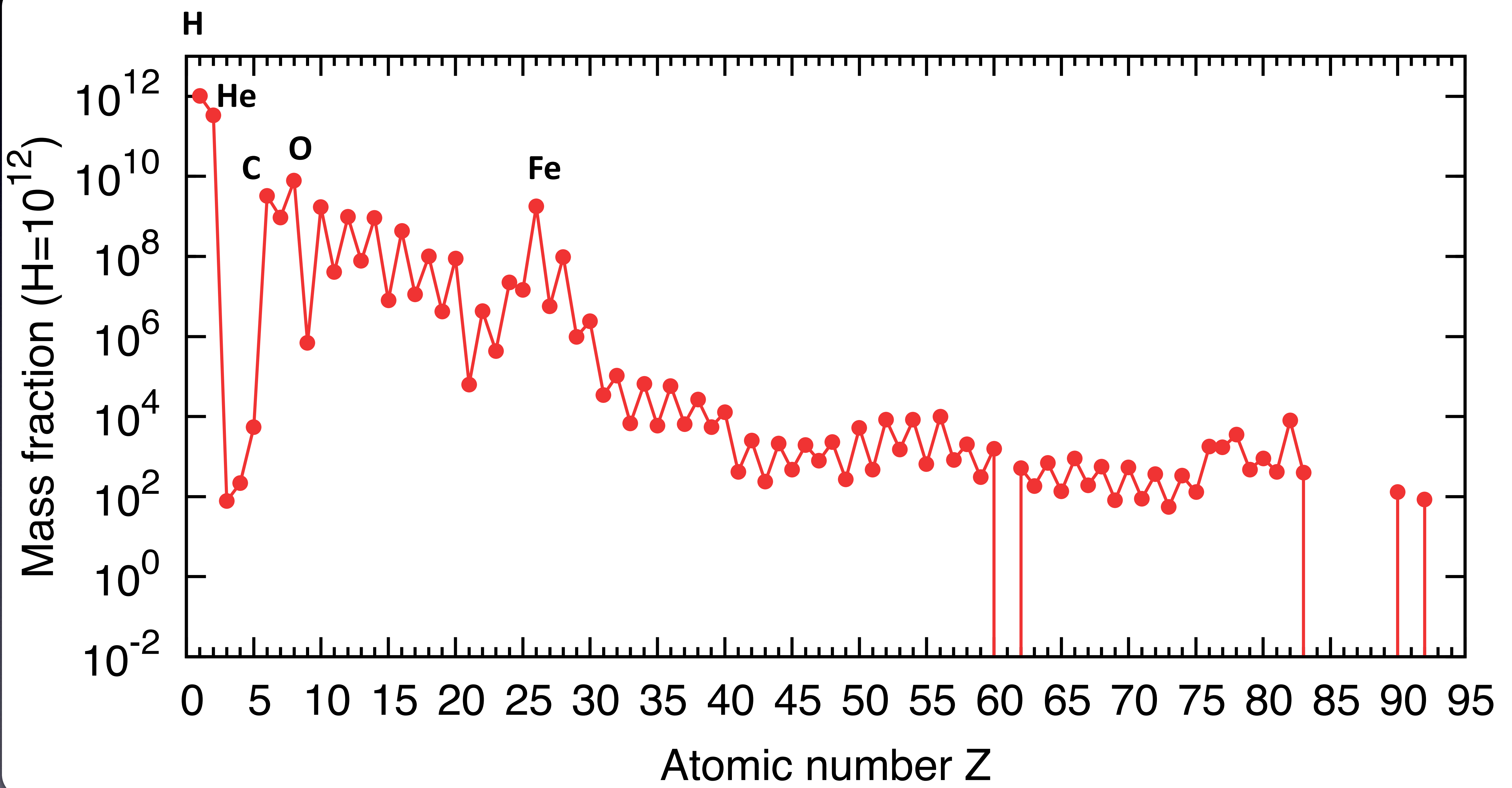
Section 10.
Origin of the elements in the Universe

10.1 Light elements

10.2 Heavy elements

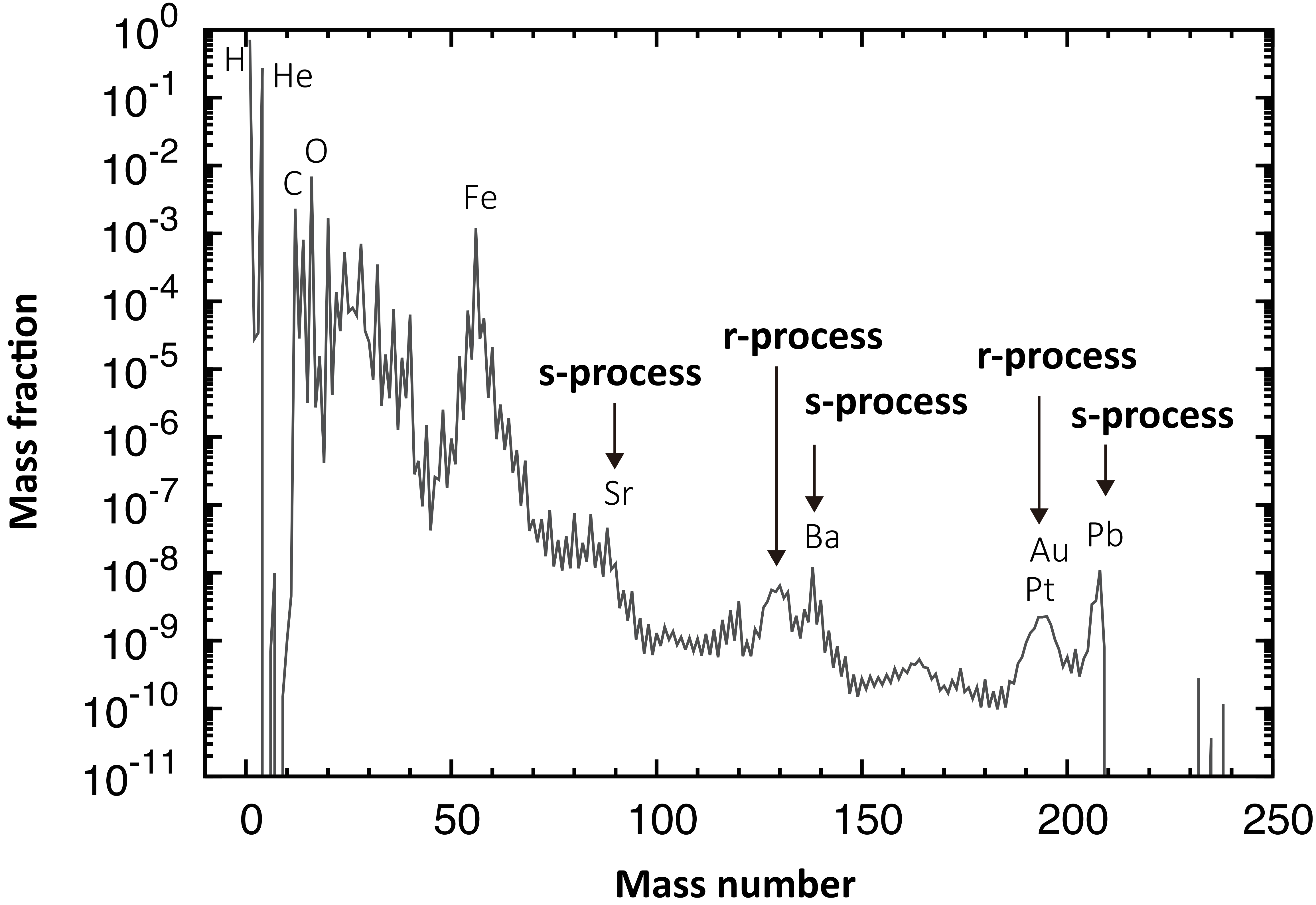
10.3 Chemical evolution of the Universe

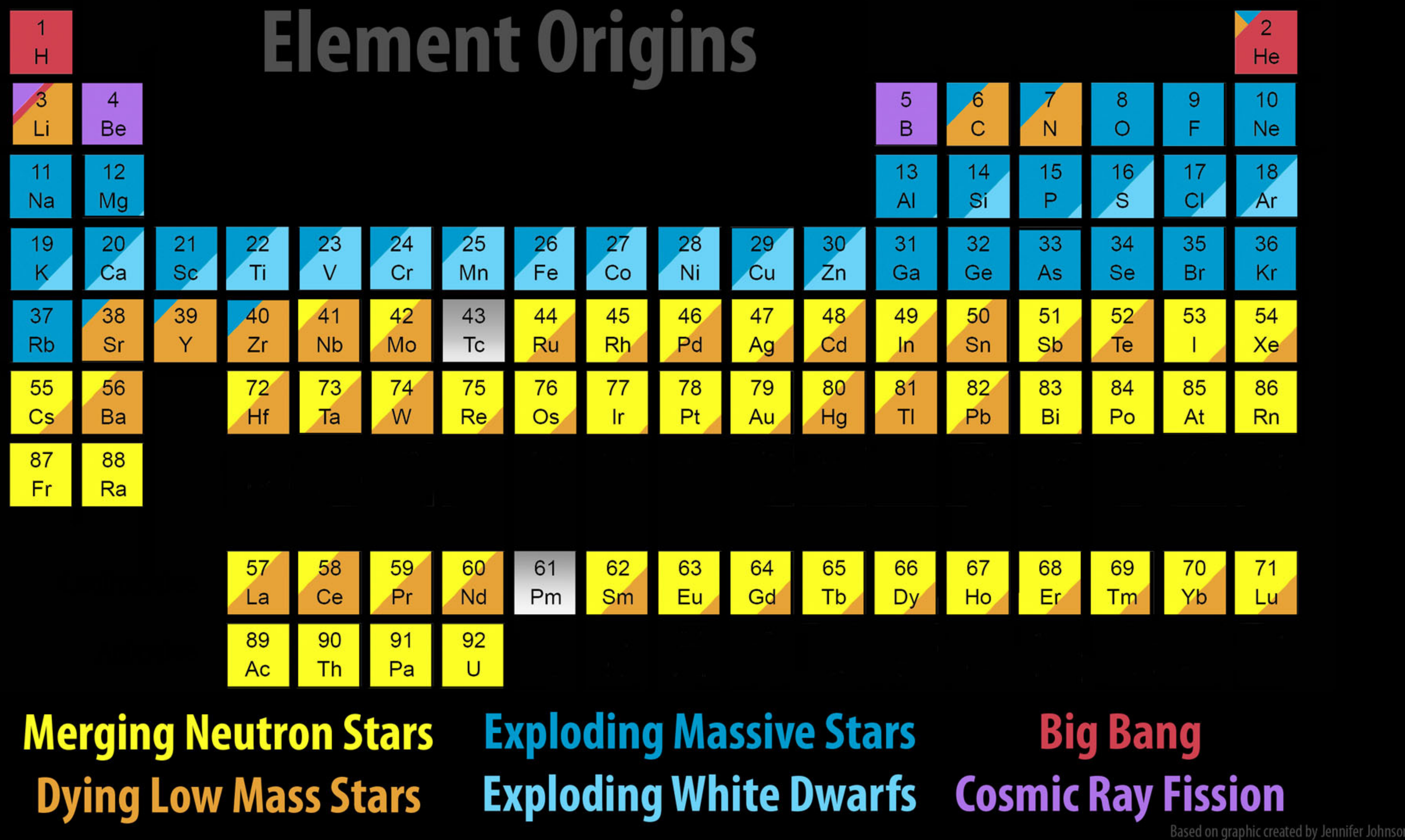
Cosmic abundances (atomic number)



*Mass ratio

Cosmic abundances (mass number)





http://www.caltech.edu/news/caltech-led-teams-strike-cosmic-gold-80074

Section 10.
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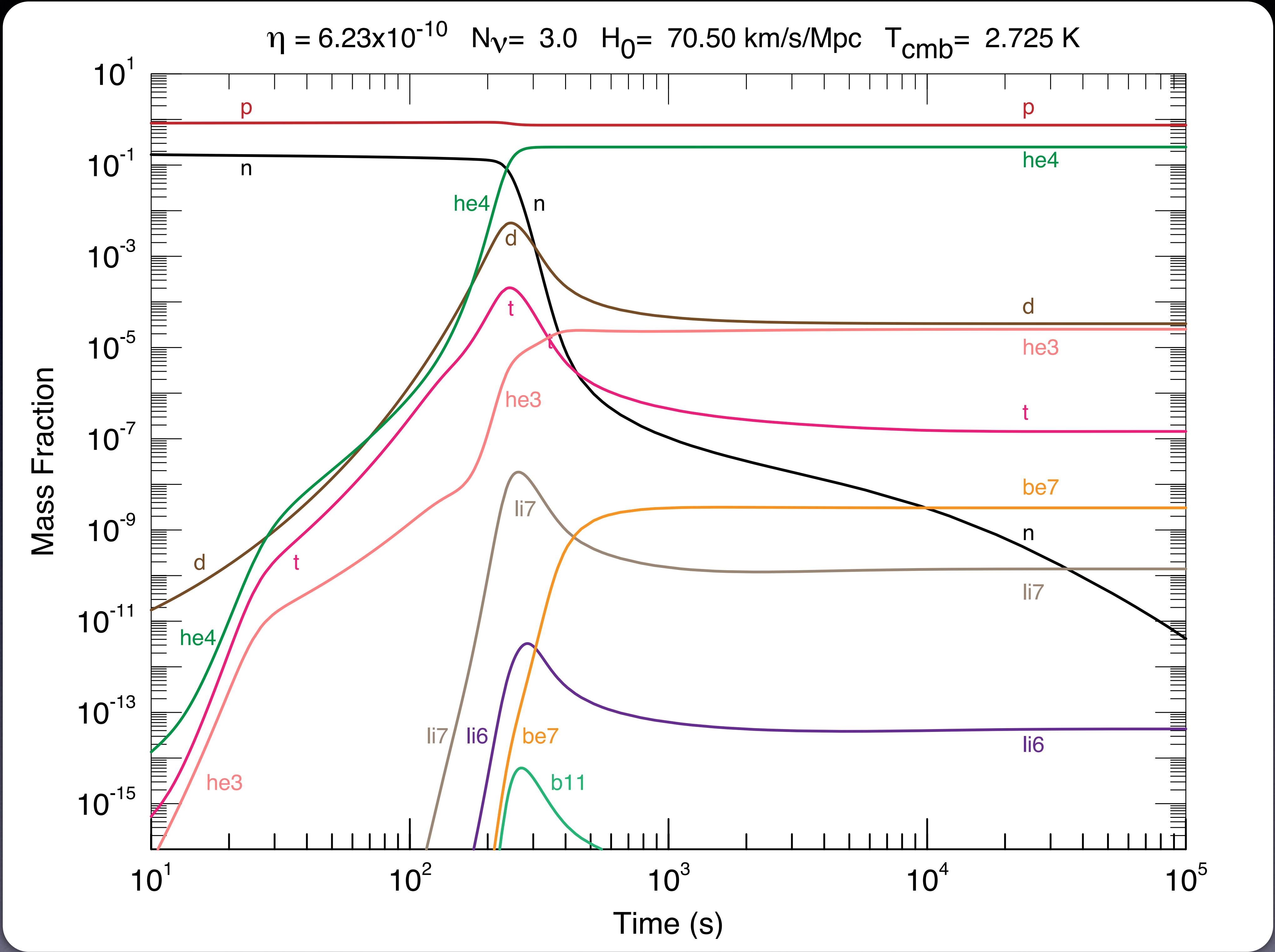
Bigbang nucleosynthesis



http://cococubed.asu.edu/code_pages/net_bigbang.shtml

~ 2 sec | ~200 sec | ~ 300 sec | ~ 900 sec | Time

n/p ~ 1/6

$$\text{n/p} = \exp(-\Delta m/T)$$

Breakdown of Equilibrium (T ~ 0.7 MeV)

$$\begin{aligned} p + e^- &\leftrightarrow n + \nu_e \\ p + \bar{\nu}_e &\leftrightarrow n + e^+ \\ n &\leftrightarrow p + e^- + \bar{\nu}. \end{aligned}$$

n/p ~ 1/7

(n decay)

Nucleo-synthesis

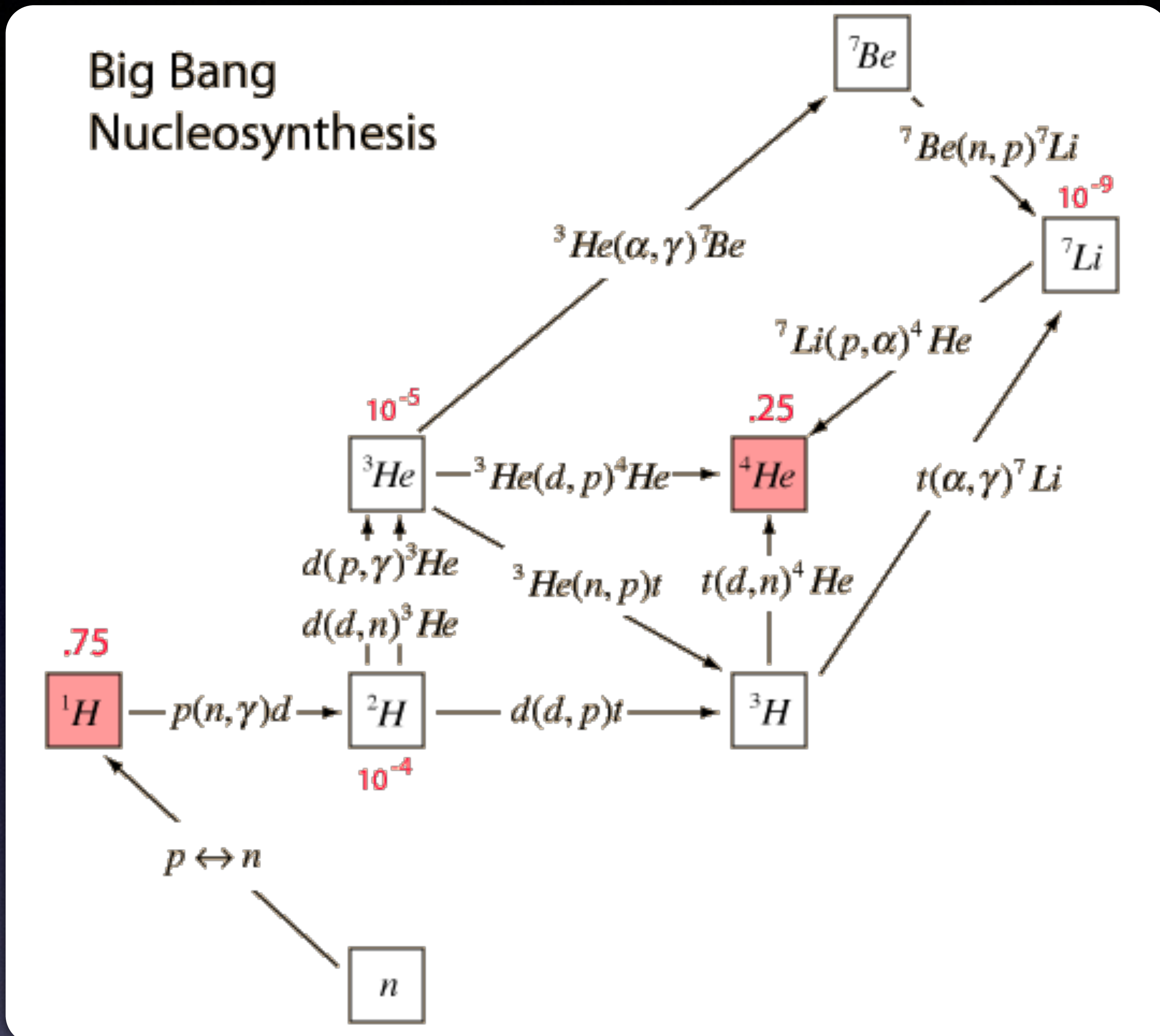
Life time of neutron

The first reaction

$$p + n \longleftrightarrow \mathrm{D} + \gamma$$

- After photon energy decreases (T ~ 0.1 MeV)
- Before neutron decay

* Binding energy of D ~ 2 MeV



http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/bbnuc.html

All neutrons go to 4He
(n/p ~ 1/7)

$$Y = \frac{(n_n/2)(2m_p + 2m_n)}{n_p m_p + n_n m_n} \sim 0.25$$

→ **Consistent with Cosmic abundance**

No stable nuclei with mass number of 5 and 8

→ **Next reaction will be ^{4}He x 3 inside of stars**
(Not possible in bigbang due to low density)

Li problem

$$[\mathrm{A/B}] = \log(N_\mathrm{A}/N_\mathrm{B}) - \log(N_\mathrm{A}/N_\mathrm{B})_\odot$$

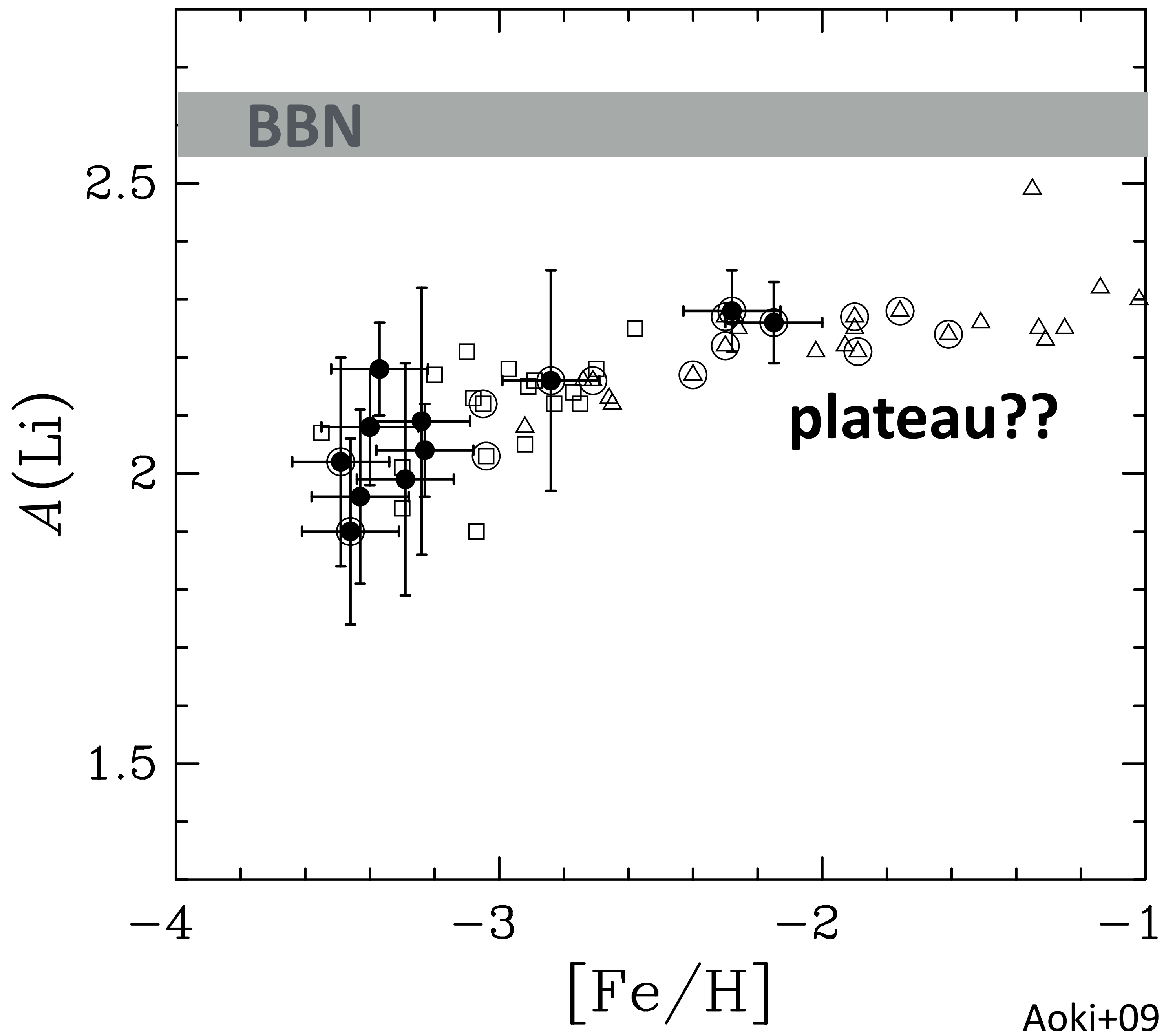
$$A(\mathrm{Li}) = \log(\mathrm{Li/H}) + 12$$

Li abundance

Destruction inside of stars

+

Production by Cosmic ray spallation



Metallicity

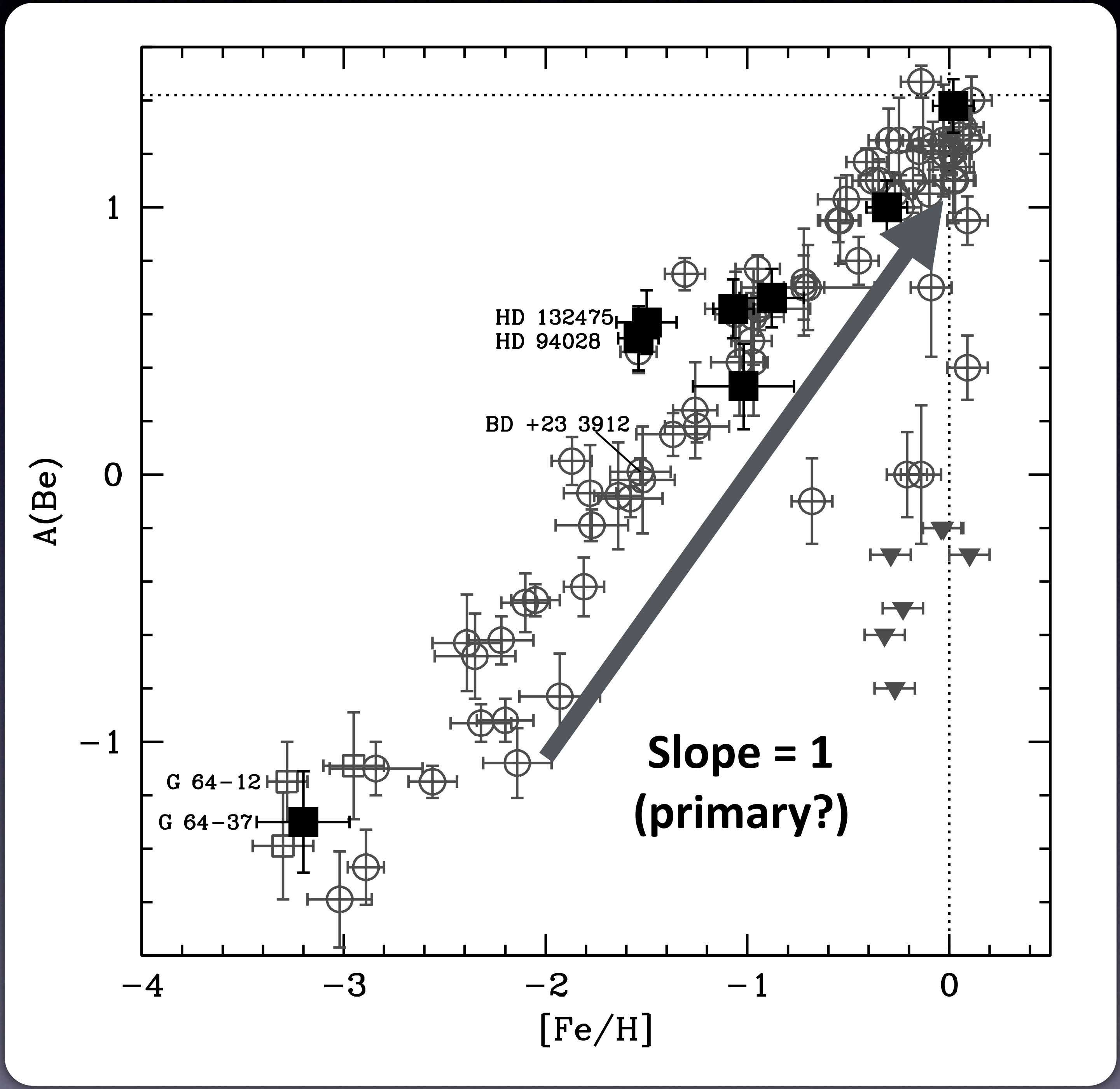
Cosmic ray spallation (Li, Be, B)

Cosmic ray(p, alpha)
+ targets (C, N, O)
=> Li, Be, B

Cosmic rays (<= SN)

C, N, O (<= past nucleosynthesis)

=> secondary process (slope = 2)



Boesgaard+06

Section 10.
Origin of the elements in the Universe

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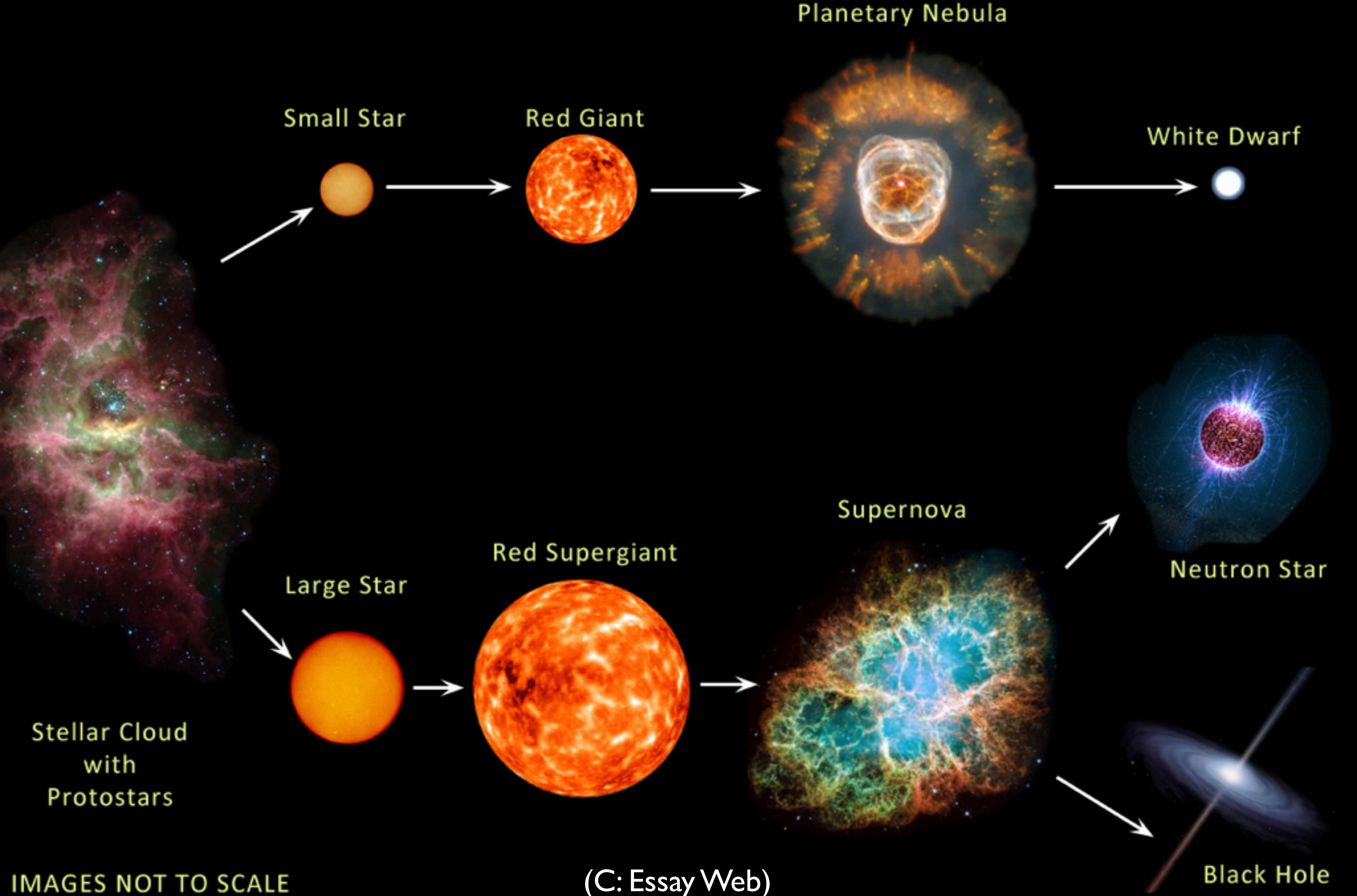
Stellar life



(C: Essay Web)

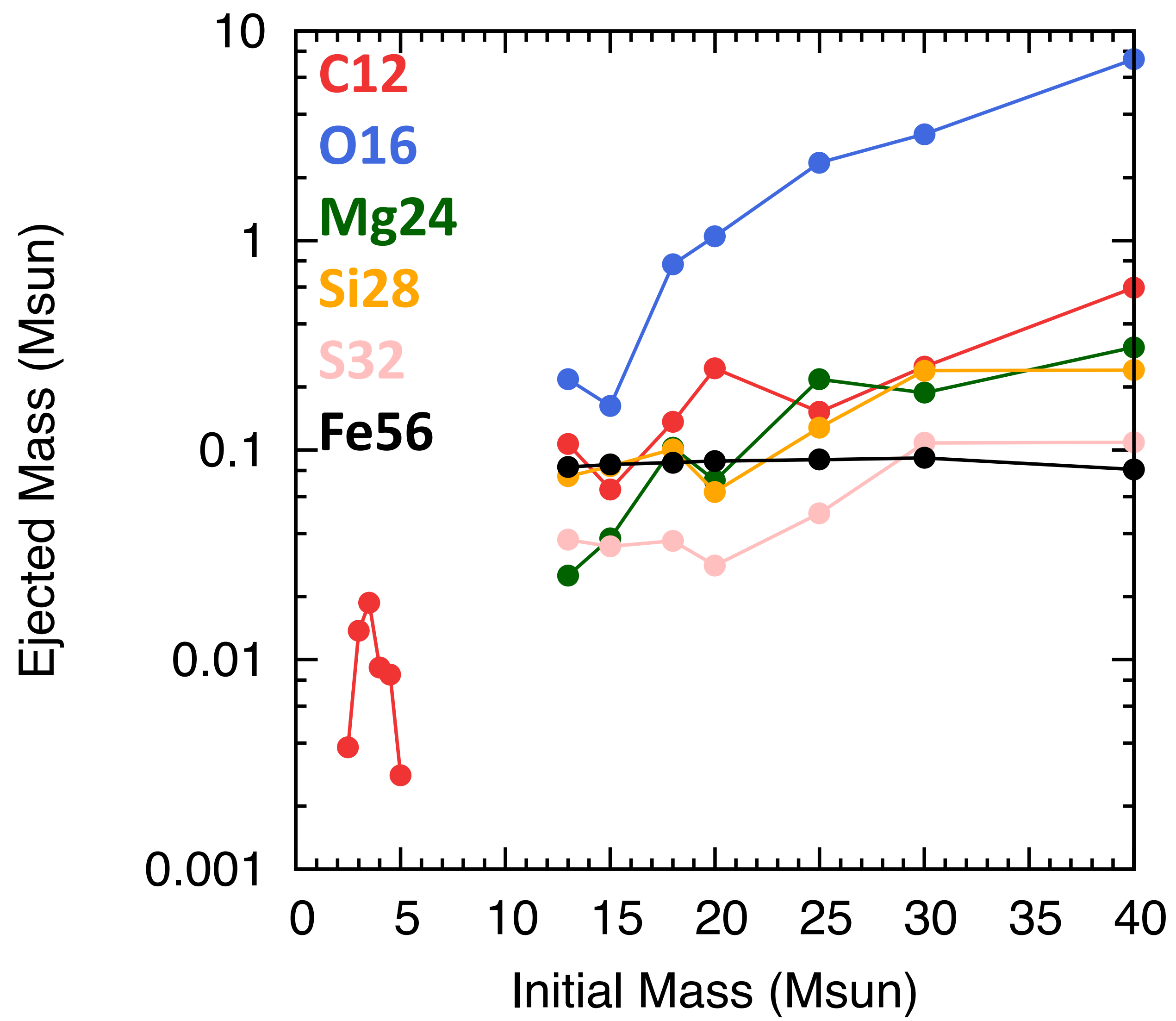
Phase	Main reactions	Products	T
燃焼段階	おもな反応	おもな生成物	温度 (10^8 K)
H	pp チェイン CNO サイクル	^{4}He ^{14}N	0.15-0.2
He	$3\,^4\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$ $^{12}\mathrm{C} + {}^4\mathrm{He} \longrightarrow {}^{16}\mathrm{O} + \gamma$	^{12}C ^{16}O	1.5
C	$^{12}\mathrm{C} + {}^{12}\mathrm{C} \longrightarrow \begin{cases} {}^{23}\mathrm{Na} + \mathrm{p} \\ {}^{20}\mathrm{Ne} + \alpha \end{cases}$	Ne,Na Mg,Al	7
Ne	$^{20}\mathrm{Ne} + \gamma \longrightarrow {}^{16}\mathrm{O} + \alpha$ $^{20}\mathrm{Ne} + \alpha \longrightarrow {}^{24}\mathrm{Mg} + \gamma$	O Mg	15
O	$^{16}\mathrm{O} + {}^{16}\mathrm{O} \longrightarrow \begin{cases} {}^{28}\mathrm{Si} + \alpha \\ {}^{31}\mathrm{P} + \mathrm{p} \end{cases}$	Si,P,S, Cl,Ar,Ca	30
Si	$^{28}\mathrm{Si} + \gamma \longrightarrow {}^{24}\mathrm{Mg} + \alpha$ $^{24}\mathrm{Mg} + \gamma \longrightarrow \begin{cases} {}^{23}\mathrm{Na} + \mathrm{p} \\ {}^{20}\mathrm{Ne} + \alpha \end{cases}$ 多くの反応 ⟶ 統計平衡	Cr,Mn, Fe,Co, Ni,Cu	40

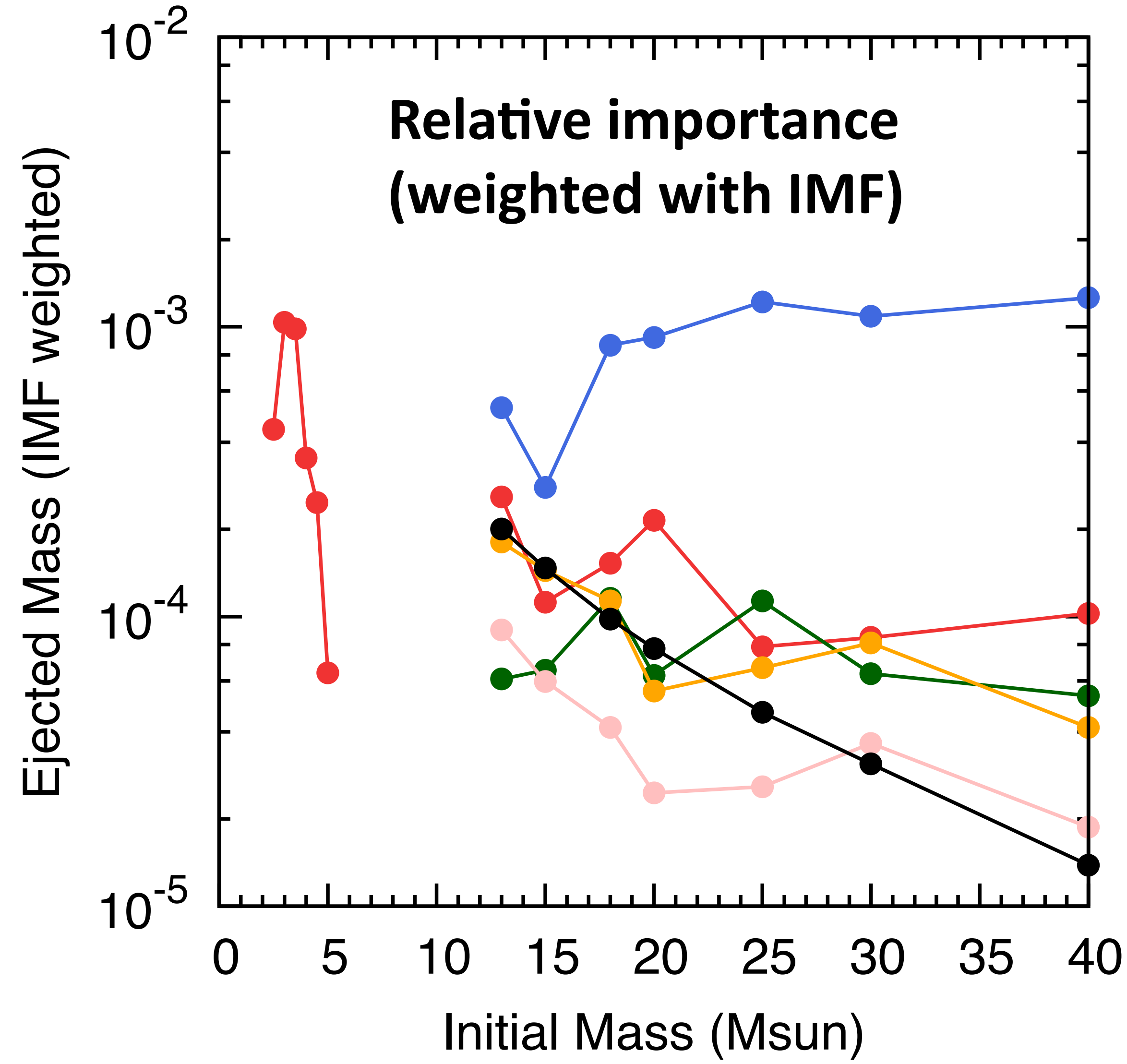
Nuclear statistical equilibrium

元素はいかにつくられたか（岩波書店）

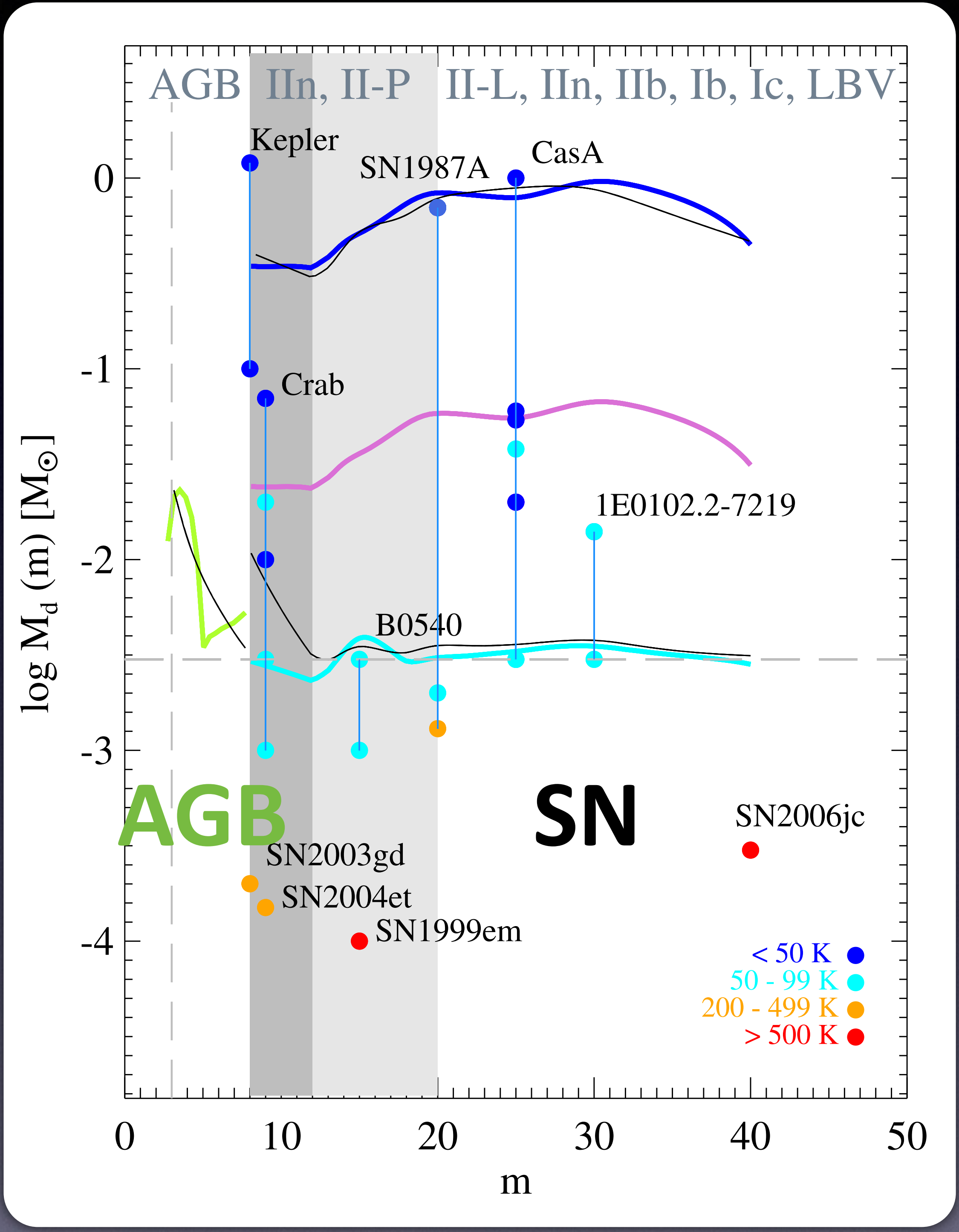
Element ejection from stars

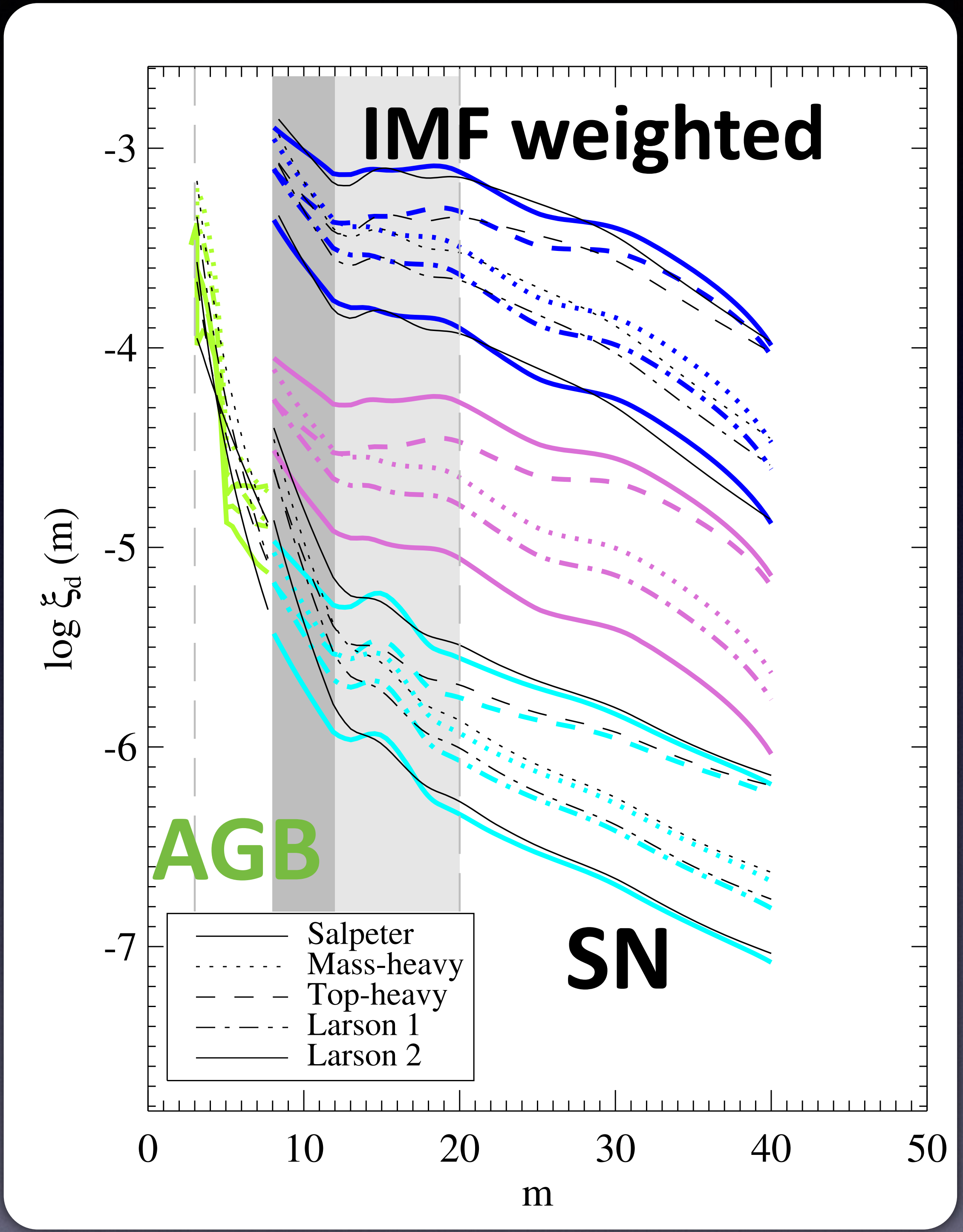
1-6 Msun: AGB mass loss (Karakas 2010, MNRAS, 403, 1413)
> 10 Msun: supernovae (Kobayashi et al. 2006, ApJ, 653, 1145)





Dust production in the Universe



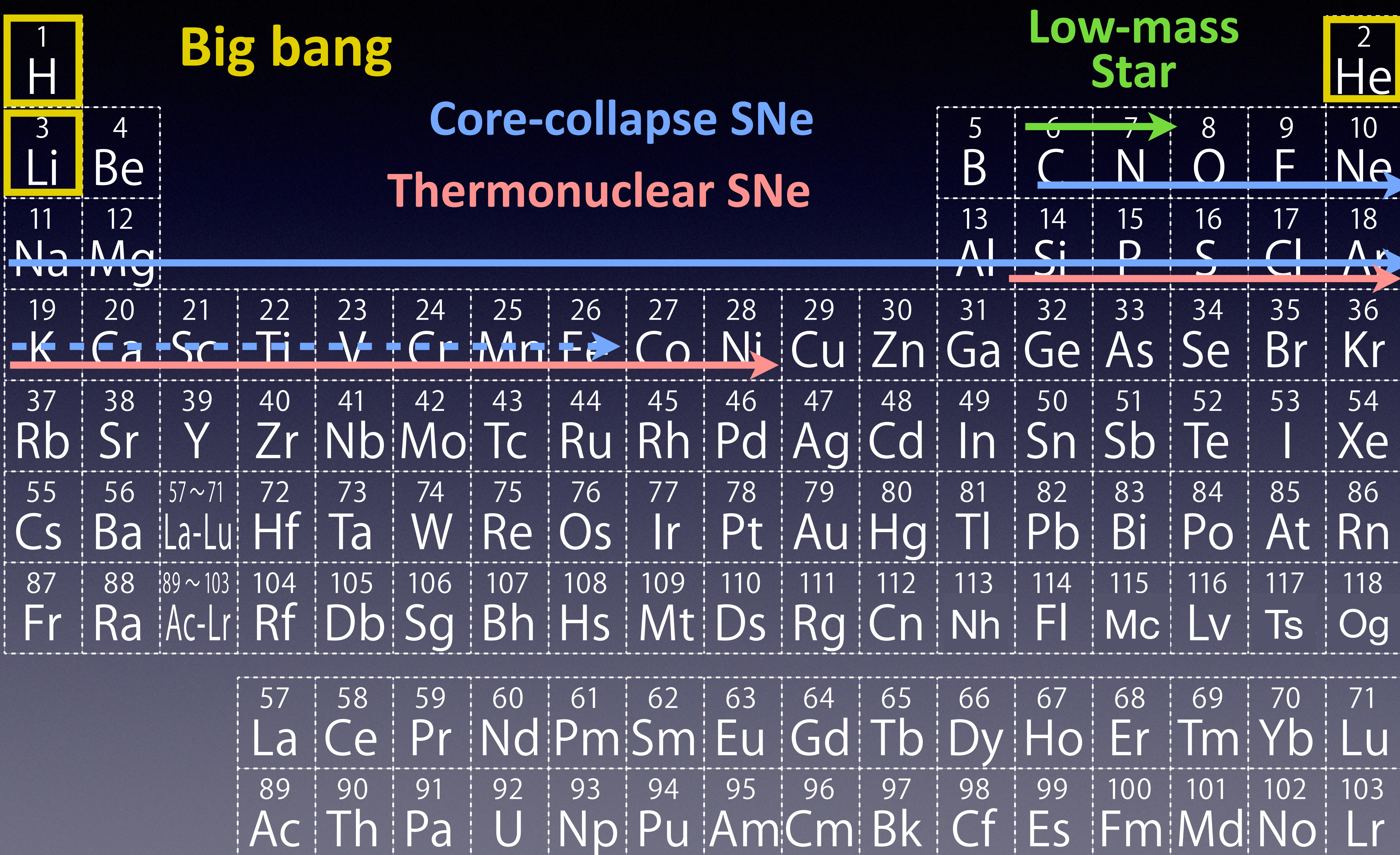


Gall et al. 2011

Probably dominated by AGB stars

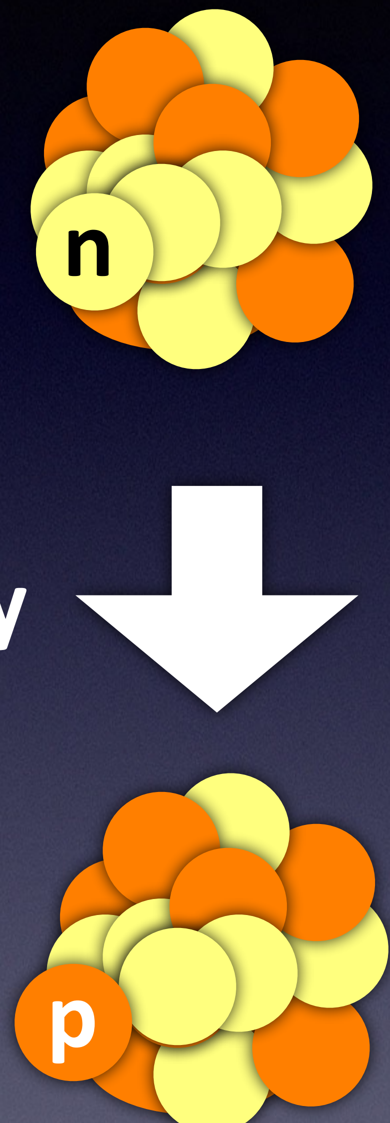
(But need SN in the early Universe)

The origin of elements



Neutron-capture nucleosynthesis

s (slow)-process

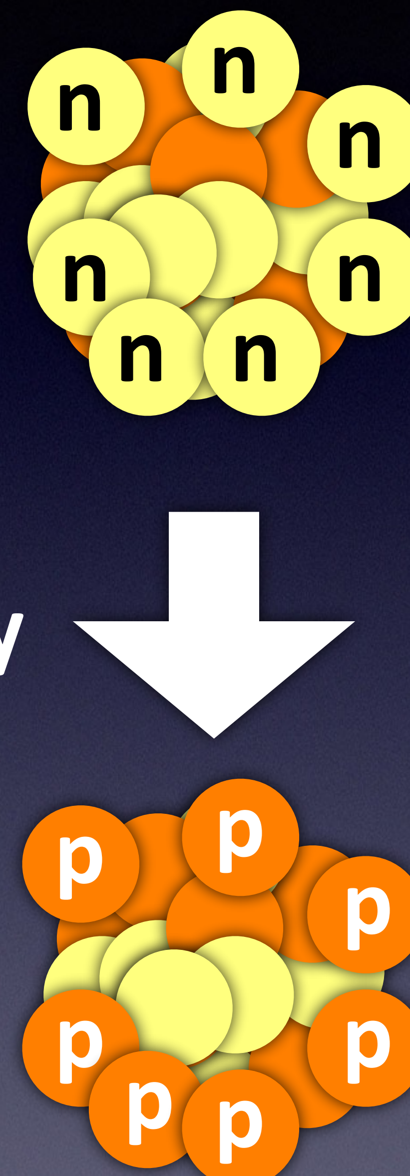


Decay

Ba, Pb, …

Inside of stars

r (rapid)-process

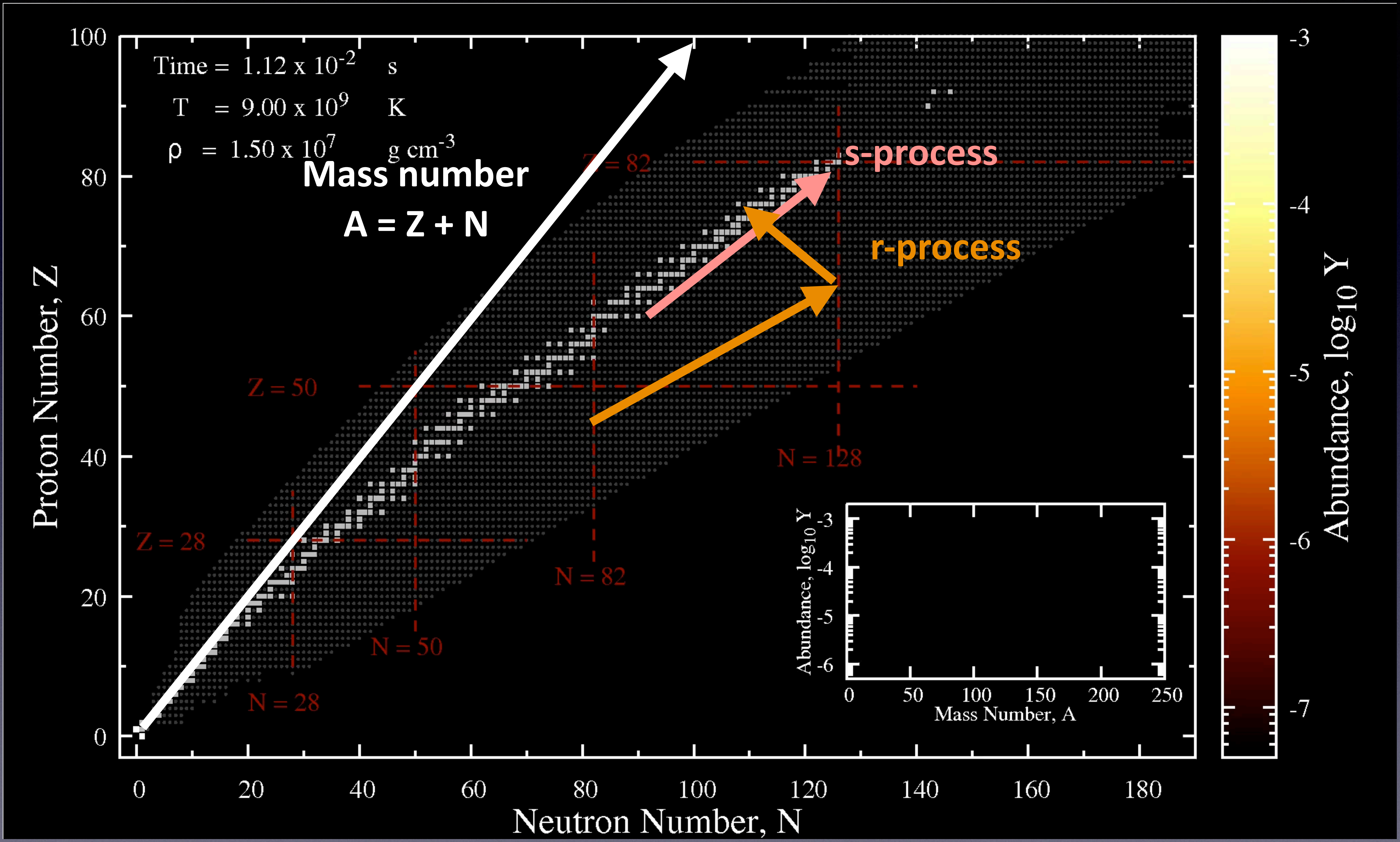


Decay

Au, Pt, U, …

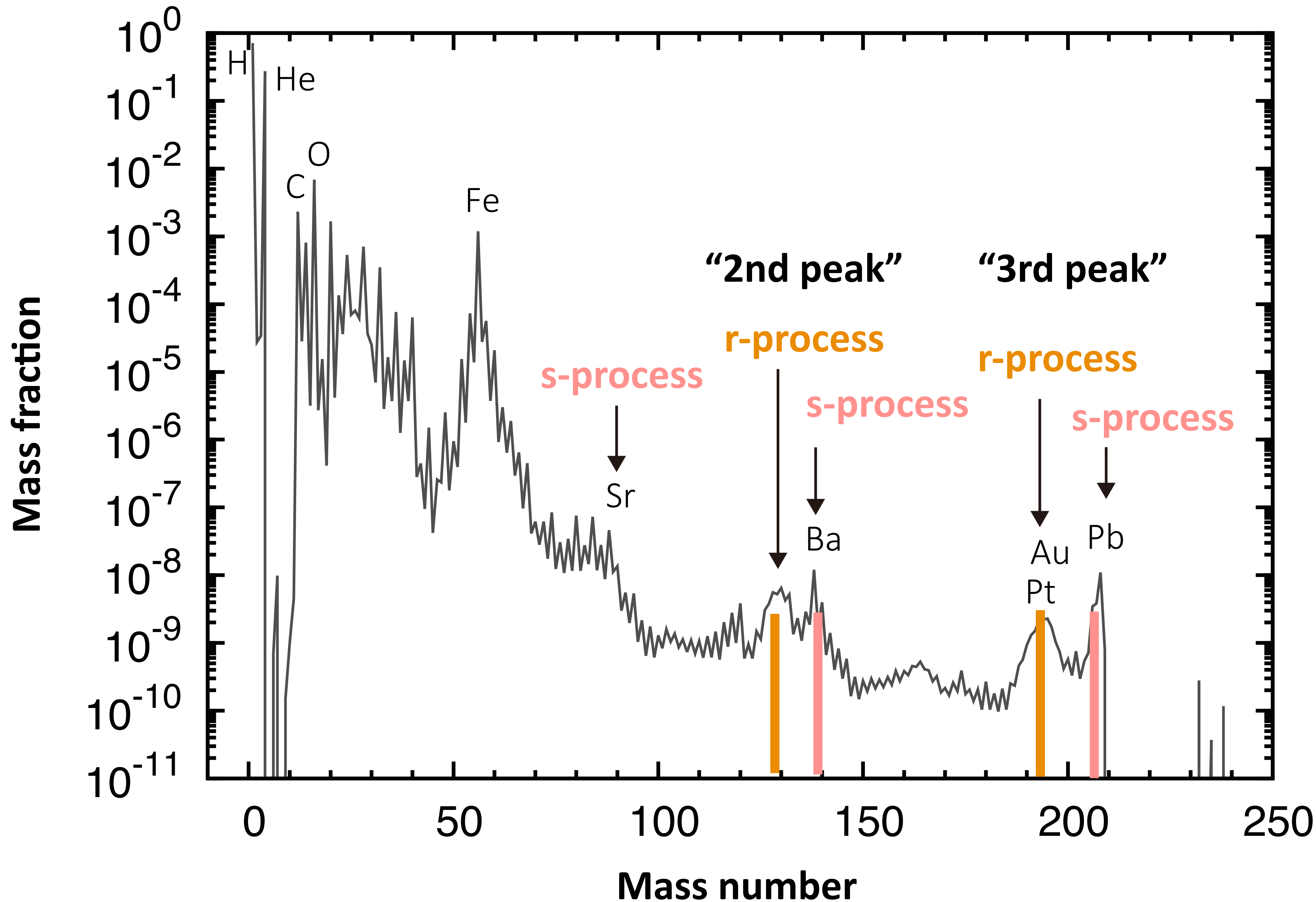
SN? NS merger?

s-process and r-process



(C) Nobuya Nishimura

Cosmic abundances

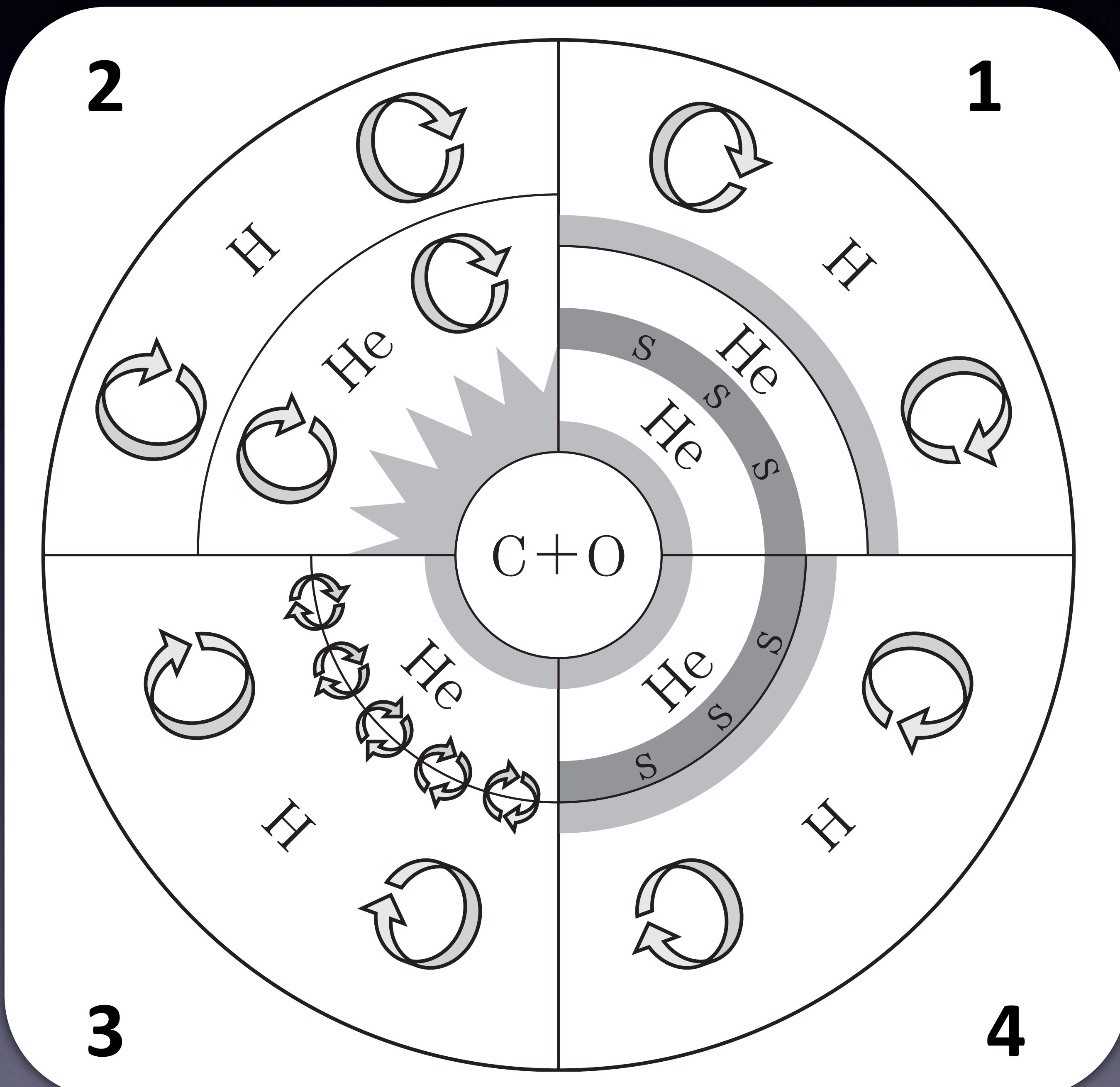


s-process in AGB stars

Seed reaction of neutron

$$^{13}\mathrm{C}+{}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O}+\mathrm{n}$$

T > 8 x 10⁷ K



1. Shell burning
   (at the bottoms of He H layers)
2. He is enriched
   => Shell flash
3. Convection
   => mixing in the envelope
   + H is mixed to the He layer
4. 12C + H => 13N => 13C
   13C + He => 16O + n
   => s-process

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma$$

$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu$$

元素はいかにつくられたか（岩波書店）

CNO cycle

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma$$

$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu$$

$$^{13}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + \gamma$$

$$^{14}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{15}\mathrm{O} + \gamma$$

$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu$$

$$^{15}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$

$$\rightarrow {}^{16}\mathrm{O} + \gamma$$

$$^{16}\mathrm{O} + {}^{1}\mathrm{H} \rightarrow {}^{17}\mathrm{F} + \gamma$$

$$^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + \mathrm{e}^{+} + \nu$$

$$^{17}\mathrm{O} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$$

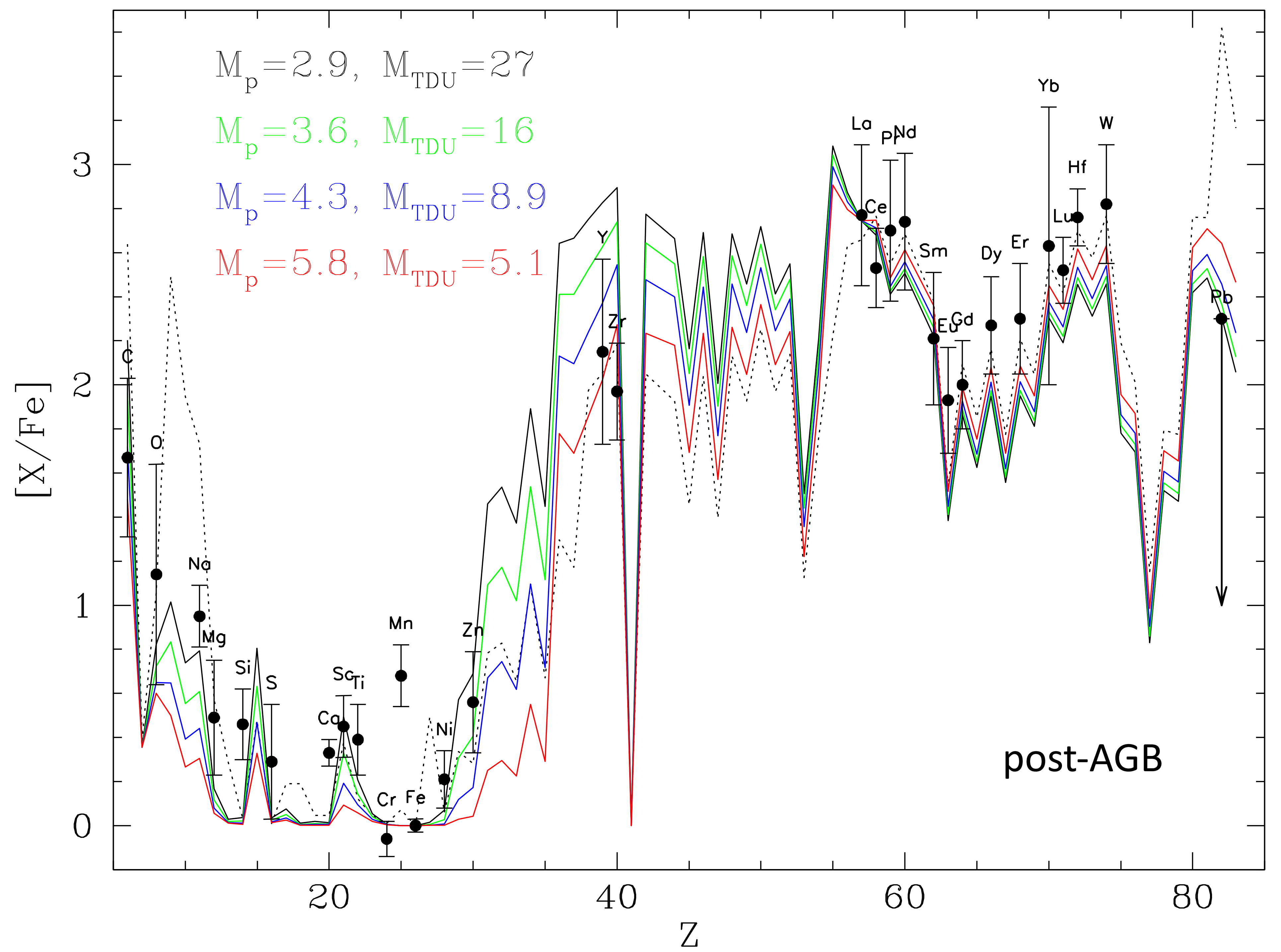
Textbook by Pols

13C should be produced under H-poor condition for s-process

H is provided in the He-burning layer (unique in AGB stars)

Observational evidence

First evidence
Tc (Z = 43, no stable ist)
(Merrill 1952)



Lugaro+16

s-process in massive stars (weak s-process)

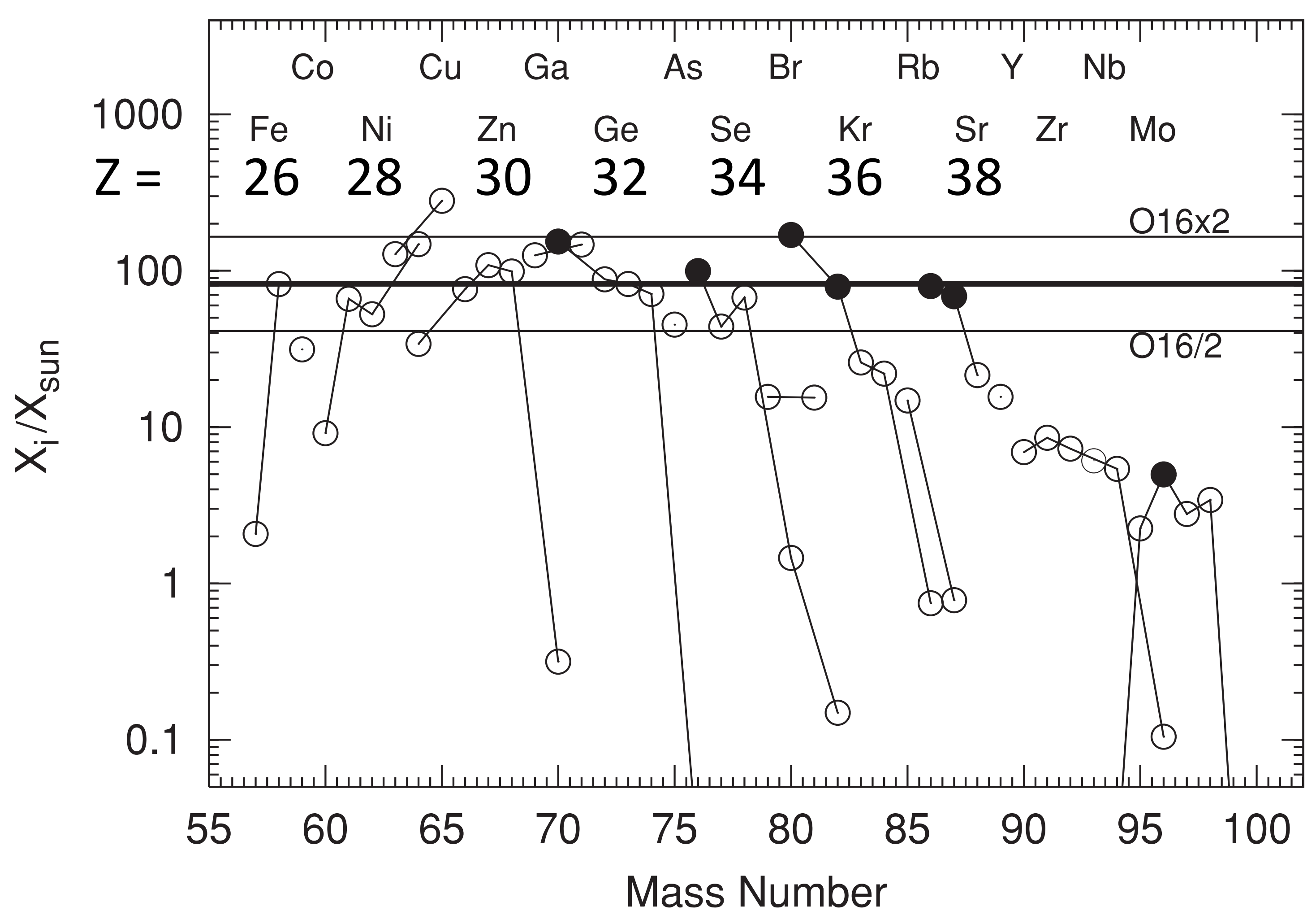
Seed reaction

$$^{22}\mathrm{Ne}+^{4}\mathrm{He} \rightarrow ^{25}\mathrm{Mg}+\mathrm{n}$$

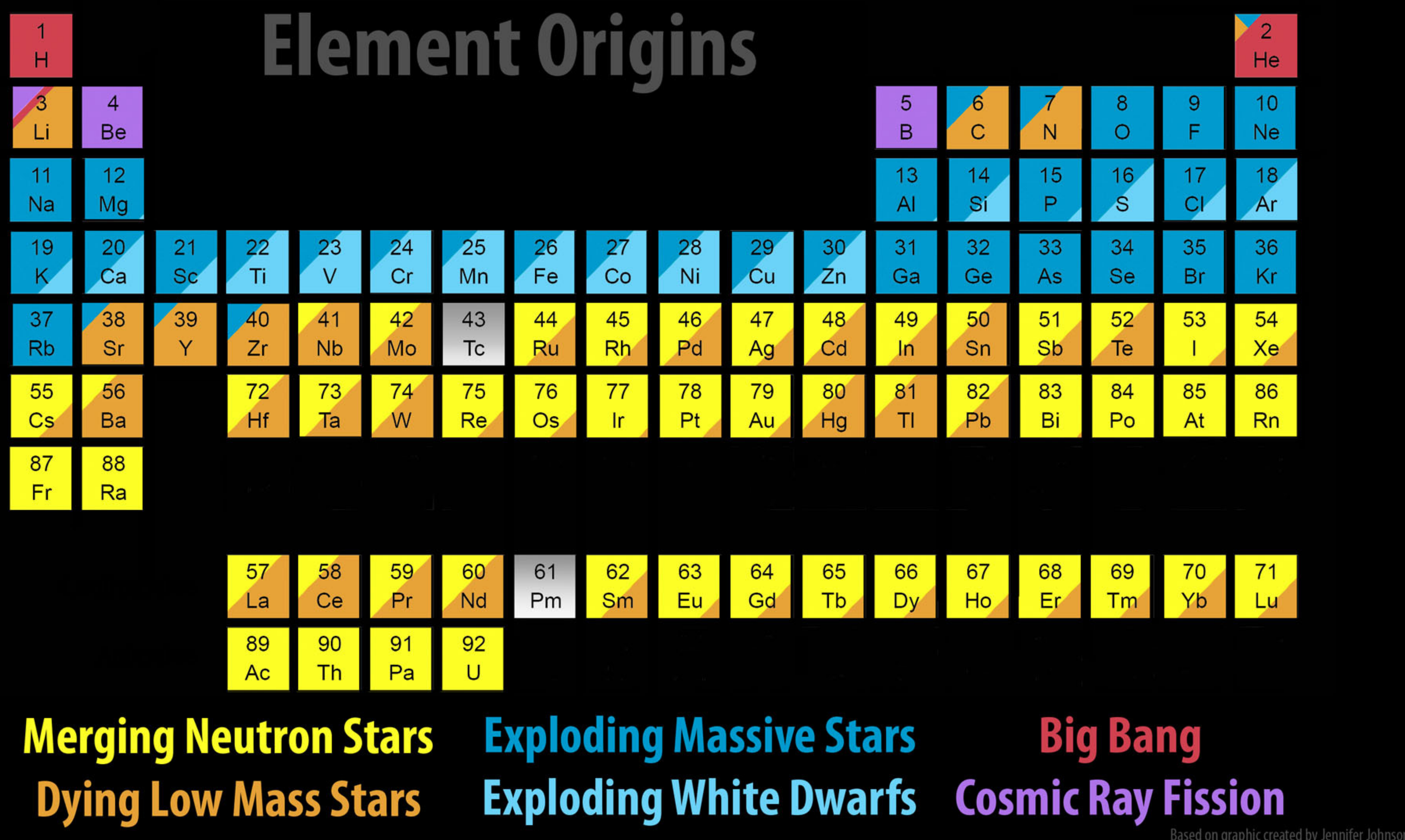
T > 2.5 x 10^8 K

He burning core

$^{14}N(\alpha,\gamma)\,^{18}F(\beta+\nu)\,^{18}O\,(\alpha,\gamma)\,^{22}Ne$



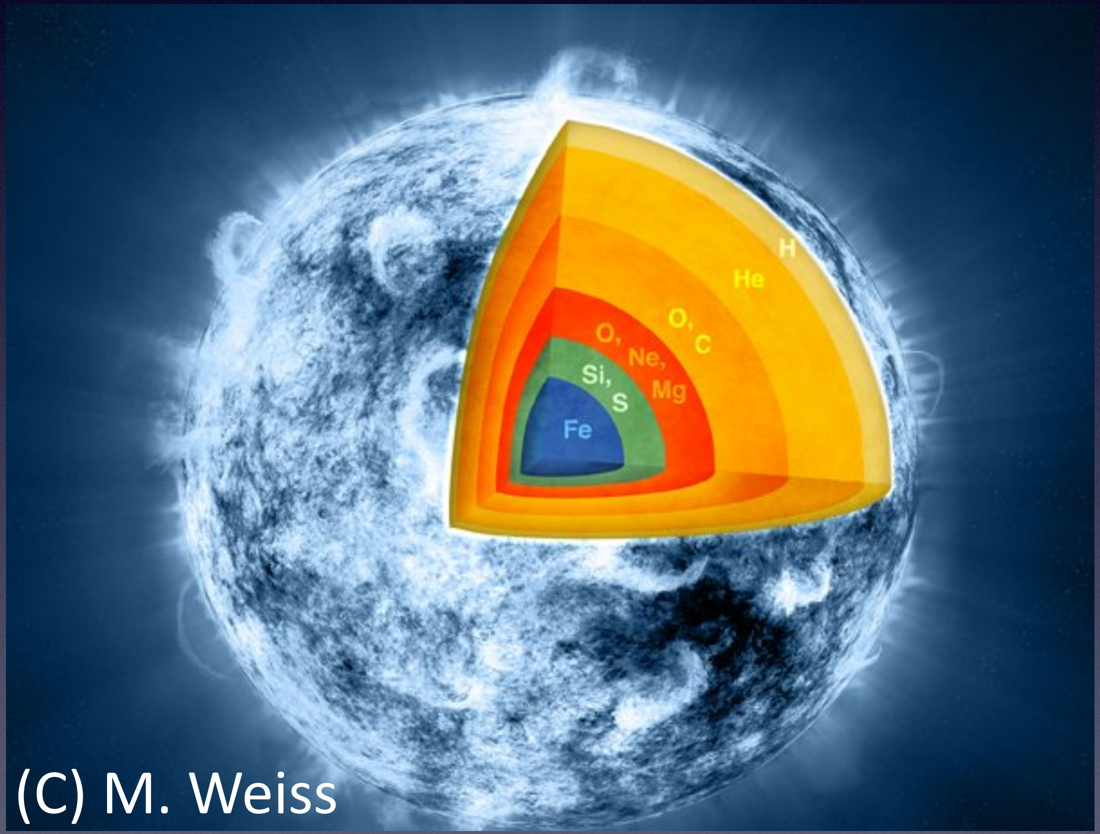
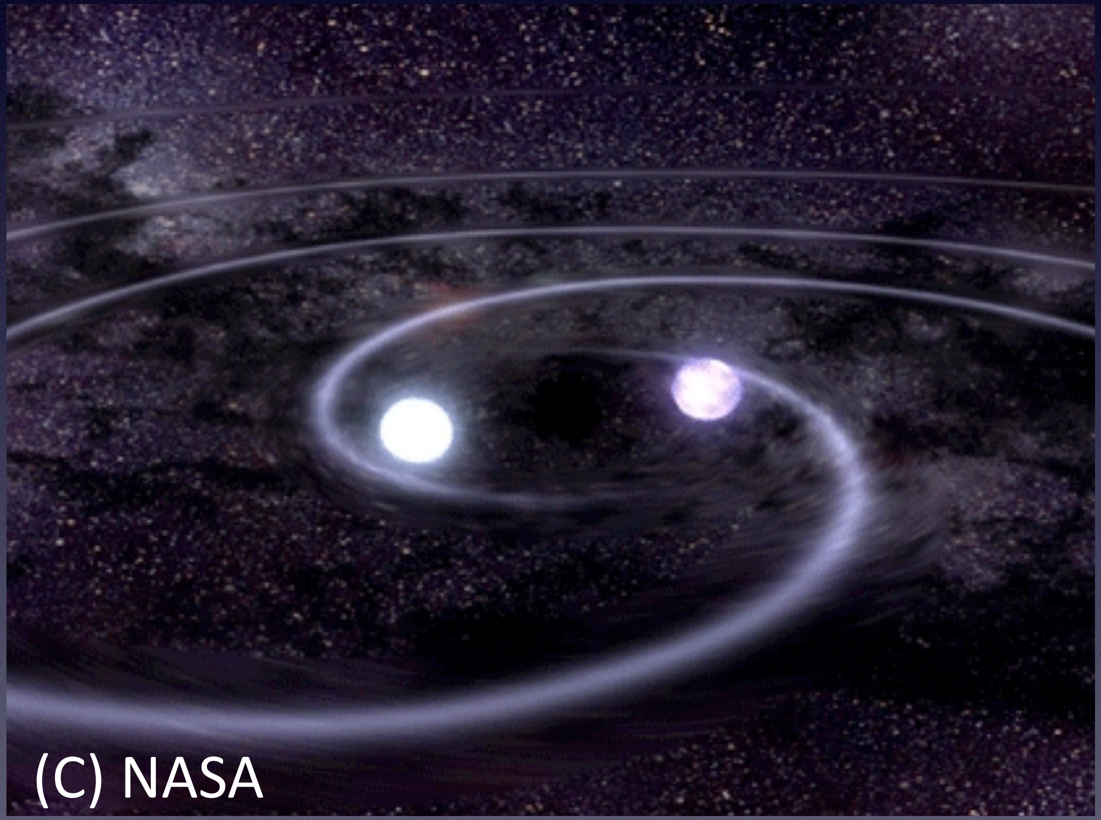
Pignatari+10



http://www.caltech.edu/news/caltech-led-teams-strike-cosmic-gold-80074

Origin of r-process elements?

Some phenomena related to neutron star

Supernova	Neutron star merger
	
(C) M. Weiss	(C) NASA
~ 1 event per 100 yr in a galaxy (R ~ 10^{-2} yr-1)	~ 1 event per 10,000 yr in a galaxy (R ~ 10^{-4} yr-1)

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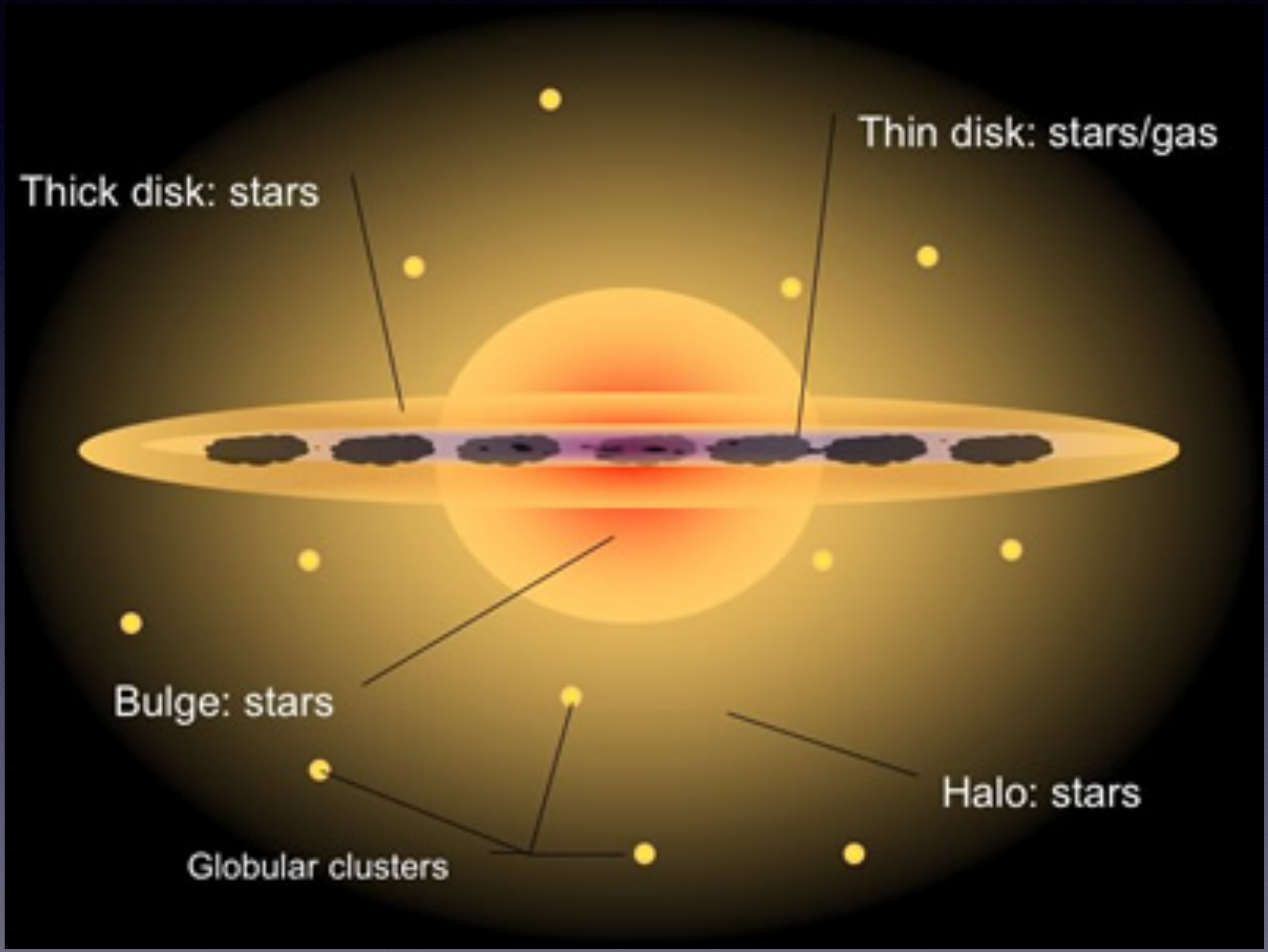
Our Galaxy

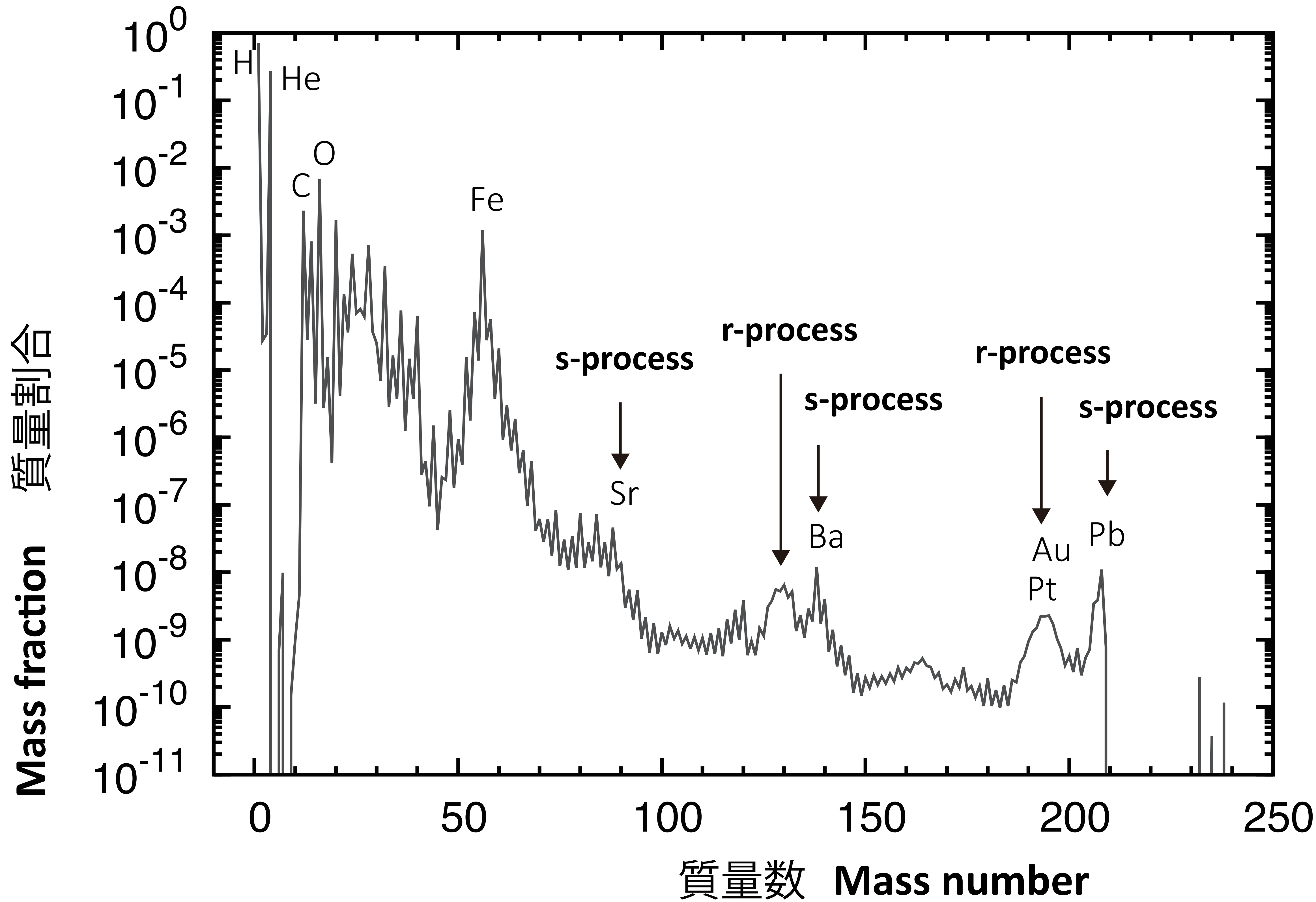
Stars keep information about nucleosynthesis in the past "Galactic archeology"



http://astronomy.swin.edu.au/cms/astro/cosmos/T/Thick+Disk

Cosmic abundance

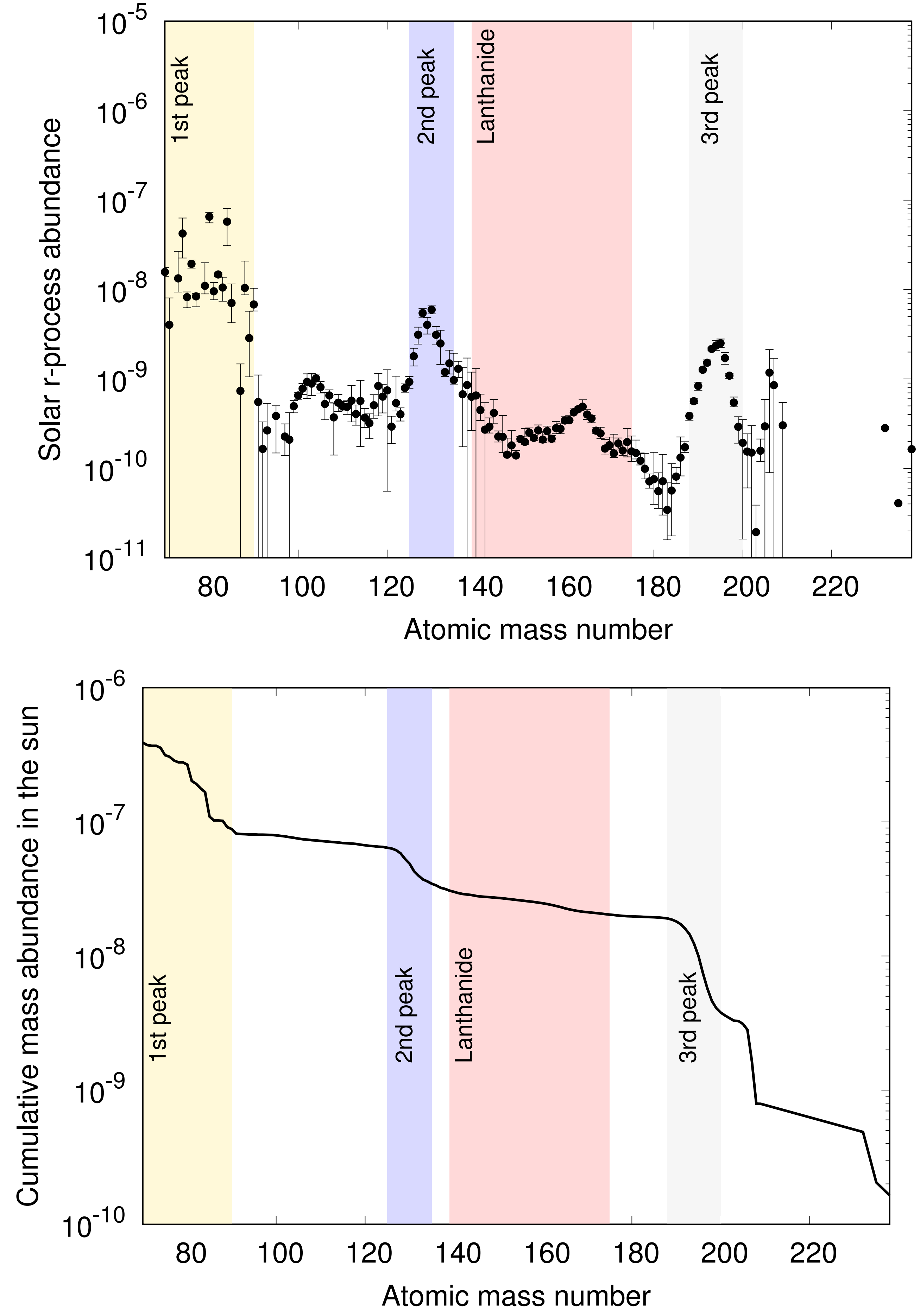
$X(Fe) \sim 10^{-3}$



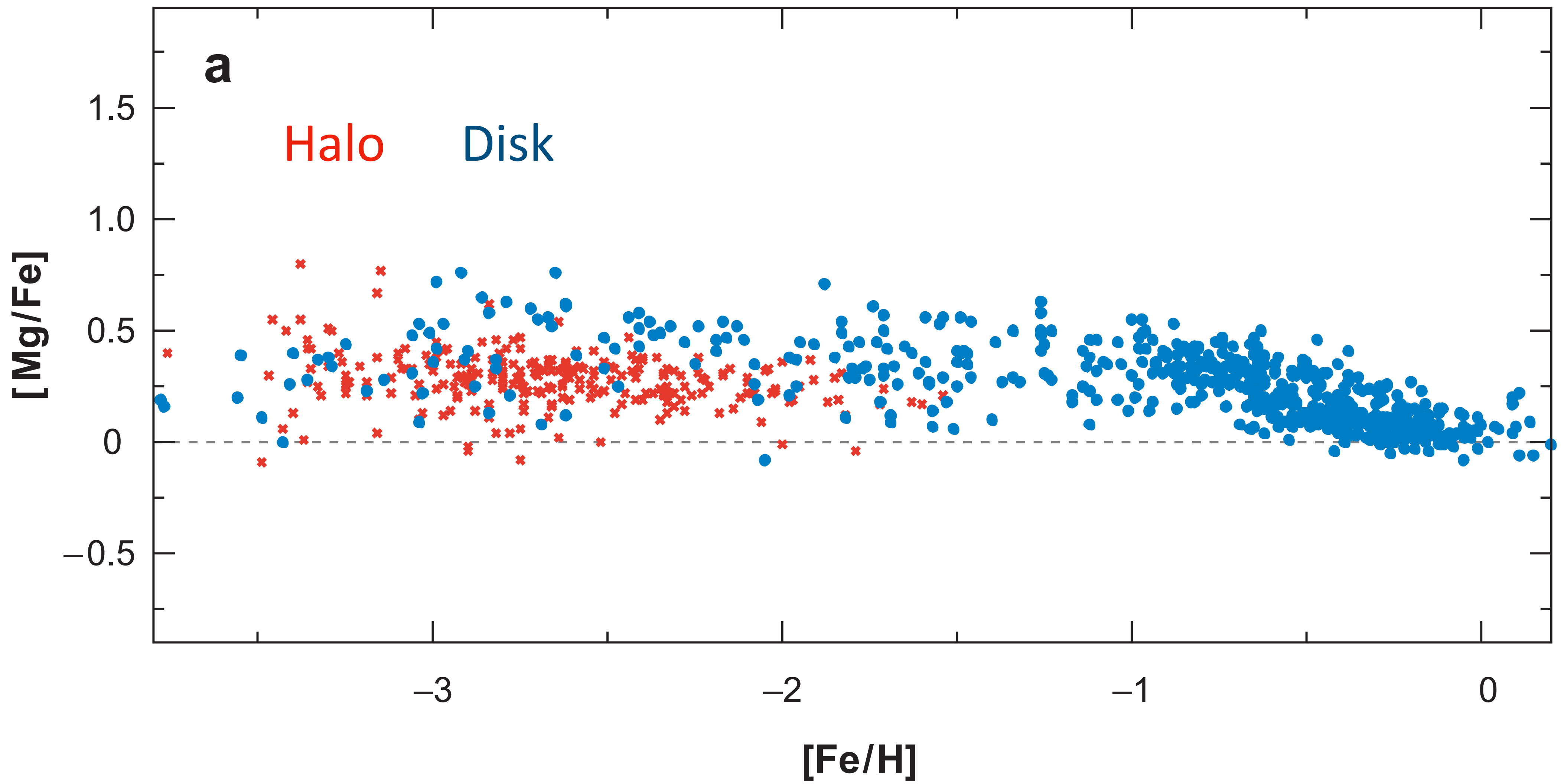
R-process elements

X(r) ~ 10^{-7}
(A > 90)

Cumulative mass fraction (from the heavier side)

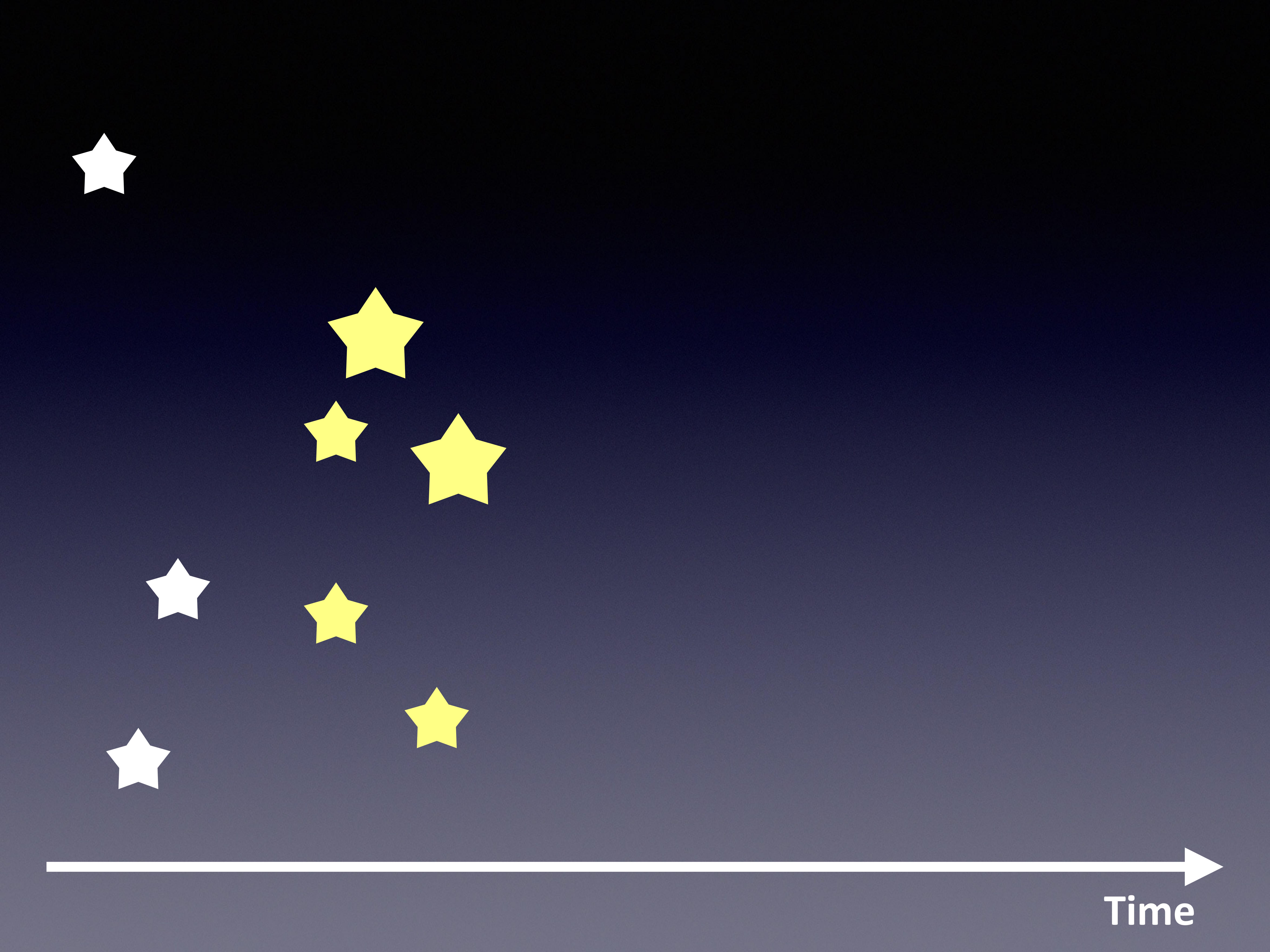


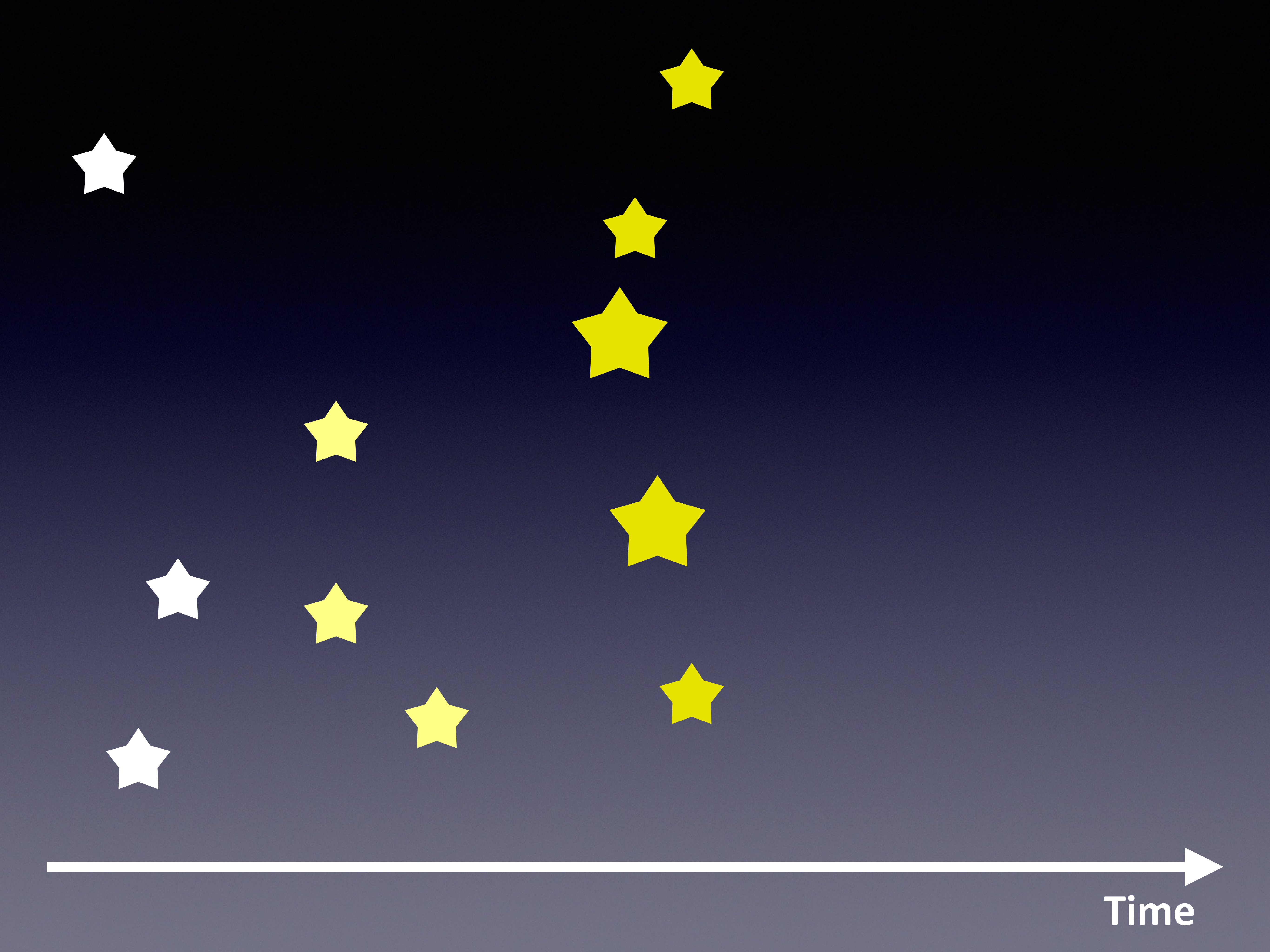
Abundance ratio in Galactic stars (Mg/Fe)



Sneden+08


Time


Time

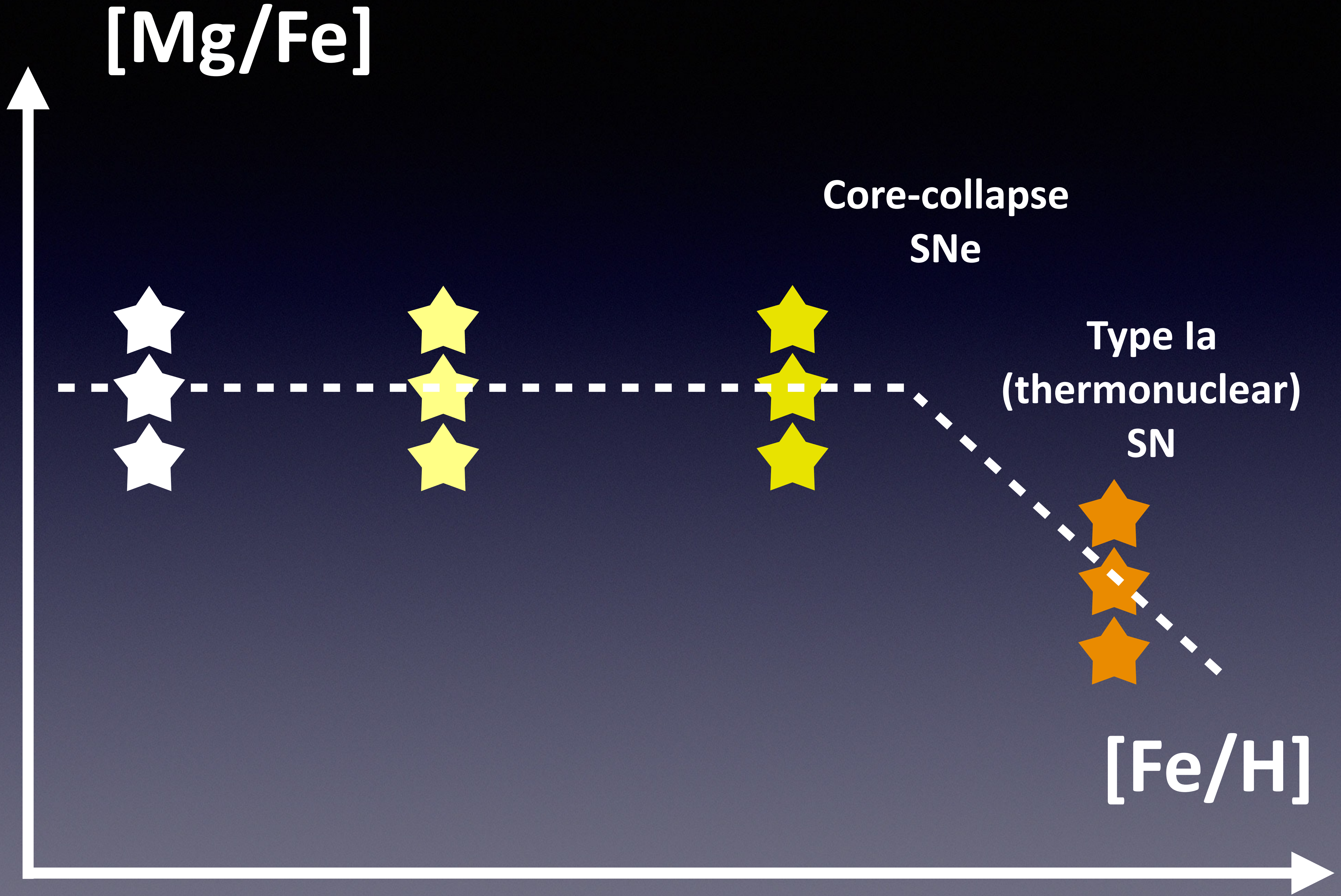

Time


Time

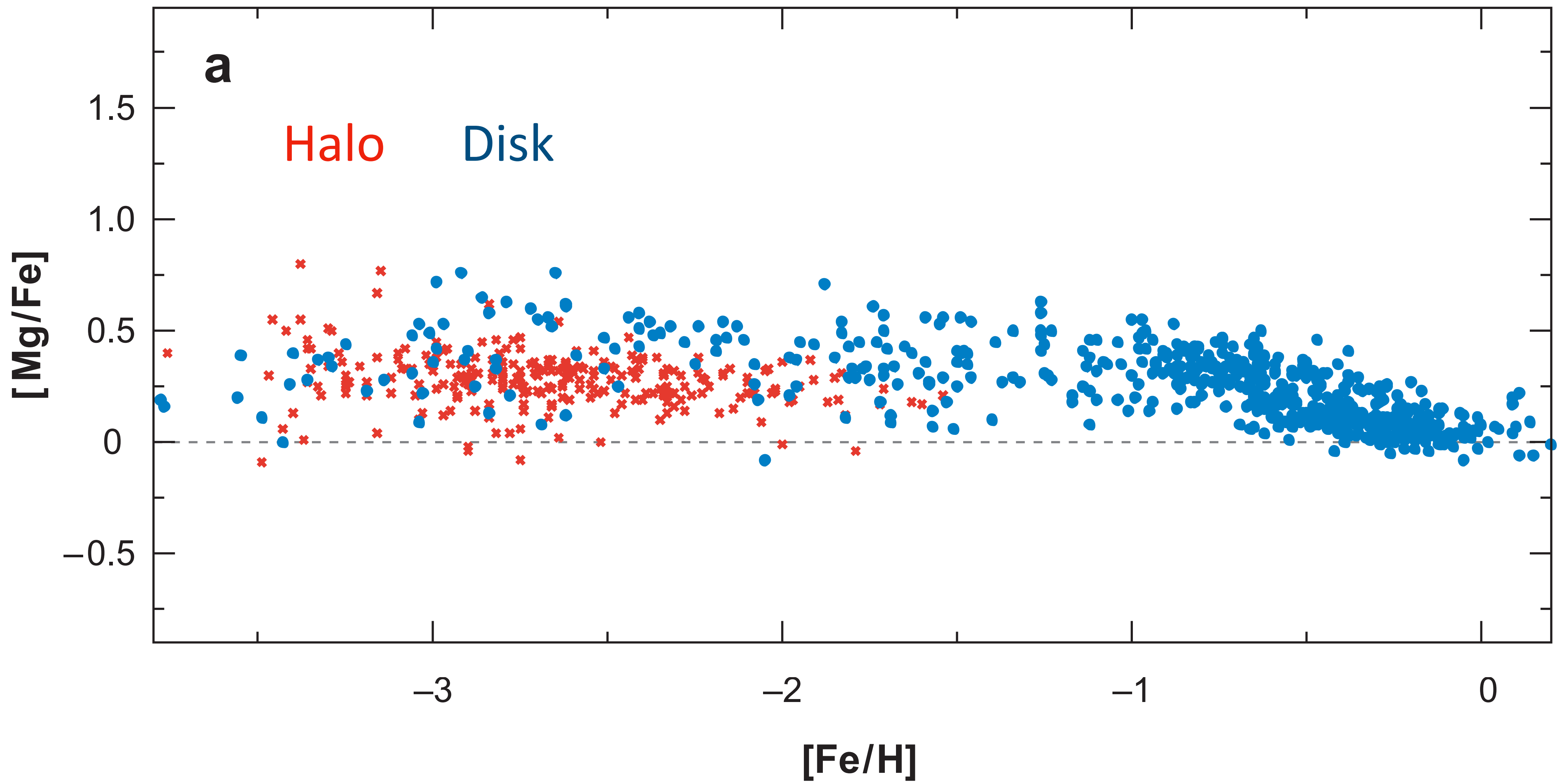

Time


[Fe/H]


[Fe/H]


[Mg/Fe]
Core-collapse
SNe
Type Ia
(thermonuclear)
SN
[Fe/H]

Abundance ratio in Galactic stars (Mg/Fe)



Sneden+08

Time

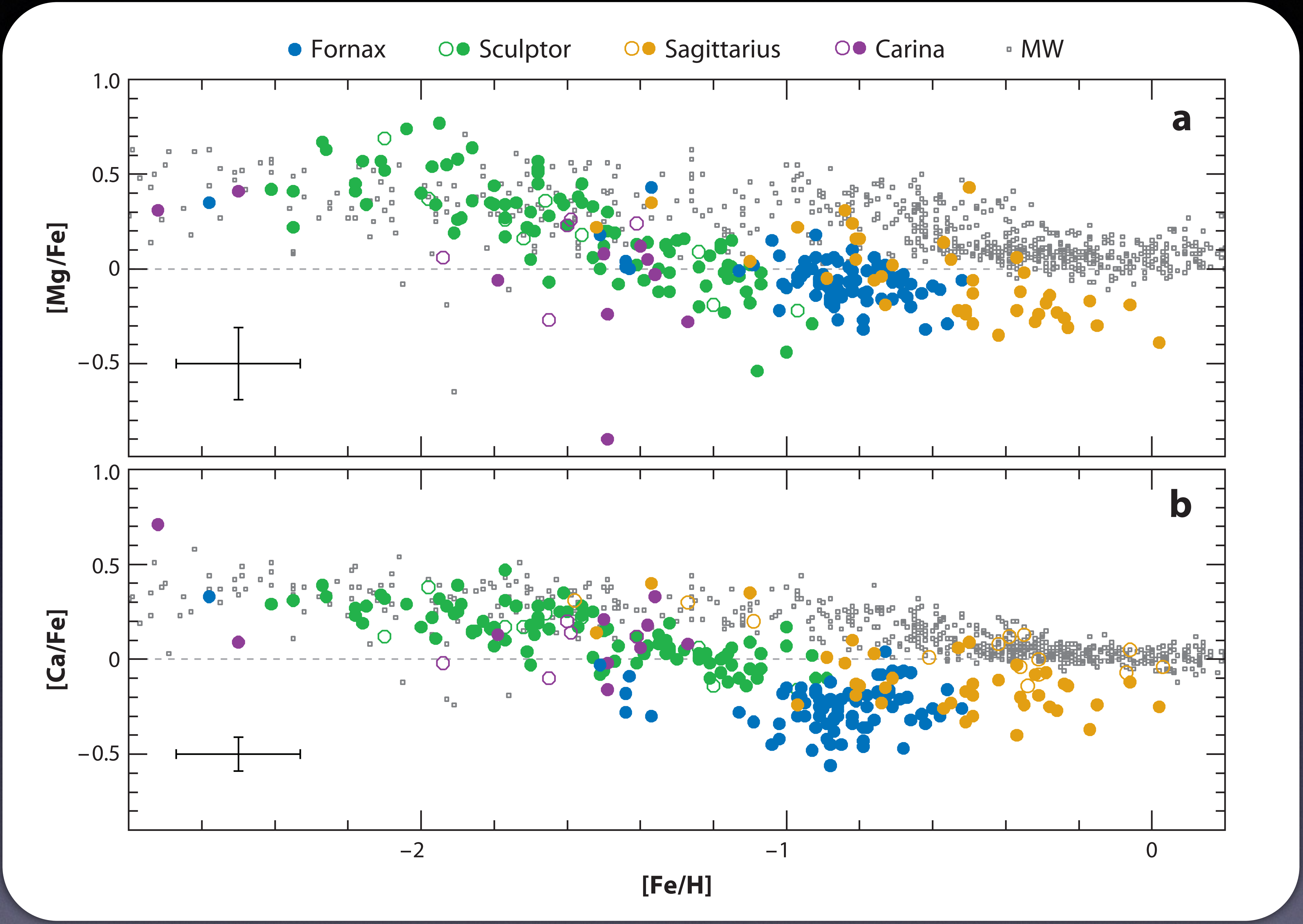
Longer delay time for Type Ia SNe

Our understanding about the nucleosynthesis is correct??

(A) Total amount

(B) Time scale

Role as a "clock" in galaxy formation



Tolstoy 08

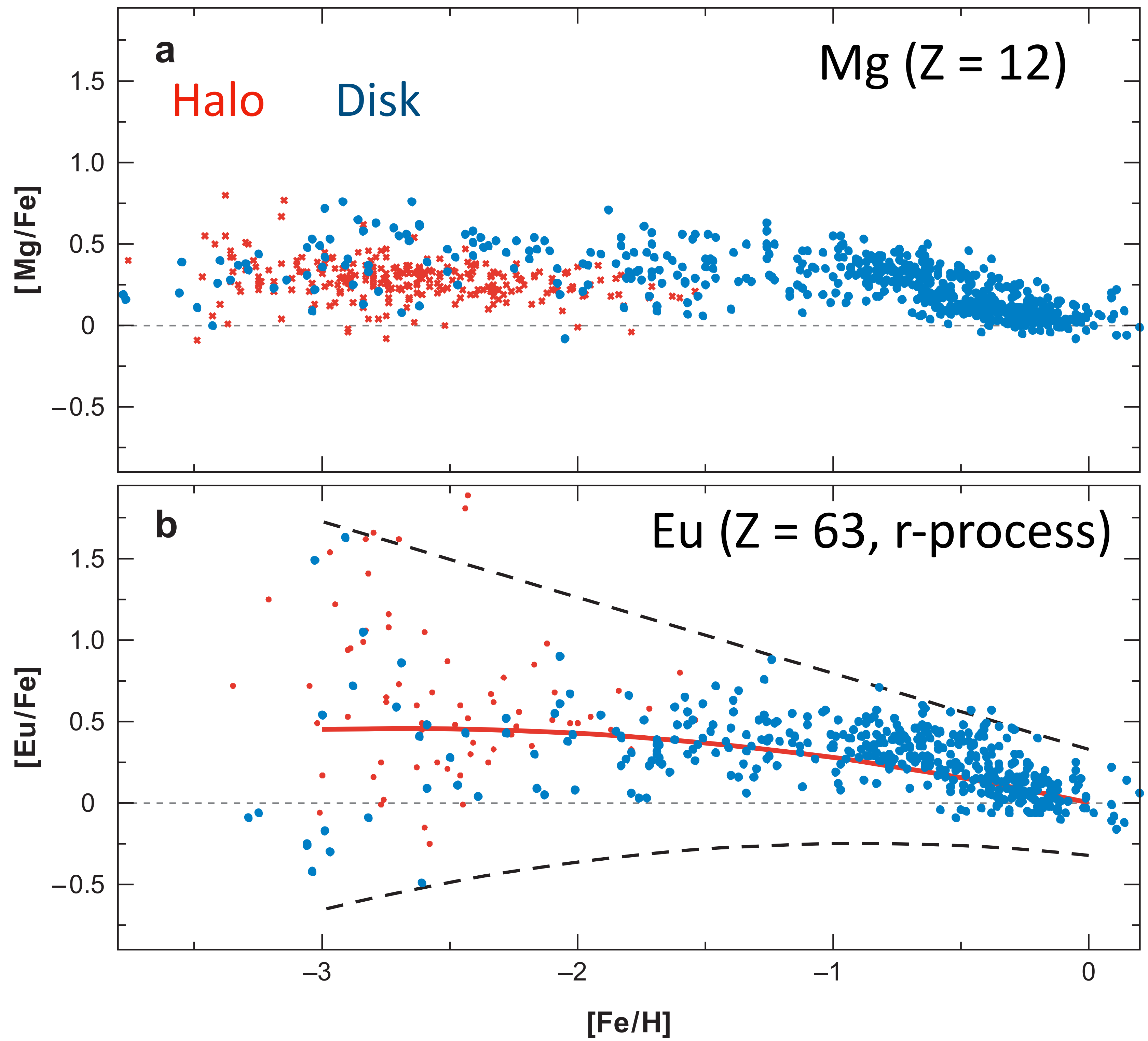
Fe in dwarf galaxies were smaller when Type Ia SNe begun to operate

Abundance ratio in Galactic stars (r-process/Fe)

r-process

Larger scatter

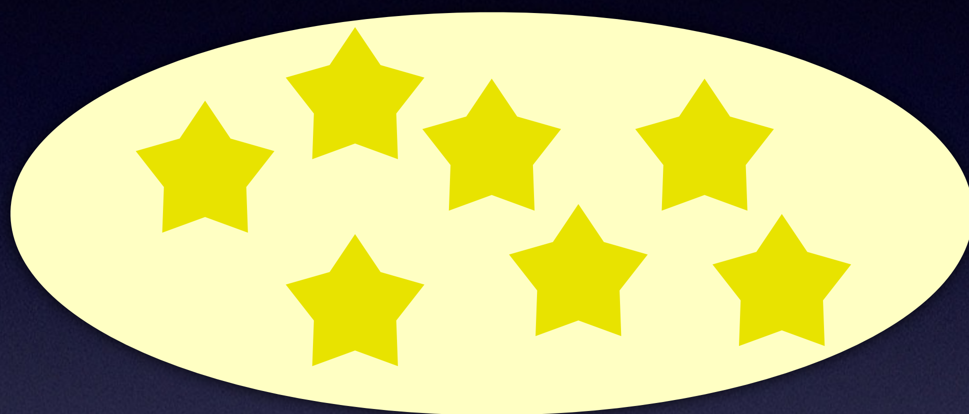
=> Rare event than normal core-collapse supernovae

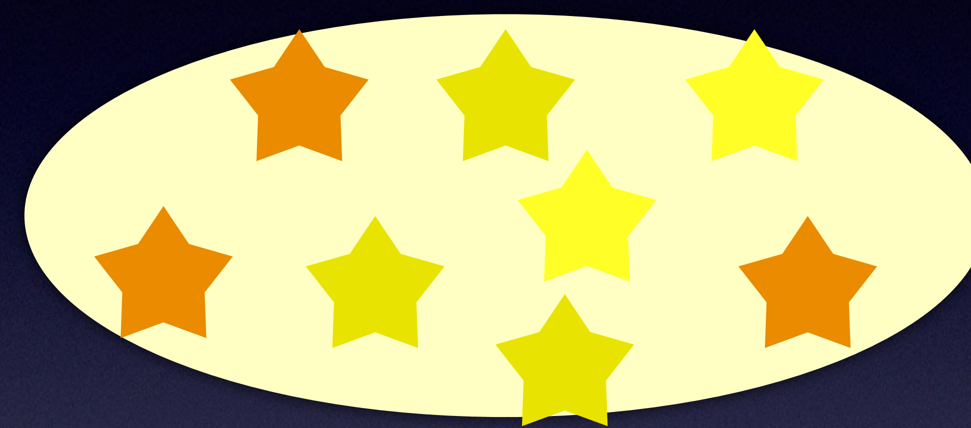


Sneden+08

High rate
Low ejection

Low rate
High ejection





Smaller scatter in abundance (e.g., Mg)

Larger scatter in abundance (e.g., Eu)

Mixing timescale ~ 100 Myr

Assignment 5

Read one paper focusing on chemical elements or metallicity
in your research area and summarize the contents in 2 pages.

(ex.) Measure the metal abundances of galaxy to know XXX.
Phenomena XXX is affected by metallicity because YYY.
An instrument using the property XXX of the element XXX.

レポート課題 5

自分が研究している(興味のある)現象・対象で
「元素」や「金属量」に着目している論文を探し、
その内容をA4 2ページ程度にまとめよ。

(例) 銀河の元素量を測って、... を知る
金属量が異なると、...の効果で... はこのように影響を受ける
この装置は...という元素の ... という性質を使っている

Summary: Origin of the elements in the Universe

- **Origin of the elements**
  - Bigbang nucleosynthesis: H, He, Li
  - Cosmic-ray spallation: Li, Be, B
  - Stellar interior: C-Fe
    (AGB stars, core-collapse SNe, thermonuclear SNe)
  - Neutron capture: > Fe
    s-process: AGB stars
    r-process: SN? NS merger?
- **Test with stars in our Galaxy and dwarf galaxies**
  - Close relation with galaxy formation