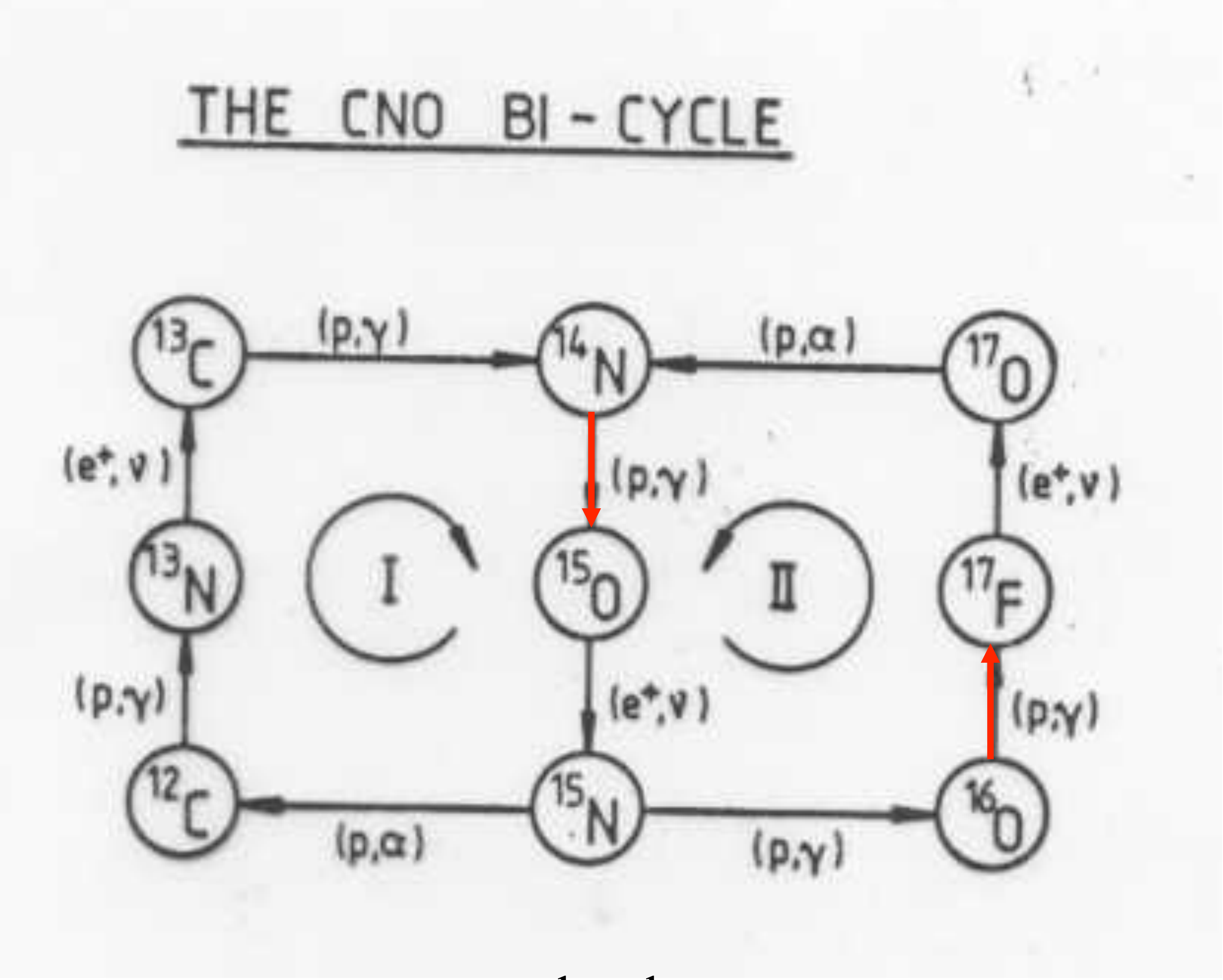
Lecture 9

Hydrogen Burning Nucleosynthesis, Classical Novae, and X-Ray Bursts



red = slow

Once the relevant nuclear physics is known in terms of the necessary rate factors, $\lambda = N_A \langle \sigma v \rangle = f(T,\rho)$, the evolution of the composition can be solved from the coupled set of rate equations:

$$\frac{dY_I}{dt} = -\sum_{j,k} Y_I Y_j \rho \lambda_{jk}(I) + \sum_{k,j,L \ni L+k=I+j} Y_L Y_k \rho \lambda_{kj}(L)$$

The rather complicated looking restriction on the second summation simply reflects the necessary conservation conditions for the generic forward reaction, $I(j,k)L$ and its reverse, $L(k,j)I$.

k and j are typically n, p, α, or γ.

In the special case of weak decay one substitutes for $Y_j \rho \lambda$ the inverse mean lifetime against the weak interaction, $\lambda = 1/\tau_{beta}$. The mean lifetime is the half-life divided by ln 2 = 0.693. Then one has a term with a single Y_i times λ.

Suppose we wrote the de for ^{14}N in the CNO bicycle (In general ^{14}N might have a lot of reactions (α,γ), (α,p), (n,γ), $+ ^{12}C$, etc that we are not interested during hydrogen burning)

Here make ^{14}N by $^{13}C(p,\gamma)^{14}N$
destroy " " $^{14}N(p,\gamma)^{15}O$

$$\frac{dY(^{14}N)}{dt} = +Y(^{13}C)Y_p \rho \lambda_{p\gamma}(^{13}C) - Y(^{14}N)Y_p \rho \lambda_{p\gamma}(^{14}N)$$

Now suppose ^{14}N and ^{13}C were in steady state. For every ^{14}N produced by $^{13}C(p,\gamma)$ one is destroyed by $^{14}N(p,\gamma)$

(actually one would need to worry about other reactions that might affect the abundance of either, but this is just an example to make a point)

Then

$$\frac{dY(^{14}N)}{dt} = 0 \Rightarrow \frac{Y(^{13}C)}{Y(^{14}N)} = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\gamma}(^{13}C)}$$

By similar reasoning (sticking to just the one loop of the CNO cycle)

Everywhere that $\frac{dY_i}{dt} \approx 0$

$$\frac{Y(^{13}C)}{Y(^{12}C)} = \frac{\lambda_{p\gamma}(^{12}C)}{\lambda_{p\gamma}(^{13}C)} \qquad \frac{Y(^{15}N)}{Y(^{14}N)} = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\gamma}(^{15}N) + \lambda_{p\alpha}(^{15}N)}$$

↑ if consider bicycle

And, if the entire cycle were in steady state

$$\frac{Y(^{14}N)}{Y(^{12}C)} = \frac{\lambda_{p\gamma}(^{12}C)}{\lambda_{p\gamma}(^{14}N)}$$

etc.

$$i.e., \quad \frac{Y(^{14}N)}{Y(^{12}C)} = \left(\frac{Y(^{14}N)}{Y(^{13}C)}\right)\left(\frac{Y(^{13}C)}{Y(^{12}C)}\right) = \left(\frac{\lambda_{p\gamma}(^{13}C)}{\lambda_{p\gamma}(^{14}N)}\right)\left(\frac{\lambda_{p\gamma}(^{12}C)}{\lambda_{p\gamma}(^{13}C)}\right)$$

if all three isotopes are in steady state

That is, the ratio of the abundances of any two species in steady state is the inverse ratio of their destruction rates

How long does it take for a pair of nuclei to reach steady state?

The time to reach steady state is approximately the reciprocal of the *destruction rate for the more fragile nucleus*.

Eg. for ^{13}C [absorb ρY_p into λ for simplicity];

i.e. $\lambda_{12} = \rho Y_p \lambda_{p\gamma}(^{12}C)$; $\lambda_{13} = \rho Y_p \lambda_{p\gamma}(^{13}C)$]

$$\frac{dY_{13}}{dt} = -Y_{13}\lambda_{13} + Y_{12}\lambda_{12} \qquad \frac{dY_{12}}{dt} \approx -Y_{12}\lambda_{12}$$

Let u = Y_{13}/Y_{12} then

$$\frac{du}{dt} = \frac{1}{Y_{12}}\frac{dY_{13}}{dt} - \frac{Y_{13}}{Y_{12}^2}\frac{dY_{12}}{dt} = \lambda_{12} - \frac{Y_{13}}{Y_{12}}\lambda_{13} + \frac{Y_{13}}{Y_{12}}\lambda_{12}$$

$$= \lambda_{12} + u\,(\lambda_{12} - \lambda_{13})$$

Integrating and assuming $Y_{13} = 0$ at $t = 0$ and $\frac{Y_{13}}{Y_{12}} = \frac{\lambda_{12}}{\lambda_{13}}$

after a time τ_{ss} = time required to reach steady state, one has with some algebra

$$\tau_{ss} = \frac{\ln\left(\frac{\lambda_{12}}{\lambda_{13}}\right)}{\left(\lambda_{12} - \lambda_{13}\right)}$$

nb. always > 0
since ln of a number < 1
is negative

which says steady state will be reached on the faster of the two reaction time scales, $1/\lambda_{12}$ or $1/\lambda_{13}$

A sampling of Rates from Caughlan and Fowler (1988)

T6	12C(pg)	13C(pg)	14N(pg)
2	8.51(-39)	2.69(-38)	9.88(-44)
4	2.95(-29)	9.71(-29)	4.17(-33)
6	1.24(-24)	4.15(-24)	5.85(-28)
8	1.01(-21)	3.44(-21)	1.02(-24)
10	1.19(-19)	4.07(-19)	2.06(-22)
12	4.51(-18)	1.55(-17)	1.17(-20)
15	2.86(-16)	9.90(-16)	1.18(-18)
20	3.85(-14)	1.34(-13)	2.73(-16)
25	1.26(-12)	4.39(-12)	1.30(-14)
30	1.79(-11)	6.27(-11)	2.46(-13)
40	8.57(-10)	3.01(-9)	1.76(-11)
50	3.88(-11)	4.71(-8)	3.64(-10)

T6	15N(pa)	16O(pg)	17O(pa)
2	1.92(-39)	2.68(-48)	2.64(-49)
4	8.69(-29)	1.23(-36)	1.36(-37)
6	1.28(-23)	5.52(-31)	6.70(-32)
8	2.32(-20)	2.00(-27)	2.65(-28)
10	4.81(-18)	6.79(-25)	9.68(-26)
12	2.82(-16)	5.75(-23)	8.82(-24)
15	2.95(-14)	9.11(-21)	1.55(-21)
20	7.23(-12)	3.60(-18)	1.06(-18)
25	3.62(-10)	2.51(-16)	4.07(-16)
fastest at 30 * 30	7.18(-9)	6.35(-15)	3.47(-14)
40	5.60(-7)	6.94(-13)	9.11(-12)
50	1.25(-5)	1.93(-11)	2.43(-10)

At $T_6 = 30$ $\rho Y_p = 100$

$\left(\rho Y_p \lambda_{p\gamma}(^{13}C)\right)^{-1} = 1.5\times10^8$ sec $^{12}C \leftrightarrow ^{13}C$ (2^{nd} quick)

$\left(\rho Y_p \lambda_{p\gamma}(^{15}N)\right)^{-1} = 1.4\times10^6$ sec !5N $\leftrightarrow$ ^{14}N (quickest)

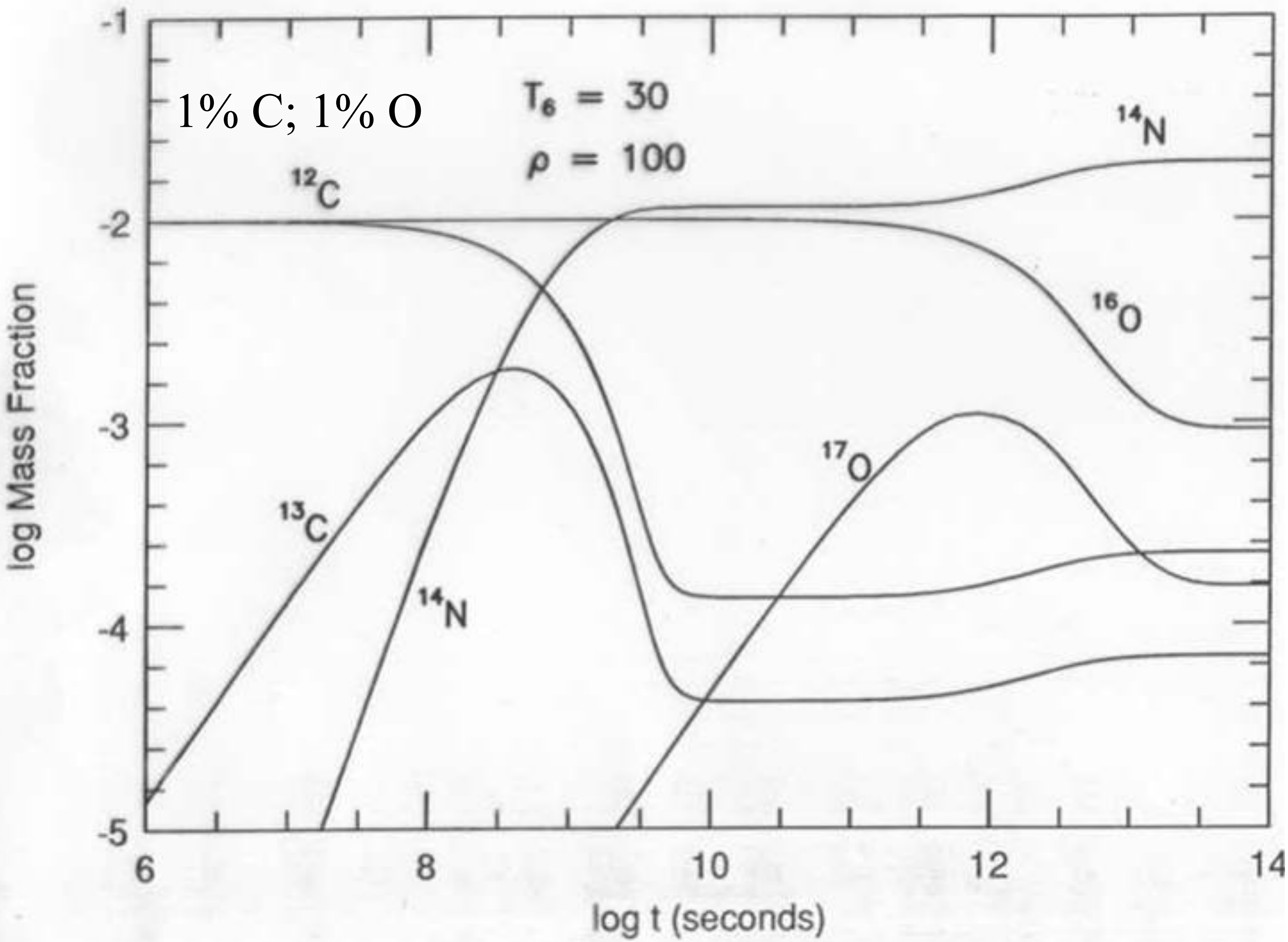
$\left(\rho Y_p \lambda_{p\alpha}(^{17}O)\right)^{-1} = 2.9\times10^{11}$ sec $^{17}O \leftrightarrow ^{16}O$ (slow)

$\left(\rho Y_p \lambda_{p\gamma}(^{14}N)\right)^{-1} = 4.2\times10^{10}$ sec one cycle of the main CNO cycle

$\left(\rho Y_p \lambda_{p\gamma}(^{16}O)\right)^{-1} = 1.6\times10^{12}$ sec $^{16}O \leftrightarrow ^{14}N$ (slow)

$\left(\rho Y_p \lambda_{p\gamma}(^{12}C)\right)^{-1} = 5.6\times10^8$ sec $^{12}C \leftrightarrow ^{14}N$ (quick)

Steady state after several times these time scales.



ρ = 1 to 10 would be more appropriate for massive stars where T is this high,
so the real time scale should be about 10 times greater. Also lengthened by convection.

Provided steady state has been achieved the abundance ratios are just given by the λ' s.

e.g. ^{13}C

$$^{13}C/^{12}C = \frac{\lambda_{p\gamma}(^{12}C)}{\lambda_{p\gamma}(^{13}C)}$$

$$\left.\frac{^{13}C}{^{12}C}\right)_{\odot} = 1/89$$

T_H	$^{13}C/^{12}C$
20	1/3.45
30	1/3.50
50	1/3.51

Giant stars in the globular cluster M4

Suntzeff and Smith (ApJ, 381, 160, (1991))

TABLE 2

STELLAR PARAMETERS AND DERIVED ABUNDANCES

Star	T_{eff} (K)	log g	log $\epsilon(^{12}C)$	$^{12}C/^{13}C$	[C/M]
			M4		
1403	4200	1.3	6.70	5	−0.67
1408	4350	1.6	6.65	5	−0.72
1412/V4	4100	0.5	$\lesssim$5.6	...	$\lesssim$ −1.85
1514	3800	0.4	6.25	5	−1.12
1608	4600	2.0	6.75	6	−0.63
1617	4350	1.6	6.40	3:	−0.93
1622	4650	2.1	7.00	3–5:	−0.35
1625	4200	1.3	6.30	5:	−1.07
1701	4500	1.9	7.10	4	−0.25
2206	4150	1.2	6.75	4	−0.60
2307	3950	0.9	6.40	4	−0.95
2406/V13	3950	0.6	6.30	3	−1.02
2410	4350	1.6	6.80	5–10:	−0.59
2422	4300	1.5	6.50	3	−0.83
2519	4200	1.3	6.85	4	−0.50
2608	4300	1.5	6.85	5	−0.52
2617	4050	1.1	6.60	5	−0.77
2623	4500	1.9	6.65	3–5:	−0.70
3309	4700	2.2	7.15	...	−0.30
3404	4700	2.2	7.05	...	−0.40
3612	4150	1.2	6.60	3	−0.73
3624	4100	1.1	6.70	5	−0.67
4201	4300	1.5	6.70	5	−0.67
4310	4250	1.4	6.90	5	−0.47
4404	4650	2.1	7.10	...	−0.35
4413	4550	1.9	7.00	3	−0.32
4415	4300	1.5	6.70	5:	−0.67
4416	4450	1.8	6.50	5–10:	−0.89
4421	4350	1.6	6.55	6:	−0.83
4509	4650	2.1	6.95	5–10:	−0.44
4511	4050	1.0	6.55	6	−0.83
4630	4200	1.4	6.75	5	−0.62

but it doesn't always work so well

eg. ^{15}N

$$^{15}N/^{14}N = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\alpha}(^{15}N)}$$

T_H	$^{15}N/^{14}N$
20	3.8 (-5)
30	3.4 (-5)
50	2.9 (-5)

$$^{15}N/^{14}N)_\odot = 3.7\times10^{-3}$$

Will have to make ^{15}N somewhere else not in steady state with ^{14}N

$$\left.\frac{^{13}\mathrm{C}}{^{14}\mathrm{N}}\right)_{\odot} = 0.035$$

T_6	$\left.\frac{^{13}\mathrm{C}}{^{14}\mathrm{N}}\right)_{SS} = \frac{\lambda_{p\gamma}(^{14}\mathrm{N})}{\lambda_{p\gamma}(^{12}\mathrm{C})}$
20	2.0(-3)
30	7.9(-3)
40	7.7(-3)

So one can make $\frac{^{13}C}{^{12}C}$ large but cannot make $\frac{^{13}C}{^{14}N}$ big compared with its solar value. Cardinal rule of nucleosynthesis - you must normalize to your biggest overproduction, nitrogen in this case.

Way out: Make ^{13}C in a CN process that has not reached steady state (because of the longer life of ^{13}C(p,γ)^{14}N, e.g., make ^{13}C in a region where just a few protons are mixed in with the carbon and then convection cools the material.

Hydrogen Burning Nucleosynthesis Summary

^{12}C - destroyed by hydogen burning. Turned into ^{13}C if incomplete cycle. ^{14}N otherwise.

^{13}C - produced by incomplete CNcycle. Made in low mass stars. Ejected in red giant winds and planetary nebulae

^{14}N - produced by the CNO cycle from primordial ^{12}C and ^{16}O present in the star since its birth. A secondary element. Made in low mass ($M < 8\ M_\odot$) stars and ejected in red giant winds and planetary nebulae. Exception: Large quantities of "primary" nitrogen can be made in very massive stars when the helium convective core encroaches on the hydrogen envelope.

^{15}N - Not made sufficiently in any normal CNO cycle>
Probably made in classical novae as radioactive ^{15}O

^{16}O - Destroyed in the CNO cycle. Made in massive stars by helium burning

^{17}O - Used to be made in massive stars until the rate for $^{17}O(p,\alpha)^{14}N$ was remeasured and found to be large.
probably made in classical novae

^{18}O - made in helium burning by $^{14}N(\alpha,\gamma)^{18}F(e^{+}\nu)^{18}O$

^{23}Na - Partly made by a branch of the CNO cycle but mostly made by carbon burning in massive stars.

^{26}Al - long lived radioactivity made by hydrogen burning but more by explosive neon burning in massive stars

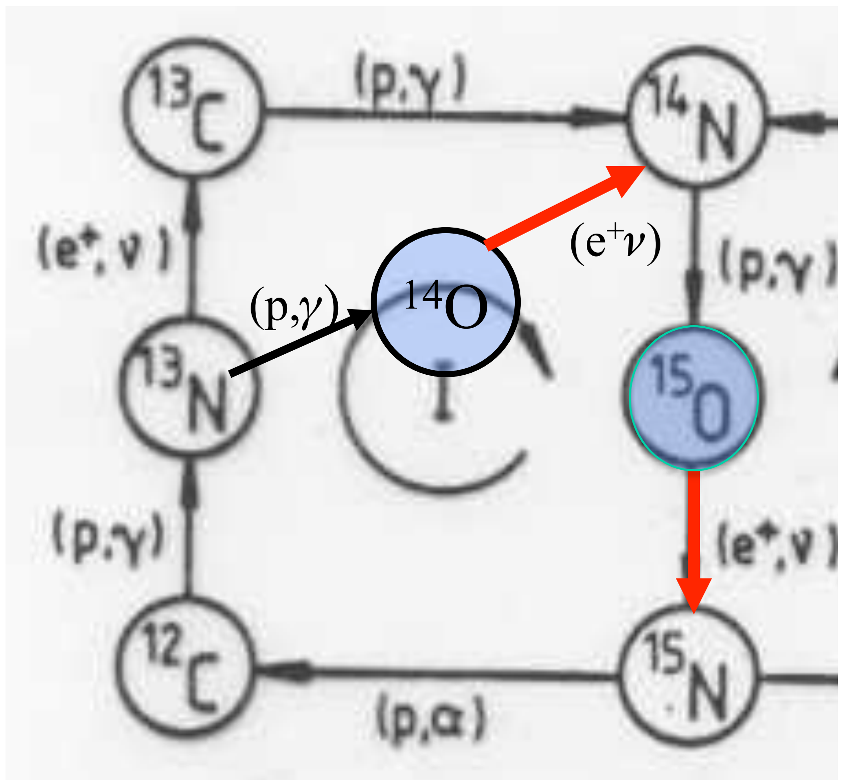
Hydrogen burning under extreme conditions

Scenarios:

- Hot bottom burning in massive AGB stars (> 4 solar masses)
  ($T_9 \sim 0.08$)
- Nova explosions on accreting white dwarfs
  ($T_9 \sim 0.4$)
- X-ray bursts on accreting neutron stars
  ($T_9 \sim 1 - 2$)
- accretion disks around low mass black holes ?
- neutrino driven wind in core collapse supernovae ?

Suppose keep raising the temperature of the CNO cycle. Is there a limit how fast it can go?

Eventually one gets hung up on the finite life times for ^{14}O (70.6 s) and ^{15}O (122 s) to decay by positron emission. This has several interesting consequences:



Slowest rates are weak decays of ^{14}O and ^{15}O.

The β-limited CNO cycle

- Material accumulates in ^{14}O and ^{15}O rather than ^{14}N, with interesting nucleosynthetic consequences for ^{15}N. But can the material cool down fast enough that ^{15}N is not destroyed by $^{15}N(p,\alpha)^{12}C$ in the process?

- The nuclear energy generation rate becomes temperature insensitive and exceptionally simple

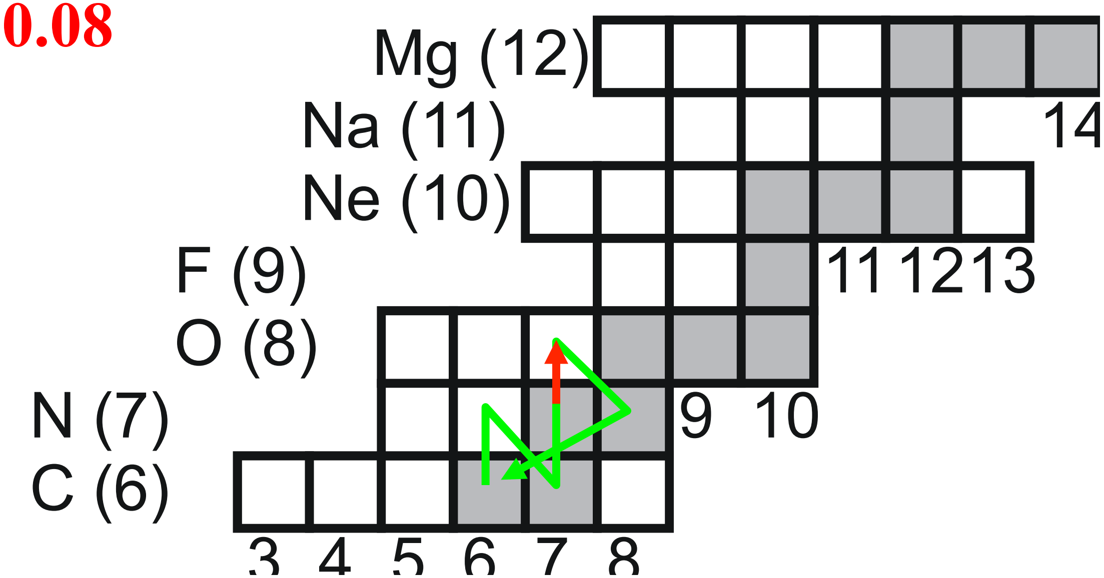
$$\varepsilon_{nuc} = 5.9\times10^{15}\ \ Z\ \ \text{erg g}^{-1}\ \text{s}^{-1}$$

- As the temperature continues to rise matter can eventually break out of ^{14}O and ^{15}O especially by the reaction $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na(p,\gamma)^{21}Mg(e^{+}\nu)$ …. The *rp*-process.

"Cold" CN(O)-Cycle $T_9 < 0.08$

Energy production rate:

$$\varepsilon \propto \langle \sigma v \rangle_{14N(p,\gamma)}$$



Hot CN(O)-Cycle $T_9 \sim 0.08\text{-}0.1$

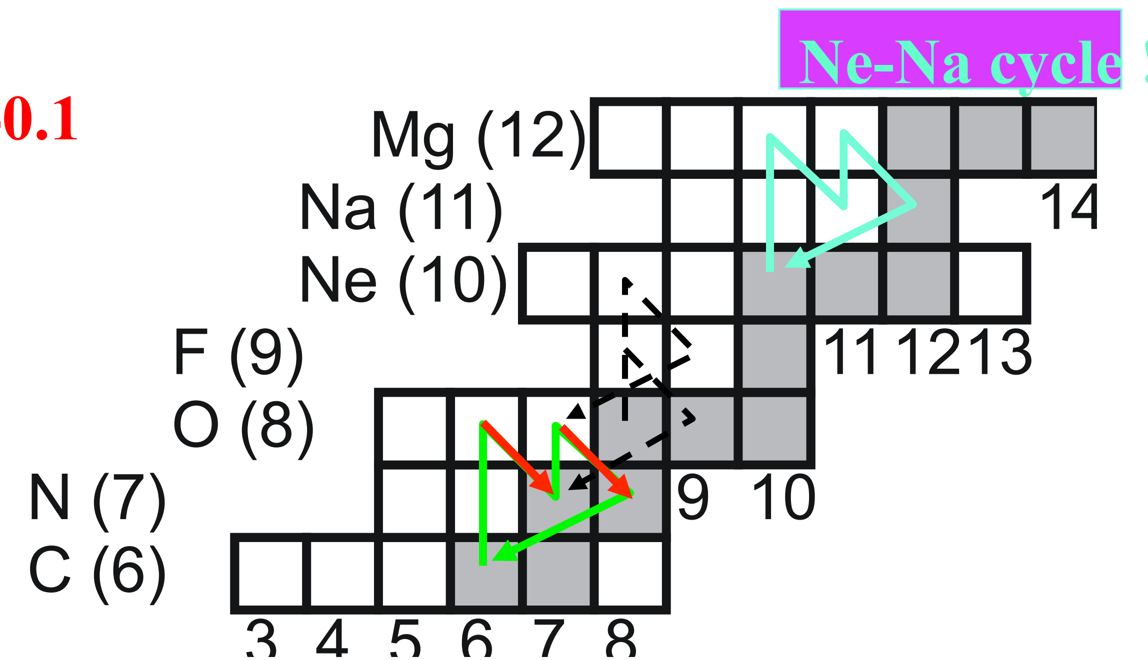
"beta limited CNO cycle"

$$\varepsilon \propto 1/(\lambda^{-1}_{14O(\beta+)} + \lambda^{-1}_{15O(\beta+)}) = \text{const}$$

Note: condition for hot CNO cycle depend also on density and Y_p:

on ^{13}N: $\lambda_{p,\gamma} > \lambda_\beta$

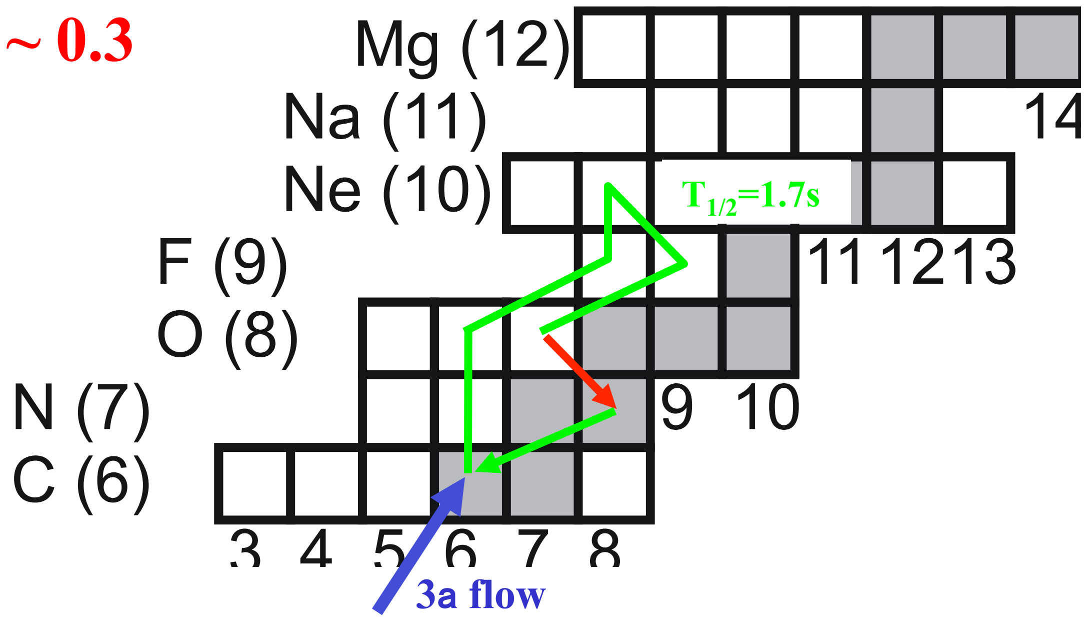
$\Leftrightarrow Y_p \rho N_A \langle \sigma v \rangle > \lambda_\beta$



Very Hot CN(O)-Cycle

$T_9 \sim 0.3$

still "beta limited"

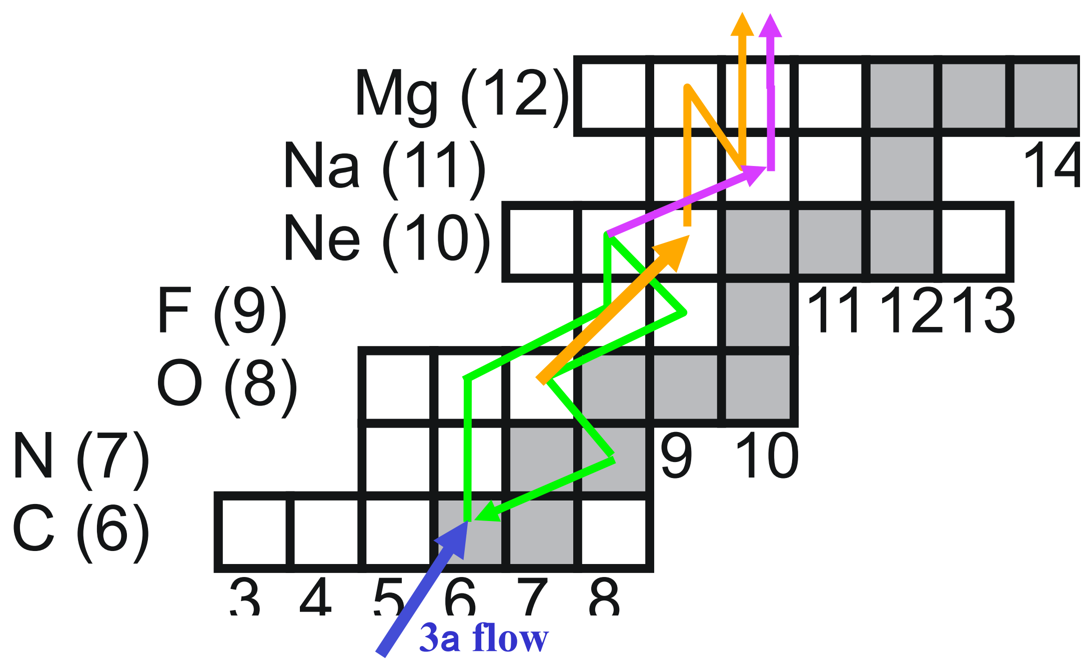


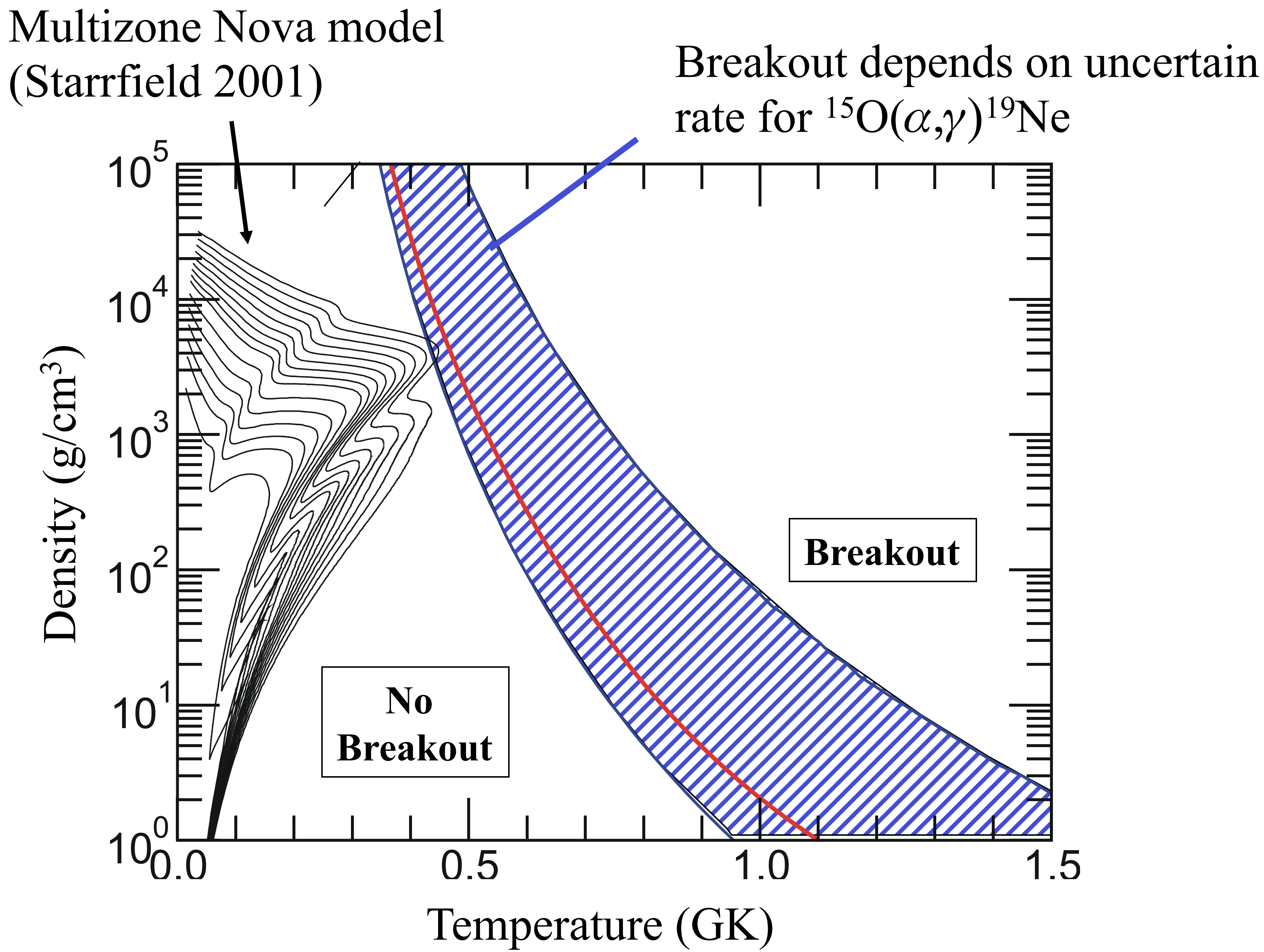
Breakout

processing beyond CNO cycle
after breakout via:

$T_9 >\sim 0.3$ $^{15}O(\alpha,\gamma)^{19}Ne$

$T_9 >\sim 0.6$ $^{18}Ne(\alpha,p)^{21}Na$





Multizone Nova model
(Starrfield 2001)
Breakout depends on uncertain rate for $^{15}O(\alpha,\gamma)^{19}Ne$
10^5
10^4
10^3
10^2
10^1
10^0
Density (g/cm^3)
0.0
0.5
1.0
1.5
Temperature (GK)
No Breakout
Breakout

One place where the β-limited CNO cycle is important is classical novae. Another is in x-ray bursts on neutron stars.

Classical Novae

- Distinct from "dwarf novae" which are probably accretion disk instabilities
- Thermonuclear explosions on accreting white dwarfs. Unlike supernovae, they recur, though generally on long (>1000 year) time scales.
- Rise in optical brightness by > 9 magnitudes
- Significant brightness change thereafter in < 1000 days
- Evidence for mass outflow from 100's to 5000 km s^{-1}
- Anomalous (non-solar) abundances of elements from carbon to sulfur

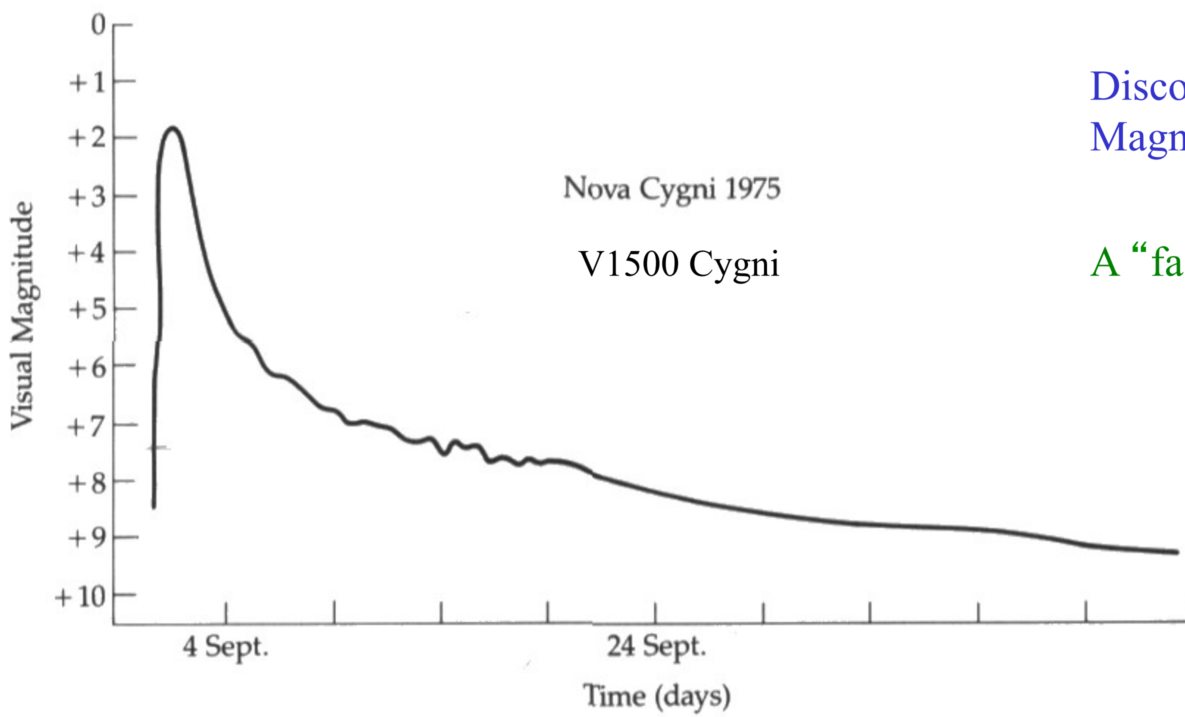
- Typically the luminosity rises rapidly to the Eddington luminosity for one solar mass (~10^{38} erg s^{-1}) and stays there for days (fast nova) to months (slow nova)

- In Andromeda (and probably the Milky Way) about 40 per year. In the LMC a few per year.

- Evidence for membership in a close binary –

0.06 days	(GQ-Mus 1983)
2.0 days	(GK Per 1901)

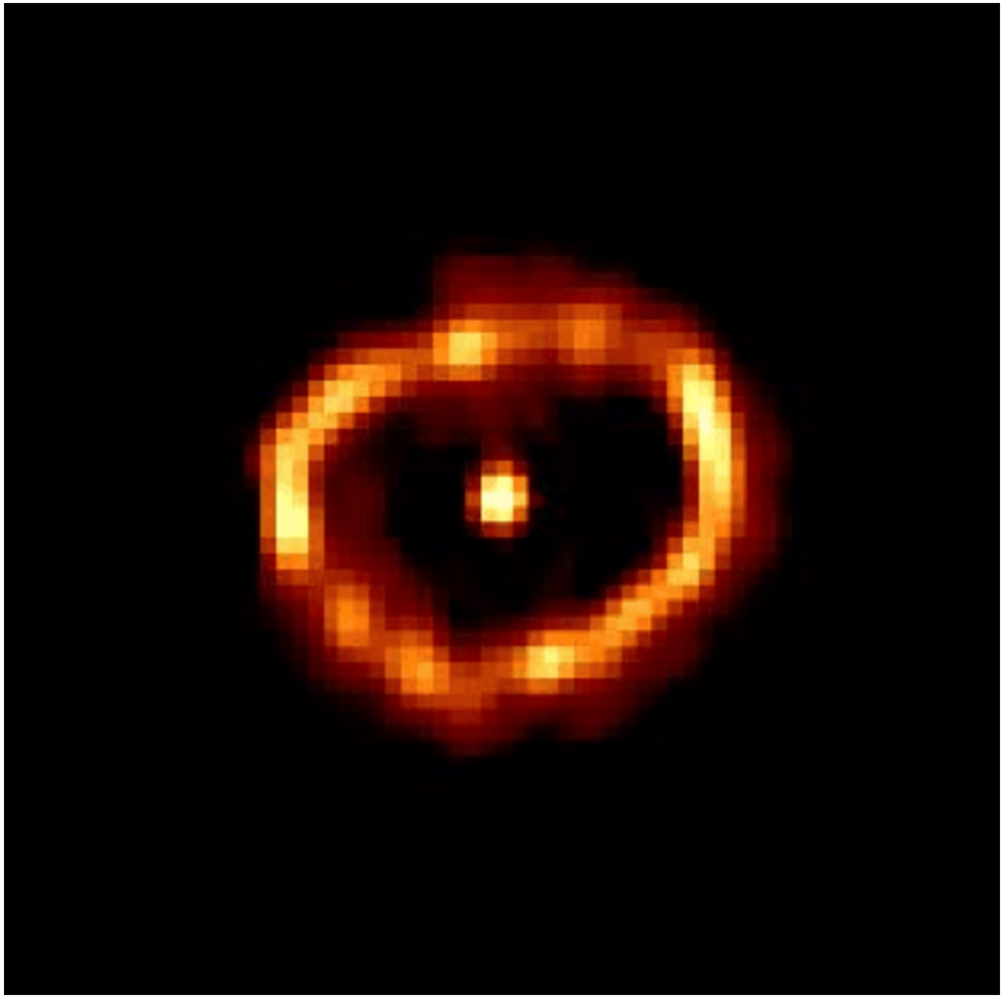
see Warner, *Physics of Classical Novae*, IAU Colloq 122, 24 (1990)



Discovery Aug 29, 1975
Magnitude 3.0

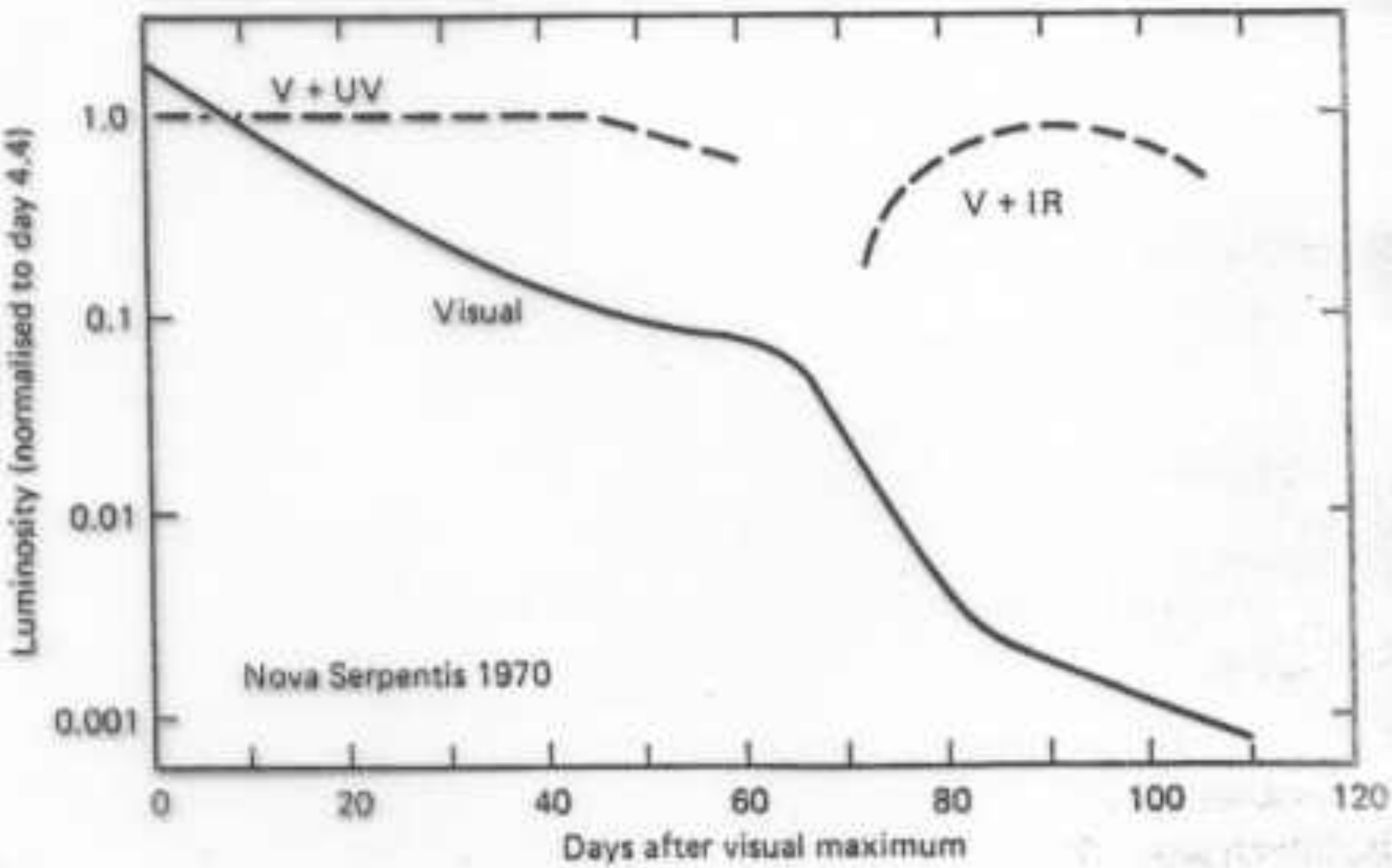
A "fast" nova

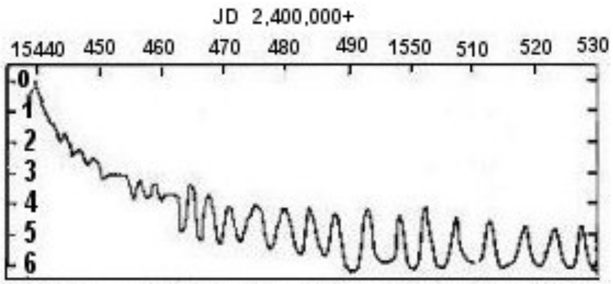
Nova Cygni 1992



The brightest recent nova.
Visible to the unaided eye (m = 4.4).
Photo at left is from HST in 1994.
Discovered Feb. 19, 1992.
Spectrum showed evidence
for ejection of large amounts
of neon, oxygen, and magnesium,

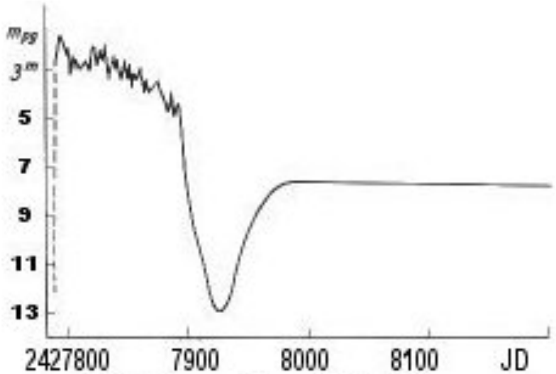
Fig. 4.1.2. The luminosity of the nova FH Serpentis as a function of time since its outburst. The visible light declined soon after outburst, to be replaced by ultraviolet radiation and later by infrared radiation. Thus the total (bolometric) luminosity of FH Ser remained high for several months (adapted from J. S. Gallagher & S. Starrfield, 1978, *Ann. Rev. Astr. Astrophys.*, 16, 171).





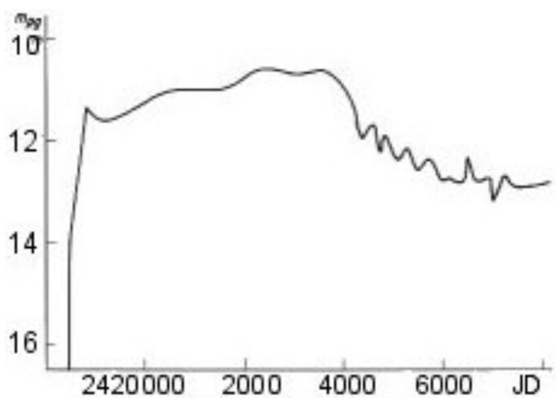
Light Curve of GK Persei from Feb 24, 1901 to May 25, 1901

Fast nova – rise is very steep and the principal display lasts only a few days. Falls > 3 mag within 110 days



Light Curve of Nova DQ Her from Dec 28, 1934 to Feb 1, 1936

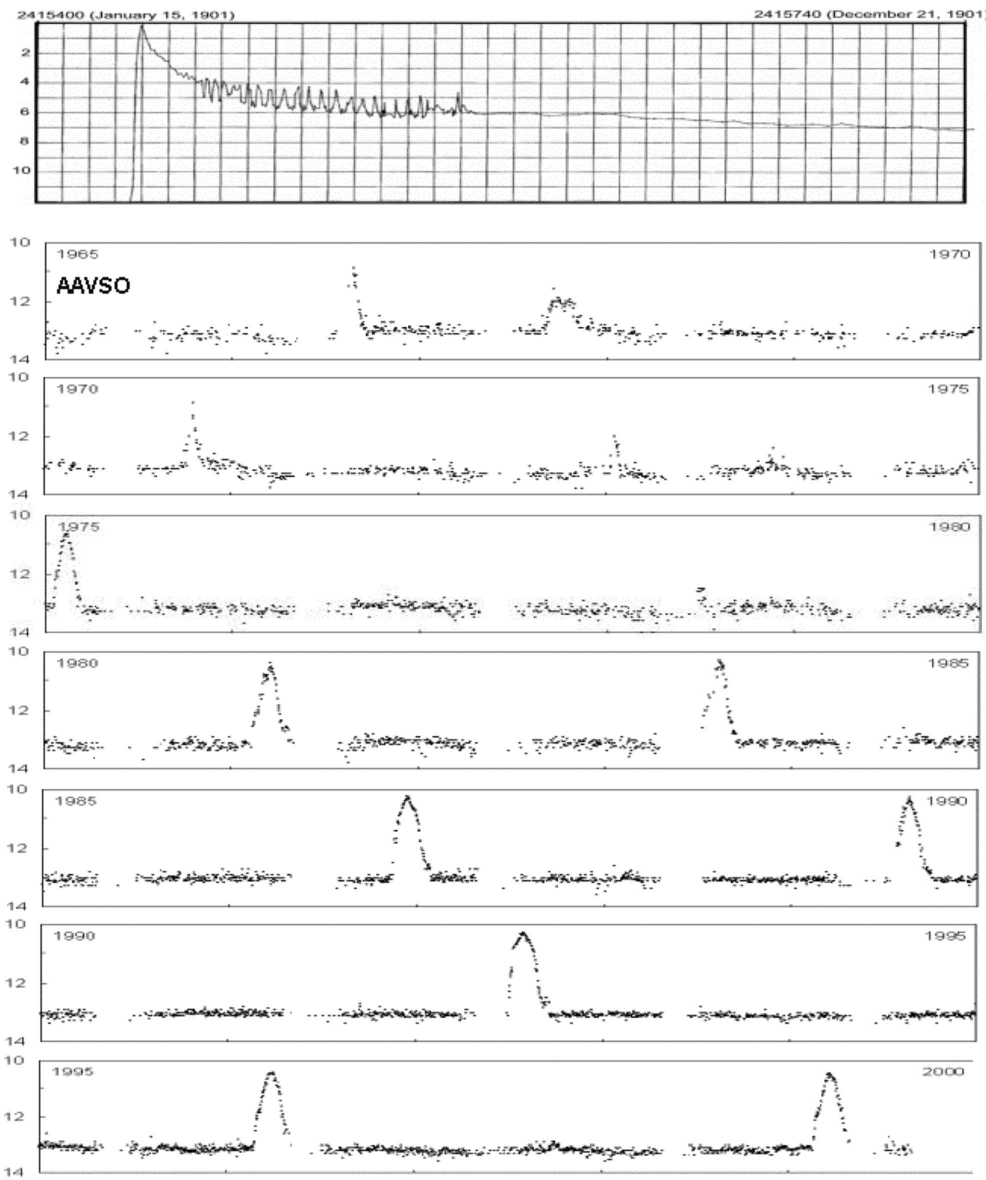
Slow nova – the decline by 3 magnitudes takes at least 100 days. There is frequently a decline and recovery at about 100 days associated with dust formation.



Light Curve of Nova RT Ser from the beginning of 1908 to July 16, 1935

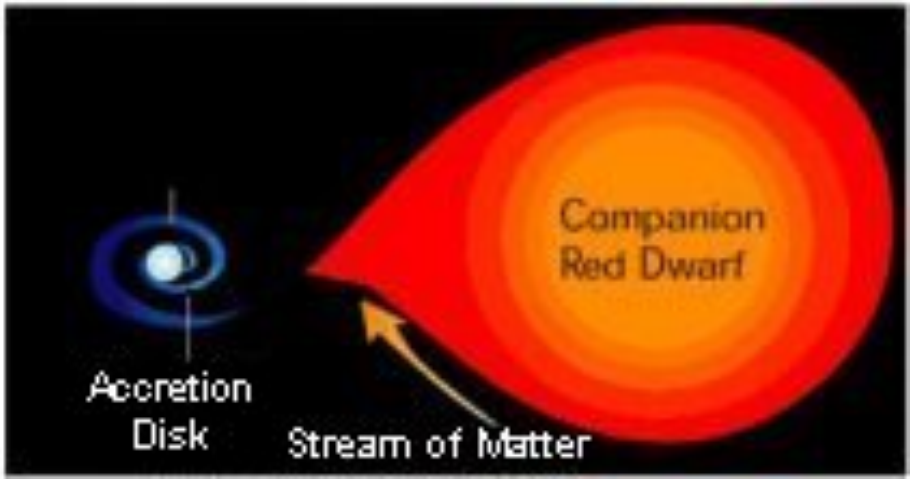
Very slow nova – display lasts for years.

GK Persei is a bright nova of 1901. In this close binary system, eruptions occur due to explosive nuclear burning, on the surface of the white dwarf, of material transferred from the red dwarf. GK Persei is unique in that after the initial fading of 30 days, the star showed semiperiodic rapid variations for three weeks and then slowly continued to fade. Decades later, it began having small dwarf nova-like outbursts about every three years.

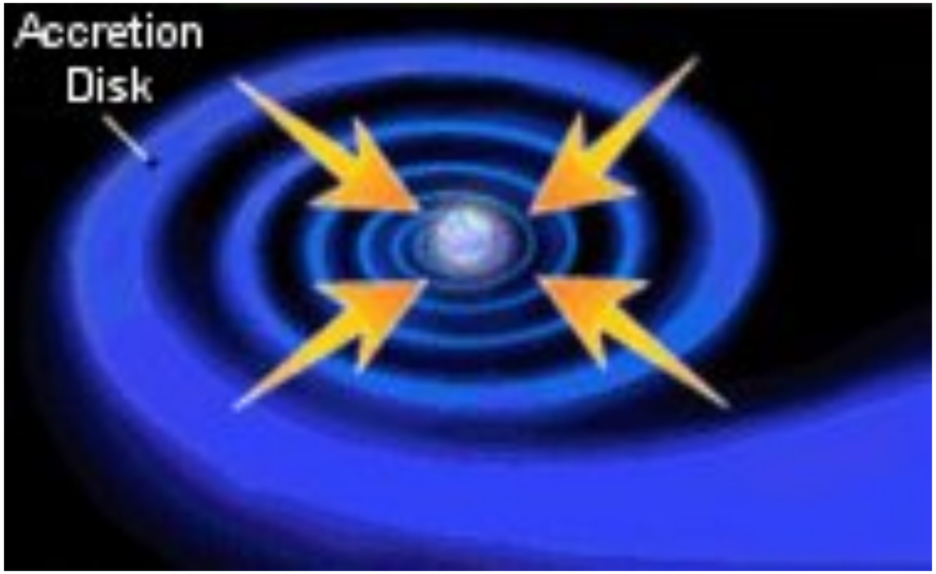


Effect of embedded companion star?

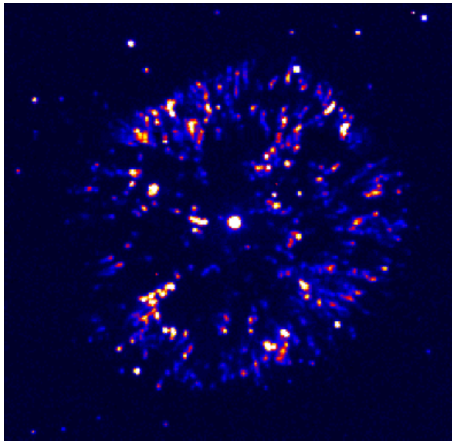
Recurrent novae – observed to recur on human time scales. Some of these are accretion disk instabilities



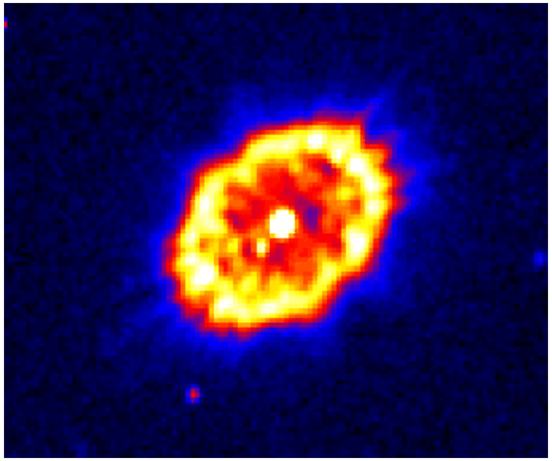
Red dwarf stars are very low mass main sequence stars



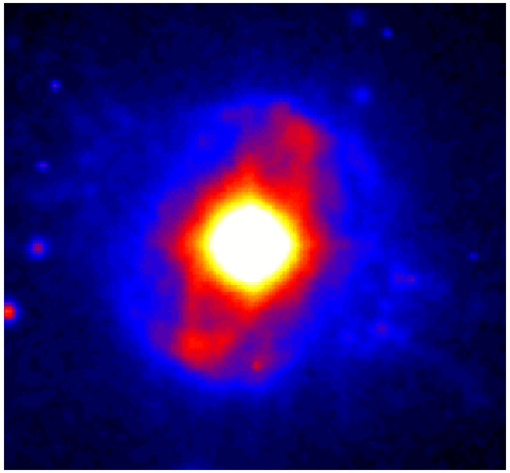
An earth mass or so is ejected at speeds of 100s to 1000s of km/s. Years later the ejected shells are still visible. The next page shows imgaes from a ground-based optical survey between 1993 and 1995 at the William Hershel Telescope and the Anglo-Australian Telescope.



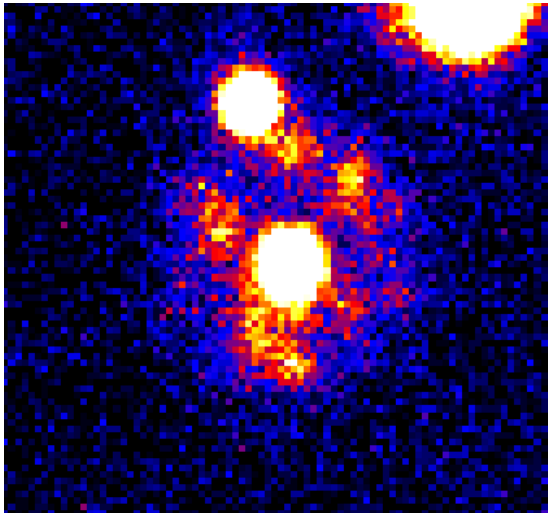
Nova Persei (1901)
GK Per



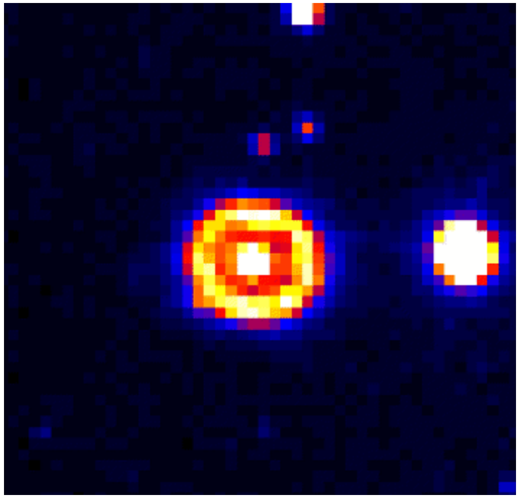
Nova Hercules (1934)
DQ - Her



Nova Pictoris (1927)
RR Pic



Nova Cygni (1975)
V1500 Cygni



Nova Serpentis (1970)
FH Ser

http://www.jb.man.ac.uk/~tob/novae/

Models

A white dwarf composedof either C and O ($< 1.06\ M_\odot$) or O, Mg, and Ne ($> 1.06\ M_\odot$) accretes hydrogen-rich material from a companion star at a rate of $10^{-9\pm1}\ M_\odot$ / yr

As the matter piles up, it becomes dense and hot. It is heated at its base chiefly by gravitational compression, though the temperature of the white dwarf itself may play a role.

Ignition occurs at a critical pressure of 2×10^{19} dyne cm^{-2} (Truran and Livio 1986); basically this is the condition that $T_{base} \sim 10^7$ K

This implies a certain critical mass since

$$i.e.,\quad \frac{dP}{dm} = \frac{GM}{4\pi r^4};$$

$$dm = 4\pi r^2 \rho\, dr$$

$$\Delta M_{ign} \approx \frac{4\pi P_{ign}}{G} \frac{R_{WD}^4}{M_{WD}} \sim 10^{-5}\text{-}10^{-4}\ M_\odot$$

Models

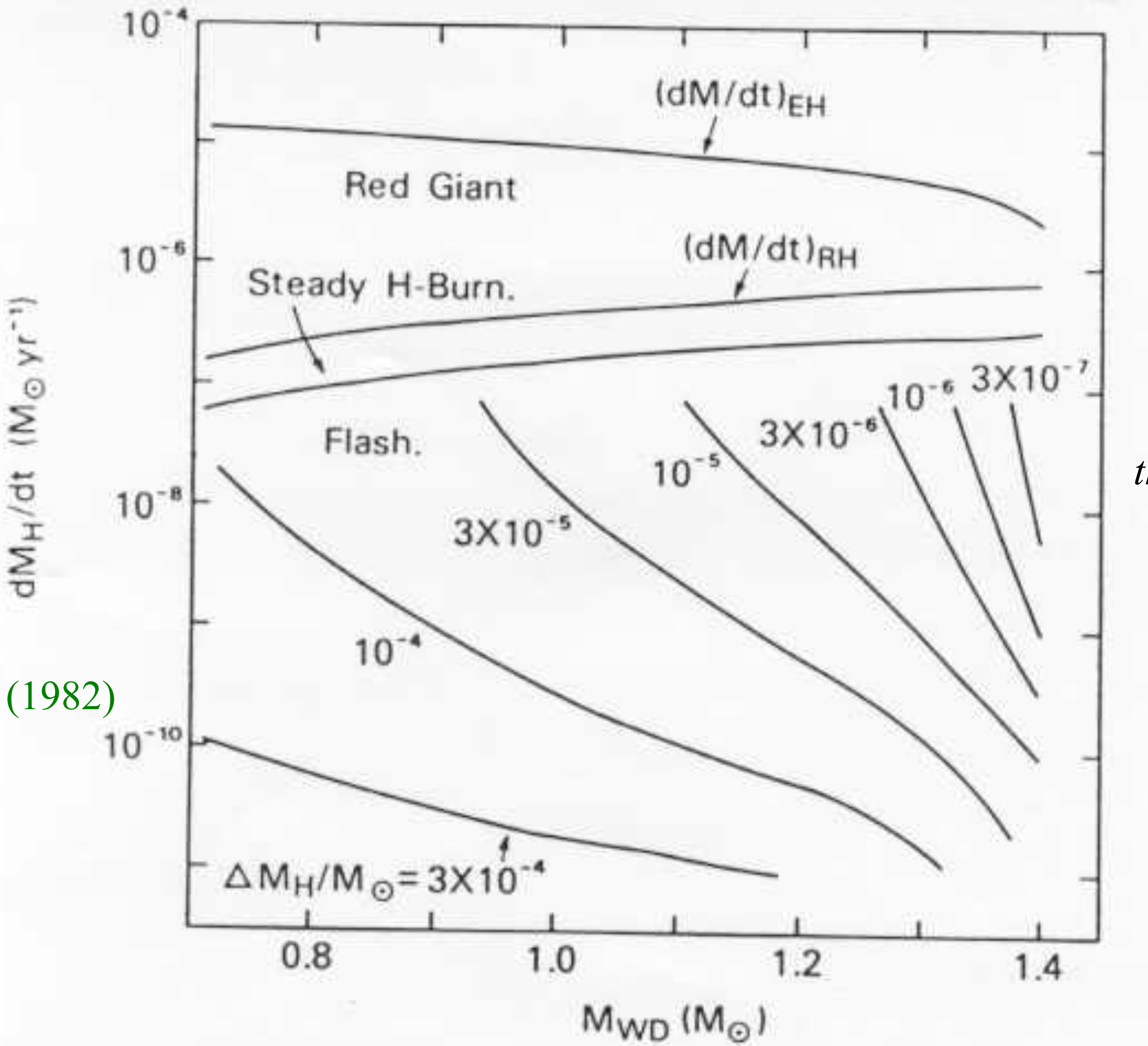
where we have used for the white dwarf radius:

$$R_{WD} \approx 8.5\times10^{8}\left[1.286\left(\frac{M_{WD}}{M_{\odot}}\right)^{-2/3} - 0.777\left(\frac{M_{WD}}{M_{\odot}}\right)^{2/3}\right]^{1/2} \text{cm}$$

Approximately,
$R \propto M^{-1/3}$

Eggleton (1982) as quoted in Politano et al (1990)

This gives a critical mass that decreases rapidly (as $M^{-7/3}$) with mass. Since the recurrence interval is this critical mass divided by the accretion rate, bursts on high mass white dwarfs occur more frequently



For a given accretion rate the critical mass is smaller for larger mass white dwarfs

Nomoto (1982)

The mass of the accreted hydrogen envelope at the time the hydrogen ignites is a function of the white dwarf mass and accretion rate.

Truran and Livio (1986)
using Iben (1982) – lower limits
especially for high masses

Mass WD	Interval (10^5 yr)
0.60	12.9
0.70	7.3
0.80	4.2
0.90	2.4
1.00	1.2
1.10	0.64
1.20	0.28
1.30	0.09
1.35	0.04

Even though the average mass white dwarf is 0.6 – 0.7 solar masses the most often observed novae have masses around 1.14 solar masses.

These would be white dwarfs composed of Ne, O, and Mg. It is estimated that ~ 1/3 of novae, by number, occur on NeOMg WDs even though they are quite rare.

see also Ritter et al, ApJ, 376, 177, (1991)

Politano et al (1990) in *Physics of Classical Novae*

For typical values:

$$\mathrm{M_{WD}} = 1.0\ \mathrm{M_\odot}$$

$$R_{WD} \approx 5500\,\mathrm{km}$$

Accreted layer $\Delta\mathrm{R} \approx 150\ \mathrm{km}$

$$\Delta M \approx \frac{4\pi R^4 P_{crit}}{GM} = 7\times10^{-5}\ M_\odot$$

$$\bar{\rho} \sim \frac{\Delta M}{4\pi R^2 \Delta R} \sim 3000\ \mathrm{g\ cm^{-3}}$$

Partially degenerate at 10^7 K

Nature of the burning:

Confusing statements exist in the literature. A nova is not a degenerate flash that happens in seconds and then is over (like a SN Ia). The ignition is partly degenerate but actually resembles a thin shell instability more than a nuclear runaway. So long as the radius of the center of mass of the burning layer does not increase dramatically, the pressure at the base stays constant. Some expansion occurs but not enough to put the burning out. At constant P, when density goes down, T goes up.

So the hydrogen continues to burn for a long time, dredging up C and O as it proceeds. Hydrostatic equilibrium maintains the luminosity at near the Eddington value. Matter is lost as a “super-wind”, not as a blast wave.

The dredge up of C and O is very important to the energetics and nucleosynthesis

For the beta-limited CNO cycle

$$\varepsilon_{nuc} = 5.9 \times 10^{15}\ \mathrm{Z\ \ erg\ g^{-1}\ s^{-1}} \qquad \mathrm{Z} \sim 0.01 - 0.1$$

for $\mathrm{M} = 10^{-5}\,\mathrm{M}_{\odot};\ \mathrm{Z} = 0.01$

$$L = \varepsilon_{nuc}\, M \sim 10^{42}\ \mathrm{erg\ s^{-1}}$$

So the initial flash is quite super-Eddington, but that drives convection and expansion until a smaller region is burning and $\mathrm{L} \sim 10^{38} - 10^{39}\ \ \mathrm{erg\ s^{-1}}$.

The binding energy per gram of material at the white dwarf edge is about

$$\frac{GM}{R} \approx \frac{(6.67E-8)(2E33)}{5E8} \approx 2 \times 10^{17} \text{ erg gm}^{-1}$$

So to eject e.g., 3 x 10^{-5} solar masses takes about 10^{46} erg. The kinetic energy (e.g., 1000 km/s) is about 10^{45} The integral of the Eddington luminosity for 10^7 s is also about 10^{45} erg. So the binding energy dominates the energy budget ad the light and kinetic energy are a small fraction of that.

In some cases common envelope effects may also be important. The companion star is inside the nova.

Nucleosynthesis in Novae

Basically ^{15}N and ^{17}O

The mass fraction of both in the ejecta is ~0.01, so crudely …

$$M_{nova}(^{15}\mathrm{O}) \sim (0.01)(3\times10^{-5})(30)(10^{10}) \sim 10^5\, M_\odot$$

Woosley (1986)

$$X_{\mathrm{Pop\ I}}(^{15}\mathrm{N}) \sim 10^5 / \underbrace{3\times10^{10}} \sim 4\times10^{-6} \approx \text{the solar mass fraction}$$

approximate Pop I material in the Galaxy within solar orbit

of ^{15}N and ^{17}O in the sun.

Novae also make interesting amounts of ^{22}Na and ^{26}Al for gamma-ray astronomy

Heavy Element Abundances in Classical Novae

			Mass Fractions											
Object	Year	Ref.	H	He	C	N	O	Ne	Na	Mg	Al	Si	S	Fe
RR Pic	1925	1	0.53	0.43	0.0039	0.022	0.0058	0.011						
HR Del	1967	2	0.45	0.48		0.027	0.047	0.0030						
T Aur	1891	3	0.47	0.40		0.079	0.051							
PW Vul	1984	4	0.49	0.23	0.064	0.12	0.093	0.0019		0.00027		0.0058		0.00092
PW Vul	1984	5	0.69	0.25	0.0033	0.049	0.014	0.00066						
V1500 Cyg	1975	6	0.49	0.21	0.070	0.075	0.013	0.023						
V1668 Cyg	1978	7	0.45	0.23	0.047	0.14	0.013	0.0068						
V693 CrA	1981	8	0.29	0.32	0.0046	0.080	0.12	0.17	0.0016	0.0076	0.0043	0.0022		
GQ Mus	1983	9	0.27	0.32	0.016	0.19	0.19	0.0034		0.0014	0.00056	0.0028	0.0016	0.00047
DQ Her	1934	10	0.34	0.095	0.045	0.23	0.29							
V1370 Aql	1982	11	0.053	0.088	0.035	0.14	0.051	0.52		0.0067		0.0018	0.10	0.0045
QU Vul	1984	12	0.30	0.59	0.0010	0.021	0.041	0.044		0.0017	0.0021	0.00039		

References.—(1) Williams & Gallagher 1979. (2) Tylenda 1978. (3) Gallagher et al. 1980. (4) Andreae & Drechsel 1990. (5) Saizar et al. 1991. (6) Ferland & Shields 1978. (7) Stickland et al. 1981. (8) Williams et al. 1985. (9) Hassal et al. 1990. (10) Williams et al. 1978. (11) Snijders et al. 1987. (12) Saizar et al. 1992.

Some issues

- Burning is not violent enough to give fast novae unless the accreted layer is significantly enriched with CNO prior to or early during the runaway.

Shear mixing during accretion

Convective “undershoot” during burst

- Understanding luminosity – speed classes. Fast novae are brighter.

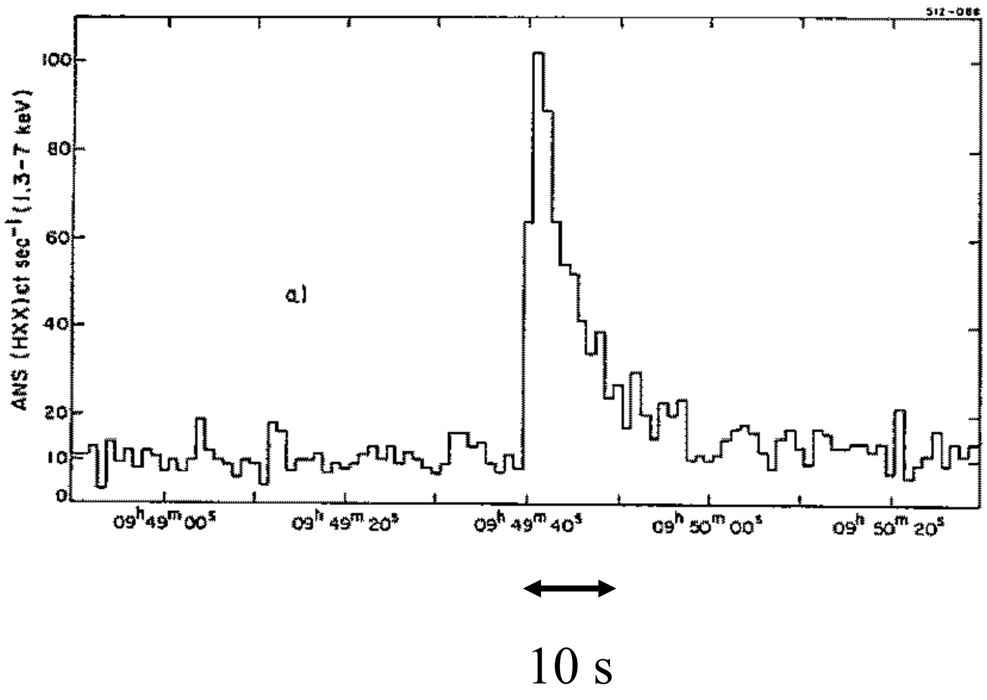
- Relation to Type Ia supernovae. How to grow M_{WD} when models suggest it is actually shrinking?

Kercek + Hillebrandt (1998)

Nova 3D

Type I X-Ray Bursts

First **X-ray burst**: 3U 1820-30 (Grindlay et al. 1976) with ANS (Astronomical Netherlands Satellite)



Type I X-Ray Bursts

(e.g., Strohmayer & Bildsten 2003)

- Burst rise times < 1 s to 10 s
- Burst duration 10's of seconds to minutes (some much longer "superbursts")
- Occur in low mass x-ray binaries
- Persistent luminosity from <0.01 Eddington to 0.2 Eddington (i.e., 10^{36}- 10^{38} erg s^{-1})
- Spectrum softens as burst proceeds. Spectrum thermal. A cooling blackbody
- $L_{peak} < 4 \times 10^{38}$ erg s^{-1}. i.e., about Eddington. Evidence for radius expansion in some bursts. T initially 3 keV, decreases to 0.5 keV, then gets hotter again.

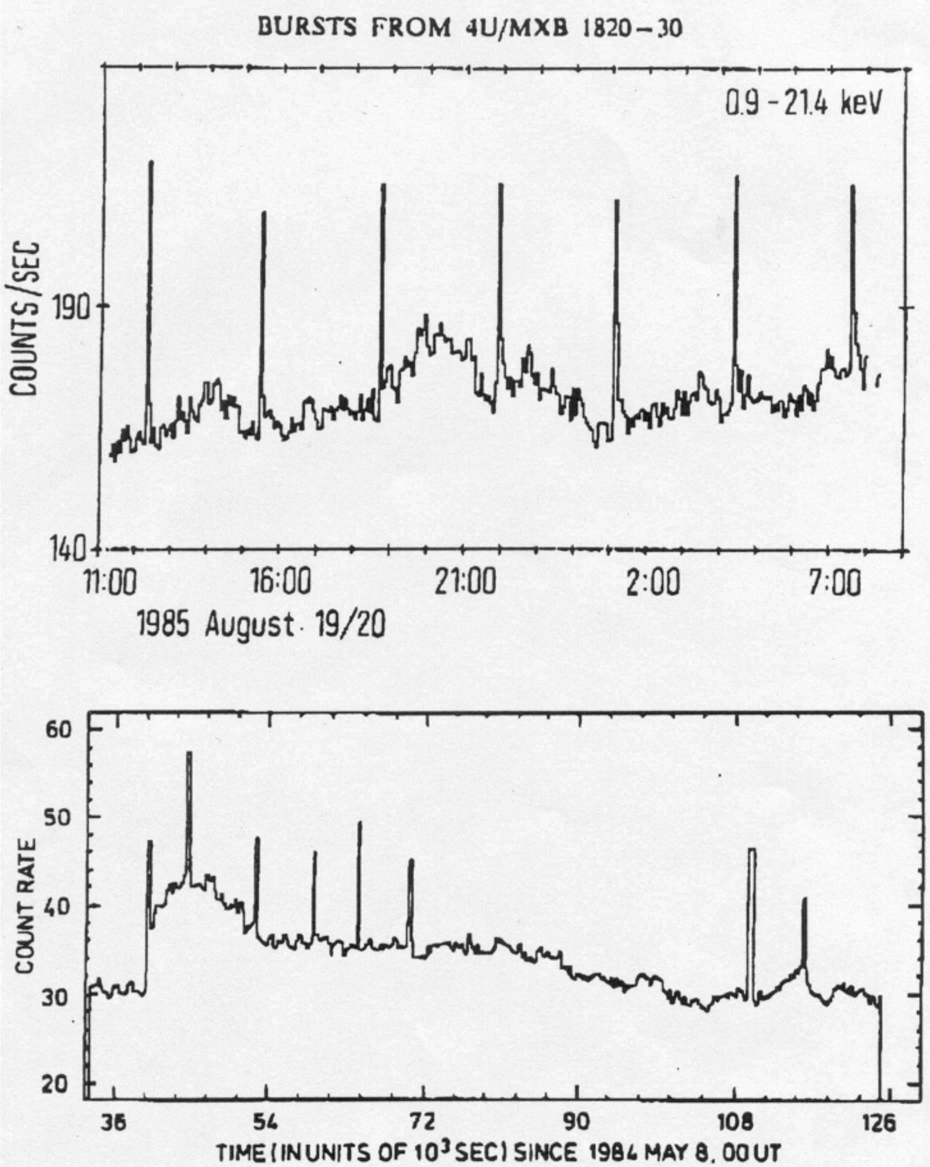
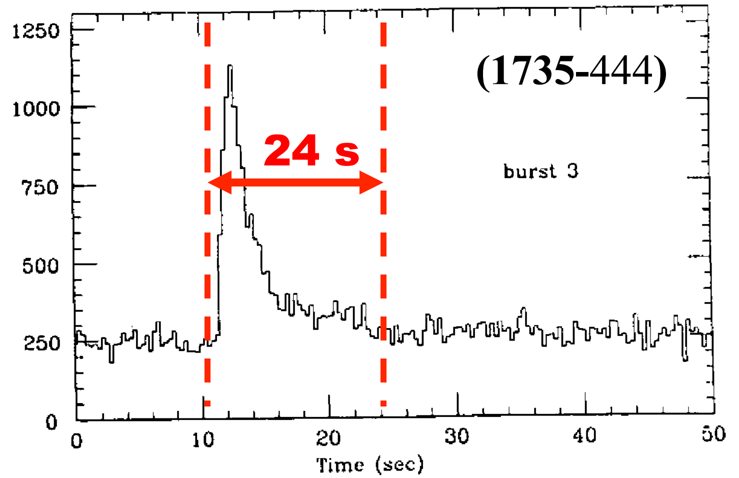


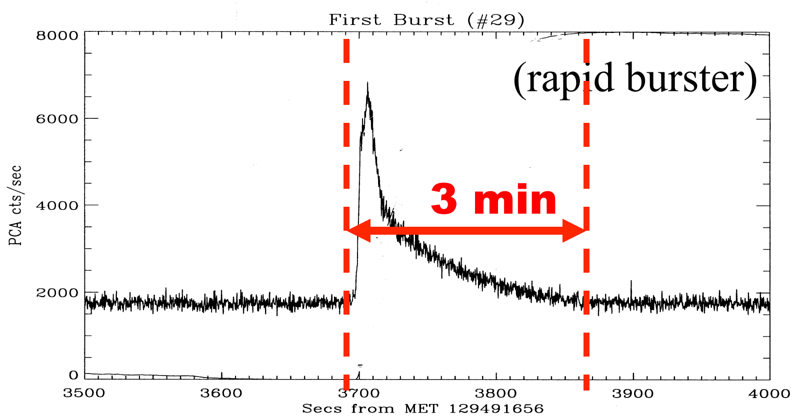
Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

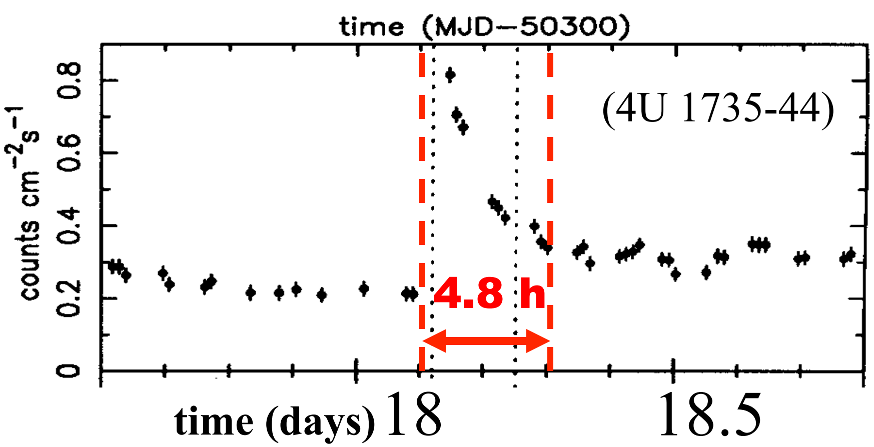
<u>Typical X-ray bursts:</u>

- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon !







<u>Normal type I bursts:</u>

- duration 10-100 s
- ~10^{39} erg

<u>Superbursts:</u>

(discovered 2001, so far 7 seen in 6 sources)

- ~10^{43} erg
- rare (every 3.5 yr ?)

- Of 13 known luminous globular cluster x-ray sources, 12 show x-ray bursts. Over 70 total X-ray bursters were known in 2002.

- Distances 4 – 12 kpc. Two discovered in M31 (Pietsch and Haberl, *A&A,* **430**, L45 (2005).

- Low B-field $< 10^{8\text{-}9}$ gauss

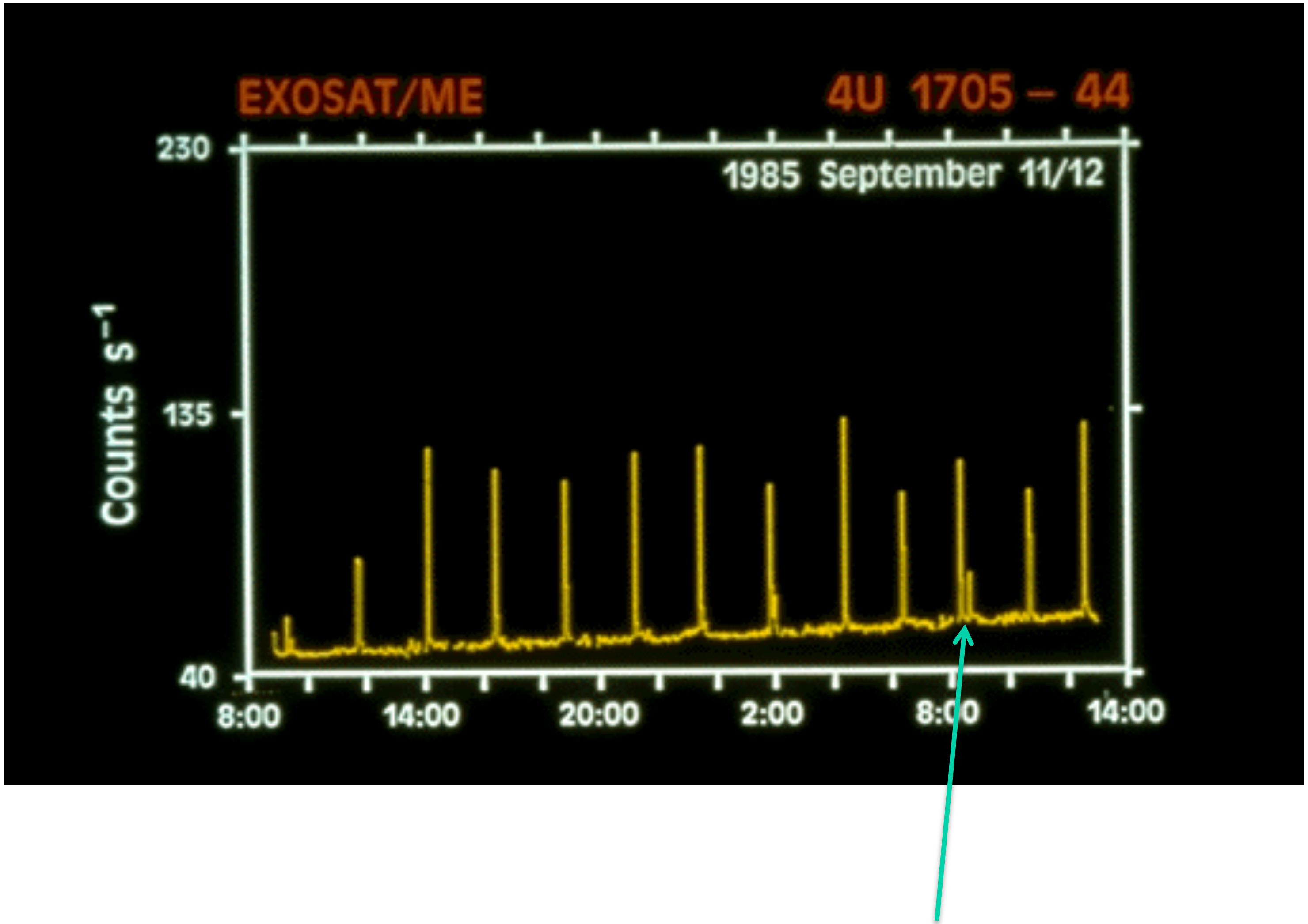
- Rapid rotation (at break up? due to accretion?). In transition to becoming ms pulsars?

- Very little mass lost (based upon models). Unimportant to nucleosynthesis

- Back-of-the envelope calculation:

$E_{burst} \sim 10^{39}$ erg;
$E_{nuclear} \sim 1$ MeV/nucleon
($\sim 10^{18}$ erg/g)
$\Rightarrow$ fuel $\Delta M \sim 10^{21}$ g;
for $\dot{M} \sim 10^{-10}$ to 10^{-9} $M_\odot$/yr
$\Rightarrow$ $t_{recur} \sim$ hrs–days

But 1 MeV/nucleon << BE at edge of neutron star
(~200 MeV/nucleon)



EXOSAT/ME
4U 1705 – 44
1985 September 11/12
Counts s^{-1}
230
135
40
8:00
14:00
20:00
2:00
8:00
14:00

say what?

X-ray burst theory predicts (at least) two regimes of burning:

1) intermediate accretion rates;
$2 \times 10^{-10}\, M_\odot\, yr^{-1} \lesssim \dot{M} \lesssim 4\text{–}11 \times 10^{-10}\, M_\odot\, yr^{-1}$:
pure He shell ignition after steady H burning

2) high accretion rates;
$4\text{–}11 \times 10^{-10}\, M_\odot\, yr^{-1} \lesssim \dot{M} \lesssim 2 \times 10^{-8}\, M_\odot\, yr^{-1}$:
mixed H/He burning triggered by thermally unstable He ignition

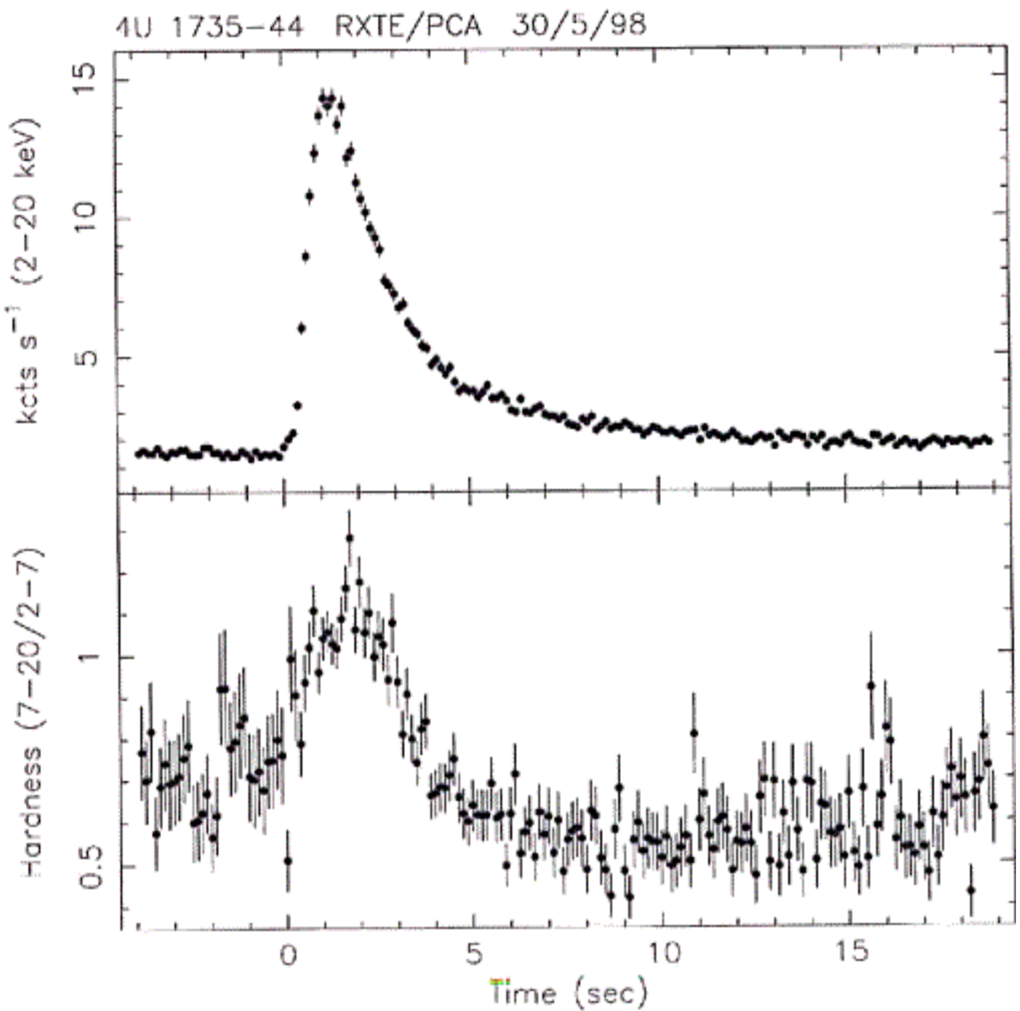
During pure helium flashes the fuel is burned rapidly; they last only

~5-30 s

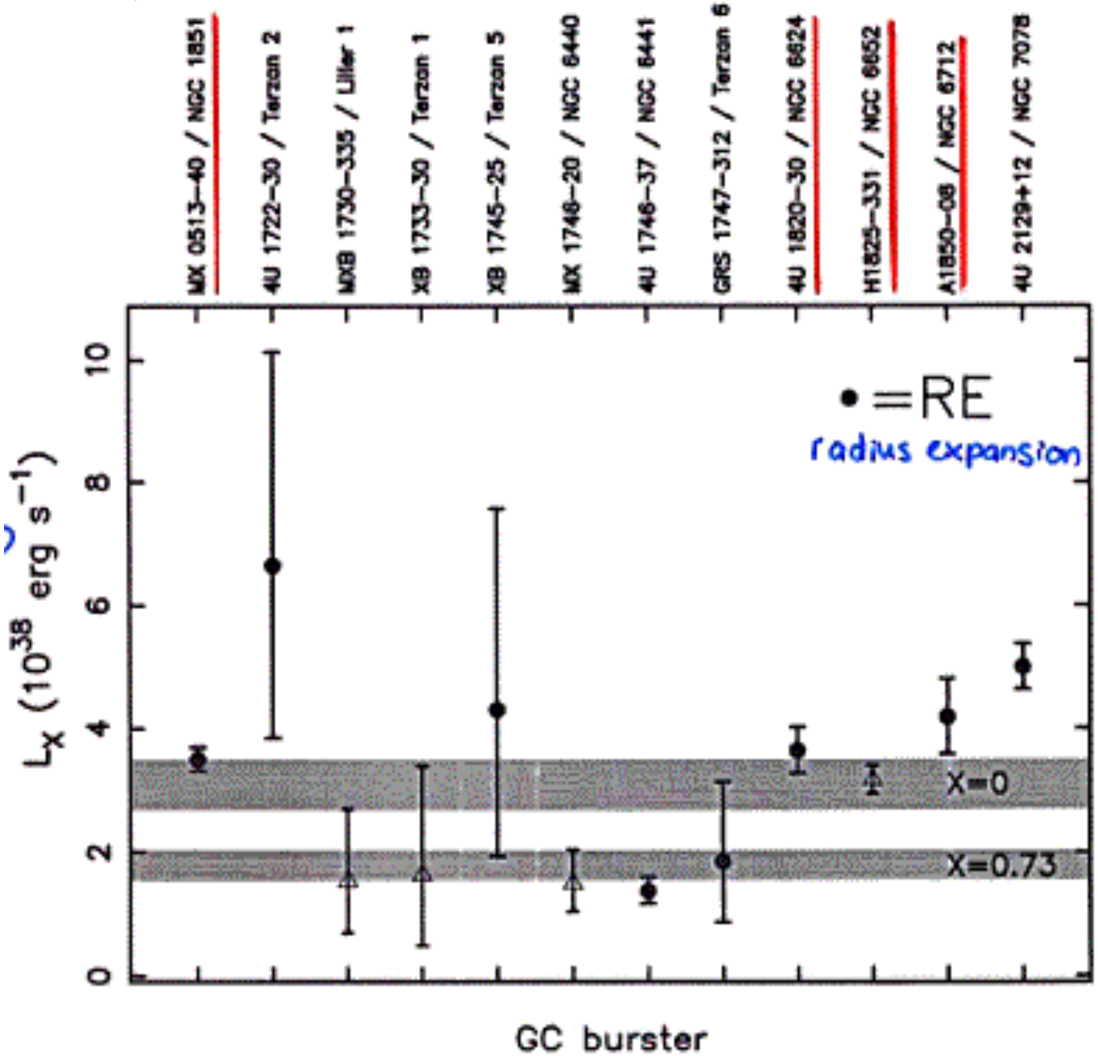
Bursts with unstable mixed H/He burning release their energies on a longer, 10–100 s, timescale, due to the long series of β decays in the rp-process

Medium mass accretion rates: 4U 1735−44

- Fast rise (∼1 sec) + fast decay (<10 sec) ⇒ pure He flash

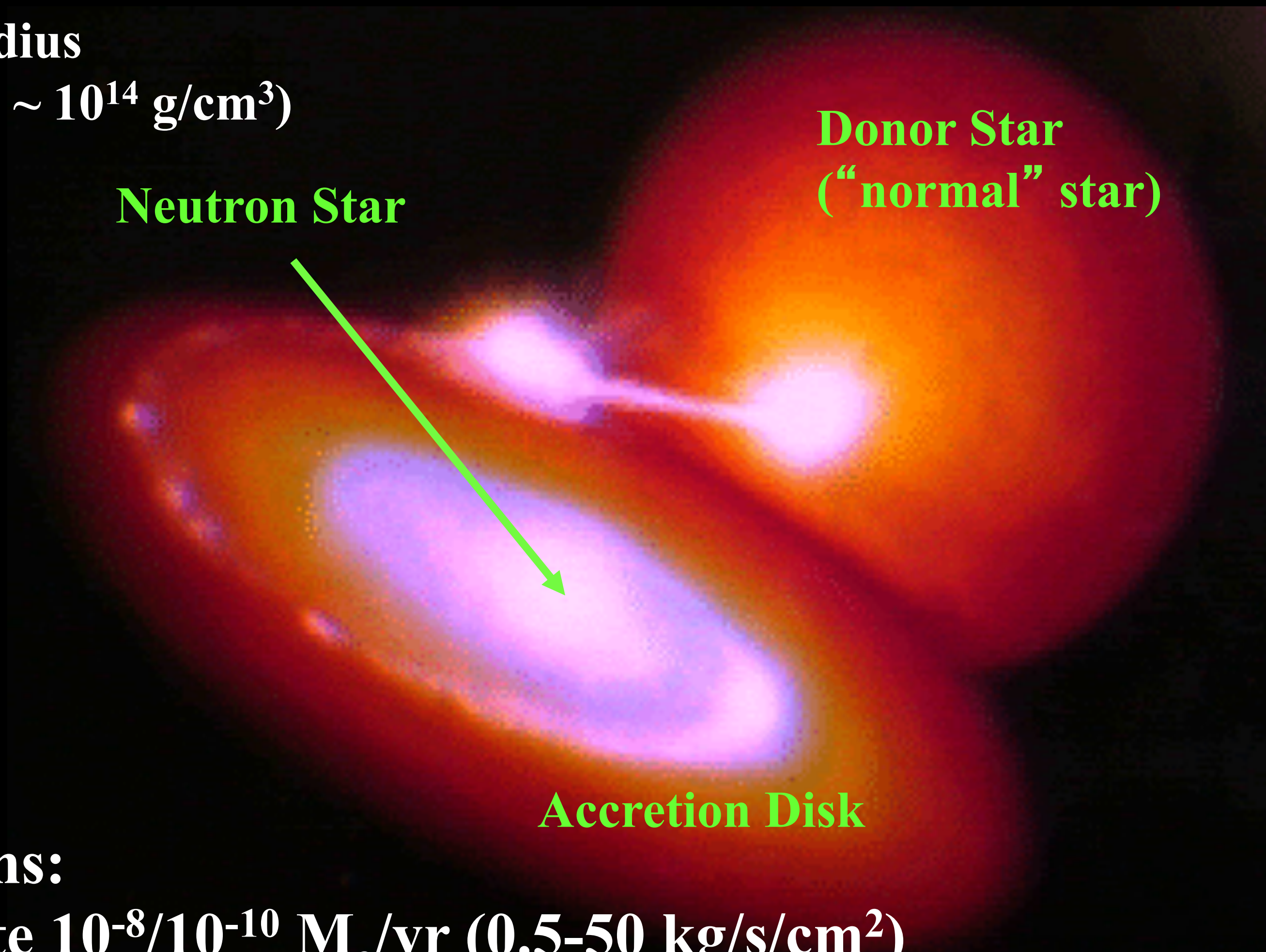


Radius expansion is also inferred from a decrease in T_{eff} at constant L, but some of the L's themselves are super-Eddington



The Model

Neutron stars:
1.4 M_o, 10 km radius
(average density: ~ 10^{14} g/cm^3)

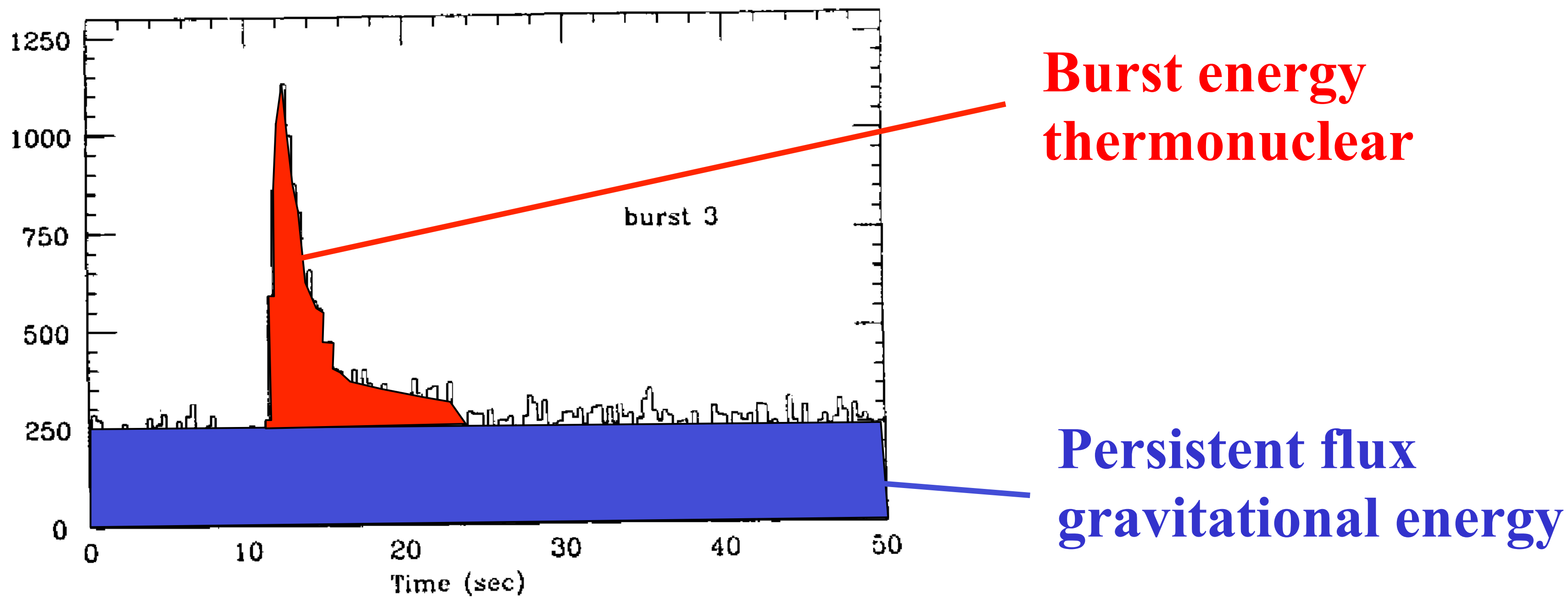


Typical systems:

- **accretion rate $10^{-8}/10^{-10}$ M_o/yr (0.5-50 kg/s/cm^2)**
- **orbital periods 0.01-100 days**
- **orbital separations 0.001-1 AU's**

Observation of thermonuclear energy:

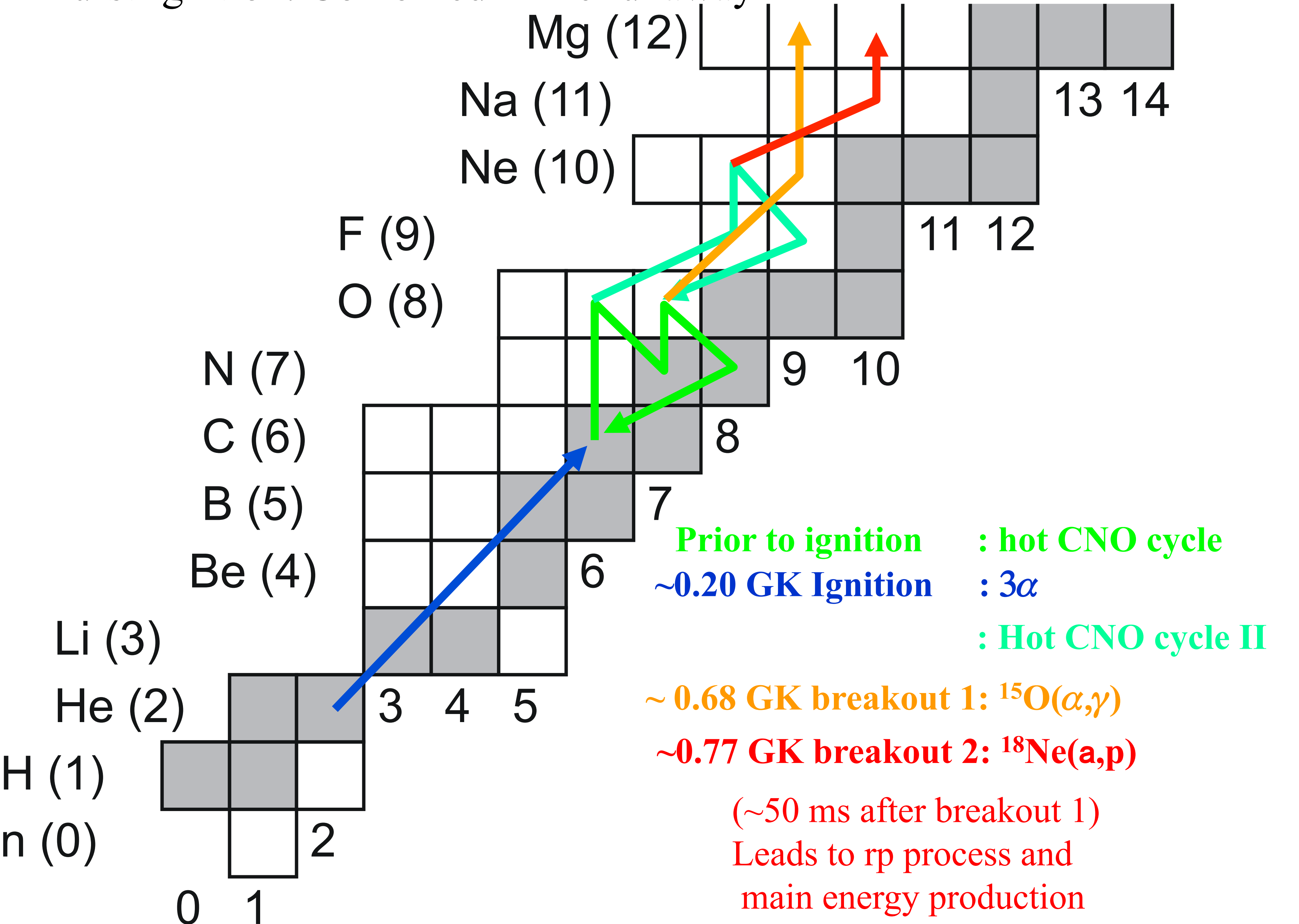
Unstable, explosive burning in bursts (release over short time)



$$\frac{\textit{Gravitational energy}}{\textit{Nuclear energy}} \sim 30 - 40$$

Very little matter if any is ejected by a x-ray burst. Nucleosynthetically sterile.

Burst Ignition: Combined H-He runaway



Models: Typical reaction flows

Schatz et al. 2001 (M. Ouellette) Phys. Rev. Lett. 68 (2001) 3471

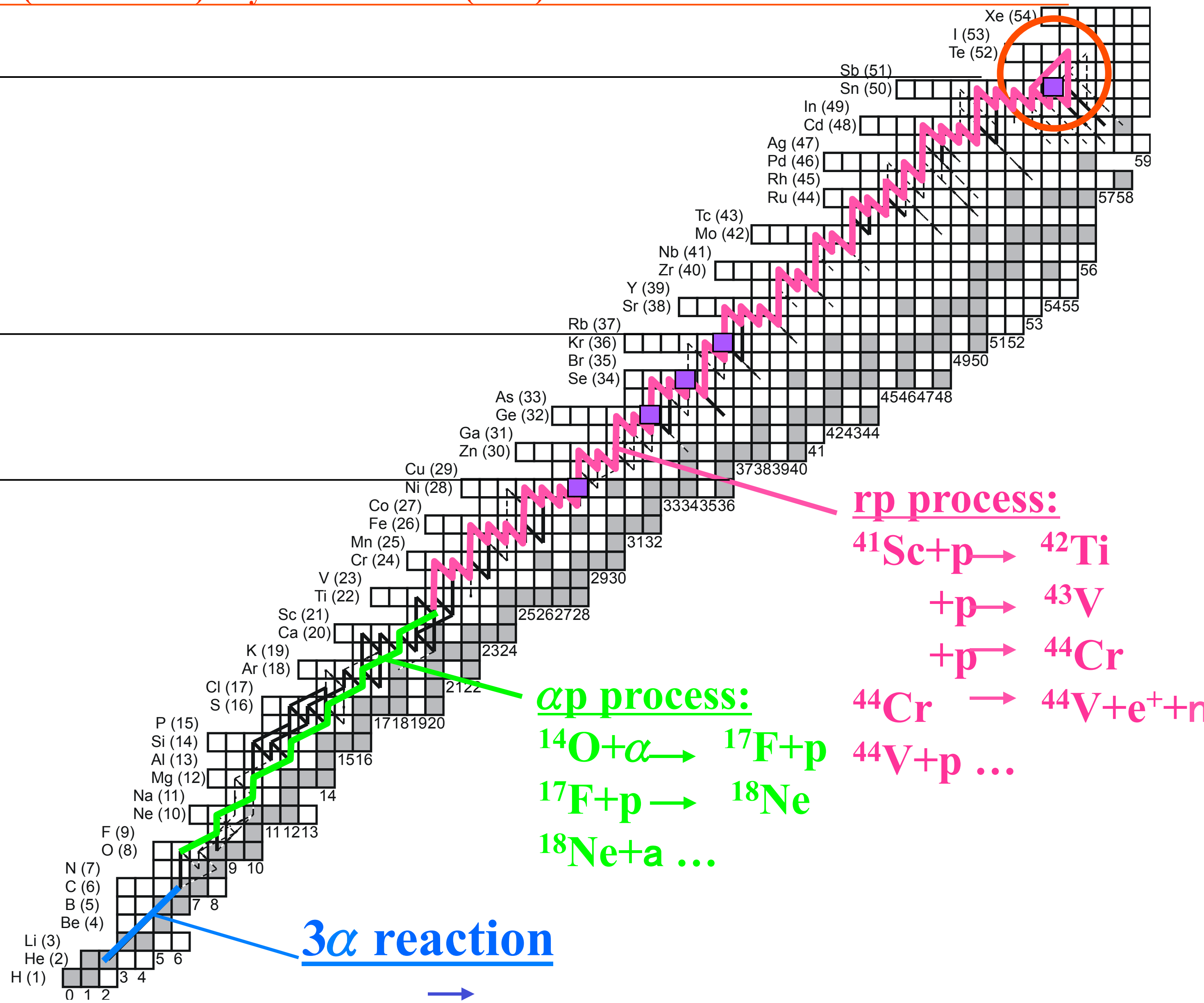
Schatz et al. 1998

Wallace and Woosley 1981

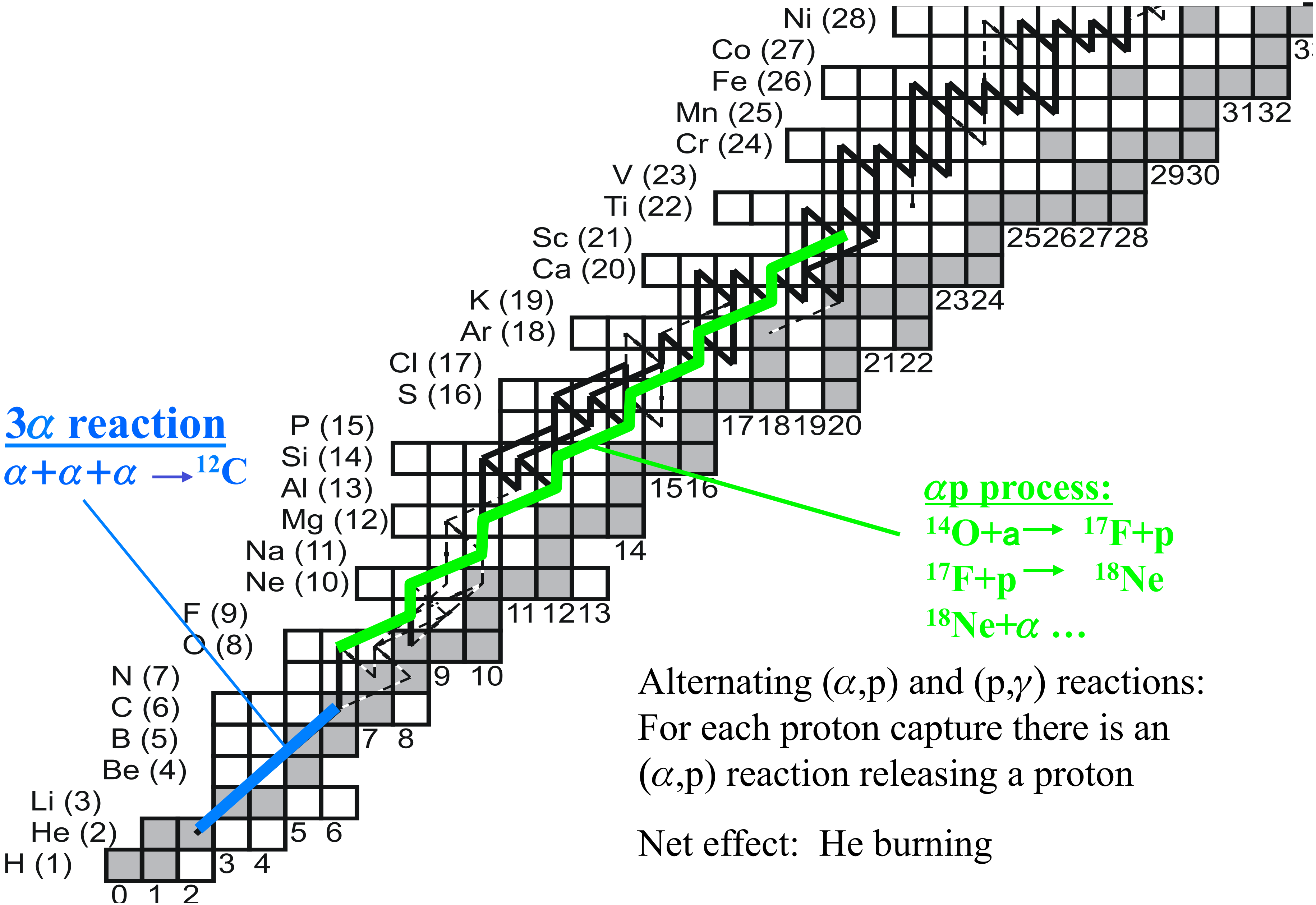
Hanawa et al. 1981

Koike et al. 1998

etc



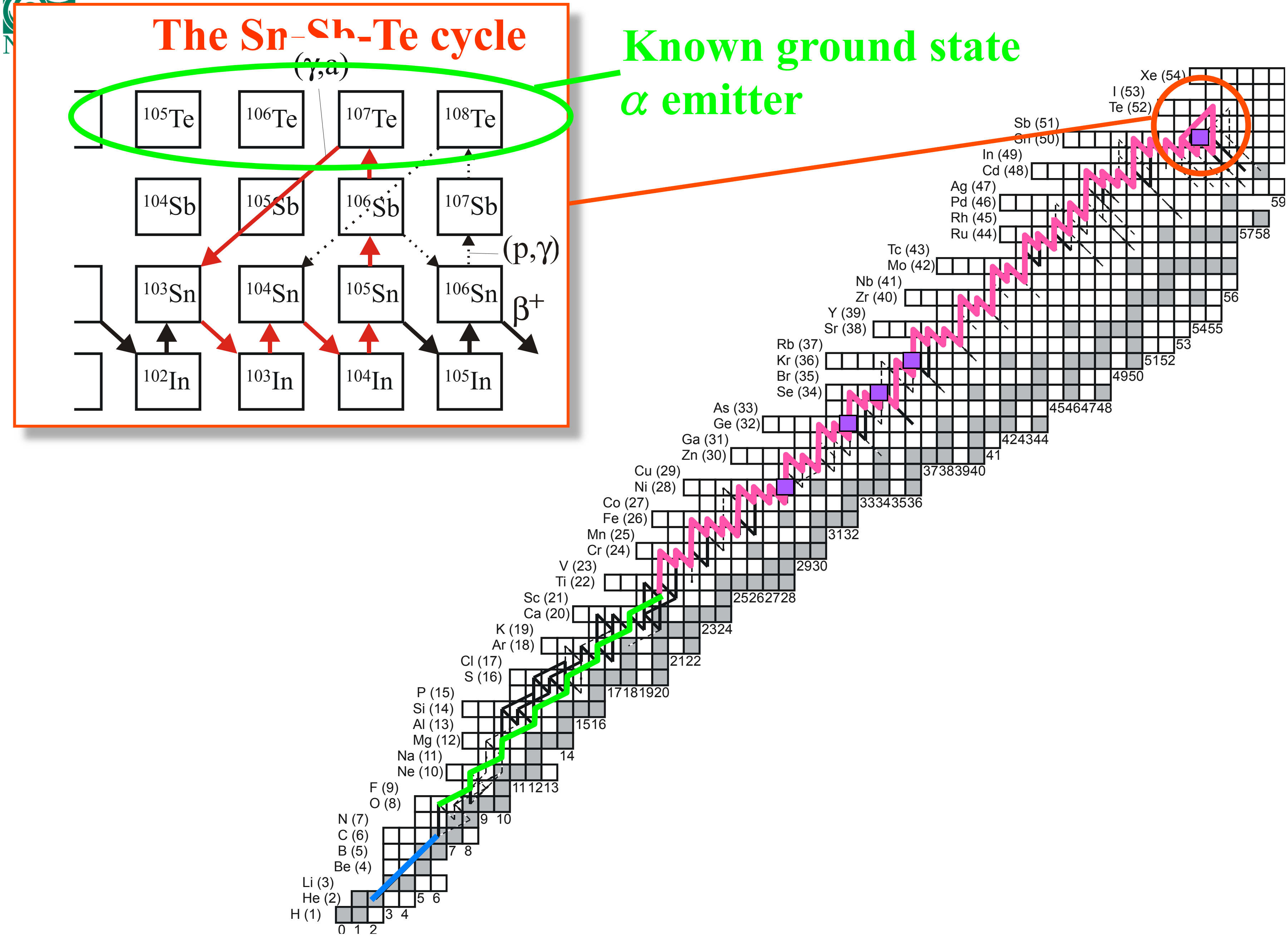
At still higher T: αp process

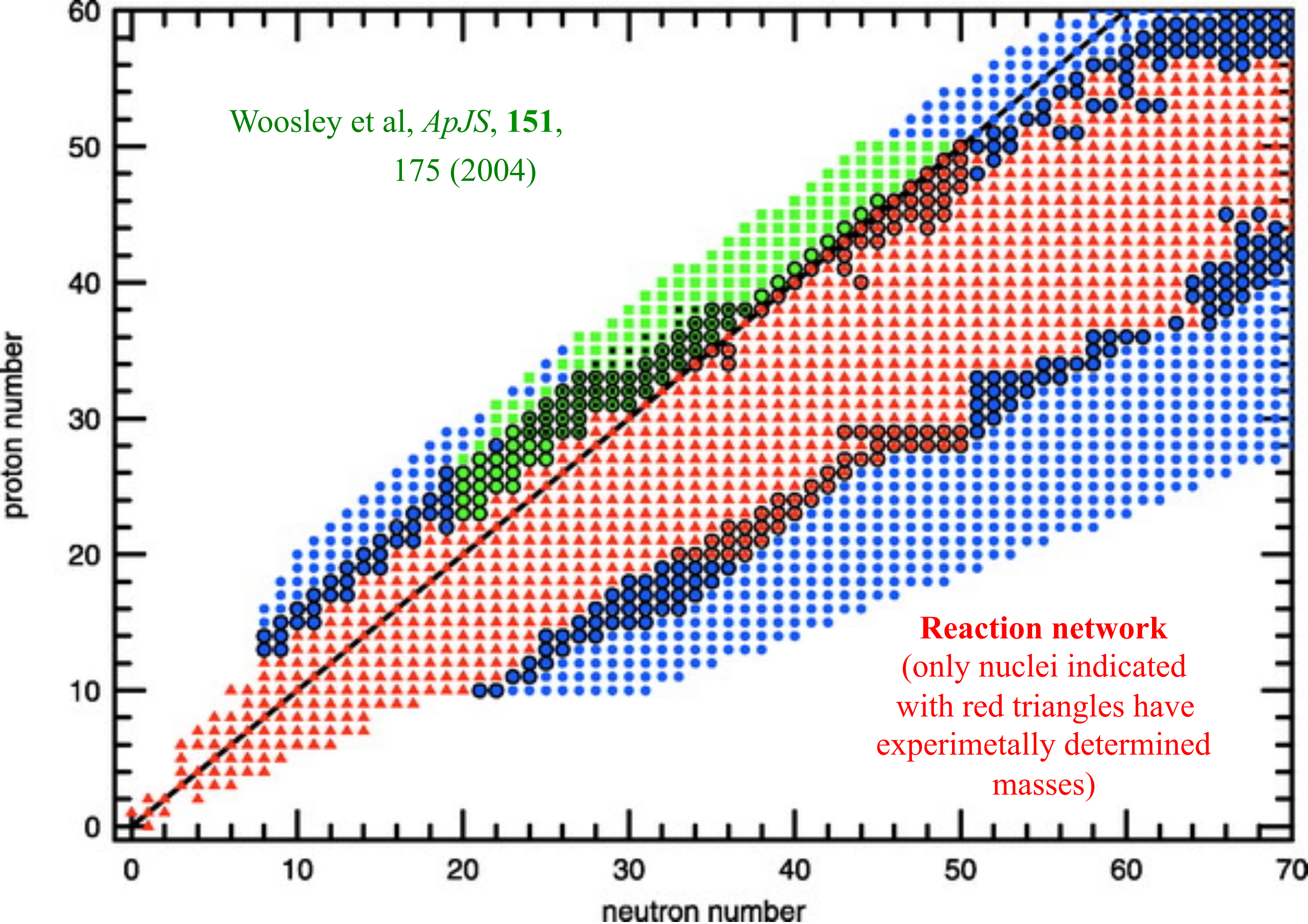


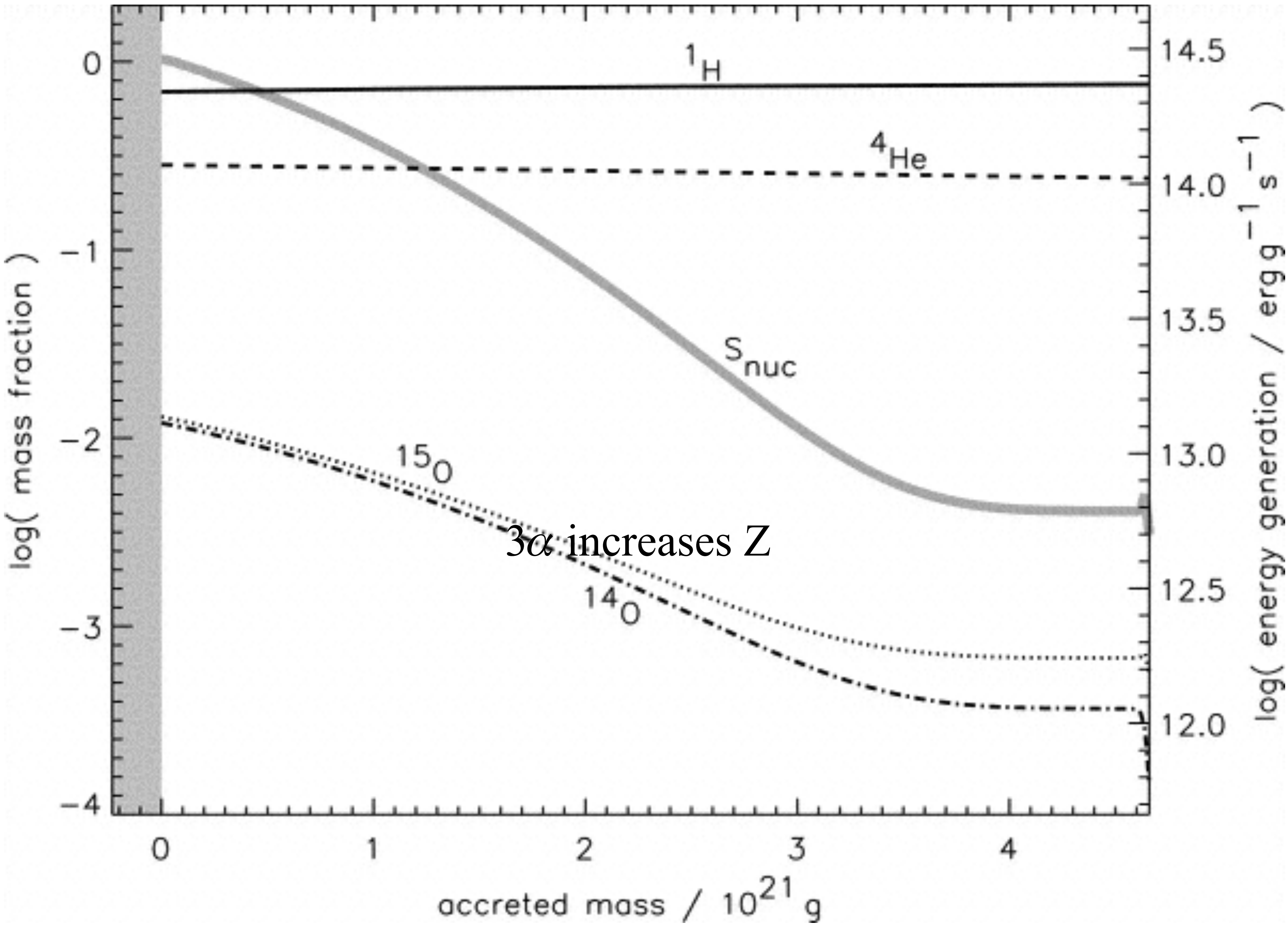
Alternating (α,p) and (p,γ) reactions:
For each proton capture there is an (α,p) reaction releasing a proton

Net effect: He burning

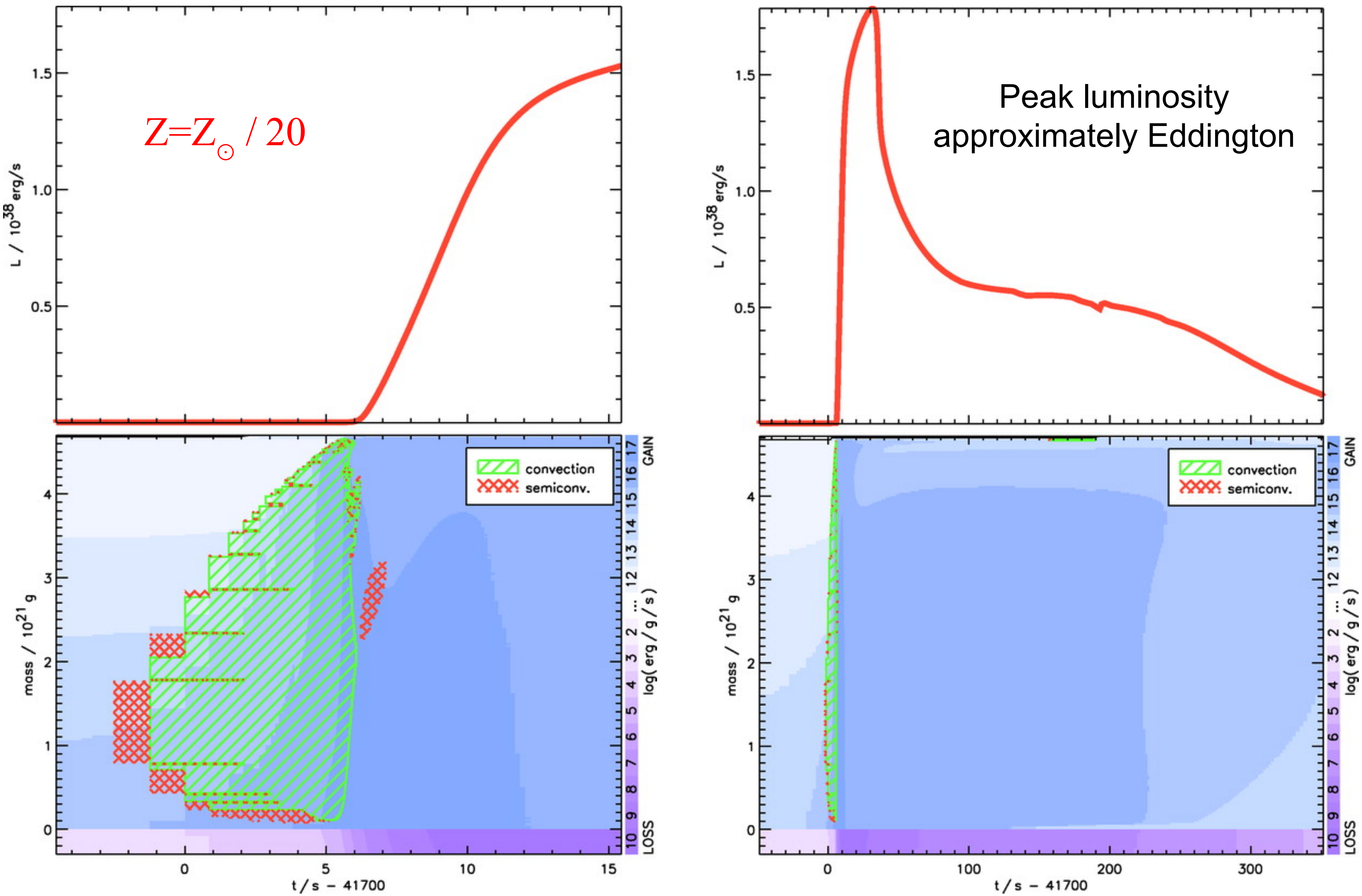
Endpoint: Limiting factor I – SnSbTe Cycle



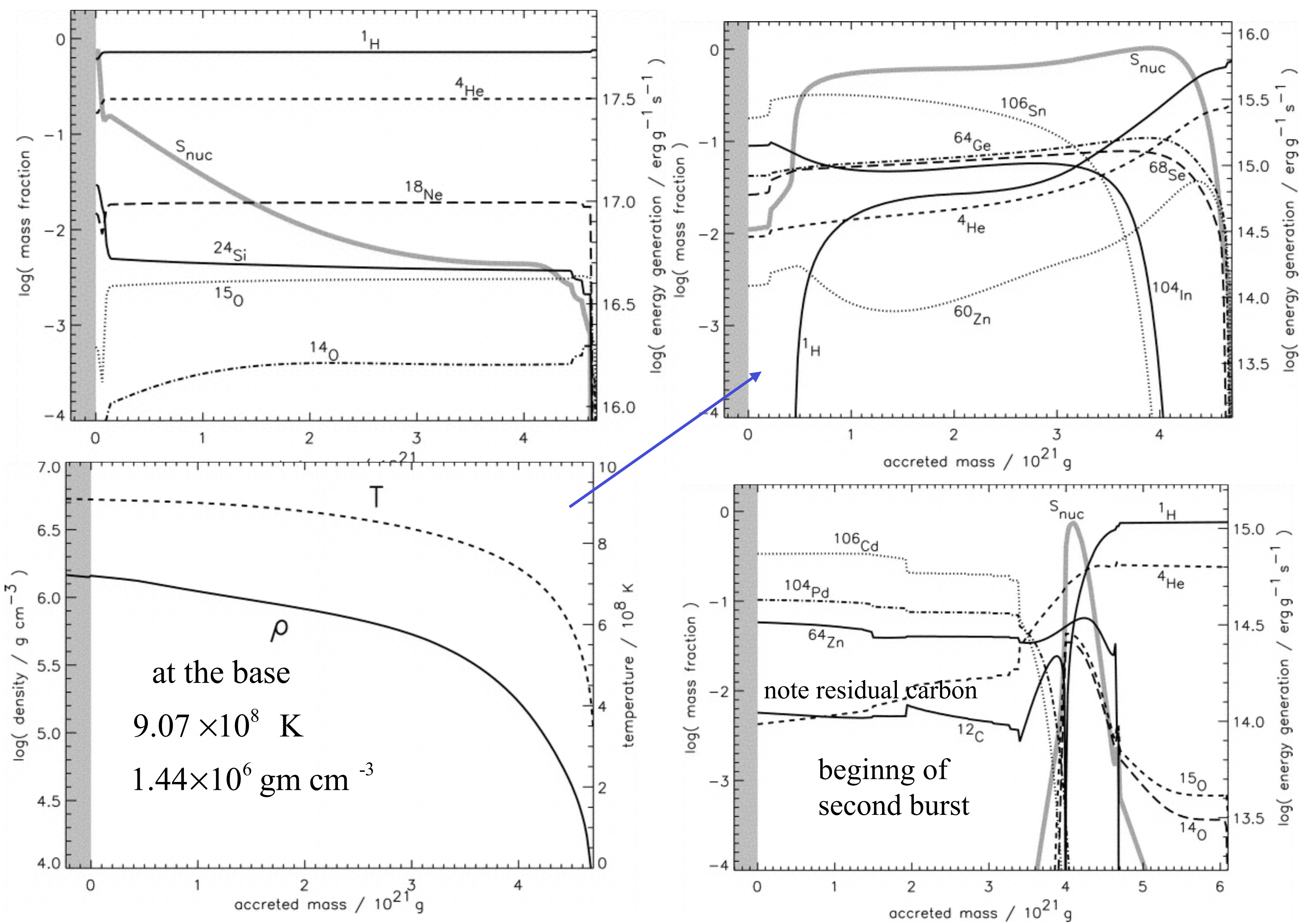

Woosley et al, *ApJS*, **151**, 175 (2004)
Reaction network
(only nuclei indicated with red triangles have experimetally determined masses)
proton number
neutron number
0
10
20
30
40
50
60
70

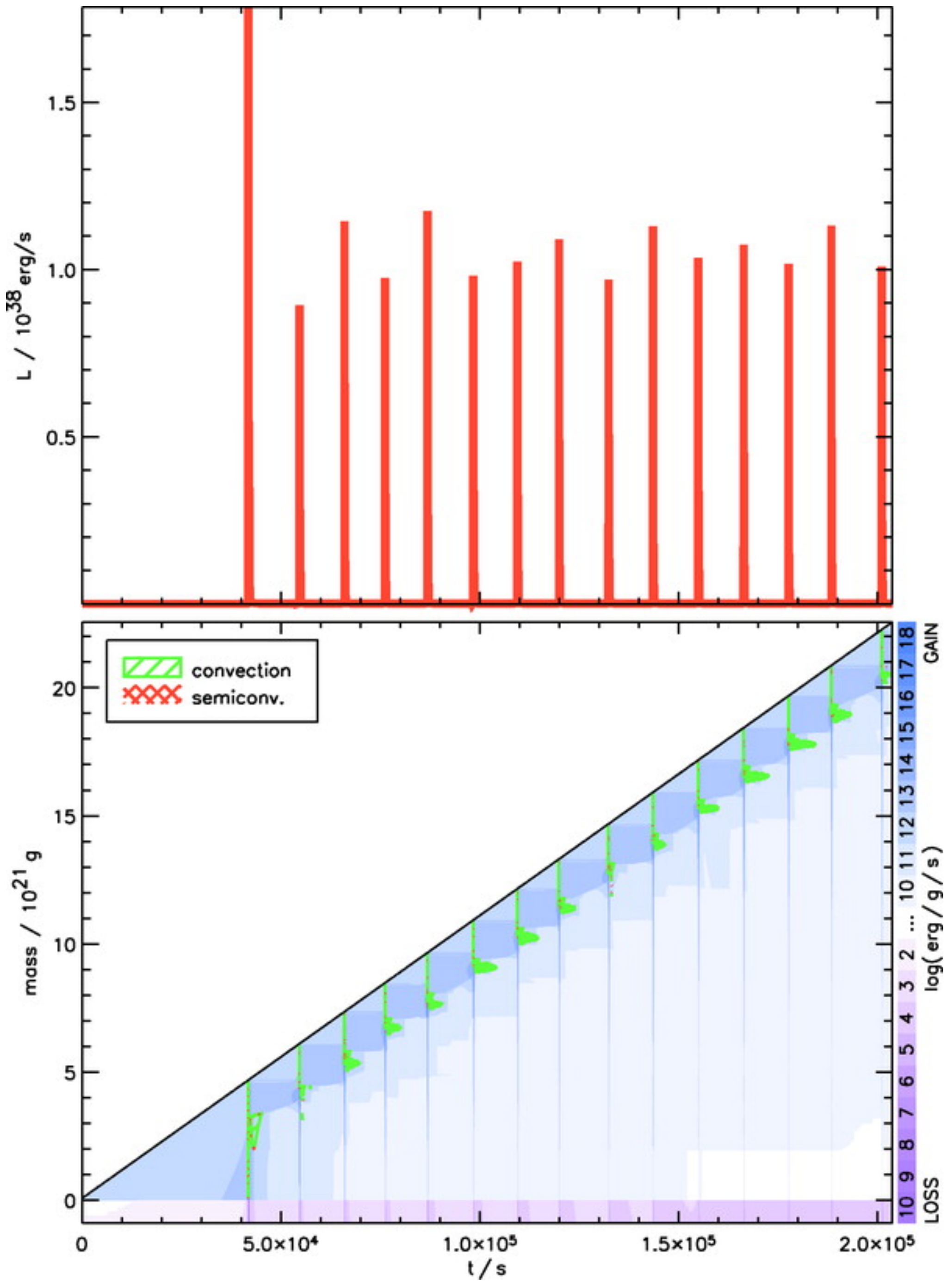


1H
4He
S_nuc
15O
14O
3α increases Z
log(mass fraction)
log(energy generation / erg g⁻¹ s⁻¹)
accreted mass / 10^21 g
0
−1
−2
−3
−4
14.5
14.0
13.5
13.0
12.5
12.0
0
1
2
3
4



Times offset by 41,700 s of accretion at 1.75 x 10^{-9} solar masses/yr

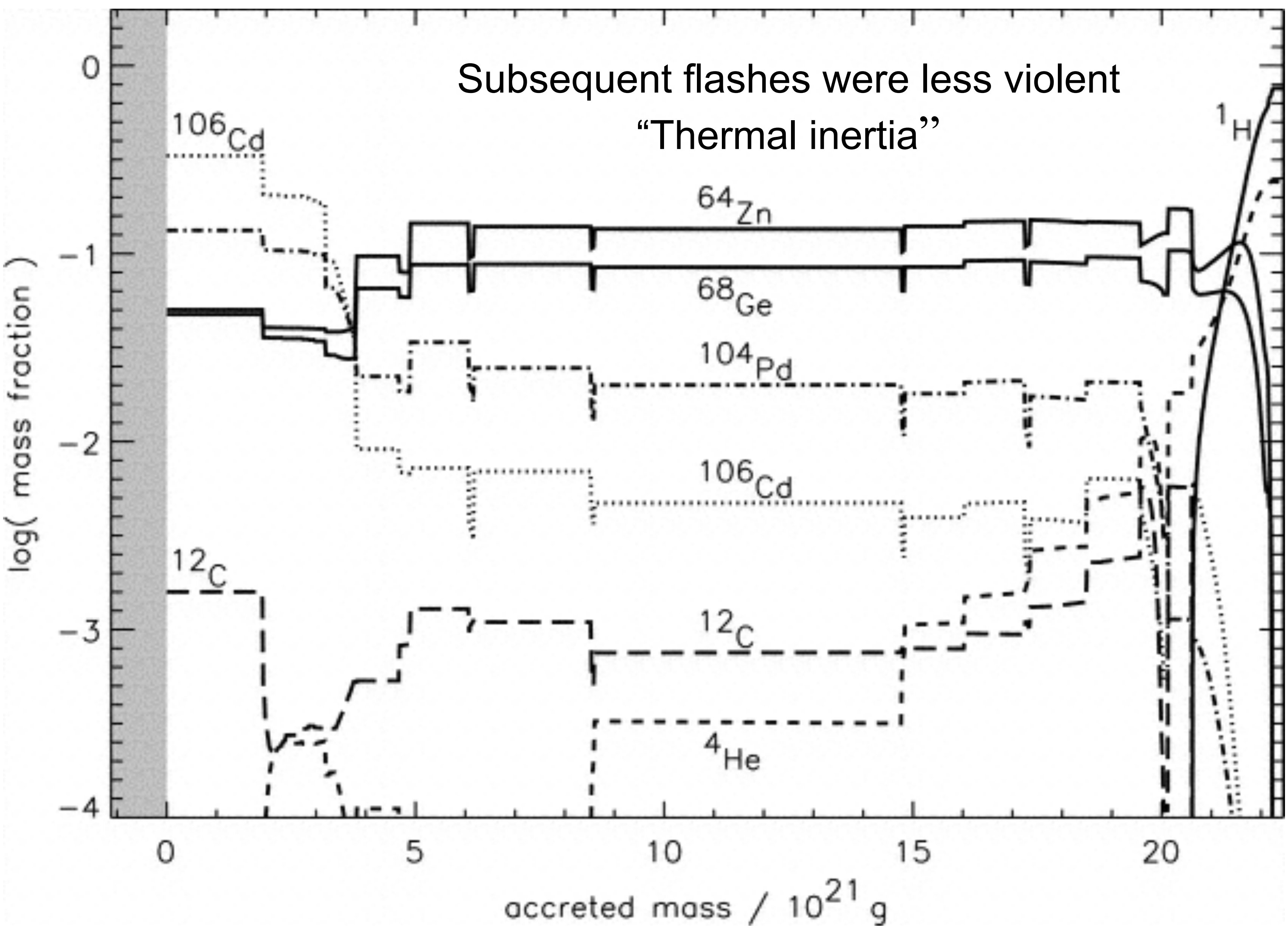

1H
4He
Snuc
18Ne
24Si
15O
14O
log(mass fraction)
log(energy generation / erg g−1 s−1)
106Sn
64Ge
68Se
4He
104In
60Zn
1H
accreted mass / 10^21 g
T
ρ
at the base
9.07 ×10^8 K
1.44×10^6 gm cm^-3
log(density / g cm−3)
temperature / 10^8 K
106Cd
104Pd
64Zn
12C
15O
14O
note residual carbon
beginng of
second burst

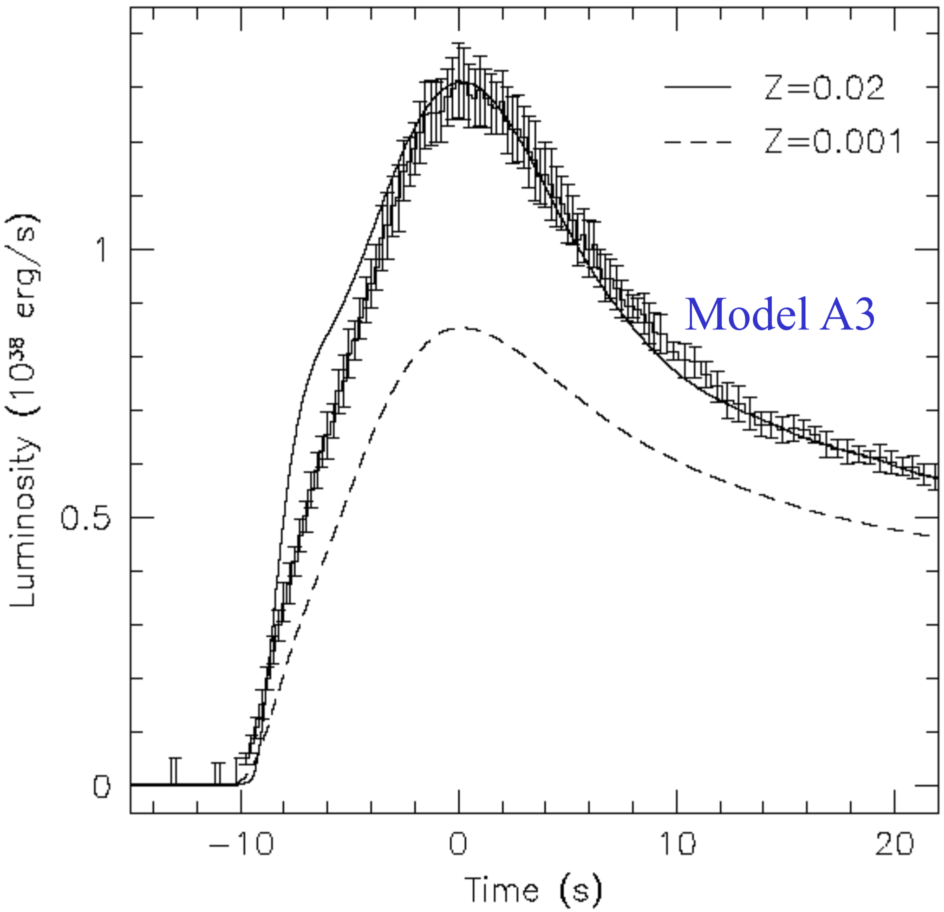


Fourteen consecutive flashes.
The first is a start up transient.

$$\dot{M} = 1.75 \times 10^{-9}\ M_\odot\ yr^{-1}$$

$$Z = Z_\odot / 20$$


Subsequent flashes were less violent
"Thermal inertia"
106Cd
64Zn
68Ge
104Pd
106Cd
12C
12C
4He
1H
0
−1
−2
−3
−4
log(mass fraction)
0
5
10
15
20
accreted mass / 10^21 g



GS 1826-24

Heger, Cumming, Gallaoway and Woosley (2005, in prep)

TABLE 1. AVERAGE BURST PROPERTIES[a]

Model	Z	$\dot{M}$ ($10^{-9}\ M_\odot\ yr^{-1}$)	Δt (h)	E_{burst} (10^{39} ergs)	α	ΔM (10^{21} g)
A1	0.02	1.17	5.4	4.52	60	1.15
A2	0.02	1.43	4.3	4.55	57	1.11
A3	0.02	1.58	3.9	4.61	55	1.10
A4	0.02	1.75	3.4	4.64	54	1.08

Current Issues:

- What is the physical nature of "superbursts"? Are they carbon runaways? How to accumulate the carbon. Further evolution of ashes

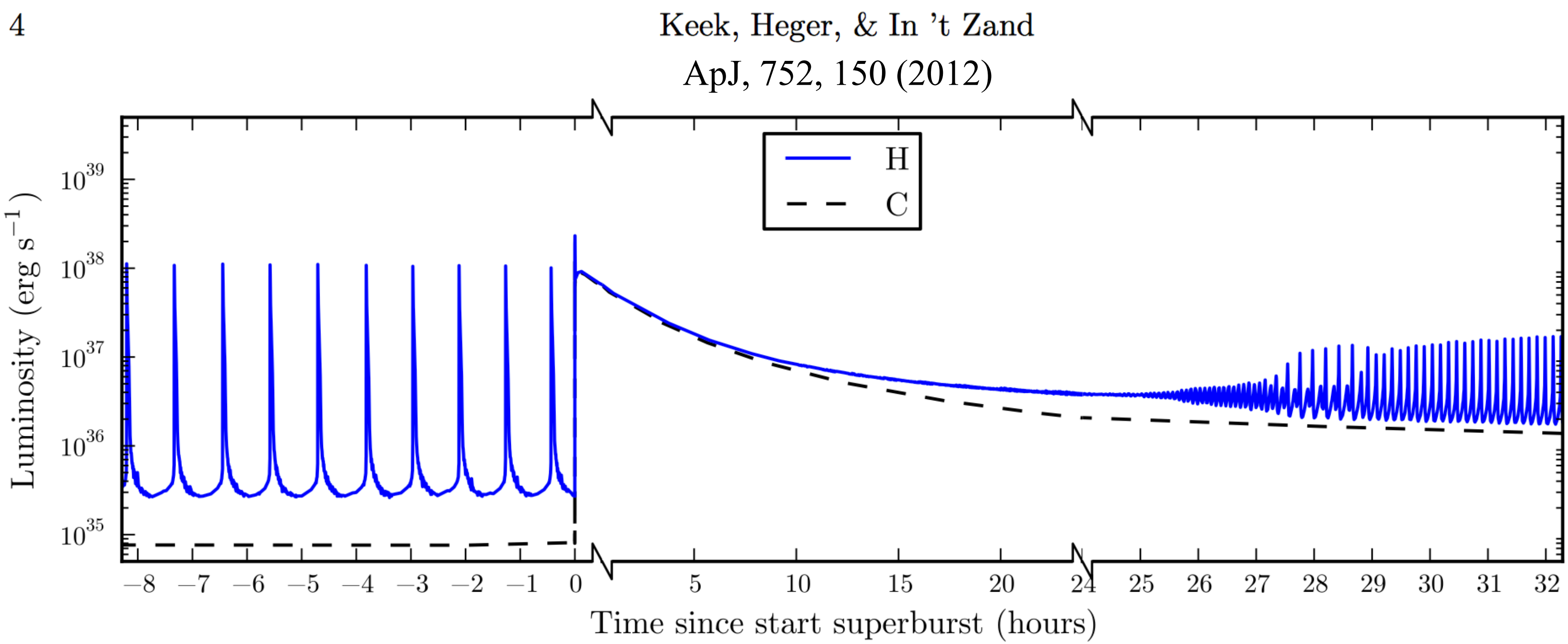
- Detailed comparison with an accumulating wealth of observational data, especially time histories of multiple bursts and the effects of thermal inertia

- Large volume of uncertain, yet important reaction rates (FRIB)

- Multi-D models with B fields and rotation – spreading of the burning

- Can XRB's be used to obtain neutron star radii, crustal structure, and/or distances

“Superbursts”



About 2 dozen superbursts have been observed. They are thought to be produced by carbon runaways as predicted by Woosley and Taam (1976). The fine structure in the above simulation has not yet been observed

Recent 2D simulations from Chris Malone
using MAESTRO

http://www.astro.sunysb.edu/cmalone/research/pure_he4_xrb/index.html

XRB models by Alex Heger et al.

http://2sn.org/xrb/movie/