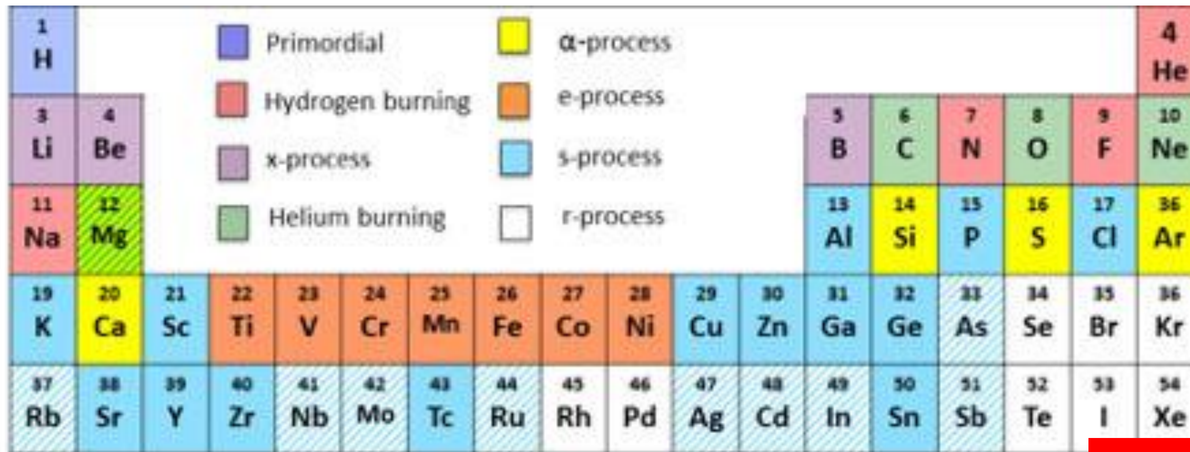
Big Bang and stars,
two hot environments for making elements

Georges Meynet
Geneva University

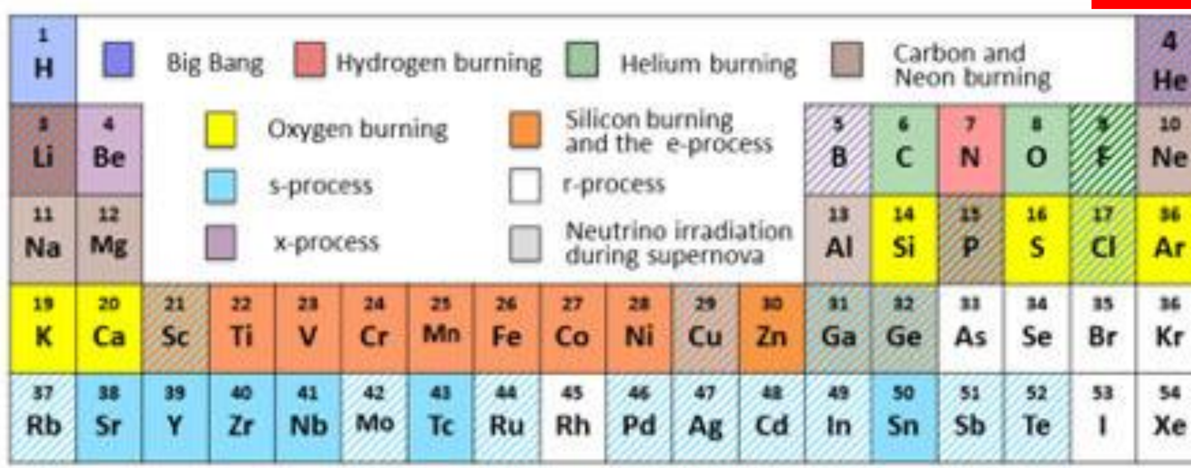
All things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence ... there is an enormous amount of information about the world.

Richard Feyman

B2FH 1957



2019



Woosley, Trimble, Thielemann, Physics Today 2019

1- A BIT OF HISTORY

THE COOKING OF THE ELEMENTS NEEDS MORE THAN ONE POT

A Tale of two theories
And One Dogma

The two theories

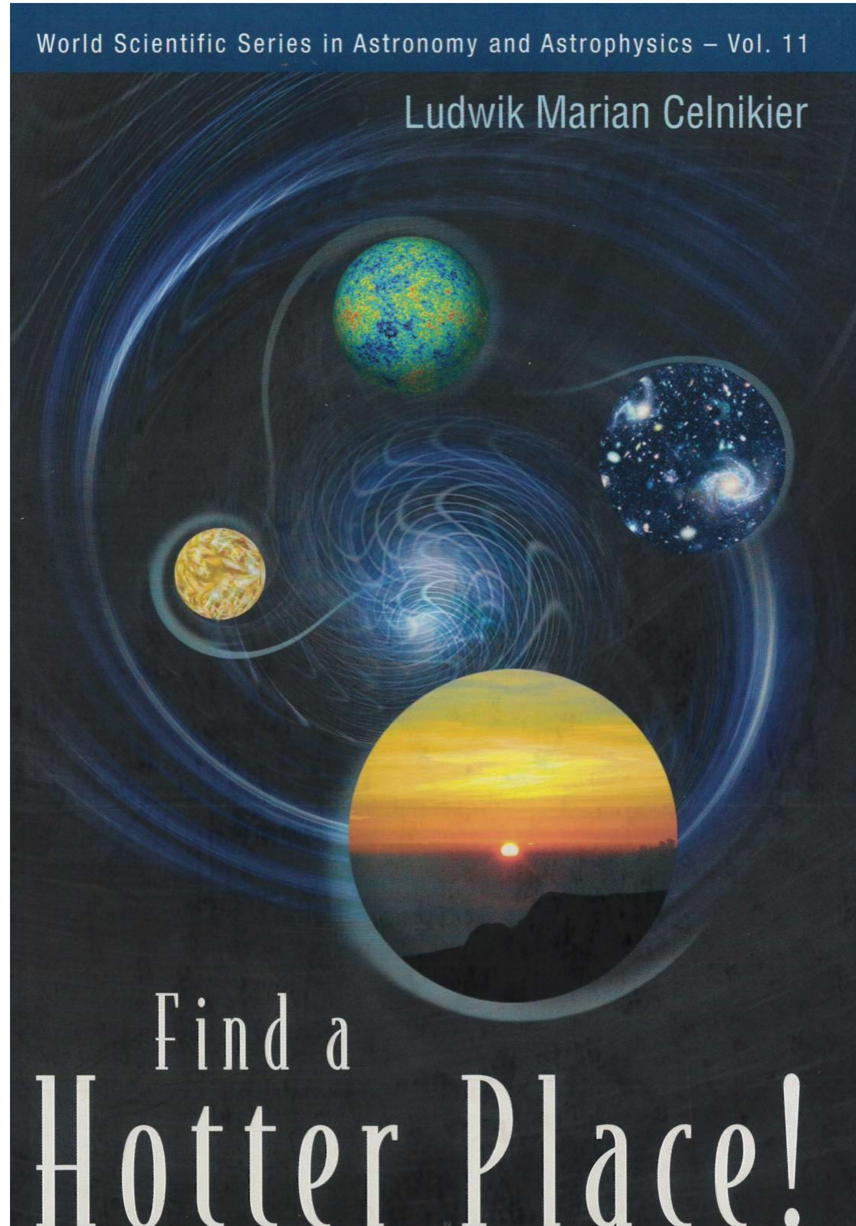
Elements all made in the early Universe

Elements all made in stars

The Dogma

A single site to create all the elements

But at least three nucleosynthetic sites
→ Big Bang
→ Stars
→ Interstellar medium irradiated
by energetic particles



Document University of Colorado and Collection T. Lombry

https://www.britannica.com/biography/Fred-Hoyle/images-videos

George Gamow 1904-1968

Big Bang Nucleosynthesis

Fred Hoyle 1915-2001

Stars
(stationary universe)

2- AN ARGUMENT AGAINST STARS

Helium must be produced during the Big Bang

Each time 4 nucleons are transformed into one He, an energy of 26 MeV is emitted

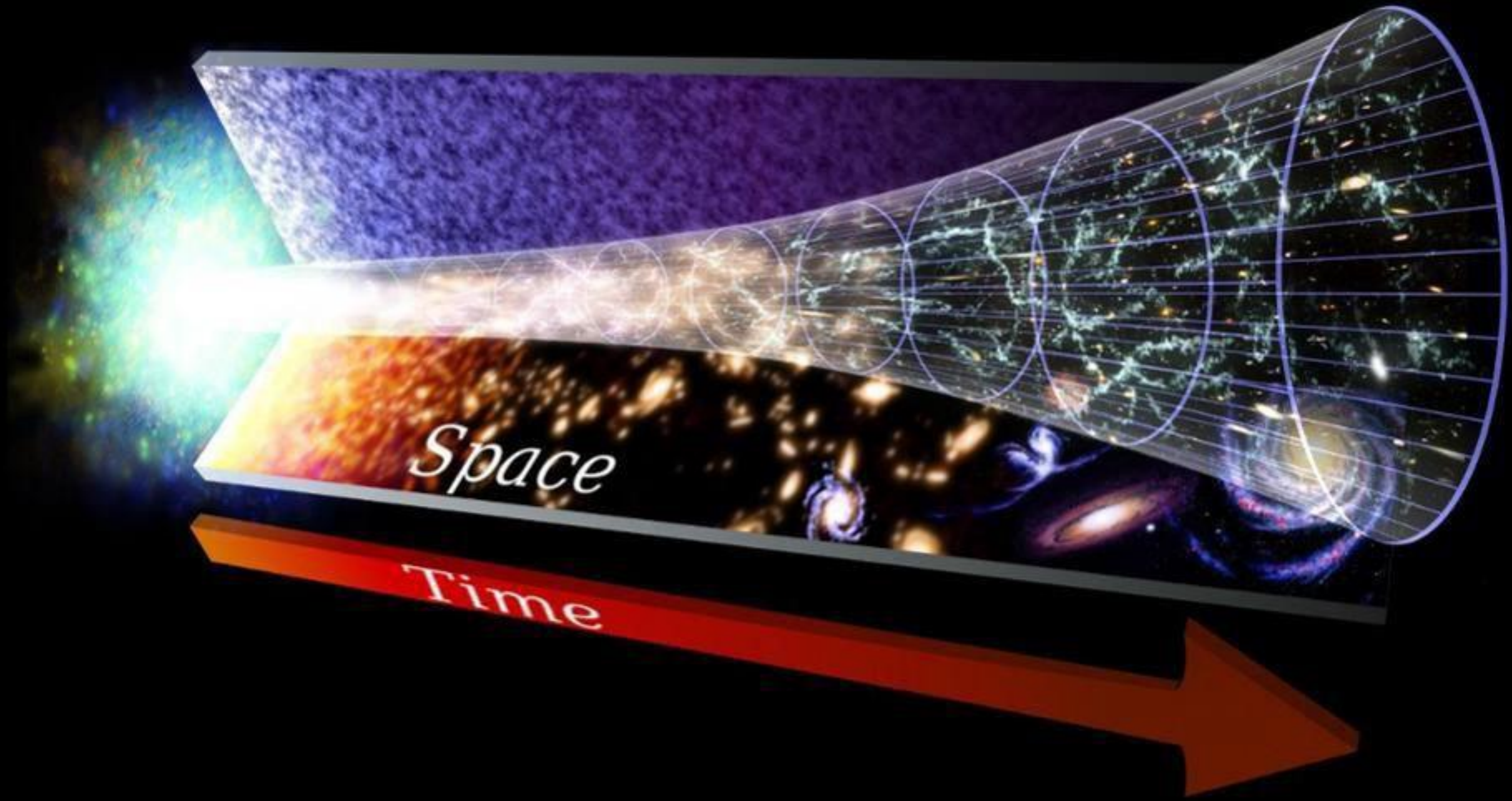
BUT 28% observed

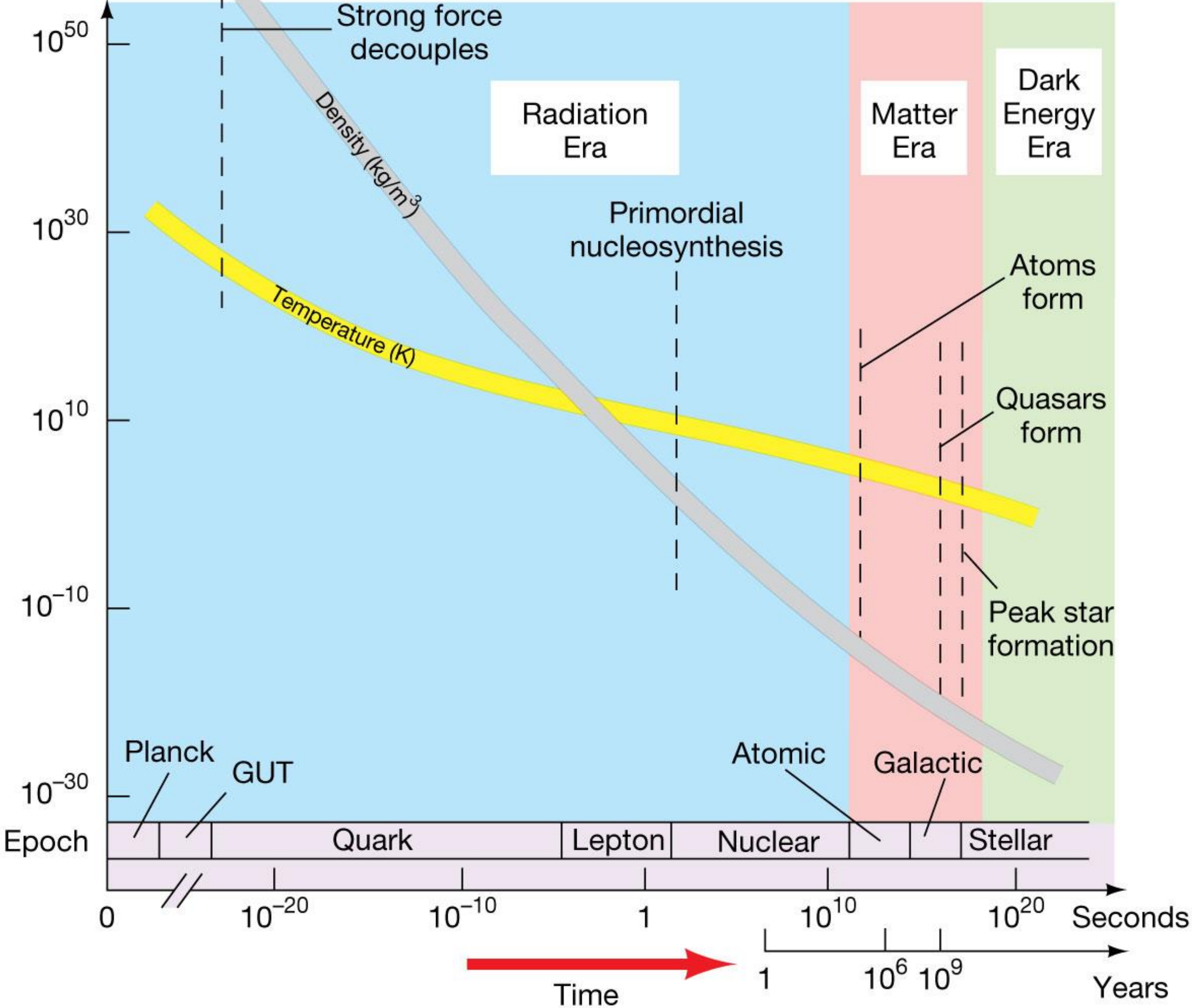
The amount of Helium nuclei required to be produced would represent

→ 10%

Of the mass of the Galaxy

3- MORE CHANCE IN THE EARLY UNIVERSE?





https://pages.uoregon.edu/jimbrau/BraulmNew/Chap27/7th/AT_7e_Figure_27_04.jpg

A first step towards Helium production → deuterium

$$p + n \rightarrow d + \gamma$$

Binding energy $2.2\,\text{MeV} \rightarrow 2.6 \times 10^{10}\,\text{K}$

Actually, for substantial d production, the temperature must decrease to

$$T = 9 \times 10^{8}\,\text{K}$$

<u>This happen ~270 s after BB</u>

It is possible to estimate the ratio of the number of neutrons to the number of proton when deuterium begins to be synthesized

Number of neutrons/Number of protons=

$$e^{-\frac{(m_n - m_p)c^2}{kT}}$$

When kT is about 0.6 MeV
→ no longer pairs formed,
→ ratio frozen→

$$e^{-\frac{1.2MeV}{0.6MeV}} = 0.135$$

$$\frac{N_D}{N_D + N_{p(noD)}} = \frac{N_n}{N_n + (N_p - N_n)} = \frac{N_n}{N_p} = 0.135$$

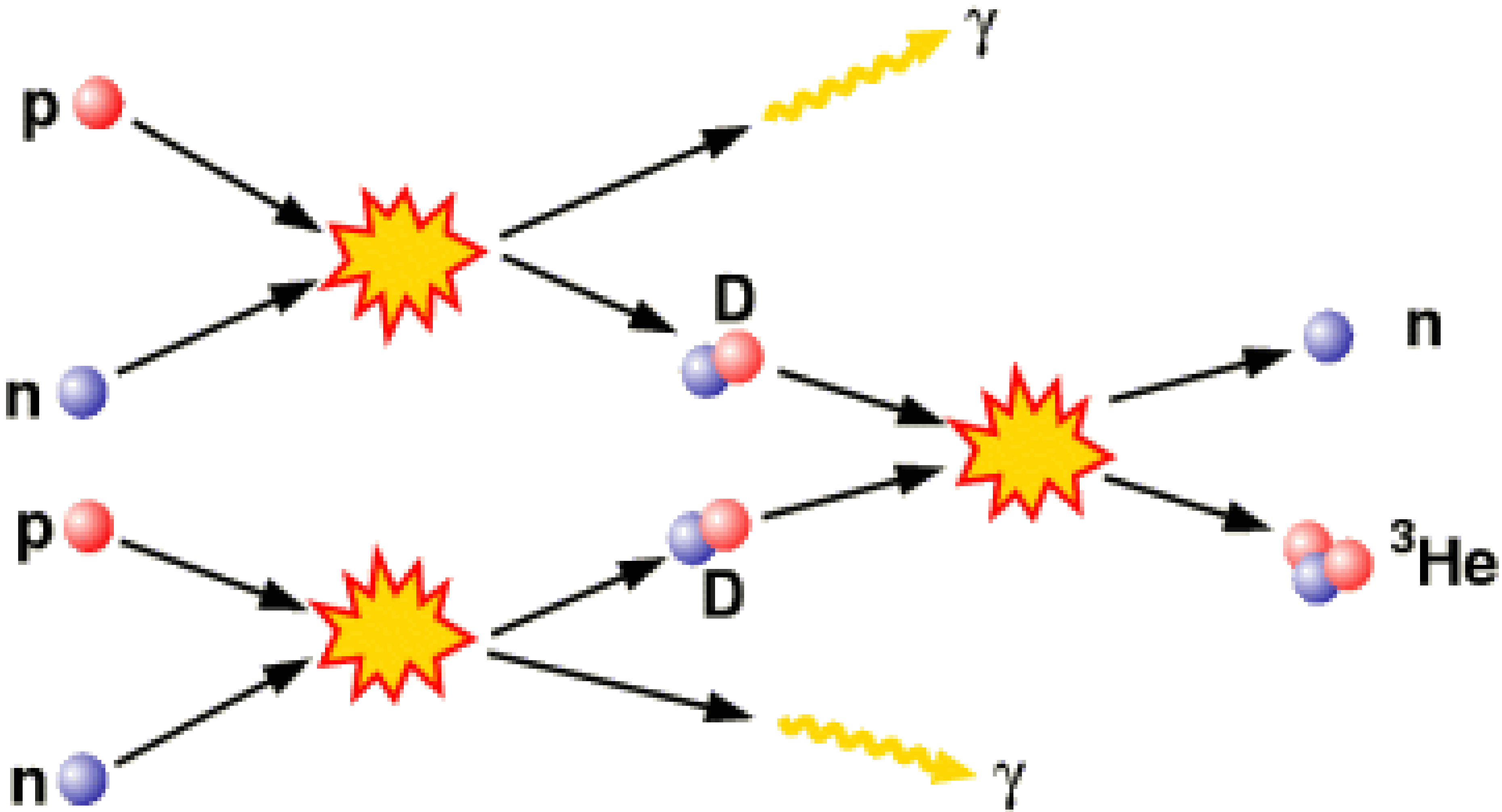
One can estimate the mass fraction of helium formed if all neutrons are assumed to be locked into helium

He fraction in number 0.07

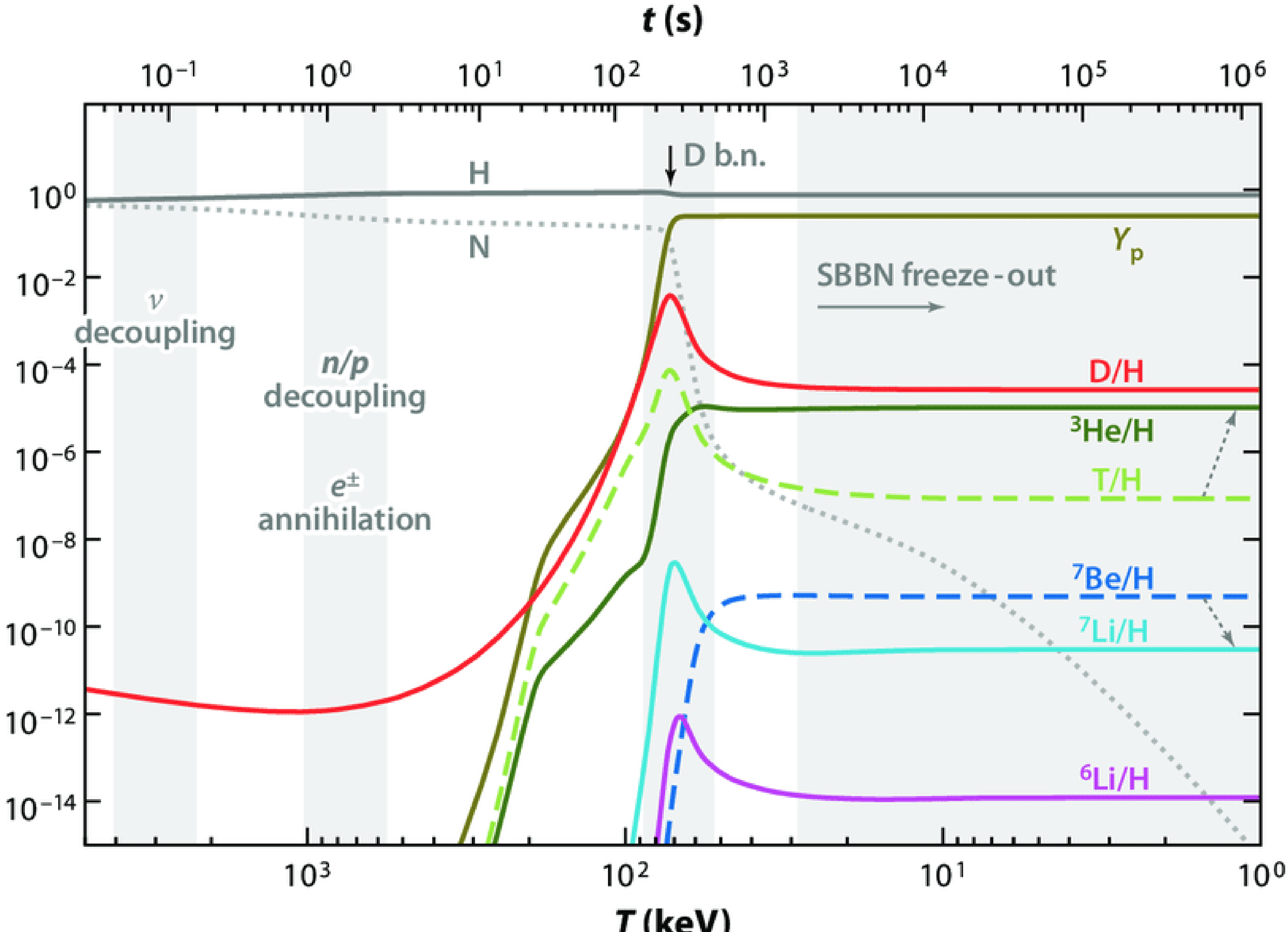
→In mass 0.28

OK! 28% observed

4- What else beyond helium?



The Big Bang nucleosynthesis: only a few light elements



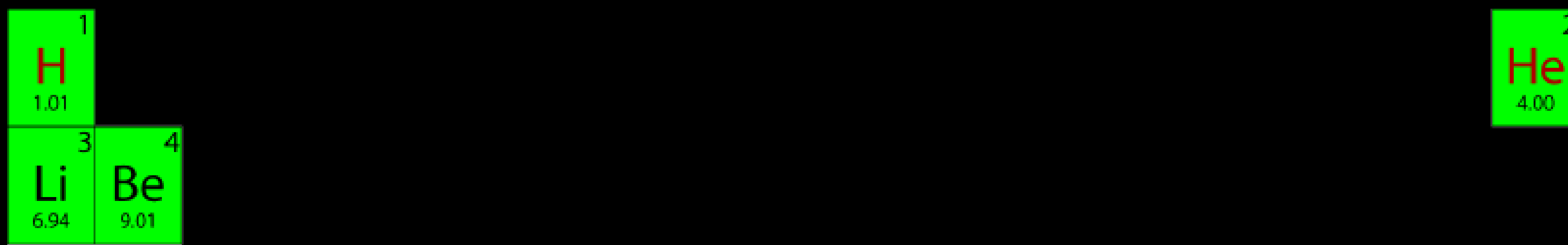
What are the factors that limits the BBN to only a few light elements?

- The time available at sufficiently high T and densities (expansion)
- The absence of any stable element with atomic masses equal to 5 and 8

There is no stable element with $A = 5$ or 8

- $A = 5$
  - ^{5}He: $7.2 \cdot 10^{-22}$ s
  - ^{5}Li: $3.7 \cdot 10^{-22}$ s
- $A = 8$
  - ^{8}Li: 838 ms
  - ^{8}Be: $6.7 \cdot 10^{-17}$ s
  - ^{8}B: 770 ms
  - ^{8}C: $2.0 \cdot 10^{-21}$ s

Primordial nucleosynthesis



At that point, the periodic table is still scarce

Adage

Starting from nothing and having only 15 minutes ahead, one cannot achieve great things...

5-Big Bang nucleosynthesis and the baryons

Pitrou et al. 2018

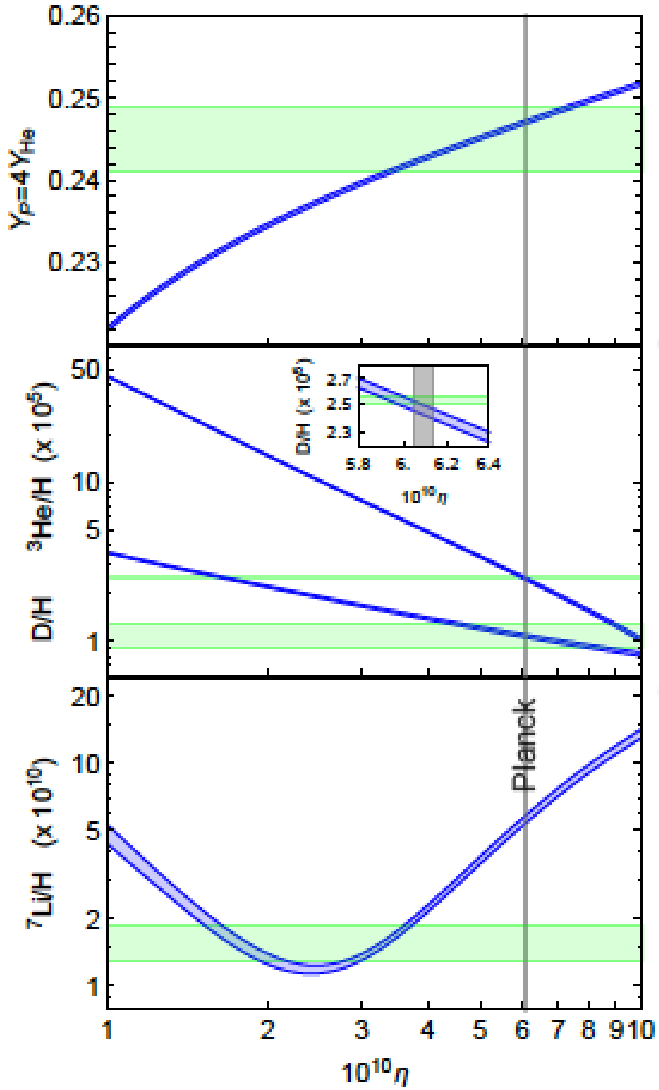


FIG. 26 *Top* : Dependence of $Y_P = 4Y_{^4He}$ in η and observational constraints. *Middle* : Dependence of deuterium (top curve) and ^{3}He (bottom curve) in η with observational constraints. The ^{3}H has been added since it decays radioactively in ^{3}He. *Bottom* : Dependence of ^{7}Li in η with observational constraints. The ^{7}Be has been added since it decays radioactively in ^{7}Li. In all these plots, the width of the curves represents the $\pm\sigma$ uncertainty from nuclear rates and neutron lifetime.

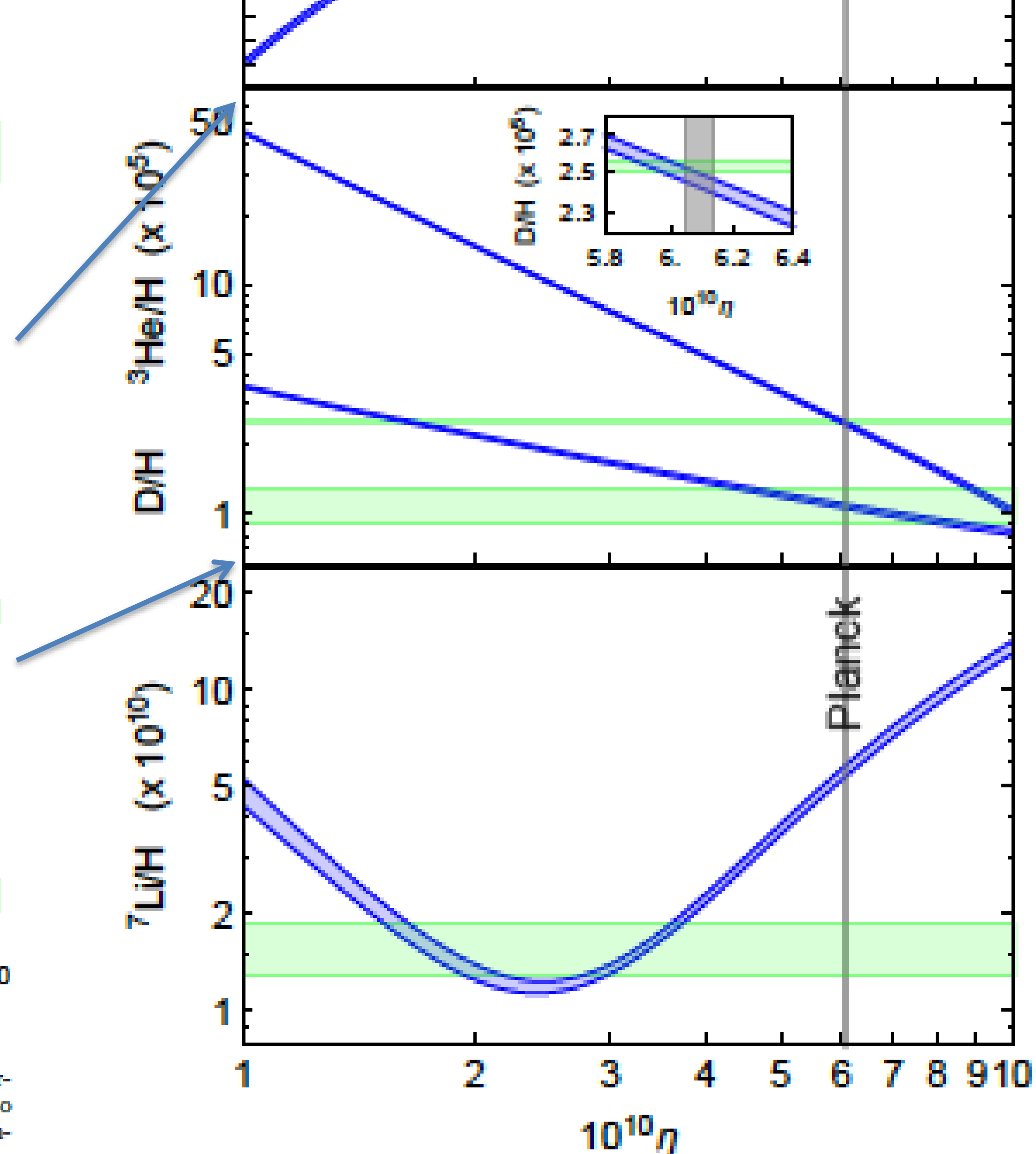
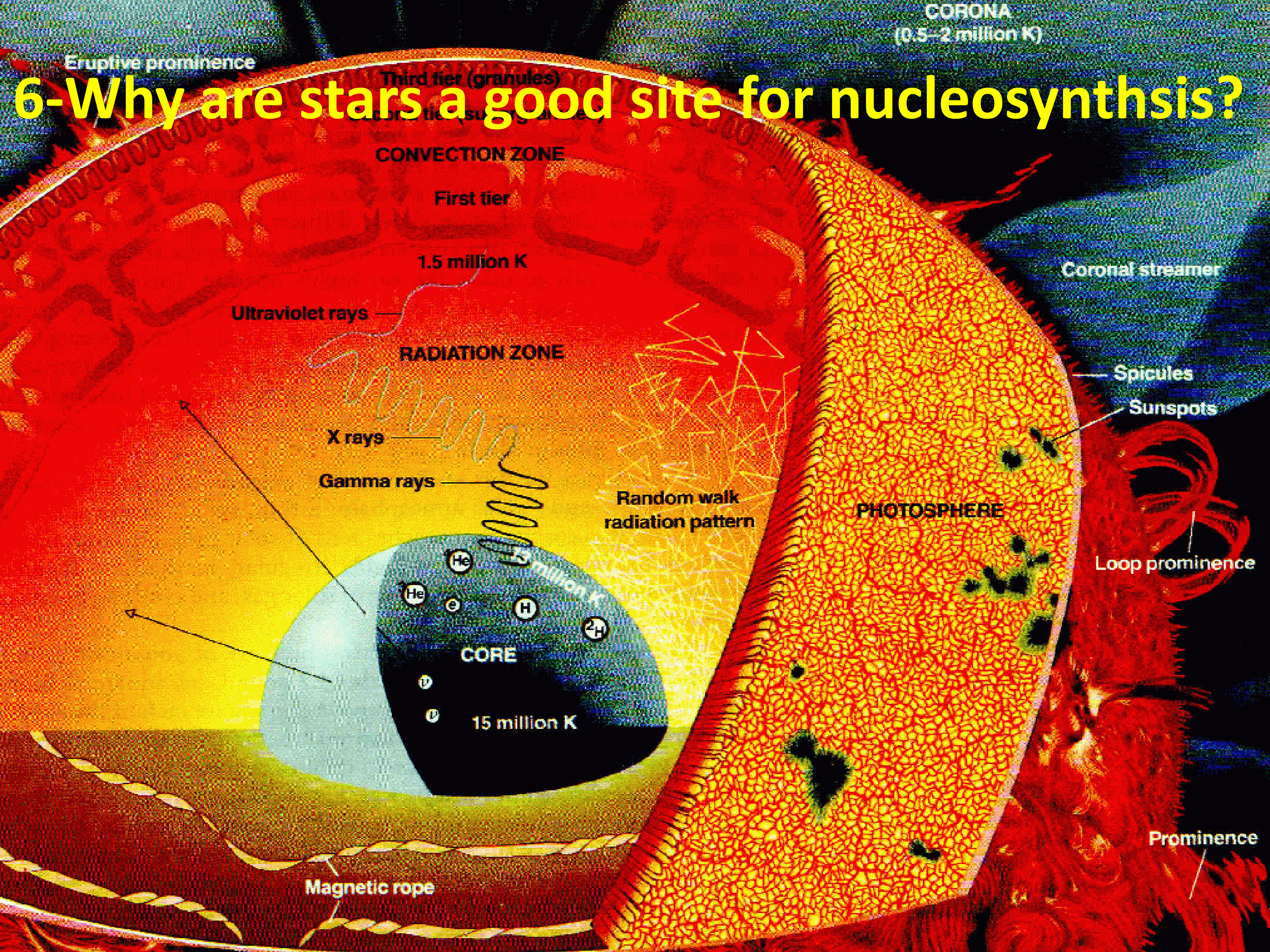


FIG. 26 *Top* : Dependence of $Y_P = 4Y_{^4He}$ in η and observational constraints. *Middle* : Dependence of deuterium (top curve) and ^{3}He (bottom curve) in η with observational con-

6-Why are stars a good site for nucleosynthsis?



A SIMPLE ESTIMATE OF THE CENTRAL PRESSURE

$$\frac{dP}{dr} = -\rho g$$

$$\frac{P_s - P_c}{R} \approx -\frac{M}{\frac{4}{3}\pi R^3}\frac{GM/2}{(R/2)^2}$$

$$P_c \approx \frac{1}{2} G \frac{M^2}{R^4}$$

A SIMPLE ESTIMATE OF THE CENTRAL TEMPERATURE

$$P_c \approx \frac{1}{2} G \frac{M^2}{R^4}$$

$$P = \frac{k}{\mu m_H} \rho T$$

$$\rho_c = f\rho$$

$$T_c = \frac{2Gm_H}{k} \frac{\mu_c M}{fR}$$

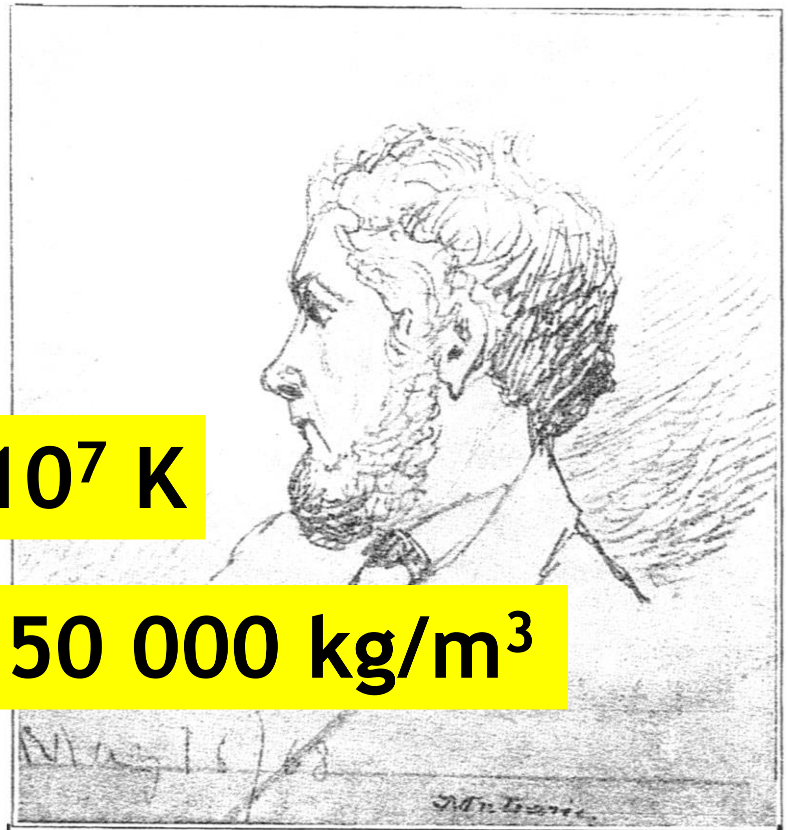
Holmer Lane, assuming the Sun is made of gaz, deduced the values of the central temperature and of the central density of the Sun and obtained for the central density a value of 150 g cm-3 denser than The lead on Earth. What is wrong?

J. Homer Lane 1869
Amer. J. Sci.,
2d ser., 50, 57

Temperature → 10^7 K

Densité → 150 000 kg/m^3

LEAD DENSITY: 11 350 kg/m^3



J. Homer Lane

August 9, 1819—May 3, 1880.

7. Is it sufficient?

ACTUALLY THEY ARE NOT SO APPROPRIATE AT FIRST SIGHT

kT= 8.68 10^{-8} T [keV]

FOR T= 10^7 K, kT is about 1 keV

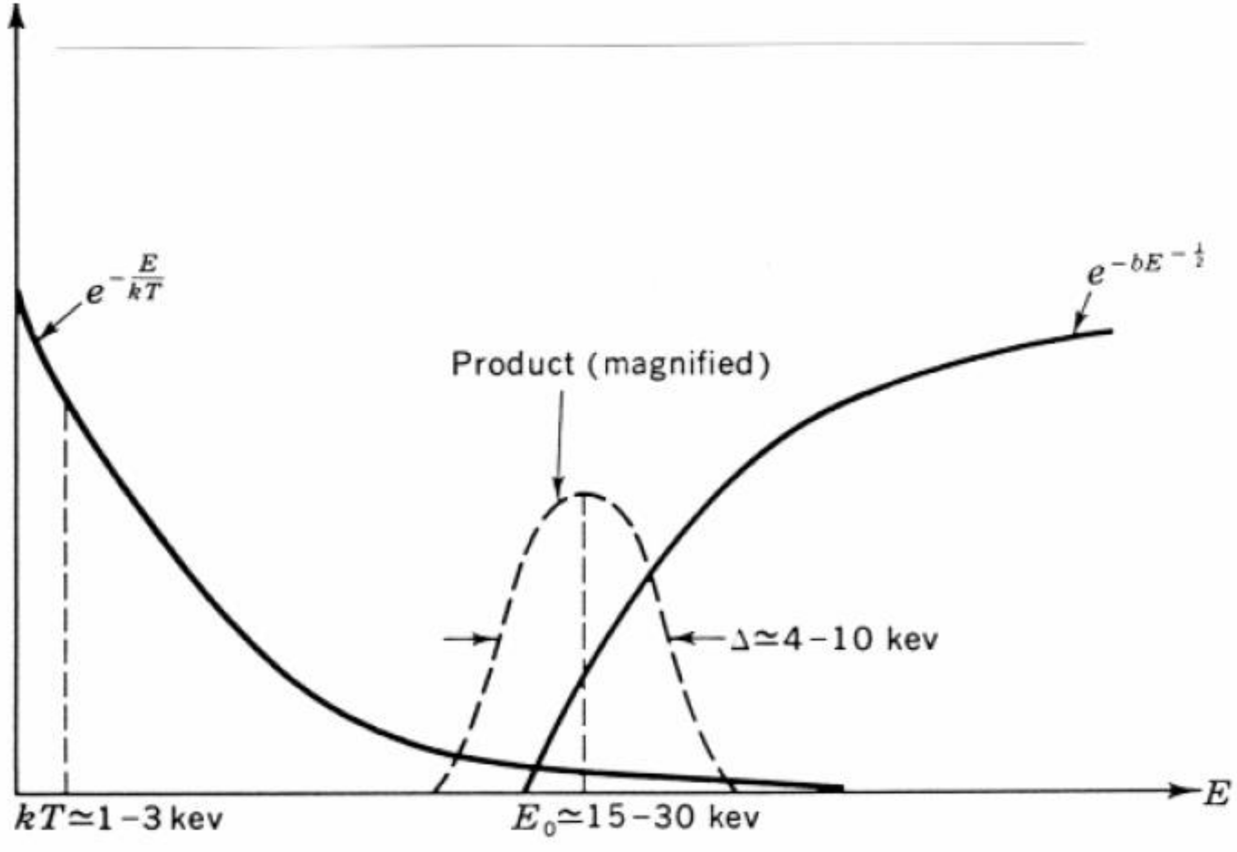
The coulomb potential $V = \frac{1.44 Z_1 Z_2}{d}$ MeV, d in Fermi [10^{-15}m]

FOR d= 2 Fermi, V is about 700 keV

TWO EFFECTS ALLOW TO MITIGATE THIS DIFFICULTY

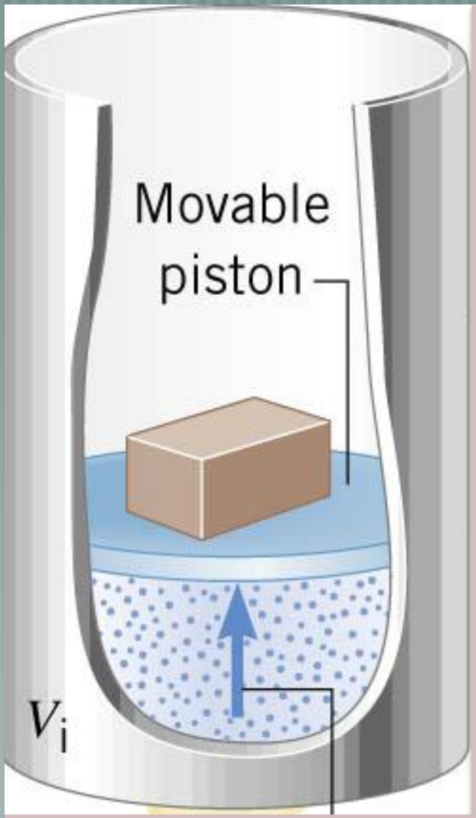
1) kT is the mean kinetic energy, but actually there is a maxwellian distribution with a branch at much higher energies

2) There is a Tunnel effet



8. Would stars exist without nuclear reaction?

GRAVITATIONAL SOURCE MAKE TOO SHORT LIFETIME, ANOTHER SOURCE IS NEEDED ALLOWING TO OBTAIN LONGER AGES



THE LIFETIME OF THE SUN IN CASE IT WOULD HAVE ONLY THE GRAVITATIONAL SOURCE WOULD BE GIVEN BY THE RATIO OF ITS GRAVITATIONAL ENERGY CONTENT ON ITS LUMINOSITY

$$\tau_{KH} = \frac{GM^2}{RL} \rightarrow \tau_{KH} = 10^7\, years$$

KELVIN-HELMHOLTZ TIMESCALE

NUCLEAR REACTIONS ARE RESPONSIBLE FOR THE LONG STELLAR LIFETIMES

- NUCLEAR ENERGY

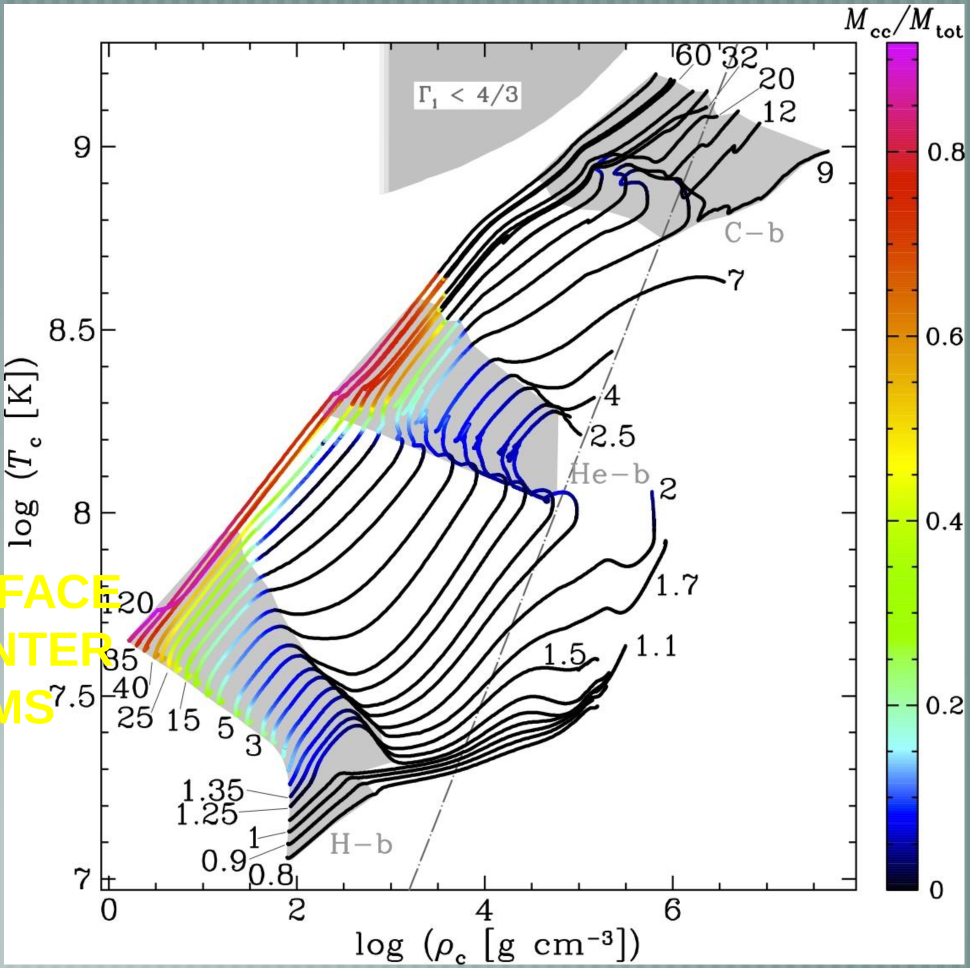
HOW LONG CAN IT LAST?

$$\tau_{nucl} \approx \frac{MqX\,0.007c^2}{L} \rightarrow \tau_{nucl} \approx 10^{10}\,years$$

THE LIFE OF A STAR IS GOVERNED BY THE GRAVITY. IT CONSISTS IN A SUCCESSION OF CONTRACTION PHASES AND OF PHASES WHEN CONTRACTION IS NEARLY STOPPED BECAUSE NUCLEAR REACTIONS ARE ACTIVE

Models by

Ekström et al. (2012)
A&A, 537, A146)



A STAR LOSES ENERGY AT THE SURFACE BUT BECOMES WARMER AT THE CENTER
→ NEGATIVE SPECIFIC HEAT SYSTEMS

9. What is the origin of oxygen?

THE NUCLEAR PATHWAY: IN H-BURNING REGIONS IN STARS MORE MASSIVE THAN 1.2 M_{sol} (NEAR SOLAR METALLICITY)

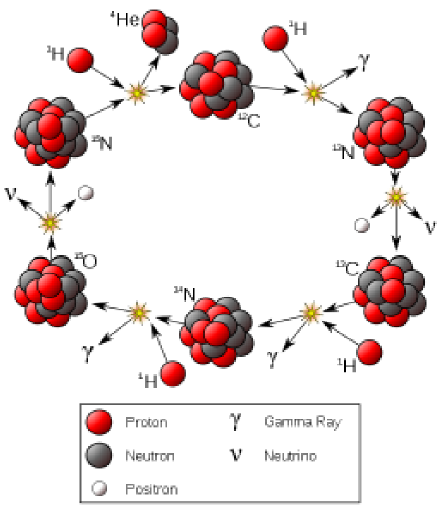
CNO cycle

C, N, and O are used as catalysts

dominant at $T > 18$ MK

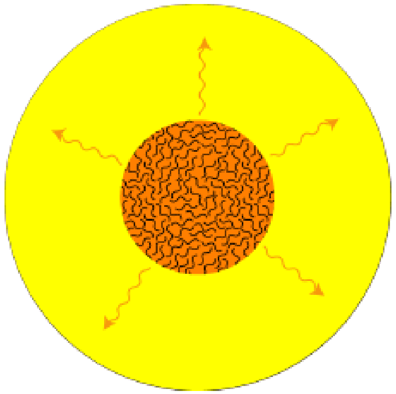
highly temperature sensitive:

$$\varepsilon_{CNO} \simeq \varepsilon_0 \rho T^{17}$$



stellar structure:

- convective core
- radiative envelope



energy produced through one cycle: 25.03 MeV

NB : C+N+O = constant

OXYGEN IS DESTROYED AT THE PROFIT OF NITROGEN

THE NUCLEAR PATHWAY: IN He-BURNING REGIONS OXYGEN IS SYNTHESIZED

He burning

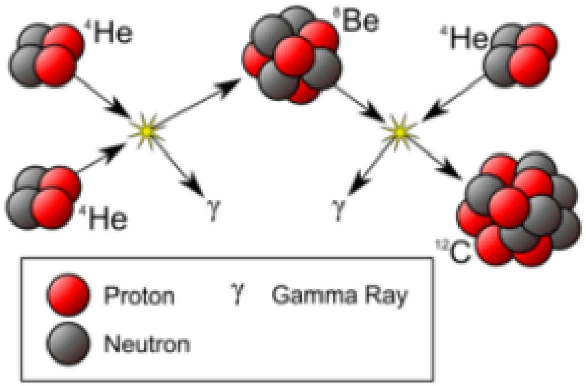
Salpeter (1952) proposes the 3α reaction

$$
\begin{aligned}
{}^4\text{He} + {}^4\text{He} &= {}^8\text{Be} + \gamma \\
{}^8\text{Be} + {}^4\text{He} &= {}^{12}\text{C}^\star \\
&\rightarrow {}^{12}\text{C} + \gamma
\end{aligned}
$$

$${}^{12}\text{C} + {}^4\text{He} \rightarrow {}^{16}\text{O} + \gamma$$

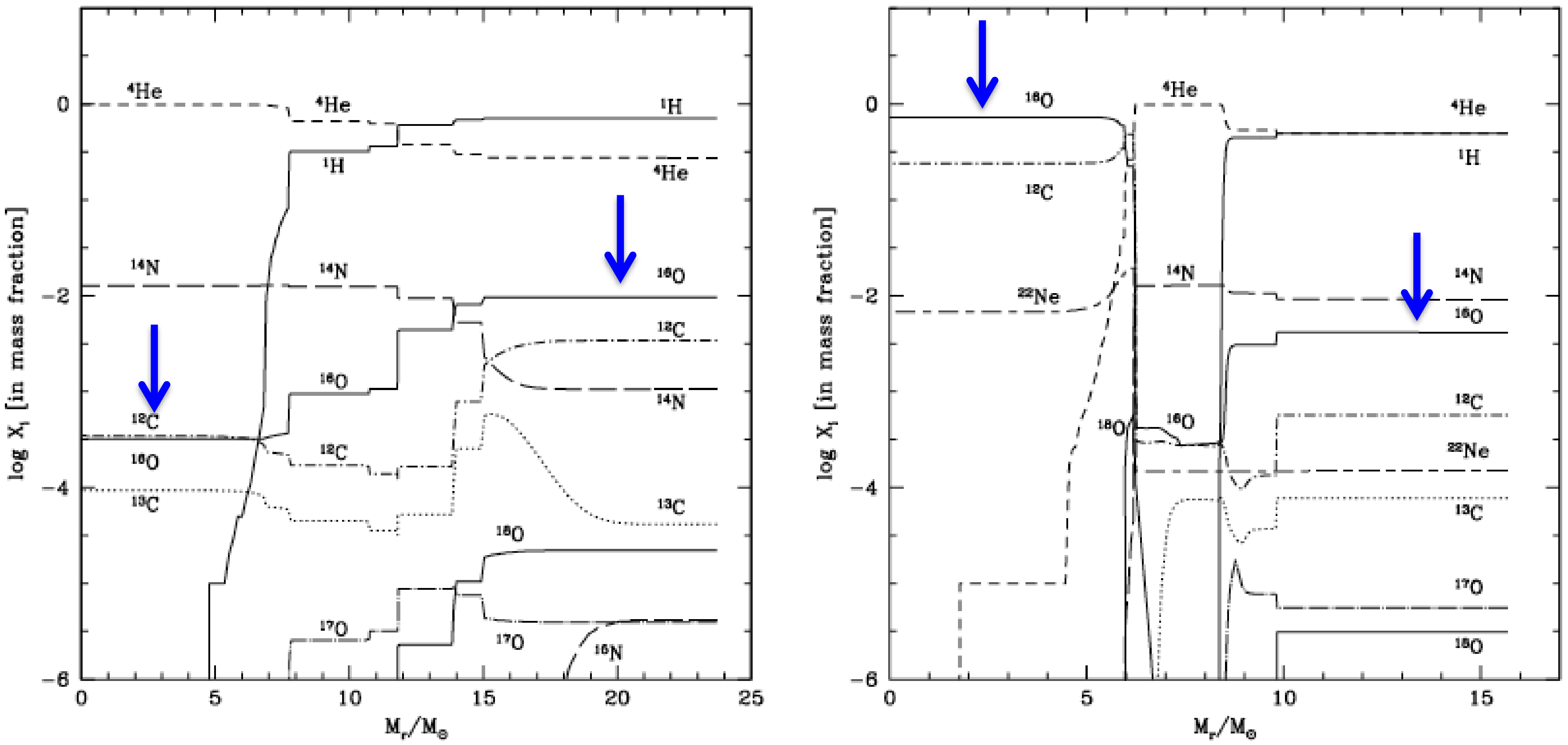
Hoyle (1954) predicts the level of excitation at 7.7 MeV, explaining the observed ^{12}C abundance.

$$\varepsilon_{3\alpha} \propto \rho^2 T^{25}$$



energy released by the reaction : 7.28 MeV

COMPOSITION OF A 25 Msol STAR AT THE END OF THE CORE H-BURNING PHASE AND OF THE CORE HE-BURNING PHASE (Z=0.02)



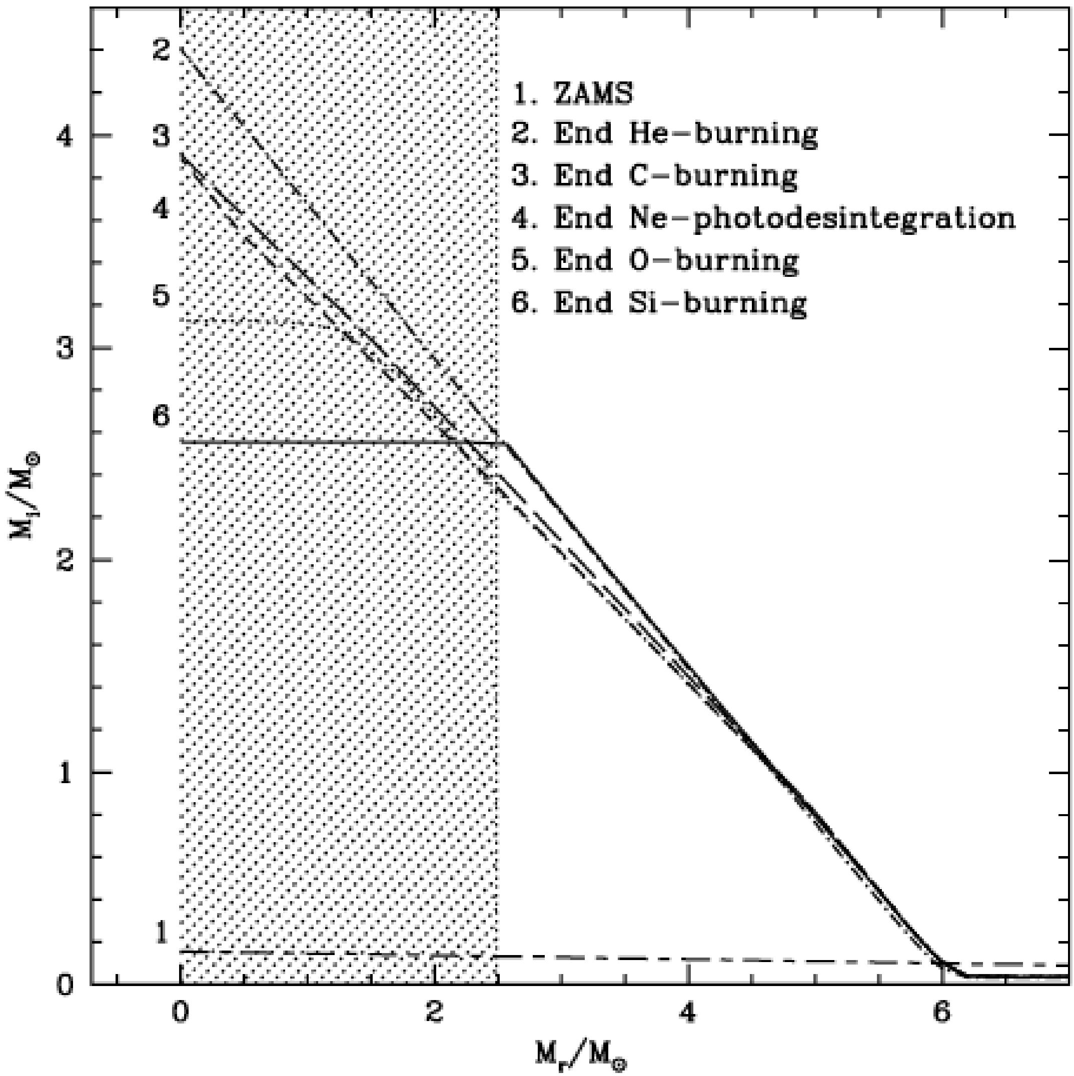
-QUESTION 5-
WHY IS THE CORE H-BURNING PHASE THE LONGEST PHASE?

Phase	Age [My.]	Mass $M_\odot$	log T_c	log ρ_c	q_{cc}	q_{env}	N/C	N/O
End H	6.60	24.20	7.875	1.518	0.090	0.000	0.31	0.11
End He	7.30	16.17	8.539	3.554	0.013	0.000	16.2	2.21
End C	7.32	16.00	9.127	6.563	0.000	0.464	19.1	2.38
End Ne	+50.4y	16.00	9.218	6.594	0.000	0.464	19.1	2.38
End O	+0.3 y	16.00	9.411	7.374	0.000	0.166	19.1	2.38
End Si	+0.1 y	16.00	9.787	8.638	0.001	0.062	19.1	2.38

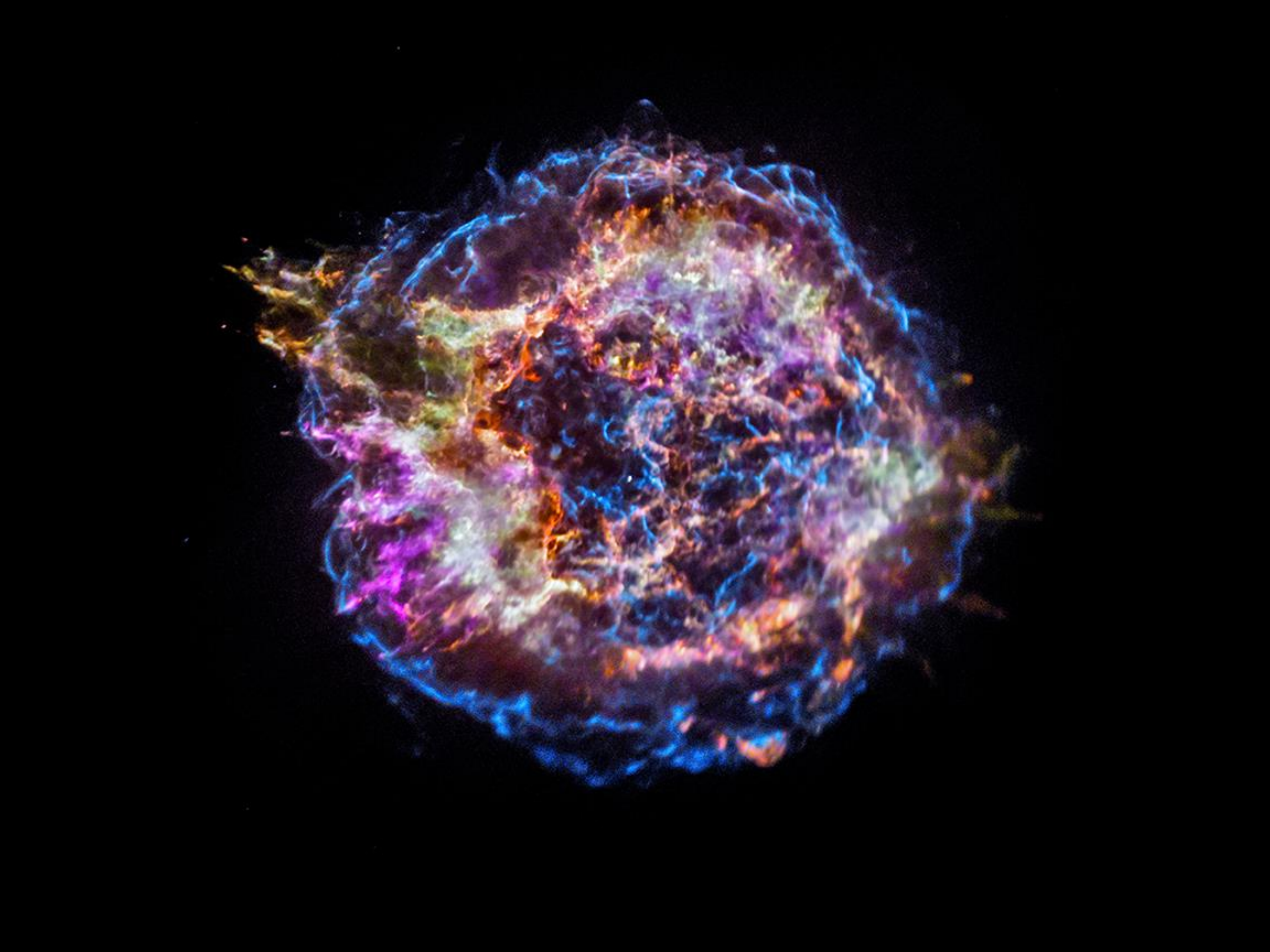
- Energy released by nucleon is the largest
- The convective core is the largest
- The Luminosity tends to increase with time.

VARIATIONS OF THE INTEGRATED ABUNDANCE OF OXYGEN (STARTING FROM THE SURFACE) AT DIFFERENT STAGES IN A 25 M_{sol} MODEL. THE GREY PART IS EXPECTED TO REMAIN LOCKED INTO THE REMNANT

$$M_i(M_r) = \int_{M_r}^{M} X_i(m_r)\mathrm{d}m_r$$



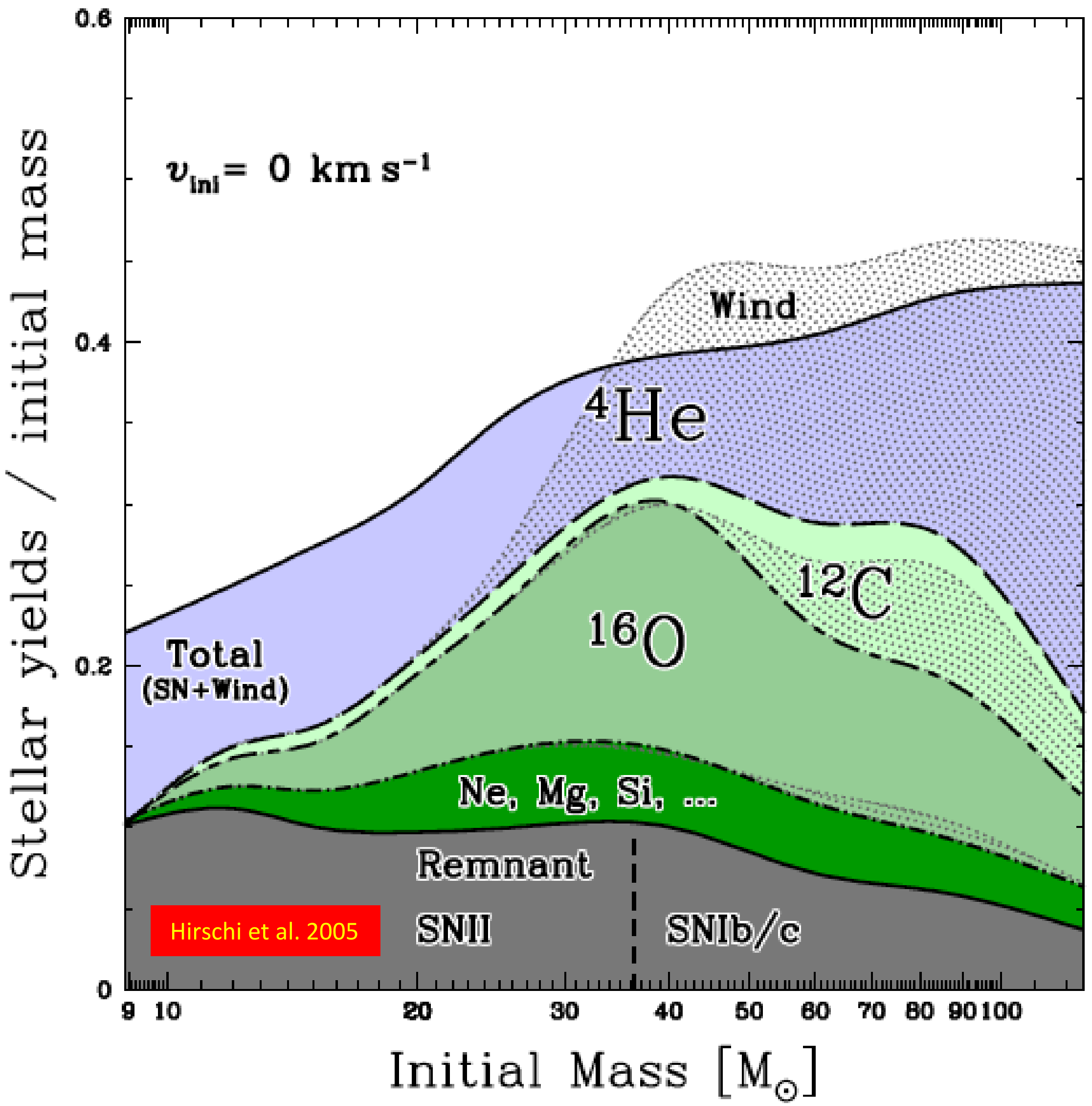
10. How this new syntehsized oxygen is ejected?



STELLAR YIELDS AS A FUNCTION OF THE INITIAL MASS FOR SINGLE NON-ROTATING SOLAR METALLICITY STARS

$$M_i(M_r) = \int_{M_r}^{M} X_i(m_r) \mathrm{d}m_r$$

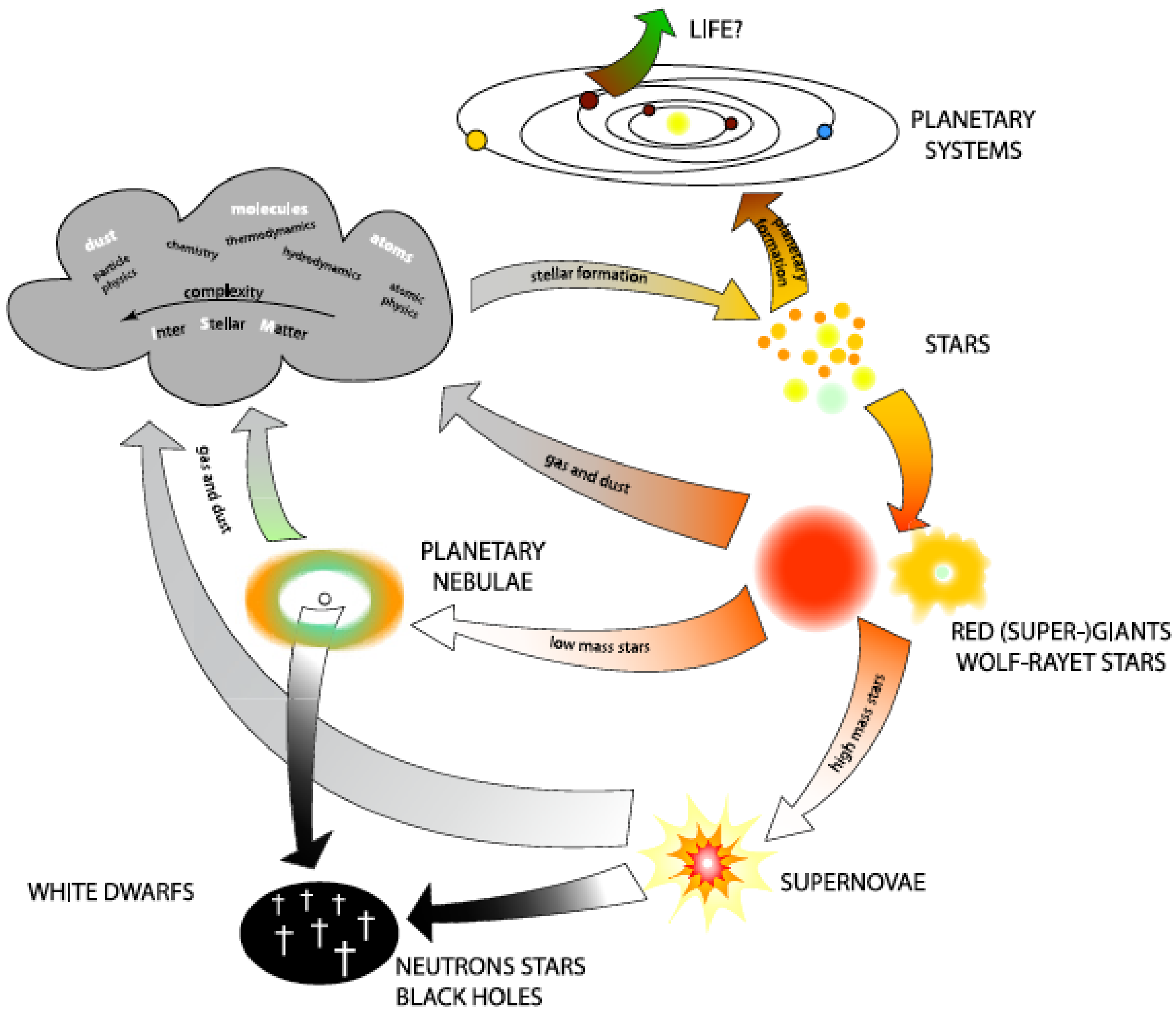
Stellar yield=
$M_i(M_r)-(M-M_r)X_i(m_r,t=0)$



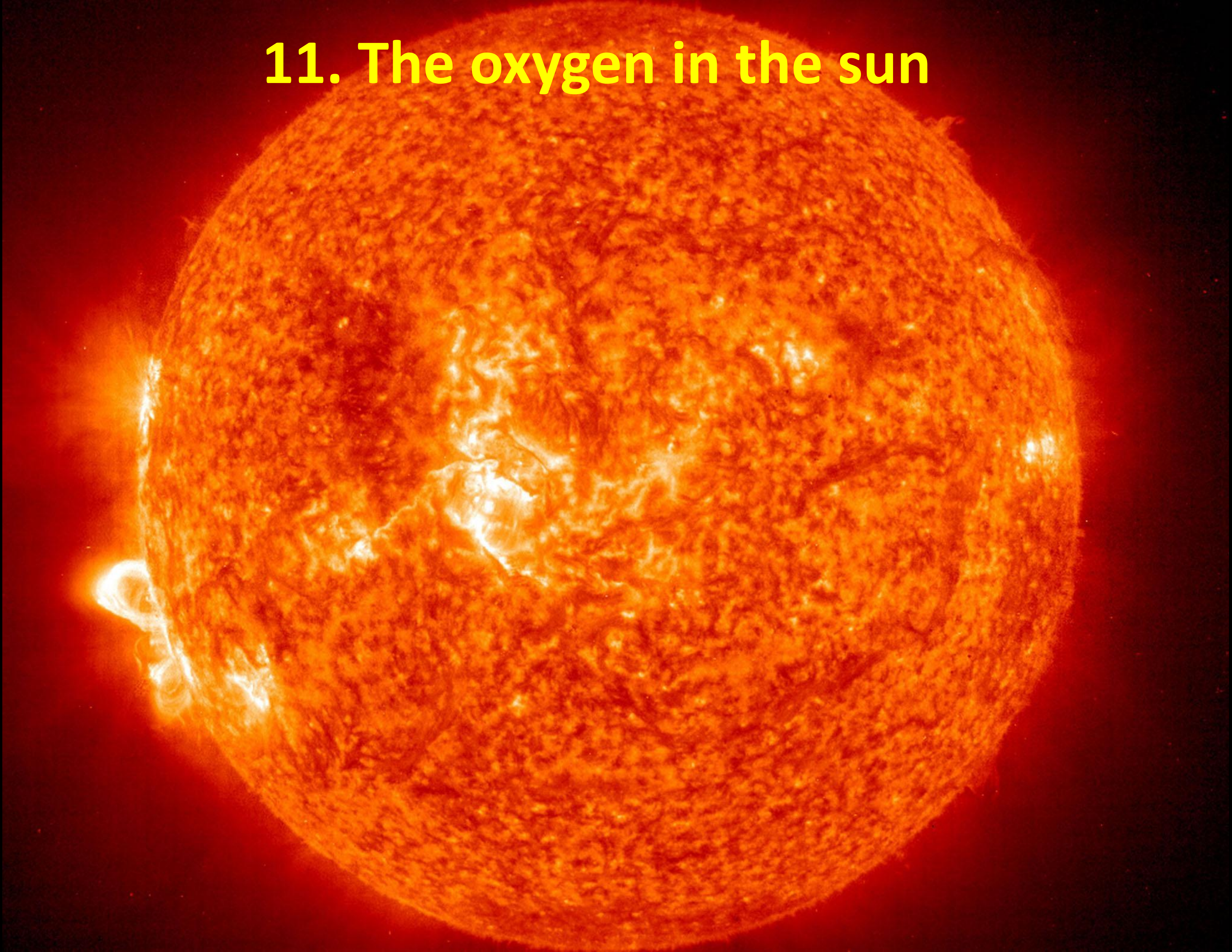
The life of stars, or the great cycle of matter

Main steps:

- Collapse of a cloud
- Nuclear reactions ignite
- Mass loss and/or explosion
- Induced star formation



11. The oxygen in the sun



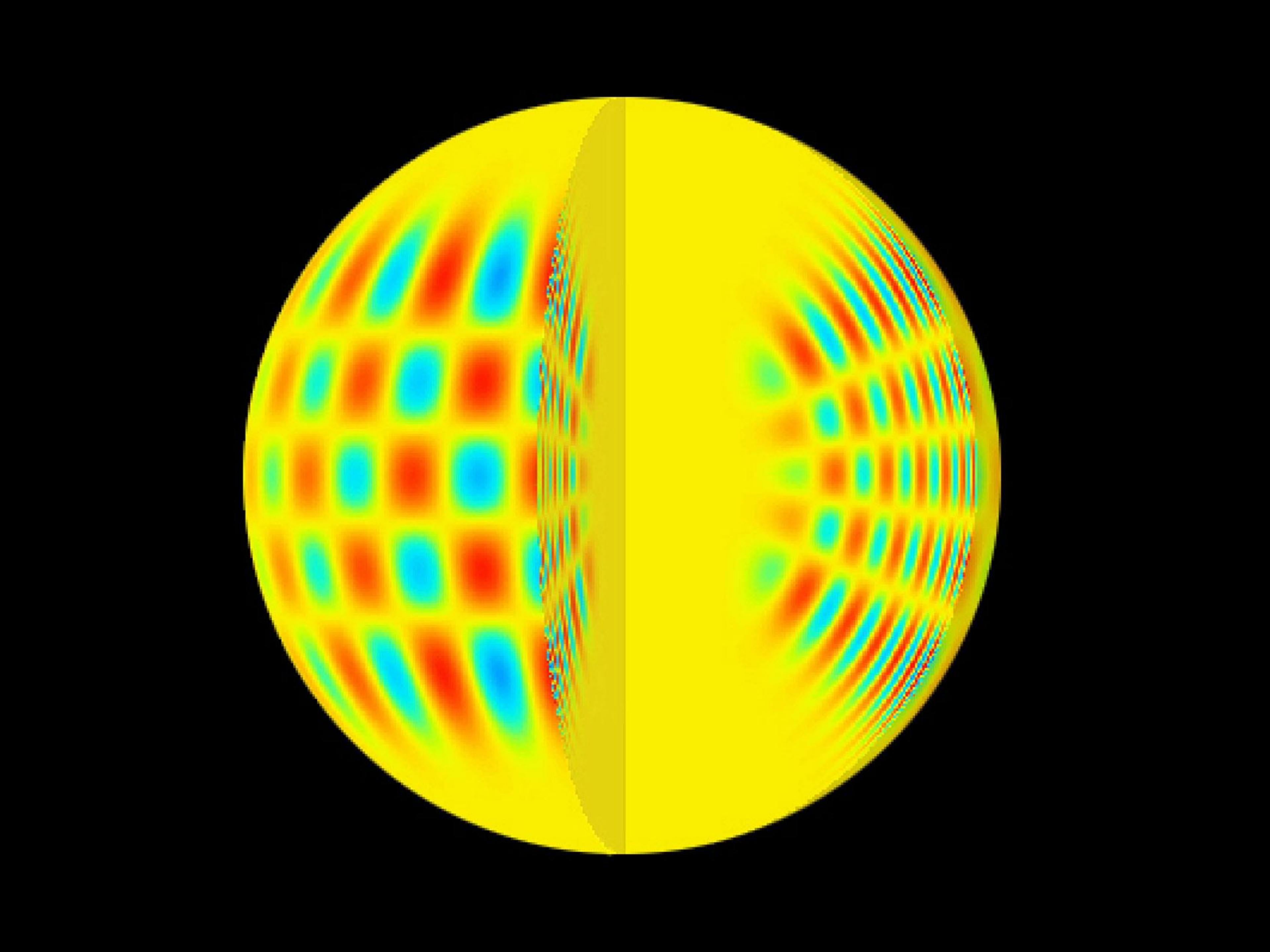
Solar abundances revisited

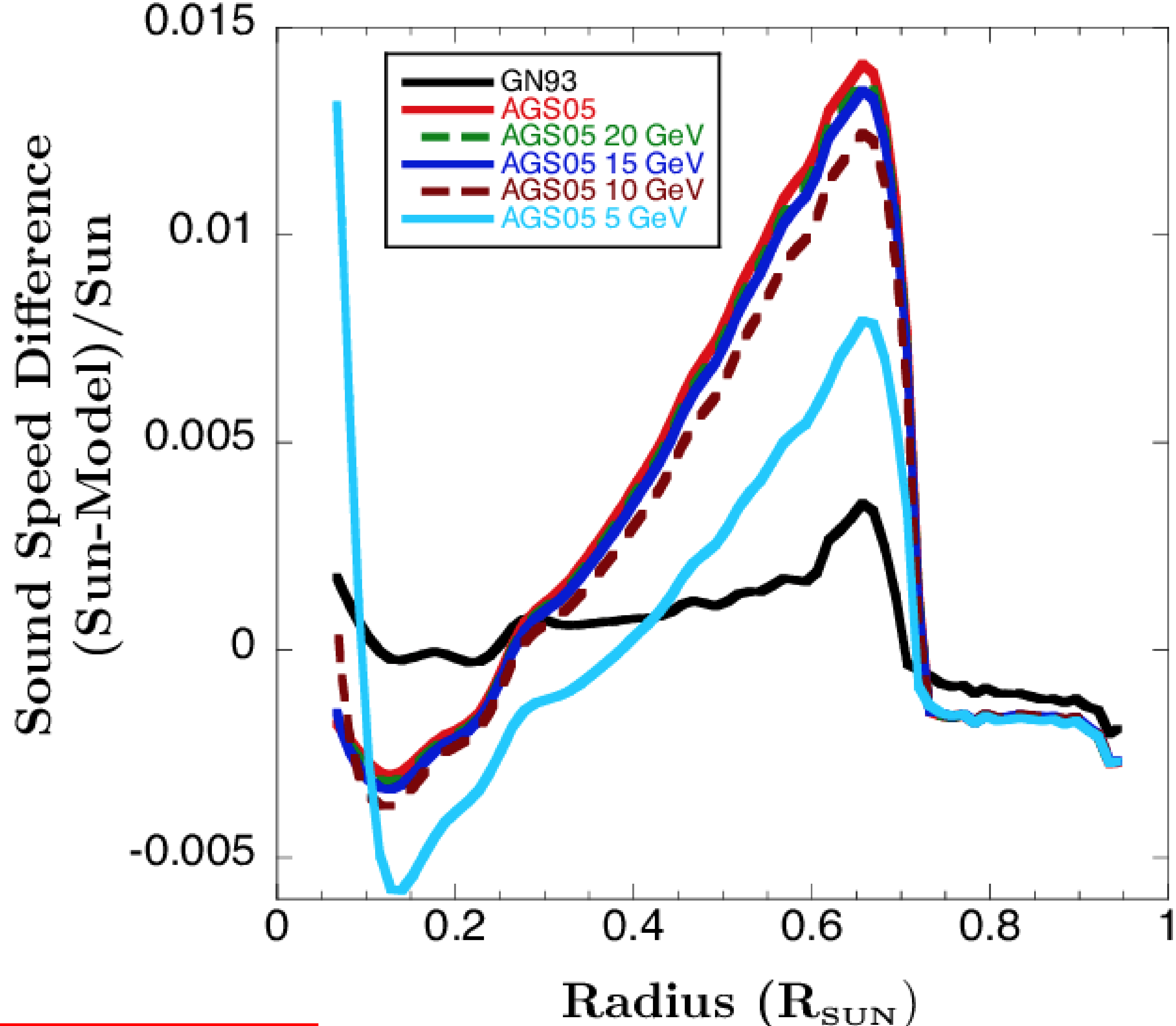
logarithmic scale with H defined to have 12.00

Element	Anders & Grevesse (1989)	Asplund et al. (2005)	Mass fractions Decreased
Carbon	8.56+/-0.06	8.39+/-0.05	-32%
Nitrogen	8.05+/-0.04	7.80+/-0.05	-44%
Oxygen	8.93+/-0.03	8.66+/-0.05	-54%

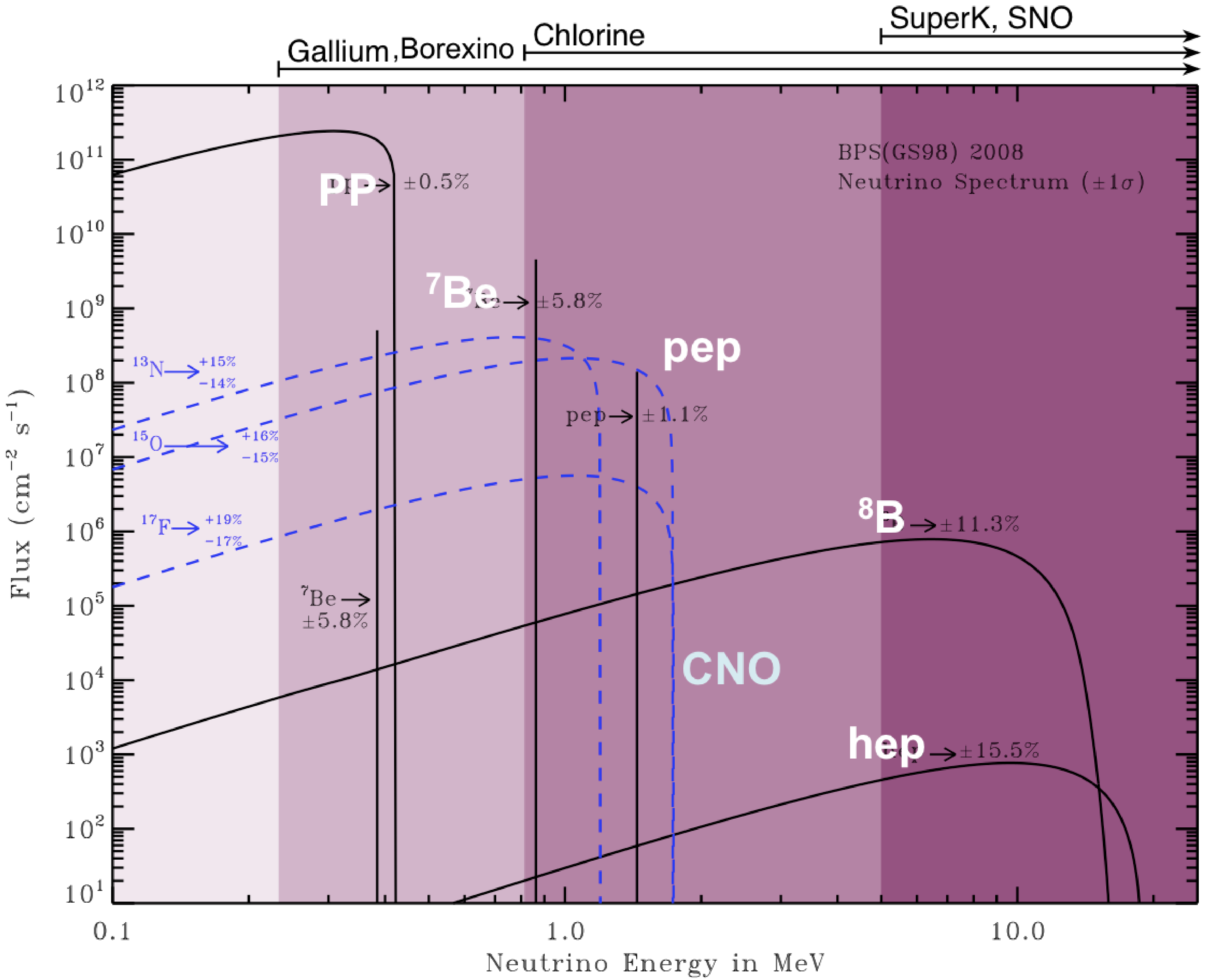
C+N+O→ 0.015 C+N+O→ 0.080

- 3D hydrodynamical solar model atmosphere
- Non-LTE line formation when necessary
- Atomic and molecular lines with improved data





Cumberbatch et al. 2010



Gallium,Borexino
Chlorine
SuperK, SNO
BPS(GS98) 2008
Neutrino Spectrum (±1σ)
PP
±0.5%
7Be
±5.8%
pep
pep
±1.1%
13N
+15%
-14%
15O
+16%
-15%
17F
+19%
-17%
8B
±11.3%
7Be
±5.8%
CNO
hep
±15.5%
Flux (cm^-2 s^-1)
Neutrino Energy in MeV
0.1
1.0
10.0

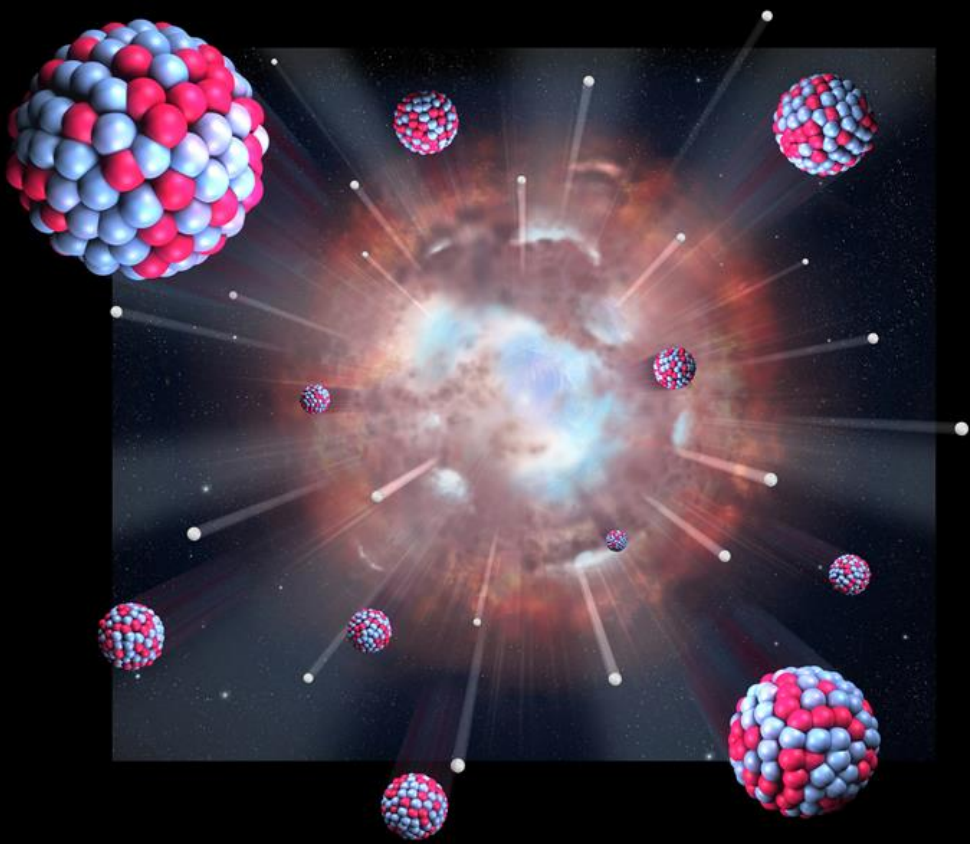
Table 3
Comparison of the solar neutrino fluxes measured by Borexino with the SSM expectations and a global fit which includes all experimental results obtained with solar, reactor, accelerator neutrinos.

Solar neutrino flux	GS98 (cm^{-2} s^{-1}) high metallicity $Z/X = 0.0229$	AGS09 (cm^{-2} s^{-1}) high metallicity $Z/X = 0.0178$	Experimental results (Borexino)	Global fit including solar, reactor, accel. data [11] (cm^{-2} s^{-1})
pp	$5.97\ (1 \pm 0.007) \times 10^{10}$	$6.04\ (1 \pm 0.007) \times 10^{10}$	$6.6\ (1 \pm 0.106) \times 10^{10}$	$5.97^{+0.037}_{-0.033} \times 10^{10}$
^{7}Be	$5.00\ (1 \pm 0.07) \times 10^{9}$	$4.56\ (1 \pm 0.07) \times 10^{9}$	$4.43 \pm 0.22 \times 10^{9}$	$4.80^{+0.24}_{-0.22} \times 10^{9}$
pep	$1.44\ (1 \pm 0.012) \times 10^{8}$	$1.47\ (1 \pm 0.012) \times 10^{8}$	$1.63 \pm 0.35 \times 10^{8}$	$1.448 \pm 0.013 \times 10^{8}$
^{13}N	$2.96\ (1 \pm 0.14) \times 10^{8}$	$2.17\ (1 \pm 0.14) \times 10^{8}$		$\leq 13.7 \times 10^{8}$
^{15}O	$2.23\ (1 \pm 0.15) \times 10^{8}$	$1.56\ (1 \pm 0.15) \times 10^{8}$	$<7.7 \times 10^{8}$ total CNO	$\leq 2.8 \times 10^{8}$
^{17}F	$5.52\ (1 \pm 0.17) \times 10^{8}$	$3.40\ (1 \pm 0.16) \times 10^{8}$		$\leq 8.5 \times 10^{7}$
^{8}B	$5.58\ (1 \pm 0.14) \times 10^{6}$	$4.59\ (1 \pm 0.14) \times 10^{6}$	$5.2 \pm 0.3 \times 10^{6}$	$5.16^{+0.13\ +0.30}_{-0.09\ -0.26} \times 10^{6}$

Bellini 2016

Conclusion

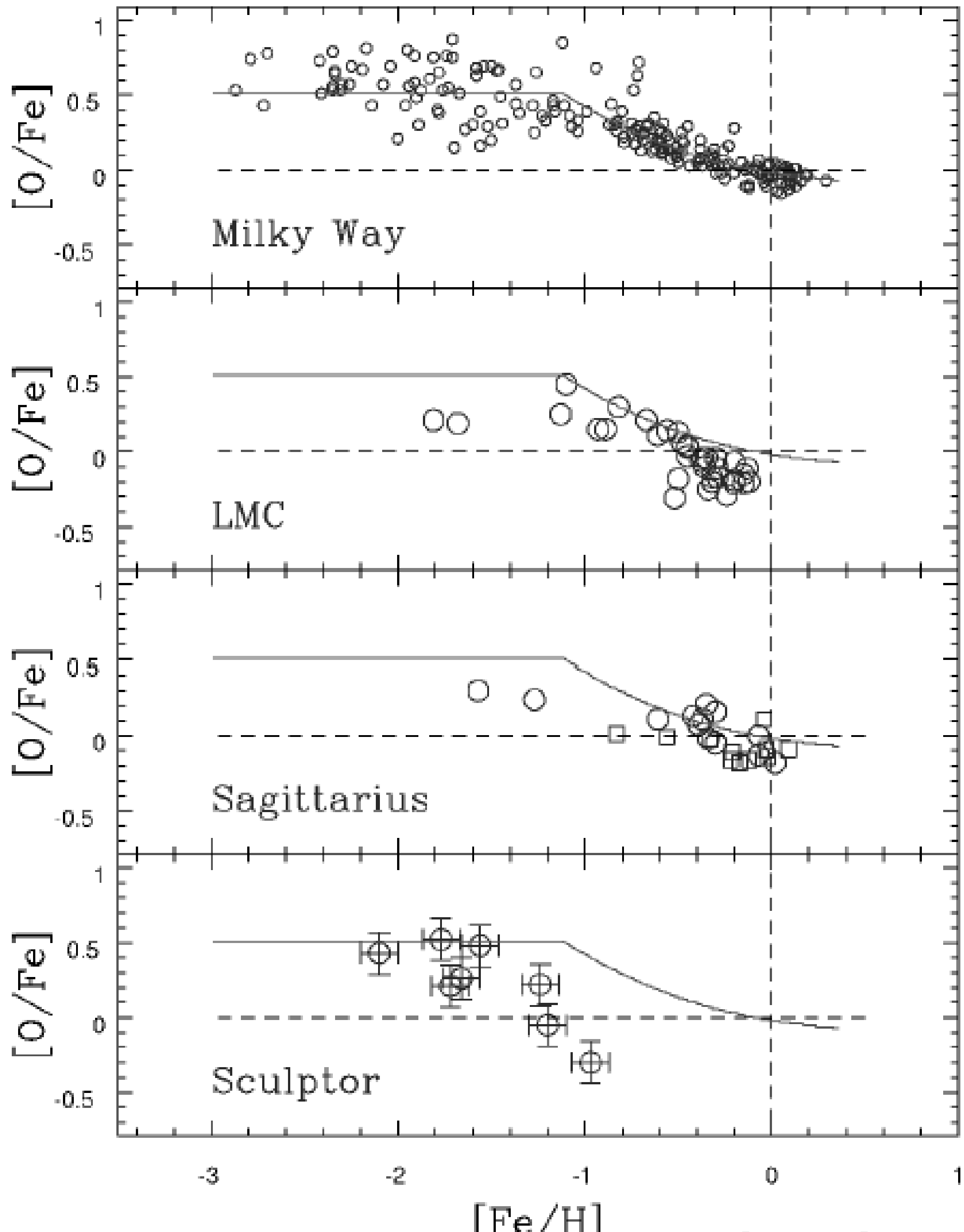
- To make a single element, we need the whole Universe
- Abundances in the Universe integrate over time many fascinating complex processes
- Nucleosynthesis is a part of the quest of the origins



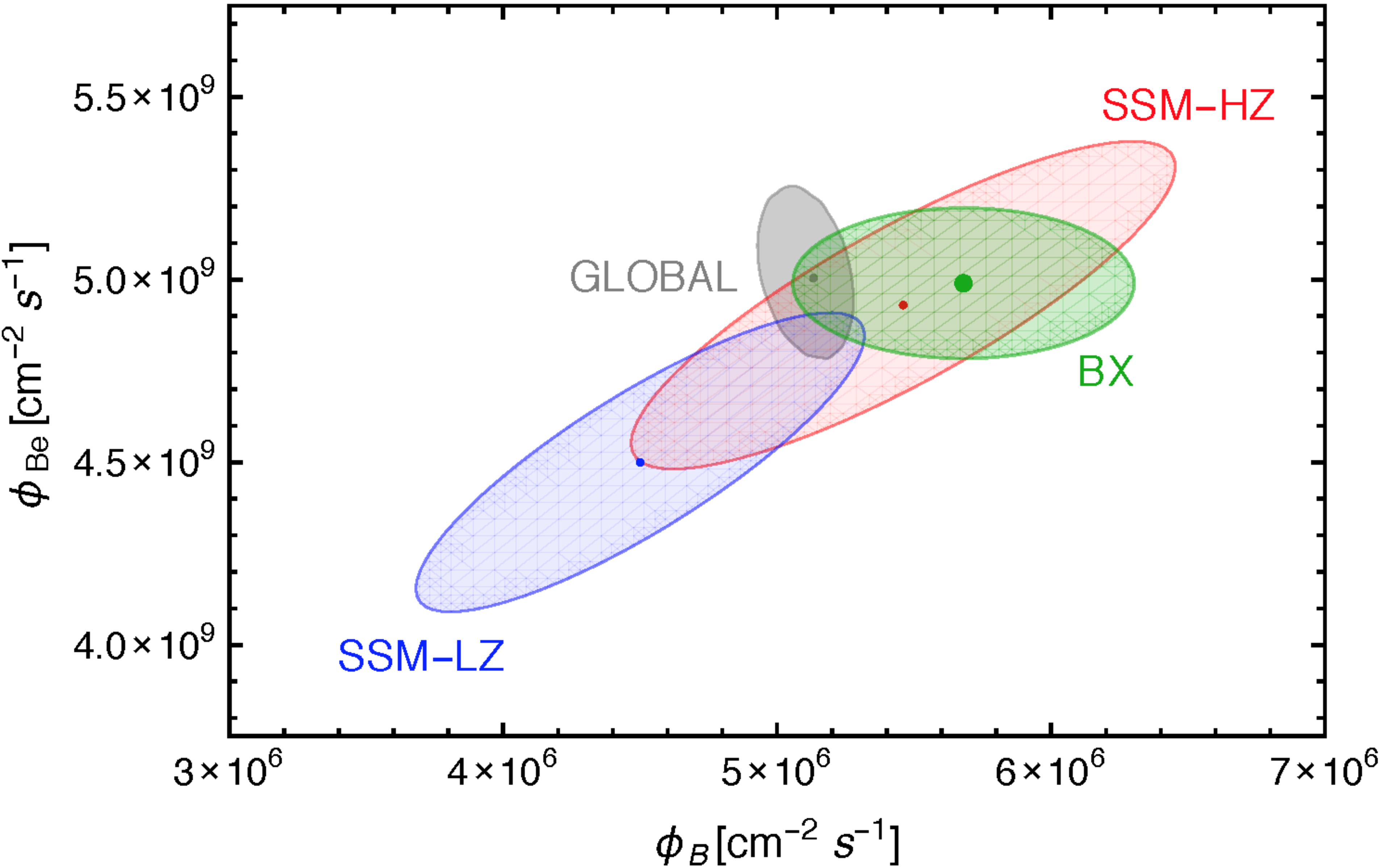
Credit: Supernova illustration: Akihiro Ikeshita/
Particle CG: Naotsugu Mikami (NAOJ)

The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes and smoke. Standing on a well-chilled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of worlds.

Model for the chemical evolution of galaxies

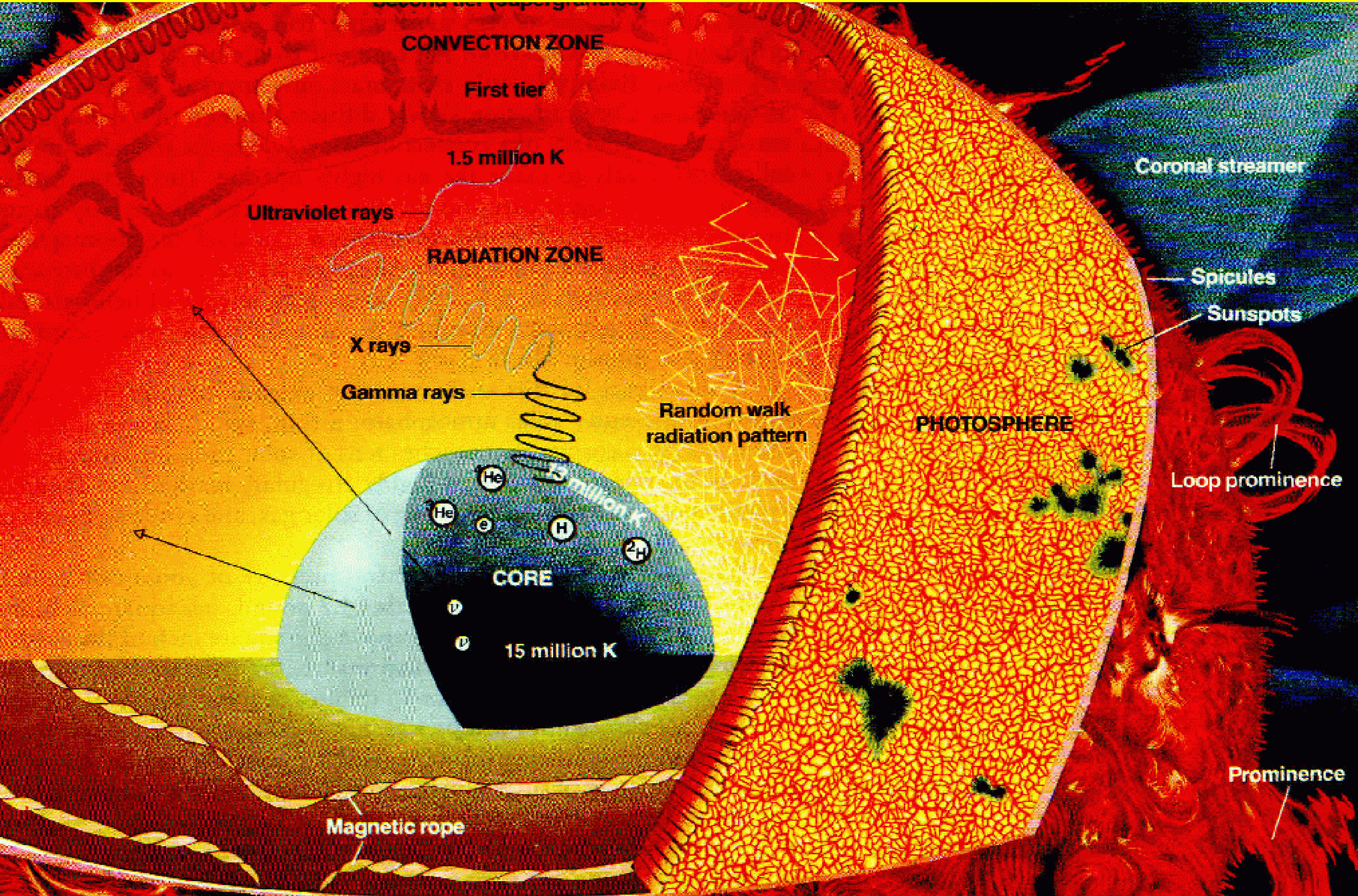


Geisler et al. 2007

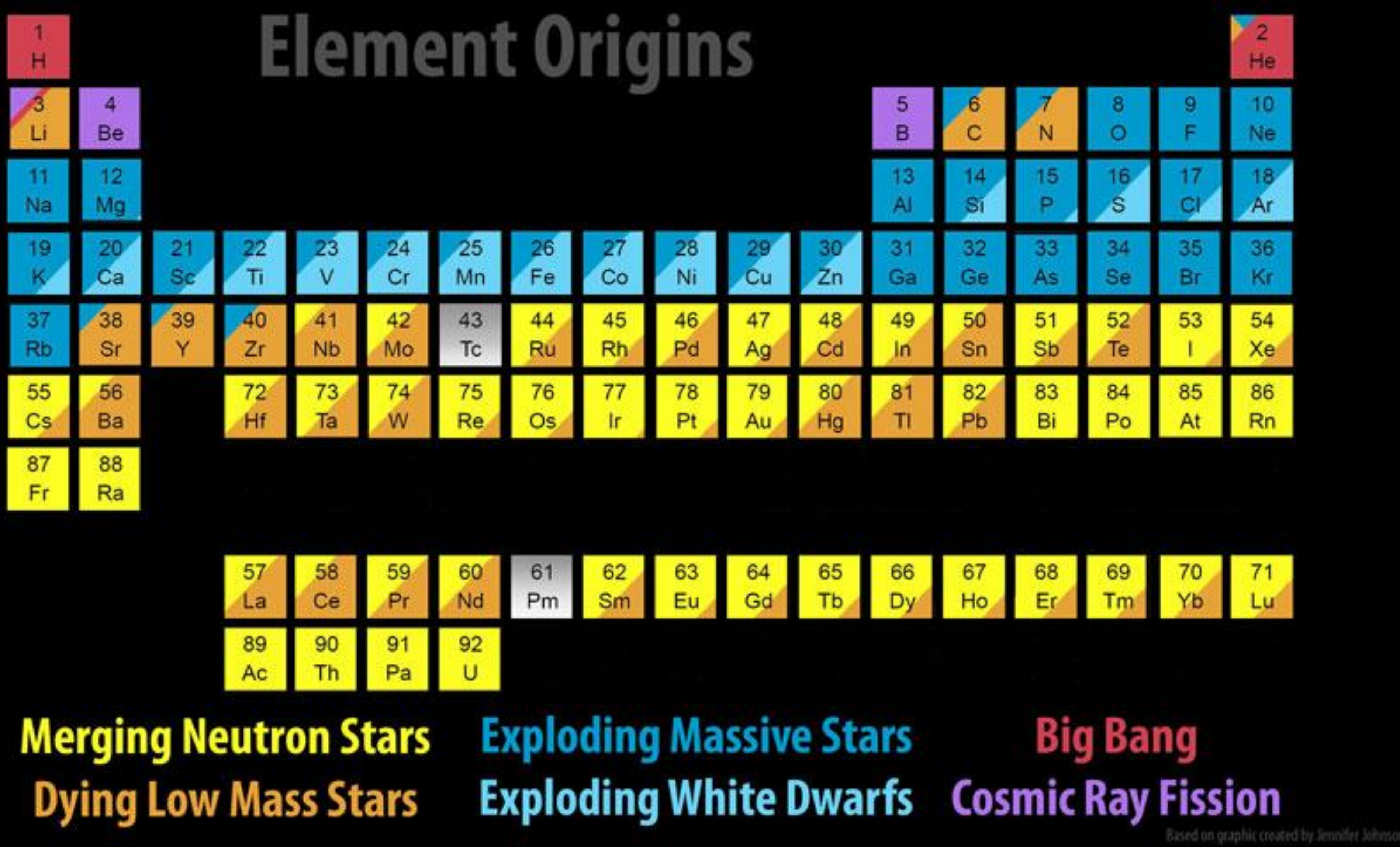


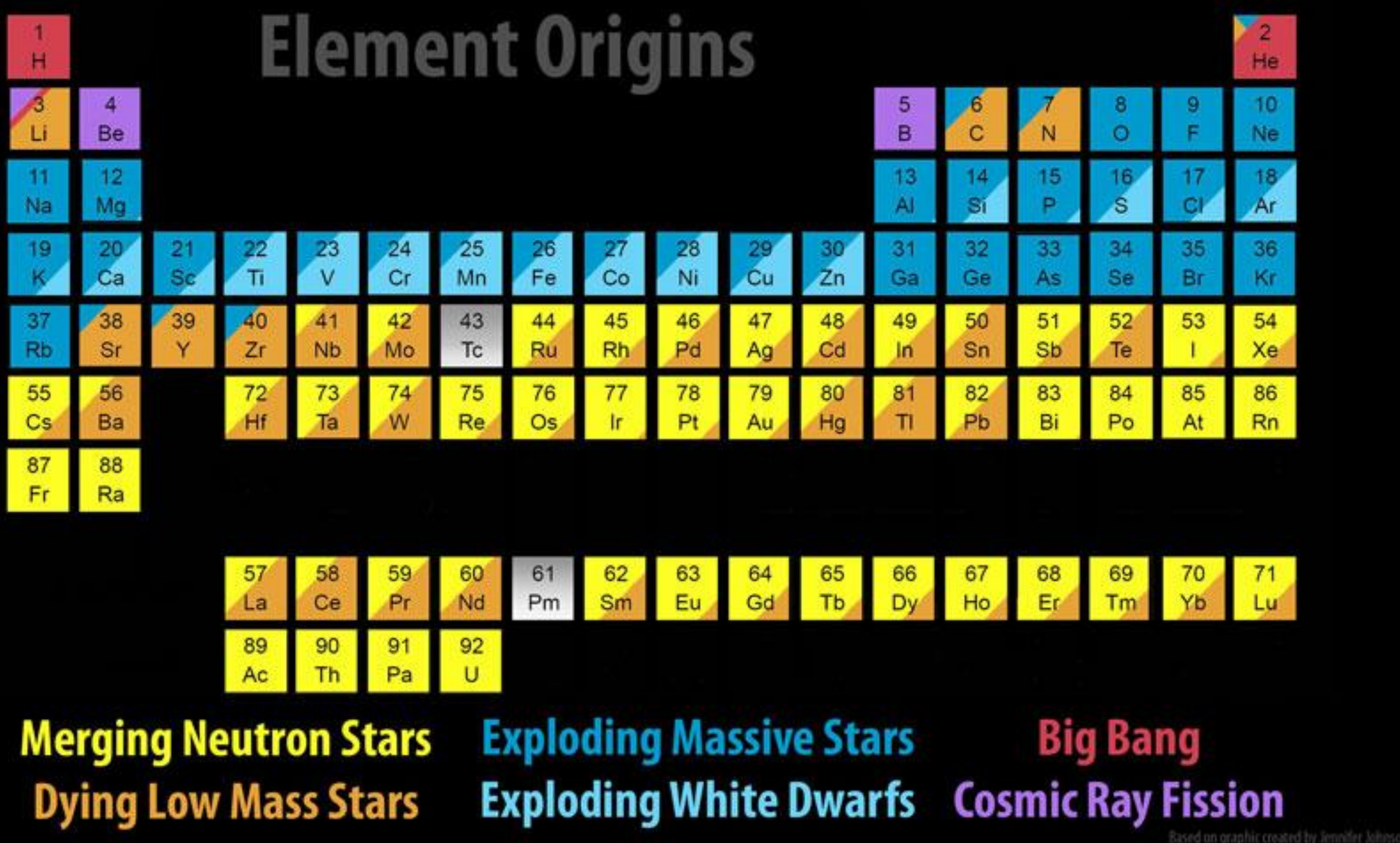
SSM-HZ
GLOBAL
BX
SSM-LZ
5.5×10^9
5.0×10^9
4.5×10^9
4.0×10^9
3×10^6
4×10^6
5×10^6
6×10^6
7×10^6
φ_B [cm^-2 s^-1]
φ_Be [cm^-2 s^-1]

AT THE CENTERS OF STARS, PHYSICAL CONDITIONS ARE APPROPRIATE FOR ACTIVATING NUCLEAR REACTIONS



THE DIFFERENT SITES




Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
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
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
55 Cs
56 Ba
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
87 Fr
88 Ra
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
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson