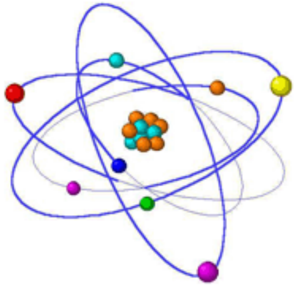
Radiation Biology, Protection and Applications (FS2018)



Origin of the Nuclides (Week 10, Seminar)

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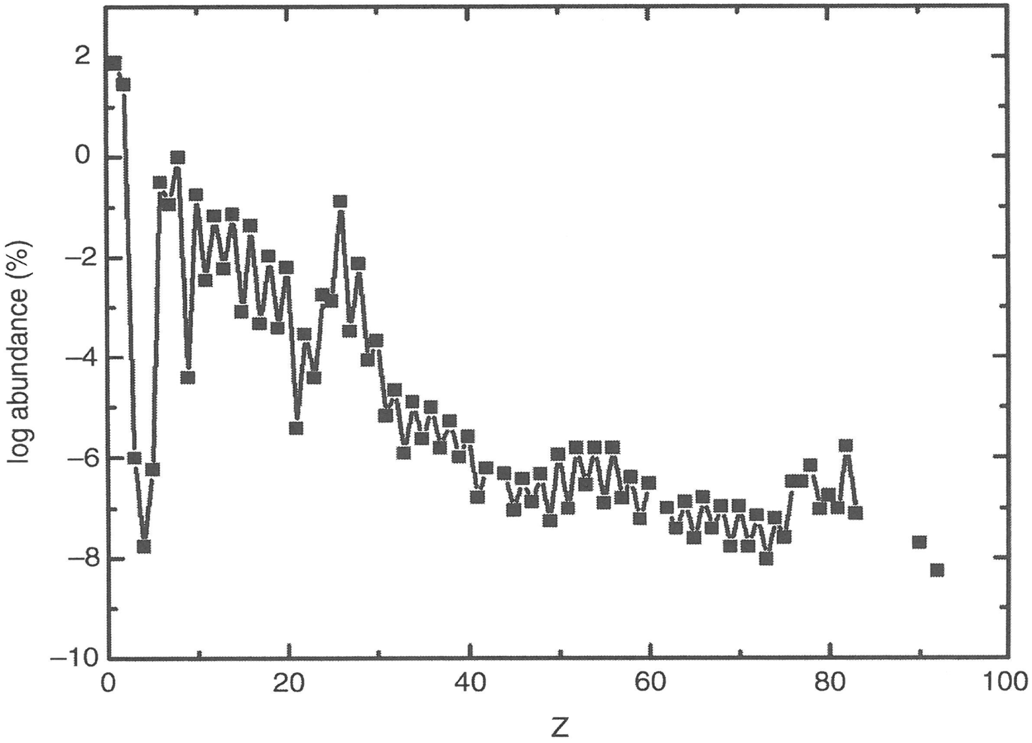
19.11. 2018

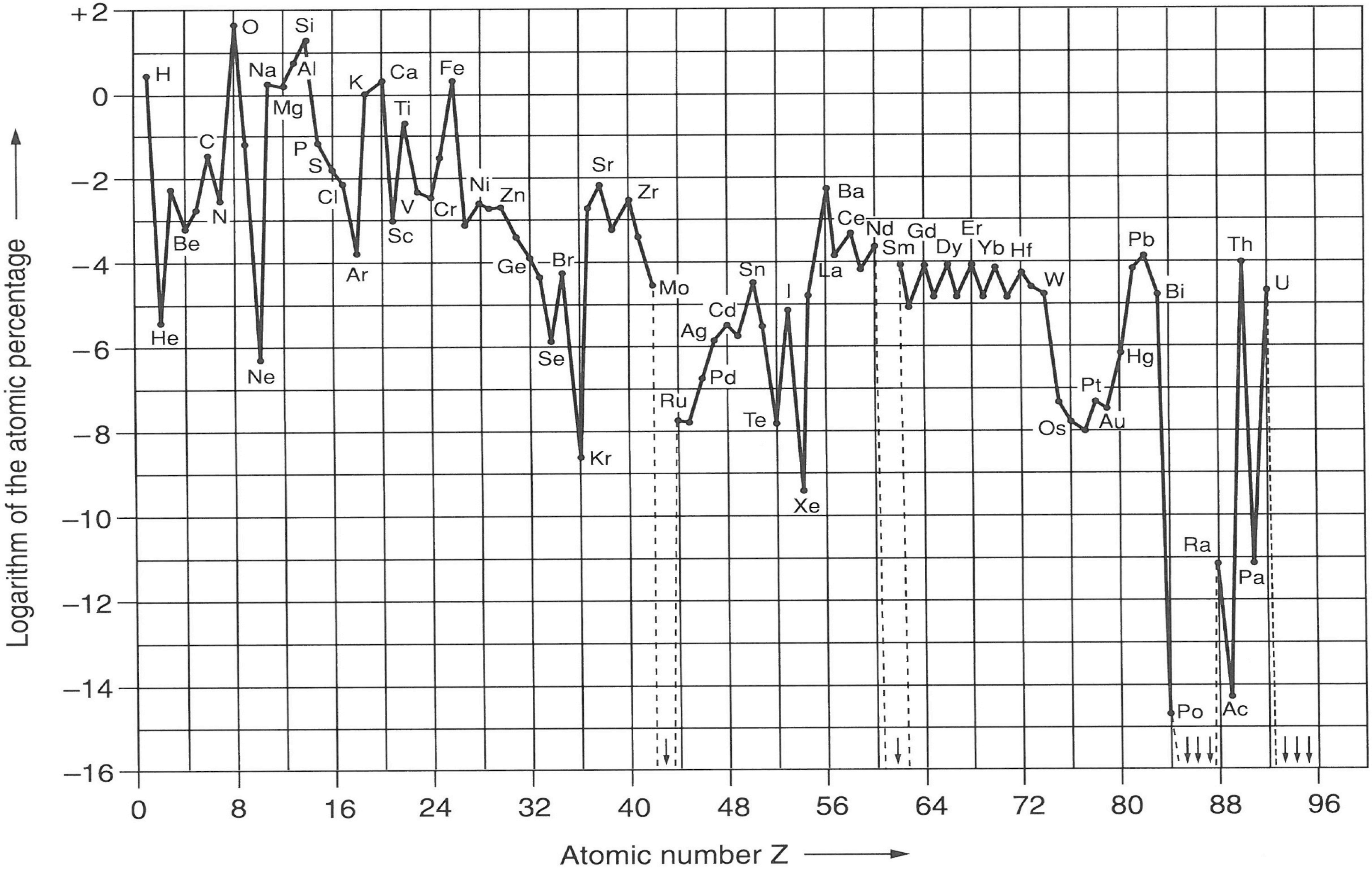
Origin of the Nuclides: Table of Contents

(Nuclear) Astrophysics

- ❑ Is the offspring of the marriage of (nuclear) physics and astronomy.
- ❑ Topics in Astrophysics are: Astronomy (radio, infrared, optical, ultraviolet, X-ray, γ-ray), stellar dynamics and evolution, galaxy formation, large-scale structure of matter in the universe, origin of cosmic rays, black holes, gravitational waves (general relativity), physical cosmology, astroparticle physics.
- ❑ Nuclear Astrophysics strives to answer the following questions:
  - How did the chemical elements we have on Earth come into
  - Where in space were they formed?
  - How does stellar energy production work (How does the sun shine?)
- ❑ Diagram shows the abundances of the elements in the solar system (mass-%).



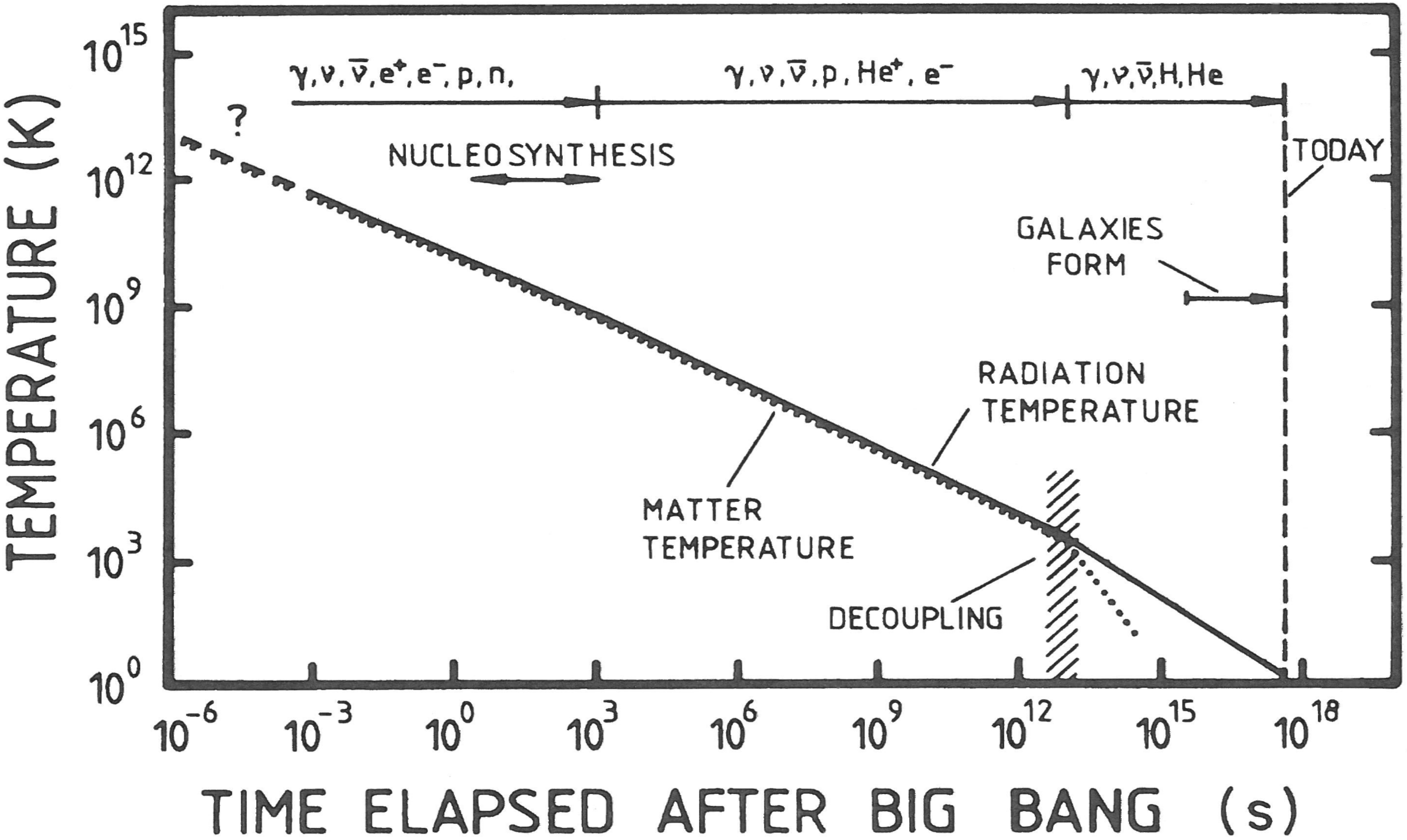
Astrophysics: Explain abundances of the elements and isotope variations



Abundance of the elements on the surface of the earth (lithosphere, hydrosphere and atmosphere).

Big Bang

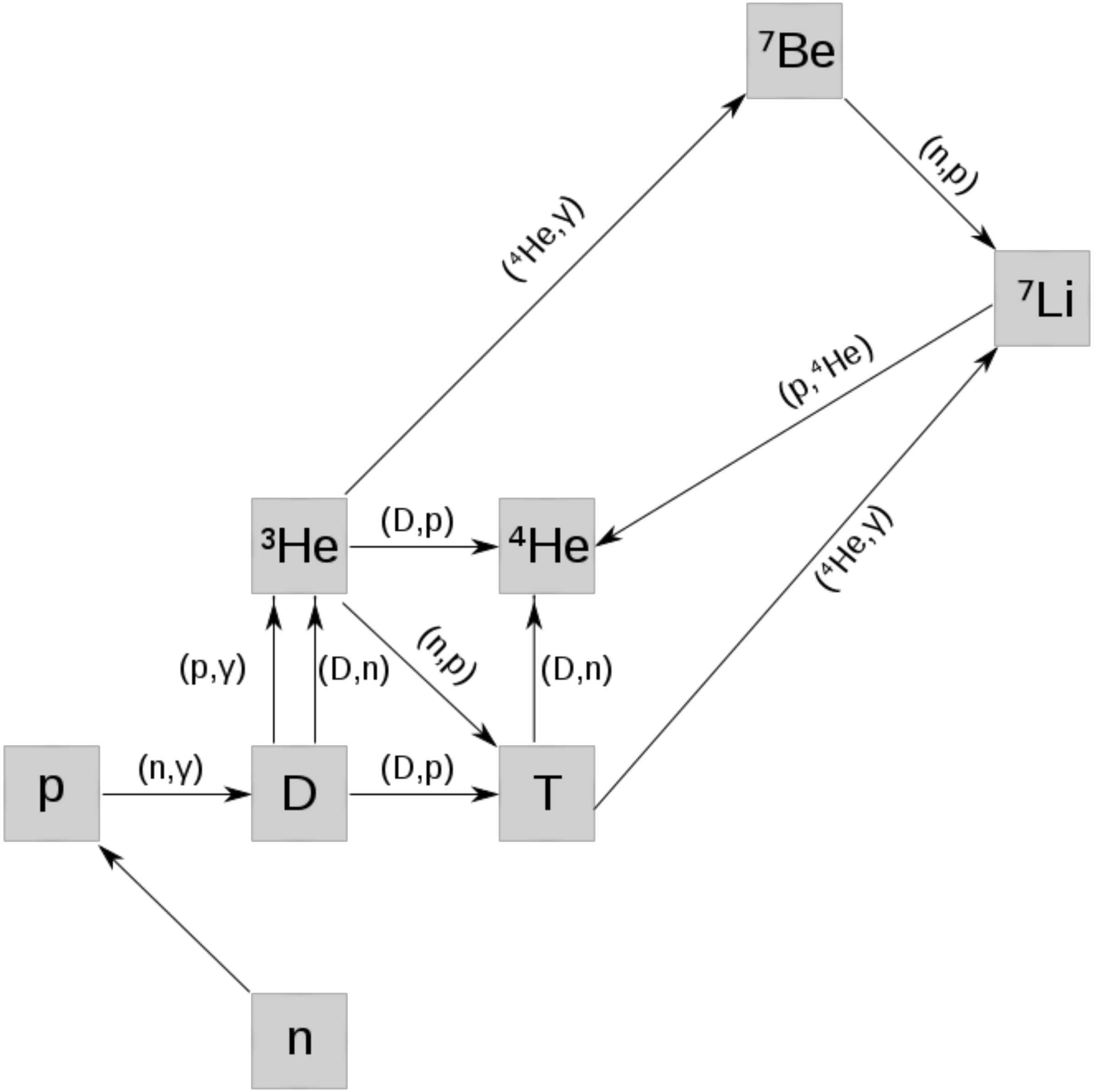
- ☐ The universe is thought to have begun with a cataclysmic explosion. Pieces of evidence for this "Big Bang" are:
  - Astronomical observations show that the universe is isotropically expanding (red shift).
  - There is a 2.7 K universal microwave background radiation, the thermal remnant of the Big Bang EM-radiation.



Big Bang Nucleosynthesis (BBN)

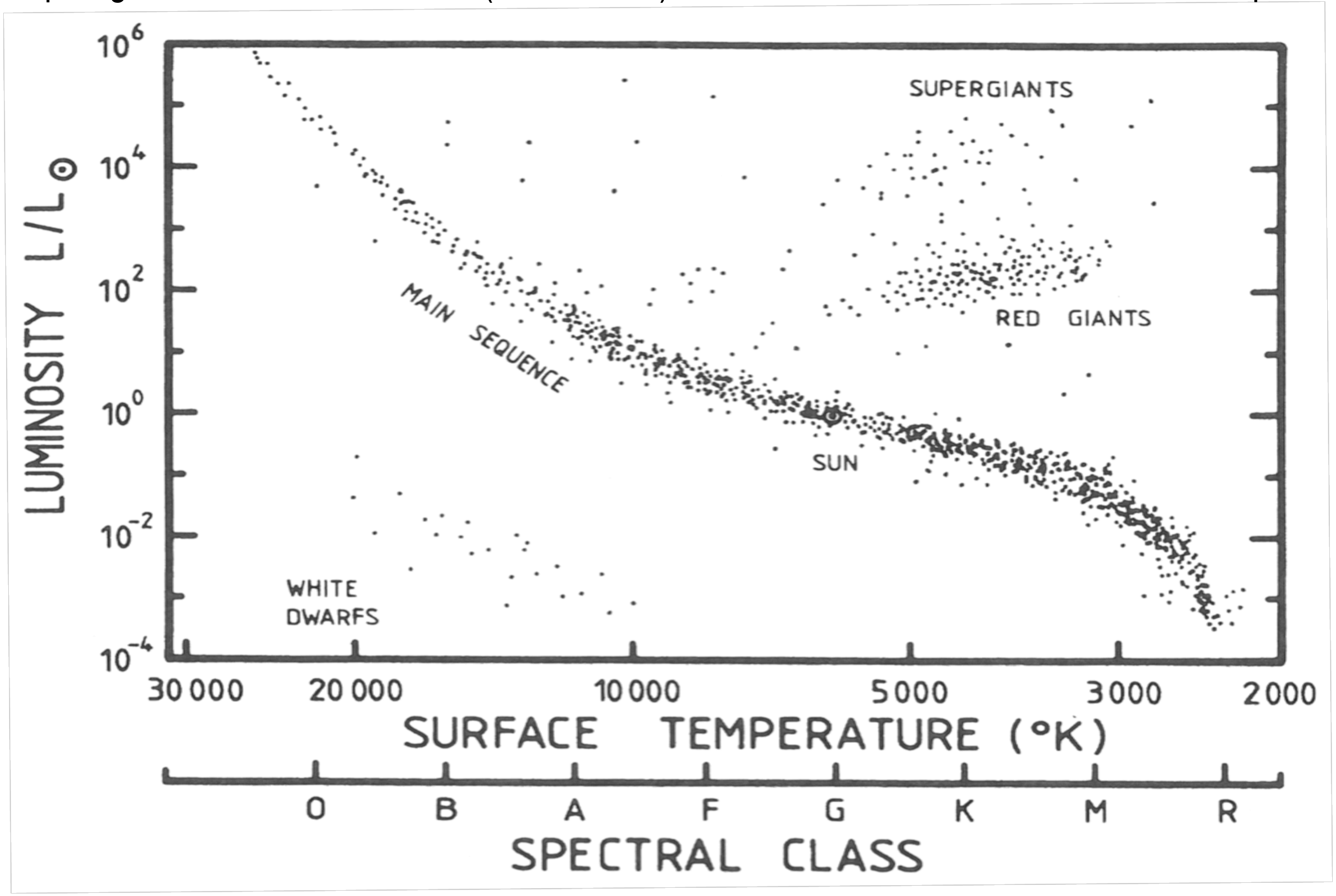
- ☐ After about 200 s and at a temperature of about 10^9 K primordial nucleosynthesis (or BBN) began with the reaction: $n + p \rightarrow d + \gamma$
- ☐ At this time the reverse reaction $d + \gamma \rightarrow n + p$ declined, such that the deuteron lived long enough to allow for the reactions:
  - $p + d \rightarrow {}^3He + \gamma$
  - $n + d \rightarrow {}^3H + \gamma$
- ☐ As ^{3}He and ^{3}H are more strongly bound, further reactions leading to the very stable α–particle can occur:
  - ${}^3H + p \rightarrow {}^4He + \gamma$
  - ${}^3He + n \rightarrow {}^4He + \gamma$
  - ${}^3H + d \rightarrow {}^4He + n$
  - $d + d \rightarrow {}^4He + \gamma$
- ☐ As stable nuclei with A=5 and A=8 do NOT exist, further (A=1 step) reactions cannot take place. Just some ^{7}Li is produced by:
  - ${}^4He + {}^3H \rightarrow {}^7Li + \gamma$
  - ${}^4He + {}^3He \rightarrow {}^7Be + \gamma$ and ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
- ☐ ^{7}Li is very weakly bound and rapidly destroyed. Thus the synthesis of larger nuclei was blocked. Further nucleosynthesis goes on in stars.

The main nuclear reaction chains for BBN

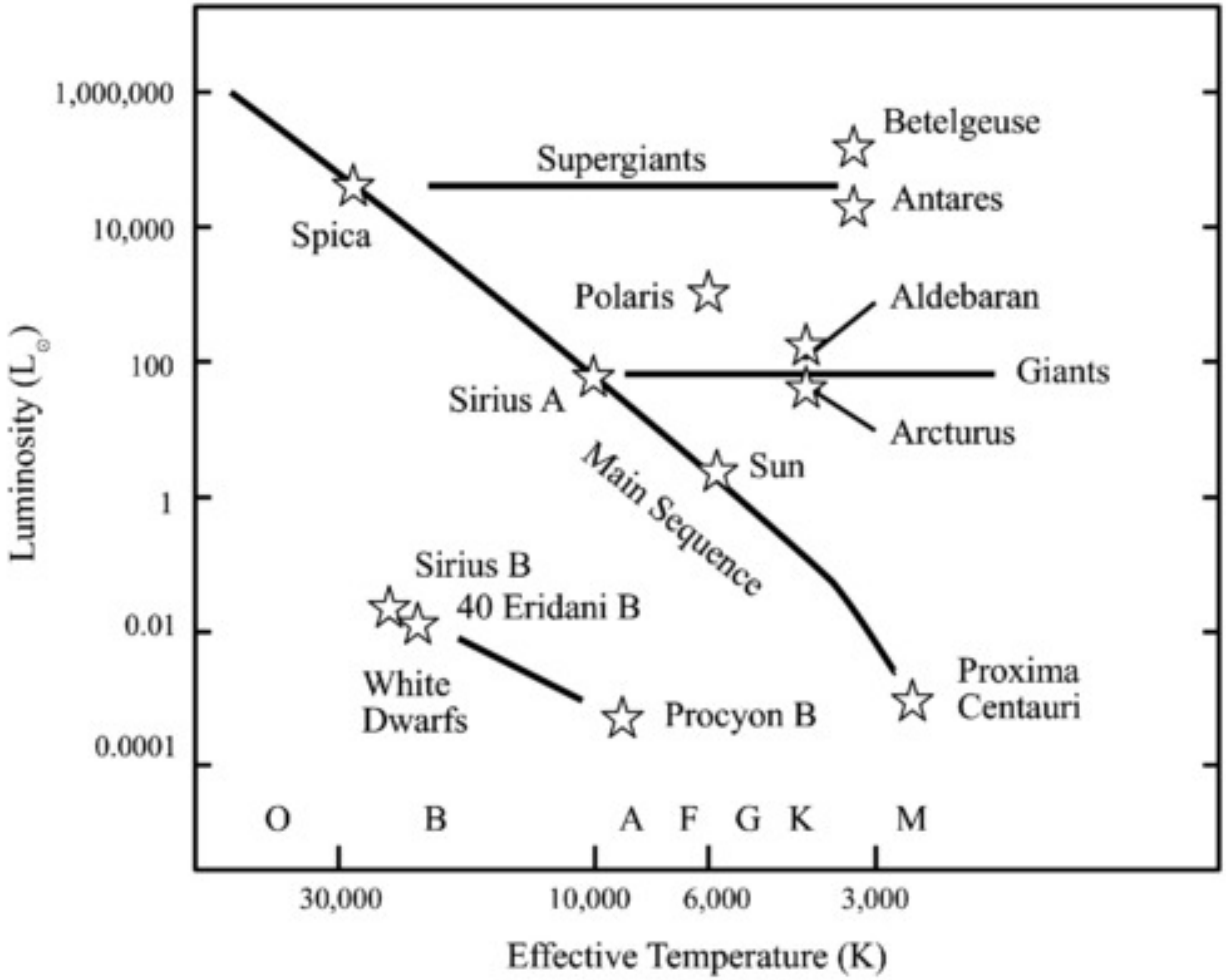


Stellar Evolution: Hertzsprung-Russell diagram (1)

- A well defined correlation between luminosity and surface temperature of stars was observed by Hertzsprung and Russell. Most stars (like our sun) fall in a narrow band called the main sequence.



Stellar Evolution: Hertzsprung-Russell diagram (2)



Stellar Evolution: Hertzsprung-Russell diagram (3)

There are 3 main regions (or evolutionary stages):

The main sequence stars:

- spend about 90% of their lives burning hydrogen into helium in their core

Red giant and supergiant stars:

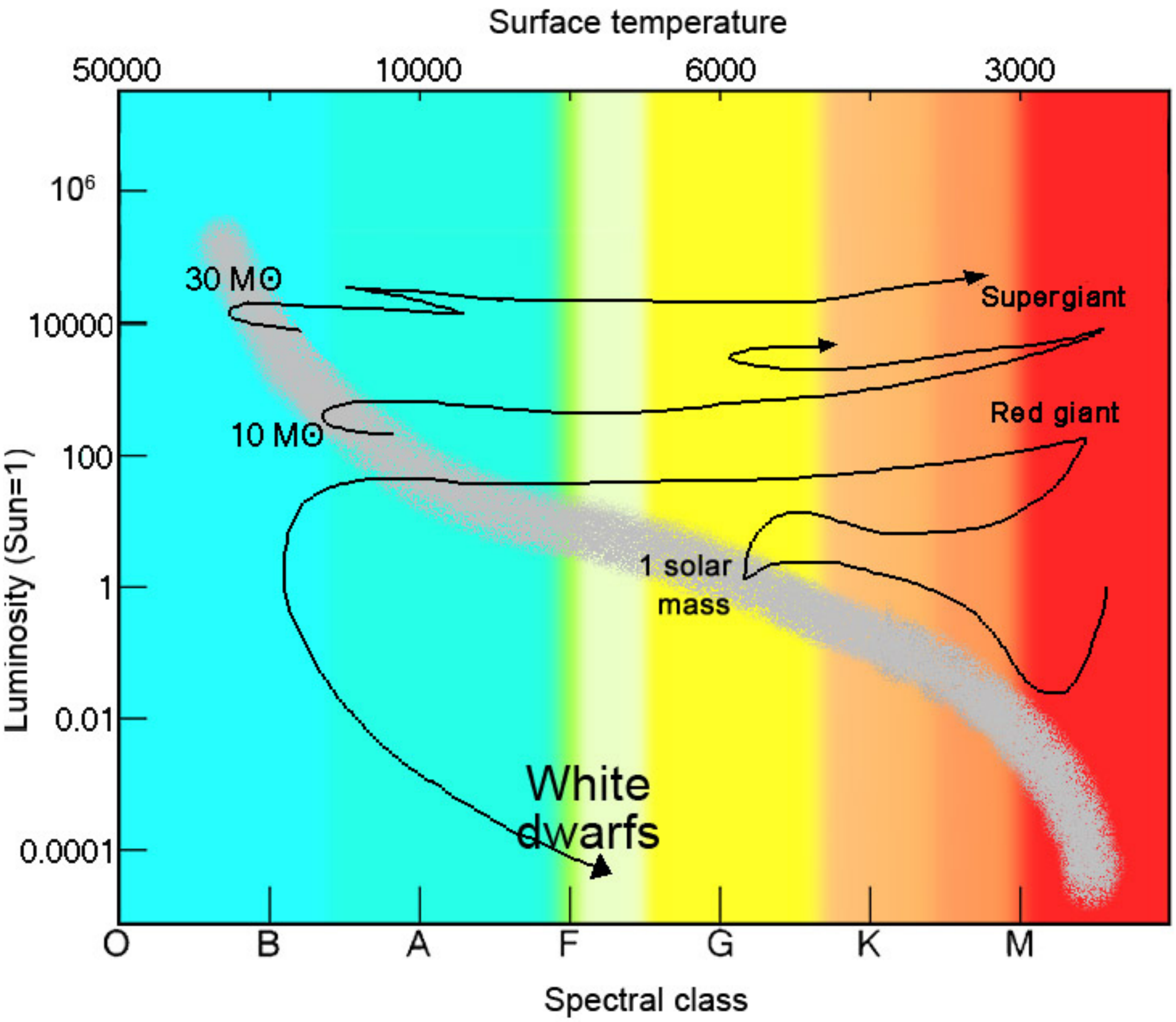
- occupy the region above the main sequence
- have low surface temperatures and high luminosities which, according to the Stefan-Boltzmann law, means they also have large radii
- enter this evolutionary stage once they have exhausted the hydrogen fuel in their cores and have started to burn helium and other heavier elements.

White dwarf stars:

- are the final evolutionary stage of low to intermediate mass stars
- are found in the bottom left of the HR diagram
- are very hot but have low luminosities due to their small size.

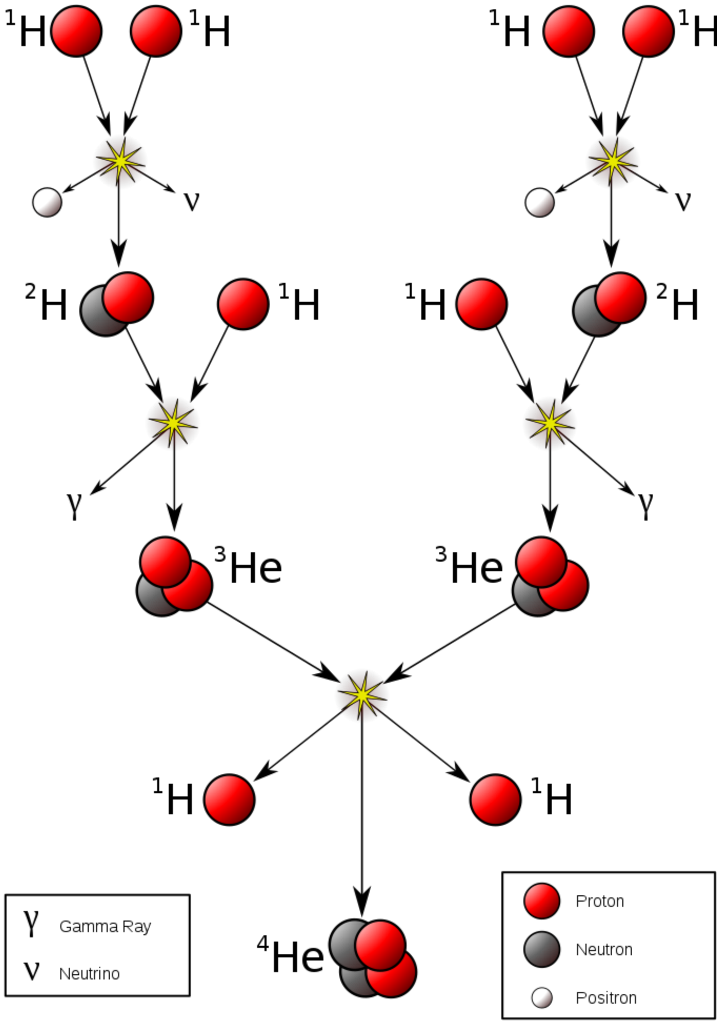
The **Sun** is found on the main sequence with a luminosity of 1 and a temperature of around 5,400 Kelvin.

Stellar Evolution: Hertzsprung-Russell diagram (4)

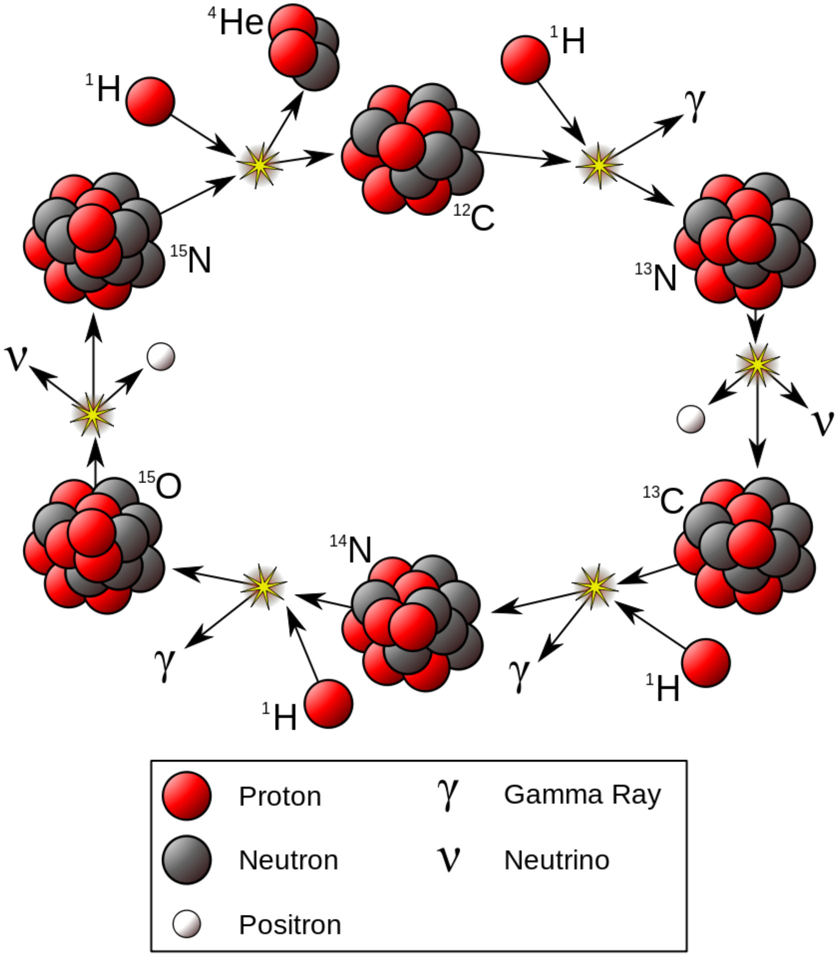


Nuclear Fusion in Stars

- ☐ The proton-proton chain dominates in stars the size of the Sun or smaller.



- ☐ The CNO cycle dominates in stars heavier than the Sun.



Hydrogen Burning

- Three chains of nuclear reactions that constitute hydrogen burning and convert protons into ^{4}He. The rate-limiting step in all reactions is the first reaction to create the deuterium.

$p\,(p, e^{+}\upsilon)\,d$

$d\,(p,\gamma)\,^{3}He$

86 %

$^{3}He\,(p, 2p)\,^{4}He$

Chain I
$Q_{\text{effective}} = 26.20$ MeV

$^{3}He\,(\alpha,\gamma)\,^{7}Be$

14 %

$^{7}Be\,(\beta^{-})\,^{7}Li$

$^{7}Li\,(p,\alpha)\,^{4}He$

Chain II
$Q_{\text{effective}} = 25.66$ MeV

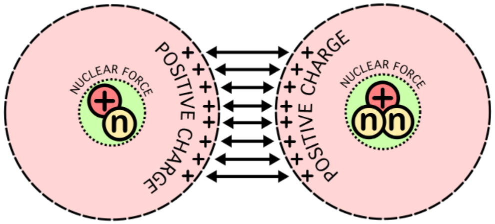
0.02 %

$^{7}Be\,(p,\gamma)\,^{8}B$

$^{8}B\,(\beta^{+})\,^{8}Be^{*}$

$^{8}Be^{*}\,(\alpha)\alpha$

Chain III
$Q_{\text{effective}} = 19.17$ MeV



The electrostat. force between the +charged nuclei is repulsive, but when the separation is small enough, the QE will tunnel through the wall.

Helium Burning and Higher Burning Stages

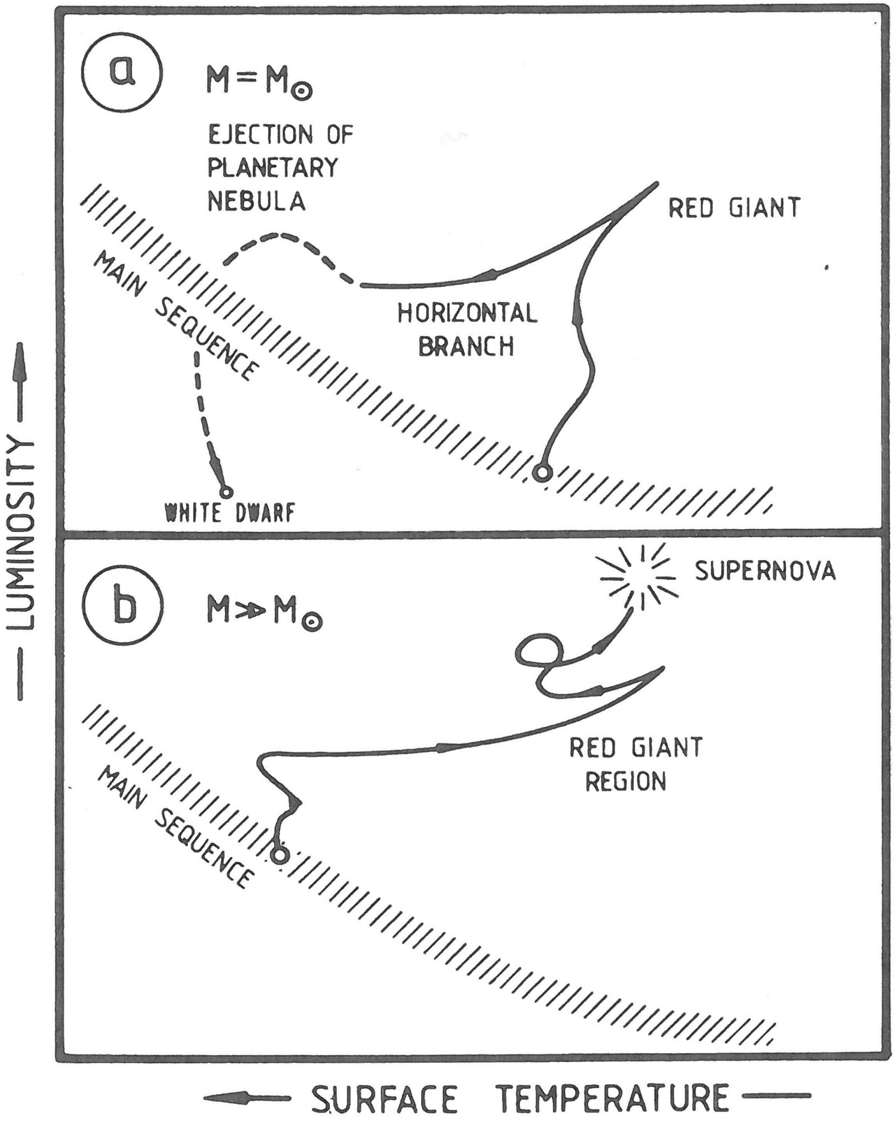
- ☐ When the hydrogen fuel of a star is exhausted a further gravitational collapse will occur leading to temperatures up to 1-2 x 10^8K. In this red giant helium burning will start by the triple-α-process:
  - $3\,^4He \rightarrow {}^{12}C + \gamma$ (through a resonance in ^{12}C)
- ☐ After some amount of ^{12}C has been formed the following reactions can take place:
  - $^4He + {}^{12}C \rightarrow {}^{16}O + \gamma$
  - $^4He + {}^{16}O \rightarrow {}^{20}Ne + \gamma$
- ☐ And nucleosynthesis may continue with neon-burning:
  - $^4He + {}^{20}Ne \rightarrow {}^{24}Mg + \gamma$
- ☐ … and carbon and oxygen burning:
  - $^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^4He\ ;\ {}^{23}Na + p\ ;\ {}^{23}Mg + n\ ;\ {}^{24}Mg + \gamma$
  - $^{16}O + {}^{16}O \rightarrow {}^{24}Mg + 2\,^4He\ ;\ {}^{28}Si + {}^4He\ ;\ {}^{31}P + p\ ;\ {}^{31}S + n\ ;\ {}^{32}S + \gamma$
- ☐ … and silicon burning up to nuclei with A~60:
  - $^{28}Si + {}^4He \leftrightarrow {}^{32}S + \gamma$
  - $^{32}S + {}^4He \leftrightarrow {}^{36}Ar + \gamma$
  - …
  - $^{52}Fe + {}^4He \leftrightarrow {}^{56}Ni + \gamma$

Time scale of Nucleosynthetic Reactions in a 1 Solar Mass Star

Reaction	Time
H burning	6 x 10^9 y
He burning	0.5 x 10^6 y
C burning	200 y
Ne burning	1 y
O burning	Few months
Si burning	Days

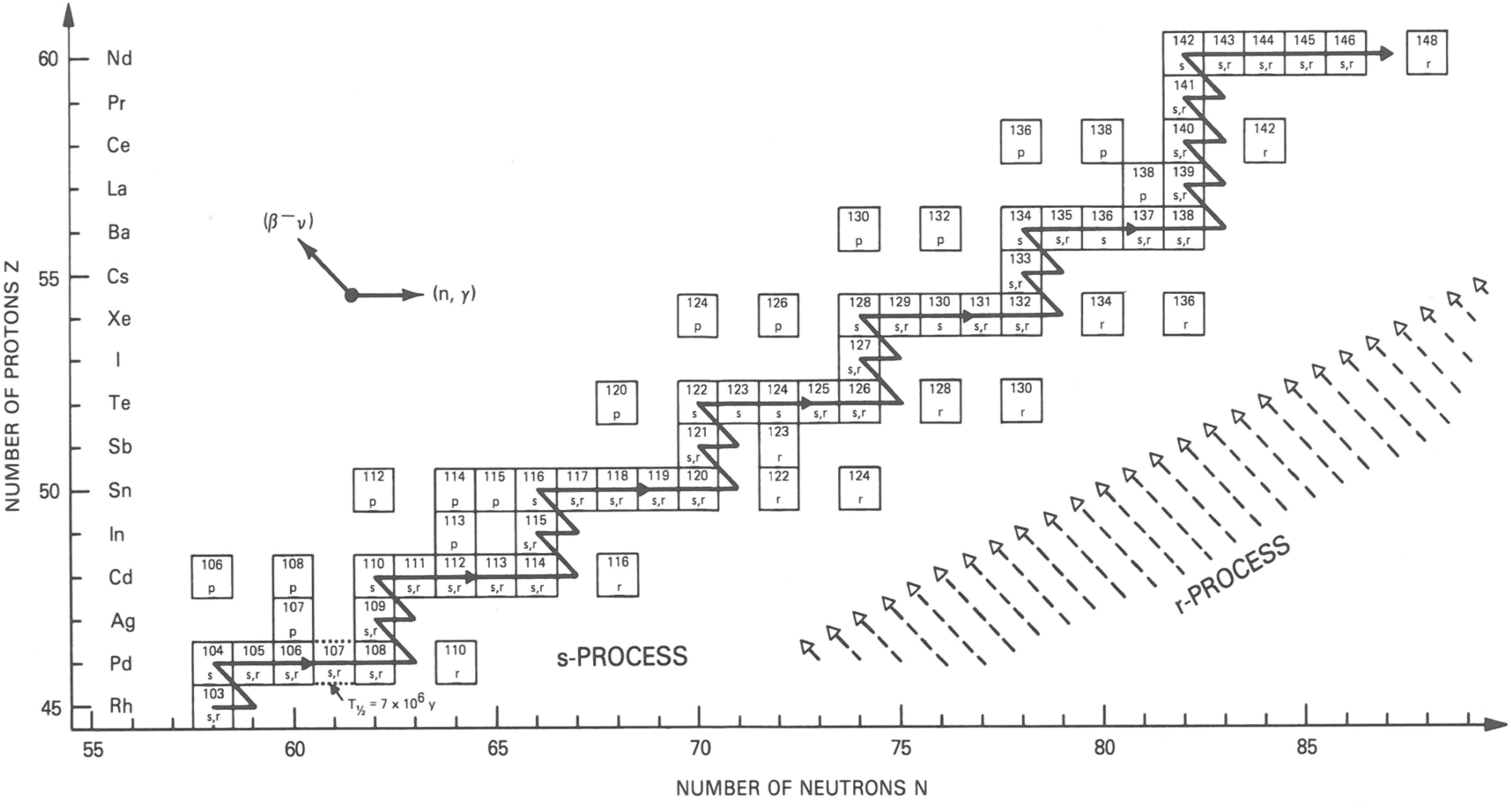
Death of Stars: White Dwarfs and Supernovas

- How the life of a star ends depends to a large extent on the mass of the star:
  - Stars with masses ~ M_{solar} do not reach the temperatures in their center to complete all burning stages. They extinguish and end as white dwarfs.
  - Stars with masses > 8 M_{solar} complete all stellar burning stages and can have an explosive end (supernova). The brightness of the star increases by a factor of $10^6 - 10^9$ releasing ~10^{51} ergs on a time scale of seconds. During the stellar explosion a lot of neutrons can be released leading to (n, γ)-reactions on iron-seed nuclei in the core.

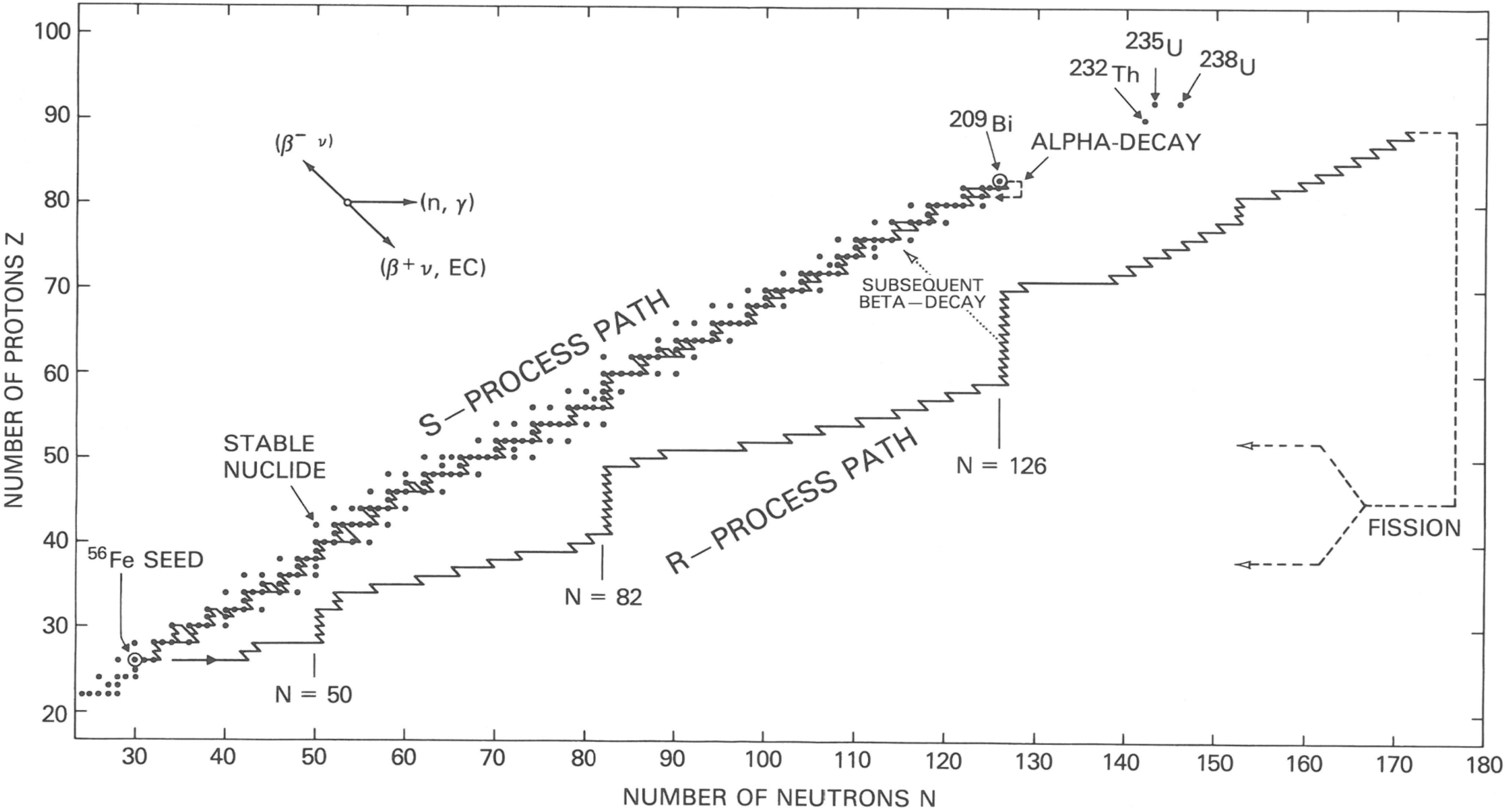


s-process: Buildup of A>60 nuclei by slow n-capture

- ☐ ^{56}Fe+n→^{57}Fe(stable)+γ ; ^{57}Fe+n→^{58}Fe(stable)+ γ ; ^{58}Fe+n→^{59}Fe($t_{1/2}$=44.5d)+ γ ; ^{59}Fe(β^-)^{59}Co(stable)…
- ☐ The s-process terminates at ^{209}Bi: ^{209}Bi(n, γ)^{210}Bi(β^-)^{210}Po(α)^{206}Pb(n, γ)(n, γ)(n, γ)^{209}Pb(β^-) ^{209}Bi



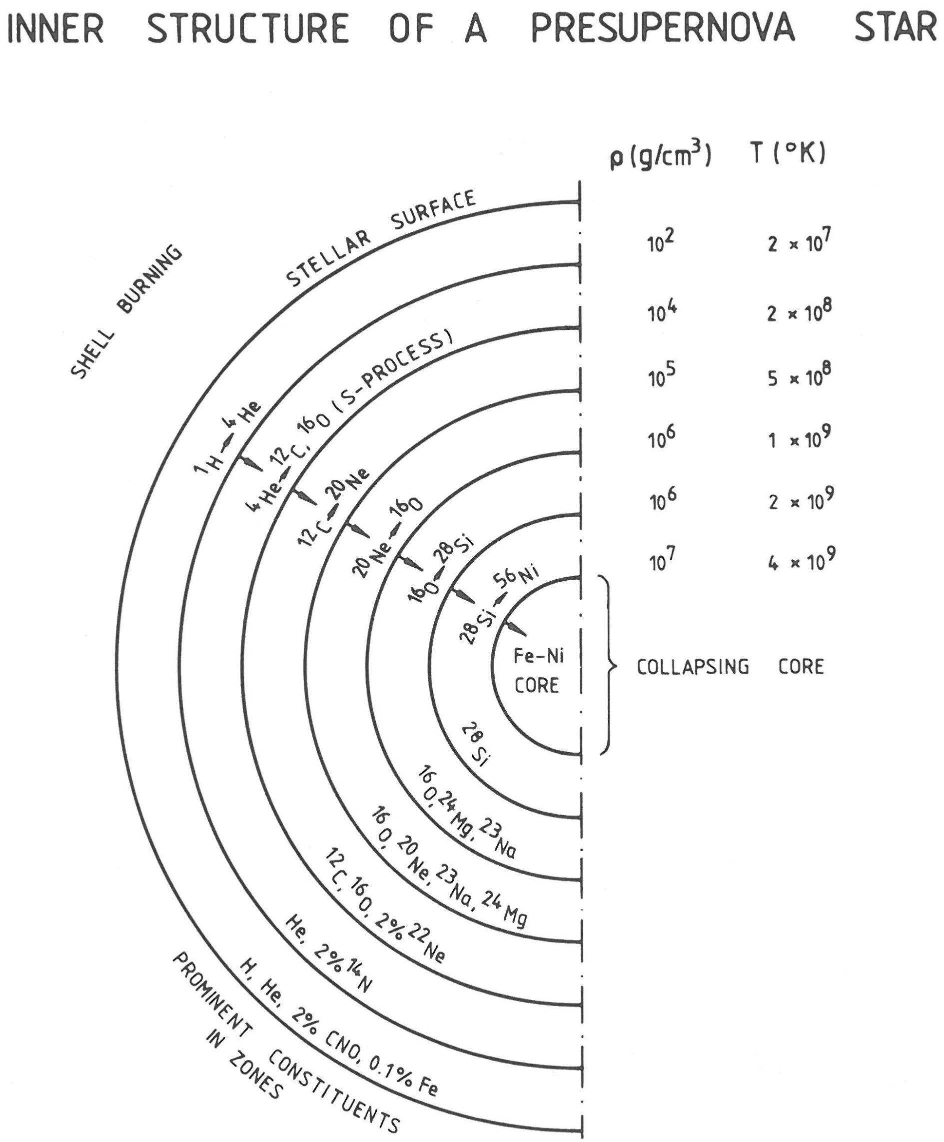
r-process: Buildup of A>60 nuclei by rapid n-capture



Neutron-capture paths for the *s*-process and the *r*-process are shown in the (*N*, *Z*)-plane. Both paths start with the iron-peak nuclei as seeds (mainly ^{56}Fe). The *s*-process follows a path along the stability line and terminates finally above ^{209}Bi via α-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (*N*, *Z*)-plane until β-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm^{-3}.

Other Processes that can synthesize Elements

- ☐ p-process:
  - Consists of a series of photonuclear reactions (γ,p), (γ,α), (γ,n) on seed nuclei from the s- or r-process.
  - Leads to the synthesis of some proton-rich nuclei with $70 < A < 200$.
  - Contribution to the abundances of most elements is very small, but there are some nuclei (^{190}Pt, ^{168}Yb) that seem to have been exclusively made by it.
- ☐ rp-process:
  - Rapid proton capture process that makes proton-rich nuclei with $7 < Z < 27$ by (p, γ)-reactions and β^+-decays
  - Creates p-rich nuclei like ^{21}Na, ^{19}Ne, and a small number of nuclei with $A < 100$.
- ☐ ν-nucleosynthesis:
  - In a type II supernova the intense neutrino flux of all flavors that passes through the onion layers of the PNS can cause a transmutation of nuclei via (ν, ν')- and (ν_e,e^-)-, $(\nu\mathrm{bar}_e,e^+)$-reactions on nuclei.
  - Some rare isotopes that could be due to this process are ^{7}Li, ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta.
- ☐ νp-process:
  - Occurs in supernovae when strong neutrino fluxes create proton-rich ejecta.
  - In this process antineutrino absorptions produce neutrons that are immediately captured by proton rich nuclei.
  - Nuclei with $A > 64$ can be produced, e.g., ^{92,94}Mo and ^{96,98}Ru.



Radionuclides in the Environment (1)

Stages of the evolution of the Earth

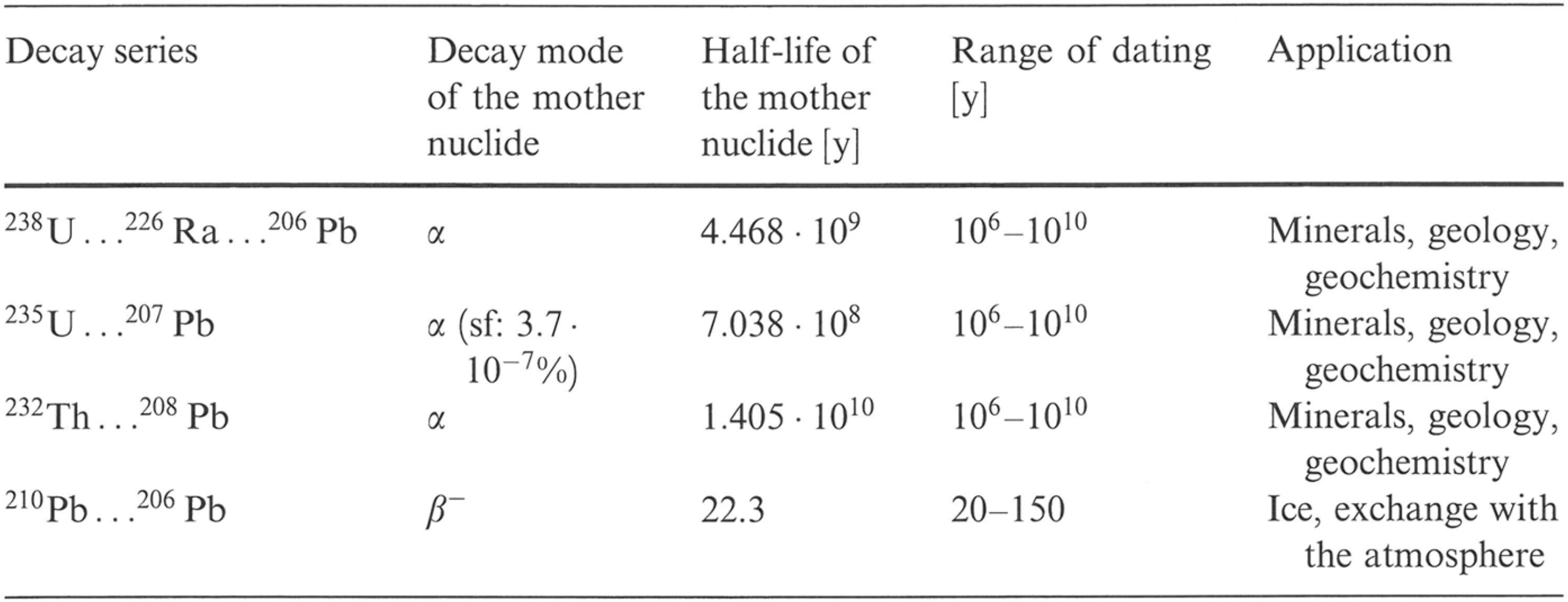
Time before present	Stage
5,0 . 10^9 y	Solar nebula
4,6 . 10^9 y	Formation of the solar system
4,5 . 10^9 y	Formation of the earth, the moon and of meteorites
4,3 . 10^9 y	First stages of the earth's crust, formation of the oldest minerals found on the earth, formation of hydrosphere and atmosphere
3,9 . 10^9 y	End of major meteoritic impacts
3,8 . 10^9 y	Beginning of formation of rocks
(3,8 - 3,5) . 10^9 y	Formation of oldest rocks
3,5 . 10^9 y	First traces of life (stromatolites)

Ratio of the activities of some long-lived radionuclides at the time of the birth of the Earth to those present.

Radionuclide	Activity Ratio A/A_0
^{40}K	11.40
^{87}Rb	1.07
^{232}Th	1.02
^{235}U	84.10
^{238}U	2.01

Radionuclides in the Environment (2)

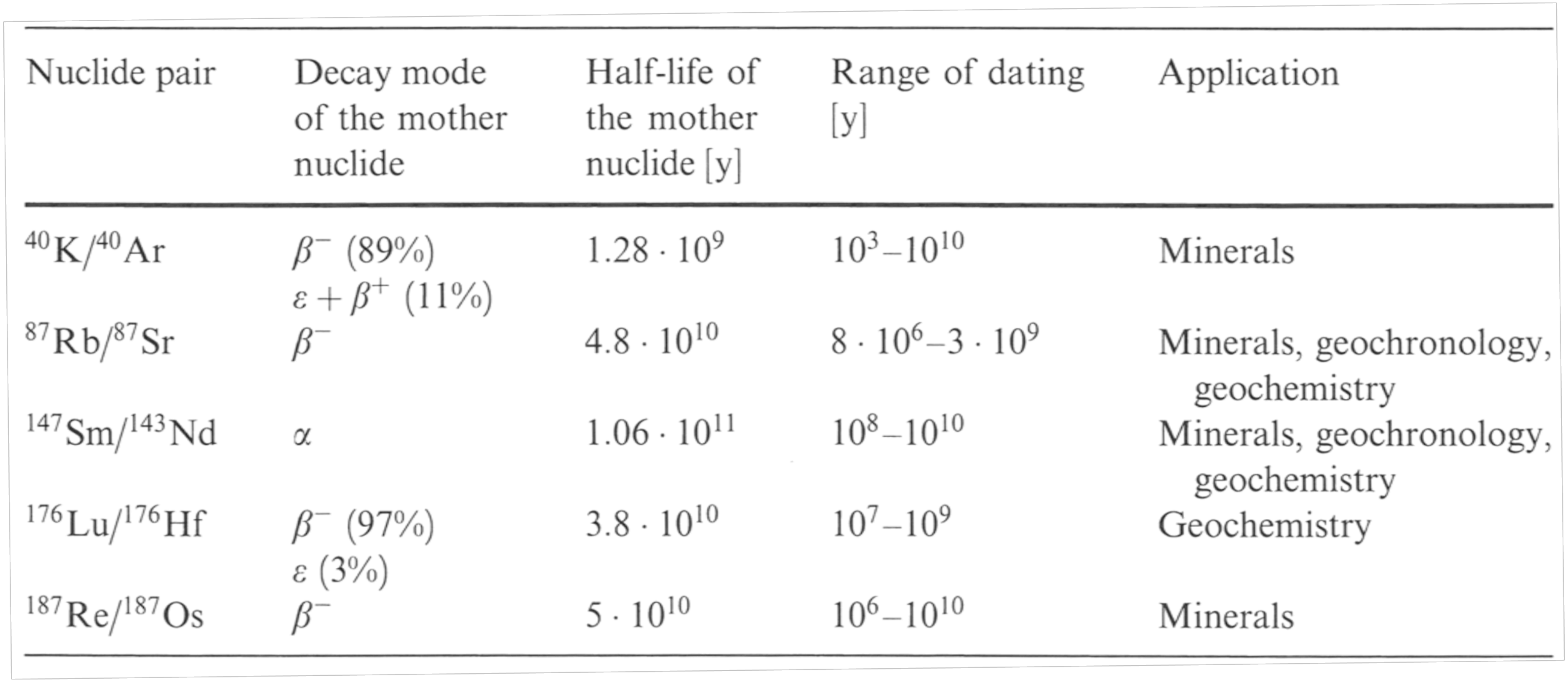
Radionuclides from natural decay series



Decay series	Decay mode of the mother nuclide	Half-life of the mother nuclide [y]	Range of dating [y]	Application
$^{238}\mathrm{U}\ldots{}^{226}\mathrm{Ra}\ldots{}^{206}\mathrm{Pb}$	α	$4.468 \cdot 10^{9}$	10^{6}–10^{10}	Minerals, geology, geochemistry
$^{235}\mathrm{U}\ldots{}^{207}\mathrm{Pb}$	α (sf: $3.7 \cdot 10^{-7}$%)	$7.038 \cdot 10^{8}$	10^{6}–10^{10}	Minerals, geology, geochemistry
$^{232}\mathrm{Th}\ldots{}^{208}\mathrm{Pb}$	α	$1.405 \cdot 10^{10}$	10^{6}–10^{10}	Minerals, geology, geochemistry
$^{210}\mathrm{Pb}\ldots{}^{206}\mathrm{Pb}$	β^{-}	22.3	20–150	Ice, exchange with the atmosphere

Radionuclides in the Environment (3)

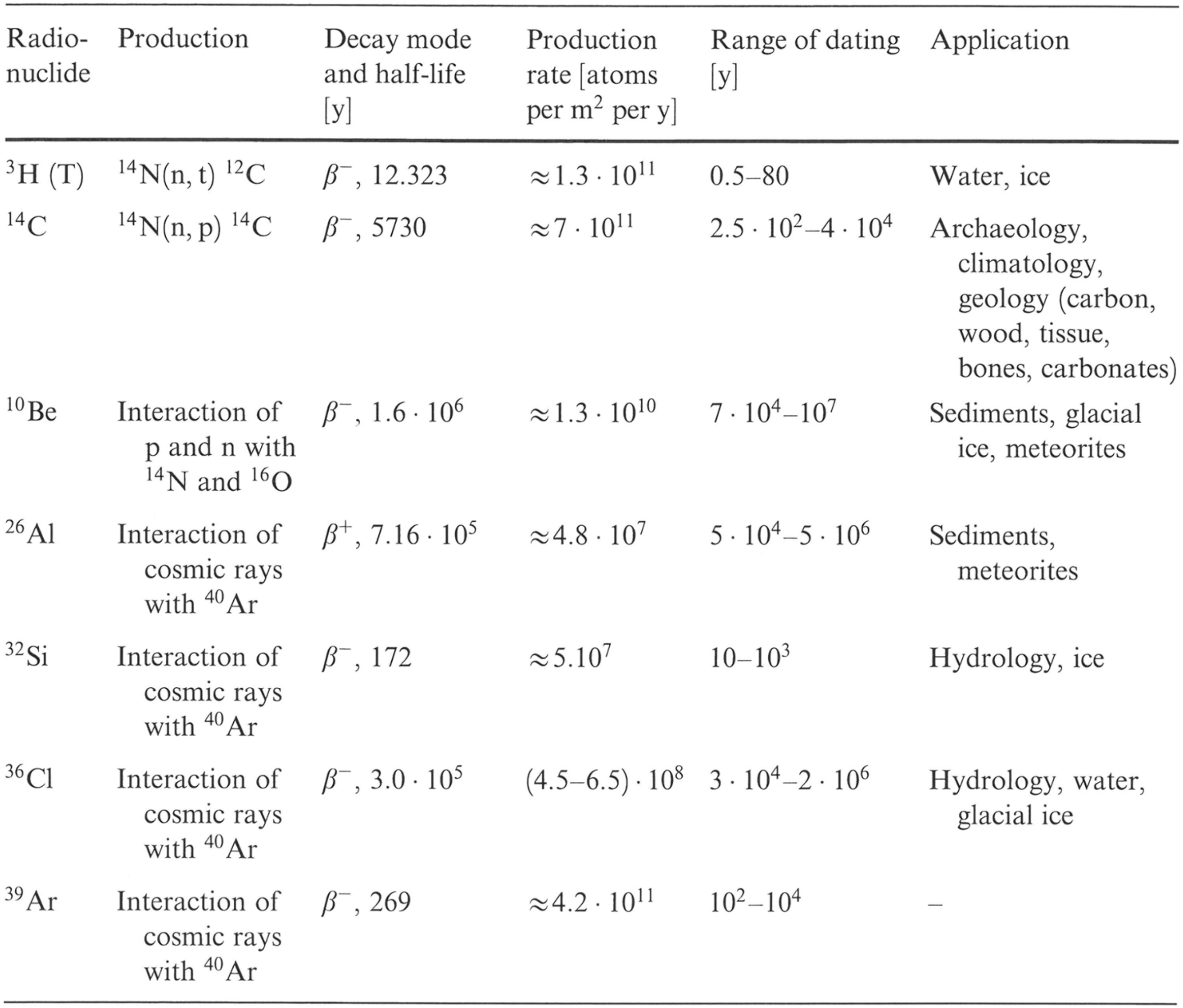
Terrestrial radionuclides



Nuclide pair	Decay mode of the mother nuclide	Half-life of the mother nuclide [y]	Range of dating [y]	Application
$^{40}K/^{40}Ar$	β^- (89%) $\varepsilon + \beta^+$ (11%)	$1.28 \cdot 10^9$	10^3–10^{10}	Minerals
$^{87}Rb/^{87}Sr$	β^-	$4.8 \cdot 10^{10}$	$8 \cdot 10^6$–$3 \cdot 10^9$	Minerals, geochronology, geochemistry
$^{147}Sm/^{143}Nd$	α	$1.06 \cdot 10^{11}$	10^8–10^{10}	Minerals, geochronology, geochemistry
$^{176}Lu/^{176}Hf$	β^- (97%) ε (3%)	$3.8 \cdot 10^{10}$	10^7–10^9	Geochemistry
$^{187}Re/^{187}Os$	β^-	$5 \cdot 10^{10}$	10^6–10^{10}	Minerals

Radionuclides in the Environment (4)

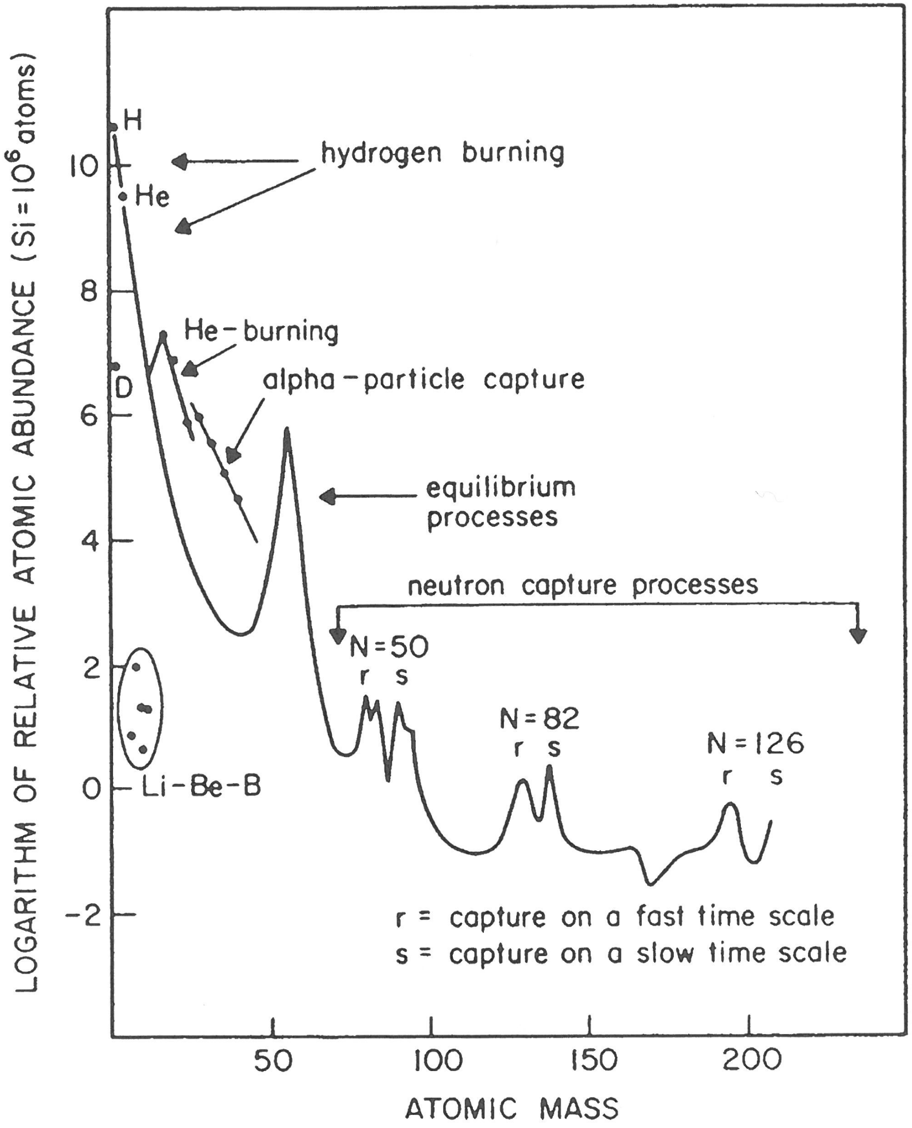
Cosmogenic radionuclides



Radio-nuclide	Production	Decay mode and half-life [y]	Production rate [atoms per m^2 per y]	Range of dating [y]	Application
^{3}H (T)	$^{14}N(n, t)\ ^{12}C$	β^-, 12.323	$\approx 1.3 \cdot 10^{11}$	0.5–80	Water, ice
^{14}C	$^{14}N(n, p)\ ^{14}C$	β^-, 5730	$\approx 7 \cdot 10^{11}$	$2.5 \cdot 10^2$–$4 \cdot 10^4$	Archaeology, climatology, geology (carbon, wood, tissue, bones, carbonates)
^{10}Be	Interaction of p and n with ^{14}N and ^{16}O	β^-, $1.6 \cdot 10^6$	$\approx 1.3 \cdot 10^{10}$	$7 \cdot 10^4$–10^7	Sediments, glacial ice, meteorites
^{26}Al	Interaction of cosmic rays with ^{40}Ar	β^+, $7.16 \cdot 10^5$	$\approx 4.8 \cdot 10^7$	$5 \cdot 10^4$–$5 \cdot 10^6$	Sediments, meteorites
^{32}Si	Interaction of cosmic rays with ^{40}Ar	β^-, 172	$\approx 5.10^7$	10–10^3	Hydrology, ice
^{36}Cl	Interaction of cosmic rays with ^{40}Ar	β^-, $3.0 \cdot 10^5$	$(4.5$–$6.5) \cdot 10^8$	$3 \cdot 10^4$–$2 \cdot 10^6$	Hydrology, water, glacial ice
^{39}Ar	Interaction of cosmic rays with ^{40}Ar	β^-, 269	$\approx 4.2 \cdot 10^{11}$	10^2–10^4	–

Summary

- ☐ Stars are Cauldrons in the Cosmos.
- ☐ The atomic abundances of the elements/isotopes in the solar system can largely be explained by astrophysical processes:
  - Big Bang Nucleosynthesis
  - Stellar burning phases
  - Explosive burning (s- and p-process)
- ☐ The radionuclides found in the lithosphere, hydrosphere and atmosphere are largely leftovers (decay-products) from supernova explosions.
- ☐ We consist of “star-dust”.
- ☐ **Radionuclides are a part of nature!**



Literature / WWW-reference

- ☐ C.E. Rolfs and W.S. Rodney, *“Cauldrons in the Cosmos”*, Chicago University Press (1988)
- ☐ W. Loveland, D.J. Morrissey, G.T. Seaborg, *“Modern Nuclear Chemistry”*, WILEY (2006)
- ☐ K.H. Lieser, *“Nuclear and Radiochemistry”*, WILEY-VCH (2nd edition, 2001), Chapter 15