End Point of the rp Process on Accreting Neutron Stars

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And Introduction to X-ray binary pulsars

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Contents

I. General Introduction: Neutron stars & X-ray binaries

Neutron stars: compact celestial object with M~1.4Msun, R ~ 10km.

·Landau 1932: "gigantic nucleus"

considerations)[1]. We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

(in between: Chadwick 1932: neutron's discovery)

·Baade & Zwicky 1934: "neutron star"
(result from supernovae)

super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be

·Oppenheimer & Volkoff 1939: Tolman-Oppenheimer-Volkoff Equations
(GR spherical static ideal fluid: gravity v.s. pressure)

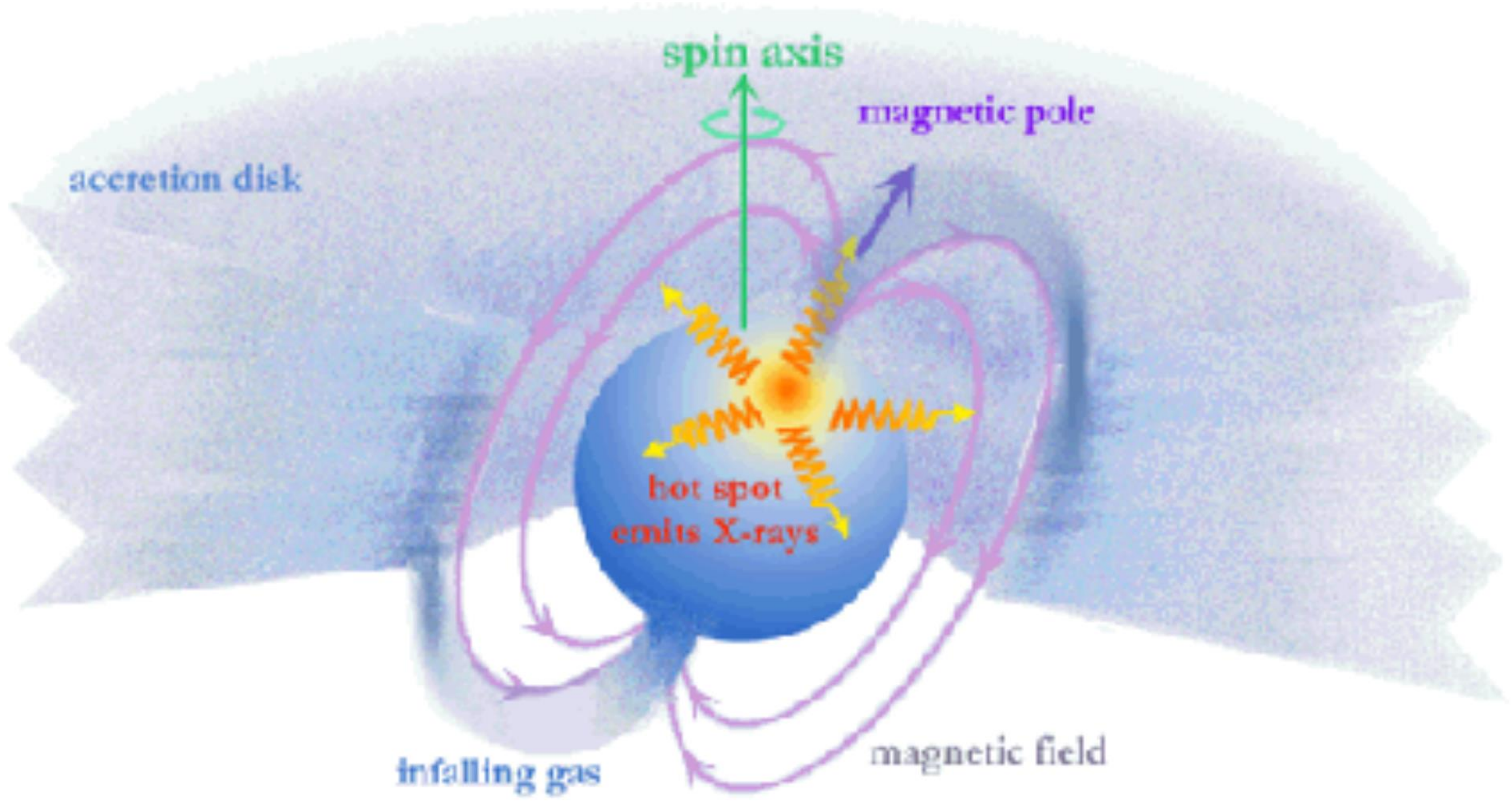
$$du/dr = 4\pi\rho(p)r^2$$

$$\frac{dp}{dr} = -\frac{p+\rho(p)}{r(r-2u)}[4\pi p r^3 + u]$$

What is $\rho(p)$? ➔➔ Equation of State problem.

Neutron stars’ electromagnetic radiation:
——From radio, optical, X-ray, to gamma ray.

An example: accreting neutron star (NS) in a binary.
➔➔can cause thermal X-ray emission.



A sketch for accreting neutron star’s X-ray emission.
https://chandra.harvard.edu/xray_sources/neutron_stars.html

NS accretes matter from the companion star

NS surface ρ↑, T↑, p↑

Thermonuclear burning
High-energy photons emission

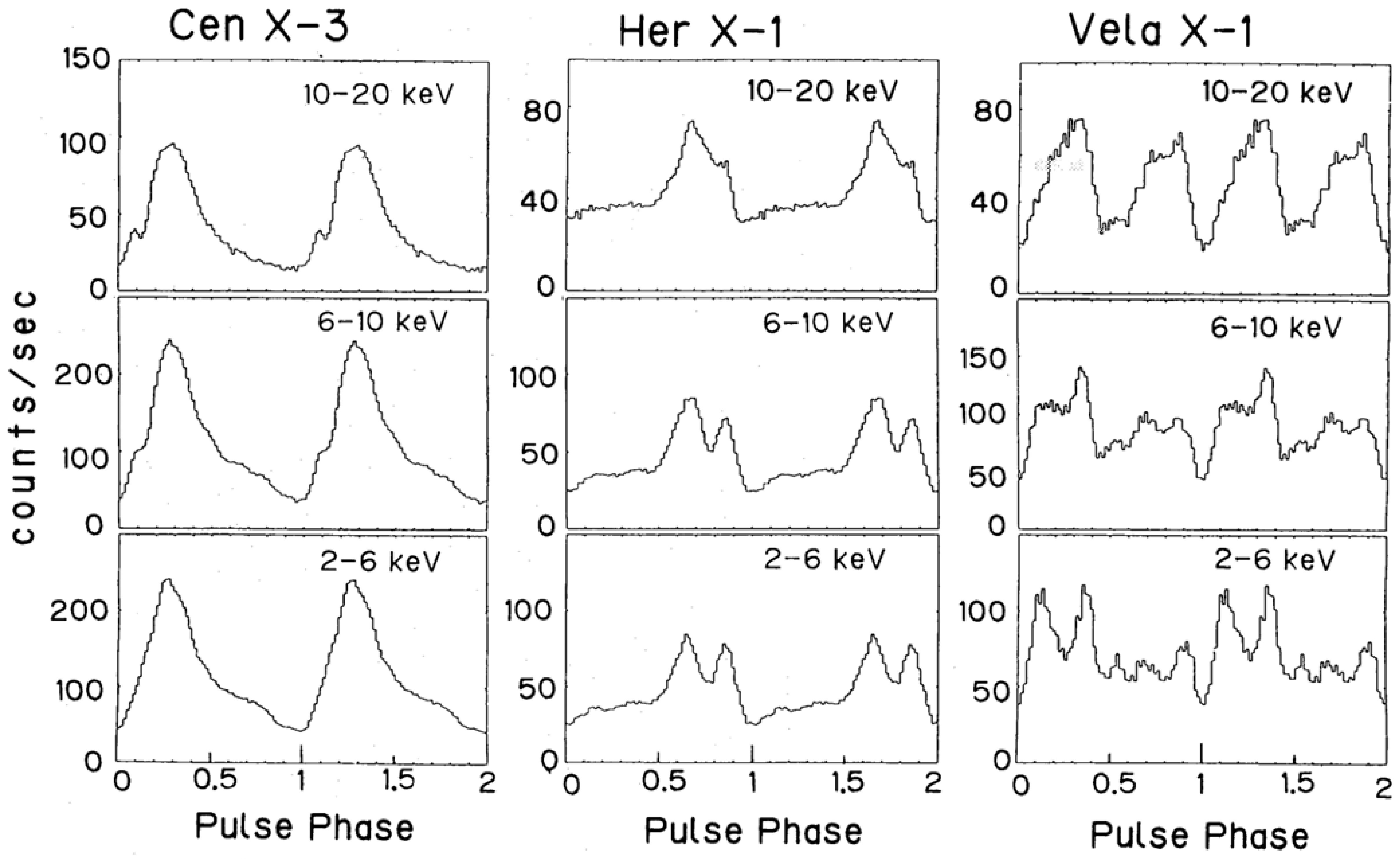
Stable

Accreting X-ray pulsars (AXPs)
Giacconi et al. 1971 *ApJ*, 167, 67.

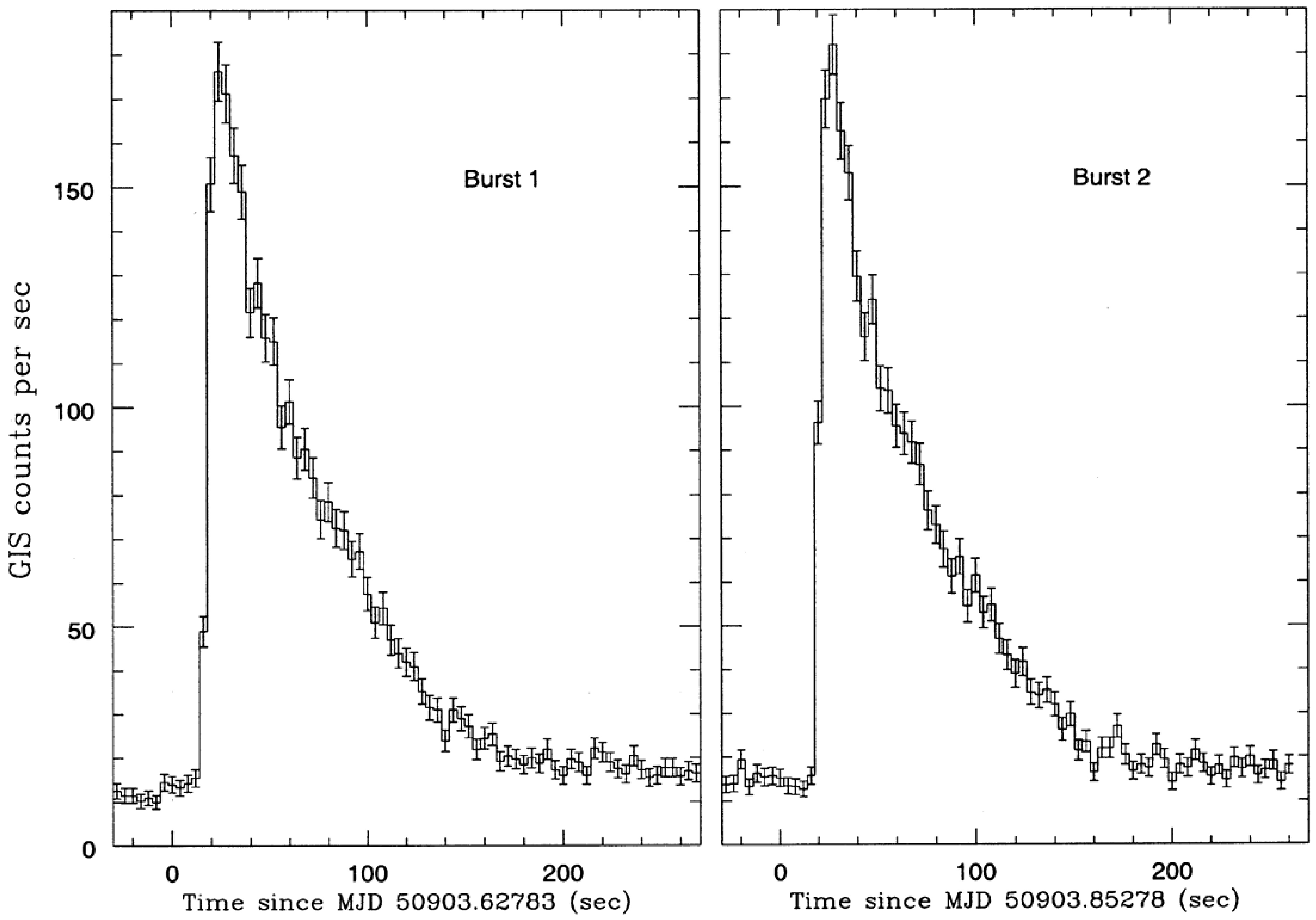
Unstable

Type-I X-ray burst
Babushkina et al. 1975 *Soviet Astronomy Letters*, 1, 32

Examples of X-ray light curves.



Accreting X-ray pulsars
(Nagase 1989, *PASJ*, 41, 1)



Type-I X-ray bursts
(Kong et al. 2000, *MNRAS*, 311, 2)

Let’s see what has been done
in Schatz et al. 2001 ➔➔➔

II. Paper's Introduction

Accreting material: Hydrogen rich.

➔rapid proton capture process (rp-process: X+p➔Y+…)
(Wallace & Woosley 1981, *ApJS*, 45, 398)

Hydrogen ➔ rp-process + beta decay ➔ heavier elements

This paper's finding: a natural termination of this process.

Importance: understanding X-ray lightcurves

➔Reveal NS crust properties (thermal & electrical)

➔➔Figure out Magnetic field evolution, quiescent luminosity (when no burst)

(Brown & Bildsten 1998, *ApJ*, 496, 2; Brown, Bildsten & Rutledge 1998, *ApJ*, 504, 2)

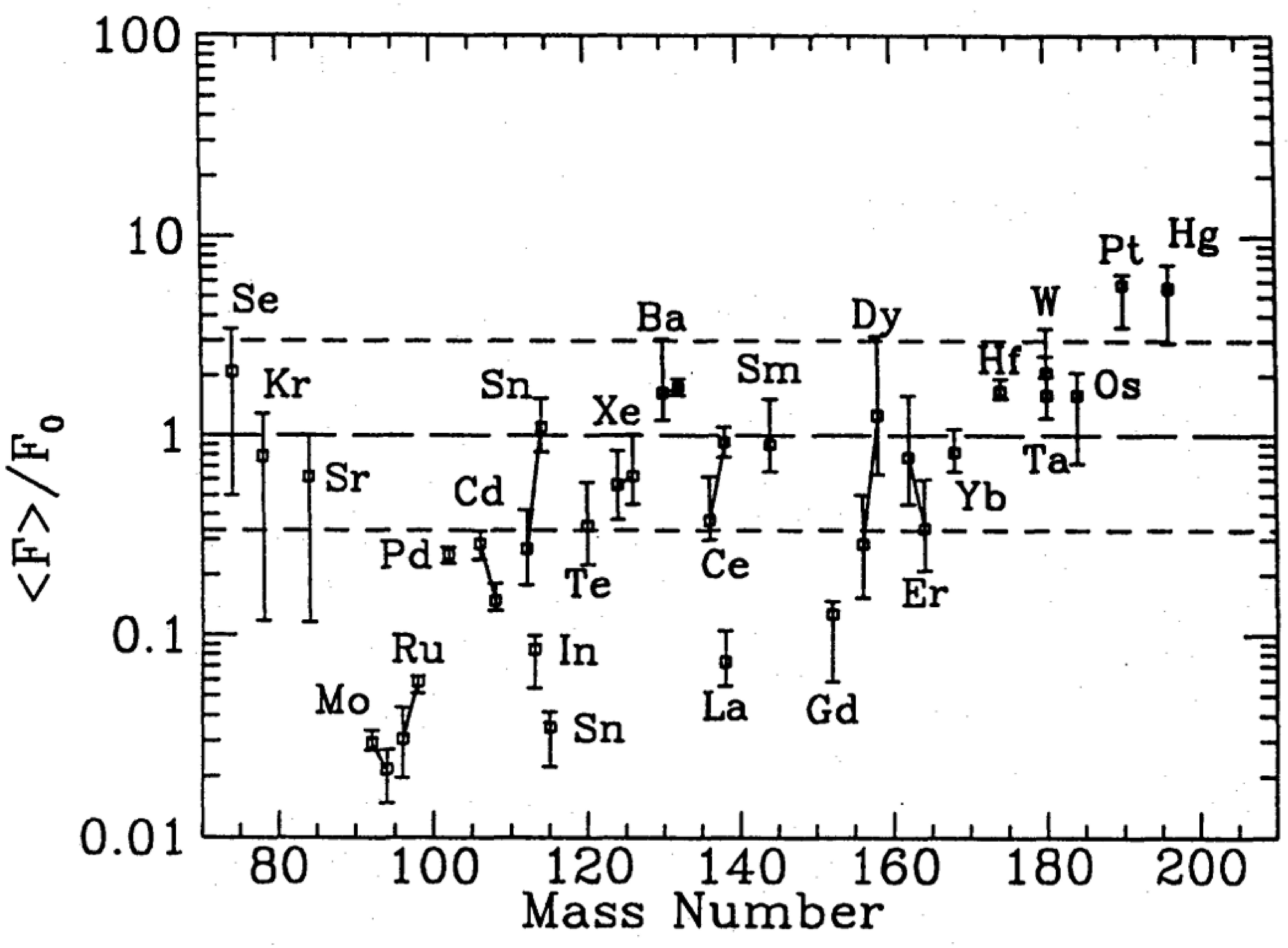
➔Understand Gravitational Waves from deformed crust

(Bildsten 1998, *ApJ*, 501, 1; Ushomirsky, Bildsten & Cutler 2000, *MNRAS*, 319, 3)

➔Understand nucleosynthesis of some light p nuclei $^{92,94}\mathrm{Mo}$ $^{96,98}\mathrm{Ru}$

➔Nucleosynthesis of some proton-rich nuclei: if only through p-process in Type II Supernovae:

(Rayet et al. 1995, *A&A*, 298, 517)



Mean p-process layer overproduction factor (with respect to solar):

$$\langle F_i \rangle(M) = m_i(M)/(M_p(M) X_{i,\odot})$$

$$F_0(M) = \sum_i \langle F_i \rangle(M)/35$$

A severe **underproduction** of Mo, Ru p-isotropes.

➔Need to be solved.
(Other routines?)

Dash line: range of solar system composition.

·Previous rp(p)-process simulation on X-ray bursts:
Review the end points…

Many early studies: based on ending up at $^{56}\mathrm{Ni}$.

The nonstandard nuclear burning has led to the unexpected result that in the regime of high mass accretion rates, $\dot{M} \gtrsim 2 \times 10^{-9} M_{\odot}\,\mathrm{yr}^{-1}$, no carbon and little helium is produced. Hydrogen burning proceeds via proton capture onto heavy nuclei, perhaps leading ultimately to the buildup of iron-group species. We believe that this type of nuclear processing proceeds in X-ray pulsars where current models (Davidsen and Ostriker 1973) attribute the pulses as arising from the accretion of matter onto the polar caps. Since the high

Taam & Picklum 1978, *ApJ*, 224, 210

Several later studies: larger networks ending in **Kr-Y** region.
(e.g., Wallace & Woosley 1981, *ApJS*, 45, 398)

or a simplified 16 nuclei network ➔ **Cd**
(e.g., Wallace & Woosley 1984, AIP Conference Proceedings, 115, 319)

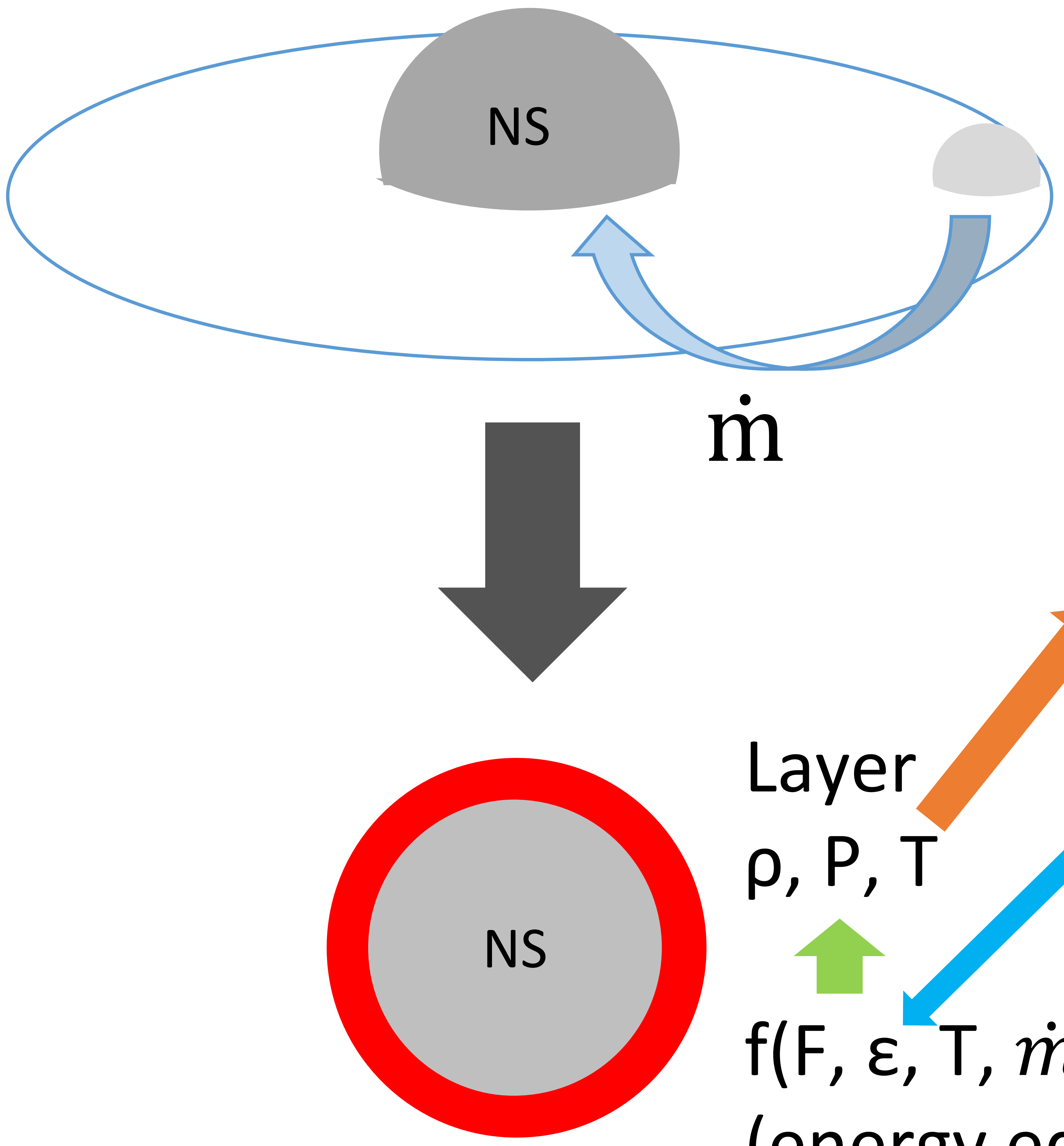
More recent: the network has been extended to **Sn** (Schatz et al. 1998, *PhR*, 294, 167).

(The introduction to network calculation lies in Method section later.)

$$\dot{m}_{\rm Edd} = 8.8 \times 10^4 \ {\rm g/cm^2/s}$$

III. Methods

(i) Physical models:



Layer

ρ, P, T

Nuclear reaction

Network calculation

f(F, ε, T, $\dot{m}$, t, …) = 0

(energy equation)

(and pressure balance…)

Initial conditions:

X-ray burst: Z = 0.001, $\dot{m}$ = 0.1 $\dot{m}_{\rm Edd}$

Crust out flow: 0.15MeV/accreted nucleon.

AXP: XYZ=solar, $\dot{m}$ = 40 $\dot{m}_{\rm Edd}$

g = $1.9 \times 10^{14} \ {\rm cm/s^2}$

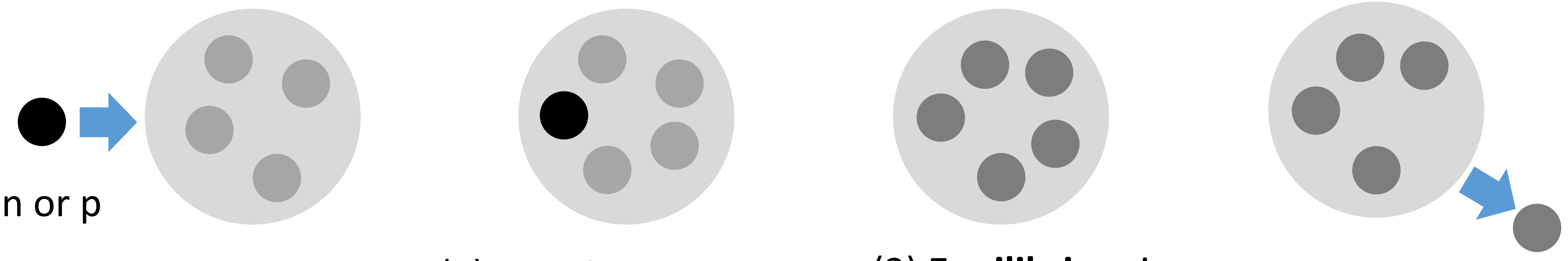
$$P = gy \quad dy = -\rho \ dz \quad g \approx GM/R^2$$

Schatz et al. 1999, *ApJ*, 524, 2

$$\frac{\partial F}{\partial y} + \epsilon = C_p \left(\frac{\partial T}{\partial t} + \dot{m} \frac{\partial T}{\partial y} \right) - \frac{C_p T \dot{m}}{y} \nabla_{\rm ad}$$

L. Bildsten in *The Many Faces of Neutron Stars*

(ii) Nuclear reaction network calculation: Wolfenstein-Hauser-Feshbach approach (Bohr 1936; Wolfenstein 1951; Hauser & Feshbach 1952)



(1) Injection (Pre-collision)

(2) Forming a compound nucleus (CN)

(3) **Equilibrium** in The compound nucleus

(4) Further decay…

$$\underset{\alpha}{A + a} \rightarrow C \rightarrow \begin{cases} B_0 + b_0 \\ B_1^* + b_1 \\ \quad \cdots \\ B_n^* + b_n \\ \quad \cdots \end{cases} \quad \beta$$

$$\sigma_{\alpha\beta,l} = \sigma_{CN,l}(\alpha) G_b \begin{cases} \sigma_{CN,l}(\alpha) = \pi \lambda_\alpha^2 T_\alpha g_\alpha \\ G_b = \dfrac{\Gamma_b}{\Gamma} \end{cases}$$

T: transmission coef

Decay **possibility** through β

$$\Sigma_i G_i = \Sigma_i \frac{\Gamma_i}{\Gamma} = 1$$

Γ: energy level width = $\hbar/\tau$ = $\hbar W = \hbar(W_1 + W_2 + W_3 + \cdots)$

Refer to 《原子核物理学》卢希庭 9.9节

Nuclear reaction network calculation: Wolfenstein-Hauser-Feshbach approach
(Bohr 1936; Wolfenstein 1951; Hauser & Feshbach 1952)

$$\sigma_{\alpha\beta,l} = \sigma_{CN,l}(\alpha)G_b \quad \begin{cases} \sigma_{CN,l}(\alpha) = \pi\lambda_\alpha^2 T_\alpha g_\alpha \\ G_b = \dfrac{\Gamma_b}{\Gamma} \end{cases}$$

T: transmission coef calculated

$$\underset{\alpha}{A + a} \rightarrow C \rightarrow \begin{cases} B_0 + b_0 \\ B_1^* + b_1 \\ \quad \ldots \\ B_n^* + b_n \\ \quad \ldots \end{cases} \beta$$

$$g_\alpha = \frac{2I_C + 1}{(2I_a + 1)(2I_A + 1)}$$

$$\Sigma_i G_i = \Sigma_i \frac{\Gamma_i}{\Gamma} = 1$$

Decay possibility through β

Detailed balance:
(散射矩阵元对角项相等)

$$\frac{\sigma_{CN,l}(\alpha)p_\alpha^2}{g_\alpha \Gamma_a} = \frac{\sigma_{CN,l}(\beta)p_\beta^2}{g_\beta \Gamma_b}$$

p: momentum

H-F equation:

$$\sigma_{\alpha\beta,l} = \pi\lambda_\alpha^2 T_\alpha g_\alpha \frac{\sigma_{CN,l}(\beta)p_\beta^2/g_\beta}{\Sigma_i \sigma_{CN,l}(i)p_i^2/g_i} = \pi\lambda_\alpha^2 T_\alpha T_\beta g_\alpha / \Sigma_i T_i$$

In this paper, the calculations are done with a code NON-SMOKER .
(Rauscher & Thielemann 2000, *ADNDT*, 75, 1)

Refer to 《原子核物理学》卢希庭 9.9节

SMOKER: Statistisches Model fur Kern Reaktionen.

IV. Results

(i) Nuclear reaction network

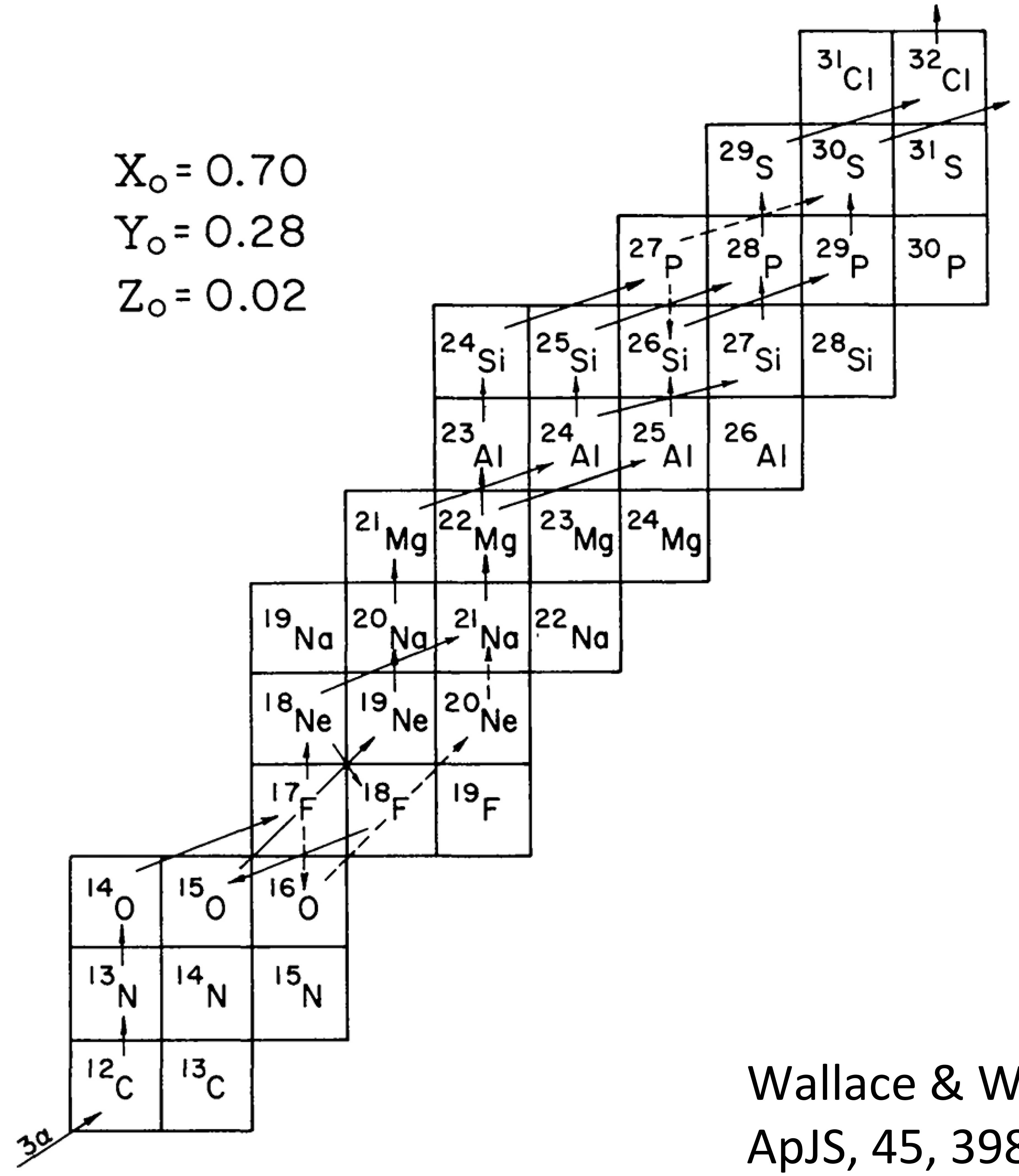
From He to the Sc region:
3α-reaction, (α, p), (p, γ) processes
(Follow Wallace & Woosley 1981, ApJS, 45, 398).

Ignition density: $1.1 \times 10^6 \ \mathrm{g/cm^3}$

Peak temperature: 1.9 GK

Rise timescale: 4s

Cooling phase: 200s



Wallace & Woosley 1981
ApJS, 45, 398

FIG. 10.—The dominant nuclear flows during a thermonuclear runaway of the hydrogen-helium shell on the surface of an accreting neutron star (model B). Flows are evaluated when the runaway has progressed to a temperature $T_9 \approx 0.8$, and density $\rho = 6.1 \times 10^5$ g cm^{-3} ($t \approx 6308$ s). Two major chains of (α, p) and (p, γ) reactions extend from ^{18}Ne to ^{30}S and from ^{19}Ne to ^{29}S and beyond.

Beyond Fe: (p,γ), (α,p), EC/β+decay, reaches (99-101)Sn ~ 80s after burst peak.

proton

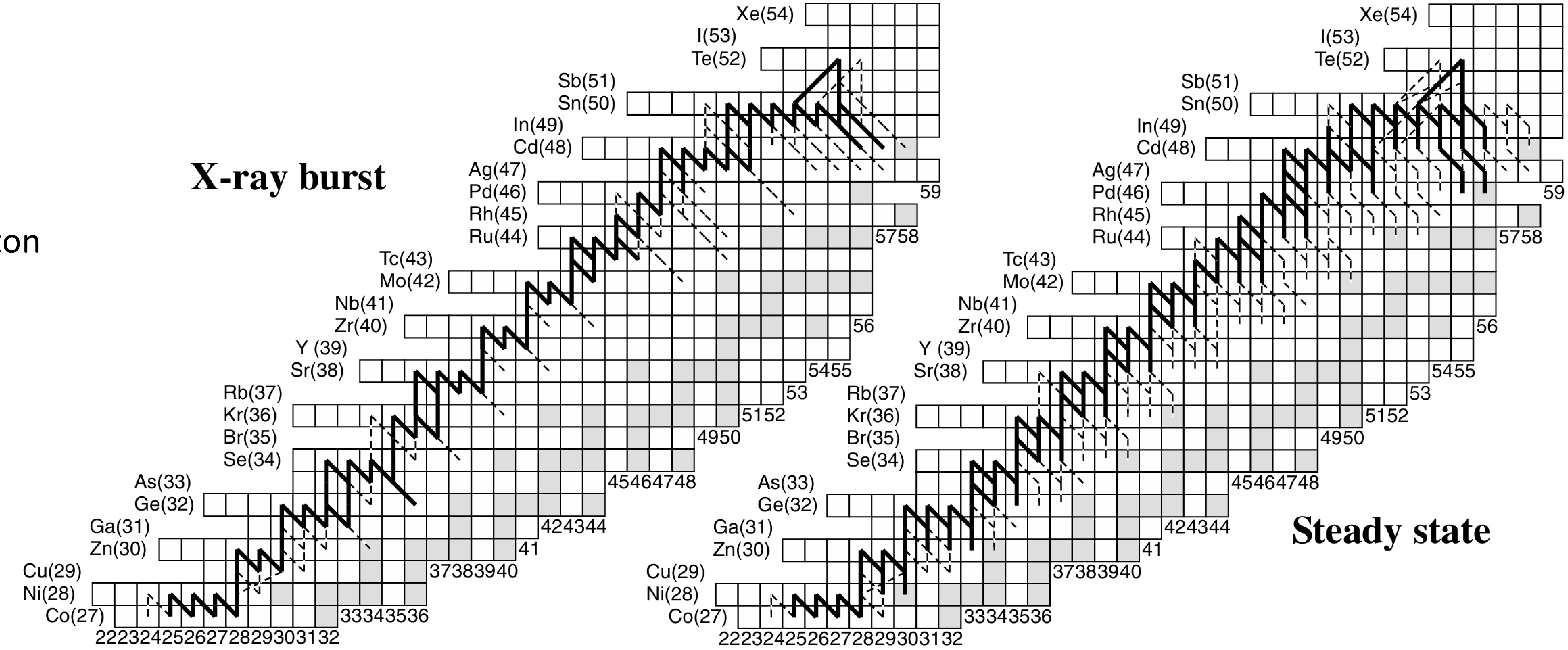


FIG. 1. The time integrated reaction flow above Ga during an x-ray burst and for steady-state burning. Shown are reaction flows of more than 10% (solid line) and of 1%−10% (dashed line) of the reaction flow through the 3α reaction.

neutron

Beyond Sn: 105 Sn(p,γ)106 Sb(p,γ)107 Te(γ,α)103 Sn

105Sn	106Sb	107Te
32.7 s	0.6 s	3.1 ms
ε = 100.00%	ε	α = 70.00%
εp = 0.01%		ε = 30.00%

Credit: NNDC

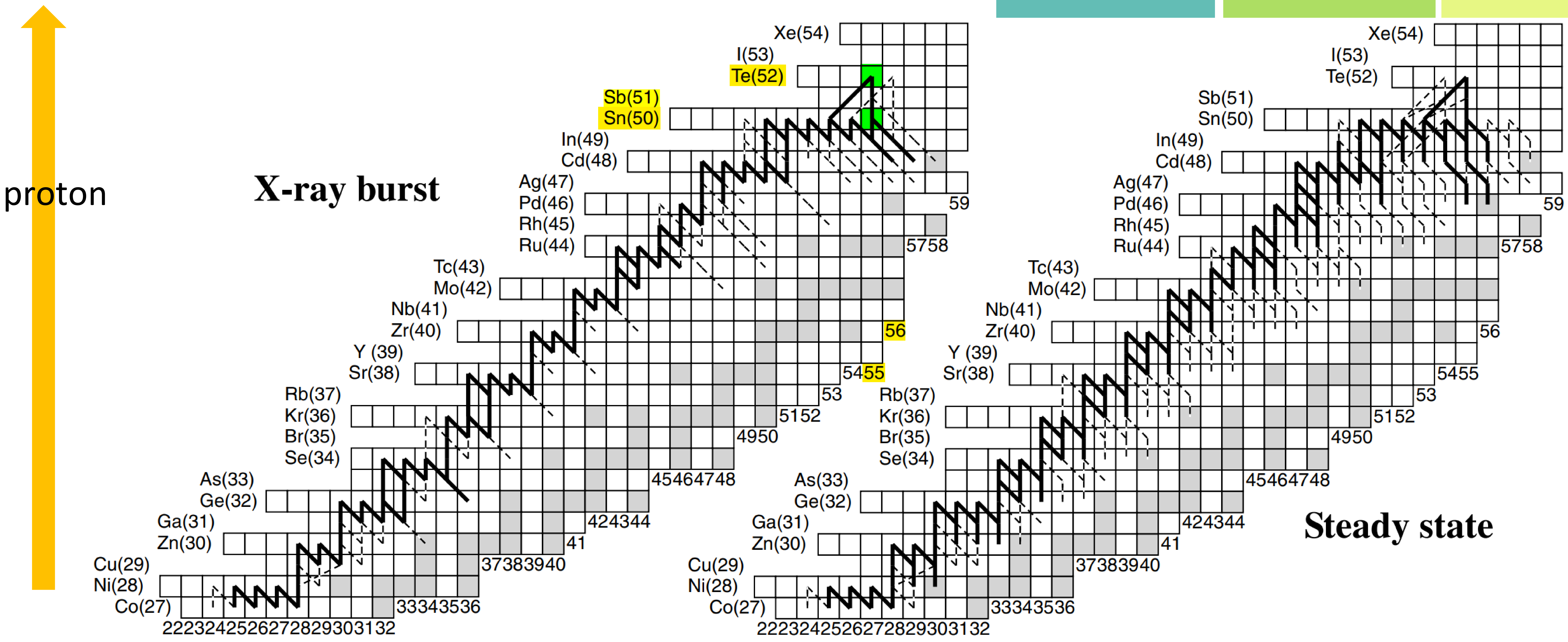
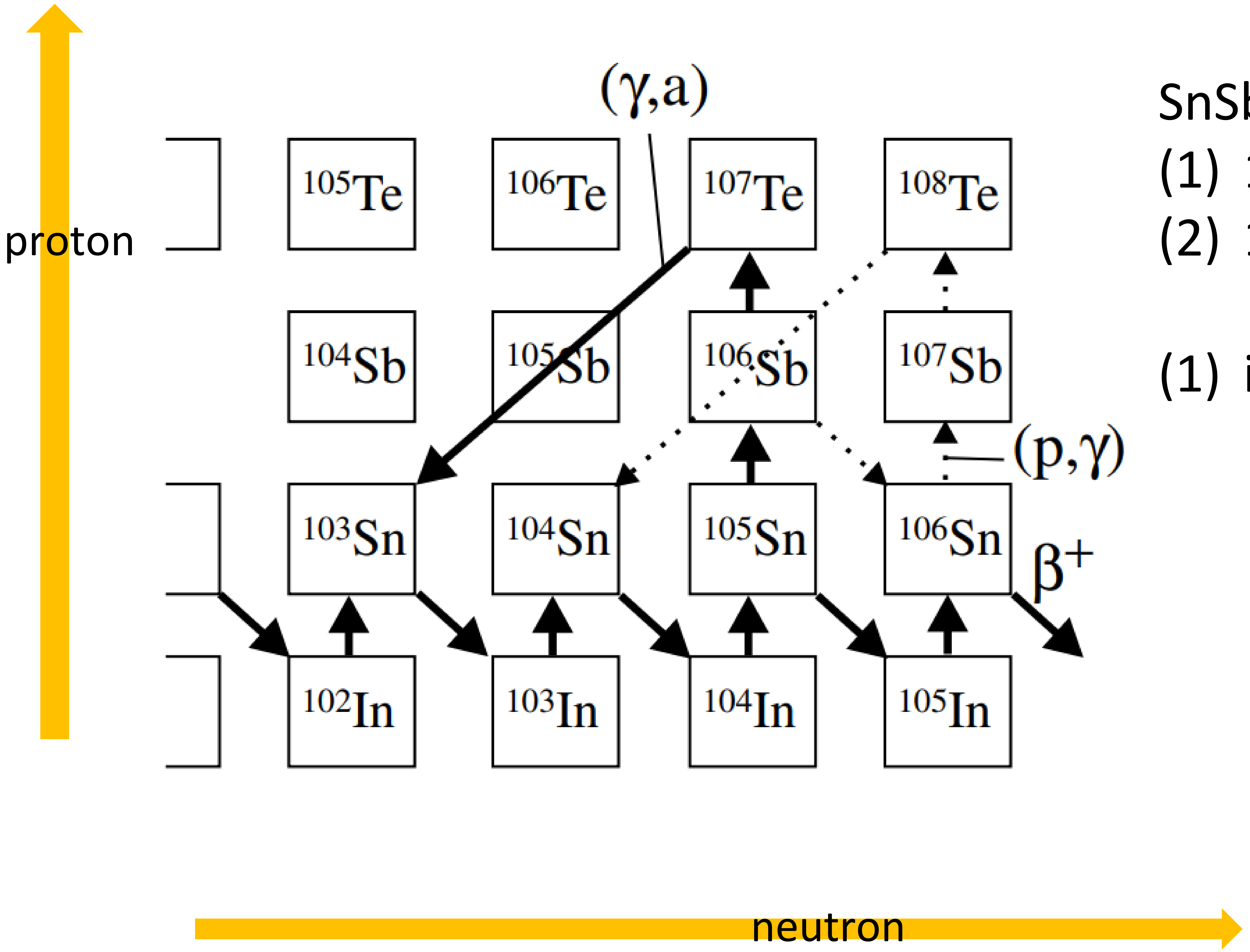


FIG. 1. The time integrated reaction flow above Ga during an x-ray burst and for steady-state burning. Shown are reaction flows of more than 10% (solid line) and of 1%−10% (dashed line) of the reaction flow through the 3α reaction.

neutron

106-108 Te: α unbounded by ~4MeV (Page et al. 1994, *PRC*, 49, 6).
107 Te: a known ground state α emitter (Schardt et al. 1979, *NuPhA*, 326, 1).



SnSbTe cycles: two cycles

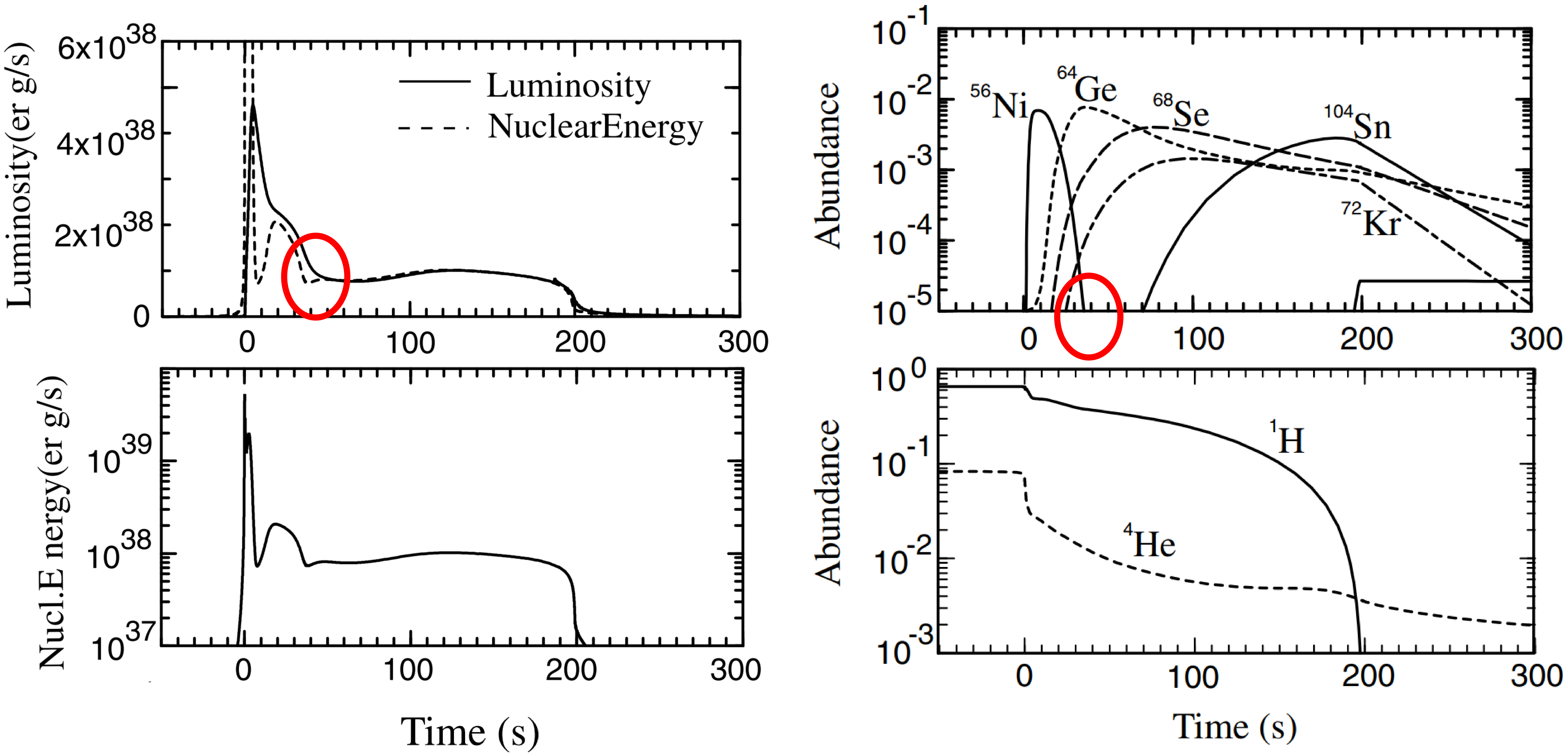
(1) 105 Sn(p,γ)106 Sb(p,γ)107 Te(γ,α)103 Sn
(2) 106 Sn(p,γ)107 Sb(p,γ)108 Te(γ,α)104 Sn

(1) is stronger than (2).

Change initial conditions:
can not beyond SnSbTe.

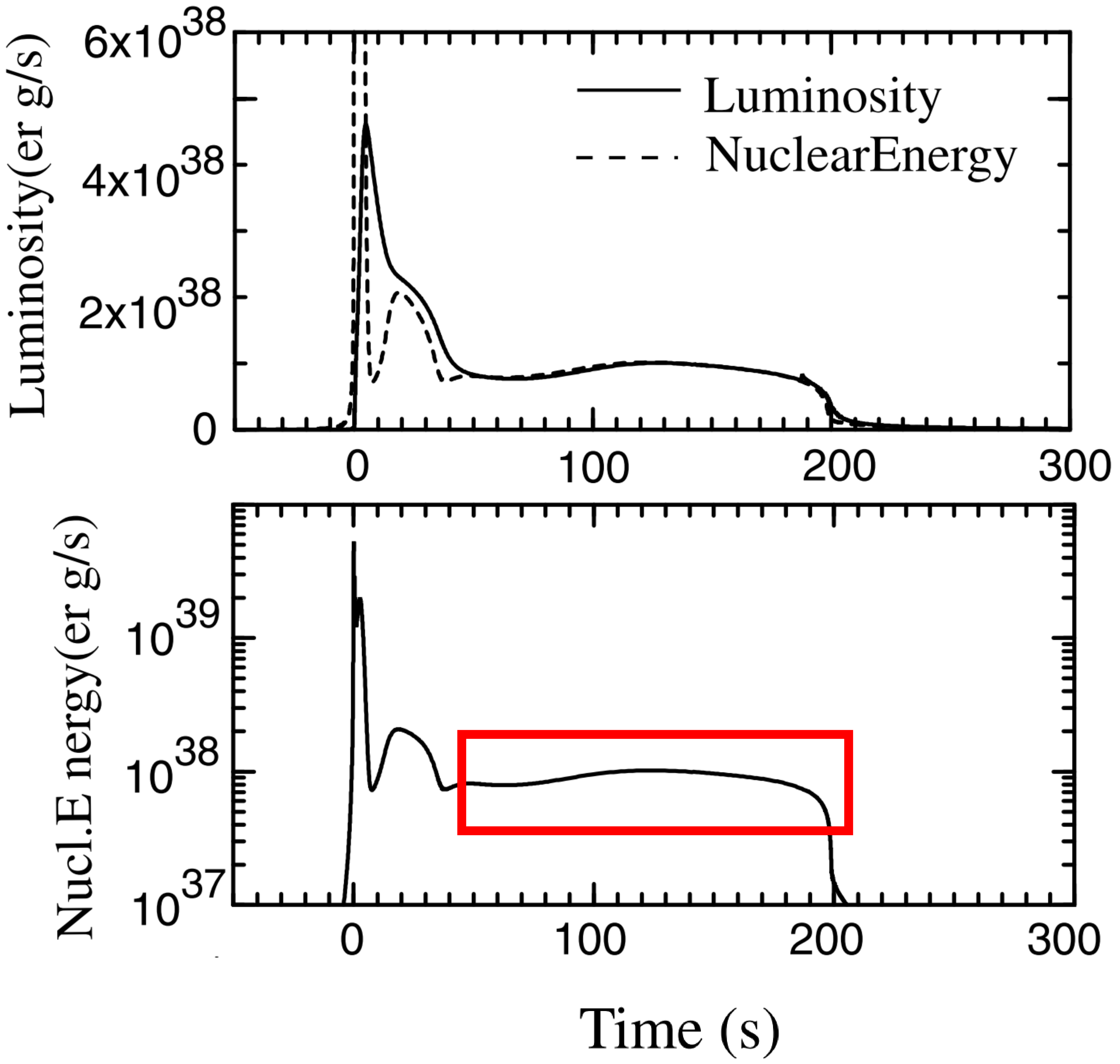
(ii) Light curves, changes of energy & Abundance

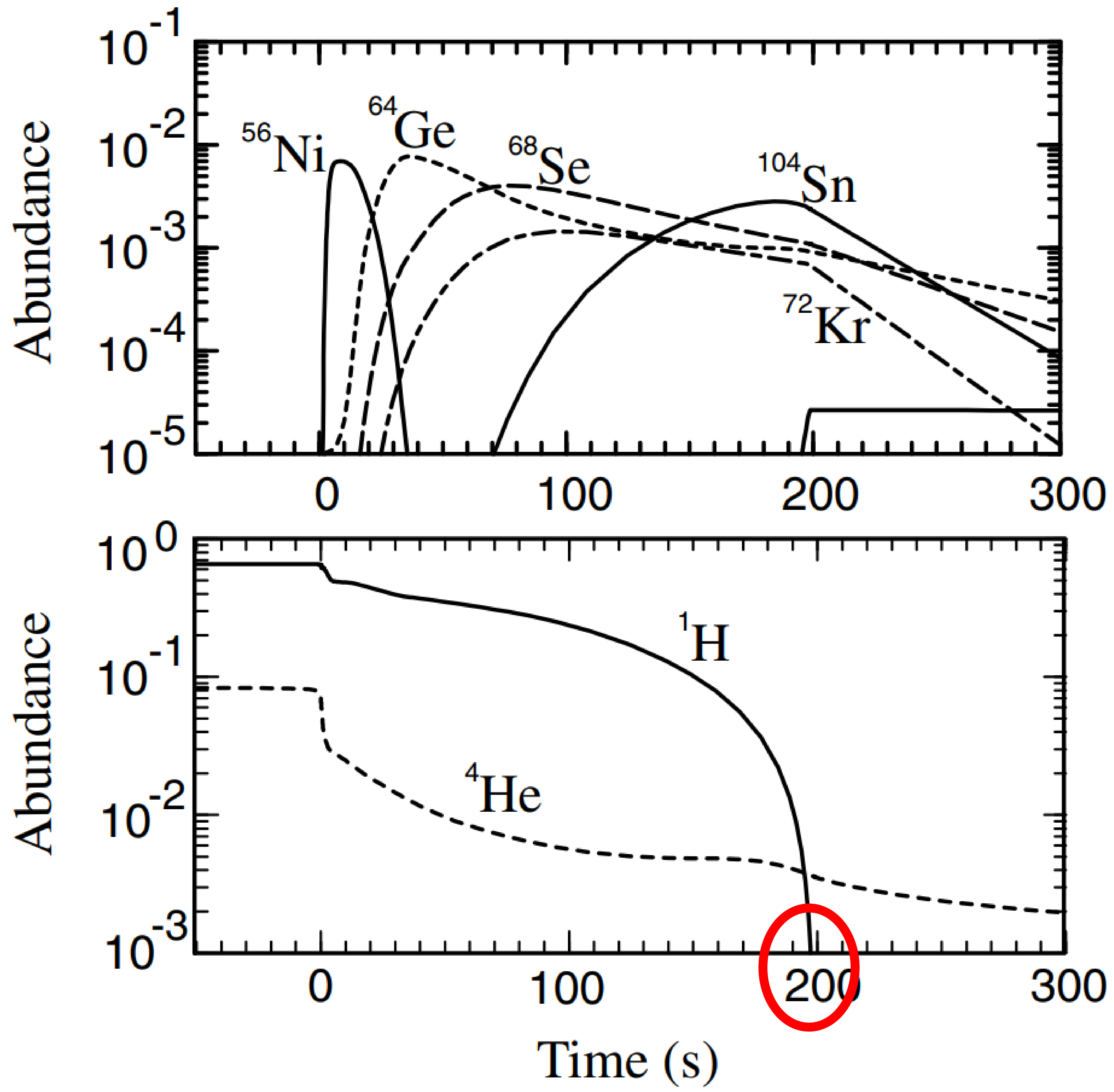
Some long-lived "waiting point" nuclei.



Burning beyond 56 Ni ➔ Extended burst tail.

Some long-lived “waiting point” nuclei.

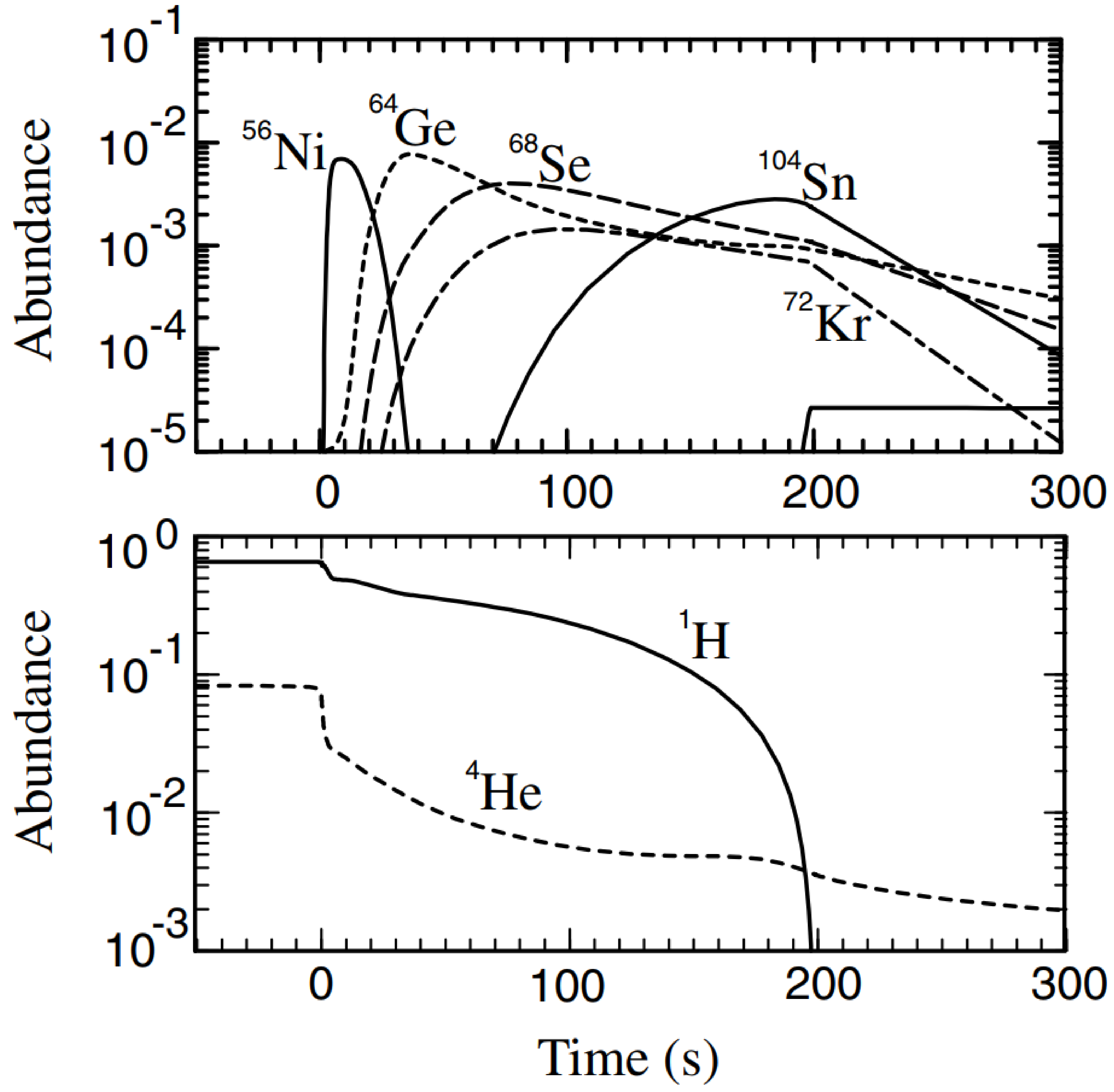




SnSbTe cycle: produce 104 Sn mostly (τ = 20.8s).

produce α ➔ 3α increase ➔ energy release ➔ Hydrogen completely burned.

Some long-lived “waiting point” nuclei.



56Ni
6.075 d
ε = 100.00%

64Ge
63.7 s
ε = 100.00%

68Se
35.5 s
ε = 100.00%

72Kr
17.1 s
ε = 100.00%
εp < 1.0E-6%

104Sn
20.8 s
ε = 100.00%

Credit:
NNDC

103Sn
7.0 s
ε = 100.00%
εp = 1.20%

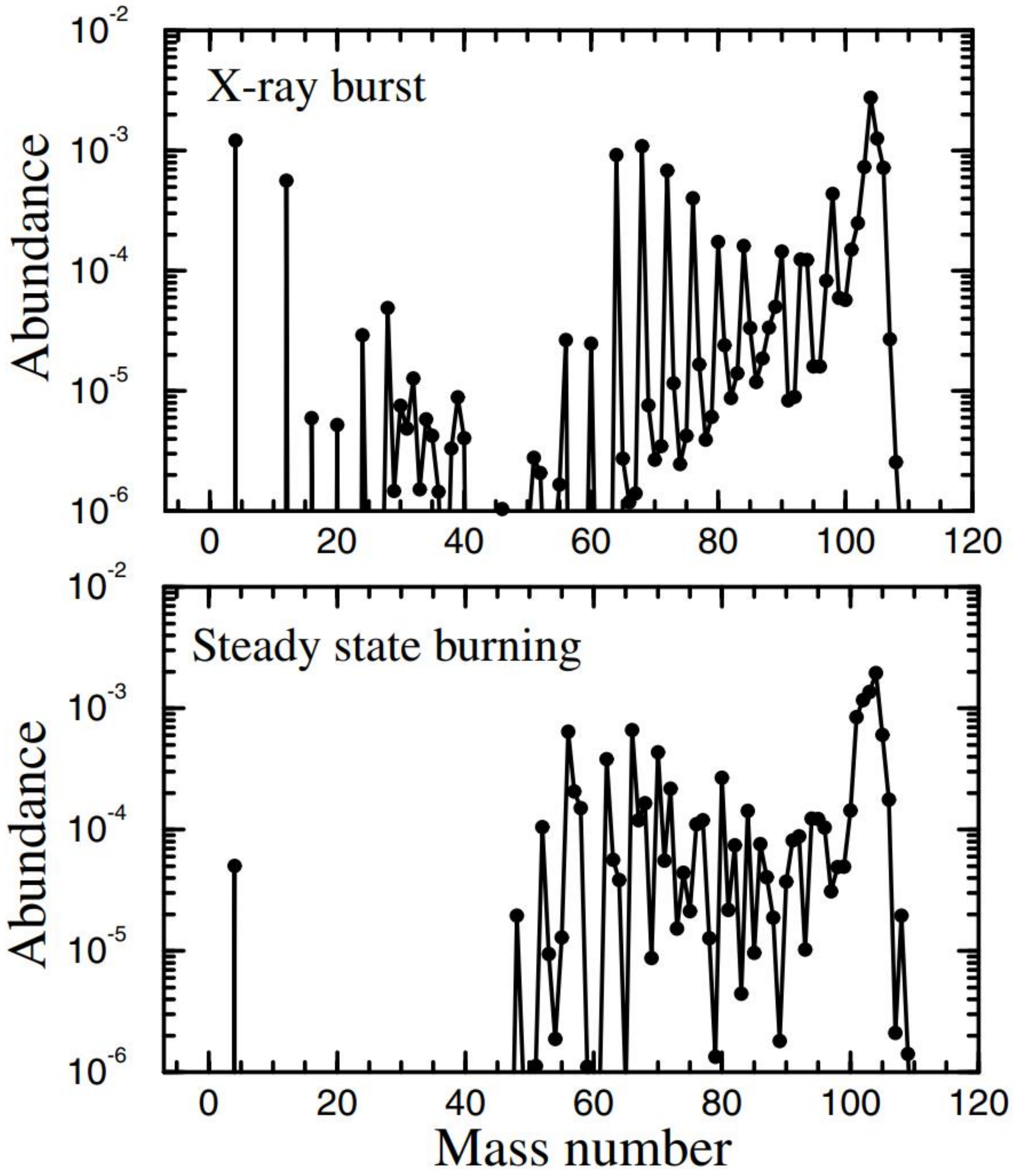
105Sn
32.7 s
ε = 100.00%
εp = 0.01%

106Sb
0.6 s
ε

107Sb
4.0 s
ε = 100.00%

107Te
3.1 ms
α = 70.00%
ε = 30.00%

Final abundance (rp process ashes):

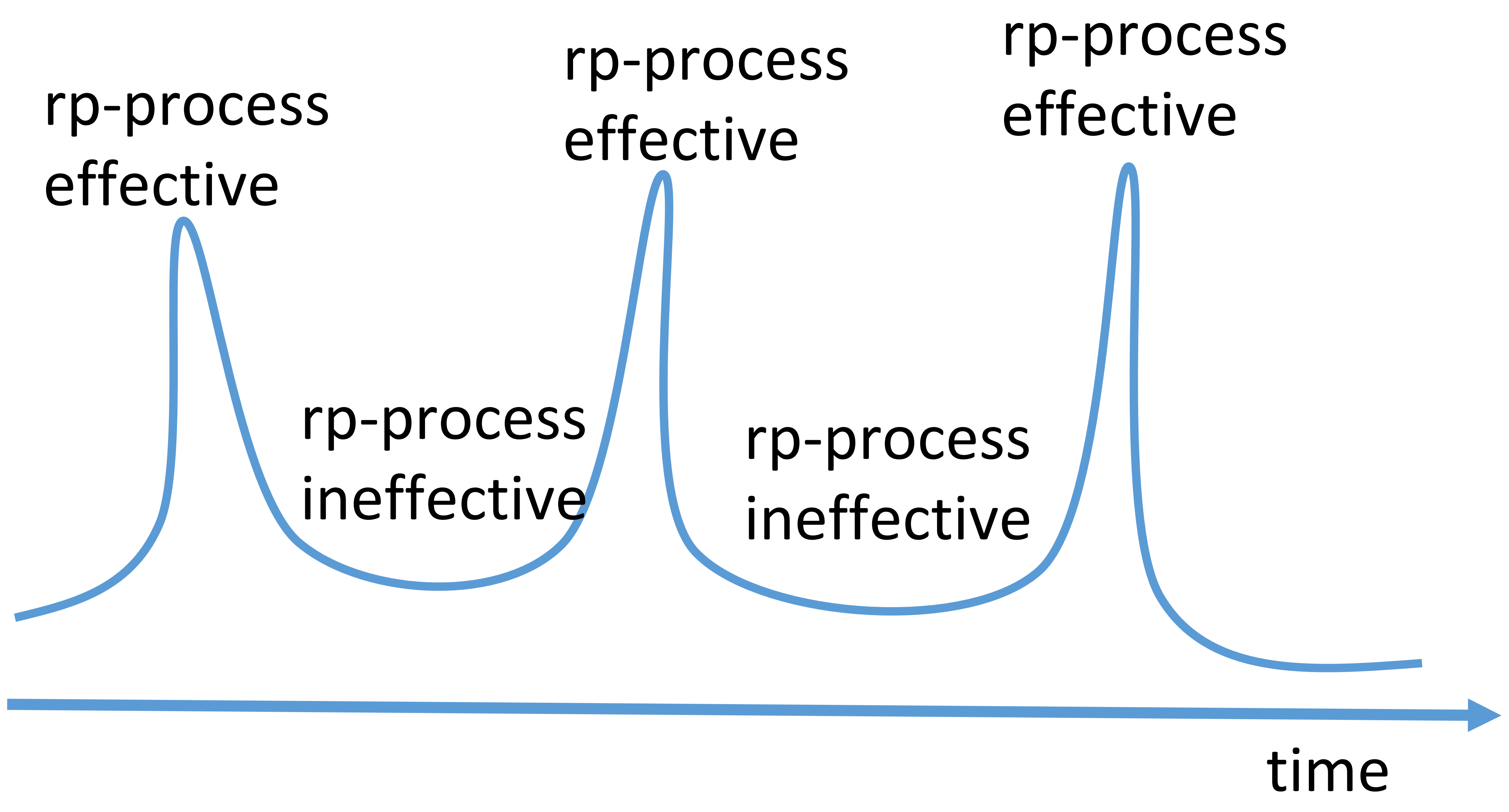


(1) Lack of nuclei with A > 107.

(2) Broad distribution of 64 < A < 107.
(due to long-lived waiting nuclei & enough helium)

V. Discussion

(i) To bypass SnSbTe cycle?



Only way: a pulsed rp-process.

Between pulses, matter decay to stable nuclei.

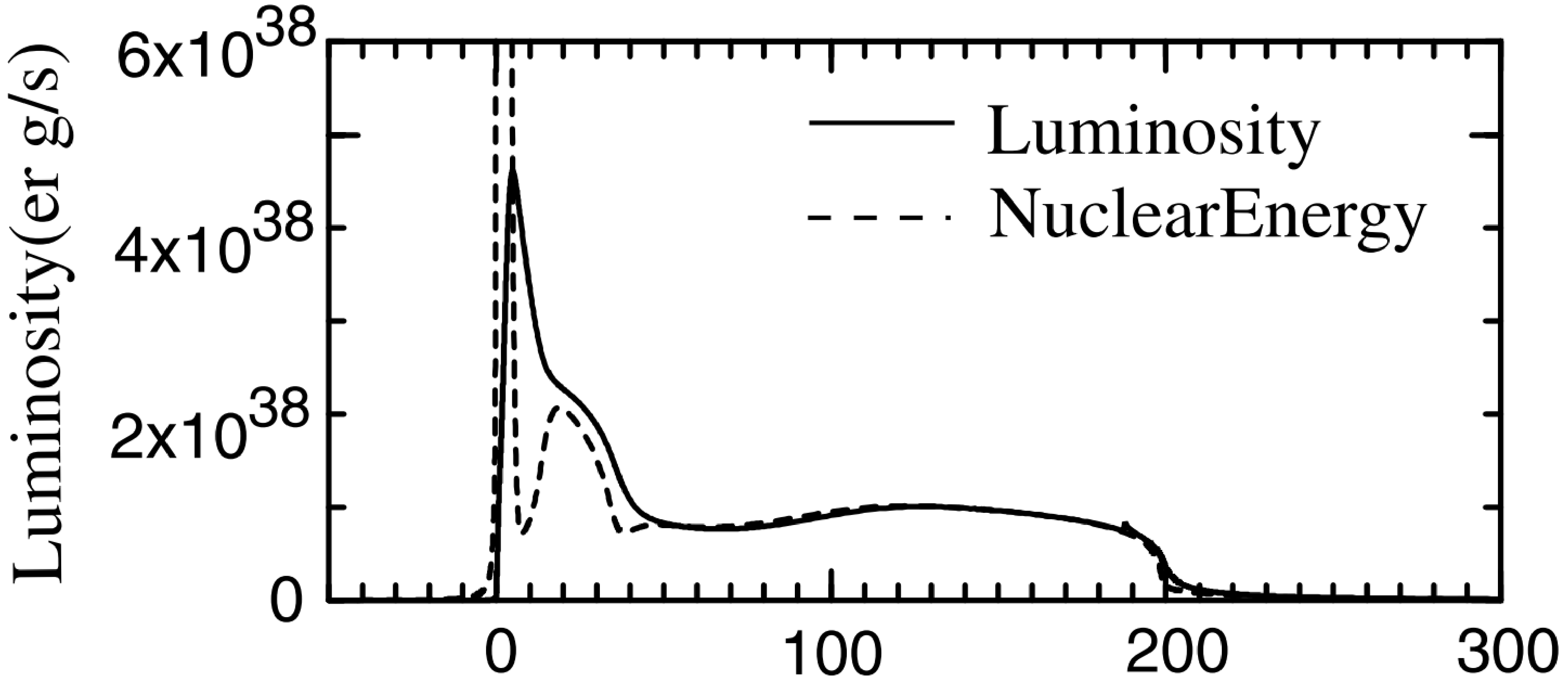
➔ Need reignition of ashes ← unburned Hydrogen (or) extensive vertical mixing (of nuclei)

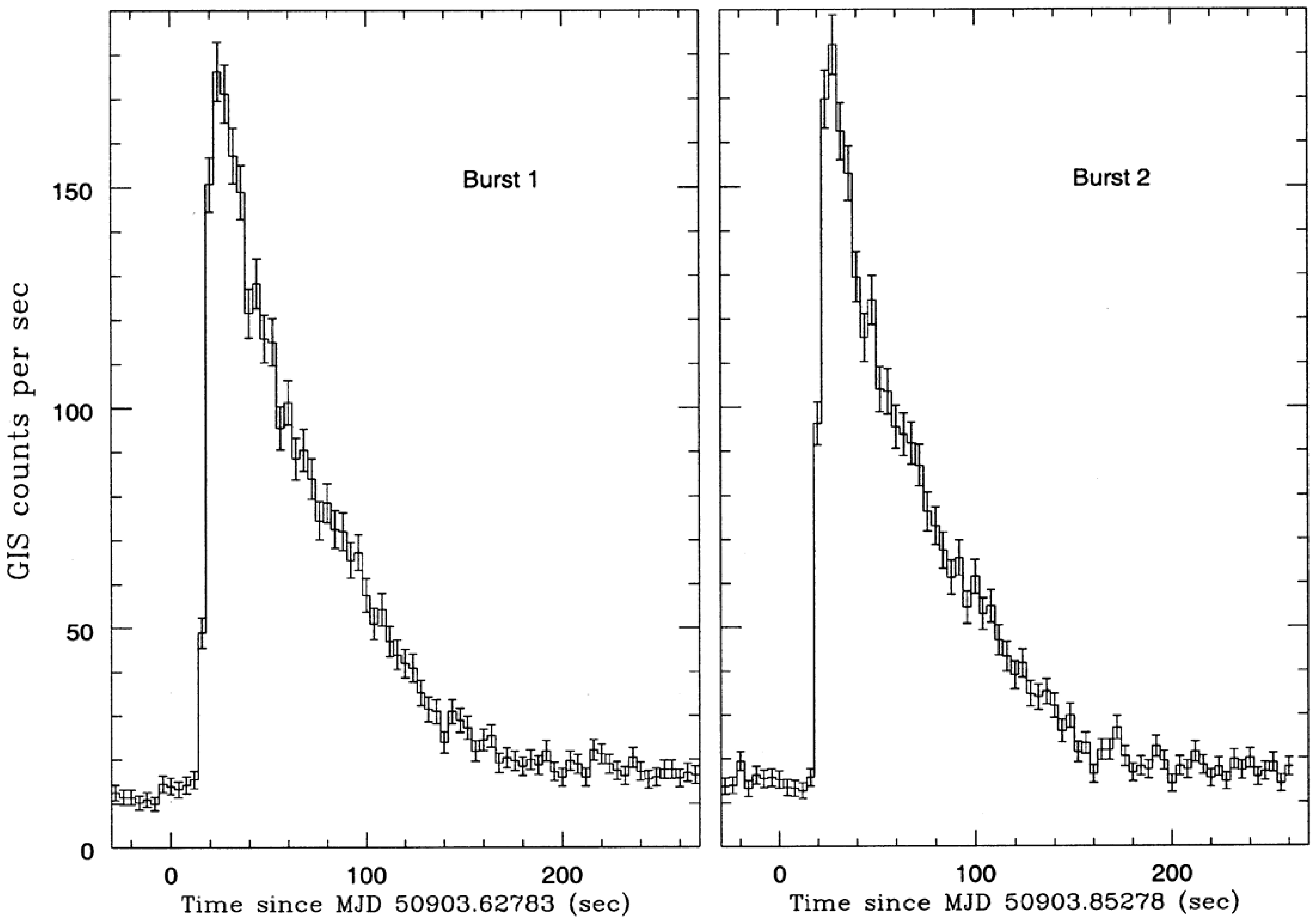
(Fujimoto et al. 1987, *ApJ*, 319, 902)

"Dwarf Bursts"
(Taam et al. 1993
ApJ, 413, 324)
Lower luminosity…

Little unburned Hydrogen
in this paper's calculation.

(ii) Duration of a burst:
Long enough to match observations.

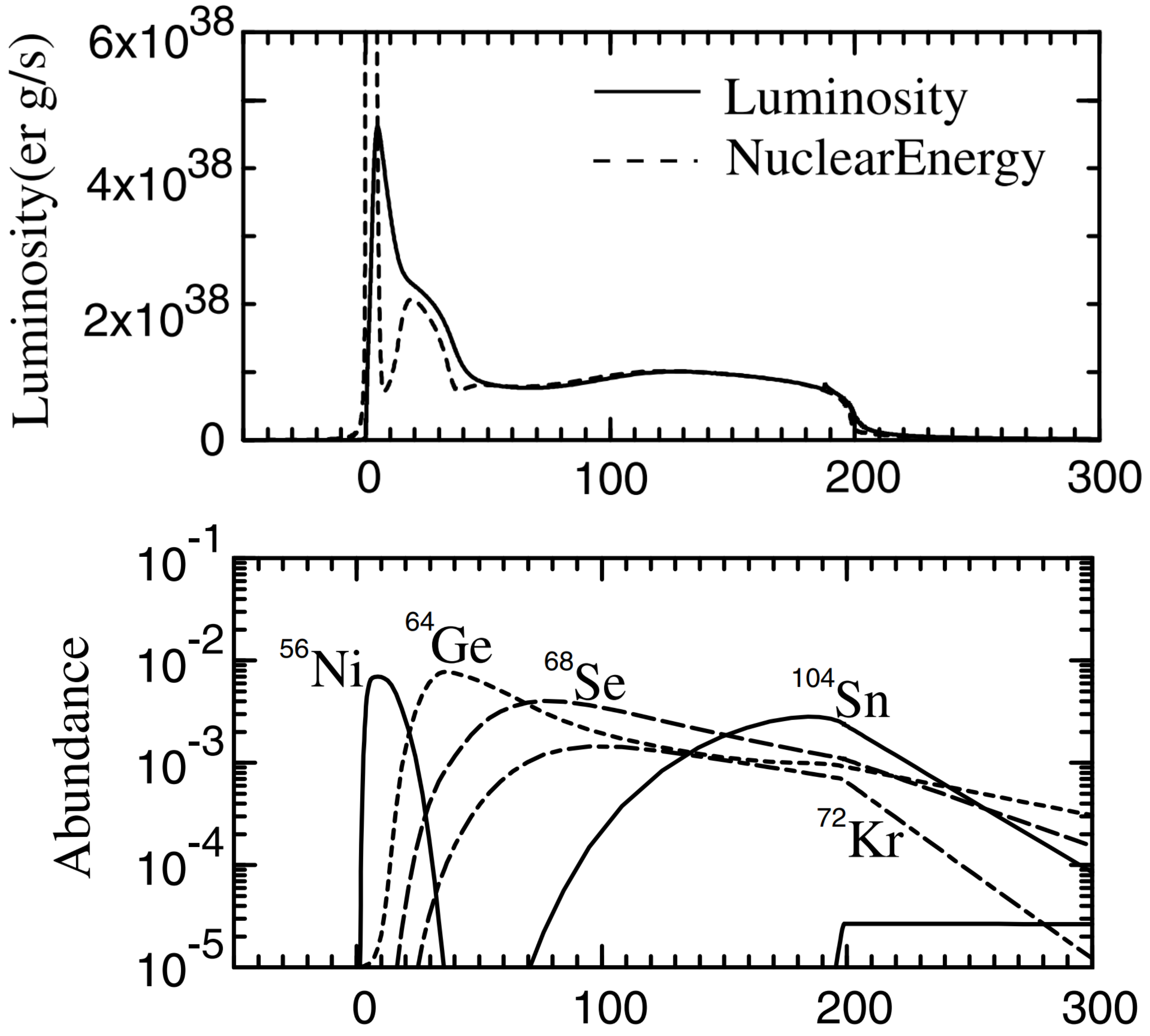




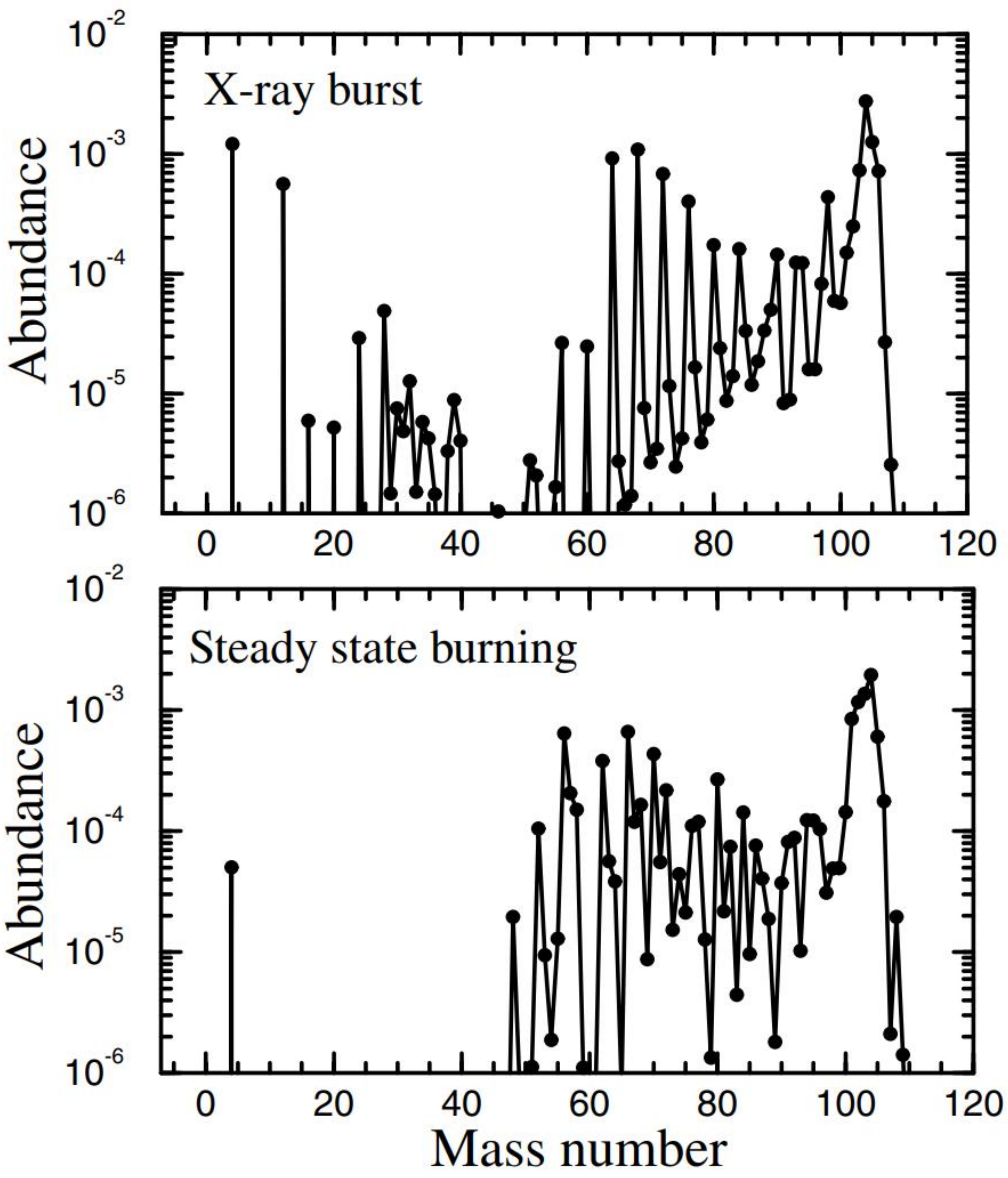
Type-I X-ray burst example (Kong et al. 2000 *MNRAS*, 311, 2)

(iii) Nucleosynthesis:
Large overproduction factors (>1e9 *solar) of p nuclei 98 Ru, 102 Pd, 106 Cd.

➔To explain solar system abundance' origin
➔➔1% of them are ejected
(Schatz et al. 1998, *PhR*, 294, 167)
➔➔➔The ejection mechanism…(not sure)



· Synthesis of p-nuclei most likely related to long burst tails…



The rp-process on accreting NS ends at SnSbTe cycle.

➔Long (~200s) burst duration & long tail.

➔Effective synthesis of 65 < A < 107 nuclei.

➔More p-nuclei produced (than if only SNe II).

Thank you for your attention ☺