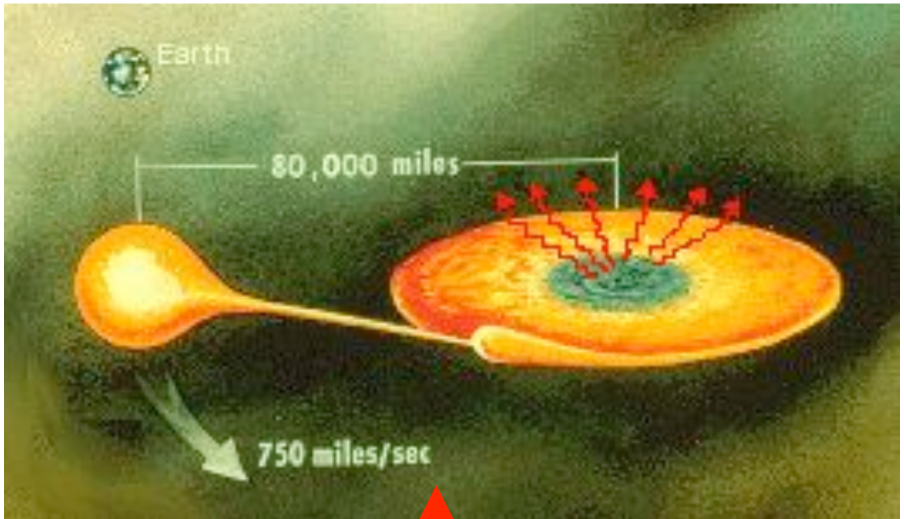
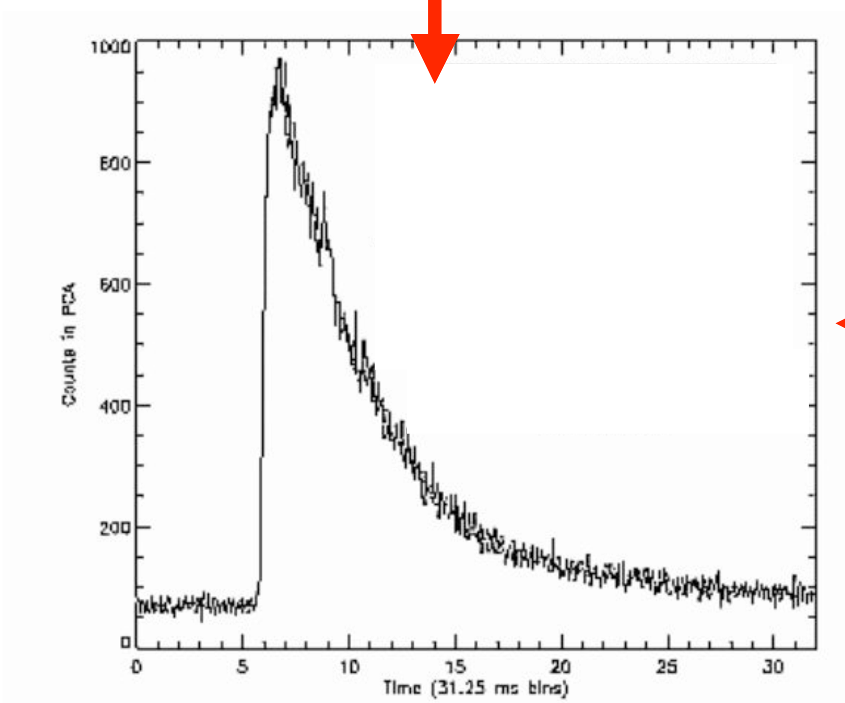
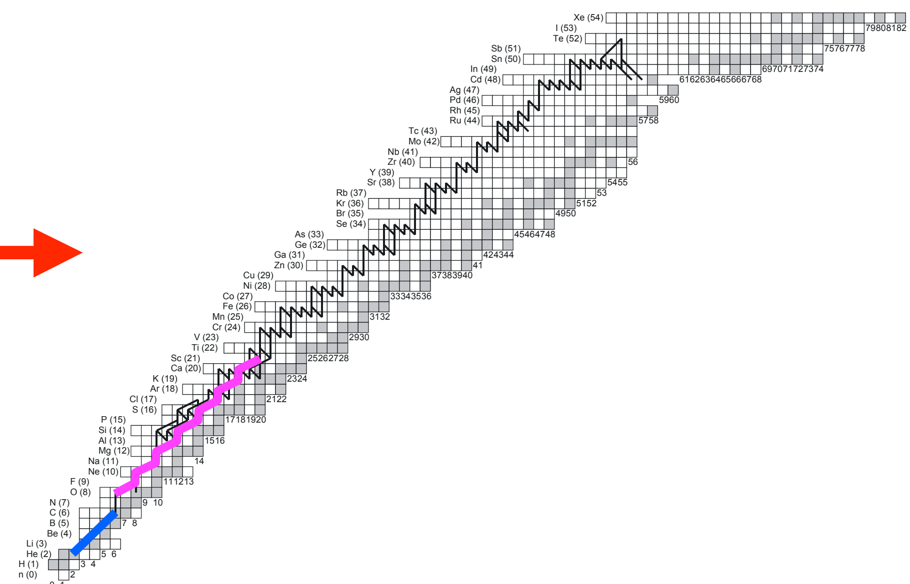


Thermonuclear X-ray bursts and the rp-process

Andrew Cumming
McGill University





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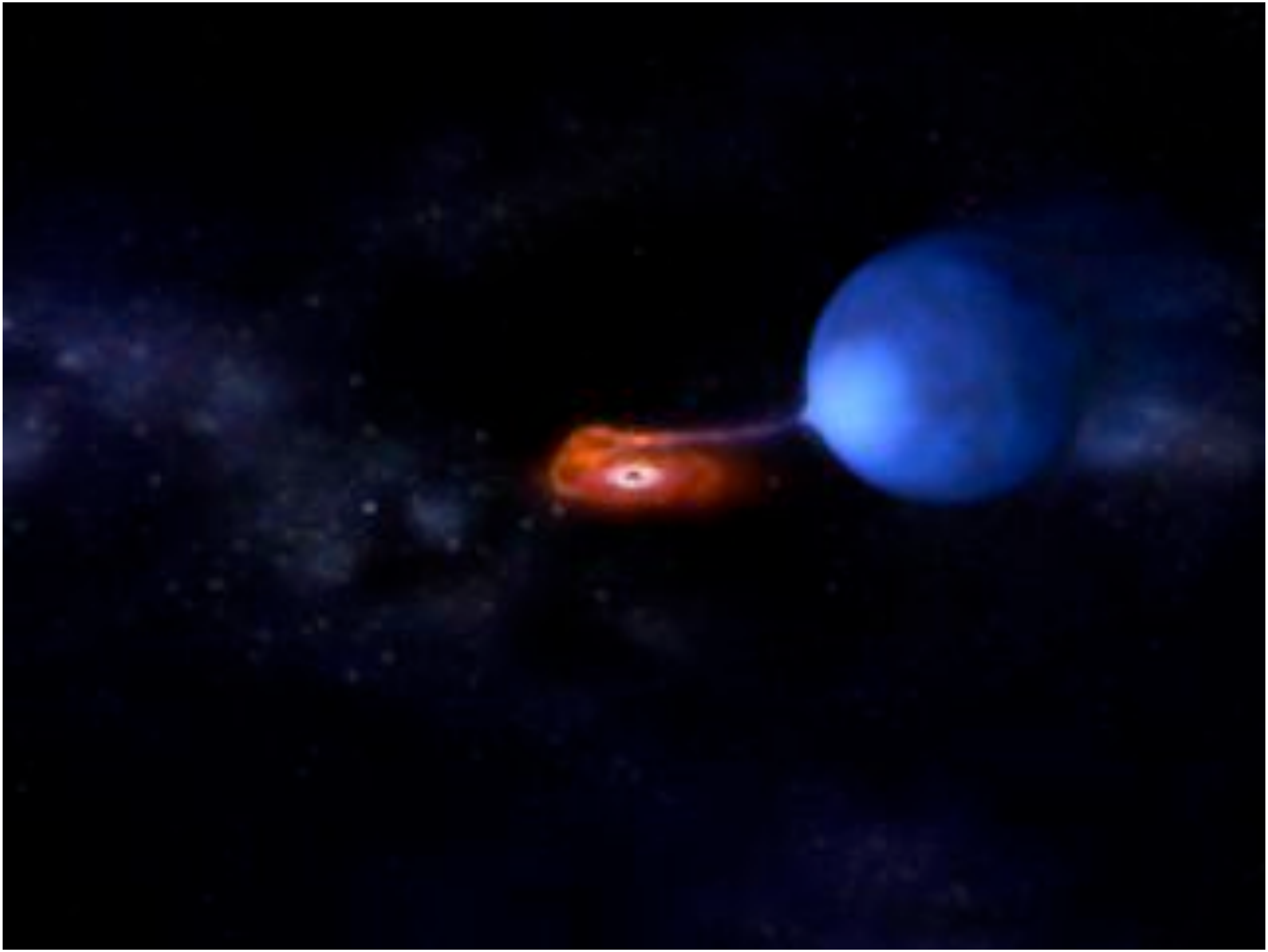
Jared Macbeth (UCSC)
Dany Page (UNAM)
Hendrik Schatz, Michelle Ouellette (MSU)
Stan Woosley (UCSC)



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

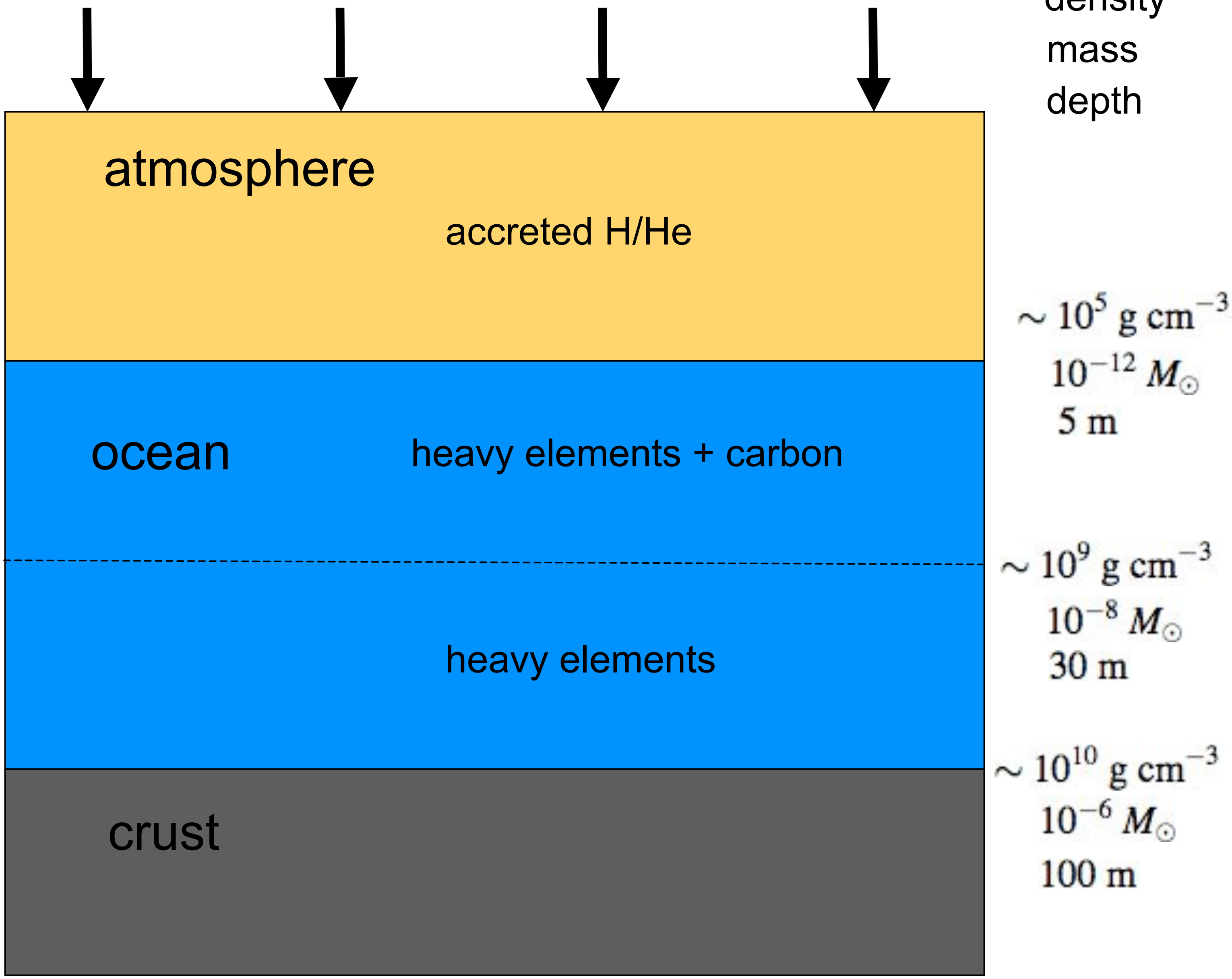
astrophysics

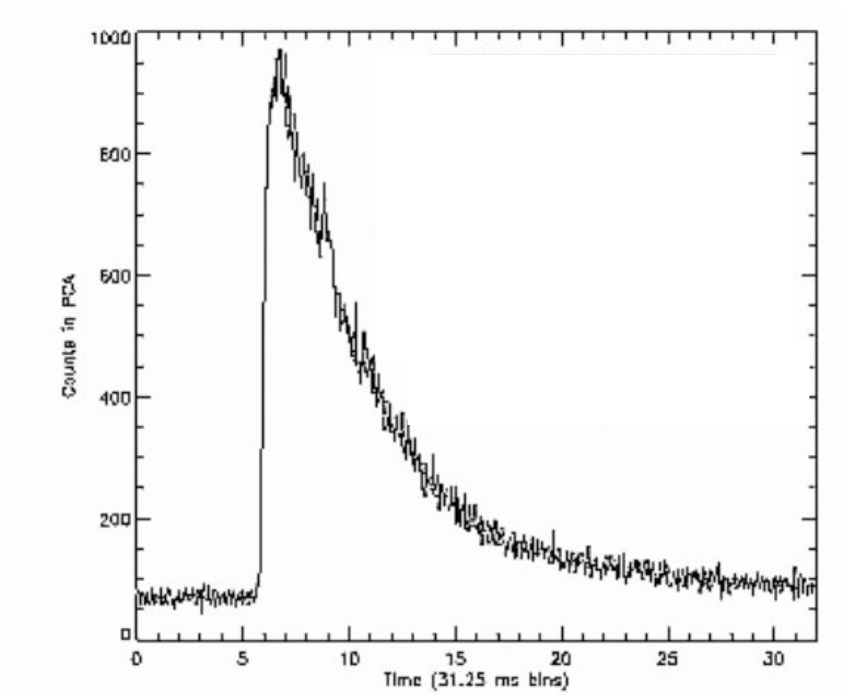
- what is the neutron star spin and magnetic field?
- how to make these binaries?
- fluids: dynamics of reactive flow, turbulent mixing, angular momentum transport…

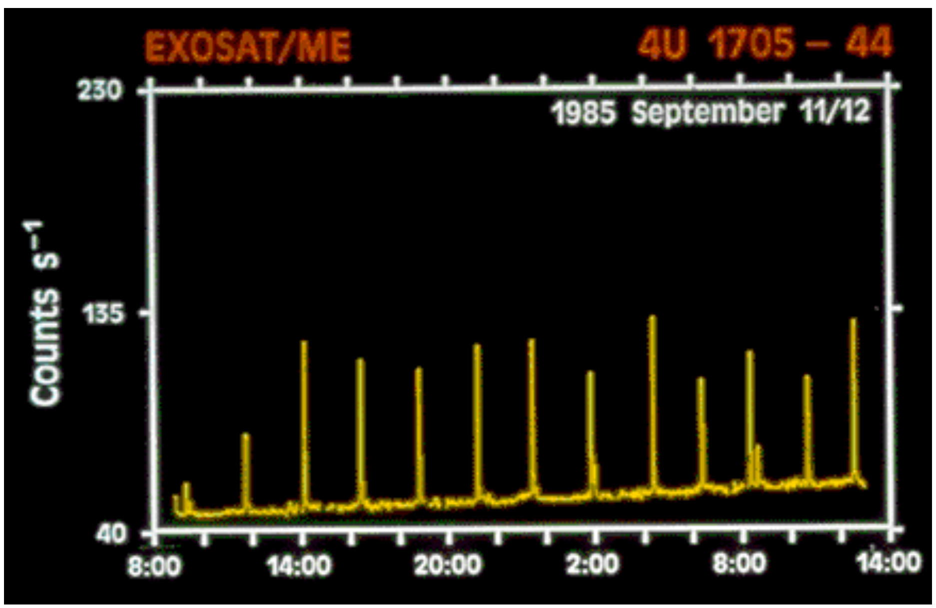
nuclear physics

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

History of a fluid element







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) hydrostatic balance

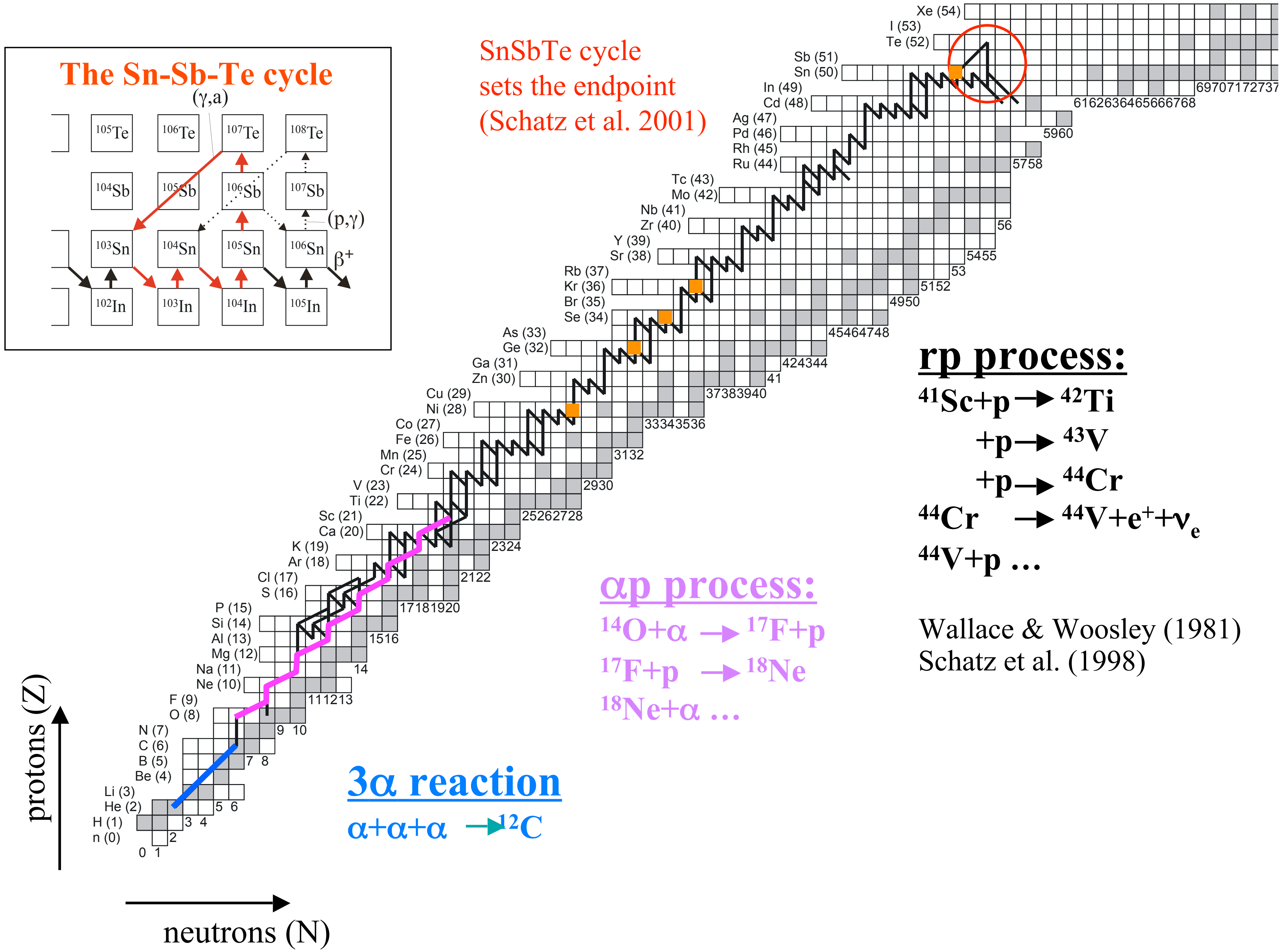
$$P = \frac{GM}{R^2}\frac{\Delta M}{4\pi R^2}$$

entropy

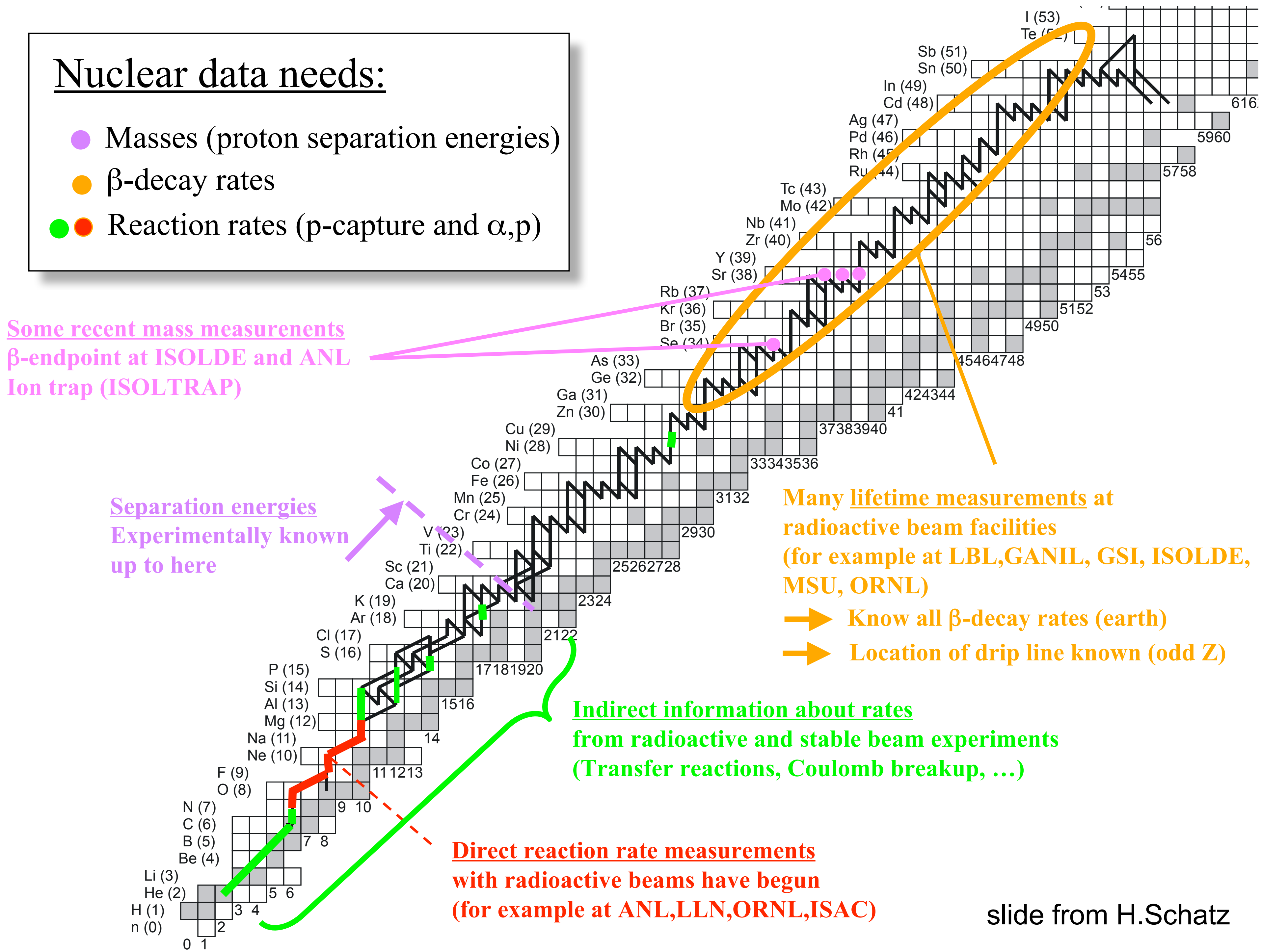
$$c_P \frac{\partial T}{\partial t} = \varepsilon - \varepsilon_\nu - \frac{1}{\rho}\frac{\partial F}{\partial r}$$

heat flux

$$F = F_C - \frac{4acT^3}{\kappa\rho}\frac{\partial T}{\partial r}$$



The Sn-Sb-Te cycle
(γ,a)
105Te
106Te
107Te
108Te
104Sb
105Sb
106Sb
107Sb
(p,γ)
103Sn
104Sn
105Sn
106Sn
β+
102In
103In
104In
105In
SnSbTe cycle
sets the endpoint
(Schatz et al. 2001)
Xe (54)
I (53)
Te (52)
Sb (51)
Sn (50)
In (49)
Cd (48)
Ag (47)
Pd (46)
Rh (45)
Ru (44)
Tc (43)
Mo (42)
Nb (41)
Zr (40)
Y (39)
Sr (38)
Rb (37)
Kr (36)
Br (35)
Se (34)
As (33)
Ge (32)
Ga (31)
Zn (30)
Cu (29)
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
V (23)
Ti (22)
Sc (21)
Ca (20)
K (19)
Ar (18)
Cl (17)
S (16)
P (15)
Si (14)
Al (13)
Mg (12)
Na (11)
Ne (10)
F (9)
O (8)
N (7)
C (6)
B (5)
Be (4)
Li (3)
He (2)
H (1)
n (0)
rp process:
41Sc+p → 42Ti
+p → 43V
+p → 44Cr
44Cr → 44V+e+ +νe
44V+p …
Wallace & Woosley (1981)
Schatz et al. (1998)
αp process:
14O+α → 17F+p
17F+p → 18Ne
18Ne+α …
3α reaction
α+α+α → 12C
protons (Z)
neutrons (N)

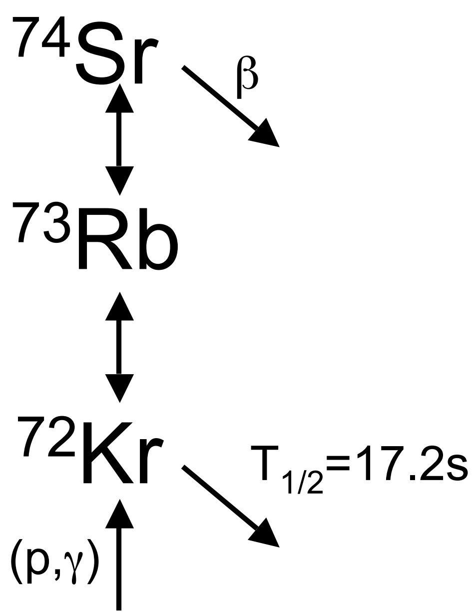


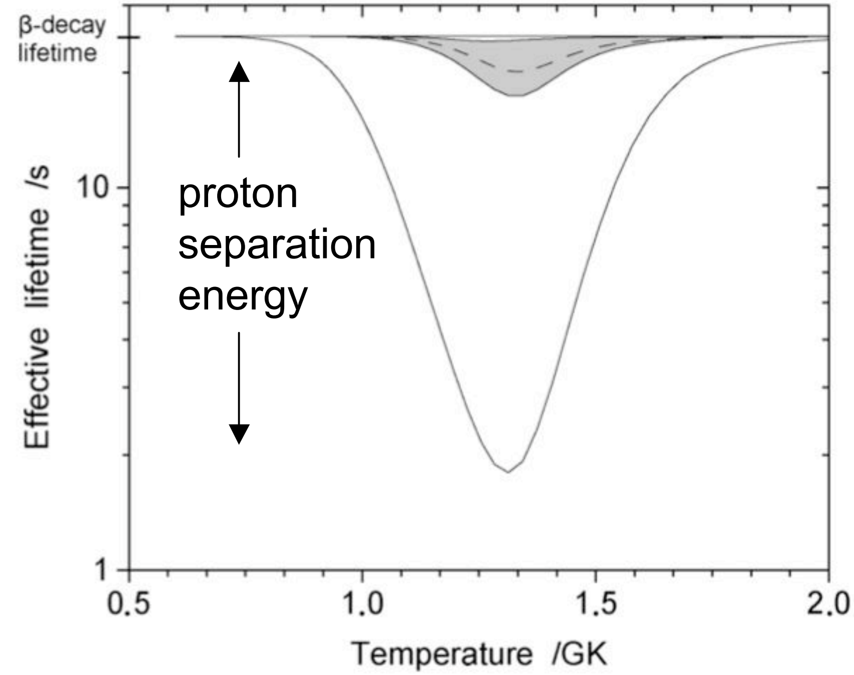
Nuclear data needs:
Masses (proton separation energies)
β-decay rates
Reaction rates (p-capture and α,p)
Some recent mass measurements
β-endpoint at ISOLDE and ANL
Ion trap (ISOLTRAP)
Separation energies
Experimentally known
up to here
Many lifetime measurements at
radioactive beam facilities
(for example at LBL,GANIL, GSI, ISOLDE,
MSU, ORNL)
Know all β-decay rates (earth)
Location of drip line known (odd Z)
Indirect information about rates
from radioactive and stable beam experiments
(Transfer reactions, Coulomb breakup, …)
Direct reaction rate measurements
with radioactive beams have begun
(for example at ANL,LLN,ORNL,ISAC)
slide from H.Schatz
I (53)
Sb (51)
Sn (50)
In (49)
Cd (48)
Ag (47)
Pd (46)
Tc (43)
Mo (42)
Nb (41)
Zr (40)
Y (39)
Sr (38)
Kr (36)
Br (35)
As (33)
Ge (32)
Ga (31)
Zn (30)
Cu (29)
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
Ti (22)
Sc (21)
Ca (20)
K (19)
Ar (18)
Cl (17)
S (16)
P (15)
Si (14)
Al (13)
Mg (12)
Na (11)
Ne (10)
F (9)
O (8)
N (7)
C (6)
B (5)
Be (4)
Li (3)
He (2)
H (1)
n (0)

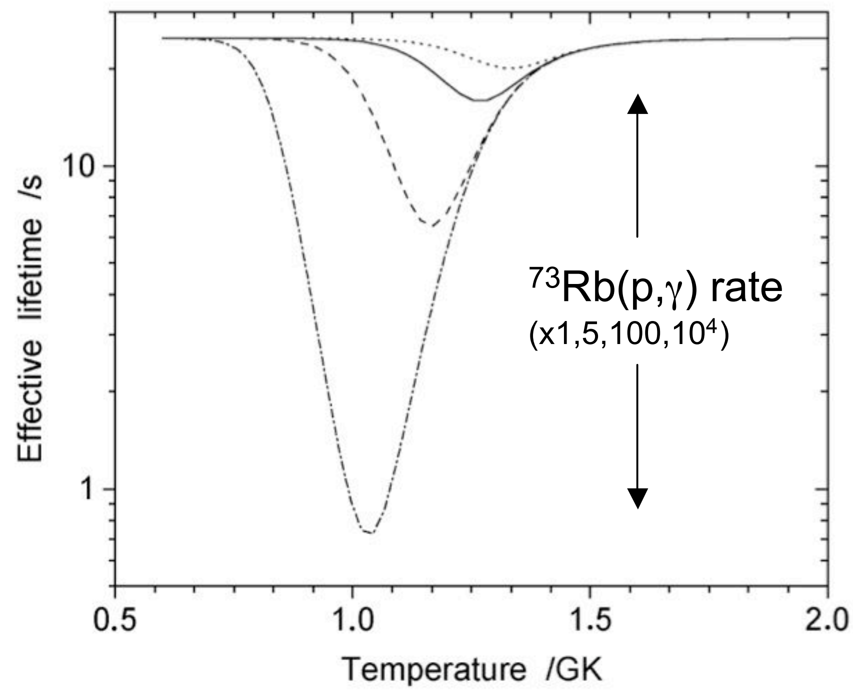
Recent mass measurements of rp-process waiting point nuclei

^{72}Kr; Rodriguez et al. (2004)
ISOLTRAP/ISOLDE

^{68}Se; Clark et al. (2004)
CPT/ATLAS







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

Energetics → **Global bursting behavior**

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

Duration → **Burst lightcurves**

- long burst tails powered by rp-process burning

Duration → **Ashes**

Ashes → **Superbursts**

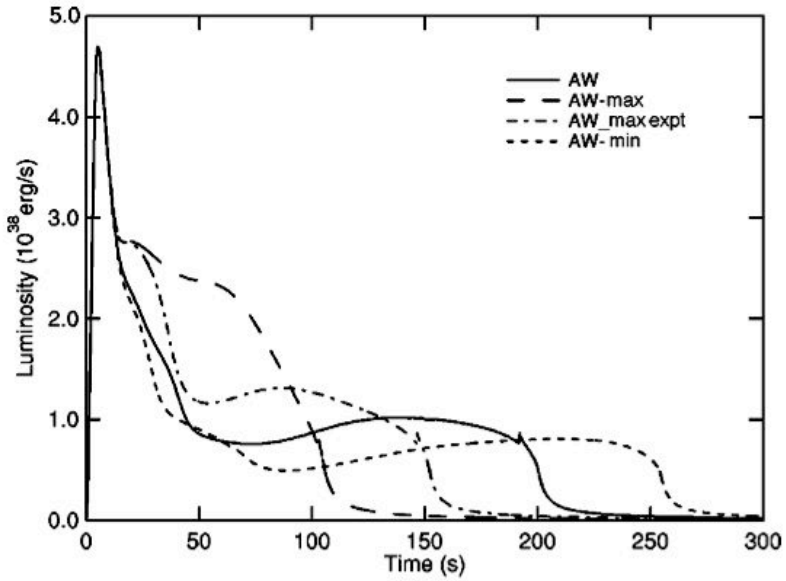
- extremely energetic flashes that occur when the rp-process ashes *reignite*

Ashes → **Crust transport and mechanical properties**

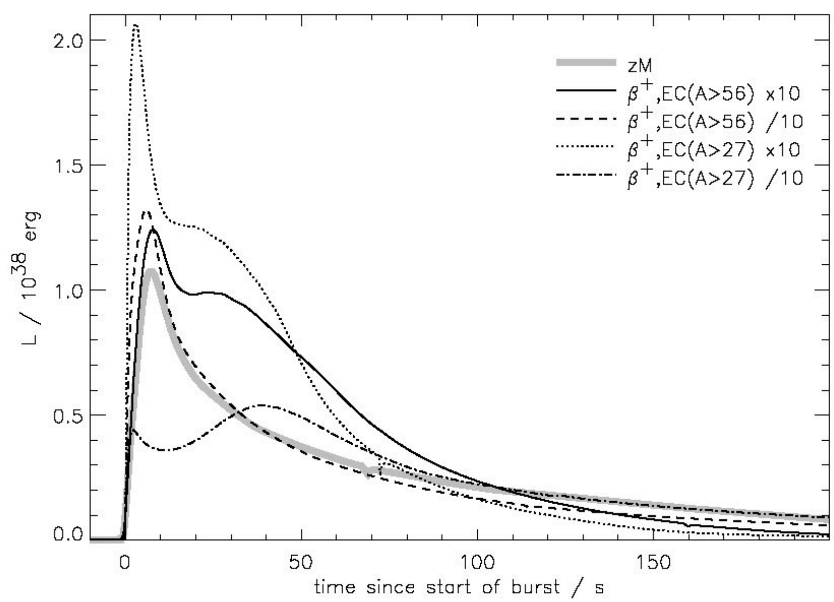
Effect of rp-process on burst lightcurves

one zone

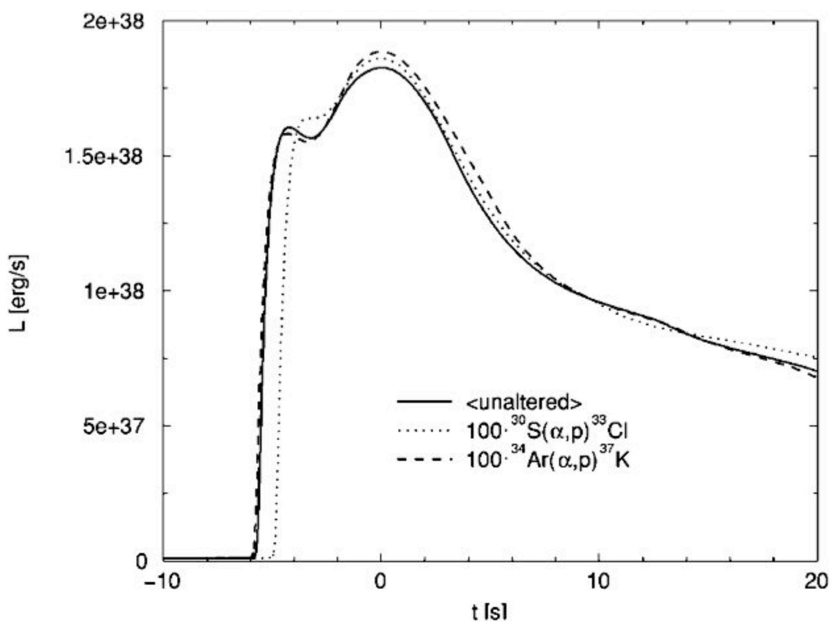
Brown et al. (2002)
(see also Koike et al.1999
Schatz et al. 2001)



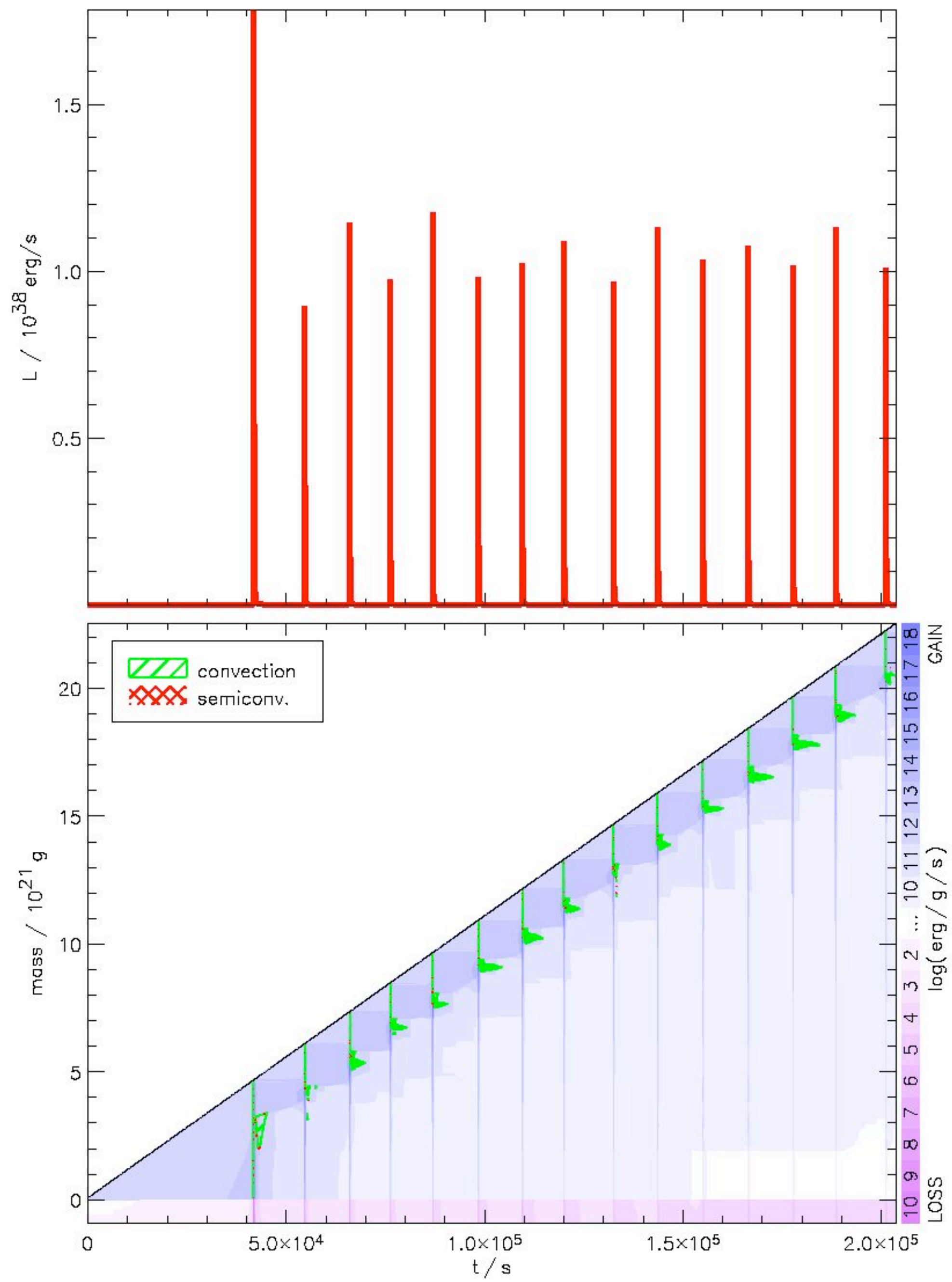
multizone



Woosley, Heger et al. (2004)



Fisker & Thielemann (2004)



Multizone models of X-ray bursts

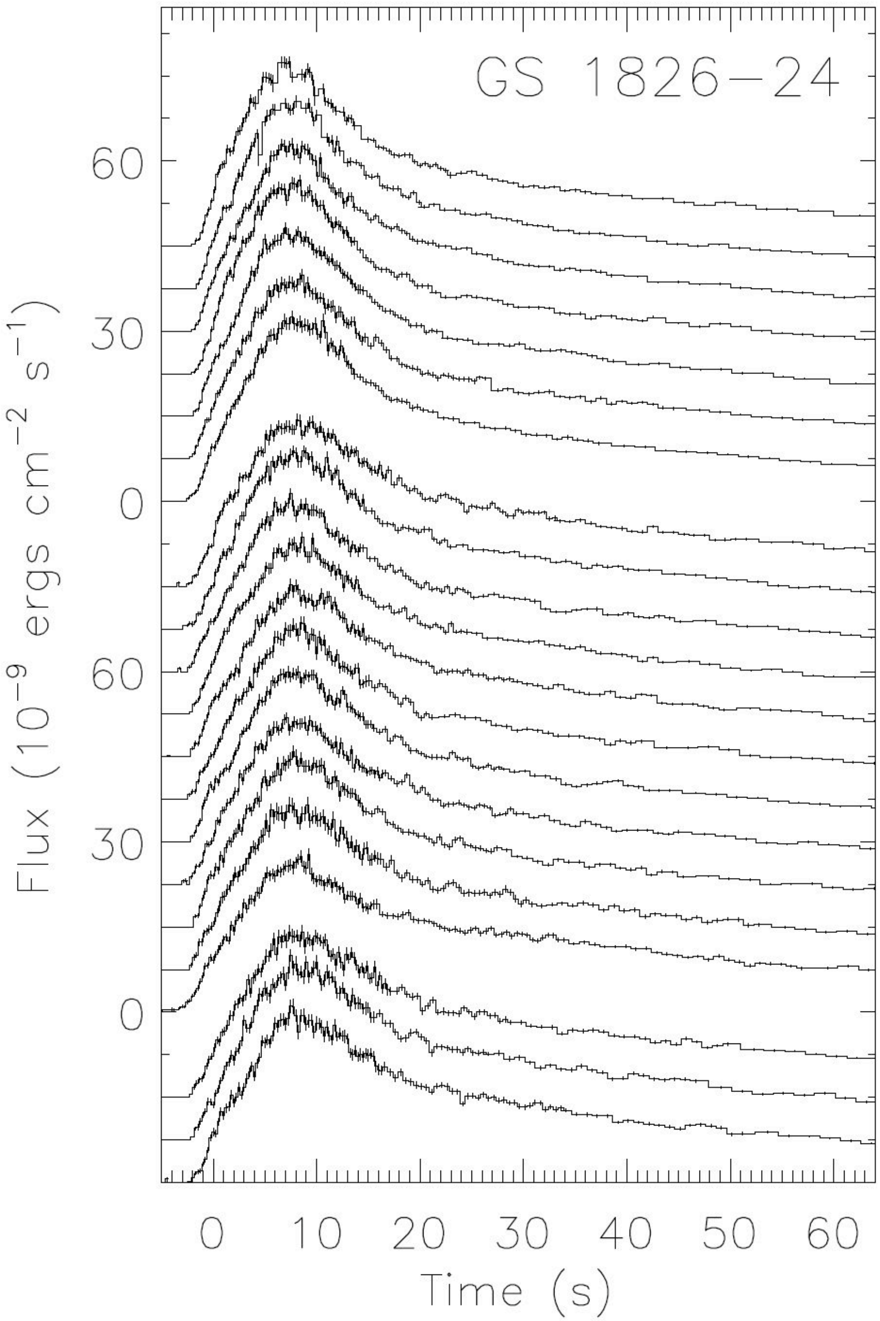
Woosley, Heger, AC, et al. (2004)

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

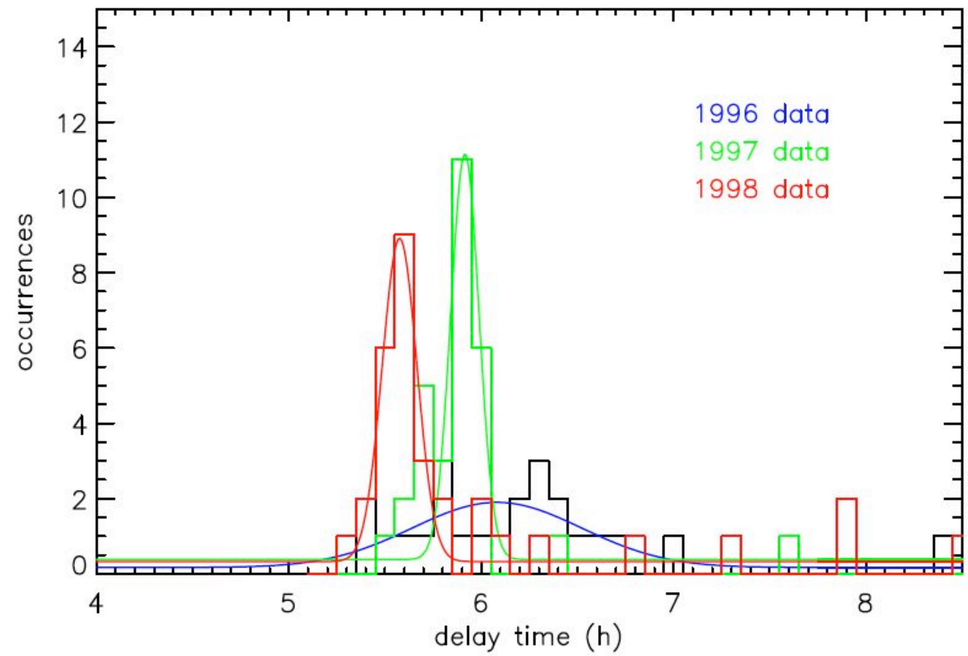
+

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

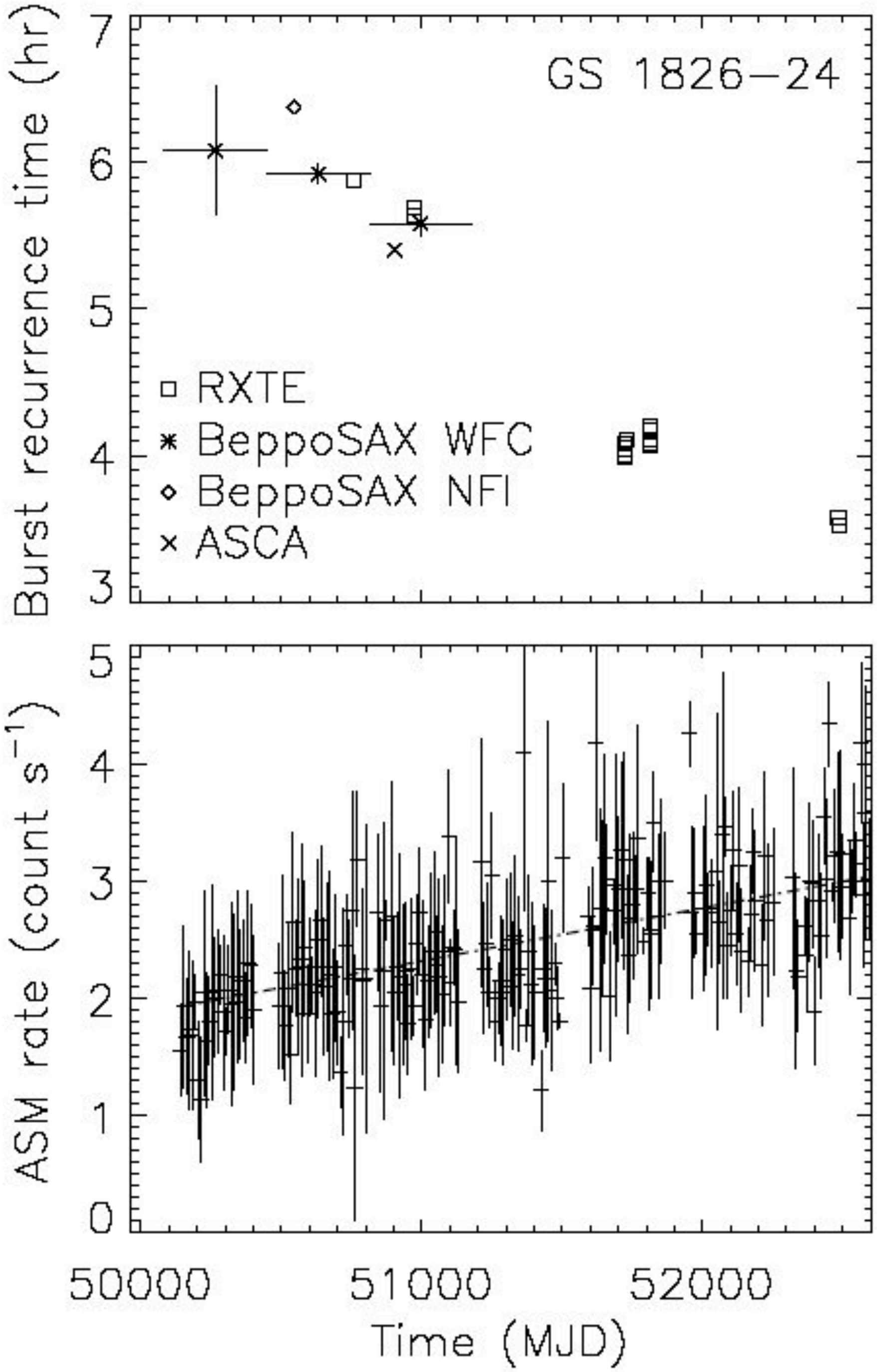
The "textbook" burster: GS 1826-24



Galloway et al. (2003)



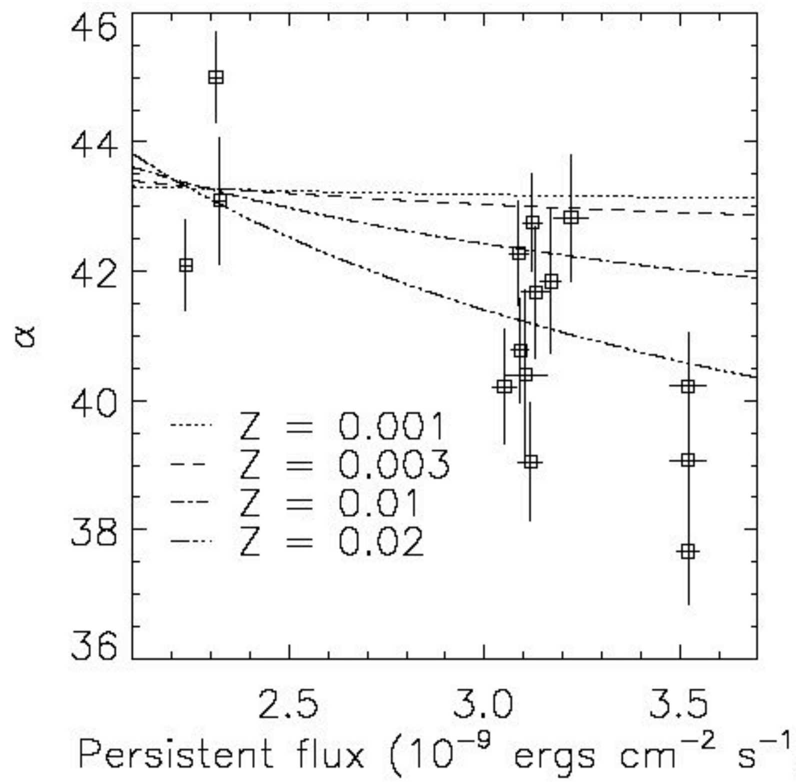
Cocchi et al. (2001)

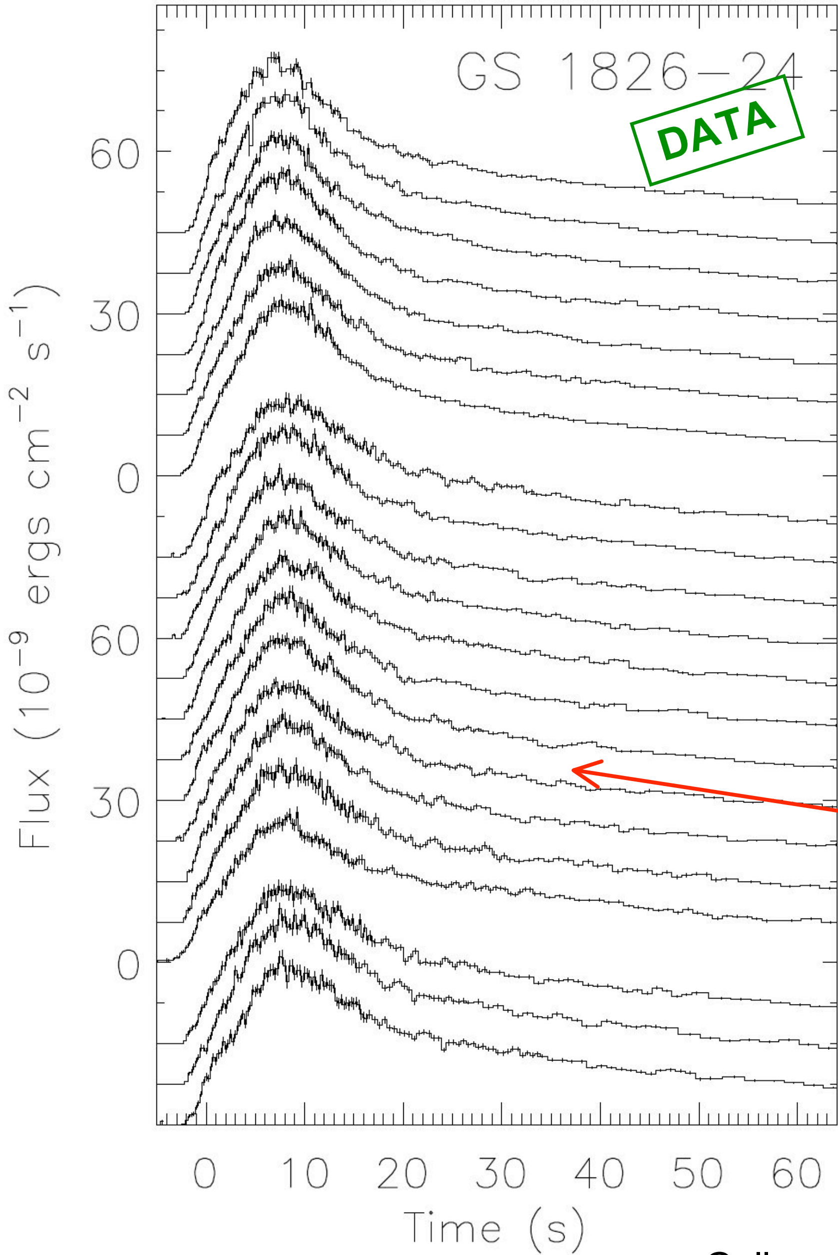


Galloway et al. (2003)

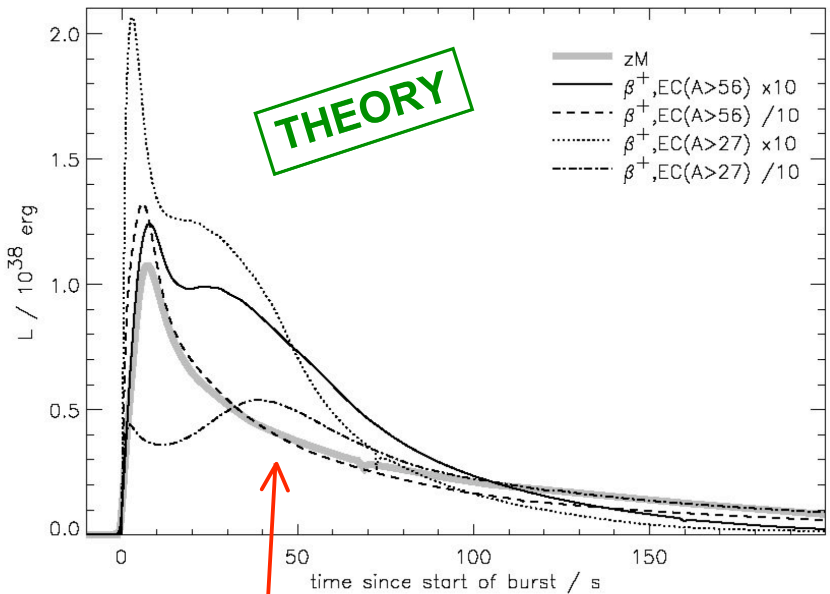
$$t_{\rm recur} \propto \dot{M}^{-1.11}$$

α variations indicate
~ solar metallicity



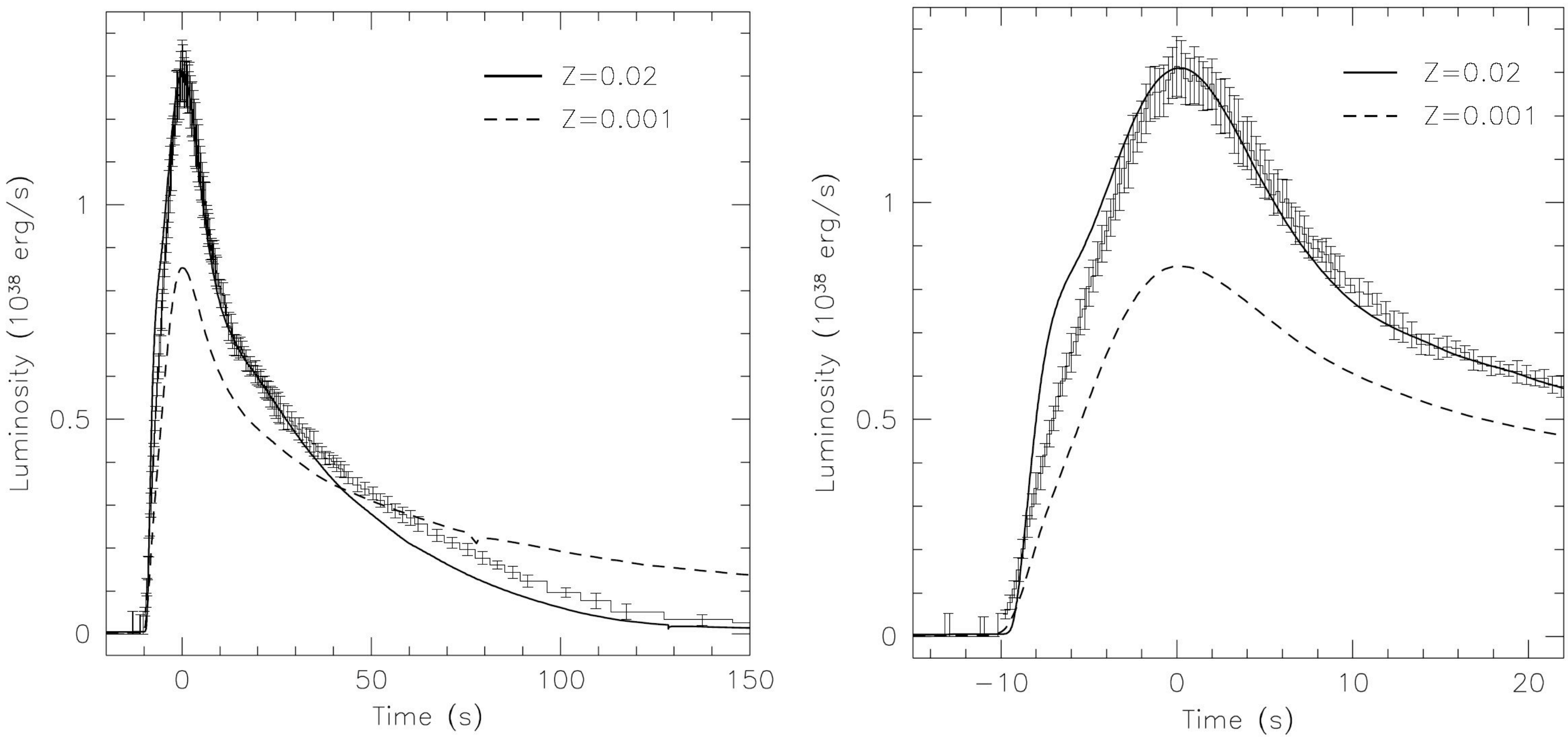


Galloway et al. (2004)



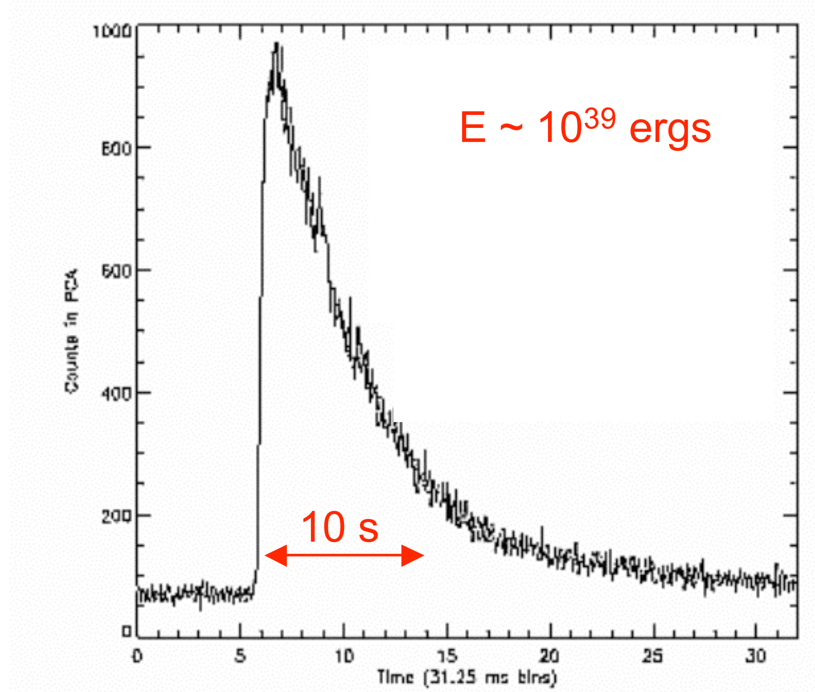
Woosley et al. (2004)

long tails powered by hydrogen burning

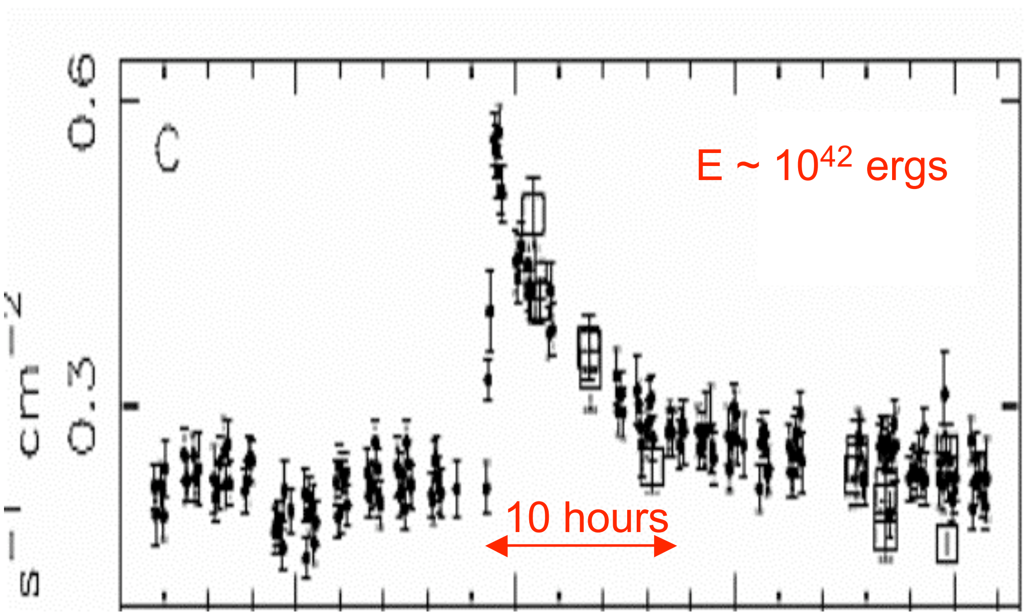


Heger, Galloway, AC (2006)

“normal”
Type I burst



superburst



Some properties of superbursts

• they are **rare**

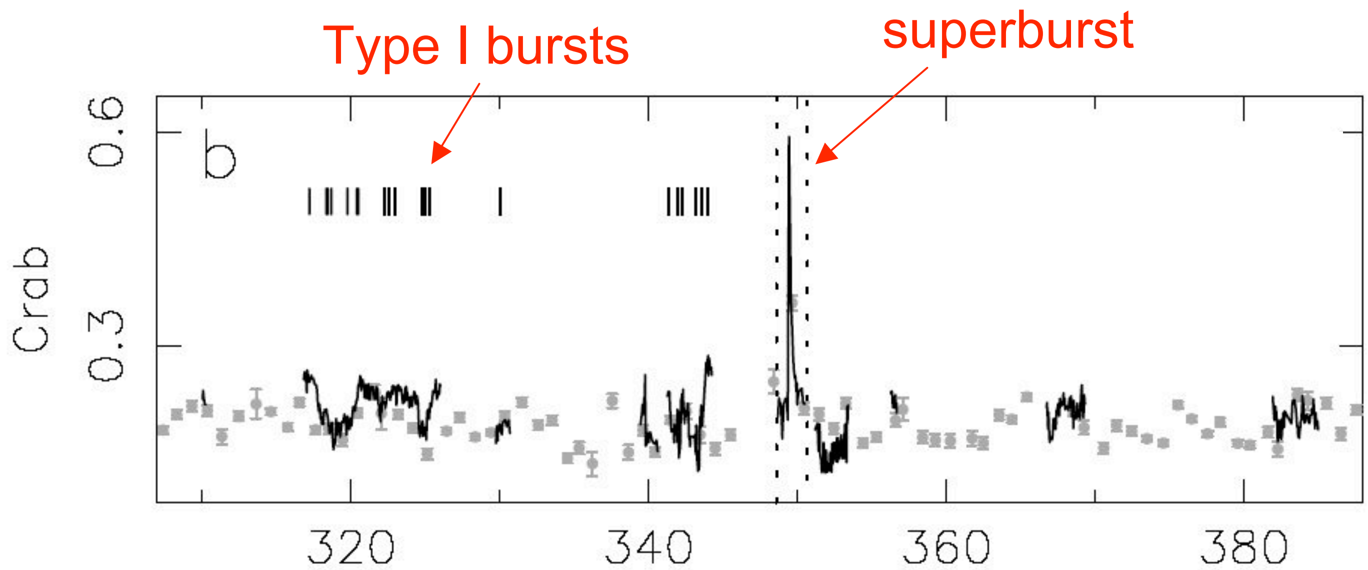
13 superbursts from 9 sources
recurrence times ~ 1-2 years

• they are **long duration** and **energetic**

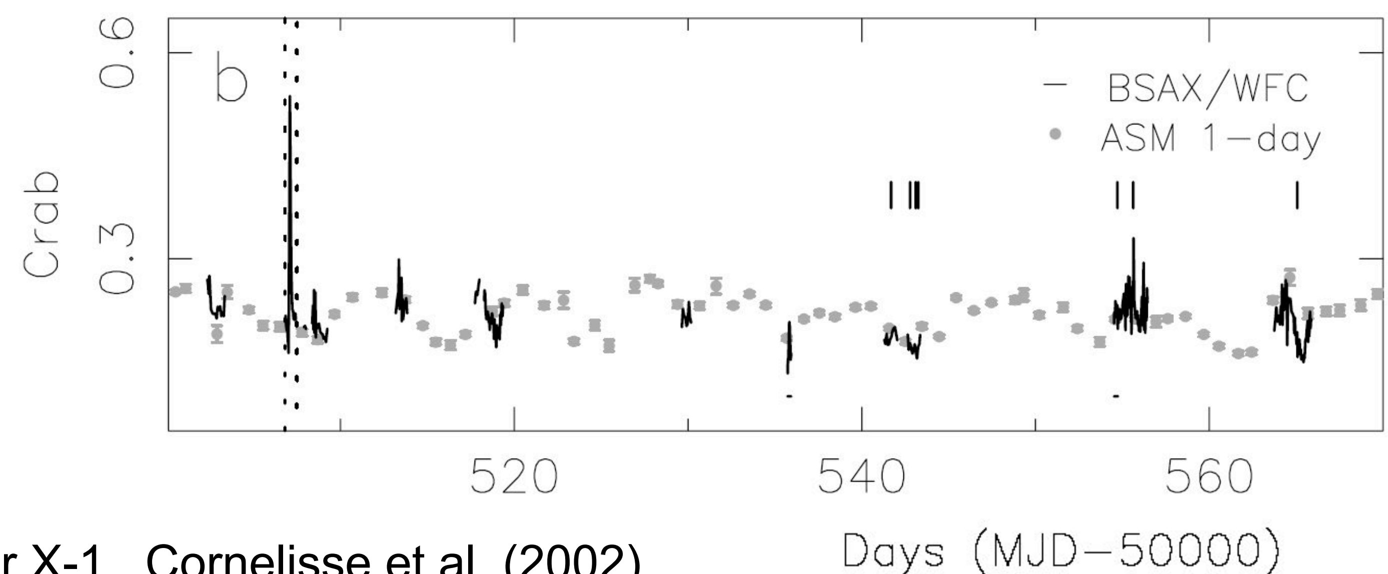
1000 times “normal” Type I bursts
energies ~ 10^{42} ergs
exponential decay times 1-3 hours

• they **“interact”** with normal Type I bursts

they “quench” normal bursting for ~ 3 weeks
normal bursts are seen as “precursors”

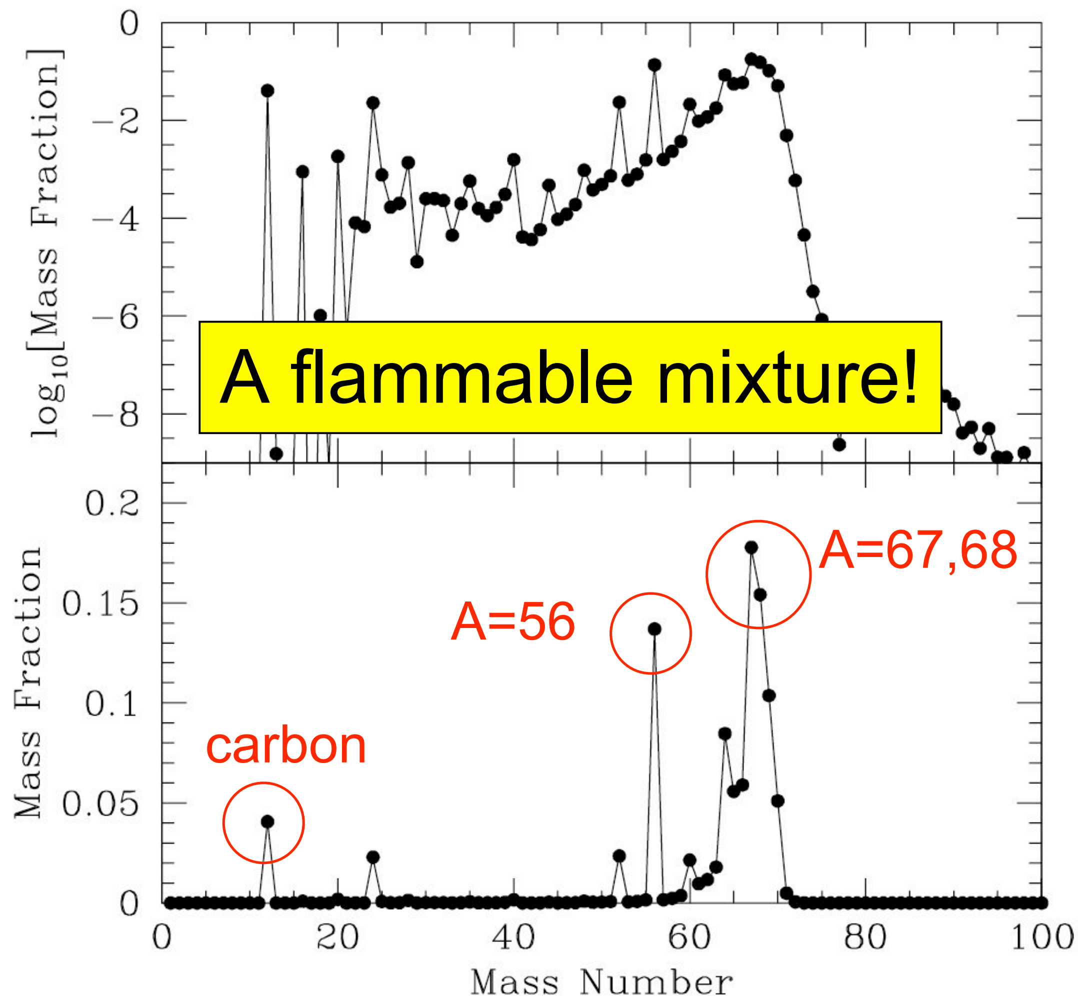


KS 1731-260 Kuulkers et al. (2002)



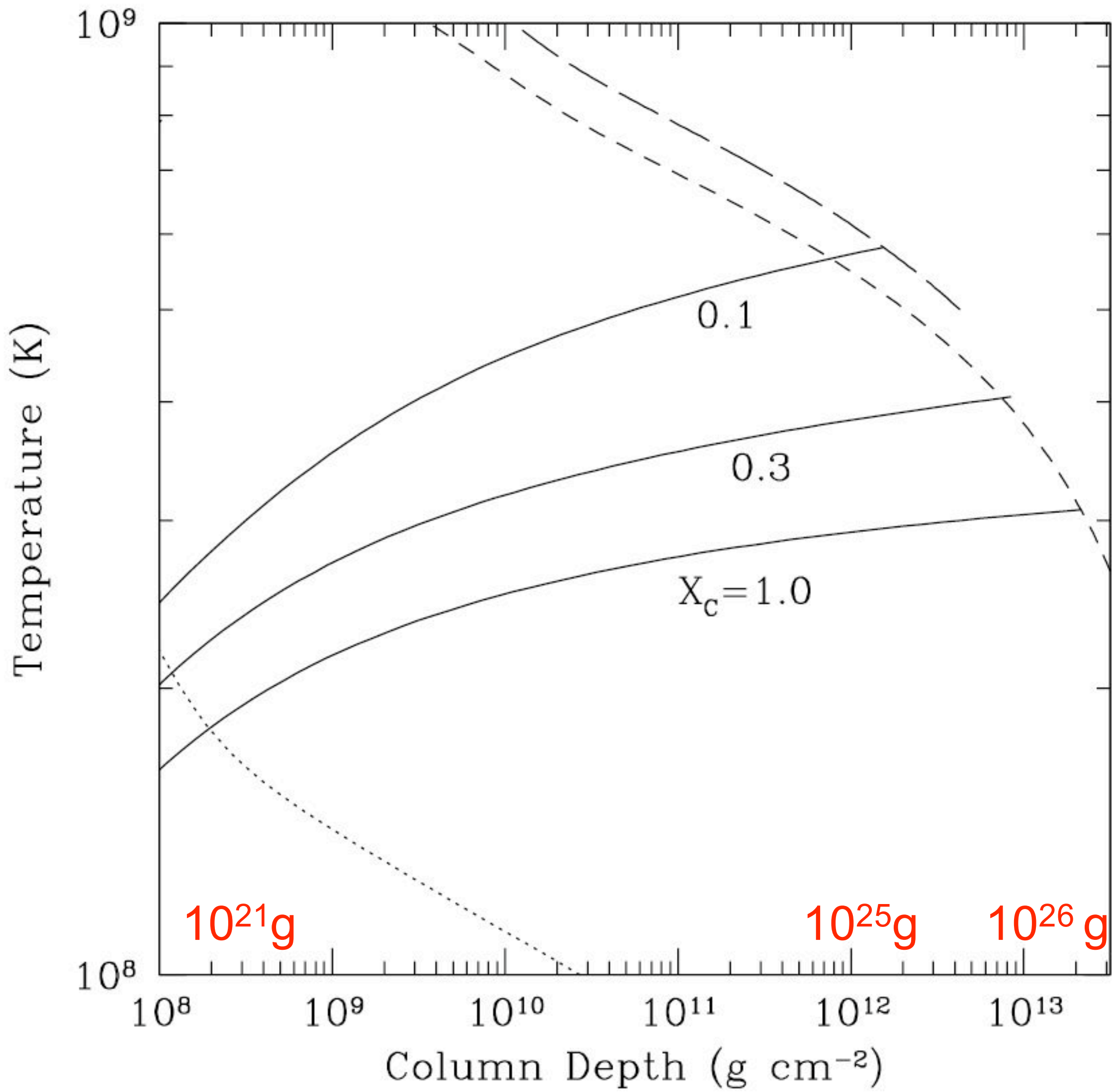
Ser X-1 Cornelisse et al. (2002)

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 ✓

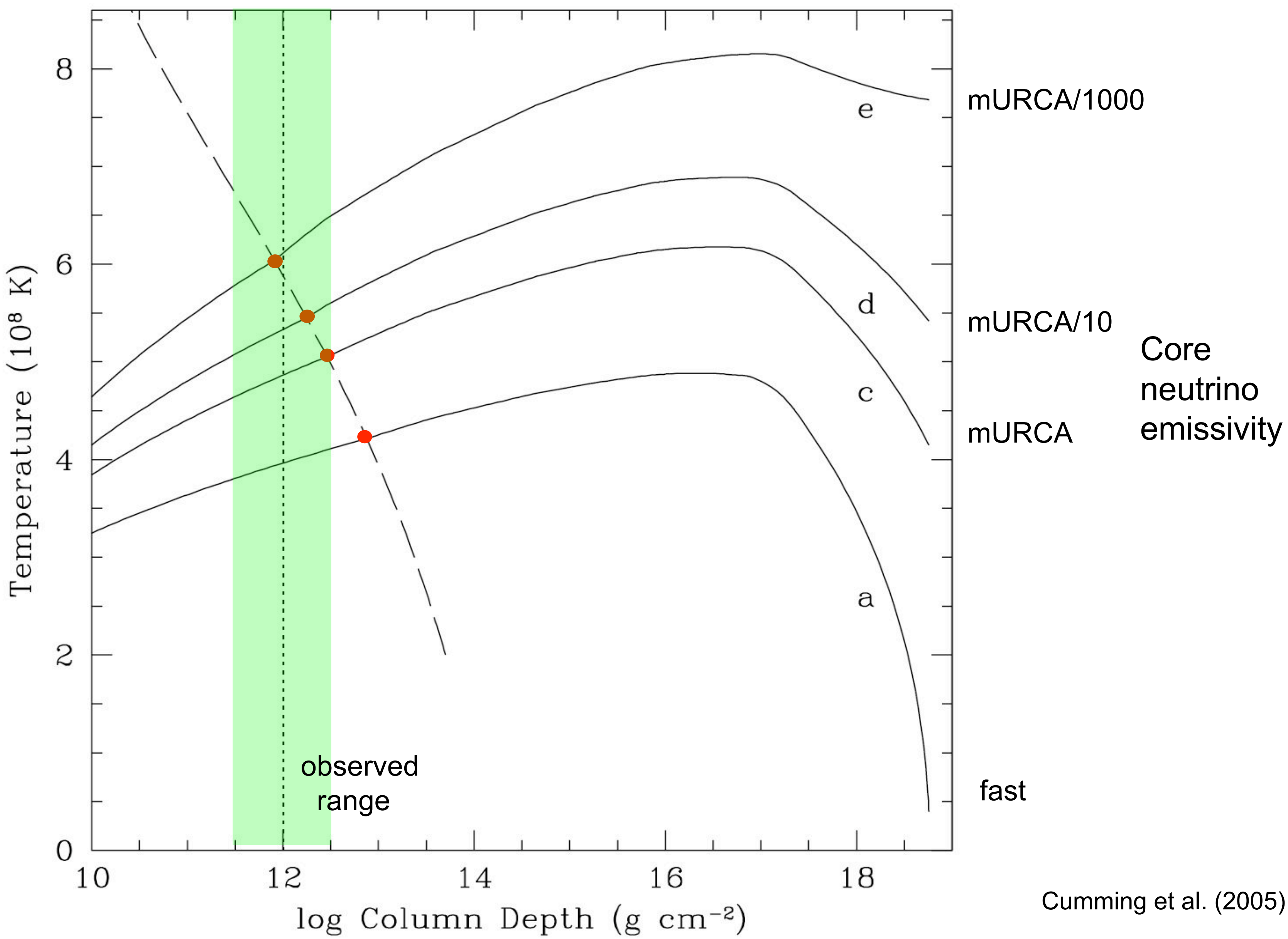
Heavy elements are important because they make the layer **opaque**

⇒ steeper temperature gradient

⇒ early ignition

Ed Brown (2004) 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. (2005)

Neutrino Cooling

1. direct URCA

$$n \rightarrow p + e^- + \bar{\nu}$$
$$p + e^- \rightarrow n + \nu$$

2. modified URCA

spectator particle

$$n + n \rightarrow p + e^- + \bar{\nu}$$
$$p + e^- \rightarrow n + \nu + n$$

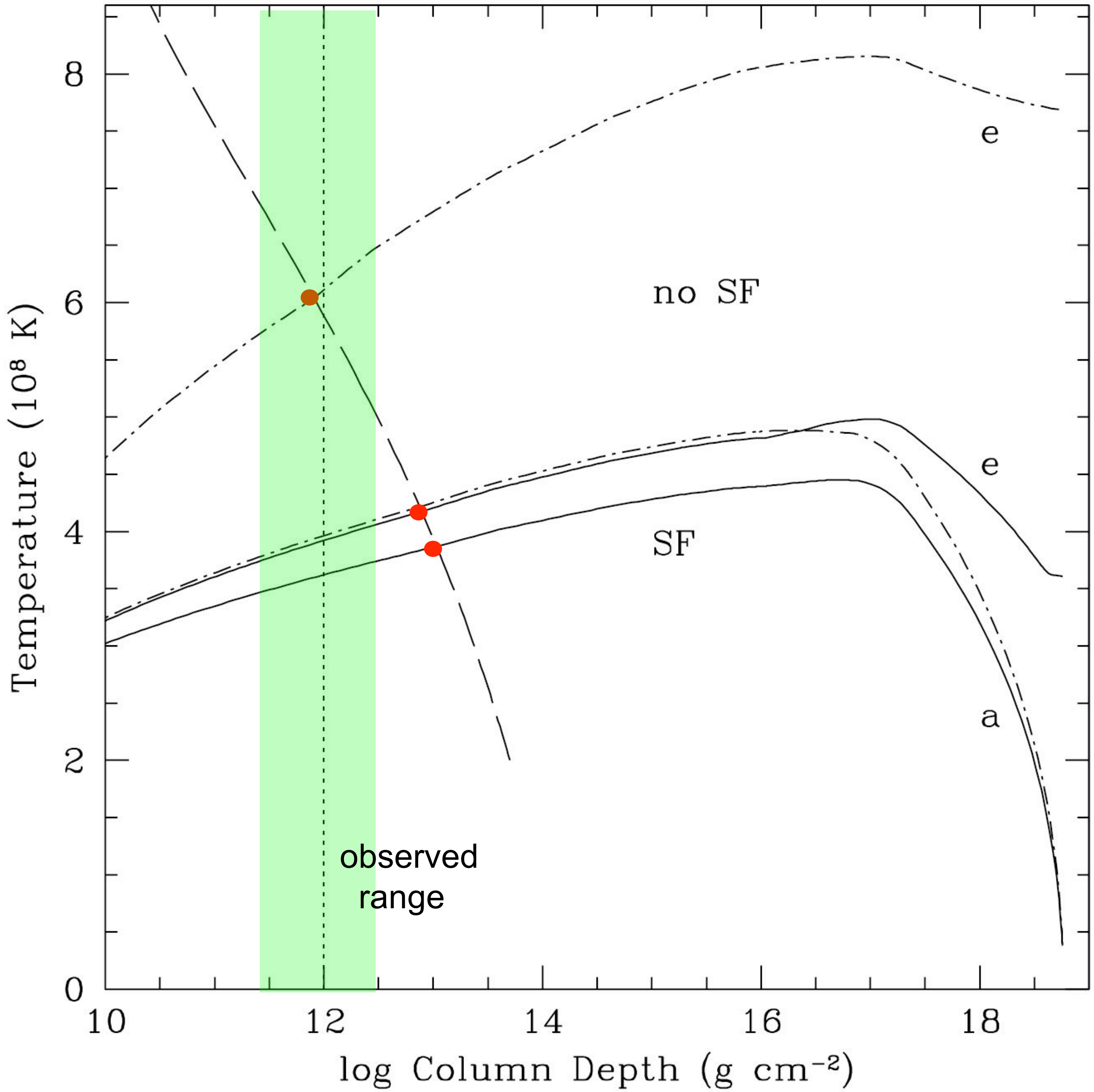
suppressed by ~ $(kT/E_F)^2$ ~ 10^{-6} at 10^9K

3. superfluidity suppresses neutrino emission

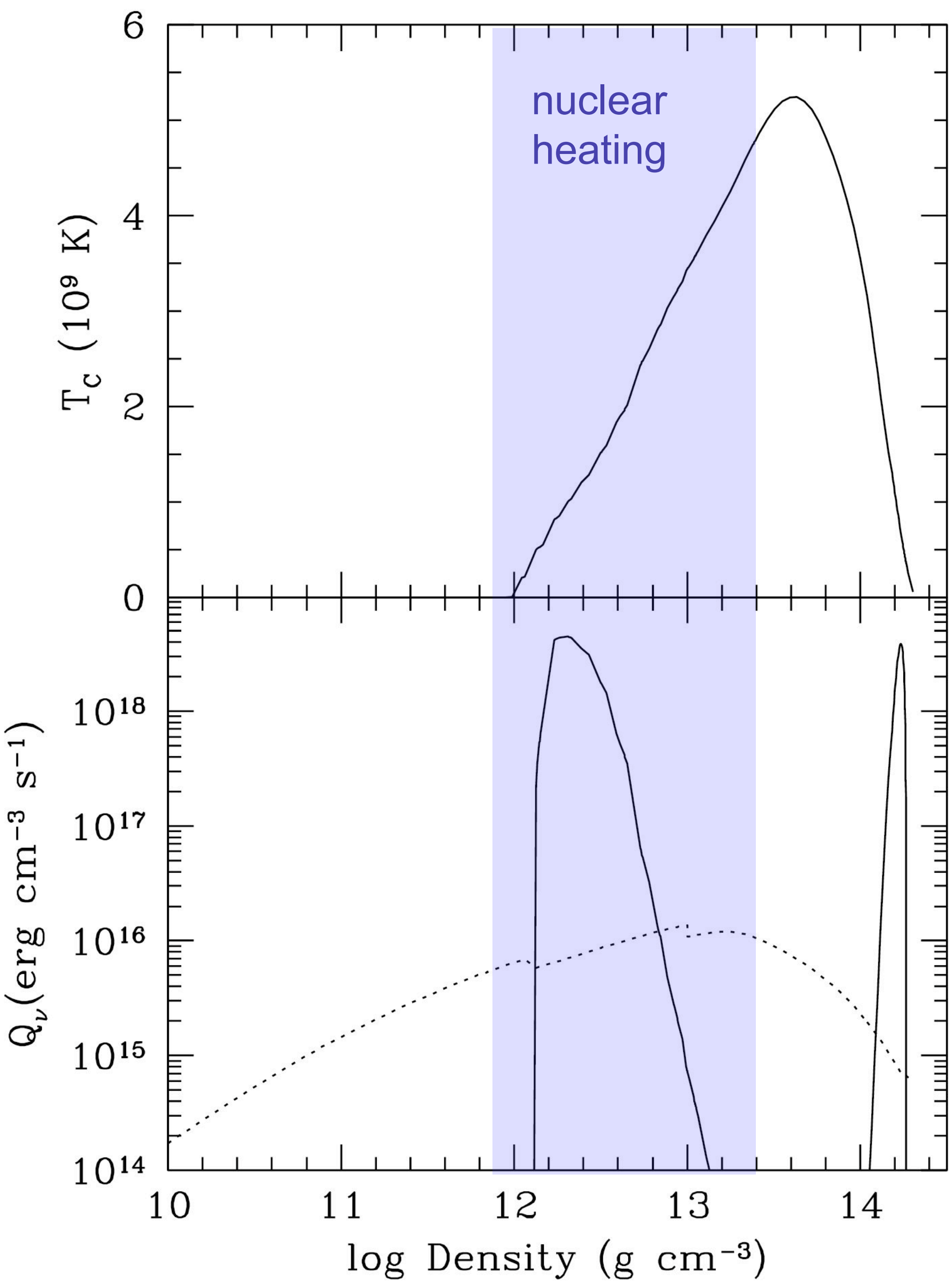
suppressed by ~ $\exp(-T_C/T)$

but **4. Cooper pair emission** for $T \sim T_C$

EFFECT OF COOPER PAIR NEUTRINOS IN CRUST

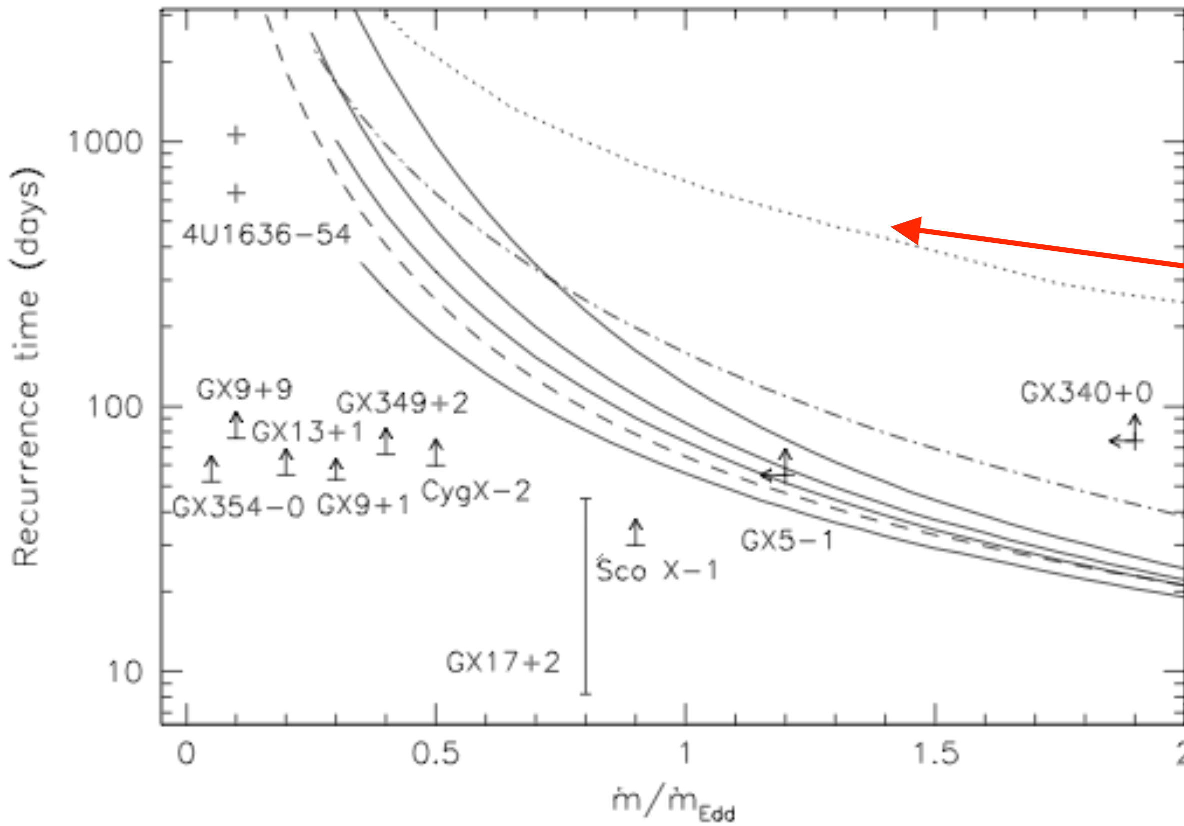


AC, Macbeth, in 't Zand, Page (2005)



nuclear
heating
T_c (10^9 K)
6
4
2
0
Q_ν(erg cm^{-3} s^{-1})
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10
11
12
13
14
log Density (g cm^{-3})

Superbursts: current state of ignition models

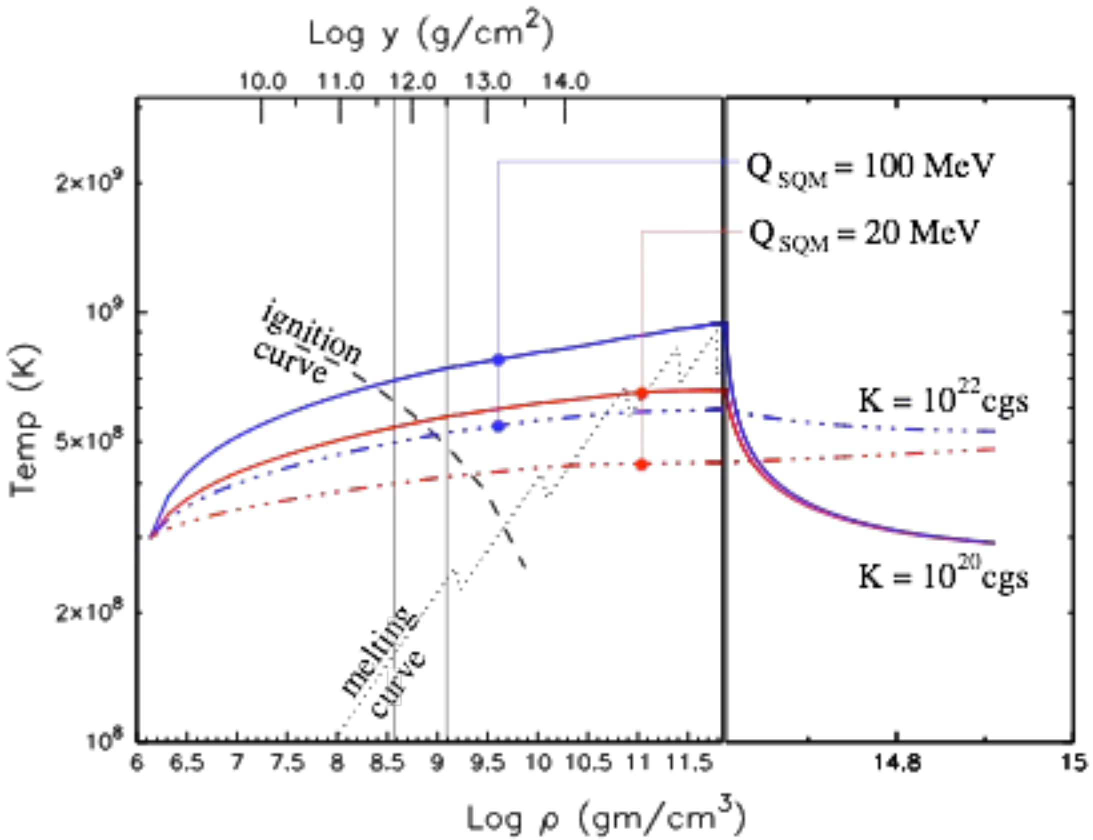


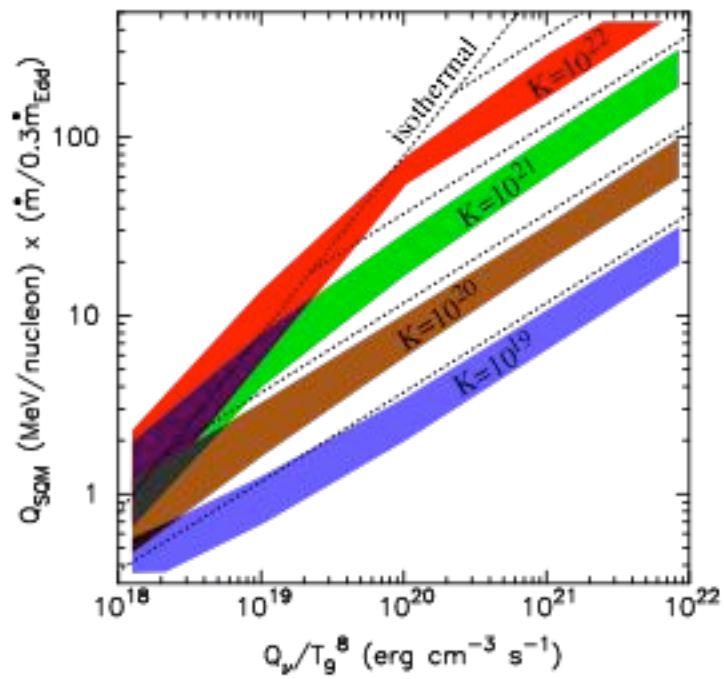
Keek, in ‘t Zand, & Cumming (2005)

models with Cooper pair cooling in the crust are too cold...
extra heating?

- upper limits 1-2 months limited by BeppoSAX total exposure
- planned Brazilian mission MIRAX will do much better (continuous exposure of GC for ~ 2 yrs)

Superbursts from strange stars



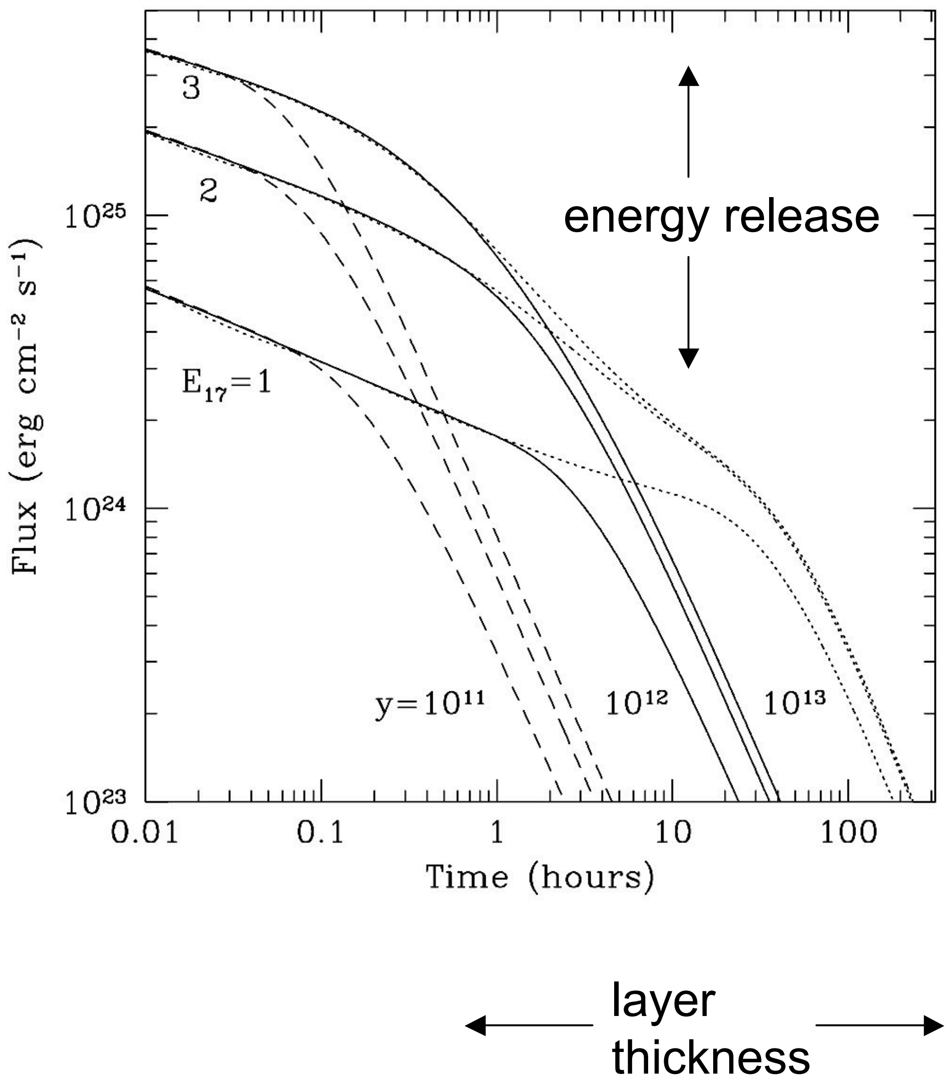


Page & Cumming 2005

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

Alcock, Farhi, & Olinto 1986

Modelling superburst lightcurves



- fits to observed lightcurves

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

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

$$(X_C = 0.1 - 0.2)$$

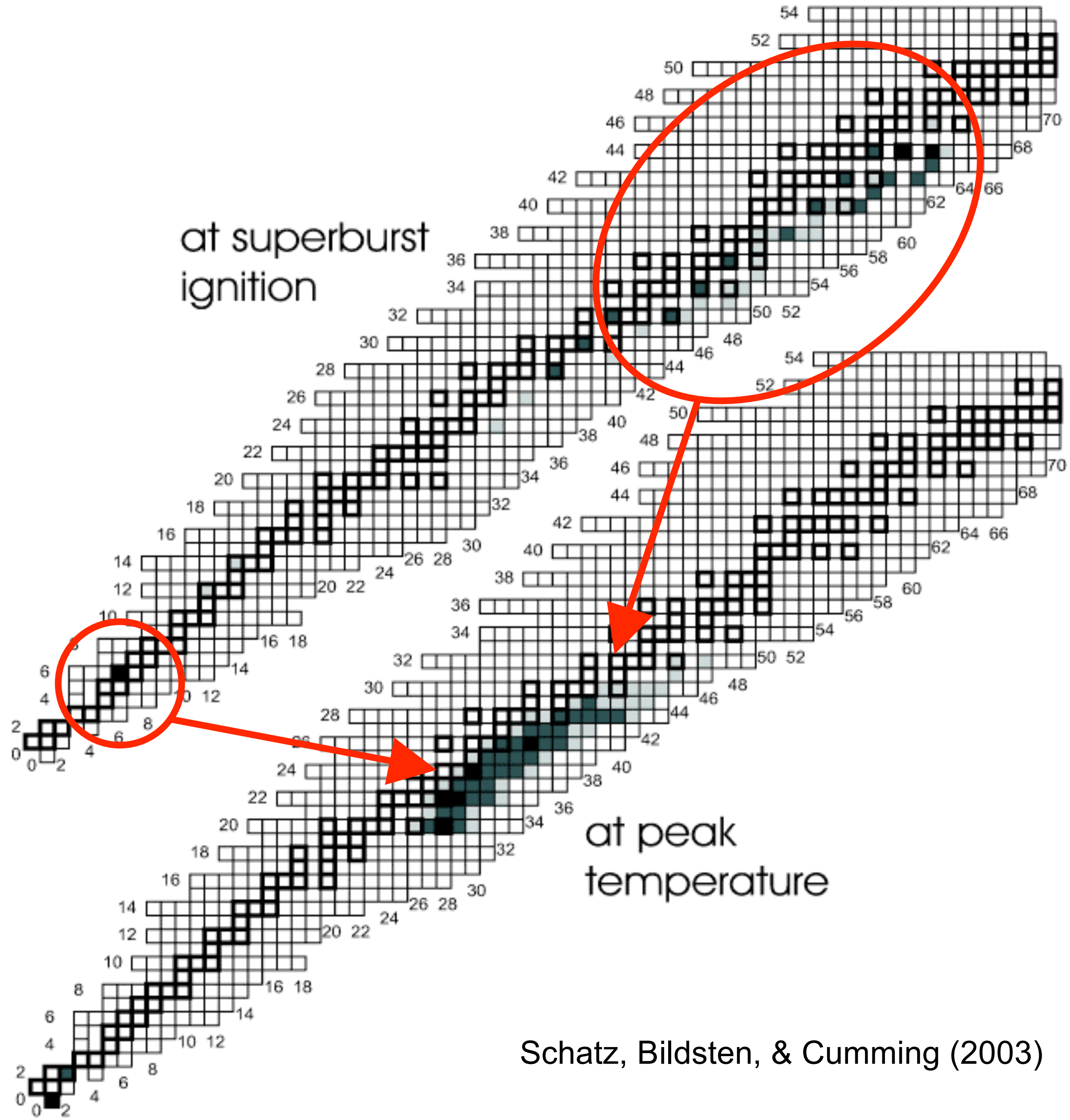
Cumming & Macbeth (2004)
Cumming et al. (2005)

Photodisintegration

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

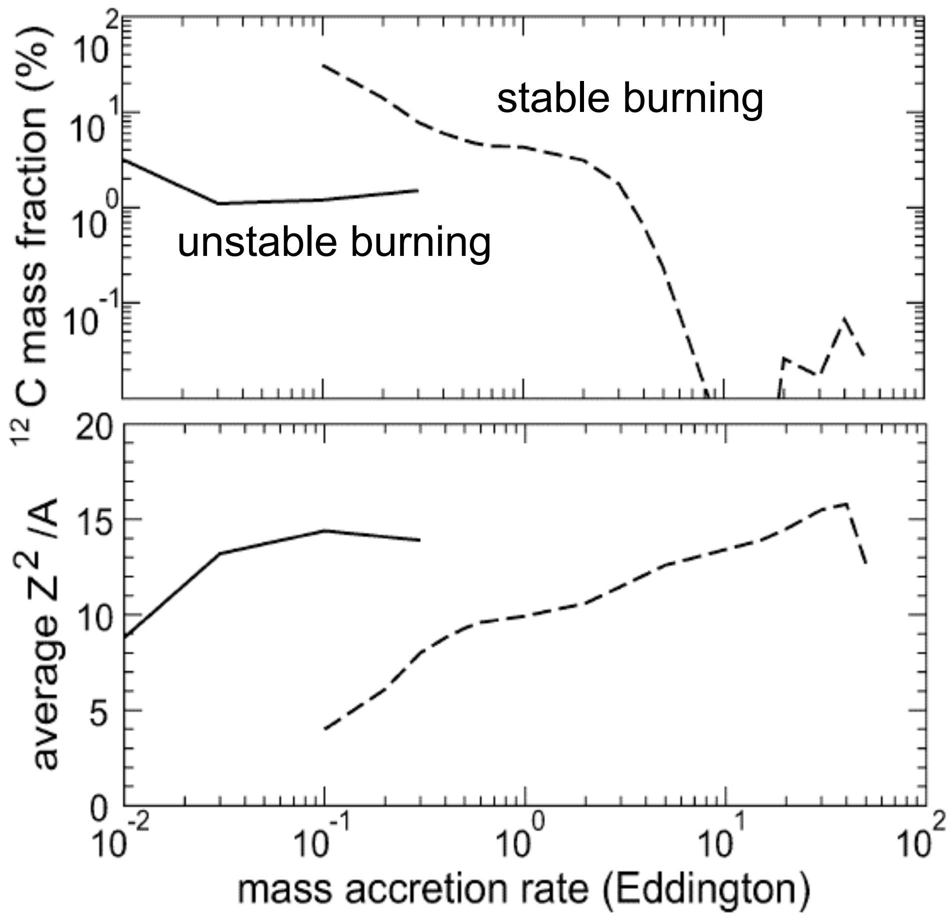
Energetics
photodisintegration
~ 0.1 MeV/nucleon
carbon burning
~ 1 MeV/nucleon

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

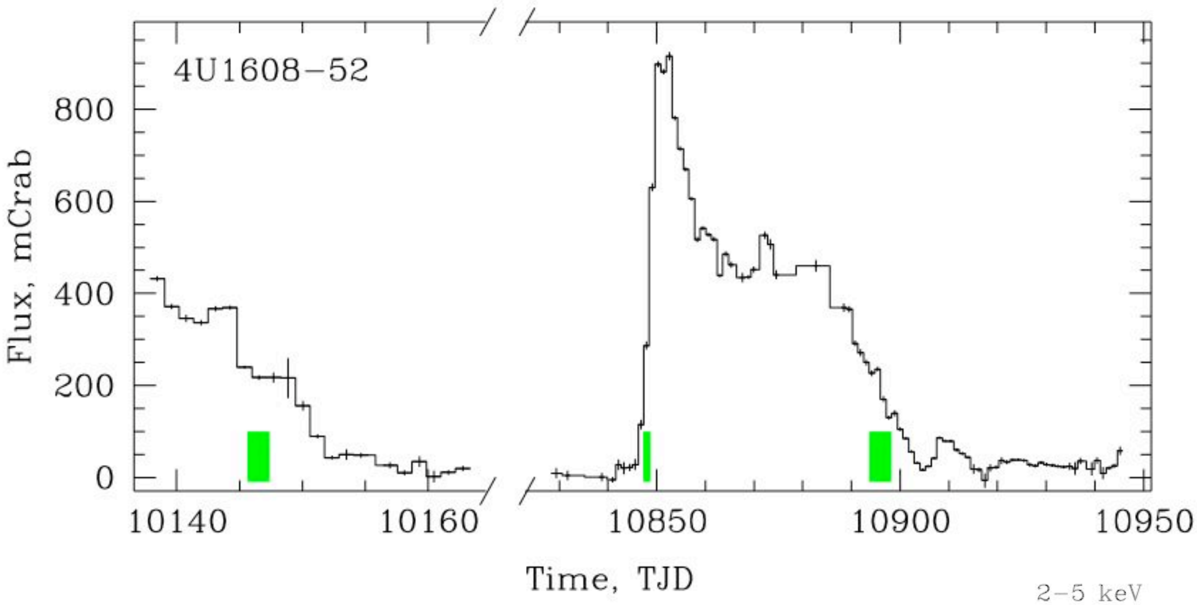
⇒ anti-correlation between X_C and heavy element mass

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

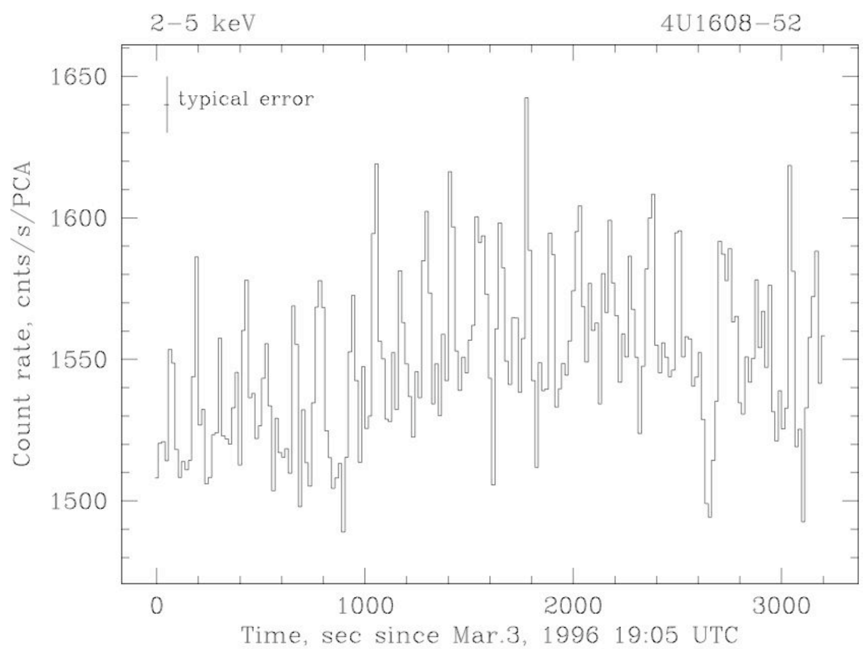
consistent with observed burst energetics in superburst sources!

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

mHz QPOs from 4U 1608-52

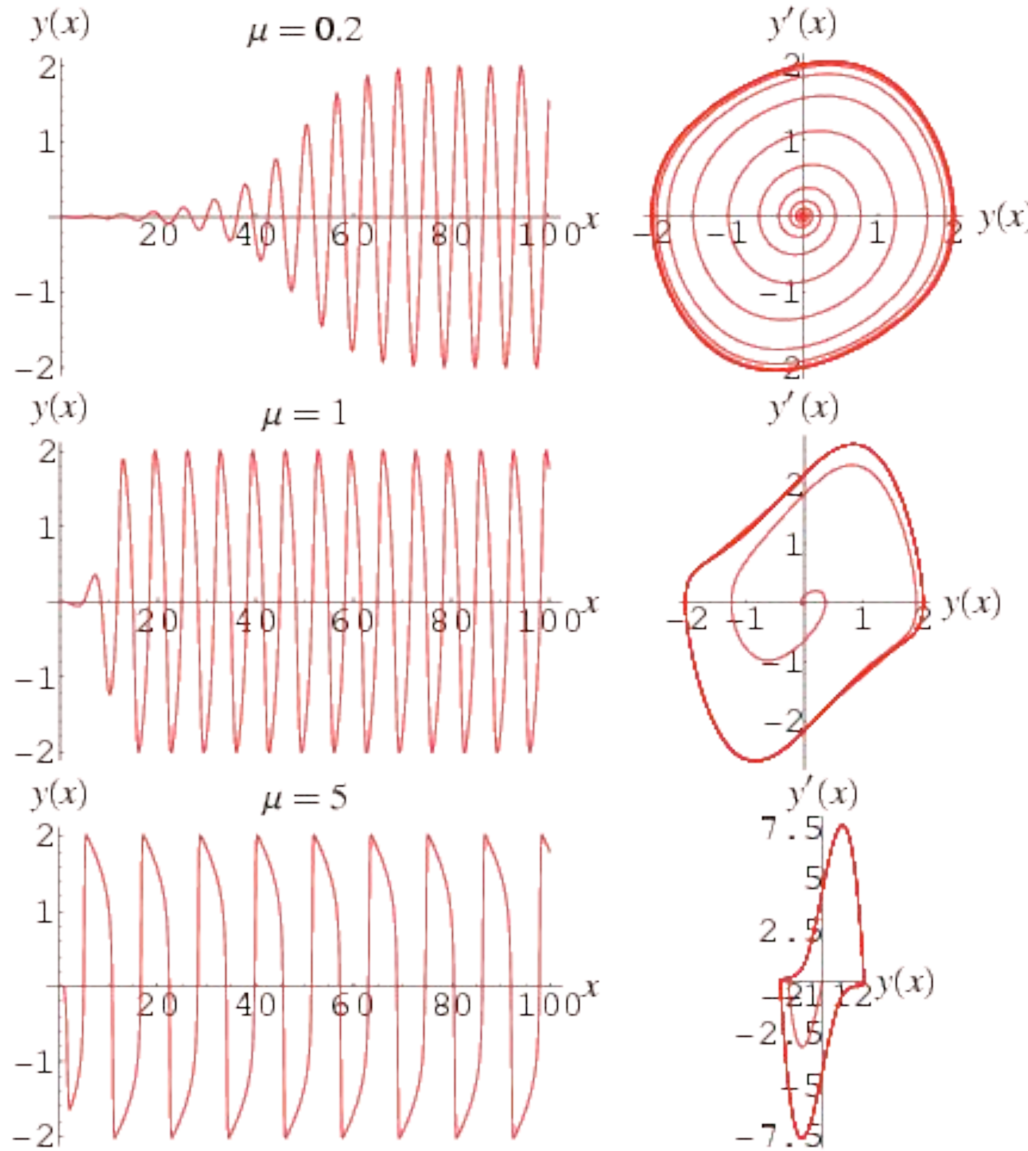


Revnivtsev et al. (2001)



- 7-9 mHz oscillations in the persistent flux
- mostly in soft photons
- only observed when L_X is in a narrow range near 10^{37} erg/s

van der Pol oscillator



One zone model

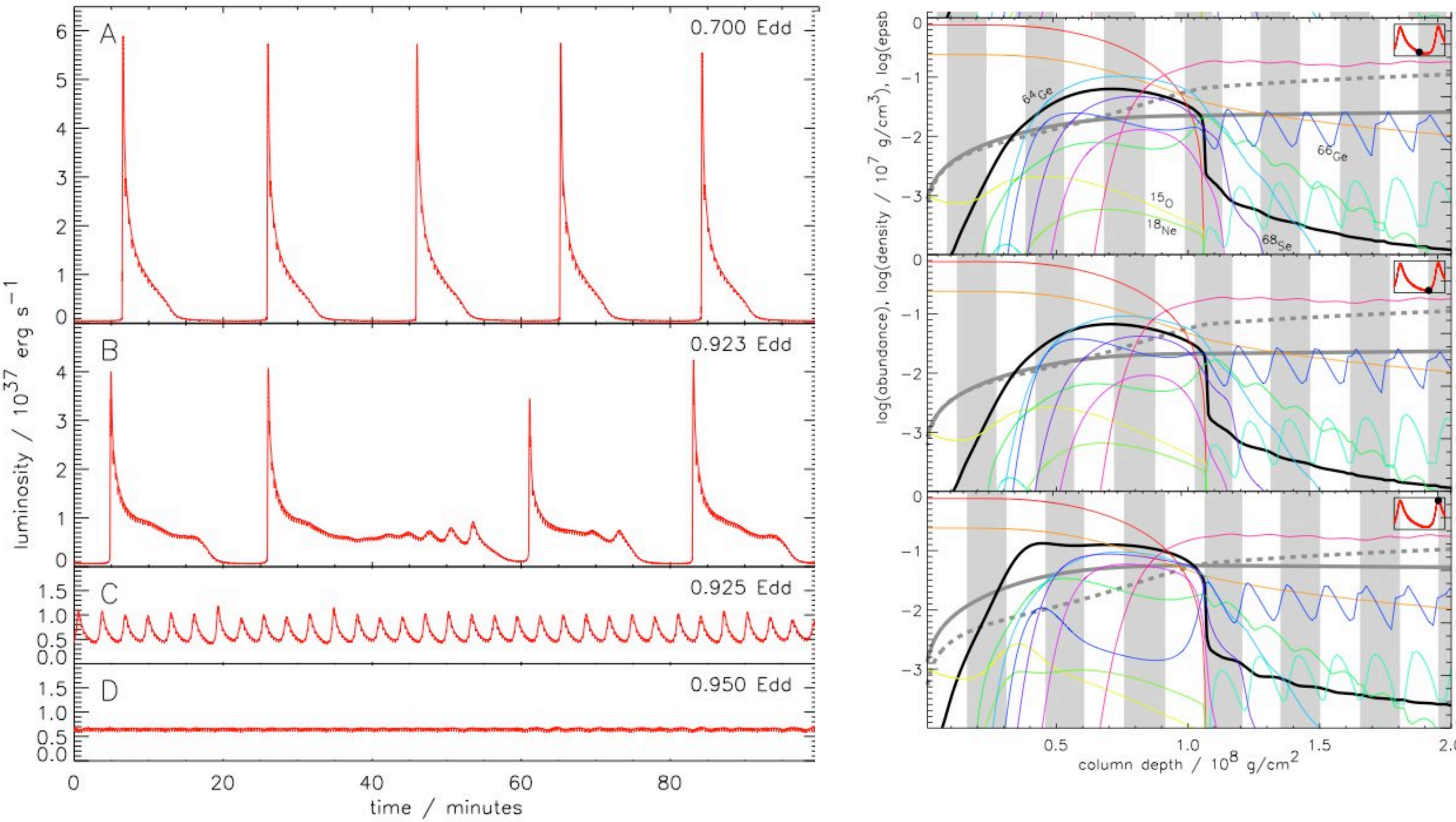
energy $$c_P \frac{dT}{dt} = \epsilon - \frac{F}{y}$$

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

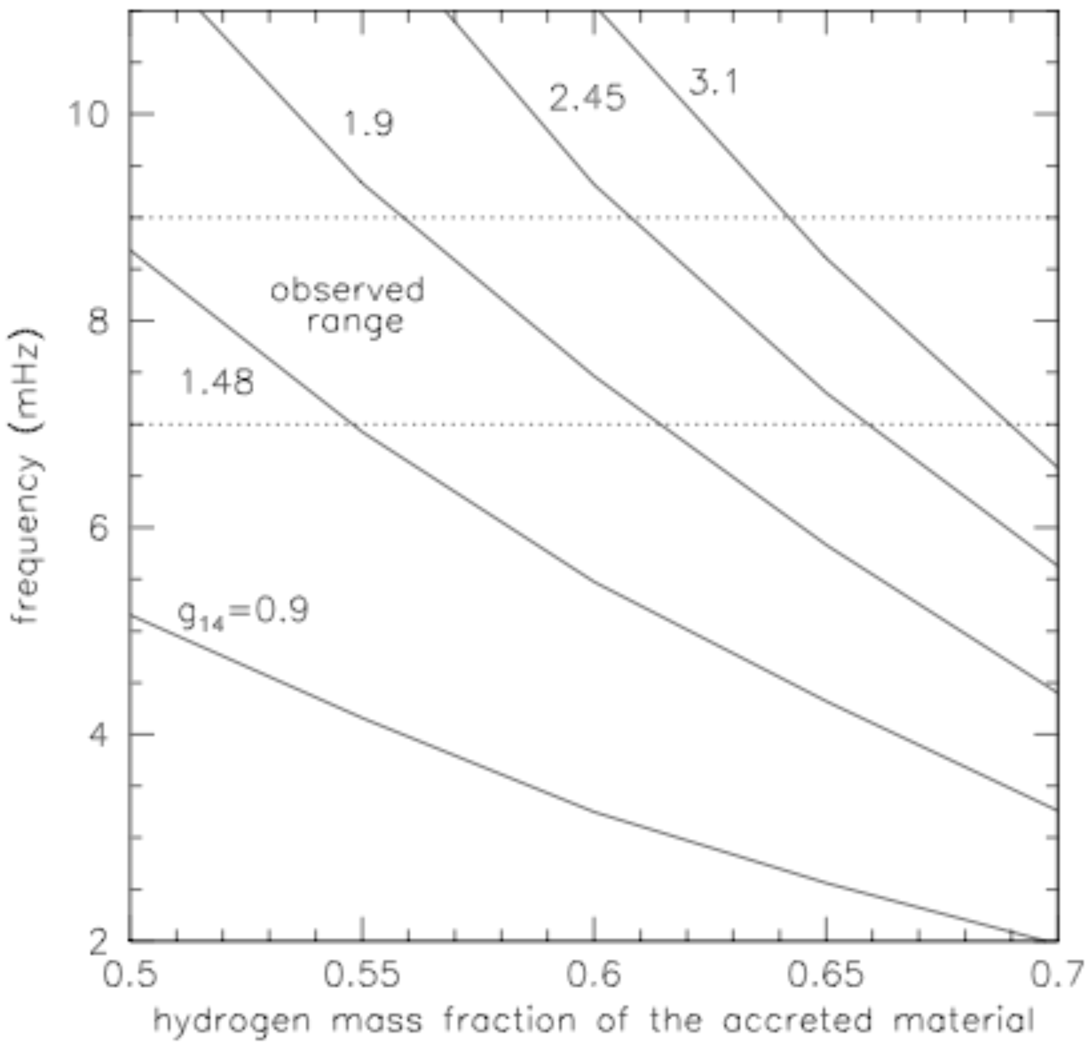
linear perturbations =>

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

oscillation period = (thermal time x accretion time)$^{1/2}$~100 s



Heger, AC, & Woosley 2005



Heger, AC, & Woosley 2005

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?

• **mHz QPOs:** just beginning to explore this.. how does the frequency depend on nuclear physics input?

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

Summary

• several new observational phenomena involving nuclear burning on accreting neutron stars have been discovered in recent years

(burst tails, mHz QPOs, superbursts)

• they are promising new probes of spin, magnetism, neutron star interior, dynamics of burning fronts…

• to understand them we need to understand the details of the rp-process (masses, lifetimes, reaction rates)