Understanding superbursts

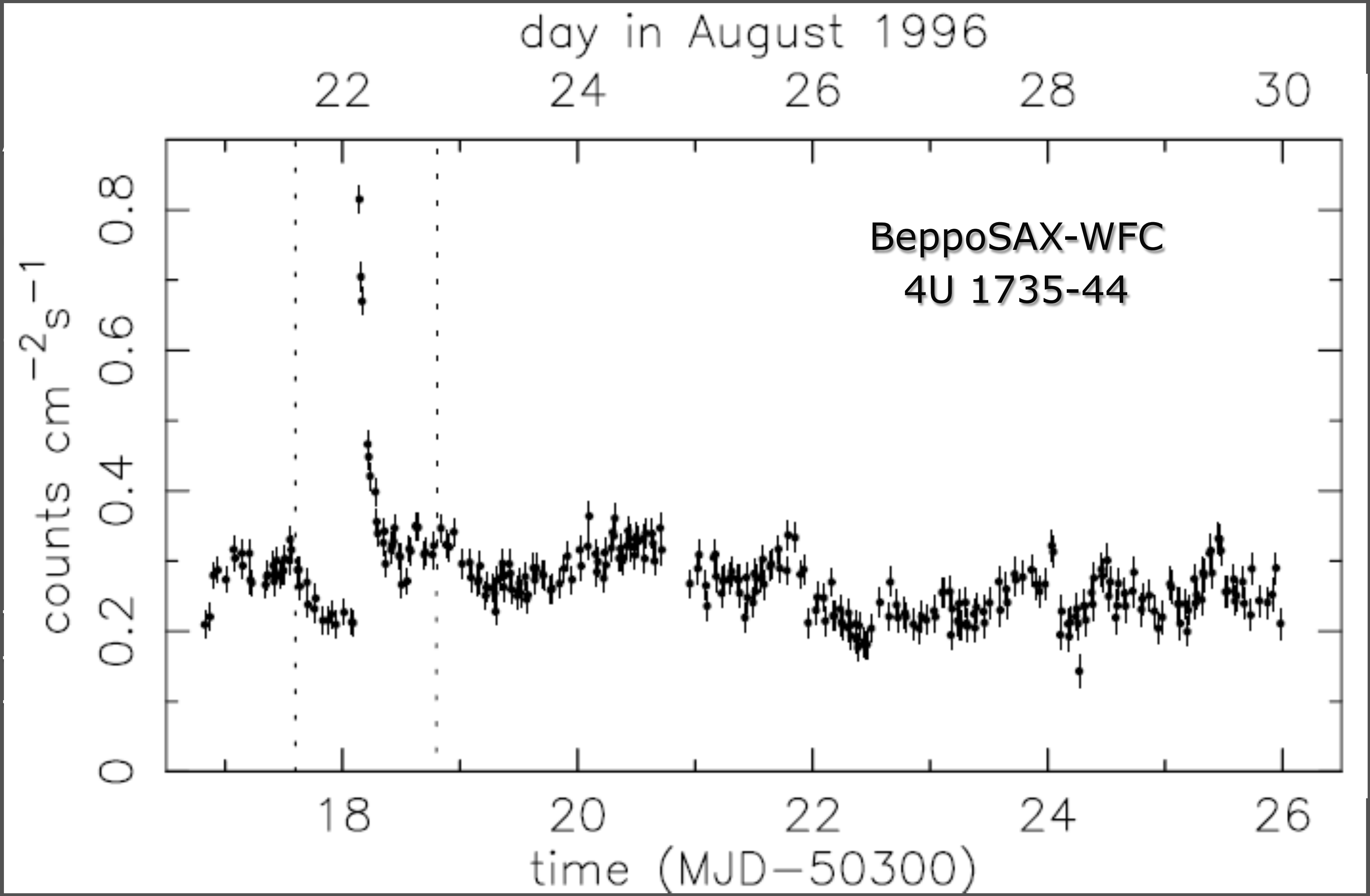
20 years after discovery

Jean in 't Zand
(SRON Netherlands Institute for Space Research)

Talk outline

- What is there to understand?
  - Observations
- What do we understand.. and what not?
  - Theory
- How can we understand more?
  - Future observations, instrumentation.

Discovery


day in August 1996
22
24
26
28
30
BeppoSAX-WFC
4U 1735-44
counts cm^{-2}s^{-1}
0
0.2
0.4
0.6
0.8
18
20
22
24
26
time (MJD−50300)

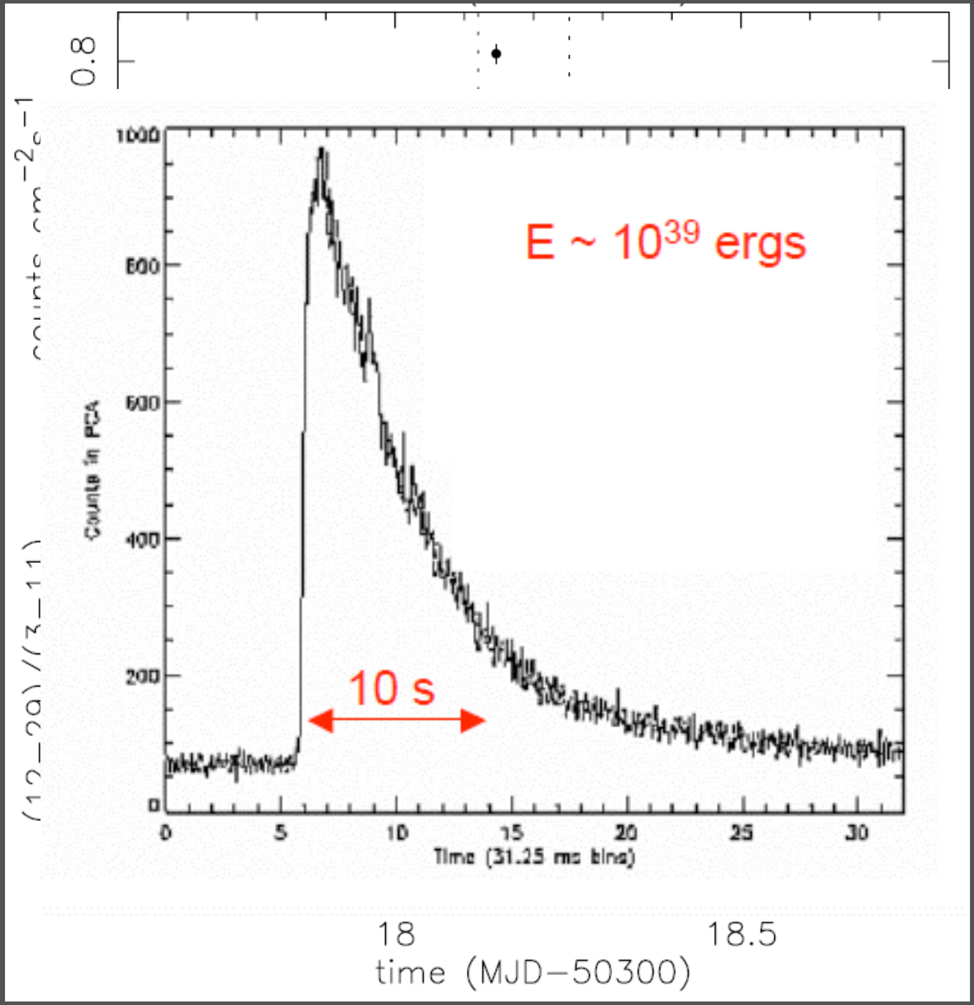
Discovery

- Fast rise, exponential decay
- Cooling in tail
- Black body spectrum
- Source type-I burster

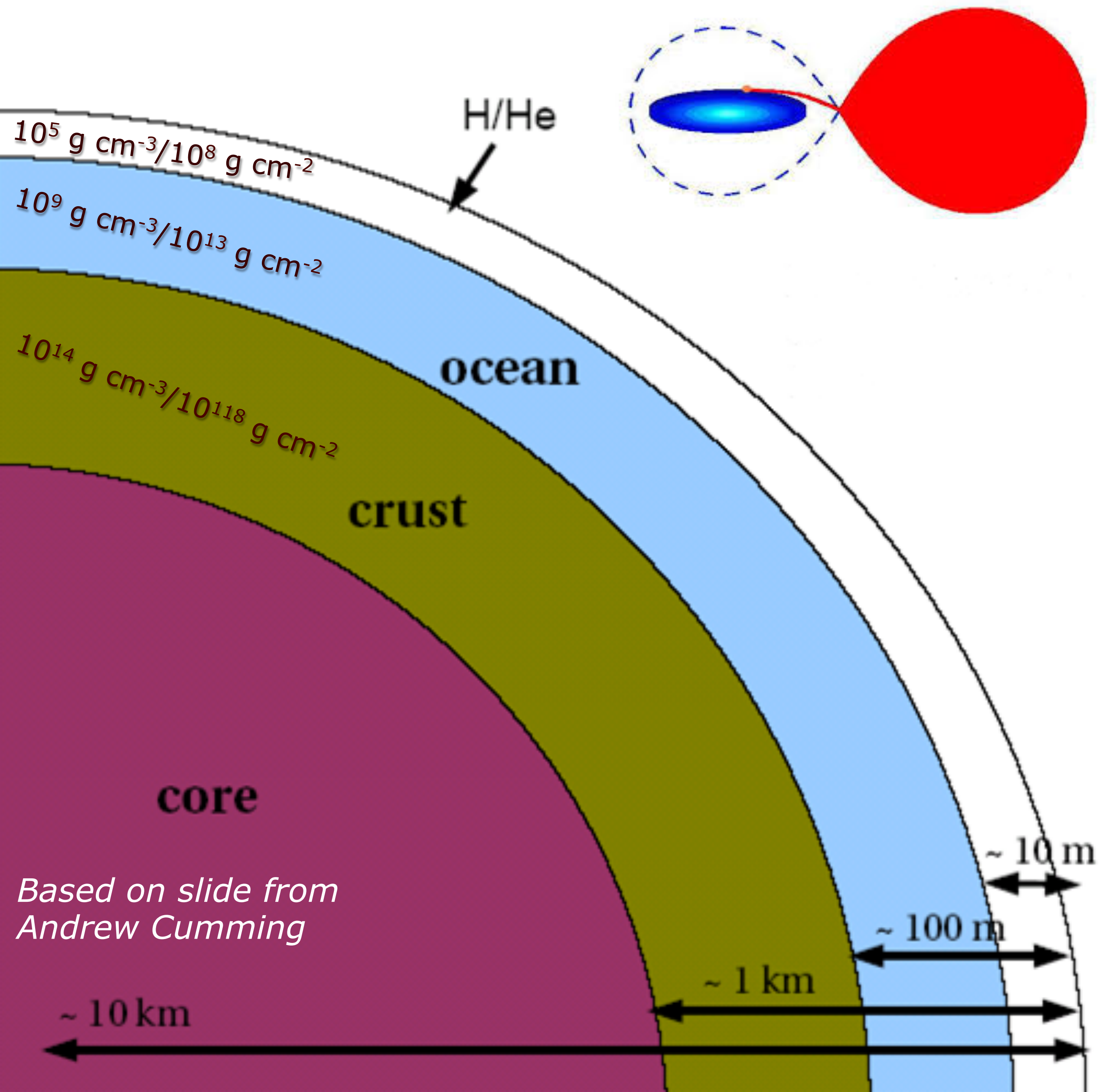
➔

- This looks like an exceptional type-I X-ray burst, 10^3 as long and 10^3 as energetic (see, e.g., poster Sakamoto P-10)

(Cornelisse et al. 2000)



Structure of an Accreting Neutron Star



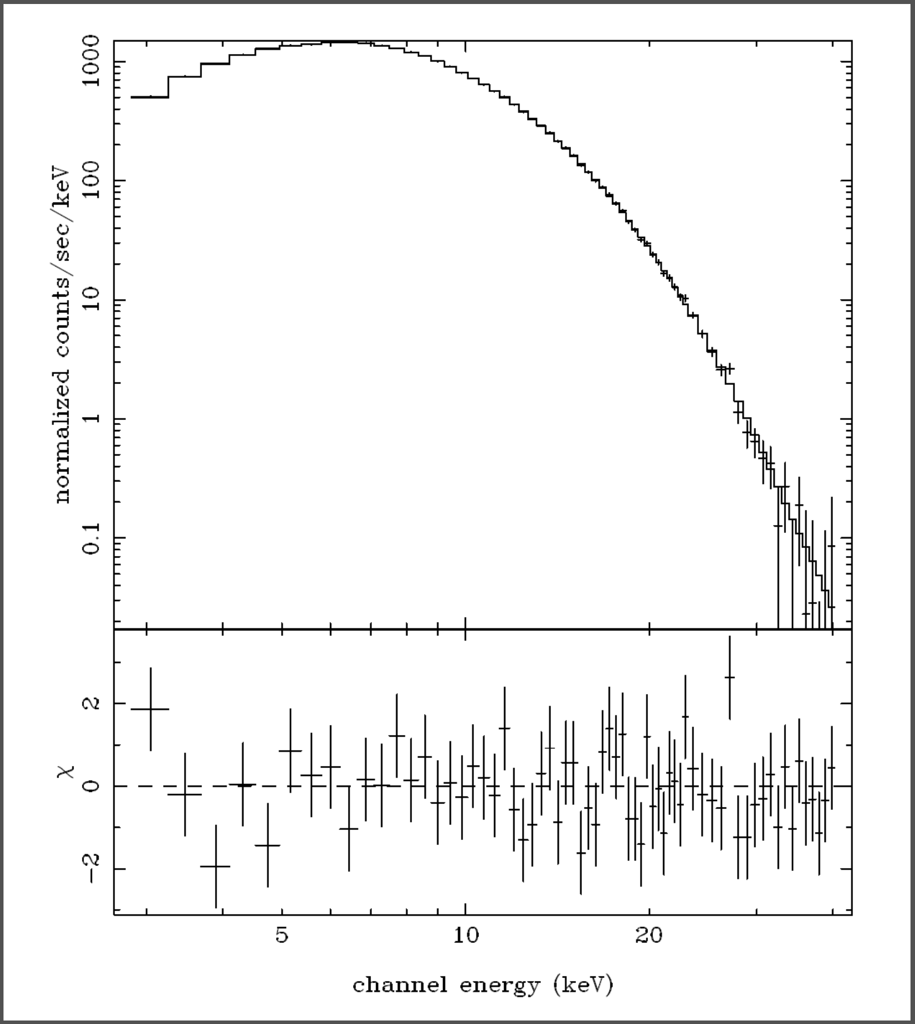
- Local accretion rate in low-B NSs 10 to 10^5 g s^{-1} cm^{-2}
- After hours to days, accumulate columns of $y=10^8$ gr cm^{-2} (cf, 10^3 for earth atmosphere)
- Pressure (y*g) builds up to ignition condition for runaway triple-alpha
- Can result in thermonuclear shell flash if

$$\frac{\partial \varepsilon_{nuc}}{\partial T} > \frac{\partial \varepsilon_{cool}}{\partial T}$$

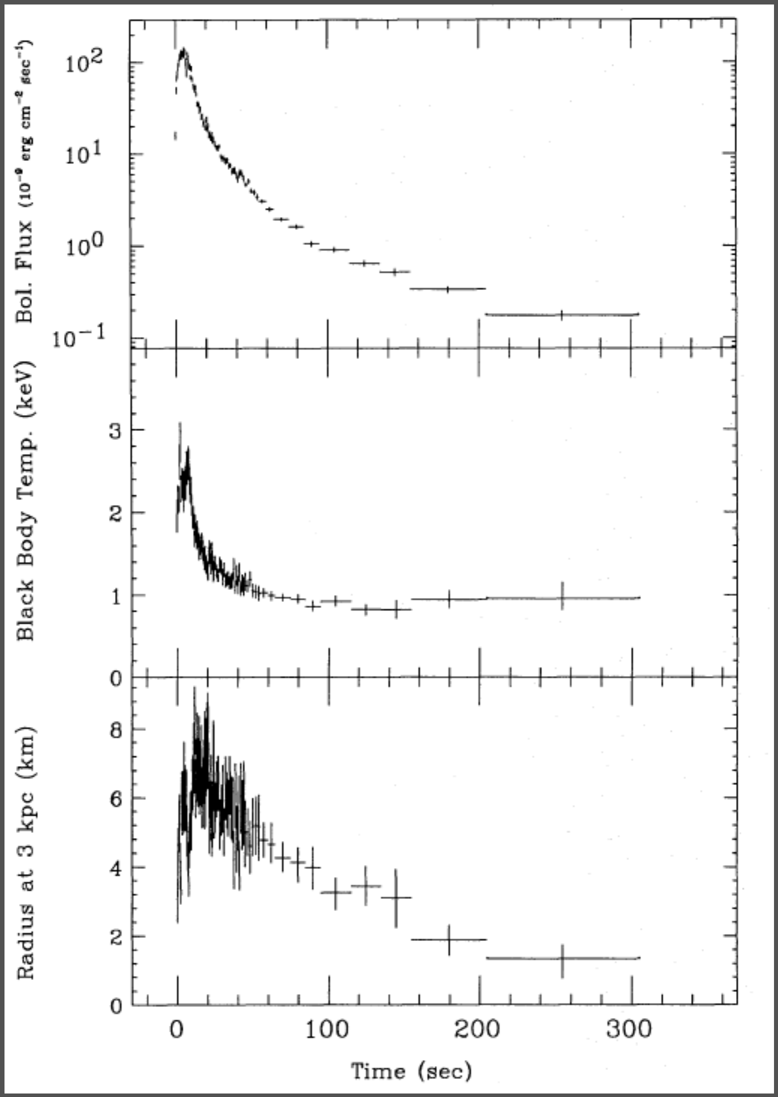
- Layer heats up to 10^9 K and then cools radiatively through 10^7 K photosphere →

X-ray burst

Cooling black body spectrum

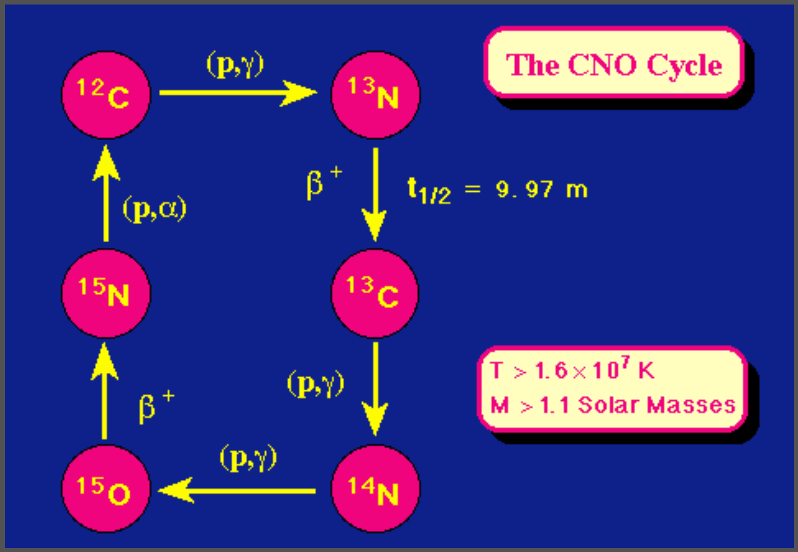


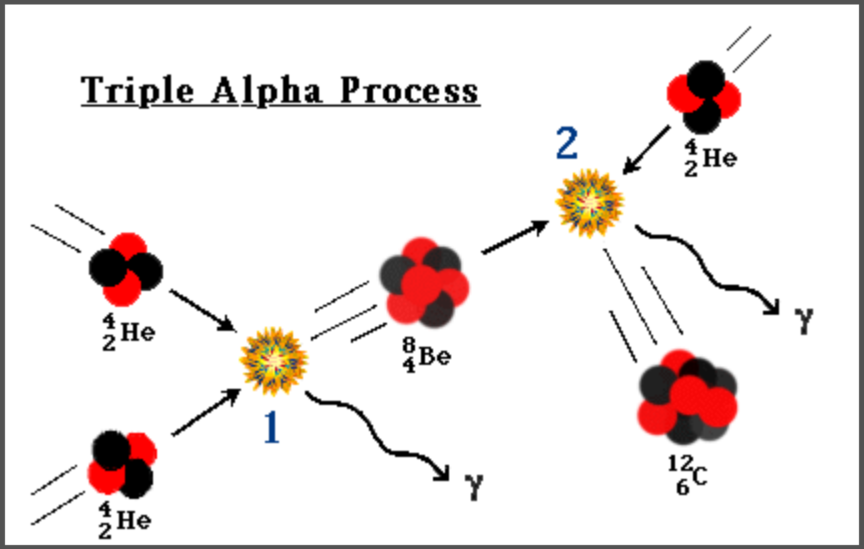
(Strohmayer & Brown 2002)

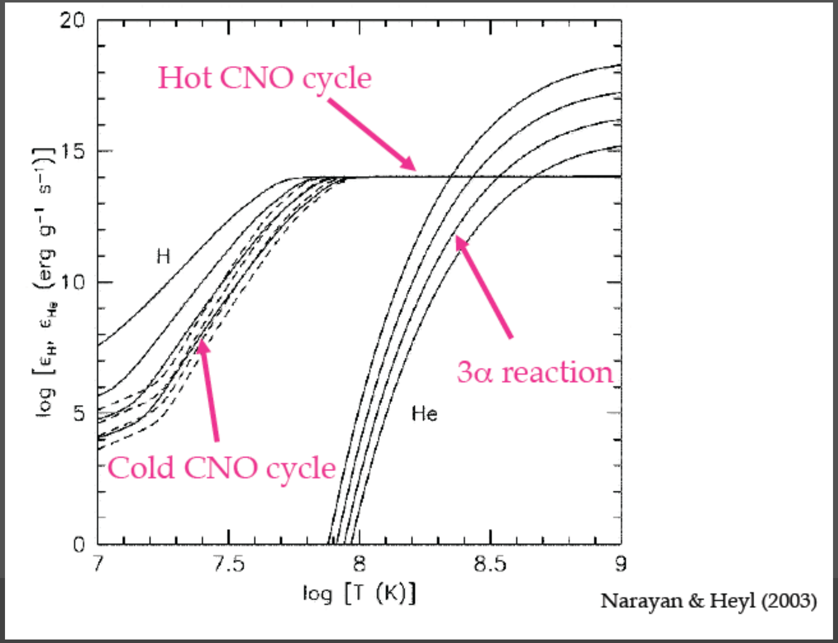


(Penninx et al. 1988)

Nuclear reactions: CNO cycle (H-burning) and 3-alpha (He burning)

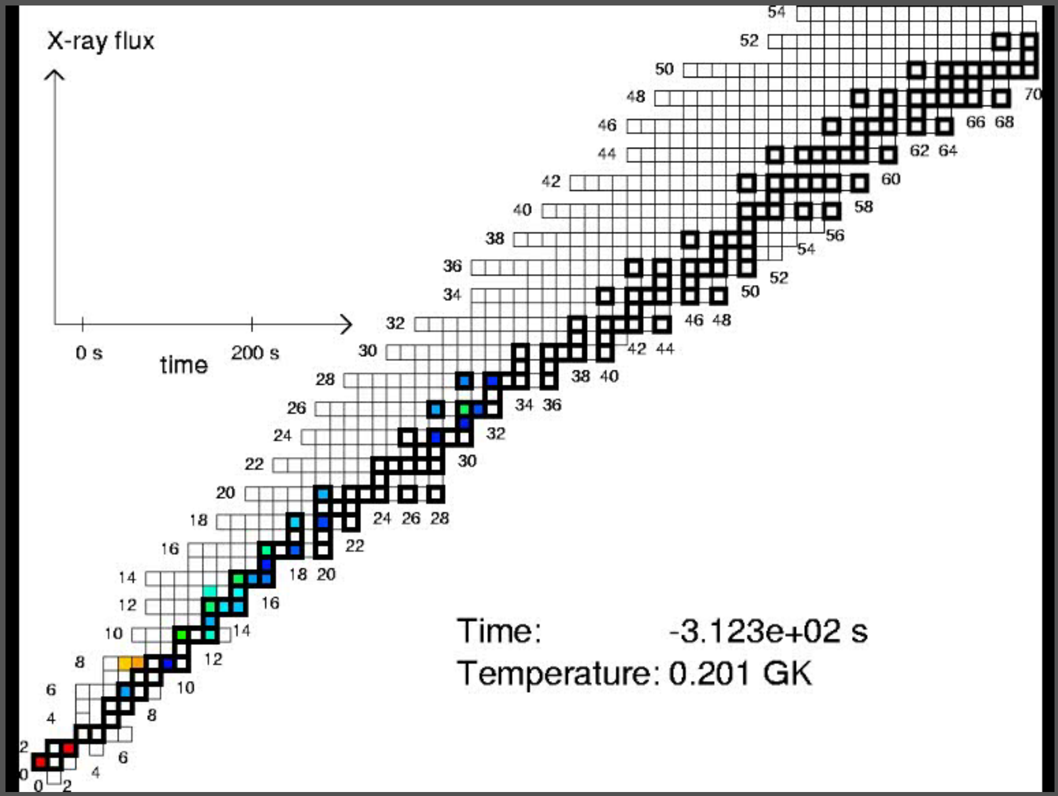






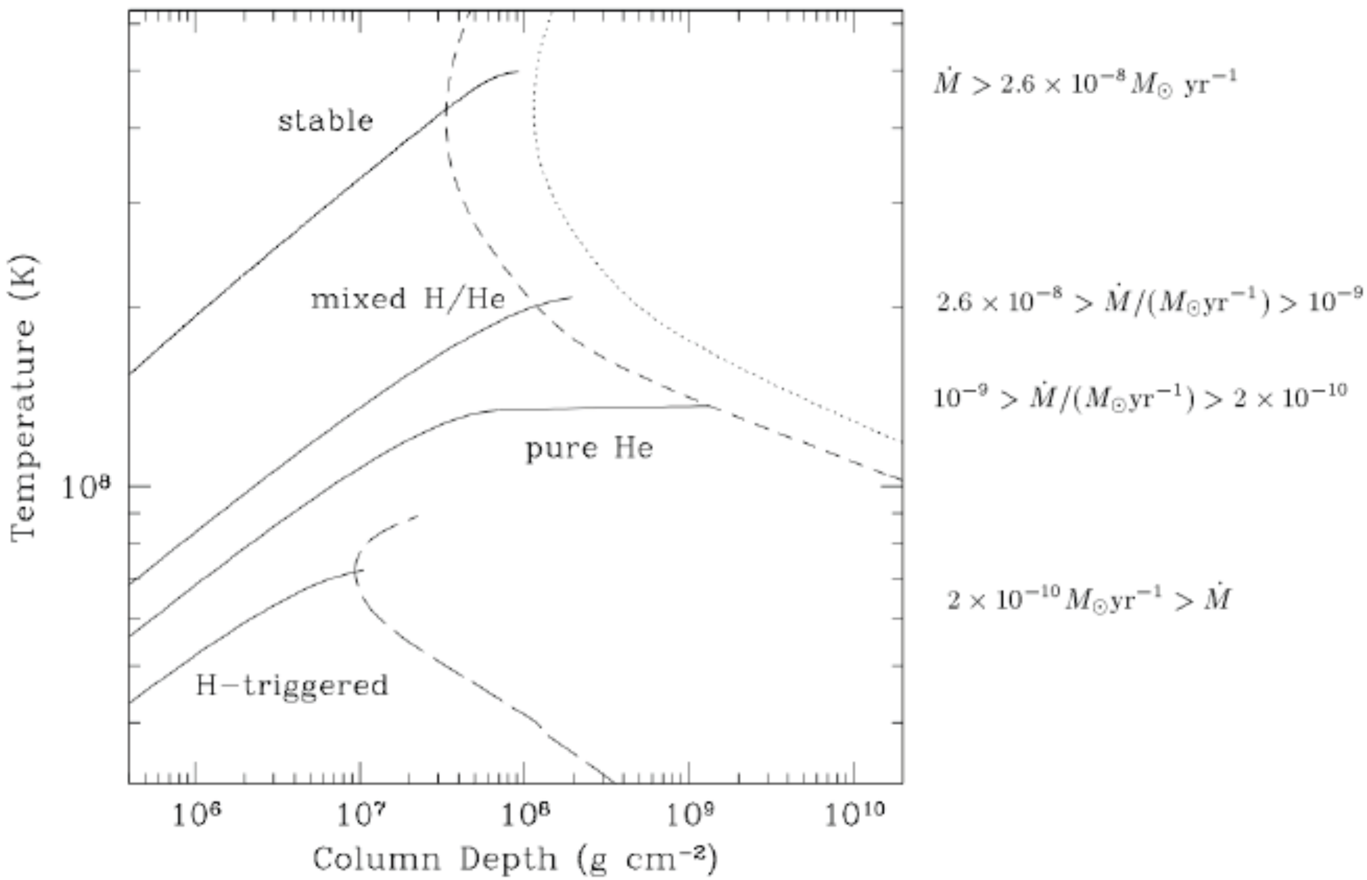
Nuclear reactions: the rp-process

- Series of (p, γ), (α,p) and beta+ decay reactions
- May extend up to mass number 100 (SnTe)
- Slow process because of beta decays
- Only active at the highest T, when waiting points are avoided through breakouts
- Slow process, may prolong burning by ~100 s
- Produces a lot of p-rich isotopes
- May explain abundances of p-rich isotopes of Mo and Ru



(Schatz et al. 1999)

Burning regimes



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

(Courtesy Andrew Cumming)

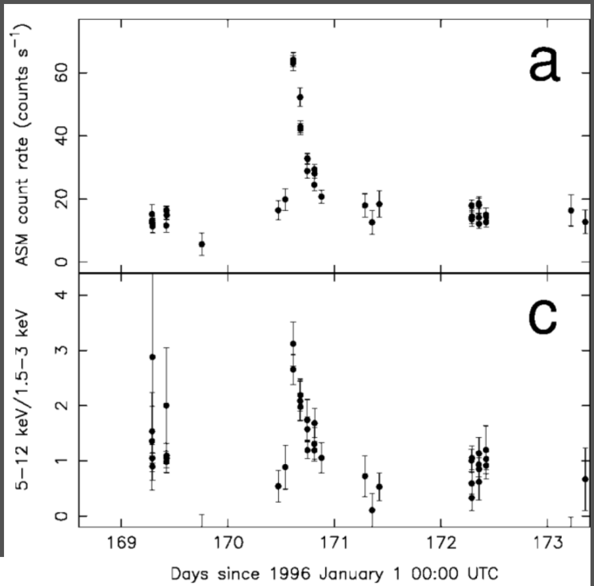
What makes superbursts 10^3x as long?

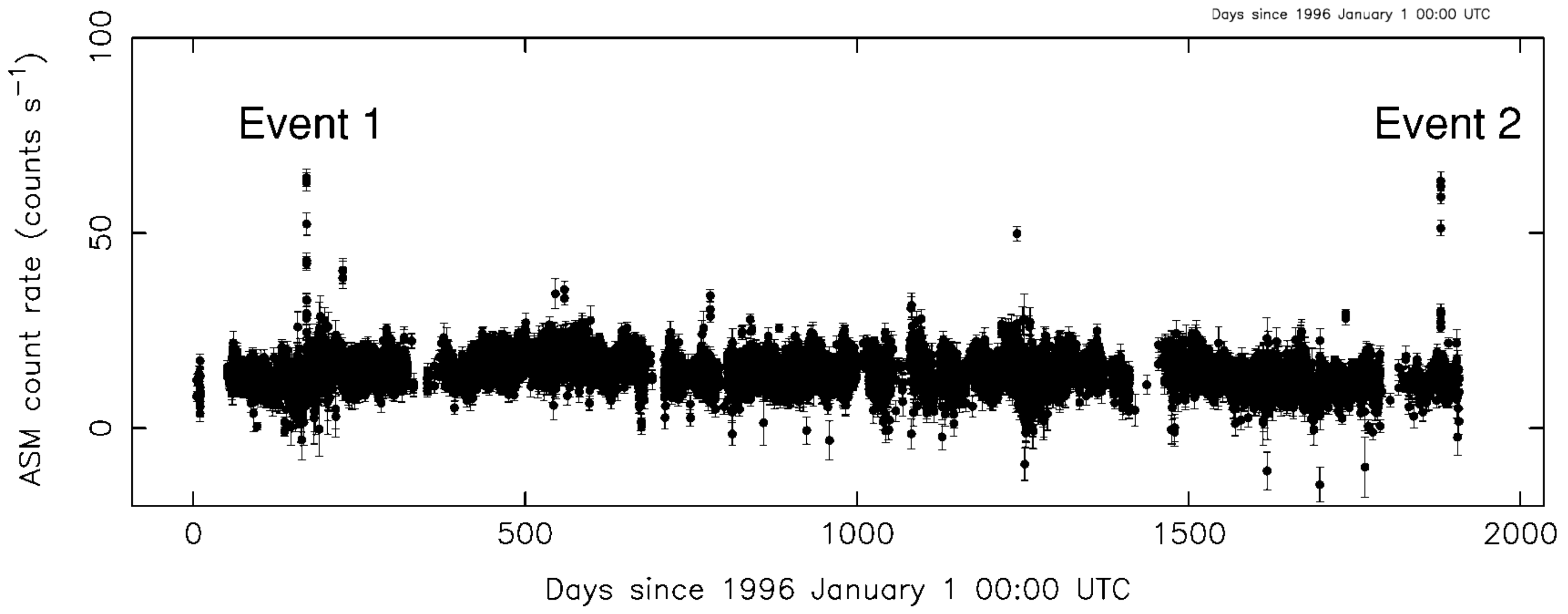
- Cooling rate is similar for all equal-sized neutron stars (Stefan-Boltzmann for thermal radiation)
- Longer cooling time → more mass to cool off
- → deeper ignition

Second.. and third superburst.. from same source

- In June 1996 and February 2001
- 4U 1636-536

(Wijnands 2001)





Superburst detected with much sensitive instrument

THE ASTROPHYSICAL JOURNAL, 566:1045–1059, 2002 February 20

A REMARKABLE 3 HOUR THERMONUCLEAR BURST FROM 4U 1820−30

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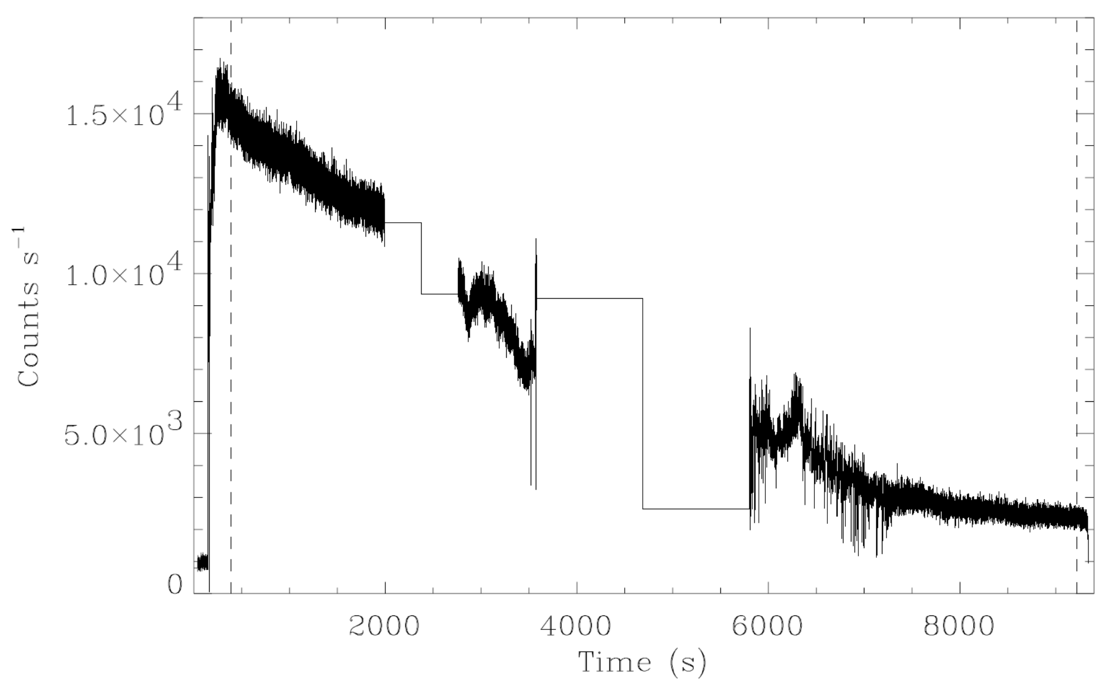
Received 2001 August 20; accepted 2001 October 25

ABSTRACT

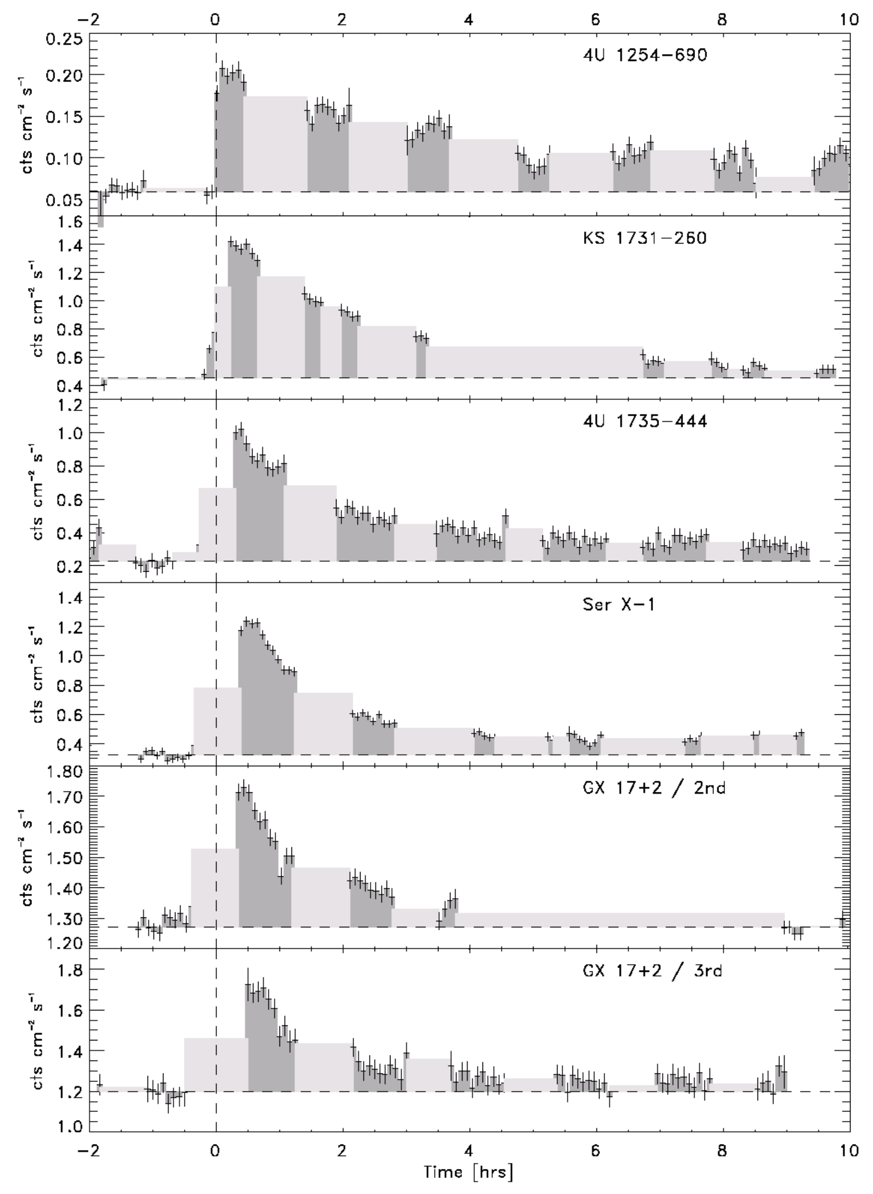
We present a detailed observational and th
"superburst") observed by the *Rossi X-Ray Timi*
4U 1820−30. This is the longest X-ray burst ev
longest ever observed in great detail from any sou
origin. Its peak luminosity of $\sim 3.4 \times 10^{38}$ ergs s
neutron star at ~7 kpc as well as the peak lumin
same source. The superburst begins in the decayi
clear burst. These shorter, more frequent bursts
level of the accretion-driven flux as well as the
indicate that helium could not be the energy sour



Suddenly, they are everywhere..

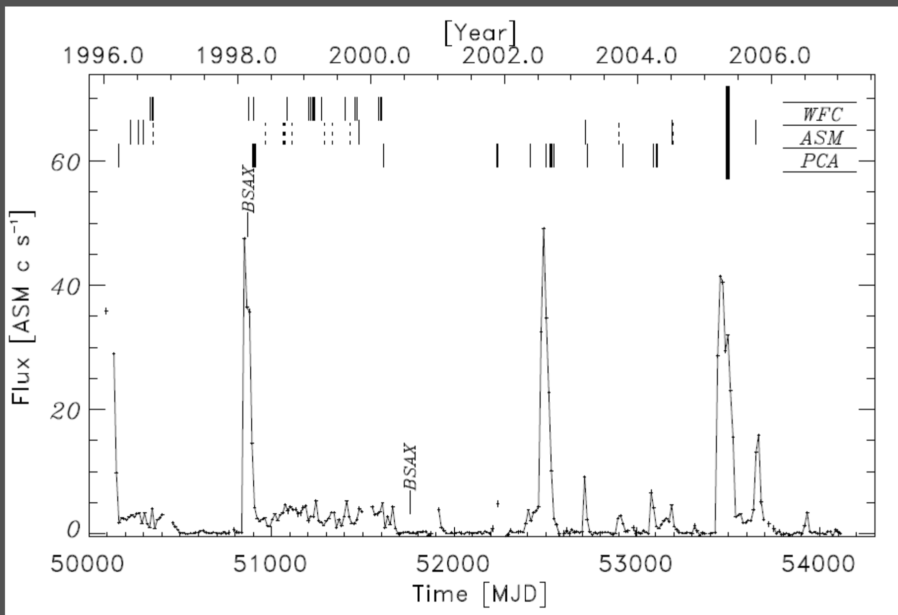
- WFC superburst from Ser X-1 (Cornelisse et al. 2002)
- 1st superburst in ASM data: GX 3+1 (Kuulkers et al. 2002)
- WFC superburst from KS 1731-260 (Kuulkers et al. 2002)
- PCA burst from 4U 1636-536 (Strohmayer & Markwardt 2002)
- WFC superburst from 4U 1254-69 (in 't Zand et al. 2003)
- WFC superbursts from GX 17+2 (in 't Zand et al. 2004)

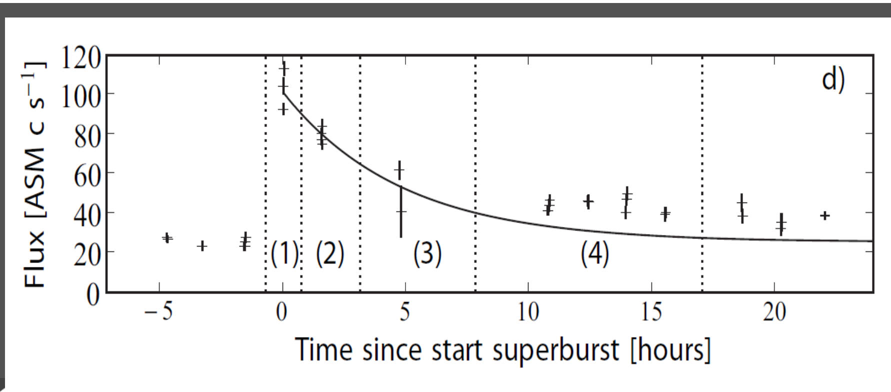
- 6 additional ASM superbursts: 2 from Ser X-1, 2 from 4U 1636-536, 1 from 4U 0614+09, 1 from 4U 1608-52

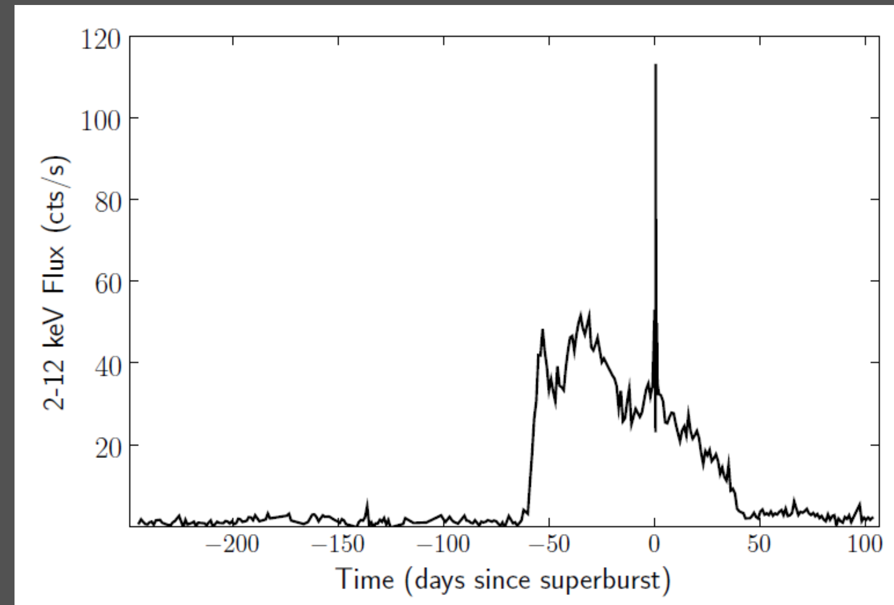


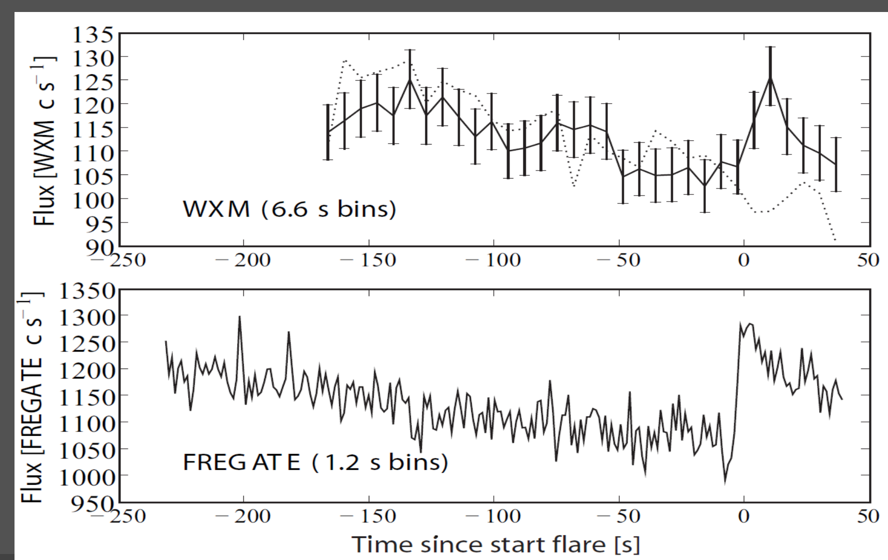
4U 1608-52: odd superburst

First time in a transient (Keek et al. 2008)



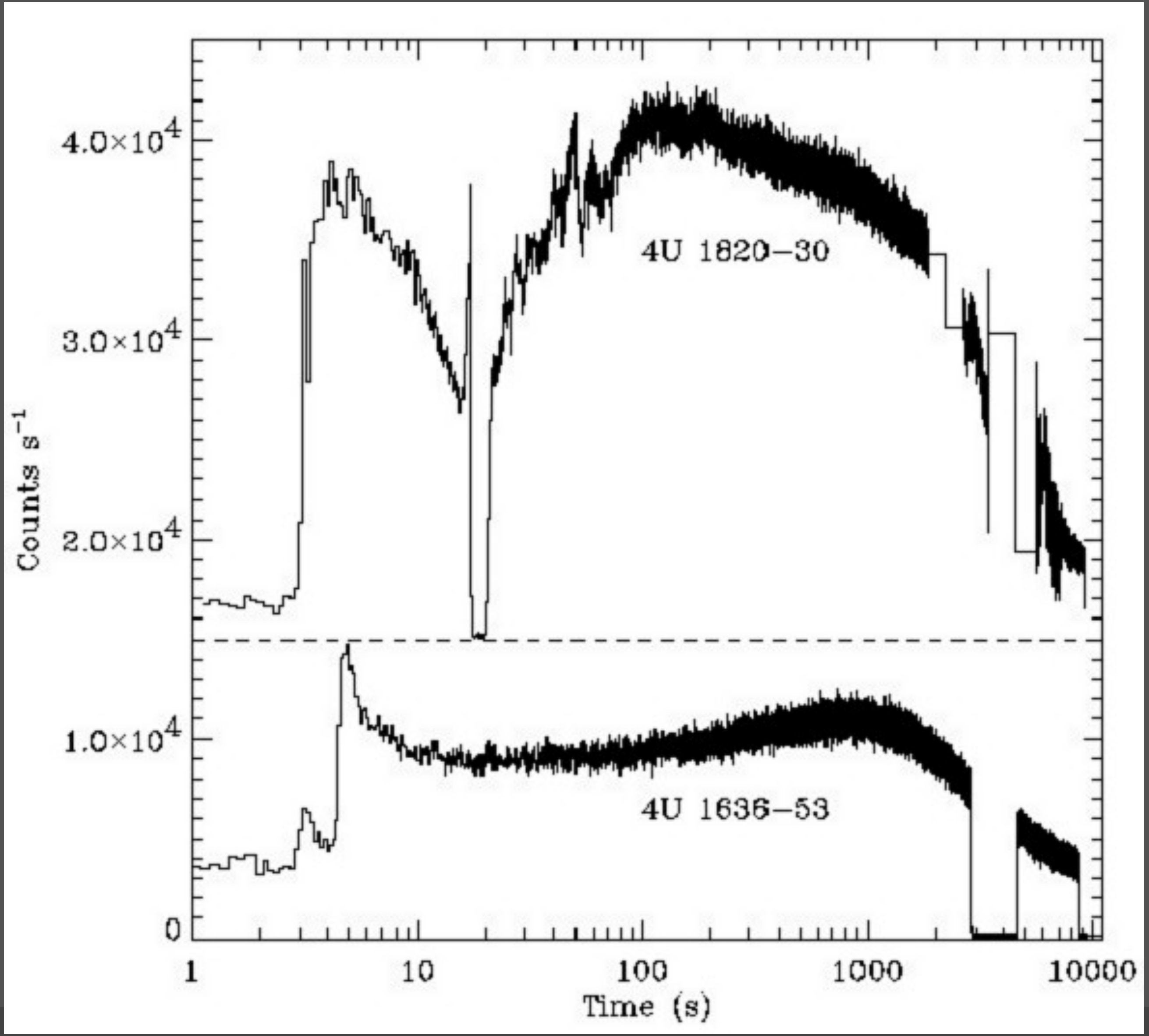






Superbursts with RXTE-PCA

- 10^2 times more effective area
- High diagnostic power, in time and spectral domain
- Coverage of onset



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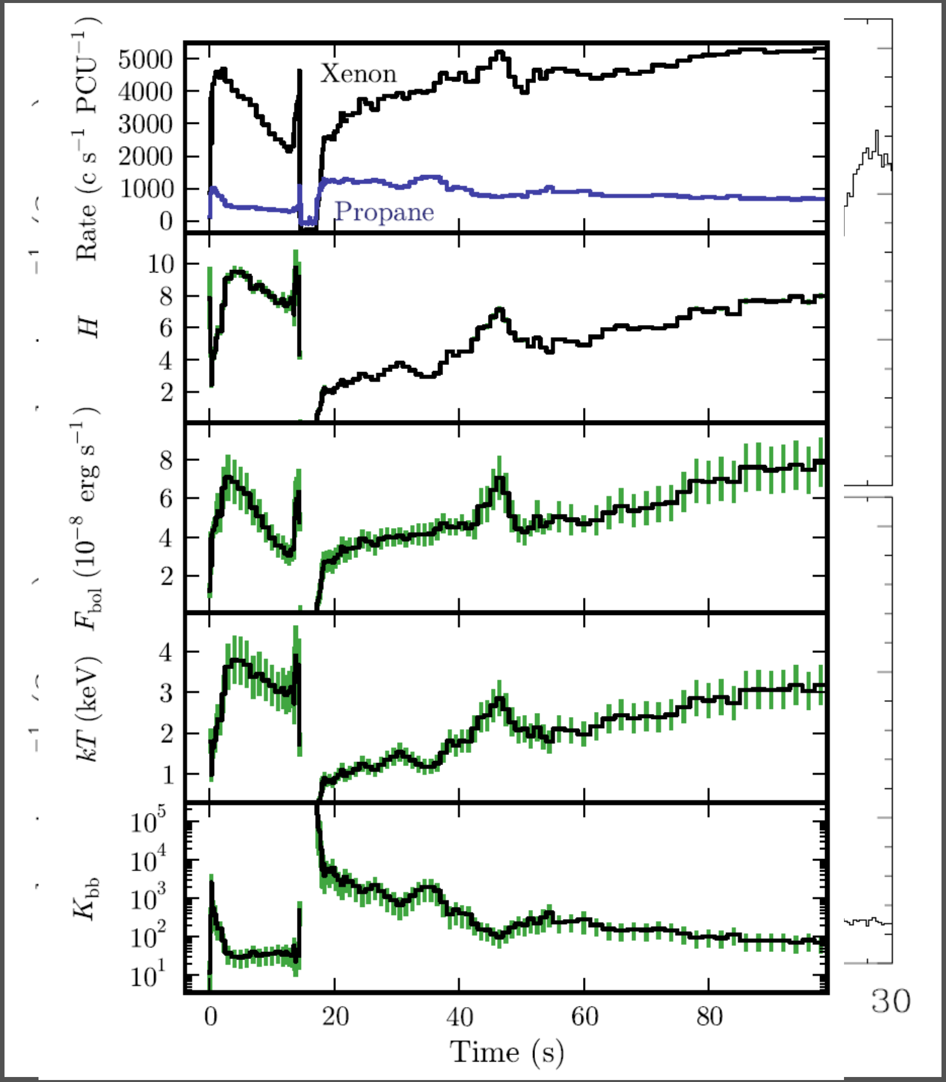
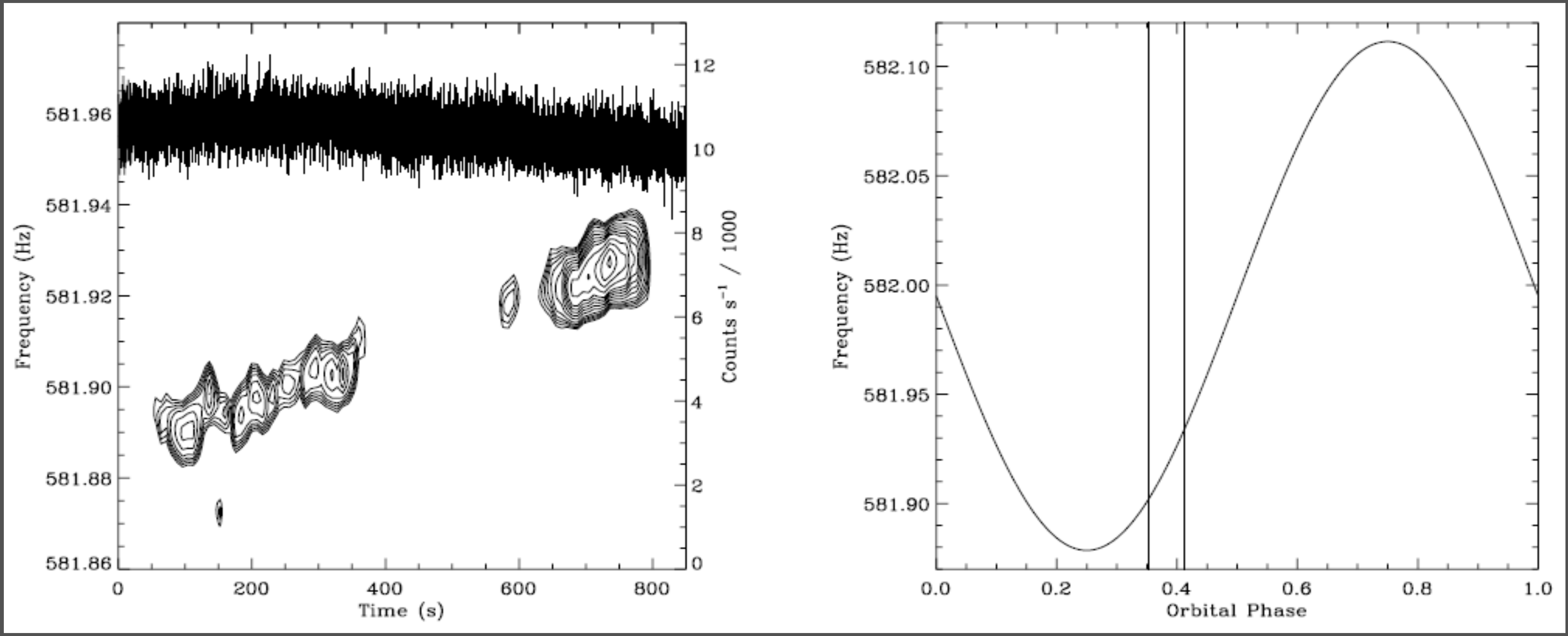
Superbursts with RXTE-PCA
Precursors in 4U 1820-30

- Two precursors → never seen before
- Weinberg et al. 2006:
  - 1st: shock breakout
  - 2nd: premature Helium flash due to same shock
- Keek et al. 2012:
  - 1st: shock breakout, fallback and premature helium flash.
  - 2nd: onset of superburst



Superbursts with RXTE-PCA
Burst oscillation in 4U 1636-536

- Extra long (~800 s)
- Frequency Doppler-shifted by binary orbit
- Amplitude ~10x smaller than in ordinary bursts
- Allows for constraint on donor mass (0.4-1.0 Msun)



(Strohmayer & Markwardt 2002)

Superburst population

See also next talk by Motoko Serino and poster P-19 by Wataru Iwakiri

Object	Instr./year	# SB	On-Set?	Exp. Decay (hr)	L_{pk} (10^{38} erg/s)	Reference SB discovery
4U 0614+091	ASM'05, MAXI'14	2		>1.5	>0.1	Kuulkers05, Serino14
4U 1254-69	WFC'99	1	1	6.0	0.4	Zand03
4U 1608-522	ASM+HETE'05	1	1	4.5	0.5	Remillard05, Keek08
4U 1636-536	ASM '96/'97/'98, PCA'01	4	1	1.5-3.1	1.3	Stroh02, Wij03, Kuu09
4U 1705-44	MAXI '16	1		2		Iwakiri poster
KS 1731-260	WFC'97	1	1	2.7	1.4	Kuulkers02
4U 1735-444	WFC'96	1		1.4	1.5	Cornelisse00
GX 3+1	ASM'99	1		1.6	0.8	Kuulkers02
GX 17+2	WFC'96/'01	4	2	0.7-1.9	1.8	Zand04
EXO 1745-248	MAXI+BAT'11**	1		10	0.7	Mihara11
SAX J1747-2843	JEM-X+MAXI' 11	1	1	~?	3	Chenevez11
4U 1820-303	PCA'99,MAXI+ASM'10*	2	1	~1	3.4	Stroh02,Zand11
Ser X-1	WFC'97, ASM'99/'08, MAXI'11	4		1.2	1.6	Cornelisse02, Kuu09, Iwakiri poster
SAX J1828-1037	MAXI'11**	1		2.3	0.7	Asada11
Aql X-1	MAXI'13	1		4.3	1.0	Serino16

*questioned by Serino et al. 2016
**questioned here

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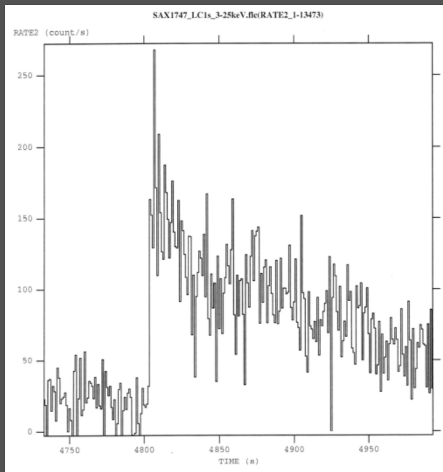
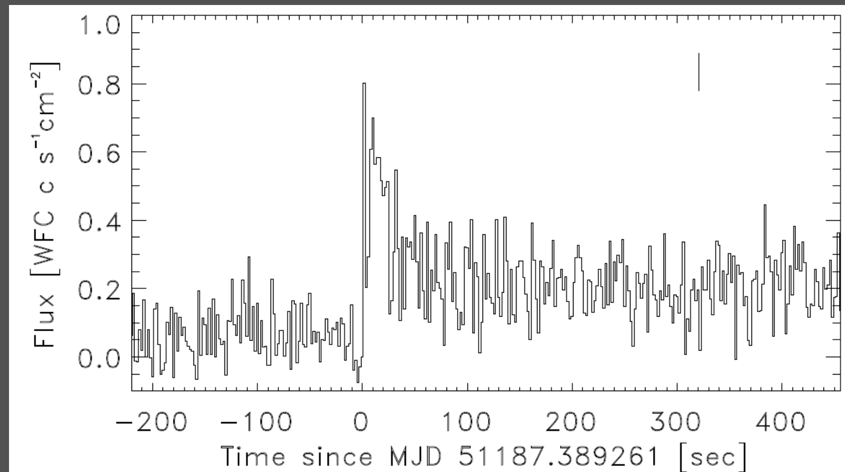
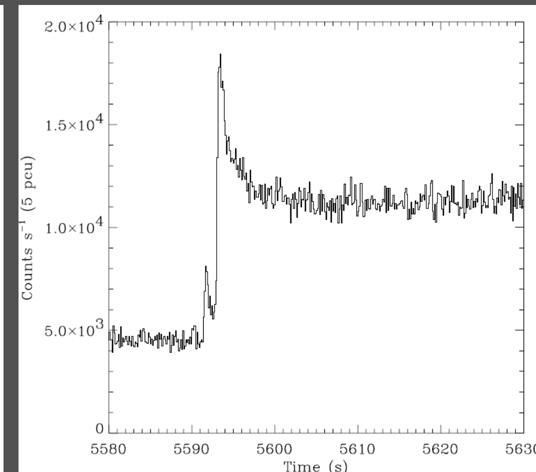
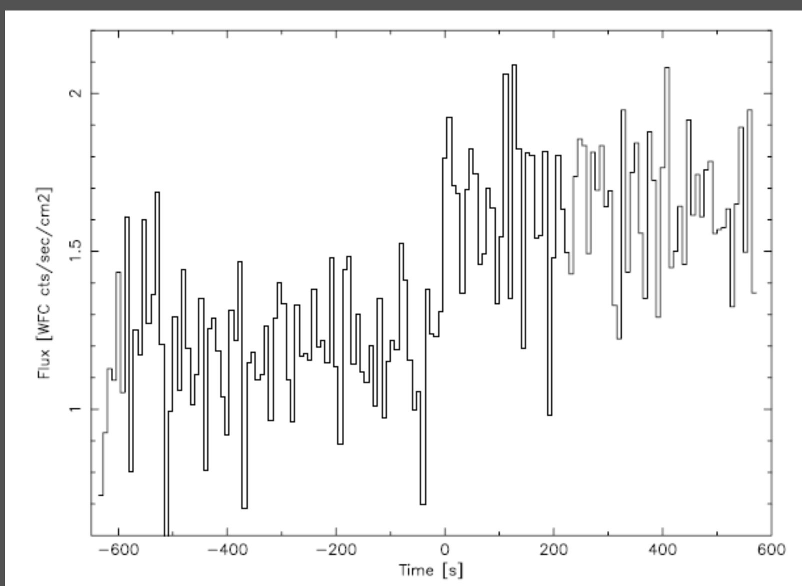
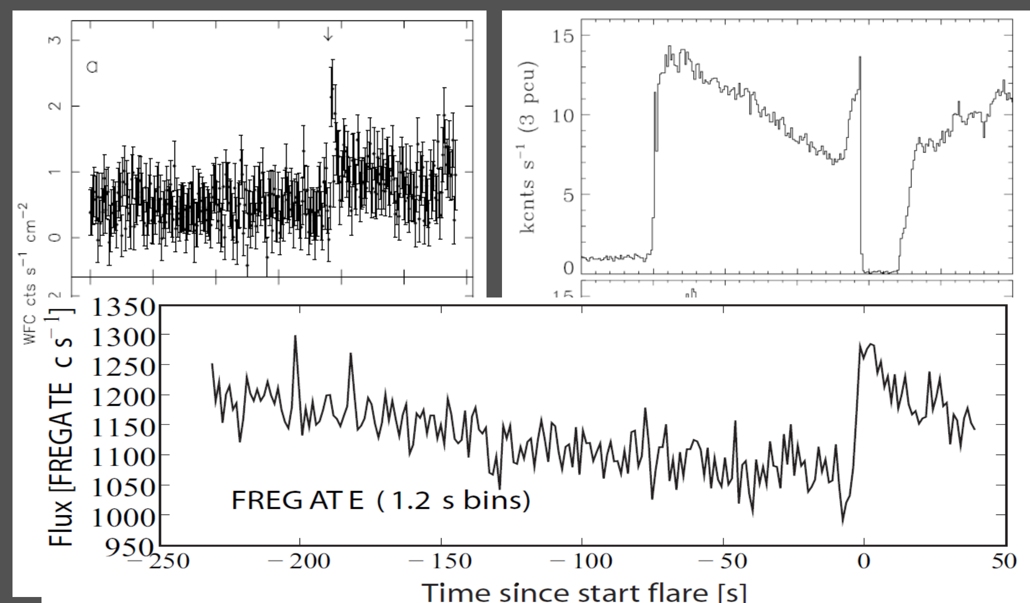
8 onsets, 7 shown











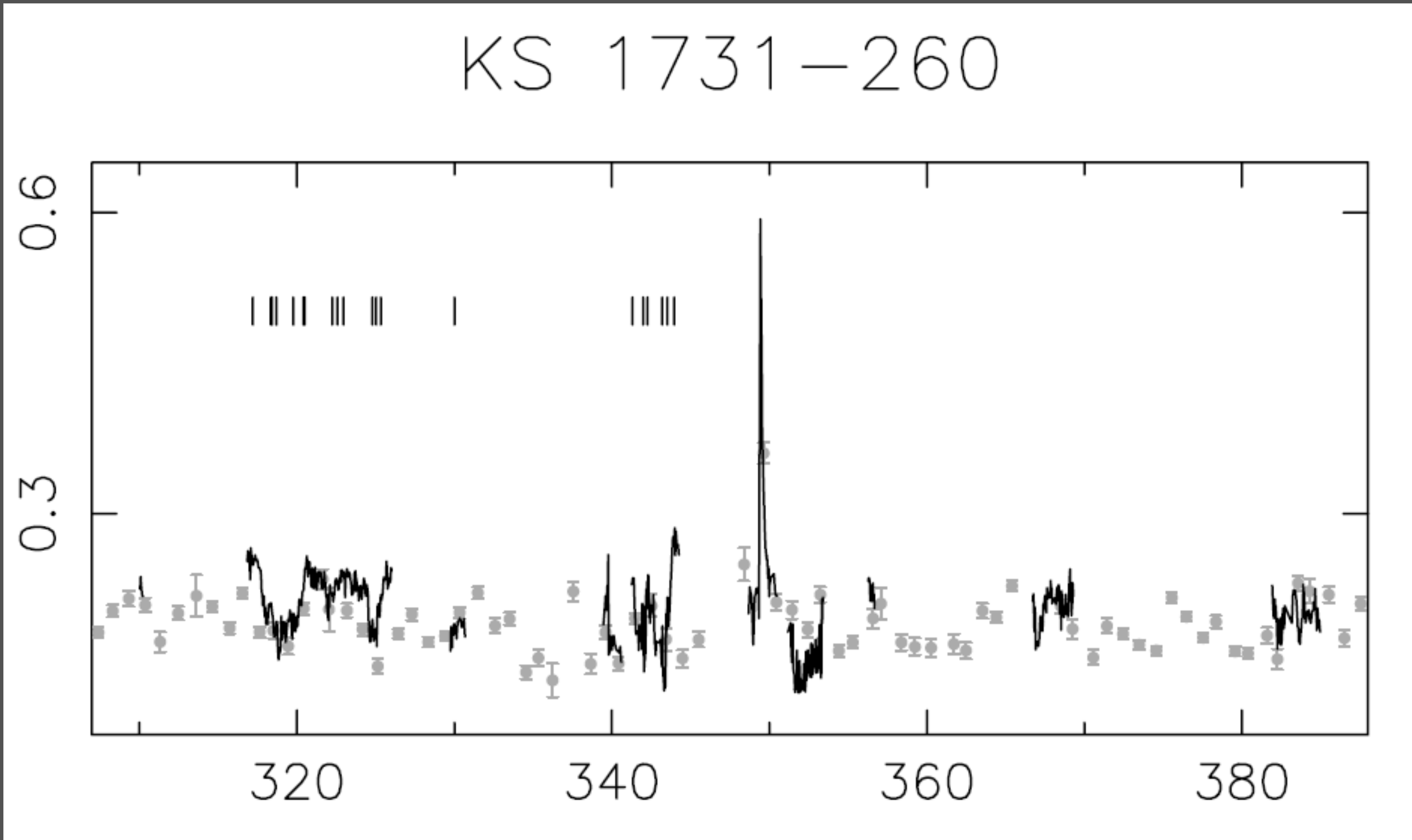
Superburst population / host binaries

Object	Instr./year	P_{orb} (min)	M / M_{edd}	Transient?	Normal burster as well?
4U 0614+091	ASM'05, MAXI'14	50?	0.01		Y
4U 1254-69	WFC'99	236	0.13		Y
4U 1608-522	ASM+HETE'05		0.03	y	Y
4U 1636-536	ASM '96/'97/'98, PCA'01	228	0.1		Y
4U 1705-44	MAXI '16				Y
KS 1731-260	WFC'97		0.1	(ong)	Y
4U 1735-444	WFC'96	279	0.25		Y
GX 3+1	ASM'99		0.2		Y
GX 17+2	WFC'96/'01	10d?	0.8		Y
EXO 1745-248	MAXI+BAT'11**		<0.01	y	Y
SAX J1747-2843	JEM-X+MAXI' 11		0.15	y	Y
4U 1820-303	PCA'99,MAXI +ASM'10*	11	0.1		Y
Ser X-1	WFC'97, ASM'99/'08, MAXI'11		0.2		Y
SAX J1828-1037	MAXI'11**		<0.01	y?	Y
Aql X-1	MAXI'13	1137	0.1	y	y

*questioned by Serino et al. 2016

**questioned here

Quenching of normal bursts after superbursts



(Kuulkers et al. 2004)

Superburst population / inferred depth and energy

Object	Instr./year	Nearest burst before and after (d)
4U 0614+091	ASM'05, MAXI'14	-367/+35
4U 1254-69	WFC'99	-51/+125
4U 1608-522	ASM+HETE'05	-57/+104
4U 1636-536	ASM '96/'97/'98, PCA'01	-2/+23
4U 1705-44	MAXI '16	
KS 1731-260	WFC'97	-6/+34
4U 1735-444	WFC'96	../+374
GX 3+1	ASM'99	-62/+94
GX 17+2	WFC'96/'01	
EXO 1745-248	MAXI+BAT'11	
SAX J1747-2843	JEM-X+MAXI' 11	-711/+25
4U 1820-303	PCA'99,MAXI+ASM'10*	-168/+167
Ser X-1	WFC'97, ASM'99/'08, MAXI'11	-162/+34
SAX J1828-1037	MAXI'11	
Aql X-1	MAXI'13	

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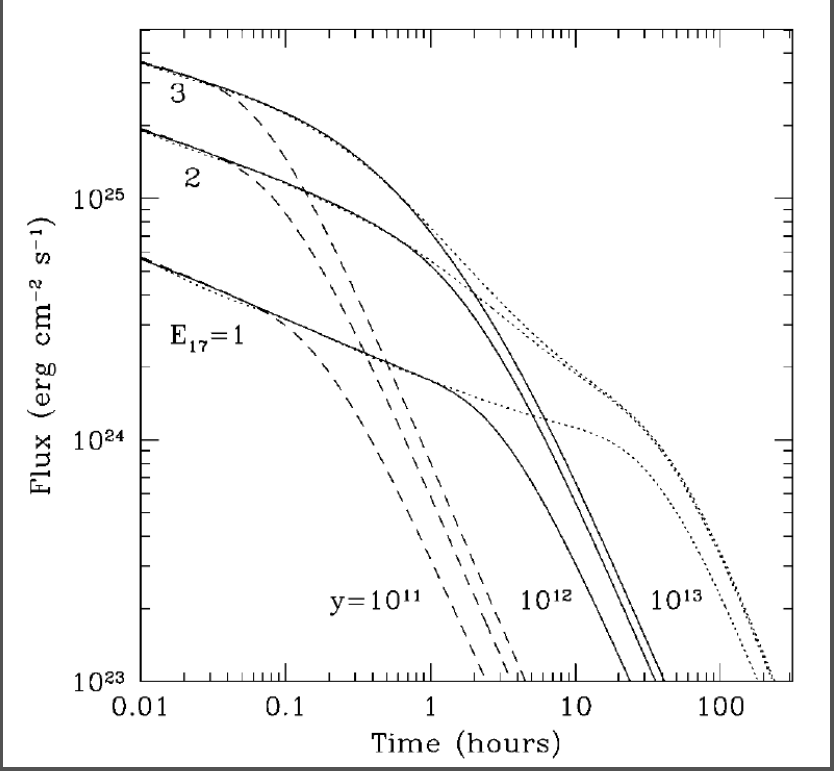
Diagnostics from light curve

- Cooling time measure for ignition depth
- Peak flux set by amount of energy released per gram
- Mass ignited determined by m-dot and recurrence time
- Quenching → probe of stable helium burning



(Cumming & Macbeth 2004)

Superburst population / inferred depth and energy

Object	Instr./year	Y (10^{12} g cm^{-2})	E (10^{17} erg g^{-1})
4U 0614+091	ASM'05, MAXI'14	0.2	5
4U 1254-69	WFC'99	2.7	1.5
4U 1608-522	ASM+HETE'05	3.0	1.5
4U 1636-536	ASM '96/'97/'98, PCA'01	0.5	2.6
4U 1705-44	MAXI '16		
KS 1731-260	WFC'97	1.0	1.9
4U 1735-444	WFC'96	1.3	2.6
GX 3+1	ASM'99		
GX 17+2	WFC'96/'01	0.6	1.8
EXO 1745-248	MAXI+BAT'11	1.0	2.5
SAX J1747-2843	JEM-X+MAXI' 11		
4U 1820-303	PCA'99,MAXI+ASM'10*	1	10
Ser X-1	WFC'97, ASM'99/'08, MAXI'11	0.6	2.3
SAX J1828-1037	MAXI'11		
Aql X-1	MAXI'13		

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Summary superburst detections 1996-2016

- 26 superbursts from 15 sources
  - 8 with WFC in 6 years
  - 9 with ASM in 16 years
  - 8 with MAXI (Serino+16, Iwakiri) in 7 seven years
  - 2 with PCA (1 double with ASM)
  - 1 with JEM-X (double with MAXI)
  - 1 with HETE-II (double with ASM) (there must be many more..?)
  - 1 with Swift-BAT (double with MAXI)
- All 15 superbursters are known normal bursters (=14% of population), but normal bursts are quenched
- Onset observed for 7 superbursts, none with low-duty cycle ASMs
- Transient and persistent sources, ultracompact and non-ultracompact binaries
- All mass accretion rates (<1-100% Eddington)
- 5 sources with multiple superbursts → recurrence of order 1 yr
- Ignition depths 0.2-3.0 x 10^{12} g cm^{-2} .
- Energy release 1.5-10.10^{18} erg g^{-1} .

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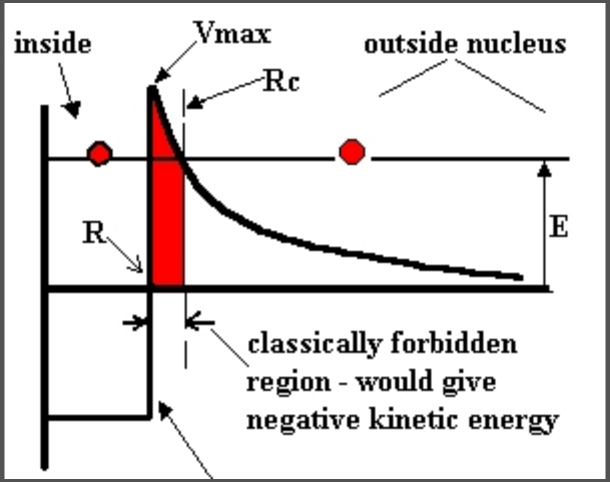
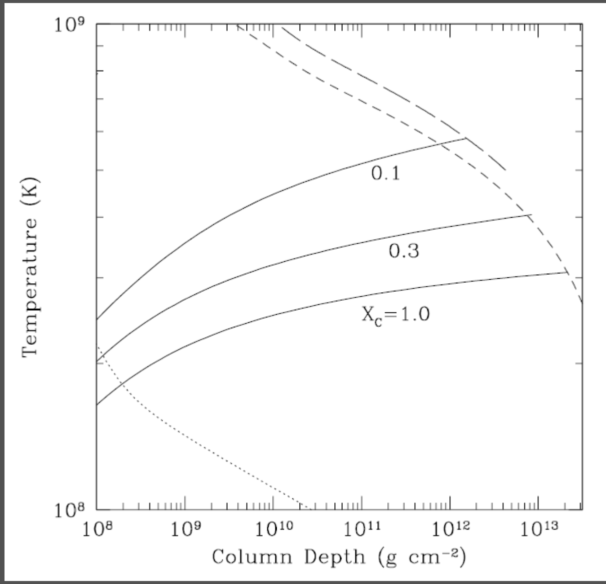
What fuel is burning?

- Deeper ignition → higher density/T → circumstances where heavier elements (with higher coulomb barriers) can fuse
- Ordinary bursts burn helium and hydrogen, what's next?
- H burns to He (in CNO cycle)
- He burns to C (in 3α process)
- → C burning





But, problem 1: how to obtain enough C?

- Plenty C produced in 3α, at least in non-transients, but it can be destroyed through proton and alpha captures, $^{12}C(p,\gamma)^{13}N$ and $^{12}C(\alpha,\gamma)^{16}O$
- These reactions are instigated at high temperatures (Coulomb barrier!) during bursts
- Solution: prevent normal bursts for some fraction of the time, run 3α in stable mode with smaller reactions rates at lower temperatures and let C sink out of the accretion layer
- Let normal bursts ignite elsewhere than in C-rich layer → make sure there is no H or He present

Problem 1
Nature seems to agree with this

Table 2. Average burst properties of all superbursters (above the dividing line) and six non-superbursters, as observed with BeppoSAX-WFC.

Object name	$T_C^{(a)}$	$\alpha^{(b)}$	$\alpha^{(c)}$	$\tau^{(d)}$ [sec]
4U 1254-690	4.6	4800		6 ± 2 (15)
4U 1636-536	0.6	440	44-336[1]	6.2 ± 0.1 (67)
KS 1731-260[e]	0.8	780	30-690[2]	5.6 ± 0.2 (37)
4U 1735-444	2.4	4400	220-7728[3]	3.2 ± 0.3 (34)
GX 3+1	1.2	2100	1700-21000[4]	4.6 ± 0.1 (61)
4U 1820-303	1.5	2200		4.5 ± 0.2 (47)
Ser X-1	2.9	5800		5.7 ± 0.9 (7)
EXO 0748-676	1.0	140	18-34[5]	12.8 ± 0.4 (155)
4U 1702-429	0.3	58		7.7 ± 0.2 (107)
4U 1705-44	1.1	1600	55–1455[6]	8.7 ± 0.4 (74)
GX 354–0	0.2	97	105-140[7]	4.7 ± 0.1 (417)
A 1742-294	0.4	130		16.8 ± 1.0 (141)
GS 1826-24	0.2	32	41[8]	30.8 ± 1.5 (248)

(in 't Zand+ 2003)

gravitational energy release

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

nuclear energy release

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

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

$$\approx (40-100)$$

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Problem 1
how to accomplish stable burning?

- Stevens et al. 2014: let rp process eat up the protons that cannot capture on carbon anymore → let rp process run faster than 3a process
  - Many uncertainties in reaction cross sections

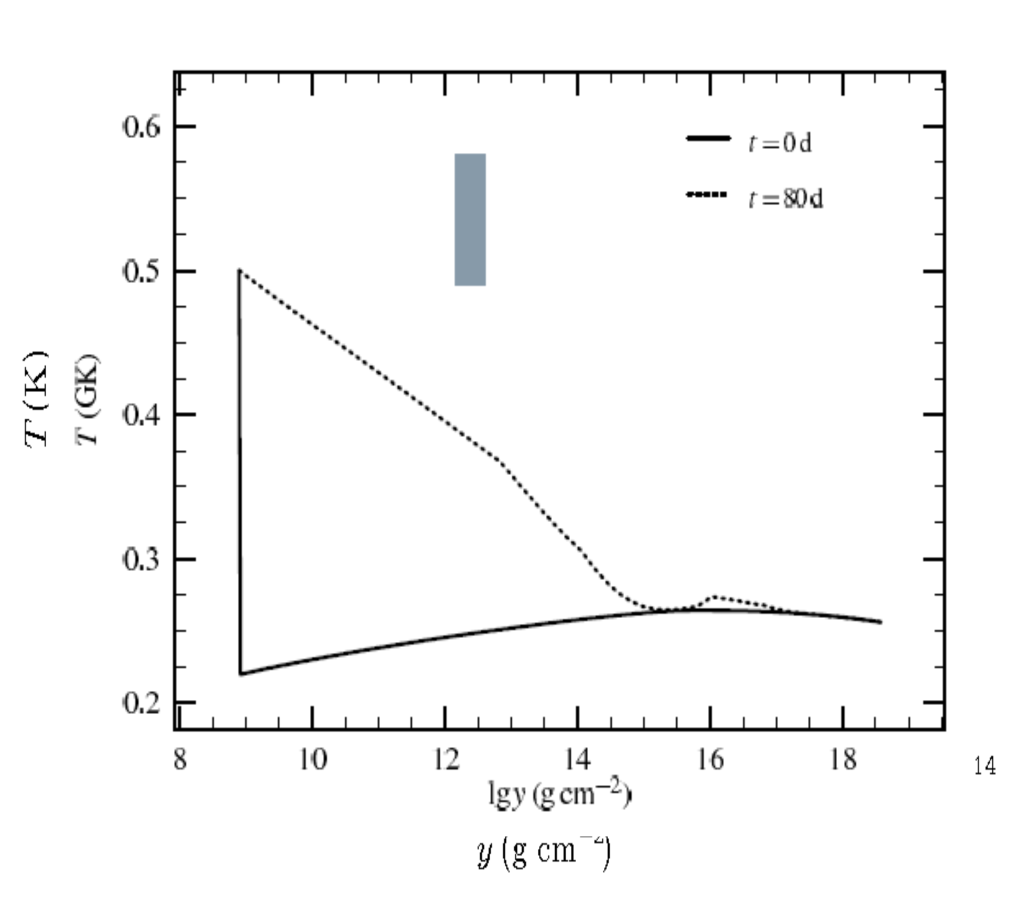
- Keek & Heger 2016: new regime of stable hydrogen burning increasing 3α rate without going runaway
  - In layer where H is exhausted by hot CNO cycle

Problem 2: how to ignite the Carbon?

- As the ignition curve shows, one needs $T>6.10^8$ K for ignition at this depth

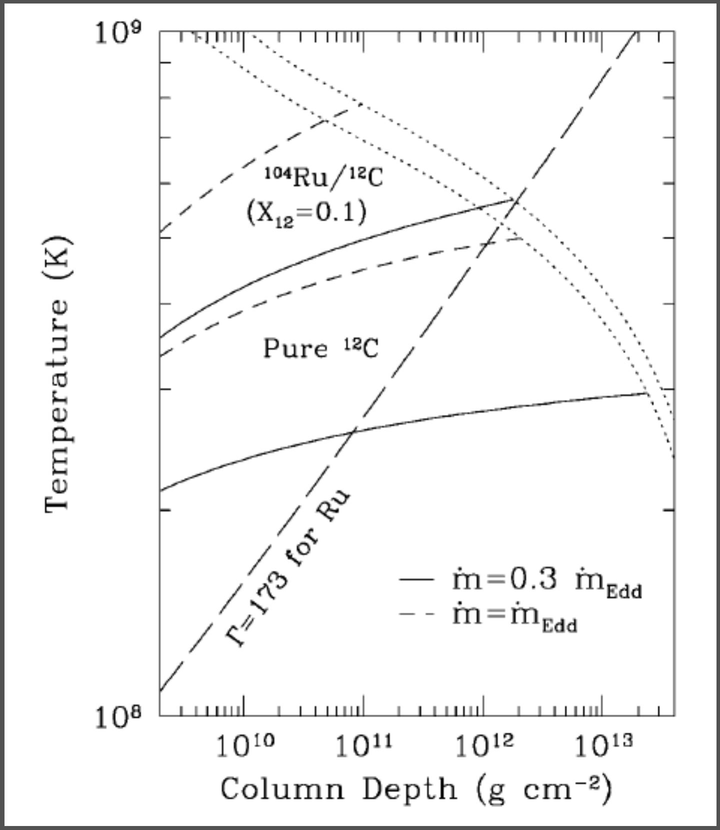
- That is a problem. Crustal heating by electron capture and pycnonuclear reactions (prop. To M-dot) provides insufficient heating (most goes inward instead of outward). 0.1 MeV/nucleon

- Problem aggravated by superbursts in transients



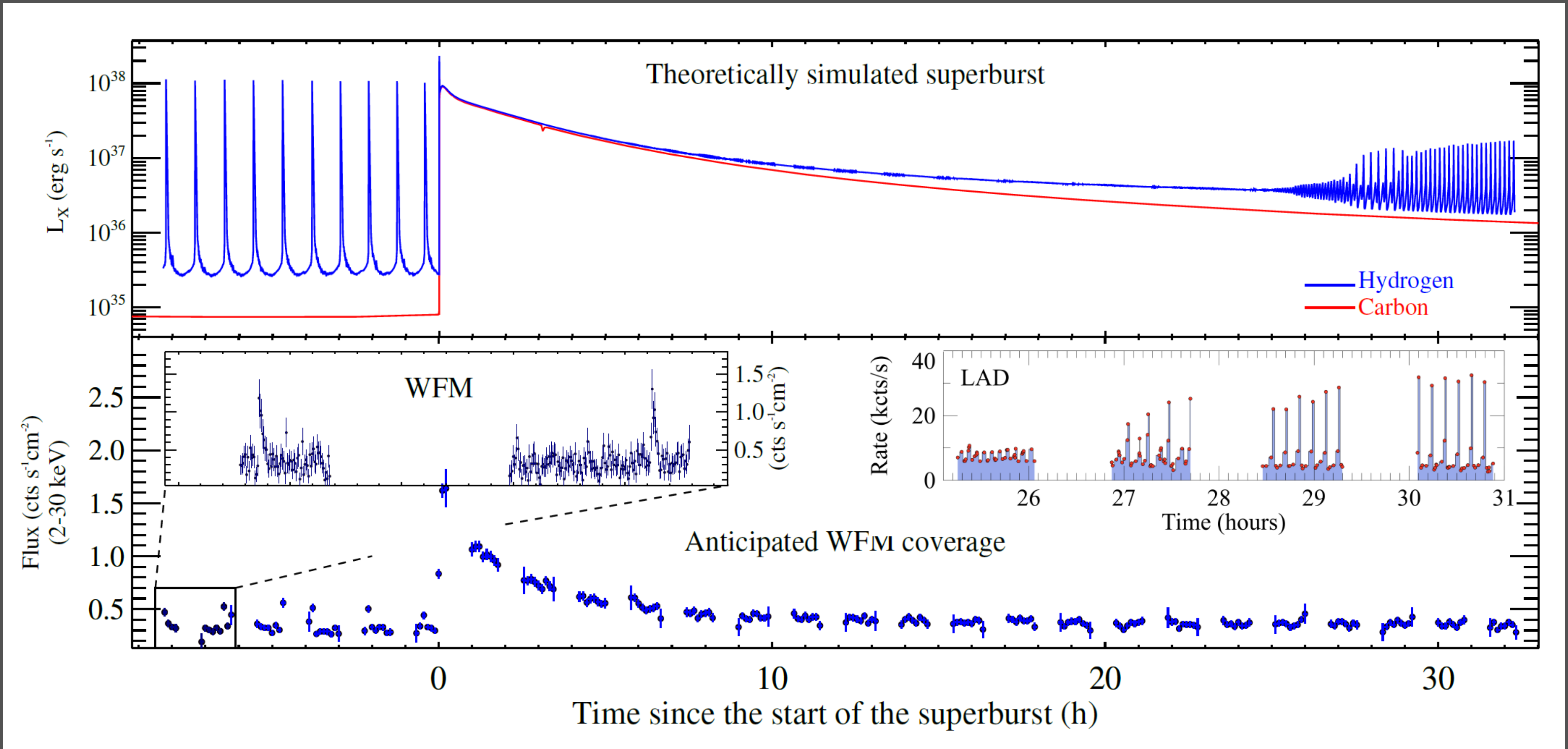
Problem 2

- Problem initially solved by decreasing layer conductivity (Cumming & Bildsten 2001) or increasing ignition depth while releasing much energy non-radiatively (Strohmayer and Brown 2002)
- Problem worsened after superburst were being detected from transient accretors (Keek et al. 2008, Mihara/Serino/ Altamirano et al. 2012, Chenevez et al. 2008, Serino et al. 2016)
- Aggravated by new strong neutrino cooling calculations in crust (efficient URCA cooling; Schatz et al. 2014) and in deep ocean (Deibel et al. 2016)
- Issue unresolved, need independent temperature measurements of crust or ttink of shallow heating process



The aftermath
from stable to unstable burning

- LOFT, eXTP or Strobe-X



The future

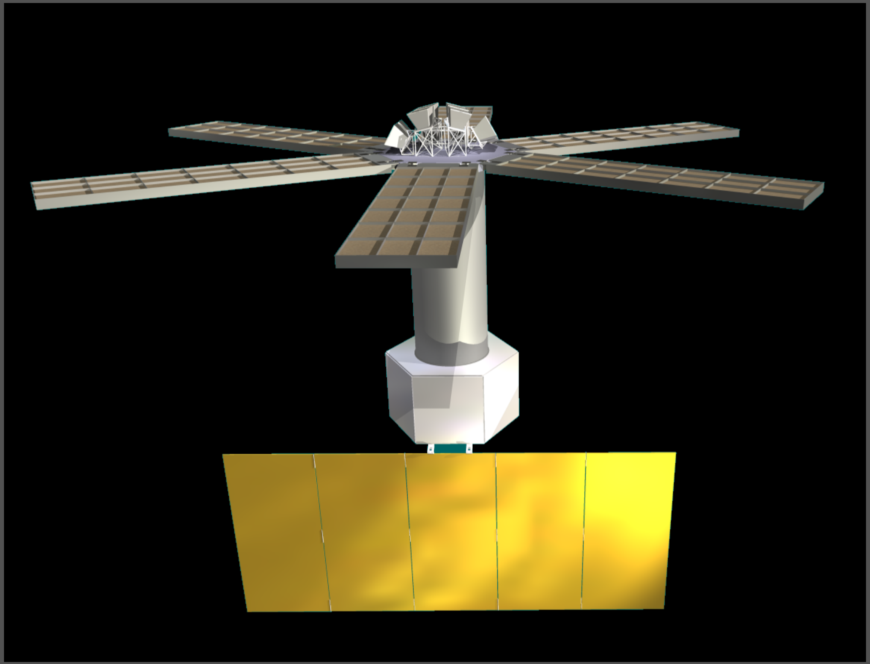
- Theory: simulate nuclear burning even more extensively, updating with new cross sections and neutrino processes. Search for shallow heating process

- Observations: Fill lack of superburst onsets → probe of shocks that depend on ignition depth
- Fill lack of superburst aftermath →
  - burst quenching measurements, extra probe of ignition depth and energy release
  - Detailed study of transition from stable to unstable burning of helium
- Probe crustal heating through transient superbursters in quiescence (already possible with for instance Aql X-1)
- Detect burst oscillations at far smaller amplitudes → measure more neutron star spins and constrain binary parameters
- Search for narrow spectral features (lines, edges) at better sensitivity than in ordinary X-ray bursts → constrain EOS

SRON

The answer for most needs lies with..

- The need for a wide/all-sky monitor with high duty cycle and moderate sensitivity to detect X-ray bursts
- The need for a high-sensitivity instrument to make detailed measurements of timing and spectrum
- → LOFT, eXTP or Strobe-X (see poster P-47 by Santangelo)



- Untill then MAXI (+NICER?), Astrosat-ASM and possibly are most important data providers on superbursters

Conclusions

- Superbursts are carbon shell flashes typically 10^3 as deep, energetic and rare as ordinary type-I bursts
- Our understanding stops with the carbon preservation during type-I bursting and the ignition conditions
- Future progress should focus on following the superburst decay more sensitively and longer

Thank you