Nuclear Astrophysics II

Lecture 7

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Nuclear Physics Inside Exploding Stars

EXPLOSIVE HYDROGEN BURNING: X-RAY BURSTS AND RP-PROCESS

We are dealing with reactions of the type: $1 + 2 \longrightarrow 3 + \gamma$, where nucleus 3 is initially formed in an excited state, and de-excites through gamma-emission.

Recall, from Lec. 7, using the detailed balance principle, we derived the photodisintegration reaction rate (inverse rate) in terms of the charged particle rate (forward rate). Their ratio was:

$$\frac{r_{3\gamma}}{r_{12}} = \frac{(1+\delta_{12})N_3}{N_1 N_2}\frac{g_1 g_2}{g_3}\left(\frac{2\pi\mu_{12}\tau}{h^2}\right)^{3/2} e^{-Q/\tau}$$

And then, using $N_i = \rho N_A \frac{X_i}{A_i}$

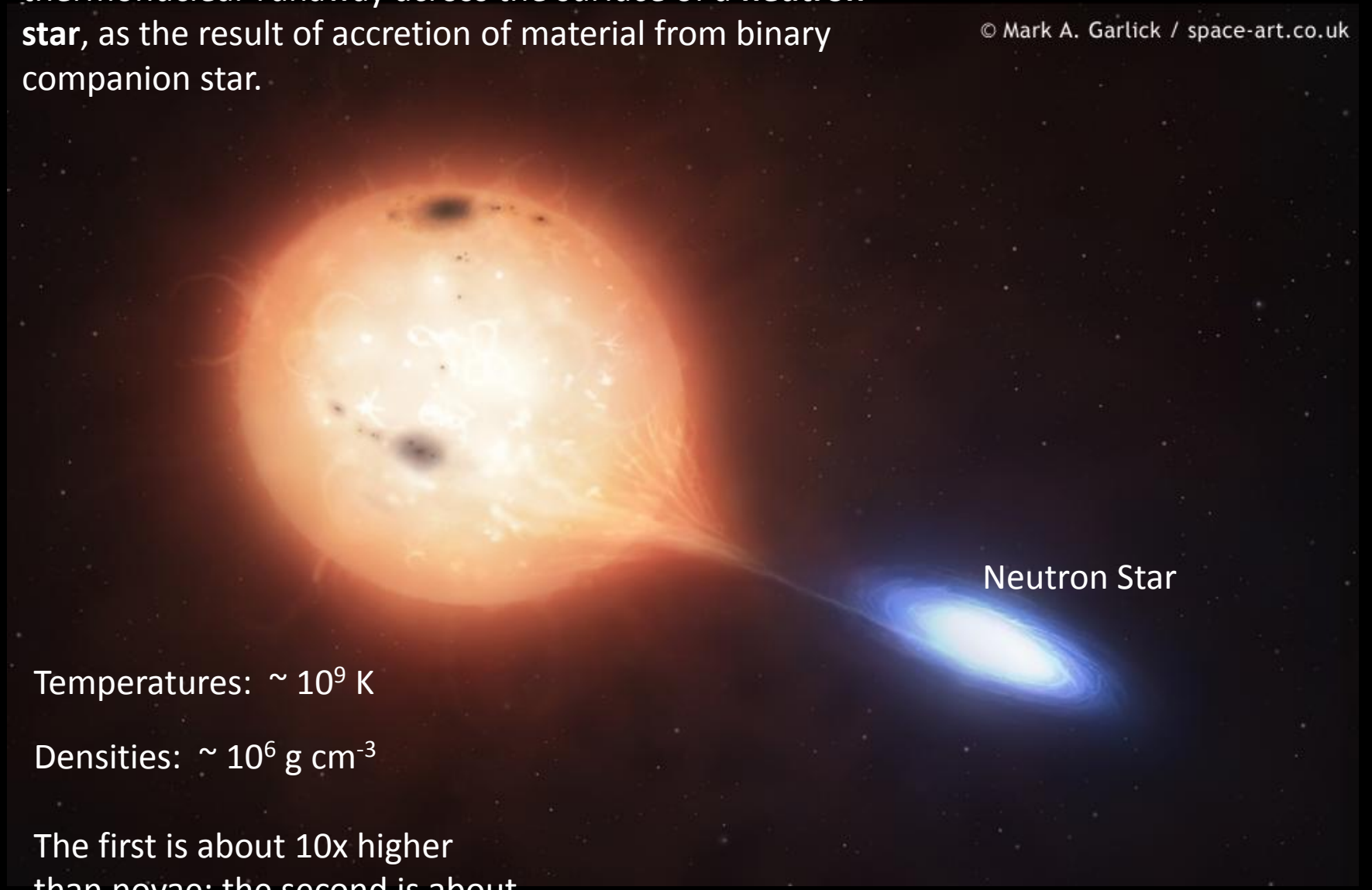
$$\frac{r_{3\gamma}}{r_{12}} = \frac{(1+\delta_{12})}{\rho N_A}\frac{X_3}{X_1 X_2}\frac{A_1 A_2}{A_3}\frac{g_1 g_2}{g_3}\left(\frac{2\pi\mu_{12}\tau}{h^2}\right)^{3/2} e^{-Q/\tau}$$

Where: $Q = m_1 + m_2 - m_3$

A_i is atomic mass of i

X_i is mass fraction of species i

Type I X-ray bursts are believed to be the result of a thermonuclear runaway across the surface of a **neutron star**, as the result of accretion of material from binary companion star.



Temperatures: ~ 10^9 K

Densities: ~ 10^6 g cm^{-3}

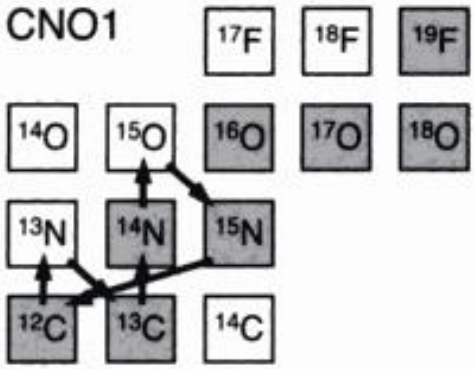
The first is about 10x higher than novae; the second is about 100x higher

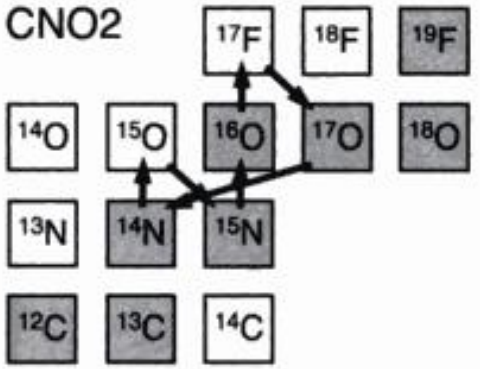
CNO burning cycles for hydrogen under non-explosive conditions.

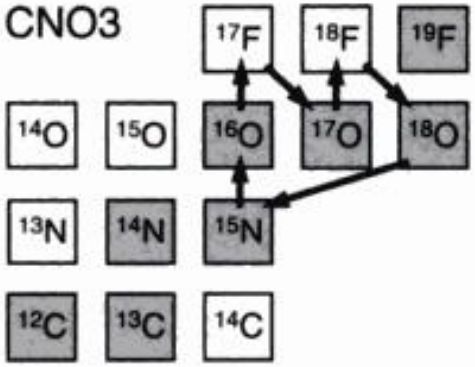
Each cycle converts 4 protons into an alpha particle.

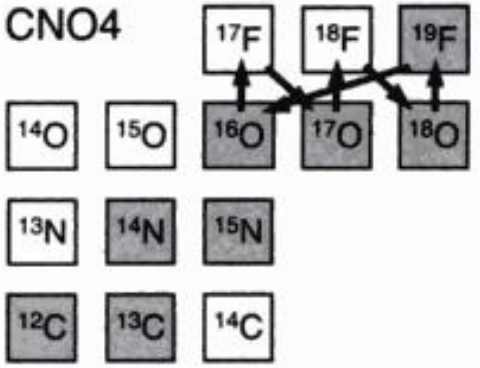
It is these cycles that nuclear burning enters once proton-proton and ^{4}He burning (by the triple-alpha process) have built up enough ^{12}C abundance.

Remember: These form cycles because, at some point along the path, we encounter a nucleus "Y" that has a binding energy for alpha particles that is ***lower*** than the minimum excitation energy of "Y" when it is made by proton capture. Example in CNO3: $^{18}O(p,\gamma)^{19}F^{*} \rightarrow \alpha + {}^{15}N$







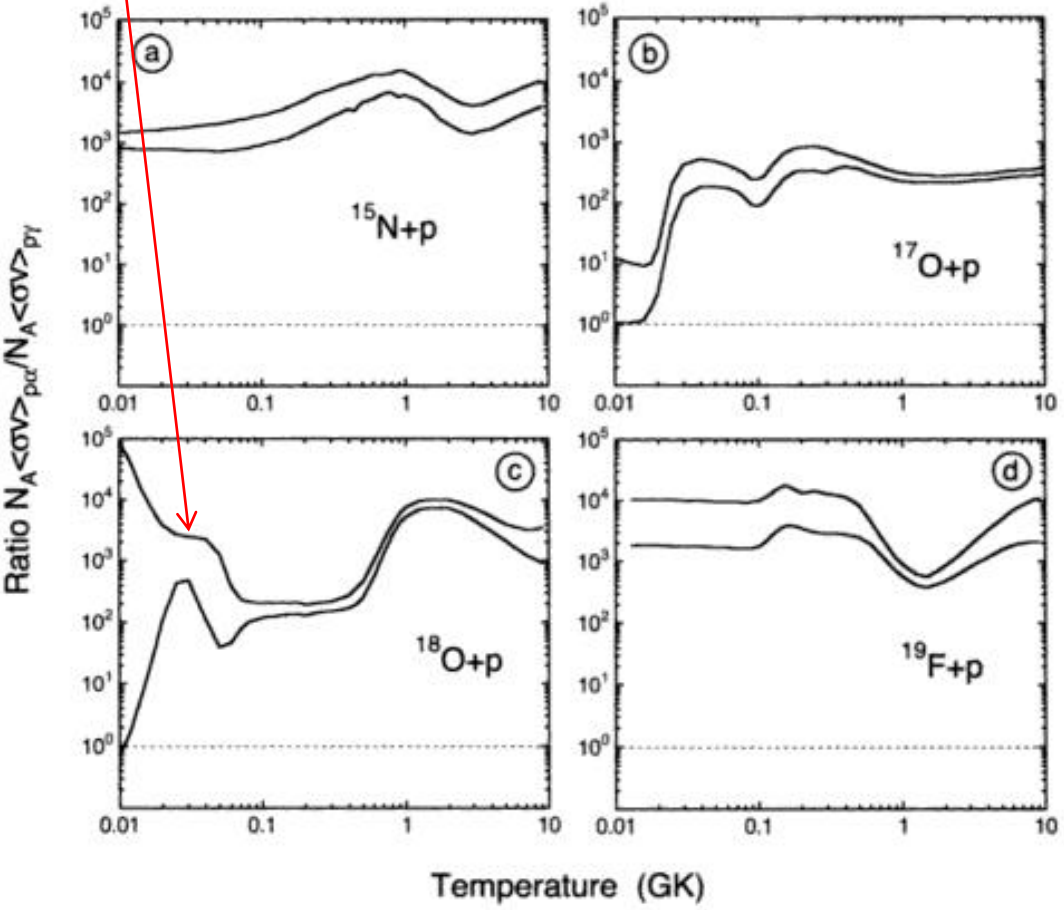


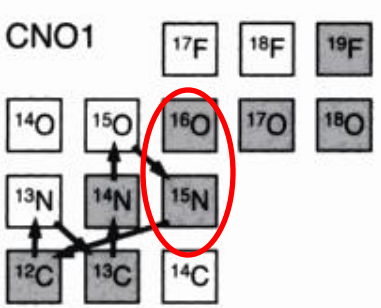
CNO1	CNO2	CNO3	CNO4
$^{12}C(p,\gamma)^{13}N$	$^{14}N(p,\gamma)^{15}O$	$^{15}N(p,\gamma)^{16}O$	$^{16}O(p,\gamma)^{17}F$
$^{13}N(\beta^{+}\nu)^{13}C$	$^{15}O(\beta^{+}\nu)^{15}N$	$^{16}O(p,\gamma)^{17}F$	$^{17}F(\beta^{+}\nu)^{17}O$
$^{13}C(p,\gamma)^{14}N$	$^{15}N(p,\gamma)^{16}O$	$^{17}F(\beta^{+}\nu)^{17}O$	$^{17}O(p,\gamma)^{18}F$
$^{14}N(p,\gamma)^{15}O$	$^{16}O(p,\gamma)^{17}F$	$^{17}O(p,\gamma)^{18}F$	$^{18}F(\beta^{+}\nu)^{18}O$
$^{15}O(\beta^{+}\nu)^{15}N$	$^{17}F(\beta^{+}\nu)^{17}O$	$^{18}F(\beta^{+}\nu)^{18}O$	$^{18}O(p,\gamma)^{19}F$
$^{15}N(p,\alpha)^{12}C$	$^{17}O(p,\alpha)^{14}N$	$^{18}O(p,\alpha)^{15}N$	$^{19}F(p,\alpha)^{16}O$

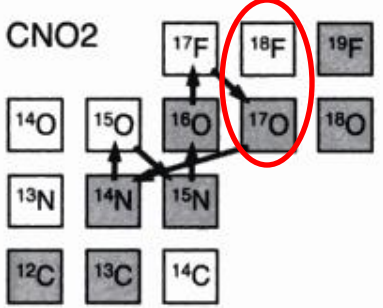
$T_{1/2}$: ^{13}N (9.965 min); ^{15}O (122.24 s); ^{17}F (64.49 s); ^{18}F (109.77 min)

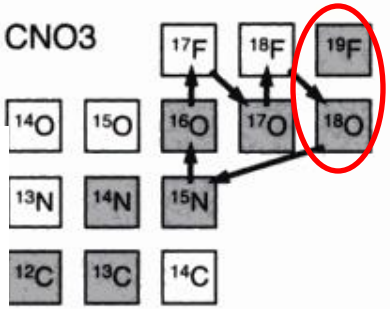
The relative probability of getting into CNO2,3,4 from CNO1 is related to the ratio of reaction rates for (p,γ) and (p,α) at the branch-point nuclei.

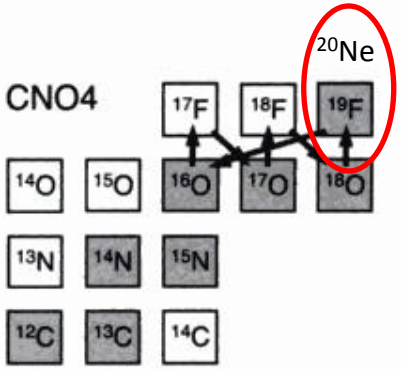
Lines denote uncertainty range! Very large for bottom left reaction ratio









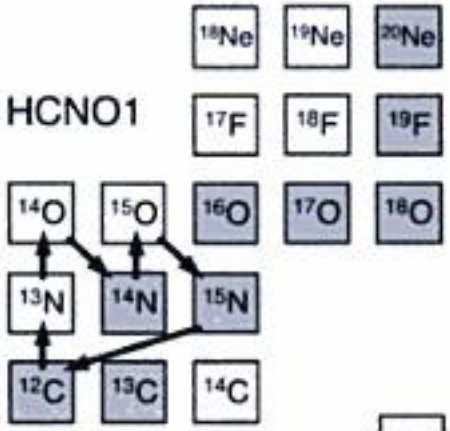


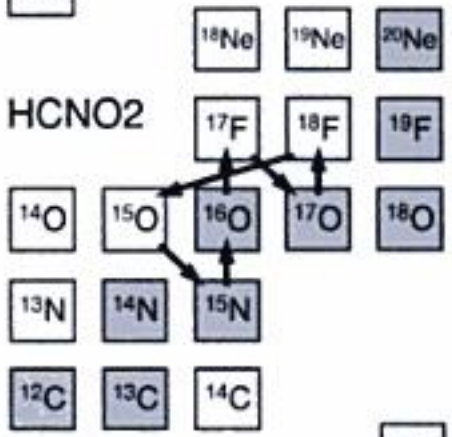
As long as the temperature remains below T < 55 MK, the beta decays of the unstable nuclei remain faster than proton capture onto them → we have no exit out of these cycles – the (p,α) reactions keep bringing us back to the beginning again – unless something new happens.

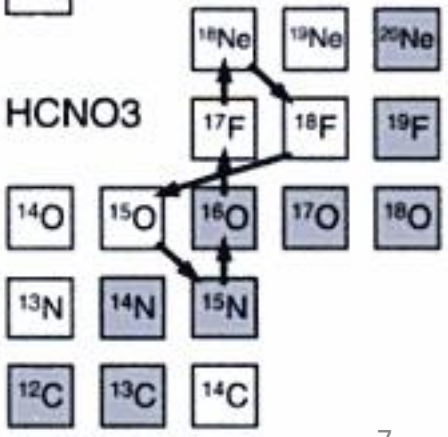
As the temperature increases beyond 55 MK, (T = 0.1 – 0.4 GK) in an explosive situation, the CNO cycles are modified somewhat. The new cycles are called the Hot CNO (HCNO) cycles.

They are modified because the beta-decay rates in the CNO cycles become comparable to, or slower, than the proton capture rates on the radioactive nuclei: ^{13}N, ^{17}F. Additionally, the higher temperature drives proton capture reactions on ^{18}F to make ^{19}Ne with excitation energies higher than its α-particle binding energy.

Upshot: We are still trapped in this mass range!





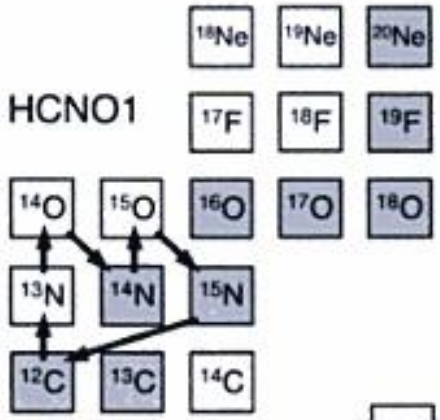


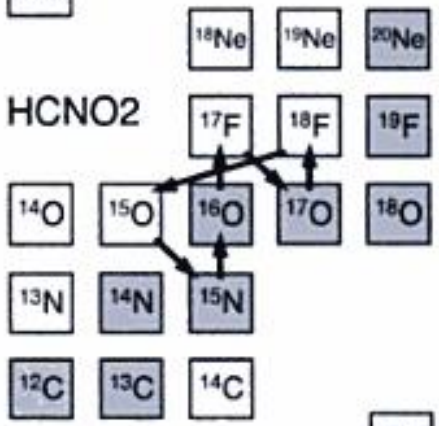
Hot CNO1	Hot CNO2	Hot CNO3
^{12}C(p,γ)^{13}N	^{15}O($\beta^+\nu$)^{15}N	^{15}O($\beta^+\nu$)^{15}N
^{13}N(p,γ)^{14}O	^{15}N(p,γ)^{16}O	^{15}N(p,γ)^{16}O
^{14}O($\beta^+\nu$)^{14}N	^{16}O(p,γ)^{17}F	^{16}O(p,γ)^{17}F
^{14}N(p,γ)^{15}O	^{17}F($\beta^+\nu$)^{17}O	^{17}F(p,γ)^{18}Ne
^{15}O($\beta^+\nu$)^{15}N	^{17}O(p,γ)^{18}F	^{18}Ne($\beta^+\nu$)^{18}F
^{15}N(p,α)^{12}C	^{18}F(p,α)^{15}O	^{18}F(p,α)^{15}O

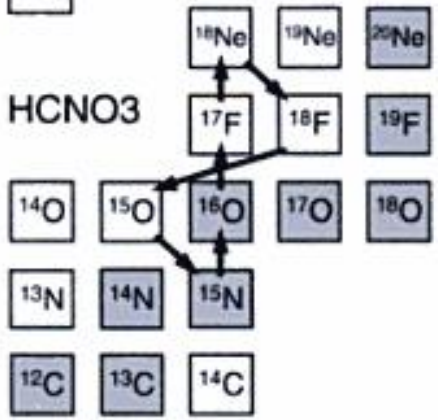
$T_{1/2}$: ^{14}O (70.61 s); ^{15}O (122.24 s); ^{17}F (64.49 s)

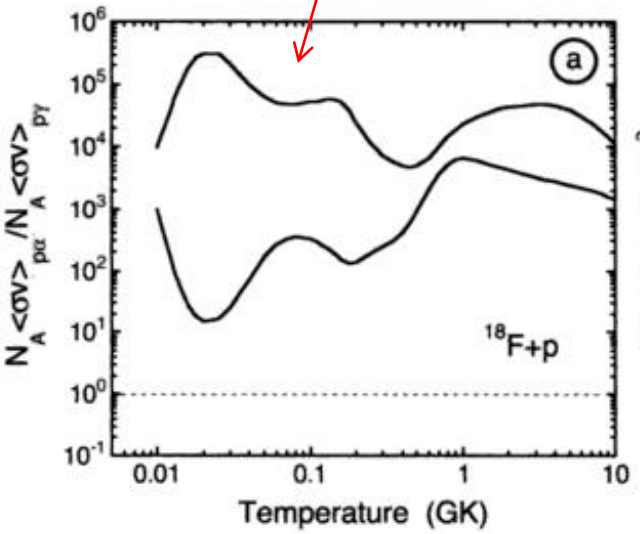
We cannot escape from the HCNO cycles, because at the heaviest mass nucleus, ^{18}F, the (p,α) reaction greatly outcompetes the (p,γ) reaction, taking us back to the start of the cycle again.

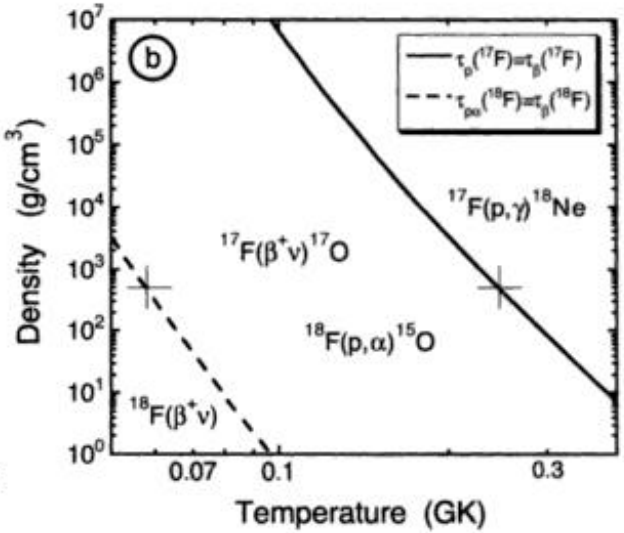
How to get out?







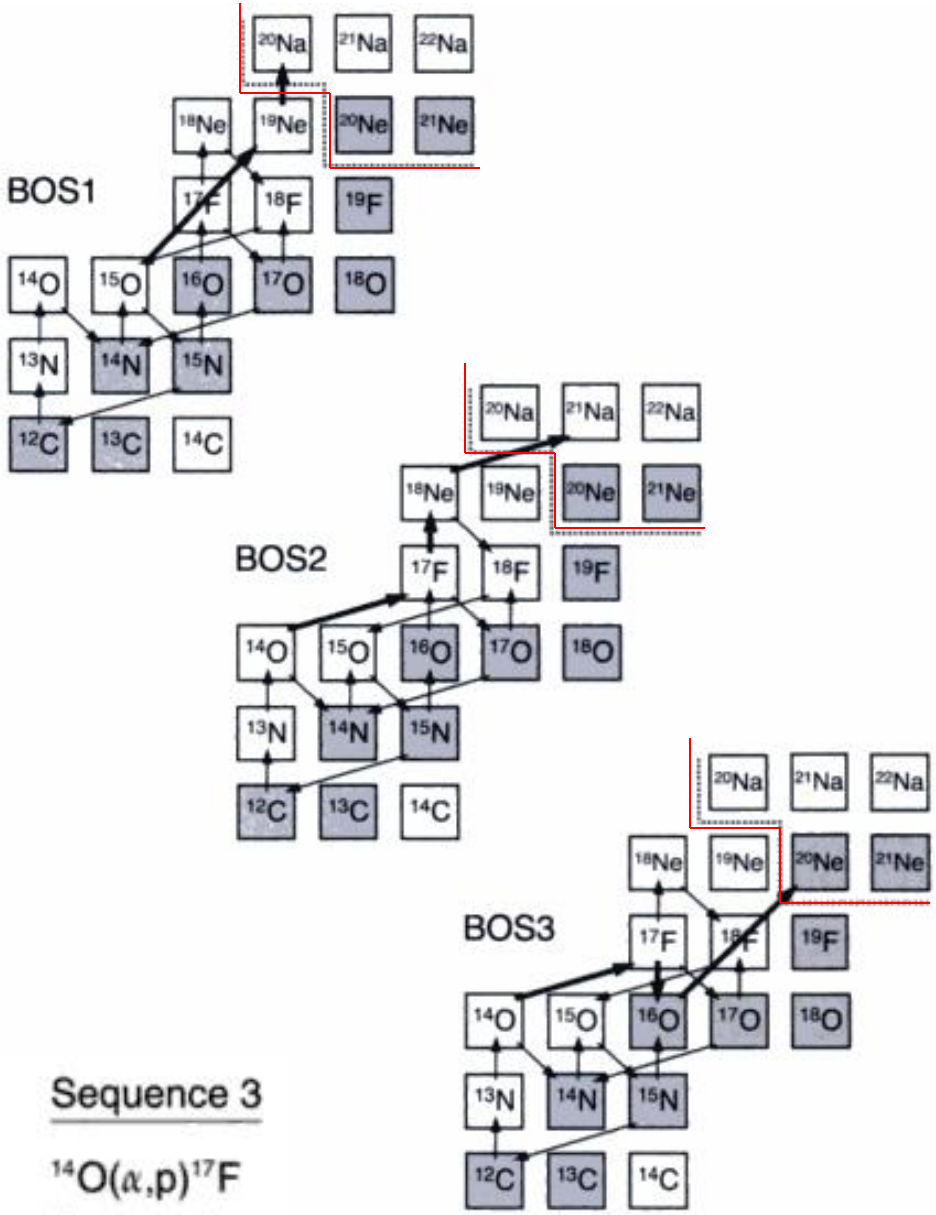




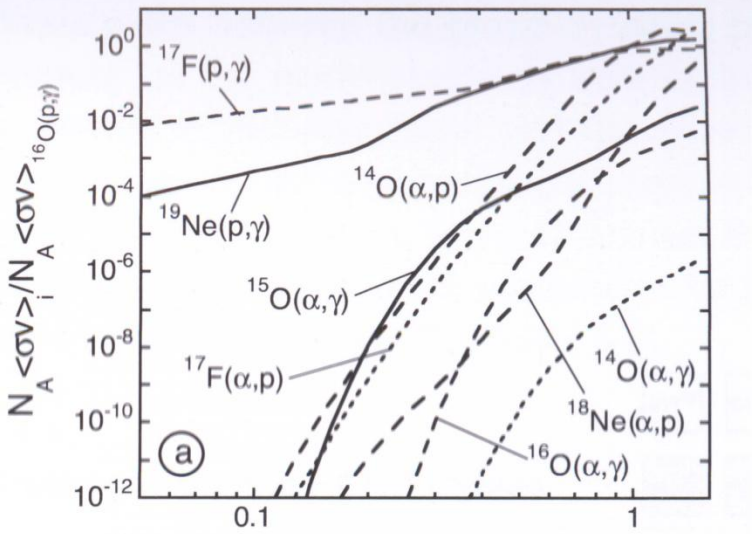
As the temperature continues to climb, a point can be reached where α-particle capture can bridge the reaction flow to masses beyond fluorine.

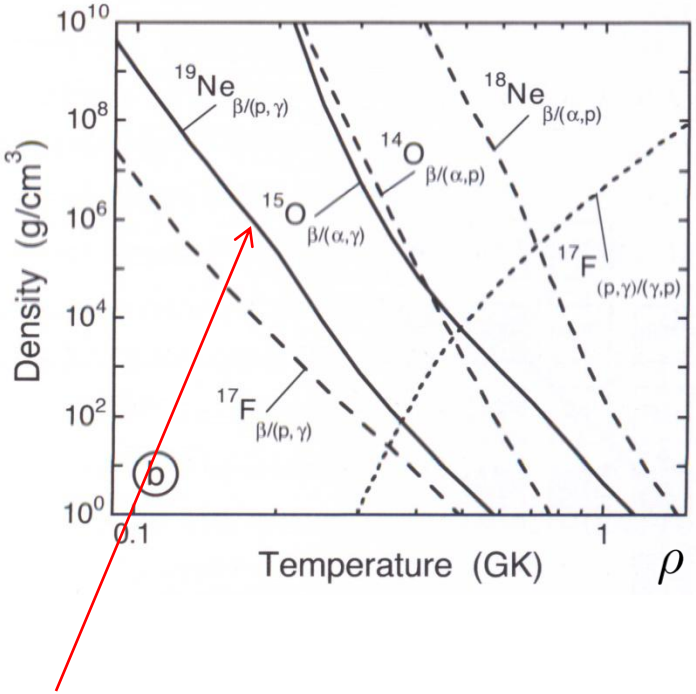
This begins to happen at temperatures $T > 0.5$ GK

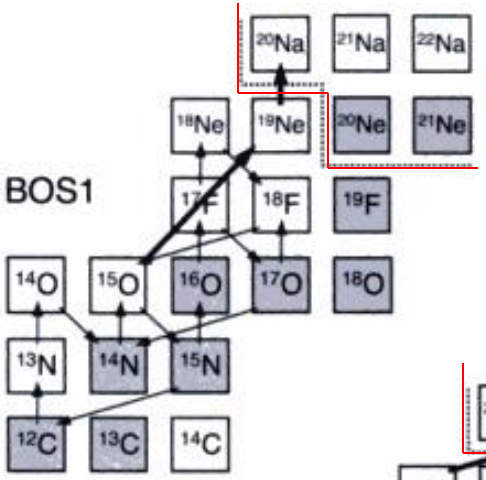
Let's take a quick closer look as to why.

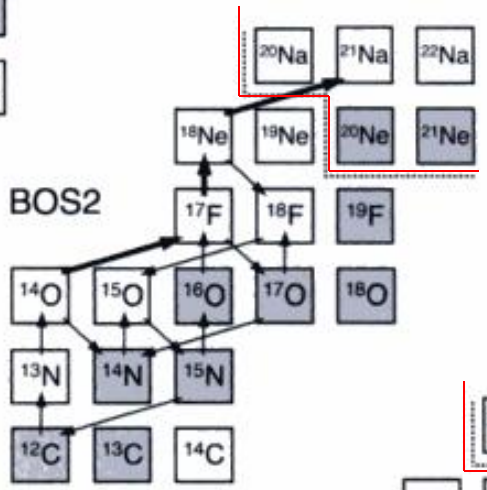


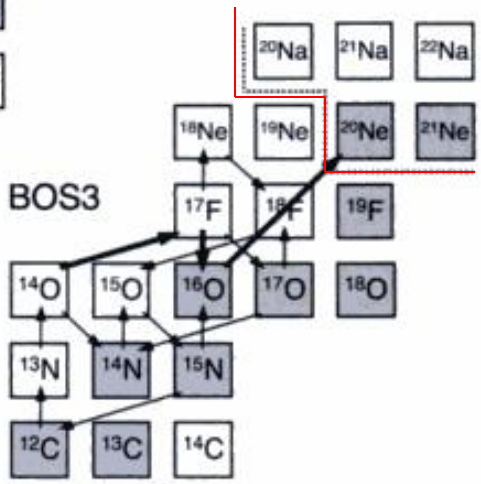
Sequence 1	Sequence 2	Sequence 3
$^{15}O(\alpha,\gamma)^{19}Ne$	$^{14}O(\alpha,p)^{17}F$	$^{14}O(\alpha,p)^{17}F$
$^{19}Ne(p,\gamma)^{20}Na$	$^{17}F(p,\gamma)^{18}Ne$	$^{17}F(\gamma,p)^{16}O$
	$^{18}Ne(\alpha,p)^{21}Na$	$^{16}O(\alpha,\gamma)^{20}Ne$











$X_p = 0.30$

$X_{He} = 0.70$

$$\rho = \frac{\ln 2}{T_{1/2(1)}(X_p/M_p)N_A\langle\sigma v\rangle_{12}}$$

To the left: β-decay dominates.

To the right: proton or α reaction dominates

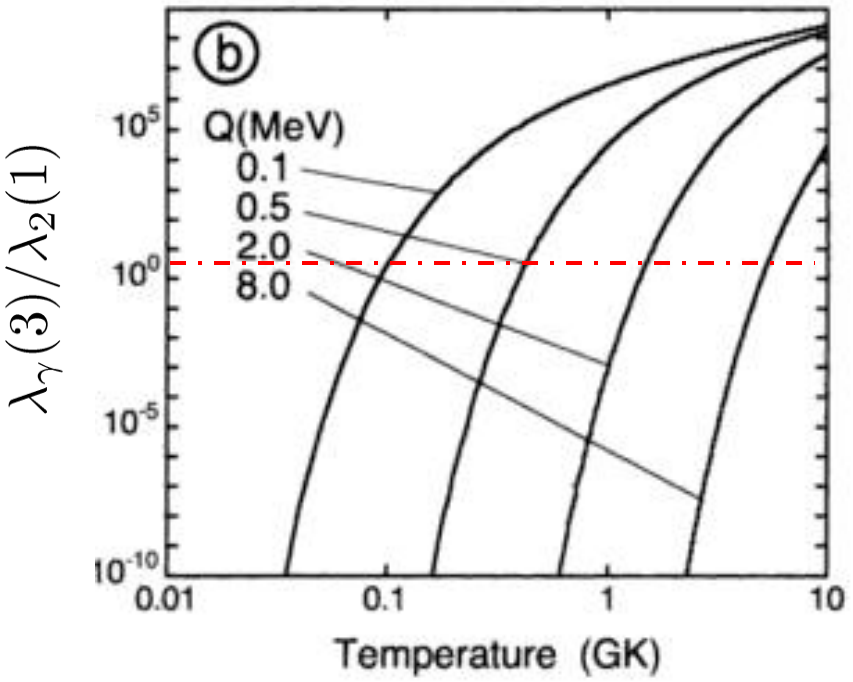
Waiting Point Nuclei

For a given stellar composition (density, mass fractions, etc), the reaction rate ratio on page 3 will, at some point be equal to unity (equilibrium) and, eventually, photodisintegration (backward rate) will begin to dominate over forward rate.

Remember: For $1 + 2 \rightarrow 3 + \gamma$
the Q-value is: $Q = m_1 + m_2 - m_3$

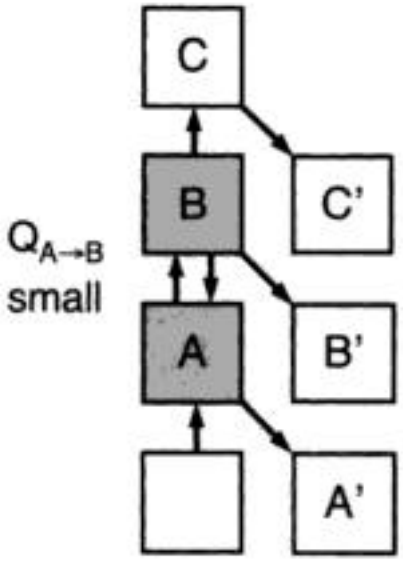
$$\rho = 10^3 \ \mathrm{g\,cm^{-3}}$$

Spin terms, M_2/X_2 and reduced mass, set to unity for plot.



$$\frac{\lambda_\gamma(3)}{\lambda_2(1)} = \frac{(r_{3\gamma}/N_3)}{(r_{12}/N_1)} = \frac{(1+\delta_{12})}{\rho N_A}\left(\frac{M_2}{X_2}\right)\frac{g_1 g_2}{g_3}\left(\frac{2\pi\mu_{12}\tau}{h^2}\right)^{3/2} e^{-Q/\tau}$$

Let's think about what happens if the nuclear mass flow in explosive hydrogen burning reaches a nucleus, "A", where the reaction Q-value to the next nucleus, "B" is small.



We want to know the following: what is the effective lifetime of nucleus "A" under various thermodynamic conditions. (We are dealing only with (p,γ) reactions here in the entrance channel).

First: when the temperature is low, photodisintegration is unimportant, thus, once B is formed, A is permanently destroyed:

$$\frac{dA}{dt} = -AN_p\langle\sigma v\rangle_{Ap}$$

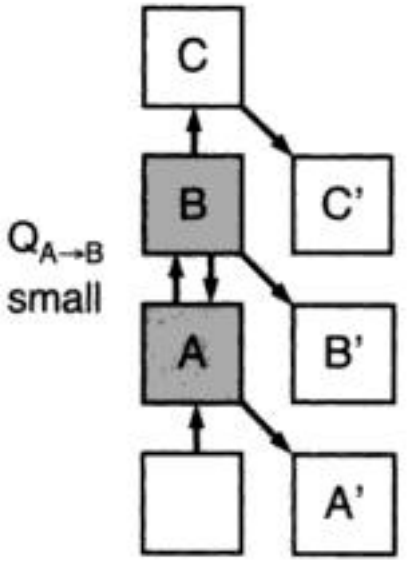
$$\Rightarrow \frac{1}{A}\frac{dA}{dt} = \lambda_p(A) = \rho N_A \frac{X_p}{M_p}\langle\sigma v\rangle_{A(p,\gamma)}$$

The lifetime of A, therefore, is just the inverse of this: $\tau_p(A) = 1/\lambda_p(A)$

This result is not surprising: the lifetime of A is just "the inverse" of its destruction rate. Once matter has flowed into B, it doesn't come back, in this regime.

But....

Now we go to higher temperatures, as the runaway becomes more energetic.



From plot on page 11, we know that photodisintegration of B will eventually become non-negligible. In that case, we need to be more general regarding the abundance change of "A" and "B".

Let's look at what "A" is doing.

$$\frac{dA}{dt} = -r_{A\to B} + r_{B\to A}$$

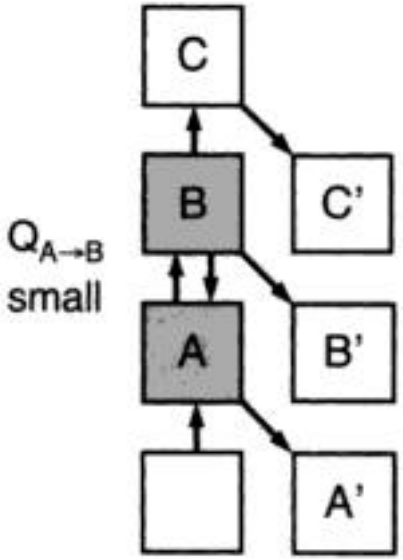
At equilibrium, the forward and backward rates are equal. (note, this does **not** mean that the abundance of A isn't changing, as we will see next).

Therefore, $r_{A\to B} = r_{B\to A}$. Using the equations on page 3 lets us write the equilibrium abundance ratio of A and B:

$$\left(\frac{B}{A}\right)_e = N_p \frac{g_3}{g_1 g_2}\left(\frac{2\pi\mu_{12}kT}{h^2}\right)^{-3/2} e^{Q/kT} = \frac{\lambda_{A\to B}}{\lambda_{B\to A}}$$

(I have dropped the Kroenecker delta-term)

Why is it abundance of A can change, even though $r_{A\to B} = r_{B\to A}$? Because, material can flow out of B to B' or to C. Let's consider the case when the beta-decay to B' and reaction channel to C opens (no photodisintegration of C back to B):



$$\frac{dA}{dt} = -r_{A\to B} + r_{B\to A}$$

$$\frac{dB}{dt} = r_{A\to B} - \left(r_{B\to A} + r_{B\to C} + B\lambda^{\beta}_{B\to B'}\right)$$

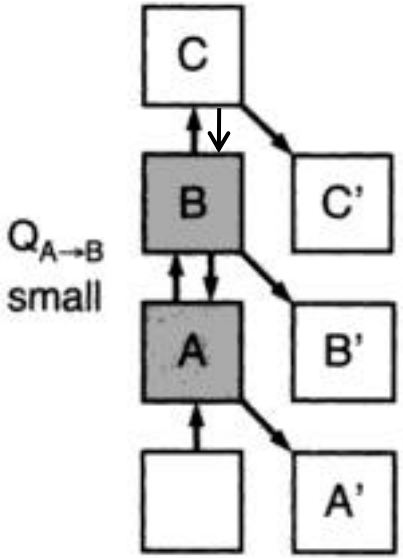
The abundance of B (the bridge) doesn't change: as fast as it decays or is destroyed, it is produced by proton capture on A). So, $dB/dt = 0$.

$$\frac{dA}{dt} = r_{B\to C} + B\lambda^{\beta}_{B\to B'}$$

$$\Rightarrow \lambda_A = \frac{1}{A}\frac{dA}{dt} = \left(\frac{B}{A}\right)_e \left(\lambda_{B\to C} + \lambda^{\beta}_{B\to B'}\right)$$

Now, the lifetime of A is the inverse of this new result.

Finally, what is the lifetime of A when C is allowed to photodisintegrate back to B, so that C and B are also in equilibrium?



$$\frac{dA}{dt} = -r_{A\to B} + r_{B\to A}$$

$$\frac{dB}{dt} = r_{A\to B} + r_{C\to B} - \left(r_{B\to A} + r_{B\to C} + B\lambda^{\beta}_{B\to B'}\right)$$

$$\frac{dC}{dt} = r_{B\to C} - \left(r_{C\to B} + C\lambda^{\beta}_{C\to C'}\right)$$

Because B and C are now in equilibrium, the abundance of C is also not changing (produced as fast as it is being destroyed) $\Rightarrow dC/dt = 0$

and $\left(\frac{C}{B}\right)_e = \frac{\lambda_{B\to C}}{\lambda_{C\to B}}$ (refer to page 11 for how to express this in terms of Q-value, etc)

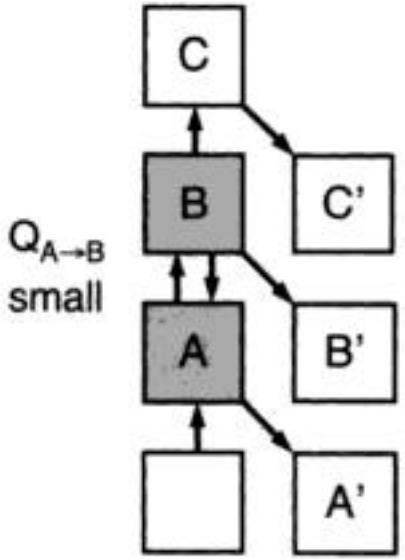
$$\lambda_A = \frac{1}{A}\frac{dA}{dt} = \frac{\lambda_{A\to B}}{\lambda_{B\to A}}\left(\frac{\lambda_{B\to C}}{\lambda_{C\to B}}\lambda_{C\to C'} + \lambda_{B\to B'}\right)$$

Lifetime of A is the inverse of this.

Summarizing thus far...

When photodisintegration on B is not yet important, the lifetime of A is just the inverse of:

$$\lambda_p(A) = \rho N_A \frac{X_p}{M_p} \langle \sigma v \rangle_{A(p,\gamma)}$$



When photodisintegration of B is important, but photodisintegration of C is not yet important, the lifetime of A is the inverse of:

$$\Rightarrow \lambda_A = \left(\frac{B}{A}\right)_e \left(\lambda_{B\to C} + \lambda^{\beta}_{B\to B'}\right)$$

Refer to page 13 for the formula

Finally, when photodisintegration of both B and C are important, the lifetime of A is the inverse of:

$$\lambda_A = \frac{\lambda_{A\to B}}{\lambda_{B\to A}} \left(\frac{\lambda_{B\to C}}{\lambda_{C\to A}} \lambda_{C\to C'} + \lambda_{B\to B'}\right)$$

Page 13 again for the formula

Continuing with summary...

The equilibrium abundance ratios (or lifetime ratios) are, from page 13, given by:

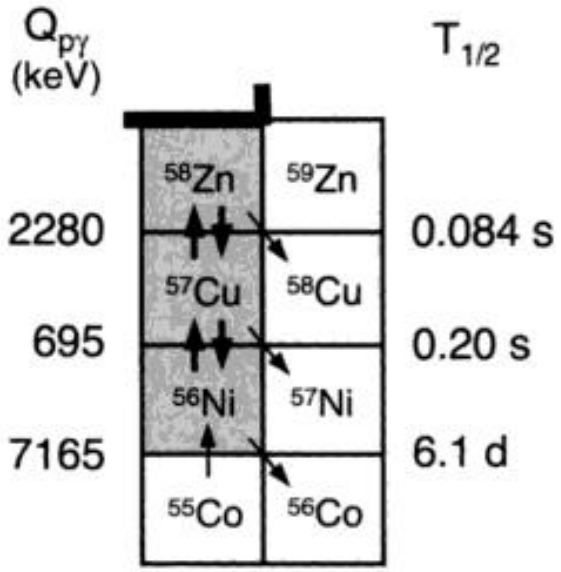
$$\left(\frac{B}{A}\right)_e = \frac{\lambda_{A\to B}}{\lambda_{B\to A}} = N_p \frac{g_3}{g_1 g_2}\left(\frac{2\pi\mu_{12}kT}{h^2}\right)^{-3/2} e^{Q/kT}$$

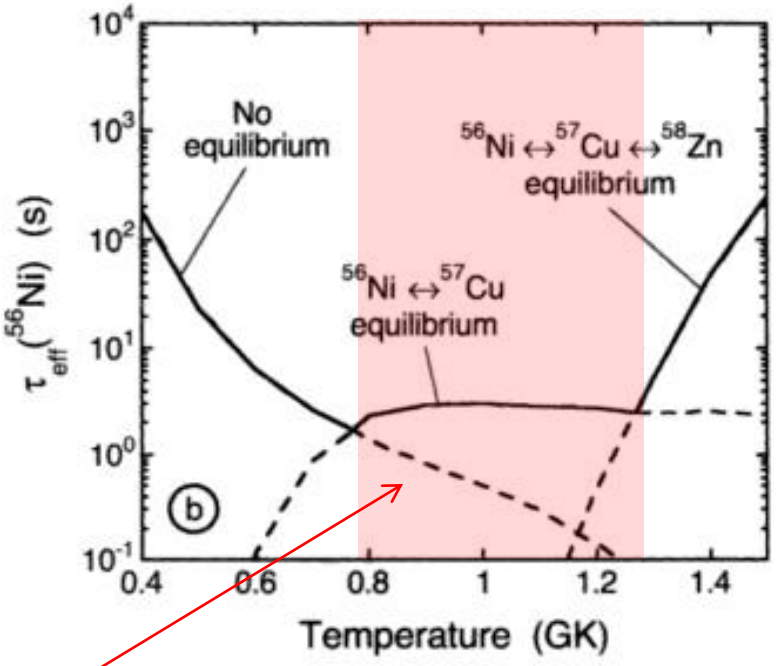
This is the Saha Equation. The nuclear parameters are the spins, contained in the g factors, and the Q-value, which depends on the nuclear masses.

This abundance ratio is ***exponentially*** dependent on the Q-value! We therefore require precise ***and*** accurate knowledge of the nuclear masses involved.

A Real Example: ^{56}Ni Bottleneck in XRB

The time scale for achieving, and then subsequent decay, from peak temperatures in X-Ray bursts is of the order ~ 10 seconds or so. If the matter flow piles up at a waiting point nucleus whose effective lifetime never gets below ~10 s, the explosion and nucleosynthesis will stall and "fizzle".





A window in temperature exists where the ^{56}Ni lifetime drops to values smaller than explosion timescale → matter flow proceeds beyond this nucleus to higher masses.

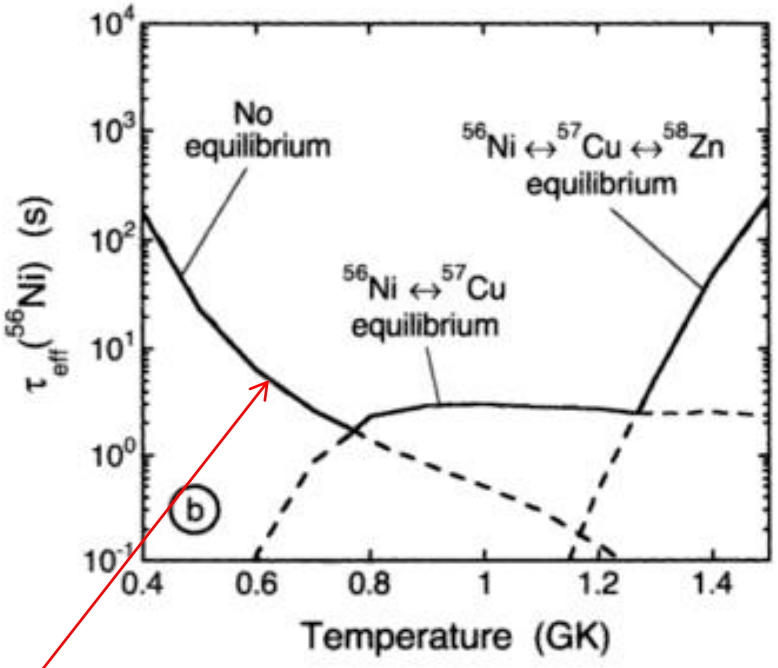
Some experimental points to keep in mind:

As the temperature of the system begins to drop, the ^{56}Ni, ^{57}Cu, ^{58}Zn system will begin to fall out of equilibrium. At that point, the (p,γ) reaction rate of ^{56}Ni(p,γ)^{57}Cu and ^{57}Cu(p,γ)^{58}Zn may become important for predictions of final abundances and shape of lightcurve.

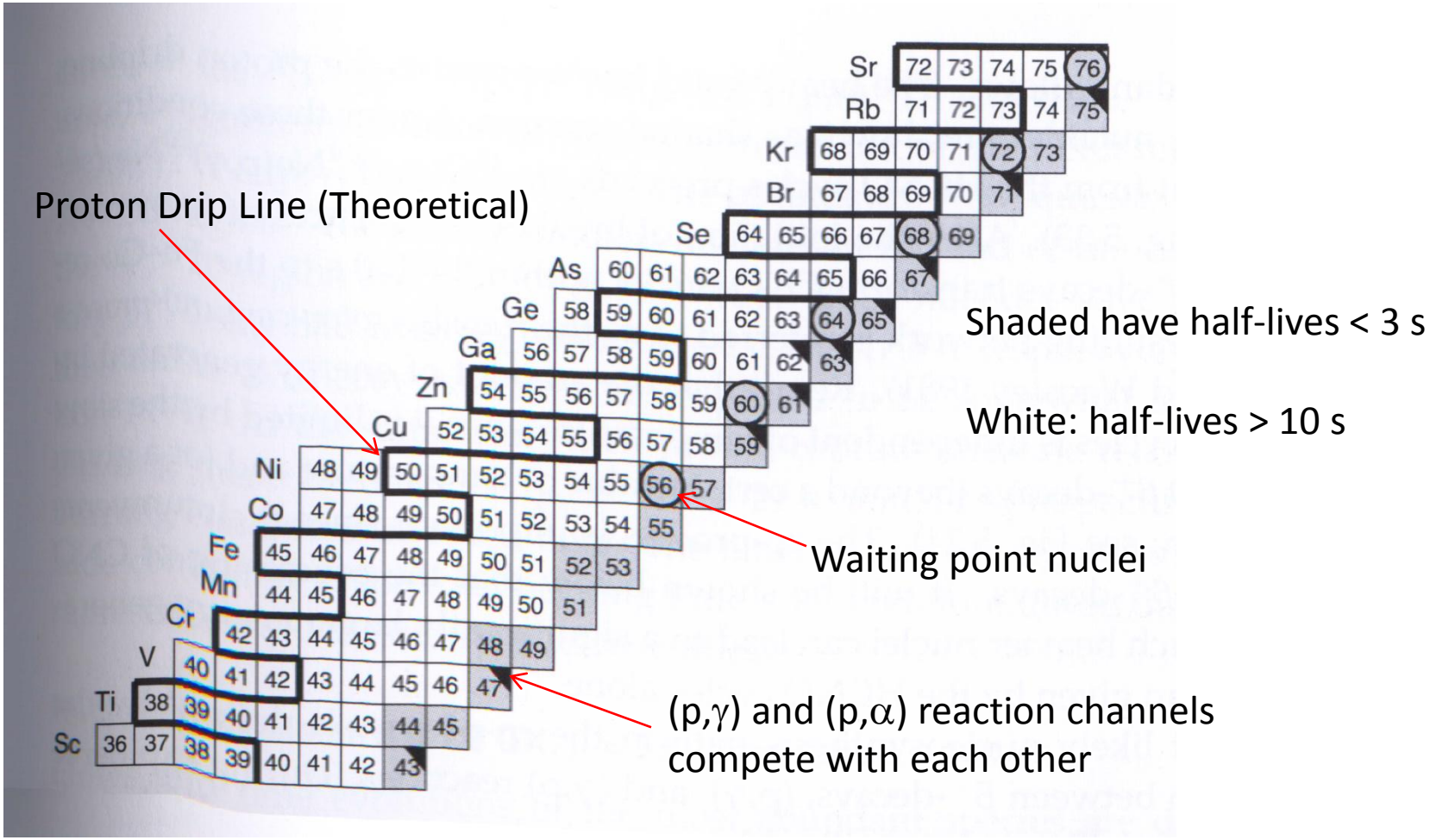
Neither have been measured.

There are other waiting point nuclei along the rp-process path in XRB's for which everything is unknown: no mass measurements, no reaction rate information, no nuclear structure information.

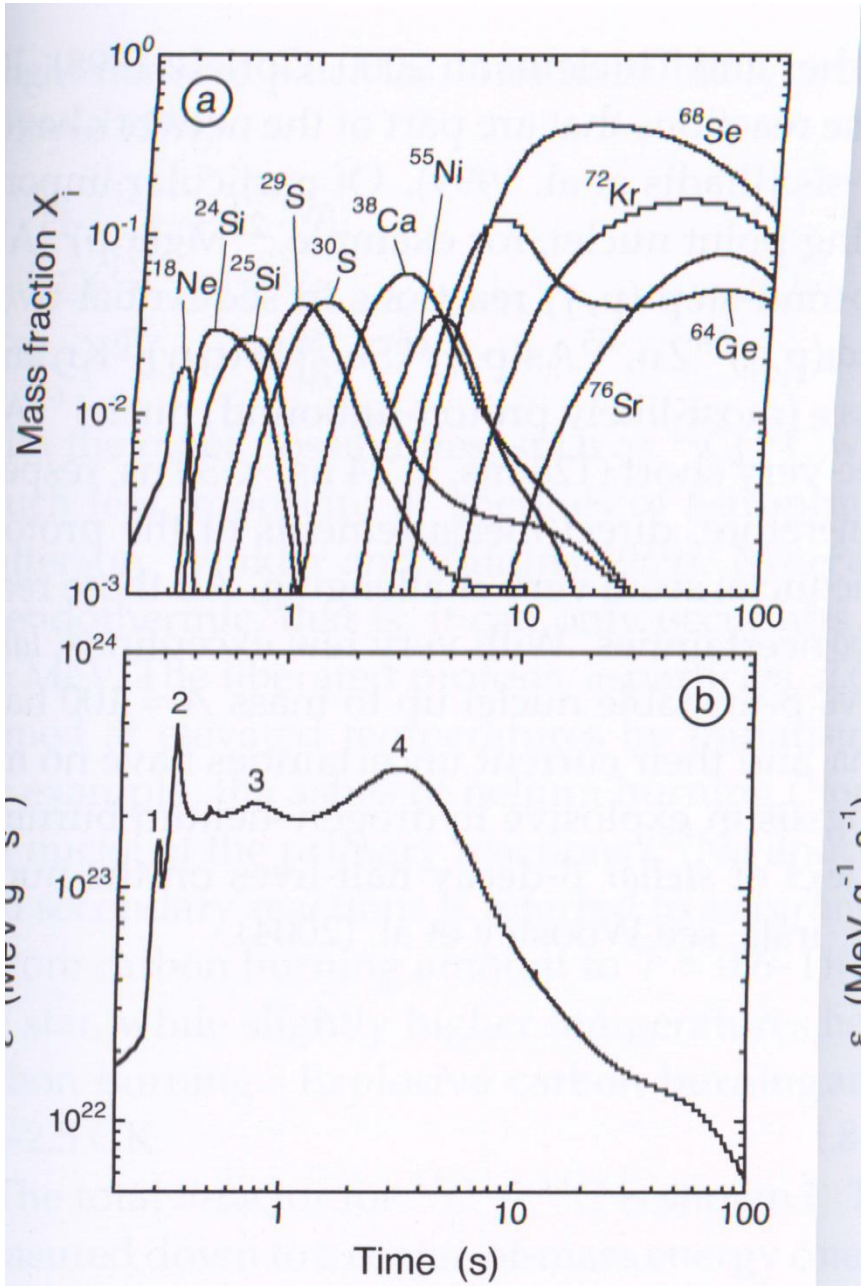
There are future experiments that need to be done: ^{68}Se is an example of one that needs mass measurements .

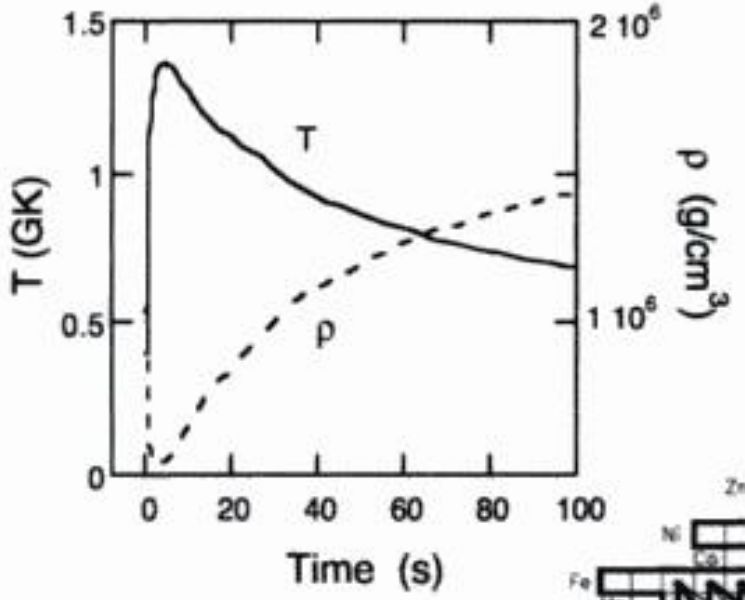


This prediction purely comes from the inverse of the ^{56}Ni(p,γ)^{57}Cu reaction rate. This rate has never been measured; this curve is from theoretical estimates with shell models.


Proton Drip Line (Theoretical)
Shaded have half-lives < 3 s
White: half-lives > 10 s
Waiting point nuclei
(p,γ) and (p,α) reaction channels
compete with each other
Sr 72 73 74 75 76
Rb 71 72 73 74 75
Kr 68 69 70 71 72 73
Br 67 68 69 70 71
Se 64 65 66 67 68 69
As 60 61 62 63 64 65 66 67
Ge 58 59 60 61 62 63 64 65
Ga 56 57 58 59 60 61 62 63
Zn 54 55 56 57 58 59 60 61
Cu 52 53 54 55 56 57 58 59
Ni 48 49 50 51 52 53 54 55 56 57
Co 47 48 49 50 51 52 53 54 55
Fe 45 46 47 48 49 50 51 52 53
Mn 44 45 46 47 48 49 50 51
Cr 42 43 44 45 46 47 48 49
V 40 41 42 43 44 45 46 47
Ti 38 39 40 41 42 43 44 45
Sc 36 37 38 39 40 41 42 43

Correlations between XRB Waiting point Abundances and Energy output

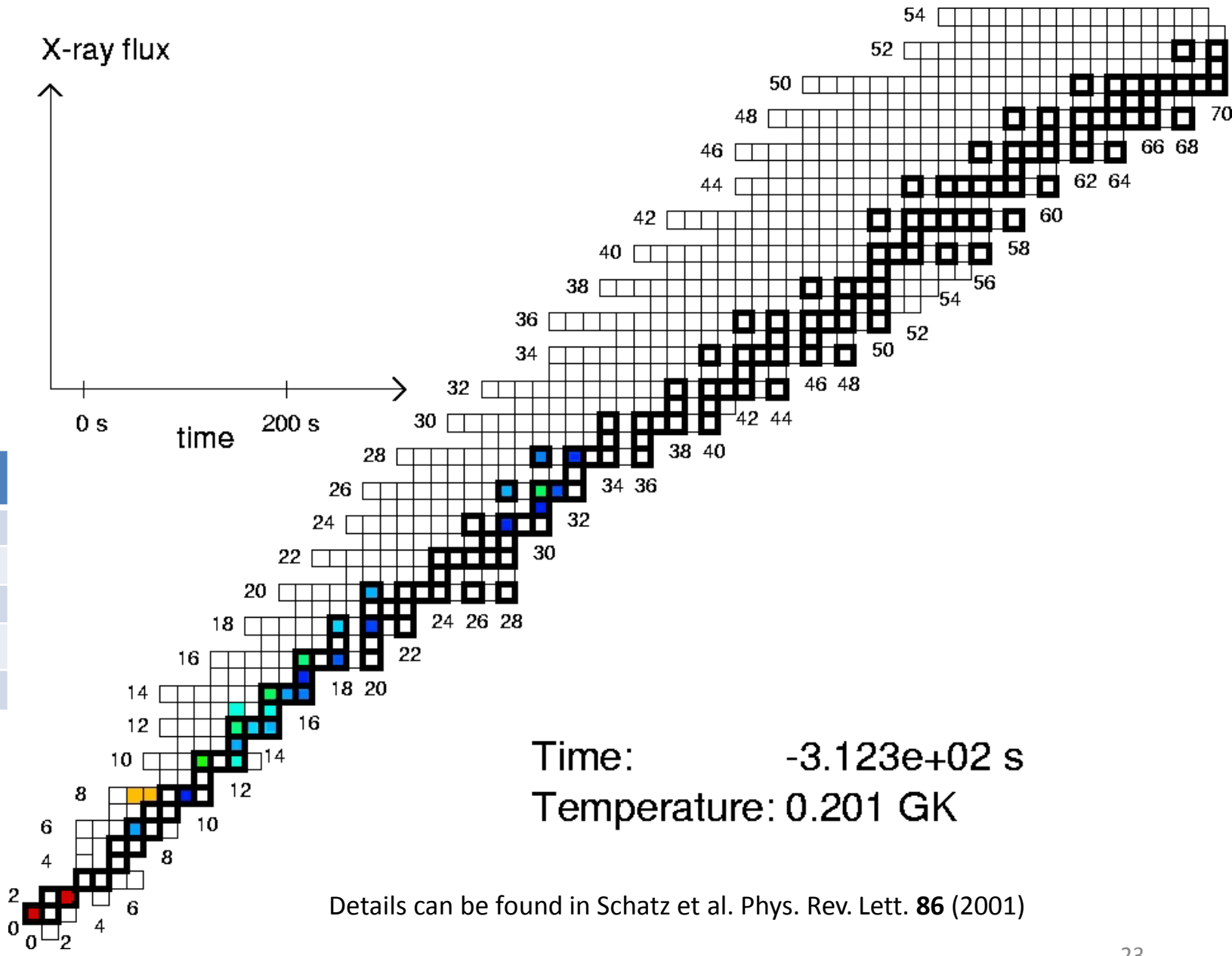



T (GK)
ρ (g/cm3)
T
ρ
Time (s)
1.5
1
0.5
0
2 10^6
1 10^6
0
20
40
60
80
100

H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
1
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52

(p,γ)
(α,γ)
(α,p)
(p,α)
(β+ν)
(β+νp)

Nuclear flow in X-Ray Burst



Colour	(X_i/Ai)
Red	1 x 10^{-3}
Yellow	~ 1 x 10^{-4}
Green	~ 1 x 10^{-5}
Turquoise	~ 1 x 10^{-6}
Blue	~ 1 x 10^{-7}

Details can be found in Schatz et al. Phys. Rev. Lett. **86** (2001)

http://www.jinaweb.org/movies/movie_burst2_v2.avi

XRB Lightcurves

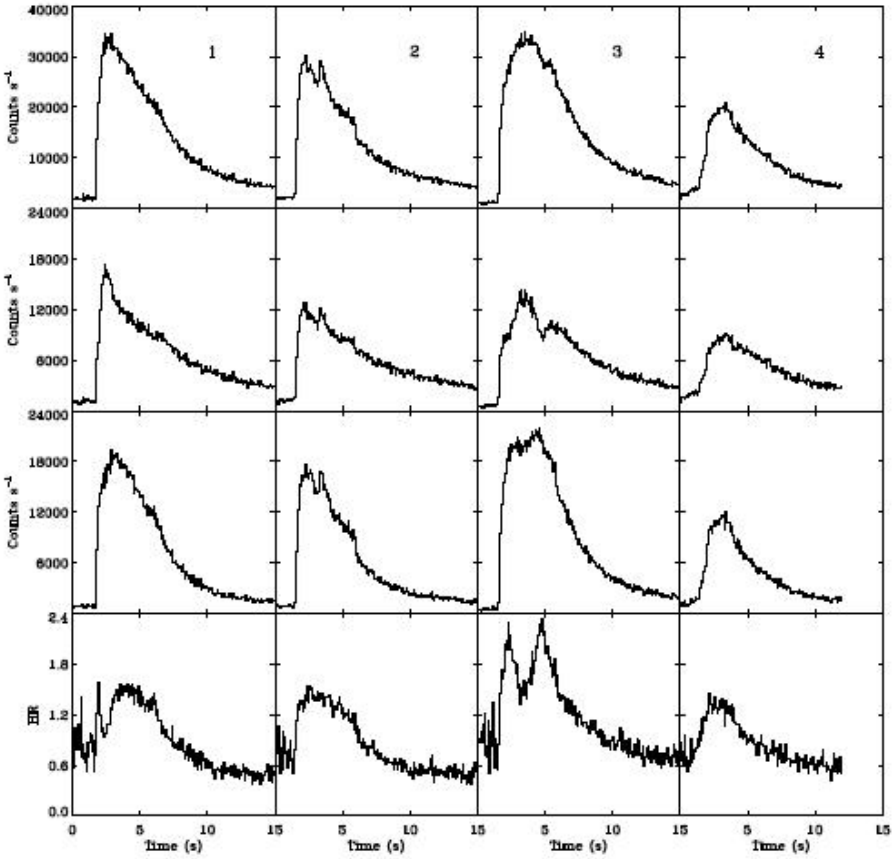
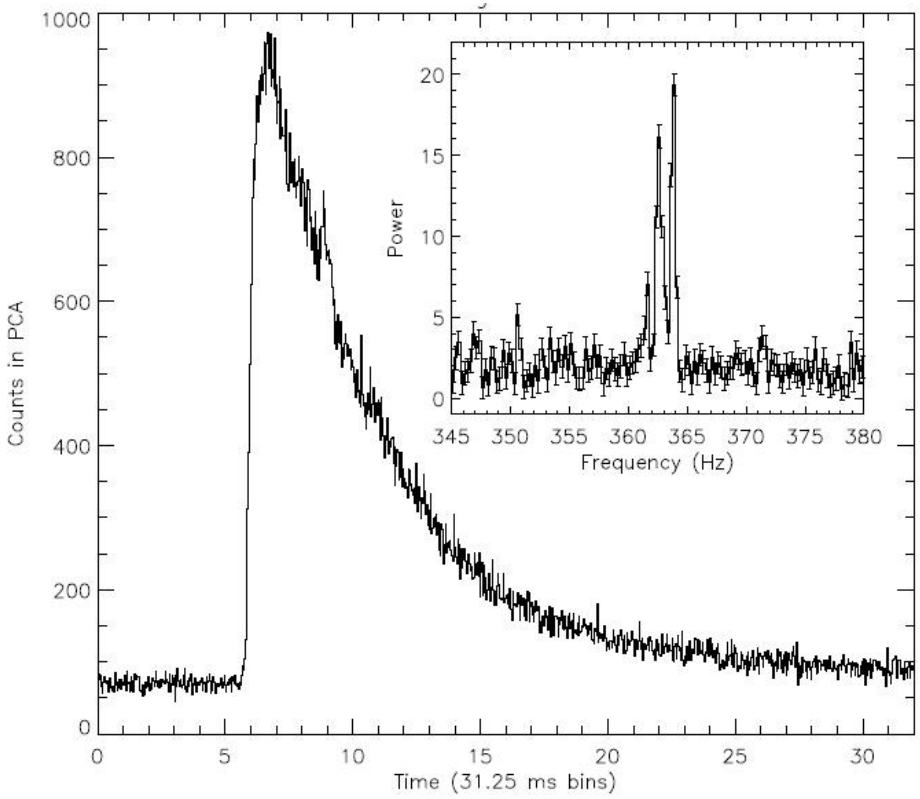


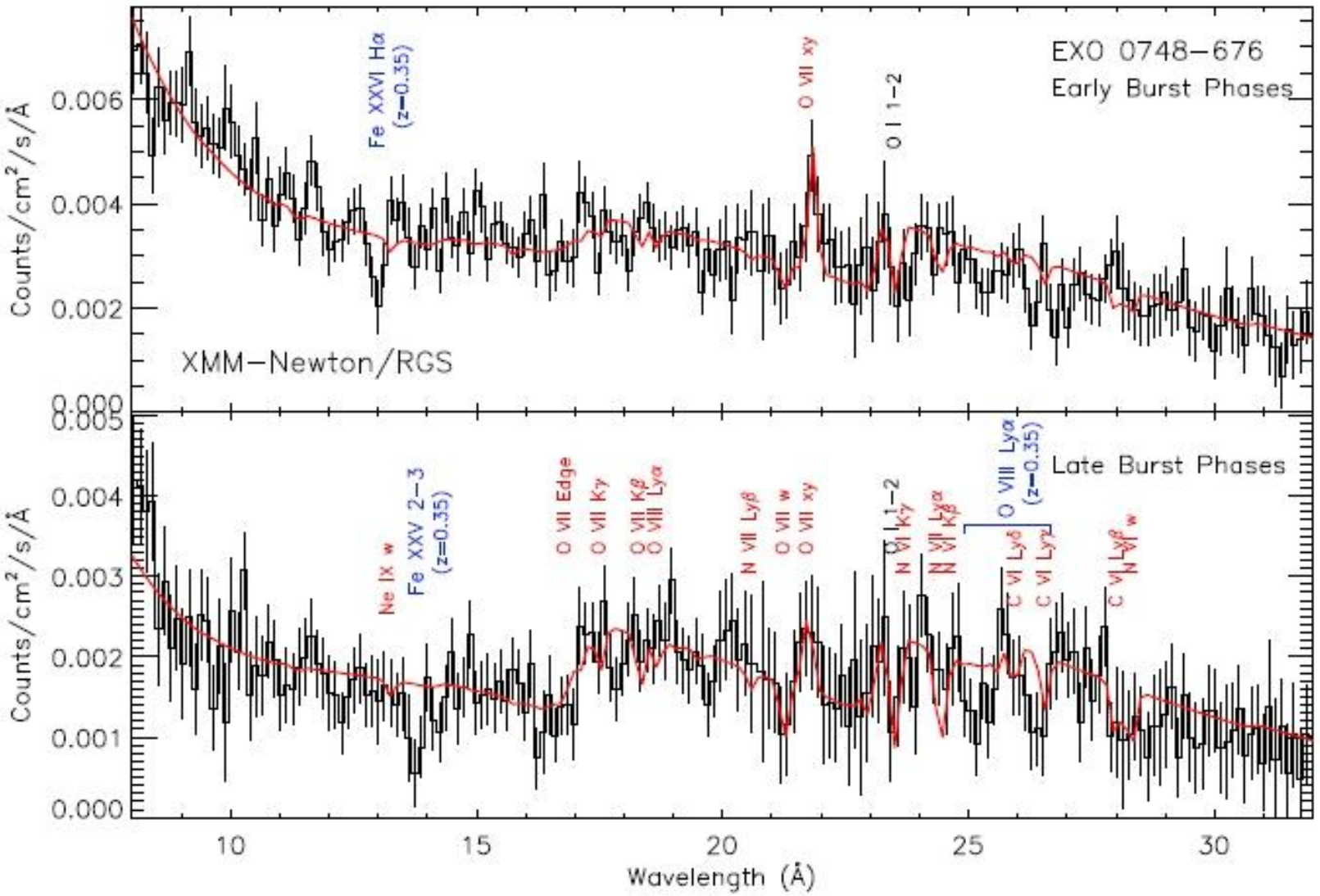
Fig. 3.4. A sample of four X-ray bursts from the LMXB 4U 1728–34 as observed with the RXTE/PCA. Each sequence shows, from top to bottom, the total 2 - 60 keV countrate, the 2 - 6 kev countrate, the 6 - 30 keV countrate, and the hardness ratio (6 - 30 keV) / (2 - 6 keV). Bursts 1 and 3 show clear evidence for PRE based on the hardness ratio evolution.

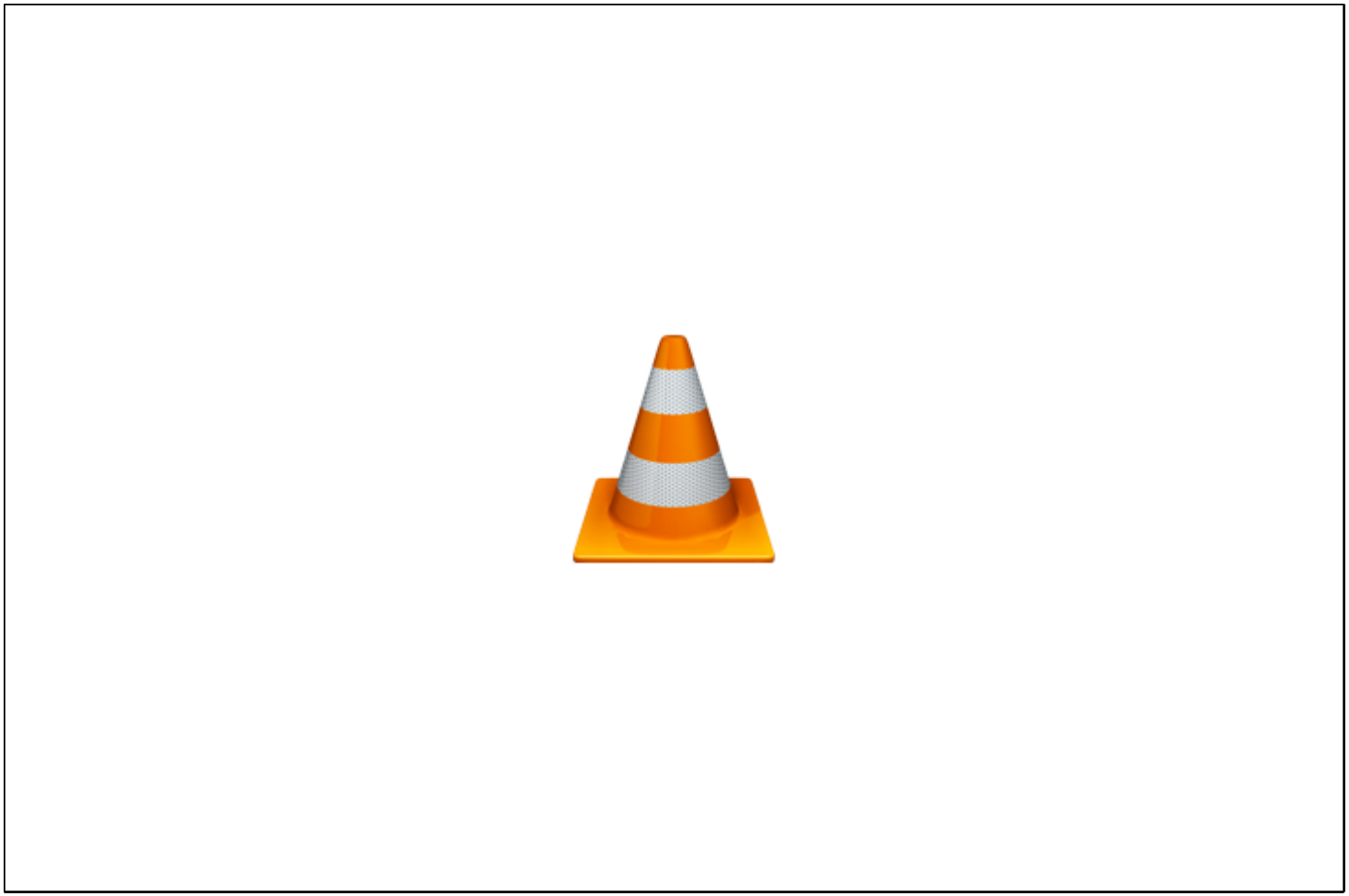


T. Strohmayer & Lars Bildsten

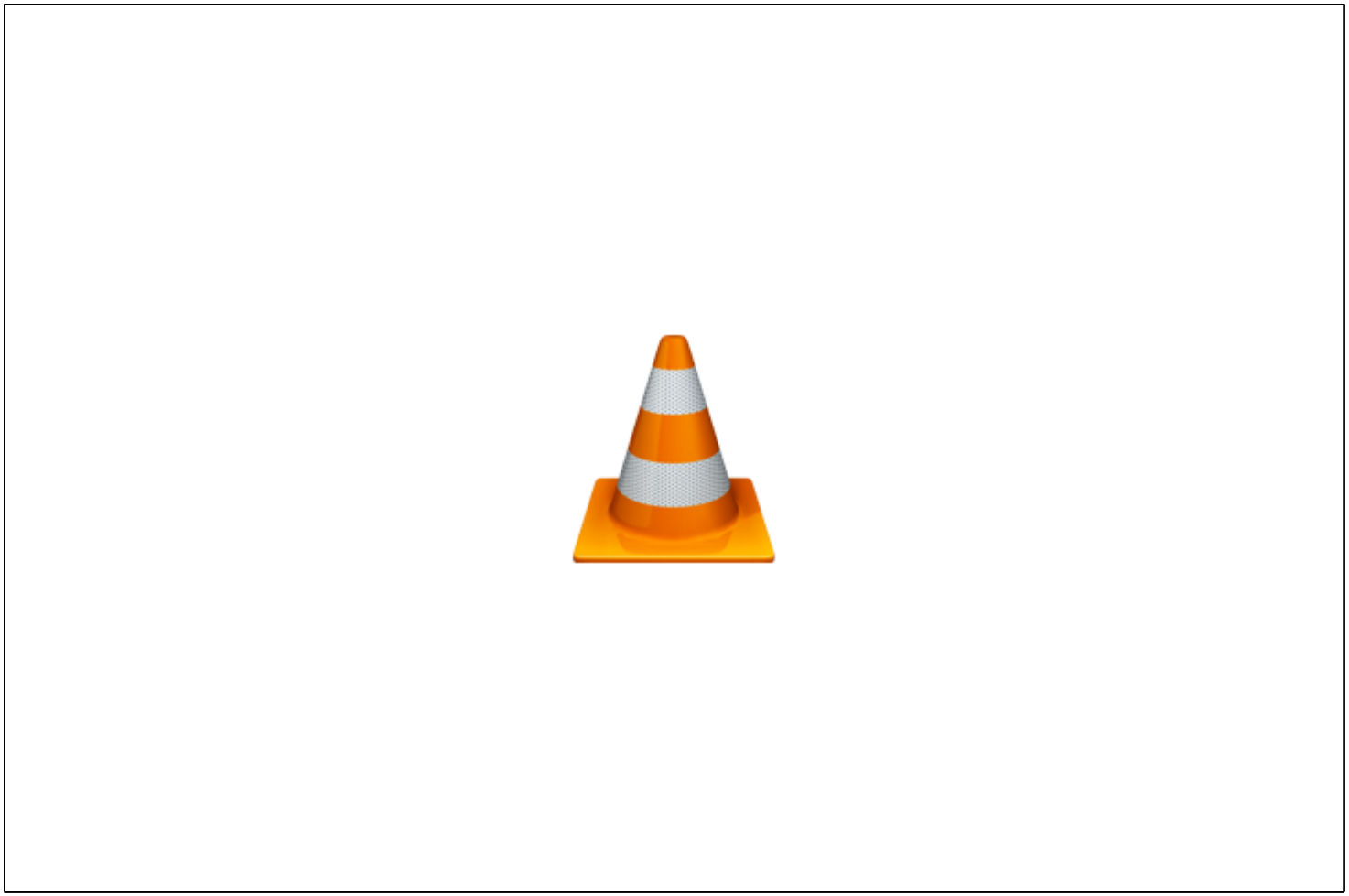
http://arxiv.org/abs/astro-ph/0301544v2

XRB Abundance Spectrum, taken with XMM Newton Telescope

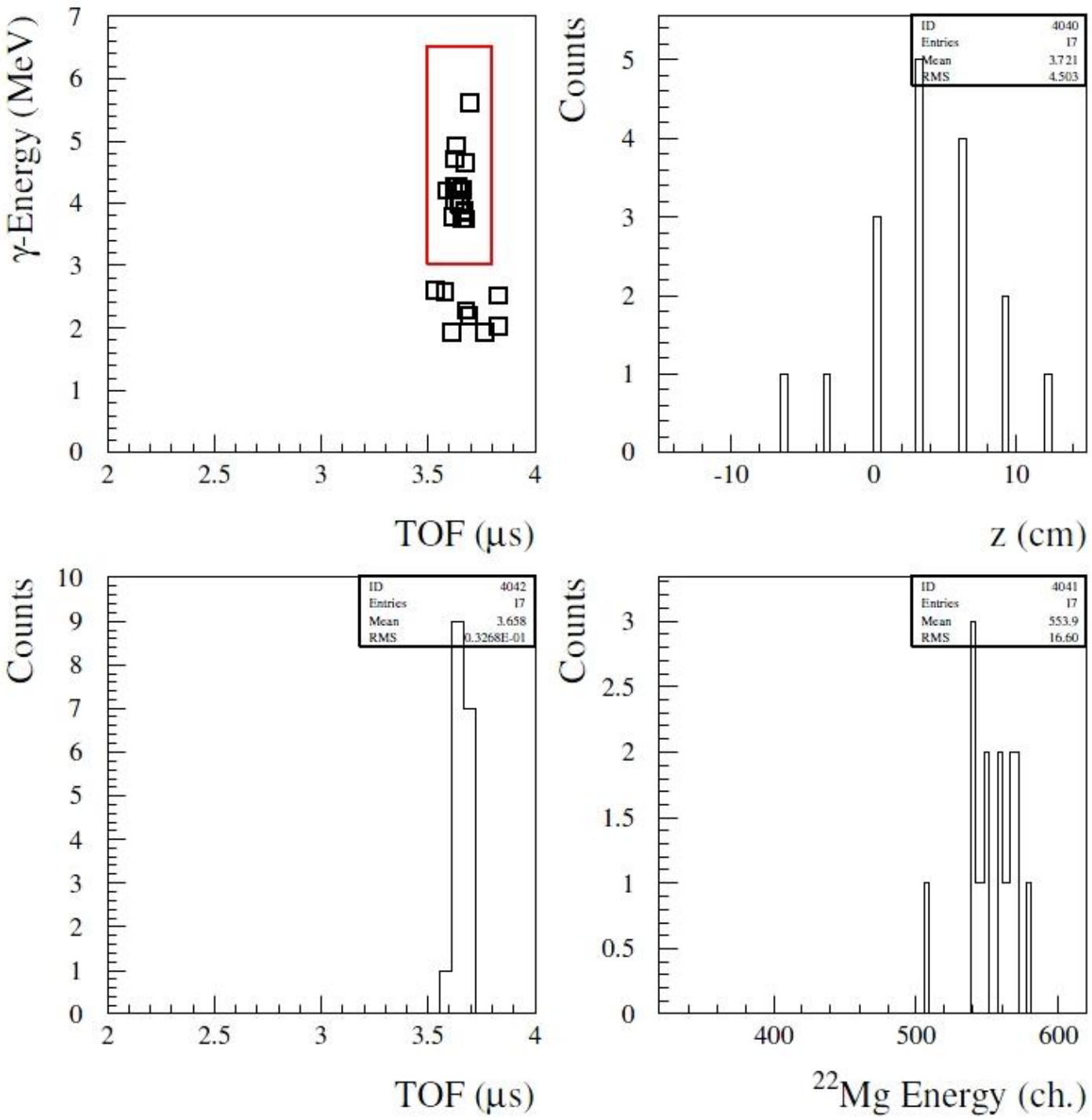




http://www.astro.sunysb.edu/mzingale/xray_gallery/xray_1.5x2_temp.mov



http://www.astro.sunysb.edu/mzingale/xray_gallery/xray_1.5x2_dens.mov


γ-Energy (MeV)
TOF (μs)
Counts
ID 4040
Entries 17
Mean 3.721
RMS 4.503
z (cm)
Counts
ID 4042
Entries 17
Mean 3.658
RMS 0.3268E-01
TOF (μs)
Counts
ID 4041
Entries 17
Mean 553.9
RMS 16.60
22Mg Energy (ch.)