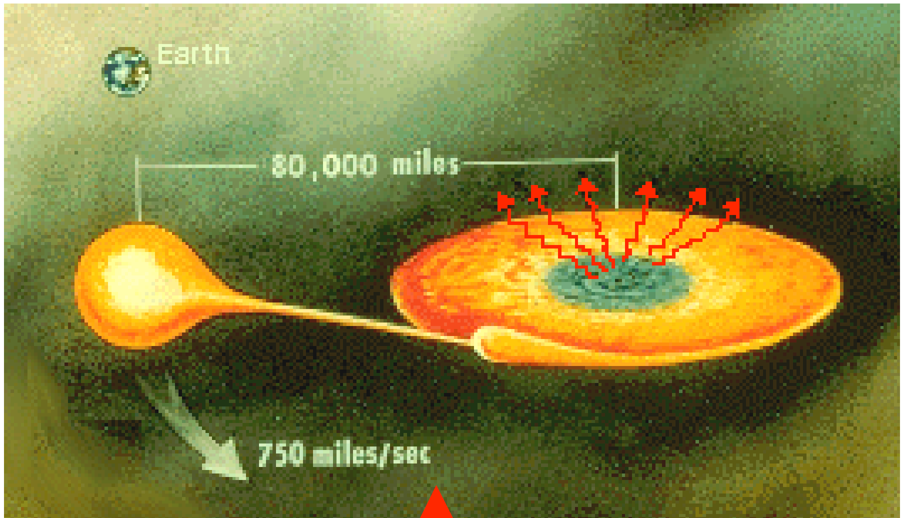
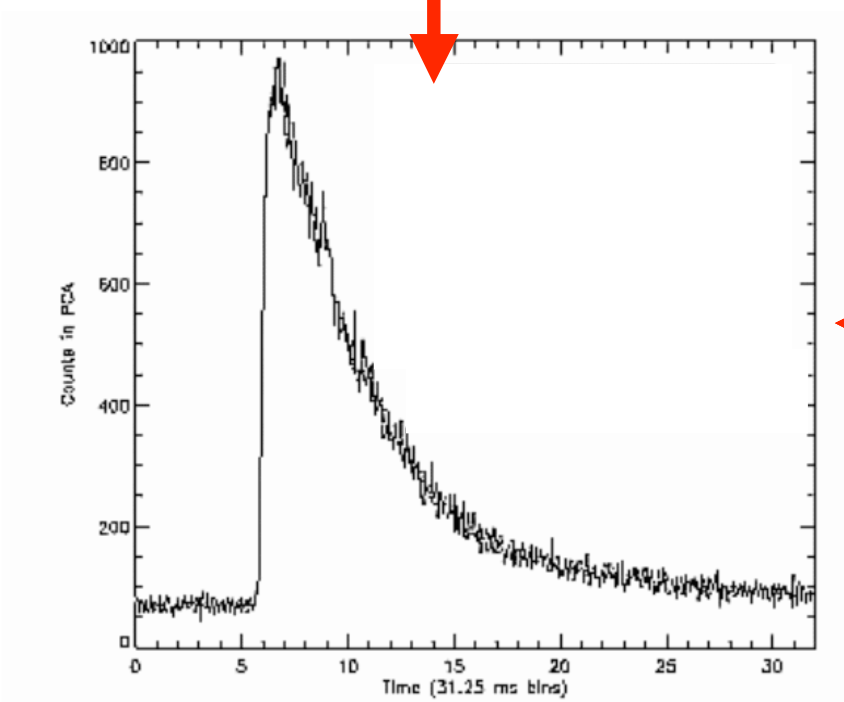
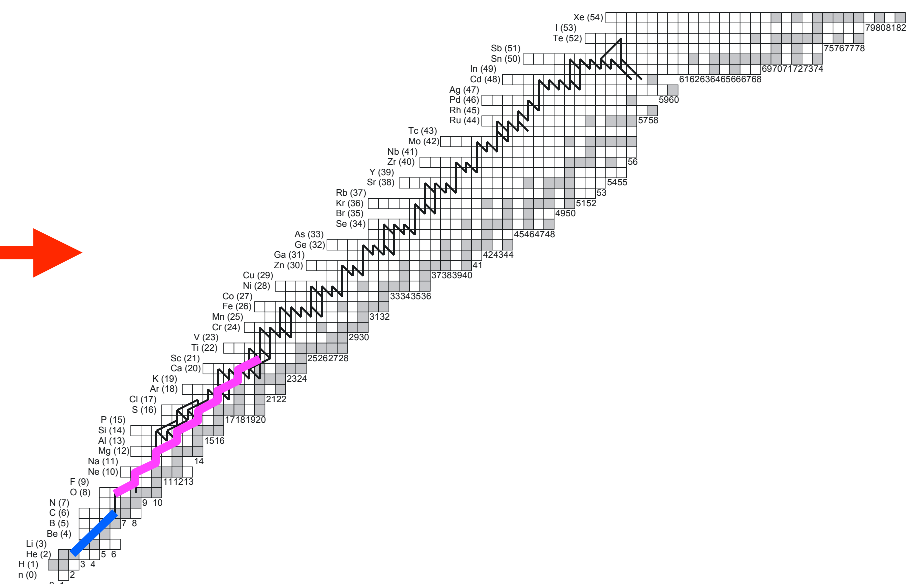


The role of the rp-process in accreting neutron stars

Andrew Cumming
McGill University





Why are we interested in neutron stars in low mass X-ray binaries?

astrophysics

- what is the neutron star spin and magnetic field?
- how to make these binaries?
- fluids: dynamics of reactive flow, turbulent mixing, angular momentum transport…

nuclear physics

- rp-process burning at high temperatures and densities
- crust reactions
- nuclear equation of state above nuclear density

How can we probe the rp-process using observations?
OR
What effect does the rp-process have on observable properties of nuclear burning?

Energetics

Duration

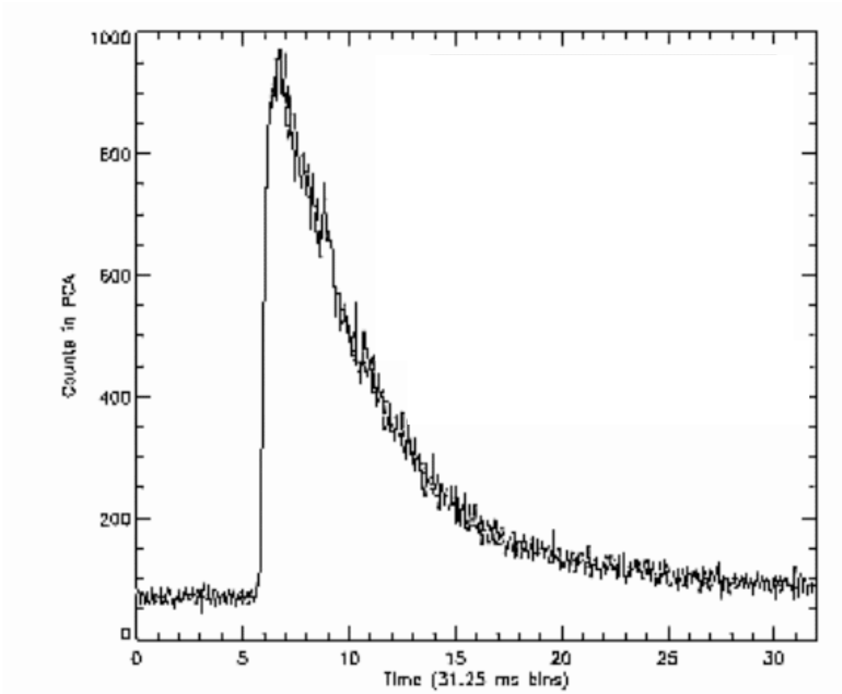
Ashes

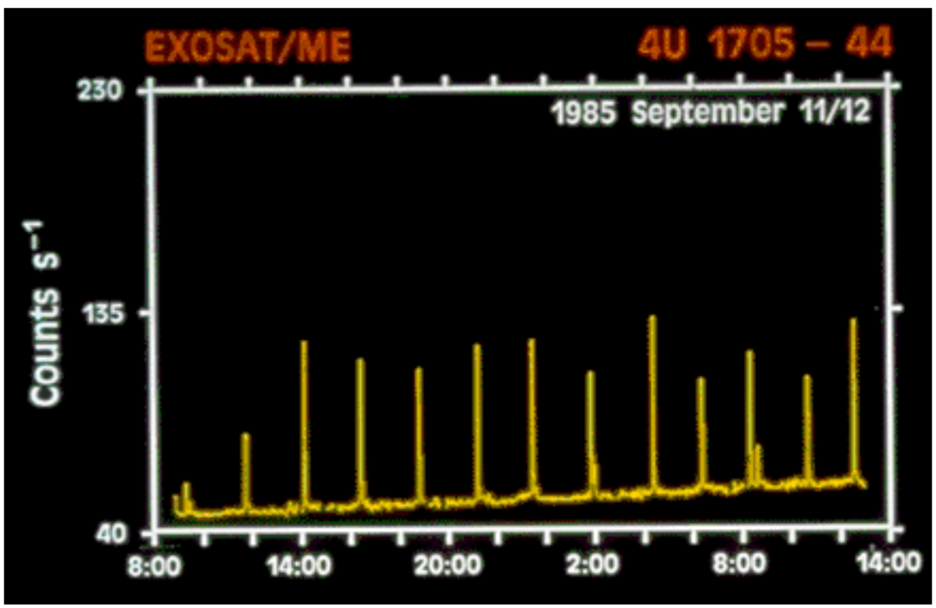
Global bursting behavior
- recurrence times as function of accretion rate
- transition to stable burning

Burst lightcurves
- long burst tails powered by rp-process burning

Superbursts
- extremely energetic flashes that occur when the rp-process ashes *reignite*

Crust transport and mechanical properties





Type I (Thermonuclear) X-ray bursts

thin shell flashes driven by unstable He burning

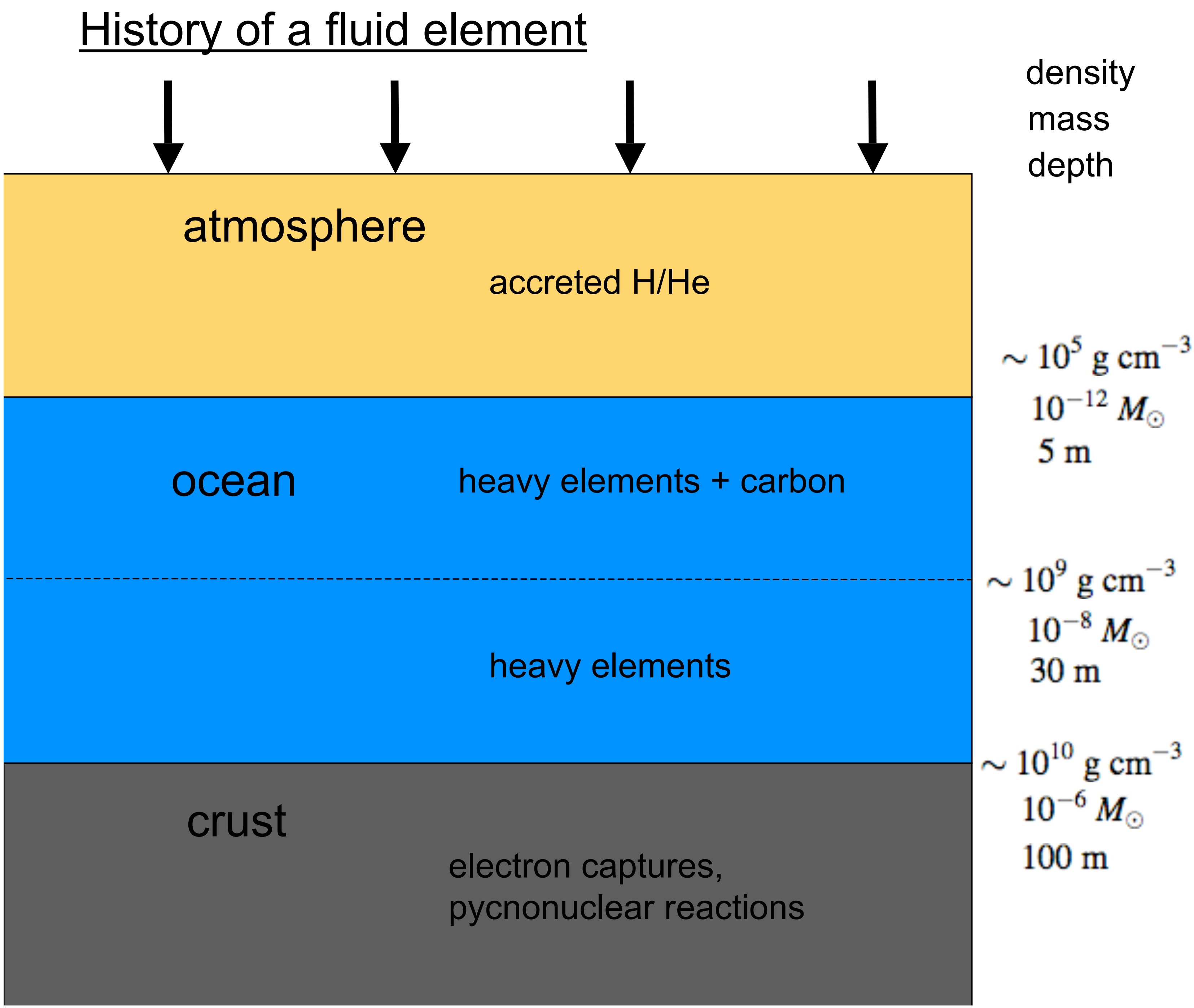
typical properties

recurrence times ~ hours to days
durations ~ 10 - 100 seconds
energies ~ 10^{39}-10^{40} ergs
spectral softening during the tail

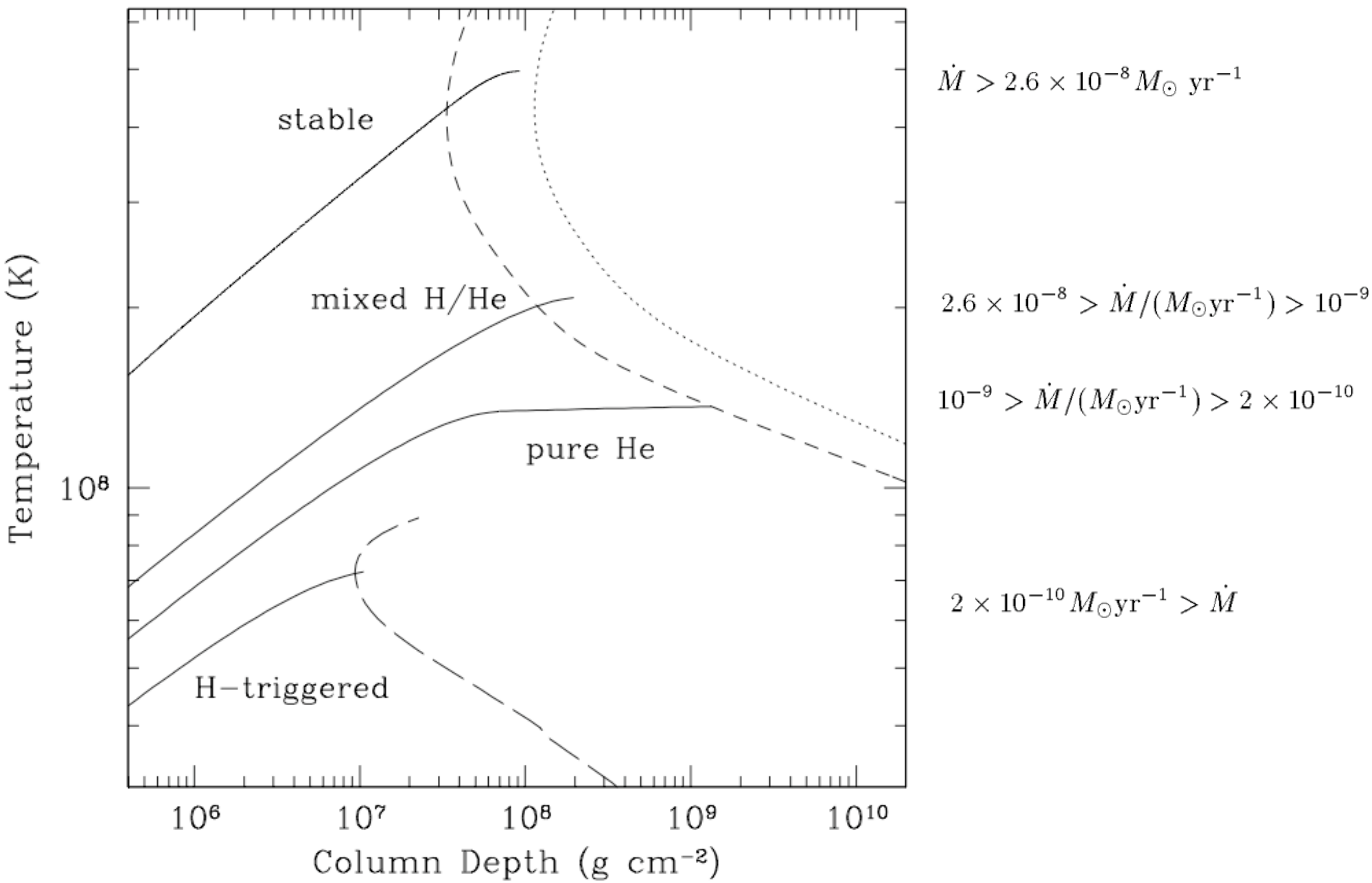
energetics

$$\alpha \equiv \frac{\int L_{\rm accr} dt}{E_{\rm burst}} \approx \frac{GM/R}{E_{\rm nuc}}$$
$$\approx \frac{200 \text{ MeV per nucleon}}{(1-5) \text{ MeV per nucleon}}$$

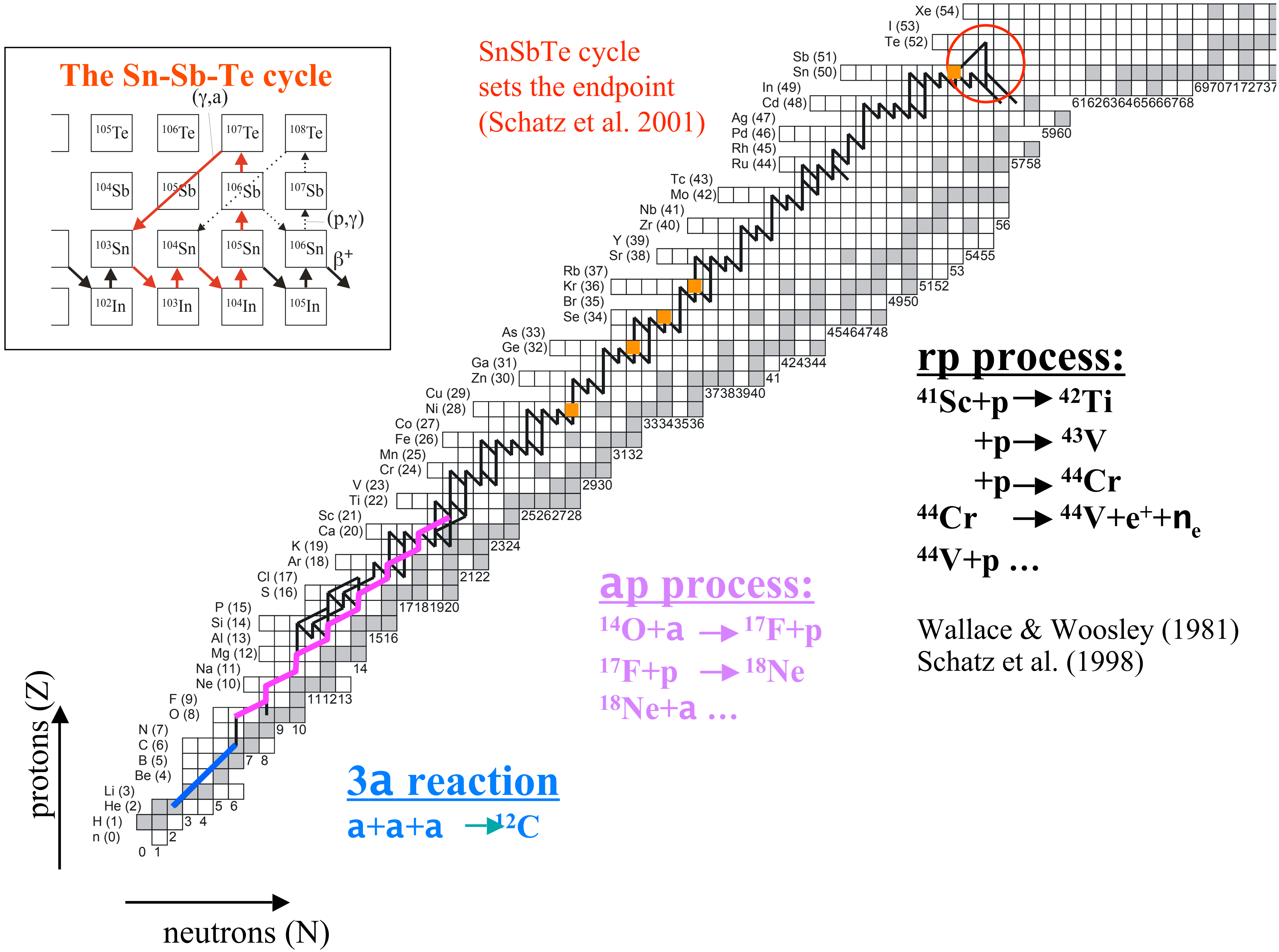
reviews: Lewin, van Paradijs, & Taam (1995); Bildsten & Strohmayer (2003)


History of a fluid element
density
mass
depth
atmosphere
accreted H/He
$\sim 10^5$ g cm^{-3}
$10^{-12}\ M_\odot$
5 m
ocean
heavy elements + carbon
$\sim 10^9$ g cm^{-3}
$10^{-8}\ M_\odot$
30 m
heavy elements
$\sim 10^{10}$ g cm^{-3}
$10^{-6}\ M_\odot$
100 m
crust
electron captures,
pycnonuclear reactions

Burning regimes



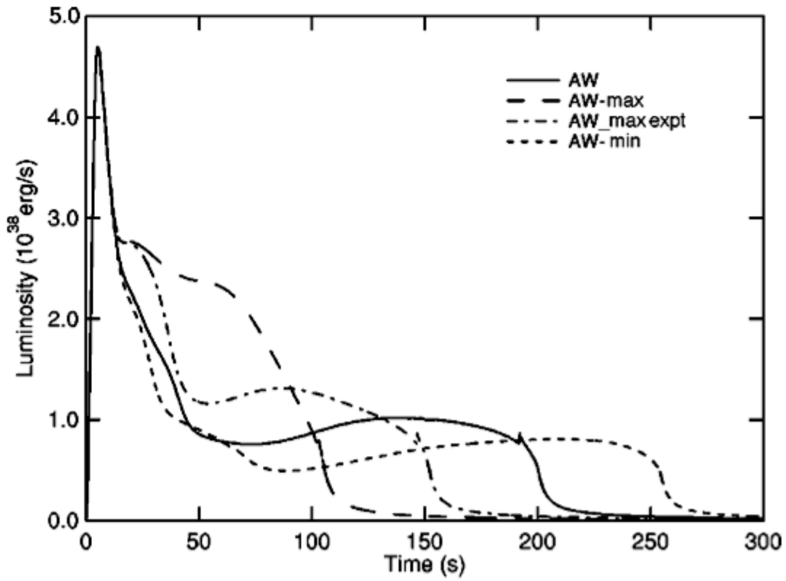
Taam, Woosley, Joss, Fujimoto (late 1970s, 1980s), Bildsten (1998)


The Sn-Sb-Te cycle
(γ,a)
(p,γ)
β+
SnSbTe cycle
sets the endpoint
(Schatz et al. 2001)
rp process:
41Sc+p → 42Ti
+p → 43V
+p → 44Cr
44Cr → 44V+e+ +ne
44V+p …
ap process:
14O+a → 17F+p
17F+p → 18Ne
18Ne+a …
3a reaction
a+a+a → 12C
Wallace & Woosley (1981)
Schatz et al. (1998)
protons (Z)
neutrons (N)

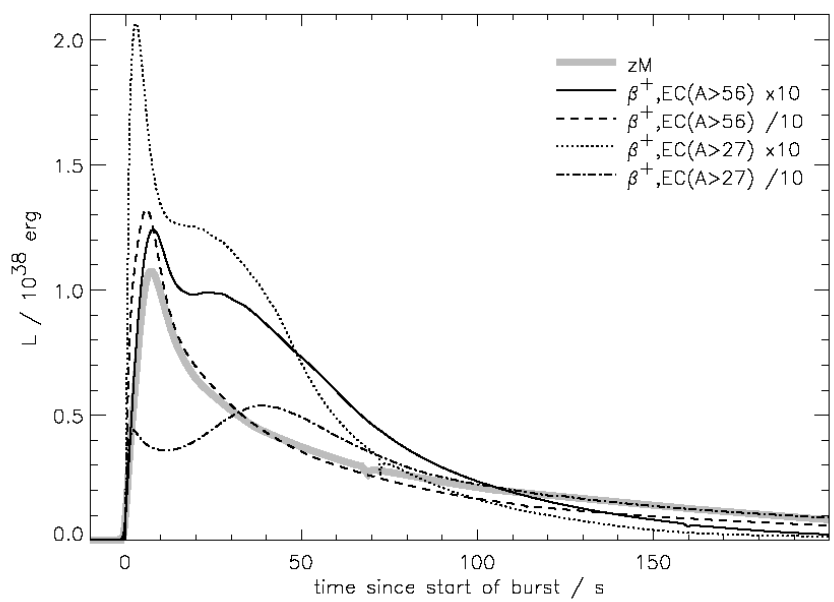
Effect of rp-process on burst lightcurves

one zone

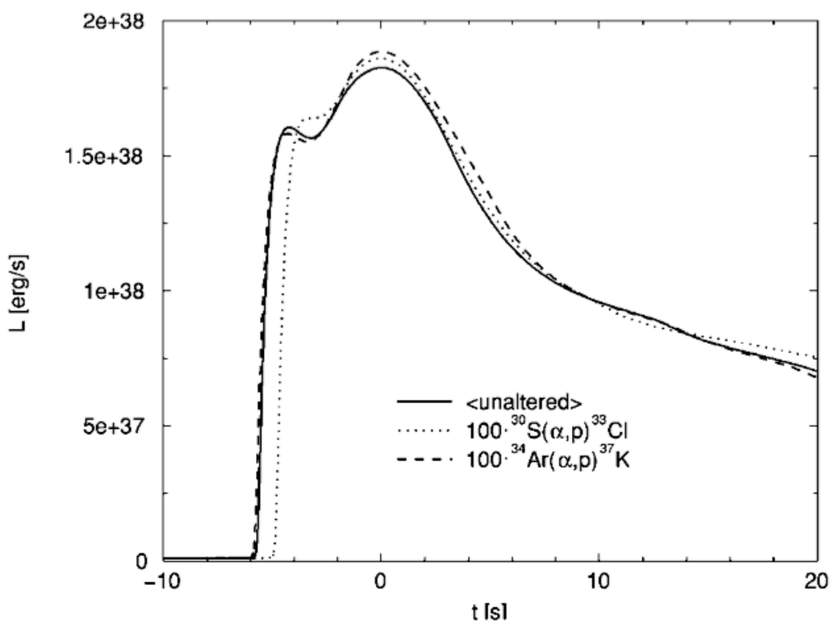
Brown et al. (2002)
(see also Koike et al.1999
Schatz et al. 2001)



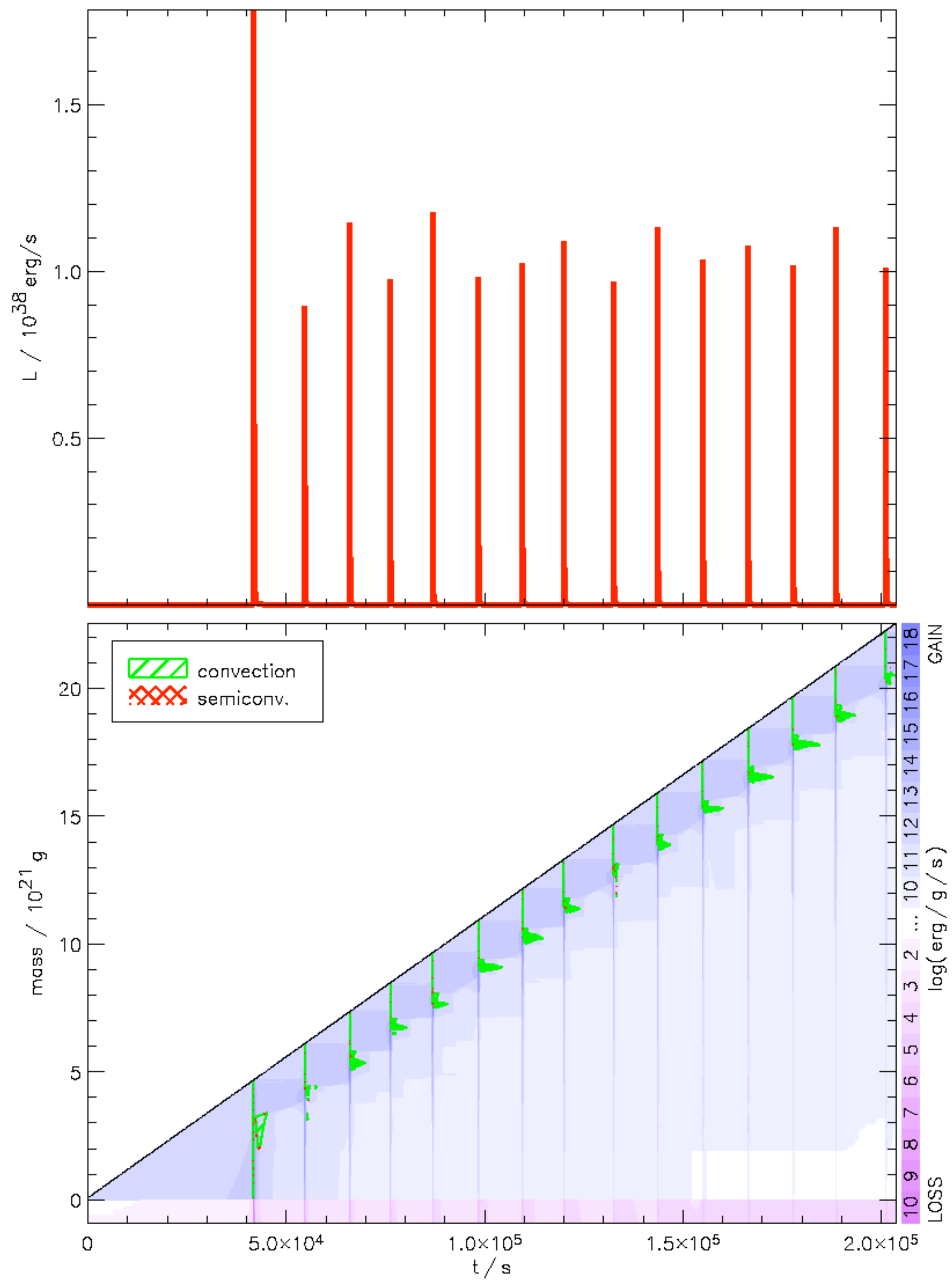
multizone



Woosley, Heger et al. (2004)



Fisker & Thielemann (2004)



Multizone models of X-ray bursts

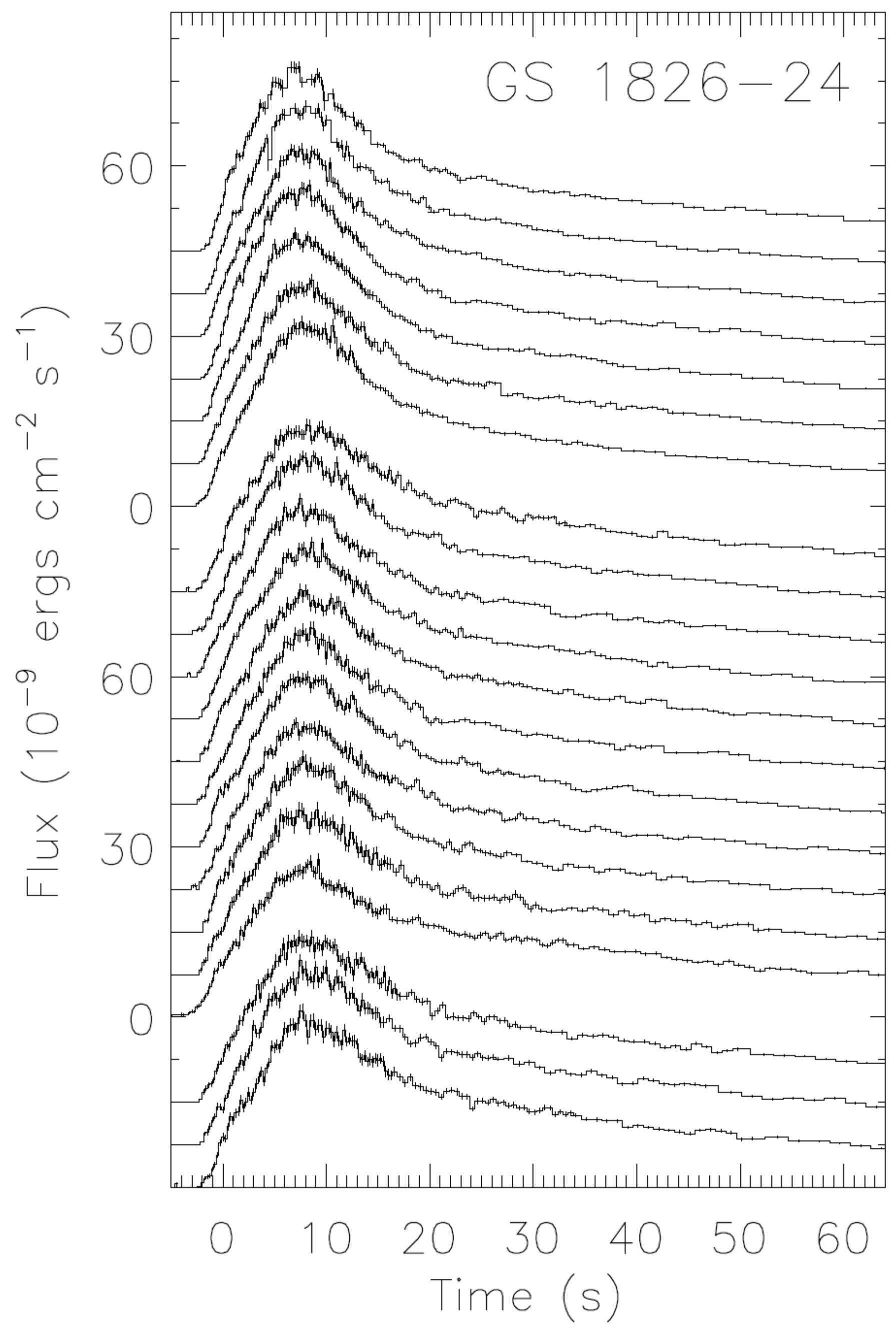
Woosley, Heger, AC, et al. (2004)

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

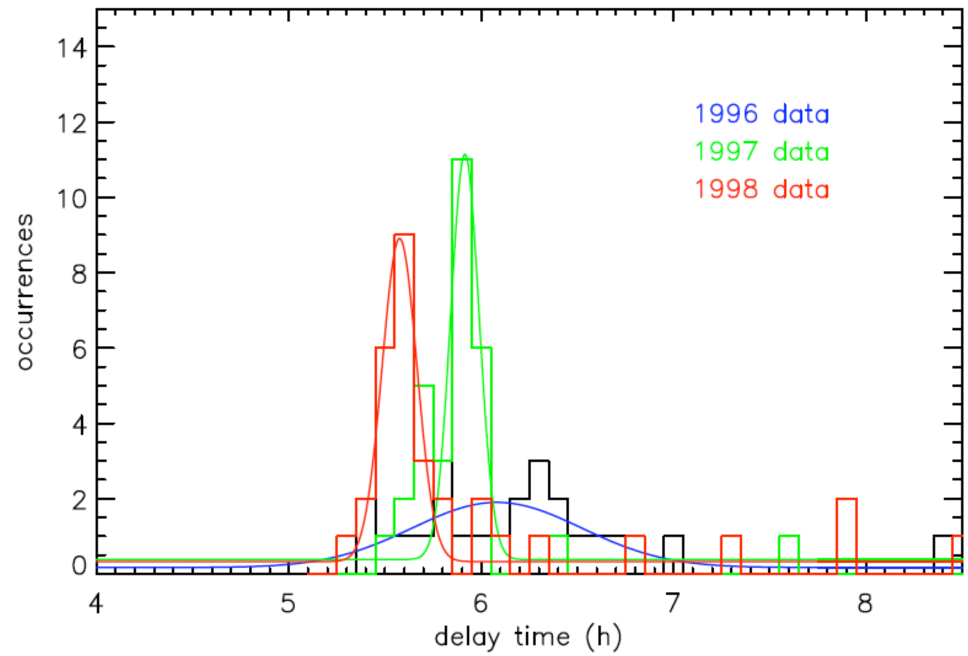
+

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

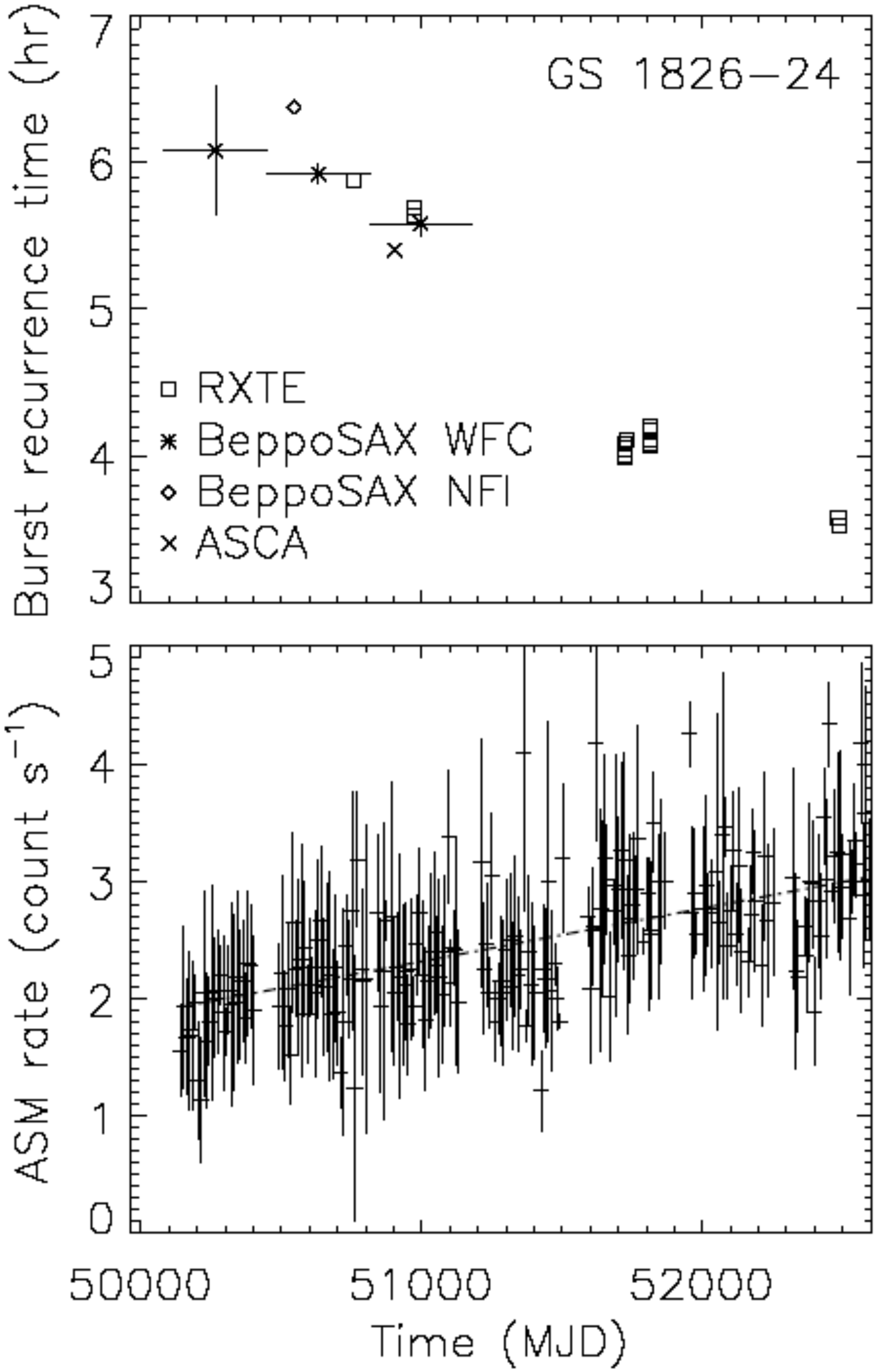
The "textbook" burster: GS 1826-24



Galloway et al. (2003)



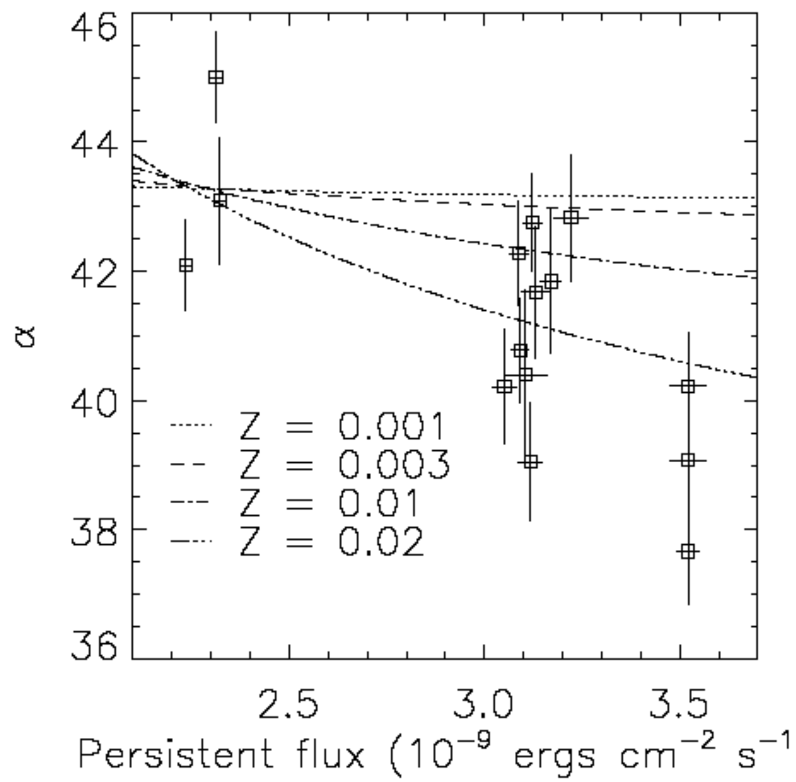
Cocchi et al. (2001)

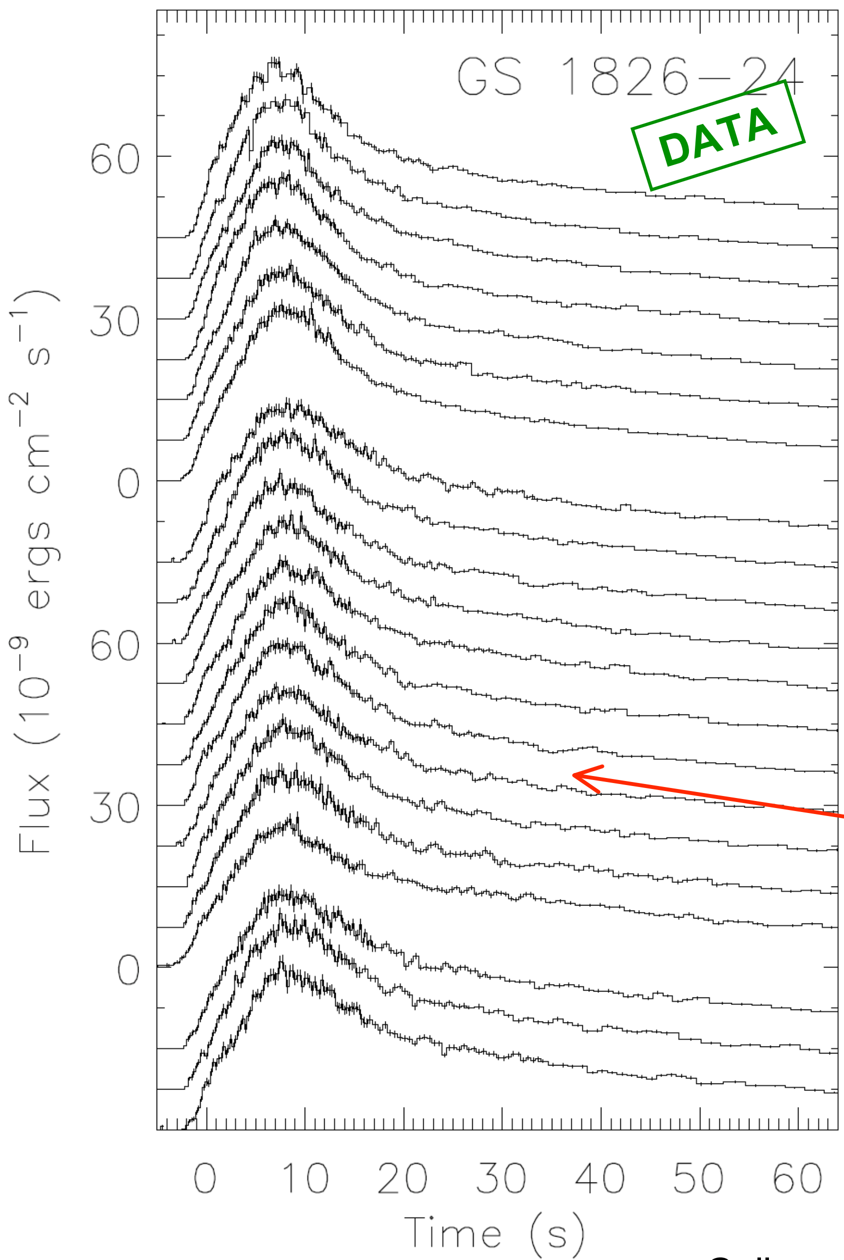


Galloway et al. (2003)

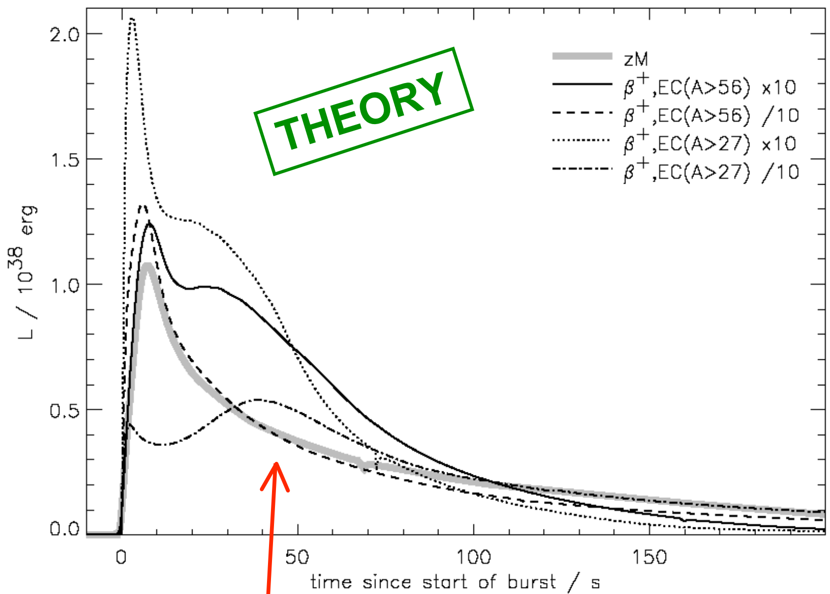
$$t_{\rm recur} \propto \dot{M}^{-1.11}$$

a variations indicate
~ solar metallicity



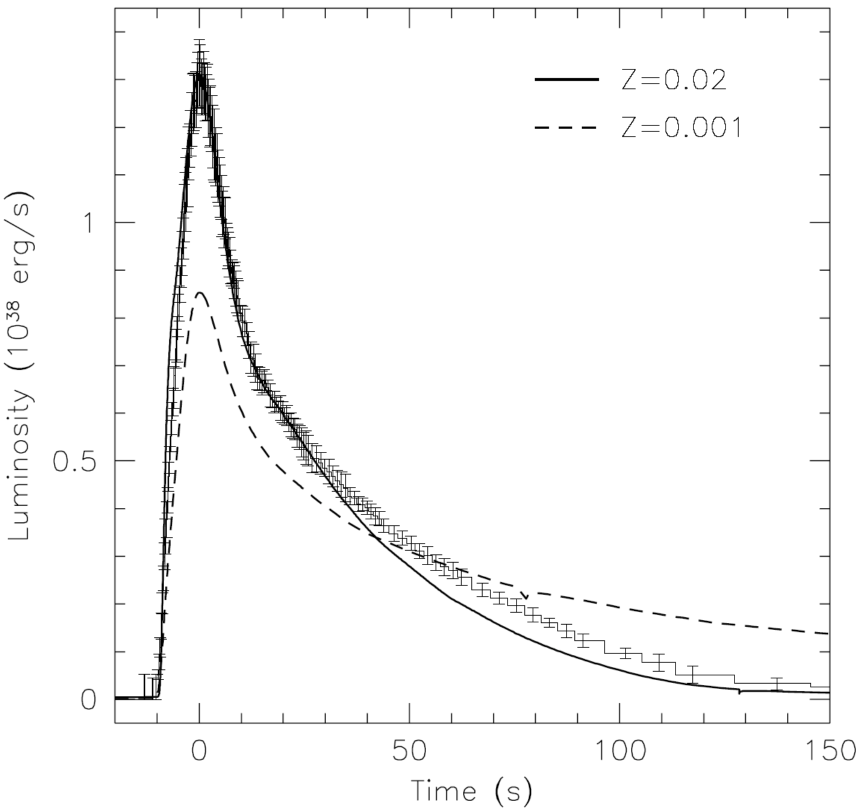


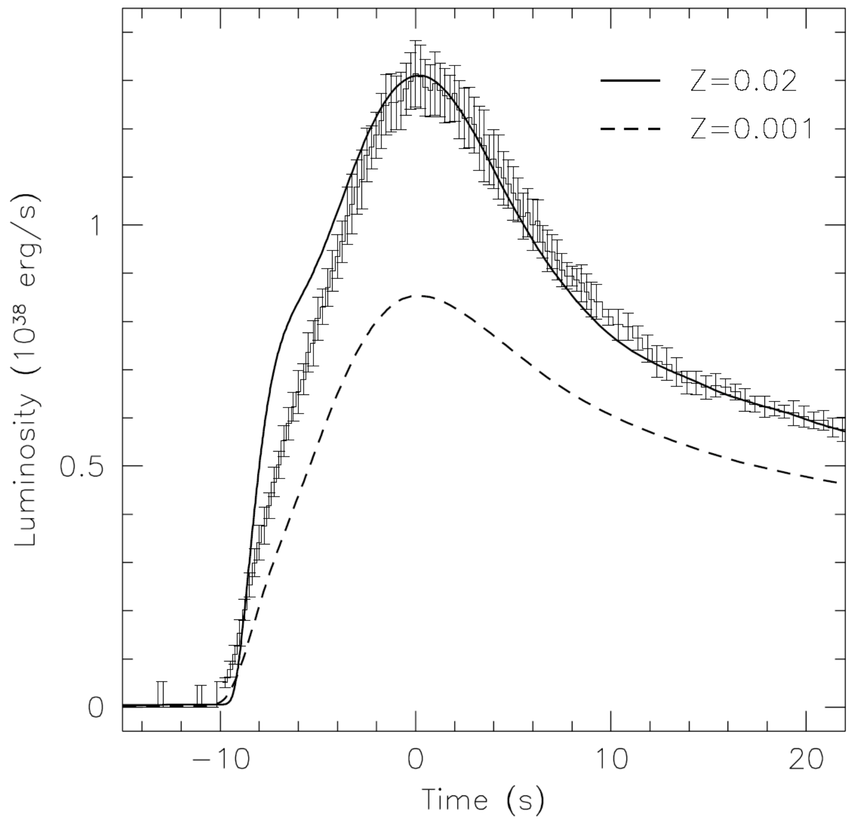
Galloway et al. (2004)



Woosley et al. (2004)

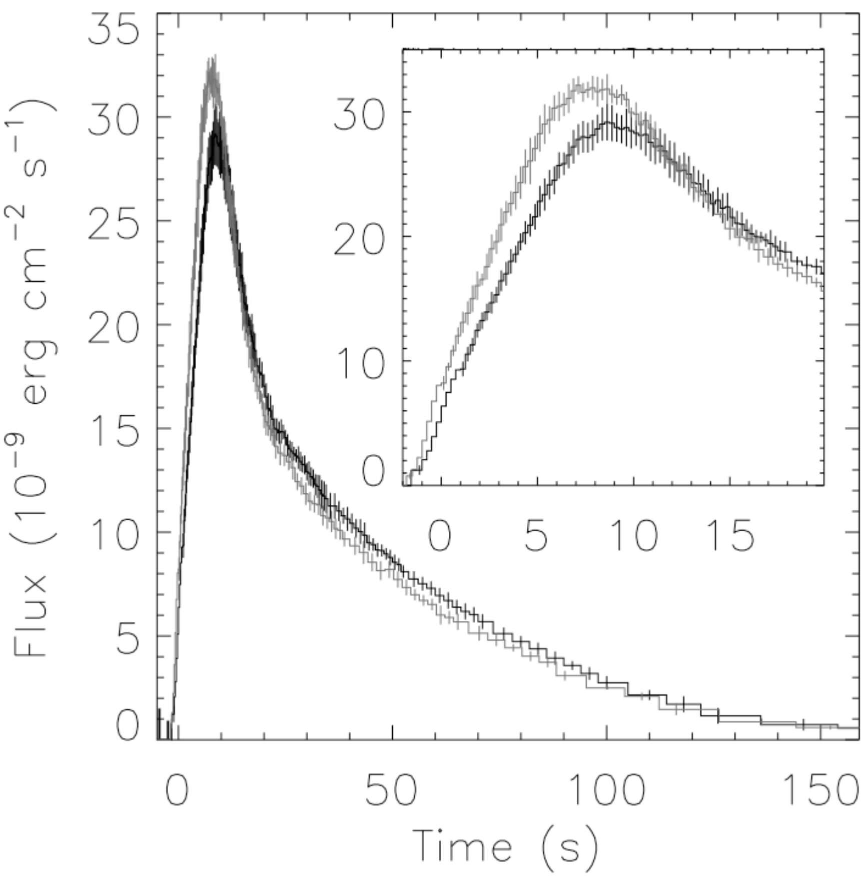
long tails powered by hydrogen burning

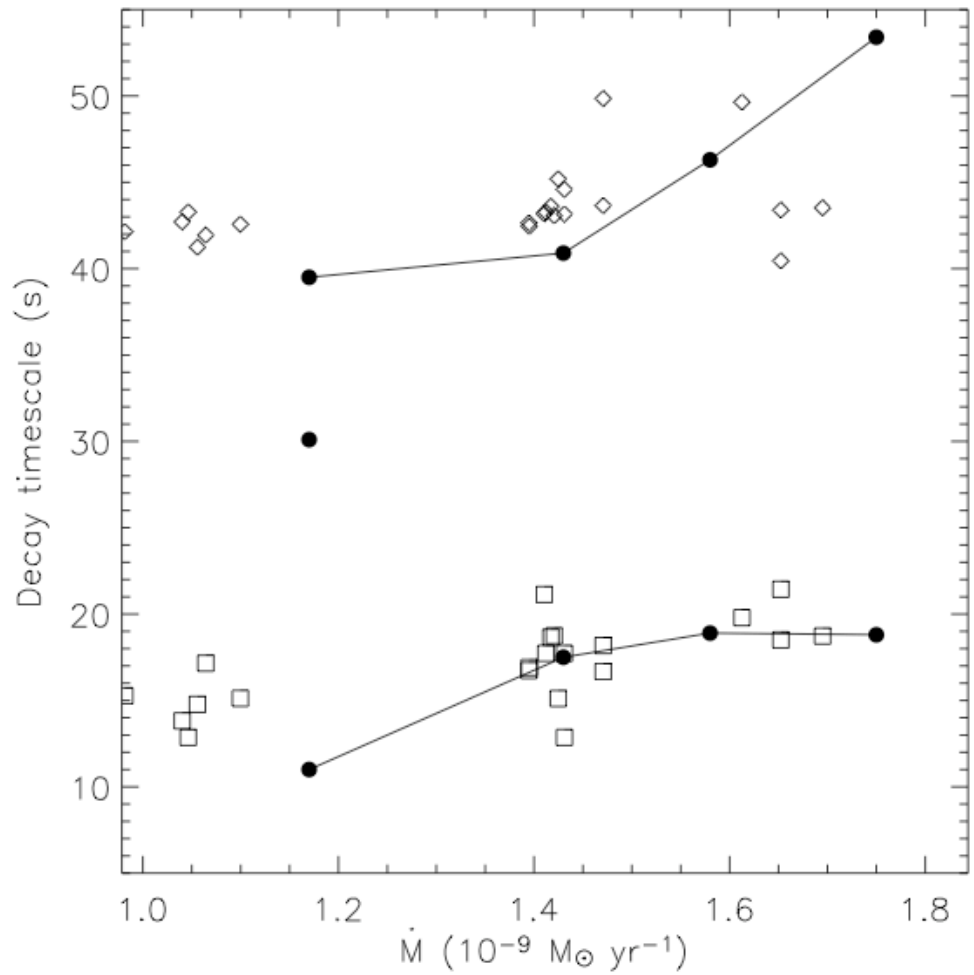




Heger, Galloway, AC (2007)

Change in the burst lightcurves with accretion rate

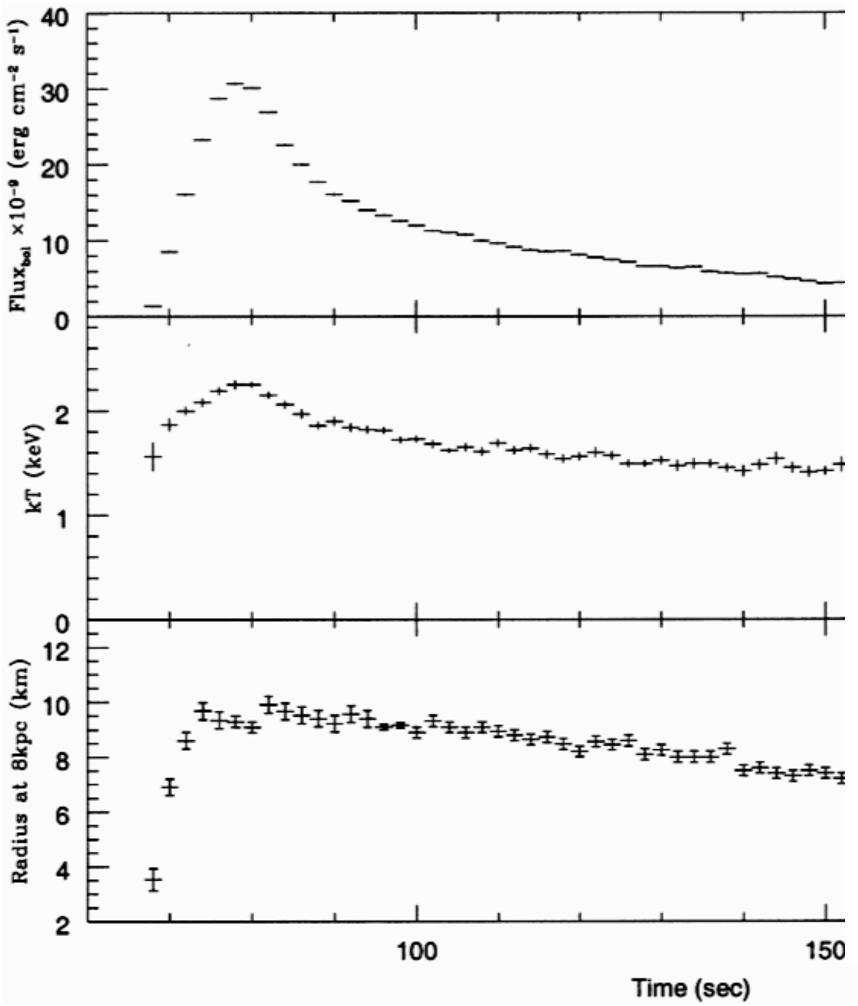


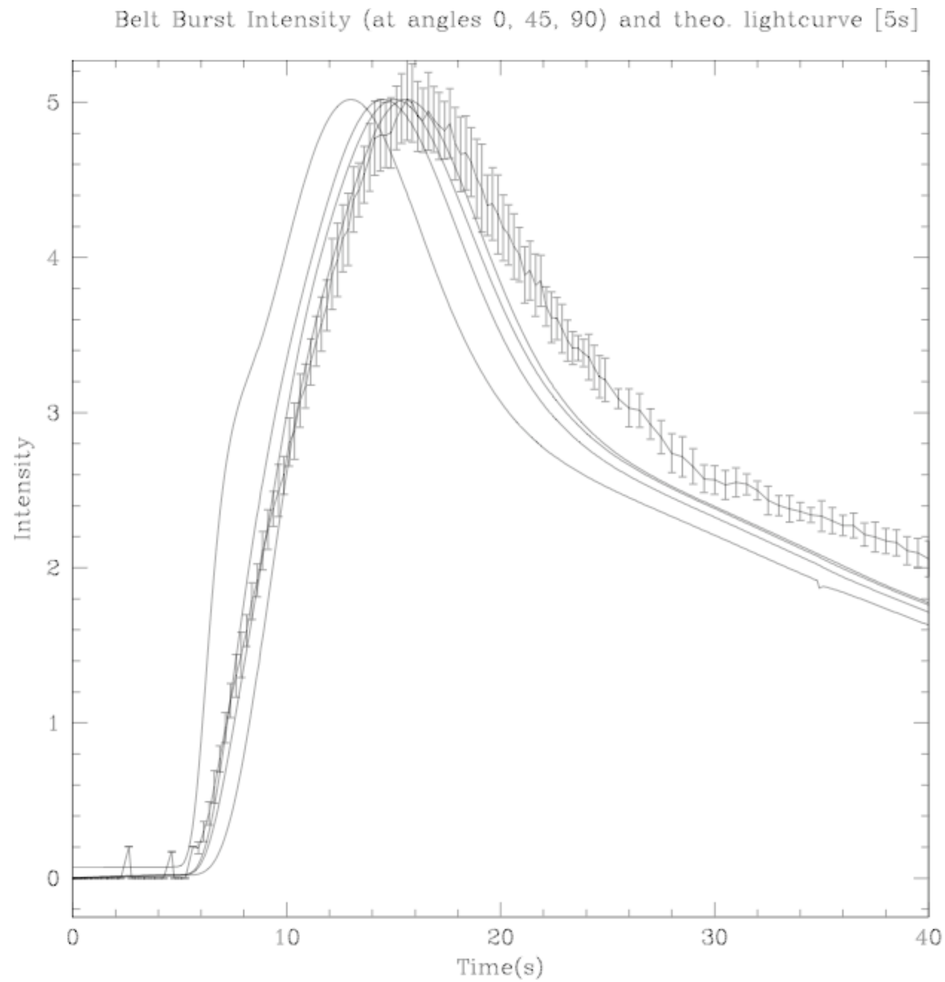


Galloway et al. (2003, 2006)

Heger et al. (2007)

Spreading during the rise?

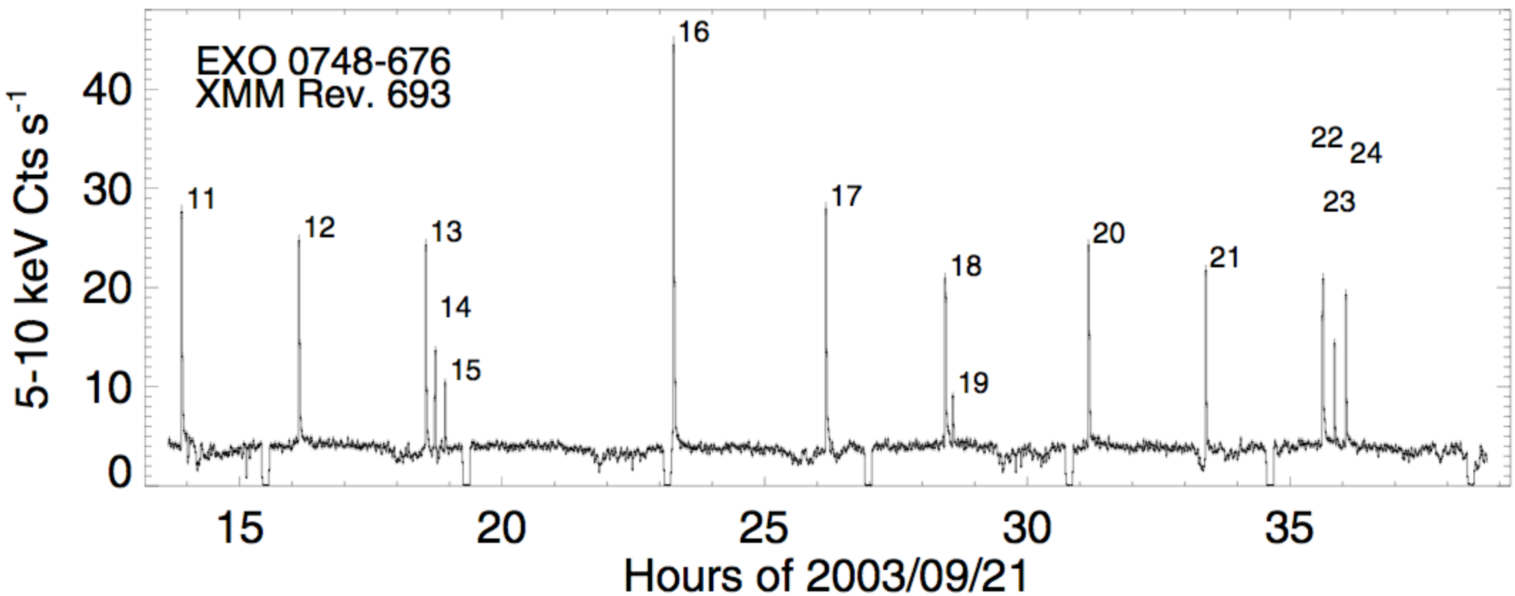




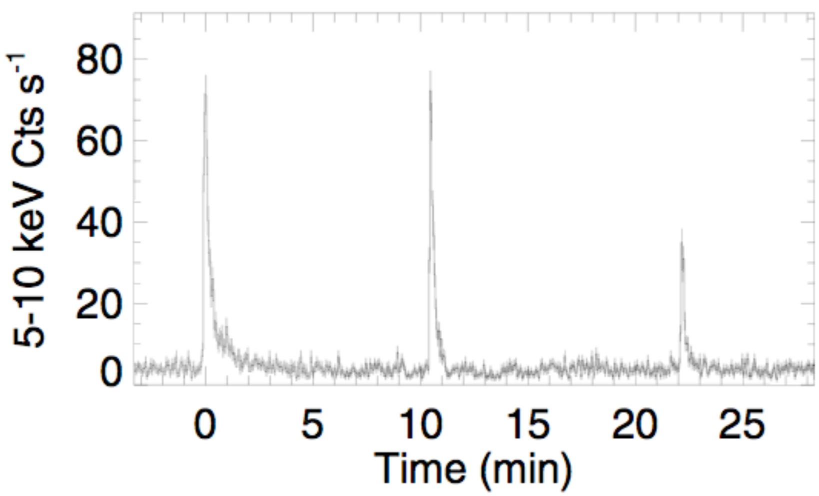
Kong et al. (2000)

calculation by Michael Zamfir

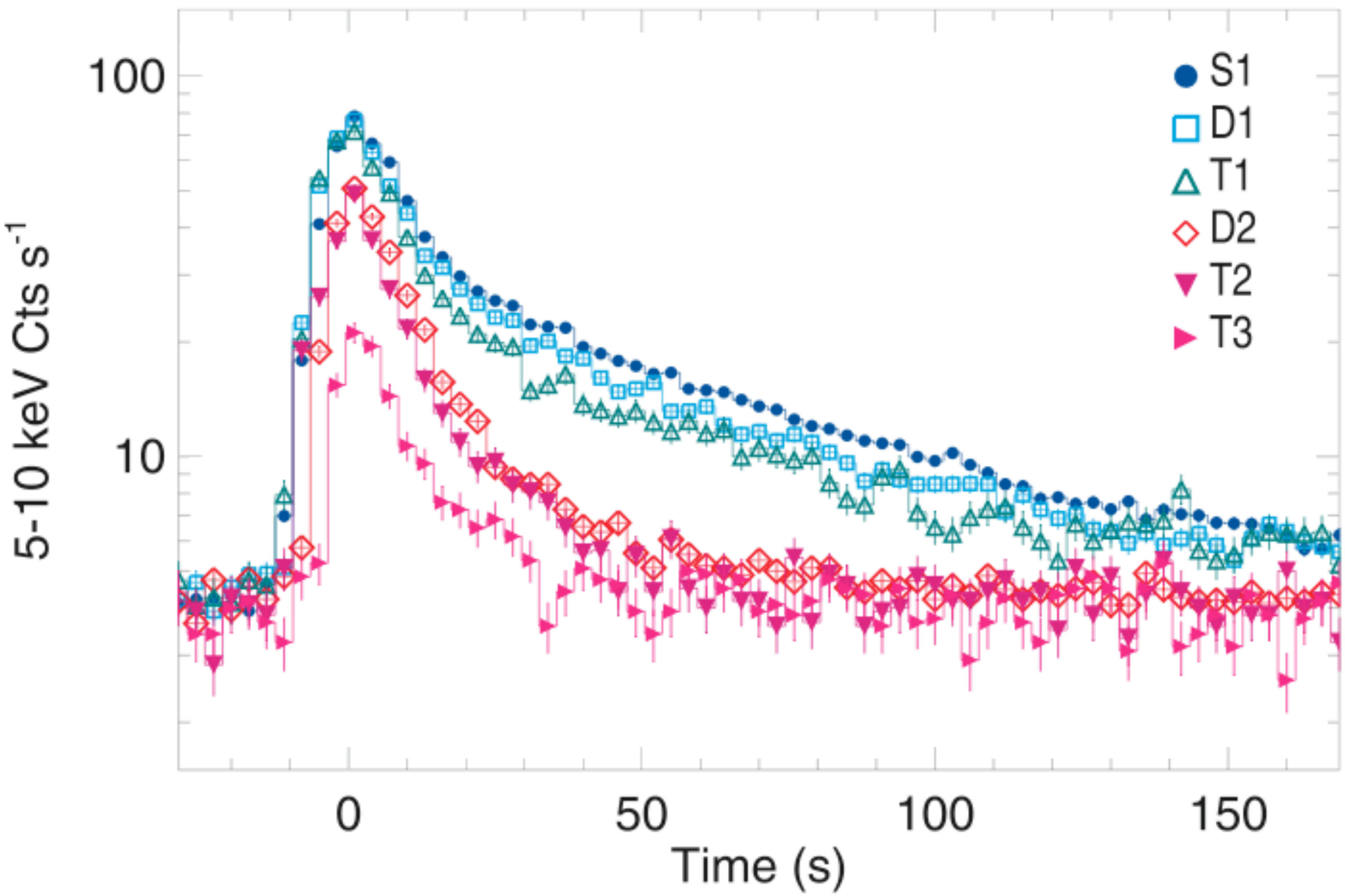
EXO 0748-676



Boirin et al. (2007)



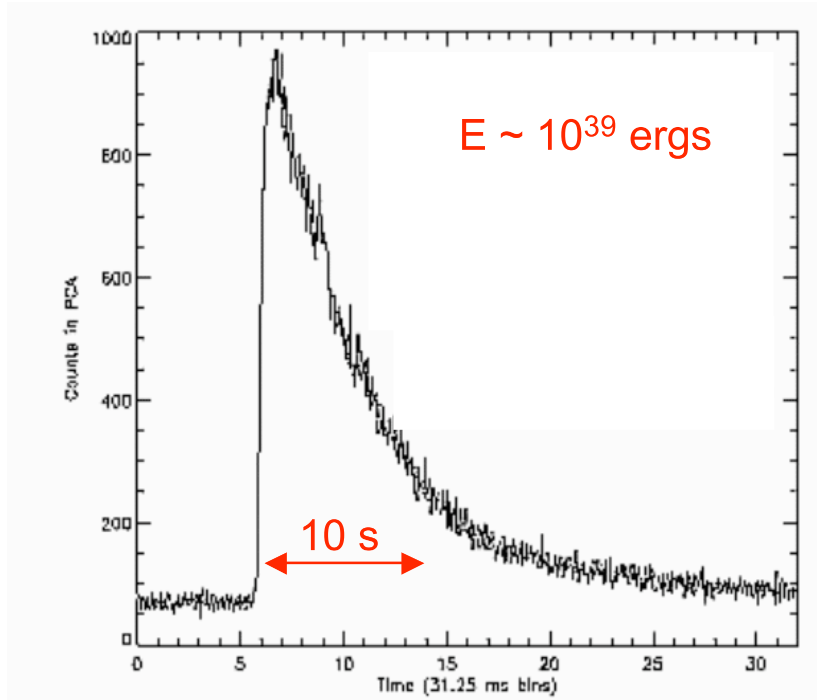
EXO 0748-676



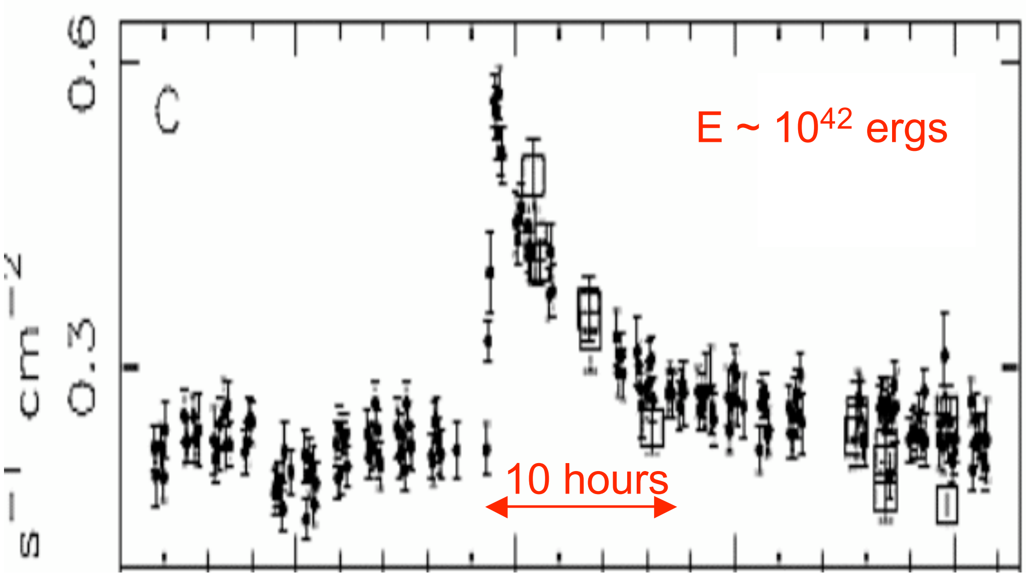
Boirin et al. (2007)

exponential decay times ~15, ~50 seconds

“normal”
Type I burst



superburst



Some properties of superbursts

- they are **rare**

  13 superbursts from 9 sources

  recurrence times ~ 1-2 years

- they are **long duration** and **energetic**

  1000 times "normal" Type I bursts

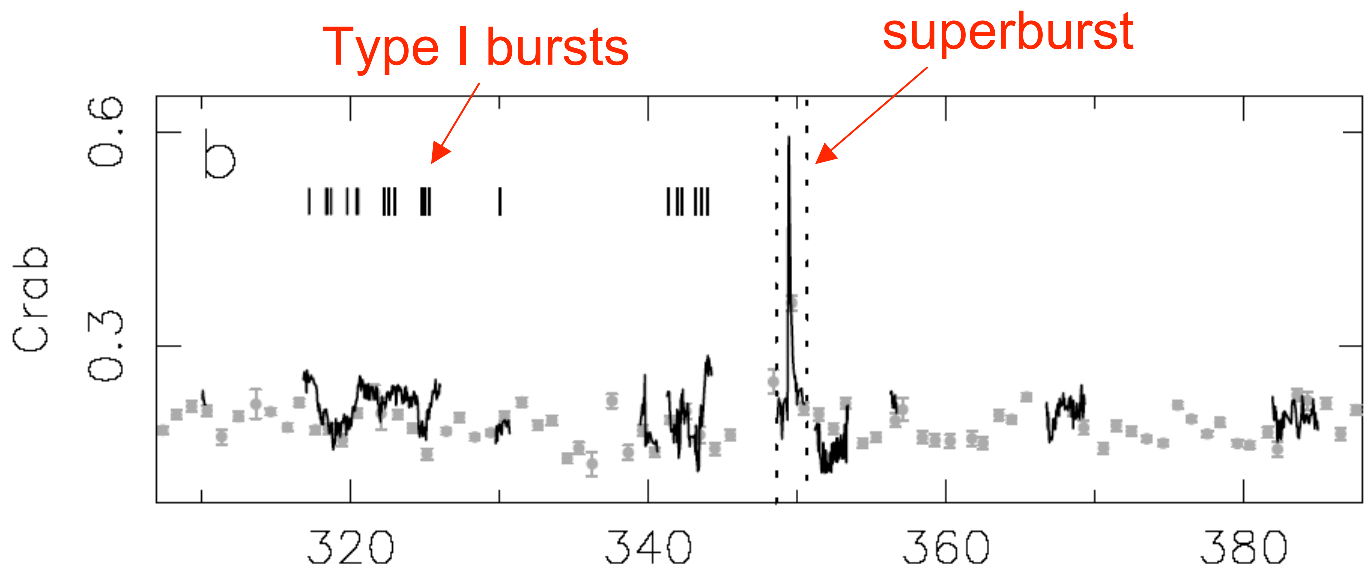
  energies ~ 10^{42} ergs

  exponential decay times 1-3 hours

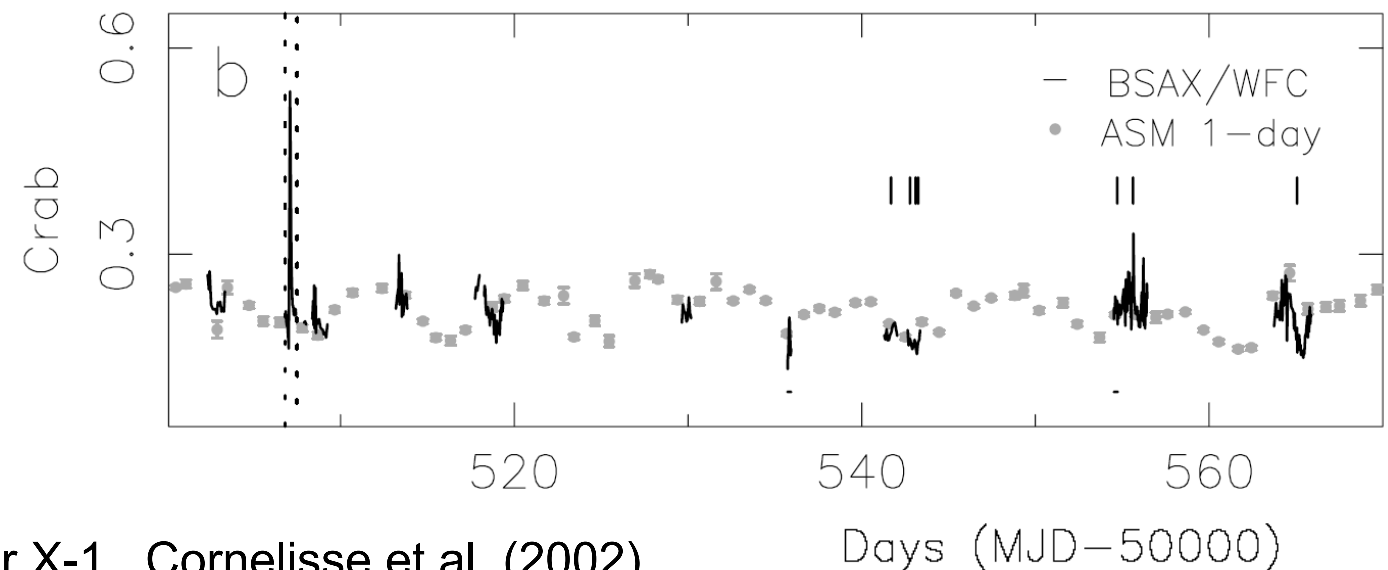
- they **"interact"** with normal Type I bursts

  they "quench" normal bursting for ~ 3 weeks

  normal bursts are seen as "precursors"

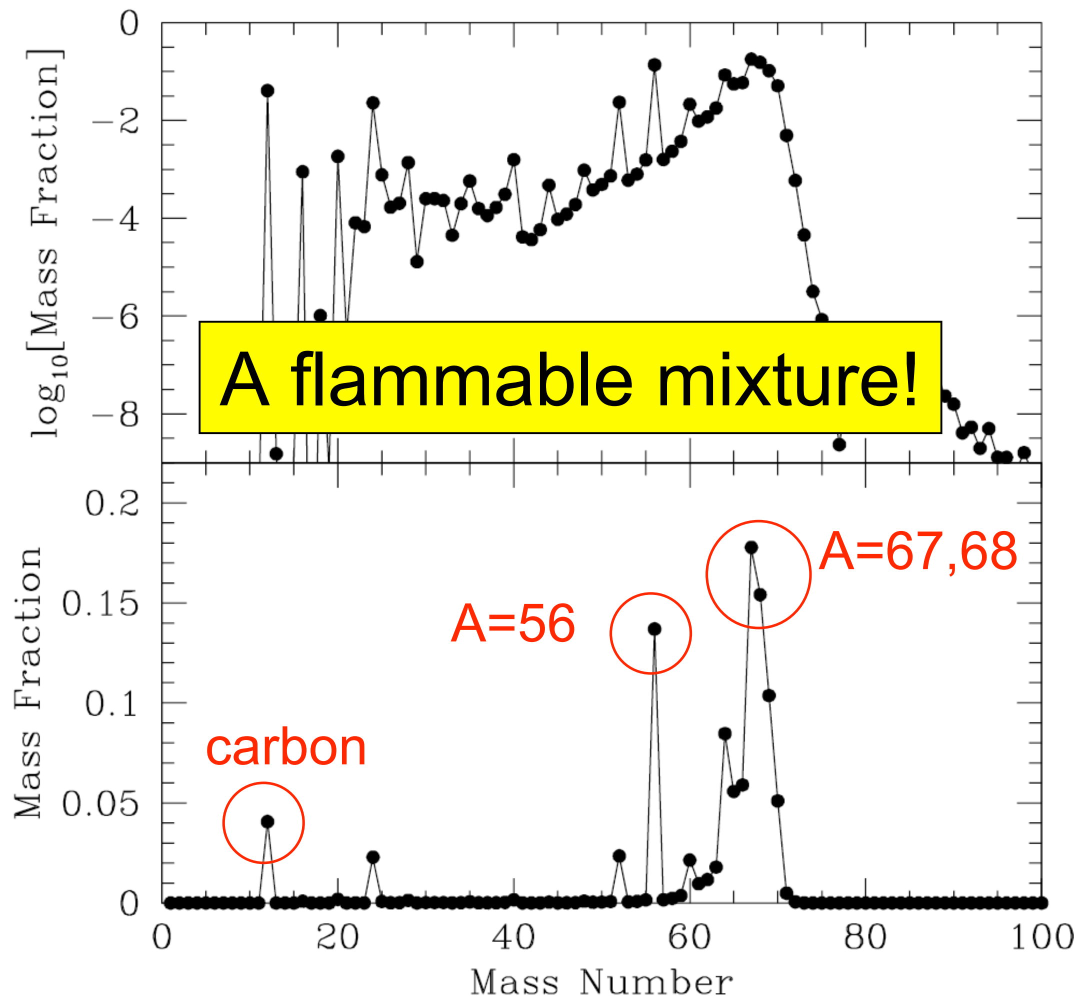


KS 1731-260 Kuulkers et al. (2002)



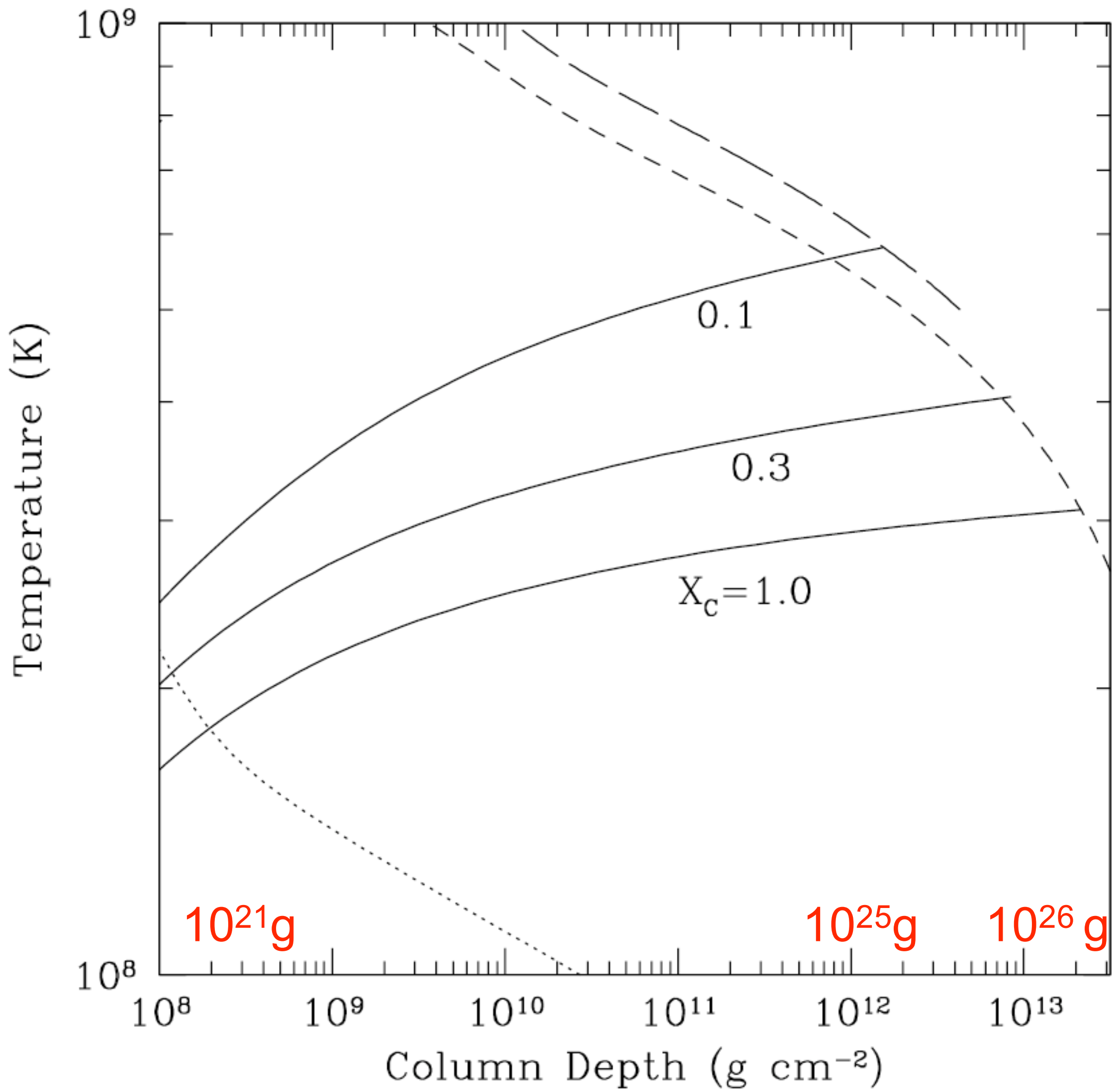
Ser X-1 Cornelisse et al. (2002)

Ashes from steady-state H/He burning



Schatz et al. (1999)

Carbon ignition in a heavy element ocean



Cumming & Bildsten (2001)

Predict ignition at $\Delta M \sim 10^{25}$g

⇒ Energy ~ 10^{42} ergs ✓

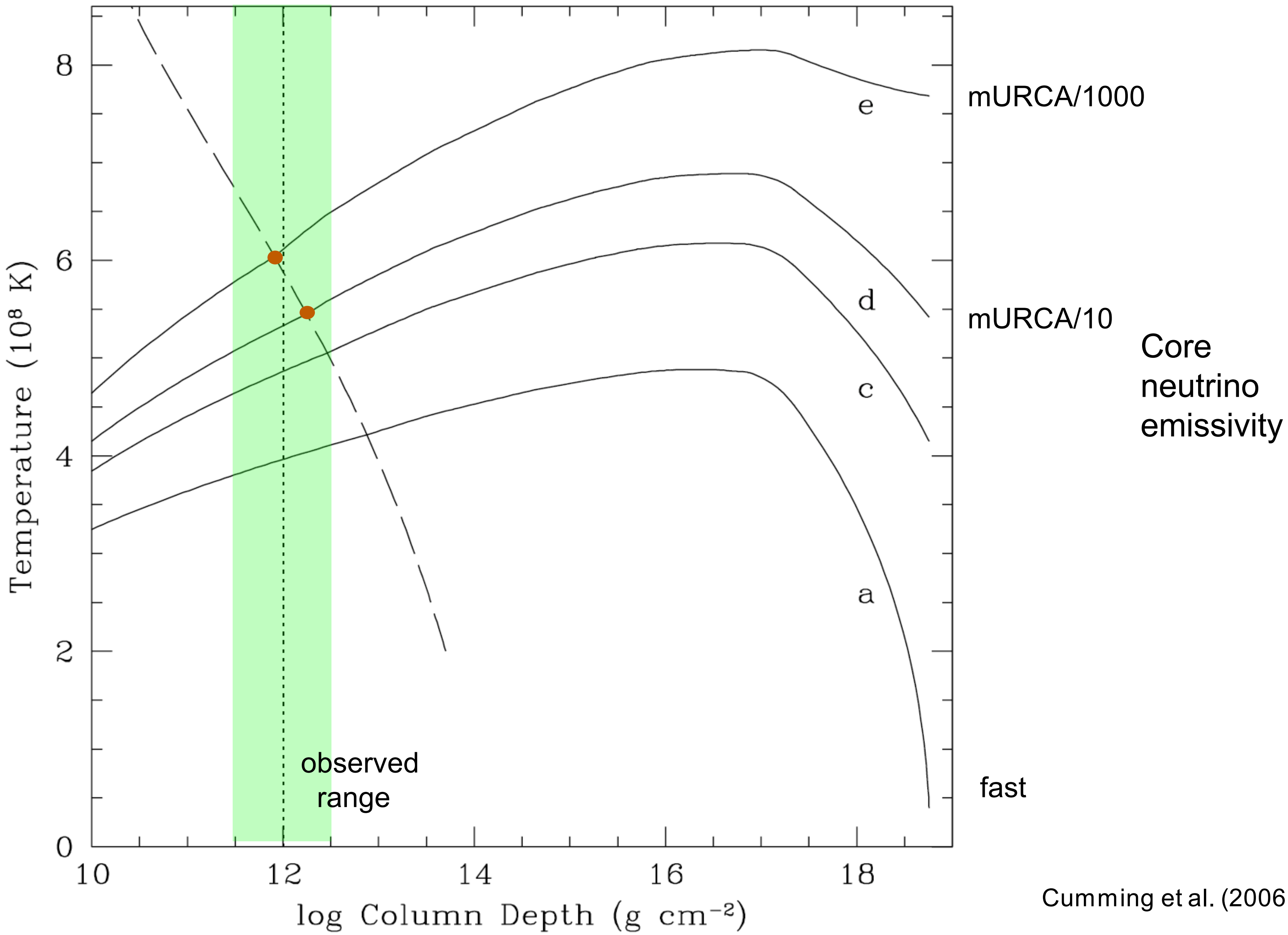
Heavy elements are important because they make the layer **opaque**

⇒ steeper temperature gradient

⇒ early ignition

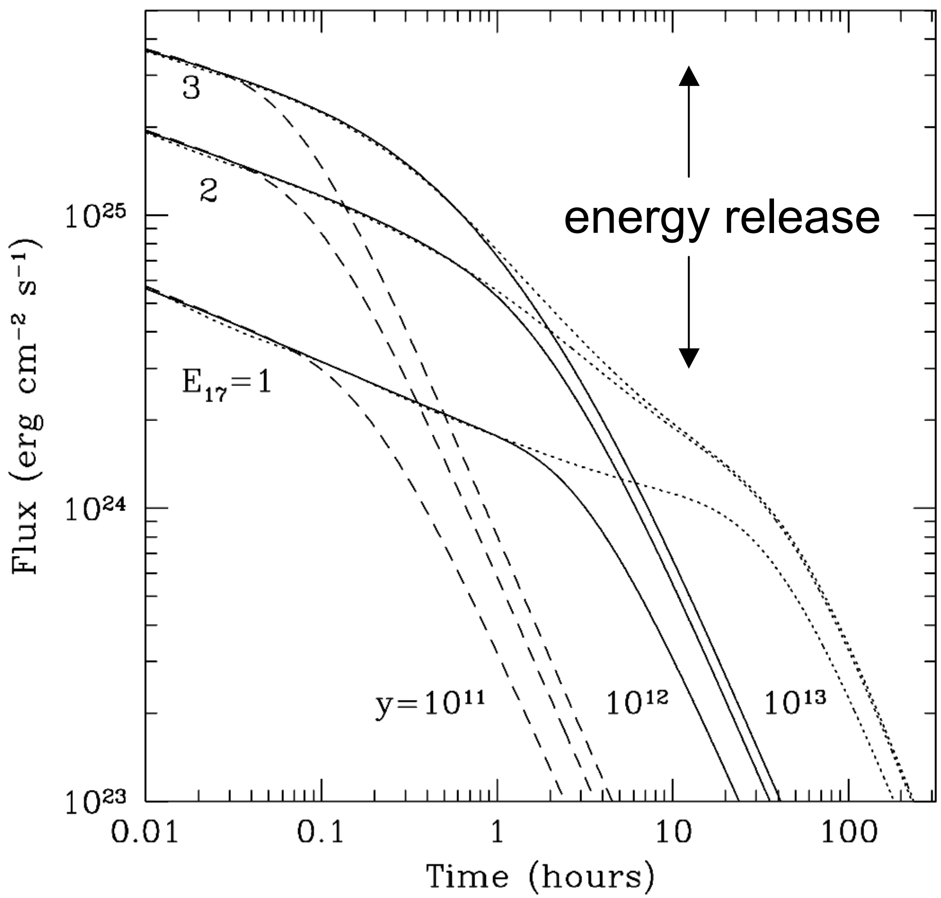
Ed Brown (2004) and Cooper & Narayan (2005) pointed out that constant outwards flux is not a good assumption, instead you should look at the entire T profile of the star.

A new way to study NS cooling!



Cumming et al. (2006)

Modelling superburst lightcurves



← layer thickness →

- fits to observed lightcurves

$$y \approx 10^{12}\ \mathrm{g\ cm^{-2}}$$

$$E \approx 2 \times 10^{17}\ \mathrm{erg\ g^{-1}}$$

$$(X_C = 0.1 - 0.2)$$

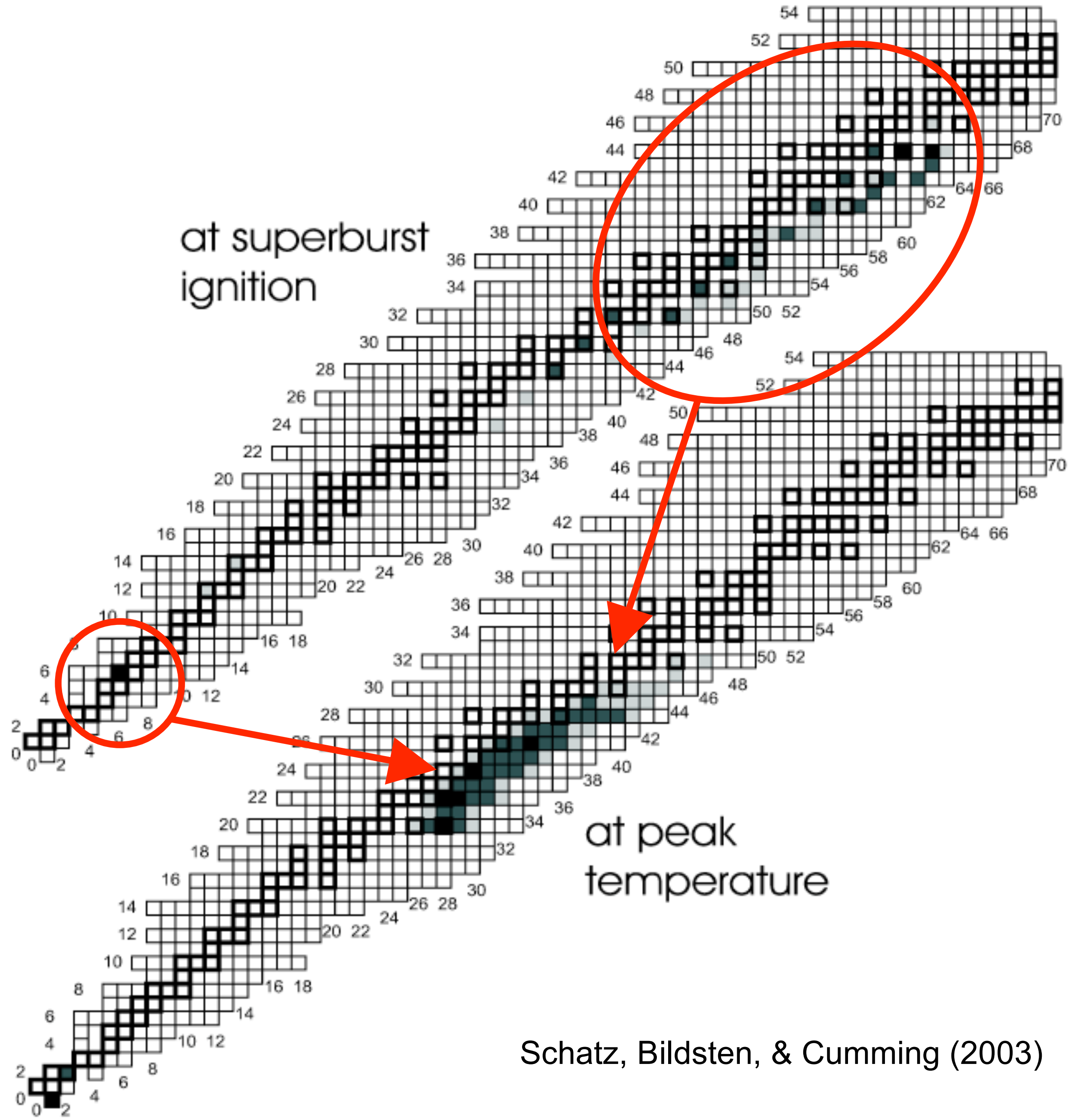
Cumming & Macbeth (2004)
Cumming et al. (2005)

Photodisintegration

$$T_{\rm peak} > 2.5 \times 10^9 \ {\rm K}$$

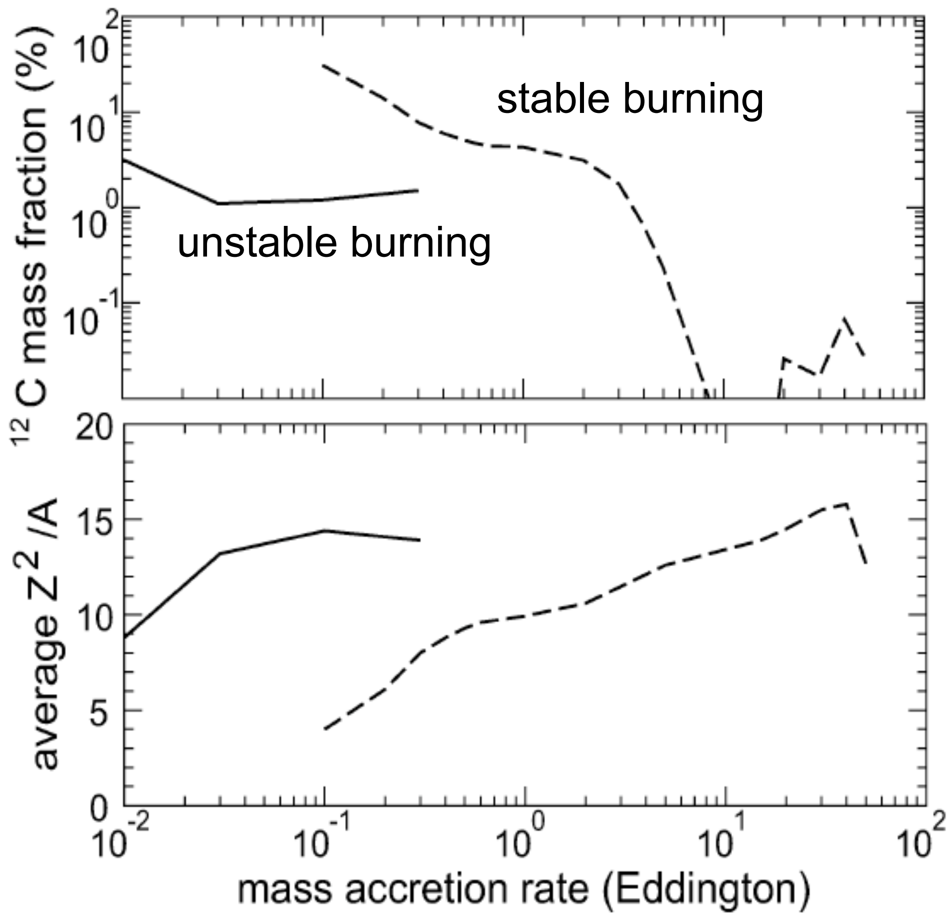
Energetics
photodisintegration
~ 0.1 MeV/nucleon
carbon burning
~ 1 MeV/nucleon

Photodisintegration
dominates for small X_C!



Schatz, Bildsten, & Cumming (2003)

Carbon production in rp process burning



Schatz, Bildsten, Cumming, Ouellette (2003)

- protons rapidly capture on carbon (carbon “poison”)

⇒ make carbon after the hydrogen runs out

⇒ anti-correlation between X_C and heavy element mass

- **stable burning needed** to make > few % ^{12}C by mass

consistent with observed burst energetics in superburst sources!

BUT stable burning at accretion rates ~ 0.1 Eddington not understood!

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

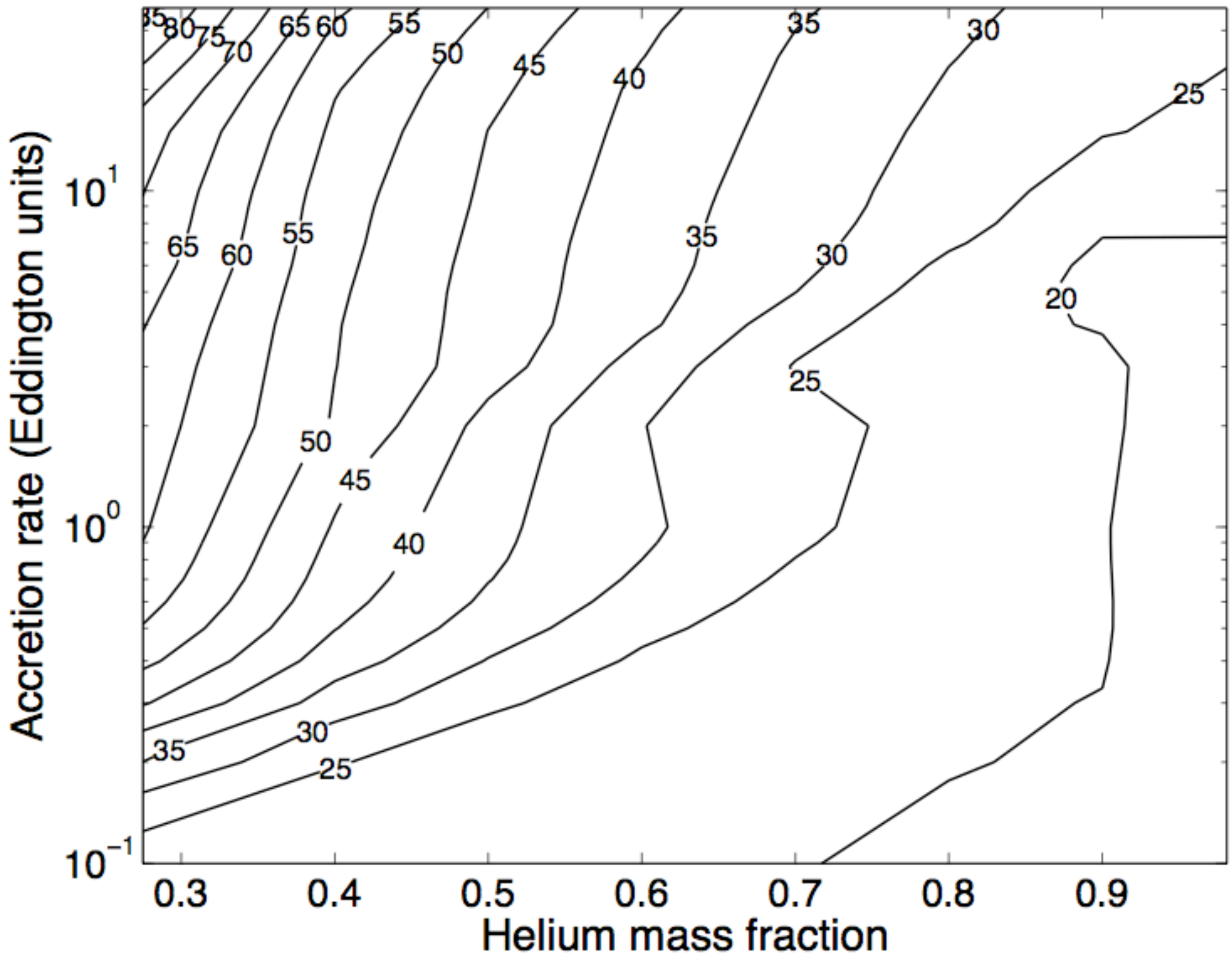
in 't Zand (2003)

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 (first group: 4U 1254-69 through Ser X-1)

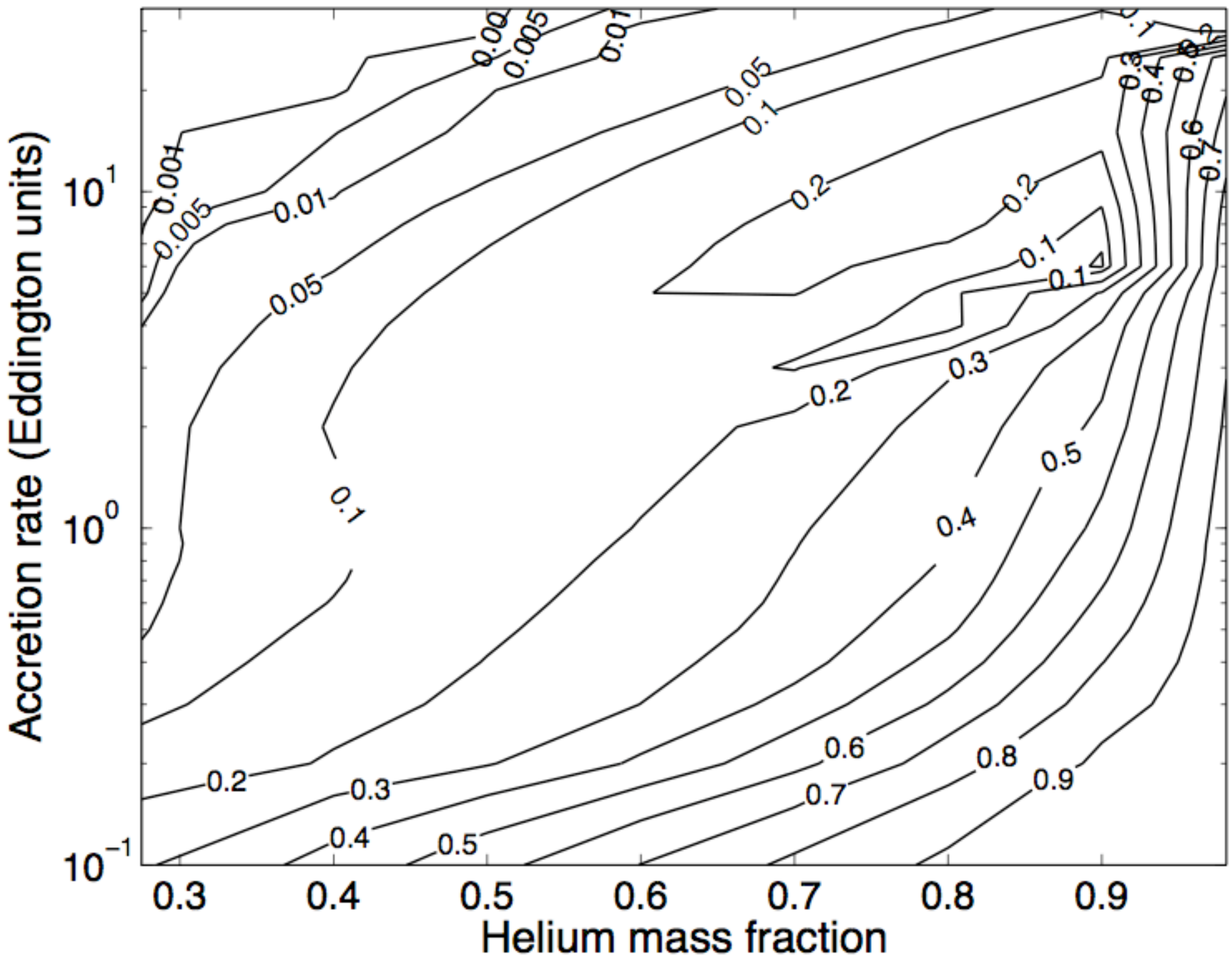
No superbursts (second group: EXO 0748-676 through GS 1826-24)

Carbon production in steady burning



Schatz et al. (2007)

Carbon production in steady burning



Schatz et al. (2007)

Summary

• **lightcurves:** need to systematically explore the dependence of multizone model lightcurves on input rp-process data

• **superbursts:** how is the carbon made? how to make the crust hot enough?

• **other questions:** transition to stable burning, mHz qpos, transport of rp-process elements to the photosphere (and beyond…?)
are the “ten minute” bursts coming from nuclear physics?