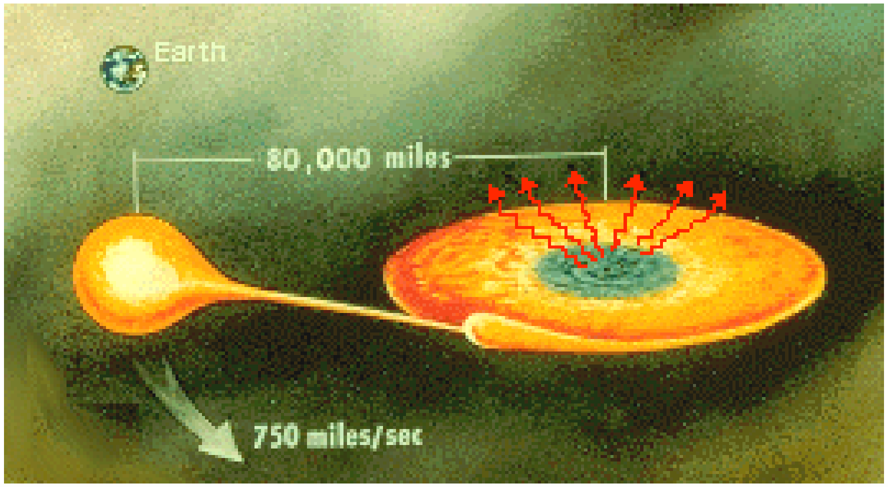
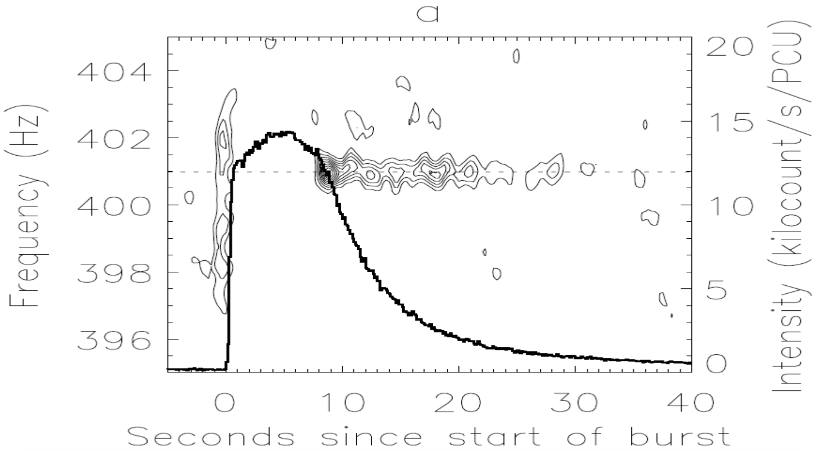
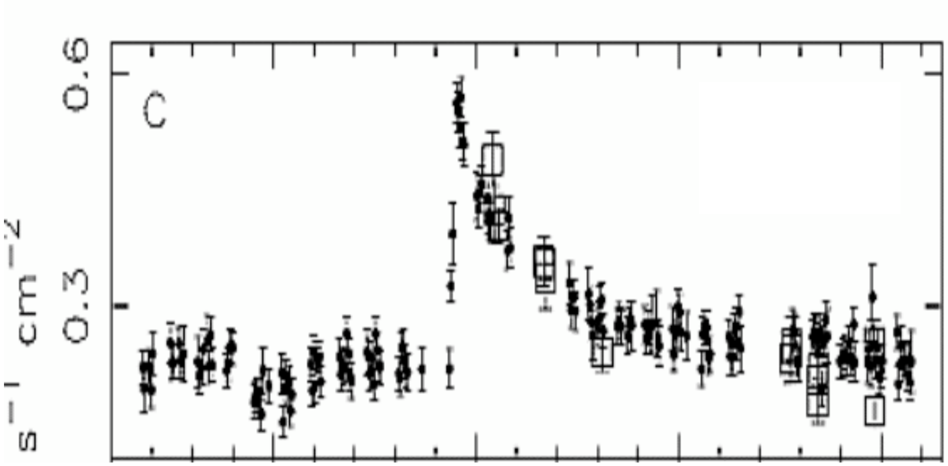
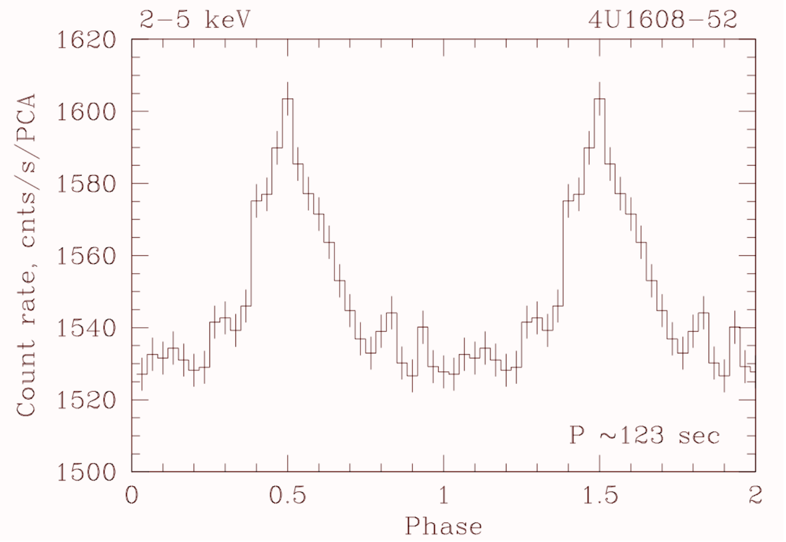
Nuclear burning on accreting neutron stars: where are we?

Andrew Cumming (McGill University)









X-ray bursts

- they are (sometimes) sensitive to the thermal state of the neutron star interior

- they determine the composition that enters the top of the crust

- they are a surface phenomena, a chance to study the neutron star while accretion is ongoing

- interesting nuclear physics on the proton rich side (rp-process) during H/He burning

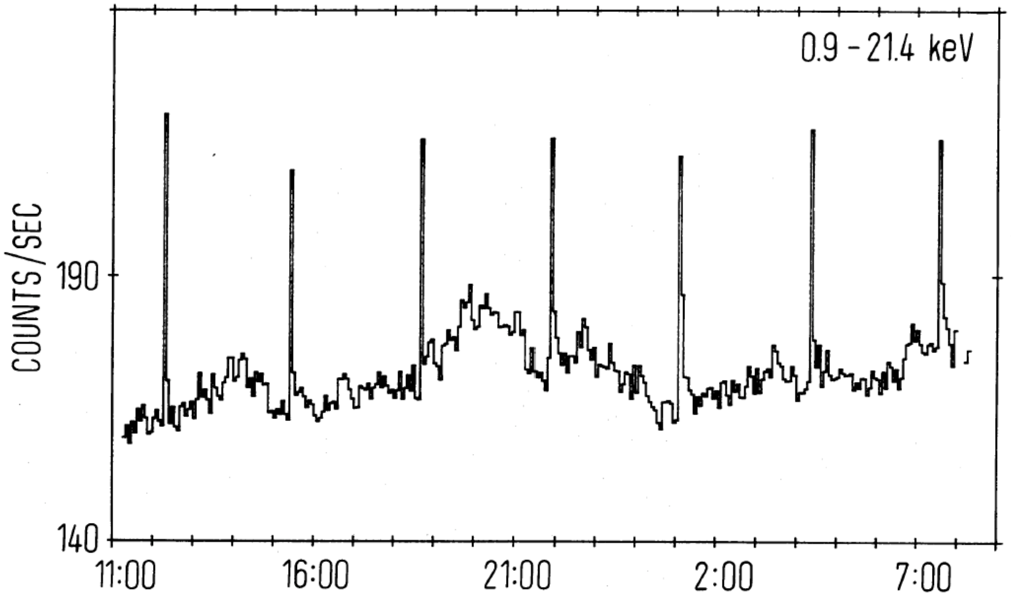
Outline

- lots of new phenomena: burst oscillations, superbursts, rare bursts (long and short)… can we put those into a global picture ?

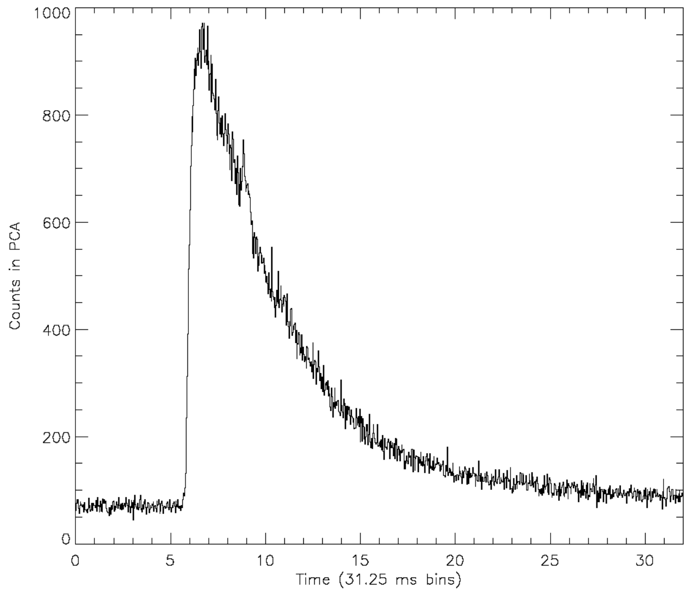
- I will argue that mHz QPOs are likely the key to doing this … are we close to solving a 20 year old puzzle?

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

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

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

$$\approx (40-100)$$

Thin shell instability

- The pressure at the base of the thin layer is fixed by the weight of the overlying material

  => the shell has a positive heat capacity

Schwarzschild & Härm (1958)

- The entropy equation for the layer is

$$c_P \frac{dT}{dt} = \varepsilon - \frac{1}{\rho} \nabla \cdot F$$

- The condition for a thermal runaway is

$$\frac{d\epsilon_{3\alpha}}{dT} > \frac{d\epsilon_{\rm cool}}{dT} \qquad \epsilon_{\rm cool} \approx \frac{acT^4}{3\kappa y^2}$$

- For H/He, predict ignition at column depth $\approx 10^8 \ {\rm g\ cm^{-2}}$

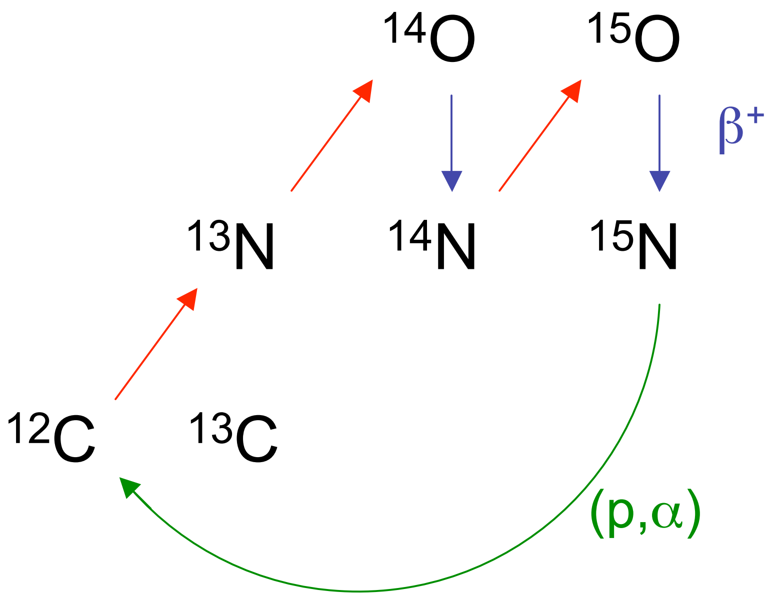
  => recurrence time at $0.1\ \dot{m}_{\rm Edd}$ is a few hours ✓

  => energy is $10^{21}\ {\rm g} \times 10^{18}\ {\rm erg\ g^{-1}} \approx 10^{39}\ {\rm ergs}$ ✓

  => cooling time is ~ 10 seconds ✓

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

At high enough accretion rates, hot CNO hydrogen burning between bursts heats the accumulating layer and depletes hydrogen



“hot” CNO cycle $T > 8 \times 10^7$ K

(Hoyle & Fowler 1965)

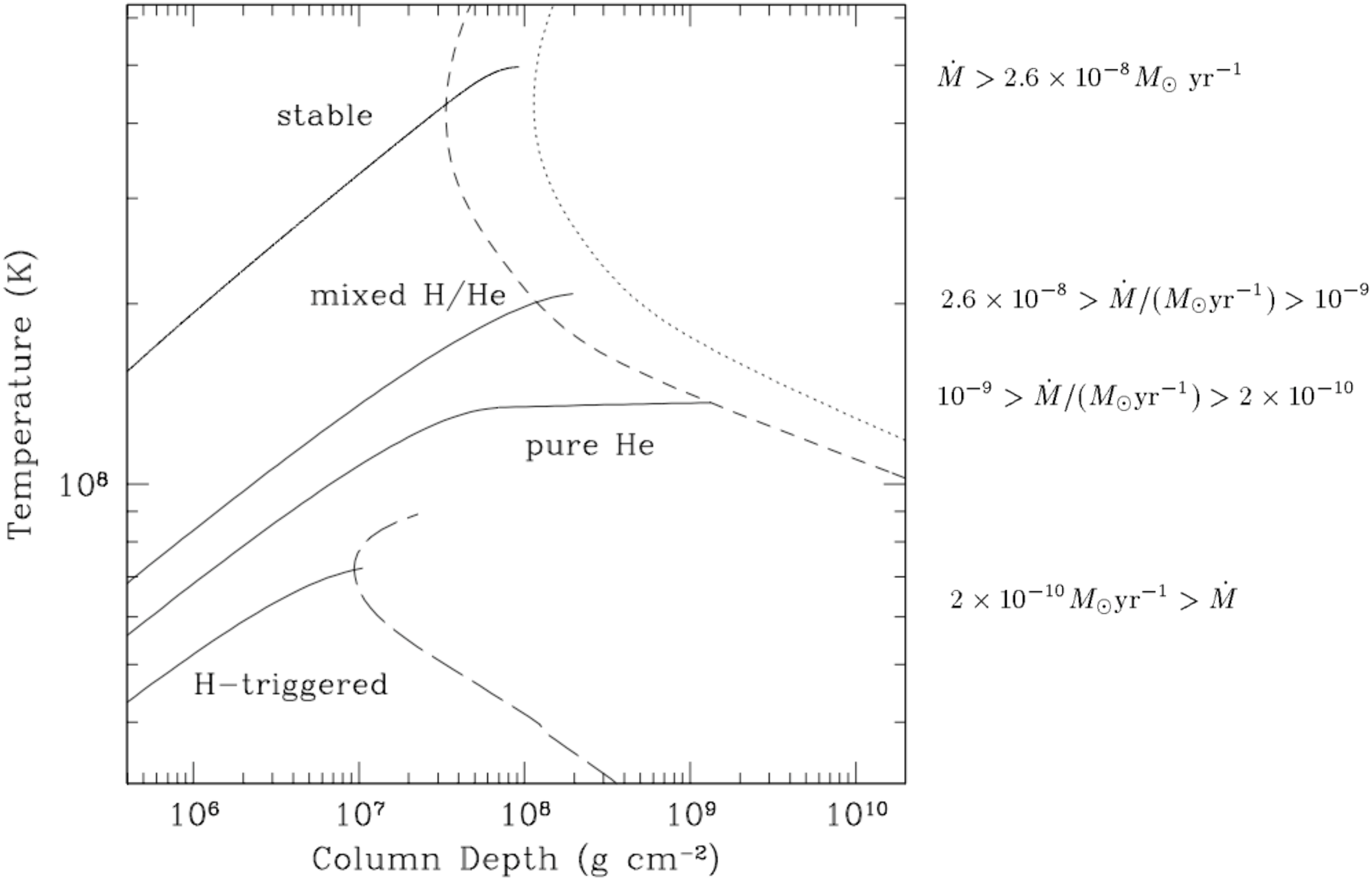
time to burn the hydrogen in a given fluid element is

$$t_H = 11 \text{ hrs} \left(\frac{0.02}{Z}\right) \left(\frac{X_0}{0.7}\right)$$

mass fraction of CNO

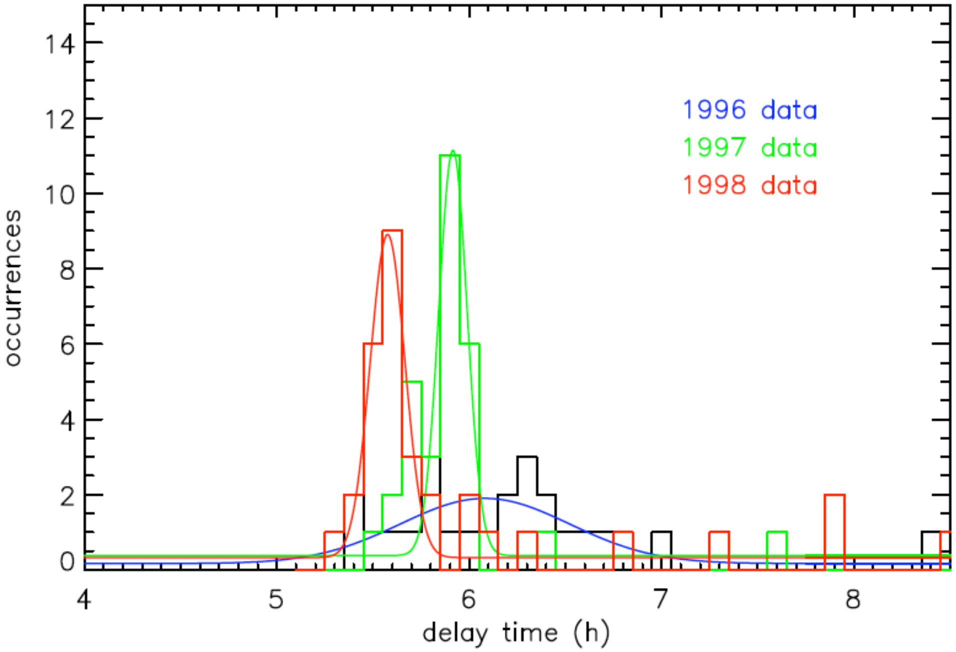
H burning gives ~ 7 MeV per nucleon compared to ~ 0.1 MeV per nucleon emerging from the crust

Burning regimes



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

The “clocked” burster: GS 1826-24



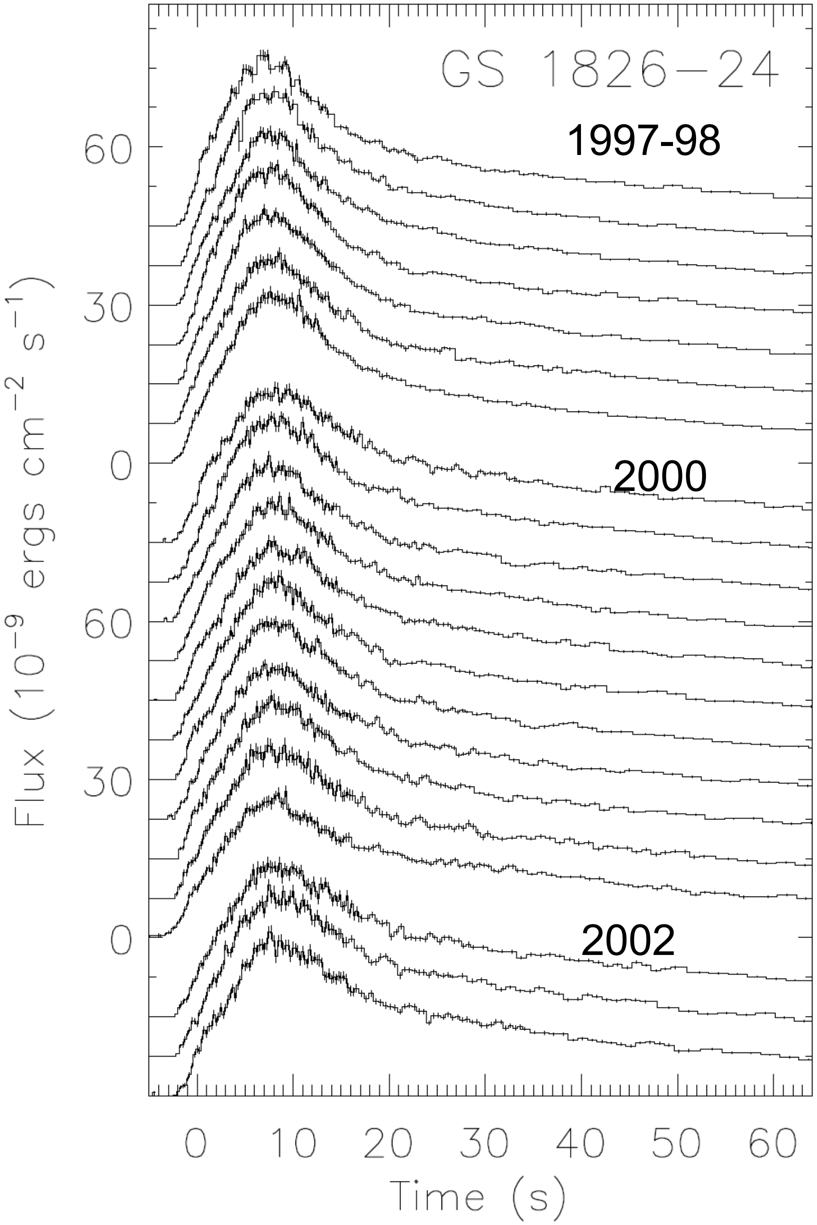
BeppoSAX (Ubertini et al. 1997; Cocchi et al. 2000)

a model of H/He accumulation gives ignition at 2 x 10^8 g/cm^2 (2 x 10^{21}g)

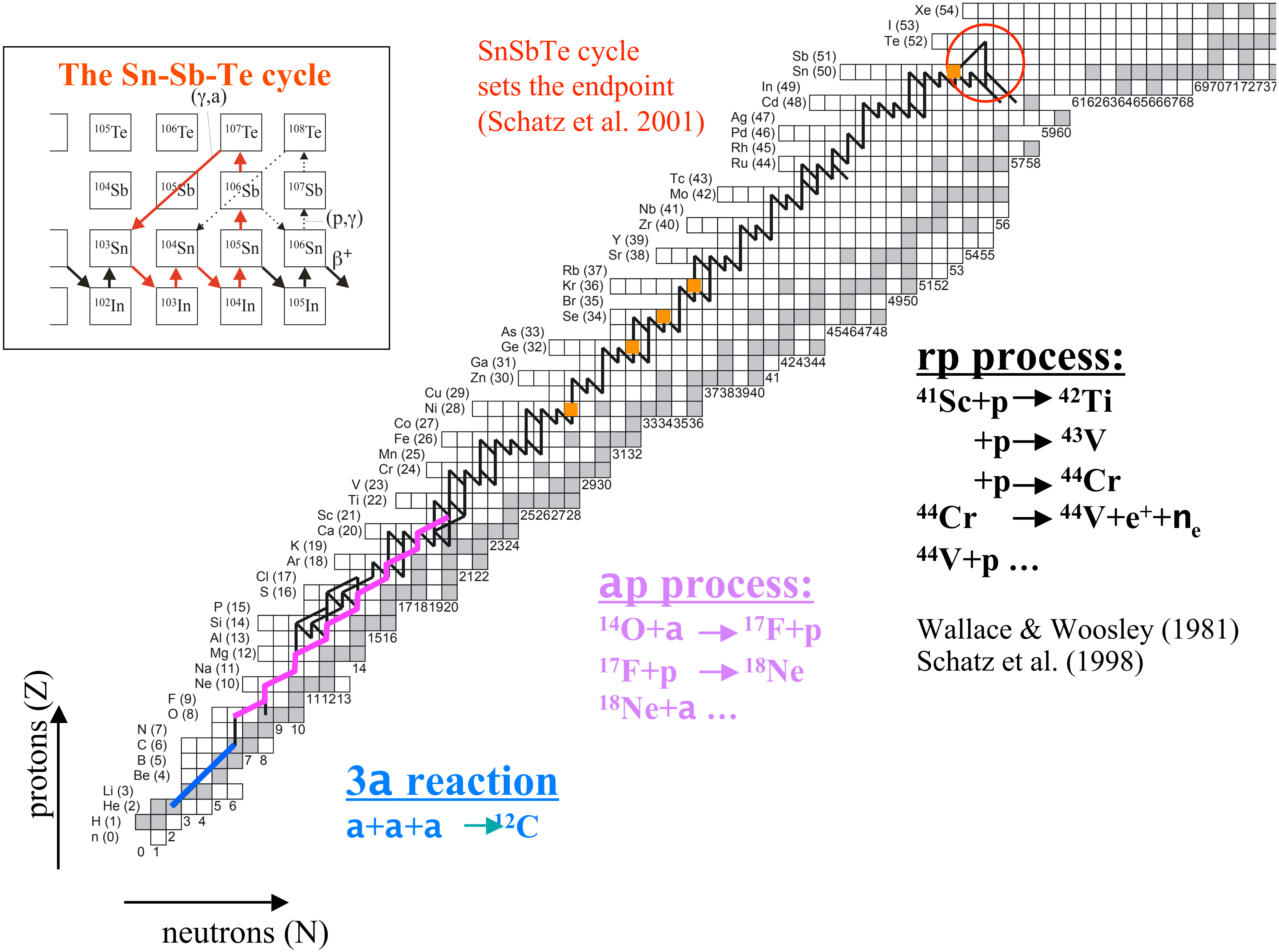
if the nuclear burning gives 3 MeV per nucleon, expect 6 x 10^{39} ergs

at an accretion rate of 0.1 Eddington, this mass is accreted in 2 x 10^4s = 5.5 hours

long tails from rp-process? Bildsten (2000)



Galloway et al. (2003)



The Sn-Sb-Te cycle

SnSbTe cycle
sets the endpoint
(Schatz et al. 2001)

rp process:

^{41}Sc+p → ^{42}Ti
+p → ^{43}V
+p → ^{44}Cr
^{44}Cr → ^{44}V+e^{+}+n$_{e}$
^{44}V+p …

Wallace & Woosley (1981)
Schatz et al. (1998)

ap process:

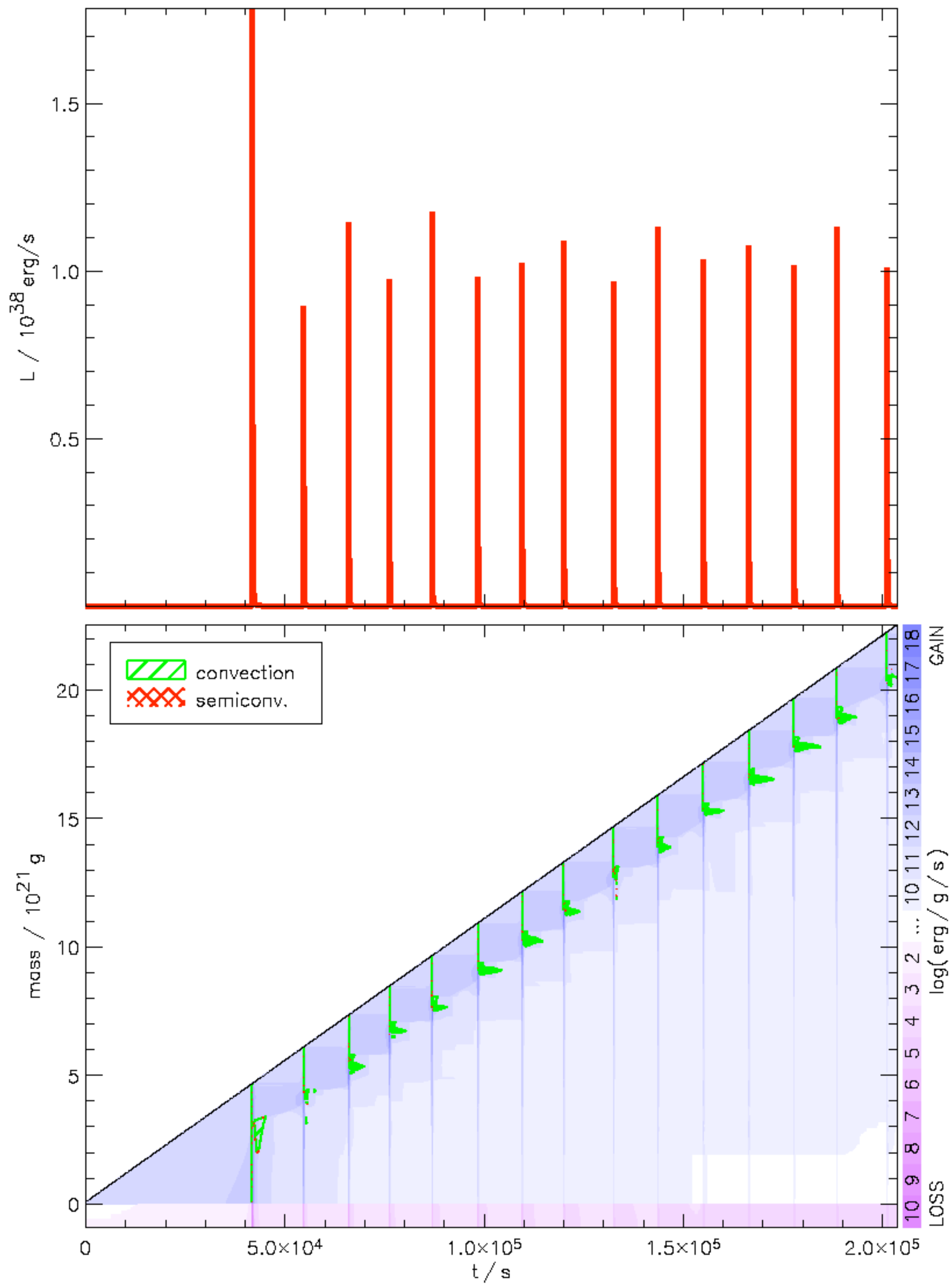
^{14}O+a → ^{17}F+p
^{17}F+p → ^{18}Ne
^{18}Ne+a …

3a reaction

a+a+a → ^{12}C

Multizone models of X-ray bursts

Woosley et al. (2004)

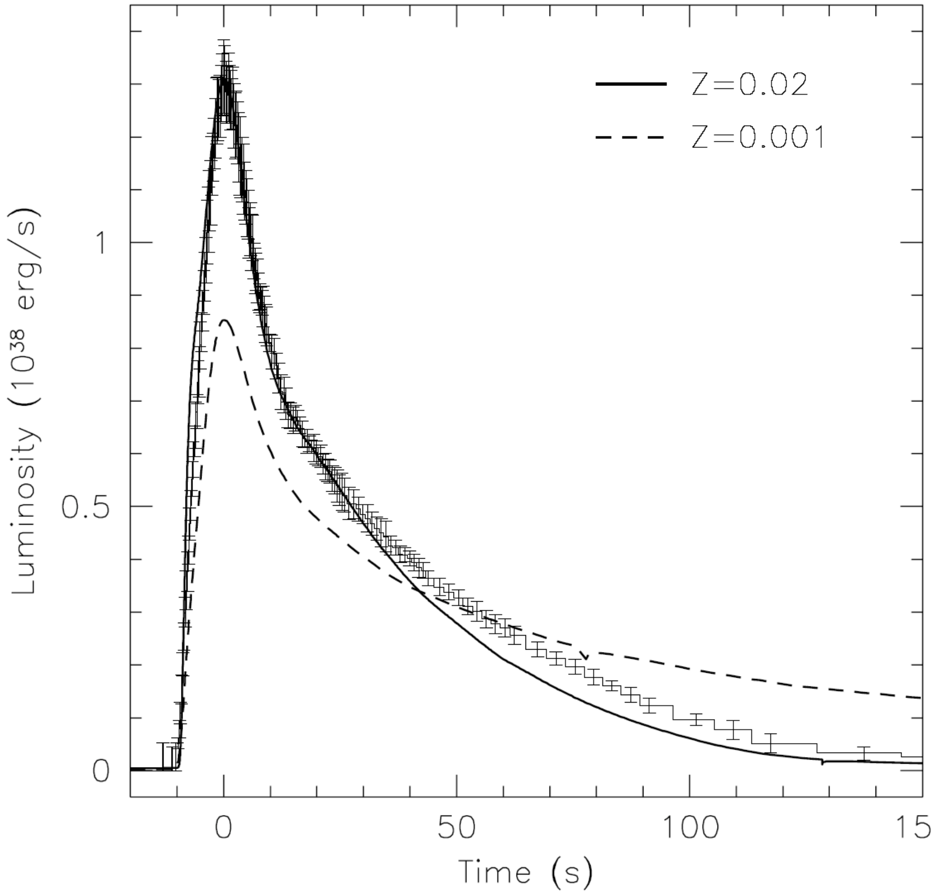


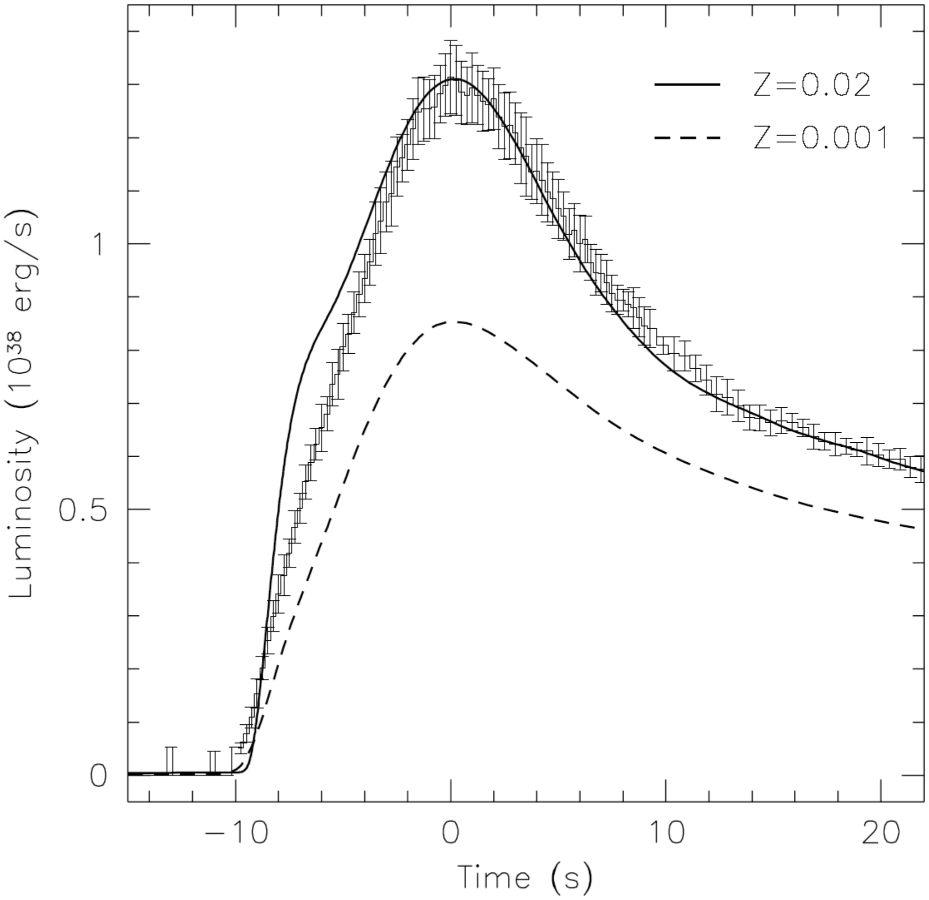
1D stellar evolution (e.g. prescription for convection)

+

adaptive nuclear network to follow rp-process in detail at each depth

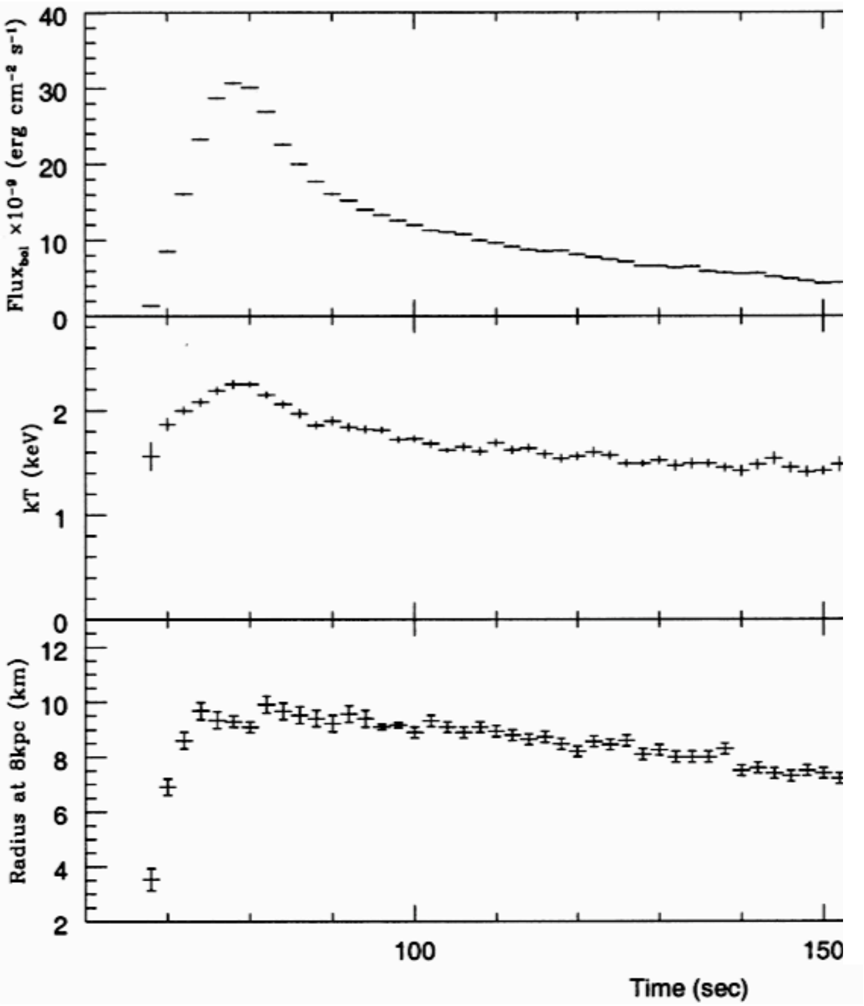
Comparison with observations: GS 1826-24

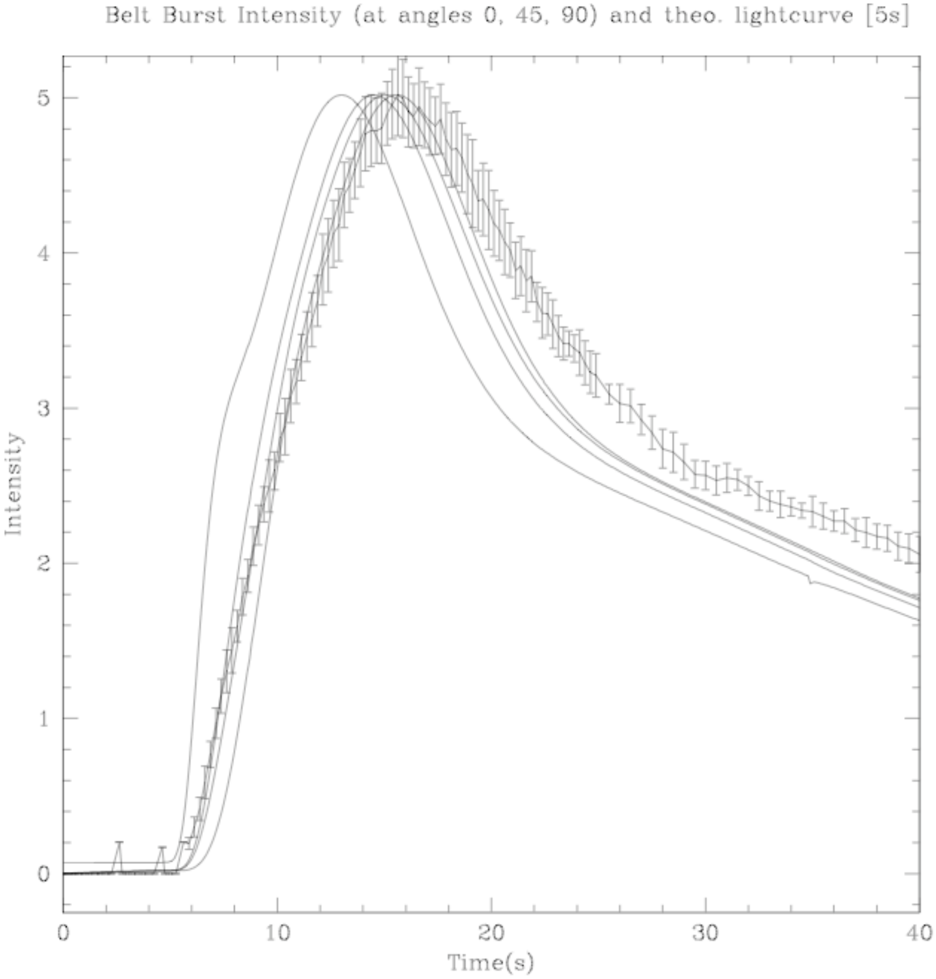




Heger, Galloway, AC (2007)

Spreading during the rise?





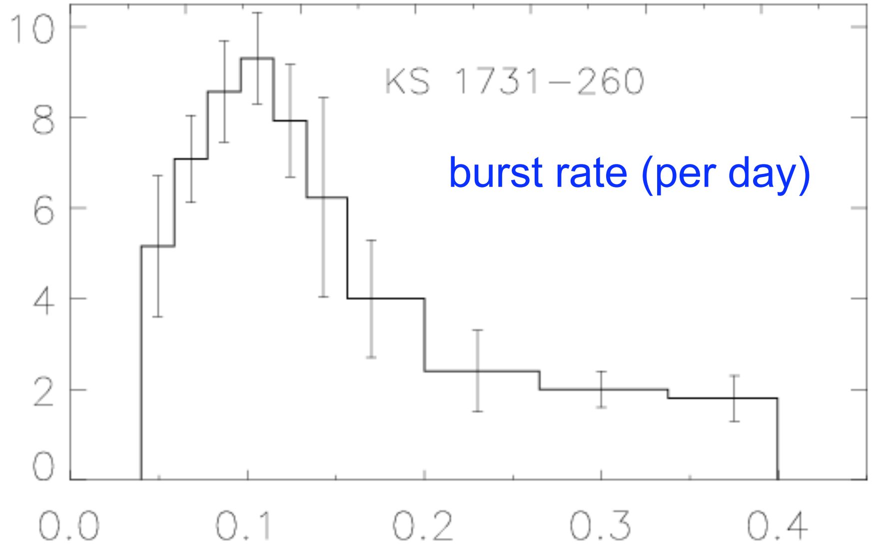
Kong et al. (2000)

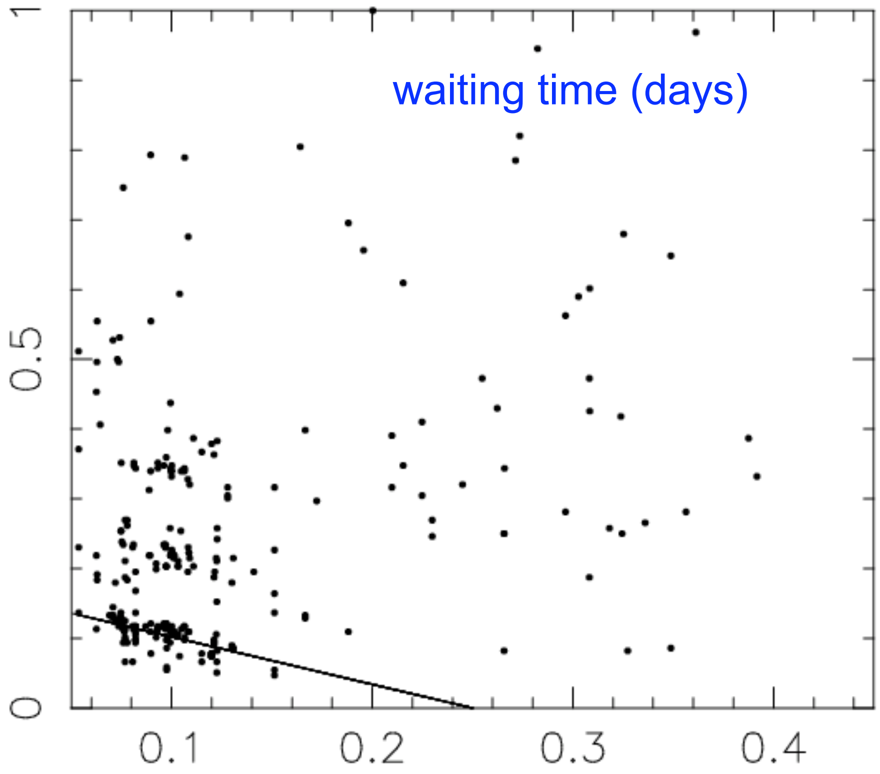
calculation by Michael Zamfir

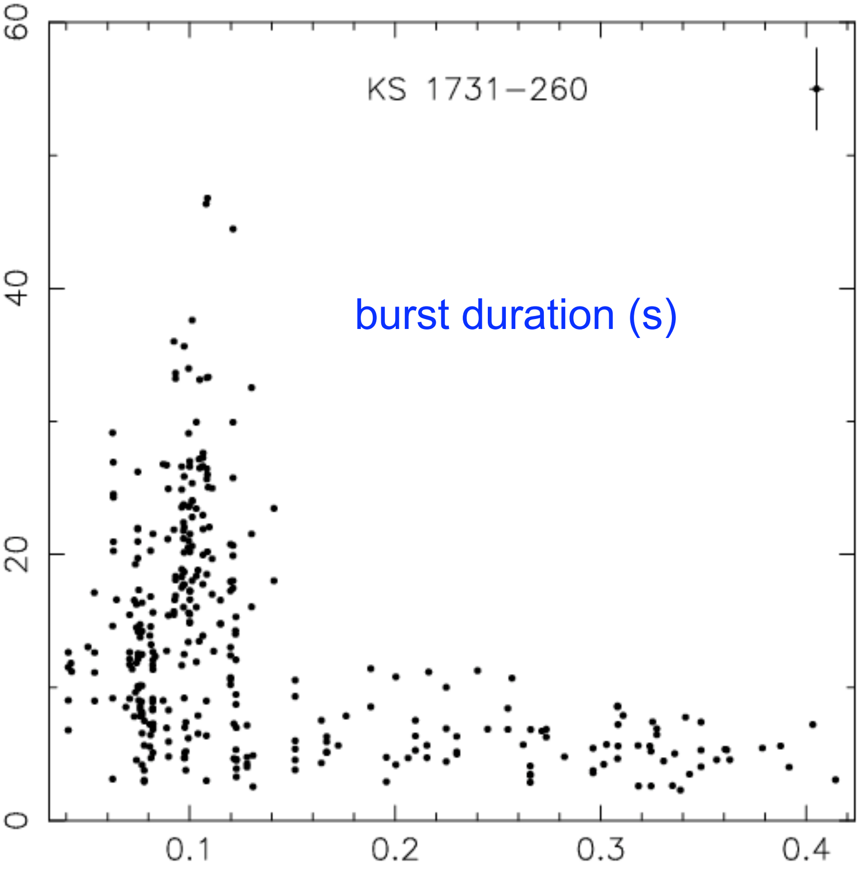
Variation of burst properties with mdot

Cornelisse et al. (2003)
data for KS 1731

see also van Paradijs et al.
(1989)


burst rate (per day)


waiting time (days)


burst duration (s)

SAX J1808.4-3654

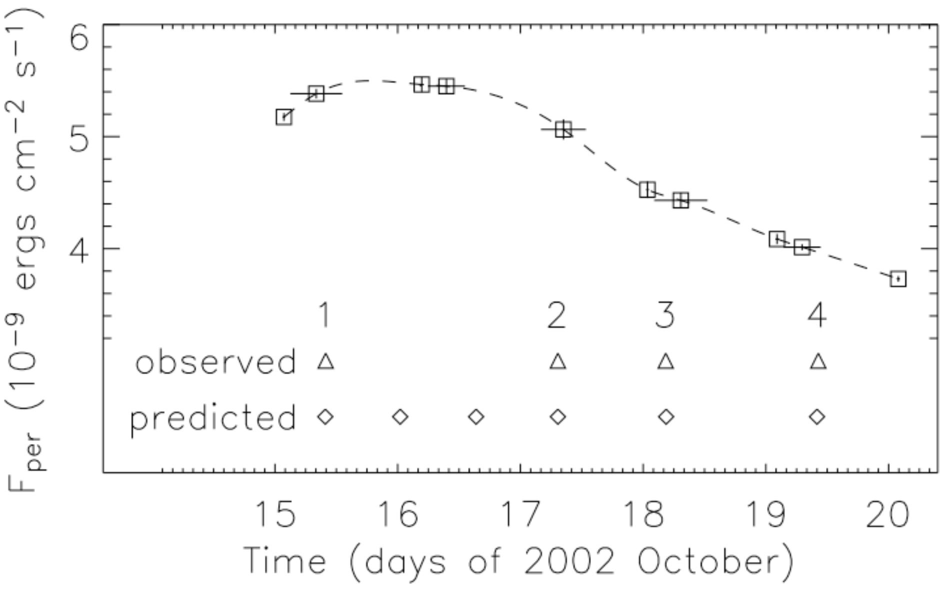
- Transiently accreting millisecond X-ray pulsar

- Burst sequence observed during 2002 outburst can be understood as accretion of solar CNO abundance material with X~0.5 at ~0.06 Edd (parameters: Q_b, Z_{CNO}, X_0)

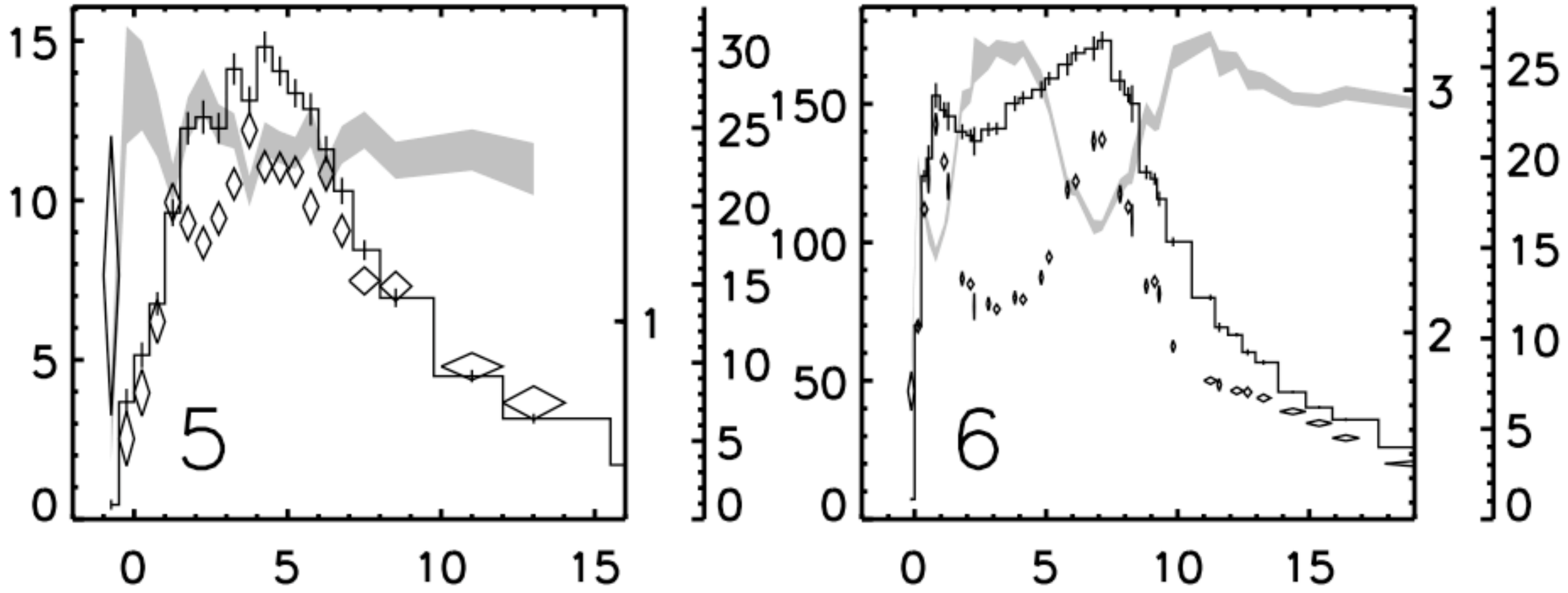
- Hydrogen burns away before ignition => pure He layer (t_{burn} = 12 hours for solar material; observed Δt ~ 24 hours)

Galloway & Cumming (2006)

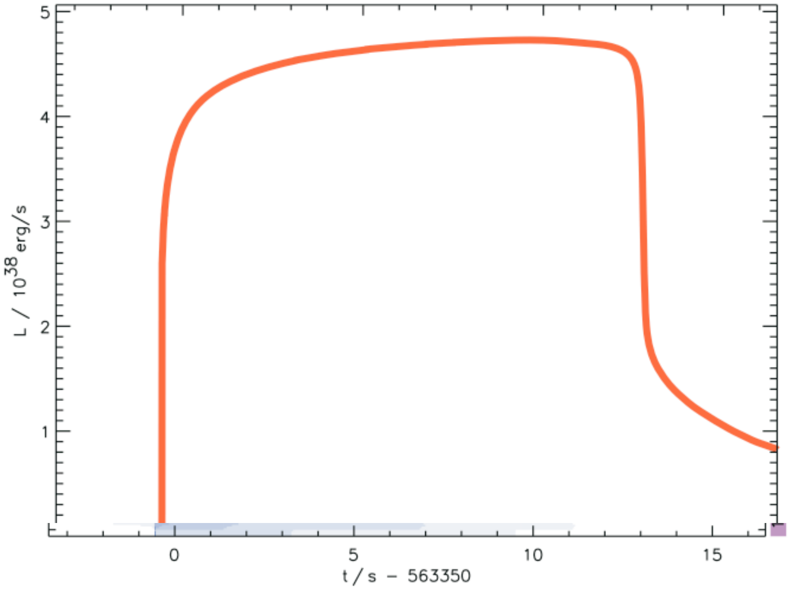
- the burst properties need Q_b=0.3 MeV/nucleon or $L_{crust} = 2 \times 10^{34}$ erg/s



SAX J1808.4-3654

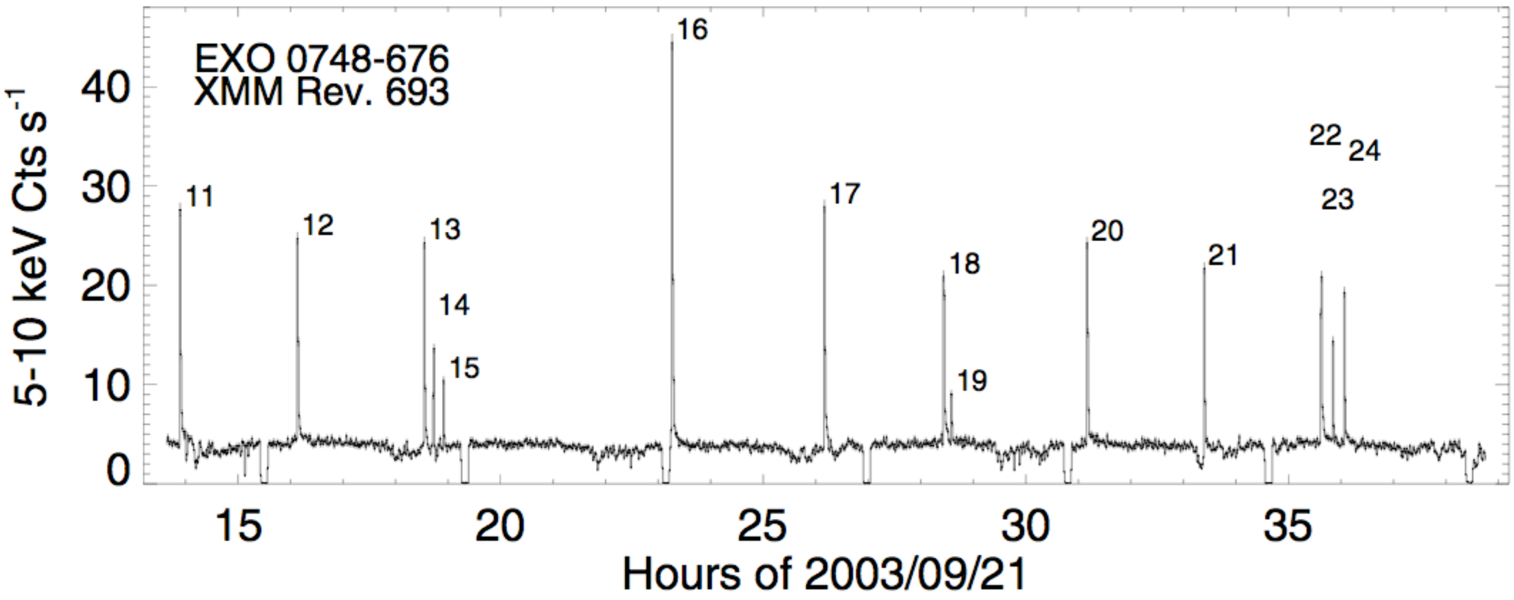


Galloway et al 2007 RXTE catalog

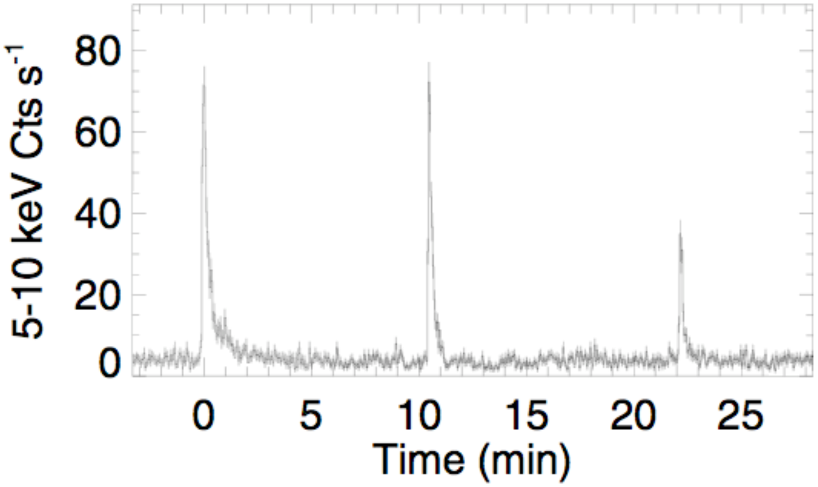


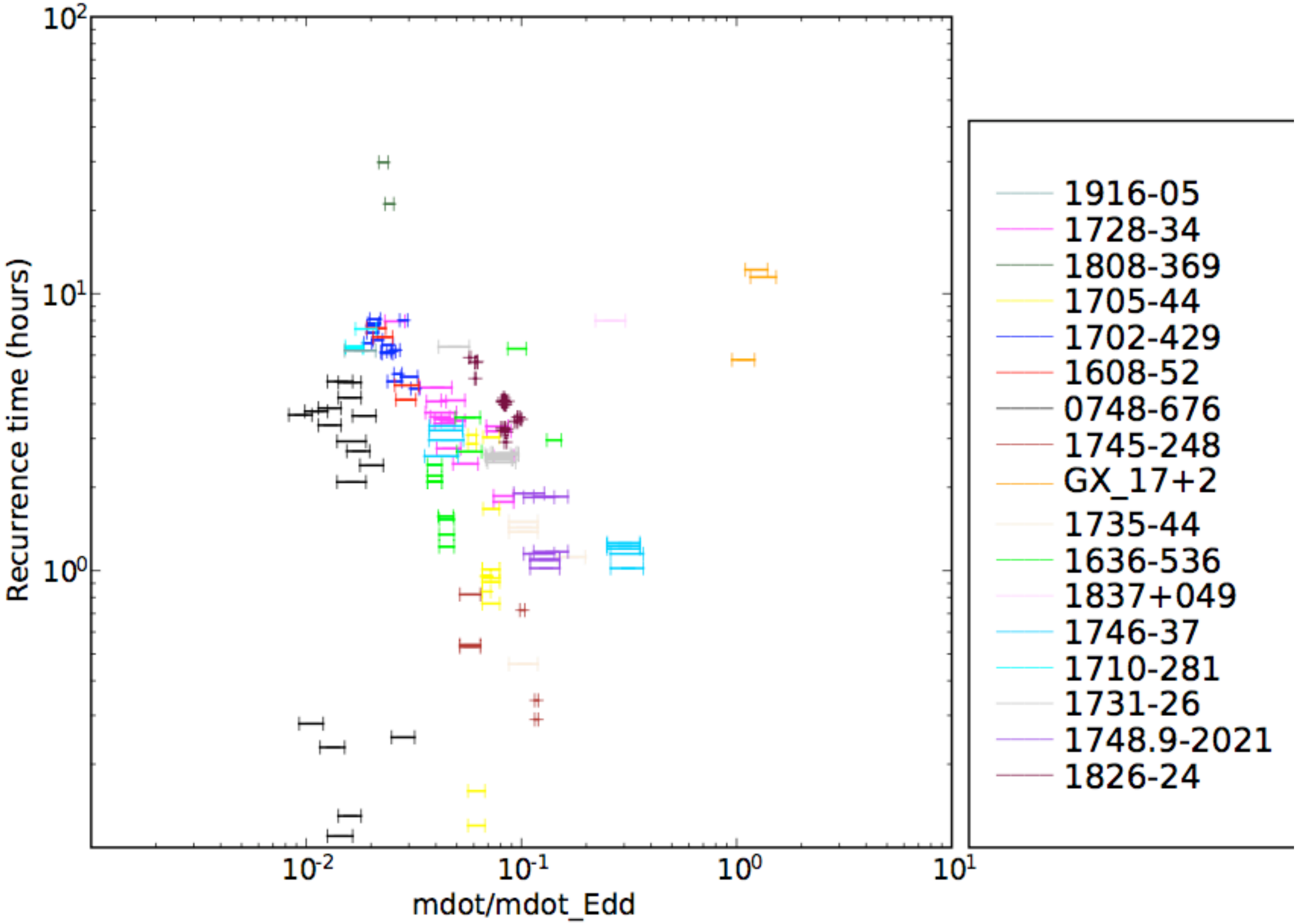
Woosley et al. 2004 ApJS

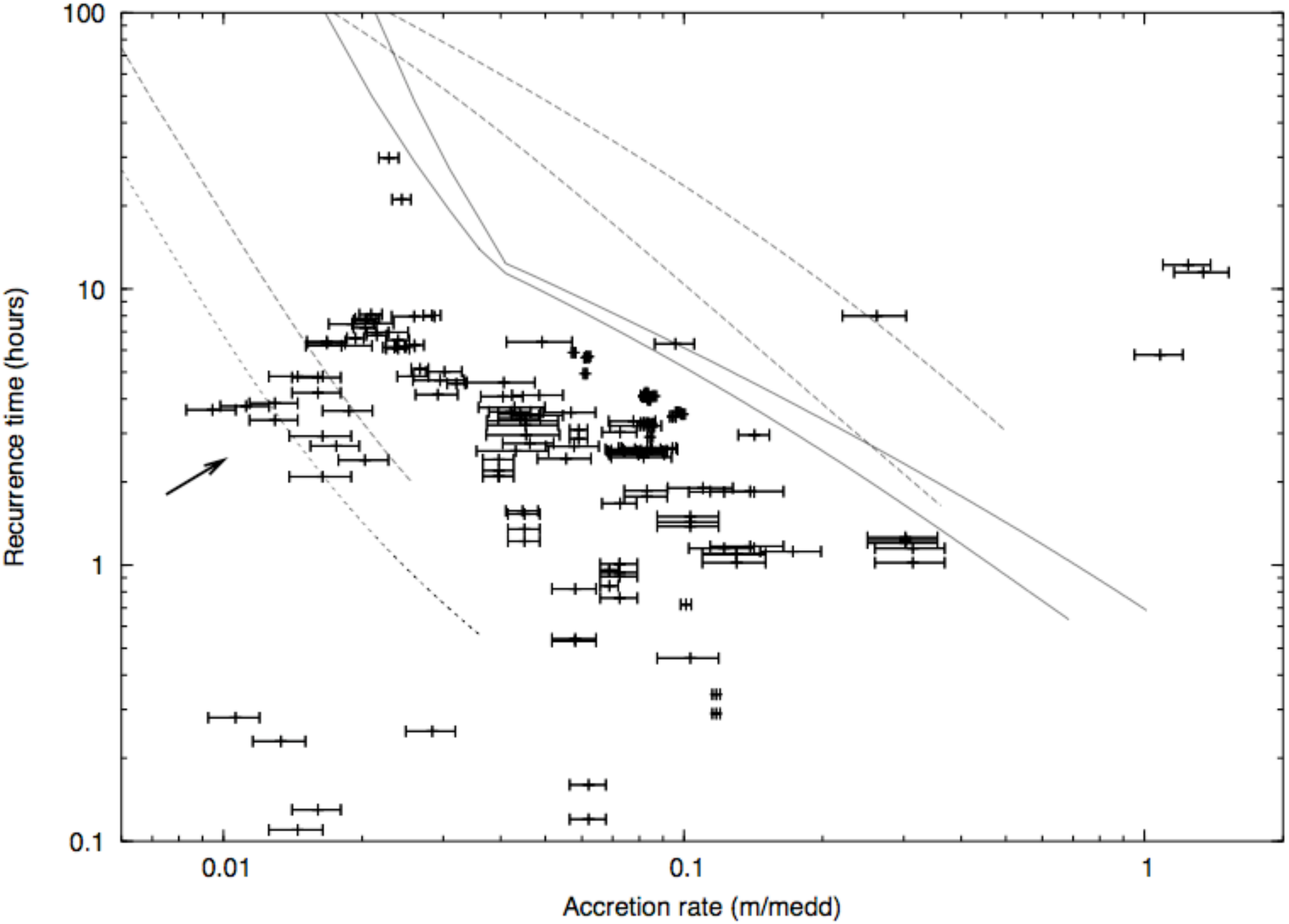
EXO 0748-676



Boirin et al. (2007)

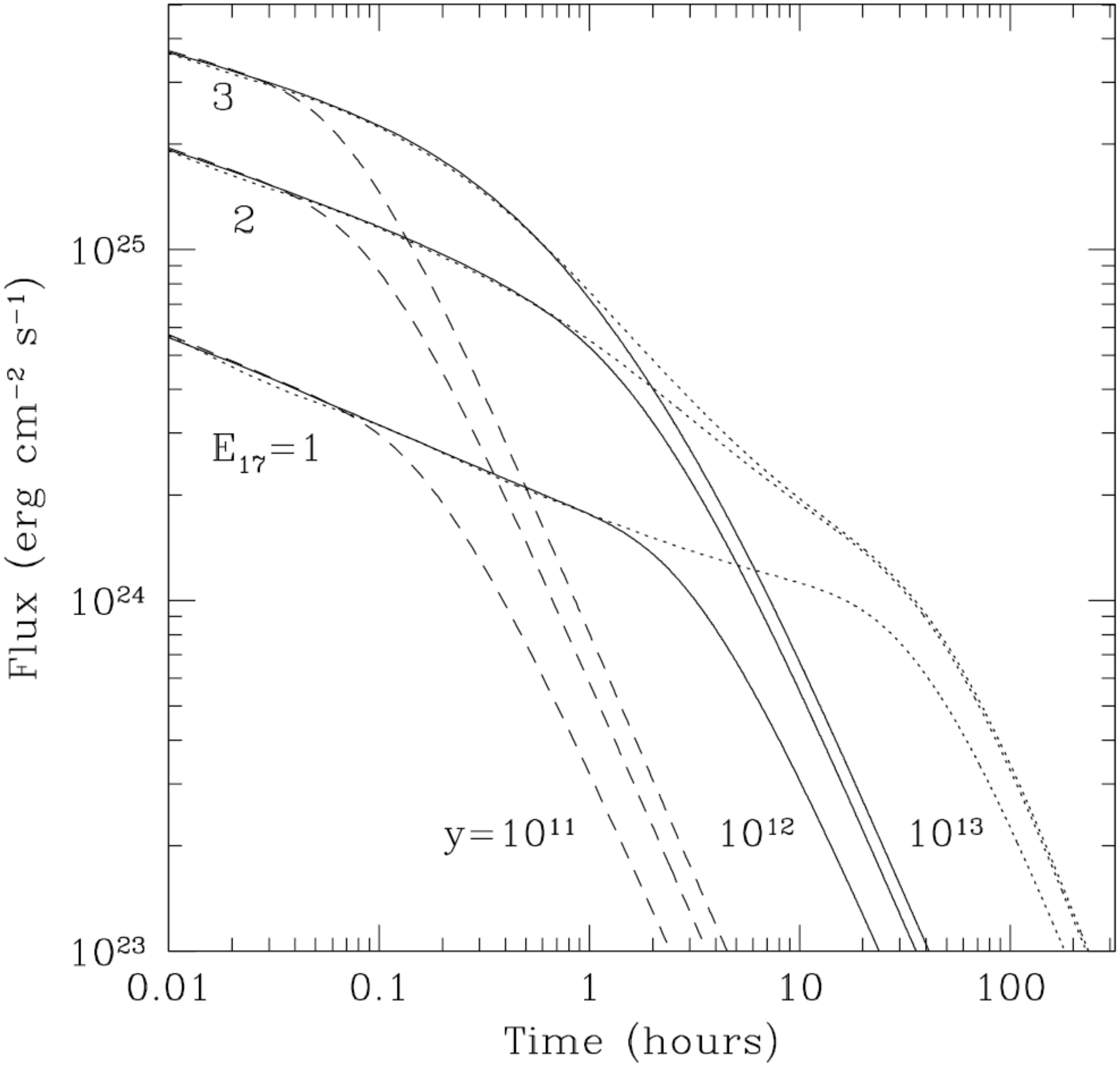



Recurrence time (hours)
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
mdot/mdot_Edd
1916-05
1728-34
1808-369
1705-44
1702-429
1608-52
0748-676
1745-248
GX_17+2
1735-44
1636-536
1837+049
1746-37
1710-281
1731-26
1748.9-2021
1826-24



Brandon Helfield et al. (2007)

Superburst lightcurves



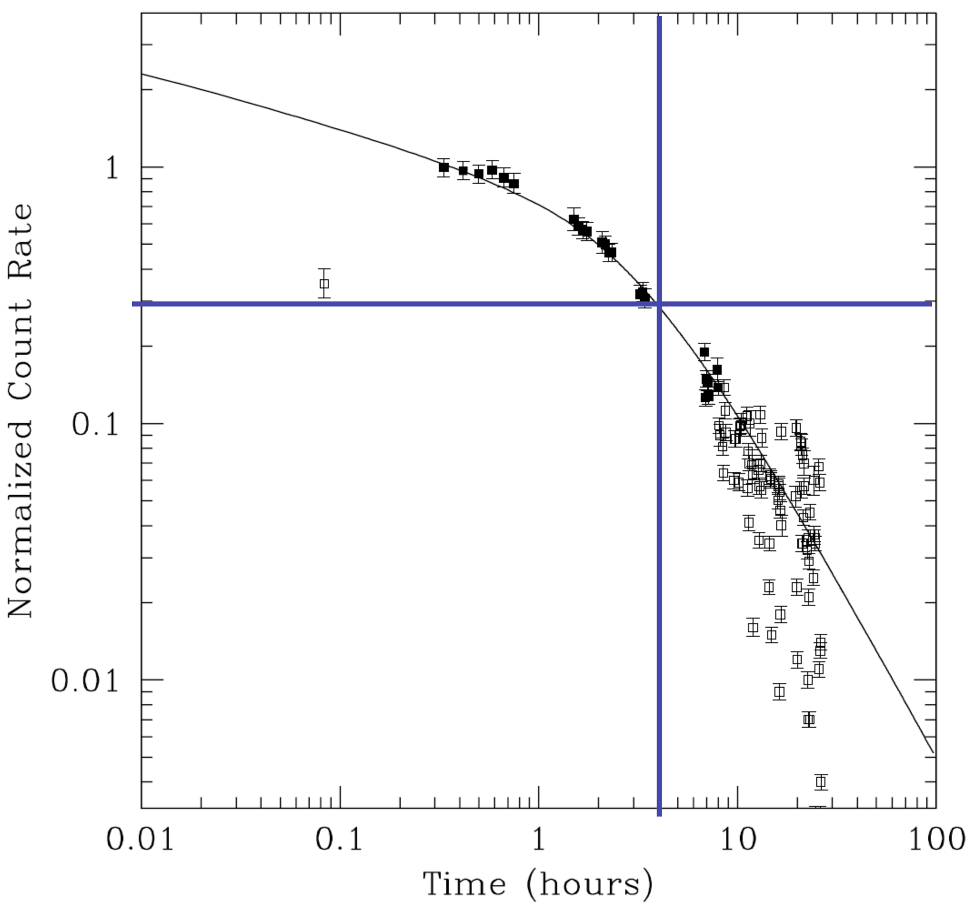
at late times

$$F \propto t^{-4/3}$$

Cumming & Macbeth (2004)

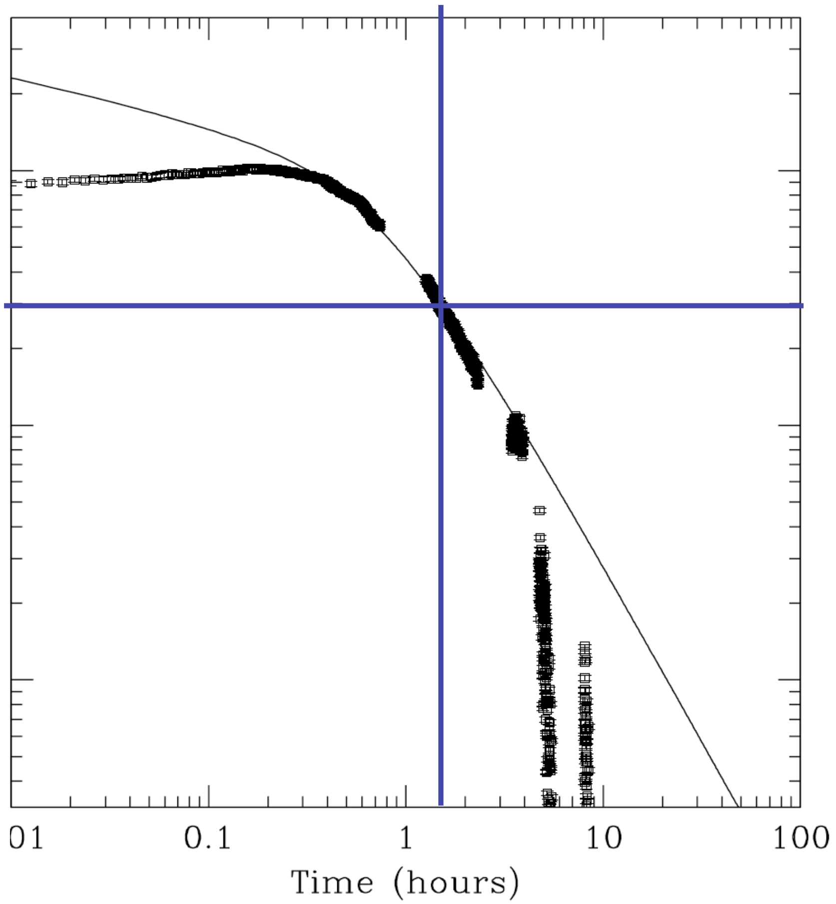
Superbursts: lightcurves

KS 1731-254 (BeppoSAX/WFC)



y_{12}=1.3

4U 1636-54 (RXTE/PCA)

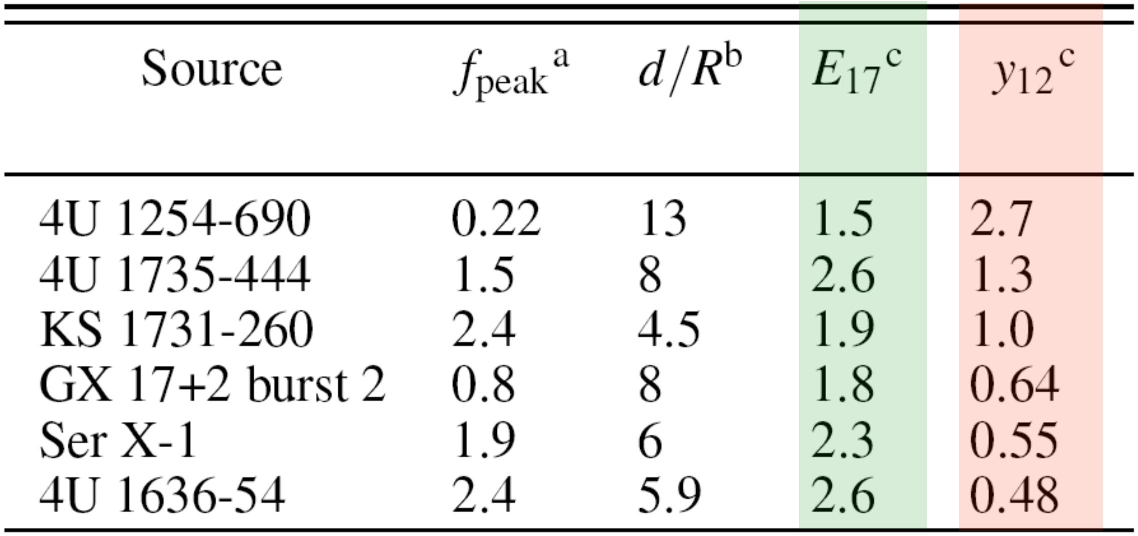


y_{12}=0.48

Cumming, Macbeth, in ‘t Zand, & Page (2005)

Superbursts: lightcurves

$E_{17}=2$ $y_{12}=0.5\text{-}3$

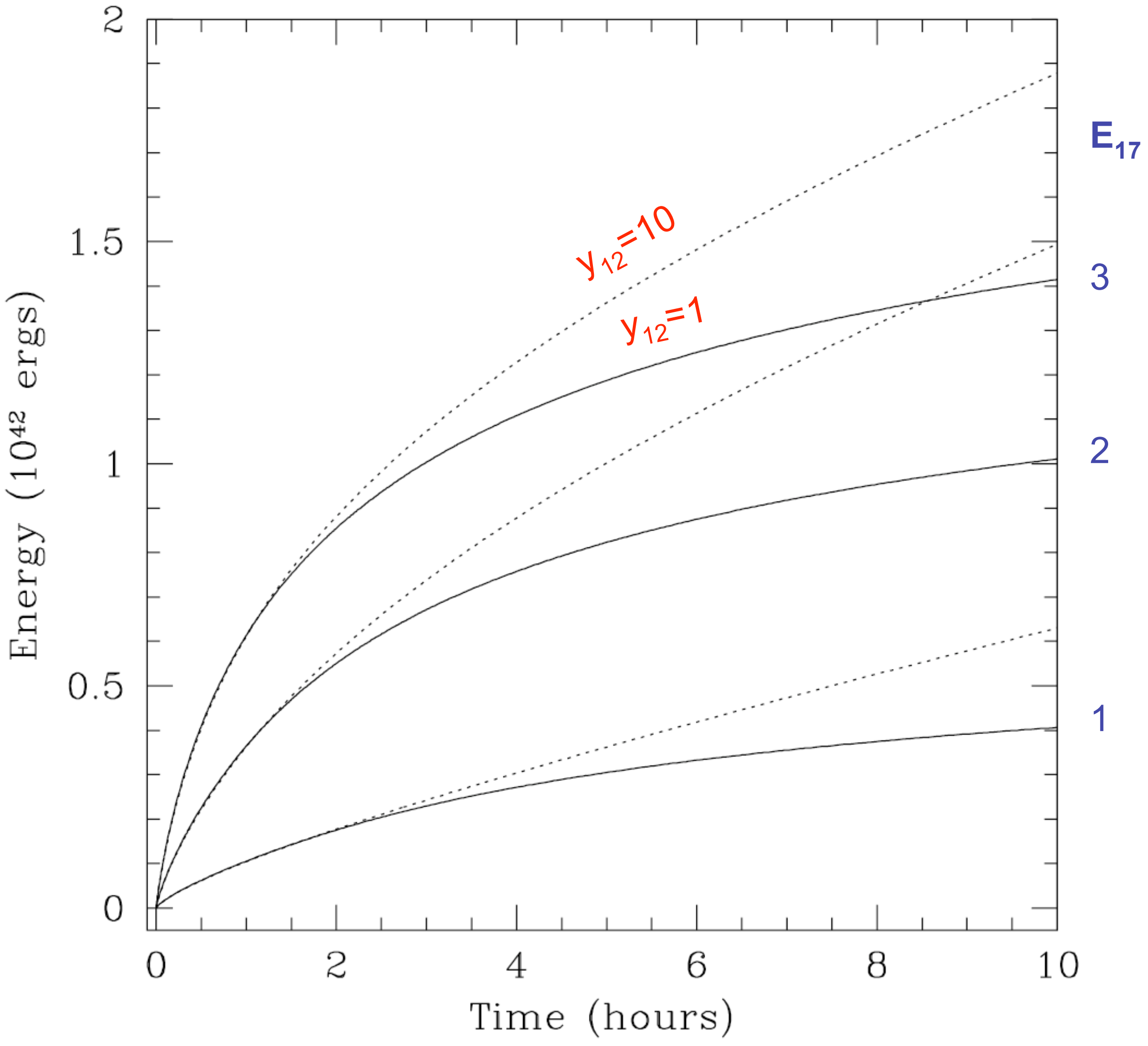


Source	$f_{\rm peak}$[a]	d/R[b]	E_{17}[c]	y_{12}[c]
4U 1254-690	0.22	13	1.5	2.7
4U 1735-444	1.5	8	2.6	1.3
KS 1731-260	2.4	4.5	1.9	1.0
GX 17+2 burst 2	0.8	8	1.8	0.64
Ser X-1	1.9	6	2.3	0.55
4U 1636-54	2.4	5.9	2.6	0.48

Cumming et al. (2006)

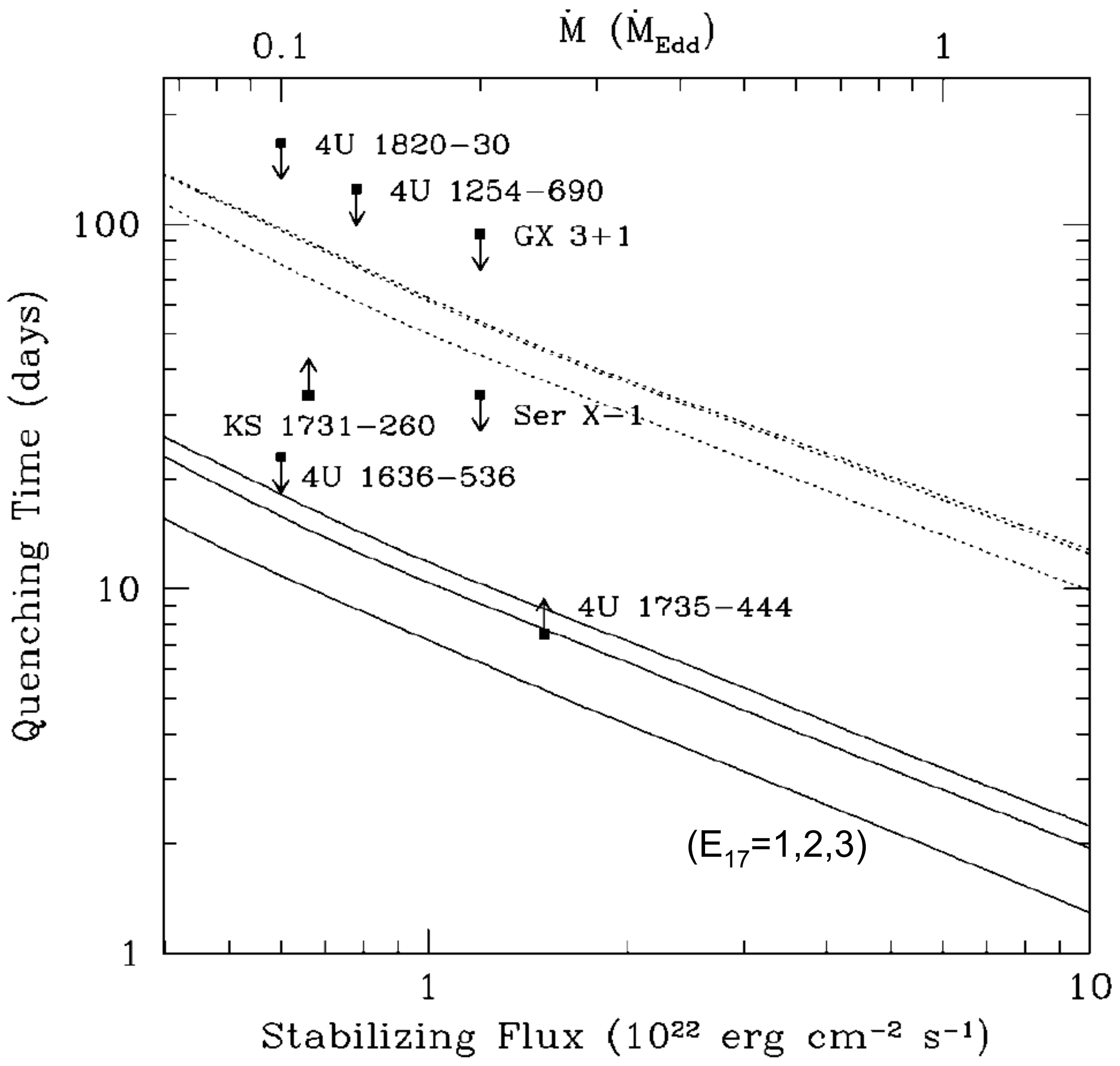
Neutrino “thermostat” sets characteristic energy of 10^{42} ergs

(see also Strohmayer & Brown 2002)



Cumming & Macbeth (2004)

Superbursts: quenching



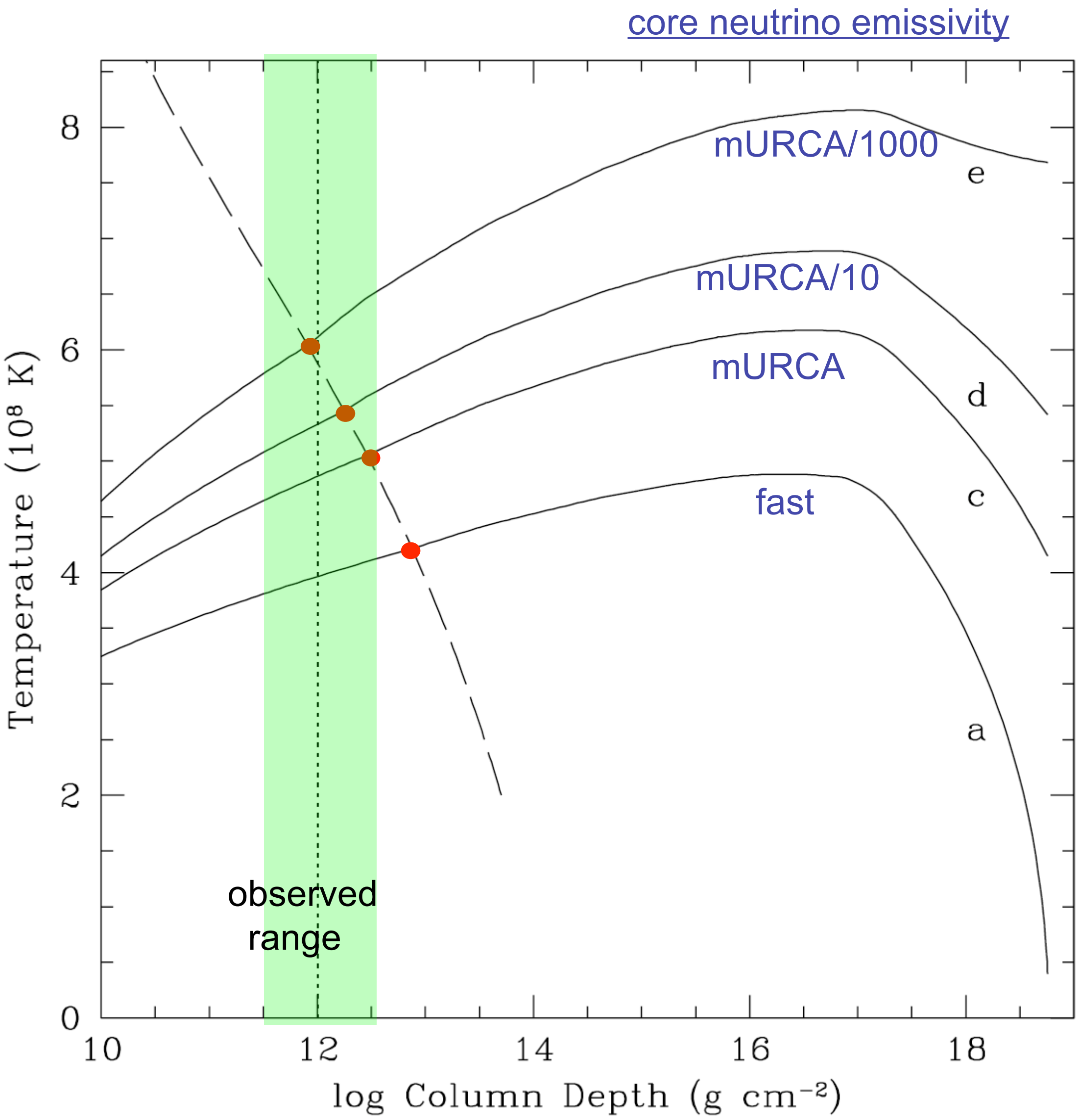
thickness

10^{13} g/cm^2

10^{12} g/cm^2

Cumming & Macbeth (2003)

Superbursts: ignition models



need *inefficient* core neutrino emission to match observations

agrees with Brown (2004), Cooper & Narayan (2005)

Ignition at $y=10^{12}$ g/cm^2 requires:

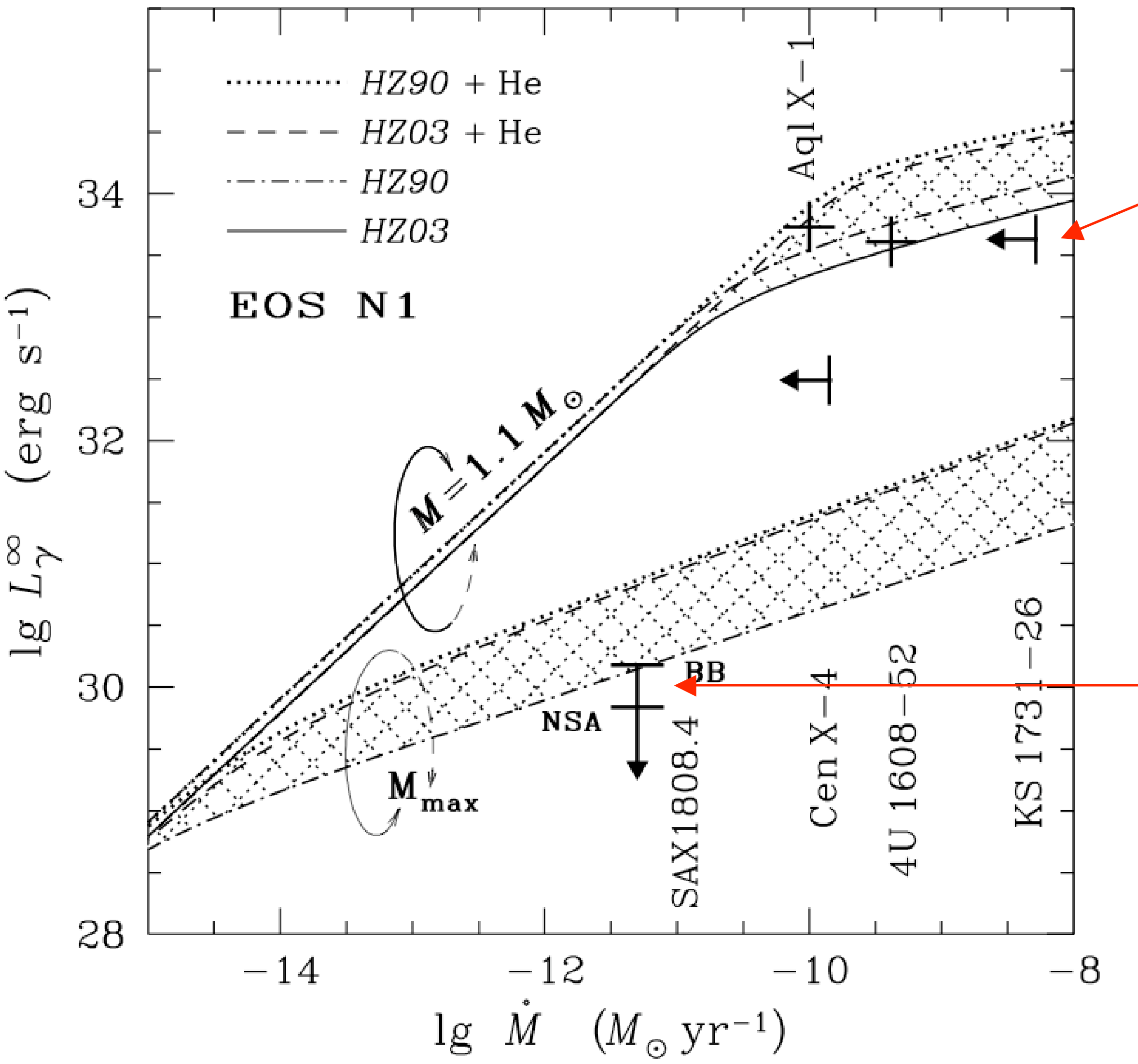
Q_b=0.2-0.3 MeV/nucleon at 0.3 Edd

L_{crust}=(6-9) x 10^{34} erg/s

T~(5-6) x 10^8K

Cumming, Macbeth, in ‘t Zand, & Page (2005)

Comparison with quiescent luminosity of transients



Yakovlev et al. (2004)

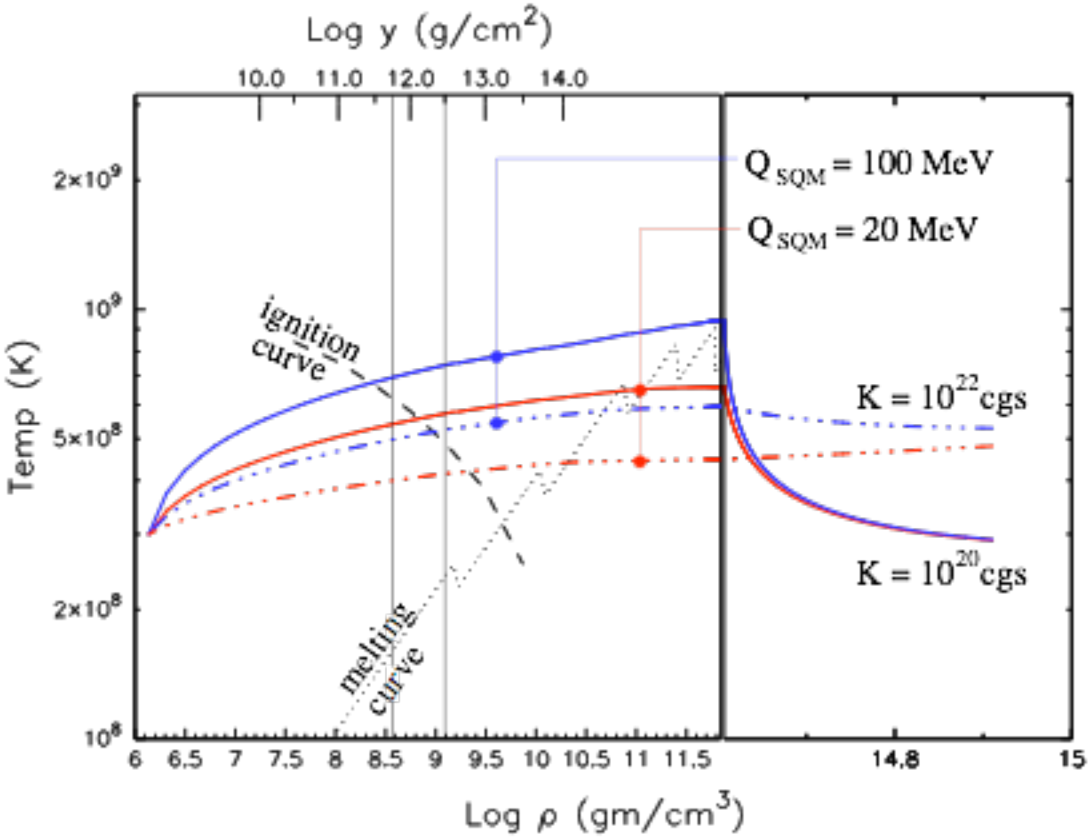
KS 1731-260
Q_b=0.02 MeV
at 0.1 Edd

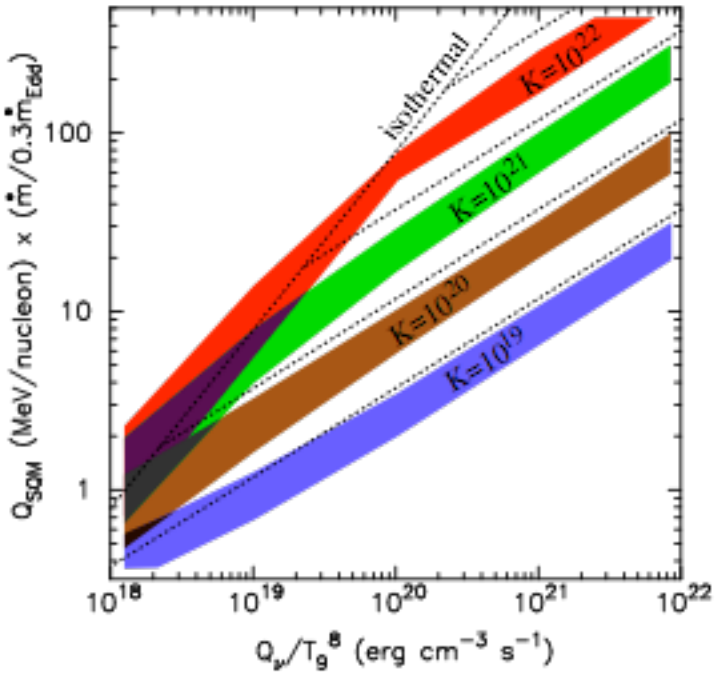
(20-30 times smaller than needed for the superburst)

SAX J1808
the burst properties need
Q_b=0.3 MeV/nucleon or
L_{crust} = 2 x 10^{34} erg/s

>100 times greater than quiescent luminosity

Superbursts from strange stars



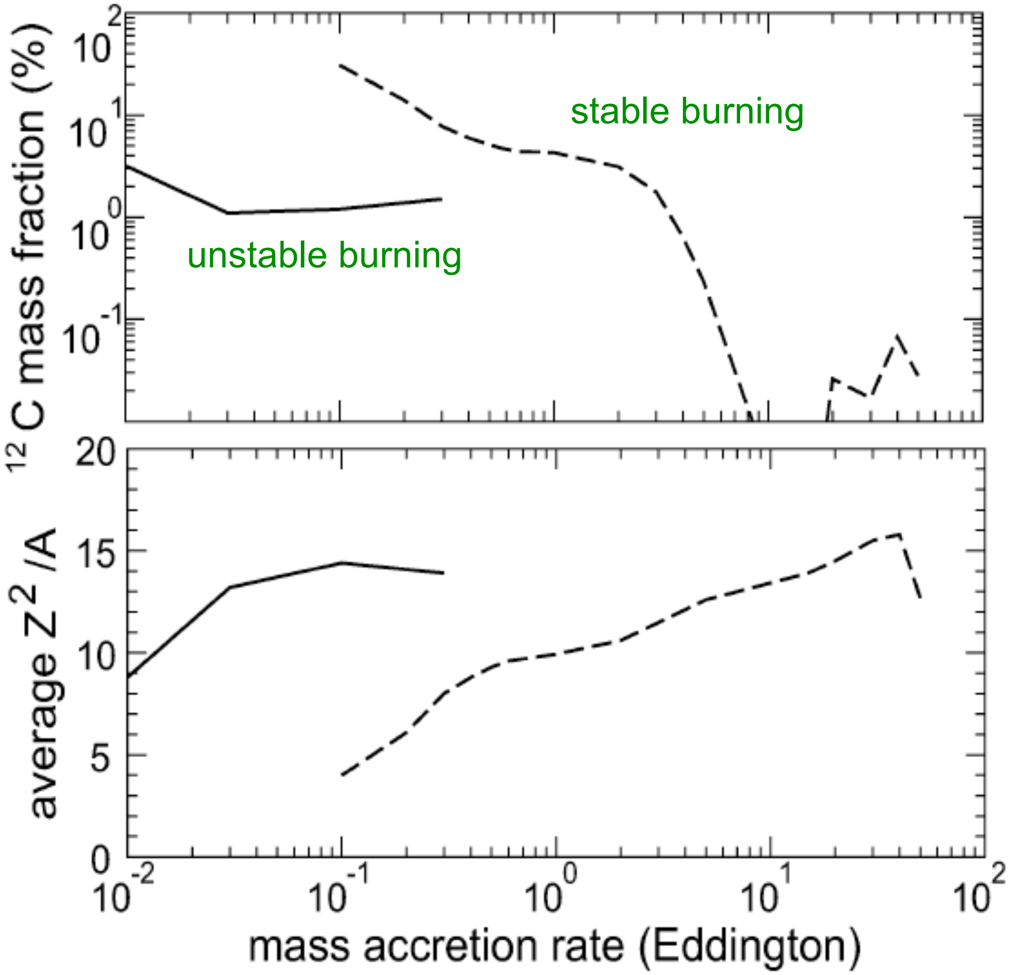


Page & Cumming 2005

Strange stars have no inner crust => no Cooper pair neutrinos!

Alcock, Farhi, & Olinto 1986

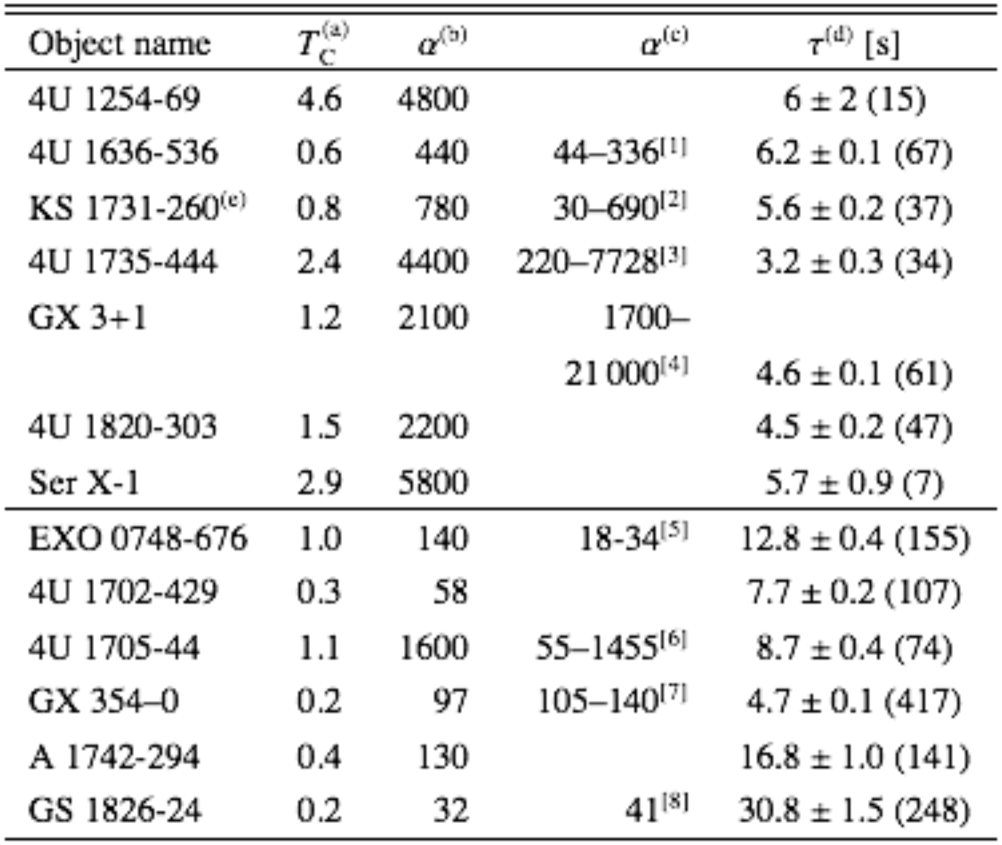
Carbon production in the rp-process



Schatz et al. (2003, 2005)

Superbursts occur when (some) hydrogen/helium is burning stably

in 't Zand (2003)

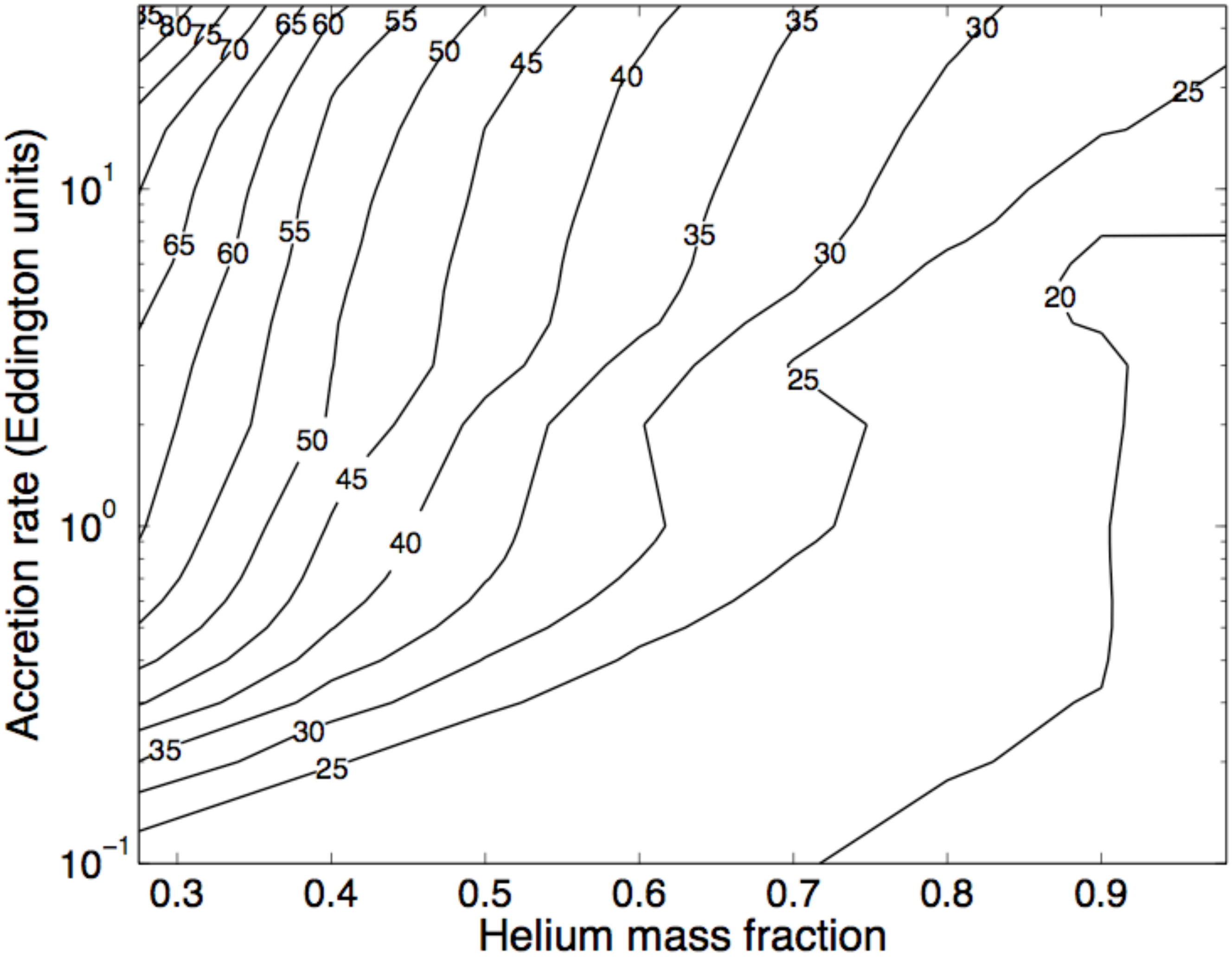


Object name	$T_C^{(a)}$	$\alpha^{(b)}$	$\alpha^{(c)}$	$\tau^{(d)}$ [s]
4U 1254-69	4.6	4800		6 ± 2 (15)
4U 1636-536	0.6	440	44–336[1]	6.2 ± 0.1 (67)
KS 1731-260(e)	0.8	780	30–690[2]	5.6 ± 0.2 (37)
4U 1735-444	2.4	4400	220–7728[3]	3.2 ± 0.3 (34)
GX 3+1	1.2	2100	1700–21 000[4]	4.6 ± 0.1 (61)
4U 1820-303	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)

Superburst sources

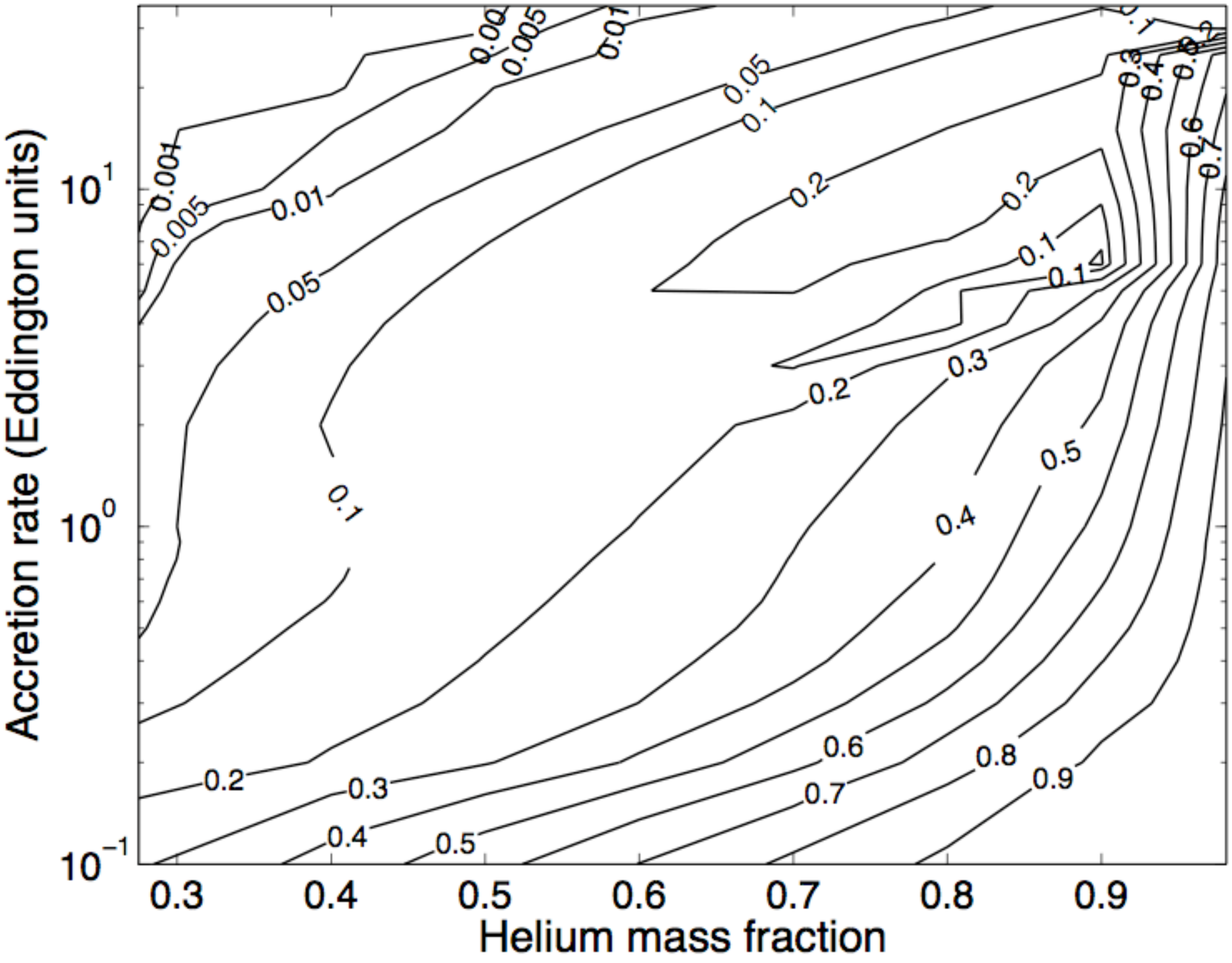
No superbursts

Carbon production in steady burning



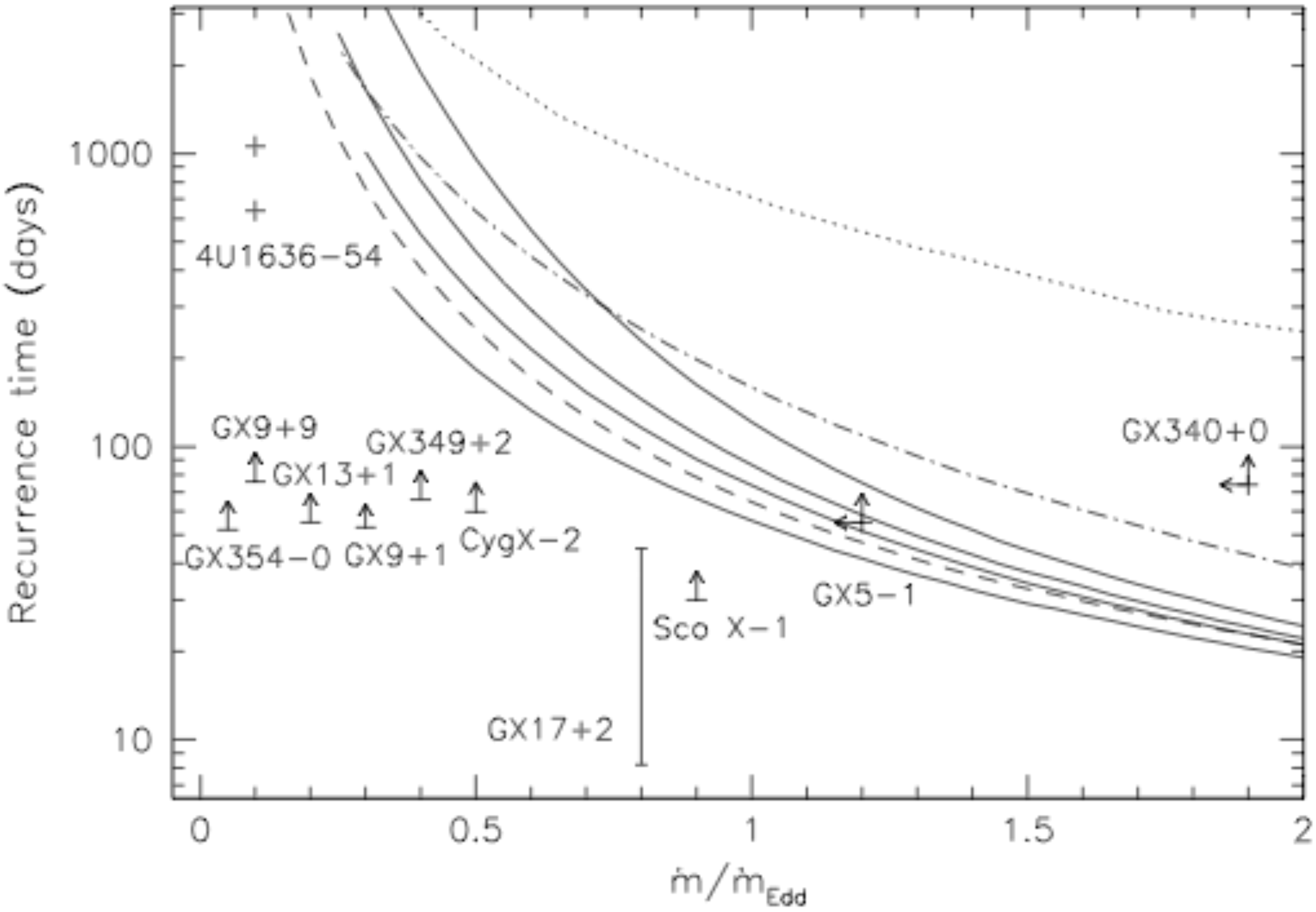
Schatz et al. (2007)

Carbon production in steady burning



Schatz et al. (2007)

Superbursts: ignition models



upper limits 1-2 months limited by BeppoSAX total exposure

Keek, in ‘t Zand, & Cumming (2005)

Superbursts as carbon flashes: scorecard

- **Fuel production** Schatz et al. 2003; in 't Zand et al. 2003
  - Can make ~ 10% carbon from the rp-process in STABLE burning ✓
  - but don't know how to burn stably at 0.1 Eddington ✗
  - Observed superbursters show stable burning (high alphas) ✓

- **Lightcurves and energies** Strohmayer & Brown 2002; Cumming & Macbeth 2004
  - model lightcurves show power-law cooling which explains long tails ✓
  - "neutrino thermostat" explains characteristic 10^{42} ergs energy ✓

- **Narrow range of accretion rates** CB01; CM04; in 't Zand et al. 2002
  - >0.1 Eddington to get unstable carbon ignition (and to make the carbon by stable burning?) ✓
  - superbursts found in the near-Eddington accretor GX 17+2 ✓

- **Quenching of normal bursts** CB01; CM04
  - late time cooling quenches unstable helium burning for about a month, agrees with disappearance of Type I bursts following superburst ✓

- **Recurrence times** Brown 2004; Cooper & Narayan 2005
  - Need large heat flux to obtain ignition temperature at the right depth ✗

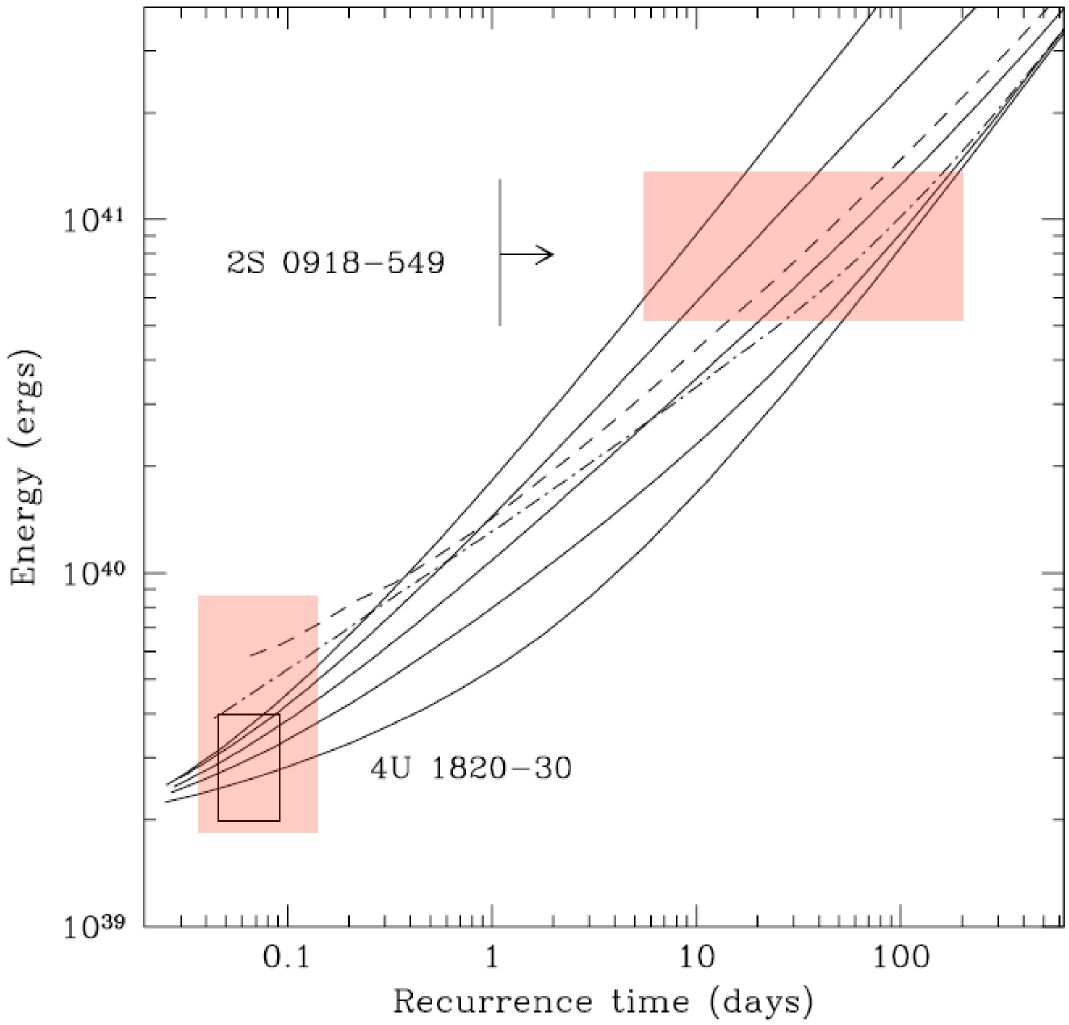
Pure helium bursts from ultracompact binaries

- Binaries with $P<80$ minutes => hydrogen deficient companion
- "What is the accreted composition?"
- Two examples:

1. **4U 1820-30** (P=10 mins)
   regular bursts with $\Delta t \sim 3$ hours
   can understand if accrete pure He but need $Q_b \sim 0.4$ MeV/nucleon at 0.3 Edd
   Bildsten (1995); Cumming (2003)
   is there a small amount of hydrogen ($X \sim 0.1$)?
   e.g. Podsiadlowski et al. (2002)

2. **2S 0918-549** (P unknown; ~20 mins?)
   enhanced Ne/O ratio => CO accretion disk?
   long burst with $E \sim 10^{41}$ erg naturally explained as pure helium accretion at the observed (persistent) 0.01 Edd
   need $Q_b \sim 1$ MeV/nucleon
   in 't Zand, AC, Verbunt, van der Sluys, Pols et al. (2005)

Pure helium bursts from ultracompact binaries



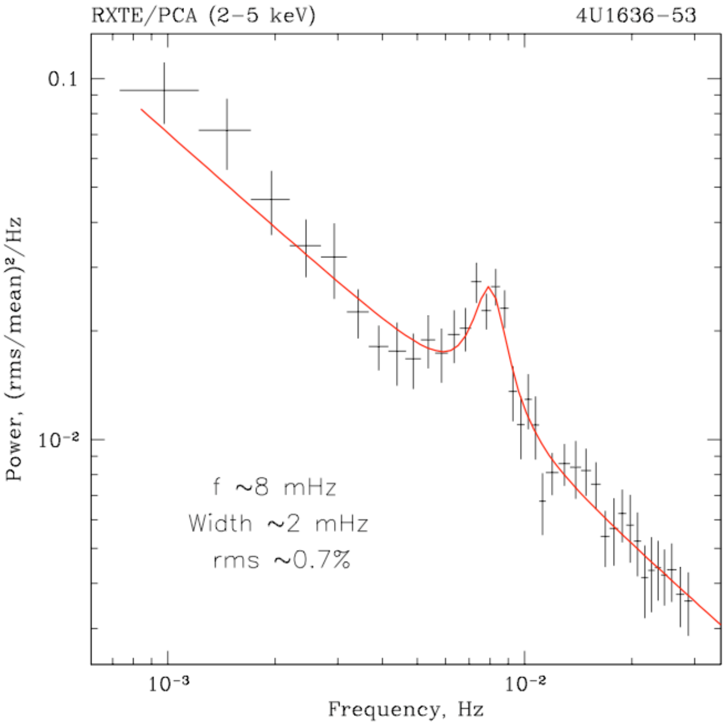
core physics

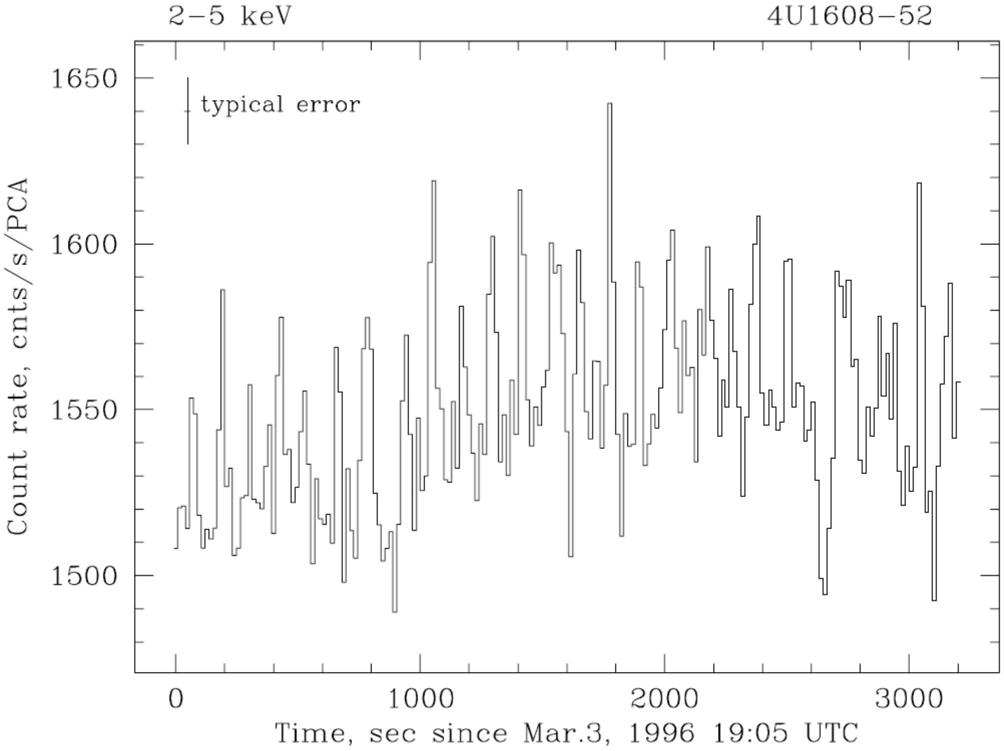
crust physics

CMZP (2005)

Observations of mHz QPOs

- discovered from Atoll sources 4U 1608-52, 4U 1636-53, Aql X-1 by Revnitsev et al. (2001) with frequencies (7-9) mHz
- flux variations at ~few percent level





Observations of mHz QPOs

- discovered from Atoll sources 4U 1608-52, 4U 1636-53, Aql X-1 by Revnitsev et al. (2001) with frequencies (7-9) mHz
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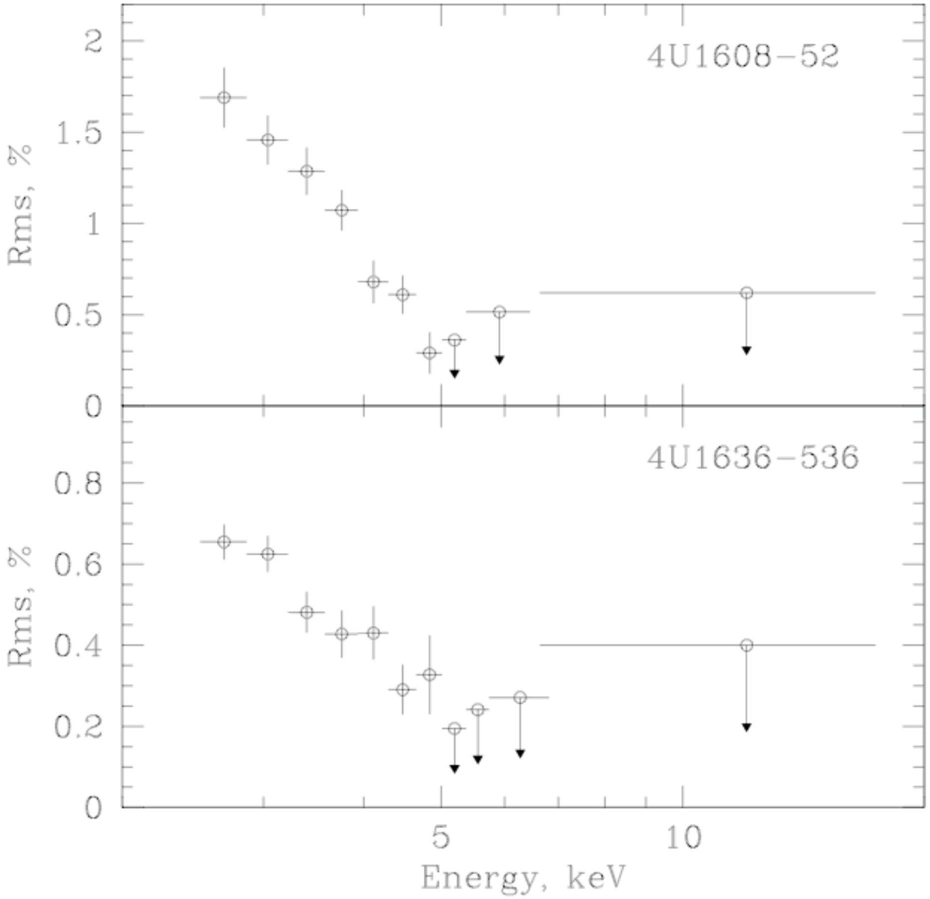

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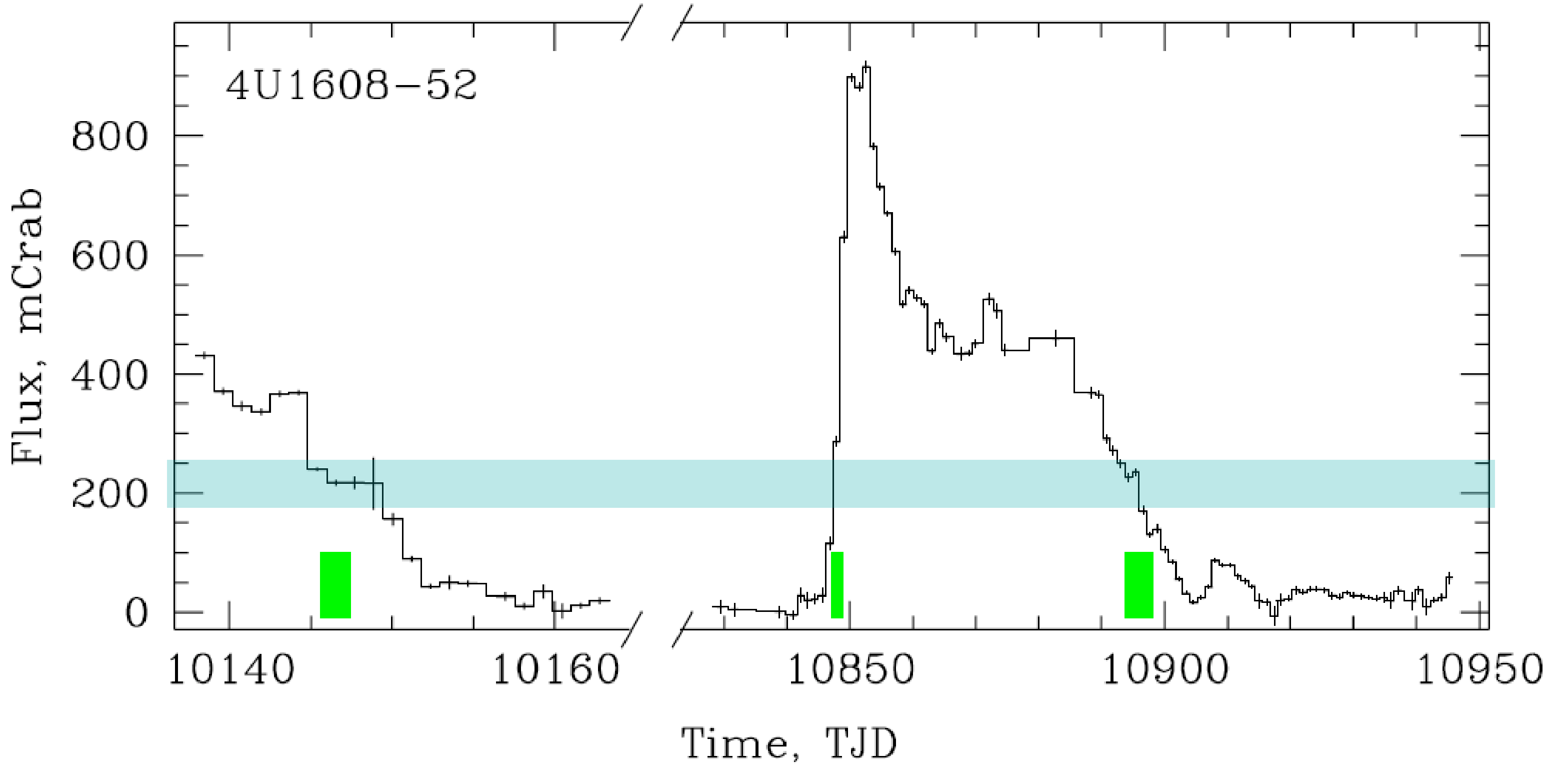

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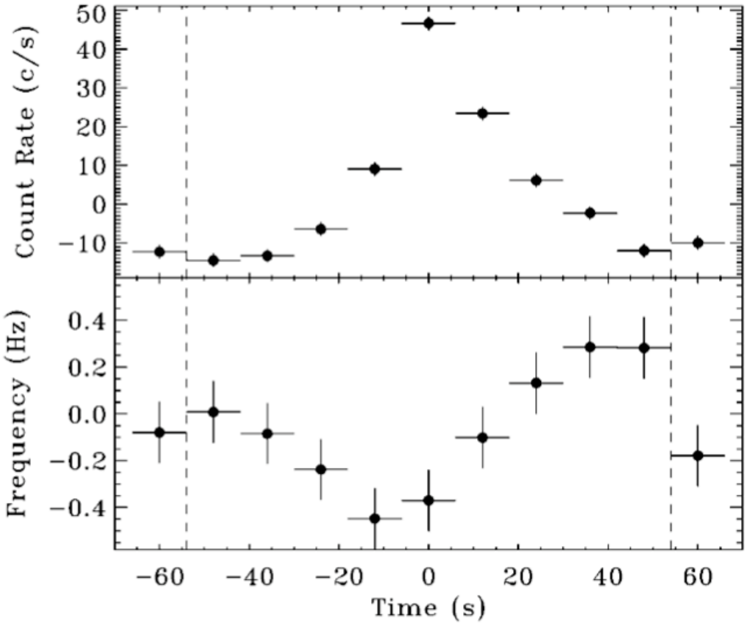
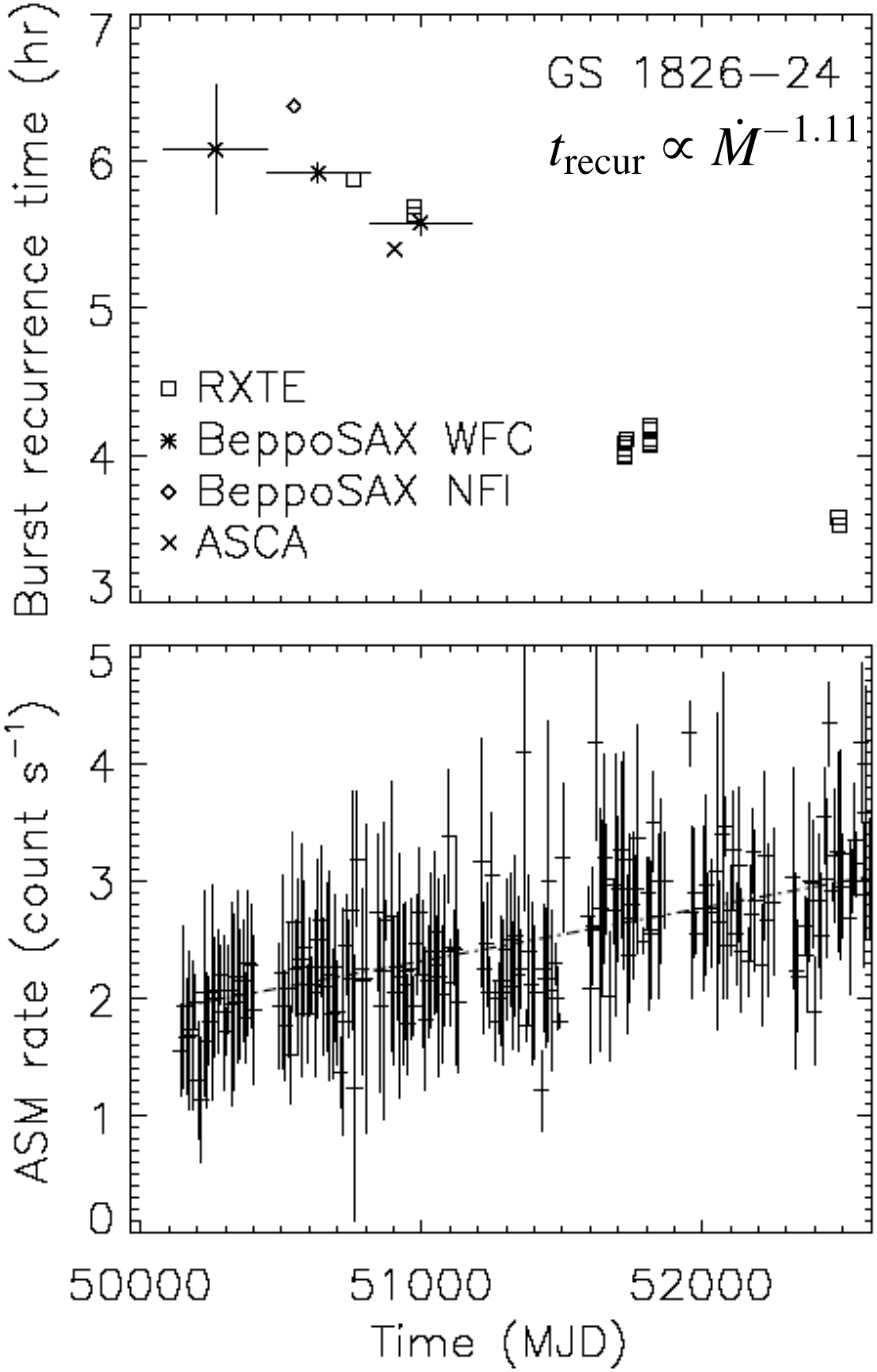
- Yu and van der Klis (2002) found an anticorrelation between mHz QPO amplitude and kHz QPO frequency

mHz QPO profile

kHz QPO frequency

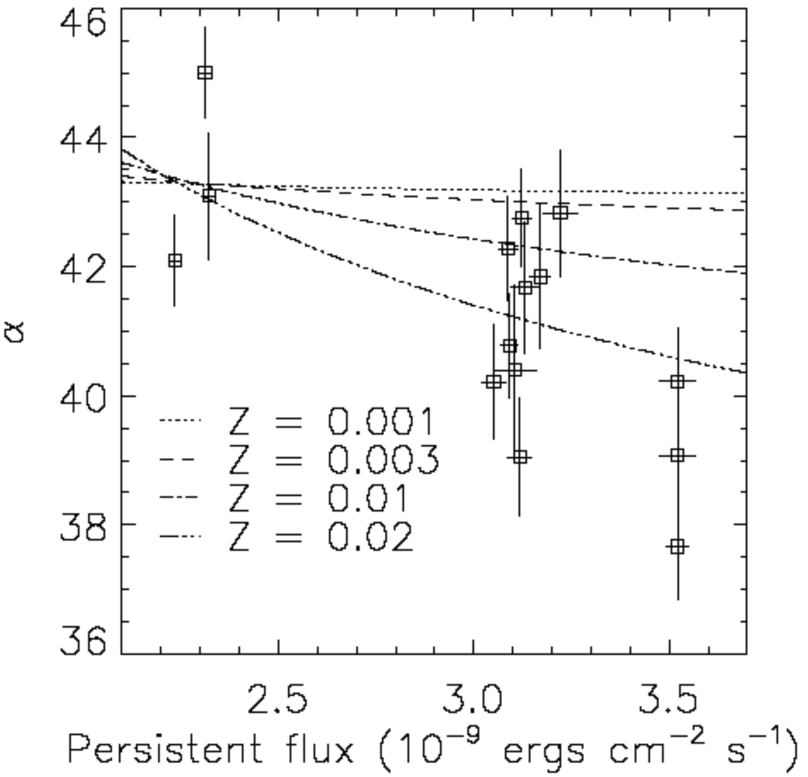




Time to burn the hydrogen in a given fluid element

$$t_H = 11 \text{ hrs} \left(\frac{0.02}{Z}\right) \left(\frac{X_0}{0.7}\right)$$

α variations indicate
~ solar metallicity



Galloway et al. (2003)

A new mode of nuclear burning?

- Revnitsev et al. (2001) suggested that we are seeing a **new mode of nuclear burning**

- Importance: first QPO identified with NS surface rather than the accretion flow

- Open questions:

  what sets the oscillation period ~ 2 mins?
  (stable over many years)

  why the narrow luminosity range?

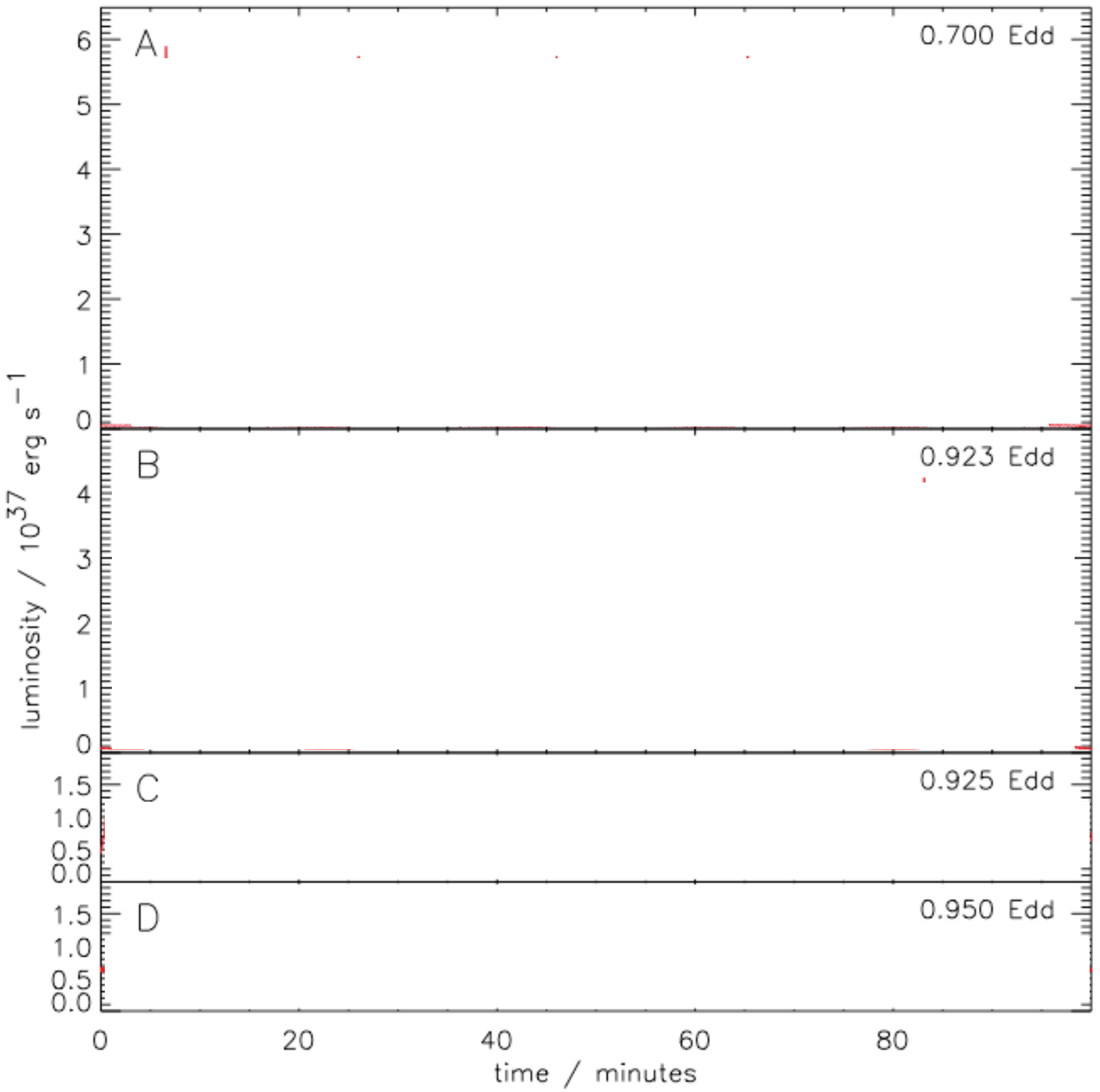
- Marginally stable nuclear burning answers these questions, but brings back an old puzzle!

Calculations of the transition to stable burning

- Extensions of the Woosley et al. 2003 ApJS calculations to higher accretion rates

- Kepler code, follow >1000 nuclei at each depth

- At the boundary between unstable and stable burning see oscillations with periods of 3 minutes



Heger, Cumming, & Woosley (2005)`

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- Extensions of the Woosley et al. 2003 ApJS calculations to higher accretion rates

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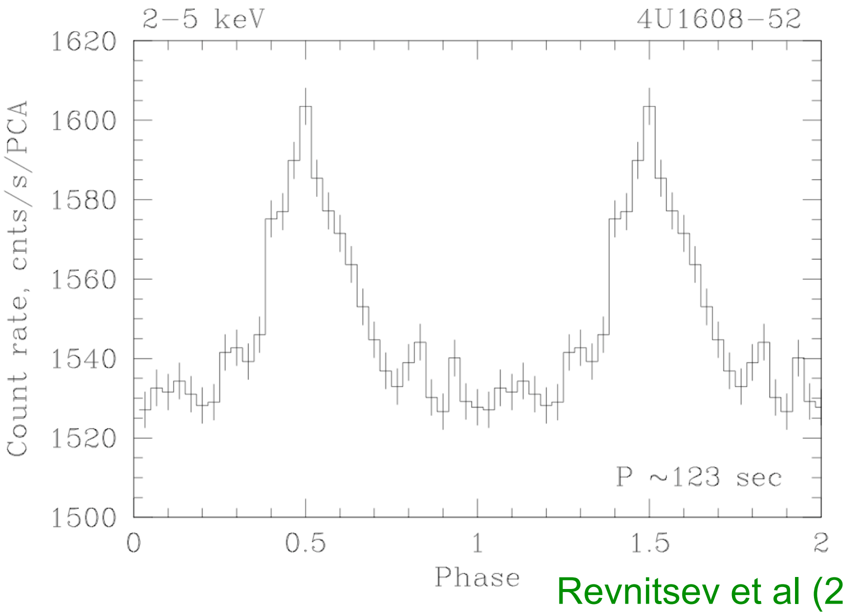
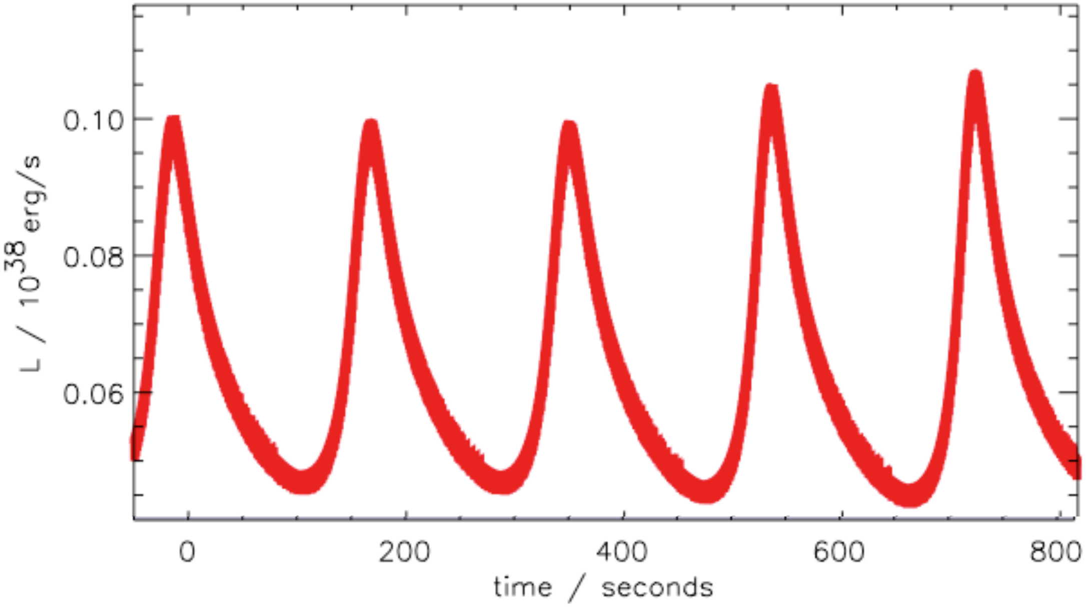
- At the boundary between unstable and stable burning see oscillations with periods of 3 minutes

- Amplitude and shape of the oscillation similar to the observed mHz QPOs



Revnitsev et al (2001)

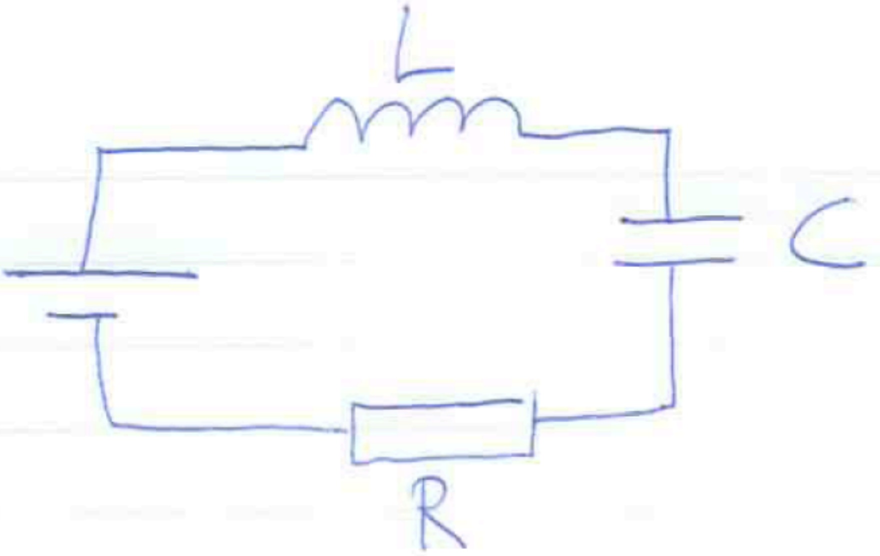


Heger, Cumming, & Woosley (2005)

The physics of the oscillation

- Paczynski (1981) suggested that oscillations should be present at the boundary between unstable and stable burning

- The physics is present in the canonical non-linear oscillator: the ***van der Pol oscillator***



The physics of the oscillation

- Simple one-zone model

$$c_P \frac{dT}{dt} = \epsilon - \frac{F}{y}$$

$$\frac{dy}{dt} = \dot{m} - \frac{\epsilon}{E_\star} y.$$

$t_{\rm therm} \sim 10$s

$t_{\rm accr} \sim 1000$s

- Linear perturbations

$$\frac{\partial^2 f}{\partial t^2} + \left(\frac{4-\alpha}{t_{\rm therm}} - \frac{1}{t_{\rm accr}} \right) \frac{\partial f}{\partial t} + \frac{2\alpha}{t_{\rm accr} t_{\rm therm}} f = 0.$$

Usually thermal time dominates
with strong driving or damping

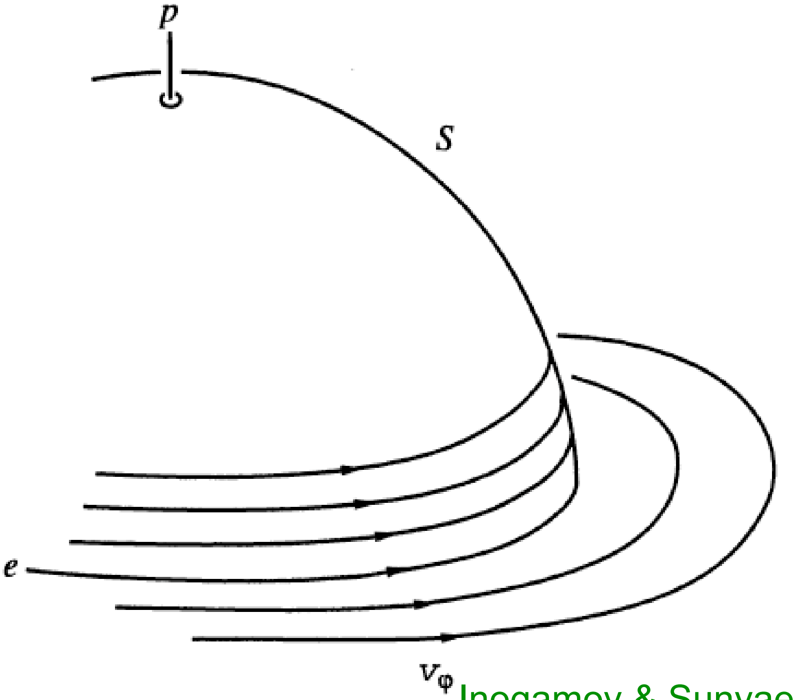
Oscillation period $\approx \left(t_{\rm therm} t_{\rm accr} \right)^{1/2}$

- A clock on the NS surface that depends on g, X … no mdot uncertainty!

BUT…

- theoretically, the transition to unstable burning occurs close to Eddington => 10^{38} erg/s whereas the observed luminosity is ~ 10^{37} erg/s

- what matters is the local accretion rate - one way out is that the accreted material covers only 10% of the area ?



Inogamov & Sunyaev (1999)

What happens at $L_X \sim 10^{37}$ erg/s?

regular bursts
long duration
$\alpha \approx 25 - 40$

burst oscillations

superbursts

stable burning $\alpha \sim 100 - 1000$
short, irregular Type I bursts

mHz QPOs

ISLAND STATE
("low hard")

→

BANANA STATE
("high soft")