Origine degli elementi pesanti nell'Universo: prime evidenze nell'evento di neutron star merger GW170817

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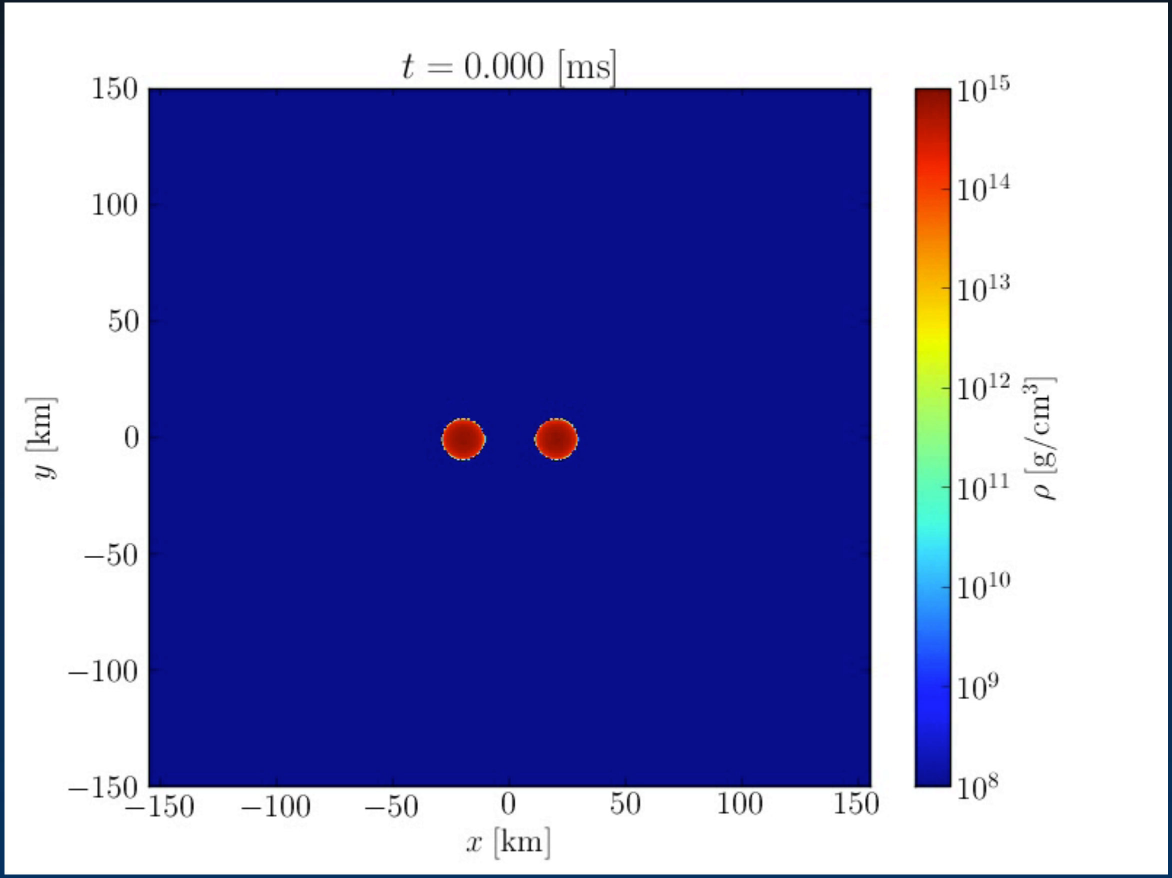


D Radice et al. (2016) - http://www.astro.princeton.edu/~dradice/

Universita' di Bologna
2 febbraio 2018

GW170817

17 August 2017: three separate observations, and strong evidence that they came from the same astronomical source:

GW170817 (collsion at 14:41.04 UCT)

GRB 170817A

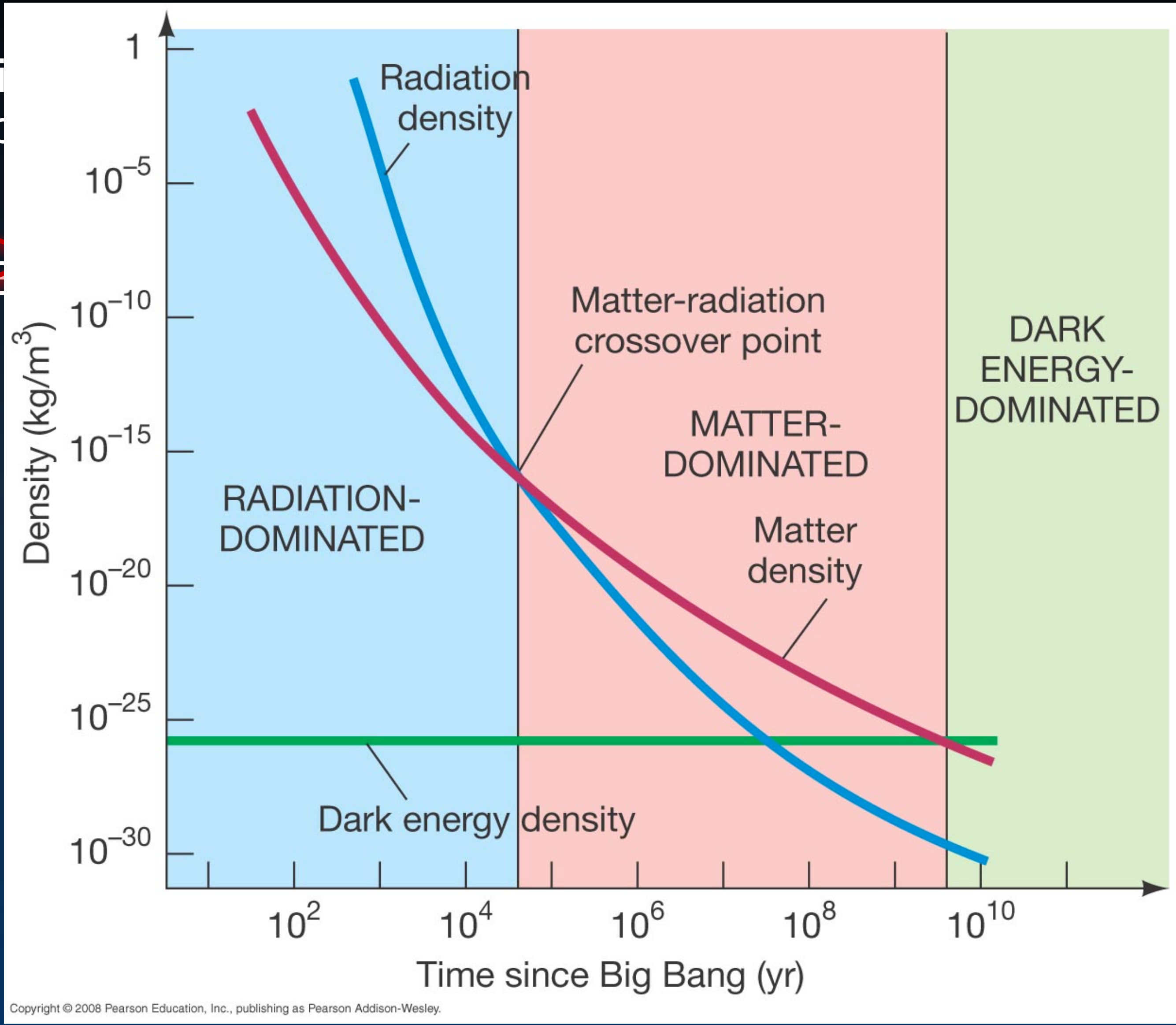
AT 2017gfo

Hubble picture of NGC 4993 with inset showing GRB 170817A over 6 days. *Credit: NASA and ESA*

Introducing the Universe

• Our universe i
Both of them c

• ~~We live (now)~~
~~$\rho(E_{mvis}) >> \rho(E$~~



Source: for example C.E. Rolfs and W.S. Rodney, "Cauldrons in the Cosmos"
The University of Chicago Press (1988)

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Introducing the Universe

- Our universe is formed of matter and radiation
  Both of them come in quantized forms (particles and photons)

- We live (now) in a Λ dominated universe

- Atomic nuclei exist in the universe
  Radioactivity and nuclear reactions show that nuclei are NOT immutable objects but that they have been formed somewhere, sometime

- The matter in the universe is essentially in the form of Hydrogen and Helium with a tiny addition of "metals"

- The distribution of the abundance of the elements show common patterns for the stars of our galaxy*

*the local distribution on the Earth surface is NOT a typical distribution. For example: there is very little Hydrogen

Source: for example C.E. Rolfs and W.S. Rodney, "Cauldrons in the Cosmos"
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Chemical elements abundance

Solar spectrum

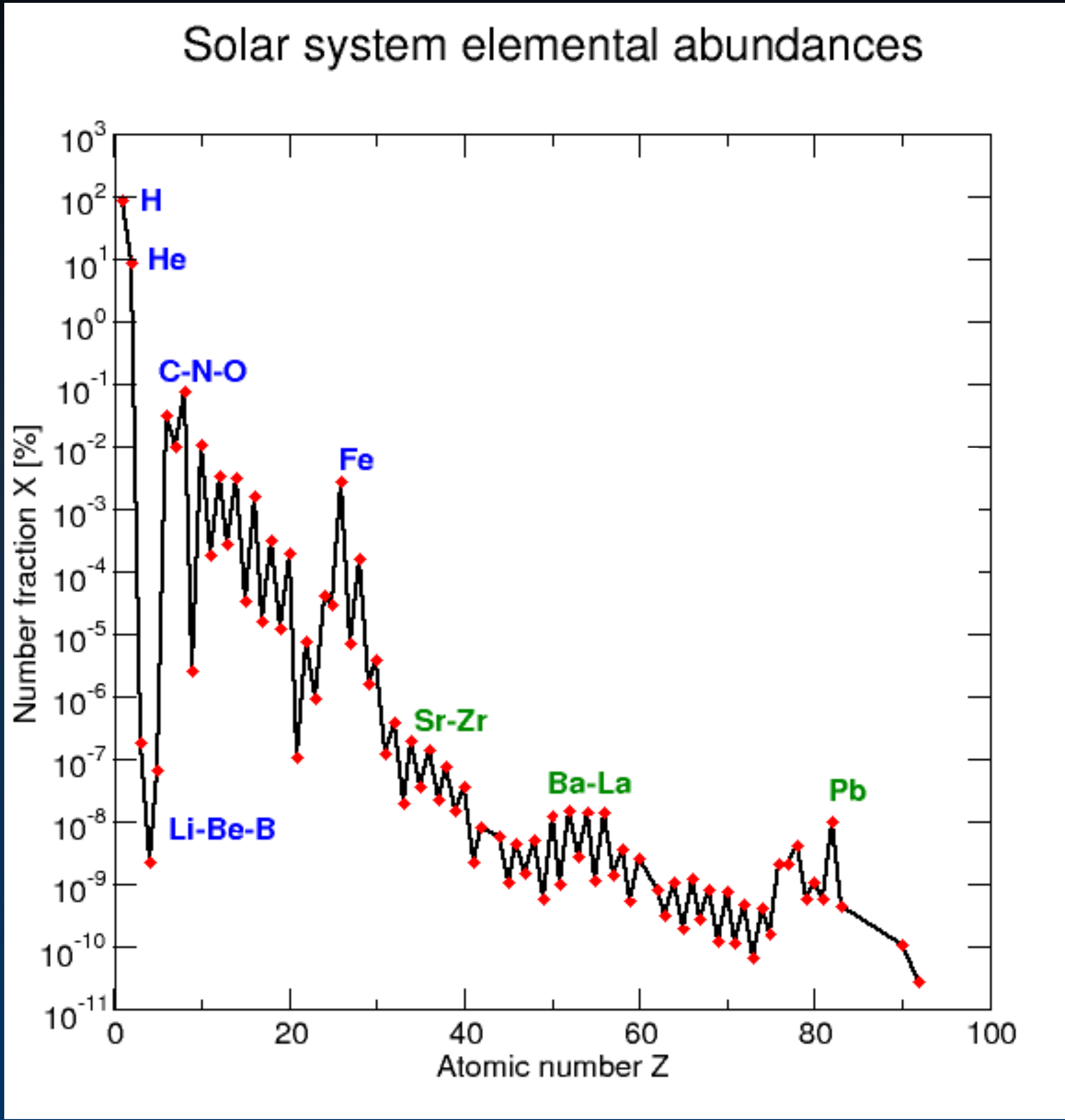
Meteorites

Earth's crust & sea

98.1%

Rank	A	Symbol	Mass Fraction
1	1	H	7.06×10^{-1}
2	4	He	2.75×10^{-1}
3	16	O	9.59×10^{-3}
4	12	C	3.03×10^{-3}
5	20	Ne	1.62×10^{-3}
6	56	Fe	1.17×10^{-3}
7	14	N	1.10×10^{-3}
8	28	Si	6.53×10^{-4}
9	24	Mg	5.15×10^{-4}
10	32	S	3.96×10^{-4}
11	22	Ne	1.30×10^{-4}
12	26	Mg	7.76×10^{-5}
13	36	Ar	7.74×10^{-5}
14	54	Fe	7.13×10^{-5}
15	25	Mg	6.77×10^{-5}

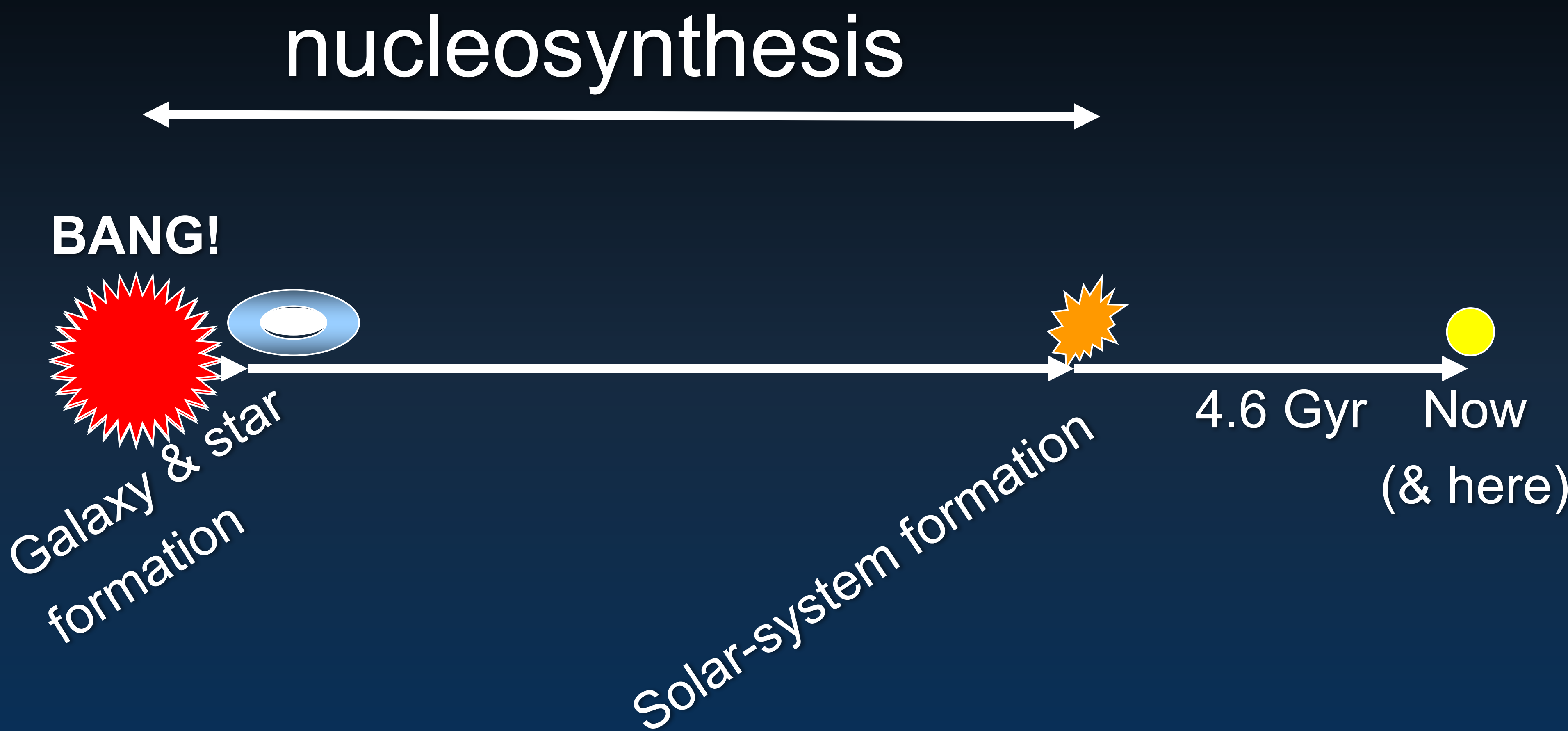
- Solar system abundances are similar for all Pop I stars (cosmic abundance)
- Gap @ the Li-Be-B group
- Strong decrease following the C-N-O elements



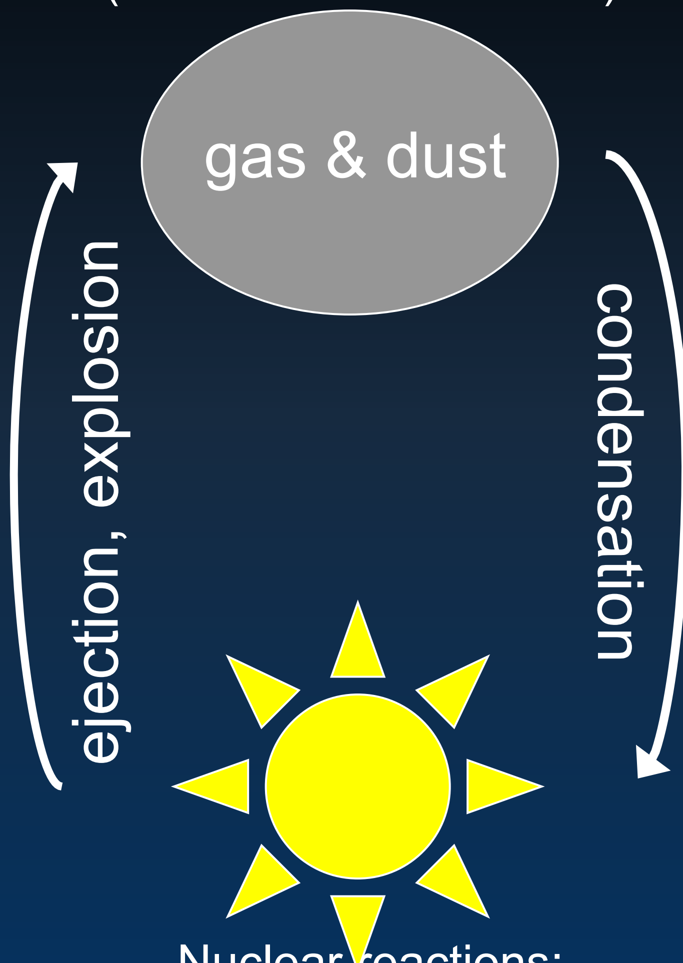
Nucleosynthesis ideas

- 1937 (von Weizäcker): a supermassive star cooks H to form all the elements after which the system explodes into an expanding universe
- 1940s (Alpher, Bethe, Gamow) universal synthesis hypothesis: all the elements are formed during a rapidly expanding hot (10^9 K) phase of the universe
- 1957 (B^2FH and Cameron) propose the mechanisms for the production of the elements in star's interior
- 1960s (Hoyle et al.) the large amount of ^4He cannot be made by stellar nucleosynthesis but it can be produced, together with other light elements, by a primeval explosion (BBN)

A brief history of the Universe



Stellar Nucleosynthesis

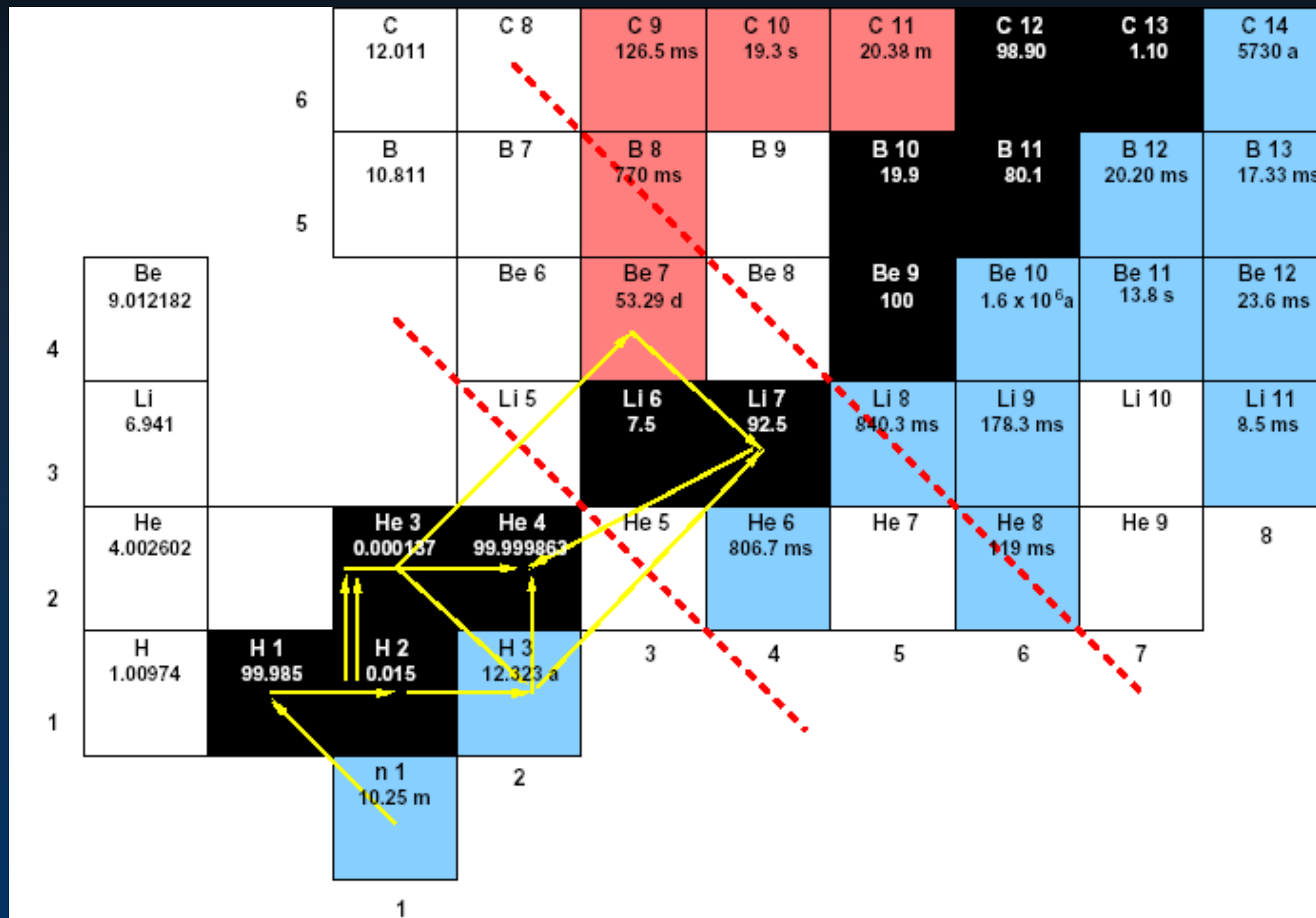


life of stars >>

Big bang nucleosynthesis

- ✓ Yp = 0.245 ± 0.004
- ✓ D/H = $(2.53 \pm 0.04) \times 10^{-5}$

Reactions
n-decay
$p(n,\gamma)d$
$d(p,\gamma)^3\mathrm{He}$
$d(d,n)^3\mathrm{He}$
$d(d,p)t$
$^3\mathrm{He}(n,p)t$
$t(d,n)^4\mathrm{He}$
$^3\mathrm{He}(d,p)^4\mathrm{He}$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
$t(\alpha,\gamma)^7\mathrm{Li}$
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$



Lithium: observation

Best value from observations:
[Li/H] = 1.6 ± 0.3

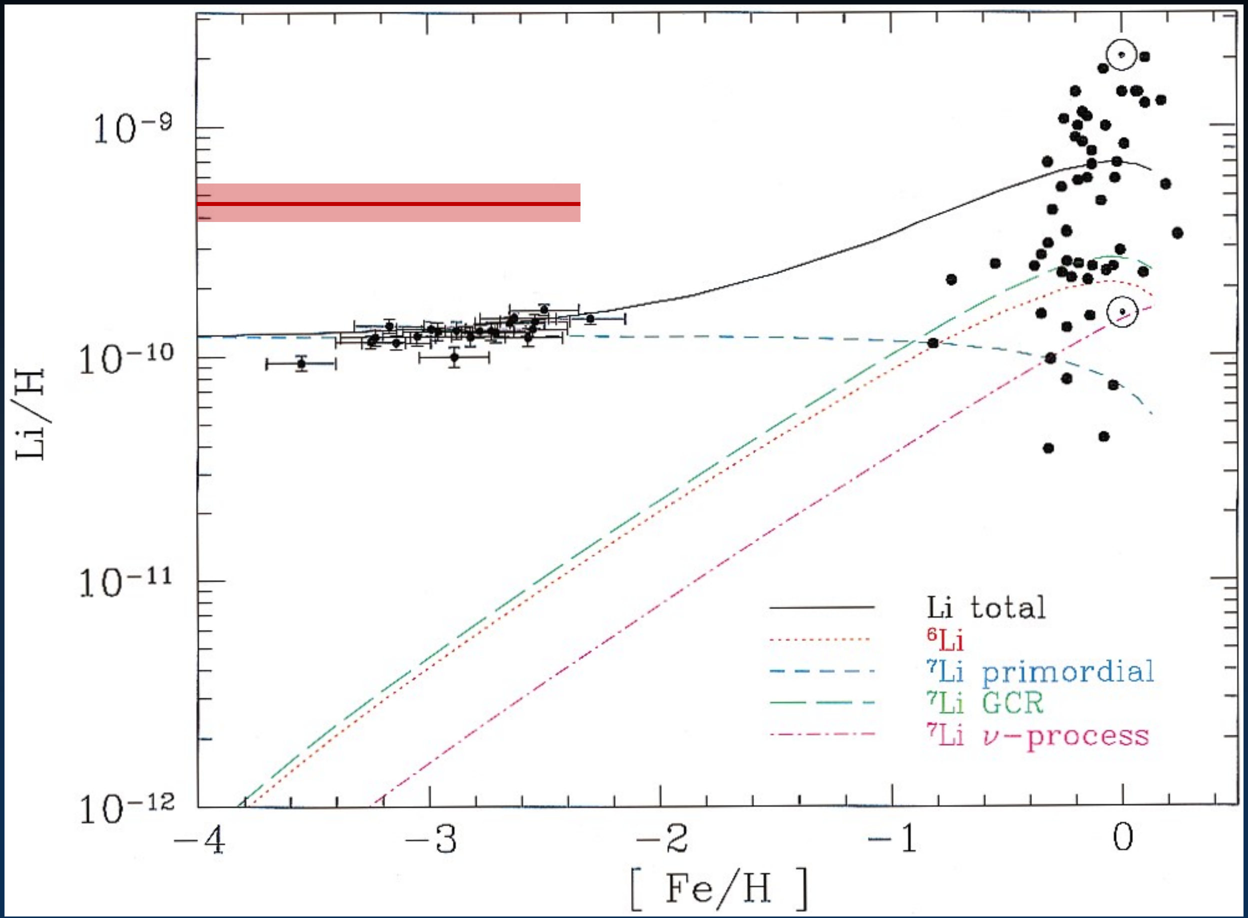
Expected from CMB analysis and standard BBN

[Li/H] = 4.45 ± 0.05

Expected from standard BBN Y_p and D abundance concordance

3.9 ≤ [Li/H] ≤ 5.3

[ ] : 10^{-10}



Contributions to the total predicted lithium abundance from the adopted GCE model of Fields & Olive (1999a, 1999b), compared with low metallicity stars (RNB) and high-metallicity stars (Lambert, Heath, & Edvardsson 1991). The solid curve is the sum of all components.

S G Ryan et al. ApJ 530 (2000) L57

BD Fields et al., PDG Review (2016)

^{7}Be destruction by neutrons

See recent measurements @ CERN n_TOF

Reactions
n-decay
$p(n,\gamma)d$
$d(p,\gamma)^3\mathrm{He}$
$d(d,n)^3\mathrm{He}$
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$t(d,n)^4\mathrm{He}$
$^3\mathrm{He}(d,p)^4\mathrm{He}$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
$t(\alpha,\gamma)^7\mathrm{Li}$
$\boxed{^7\mathrm{Be}(n,p)^7\mathrm{Li}}$
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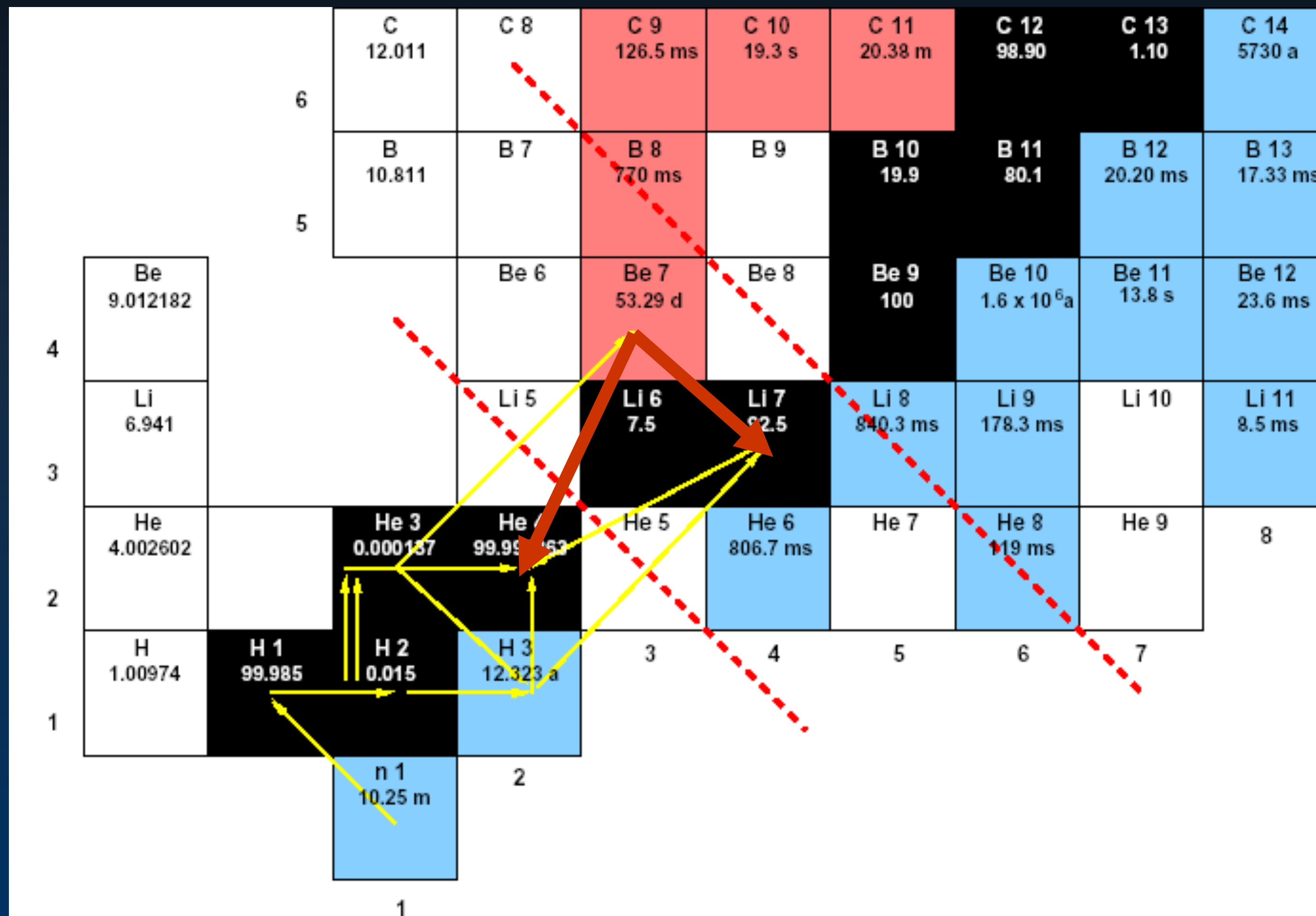


B^2HF

In 1957, the accepted cosmological models were two: the big-bang and the steady-state. Burbidge, Burbidge, Fowler and Hoyle proposed a set of burning process which accounted for the production of elements heavier than hydrogen during different phases of stellar evolution. Their work was, therefore, independent on the cosmological assumptions. The eight processes were:

1. Hydrogen burning: conversion of $4p \rightarrow {}^{4}He$ (sun energy production)

2. Helium burning: the 3α process and the formation of the CNO elements

3. α-process: nucleosynthesis beyond ${}^{16}O$ up to ${}^{40}Ca$ (now attributed to C and O burning)

4. e-process: NSE making of the iron peak (see supernovae)

5. s-process: trans-iron elements produced by neutron capture along the stability valley

6. r-process: to reproduce the double-peaks (neutron capture much faster than β-decay)

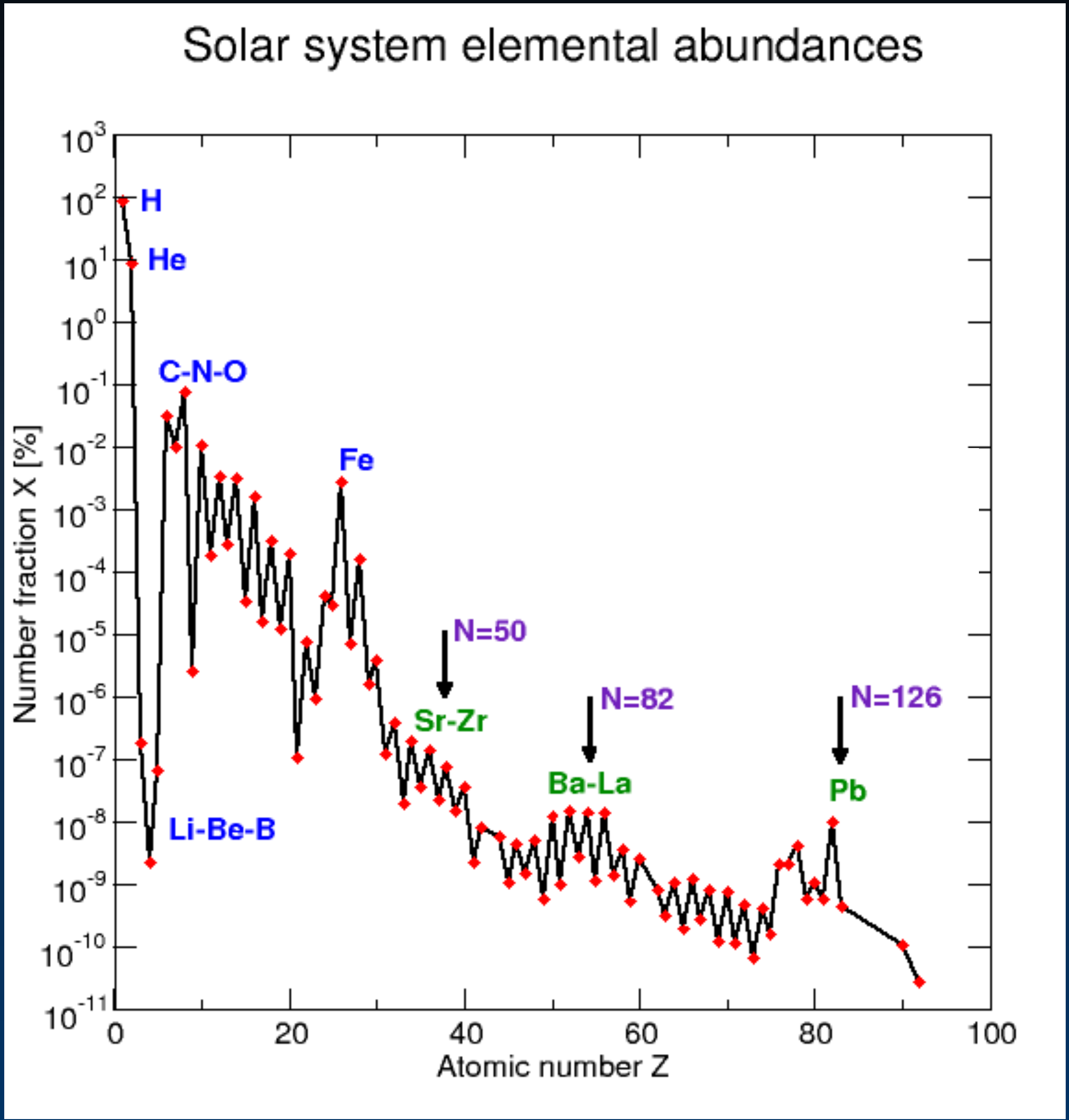
7. p-process: production of rare proton-rich nuclei

8. x-process: production of D, Li, Be and B (now attributed to BBN + cosmic-ray spallation)

Stellar Nucleosynthesis

The distribution of the abundance of the elements show common patterns for the stars of our galaxy

- Reaction rates for charged particle reactions are very slow for high-Z elements at low-Temperatures ($T \approx T_8$)
- At much higher T, there would be the onset of NSE and nuclei in the Iron-peak would be favored
- Neutrons are produced during stellar evolution
- Heavy nuclei have large $\sigma(\mathrm{n},\gamma)$, some correlated with abundances
- Double peaks can only be explained by neutron capture processes
- There is enough seed material (only ~3% of the iron-peak is needed to synthesize heavies)



s-process

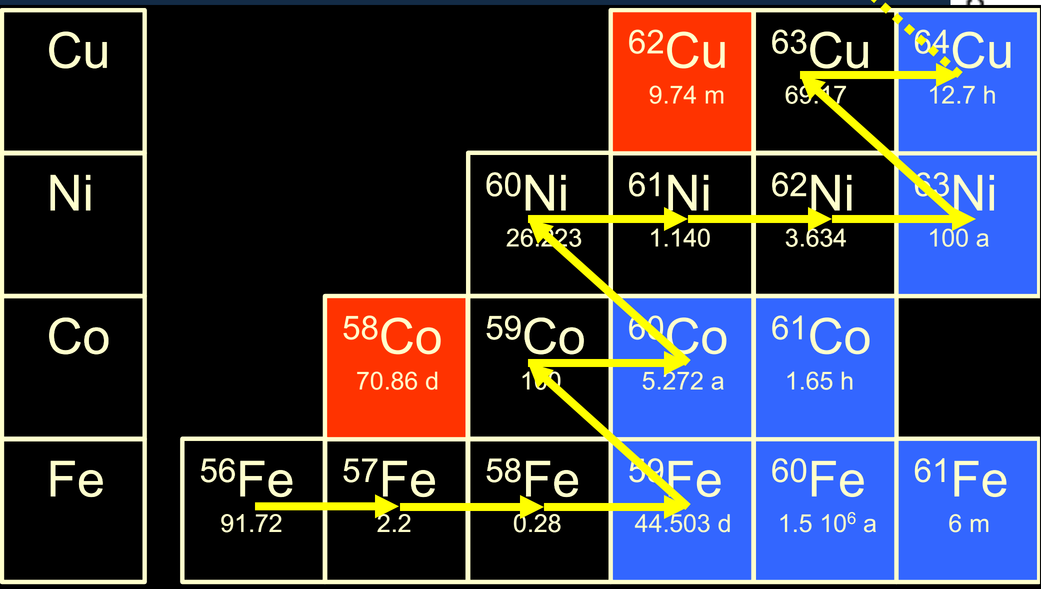
The lifetime of a nucleus against (n,γ) is:

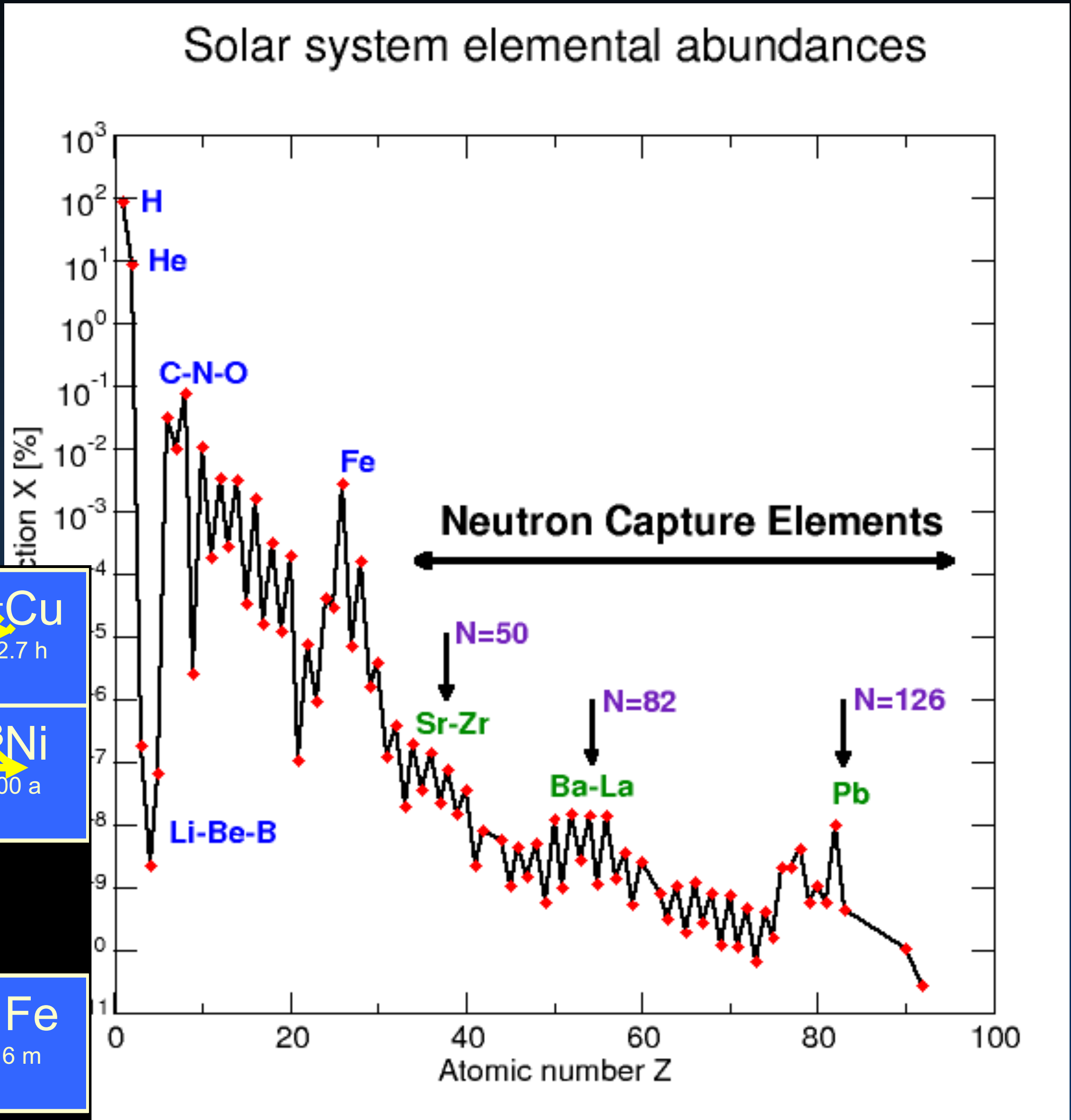
$$\tau_{n,\gamma} \equiv \frac{1}{N_n \langle \sigma_{n,\gamma} v \rangle}$$

For $\sigma_{(n,\gamma)} \approx$ 100 mb and $kT \approx$ 30 keV, it is:

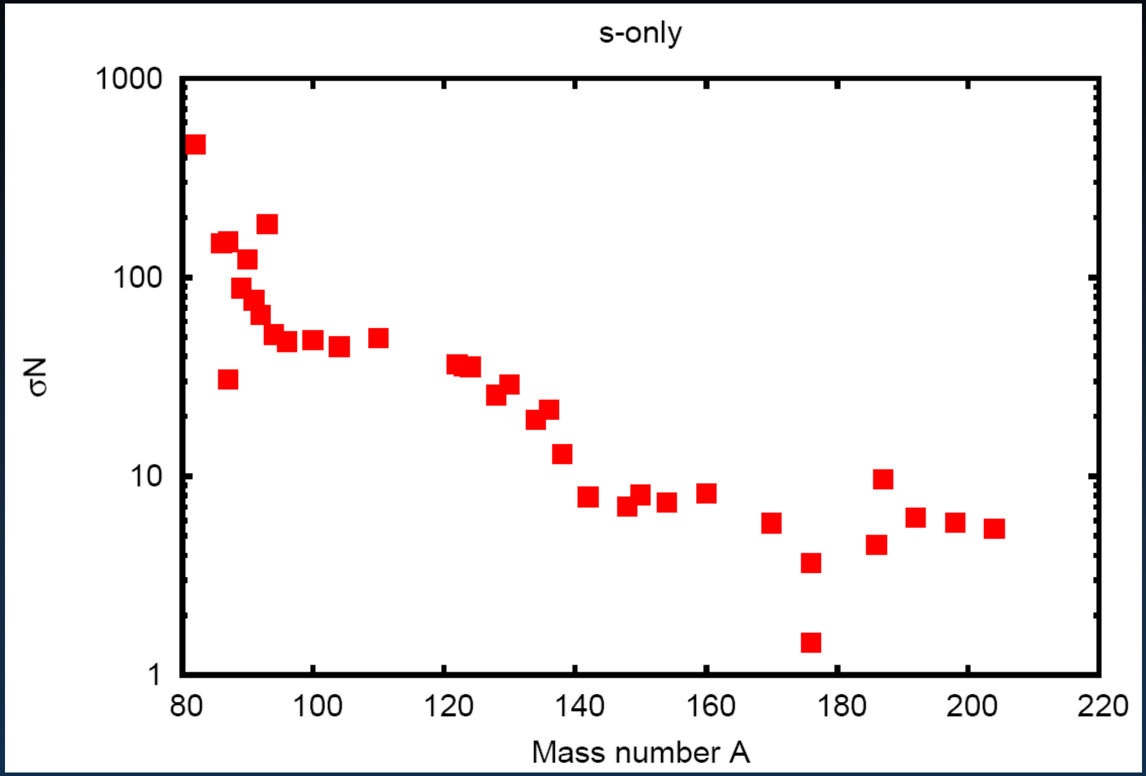
$$\tau_{n,\gamma} \approx \frac{10^9}{N_n} yr$$

The canonical s-process





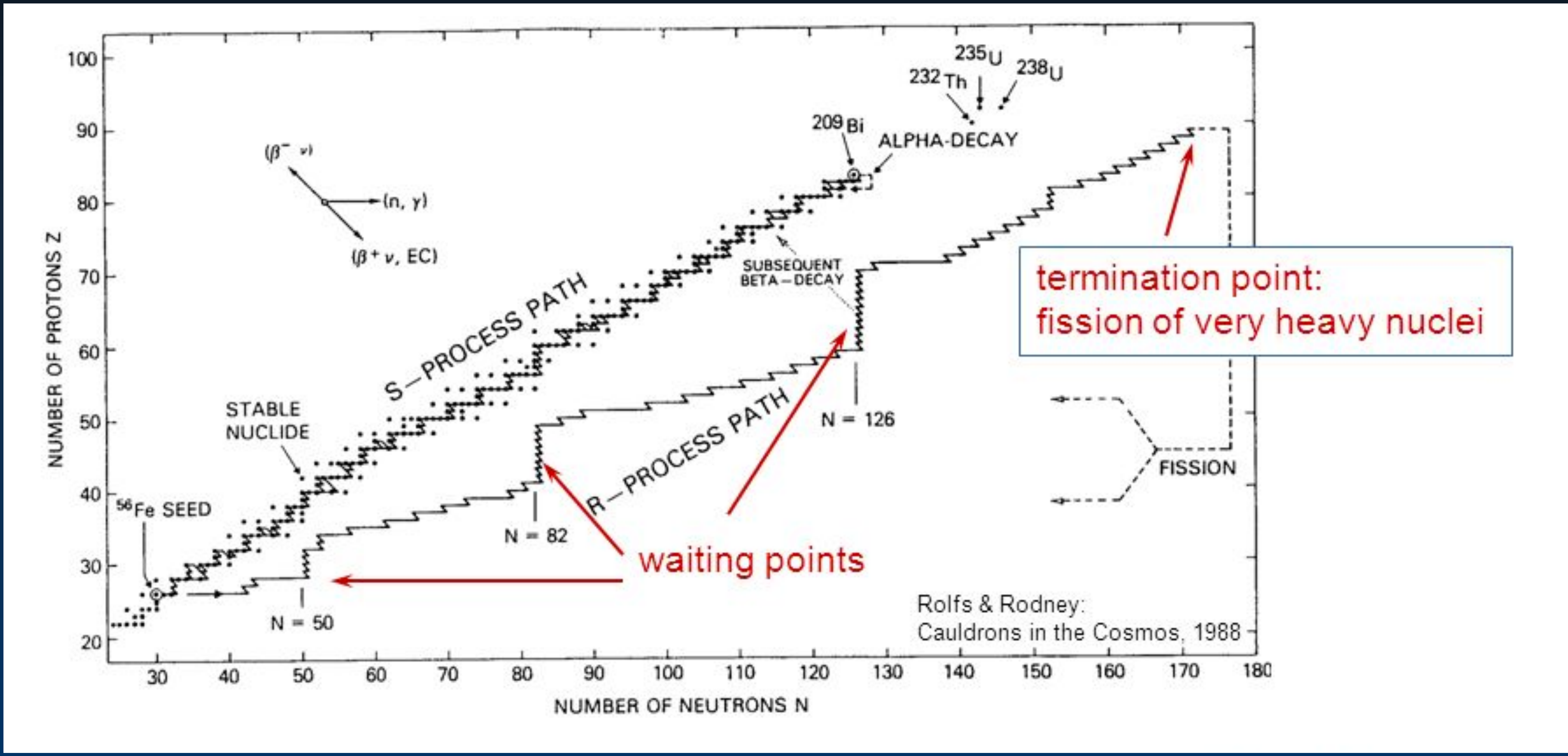
The canonical s-process



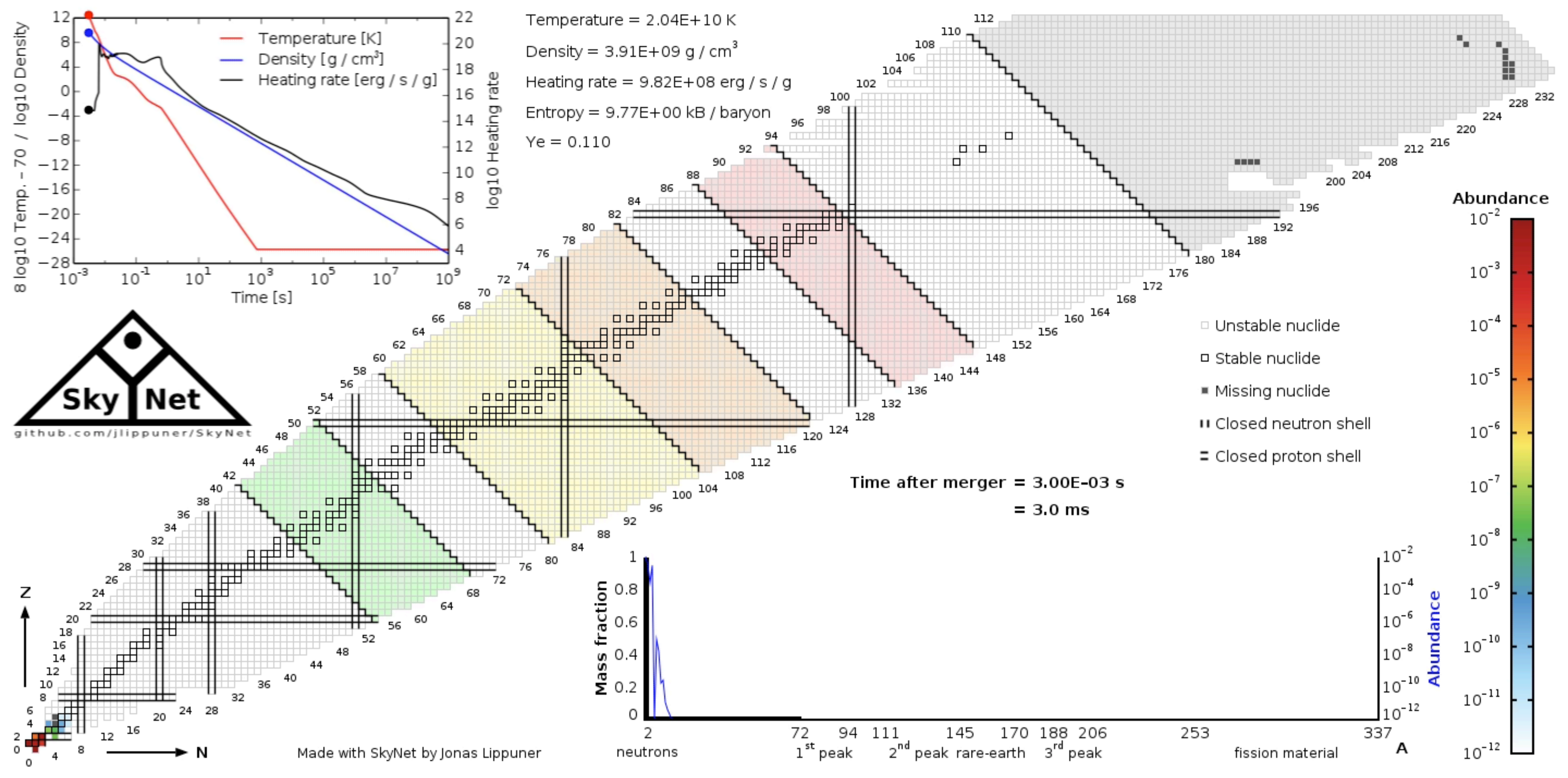
1. Direct correlation between the neutron capture cross section and the cosmic abundance: $\sigma(n,\gamma) \times N \sim const.$

2. r-process abundances: $N_r = N_{obs} - N_s$

Two classes: s-process & r-process



r-process in NS mergers

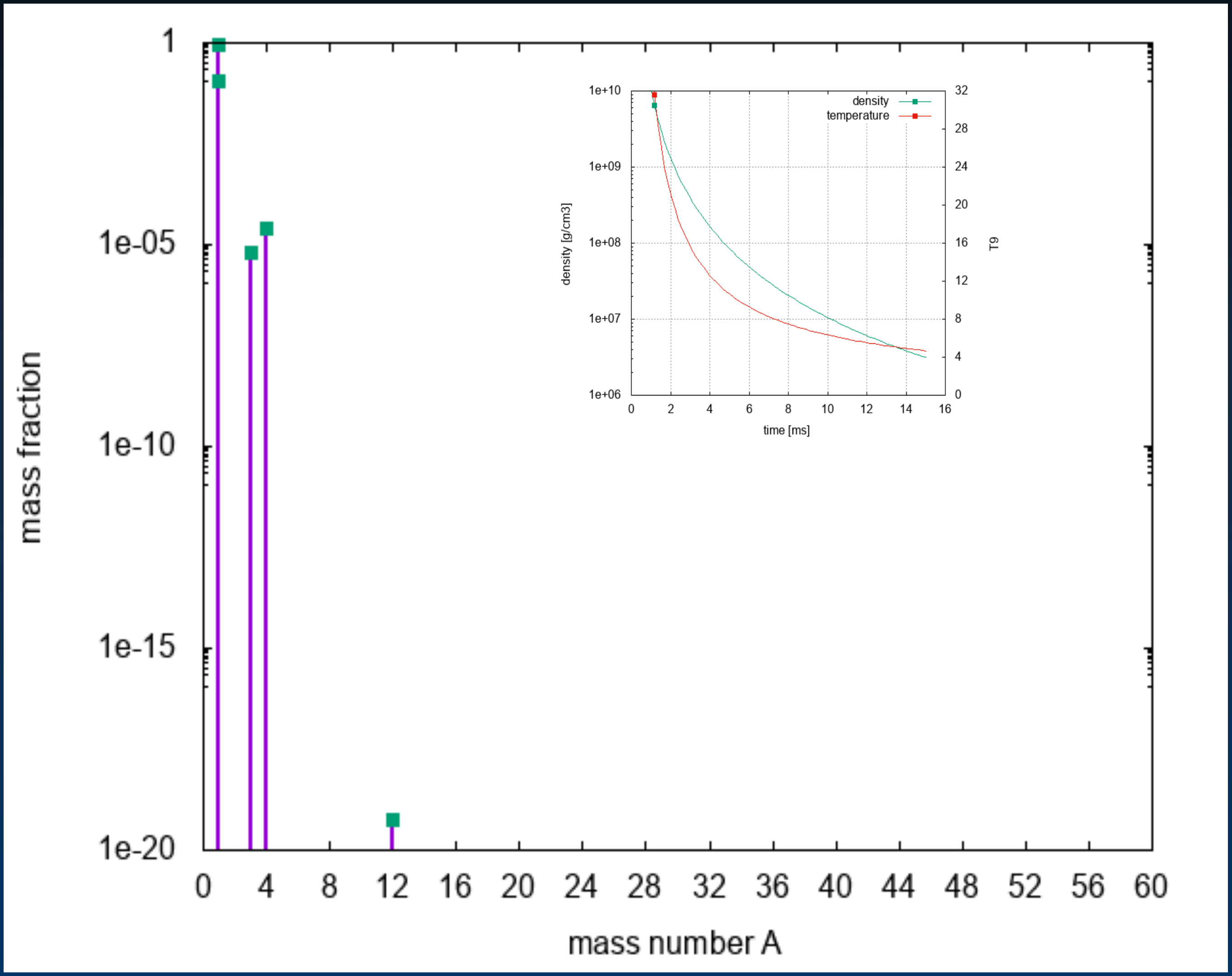


Nuclear Statistical Equilibrium

Below ≃10^6 K, the kinetic energy of constituents is not sufficient for nuclear reactions to take place.

Up to ≃5×10^9 K a full nuclear reaction network is needed to follow the abundances.

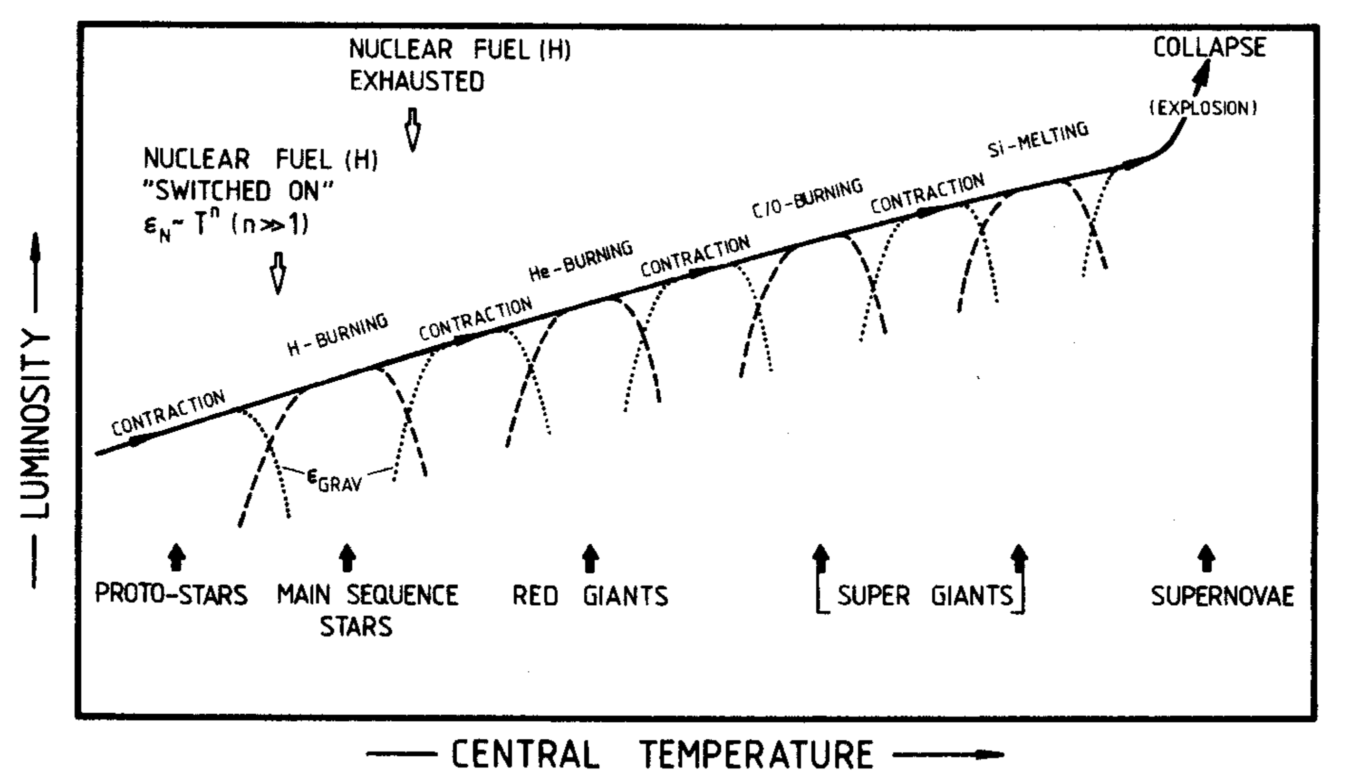
Above ≃5×10^9 K, conditions are energetic enough for forward and reverse reactions to be balanced. In this case abundances are in a state of nuclear statistical equilibrium, NSE (Maxwell-Boltzmann statistics)



NSE code by FX Timmes at:
http://cococubed.asu.edu/

The End

Life of stars



Stage	Time scale	Temperature $T_9 = 10^9$ K	Density g cm^{-3}
Hydrogen burning	7×10^6 yr	0.06	5
Helium burning	5×10^5 yr	0.23	7×10^2
Carbon burning	600 yr	0.93	2×10^5
Neon burning	1 yr	1.7	4×10^6
Silicon burning	1 d	4.1	1×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	3×10^{14}
Explosive burning	0.1 – 10 s	1.2 – 7.0	varies

Evolutionary stages of a 25 $M_\odot$ star

<< back

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Life of stars

<< back

Main sequence Stars

Spectral Class	Color	Mass $[M_\odot]$	Luminosity $[L_\odot]$	Surface Temperature K	Lifetime Myr	# of stars in Milky way	Radius $[R_\odot]$	Central Temperature T_6	Central Density g/cm^3
O	blue	32	600,000	40,000	1	20,000	18	37.3	3.3
B0		16	16,000	28,000	10		7.4	34.3	6.3
B5	blue	6	600	15,500	100	100,000,000	3.8	26.8	20.0
A0		3	60	9,900	500		2.5		
A5	white	2	20	8,500	1,000	1,200,000,000	1.7	20.9	67
F0		1.75	6	7,400	2,000		1.4	18.5	87
F5	white	1.25	3	6,500	4,000	3,700,000,000	1.2		
G0		1.06	1.3	6,000	10,000		1.1	13.5	90
G5	yellow	0.92	0.8	5,500	15,000	11,000,000,000	0.9		
K0		0.80	0.4	4,900	20,000		0.8	11.4	84
K5	orange	0.69	0.1	4,100	30,000	17,000,000,000	0.7		
M0		0.48	0.02	3,500	75,000		0.6		
M5	red	0.20	0.001	2,800	200,000	89,000,000,000	0.3		

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