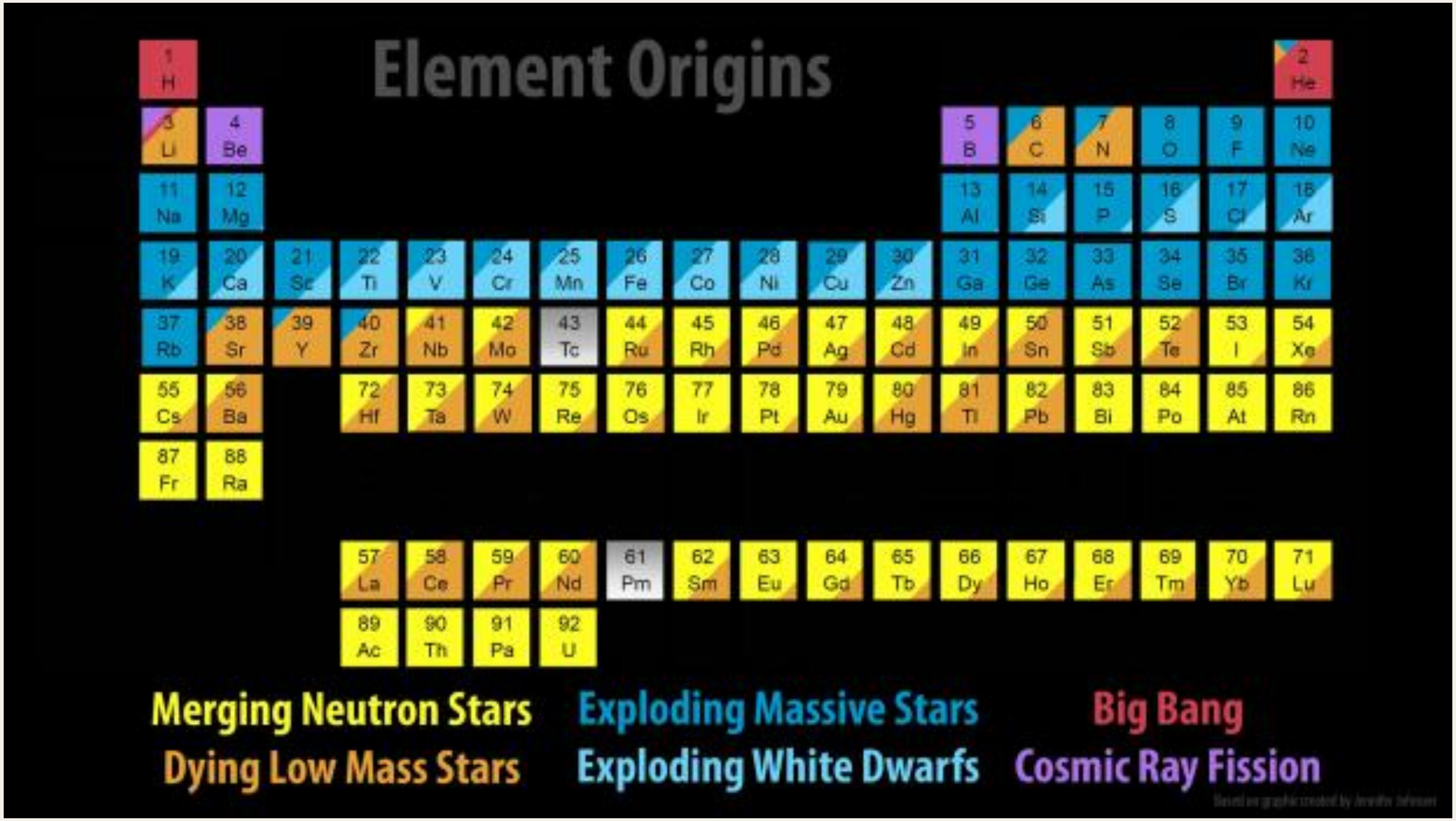
THE ORIGIN OF CHEMICAL ELEMENTS

Lezione VII- Fisica delle Galassie
Nucleosynthesis and chemical evolution, B. Pagel
and
Lectures of Langer on Nucleosynthesis

Laura Magrini

Cosmic Origin of elements

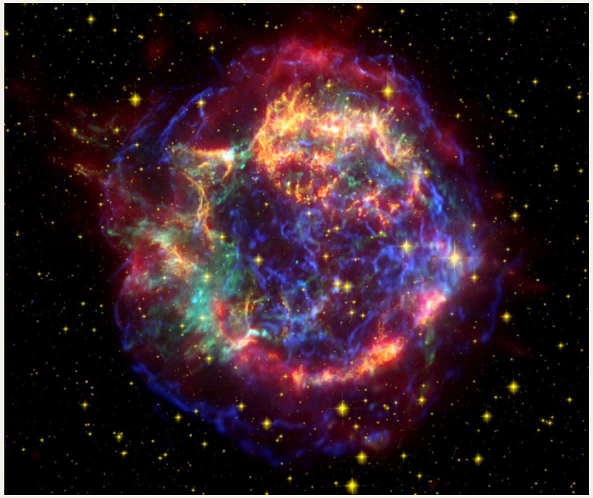


Stars as fossils

Studying stars in a **large range of ages** allows us to investigate different epochs in the lifetime of our Galaxy.

In particular, low-mass old stars allows us to do local field cosmology:

- stars with ages > 10 Gyr → formed at redshifts z > 2
- their abundances take memory of the conditions of the gas from which they formed
- complementary approach to direct study of galaxies at high redshift
- snapshots of different galaxies vs evolution of a single Galaxy, the Milky Way



But also….stars as forges of nucleosynthesis

When and where elements were produced

Solar system abundances: two types of data sources

Spectral analysis of the Sun

- Photospheric absorption (abundance ratios over H), few isotopic abundances
- Emission lines from chromosphere, corona

Direct measurements (chemical analysis, mass spectrometry)

- Earth (crust, oceans, atmosphere)-> inhomogeneous, provide isotopic ratios
- Moon rocks: same problem
- Meteorites (e.g. chondrites): uniform atomic **composition corresponds to solar photosphere**, represents Solar System abundances and also isotopic ratios

When and where elements were produced

Abundances outside the Solar system:

Chemical analysis of spectra of:

- Stars
- Gaseous nebulae (HII regions, Supernova remnants (SNR), Planetary Nebulae (PNe))
- External galaxies (integrated spectra of stellar population, individual or integrated HII regions)

Nearby (young) stars and Local interstellar medium (ISM):

- similar abundance distribution to Solar system
- same relative distribution
- define the local abundance distribution
- Isotopic abundances for few elements (lighter and heavier)

Assumption: **cosmic abundances ~ local abundances**

When and where elements were produced

Abundances outside the Solar system:

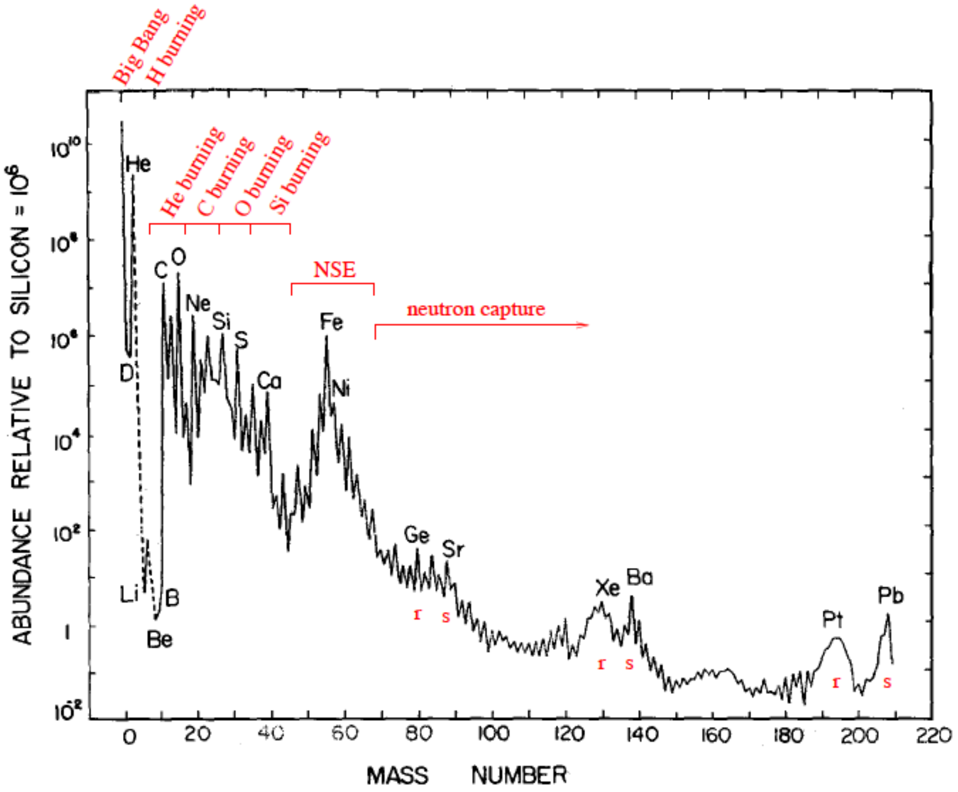
Chemical analysis of spectra of:

- Stars with different ages
- Tracers of past evolutionary history
- Different stellar populations of the MW show different abundance patterns
- **Temporal and spatial effects**

Abundances of old/distant stars ≠ local abundances

When and where elements were produced

The ’local Galactic’ abundance distribution of nuclear species



The abundance distribution of nuclear species, as a function of mass number A.

The abundances are given relative to the Si abundance which is set to 10^6.

Adapted from Cameron (1982)

Cosmic recycling

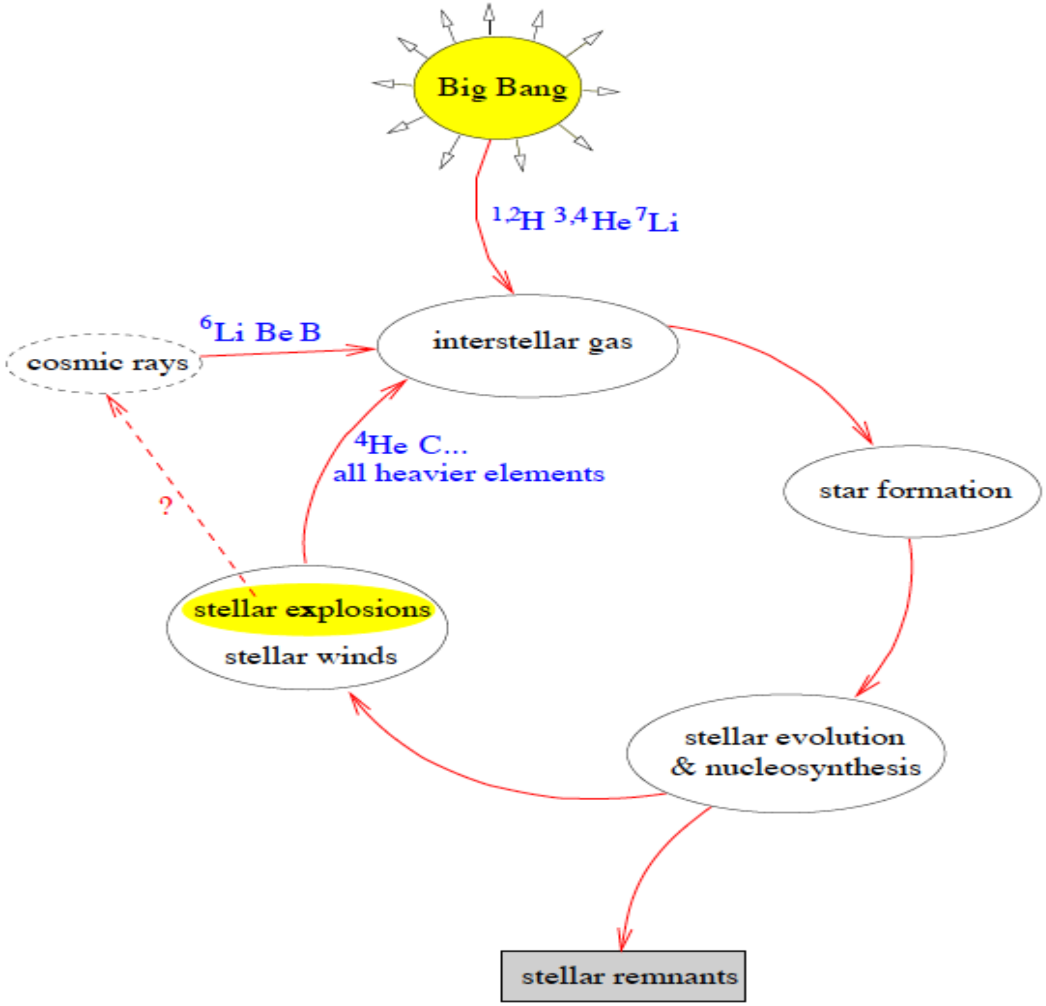
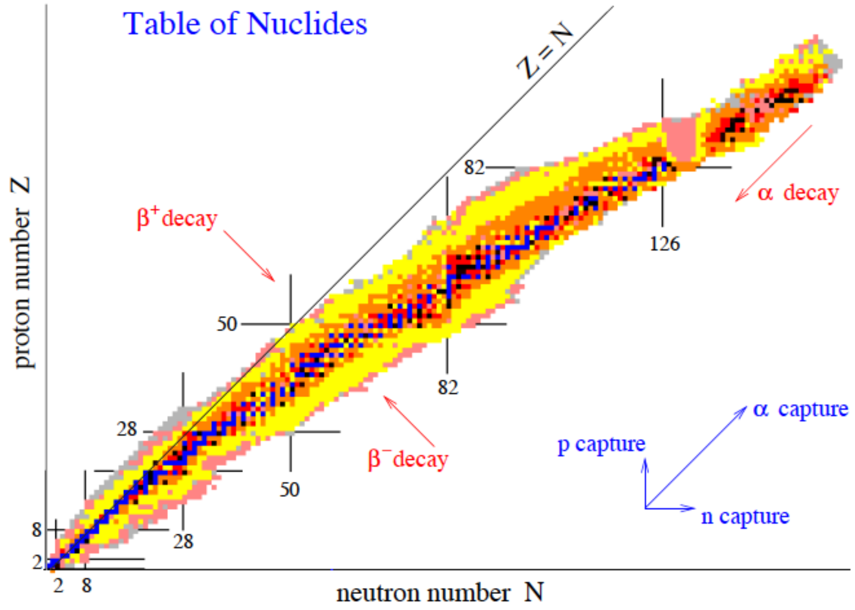


Chart of nuclides (N. Neutrons vs N. Protons)

The greater the number of protons, the more neutrons are required to stabilize a nuclide, N > Z, to be stable.



Stable nuclei are in blue, and long-lived (> 10^5 years) radioactive isotopes are in black. Other colours show isotopes with shorter decay times.

Outside the valley, there are some spontaneous radioactive decays:

$$\beta^- : (Z, A) \rightarrow (Z+1, A) + e^- + \nu$$

A neutron decays into a proton + e- is emitted

$$\beta^+ : (Z, A) \rightarrow (Z-1, A) + e^+ + \bar{\nu}$$

A proton decays into a neutron + e+ is emitted

$$\alpha : \ (Z, A) \rightarrow (Z-2, A-4) + {}^4\mathrm{He}$$

An alpha particle is emitted

Map form Korea Atomic Energy Research Institute http://atom.kaeri.re.kr/

Thermonuclear reactions

Binding energy and mass defect:

$$E_B(A_Z) := [(A - Z)m_n + Z \cdot m_p - M(A_Z)] \cdot c^2$$

$m_{\mathrm{n}} =$ neutron mass $m_{\mathrm{p}} =$ proton mass $M(A_Z) =$ mass of A_Z

$$\Delta M = (A - Z)m_n + Zm_p - M(A_Z) = \text{"mass defect"}$$

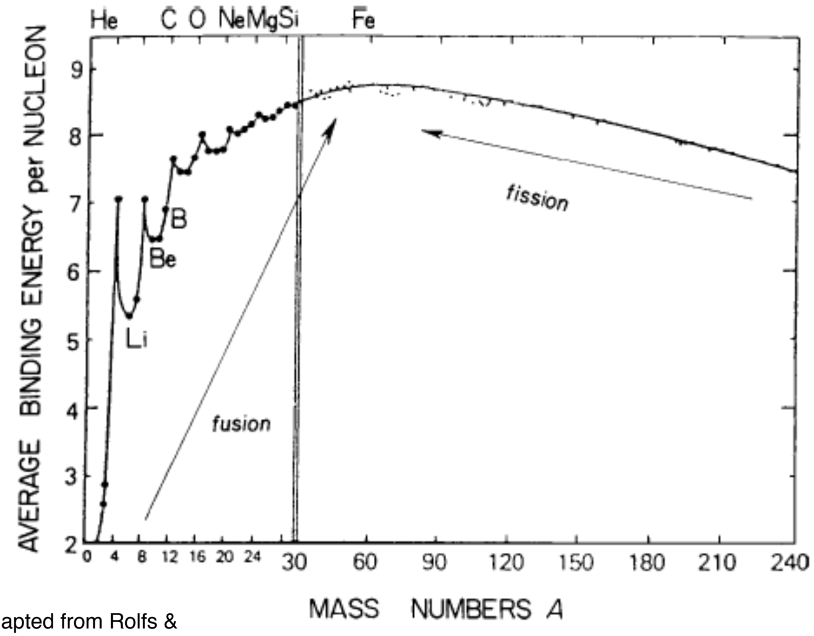
Energy generated by a nuclear reaction $X + a \to Y + b$

$$Q = (M_X + M_a - M_Y - M_b)c^2$$

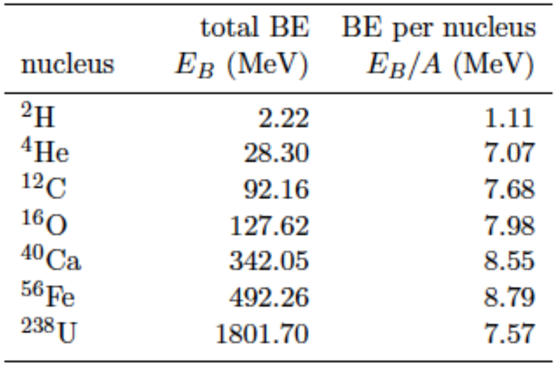
$Q > 0 \to$ reaction is exothermic
$Q < 0 \to$ reaction is endothermic

A atomic number P, Z mass number (N+P)

Binding Energy: stability of nuclei



Adapted from Rolfs & Rodney (1988).



nucleus	total BE E_B (MeV)	BE per nucleus E_B/A (MeV)
^{2}H	2.22	1.11
^{4}He	28.30	7.07
^{12}C	92.16	7.68
^{16}O	127.62	7.98
^{40}Ca	342.05	8.55
^{56}Fe	492.26	8.79
^{238}U	1801.70	7.57

The binding energy per nucleon varies with A along the stability valley:

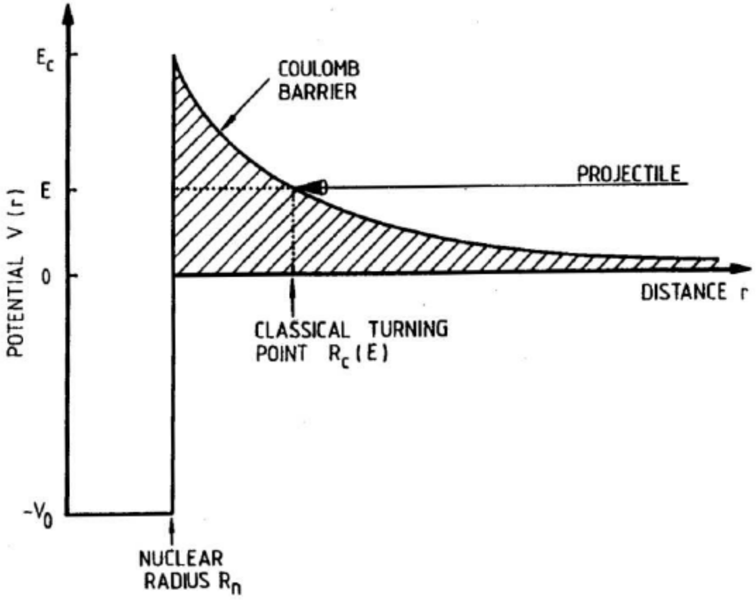
→ Alpha elements the most stable ones (^{4}He, ^{12} C, ^{16} O, ^{20} Ne, ^{24} Mg, ^{28} Si, ^{32} S, ^{36} Ar, ^{40}Ca)

→Maximum binding energy for Fe and Ni

→Elements with A=5 and A=8 are unstable (^{5}He, ^{5}Li, ^{8}Be)

→ D, ^{6,7} Li, ^{9} Be and ^{10,11} B are destroyed by thermonuclear reactions at relatively low temperatures

Cross section: measure of probability that a certain reaction occurs



Nuclear potential for a charged particle reaction, consisting of:

- the repulsive Coulomb potential ($V > 0$) for $r > R_n$
- the attractive potential of the strong nuclear force ($V < 0$) for $r < R_n$.

For R_p = projectile radius and R_t = target radius)

→ classical geometrical cross-section:

$$\sigma = \pi(R_p + R_t)^2$$

→ quantum mechanics: de Broglie-wave of particles

$$\Rightarrow \sigma = \pi\lambda^2 \quad \text{with} \quad \lambda = \left(\frac{m_p + m_t}{m_t}\right)^{1/2} \frac{\hbar}{(2m_p E)^{1/2}}$$

In ‘classical’ conditions, H-burning would need $T \sim 6\ \ 10^9$ K ($E > E_c$), but there is the relativistic **tunnel effect** which gives a finite probability that projectile penetrates Coulomb barrier ($T \sim 10^7$ K).

Nuclear reaction rates

The nuclear reaction rate:

$$r_{xy} = N_x \quad N_y \quad v \quad \sigma(v)$$

- N_x, N_y number densities of particles x, y (i.e., particles per cm3)
- v relative velocity between x and y
- $\sigma(v)$ cross section

$[r]$ = reactions per cm^3 per s = $cm^{-3}\ s^{-1}$

→In stars, the distribution of velocity is regulated by the Maxwell-Boltzmann equation which is a function of the temperature of the gas and of the kinetics energy of particle.

$$r_{xy} = N_x \quad N_y \quad <\sigma v>$$

$$\boxed{\langle \sigma v \rangle = \left(\frac{8}{\pi m}\right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE}$$

with $E=1/2\ m\ v^2$ and m is the reduced mass of x and y

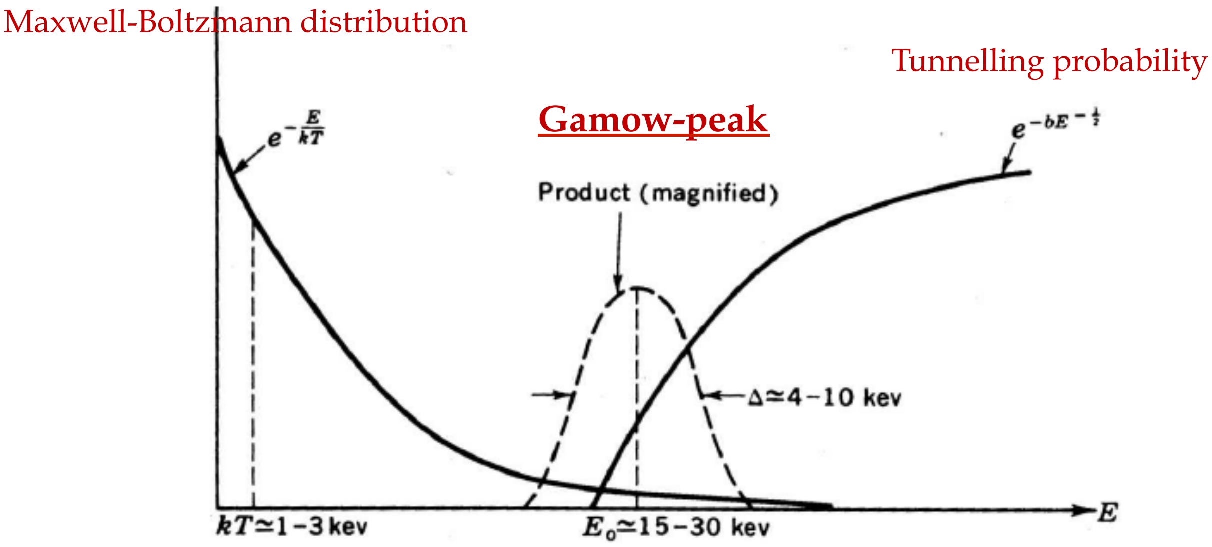
→The rate of nuclear reactions is driven by temperature and density conditions

Astrophysical S factor

The combination of the cross-section, of the velocity distribution and of the tunnel effect as functions of the energy of the particle have a maximum:

$$\text{Cross section (B)} \Rightarrow \sigma(E) \sim \pi\lambda^2 \sim 1/E$$

$$\text{Tunnel effect (D)} \Rightarrow \sigma(E) \sim \exp(-2\pi\eta), \;\; \eta \sim 1/\sqrt{E}$$


Maxwell-Boltzmann distribution

Tunnelling probability

Gamow-peak

Dominant energy dependent factors in thermonuclear reactions. Most reactions occur in the overlap between the high-E tail of the Maxwell-Boltzmann distribution, giving a factor $e^{(-E/kT),}$ and the probability of tunneling through the Coulomb barrier, giving a factor $e^{(-b/\sqrt{E})}$

→ **the S(E) function is called Astrophysical Factor, whose maximum is the Gamow peak**

Z and Temperature dependences

→ The Gamow peak:

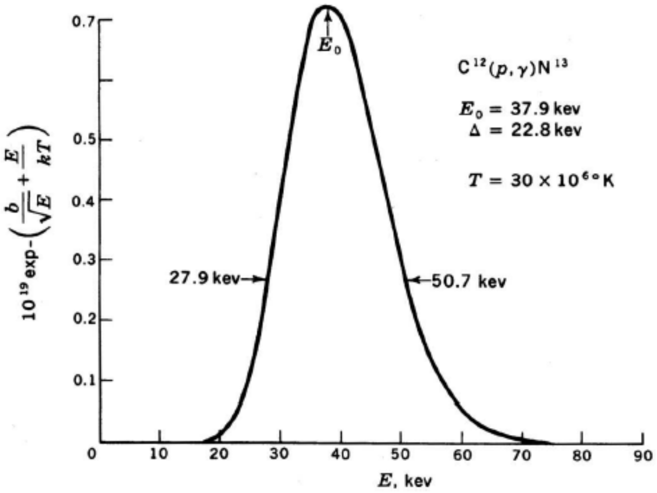
→ shifted to higher E for heavier nuclei → higher E necessary to burn heavier elements

$$E_0 \sim (Z_x Z_y)^{2/3}$$

→ thermonuclear cross sections are extremely T-dependent!

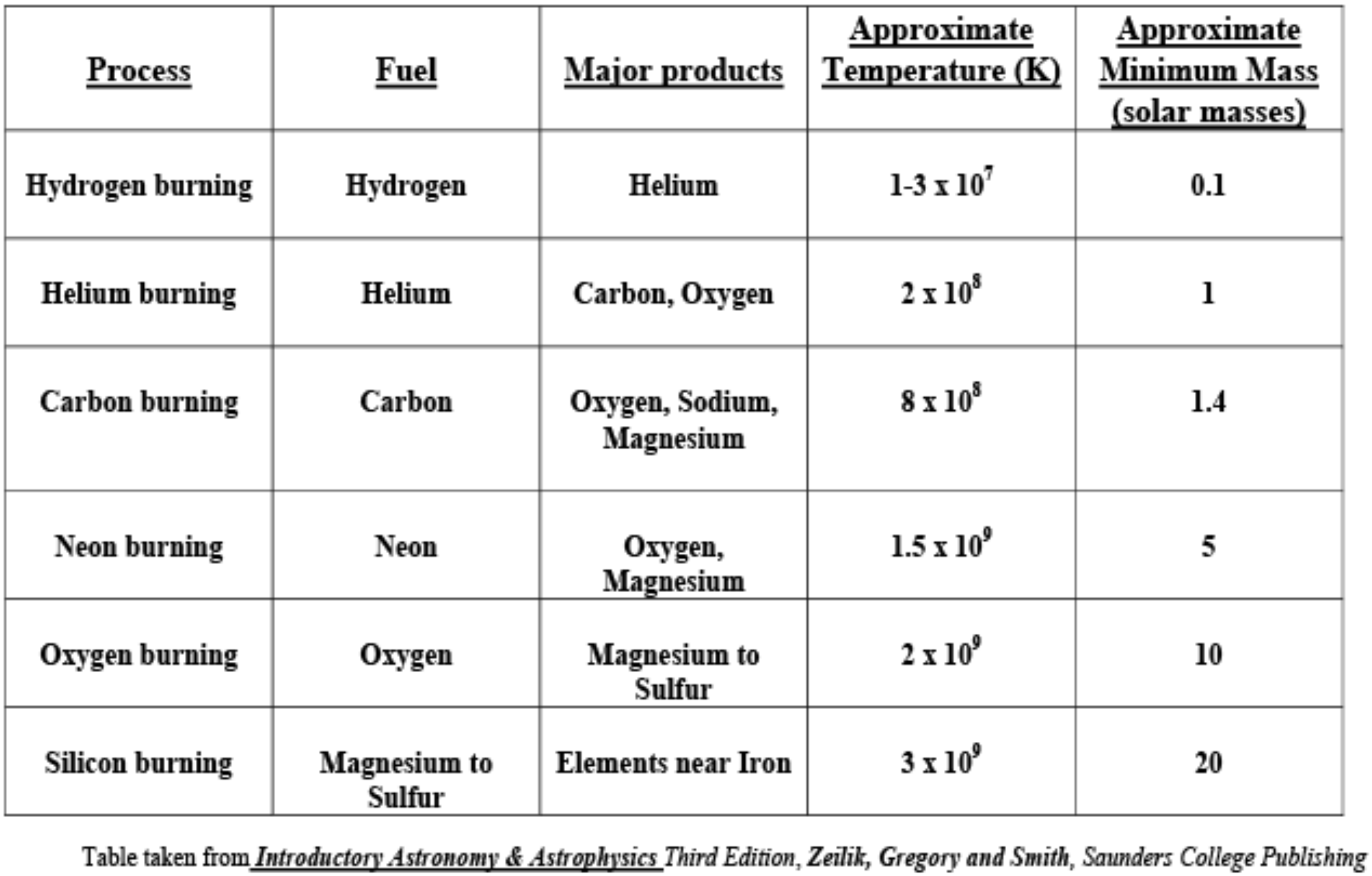
$$\boxed{\langle \sigma v \rangle \sim T^{\frac{\tau}{3} - \frac{2}{3}}} \qquad \text{with } \tau := \frac{3E_0}{kT}$$

→ burning stages in stars occur at well-defined constant temperature



Gamow peak for the ^{12}C(p, ɣ) ^{13}N reaction at T = 30 10^6 K.

Temperature dependence



Process	**Fuel**	**Major products**	**Approximate Temperature (K)**	**Approximate Minimum Mass (solar masses)**
Hydrogen burning	**Hydrogen**	**Helium**	**1-3 x 10^7**	**0.1**
Helium burning	**Helium**	**Carbon, Oxygen**	**2 x 10^8**	**1**
Carbon burning	**Carbon**	**Oxygen, Sodium, Magnesium**	**8 x 10^8**	**1.4**
Neon burning	**Neon**	**Oxygen, Magnesium**	**1.5 x 10^9**	**5**
Oxygen burning	**Oxygen**	**Magnesium to Sulfur**	**2 x 10^9**	**10**
Silicon burning	**Magnesium to Sulfur**	**Elements near Iron**	**3 x 10^9**	**20**

Table taken from *Introductory Astronomy & Astrophysics Third Edition, Zeilik, Gregory and Smith, Saunders College Publishing*

Typical reactions relevant to astrophysics

- **H-burning**:
  - in the Big Bang ($T \sim 10^9$ K, kT 0.1 MeV)
  - in stars (10^7 K < T < 10^8 K, 1 keV < kT < 10 keV).
- **He-burning:**
  - in stars ($T \sim 10^8$ K, kT~10 keV)
- **C-, Ne-, O-burning:**
  - in stars (10^8 K < T < 10^9 K, 10 keV < kT < 0.1MeV).
- **Si-burning**
  - hydrostatically near 10^9 K (0.1 MeV)
  - explosively at several times 10^9 K.
- **Neutron capture**
  - in the Big Bang
  - s-process (a few x 10^8 K)
  - r-process (a few x 10^9 K)
- **Spallation reactions**, especially those involving cosmic rays in the ISM (non-thermal, with MeV to GeV energies). Spallation reactions are those in which one or a few nucleons are split off from a nucleus.

Big Bang nucleosynthesis

The ‘Hot’ Big Bang theory:

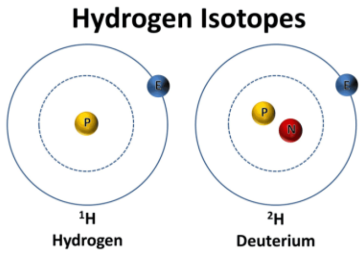
It was first proposed by Gamow, Alpher & Hermann in (1948):

- going back in time, the Universe was smaller, denser and hotter
- during the first few minutes (when $T \sim 10^9$ K), it acted like a nuclear reactor
- but a ‘defective’ reactor because it was expanding and cooling rapidly...

The are are three independent fundamental tests to this theory:

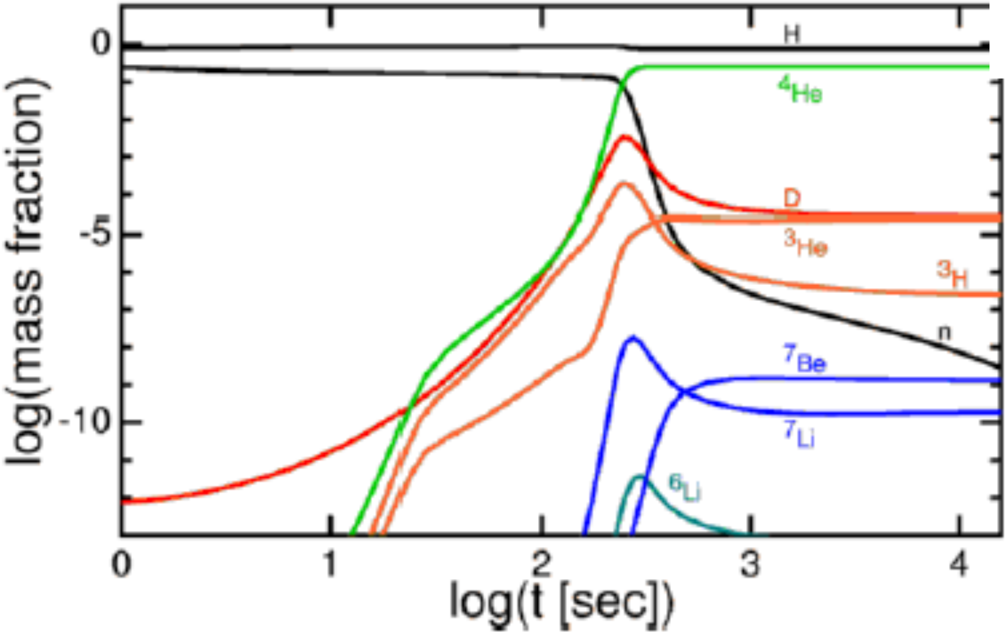
1. Hubble expansion, the expansion of galaxies is given by the Hubble law $v = H_0 D$ with D distance to the galaxy and Hubble constant, $H_0 \approx 70 \text{ kms}^{-1}\text{Mpc}^{-1}$.
2. Cosmic microwave background (CMB) radiation: blackbody with $T = 2.73 \pm 0.01\text{K}$.
3. Nucleosynthesis of light elements D, ^{3}He, ^{4}He, ^{7}Li in particular: deuterium (D) which is later only destroyed in stars

Big Bang nucleosynthesis



Nucleosynthesis of D starts at t~100 s with T ~10^9K, d~ 10^{-5} g/cm^3

$$D + p \rightarrow {}^3He + \gamma$$
$$D + D \rightarrow {}^3He + n$$
$$D + D \rightarrow {}^3H + p$$
$${}^3He + n \rightarrow {}^3H + p$$
$${}^3He + D \rightarrow {}^4He + p$$
$${}^3H + D \rightarrow {}^4He + n$$



Next bottleneck: there is no stable isotope with mass number 5

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$
$${}^3H + {}^4He \rightarrow {}^7Li + \gamma$$
$${}^7Be + n \rightarrow {}^7Li + p$$
$${}^7Li + p \rightarrow 2\,{}^4He$$

Some traces of Li and Be are produced

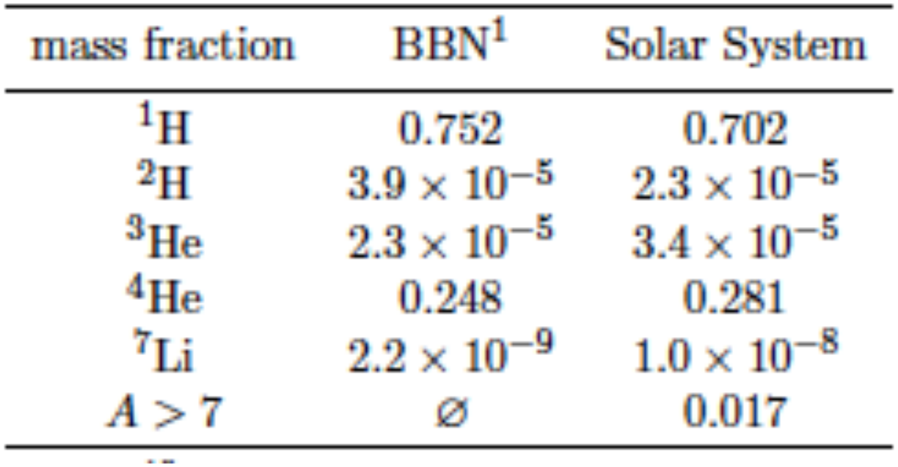
All neutrons go into ^{4}He

After 1000 seconds, T gets so low that Coulomb barriers cause the reactions to stop

Figure from http://www.astro.ucla.edu/~wright/BBNS.html.

From the Big Bang nucleosynthesis to the present Universe

No atoms with A > 7 are produced in the Bing Bang

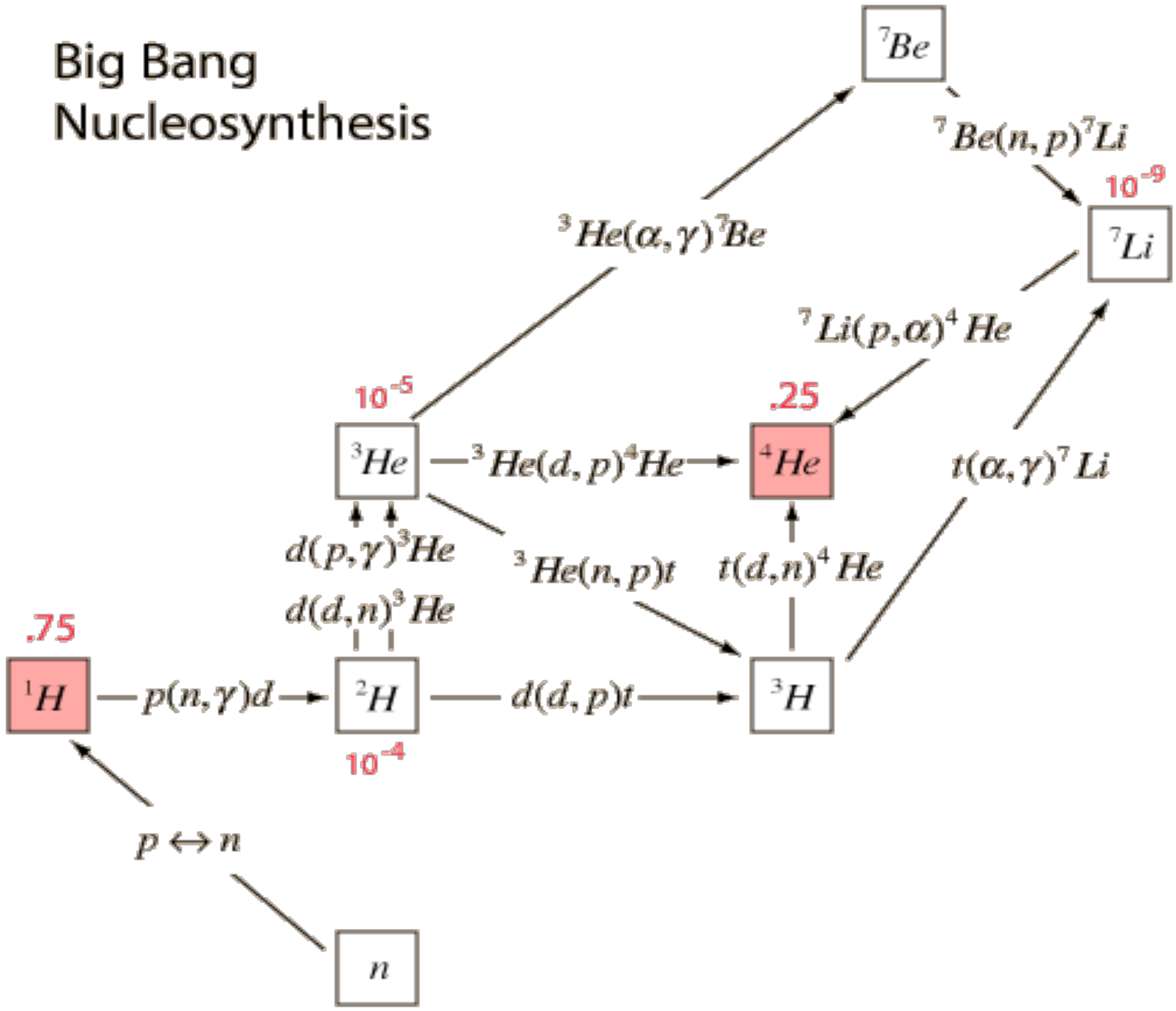


mass fraction	BBN[1]	Solar System
^{1}H	0.752	0.702
^{2}H	3.9×10^{-5}	2.3×10^{-5}
^{3}He	2.3×10^{-5}	3.4×10^{-5}
^{4}He	0.248	0.281
^{7}Li	2.2×10^{-9}	1.0×10^{-8}
$A > 7$	$\varnothing$	0.017

Stellar models:

- D is always destroyed
- ^{3}He is produced and destroyed
- ^{4}He is always produced
- ^{7}Li is produced and destroyed
- The other ‘metals’ are produced in following processes

From the Big Bang nucleosynthesis to the present Universe



Observation of the primordial abundances

To test the consistency of Big Bang Nucleosynthesis

→ compare to primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li

→ not directly observed, but inferred from observed abundances:

- in very old objects
- in very unevolved objects

^{4}He: not measurable in stars, it can be measured from emission lines in gaseous nebulae in dwarf galaxies, with low metallicity

D: from quasar absorption lines → nearly unprocessed gas

^{3}He: difficult to measure in unevolved objects

^{7}Li: from metal-poor stars in the Galactic halo

Deuterium and Helium

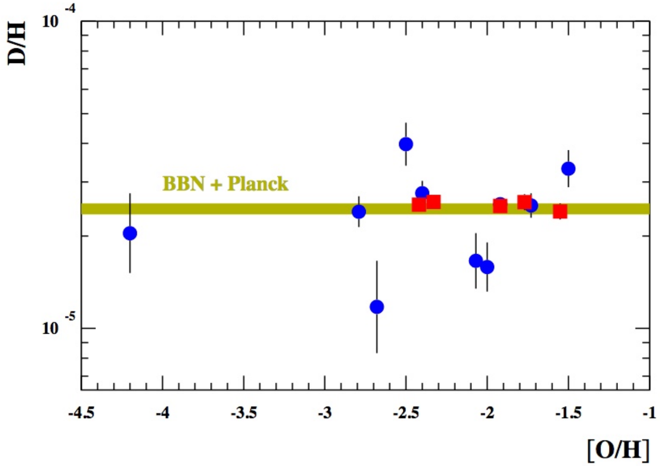
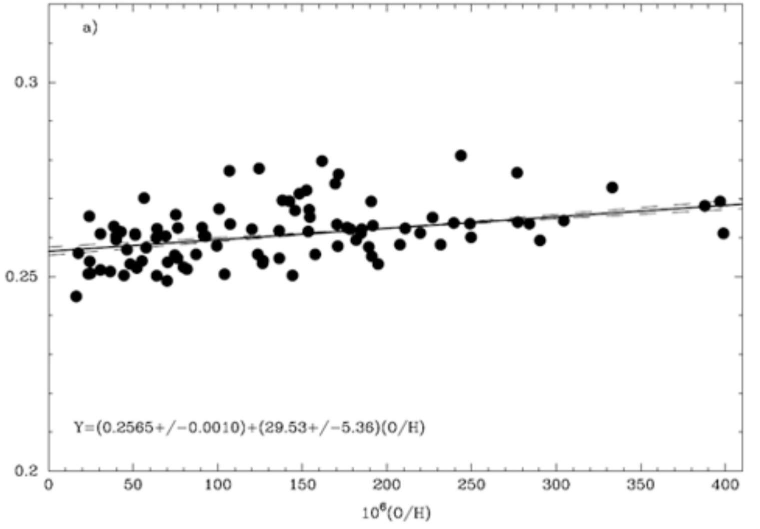
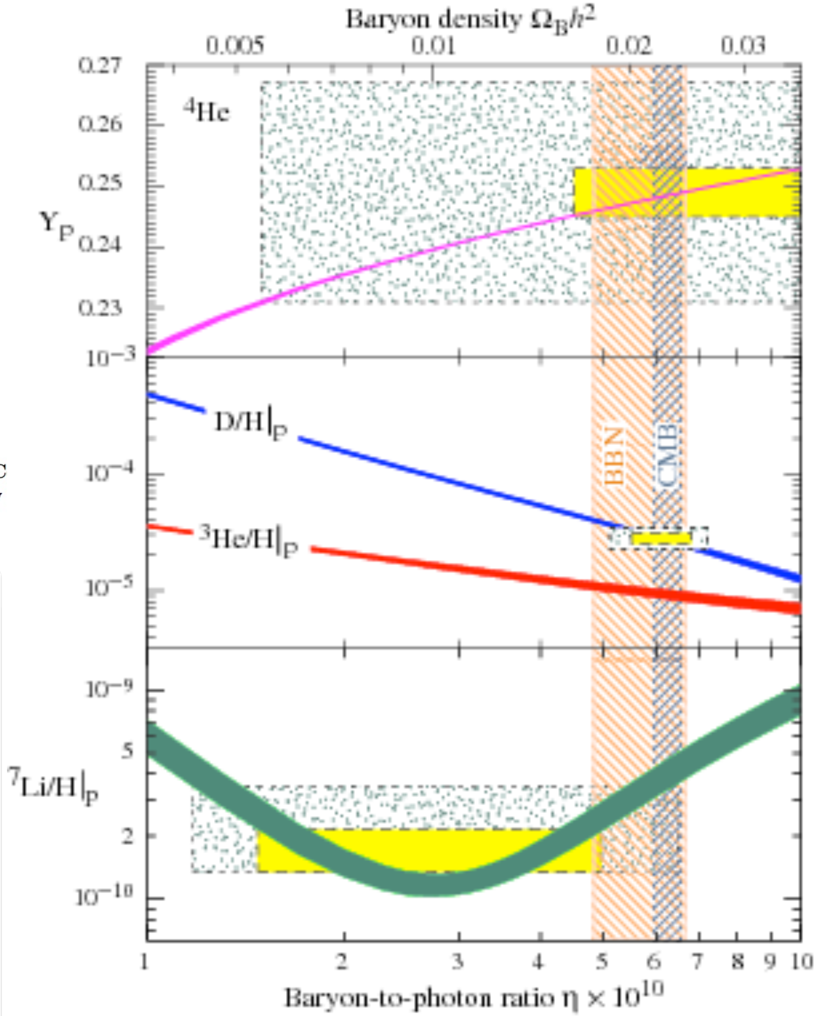


Fig. 2. D/H observations, as a function of metallicity, from Pettini et al.[18] (blue circles) and C et al.[19] (red squares). These most recent observations[19] have very small error bars and show few dispersion, and are in fair agreement with BBN calculations.[20]

From Cox et al. 2017



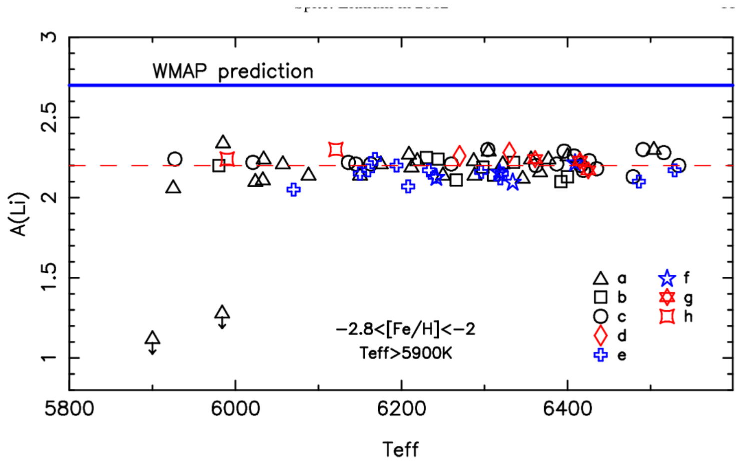


Dolgov, A.D. Phys.Atom.Nucl. 73 (2010) 815-847

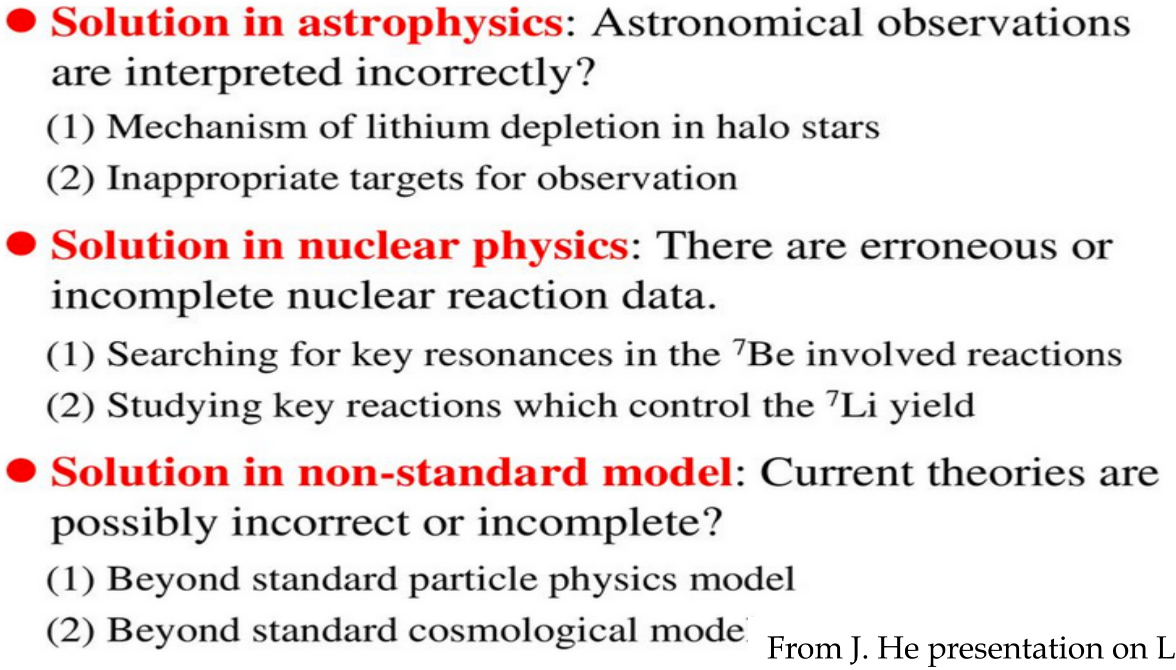
Observation of the primordial abundances: the Lithium cosmological problem

Lithium abundance vs. Teff , with A(Li) ≈ 2.2 (lithium plateau) and the prediction from the WMAP Big Bang nucleosynthesis.

The symbols correspond to: a) Charbonnel & Primas (2005), b) Asplund et al. (2006), c) Meléndez et al. (2010), d) Aoki et al. (2009), e) Hosford et al. (2009), f) Bonifacio et al. (2007), g) Sbordone et al. (2010), h) Schaeuble & King (2012).



From Spite et al. (2012)



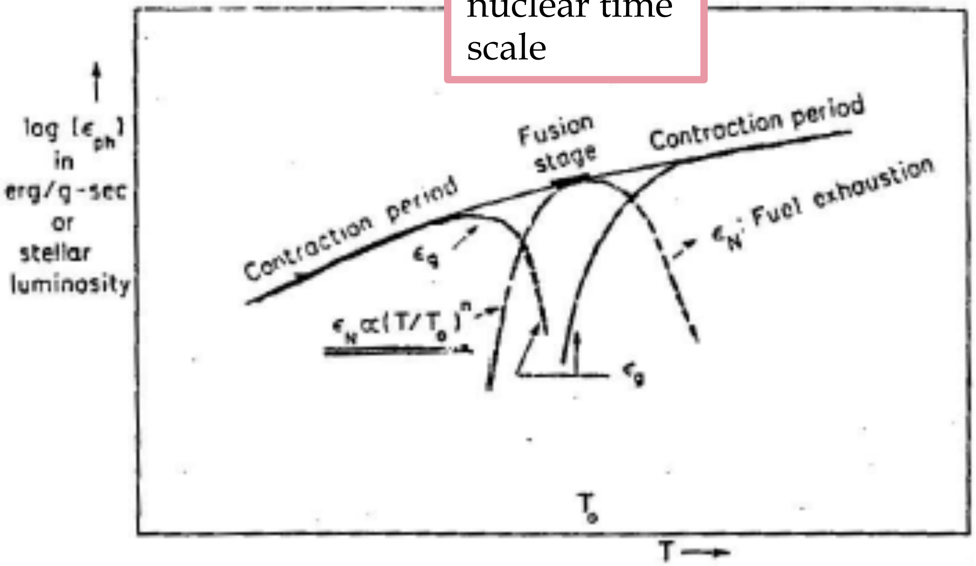
- **Solution in astrophysics**: Astronomical observations are interpreted incorrectly?
  - (1) Mechanism of lithium depletion in halo stars
  - (2) Inappropriate targets for observation
- **Solution in nuclear physics**: There are erroneous or incomplete nuclear reaction data.
  - (1) Searching for key resonances in the ^{7}Be involved reactions
  - (2) Studying key reactions which control the ^{7}Li yield
- **Solution in non-standard model**: Current theories are possibly incorrect or incomplete?
  - (1) Beyond standard particle physics model
  - (2) Beyond standard cosmological mode

From J. He presentation on Lithium Cosmological problem

Hydrostatic burning in stars A< 56: The virial theorem determines the evolution of stars (gravitational energy and internal energy)

- During star formation and evolution:
  - Star formation: gas cloud contracting under its own gravity.
  - Contraction: heating, T ↑
  - Star contracts until it reaches $T=T_{\text{H burning}}$ then T, and ρ remain constant (stop contraction)
  - When hydrogen is exhausted → contraction of the H-exhausted core
  - Core contraction, heating, T ↑
  - Star contracts until it reaches $T=T_{\text{He burning}}$ then T, and ρ remain constant

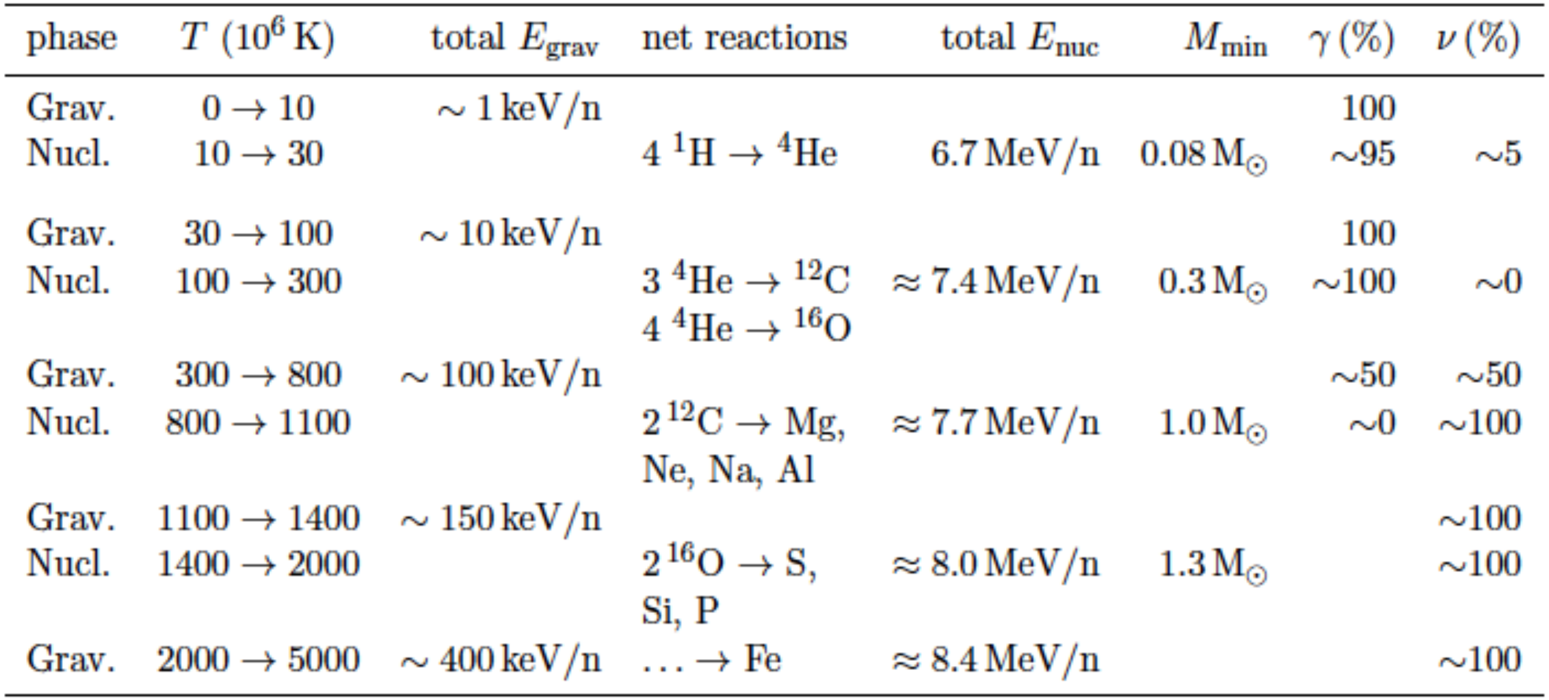
Thermal time scale



nuclear time scale

Hydrostatic burning in stars A< 56: The virial theorem determines the evolution of stars (gravitational energy and internal energy)

Photons Neutrinos



phase	T (10^6 K)	total E_{grav}	net reactions	total E_{nuc}	M_{min}	γ (%)	ν (%)
Grav.	$0 \to 10$	~ 1 keV/n				100	
Nucl.	$10 \to 30$		$4\,{}^{1}\mathrm{H} \to {}^{4}\mathrm{He}$	6.7 MeV/n	$0.08\,M_\odot$	~95	~5
Grav.	$30 \to 100$	~ 10 keV/n				100	
Nucl.	$100 \to 300$		$3\,{}^{4}\mathrm{He} \to {}^{12}\mathrm{C}$ $4\,{}^{4}\mathrm{He} \to {}^{16}\mathrm{O}$	≈ 7.4 MeV/n	$0.3\,M_\odot$	~100	~0
Grav.	$300 \to 800$	~ 100 keV/n				~50	~50
Nucl.	$800 \to 1100$		$2\,{}^{12}\mathrm{C} \to$ Mg, Ne, Na, Al	≈ 7.7 MeV/n	$1.0\,M_\odot$	~0	~100
Grav.	$1100 \to 1400$	~ 150 keV/n					~100
Nucl.	$1400 \to 2000$		$2\,{}^{16}\mathrm{O} \to$ S, Si, P	≈ 8.0 MeV/n	$1.3\,M_\odot$		~100
Grav.	$2000 \to 5000$	~ 400 keV/n	$\ldots \to$ Fe	≈ 8.4 MeV/n			~100

- Subsequent gravitational and nuclear burning stages, with typical temperature and energy production
- Nuclear reactions and energy produced per nucleon

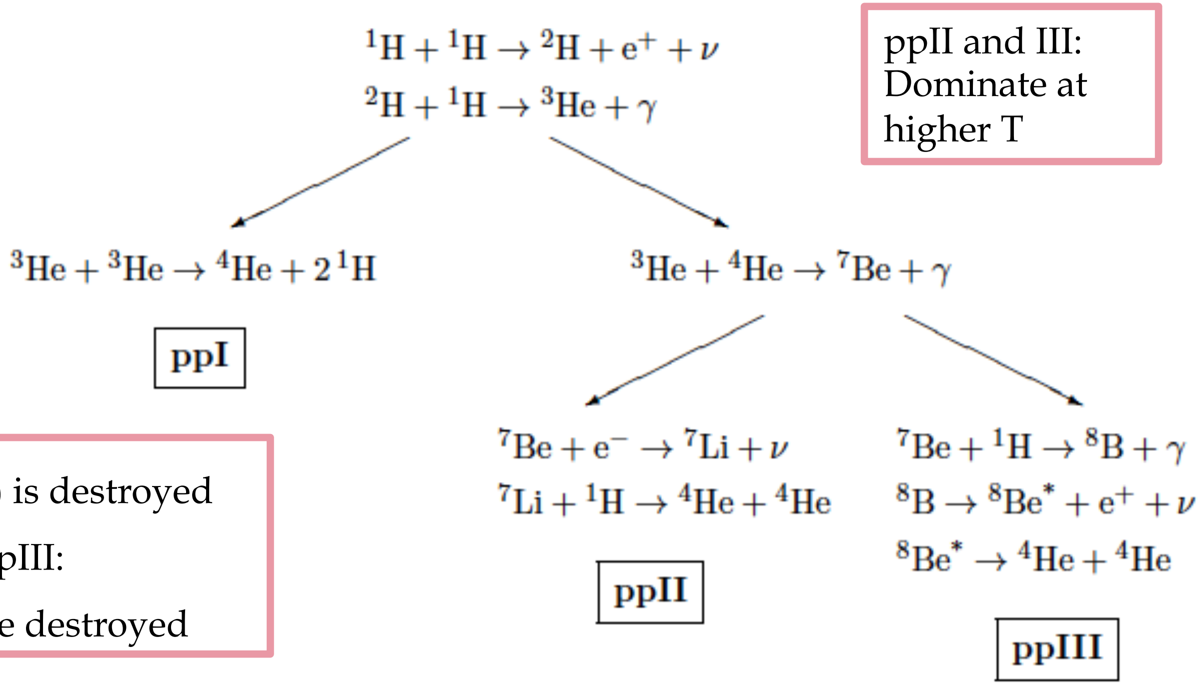
Hydrogen burning

$$4\,^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\,\mathrm{e}^{+} + 2\,\nu \quad (Q = 26.73\,\mathrm{MeV})$$

- Endothermic reaction with a positive Q=26.73 MeV
- Possible cycles:
    - p-p cycles

ppI: it works on pure H plasma, dominate at lower T

ppII and III: Dominate at higher T



$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + \nu$$
$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$$

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,^{1}\mathrm{H}$$

ppI

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

$$^{7}\mathrm{Be} + \mathrm{e}^{-} \rightarrow {}^{7}\mathrm{Li} + \nu$$
$$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

ppII

$$^{7}\mathrm{Be} + {}^{1}\mathrm{H} \rightarrow {}^{8}\mathrm{B} + \gamma$$
$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{e}^{+} + \nu$$
$$^{8}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

ppIII

ppI: D (^{2}H) is destroyed

ppII and ppIII:

Li, Be, B are destroyed

Hydrogen burning

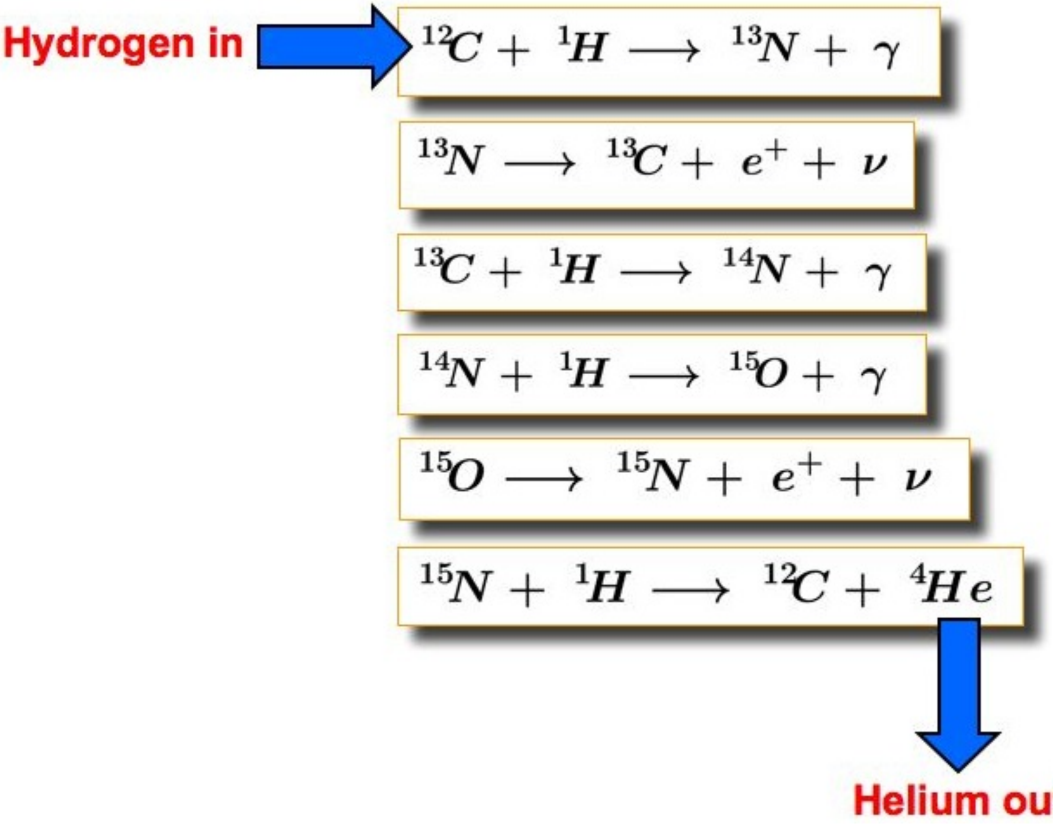
- Possible cycles:
  - CNO cycle

$$^{12}\mathrm{C}\,(\mathrm{p},\gamma)\,^{13}\mathrm{N}\,(\mathrm{e}^{+}\nu)\,^{13}\mathrm{C}\,(\mathrm{p},\gamma)\,^{14}\mathrm{N}\,(\mathrm{p},\gamma)^{15}\mathrm{O}\,(\mathrm{e}^{+}\nu)^{15}\mathrm{N}\,(p,\alpha)\,^{12}\mathrm{C}$$

The pp chains can operate in a gas consisting only of H and He

If heavier elements are present, e.g. in solar abundances, and for relatively high T and low density

$M > 1.5\,M_{\odot}$



Hydrogen in

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

$$^{13}N \longrightarrow {}^{13}C + e^{+} + \nu$$

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

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

$$^{15}O \longrightarrow {}^{15}N + e^{+} + \nu$$

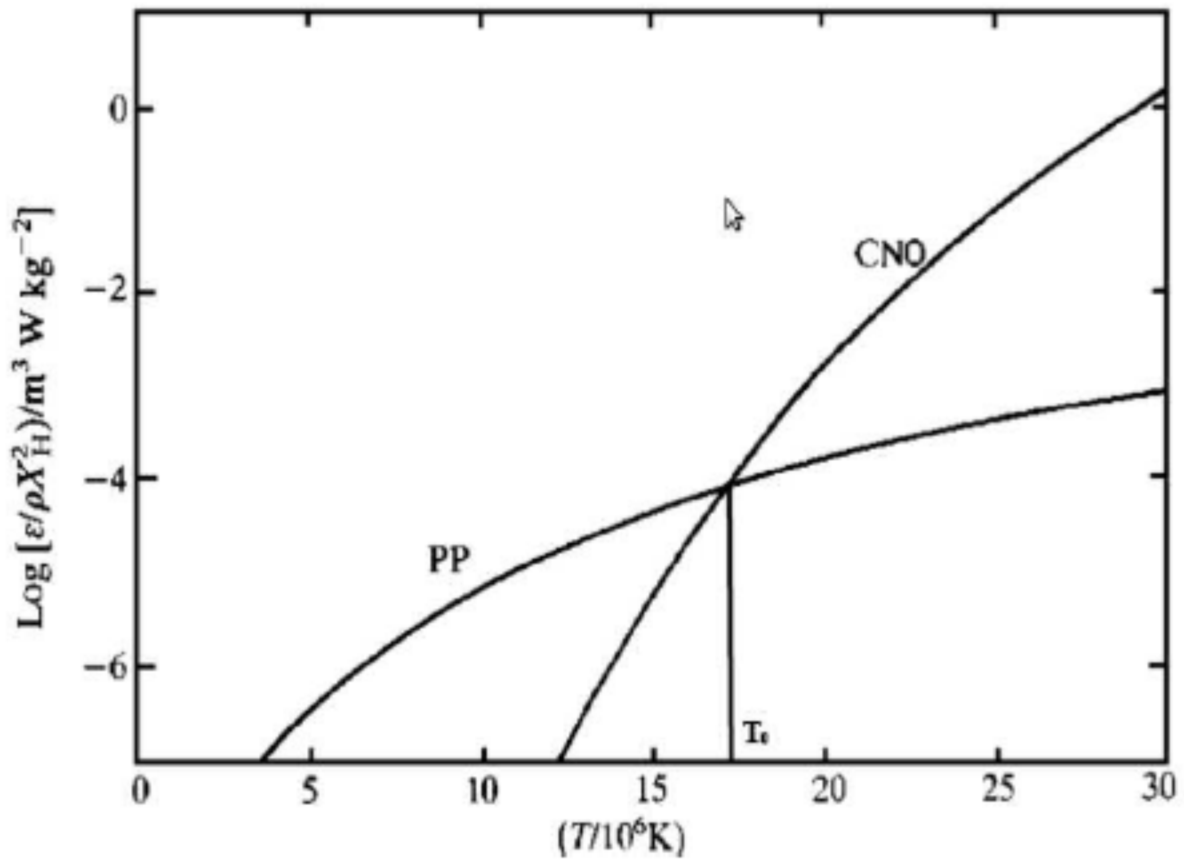
$$^{15}N + {}^{1}H \longrightarrow {}^{12}C + {}^{4}He$$

Helium out

This is a cyclic process, with the CNO-nuclei acting only as catalysts.

The total number of CNO-nuclei is conserved

Hydrogen burning: pp and CNO as a function of T



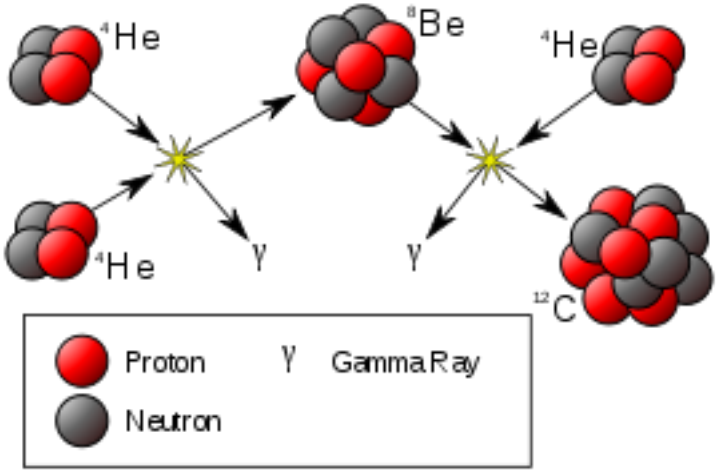
Produced energy per unit time and stellar mass versus temperature, for the pp-chain and the CNO cycle.

Helium burning

At H exhaustion, in the core of the star:

$$\text{For example } (Z = Z_\odot): \quad X = 0.70,\ Y = 0.28,\ Z = 0.02 \text{ (with } X(\mathrm{O}) \approx 0.01)$$
$$\Downarrow$$
$$\text{after H-burning:} \quad X = 0,\ Y = 0.98,\ Z = 0.02 \text{ (with } X(\mathrm{N}) \approx 0.014)$$

- Triple-alpha reaction: $\boxed{3\alpha \rightarrow {}^{12}\mathrm{C} + \gamma}$



$$\alpha + \alpha \leftrightarrow {}^8\mathrm{Be}$$

- ^{8}Be is unstable, but with larger life-time than the scatter of alpha particle.
- the concentration of ^{8}Be increases with T

$$^8\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma$$

- ^{8}Be interacts with another alpha particle producing ^{12}C

Note: The triple alpha reaction is not a three particle reaction! It involves an quite unstable isotope, ^{8}Be, as predicted by Hoyle in 1954

Helium burning: from C to O

$\boxed{^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}}$ very important

$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$ less important (only at very high T)

The rate of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ is not very well known today.

→ Important implication: unclear weather main product of He-burning is carbon or oxygen!

Secondary nucleosynthesis during helium burning:

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne} \quad (\text{already at } T \simeq 10^8\,\mathrm{K})$$

$\Rightarrow$ production of $^{18}\mathrm{O}$ and $^{22}\mathrm{Ne}$

$$^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg} \quad (\text{for } T \geq 3 \cdot 10^8\,\mathrm{K}$$

Although these are secondary reactions, they produce a flux of neutron that will allow the formation of other elements, the so-called neutron capture elements (from s-process)

Helium burning: from C to O

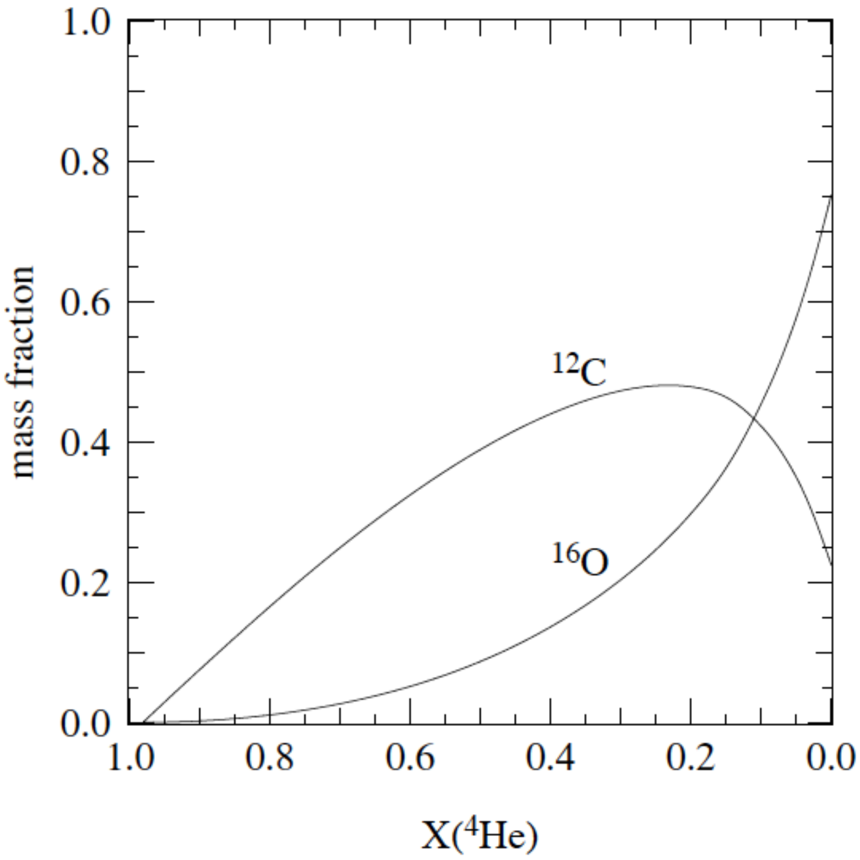
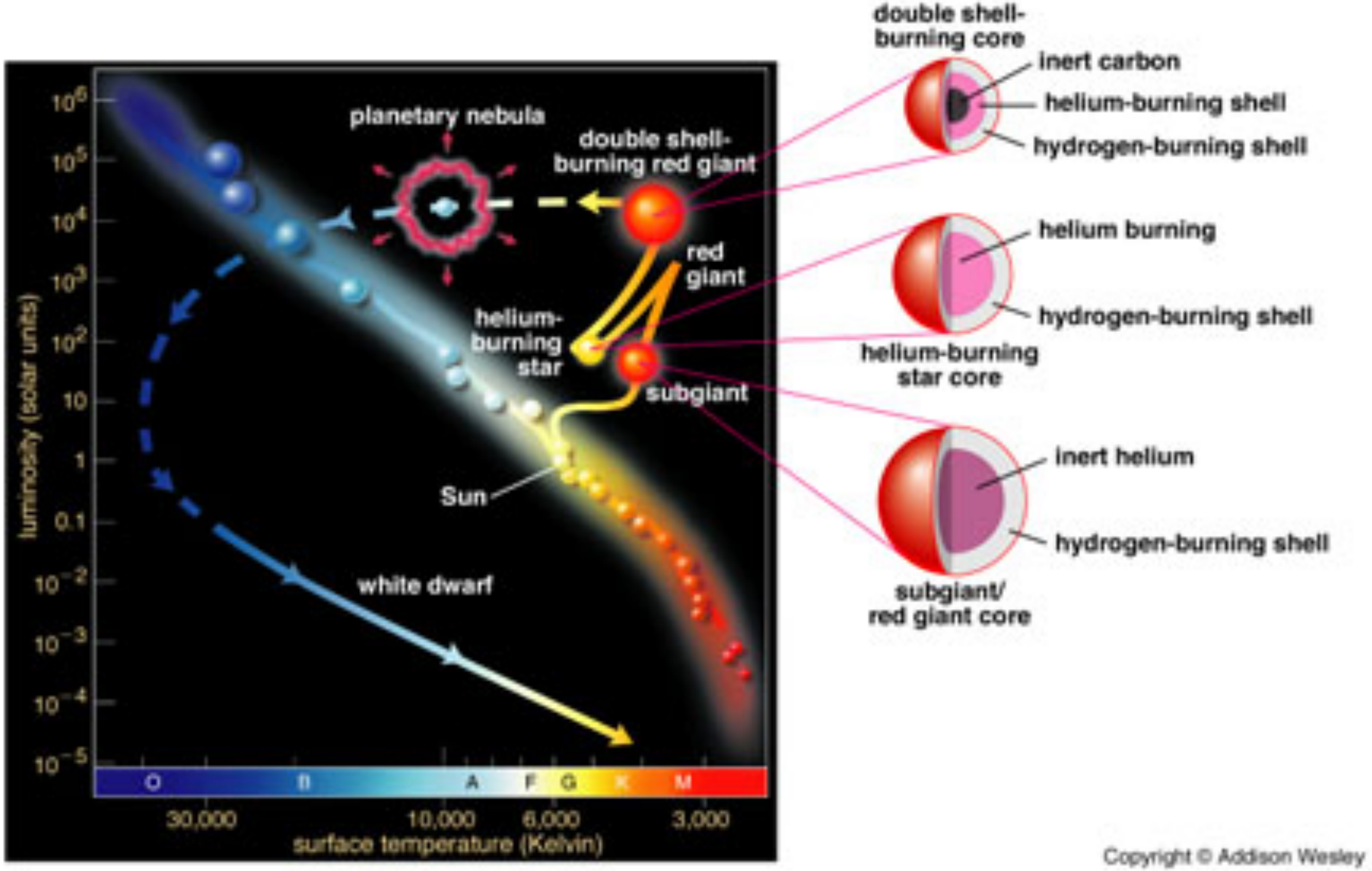


Figure 4.19: Mass fractions of ^{12}C and ^{16}O as a function of the decreasing He mass fraction, calculated for a $5\,M_\odot$ star with $Z = 0.02$.

Helium burning: latest phase of low and intermediate-mass stars



Advanced nuclear burning phases

Ashes of helium burning → mainly ^{12}C, ^{16}O → no light particles (p, n, α) available initially!

- Carbon burning

$$
\begin{aligned}
^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne} + \alpha + 4.6\,\mathrm{MeV} \quad (\sim 50\%) \\
^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{23}\mathrm{Na} + \mathrm{p} + 2.2\,\mathrm{MeV} \quad (\sim 50\%)
\end{aligned}
$$

Production of α and p particles, which activate further reactions

Composition after carbon burning:

$$\boxed{^{16}\mathrm{O},\ {}^{20}\mathrm{Ne},\ {}^{24}\mathrm{Mg}\ (\text{together: } 95\%)}$$

- Neon burning → first than O burning
- $^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ occurs at lower temperatures than $^{16}\mathrm{O} + {}^{16}\mathrm{O}$
  - higher Z than O, but burned before ^{16}O since ^{20}Ne is less stable than ^{16}O and thus its reaction occurs at lower temperature

$$
\begin{aligned}
^{20}\mathrm{Ne} + \gamma &\longleftrightarrow {}^{16}\mathrm{O} + \alpha \\
^{20}\mathrm{Ne} + \alpha &\rightarrow {}^{24}\mathrm{Mg} + \gamma
\end{aligned}
$$

Composition after neon burning:

$$\boxed{^{16}\mathrm{O},\ {}^{24}\mathrm{Mg}\ (\text{together: } 95\%)}$$

Advanced nuclear burning phases

- Oxygen burning: starting from ashes of neon burning, mainly ^{16}O, ^{24}Mg

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S}^* \rightarrow {}^{28}\mathrm{Si} + \alpha + 9.6\,\mathrm{MeV} \quad (\sim 60\%)$$
$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S}^* \rightarrow {}^{31}\mathrm{P} + \mathrm{p} + 7.7\,\mathrm{MeV} \quad (\sim 40\%)$$

Composition after oxygen burning:

$$\boxed{^{28}\mathrm{Si},\ {}^{32}\mathrm{S}\ (\text{together: } 90\%)}$$

- Silicon burning: starting from the ashes of oxygen burning, mainly ^{28}Si

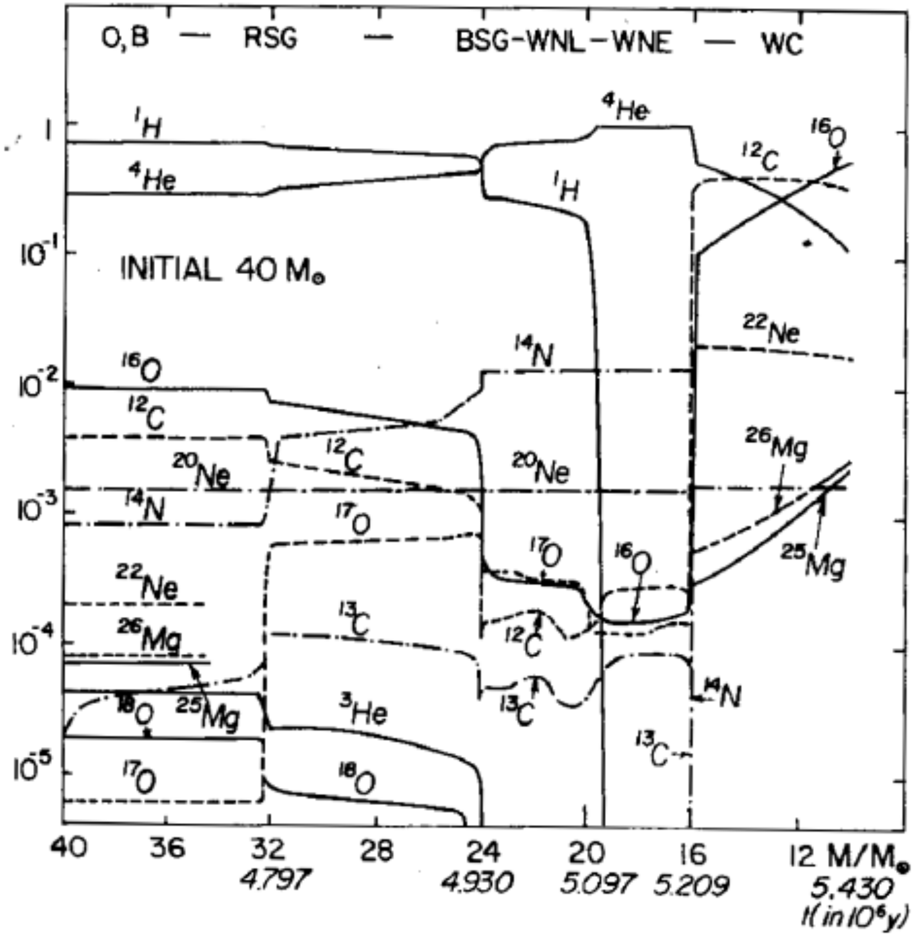
$$^{28}\mathrm{Si}\,(\alpha,\gamma)\,{}^{32}\mathrm{S}\,(\alpha,\gamma)\,{}^{36}\mathrm{Ar}\,(\alpha,\gamma)\,{}^{40}\mathrm{Ca}\,(\alpha,\gamma)\,{}^{44}\mathrm{Ti}\,(\alpha,\gamma)\,{}^{48}\mathrm{Cr}\,(\alpha,\gamma)\,{}^{52}\mathrm{Fe}\,(\alpha,\gamma)\,{}^{56}\mathrm{Ni}$$

Final composition is mostly ^{56}Fe.

Advanced nuclear burning phases

Evolution of the surface abundances of a massive stars, which is loosing mass with strong stellar winds

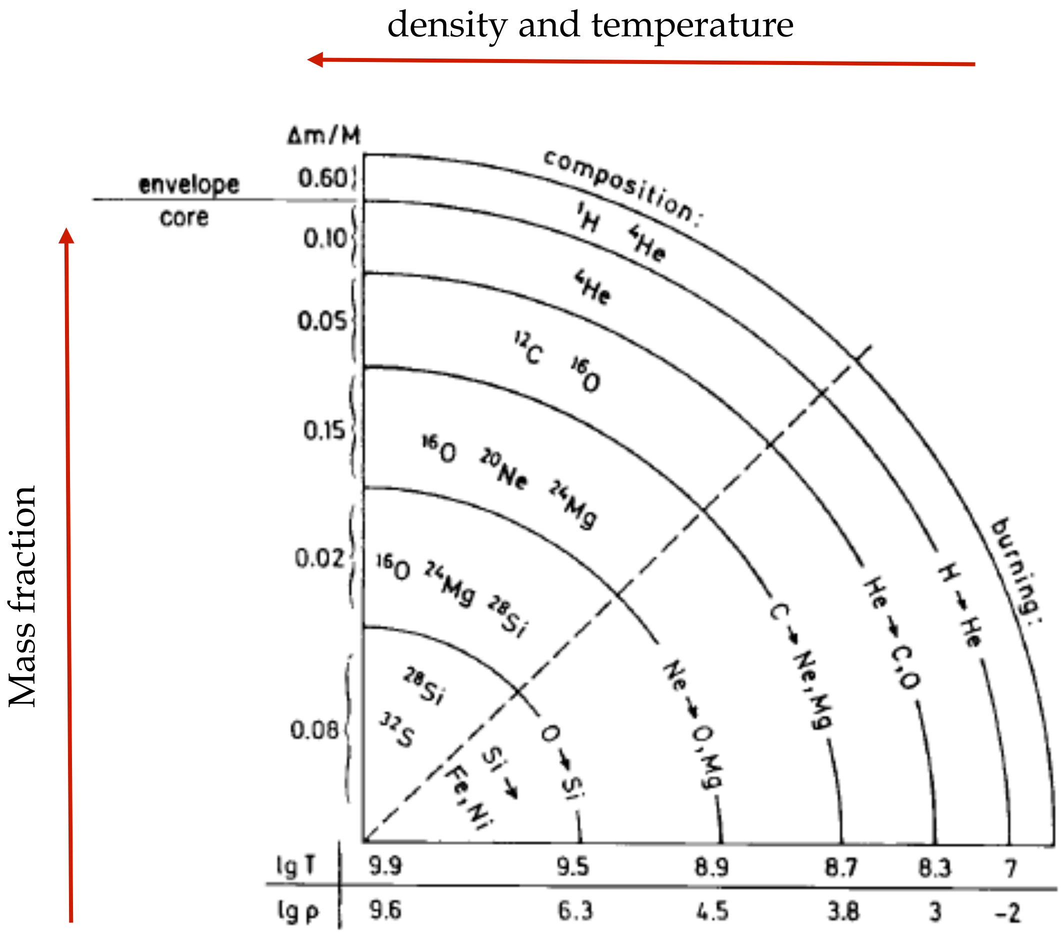
evolution



Mass loss from the final stages of massive stars probably accounts for a substantial fraction of the ^{12}C in the Universe.

Advanced nuclear burning phases

Evolution of the burning-shells in a massive star



density and temperature

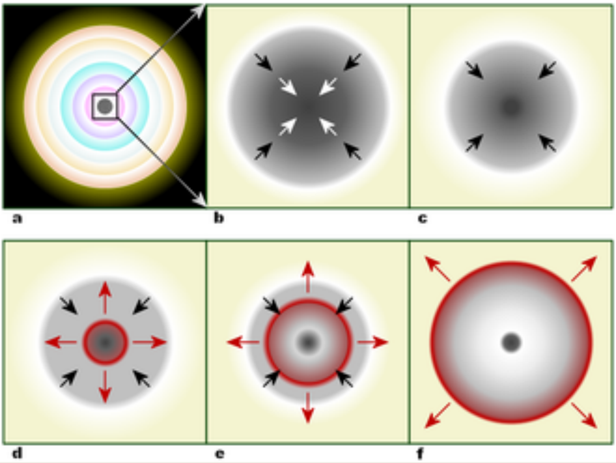
Mass fraction

Schematic illustration (not to scale) of the ‘onion-skin’ structure in the interior of a highly evolved massive star (25 M$_\odot$). Form Kippenhahn and Weigert (1990)

Advanced nuclear burning phases

The next stage is **dynamical collapse of the core**, on a dynamical timescale of milliseconds, caused by electron capture followed by photo-disintegration, from the increase in temperature in a thermal runaway following gravitational contraction **when the silicon fuel is exhausted**.

- the collapse (Chandrasekhar limits→ maximum mass for a star supported by electron degeneracy) leads to disintegration of the (mainly iron) nuclei first into α-particles and then into protons and neutrons
- electrons are crushed onto protons to make neutrons and the neutrons themselves become degenerate making a neutron star
- copious neutrino emission and a shock propagating outwards
- expulsion of the outer layers in an explosion identified with **supernovae of Type II and related types Ib (core-collapse)**
- **explosive synthesis** during the expansion timescale of the order of seconds
- **massive stars are believed to supply most elements up to and including the iron group in stars of Population II (older stars)**



Advanced nuclear burning phases

O, Ne and Mg originate mainly from hydrostatic burning

- ejected rises sharply with progenitor mass

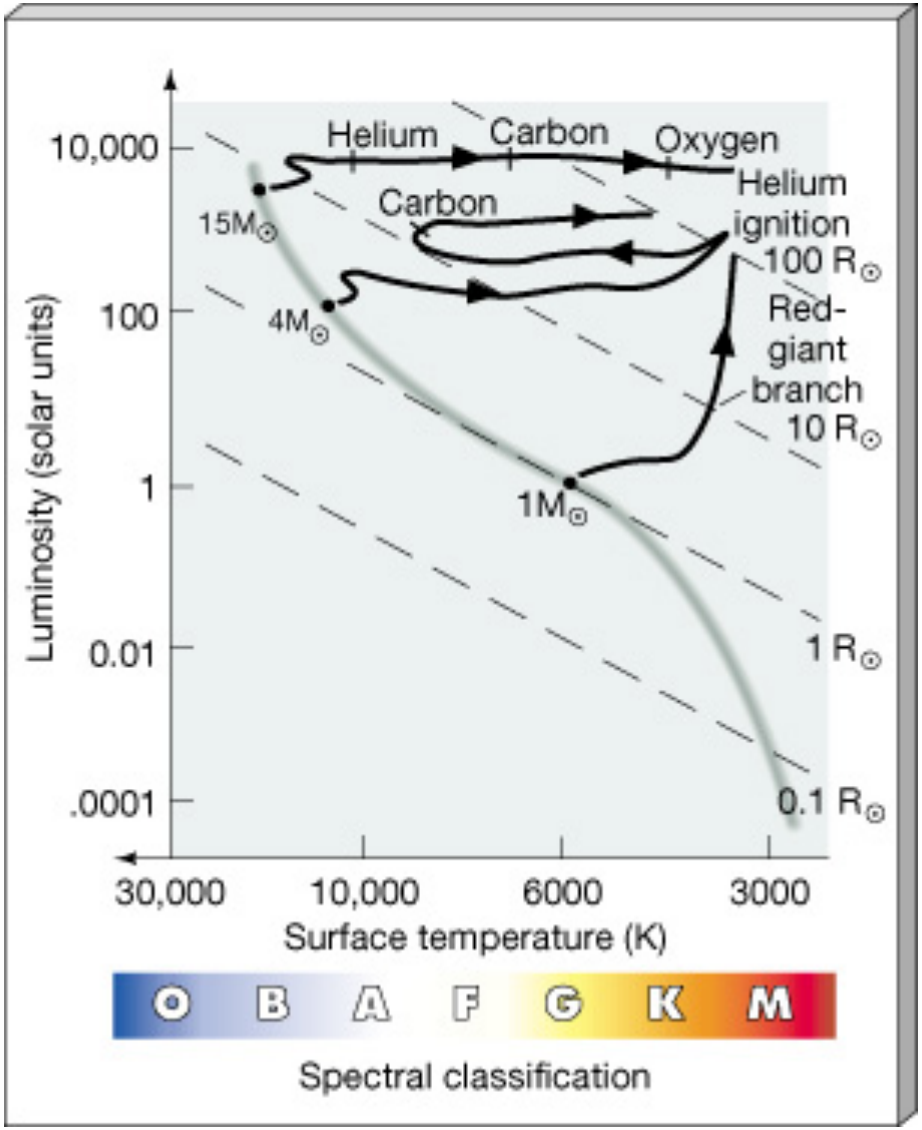
S, Ar, Ca and Fe are mostly due to explosive burning

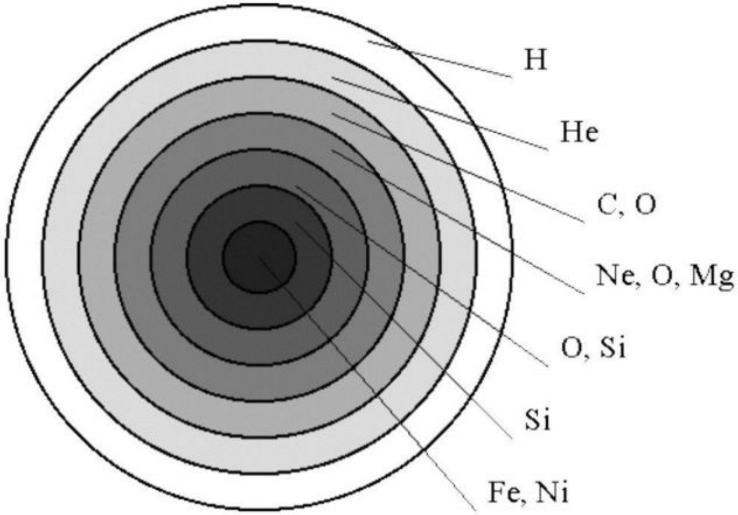
- the dependence of their ejected mass on the initial stellar mass is not very clear.

Type II supernova (SN 1987A), observed in 1987 in the LMC

- there is a deficit by a factor of the order of 2 or 3 in the relative abundance of iron-group elements compared to the Sun, which is believed to be made up by supernovae of Type Ia.

Advanced nuclear burning phases: in stars more with M> 8 $M_\odot$





Stars > 25 solar masses

carbon fusion (600 years)
↓
neon fusion (1 year)
↓
oxygen fusion (6 months)
↓
silicon fusion (1 day) → inert iron core

Neutron-capture nucleosynthesis: s-process

Elements beyond the iron group:

- not produced by charged particle reactions (high Coulomb-barriers!)
- possibility: neutron captures
- are free neutrons available in stars?

$^{22}\mathrm{Ne}(\alpha, \mathrm{n})^{25}\mathrm{Mg}$

$^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$

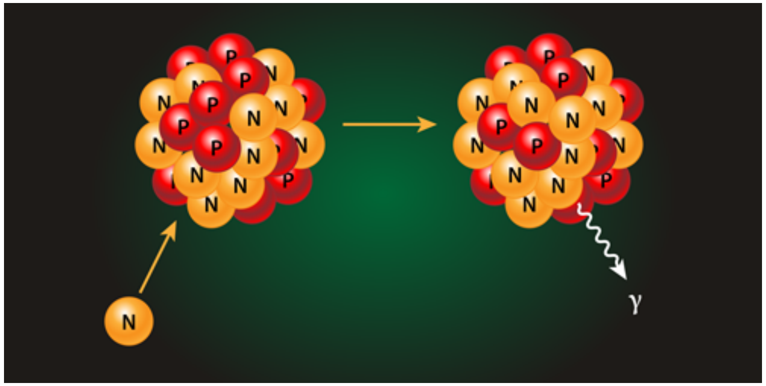
Reactions producing neutrons:
Ne-Mg→ Massive stars T> 4 10^8K, Weak component
C-O→ Thermally pulsating AGB stars, with mixing processes

β-decay times of nuclei close to the "valley of stability" in the nuclear chart are mostly of order of hours, much shorter compared to stellar evolution time scale

S (slow)-process:

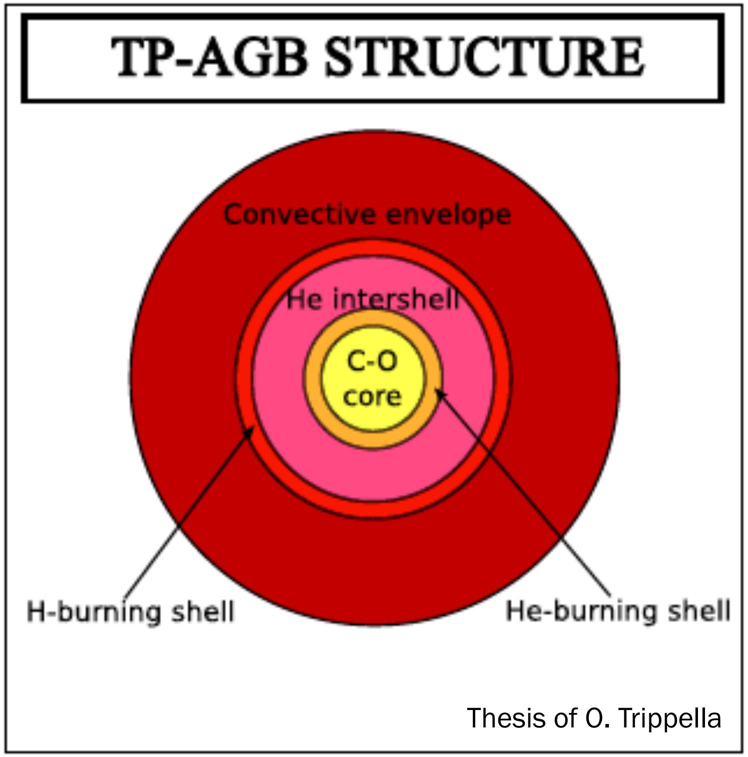
$$\boxed{\tau(\text{n-capture}) \gg \tau(\beta^-\text{-decay})}$$

In the β^--decay the neutron is transformed in a couple proton-electron.



Neutron-capture nucleosynthesis: s-process in AGB stars

In the Thermally Pulsing-AGB, the C-O core is surrounded by two shells of helium and hydrogen burning alternatively.



Thesis of O. Trippella

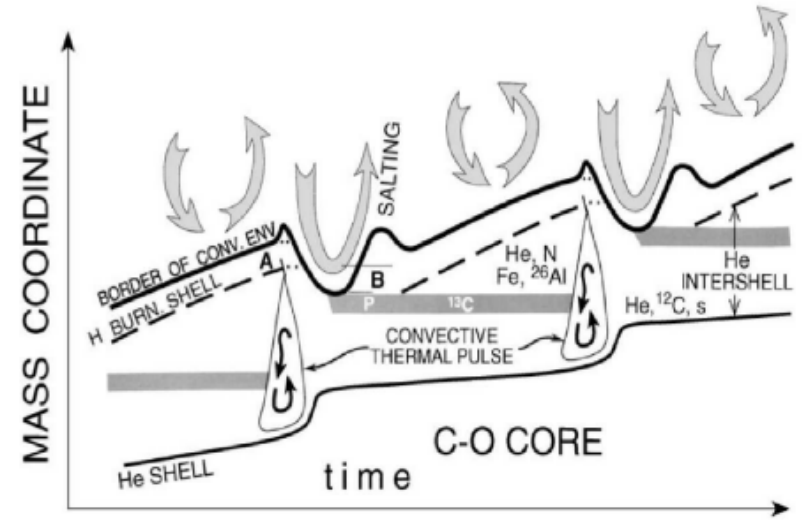
There is a helium rich intershell region between the two shells that becomes almost completely convective at intervals, while the temperature suddenly increases: it is the so-called thermal pulse (TP).

Neutron-capture nucleosynthesis: s-process in AGB stars

The thermal pulse is repeated many times (from 5 to 50 cycles) before the envelope is completely eroded by mass loss, so nucleosynthesis products manufactured by He burning and the s-process at its bottom are carried to the surface.

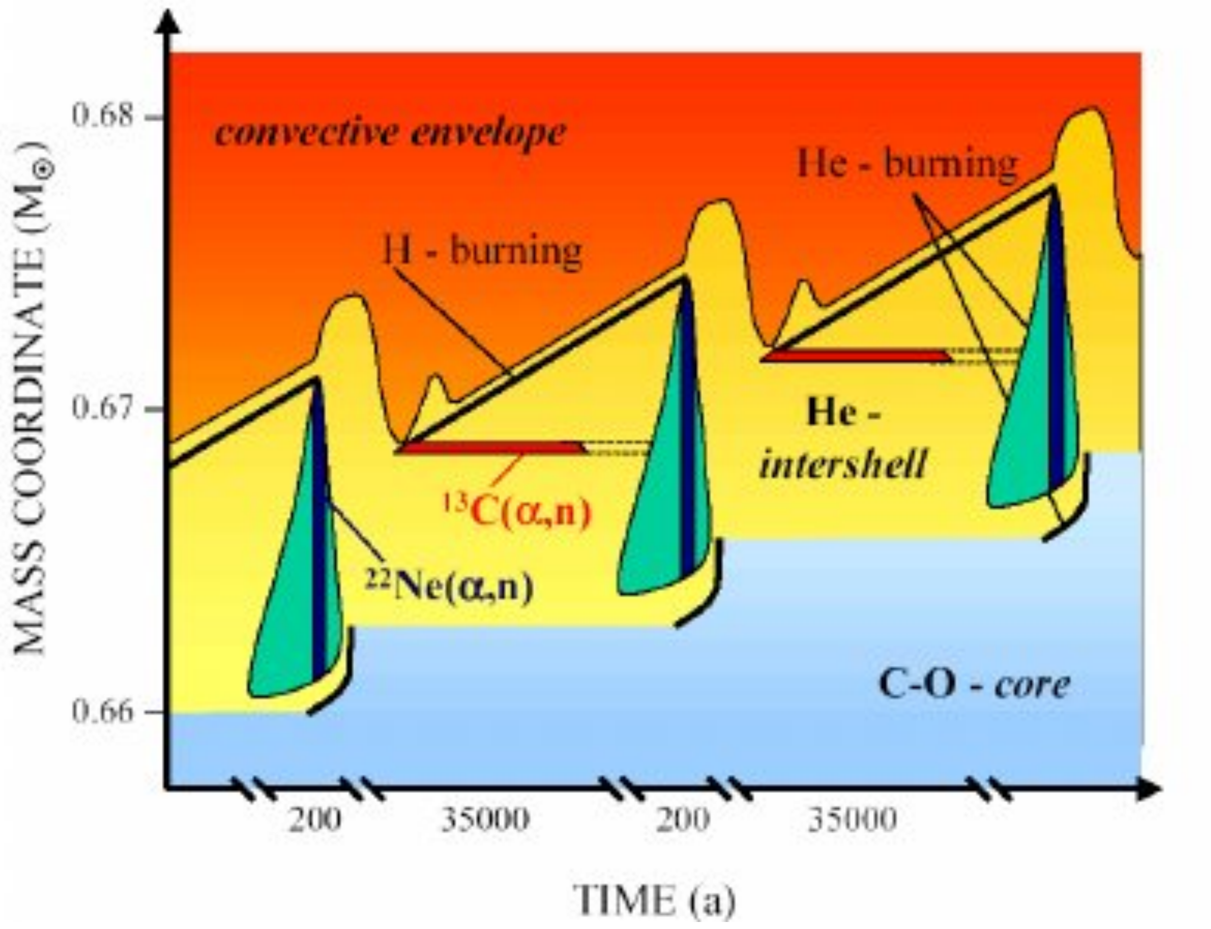
In the intershell region ^{12}C is abundant. The existence of mixing episodes carrying protons downward from the envelope yields the formation of a p- and ^{12}C-rich layer after each thermal pulse.
There, after the ignition of the H shell, p-captures generate the so-called ^{13}C pocket.

The $^{13}C(\alpha,n)^{16}O$ reaction and s-processing occurs in AGB stars, in the radiative inter-pulse phases.



Thesis of O. Trippella

Neutron-capture nucleosynthesis: s-process



Time evolution of a TP-AGB star. The star generates its energy by alternate H- and He-burning in two thin shells. The s-process nuclei are mainly produced during H-burning when the $^{13}C(\alpha,n)^{16}O$ neutron source is active → this reaction gives the necessary flux of neutron to produce slow neutron capture elements

Neutron-capture nucleosynthesis: r-process

Elements beyond the iron group:

- Time scales of seconds
- Explosive events
- High neutron fluxes
- n-capture timescale << beta-decay timescale

$$\boxed{\tau(\text{n-capture}) \ll \tau(\beta^{-}\text{-decay})}$$

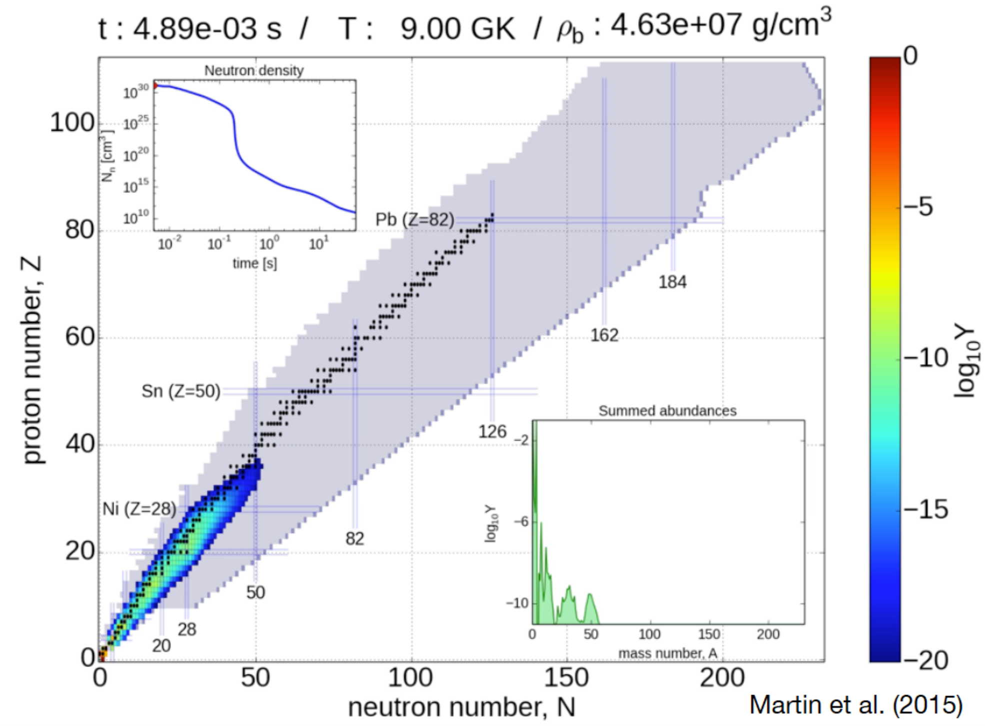
Environment:

→ He-burning shell (only He-burning site in a pre-supernova star) but liberation of neutrons on explosive time scale

→ supernova shock wave travelling through He-layer

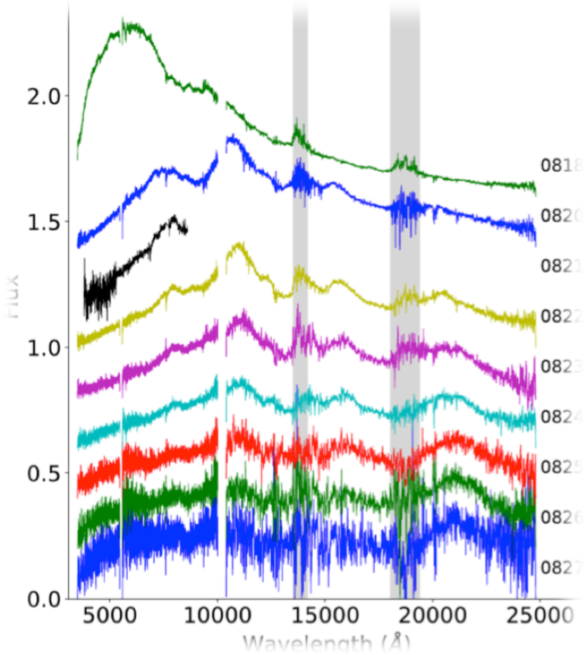
→ Neutron-neutron star mergers

Neutron-capture nucleosynthesis: neutron-star mergers



Martin et al. (2015)

From the spectrum of the so-called kilonova, they estimated a high production of heavy elements from r-process, including gold and platinum for a total mass 10 earth masses!

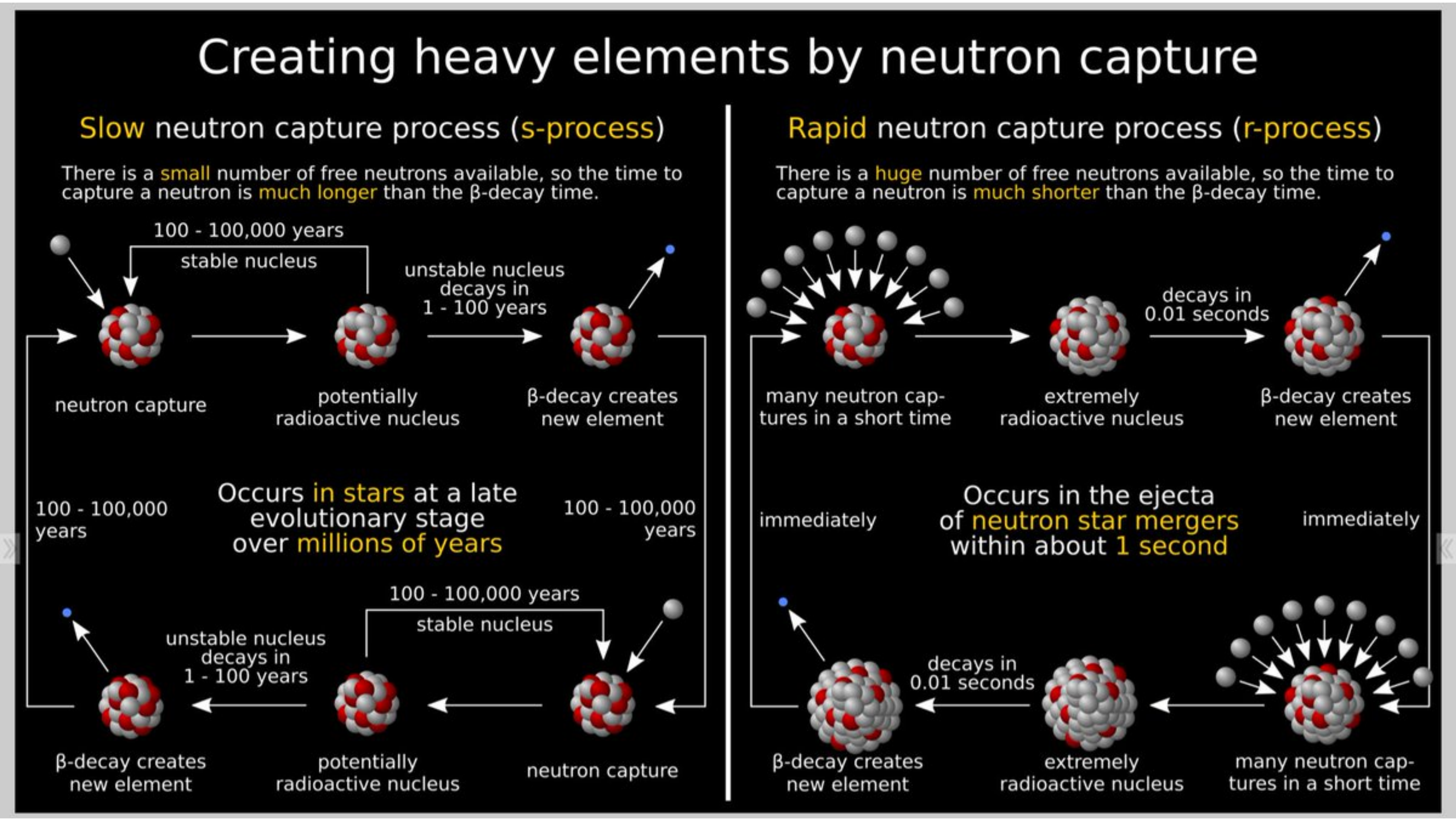


Predicted and observed:

On August 17 2017, world wide telescopes, including the ESO telescopes, followed the detection of gravitational waves produced by a neutron merger stars in the nearby galaxy.

They obtained the electromagnetic spectrum of the source.

Neutron-capture nucleosynthesis in a nutshell



Creating heavy elements by neutron capture

Slow neutron capture process (s-process)

There is a small number of free neutrons available, so the time to capture a neutron is much longer than the β-decay time.

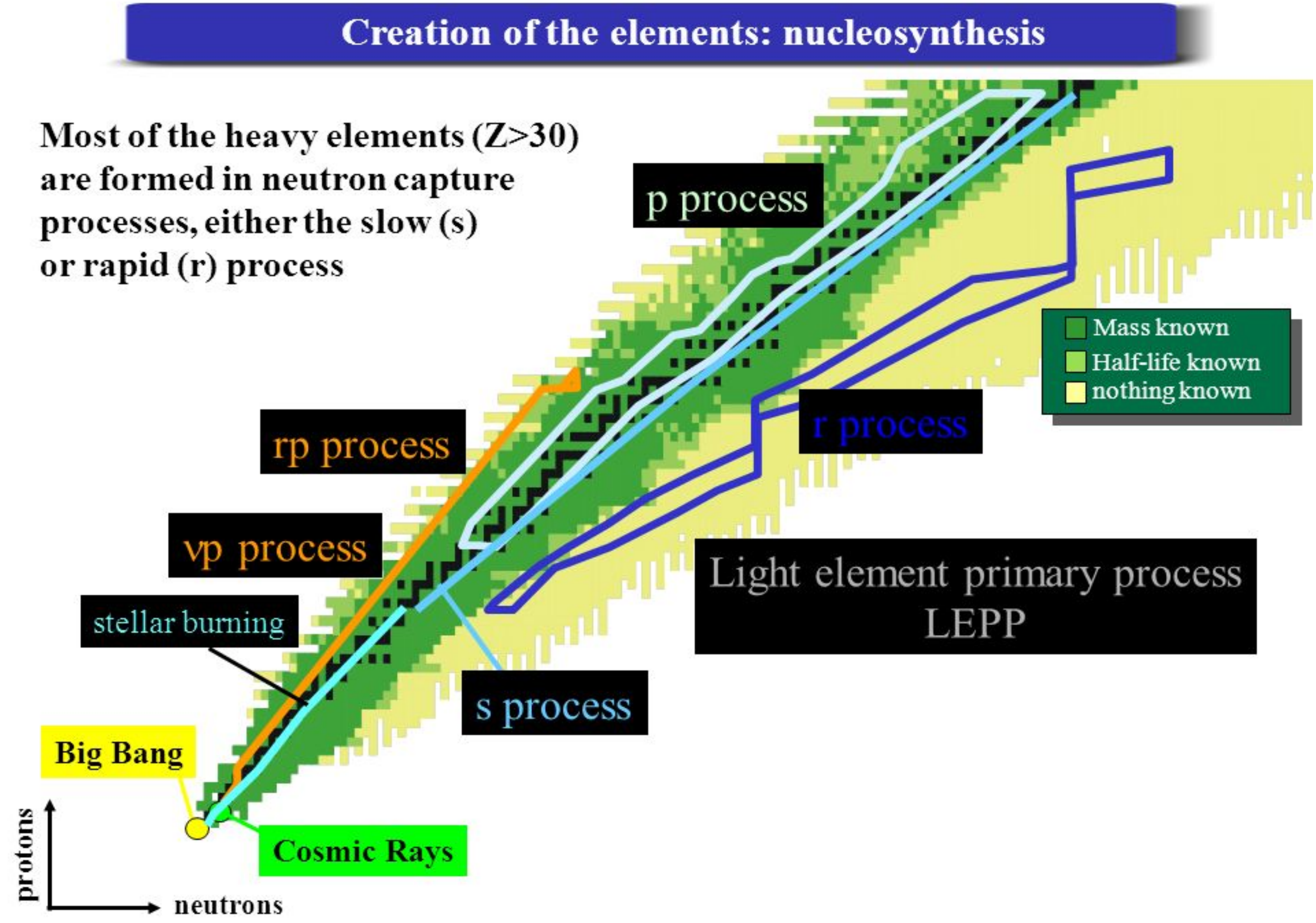
Occurs in stars at a late evolutionary stage over millions of years

Rapid neutron capture process (r-process)

There is a huge number of free neutrons available, so the time to capture a neutron is much shorter than the β-decay time.

Occurs in the ejecta of neutron star mergers within about 1 second

Neutron-capture nucleosynthesis in a nutshell



- S-process elements are formed closed to the stability valley since the accretion of neutron is much slower
- R-process elements can be created as very instable isotopes, which can decay in very short times towards the stability valley

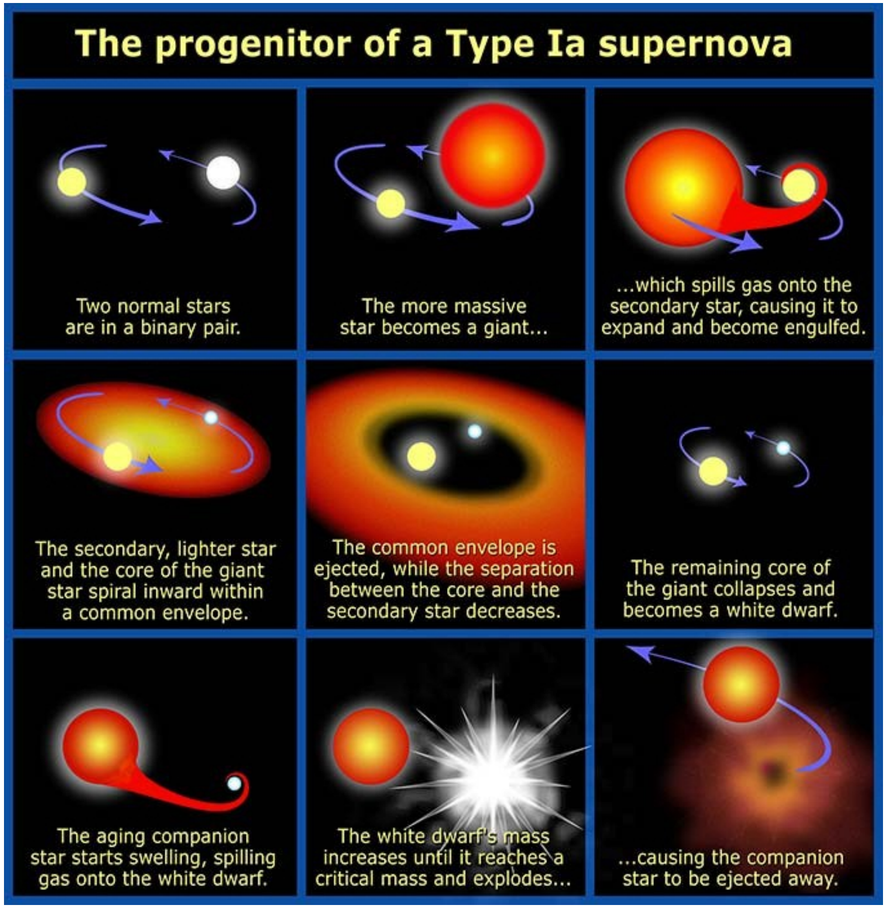
Thermonuclear supernovae (SN Ia)

If in a degenerate star nuclear energy continues to increase:

- T ↑
- P remains unchanged ($P \neq f(T)$)
- ϵ_{nuc} ↑ ↑
- T ↑ ↑
- thermonuclear runaway

Supernovae of Type I are distinguished by having no hydrogen lines in their spectra, resulting from explosive carbon-burning in a CO white dwarf.

SN Ia are believed to result from accretion of material from a companion on to a white dwarf until it reaches the Chandrasekhar limiting mass, at which point it collapses and explodes



The progenitor of a Type Ia supernova

Two normal stars are in a binary pair.

The more massive star becomes a giant...

...which spills gas onto the secondary star, causing it to expand and become engulfed.

The secondary, lighter star and the core of the giant star spiral inward within a common envelope.

The common envelope is ejected, while the separation between the core and the secondary star decreases.

The remaining core of the giant collapses and becomes a white dwarf.

The aging companion star starts swelling, spilling gas onto the white dwarf.

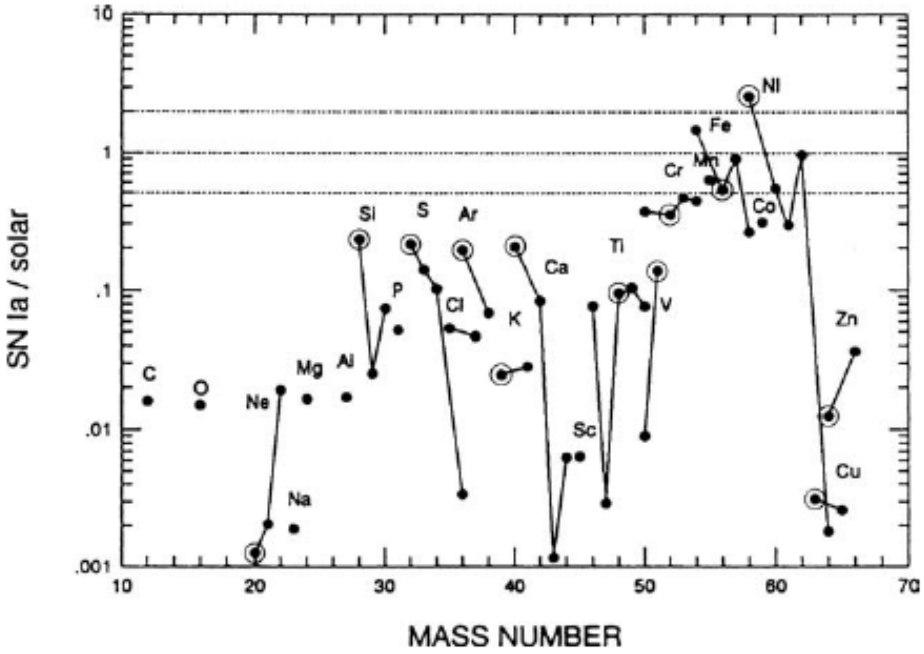
The white dwarf's mass increases until it reaches a critical mass and explodes...

...causing the companion star to be ejected away.

Thermonuclear supernovae (SN Ia)

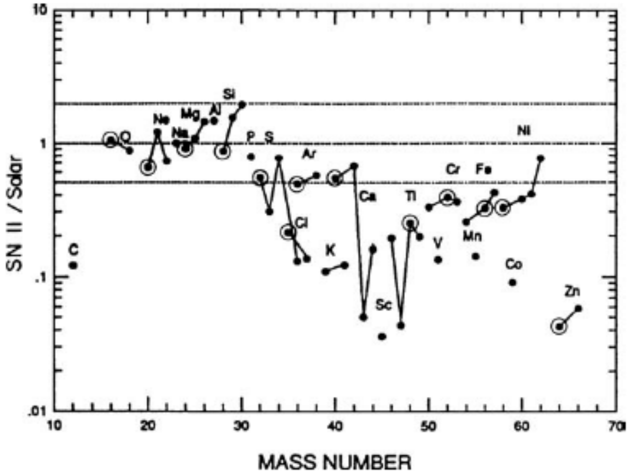
Yields from SNIa compared to Solar abundances:

- SNIa are able to produce the missing quantity of Fe, not produced by core-collapse SNe



Tsujimoto (1993)

SNII nucleosynthesis products



Cosmic rays spallation

Big Bang and stellar nucleosynthesis → abundances of almost all nuclei

With the exception: ^{6}Li, ^{9}Be, ^{10,11}B

Reason:

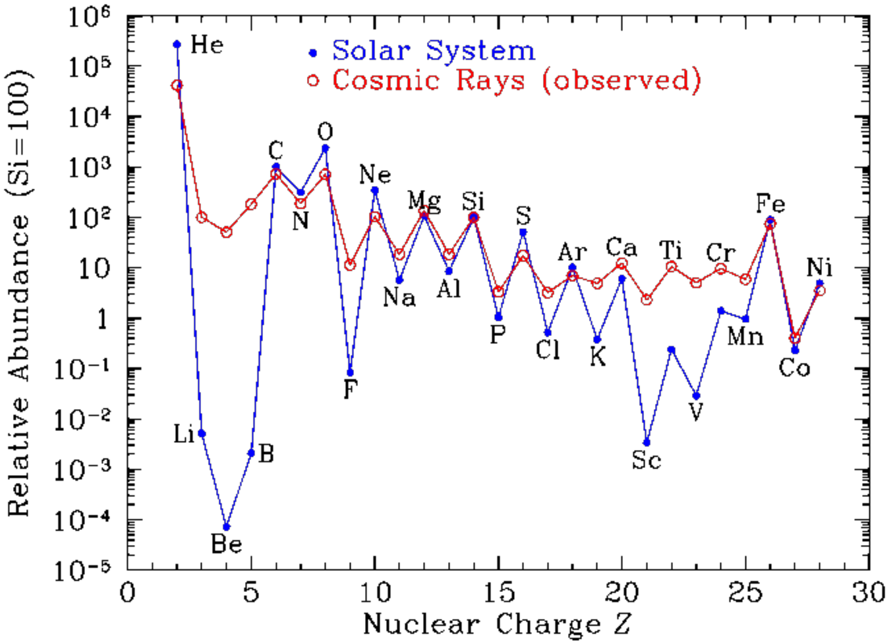
- stability gaps at mass number 5 and 8
- pp-chain produces mainly ^{4}He,
- He-burning bypasses Li Be B-region producing → ^{12}C
- even if Li, Be and B were produced, they would be completely destroyed in the stellar interior due to proton-capture reactions ($T > 10^{6}$ K)

Cosmic rays spallation

- Cosmic rays are highly energetic particles, accelerated in magnetic shock fronts of supernova remnants

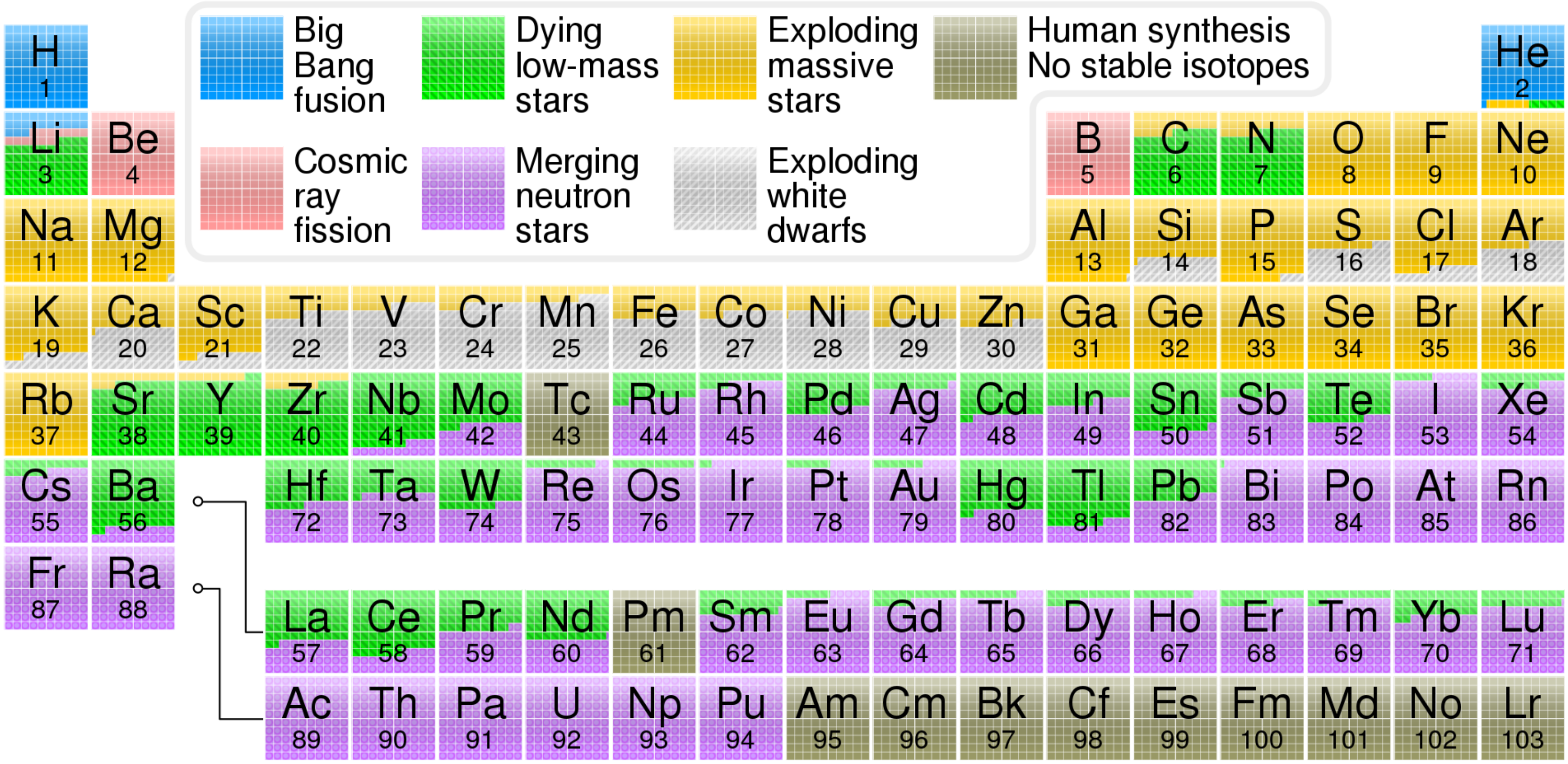
- Cosmic rays cause **spallation** when a cosmic ray particle (e.g. a proton) impacts with matter, including other cosmic rays. The result of the collision is the expulsion of large numbers of nucleons (protons and neutrons) from the object hit.

by far most important are CNO + proton - reactions



Abundance distribution: “similar” to solar system abundances but large overabundance of LiBeB

Summary of cosmic nucleosynthesis

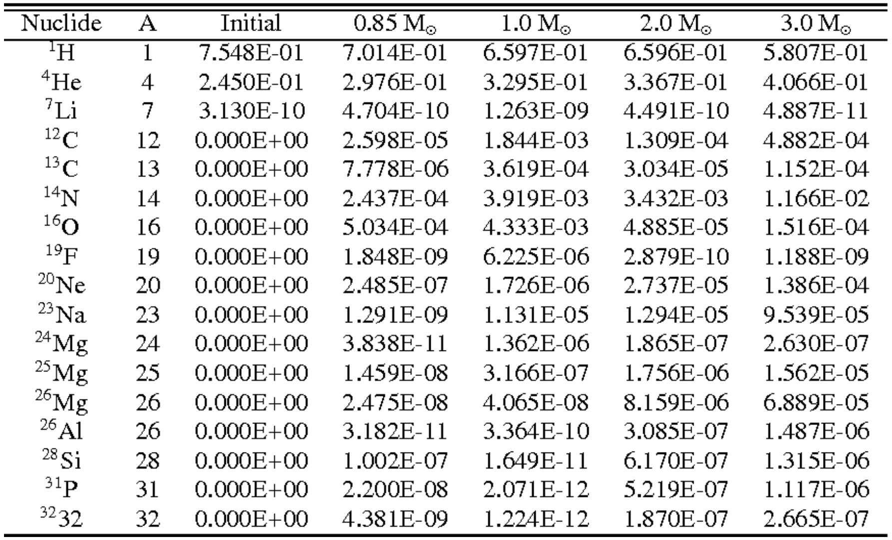


Our tools: stellar yields

The mass of the nuclides ejected by a stars in the interstellar medium, at the end or during its lifetime (i.e., with stellar winds or during the final explosion)

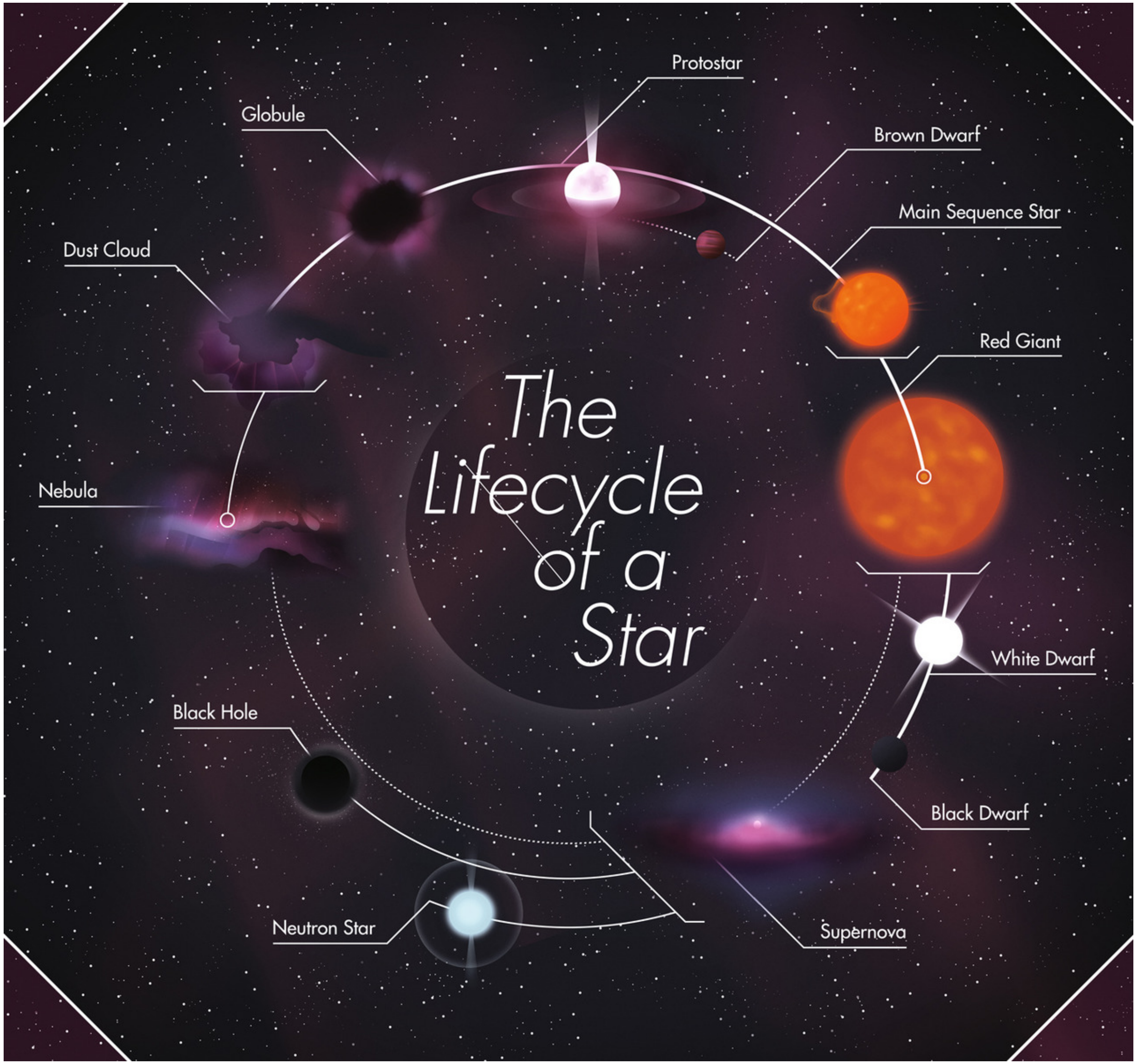
They are fuction of:

- Initial mass
- Initial metallicity
- Other aspects, as stellar rotation, winds, etc.



Nuclide	A	Initial	0.85 $M_\odot$	1.0 $M_\odot$	2.0 $M_\odot$	3.0 $M_\odot$
^{1}H	1	7.548E-01	7.014E-01	6.597E-01	6.596E-01	5.807E-01
^{4}He	4	2.450E-01	2.976E-01	3.295E-01	3.367E-01	4.066E-01
^{7}Li	7	3.130E-10	4.704E-10	1.263E-09	4.491E-10	4.887E-11
^{12}C	12	0.000E+00	2.598E-05	1.844E-03	1.309E-04	4.882E-04
^{13}C	13	0.000E+00	7.778E-06	3.619E-04	3.034E-05	1.152E-04
^{14}N	14	0.000E+00	2.437E-04	3.919E-03	3.432E-03	1.166E-02
^{16}O	16	0.000E+00	5.034E-04	4.333E-03	4.885E-05	1.516E-04
^{19}F	19	0.000E+00	1.848E-09	6.225E-06	2.879E-10	1.188E-09
^{20}Ne	20	0.000E+00	2.485E-07	1.726E-06	2.737E-05	1.386E-04
^{23}Na	23	0.000E+00	1.291E-09	1.131E-05	1.294E-05	9.539E-05
^{24}Mg	24	0.000E+00	3.838E-11	1.362E-06	1.865E-07	2.630E-07
^{25}Mg	25	0.000E+00	1.459E-08	3.166E-07	1.756E-06	1.562E-05
^{26}Mg	26	0.000E+00	2.475E-08	4.065E-08	8.159E-06	6.889E-05
^{26}Al	26	0.000E+00	3.182E-11	3.364E-10	3.085E-07	1.487E-06
^{28}Si	28	0.000E+00	1.002E-07	1.649E-11	6.170E-07	1.315E-06
^{31}P	31	0.000E+00	2.200E-08	2.071E-12	5.219E-07	1.117E-06
^{32}32	32	0.000E+00	4.381E-09	1.224E-12	1.870E-07	2.665E-07

What is left: the stellar remnants



Matter which remains locked in stellar remnants:

→ Not involved in ISM recycling

→ Do not enter in chemical evolution cycle

The global cycle

- → Studying this cycle in our Galaxy
- → Observed abundances + star/gas content
- → Chemical evolution models

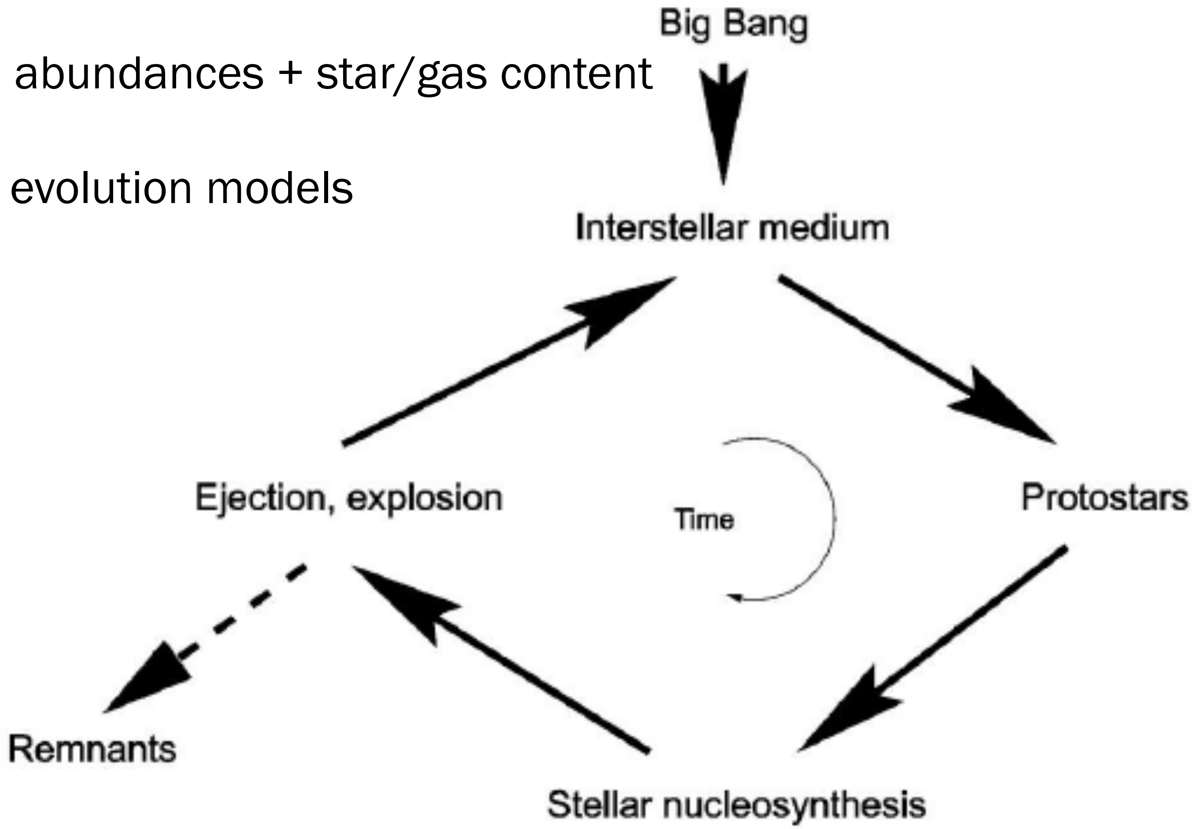


FIGURE 14. Schematic view of the cycle of matter in a galaxy.