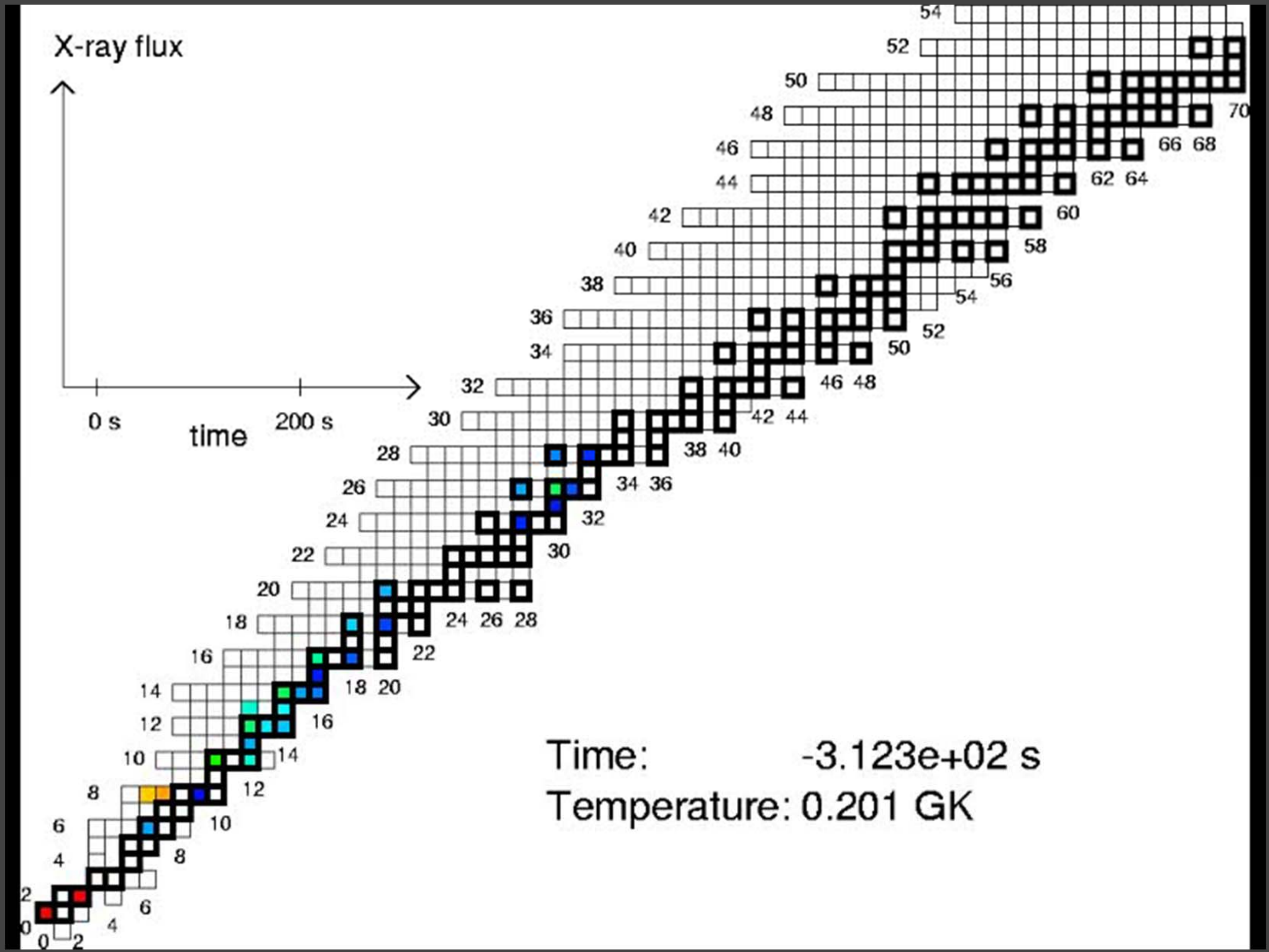
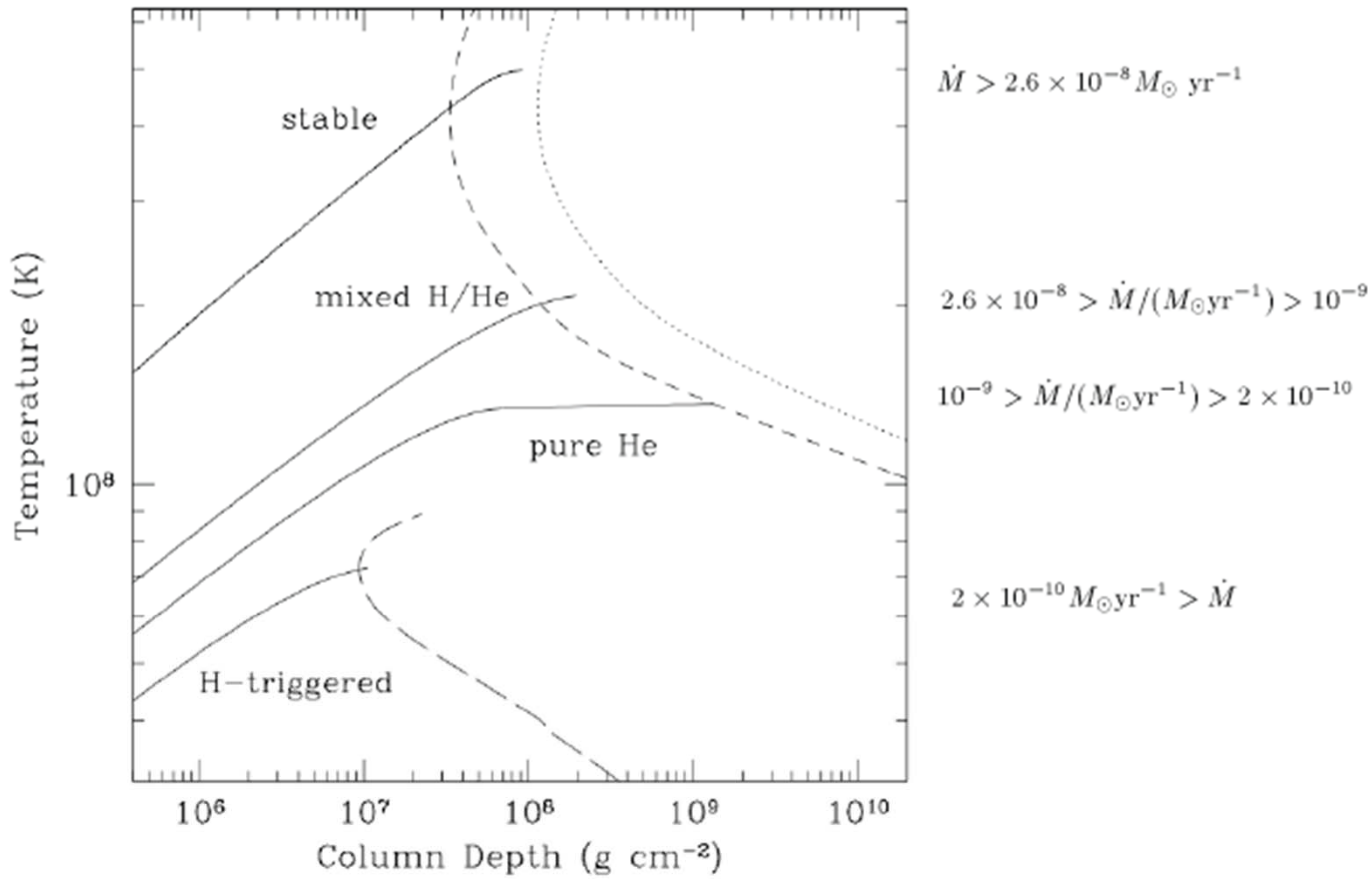
Isotope production during X-ray burst (Schatz 2003)



Burning regimes



Taam, Woosley, Joss, Fujimoto (late 1970s, 1980s), Bildsten (1998)

Courtesy Andrew Cumming

Burning regimes

Regime	$\dot{M}/\dot{M}_{\rm Edd}$	Burning
I		Mixed H/He flash (H ignites first)
	0.5%	
II		He flash (stable H burning)
	3%	
III		Mixed H/He flash (He ignites first)
	100%	
IV		Stable H/He burning

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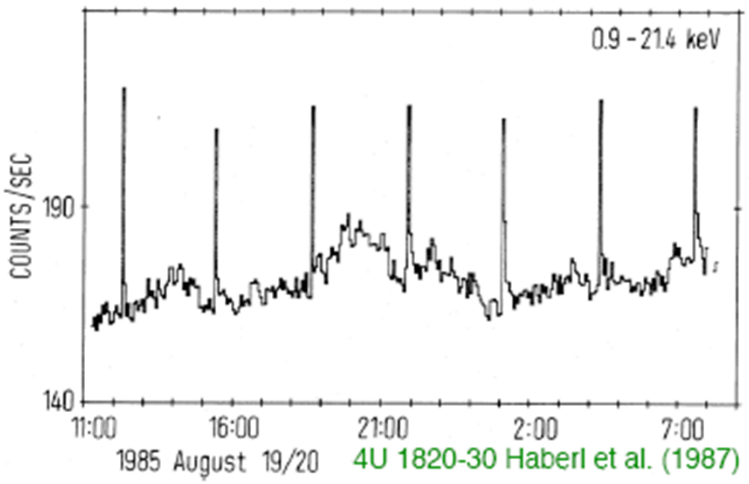
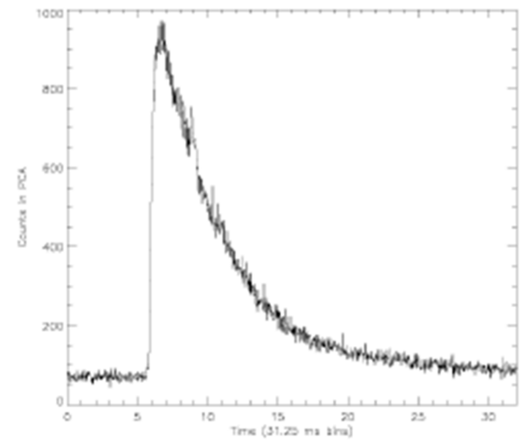
Basic understanding of Type I bursts

a relaxation oscillator: accumulation of fuel followed by rapid burning



4U 1820-30 Haberl et al. (1987)



4U 1728-34 Strohmayer et al. (1996)

gravitational energy release

$$\frac{GM}{R} \approx 200 \text{ MeV per nucleon}$$

nuclear energy release

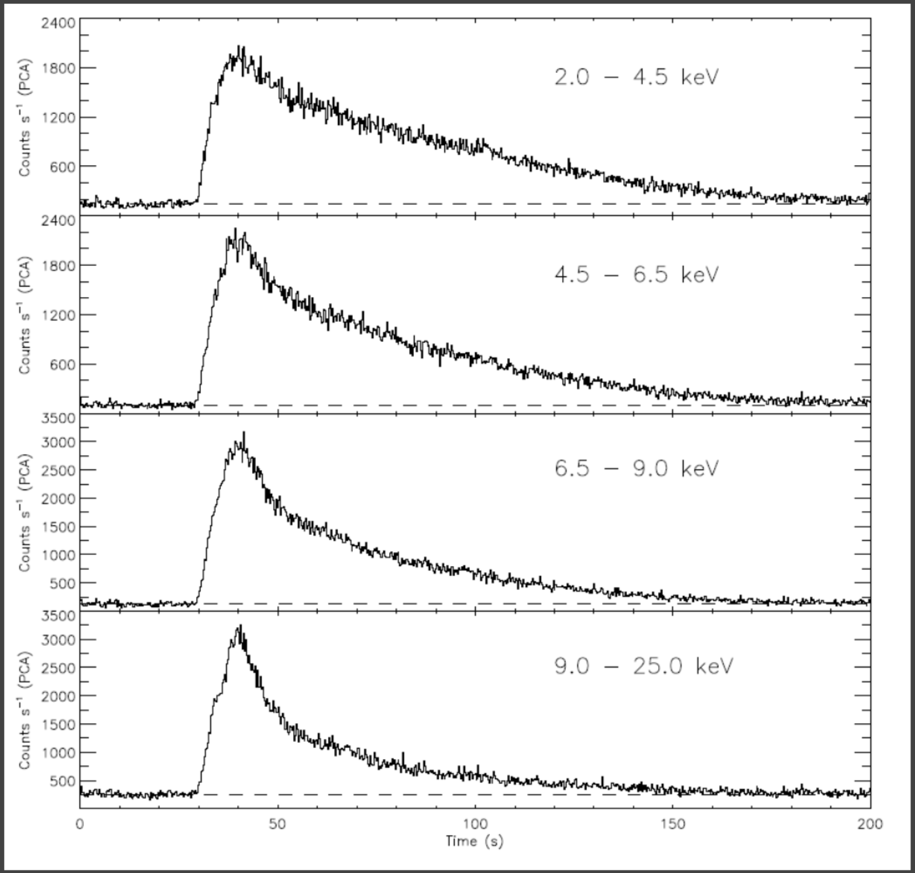
$$Q_{\rm nuc} \approx (1-5) \text{ MeV per nucleon}$$

$$\alpha \equiv \frac{\int F_p\, dt}{\int F_b\, dt} \approx \frac{GM/R}{Q_{\rm nuc}}$$

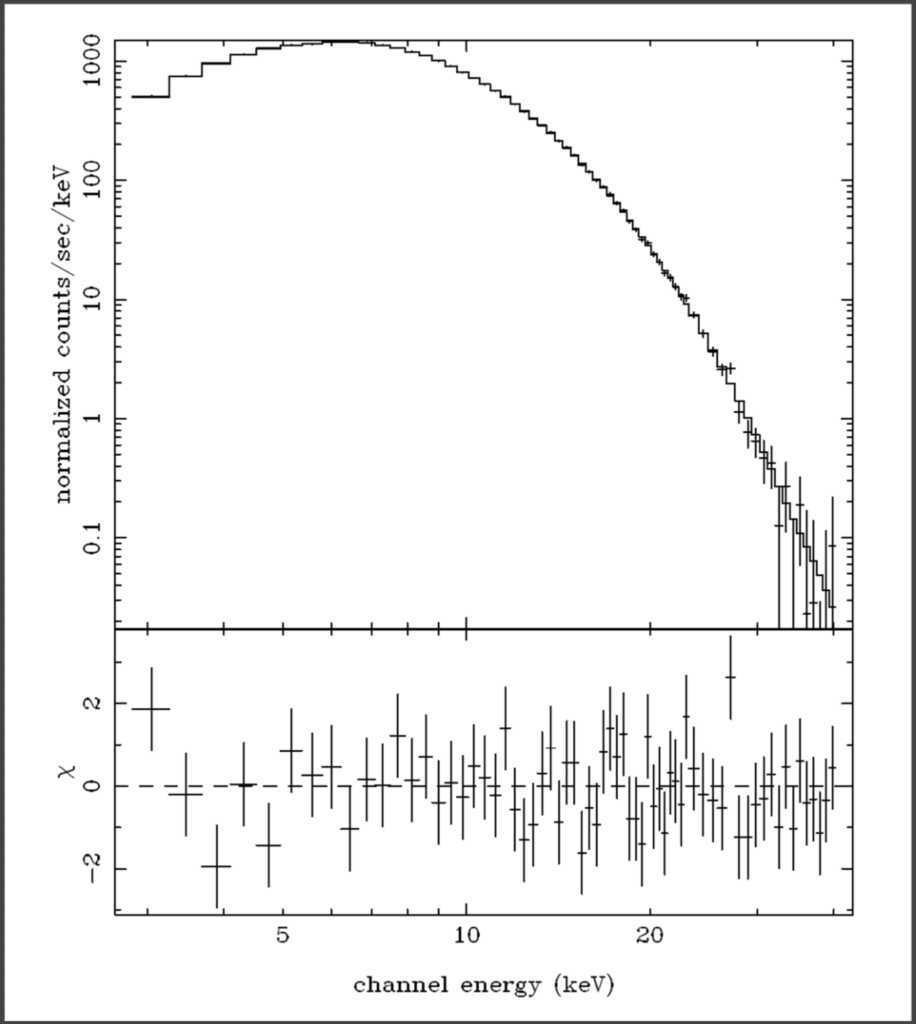
$$\approx (40-100)$$

Courtesy Andrew Cumming

Spectra → pure black body



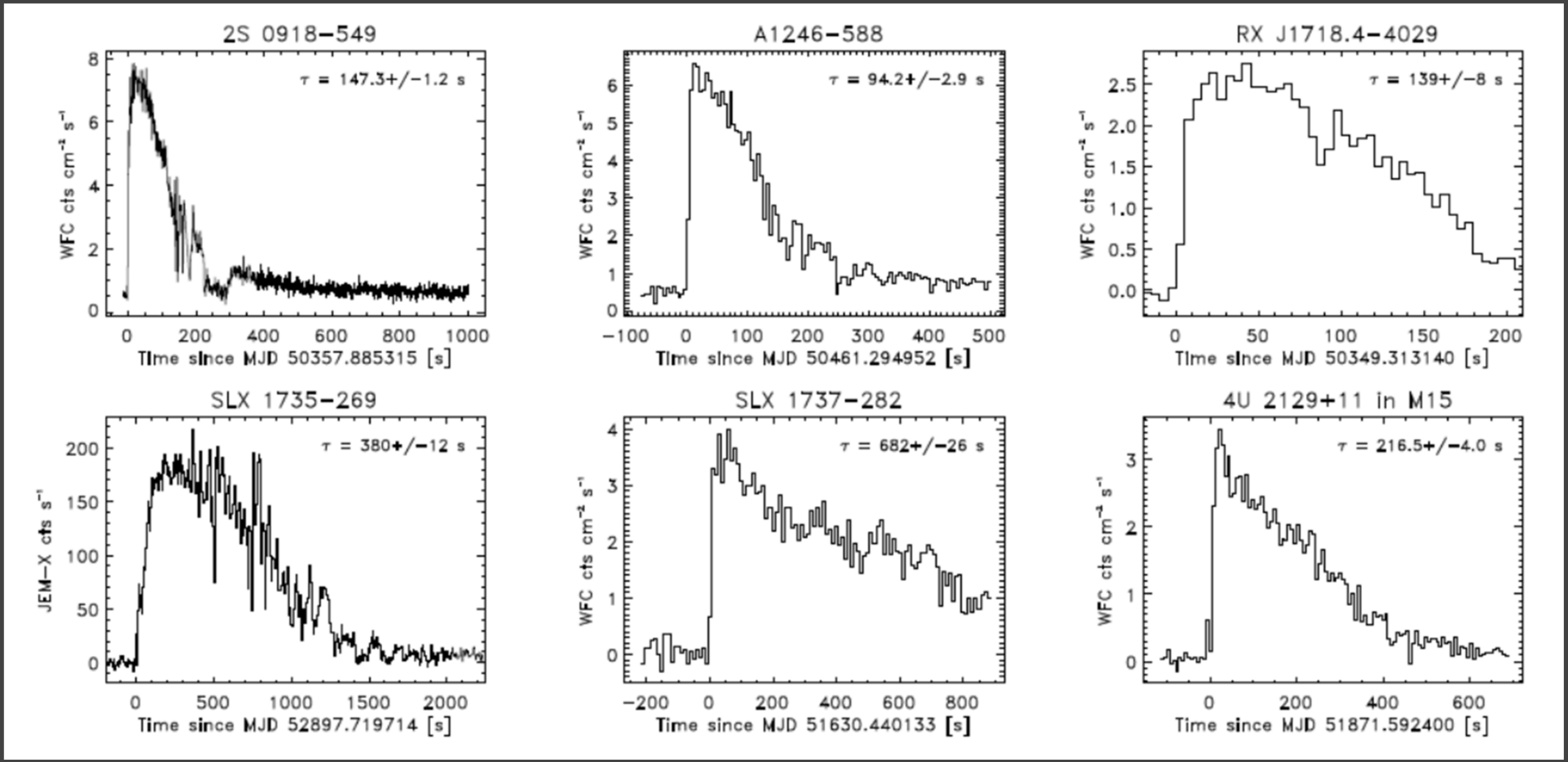
Strohmayer & Bildsten 2006



Strohmayer & Brown 2002

A special burning regime

- Hydrogen-poor accretion from white dwarf donors in ultra-compact X-ray binaries (P_{orb} < 80 min)



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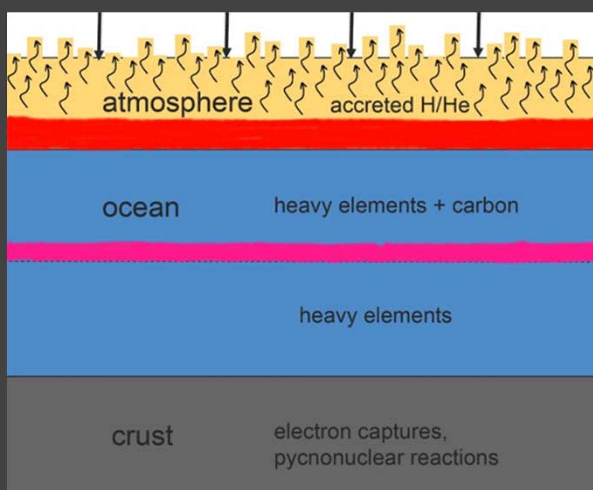
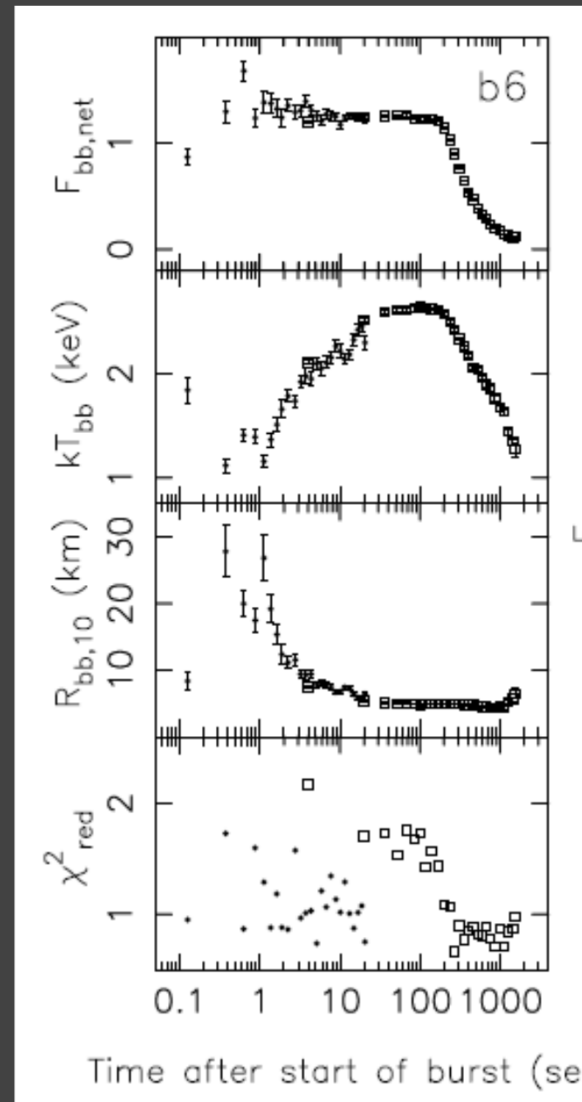
Eddington-limited bursts

- Faster burning and thicker piles result in higher nuclear energy rate→ larger L → may reach Eddington limit and drive photosphere to heights
- Eddington → L plateaus & R increases → kT decreases → PRE/Eddington-limited bursts
- 20% of all bursts are Eddington-limited (Galloway et al. 2008)



(Weinberg et al. 2006)



example from Kuulkers et al. 2002

Basic inferences from burst flux profile

- Fluence → amount of fuel
- Decay time → thickness of fuel layer
- Peak luminosity → amount of fuel X production rate of nuclear energy (or, type of nuclear process)
- PRE + peak flux → distance ($d=\sqrt{L_{edd}/4\pi F_{peak}}$)
- Flux + distance → radius ($r=d\sqrt{F/\sigma T^4}$ = Stefan Boltzmann)

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Why are X-ray bursts so fascinating?

- Exhibition of nuclear reactions seen nowhere else
- Cleanest probe of the densest matter (→ QCD) in the visible universe
- Probe of General Relativity in the strong field regime

NS structure

- 5 distinct regions
- Inner core content uncertain; $\rho \sim 10\text{-}20\ \rho_0$
- 3 possible phases with increasing compressibility:
  - normal matter
  - Bose condensate
  - Deconfined quarks
- constitution dictates mass M and radius R → constrain M and R and find out what NSs are made of and how matter behaves at supranuclear densities

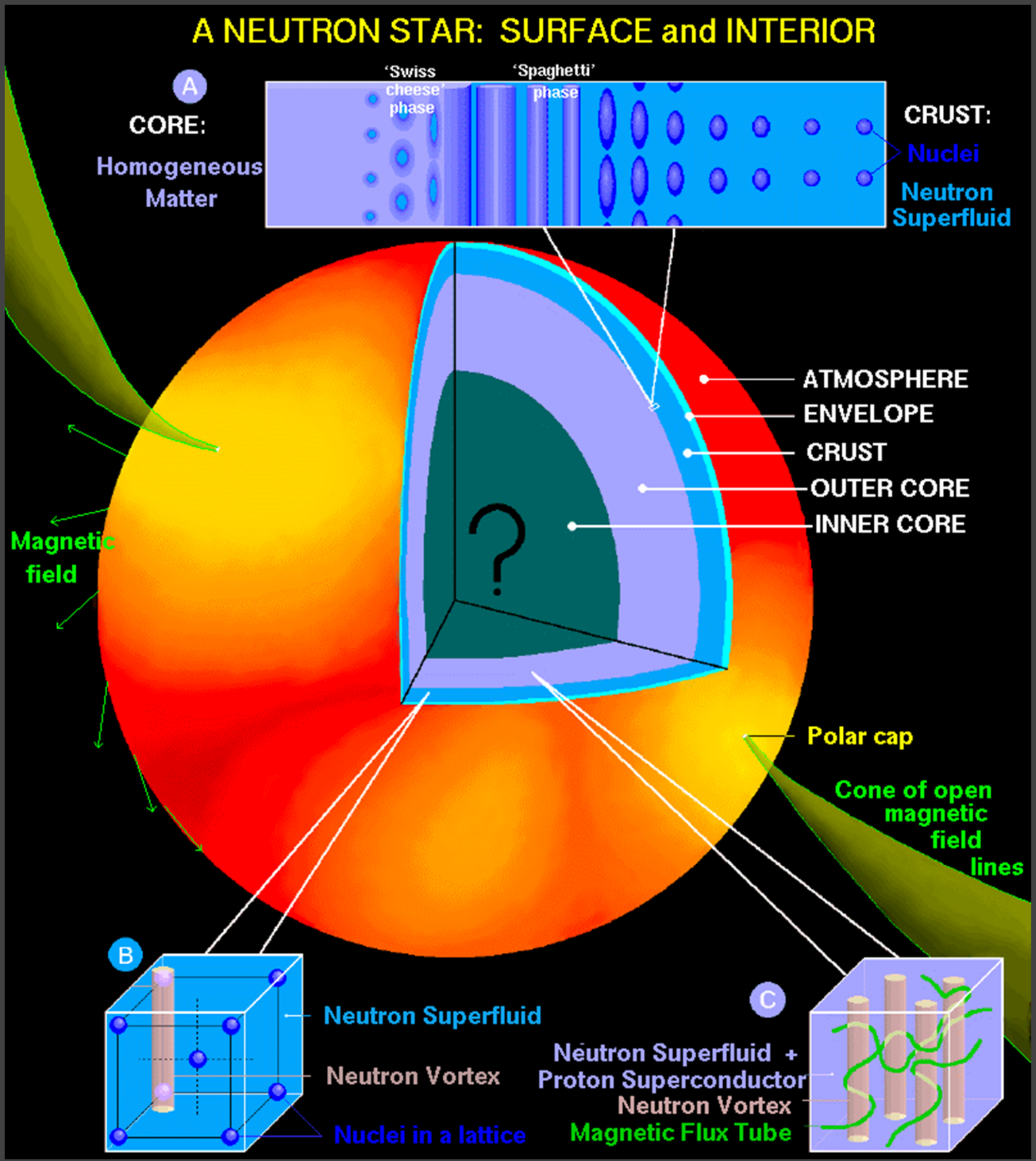
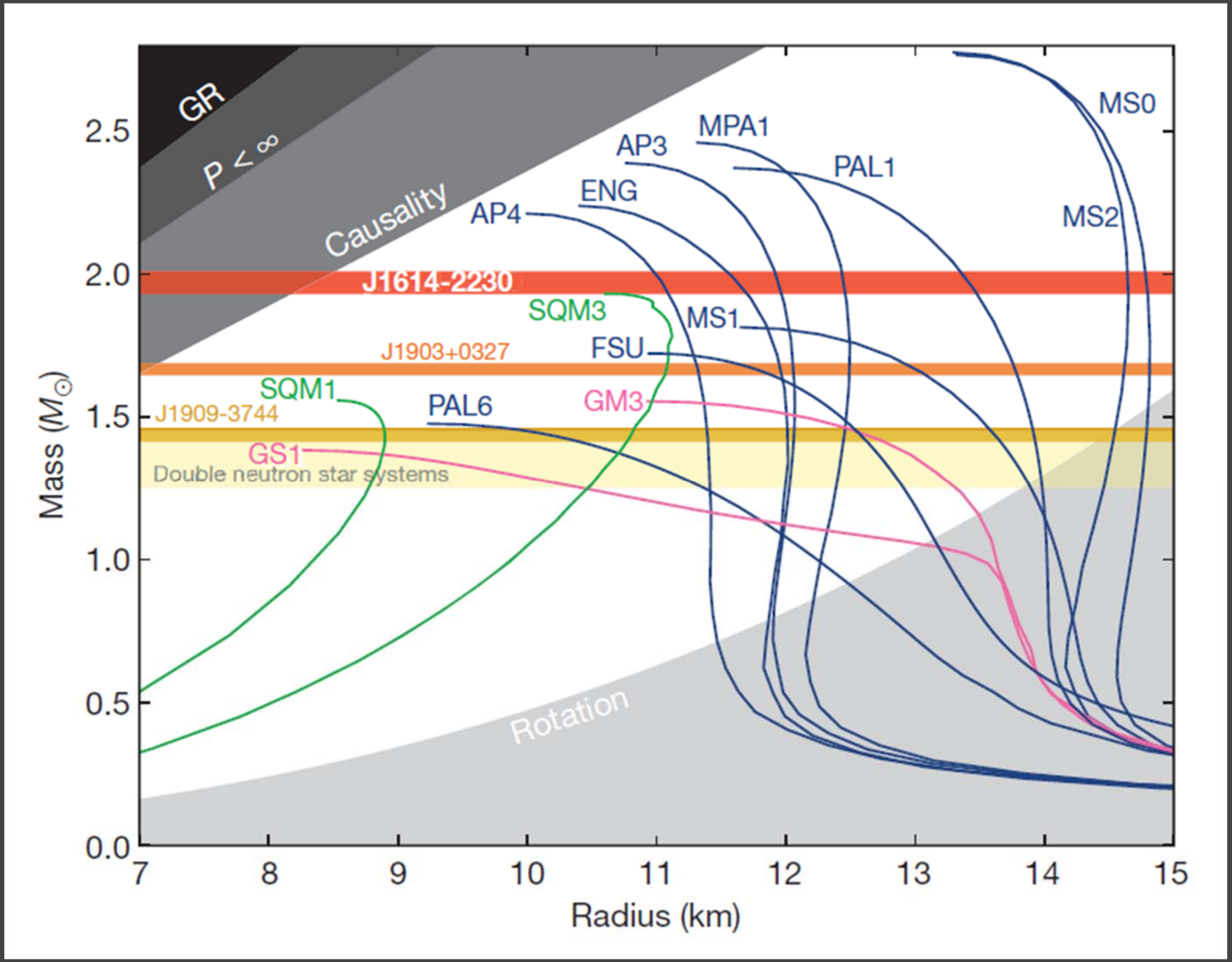


Figure from Dany Page

EOSs



Demorest et al. 2010

Masses are 'easy', radii not..

X-ray bursts may be useful, for instance:

- Continuum spectra
    - Stefan-Boltzmann for black body $L=4\pi R^2 \sigma T^4$
        - inaccurate: not exactly black body, non-isotropies
- High(er) resolution spectra
    - gravitational redshift

$$R = R_\infty (1+z)^{-1},$$

$$M = \frac{c^2}{2G} R_\infty (1+z)^{-1}[1-(1+z)^{-2}].$$

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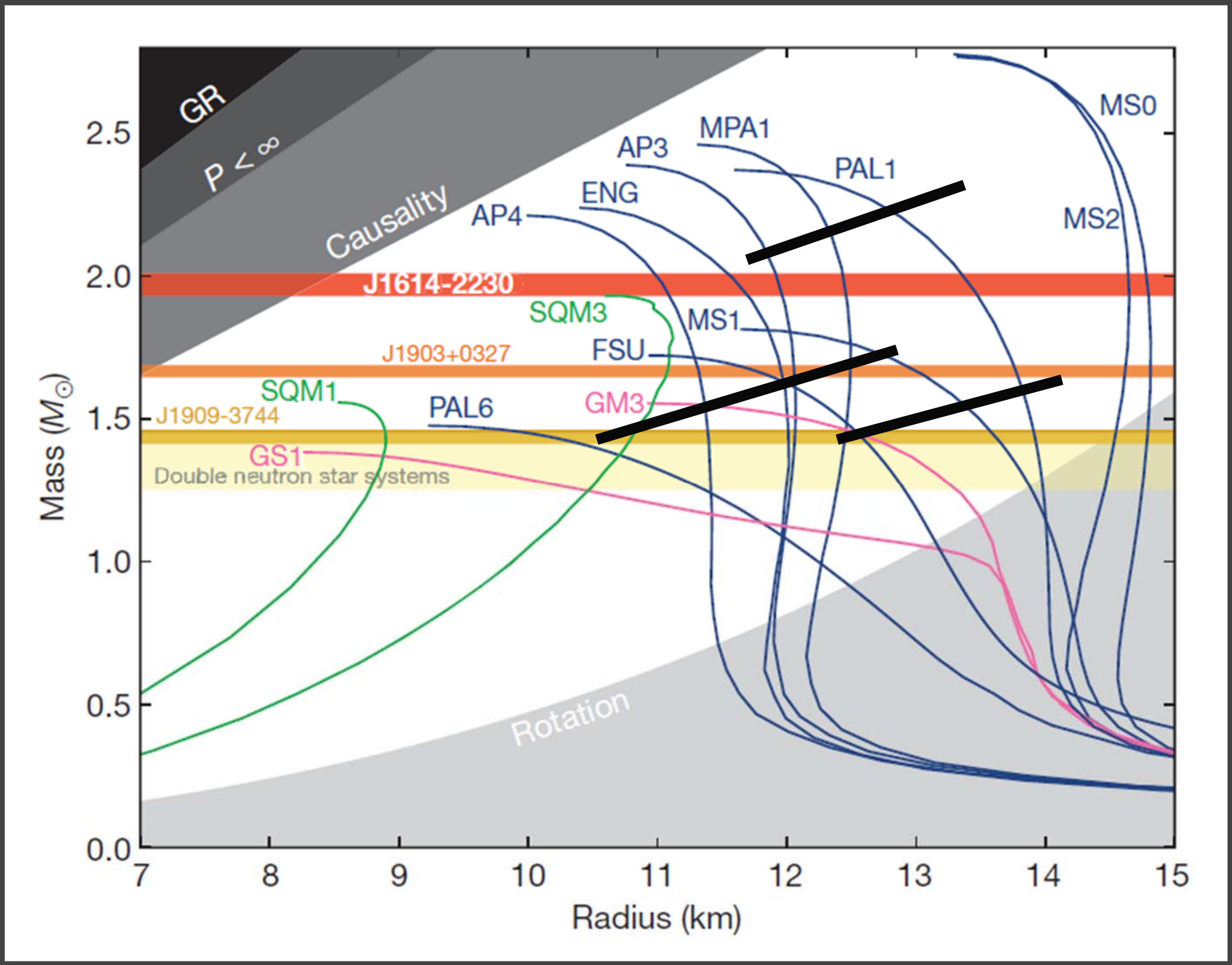
EOSs



Demorest et al. 2010

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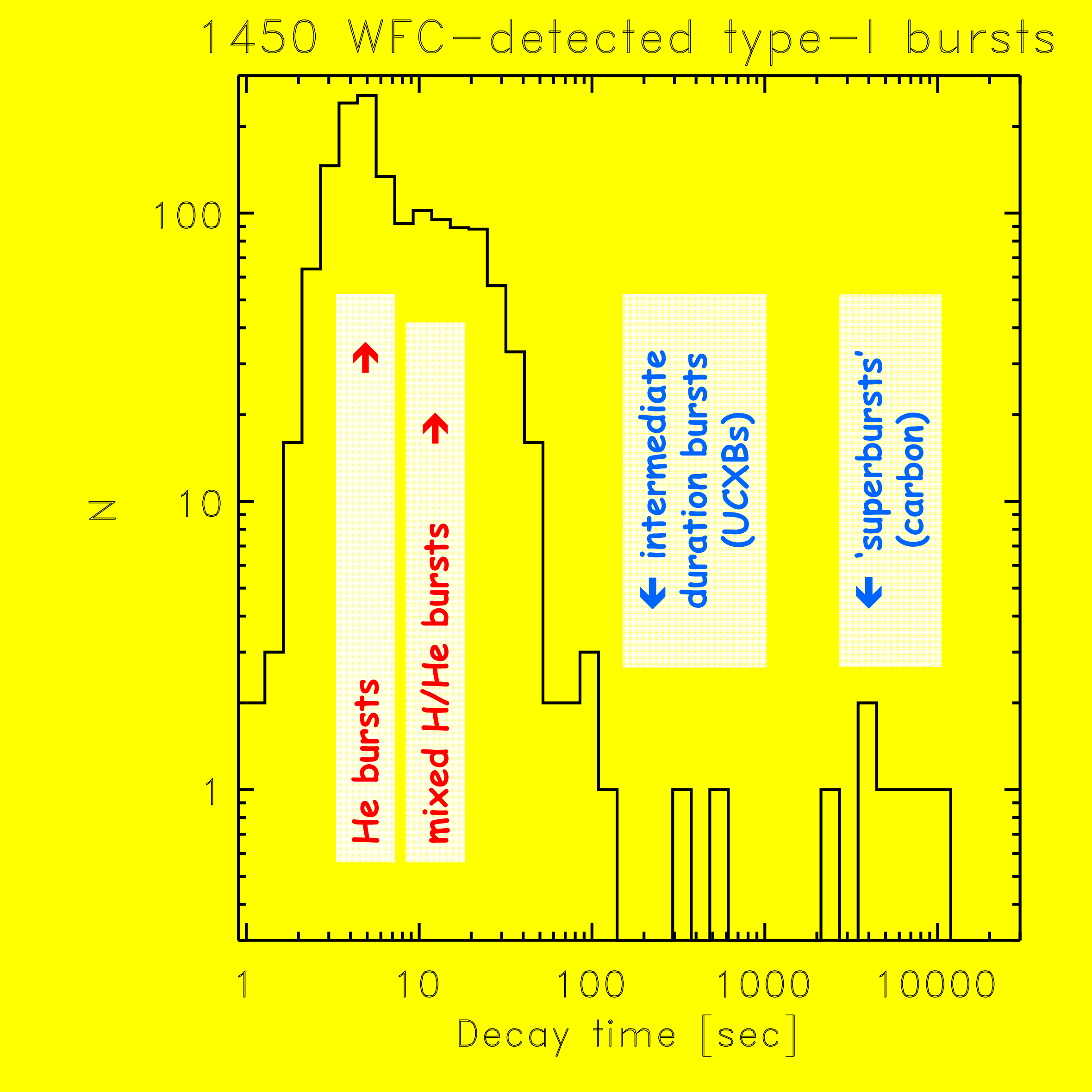
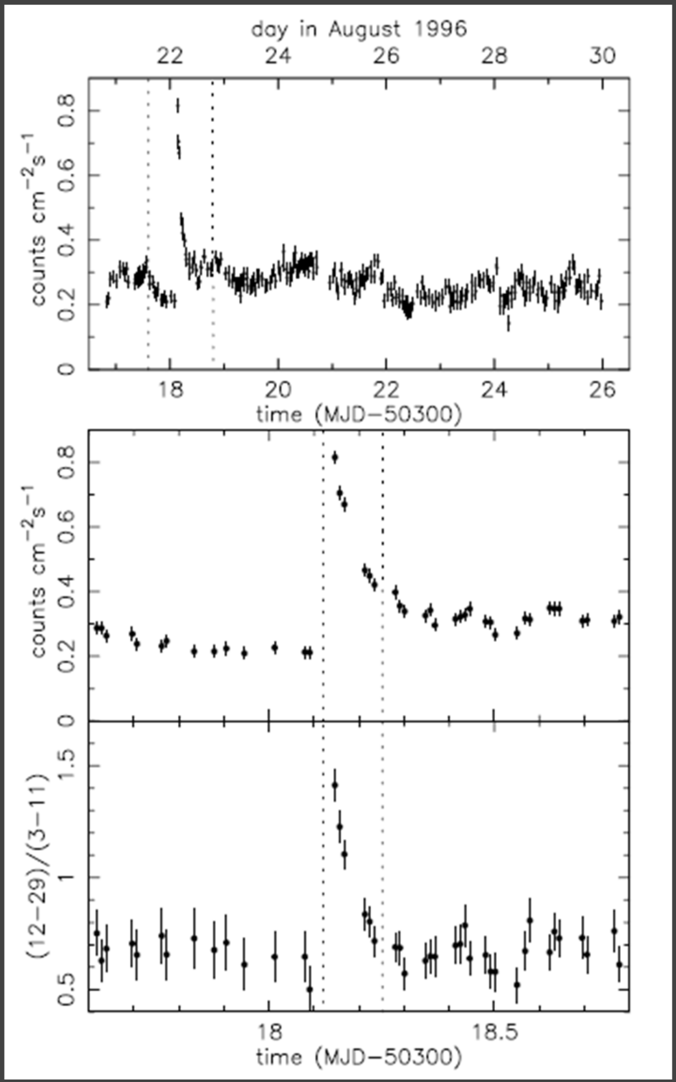
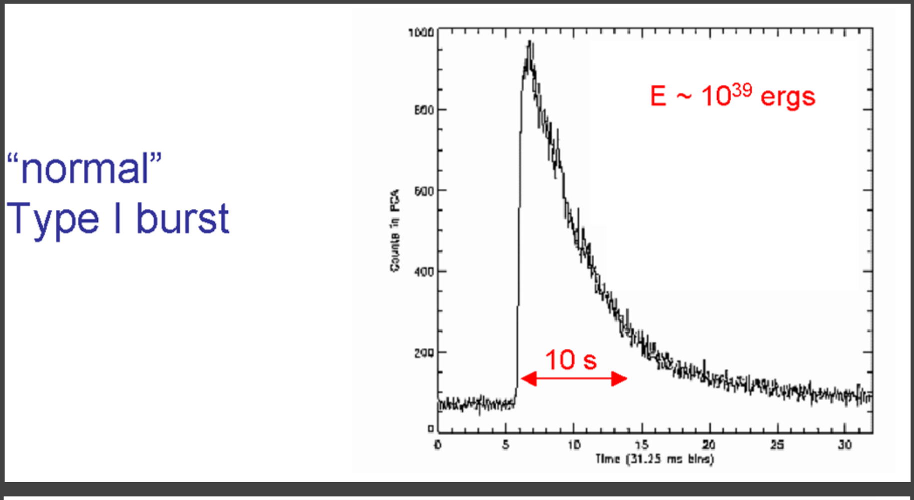
Burst durations

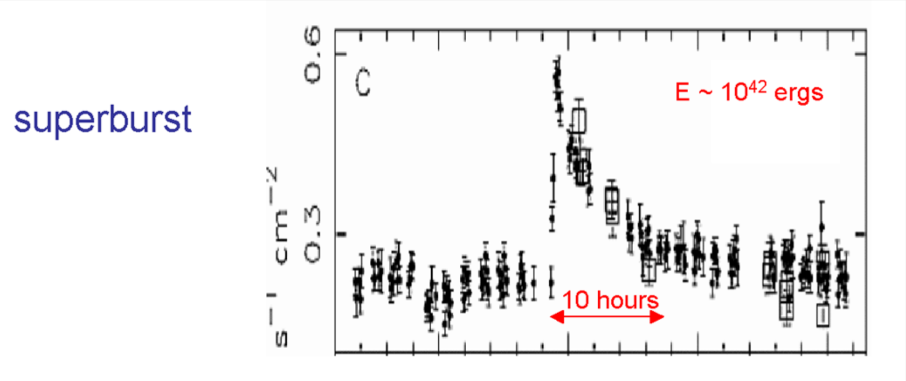


Superburst - discovery



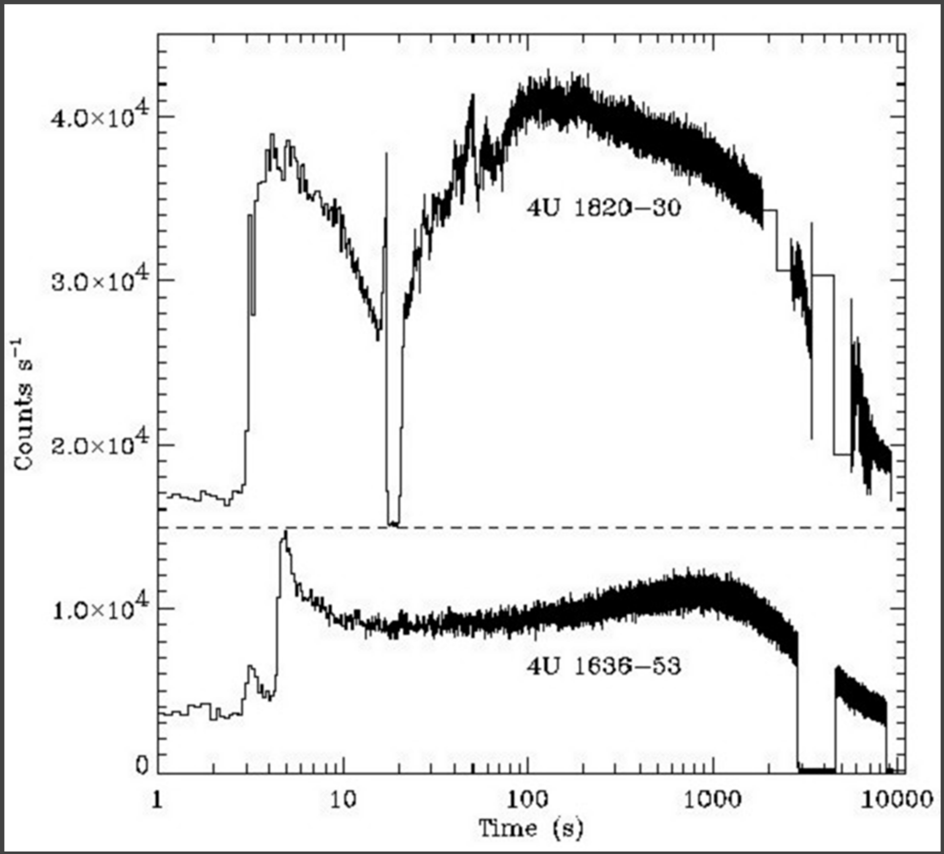
4U 1735-44 (Cornelisse et al. 2000)



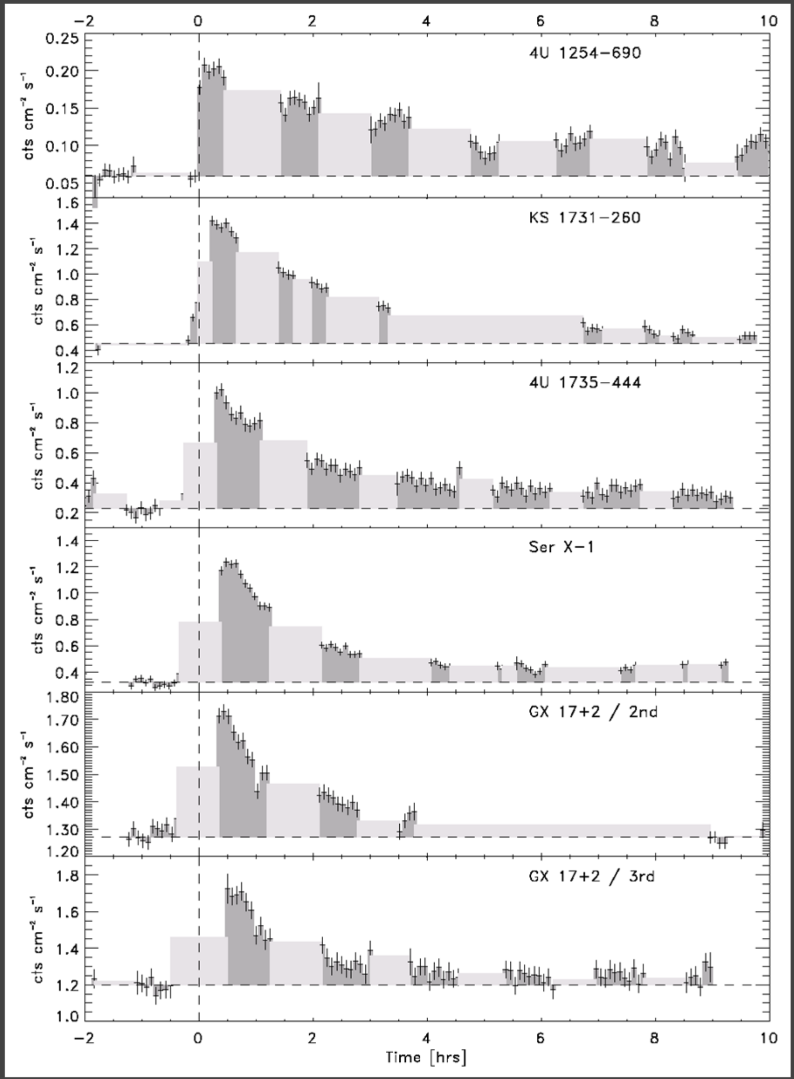


KS 1731-260 (Kuulkers et al. 2002)

Superburst – time profiles



Strohmayer & Bildsten 2006



in 't Zand, Cornelisse & Cumming 2004

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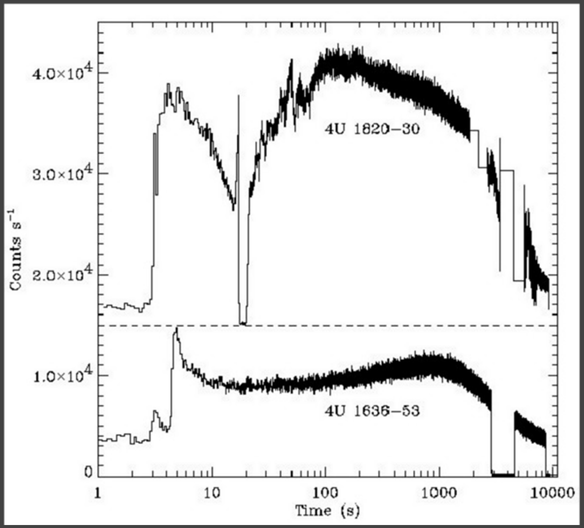
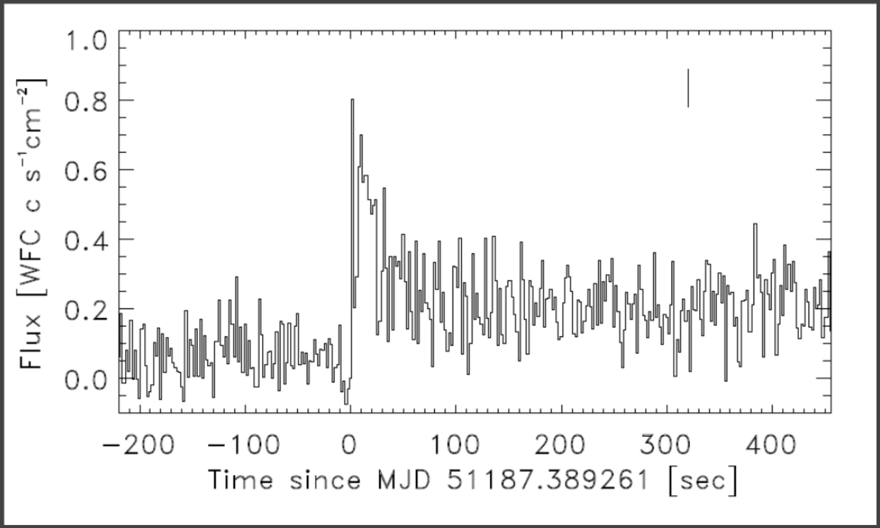
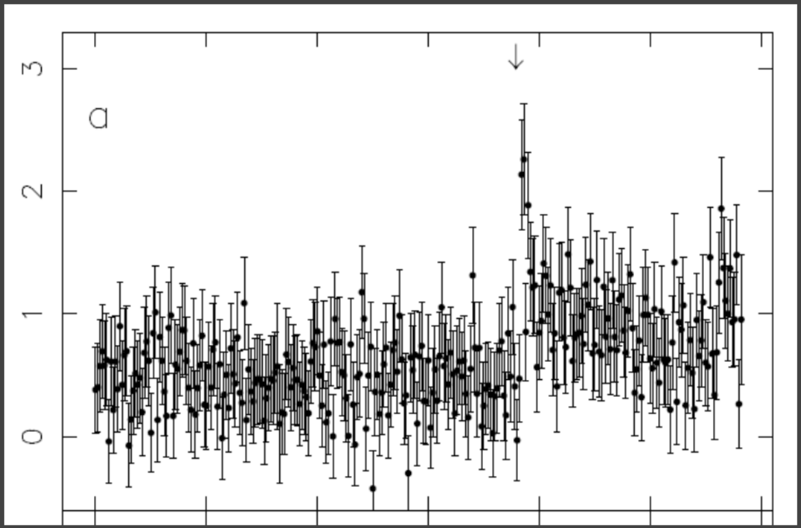
Superburst - precursors

Strohmayer & Bildsten 2006

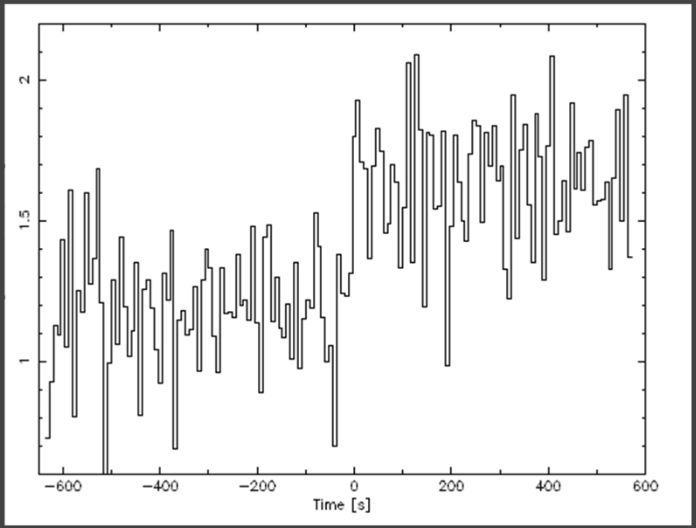


In 't Zand et al. 2003



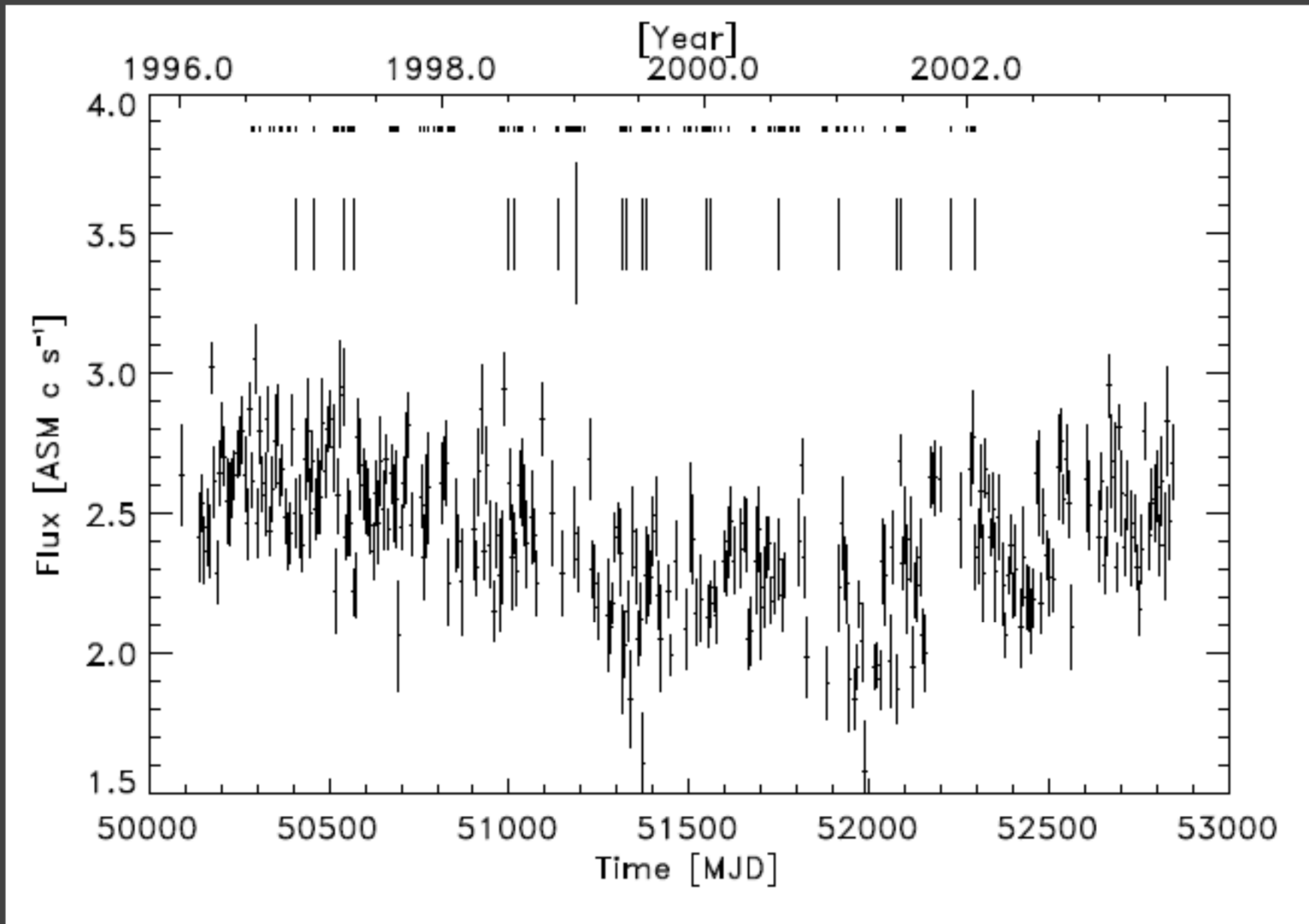


Kuulkers et al. 2002



In 't Zand, Cornelisse & Cumming 2004

Superburst – normal burst quenching



In 't Zand et al. 2003

Superburst population

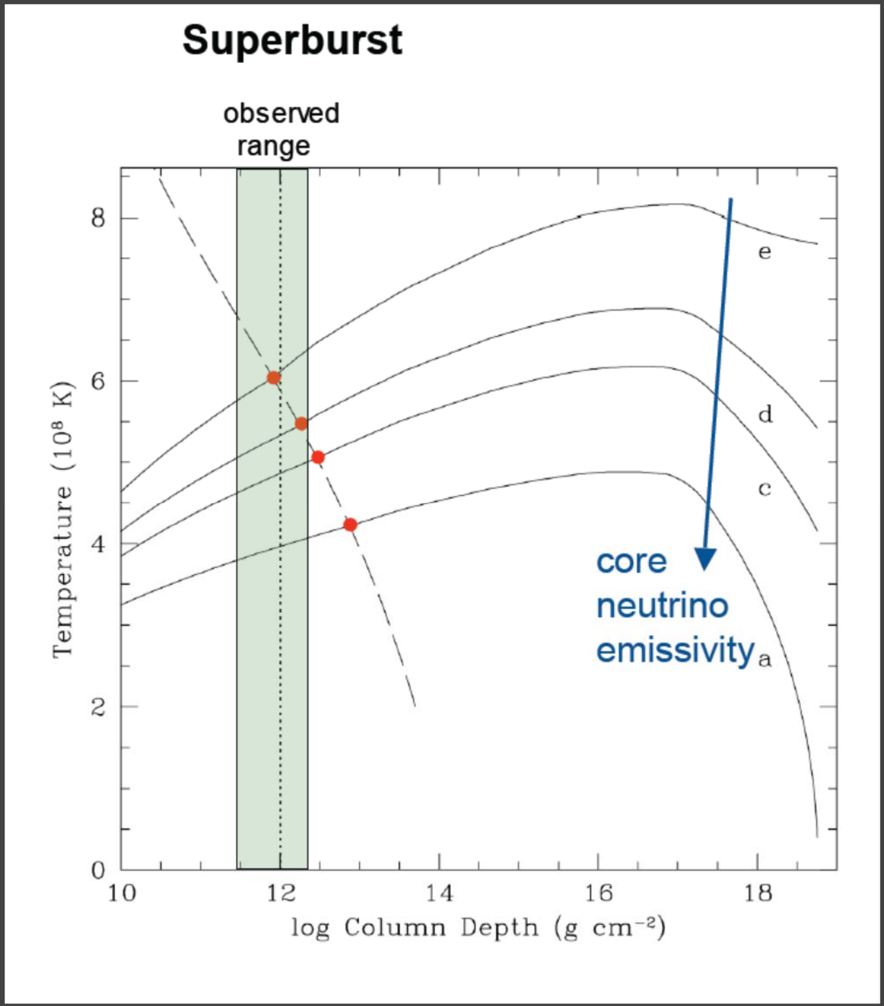
- 18 superbursts (8 ASM, 8 WFC, 2 PCA, 1 HETE) from 10 superbursters
- All superbursters are normal bursters as well, except for weeks to months after superburst (~10% of total burster population; ~25% of likely superbursters)
- 3 recurrent superbursters (few months & few years recurrence time)

Object	Instr.	P_{orb} (min)	# SB	Accretion level (fraction of Eddington)	Dur. (hr)	Peak lum. (10^{38} erg/s)	Reference SB discovery
4U 0614+091	ASM 05	50?	1	0.01	>1.5	>0.1	Kuu05
4U 1254-69	WFC 99	236	1	0.13	14	0.4	Zand03
4U 1608-522	ASM+HETE 05	773?	1	0.03 (trans)	~15	0.5	Rem05
4U 1636-536	ASM 96/97/98/01	228	3	0.1	6	1.3	Stroh02, Wij03, Kuu09
KS 1731-260	WFC 97		1	0.1 (trans.)	12	1.4	Kuu02
4U 1735-444	WFC 96	279	1	0.25	7	1.5	Cor00
GX 3+1	ASM 99		1	0.2	>3.3	0.8	Kuu02
GX 17+2	WFC 96-01	10d?	4	0.8	2	1.8	Zand04
4U 1820-303	PCA 99	11	1	0.1	>2.5	3.4	Stroh02
Ser X-1	WFC 97/ASM 99/08		1	0.2	4	1.6	Cor02, Kuu09

0.2-2 Crab

What are superbursts?

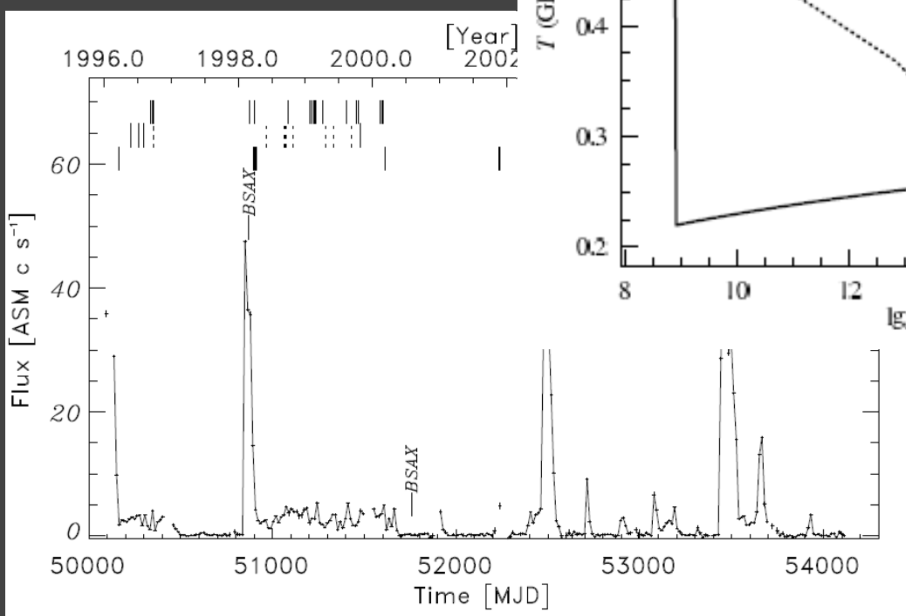
- Long duration → deep ignition ($y=10^{12}$ g cm^{-2}) → not H or He, but Carbon flash
- Fluence value → mixed Carbon (X_C~0.1), except for superburst from 4U 1820-30 (X_C~1)

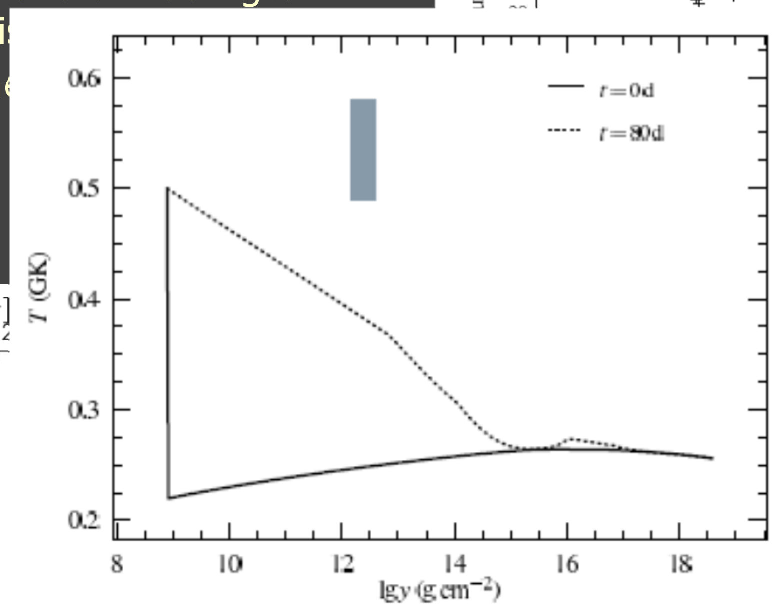


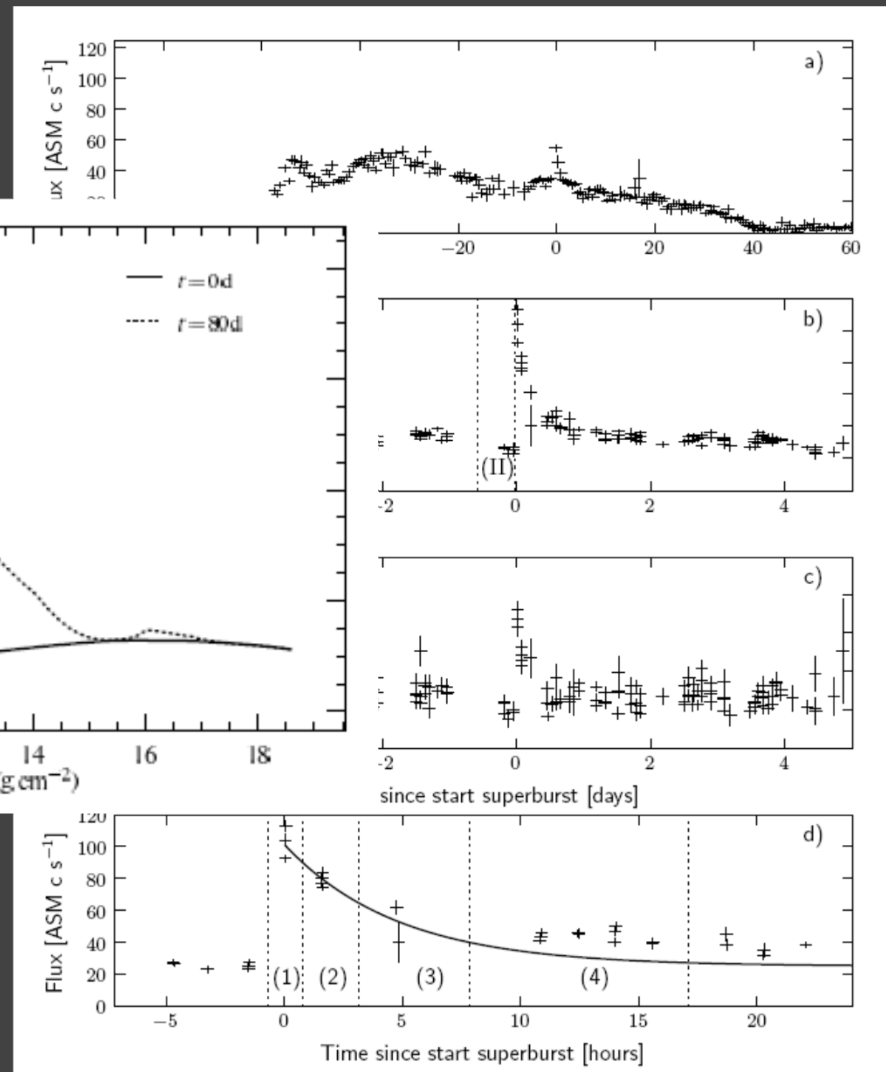
Cumming et al. 2006

Surprise: superburst from the classical transient 4U 1608-522 (Keek et al. 2008)

- All 9 other superbursters are semi-continuously accreting, not 1608
- Average accretion rate 3% of Eddington and time when >10% i…
- Implied recurrence tim…







What is going on?

- Heating due to chemical separation at solidification into crust by boyuncy-induced mixing and heating? (Medin & Cumming 2010, Horowitz et al. 2007)
- Extra electron capture energy? (Brown)
- Additional observational constraints: accurate recurrence times to define more accurately ignition conditions

Future observations

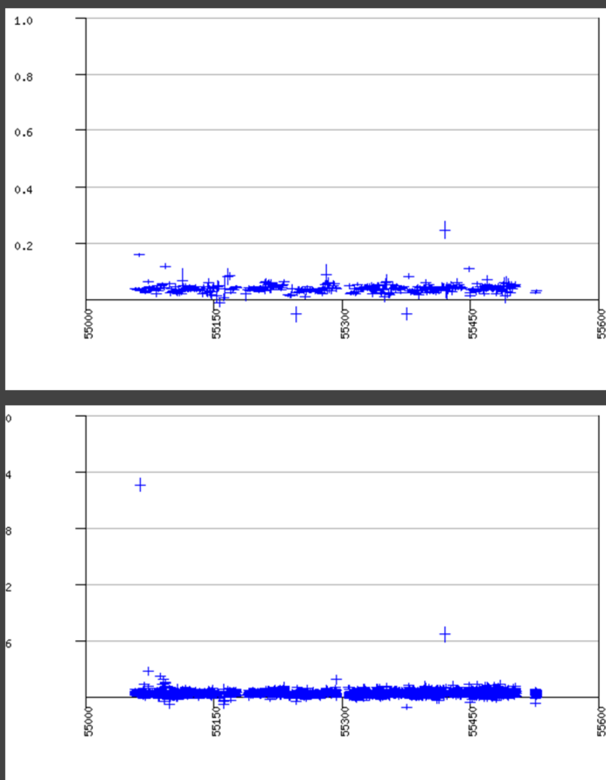
With current instruments

- High-resolution spectroscopy with XMM-Newton and Chandra of PRE bursts
- Medium-resolution (CCD) spectroscopy with Swift of PRE bursts through automatic slewing to bursts from certain sources
- High-resolution spectroscopy with XMM-Newton and high-resolution timing with RXTE of superbursts through TOO programs using triggers from RXTE, INTEGRAL and Swift
- Comprehensive observations on the brightest burster Cen X-4 when it goes in outburst again (100 times as bright as EXO bursts)
- Wide-field monitoring for rare long X-ray bursts from unexpected sources with MAXI

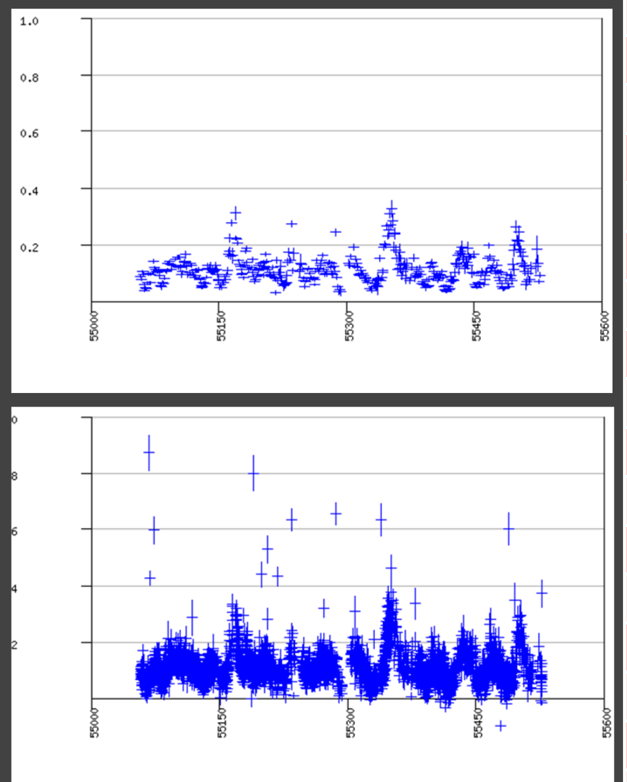
MAXI on bursts

- shows many spikes in orbital data
- X-ray bursts?
- better judgment possible with second-resolution light curves. Not public (yet?)

4U 1722-30 (Terzan 2)



4U 1636-53



Source	# bursts up to Nov 29
GS 1826-24	34
4U 1636-53	12
Aql X-1	7
NGC 6440	4
4U 1608-52	3
4U 1735-44	3
4U 1746-37	3
HETE J1900.0-	3
Terzan 2	2
4U 0513-40	2
4U 1728-34	2
4U 1820-30	2
SLX 1735-269	2
2SS 1711-34	1
Cyg X-2	1
EXO 1745-258	1
4U 0614+09	1
Ser X-1	1
18 sources	84
Rapid Burster	>30

MAXI on superbursts

- no obvious superbursts yet, let alone with 1 s rises (definitive id)
- net exposure time per source is ~200 ks
- low cycle does not matter for superbursts!

Superburster	MAXI Observation length (years)
4U 0614+091	0.61
4U 1254-69	0.80
4U 1636-536	0.63
GX 3+1	0.60
Ser X-1	0.61

- Combined exposure of 10 known superbursters ~6 yr
- If average wait time is 1 yr, 0.2% probability of not detecting a superburst ➔ any time soon now!

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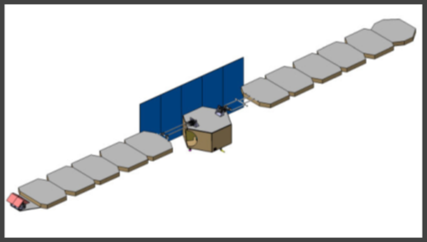
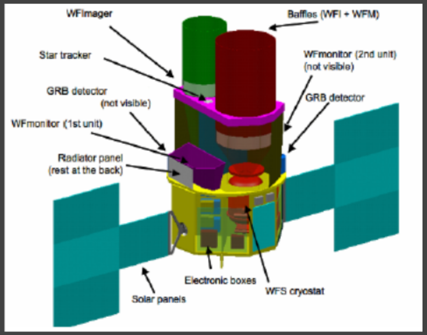
Future instrumentation = square meters: IXO or?..

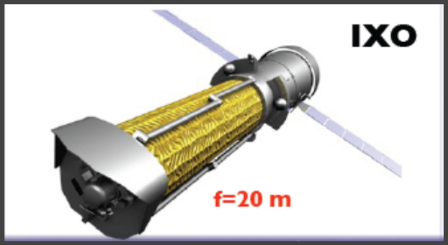
- **'next generation RXTE':** many square meters, no imaging (e.g., *AXTAR*, *LOFT*)



- **'next generation Swift':** more square cm for XRT & spectroscopy, X-ray monitor (e.g., *EDGE*, *XENIA*, *ORIGIN*)



- **'IXO pathfinder':** same square m, less spatial resolution, one detector (*GRAVITAS*)



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Conclusions

- Since the launch of RXTE and BeppoSAX in 1995/6, we are seeing many new details to thermonuclear burning on NS surfaces, such as
  - intermediate duration bursts
  - superbursts
  - first indications of narrow spectral features (lines+edges)
  - burst oscillations & mHz modulations in nuclear burning (next talk)
- which (may) provide new constraints on for instance
  - unique nuclear processes
  - thermal behavior of NS crusts
  - constitution of high-density interior
- MAXI will be instrumental to nail down superburst recurrence times and in providing superburst triggers for more sensitive telescopes such as those on XMM-Newton, better than ASM