

Kako so v vesolju nastali različni kemijski elementi?

Andreja Gomboc

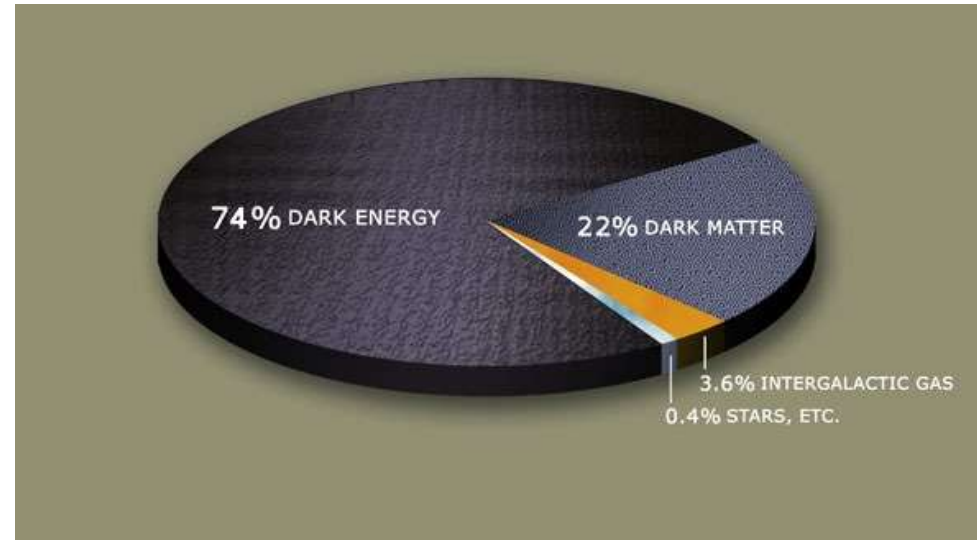
Fakulteta za matematiko in fiziko

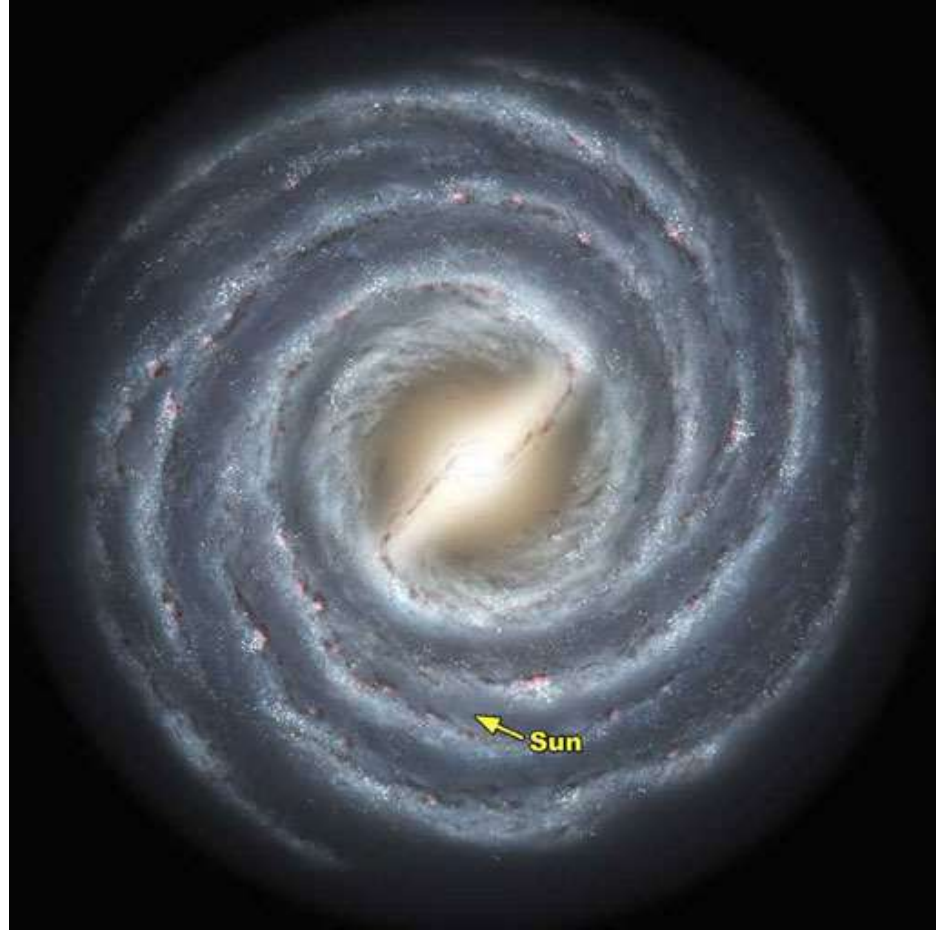
Univerza v Ljubljani

- Veliki pok
- prvinska nukleosinteza
- življenje zvezd
- nastanek elementov do železa
- nastanek elementov težjih od železa

Sestava vesolja

- Temna energija 74%
- Temna snov 22%
- **Barionska snov 4%:**
 - 73 % H
 - 25 % He
 - 2 % težjih elementov





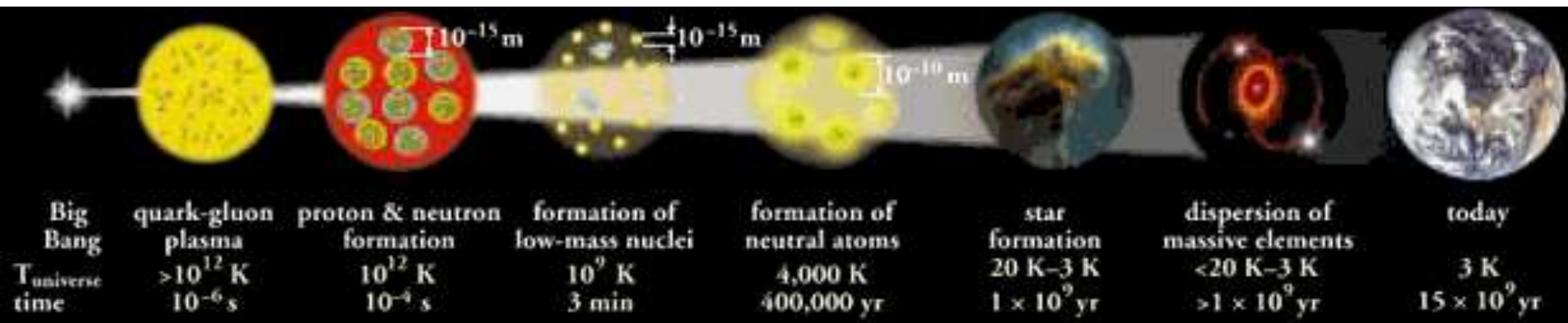
He

- zvezde v Galaksiji:

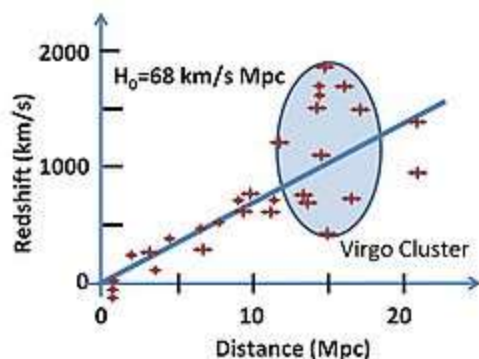
$$L_{\text{Galaksije}} = 2 \times 10^{10} L_{\text{S}}, M_{\text{Galaksije}} = 10^{11} M_{\text{S}}$$

- 10 Glet, $L_{\text{S}} = 3.8 \times 10^{26} \text{ J/s} \Rightarrow 2.4 \times 10^{54} \text{ J}$
- pri fuziji $\text{H} \rightarrow \text{He}$: $\Delta m = 0.7\% m$
- ves H: $1.3 \times 10^{56} \text{ J}$
- $2.4 \times 10^{54} \text{ J} / 1.3 \times 10^{56} \text{ J} = 2\% \ll 25\%$ helija !

Zvezde ne proizvedejo opažene količine helija!



vesolje se širi



$$\Delta\lambda/\lambda \propto d$$

Hubbllov zakon (1929):

$$v = H d$$

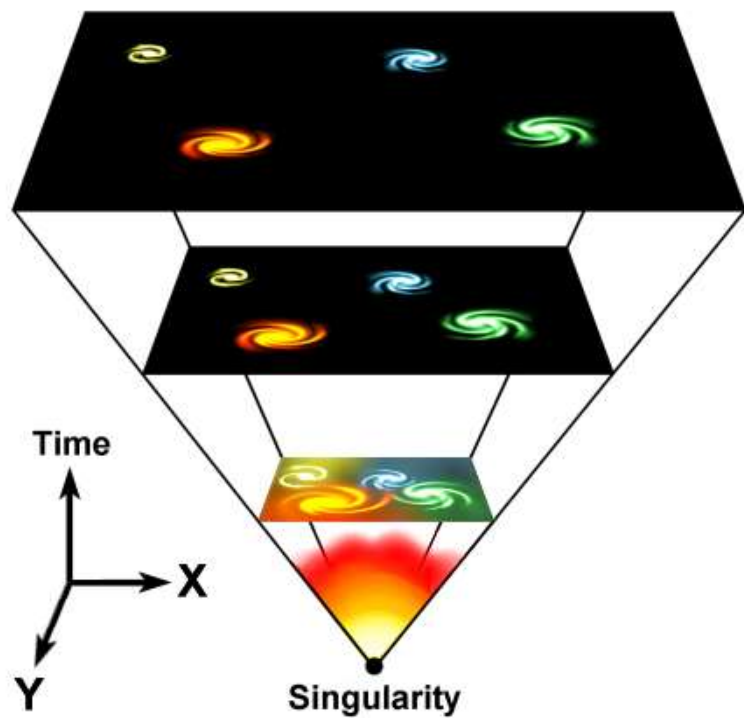


Edwin Powell Hubble (1889 -1953)

Prva opazovalna podpora teorije Velikega poka

Veliki pok

- 1927



Georges Lemaître (1894 – 1966)

- Einsteinova splošna relativnost
- Homogeno in izotropno vesolje
- (kozмолоški princip)
- Friedmannove enačbe
- opis vesolja od Velikega poka naprej

- Fred Hoyle – 1949

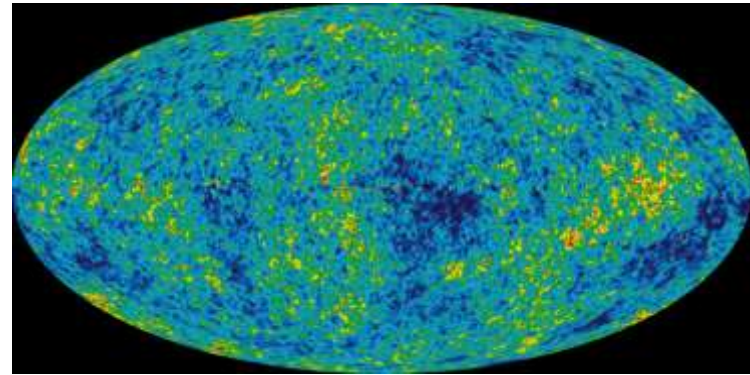


A. Friedman
Alexander Friedman
(1888 – 1925)

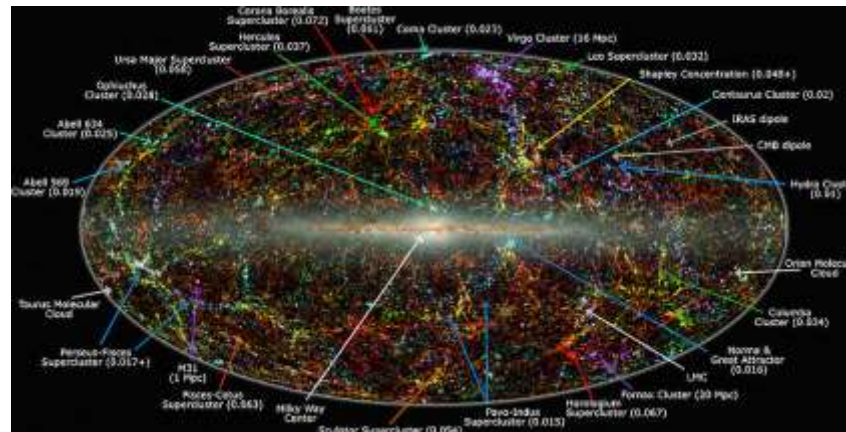


Sir Fred Hoyle
(1915 - 2001)

- 1964 – Arno Penzias and Robert Wilson - odkritje prasevanja – CMG – mikrovalovno sevanje ozadja s $T=2.726\text{ K}$



- Porazdelitev in razvoj galaksij



Prvinska nukleosinteza

- Alpher-Bethe-Gamow
- napove količino ^4He , ^3He , ^2H in ^7Li glede na ^1H
- odvisnost od $\eta = n_{\text{B}}/n_{\gamma} \leftarrow$ prasevanja

\Rightarrow masni %

- 75% H
- 25% ^4He , (\sim)
- $\sim 10^{-4}$ ^2H , (OK)
- $\sim 10^{-4}$ ^3He
- $\sim 10^{-10}$ ^7Li , ^7Be (2x)

1.nastanek do inflacije –

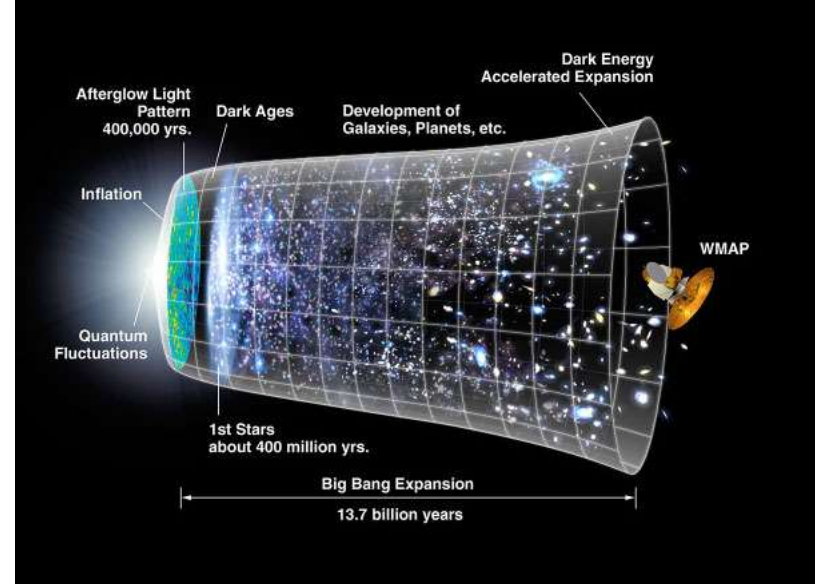
Planckova era:

$0-10^{-43}$ s, $T \sim 10^{34}$ K - odcepitev gravitacije

GUT

10^{-38} s – odcepitev močne interakcije →
sprostitvev ogromne energije →

Inflacija: se poveča za faktor 10^{35}



2. elektrošibka doba:

10^{-38} do 10^{-10} s

Fazni prehod, juha osnovnih delcev: fotoni,
gluoni, kvarki

Razklopitev šibke in EM interakcije

3. Doba delcev:

10^{-10} do 1 s

kvarki in antikvarki se anihilirajo

kršitev simetrije \rightarrow presežek kvarkov \rightarrow snov

Hadronska doba: med 10^{-6} do 10^{-5} s, $T \sim 10^{15}$ K:

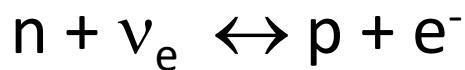
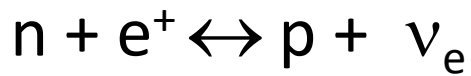
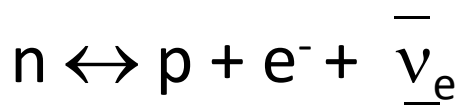
kvarki \rightarrow hadroni

nestabilni razpadejo, ostanejo p in n

Leptonska doba:

Večina leptoni in antileptoni \rightarrow anihilacija \rightarrow presežek leptonov

4. od 1 do 100 s



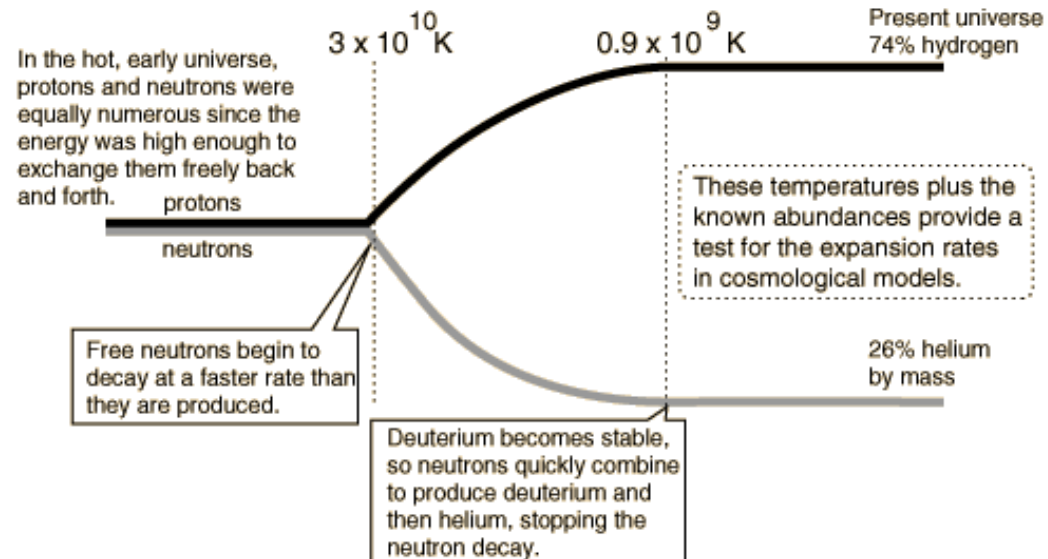
pri $T \sim 10$ GK

se ustavlja: $n_n/n_p = 0.223$

nevtroni:

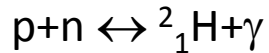
β razpad z $\tau = 617$ s

$$n_n/n_p = e^{-(m_n - m_p)/kT}$$



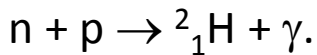
5. 3 - 20 min

ko T pade na ~ 1 GK nastaja devterij:

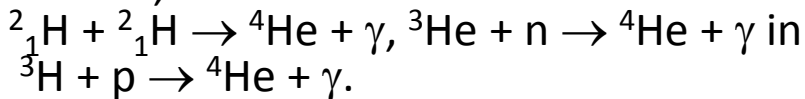


Ostane:

$$n_p:n_n=7:1 \rightarrow n_{\text{He}}:n_{\text{H}}=1:12 \text{ oz. } m_{\text{He}}:m=0.25$$



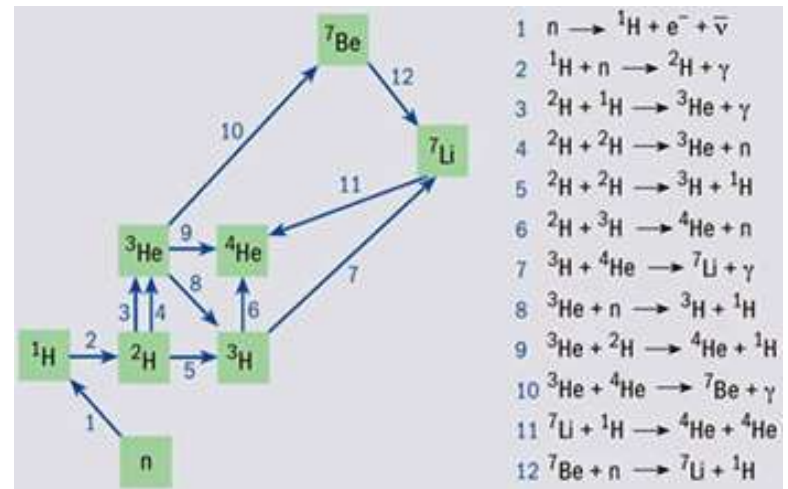
Končno, ${}^4\text{He}$ nastane:



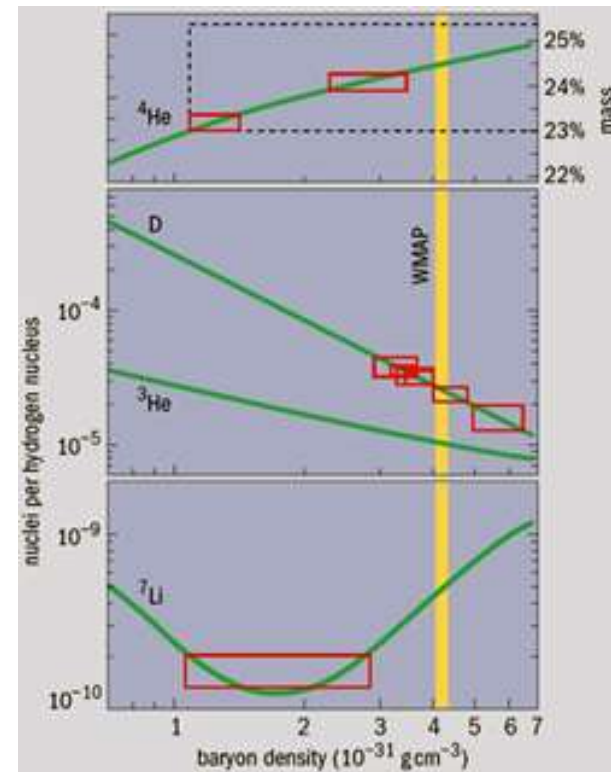
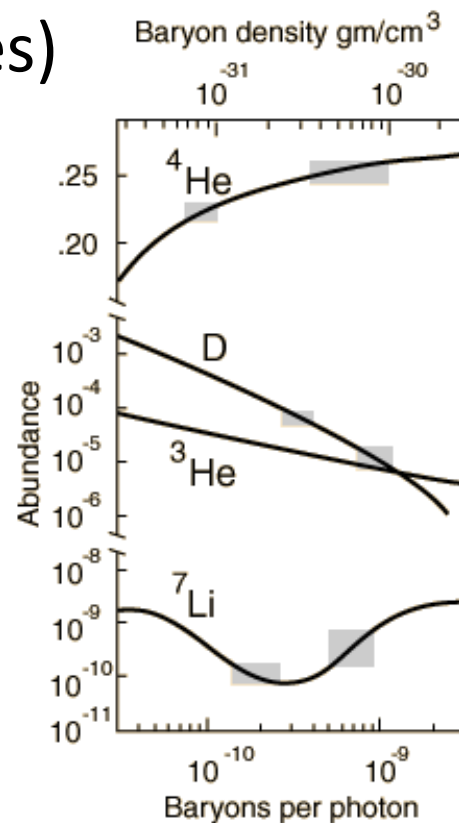
Nastajajo atomska jedra:

večina n gre v He,

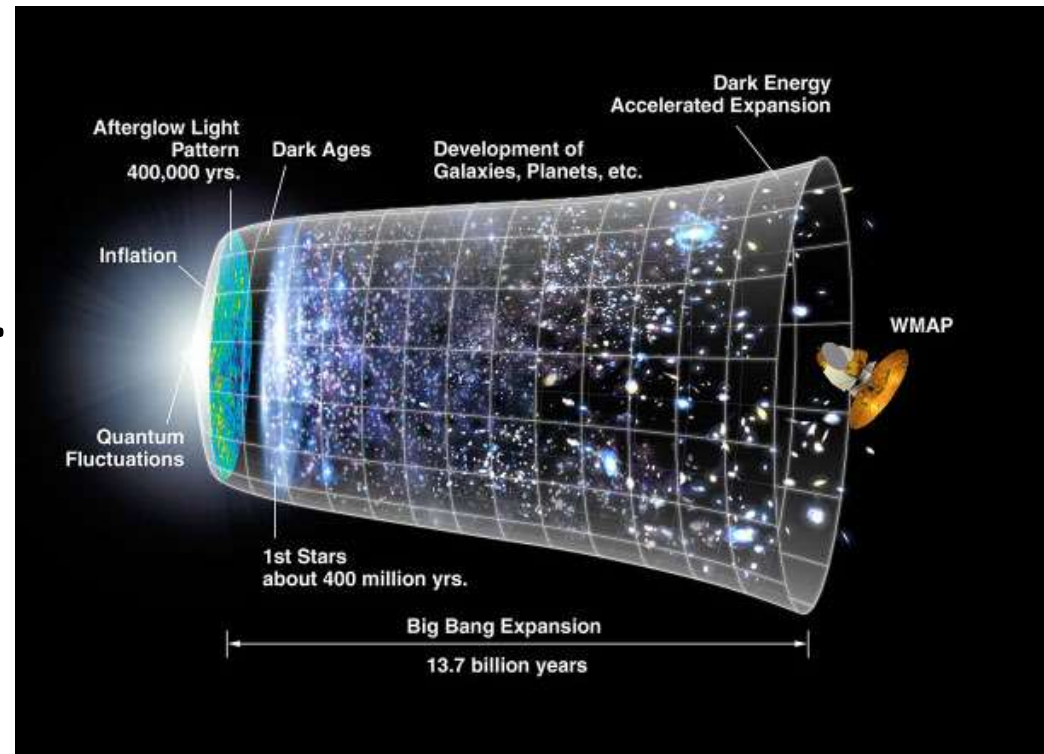
malo v litij, berilij, devterij

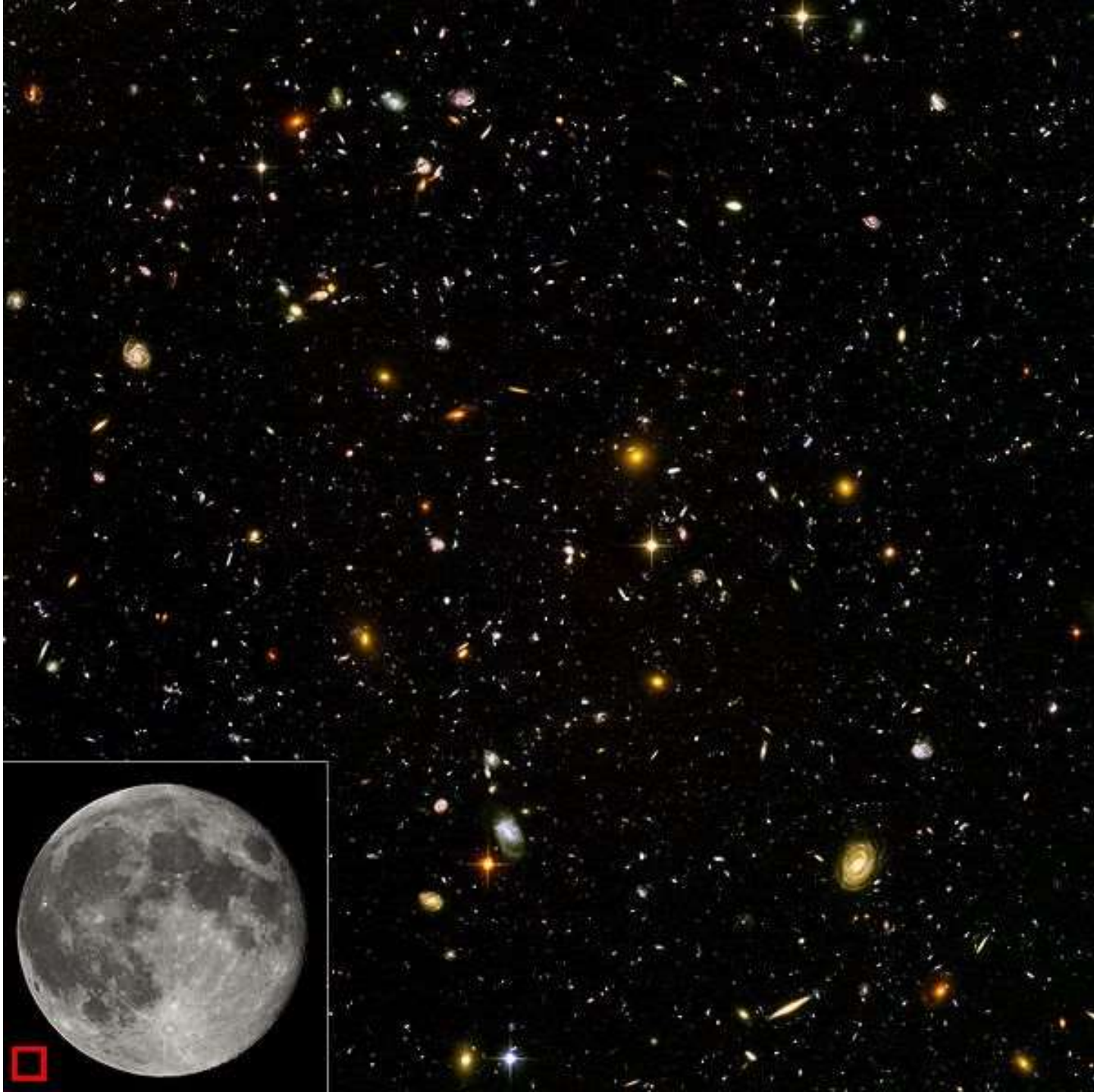


- ni elementov $> \text{Be}$
- ker ni stabilnih jeder z $A=5$ ali 8
(glej trojni alfa proces)
- vesolje se širi



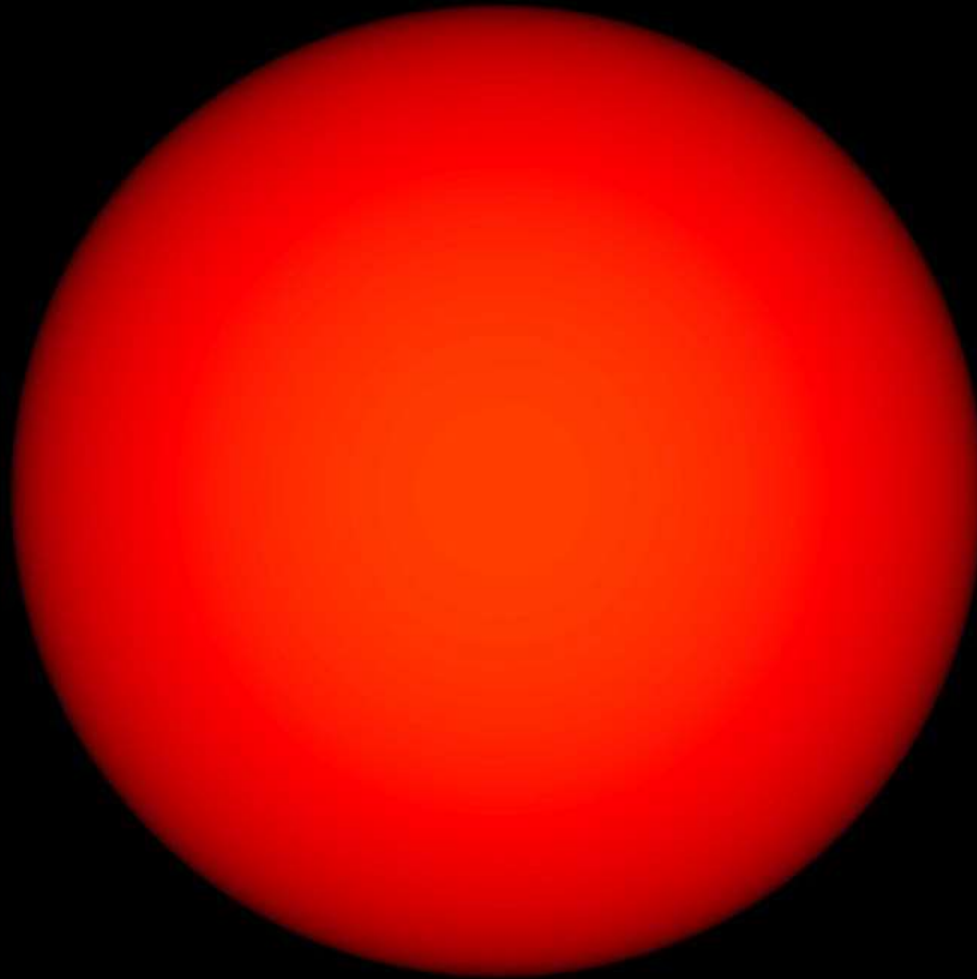
- **10.000 let:**
konec “radiation era”, začne “matter era”
- **300.000 let:**
 $T \sim 3000 \text{ K}$ – nastajajo atomi, razklopitev snovi in sevanja – vesolje postane prozorno → CMB
- **>400 Mlet:**
nastajanje zvezd, galaksij, planetov...





Življenje zvezd

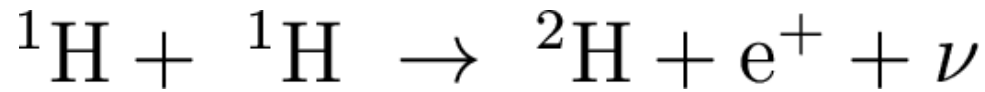
- Nastanek iz medzvezdnega plina z $m > M_{\text{Jeans}}$
- [Numerična simulacija](http://www.ukaff.ac.uk/starcluster/)
(<http://www.ukaff.ac.uk/starcluster/>)



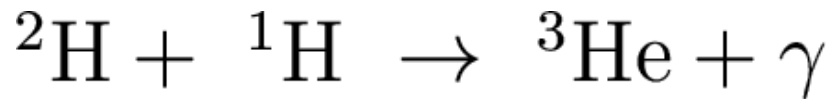
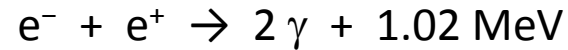
Sonce

- $L_S = 3.8 \times 10^{26} \text{ J/s}$
- $v \sim 5 \text{ Glet oddalo } 6 \times 10^{43} \text{ J}$
- $3 \times 10^{13} \text{ J/kg}$

- $4 \text{ H} \rightarrow {}^4\text{He}$ in $\Delta E = 26.7 \text{ MeV} \leftrightarrow \Delta m = 4.6 \times 10^{-29} \text{ kg}$
 $= 0.007 \text{ m}$
- $= 10^{38} \text{ reakcij/s}$
- oz. $6.3 \times 10^{14} \text{ J/kg}$

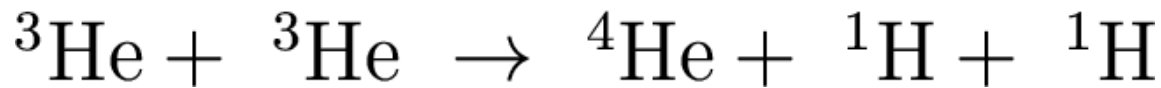


+ 0.42 MeV



+ 5.49 MeV

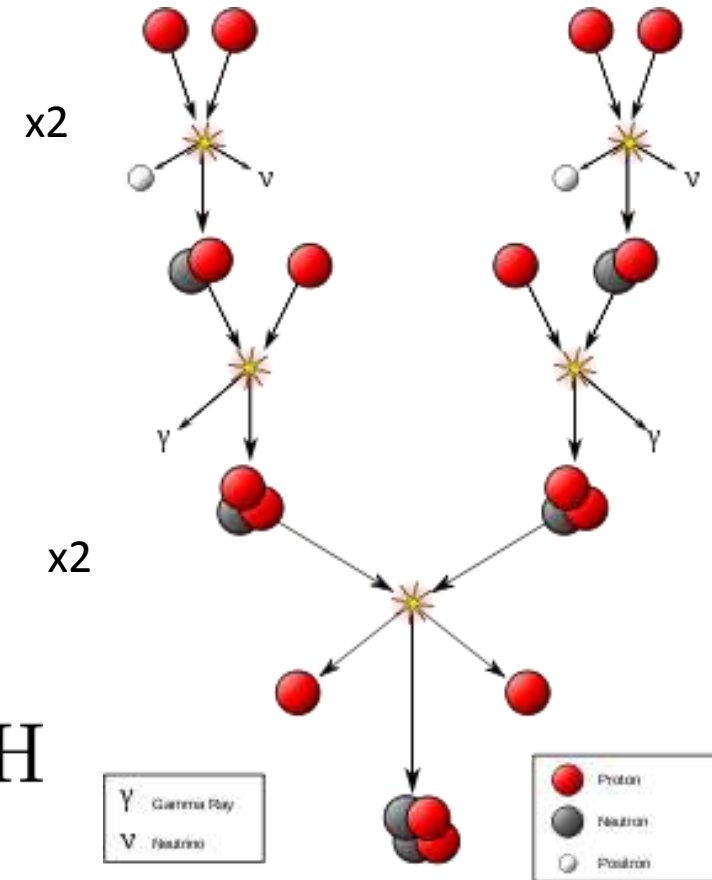
pp I veriga



+ 12.86 MeV

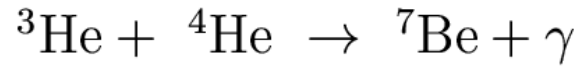
Skupno: 26.7 MeV.

veriga, $T \sim 10 - 14 \text{ MK}$.

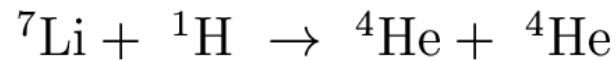


86% v Soncu

- **pp II**

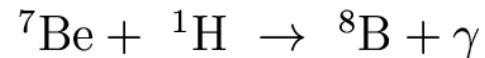


T~14 to 23 MK.



pp II 14% in pp III z 0.11%

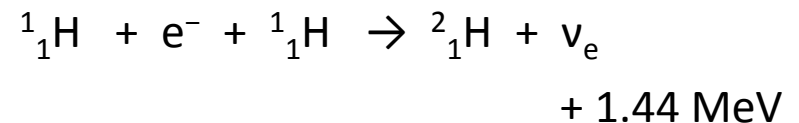
- **pp III**



T > 23 MK.



- **pp IV ali Hep**

pep

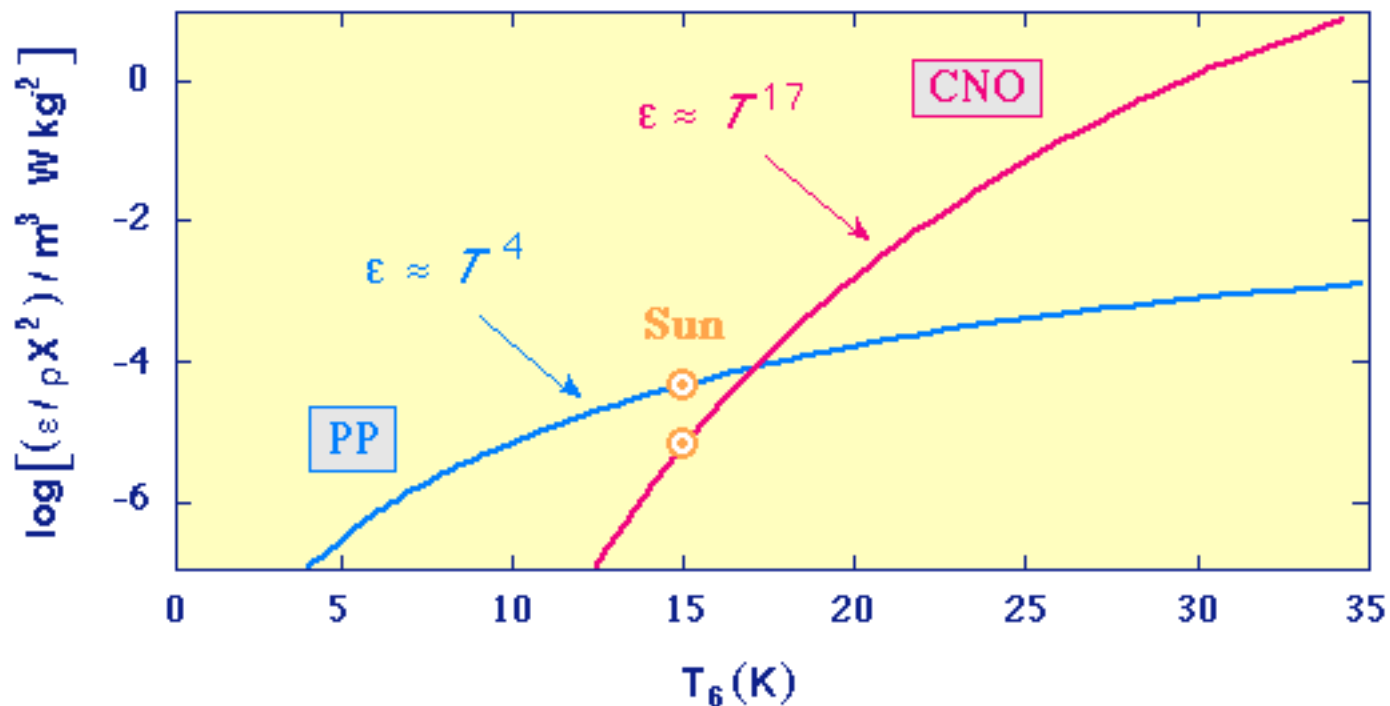
Odvisnost od temperature

- pp veriga: začne pri $T \sim 4$ MK

$$\varepsilon \propto T^4 \quad (\varepsilon = E/m)$$

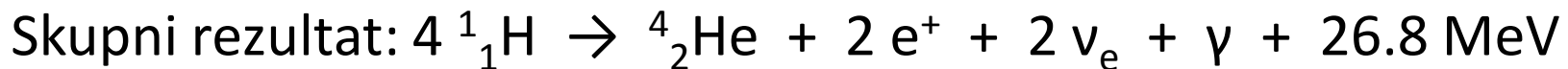
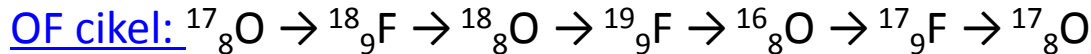
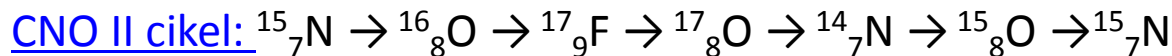
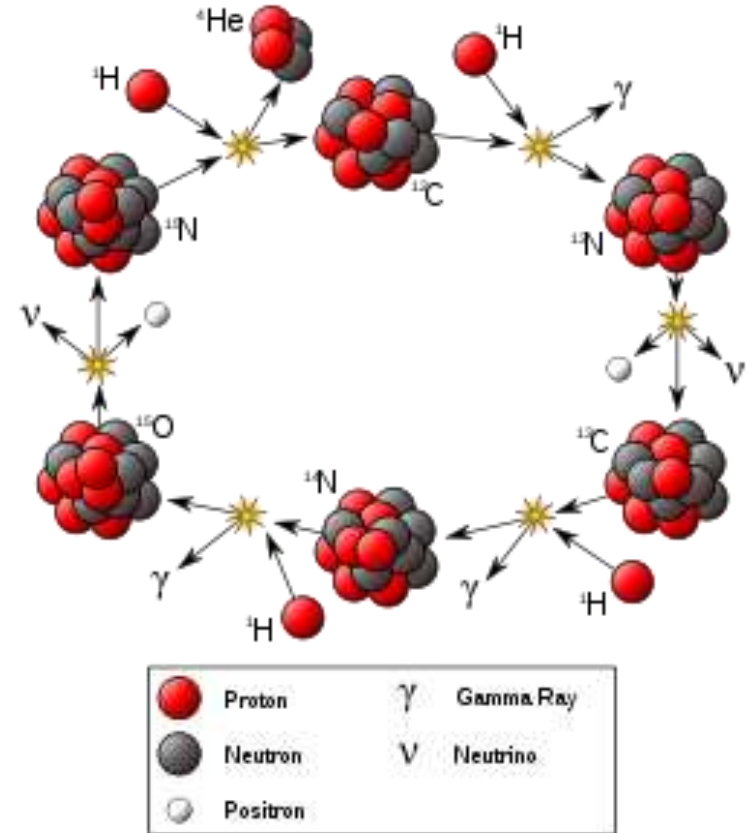
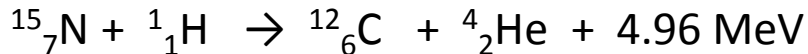
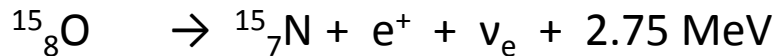
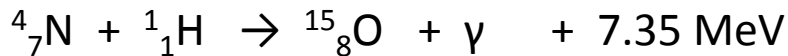
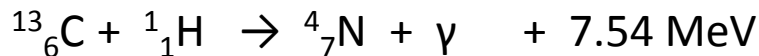
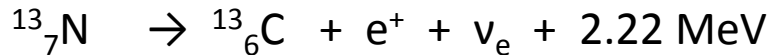
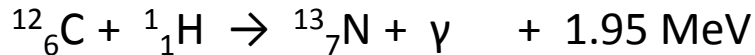
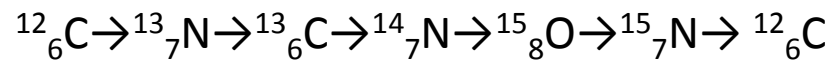
- CNO cikel: začne pri $T \sim 13$ MK

$$\varepsilon \propto T^{20} \quad - \text{v masivnih zvezdah } (M > 1.3M_{\odot})!$$



CNO cikel

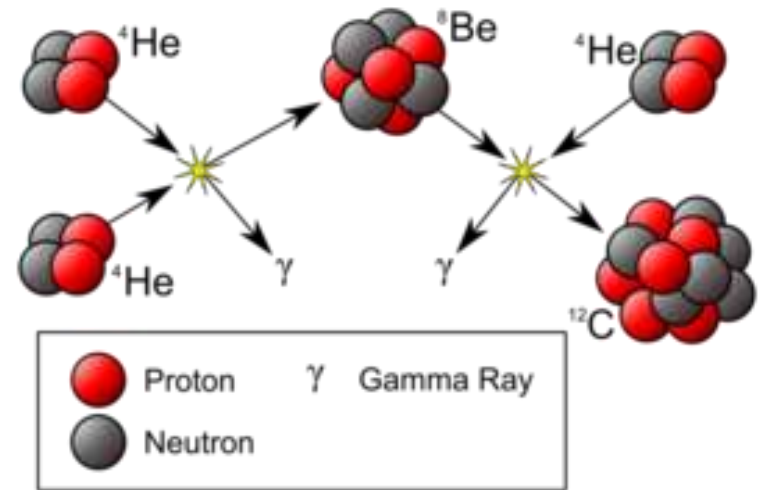
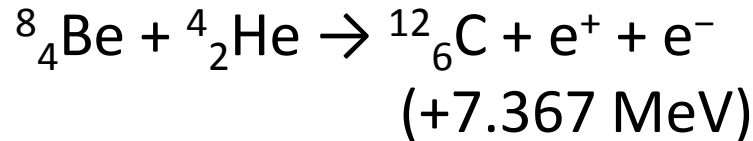
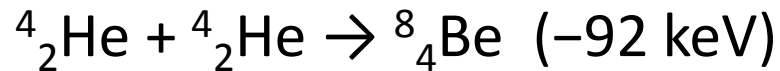
Glavne reakcije so:



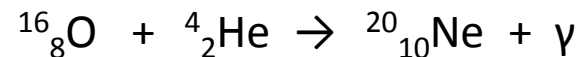
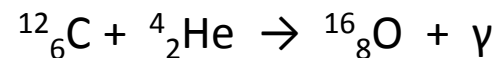
višji cikli gorenja - 3 alfa proces

- vžig (blišč) helija pri $T \sim 100$ MK

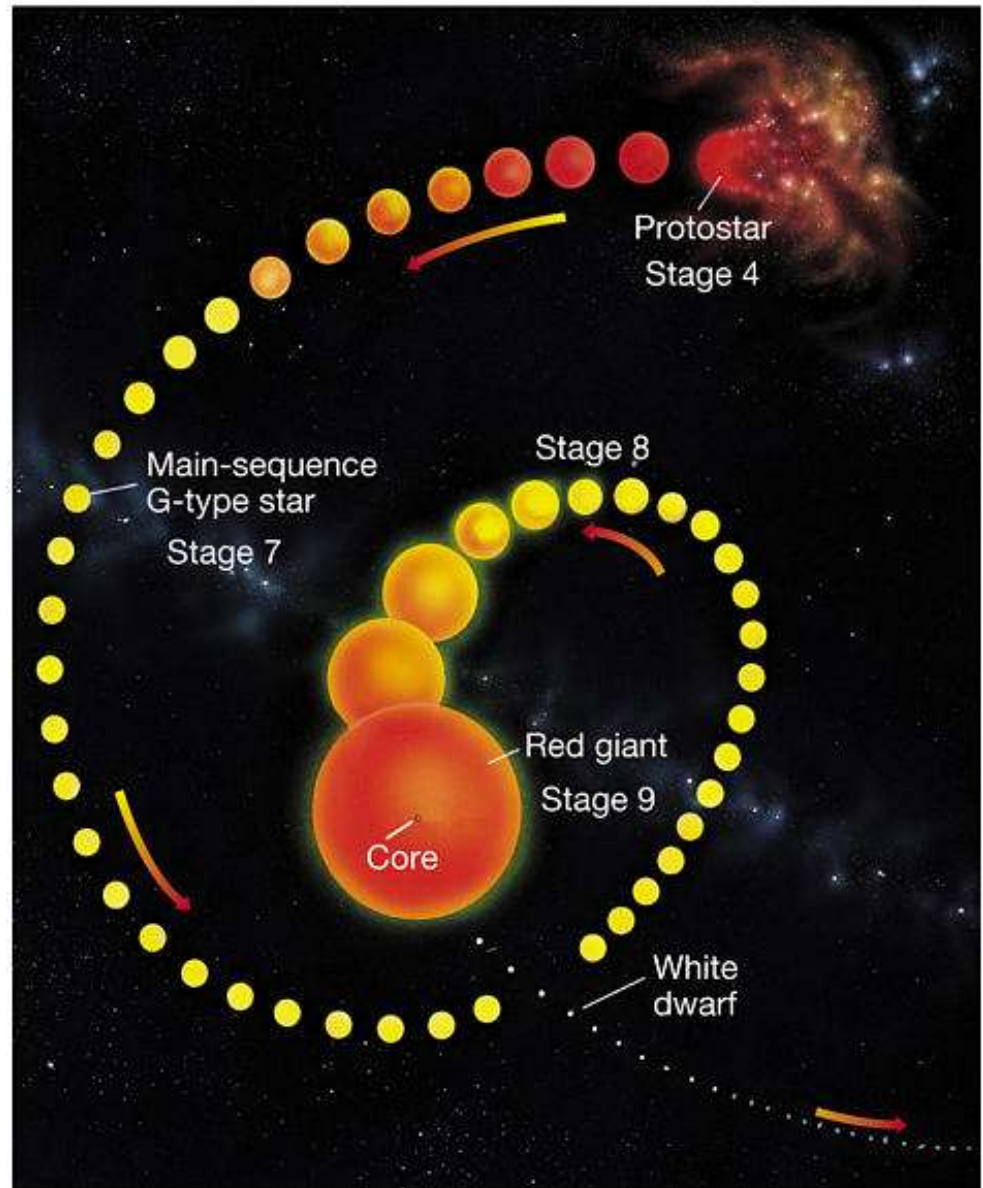
Be razpada!



Alfa procesi:

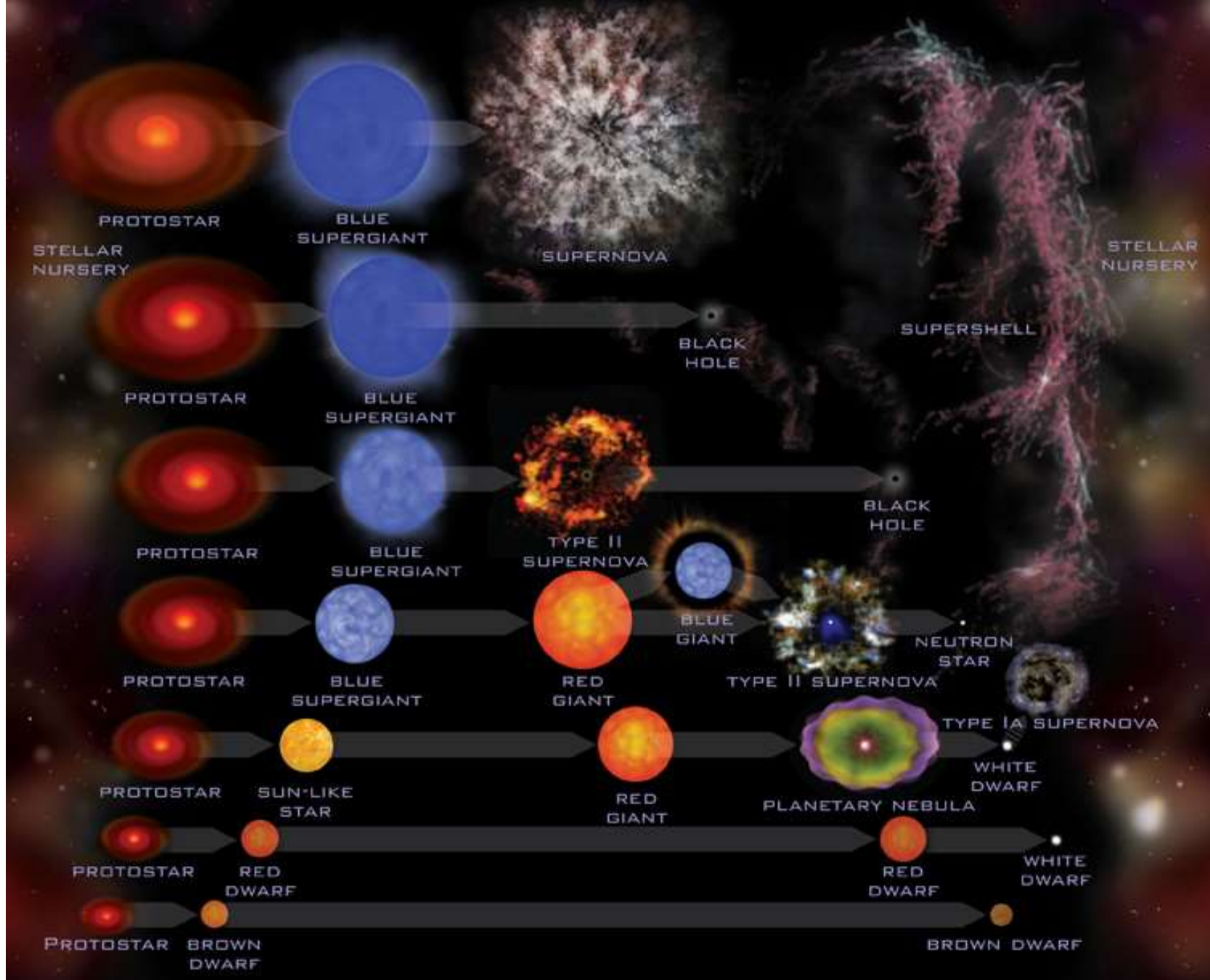


Sonce



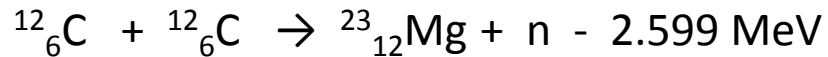
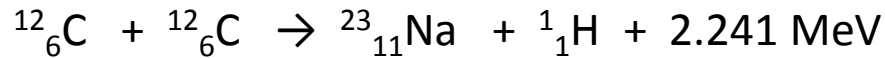


Planetarna meglica
C,O

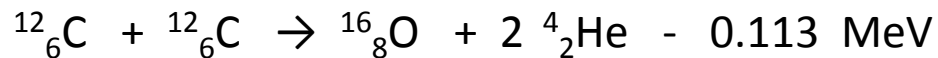
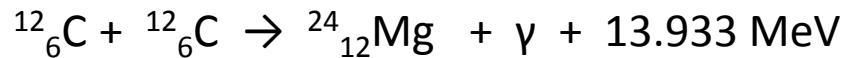


Gorenje C

- $M > 5M_{\odot}$
- $T \sim 6 \times 10^8 \text{ K}$, $\rho \sim 2 \times 10^8 \text{ kg/m}^3$

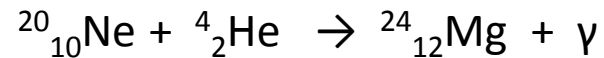
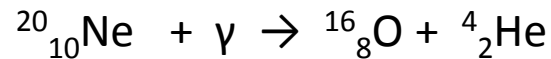


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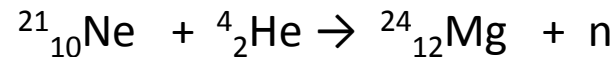
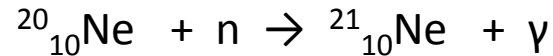


Gorenje Ne

- $M > 8M_{\odot}$
- $T \sim 1.2 \text{ GK}$, $\rho \sim 4 \times 10^9 \text{ kg/m}^3$
- fotodisentigracija



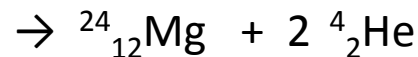
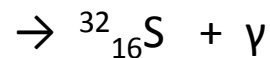
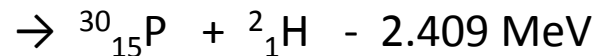
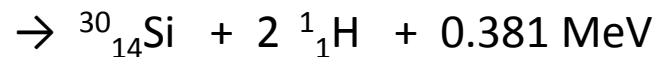
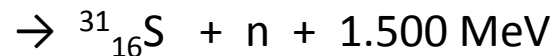
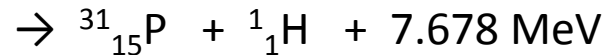
ali



Gorenje O

- Masivne zvezde, ki porabijo ostalo gorivo
- $T \sim 1.5 \text{ GK}$, $\rho \sim 10^{10} \text{ kg/m}^3$

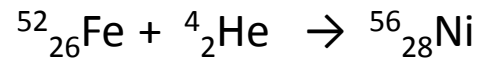
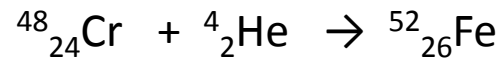
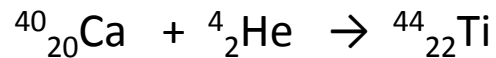
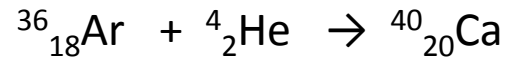
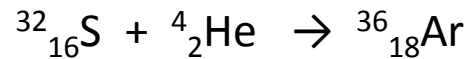
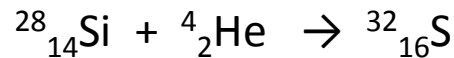
0.5-1 leto



Gorenje Si

- $M > 8-11 M_{\odot}$
- $T \sim 2.7-3.5 \text{ GK}$
- Alfa procesi

~1 dan -2 tedna

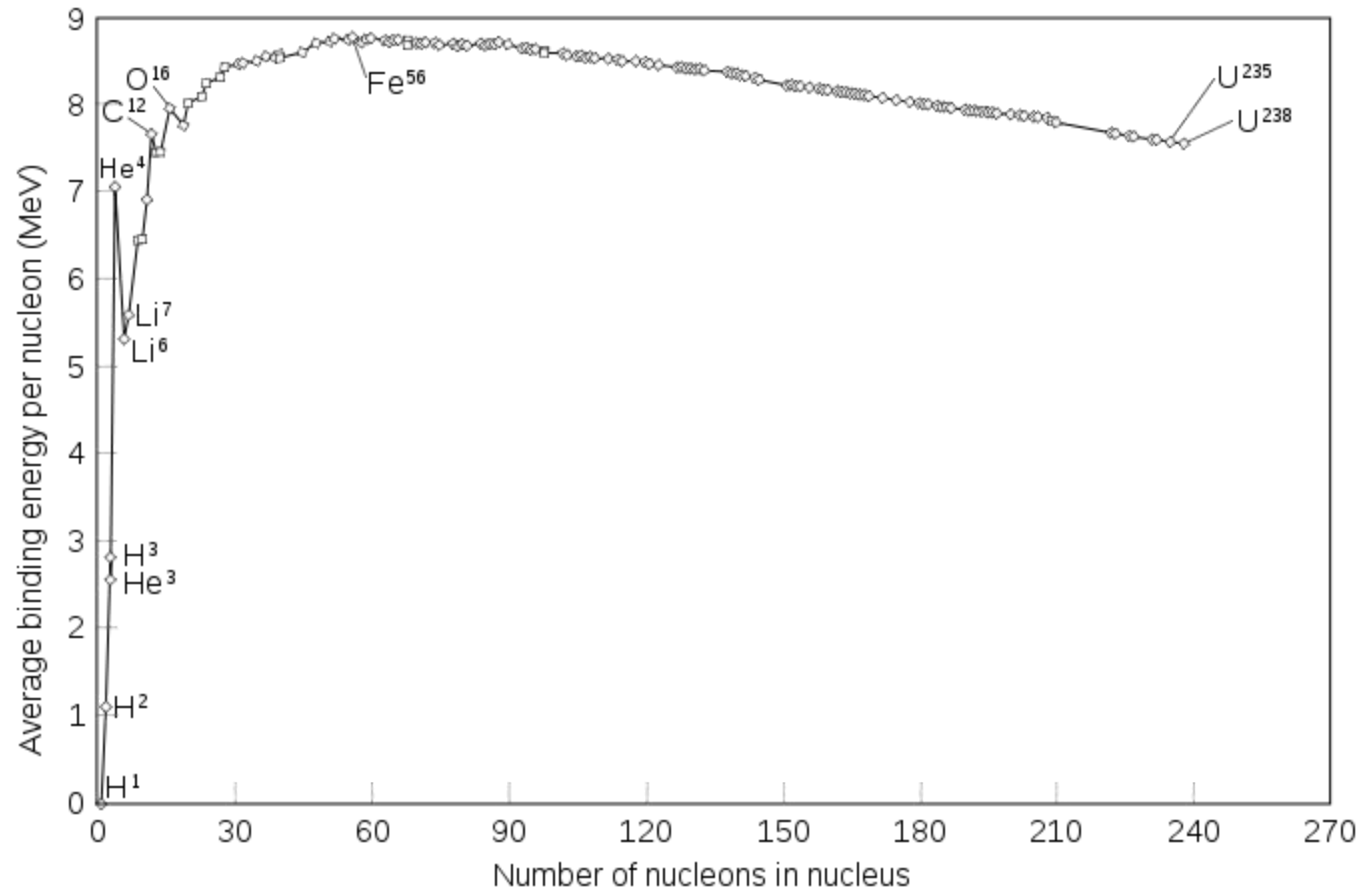


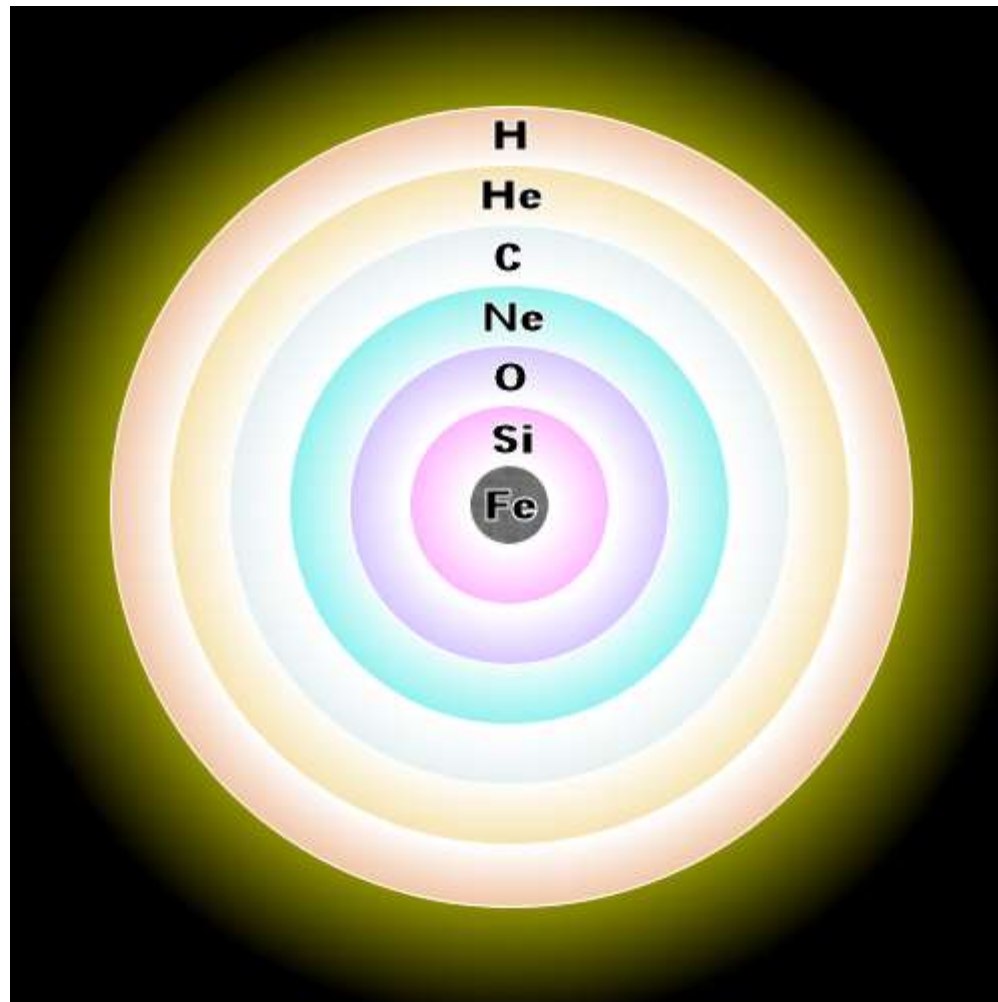
${}^{56}\text{Ni}$: β razpad z $\tau=6.02$ dni \rightarrow ${}^{56}\text{Co}$ z $\tau=77.3$ dni \rightarrow ${}^{56}\text{Fe}$

25 Ms

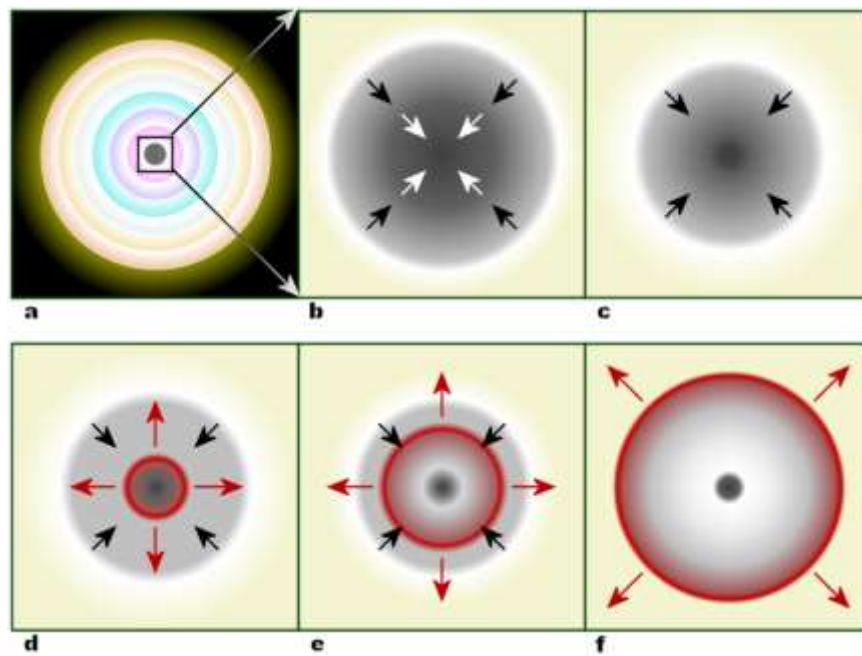
| Burning Stage | Temperature (keV) | Density (kg/m³) | Time-scale |
|----------------------|------------------------------|---------------------------------------|--------------------|
| Hydrogen | 5 | 5×10^6 | 7×10^6 yr |
| Helium | 20 | 7×10^8 | 5×10^5 yr |
| Carbon | 80 | 2×10^{11} | 600 yr |
| Neon | 150 | 4×10^{12} | 1 yr |
| Oxygen | 200 | 10^{13} | 6 months |
| Silicon | 350 | 3×10^{13} | 1 day |
| Collapse | 600 | 3×10^{15} | seconds |
| Bounce | 3000 | 10^{17} | milliseconds |
| Explosive | 100-600 | varies | 0.1-10 seconds |

Konec gorenja

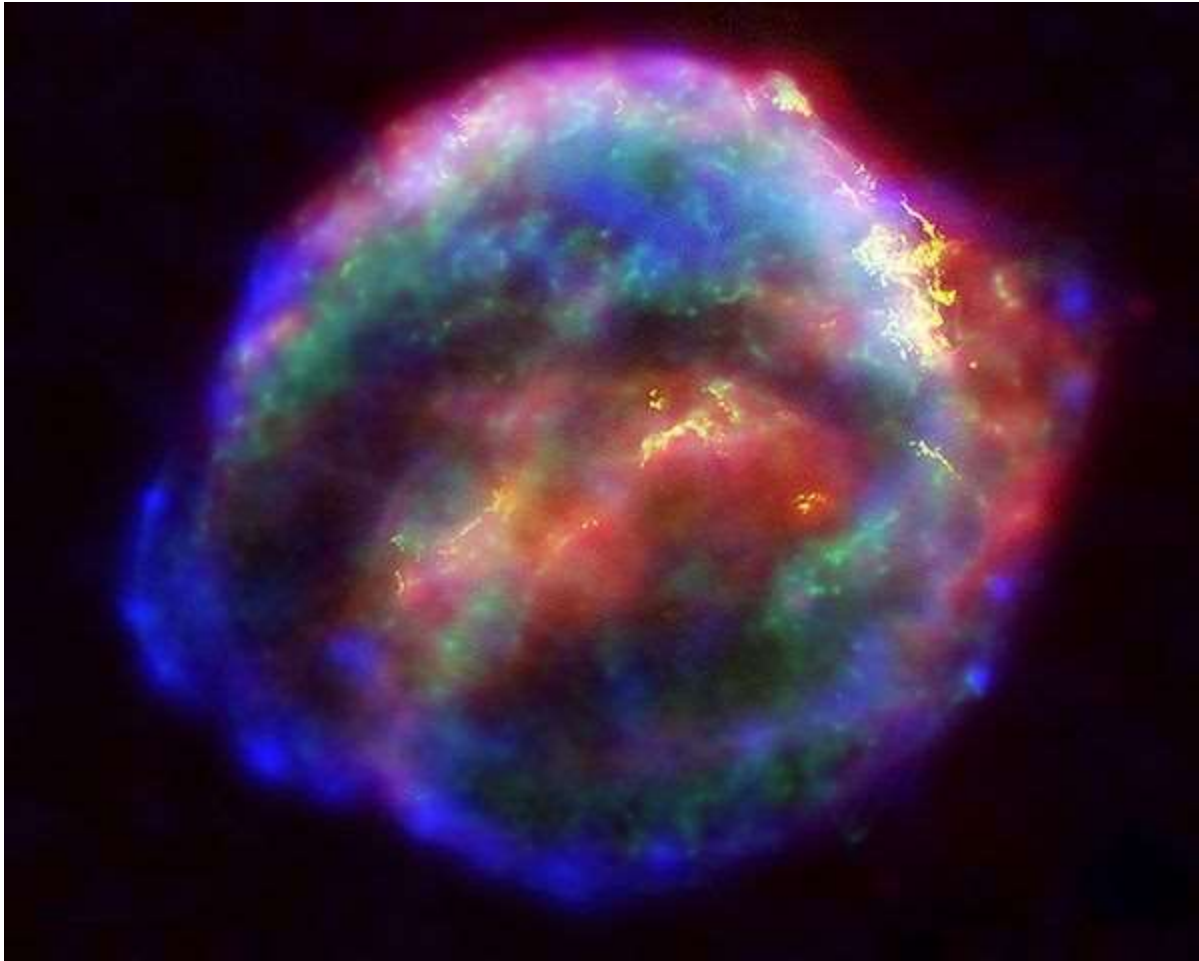


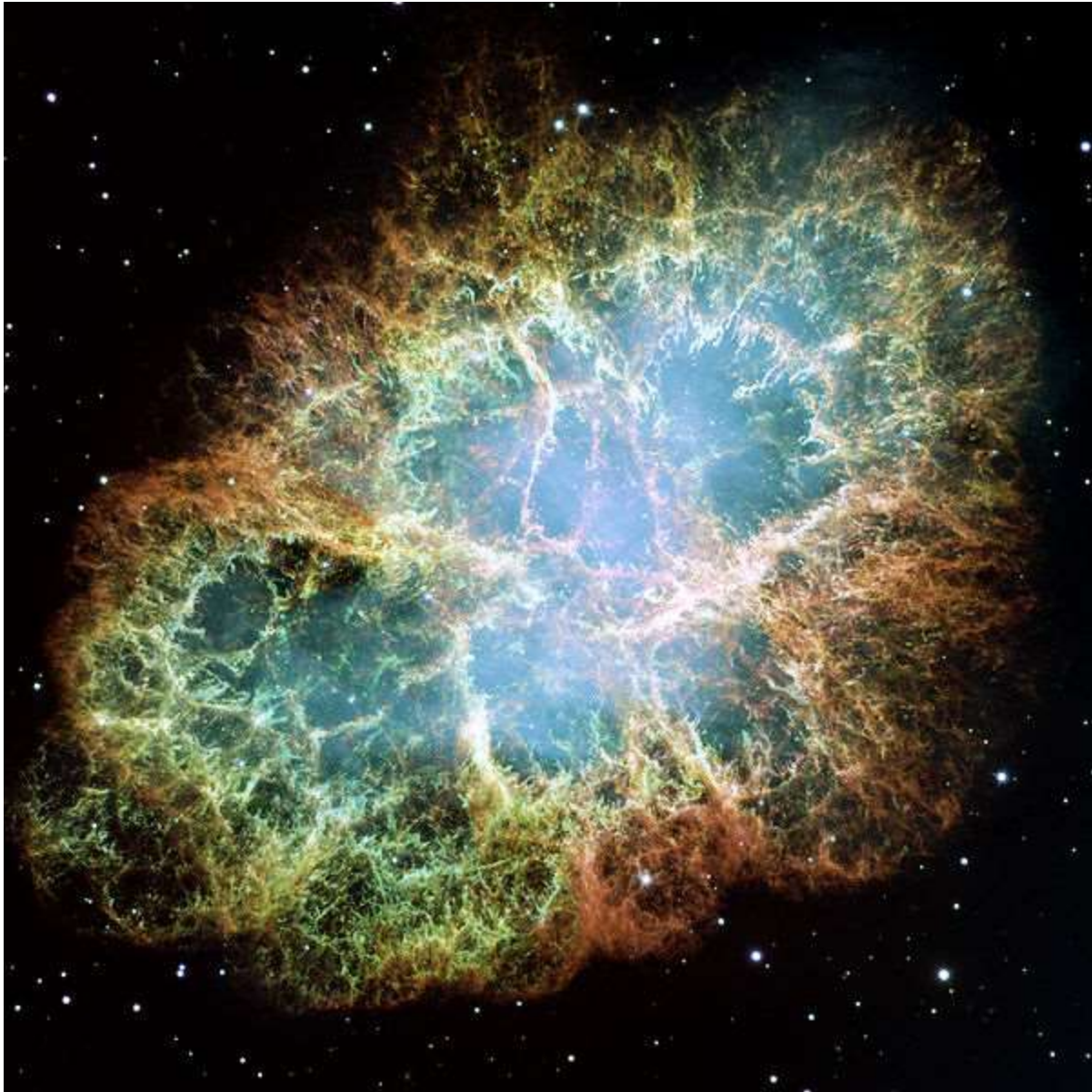


- Goriva zmanjka, zvezda se krči (nevtronsko zvezdo ali črno luknjo) → gravitacijska energija
- Eksplozija supernove: core collapse Sn ali Tip II, Tip Ib, Ic, izbruhi žarkov gama)



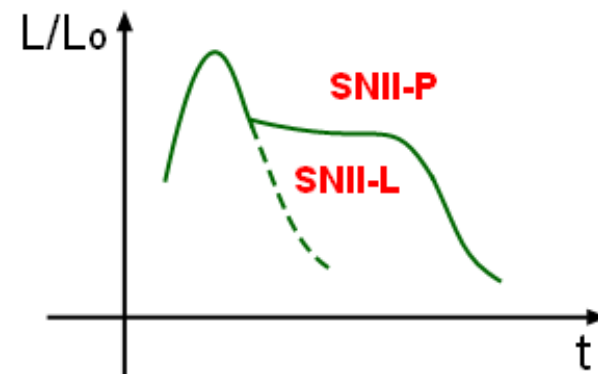
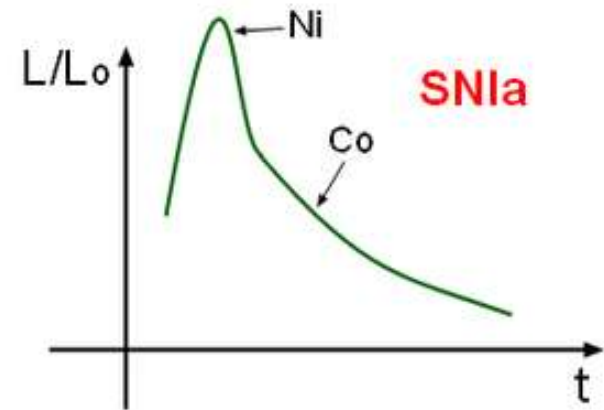
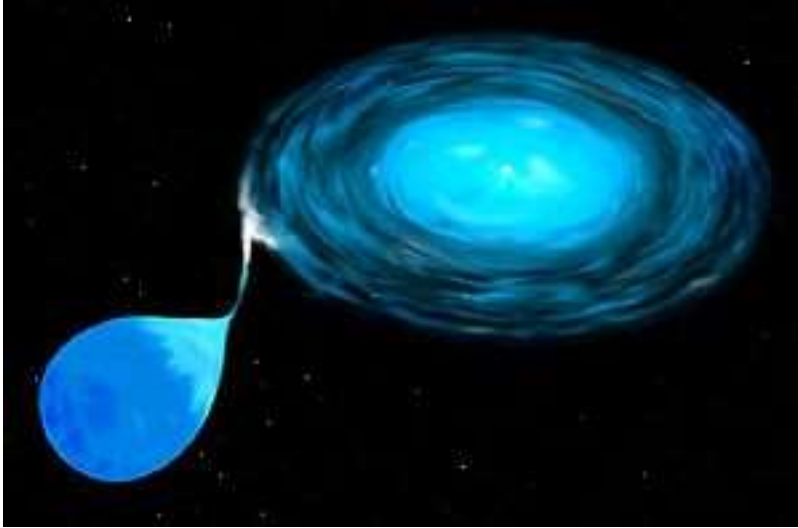
SN 1604
Keplerjeva SN





meglisa Rakovica
SN 1054

SN Tip Ia



Produkcija elementov pri SN

- T višje – do $A=254$
- v SN: r-proces – zajetje nevtrona:
fluks nevtronov $\sim 10^{22}$ nevtronov/cm² s!
“neutron-rich” izotopi
- zajetje protona
- fotodizintegracija
“neutron poor” izotopi

s proces

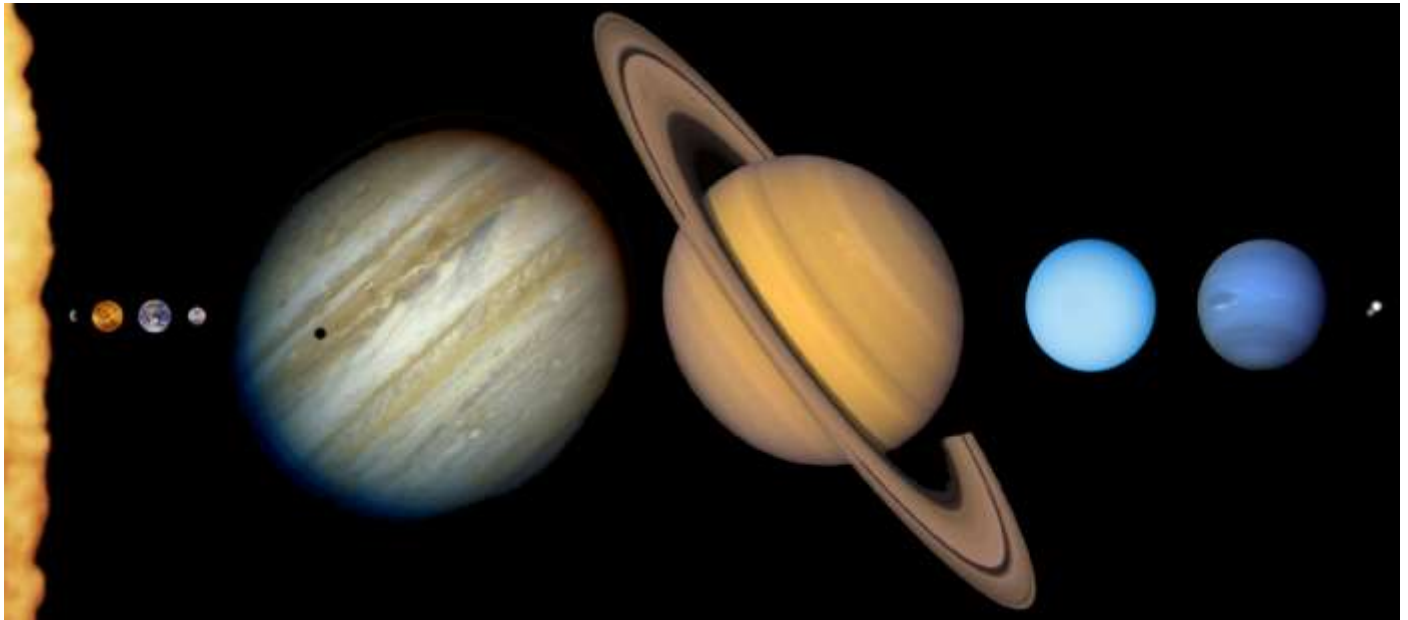
- poznamo tudi s-proces v manj masivnih zvezdah (razvijajo počasi) –
- orjakinje AGB:
zajetje nevtrona - do $A=209$

Osončje

Delitev planetov:

- notranji (Merkur, Venera, Zemlja, Mars)
- zunanji (Jupiter, Saturn, Uran, Neptun, Pluton)

- skalnati (Merkur, Venera, Zemlja, Mars)
- plinasti (Jupiter, Saturn, Uran, Neptun)



Radioaktivni razpadi grejejo notranjost Zemlje

Ljudje

- ~ 50% C
- ~ 20% O
- ~ 8.5% N
- ~ 10% težjih elementov
- ~ 11,5% H

Viri:

http://en.wikipedia.org/wiki/Big_bang

http://map.gsfc.nasa.gov/m_ig/060915/CMB_Timeline75.jpg

http://en.wikipedia.org/wiki/Milky_way

http://en.wikipedia.org/wiki/Edwin_Hubble

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<http://hubblesite.org/newscenter/archive/releases/2004/07/image/a/warn/>

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http://astrophysics.suite101.com/article.cfm/origin_of_the_chemical_elements

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http://chandra.harvard.edu/photo/2007/sn2006gy/sn2006gy_newline.jpg

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http://physics.uoregon.edu/~jimbrau/BraulmNew/Chap20/FG20_08.jpg

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