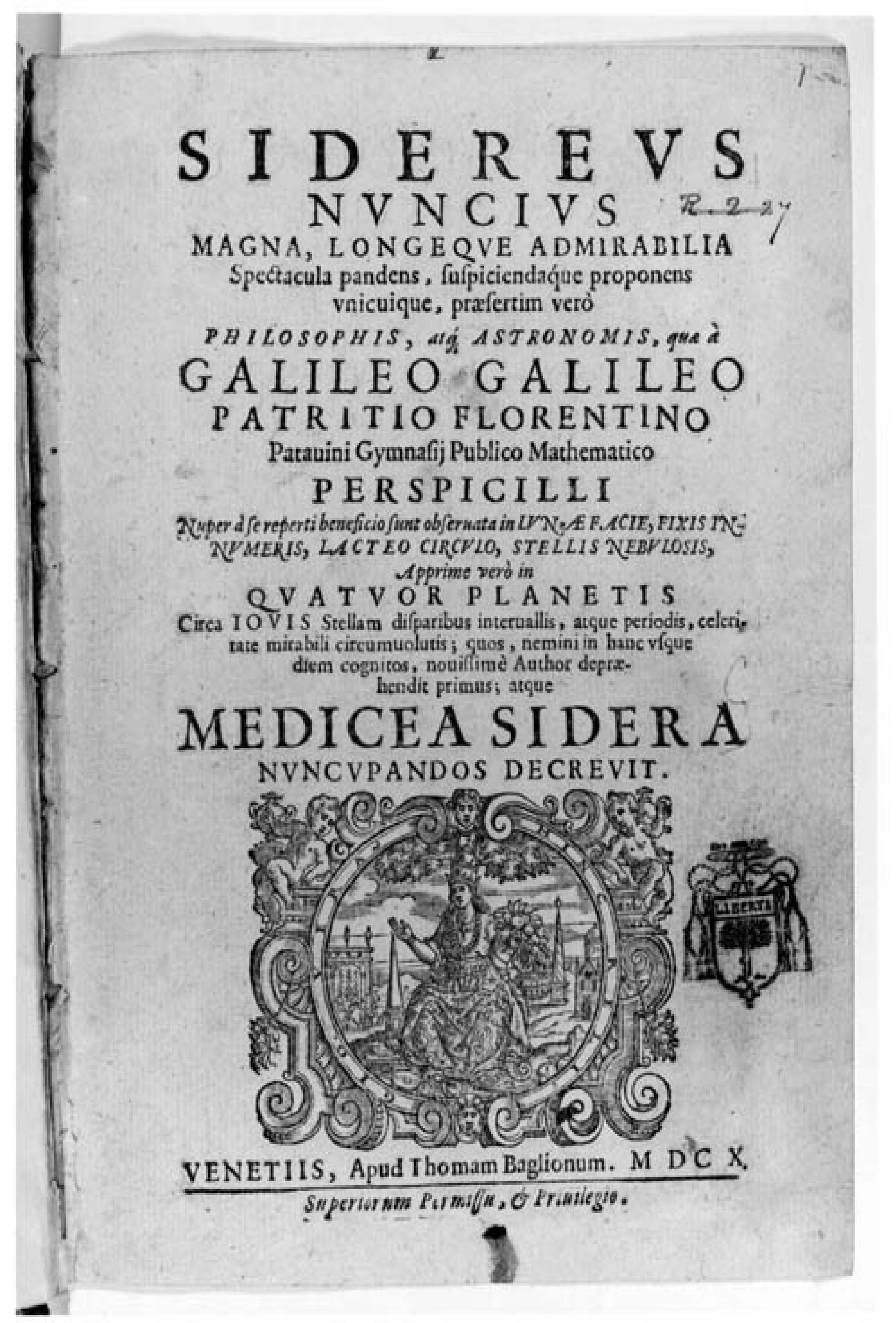
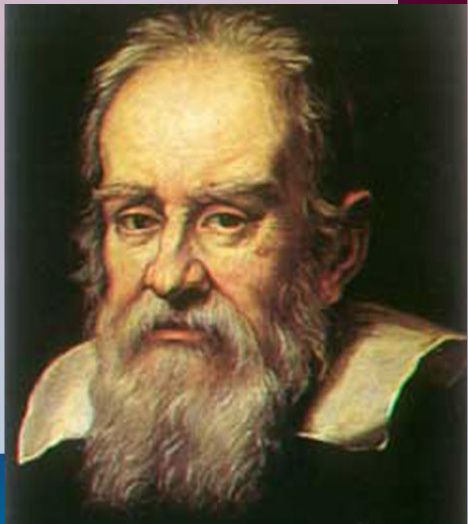


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, ſuſpiciendaque proponens
vnicuique, præſertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnaſij Publico Mathematico
PERSPICILLI
Nuper à ſe reperti beneficio ſunt obſeruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam diſparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vſque
diem cognitos, nouiſſimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permiſſu, & Priuilegio.

2009
The International
Year of Astronomy
400 Years of
telescopic
investigations



Nucleosynthesis

Ancient views of the nature of matter
Celestial Matter vs Terrestrial Matter
1609 – A Revolutionary Paradigm

1859 – Spectroscopic analysis of solar atmospheric chemistry

1868 – First measurement of a stellar Doppler shift

1925 – The sun is mostly hydrogen and helium!

Modern theories of the origin of the chemical elements
Big Bang Nucleosynthesis

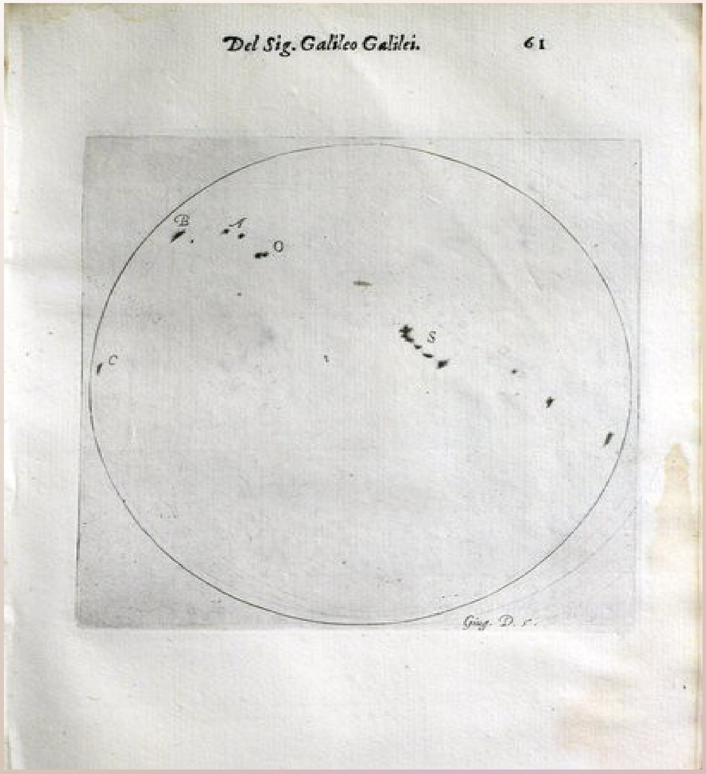
Stellar Nucleosynthesis

The origin of mass?

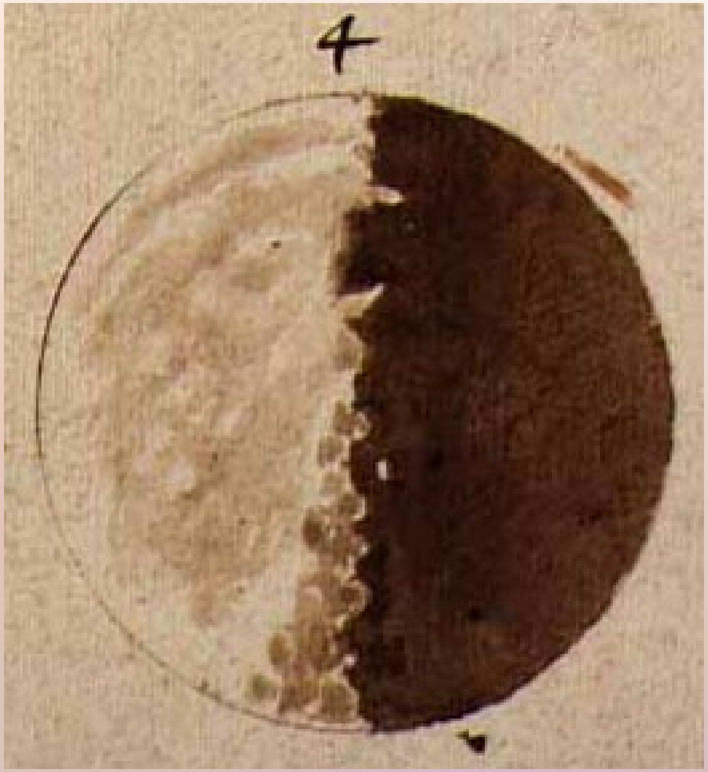
Ancient views of the nature of matter

1) Special connections exist between a body's location in space and its natural motion. Movements in the sublunar region are naturally vertical. Movements in the celestial region are naturally spherical.

2) Special connections exist between a body's location and its nature. In the sub lunar region bodies can change due to generation and corruption. These bodies are composed of 4 elements and contain opposite qualities (hot, cold), (wet, dry). Bodies in the celestial region are composed of a special element, quintessence, or celestial matter. Celestial matter is eternal and unchangeable. There is a very close connection between the nature of the substance and its motion. The circular motion was stated to be eternal and this is natural motion for an eternal object.



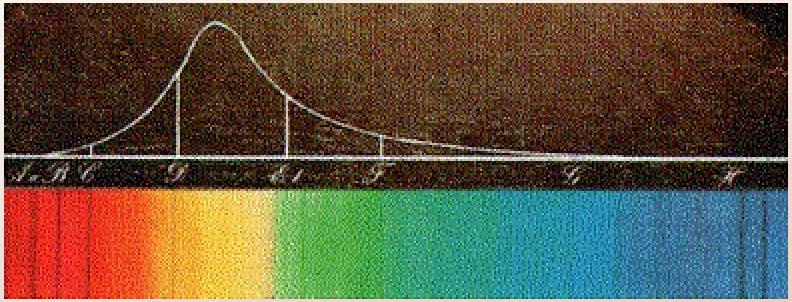
Sunspots drawn by Galileo



Moon drawing by Galileo

Galileo's observations of the rugged surface of the moon and the changing spots on the sun undermined the 2000 year belief in eternal unchanging celestial matter

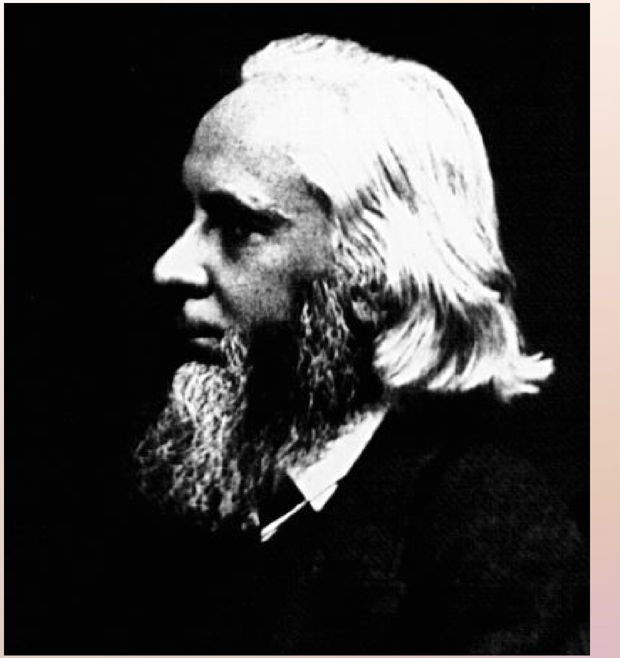
1609 A revolutionary paradigm



	angstroms	Line due to
A	7594	Telluric oxygen
B	6867	Telluric oxygen
C	6563	hydrogen, H
D1	5896	sodium
D2	5890	sodium
D3	5876	helium
E	5270	iron and calcium
b1	5184	magnesium
F	4861	hydrogen, H
G	4308	iron (and calcium)
H	3968	calcium
K	3934	calcium

1859

Kirchoff analyzed the chemical composition of the solar atmosphere



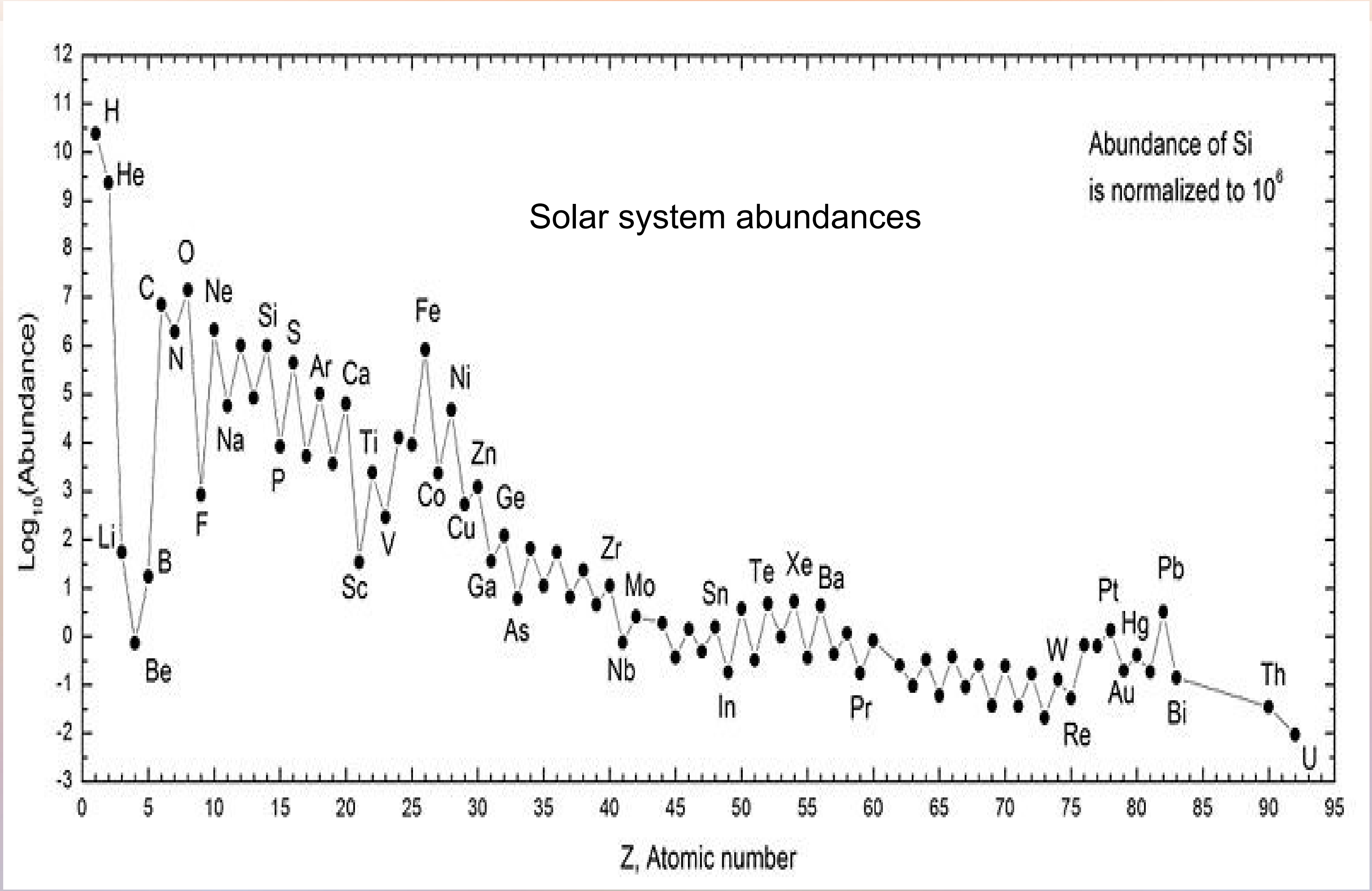
1868- Huggins measures a stellar doppler shift

" ...no attempts had been made, nor were indeed possible, to discover by this principle the motions of the heavenly bodies in the line of sight. For, to learn whether any change in the light had taken place from motion in the line of sight, it was clearly necessary to know the original wave length of the light before it left the star.

A soon as our observations had shown that certain earthly substances were present in the stars, the original wave lengths of their lines became known, and any small want of coincidence of the stellar lines with the same lines produced upon the earth might safely be interpreted as revealing the velocity of approach or recession between the star and earth. “

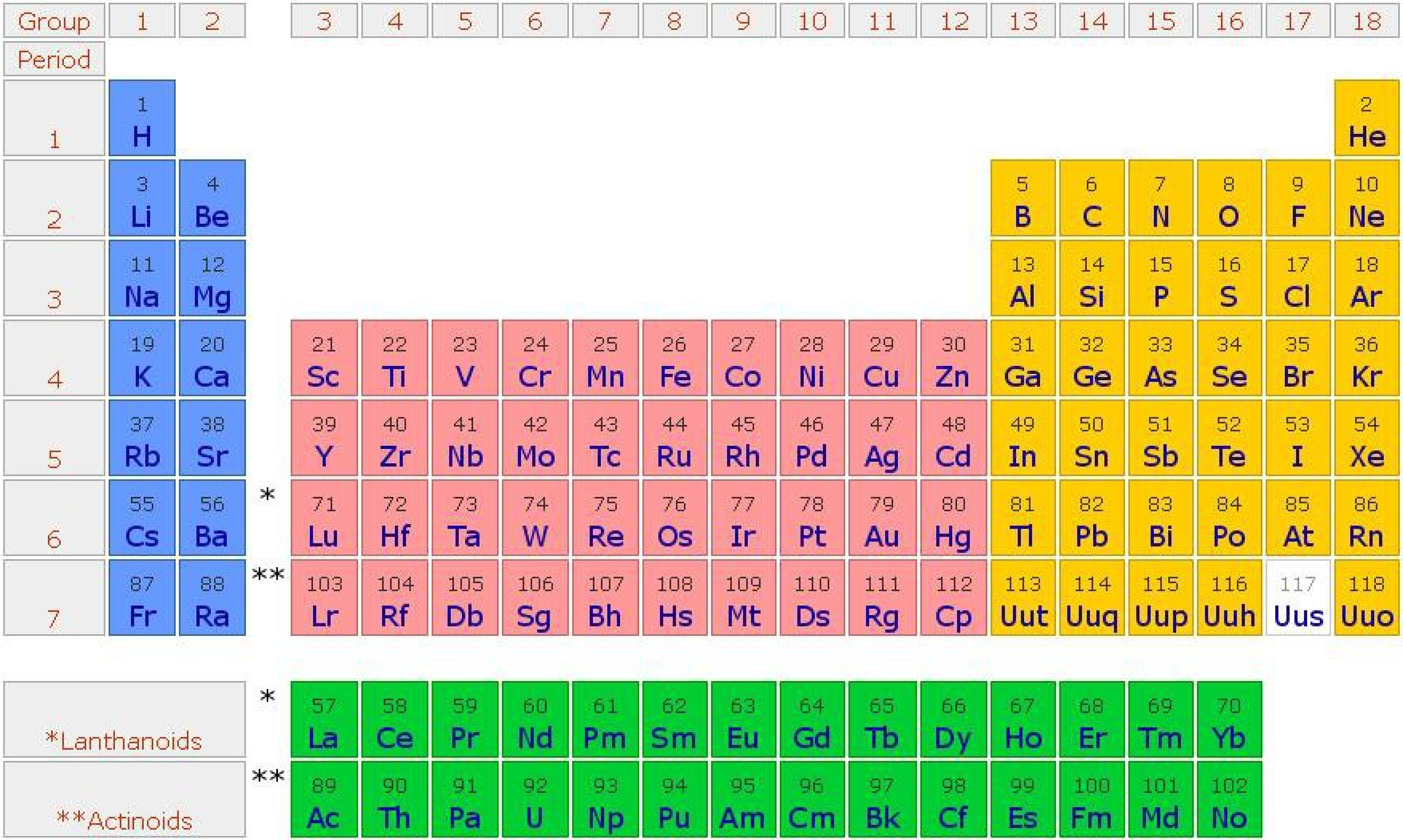
1925 - Cecelia Payne-Gaposhkin

Discovered the chemical composition of stars and, in particular, that hydrogen and helium are the most abundant elements in star and, therefore, in the universe. From the spectra of stars, she determined stellar temperature and chemical abundances using the thermal ionization equation of Saha. Her work was of fundamental importance in the development of the field of stellar atmospheres. She discovered that all stars have very similar relative chemical abundances with hydrogen and helium comprising 99% by number.



Solar system abundances

Note the logarithmic scale !



Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cp	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Where did all of these elements come from?   T = 13.7Gyr

The origin of the chemical elements - Nucleosynthesis

1) Big Bang Nucleosynthesis – BBN

2) Stellar Nucleosynthesis - SN

Physical parameters important for nucleosynthesis

Temperature

Fundamental interactions: weak, electromagnetic, strong, gravitation

Density of particles and the types

Nuclear structure

Photon spectrum

Convection in stellar environment

Basic nuclear components are protons and neutrons

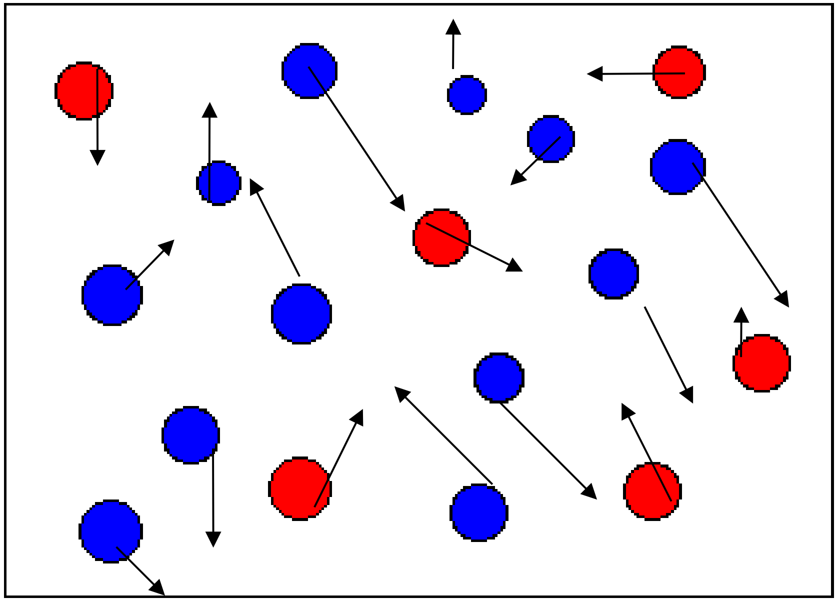
nucleon	mass(MeV)	Charge (e)
proton	938.3	+1
neutron	939.6	0

To build a nucleus we add Z protons and N neutrons together

nucleus	Z	N
^{2}H	1	1
^{3}H	1	2
^{16}O	8	8
^{17}O	8	9
^{208}Pb	82	126
^{209}Pb	82	127

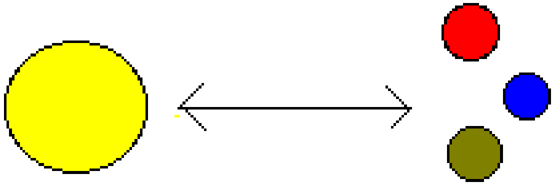
To build the chemical element we add Z electrons in orbit around the nucleus.

What governs reaction rates?



Two body reactions $a + b \rightarrow c + d$

Decay and formation $A \rightleftarrows B + e^+ +$

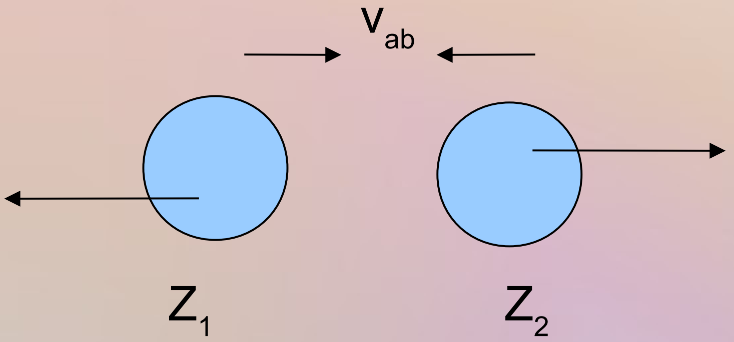


$R_{ab} = K \ {}_a \ {}_b < \ {}_{ab} v_{ab} >$

Reaction rate R_{ab}

Cross section ${}_{ab}$ depends on v_{ab}

v_{ab} depends on plasma temperature



Like charge particles repel
So v_{ab} needs to be big
enough to allow the
particles to come close
enough to fuse.

$<KE> = (1/2)mv^2 = 3kT/2$

Big Bang Nucleosynthesis

> I maintain that among all the natural phenomena whose first cause we are investigating, the origin of the planetary system and the production of the heavenly bodies, together with the causes of their movements, is the one which we may hope to consider reliably from first principles.

Immanuel Kant, 1755

An Essay on the Constitution and the Mechanical Origin of the Entire Structure of the Universe Based on Newtonian Principles

However, can we boast of such advantages for the smallest plants or insects? Are we in a position to say, give me the matter, and I will show you how a caterpillar could have developed?

Why do we believe we can predict the development of the Universe at times so distant from the present?

Why do we believe we can predict nucleosynthesis in the Universe at times so distant from the present?

1) General Relativity allows us to step backwards in time to eras when the physical processes occur at well defined temperatures and densities.

2) The temperatures/energies are all experimentally accessible in our labs.

3) The fundamental interactions are well known at these energies

4) Thermal equilibrium conditions exist allowing us to calculate the relative densities of the interacting particles.

5) GR lets us calculate $_b$ x 10^{-7} nucleons/cm^3

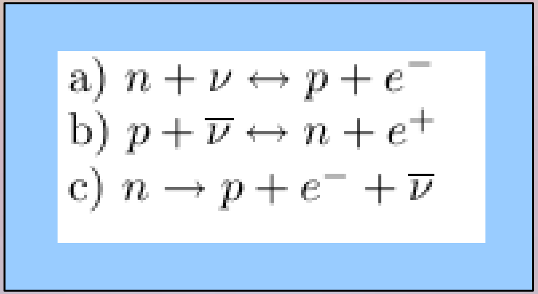
(Peebles, 'Principles of Physical Cosmology', eqn 6.21)

Time Line for Big Bang Nucleosynthesis, 1s < t < 900s

The expansion rate of the Universe depends on the energy density which is dominated by the Cosmic Microwave Background (CMB) photons, neutrinos and electrons

Baryons = nucleons = neutrons or protons, exist as a very tiny fraction of the universe's constituents

Important Weak Interaction Processes



a) $n + \nu \leftrightarrow p + e^-$

b) $p + \overline{\nu} \leftrightarrow n + e^+$

c) $n \rightarrow p + e^- + \overline{\nu}$

Up to about t = 1s rates a) and b) are high enough that the neutron to proton ratio follows the thermal equilibrium value:

n_n/n_p = exp (-Q/kT). , Q = $m_n - m_p$ = 1.2934 MeV and kT = 1MeV. n_n/n_p = 1/6.

Process c) dominates after t = 1s and the neutron decays with a half life of 614s.

Deuteron creation and photodisintegration, 1s < t < 200s

$$p + n \leftrightarrow d + \gamma$$

During this time period the temperature is between 1 MeV and 80 keV and there are sufficient numbers of energetic CMB photons to disintegrate any deuterons formed.

^{4}He nucleosynthesis, 200s < t < 400s, $n_n/n_p = 1/7$

$d + d \leftrightarrow t + p$

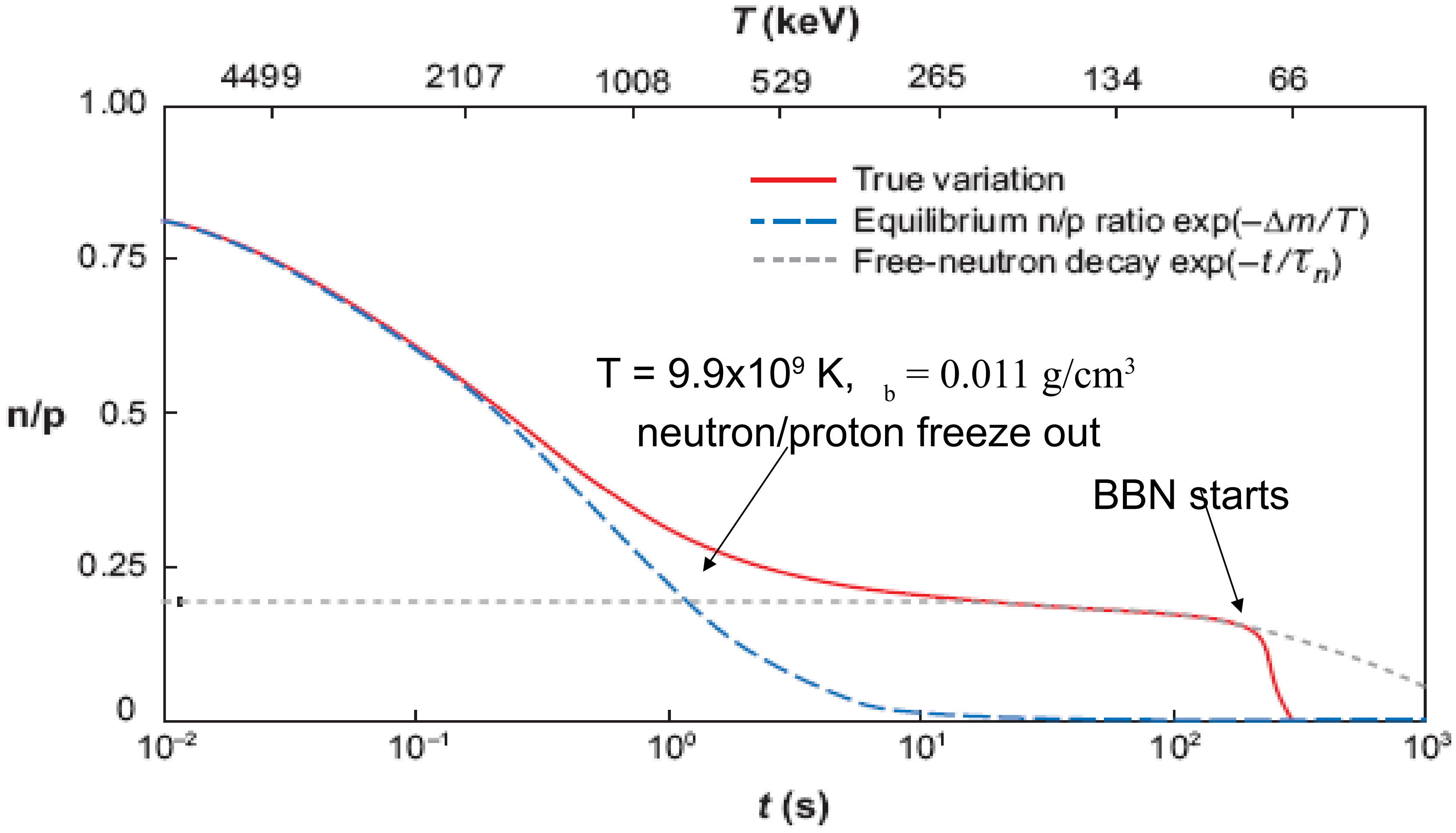
$d + d \leftrightarrow {}^3He + n$

$t + d \leftrightarrow {}^4He + n$

${}^3He + d \leftrightarrow {}^4He + p$

Almost all the neutrons left at t = 200s will be sequestered in ^{4}He by t = 400s. There is about 1 neutron for every 7 protons by the end of this period.

Big Bang Nucleosynthesis, neutron/proton ratios



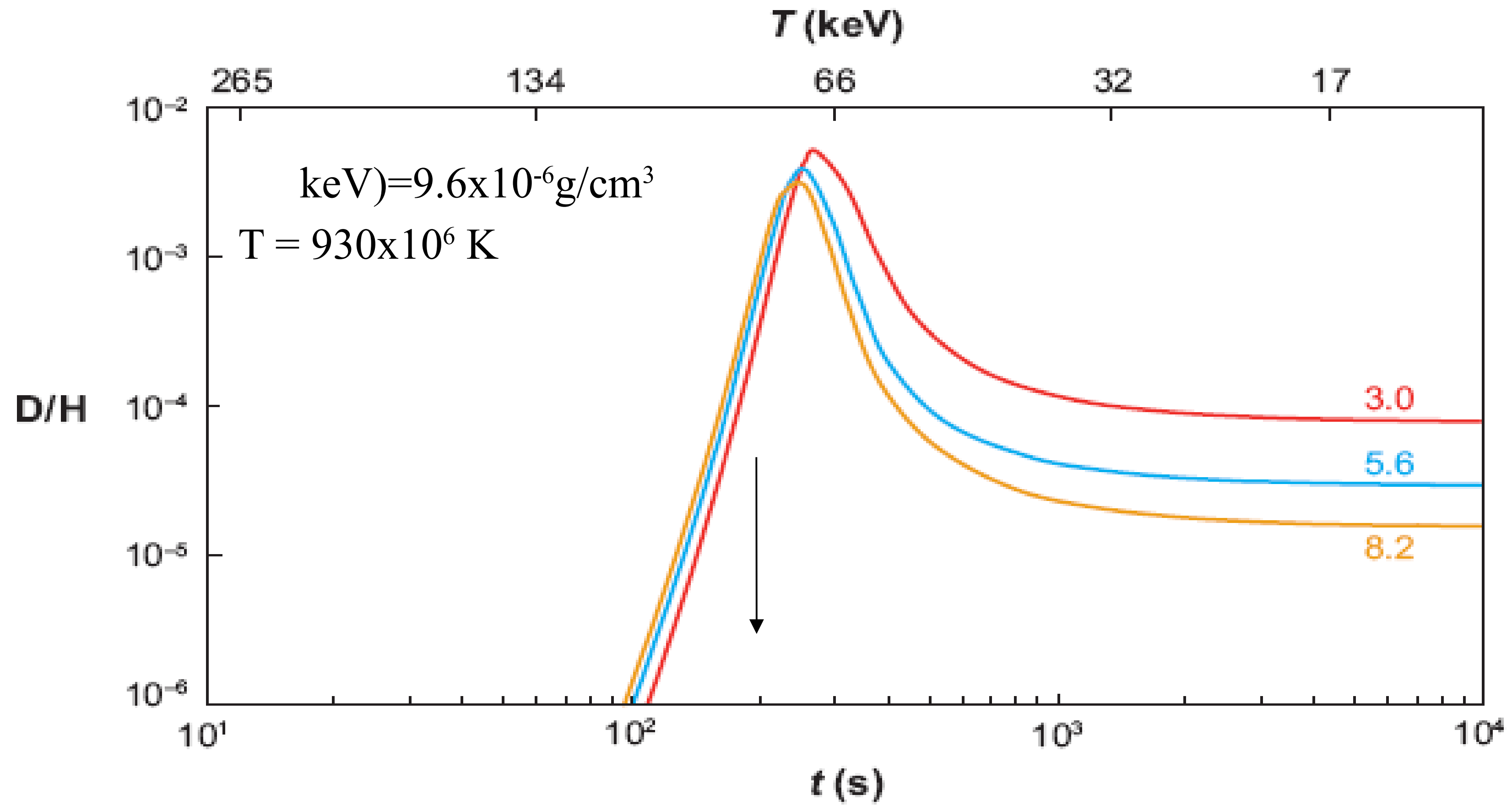
T = 9.9×10^9 K, $_b = 0.011$ g/cm^3

neutron/proton freeze out

BBN starts

Ref: G. Steigman, Ann. Rev. Nucl. Part. Sci. 57 (463) 2007

Big Bang Nucleosynthesis, deutron production

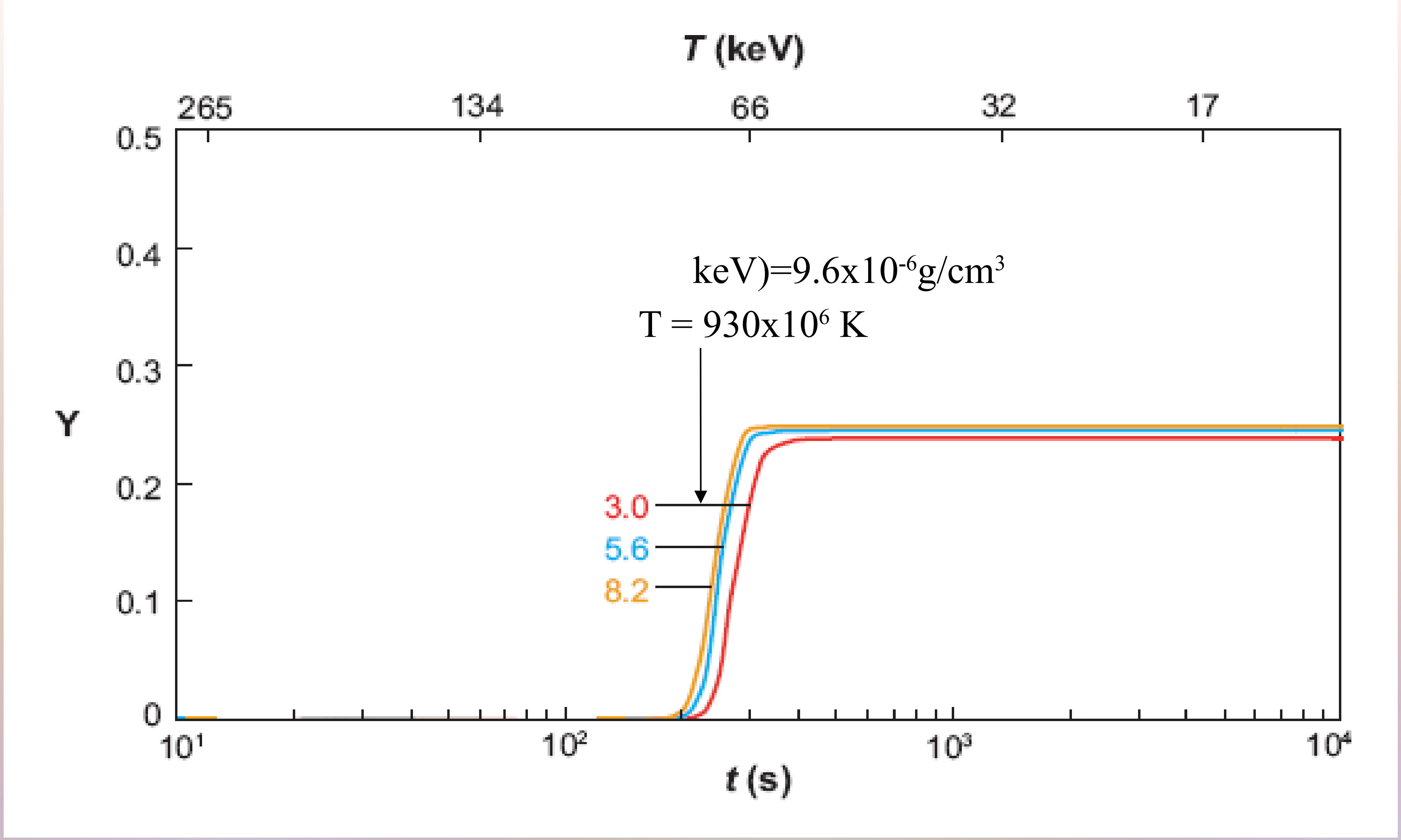


keV)=9.6×10^{-6}g/cm^3

T = 930×10^{6} K

The deuteron fraction never becomes very large during BBN because the deuterons are captured and form the A<7 nuclei. The different colored bands refer to different baryon densities.

Ref: G. Steigman, Ann. Rev. Nucl. Part. Sci. 57 (463) 2007



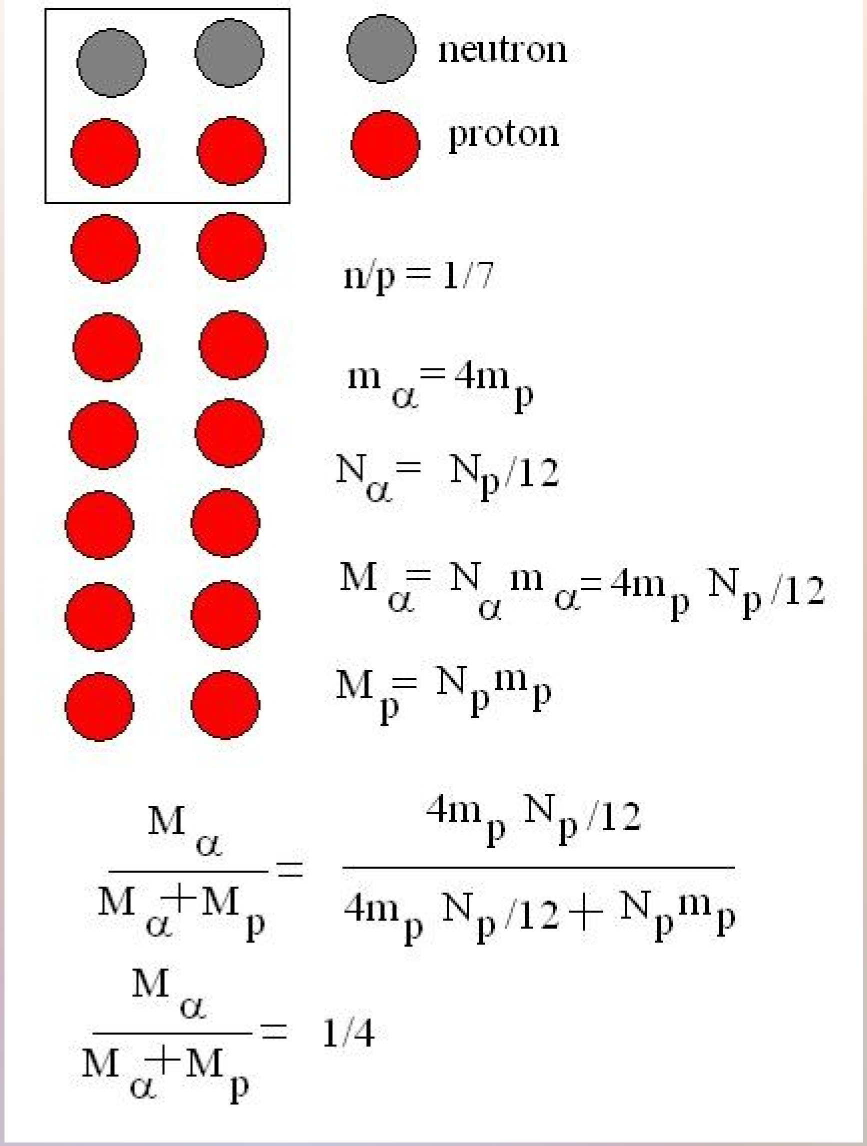
keV)=9.6×10^{-6}g/cm^3

T = 930×10^6 K

^{4}He BBN. The mass fraction Y is about 25%.

Ref: G. Steigman, Ann. Rev. Nucl. Part. Sci. 57 (463) 2007

^{4}He BBN



$n/p = 1/7$

$m_\alpha = 4m_p$

$N_\alpha = N_p/12$

$M_\alpha = N_\alpha m_\alpha = 4m_p\ N_p/12$

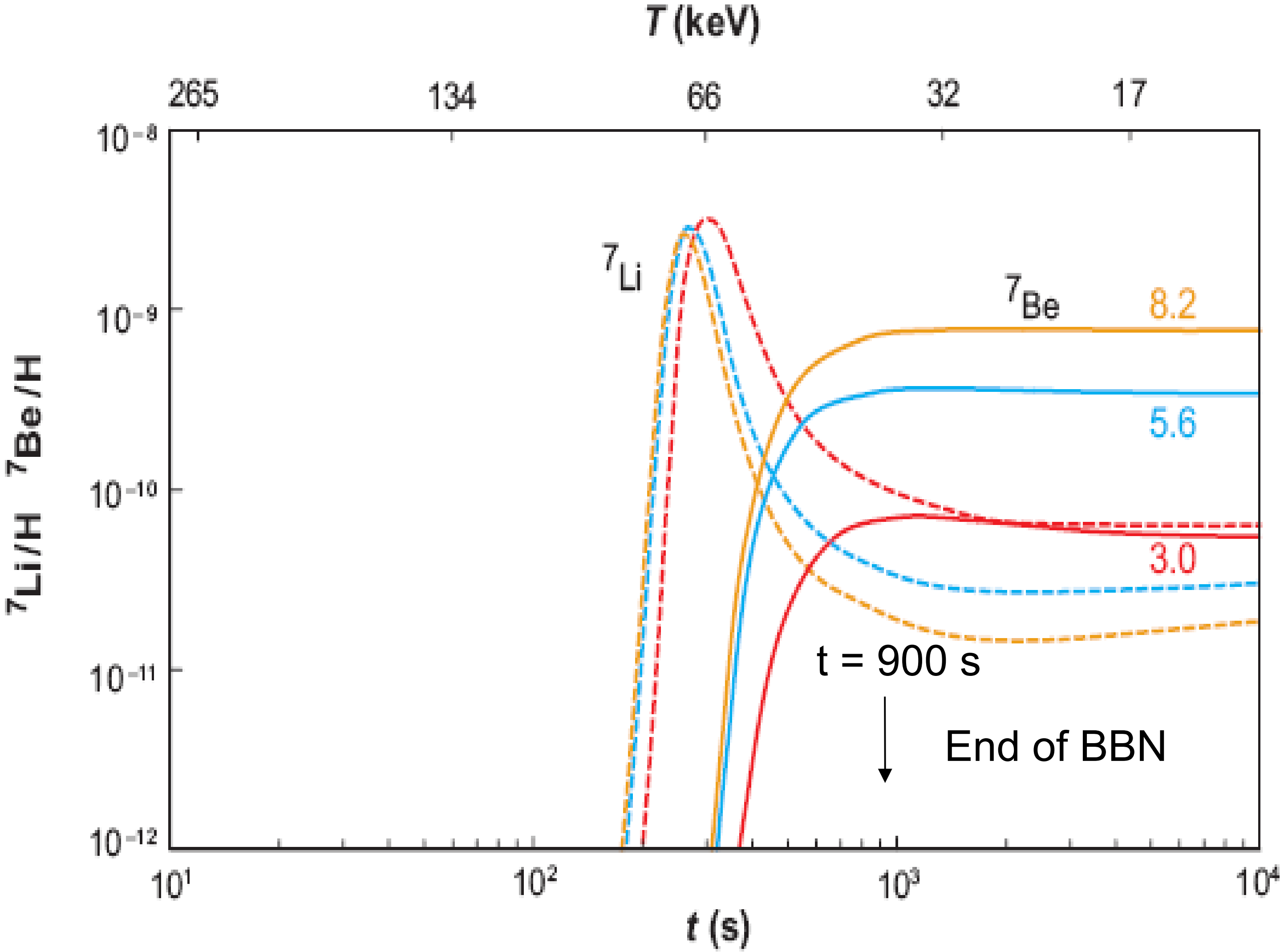
$M_p = N_p m_p$

$$\frac{M_\alpha}{M_\alpha + M_p} = \frac{4m_p\ N_p/12}{4m_p\ N_p/12 + N_p m_p}$$

$$\frac{M_\alpha}{M_\alpha + M_p} = 1/4$$

^{4}He production during BBN is not very sensitive to the baryon density. Rather it is sensitive to the rate of cooling of the Universe because the neutron decays with a mean life of 888s.

The end result of nucleosynthesis yields a mass fraction of helium of 25%. The standard cosmological model produces about 1 neutron for every 7 protons in the time interval available for ^{4}He synthesis. The alpha particle is represented by the particles in the box.



Production of the mass 7 nuclei in BBN.

Ref: G. Steigman, Ann. Rev. Nucl. Part. Sci. 57 (463) 2007

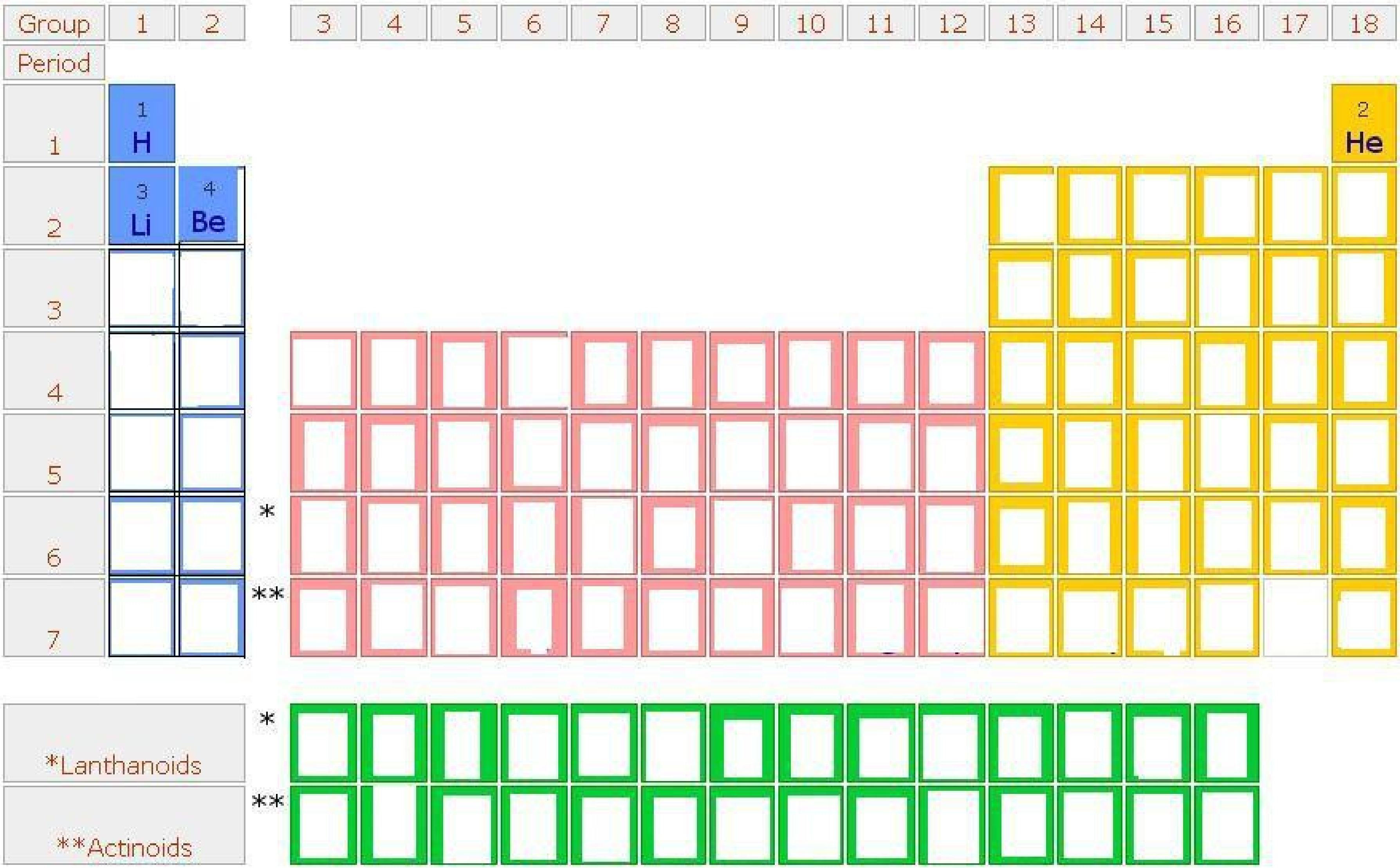
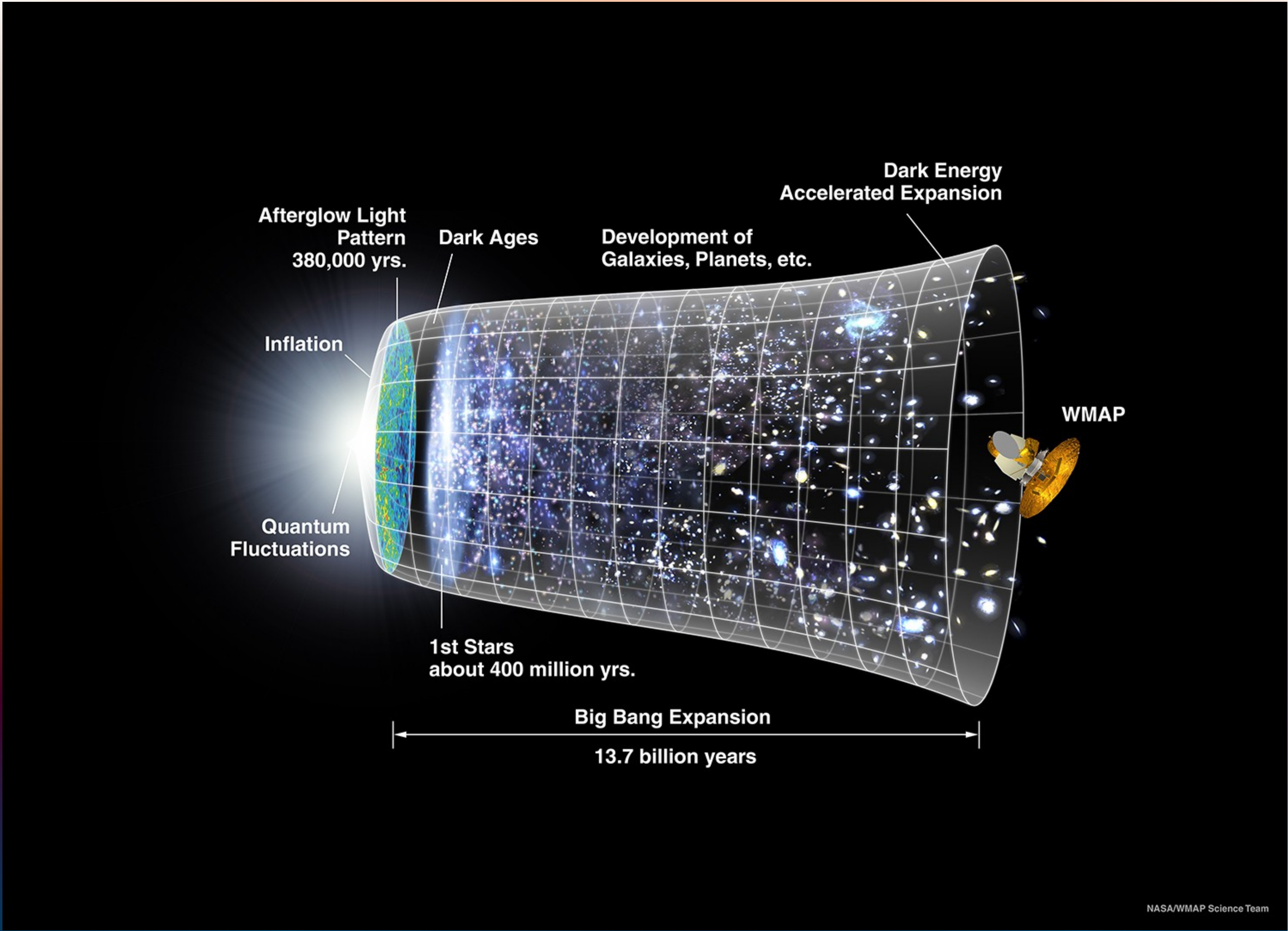


Table of the elements at T = 15 minutes

Note: At T=380,000 years neutral atoms form and ^{7}Be decays to ^{7}Li by electron capture with a half life of 53 days.



NASA/WMAP Science Team

Stellar Nucleosynthesis, t = 400 Myr to 13.7 Gyr

According to the Wilkinson Microwave Anisotropy Probe (WMAP) the first stars, called population III stars, started shining at t = 400 Myr.

These stars started their lives with the primordial nuclear composition.

The initial mass distribution of these stars is not well fixed. The masses of these stars in the calculation below is $30M_{solar}<M_{III}<100M_{solar}$.

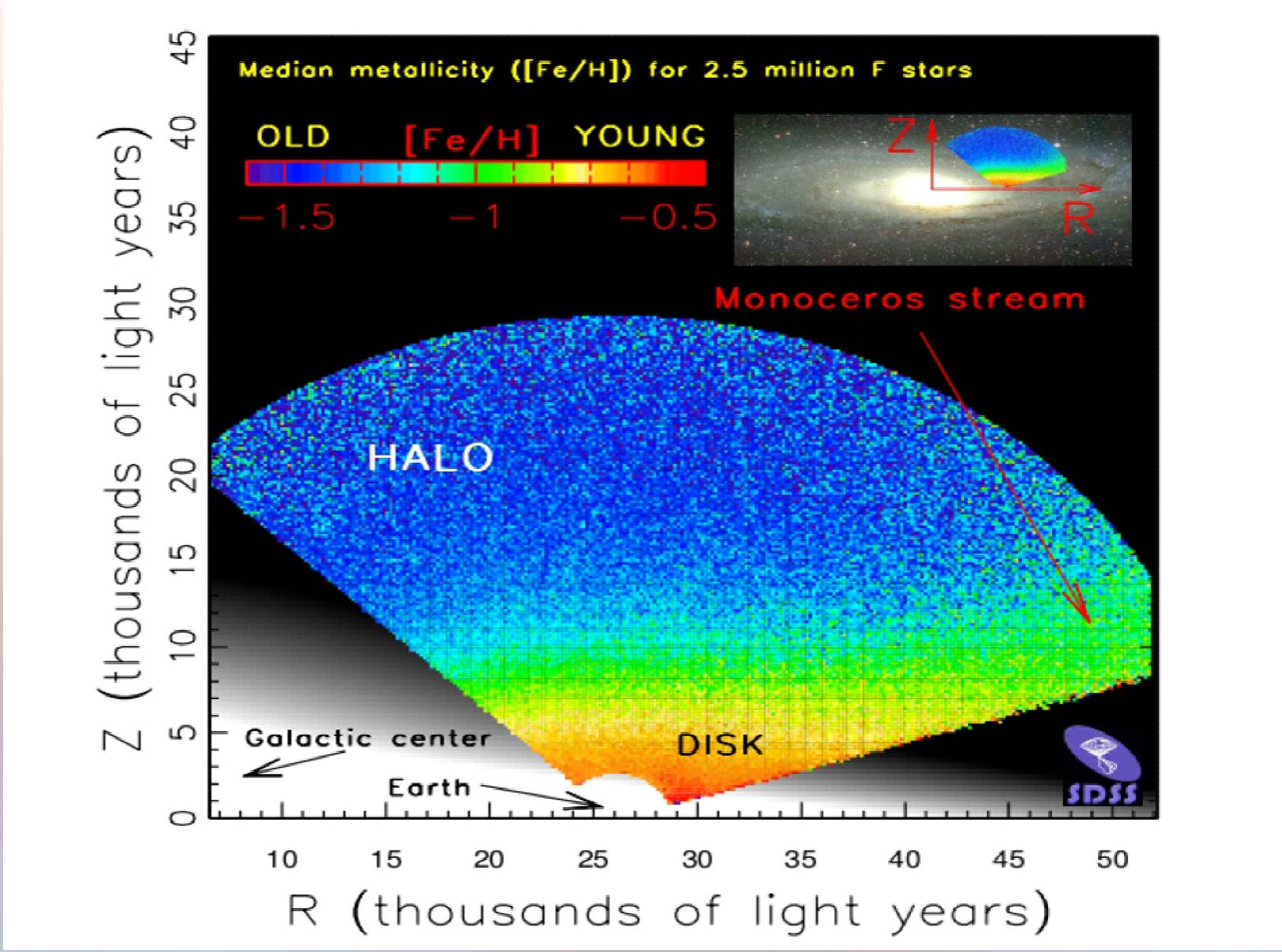
Cooling of the gas, necessary to cause condensation into higher density regions, depends on atomic and molecular (H_2) transitions.

The Formation of the First Star in the Universe Tom Abel, et al. Science 295, 93 (2002); DOI: 10.1126/science.1063991

Red shift = z = (t)/ (t0) -1 , $t = t_0 /(1 + z)$

Metallicity = $Z = \log(N_{Fe}/N_H)_{star} - \log(N_{Fe}/N_H)_{sun}$

$Z_{III} < -6$, 1 million times less iron compared to the sun.

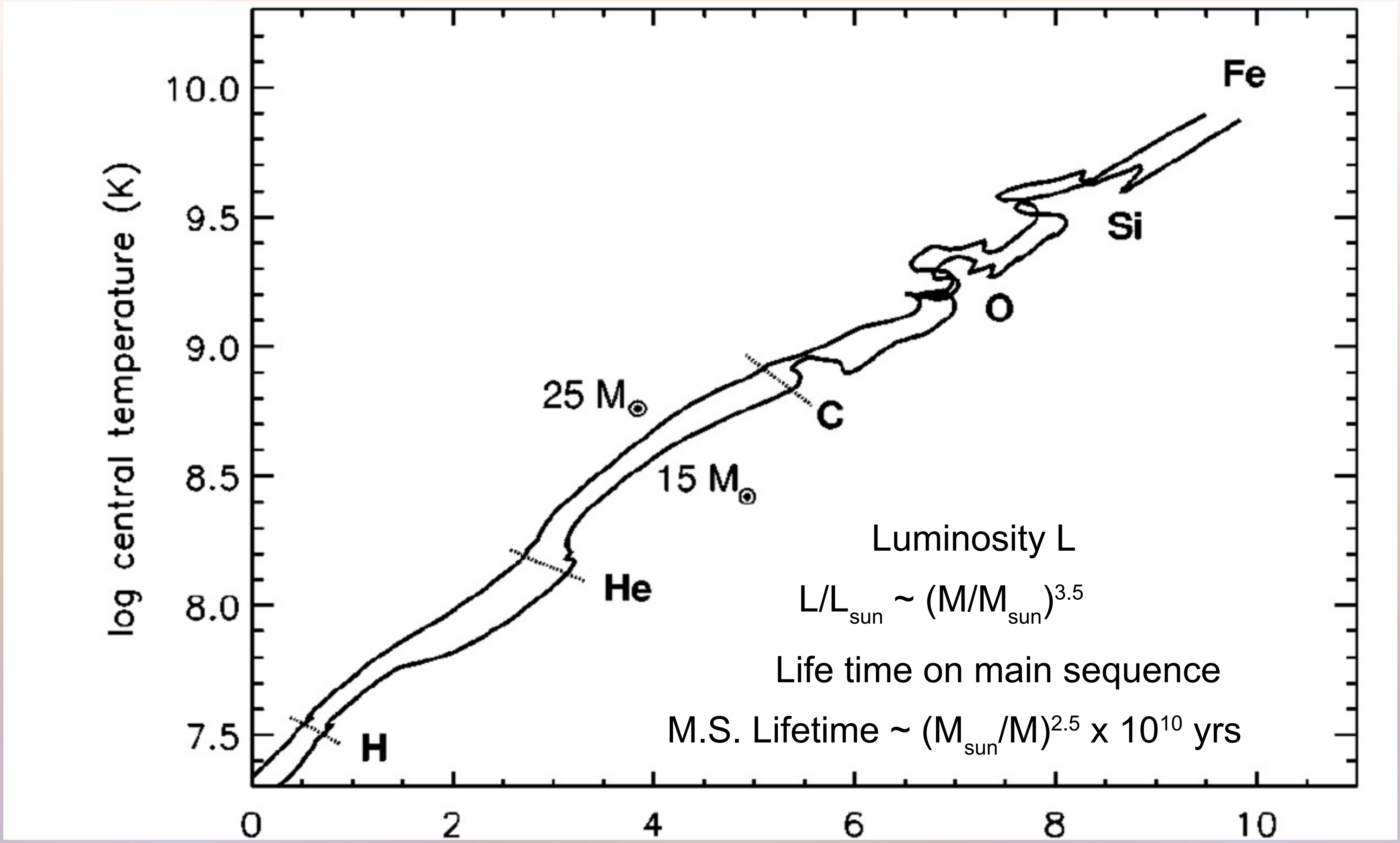


Sloan Digital Sky Survey, May 29, 2008 – Chemical composition of the Milky Way

Thermonuclear Burning Stages(D. Arnett,”Supernovae and Nucleosynthesis”)

fuel	T(10^9 K)	ashes	cooling
$^{1}\mathrm{H}$	0.02	$^{4}\mathrm{He}$, $^{14}\mathrm{N}$	photons
$^{4}\mathrm{He}$	0.2	$^{12}\mathrm{C}$,$^{16}\mathrm{O}$,$^{22}\mathrm{Ne}$	photons
$^{12}\mathrm{C}$	0.8	$^{20}\mathrm{Ne}$,$^{24}\mathrm{Mg}$,$^{16}\mathrm{O}$, $^{23}\mathrm{Na}$, $^{25,26}\mathrm{Mg}$	neutrinos
$^{20}\mathrm{Ne}$	1.5	$^{16}\mathrm{O}$,$^{24}\mathrm{Mg}$,$^{28}\mathrm{Si}$,...	neutrinos
$^{16}\mathrm{O}$	2	$^{28}\mathrm{Si}$, $^{32}\mathrm{S}$,...	neutrinos
$^{28}\mathrm{Si}$	3.5	$^{56}\mathrm{Ni}$, A~56 nuclei	neutrinos
$^{56}\mathrm{Ni}$	6~10	n, p, $^{4}\mathrm{He}$, s,r,p processes	neutrinos
A~56	Depends on density	photodisintegration, neutronization	
Super nova		Heavy elements up to uranium	

Life times
Ten solar mass star 31 million years on main sequence
1000 years on carbon burning
1 year on neon burning
½ year on oxygen burning
1 day on silicon burning
After A=56 about 1 millisecond to collapse



Luminosity L

$L/L_{sun} \sim (M/M_{sun})^{3.5}$

Life time on main sequence

M.S. Lifetime ~ $(M_{sun}/M)^{2.5} \times 10^{10}$ yrs

log central density, g/cm^3

RMP 74 1015(2002), S. E. Woosley and A. Heger

Nuclear Fusion Reactions in the Sun, a population I star

$p + p \rightarrow d + e^{+} + v_{e}$ Weak interaction, very slow, $d = {}^{2}H$

${}^{2}H + p \rightarrow {}^{3}He +$ electromagnetic interaction

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$, strong nuclear interaction

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be +$ electromagnetic interaction

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + v_{e}$, weak interaction

${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$, strong nuclear interaction

${}^{7}Be + p \rightarrow {}^{8}B +$ electromagnetic interaction

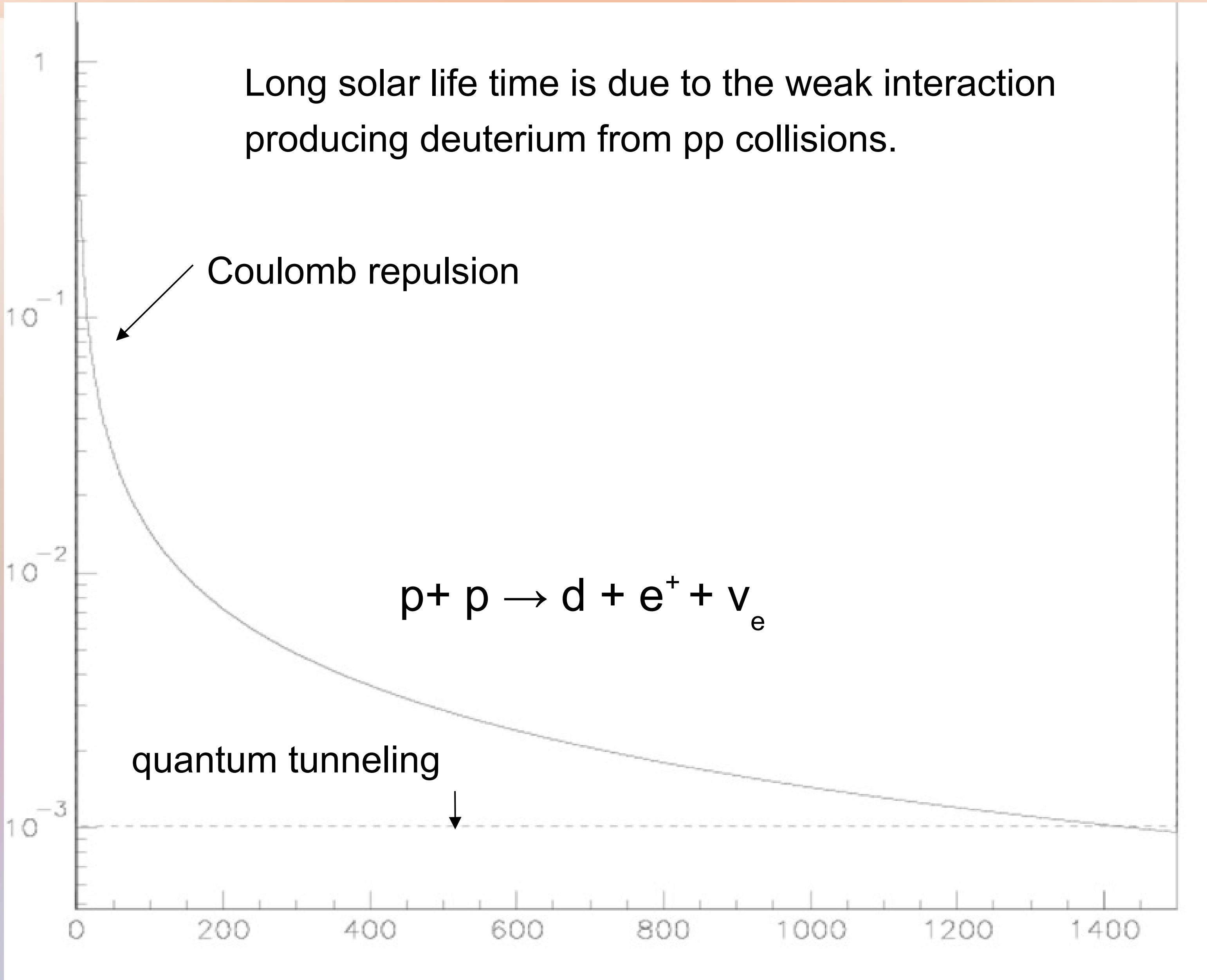
${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + v_{e}$, weak interaction

${}^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$, strong nuclear interaction, $= 9.6 \times 10^{-17}$s

For starting ingredients = $p + {}^{4}He$ all these reactions lead to ${}^{4}He$.

Mass 8 is a bottleneck because there are no stable nuclei with Z+N = 8.

The sun's core is becoming richer and richer in ${}^{4}He$.



Long solar life time is due to the weak interaction producing deuterium from pp collisions.

Coulomb repulsion

$$p + p \rightarrow d + e^{+} + \nu_e$$

quantum tunneling

Energy, MeV

proton-proton separation in F

$T_{sun} = 15.78 \times 10^{6}$K

$\langle KE_{cm} \rangle$ = 1. keV for protons in center of the sun

Nuclear Fusion Reactions in the Sun, a population I star

Hydrogen and helium are the major ingredients in the sun but not the sole components. The solar system is constructed from the products of earlier nucleosynthesis by dying stars.

Additional solar nuclear reactions in the sun, CNO cycle

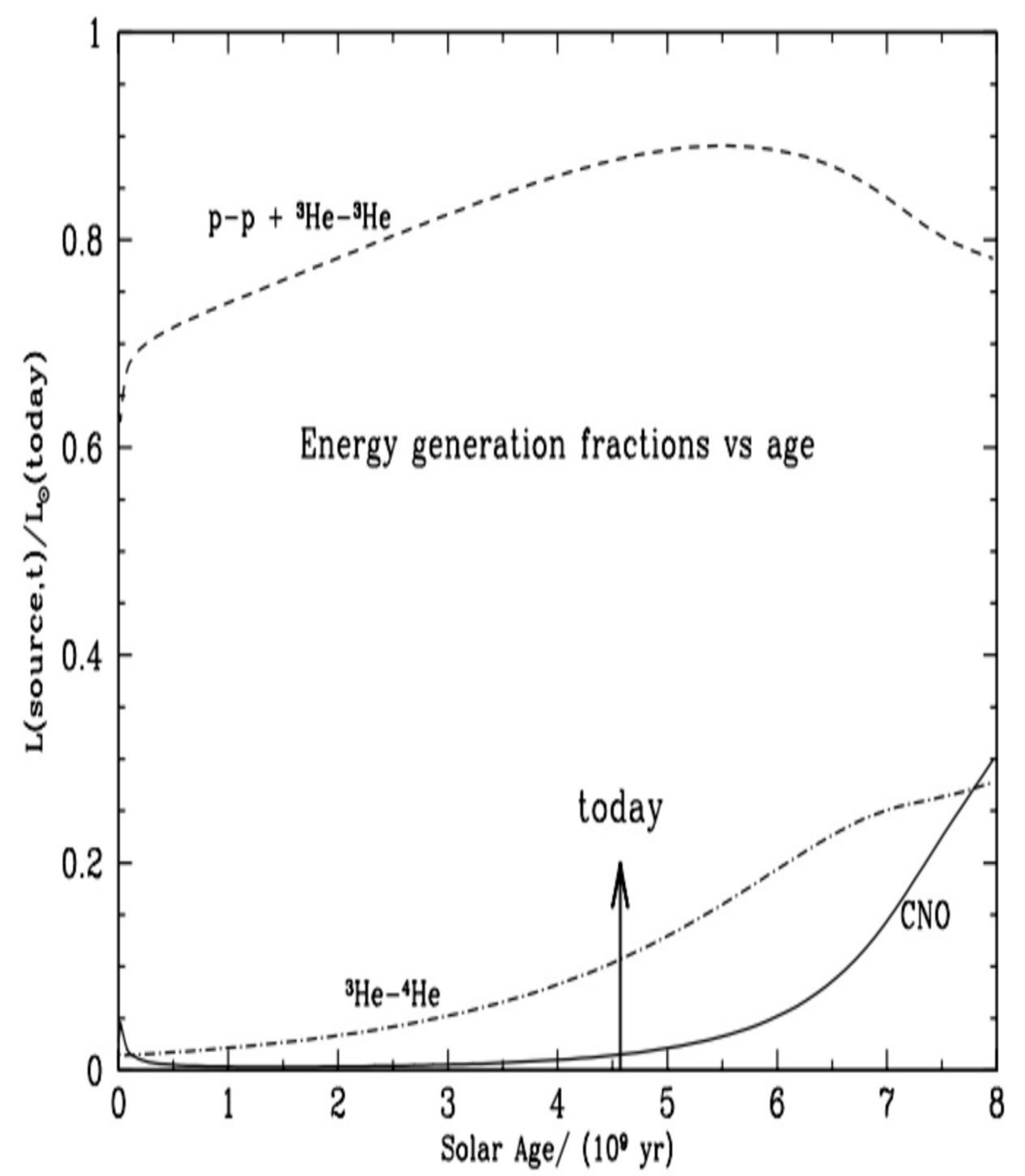
$^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \quad , \; {}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + v_{e}$

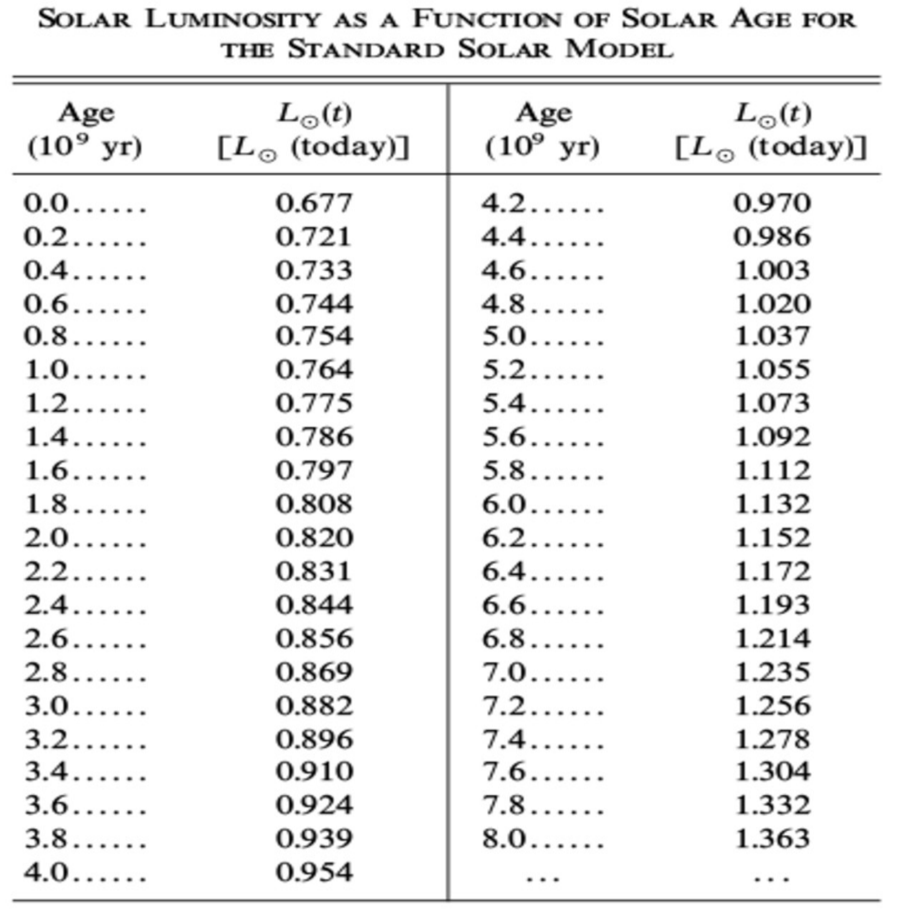
$^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} +$

$^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \quad , \; {}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + v_{e}$

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

Eventually the sun's core will be composed of helium ($^{4}\mathrm{He}$) and at a substantially higher temperature.





SOLAR LUMINOSITY AS A FUNCTION OF SOLAR AGE FOR THE STANDARD SOLAR MODEL

Age (10^9 yr)	$L_\odot(t)$ [$L_\odot$ (today)]	Age (10^9 yr)	$L_\odot(t)$ [$L_\odot$ (today)]
0.0......	0.677	4.2......	0.970
0.2......	0.721	4.4......	0.986
0.4......	0.733	4.6......	1.003
0.6......	0.744	4.8......	1.020
0.8......	0.754	5.0......	1.037
1.0......	0.764	5.2......	1.055
1.2......	0.775	5.4......	1.073
1.4......	0.786	5.6......	1.092
1.6......	0.797	5.8......	1.112
1.8......	0.808	6.0......	1.132
2.0......	0.820	6.2......	1.152
2.2......	0.831	6.4......	1.172
2.4......	0.844	6.6......	1.193
2.6......	0.856	6.8......	1.214
2.8......	0.869	7.0......	1.235
3.0......	0.882	7.2......	1.256
3.2......	0.896	7.4......	1.278
3.4......	0.910	7.6......	1.304
3.6......	0.924	7.8......	1.332
3.8......	0.939	8.0......	1.363
4.0......	0.954	...	...

Solar energy fraction today:

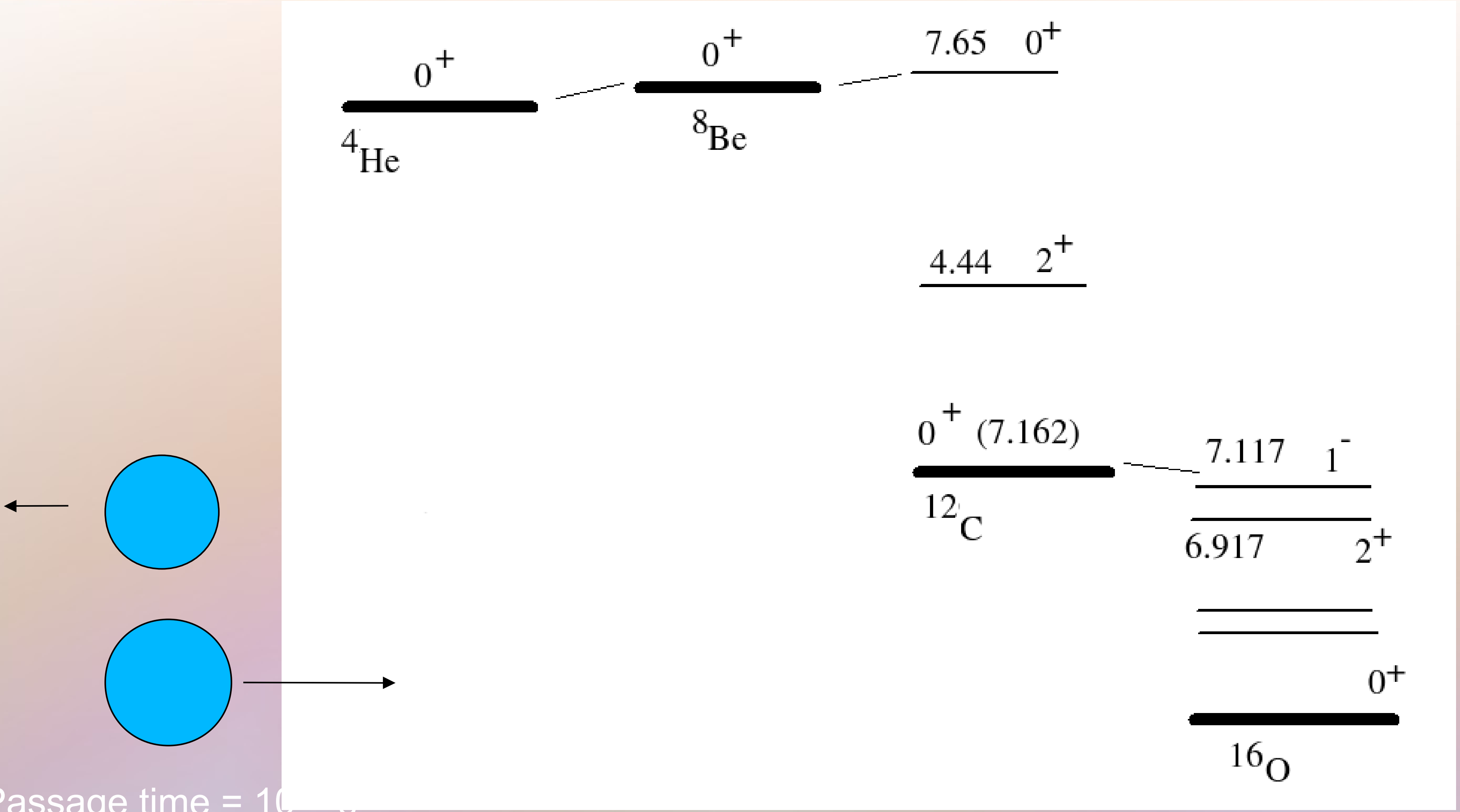
p+p and ^{3}He +^{3}He = 87.8%

^{3}He + ^{4}He = 10.7%

CNO = 1.5%

APJ, 555 : 990 È 1012, 2001 July 10,Bahcall et al.

The sun's luminosity is increasing.



Passage time = 10

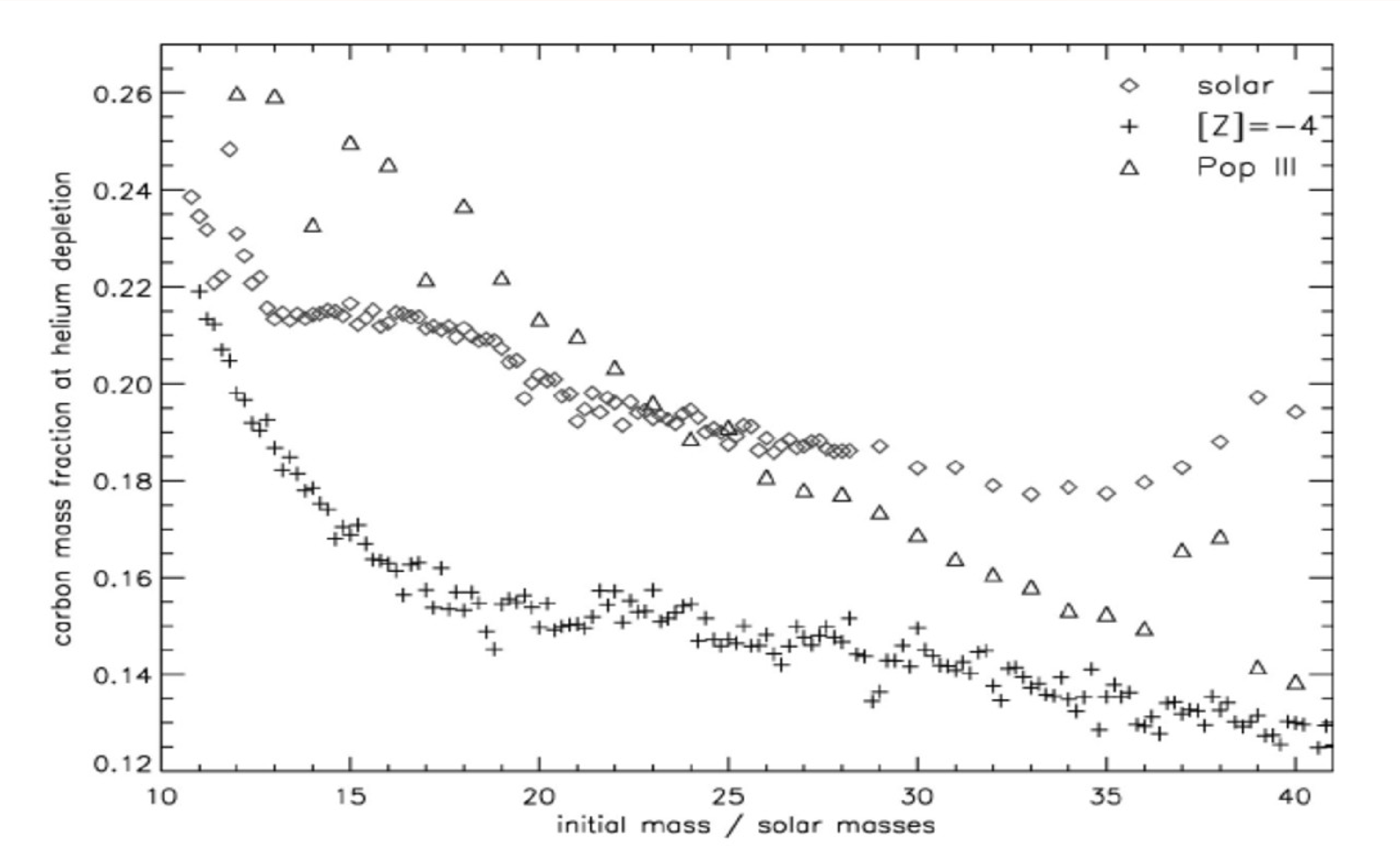
The ^{8}Be resonant ground state and triple   state at 7.65 MeV in ^{12}C are crucial for nucleosynthesis.

The ^{12}C(   )^{16}O capture is a critical step in nucleosynthesis.

Helium burning core, T = 2 x 10^{8} K, <KE> = 17 keV

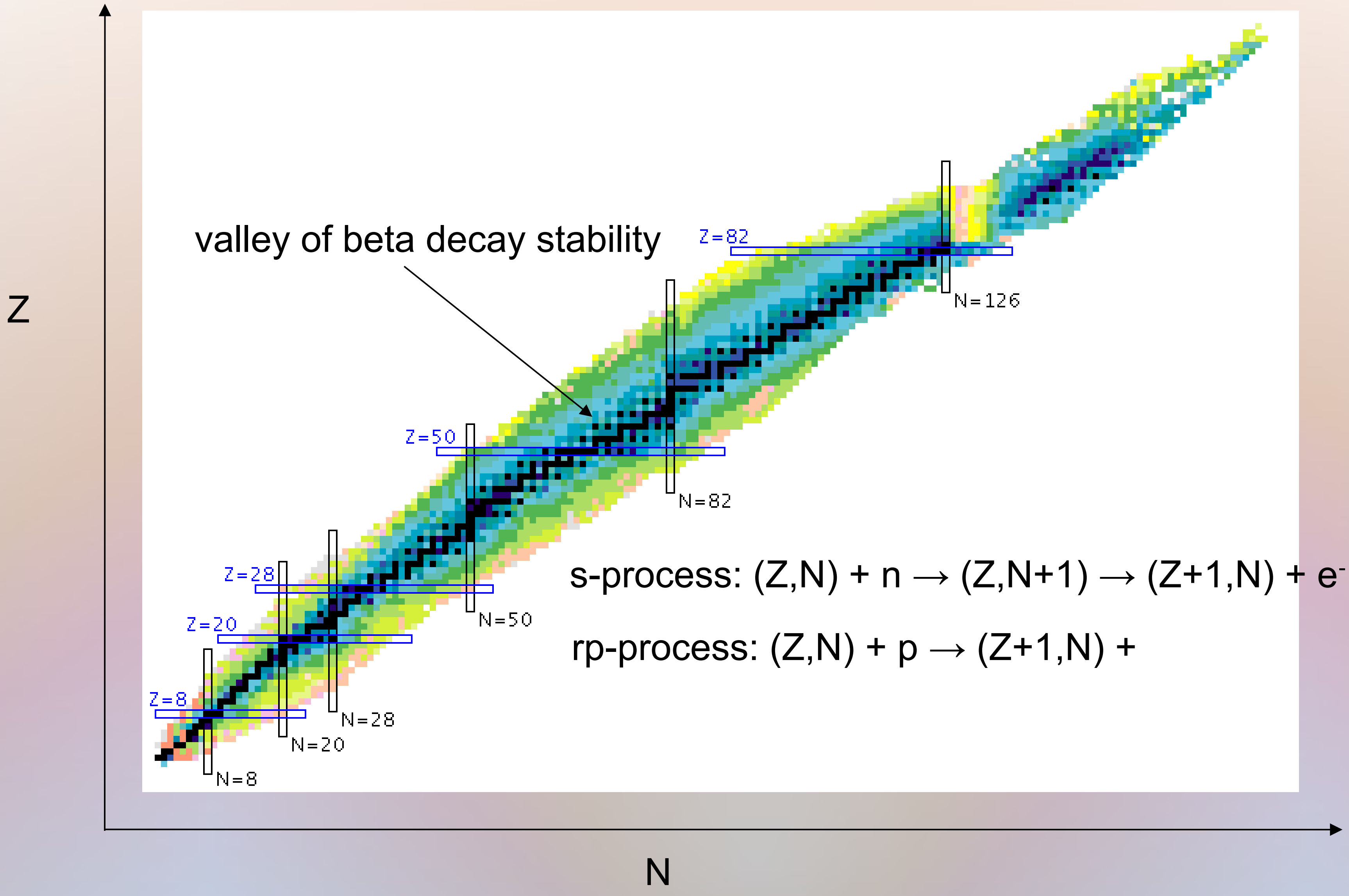
A crucial nuclear reaction for post ^{4}He burning evolution, ^{12}C(   )^{16}0

“... the reaction ^{12}C(   ) ^{16}O warrants special discussion as it affects not only the ratio of carbon and oxygen to come out of helium burning, but indirectly the nucleosynthesis of many other species and the very structure of the presupernova star. Determination of an accurate rate for this reaction is experimentally challenging because it proceeds predominantly through two subthreshold resonances whose critical alpha widths must be determined indirectly[the excited states are at 7.117 MeV and 6.917 MeV; the Q value is 7.162 MeV]. “ **RMP 74 1015 (2002) S. E. Woosley and A. Heger**



Carbon mass fraction at the end of helium burning for different beginning chemical compositions. **RMP 74 1015 (2002) S. E. Woosley and A. Heger**

Photodisintegration(p-process), s-process, r-process, rp-process



s-process: (Z,N) + n → (Z,N+1) → (Z+1,N) + e^- + v_e

rp-process: (Z,N) + p → (Z+1,N) +

r-process: (Z,N) + n → (Z,N+1) +n → (Z,N+2) → … → (Z, N+many n) → beta decays

At high temperatures the energetic photon spectrum can liberate neutrons, protons and 's.

Some Issues in Nucleosynthesis and observed chemical abundances

“The greatest source of diversity and uncertainty in attempts to model the evolution of stars of all masses is the way in which compositional mixing is handled, especially at the boundaries of convective regions. An additional problem peculiar to massive stars is that, during the latest stages of evolution, convective and nuclear time scales become comparable.”

RMP 74 1015(2002), S. E. Woosley and A. Heger

Metallicity has an effect on the mass loss of the star.

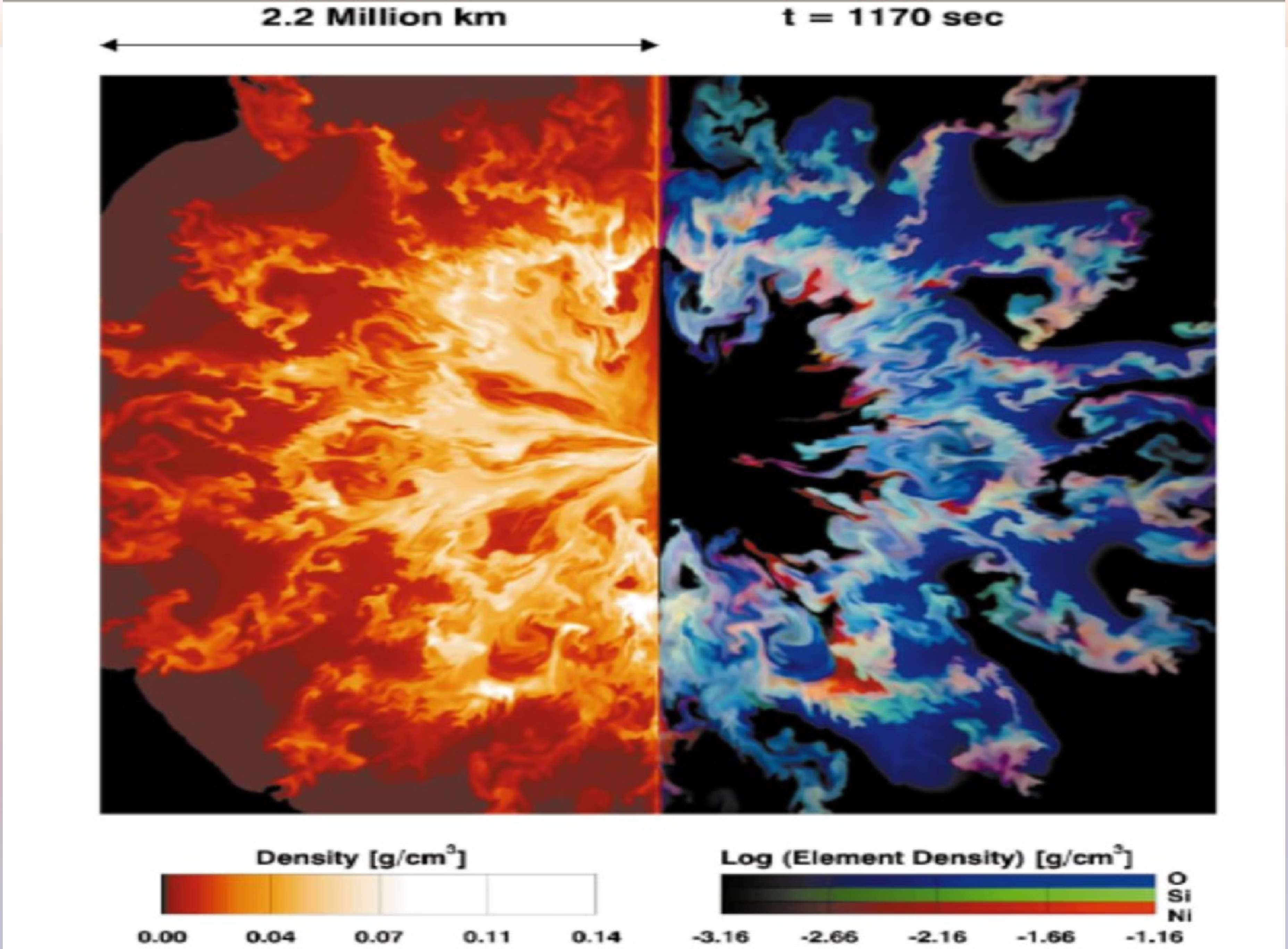
Some isotopes may be sequestered in the unexploded cores of stars so the interstellar nuclear abundances may not reflect global abundances

“ If nucleosynthesis is to become a precision science with accuracy better than a factor of 2, one also needs further improvements in the photon transmission function for nuclei in the mass range 28-64, especially better rates for (n,) and ( ) reactions.”

Origin of Mass ?

- protons and neutrons are not fundamental particles
- in physics 101 we give an operational definition of mass because we do not know what mass is
- Leptons and quarks and the W and Z bosons couple to an all pervasive field called the Higgs field and thus have mass. Photons do not couple to the Higgs field and thus have no mass.
- The Higgs field could be excited and its first vibration is the Higgs particle.
- The LHC (Geneva) and the Tevatron (Illinois) are searching for the Higgs particle.

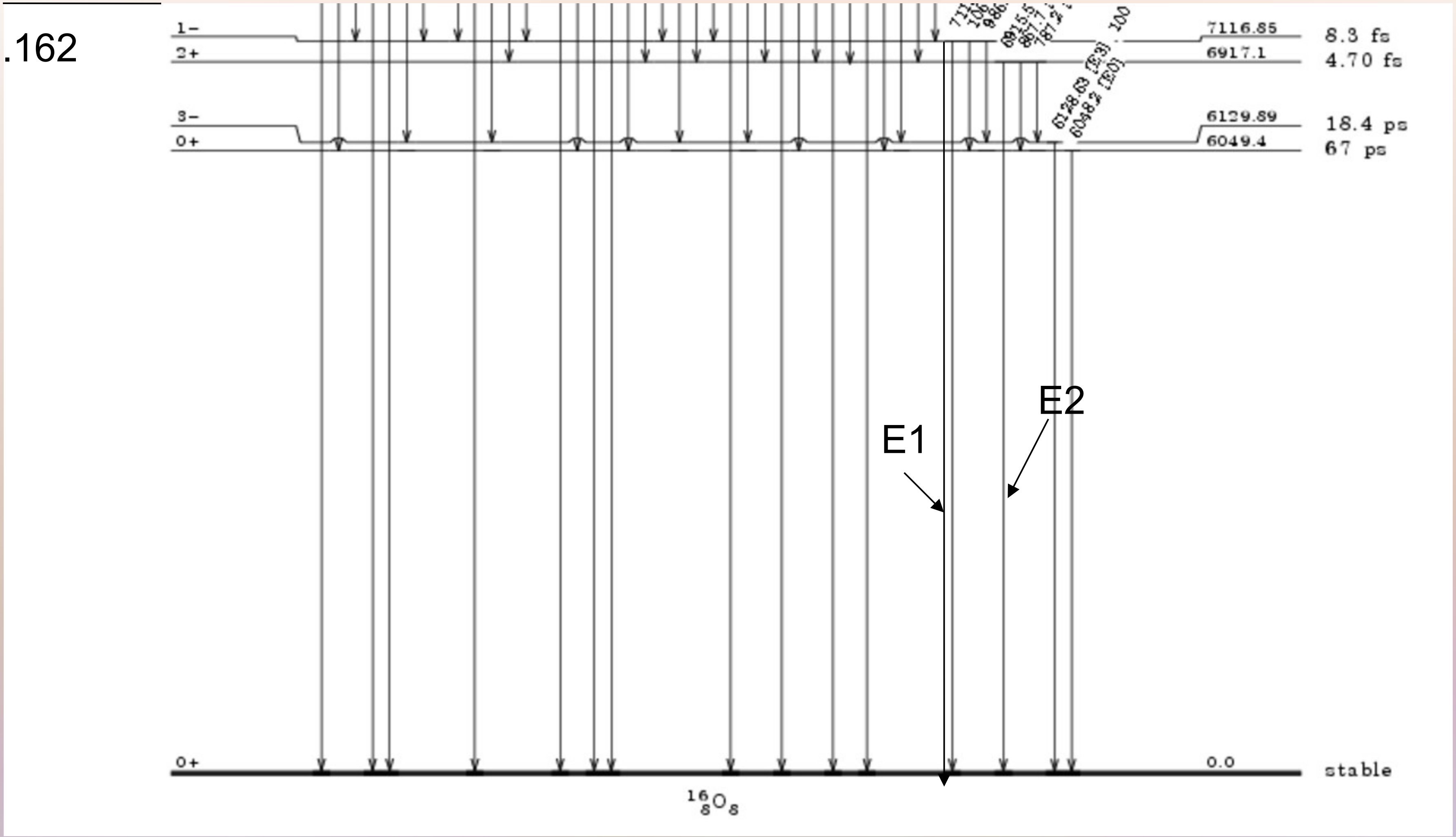
- Most of the mass in the universe is not due to the chemical elements.
- Come to the December 2 lecture by Professor Mijic to get an update on the bulk of the mass and energy in the universe!



Mixing in the explosion of a 15 solar mass red super giant. (Woosley and Heger)

^{12}C +

7.162



“... the reaction ^{12}C( ) ^{16}O warrants special discussion as it affects not only the ratio of carbon and oxygen to come out of helium burning, but indirectly the nucleosynthesis of many other species and the very structure of the presupernova star. Determination of an accurate rate for this reaction is experimentally challenging because it proceeds predominantly through two subthreshold resonances whose critical alpha widths must be determined indirectly[the excited states are at 7.117 MeV and 6.917 MeV; the Q value is 7.162 MeV]. “ **RMP 74 1015 (2002) S. E. Woosley and A. Heger**