Nuclear Astrophysics Theory: The Origin of the Elements

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- These lectures are interactive, please expect to have to do something
- You can work in groups, talk with the others
- You can ask any question anytime!

Chemical Elements: The periodic table

United Nations
Educational, Scientific and
Cultural Organization

2019 IYPT
International Year
of the Periodic Table
of Chemical Elements

Group	1	2											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 Uun	111 Uuu	112 Uub	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

Chemical Elements: The periodic table

Made in the Big Bang

By far the most abundant elements in the Universe!

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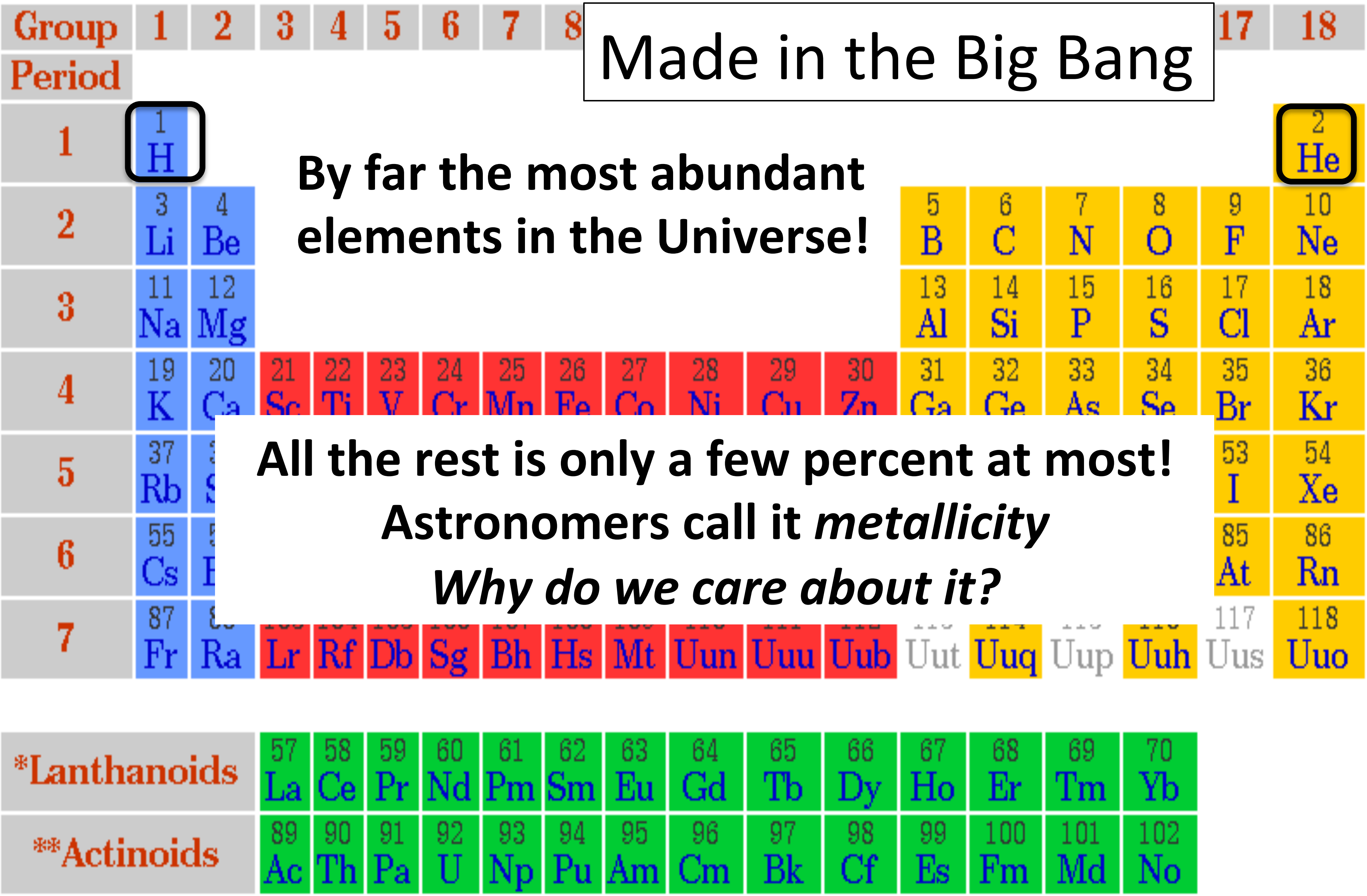
Chemical Elements: The periodic table



Made in the Big Bang

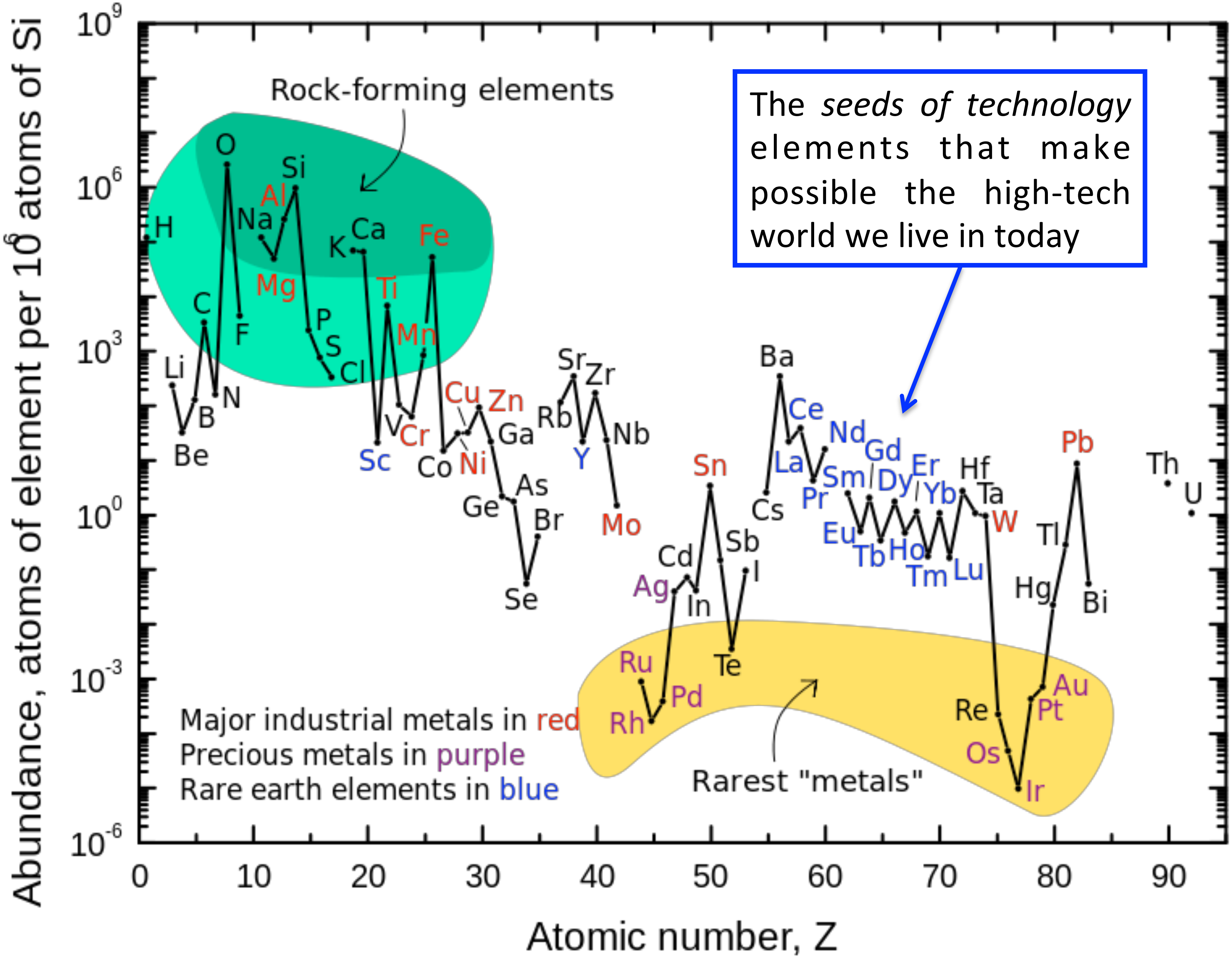
By far the most abundant elements in the Universe!

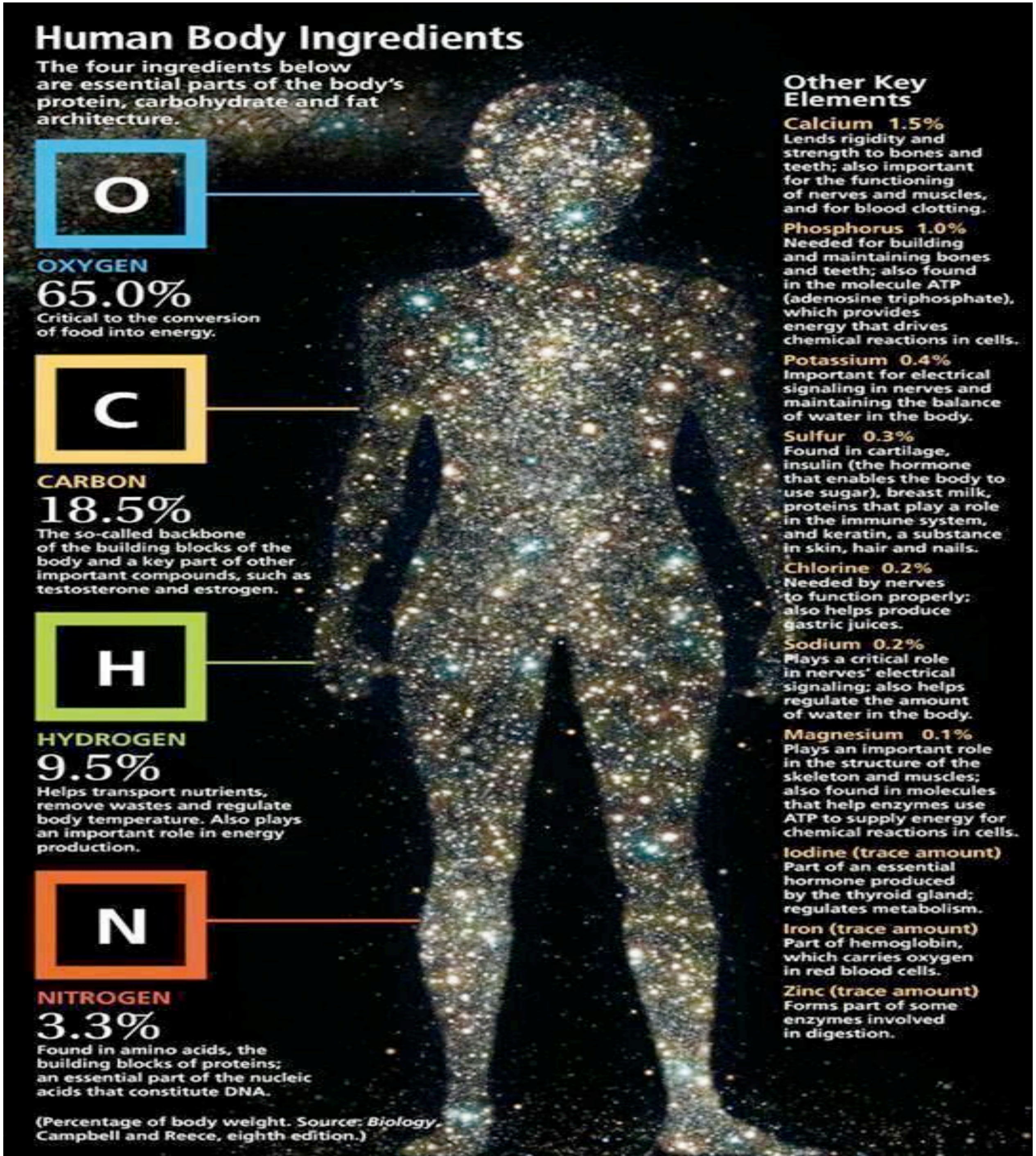
All the rest is only a few percent at most!

Astronomers call it *metallicity*

Why do we care about it?

Earth’s crust abundances





Ca

P

K

S

Cl

Na

Mg

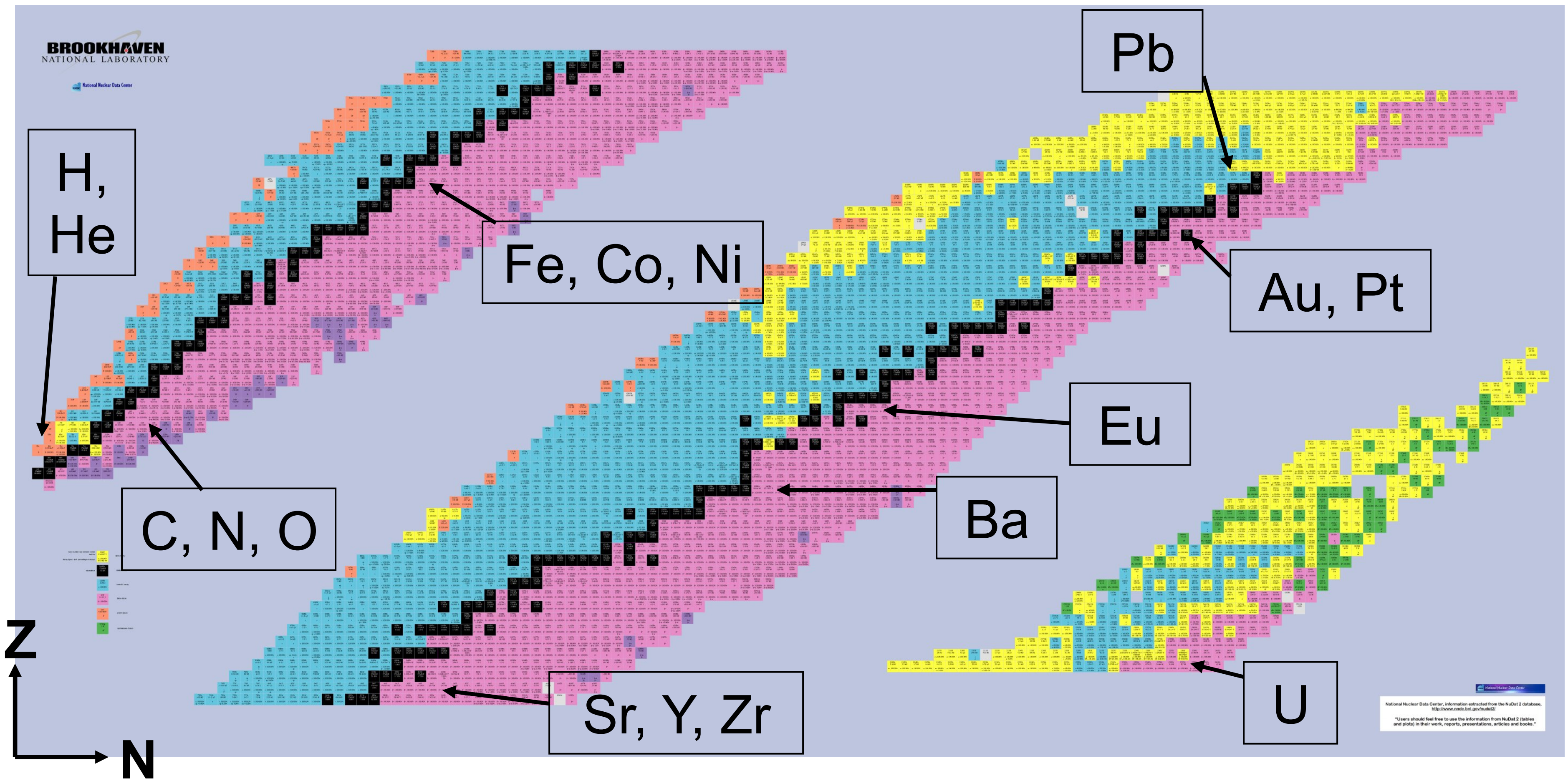
I

Fe

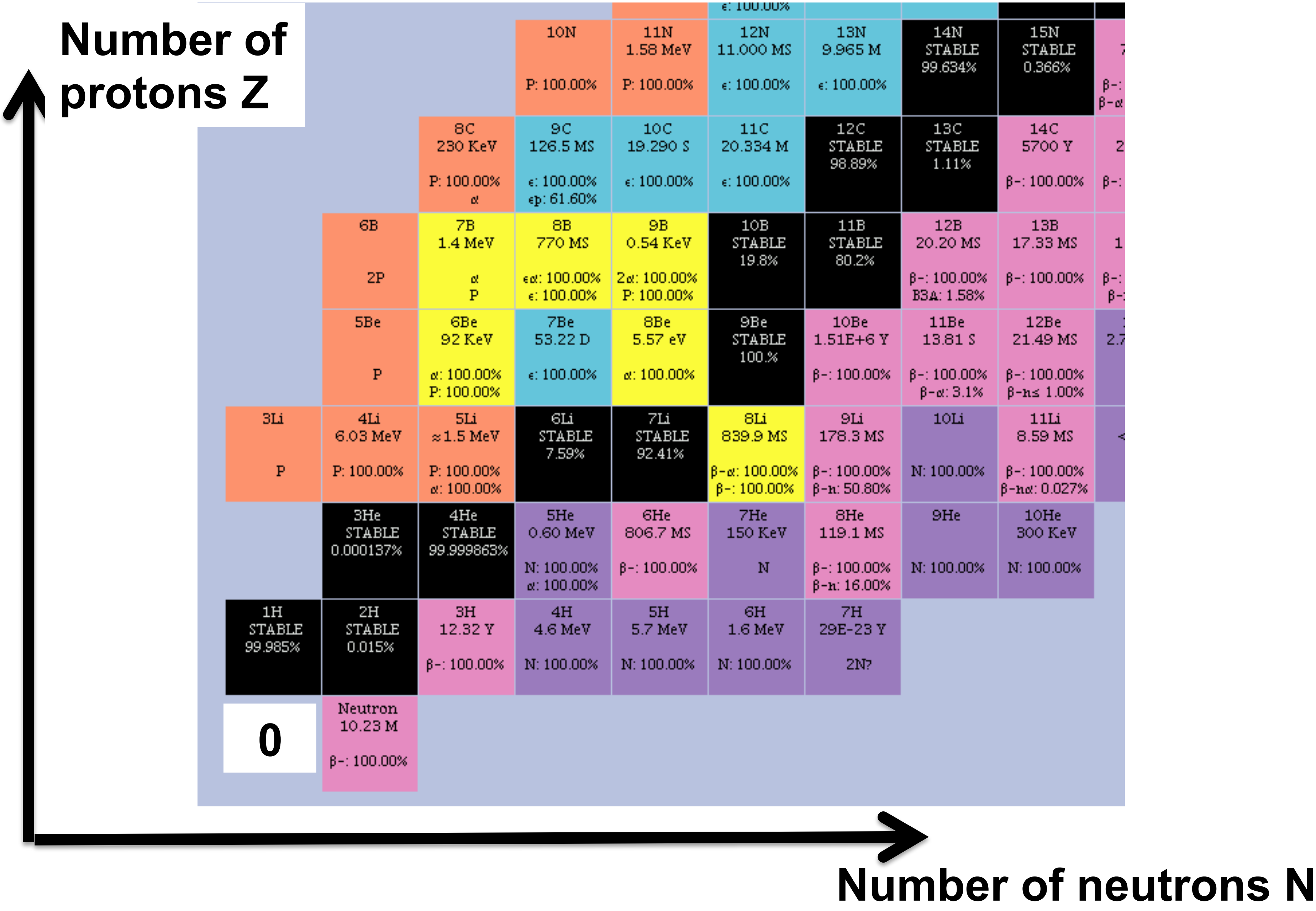
Zn

To understand the origin of the chemical elements we need to understand how their **atomic nuclei** are created.

The Chart of Nuclei represents all the elements and nuclei in the Universe. **Black boxes are stable nuclei**.



The nuclide chart



What is the number of neutrons of the stable isotopes of C:

1. 6
2. 6 and 7
3. 7
4. 12

What is the $^{12}C/^{13}C$ abundance ratio in the solar system:

1. ~1
2. ~10
3. ~100
4. ~1000

What is the half-life of ^{13}N:

1. ~1 minute
2. ~10 minutes
3. ~10 hours
4. ~10 days

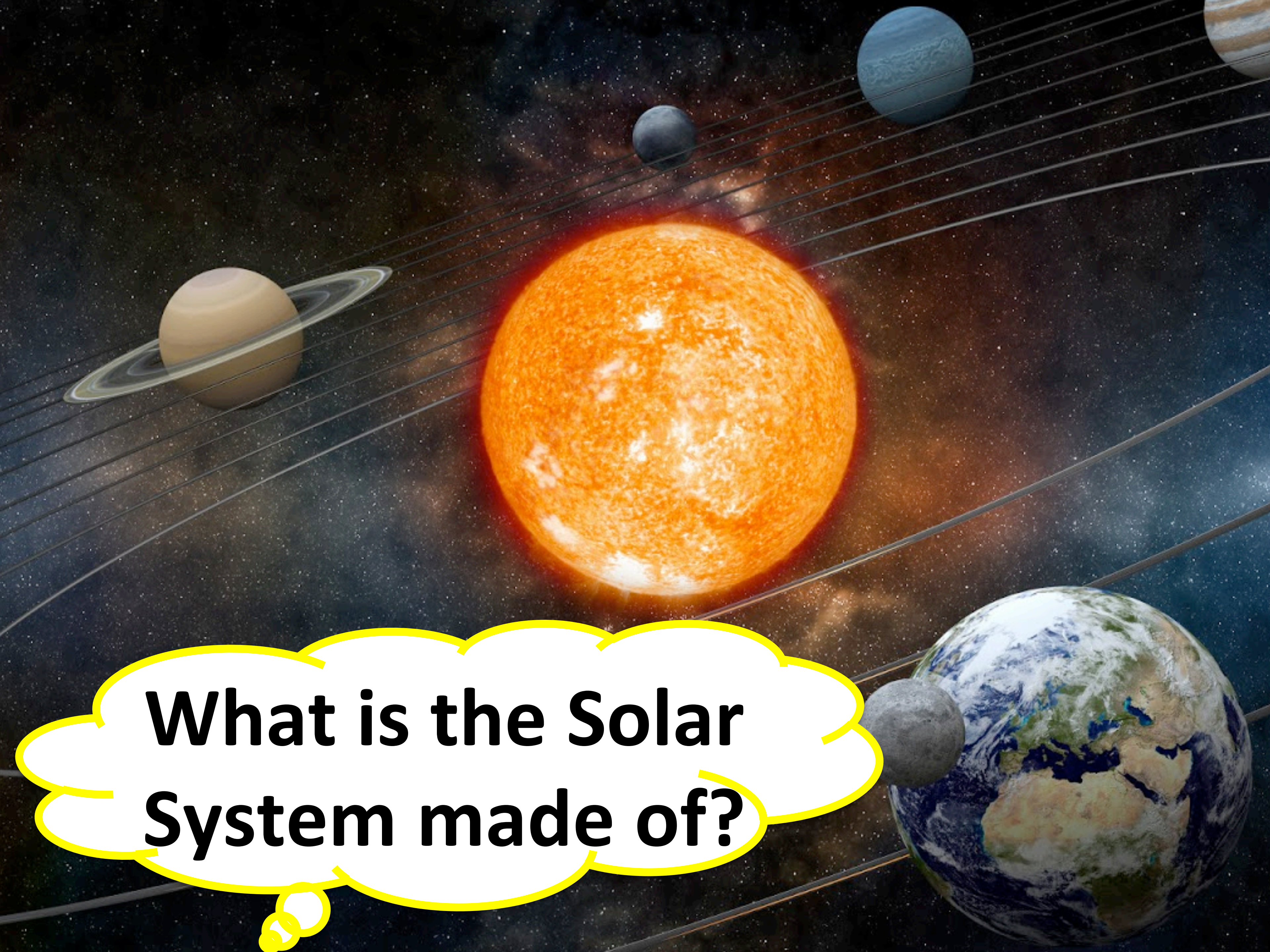

What are stars made of?
NGC 6397
Hubble Space Telescope Image

"*We shall never be able by any means to study the chemical composition* [of stars] *or their mineralogical structure.*"

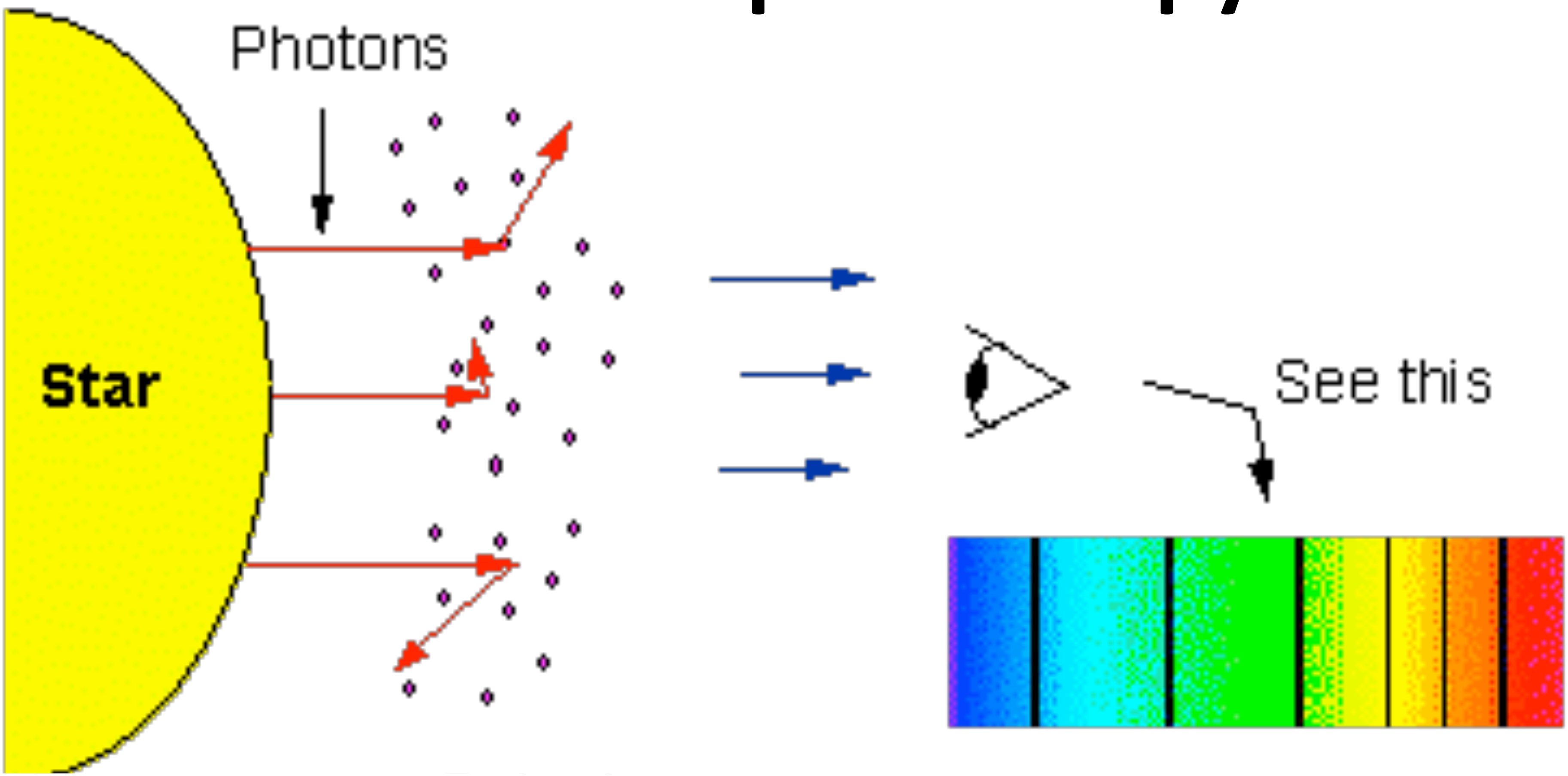
Auguste Comte

Cours de la Philosophie Positive,

1835


What is the Solar System made of?

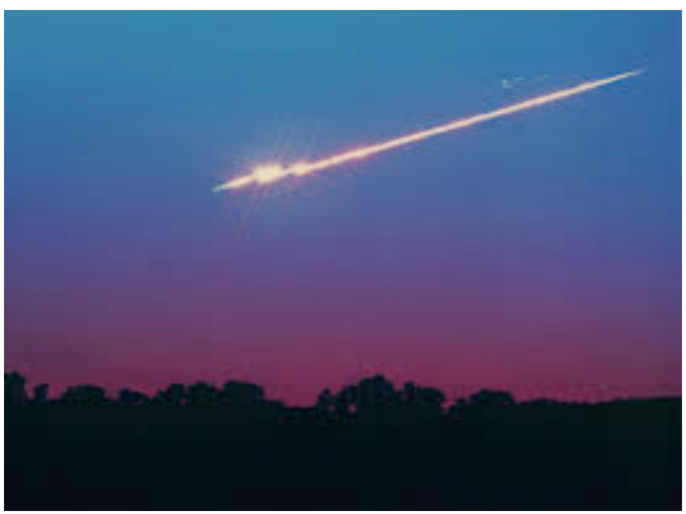
Method 1. Analyse the light from the Sun: **Spectroscopy**



Each dark line corresponds to an atomic transition of an atom/ion of a specific chemical element.

Method 2. Analyse the composition of
Extra-terrestrial rocks
that formed when the Sun formed

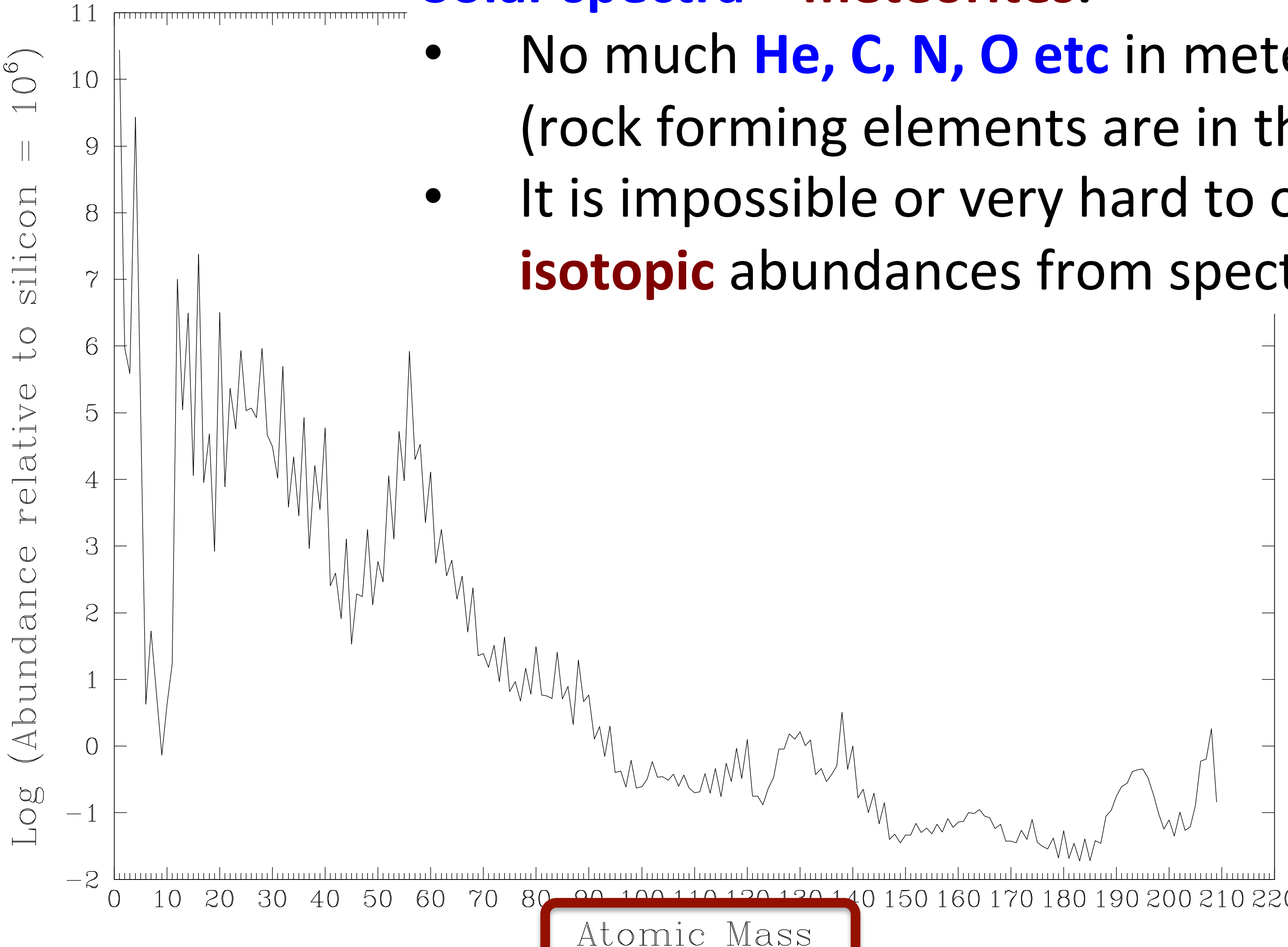
Meteor, meteoroid, meteorite:
What is the difference?



The Solar System abundances

Solar spectra + meteorites:

- No much **He, C, N, O etc** in meteorites (rock forming elements are in there)
- It is impossible or very hard to obtain **isotopic** abundances from spectra



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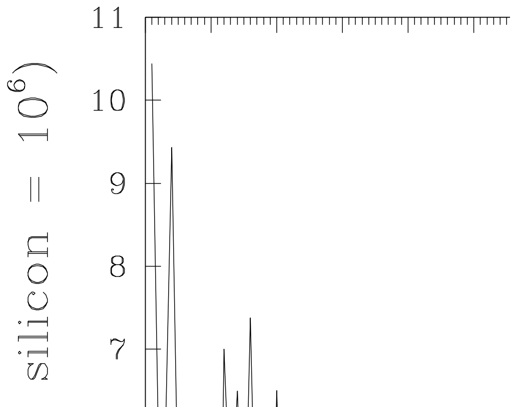

Solar spectra + meteorites:

- No much **He, C, N, O etc** in meteorites (rock forming elements are there)
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The abundances from solar spectra and meteorites show the features of nuclear physics!

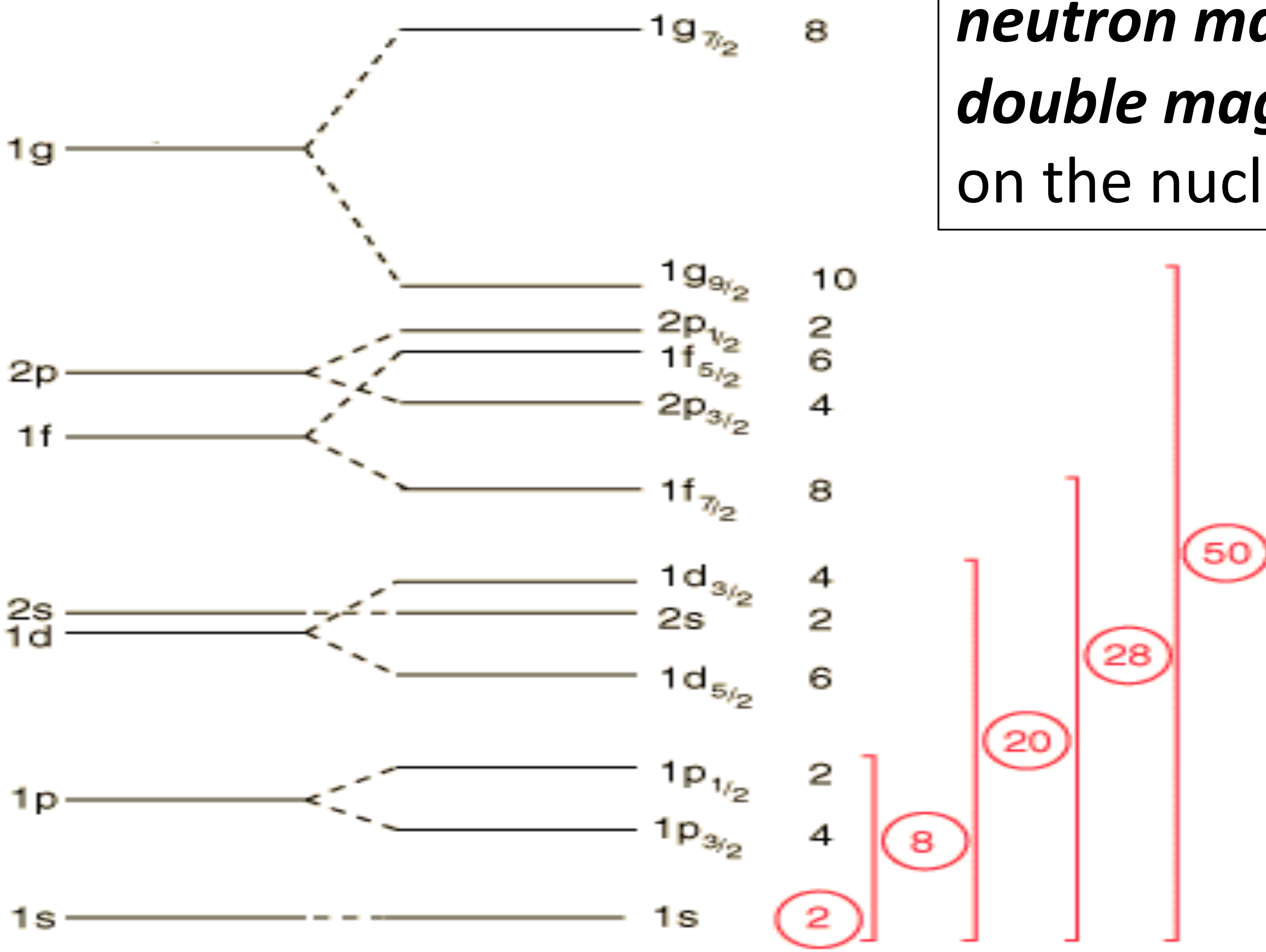
Can you find these features in the figure?

1. **Identify the peaks, which isotopes are they?**
2. **Why are these isotopes more abundant than others?**

Hints: Remember **(1)** the magic numbers: 2, 8, 20, 28, 50, 82, and 126, and **(2)** the nuclei with the highest binding energy per nucleon

Nuclear shell model, closed shells = stability → magic numbers, apply to both *protons* and *neutrons*

We can find ***proton or neutron magic*** and ***double magic*** nuclei on the nuclide chart



The binding energy per nucleon is the average energy needed to "break off" one nucleon from the nucleus.

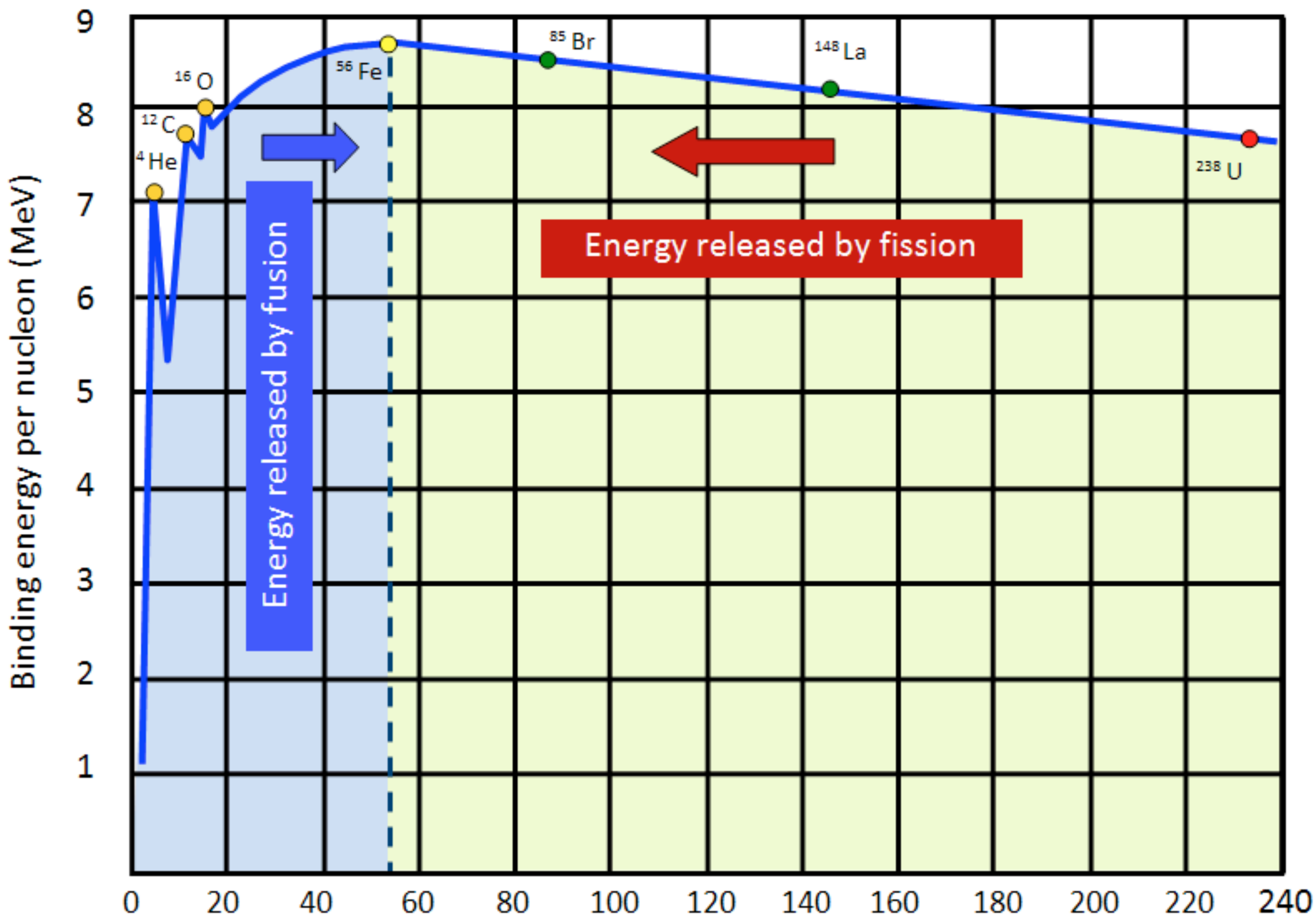
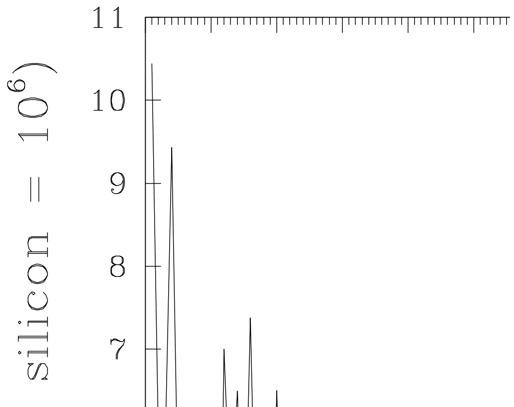


Figure 1

The Solar System abundances



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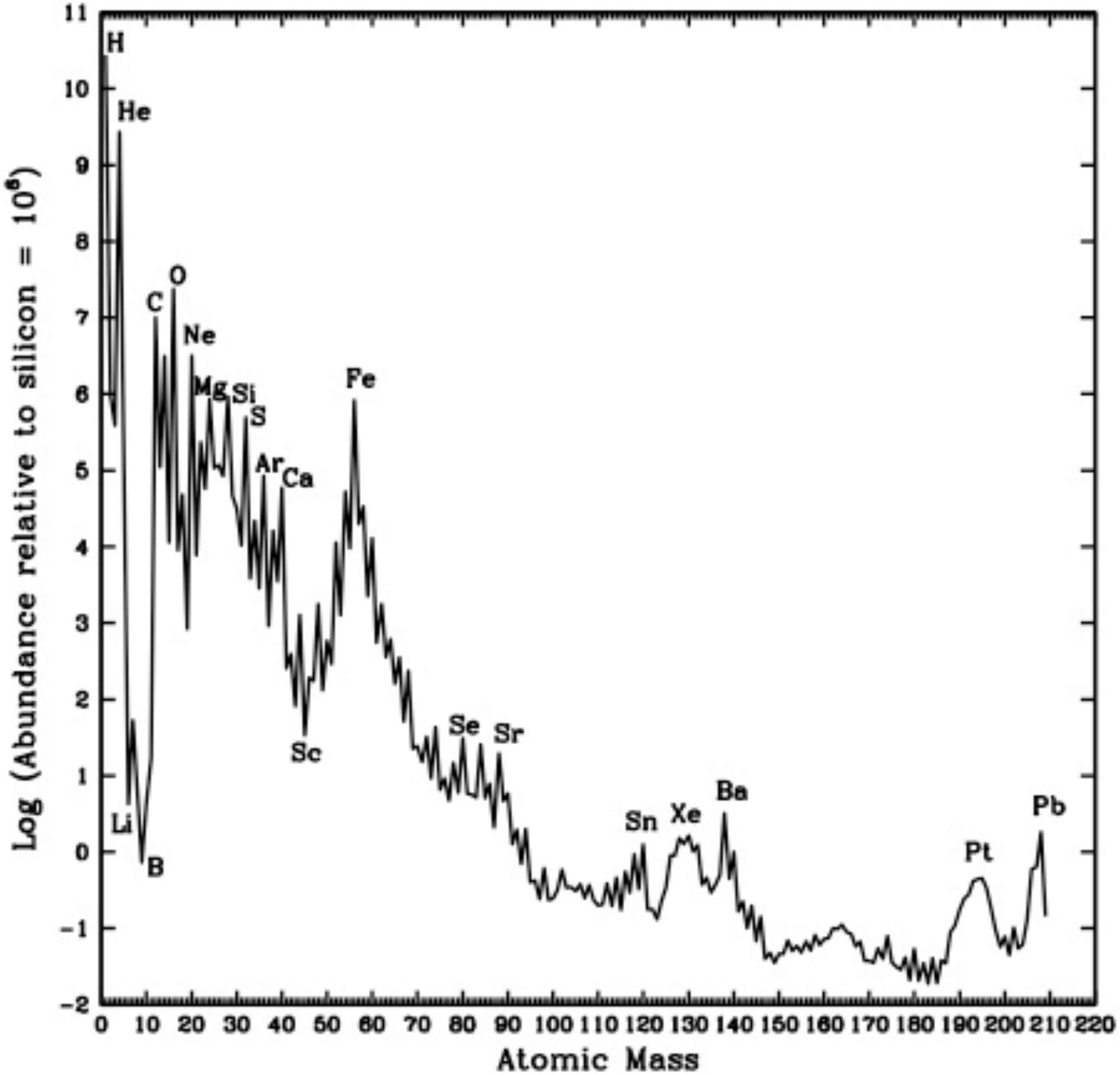
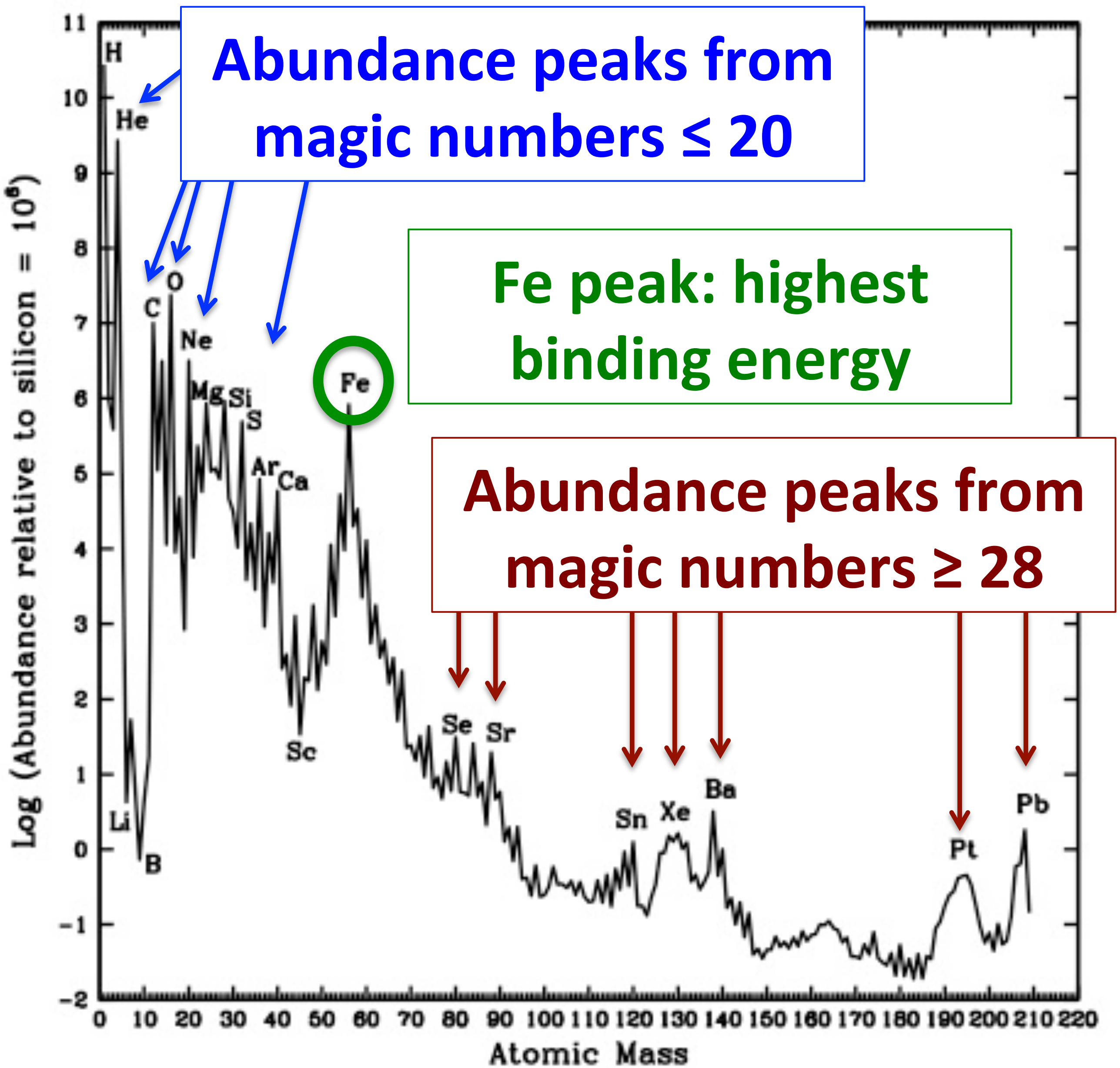
Hints: Remember the magic numbers: 2, 8, 20, 28, 50, 82, and 126, and which are the nuclei with the highest binding energy per nucleon…

The ***nuclear physics*** of the Solar System abundances



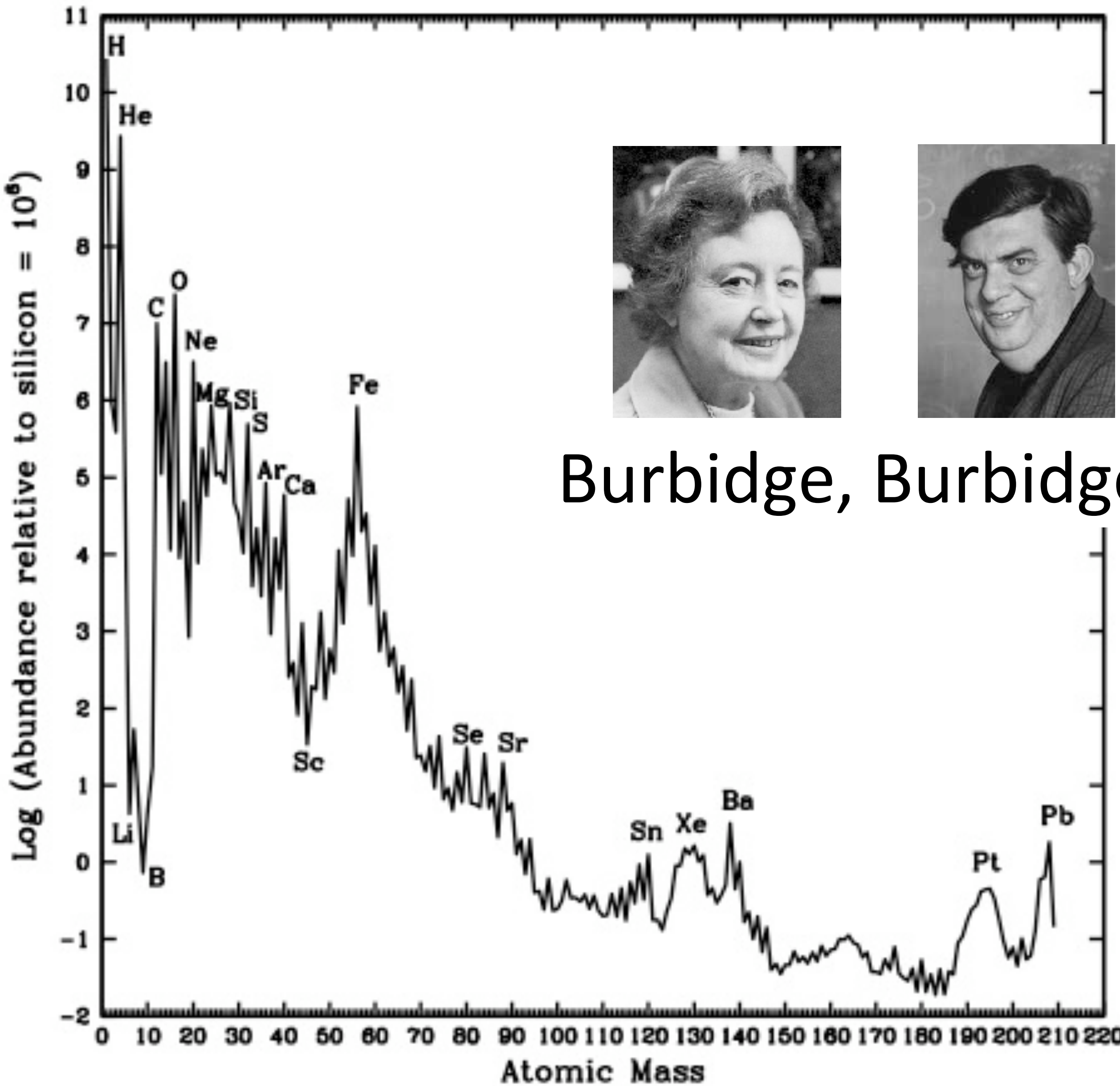
The ***nuclear physics*** of the Solar System abundances



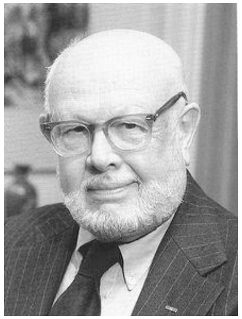
magic numbers: 2, 8, 20, 28, 50, 82, and 126.

The odd-even effect

Solar System abundances: *nucleosynthesis*



In **1957**, **B^{2}FH**

Burbidge, Burbidge, Fowler & Hoyle

publish the first classification of <u>nucleosynthesis</u> processes

Margaret Burbidge turned 100 yesterday!

Prof. Margaret Burbidge
consejoculturalmundial.org

E. Margaret Burbidge (1919-...
flickr.com

E. Margaret Burbidge on Twitter: "I ...
twitter.com

Astronomer Margar
sandiegouniontribune

William Fowler with Geoffrey and ...
archives-dc.library.caltech.edu

Wire Photo Professor Marg...
outlet.historicimages.com

Emilio Segre Visual ...
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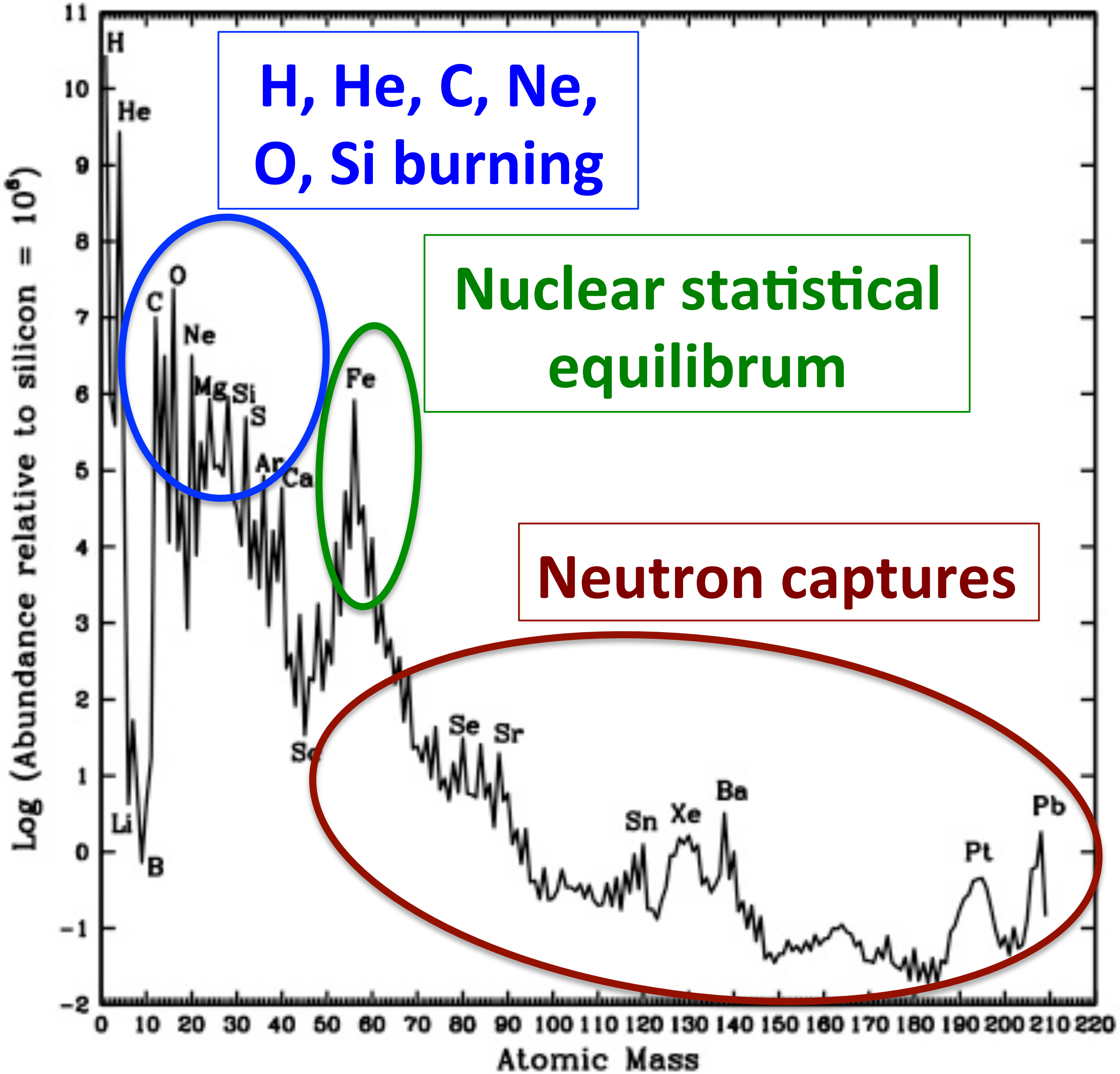
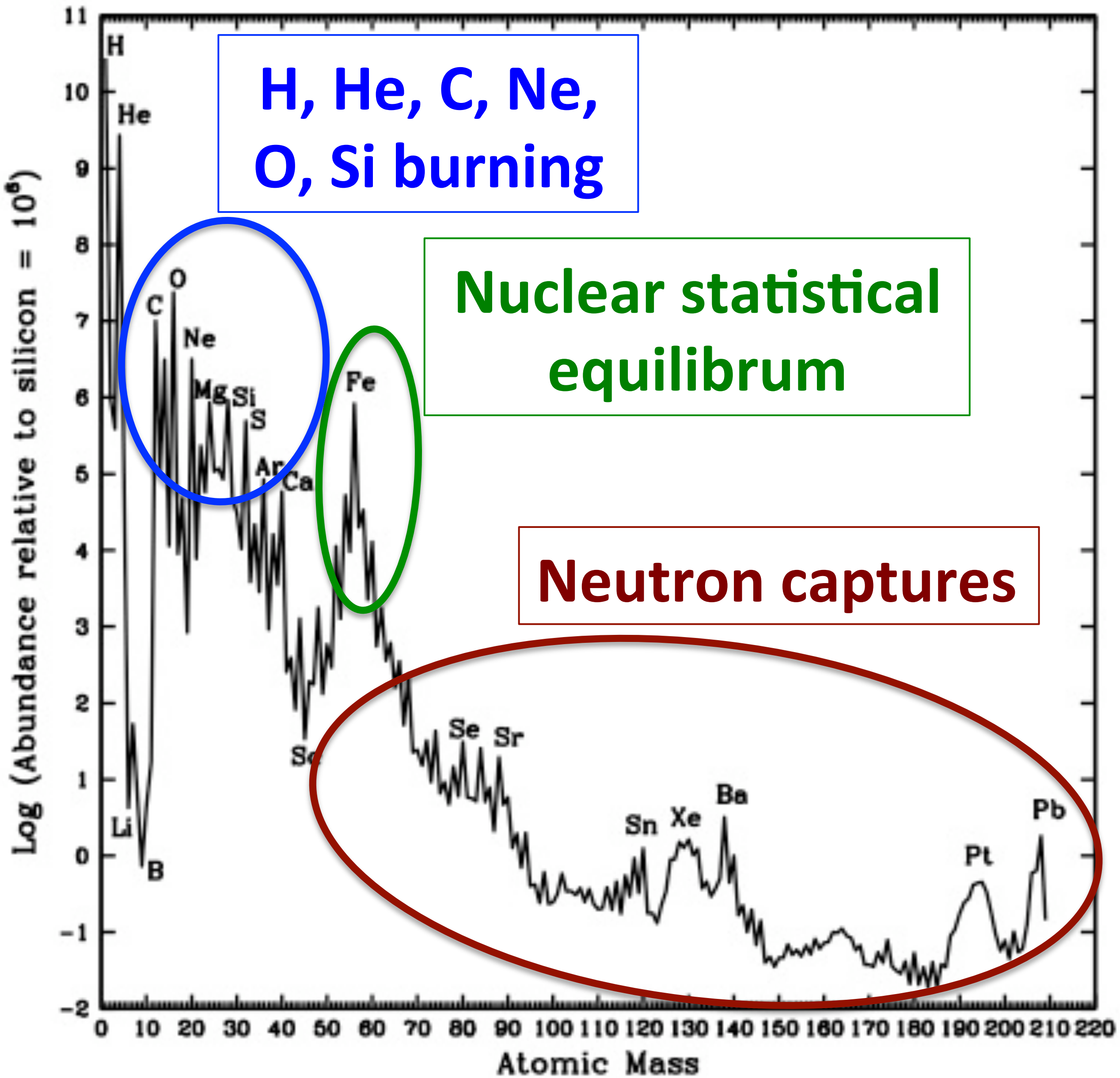
Solar System abundances: ***nucleosynthesis***

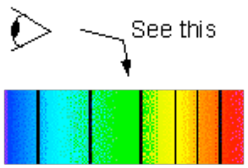


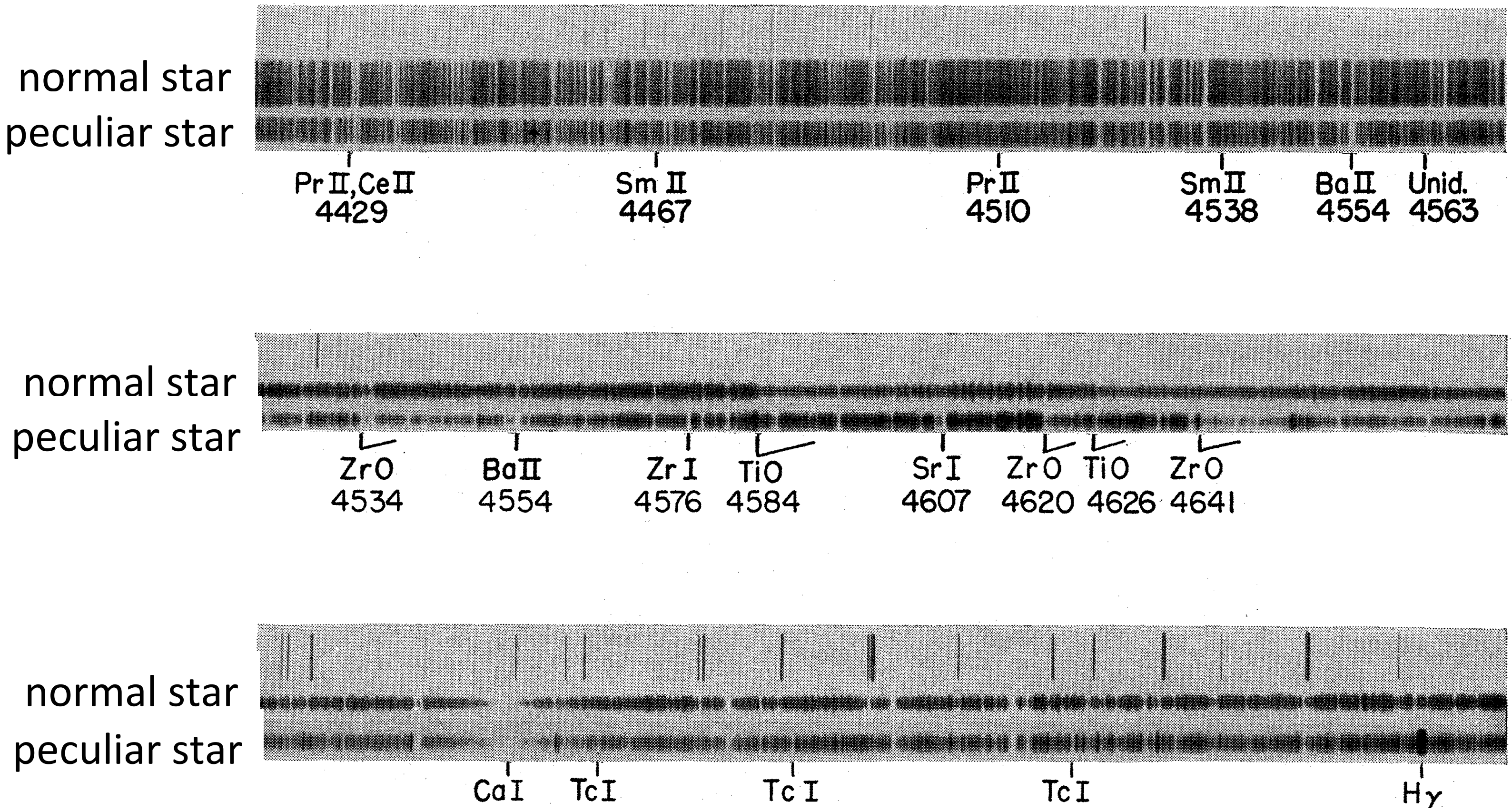
Solar System abundances: ***nucleosynthesis***



How do we know these processes happen in stars?

Spectroscopy in the 1950s…

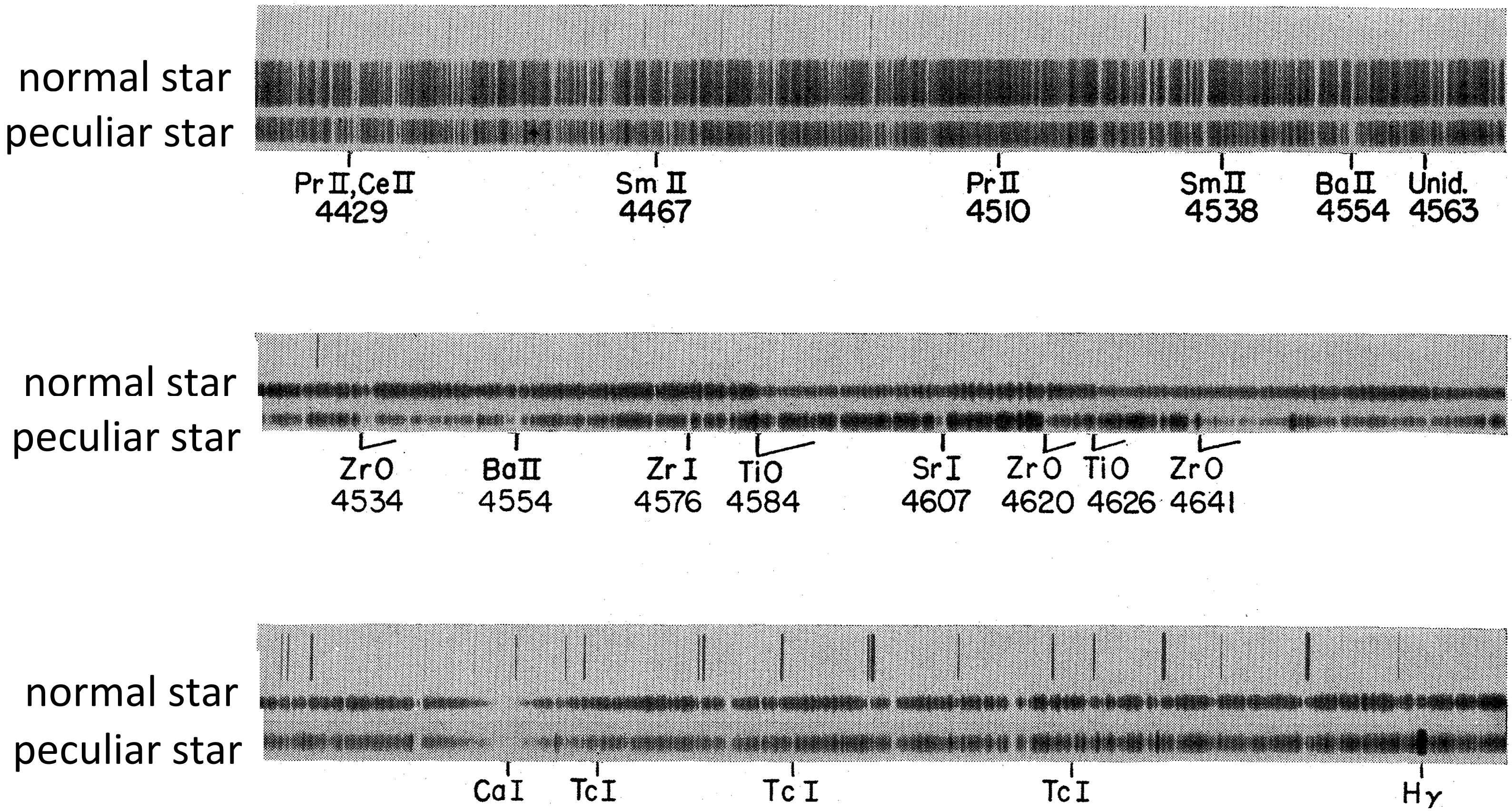




Merrill 1952, Burbidge et al. 1957

Each line originates from absorption
from a specific atomic transition
in a specific atom/ion

Spectroscopy in the 1950s…



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What is special about technetium (Tc)? Find this element on the nuclide chart!

What is special about technetium (Tc)?
Find this element on the nuclide chart!

95Rh 5.02 M ε: 100.00%	96Rh 9.90 M ε: 100.00%	97Rh 30.7 M ε: 100.00%	98Rh 8.72 M ε: 100.00%	99Rh 16.1 D ε: 100.00%	100Rh 20.8 H ε: 100.00%	101Rh 3.3 Y ε: 100.00%	102Rh 207 D ε: 78.00% β-: 22.00%	103Rh STABLE 100%	104Rh 42.3 S β-: 99.55% ε: 0.45%	105Rh 35.36 H β-: 100.00%
94Ru 51.8 M ε: 100.00%	95Ru 1.643 H ε: 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D ε: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H ε: 100.00%	94Tc 293 M ε: 100.00%	95Tc 20.0 H ε: 100.00%	96Tc 4.28 D ε: 100.00%	97Tc 4.21E+6 Y ε: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ε: 1.8E-3%	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 S β-: 100.00%
92Mo STABLE 14.84%	93Mo 4.0E+3 Y ε: 100.00%	94Mo STABLE 9.25%	95Mo STABLE 15.92%	96Mo STABLE 16.68%	97Mo STABLE 9.55%	98Mo STABLE 24.13%	99Mo 2.7489 D β-: 100.00%	100Mo 7.3E+18 Y 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%
91Nb 6.8E+2 Y ε: 100.00%	92Nb 3.47E+7 Y ε: 100.00% β- < 0.05%	93Nb STABLE 100%	94Nb 2.03E+4 Y β-: 100.00%	95Nb 34.991 D β-: 100.00%	96Nb 23.35 H β-: 100.00%	97Nb 72.1 M β-: 100.00%	98Nb 2.86 S β-: 100.00%	99Nb 15.0 S β-: 100.00%	100Nb 1.5 S β-: 100.00%	101Nb 7.1 S β-: 100.00%
90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.53E+6 Y β-: 100.00%	94Zr STABLE 17.38%	95Zr 64.032 D β-: 100.00%	96Zr >3.9E+20 Y 2.80% 2β-	97Zr 16.744 H β-: 100.00%	98Zr 30.7 S β-: 100.00%	99Zr 2.1 S β-: 100.00%	100Zr 7.1 S β-: 100.00%
89Y STABLE 100%	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.058%	98Y 0.548 S β-: 100.00% β-n: 0.33%	99Y 1.470 S β-: 100.00% β-n: 1.90%
88Sr STABLE 82.58%	89Sr 50.57 D β-: 100.00%	90Sr 28.90 Y β-: 100.00%	91Sr 9.63 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.423 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S β-: 100.00%	96Sr 1.07 S β-: 100.00%	97Sr 429 MS β-: 100.00% β-n≤ 0.05%	98Sr 0.653 S β-: 100.00% β-n: 0.25%

The Big Bang

70% by mass in the Sun

28% by mass

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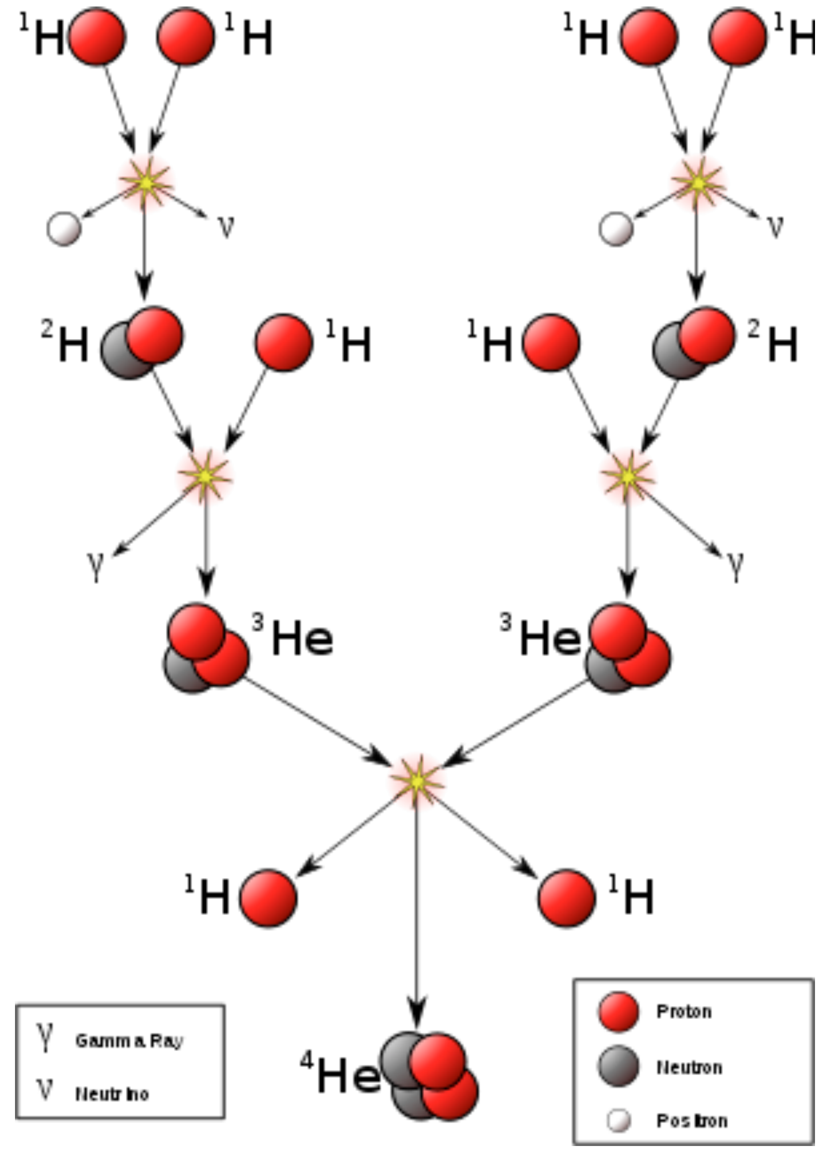
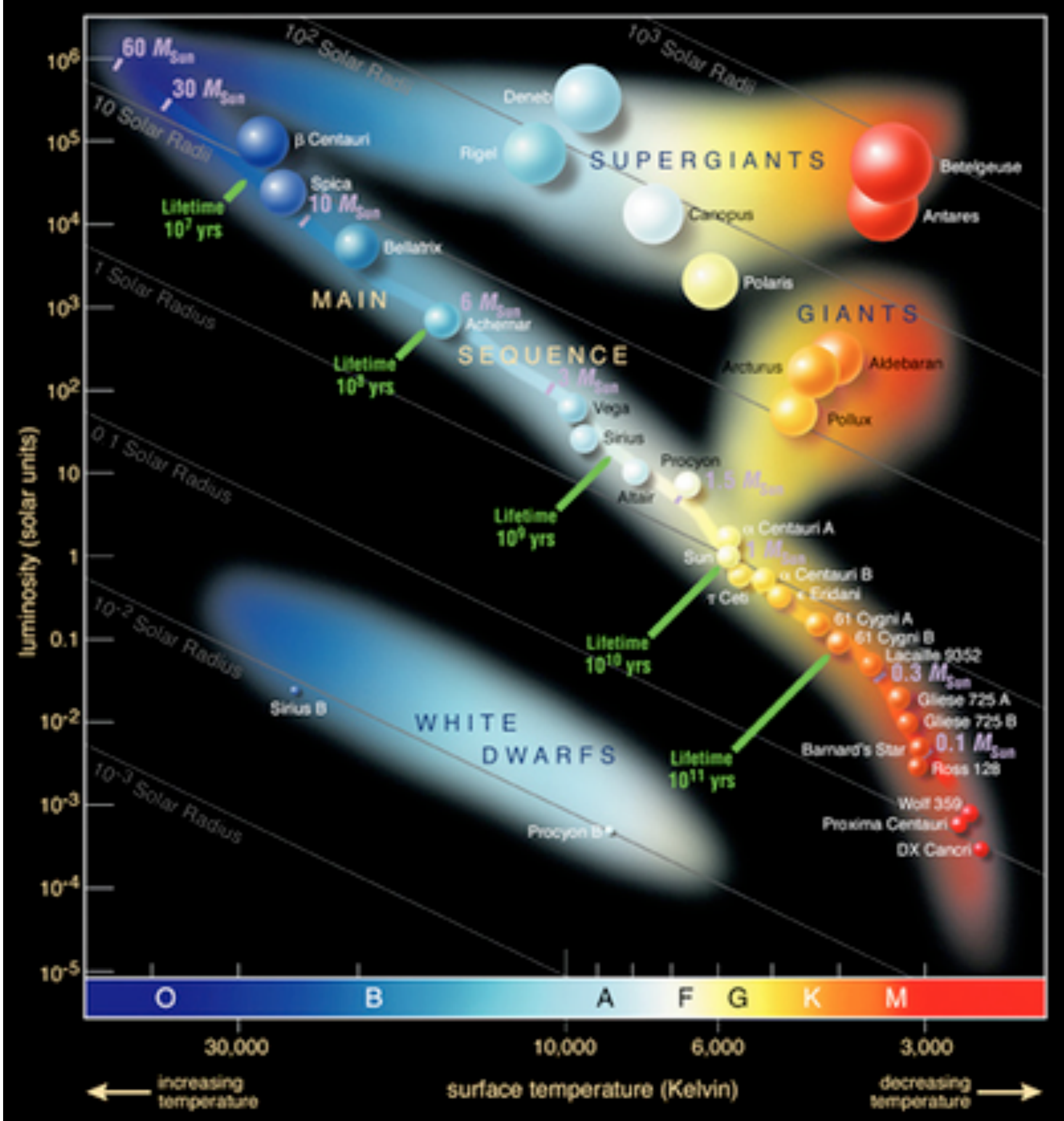
The simplest H burning: the pp chain



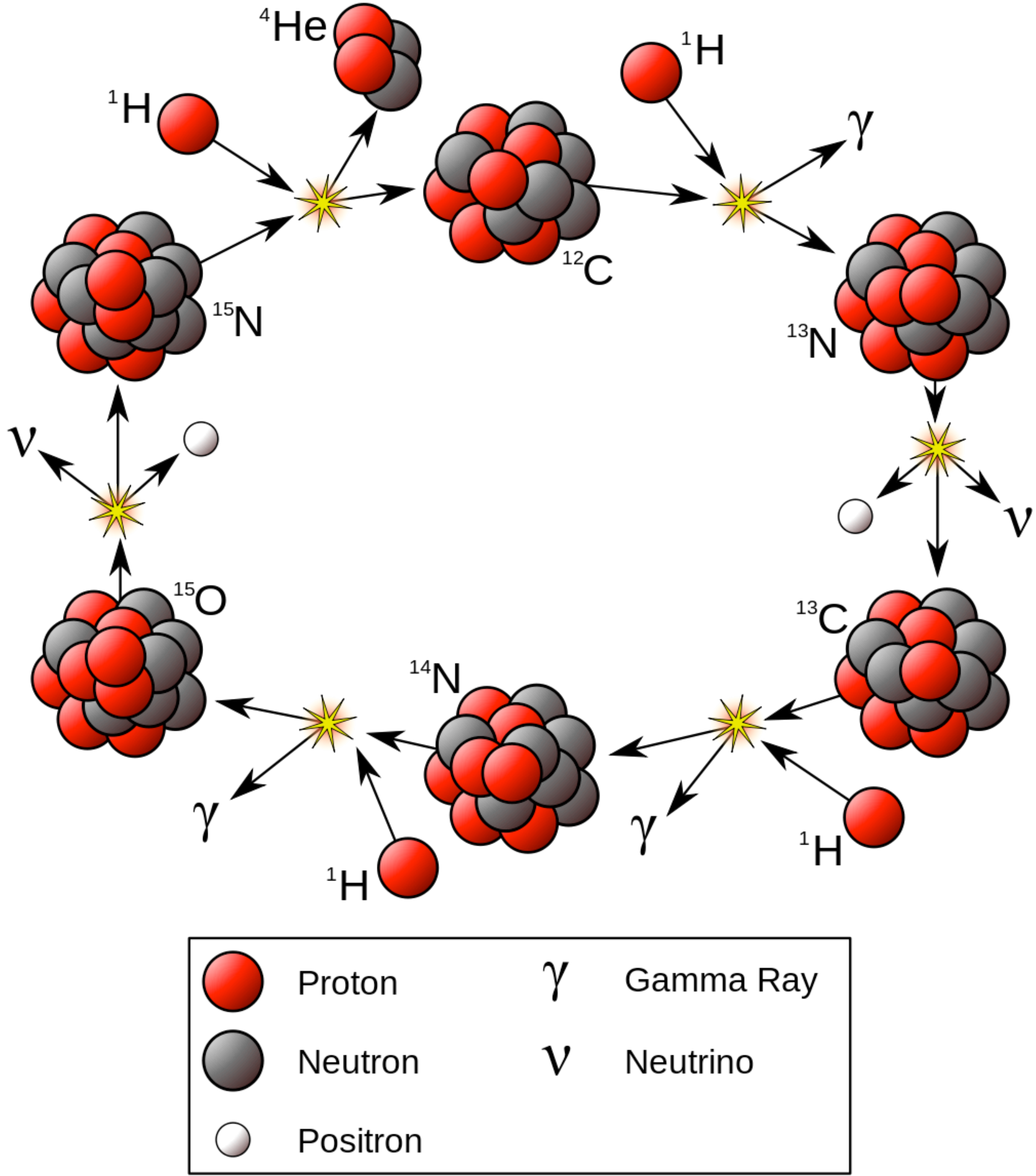
This is the nuclear burning that powers stars like the Sun:

Energy of 4 p > Energy of 1 He

The **Main Sequence** on the Herzsprung-Russell (H-R) diagram



More H burning: the CNO cycle. The net result is the **conversion of C and O into N**



The Big Bang

H burning

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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
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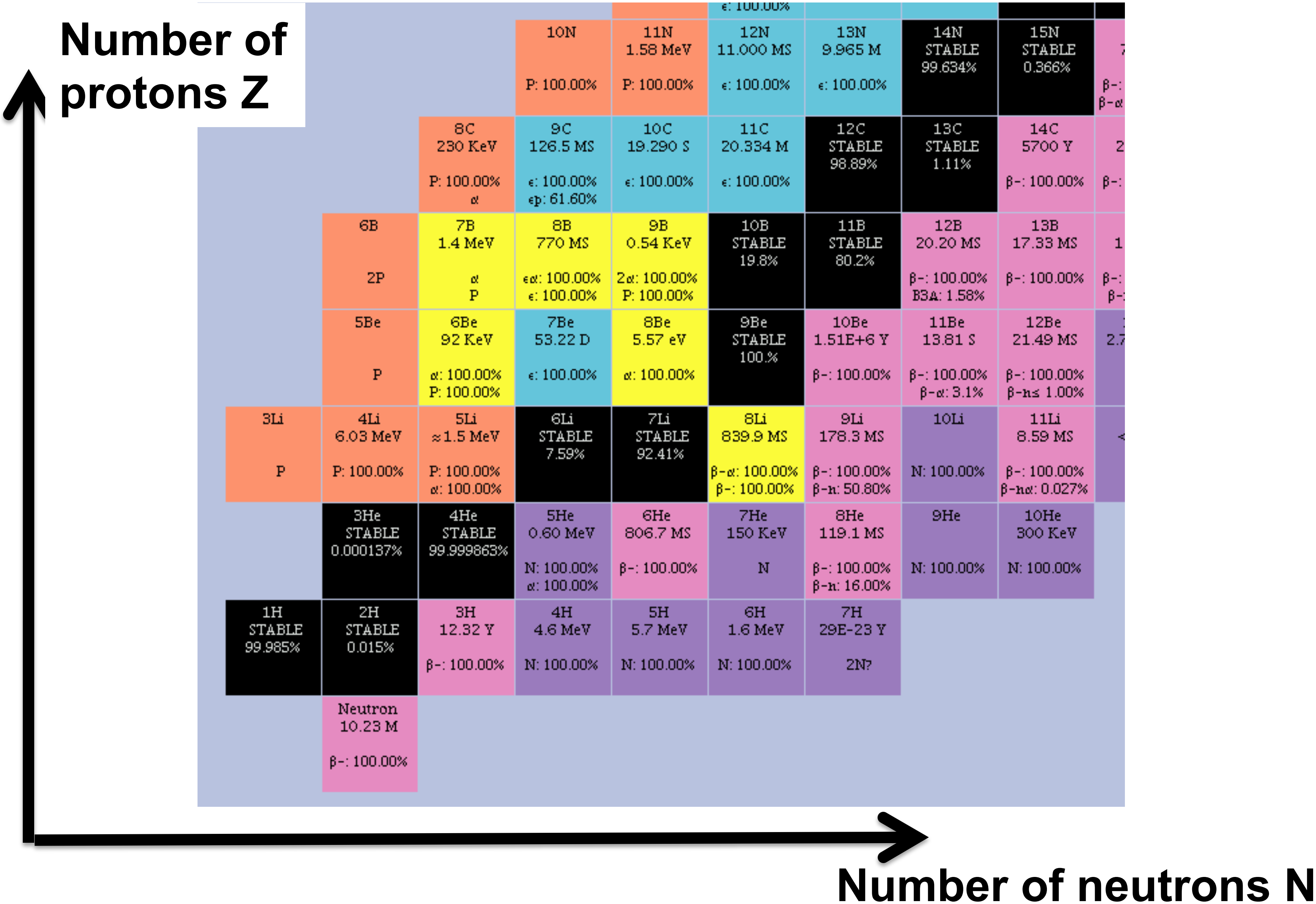
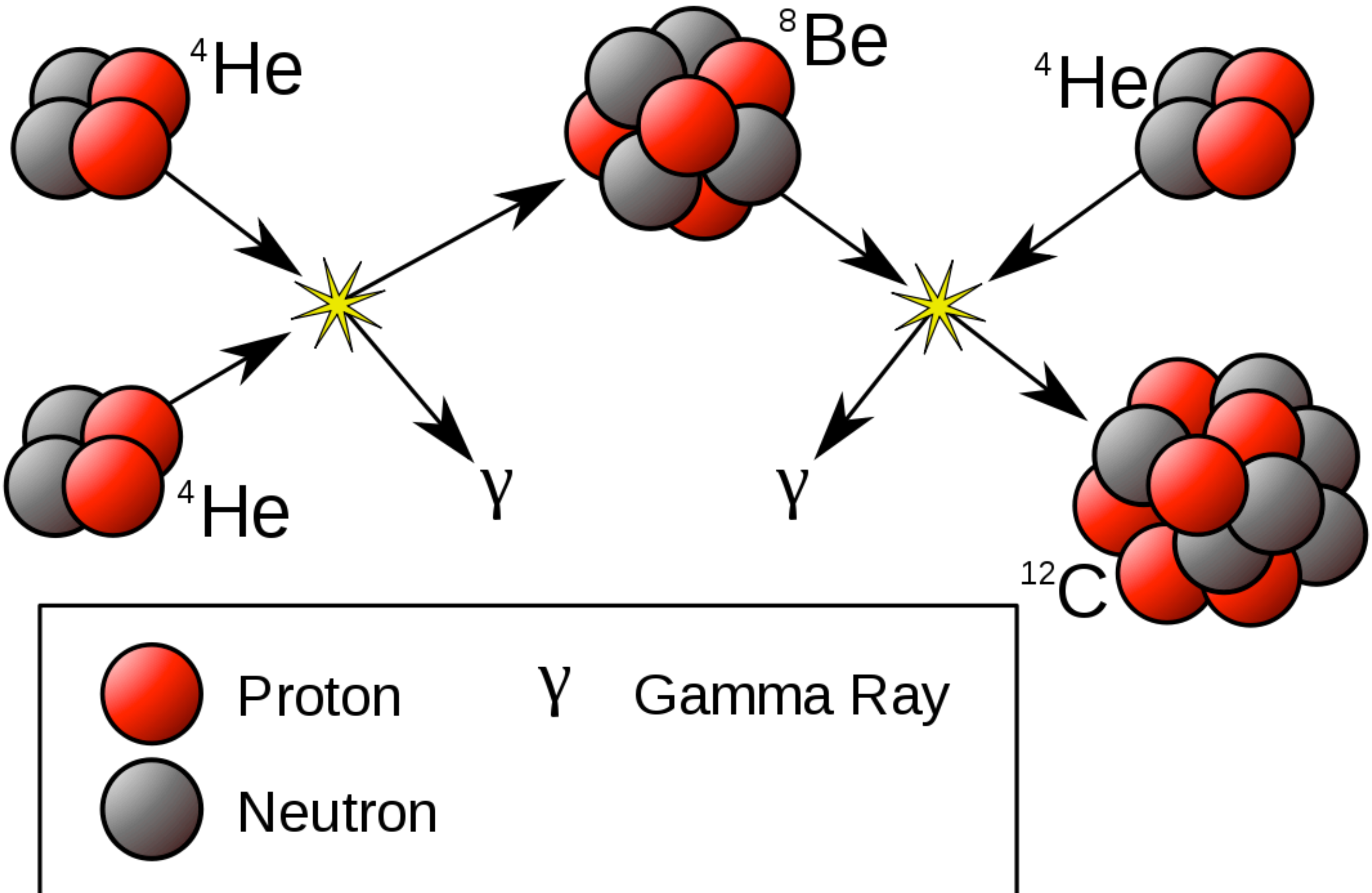
The nuclide chart



Which nuclear masses do not exist in stable form:

1. 3, 4 and 5
2. 5 and 8
3. 1, 2, and 3
4. 5 and 7

He burning:
The triple alpha (α = ^{4}He) reaction



He burning & the "Hoyle" state

$t_{1/2}(^{8}Be)=9.7 \times 10^{-17}$ s

$^{8}Be \rightleftarrows \alpha+\alpha$

$$\boxed{\frac{N(^{8}B)}{N(\alpha)} \approx 5 \times 10^{-10}}$$

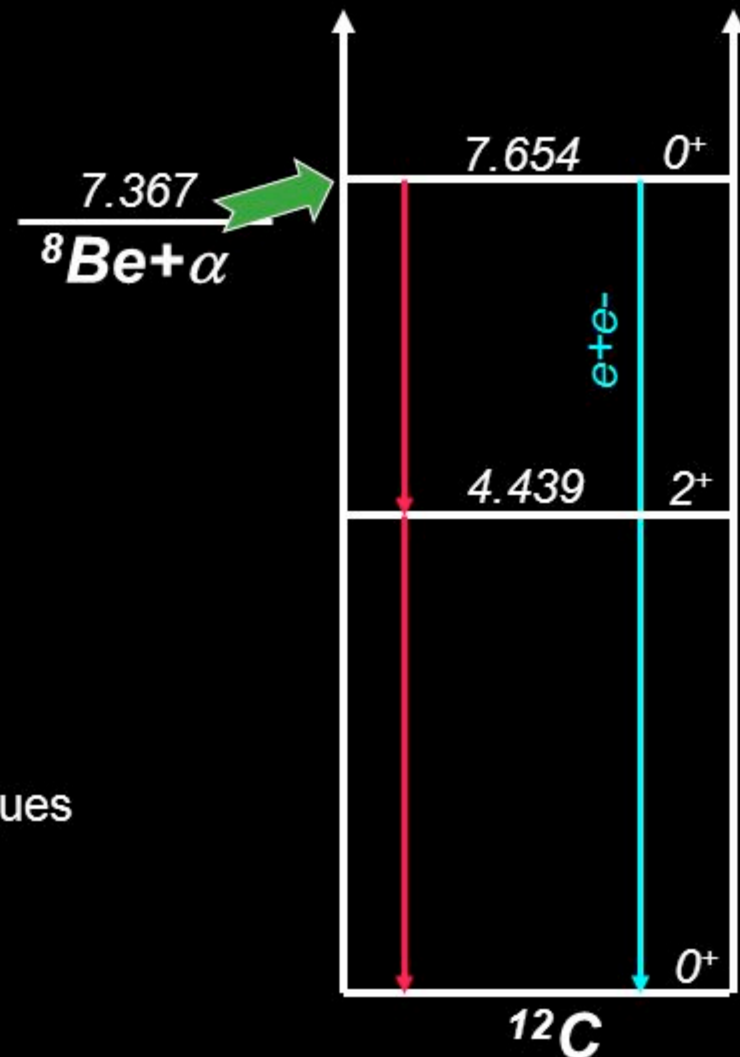
0^{+} resonance near the Gamow energy was predicted by Hoyle

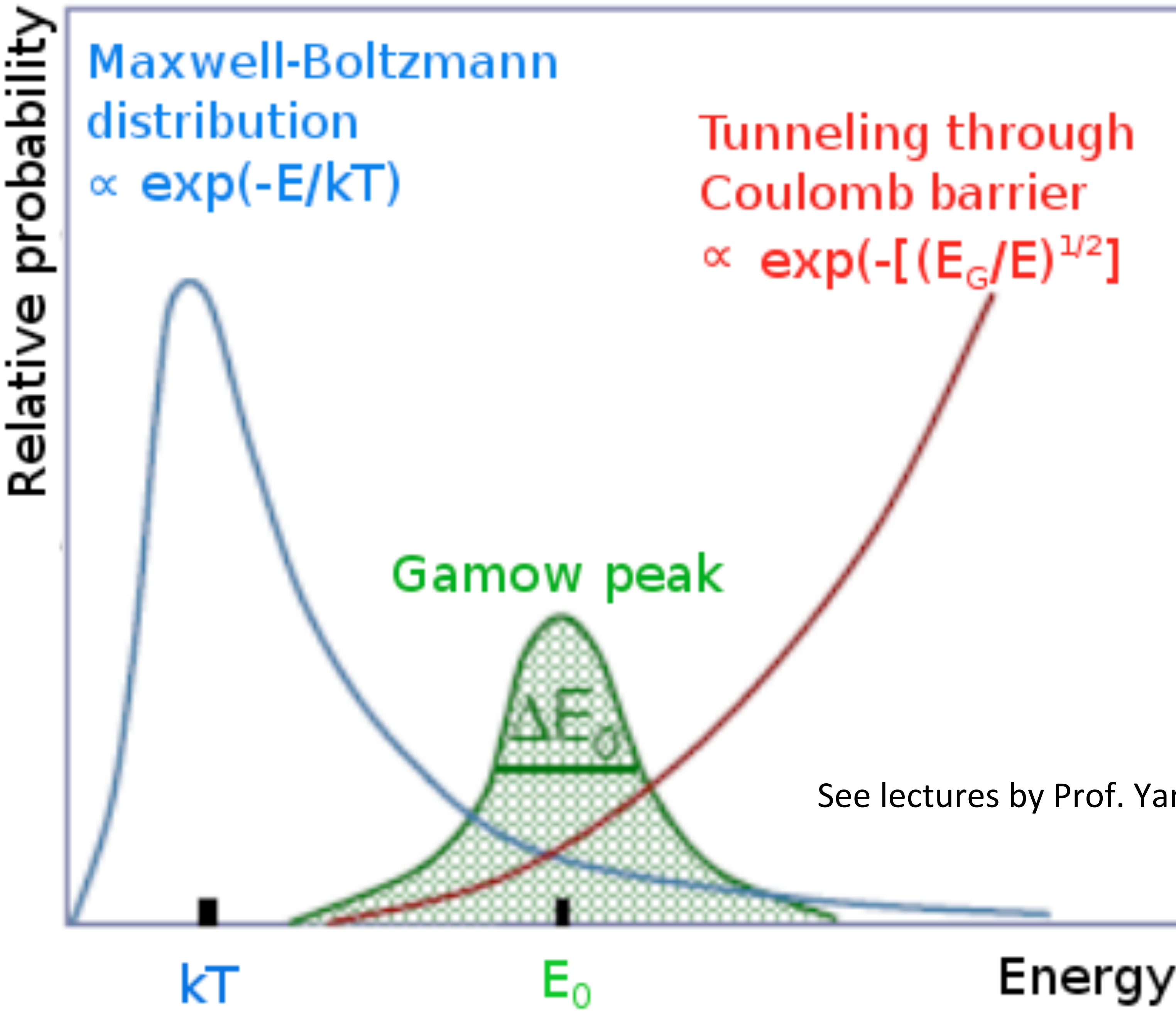
Phys Rev 92 (1953) 1095.

Numerous complementary techniques

$^{12}C(p,p')^{12}C^{*}$

$^{13}C(^{3}He,\alpha)^{12}C^{*}$ $\Rightarrow$ $\gamma\gamma$, 3α, $e^{+}e^{-}$





See lectures by Prof. Yamaguchi

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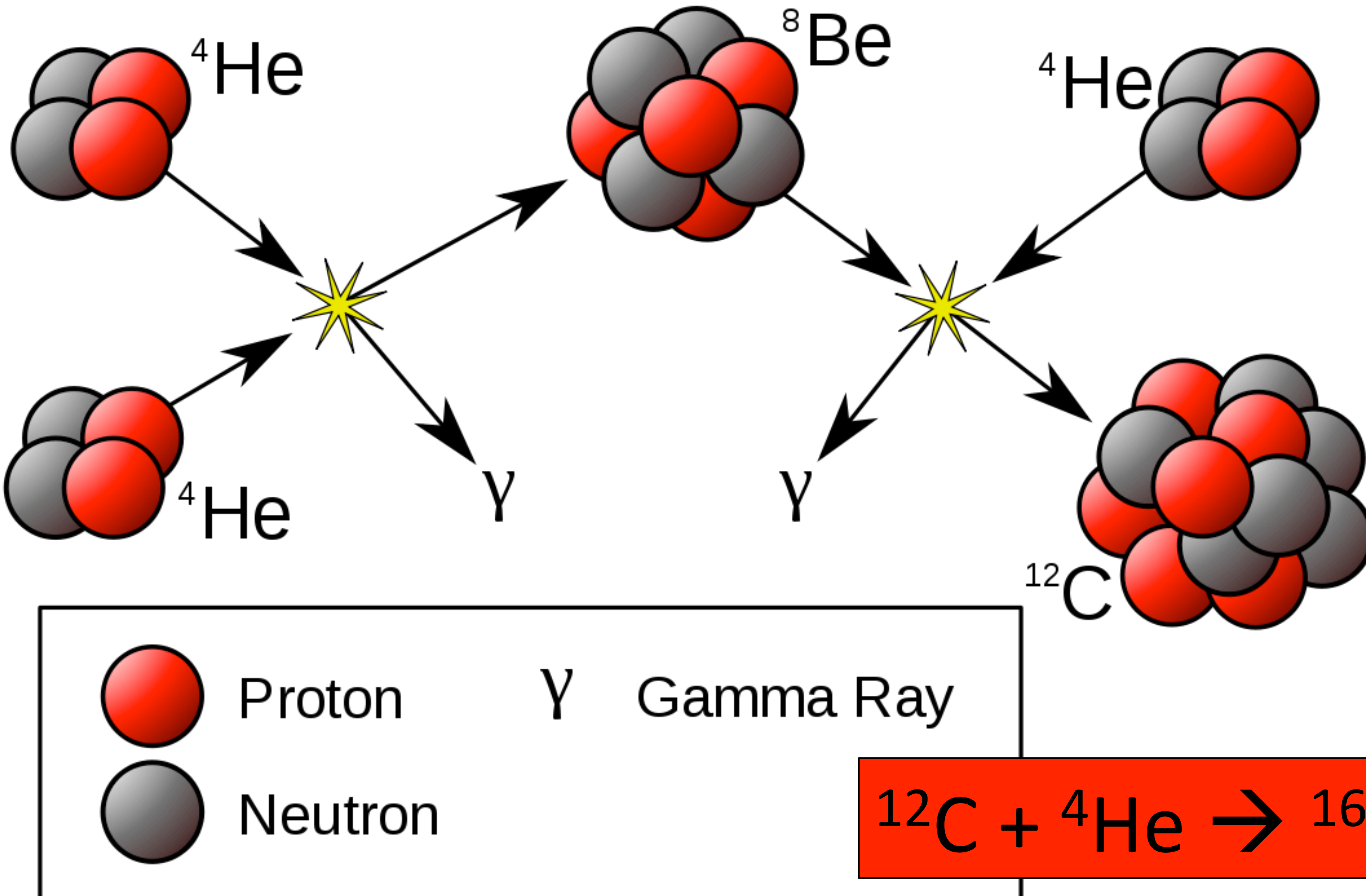
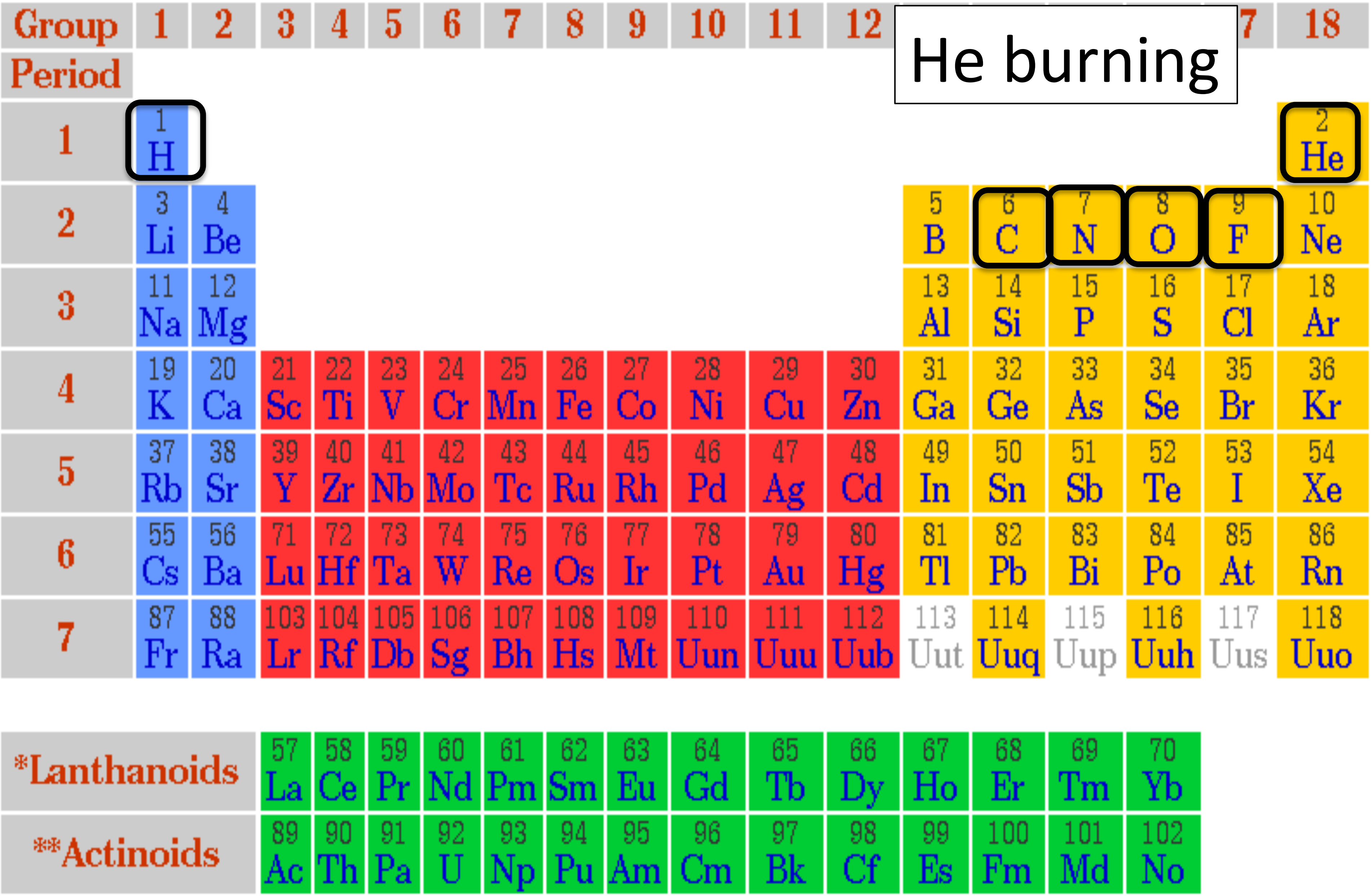


$^{12}C + ^4He \rightarrow ^{16}O$

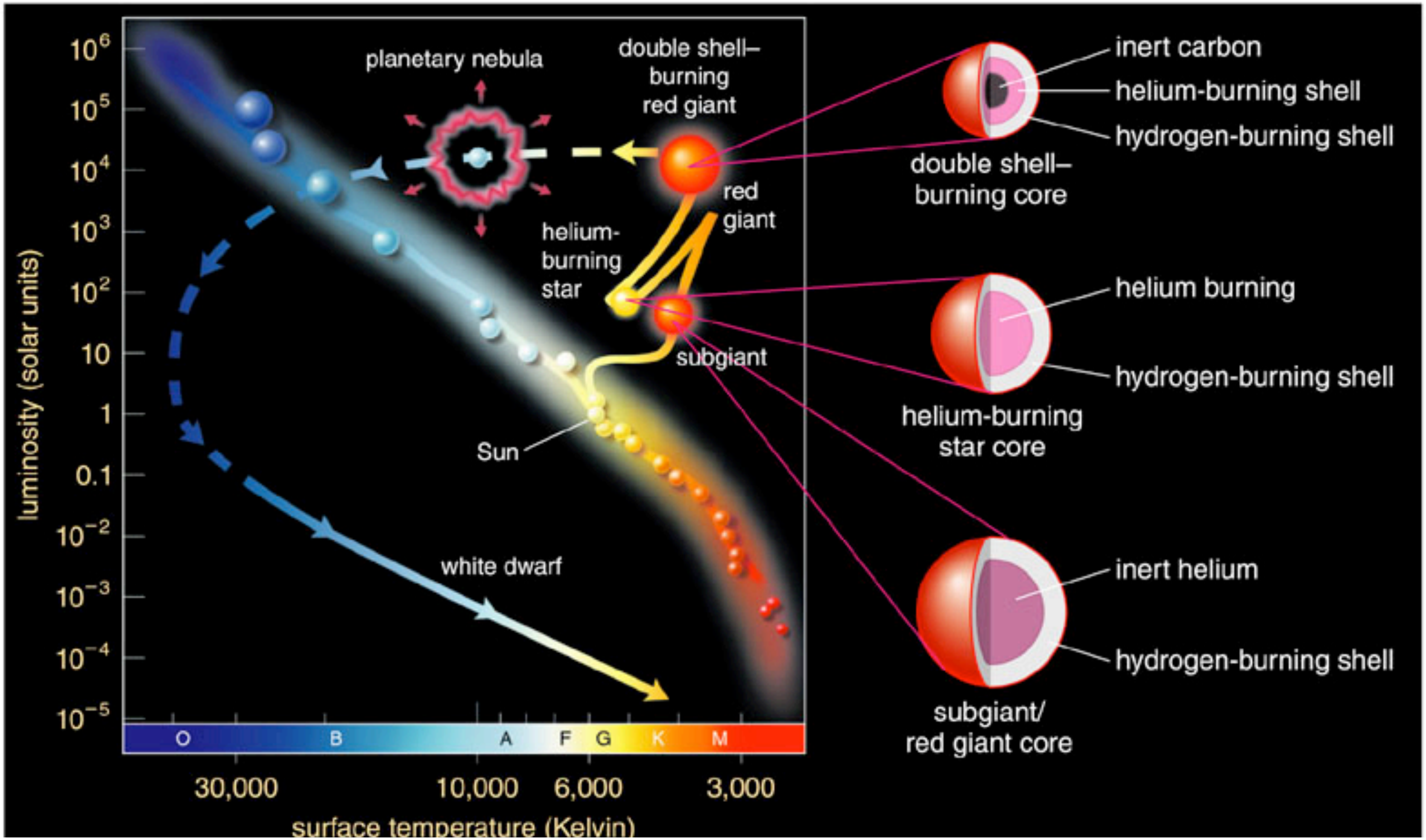
The Big Bang

H burning

He burning

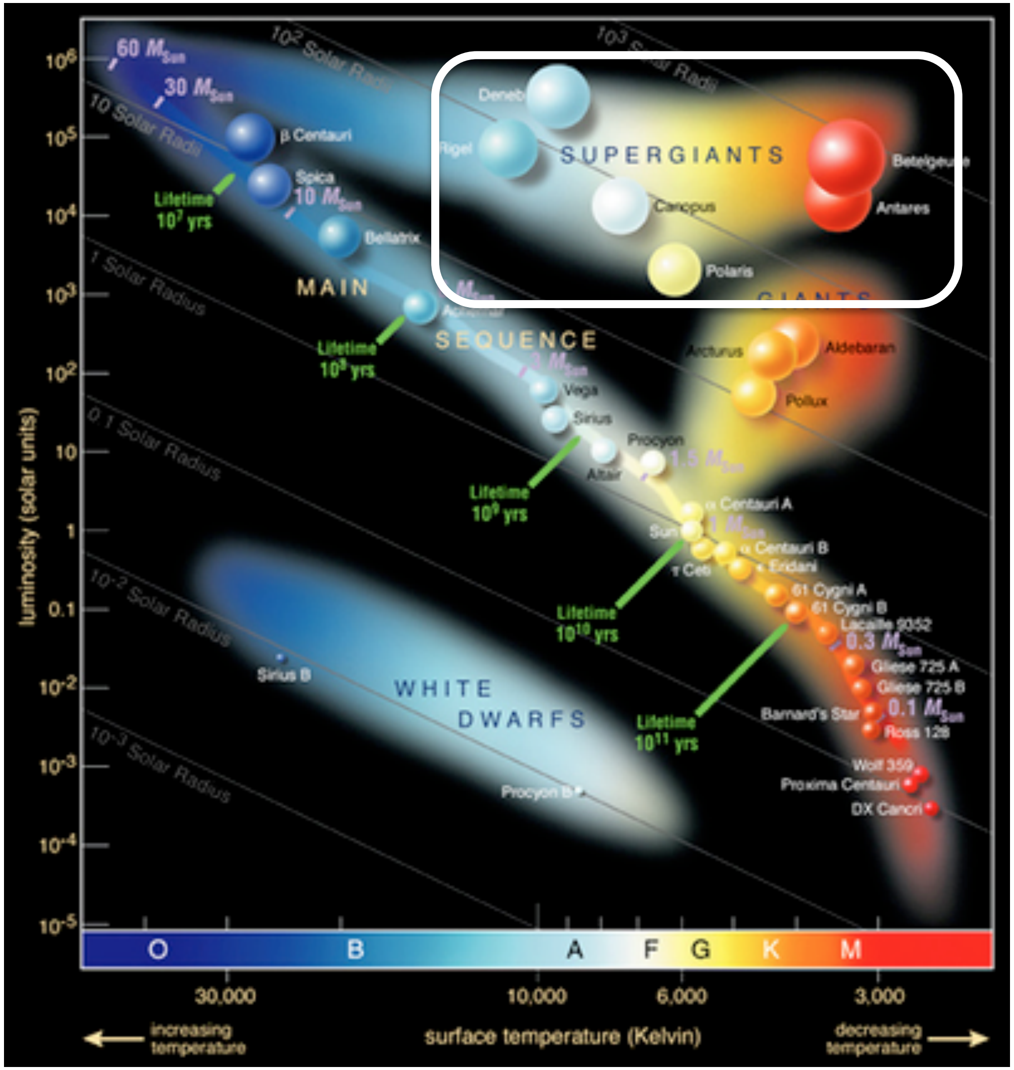


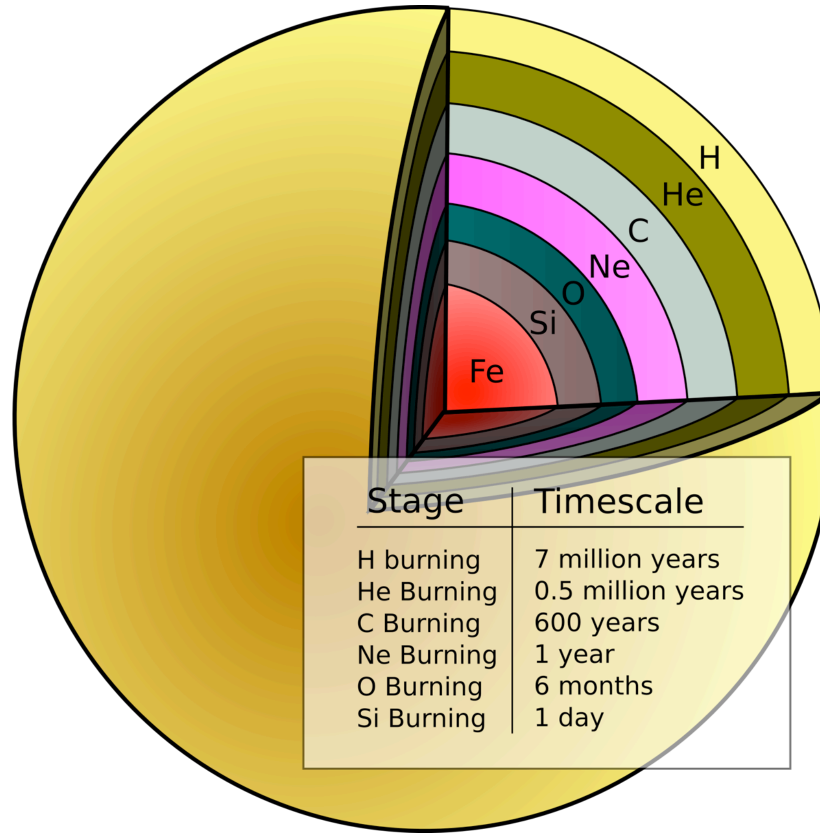
In stars < 10 the mass of the Sun…



…the core can reach 100 MK needed for He burning, after that it will become a white dwarf

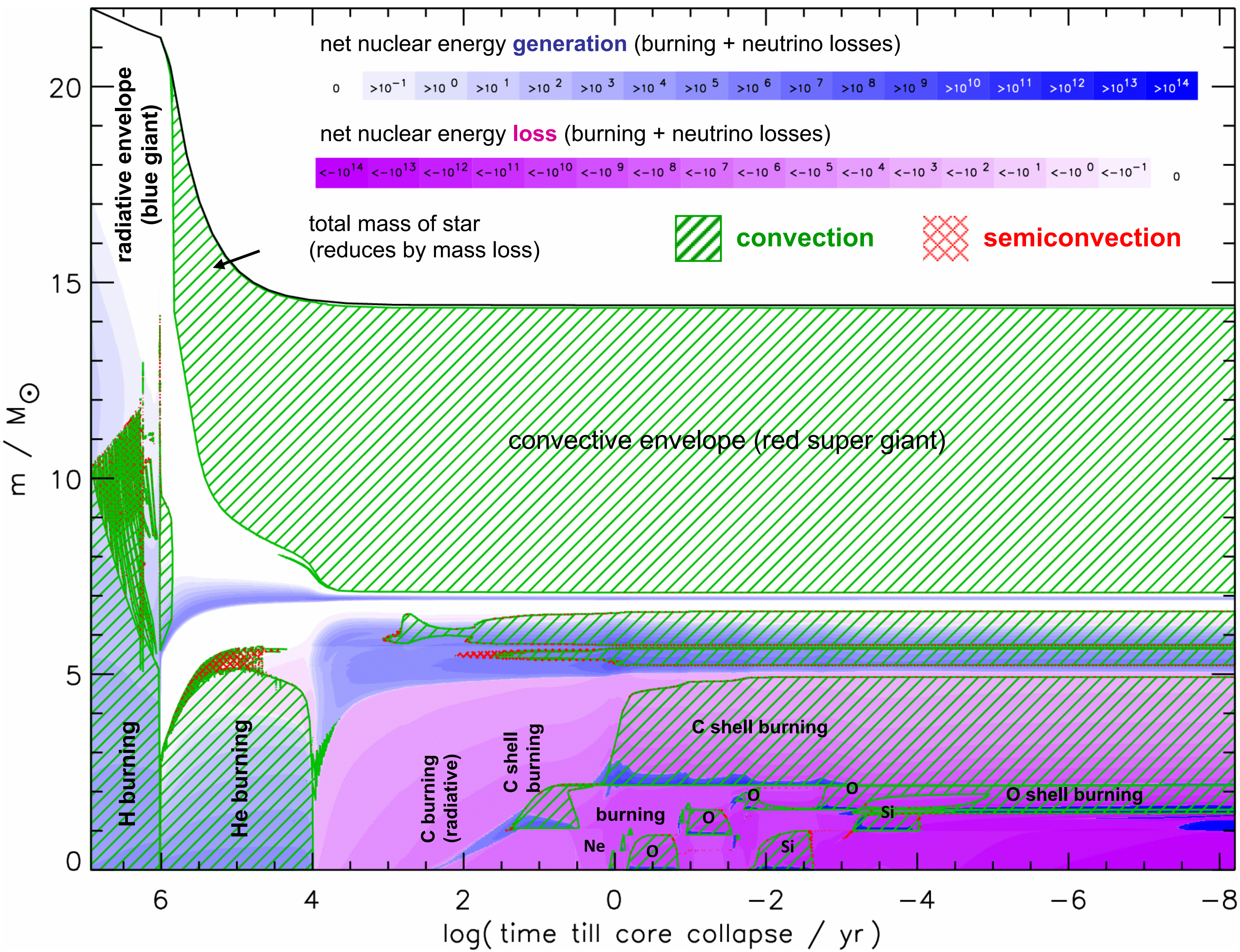
In stars > 10 the mass of the Sun…





Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

…the core can get hotter and keep burning

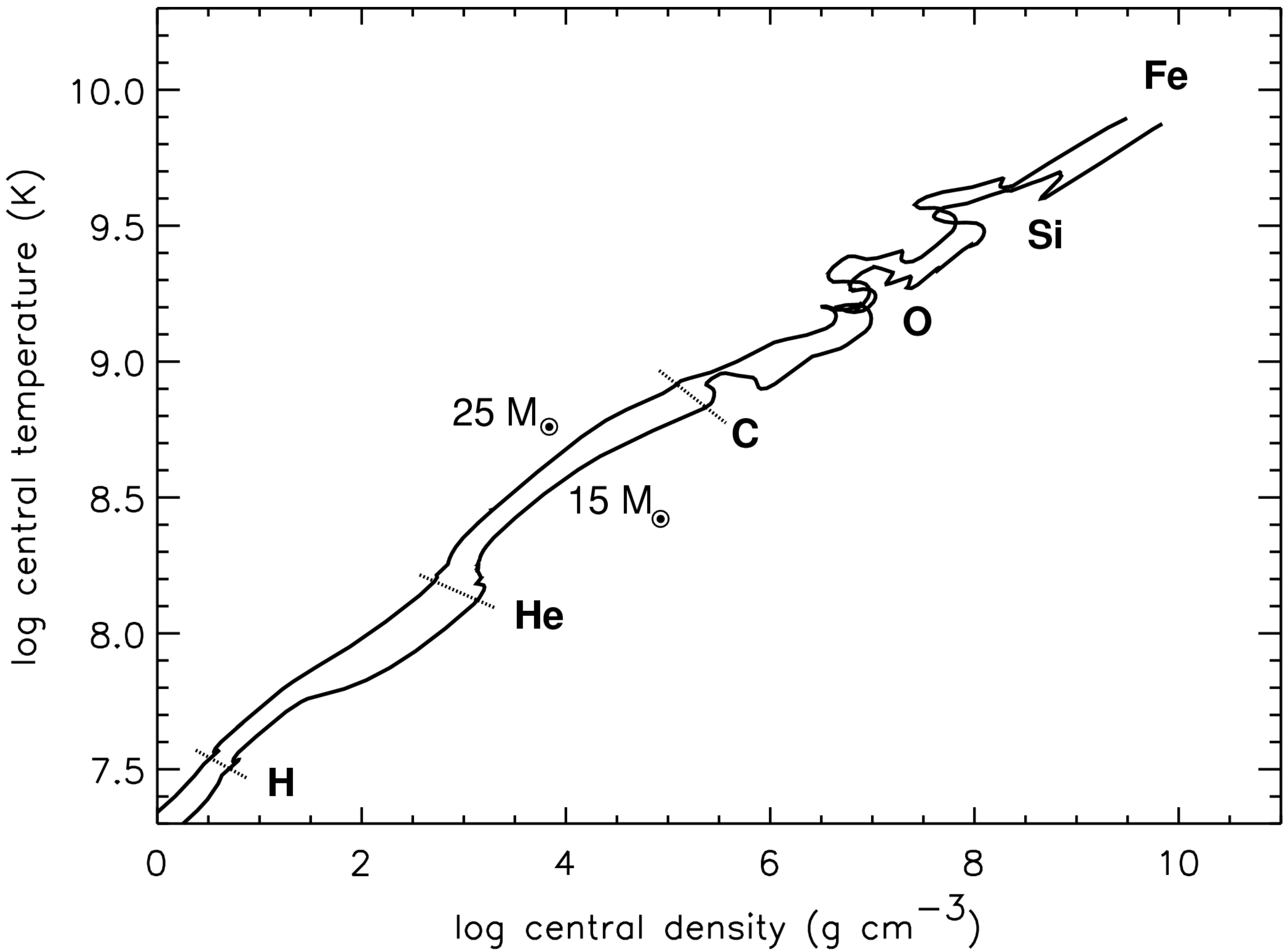


net nuclear energy generation (burning + neutrino losses)
net nuclear energy loss (burning + neutrino losses)
total mass of star
(reduces by mass loss)
convection
semiconvection
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
O shell burning
Ne
burning
O
Si
m / M⊙
log(time till core collapse / yr)

Once formed, the evolution of a star is governed by gravity:

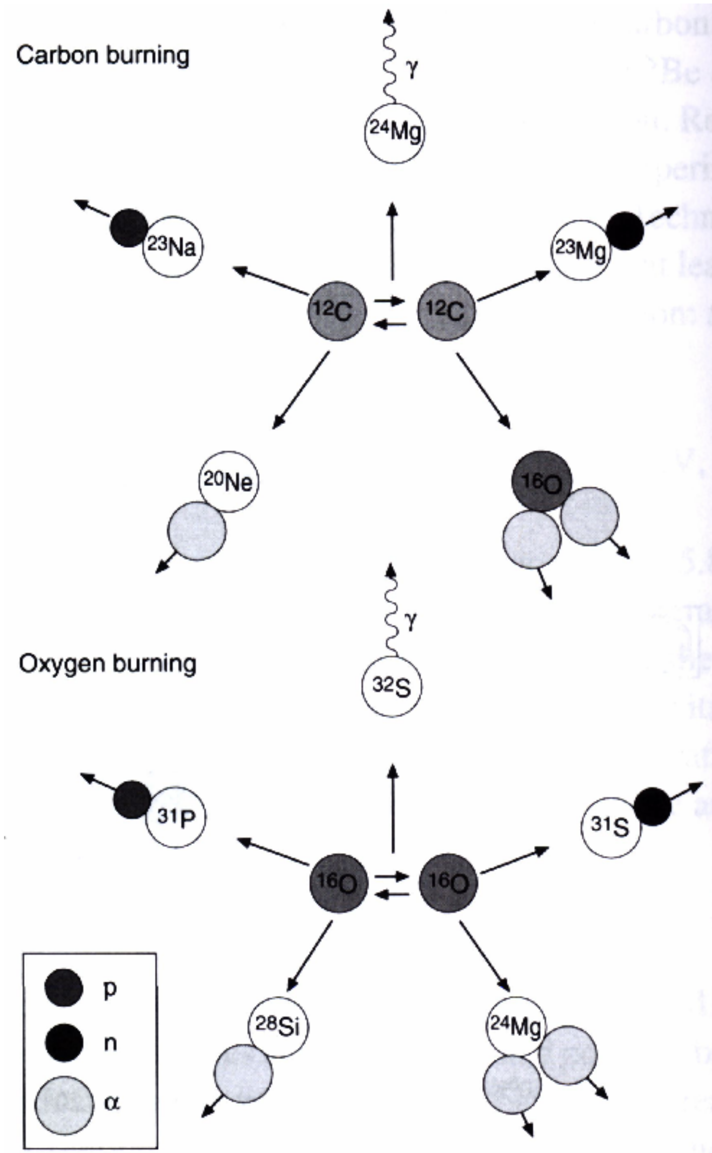
continuing contraction

to higher central densities and temperatures



Evolution of central density and temperature of 15 M$_\odot$ and 25 M$_\odot$ stars

Carbon and Oxygen Burning



Carbon Burning

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\to {}^{24}\mathrm{Mg} + \gamma \quad , && 13.931 \\
&\to {}^{23}\mathrm{Mg} + n \quad , && -2.605 \\
&\to {}^{23}\mathrm{Na} + p \quad , && 2.238 \\
&\to {}^{20}\mathrm{Ne} + \alpha \quad , && 4.616 \\
&\to {}^{16}\mathrm{O} + 2\alpha \quad , && -0.114
\end{aligned}
$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\to {}^{32}\mathrm{S} + \gamma \quad , && 16.541 \\
&\to {}^{31}\mathrm{P} + p \quad , && 7.677 \\
&\to {}^{31}\mathrm{S} + n \quad , && 1.453 \\
&\to {}^{28}\mathrm{Si} + \alpha \quad , && 9.593 \\
&\to {}^{24}\mathrm{Mg} + 2\alpha \quad , && -0.393
\end{aligned}
$$

Average $Q = 16\,\mathrm{MeV}$

Neon Burning

Neon burning proceeds by a combination of photo-disintegrations and α captures:

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}\,, \quad Q = -4.73\,\mathrm{MeV}$$

This reaction dominates over the inverse reaction known from helium burning for $T > 1.5 \times 10^9\,\mathrm{K}$.

Subsequently, the ^{4}He is captured on another ^{20}Ne nucleus:

$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma.$$

The net result is

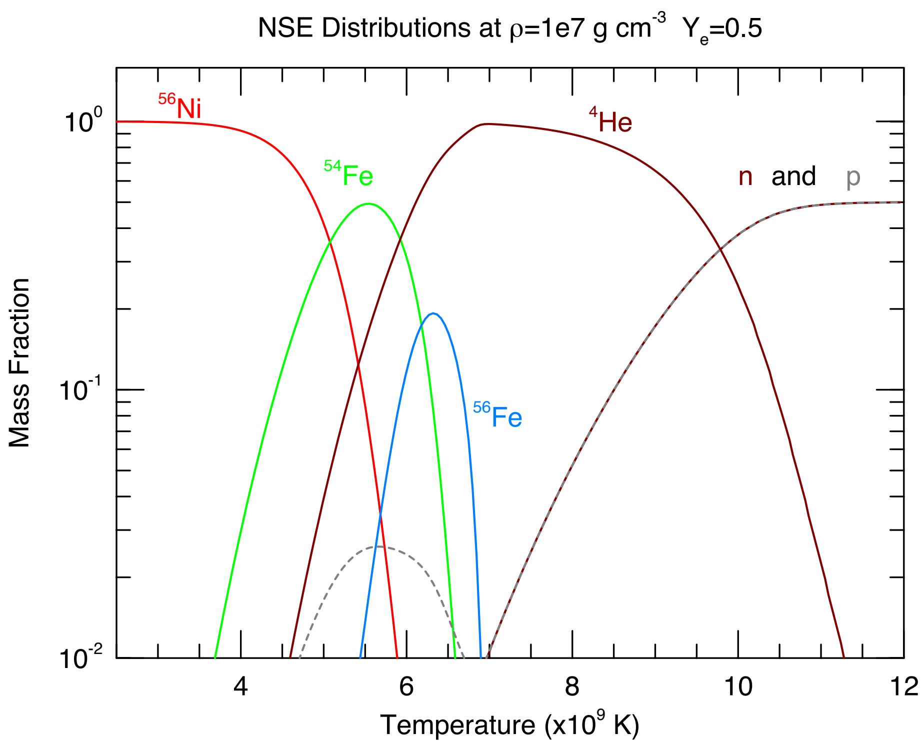
$$2\,{}^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{24}\mathrm{Mg} + \gamma\,, \quad Q = +4.583\,\mathrm{MeV}$$

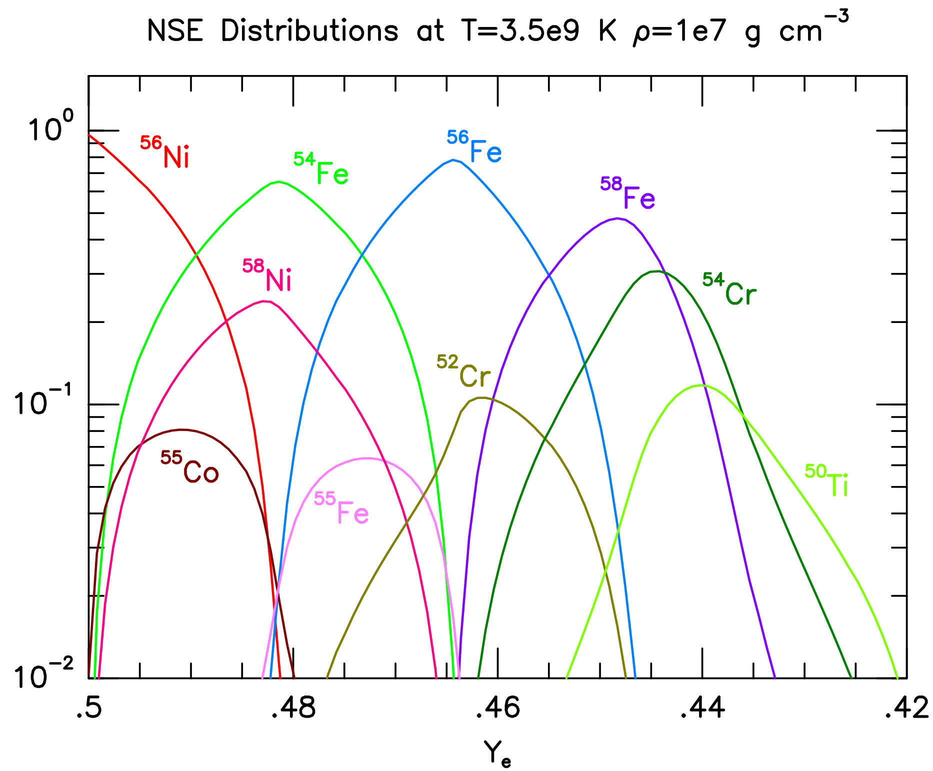
Nuclear burning phases for a 20 $M_\odot$ star

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

Nuclear Statistical Equilibrium

When the strong and the electromagnetic interactions come into equilibrium, the nuclear abundances depend only on the temperature T, density ρ, and neutron-richness Y_e.





Favours the production of the **nuclei with the highest binding energy per nucleon**

The binding energy per nucleon is the average energy needed to "break off" one nucleon from the nucleus.

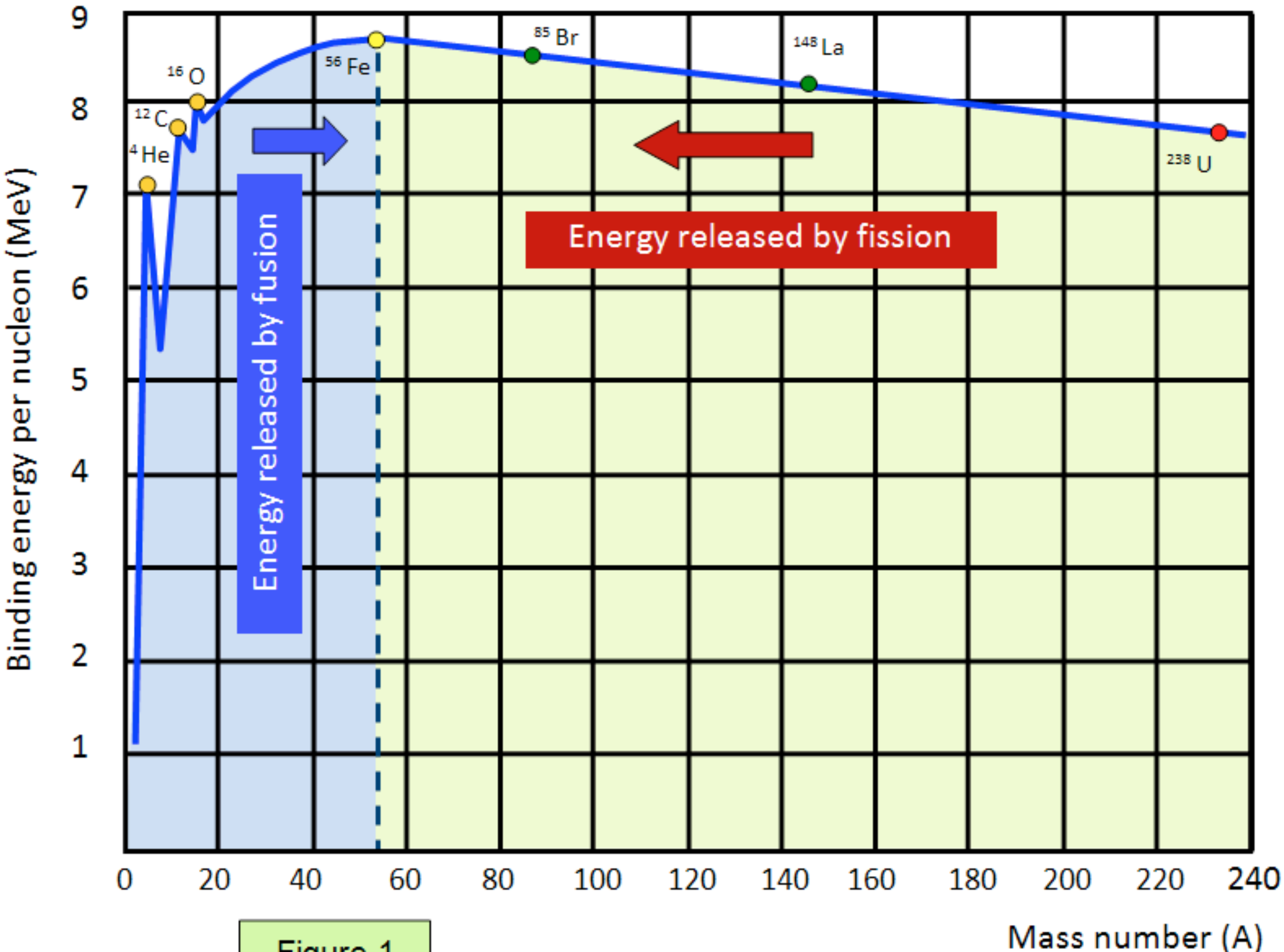
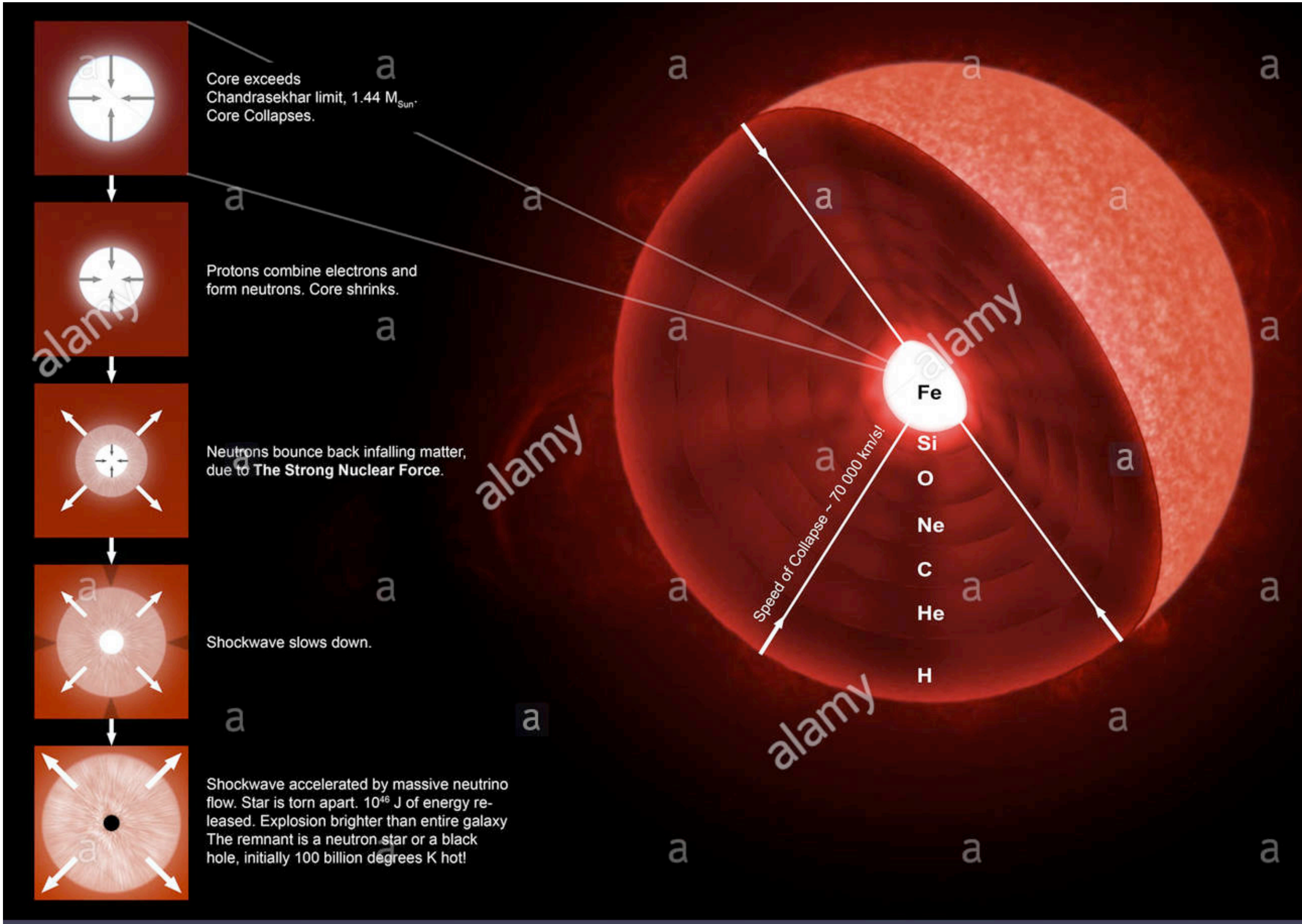


Figure 1

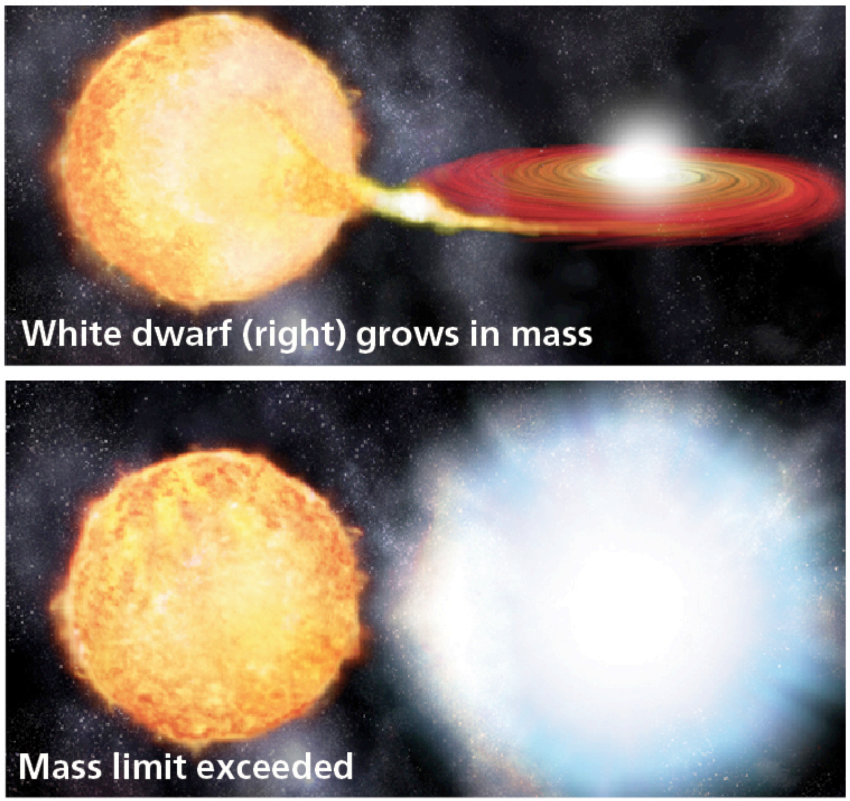
Core Collapse/*Type II (H-rich)* Supernovae



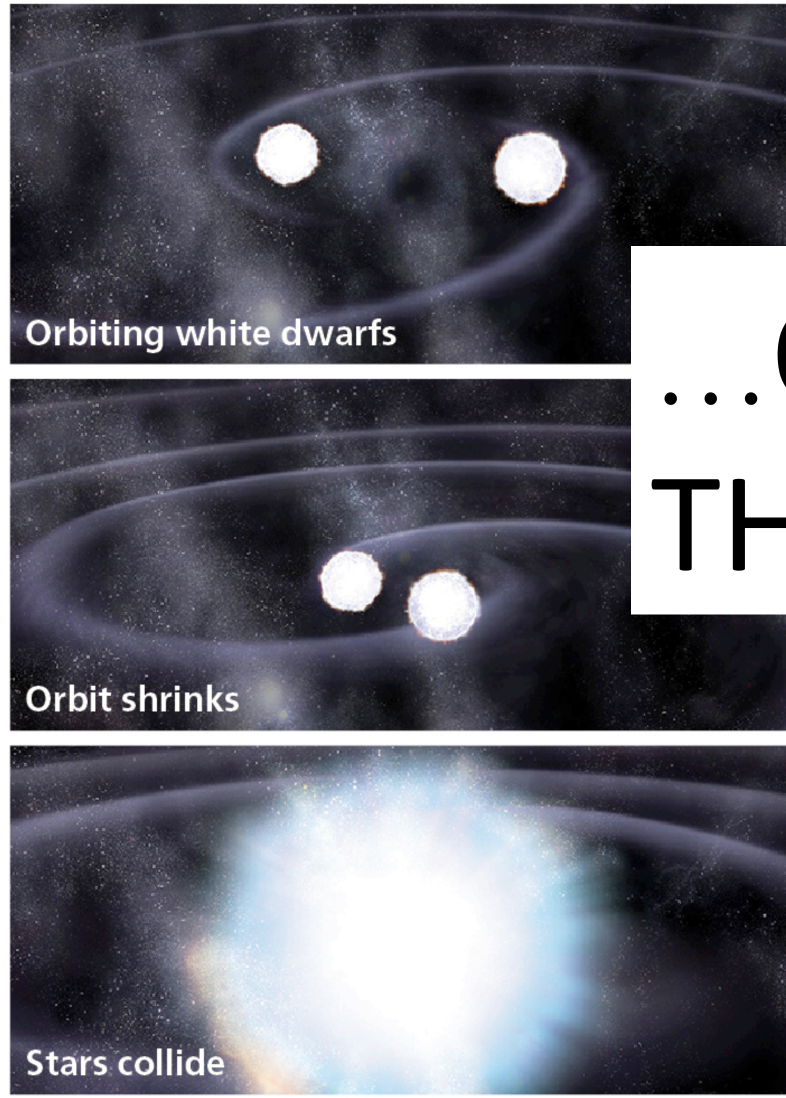
Thermonuclear/*Type I (no H)* Supernovae:

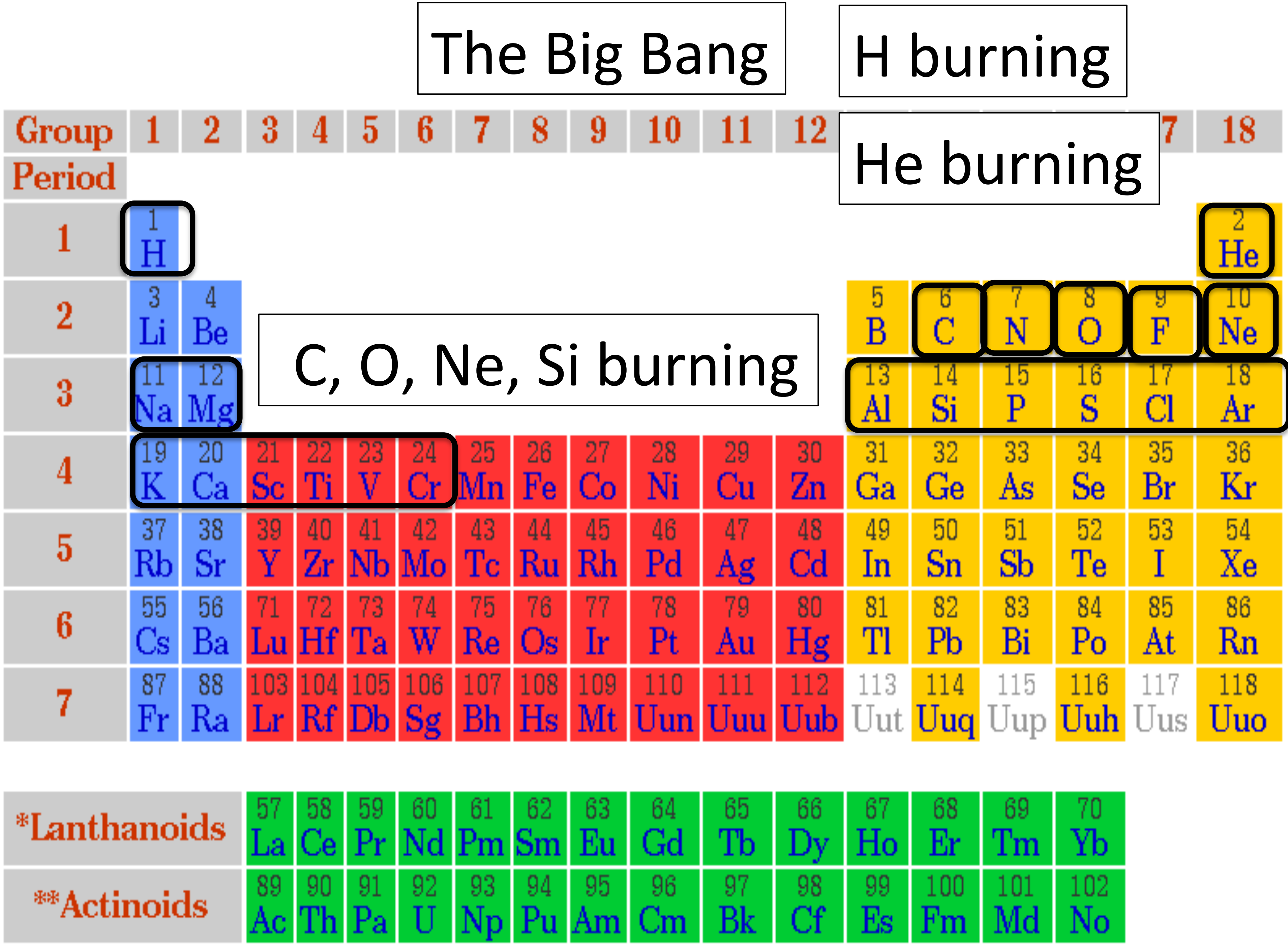
explosion of a white dwarf that has reached the Chandrasekhar mass, how?

THIS…

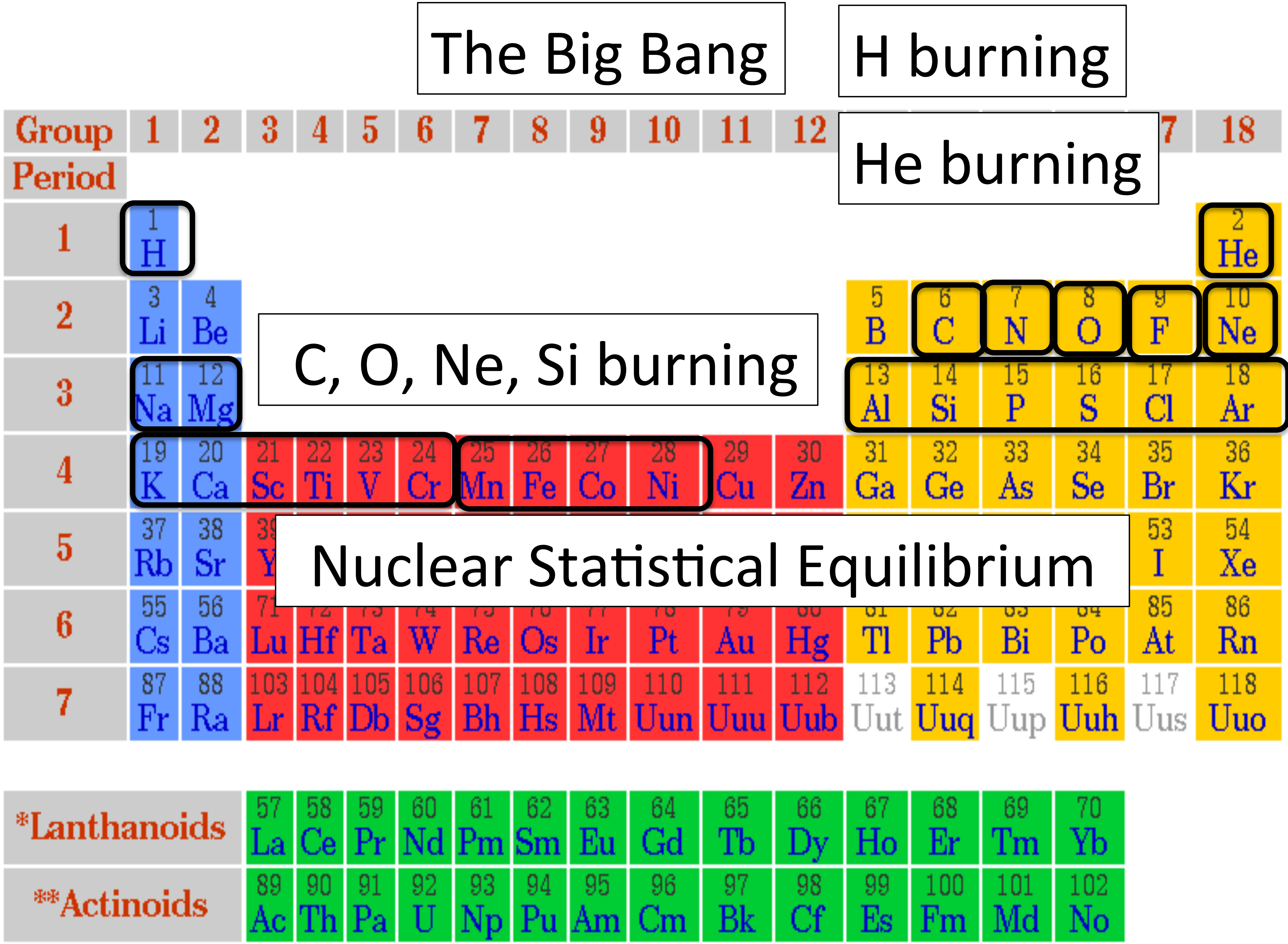


…OR THIS?

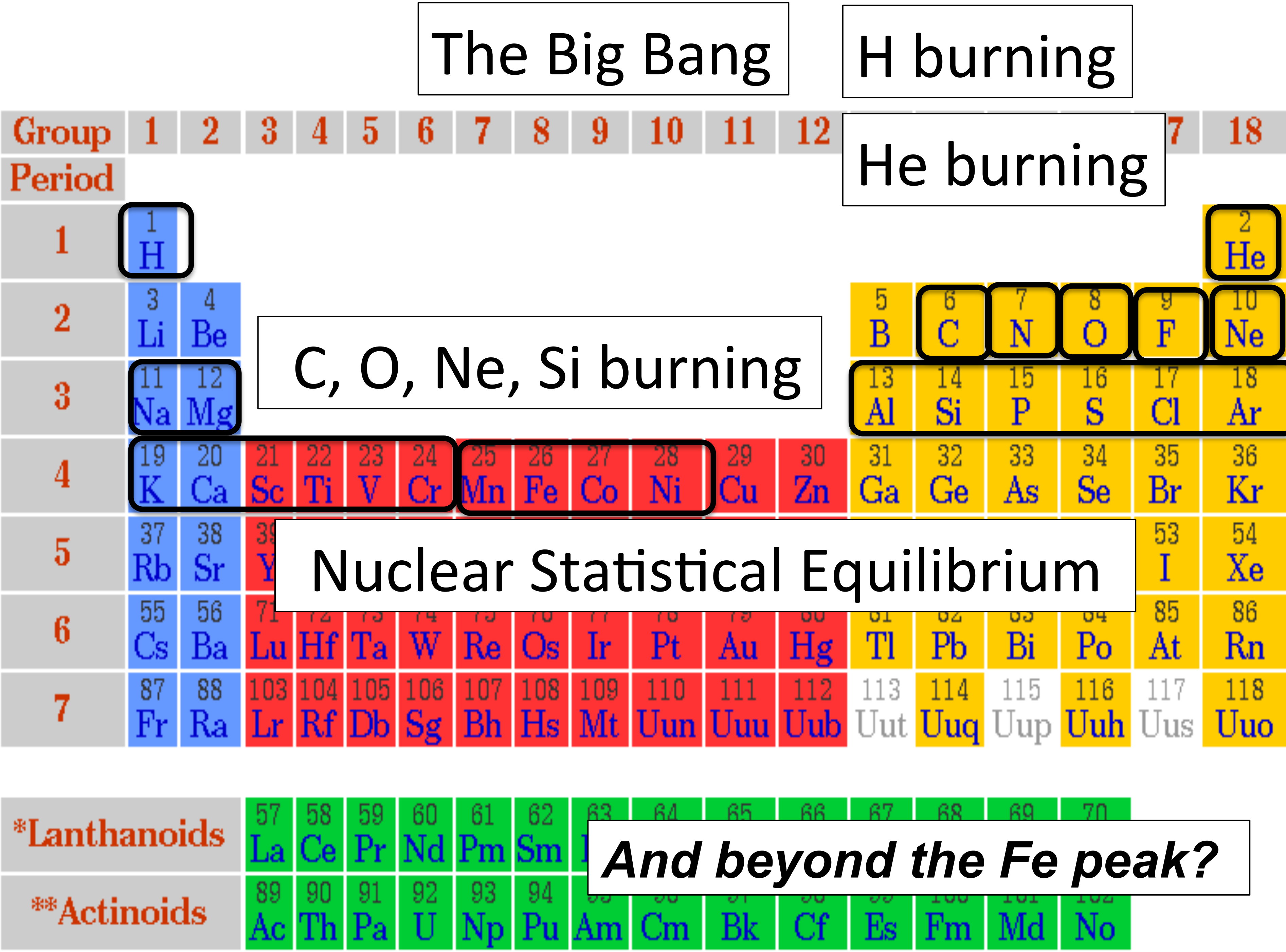




The Big Bang
H burning
He burning
C, O, Ne, Si burning
Group 1 2 3 4 5 6 7 8 9 10 11 12 18
Period
1 1 H 2 He
2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
4 19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
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 Uun 111 Uuu 112 Uub 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



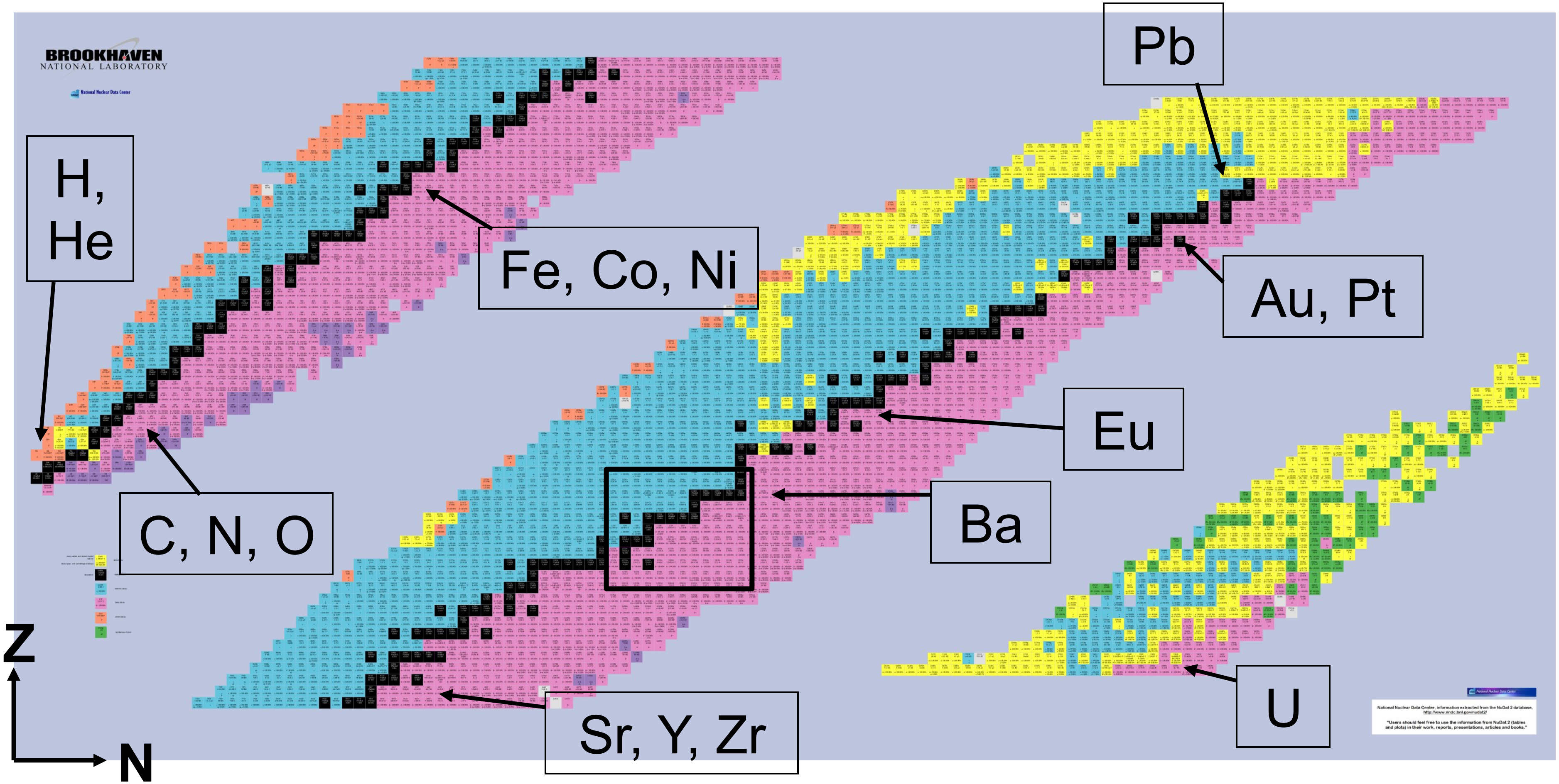
The Big Bang
H burning
He burning
C, O, Ne, Si burning
Nuclear Statistical Equilibrium
Group 1 2 3 4 5 6 7 8 9 10 11 12 18
Period
1 1 H 2 He
2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
4 19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
5 37 Rb 38 Sr 53 I 54 Xe
6 55 Cs 56 Ba Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi 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 Uun 111 Uuu 112 Uub 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



The Big Bang
H burning
He burning
C, O, Ne, Si burning
Nuclear Statistical Equilibrium
And beyond the Fe peak?
Group 1 2 3 4 5 6 7 8 9 10 11 12 18
Period
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 53 I 54 Xe
55 Cs 56 Ba Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po 85 At 86 Rn
87 Fr 88 Ra 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Uun 111 Uuu 112 Uub 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
**Actinoids 89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu Am Cm Bk Cf Es Fm Md No

Beyond Fe

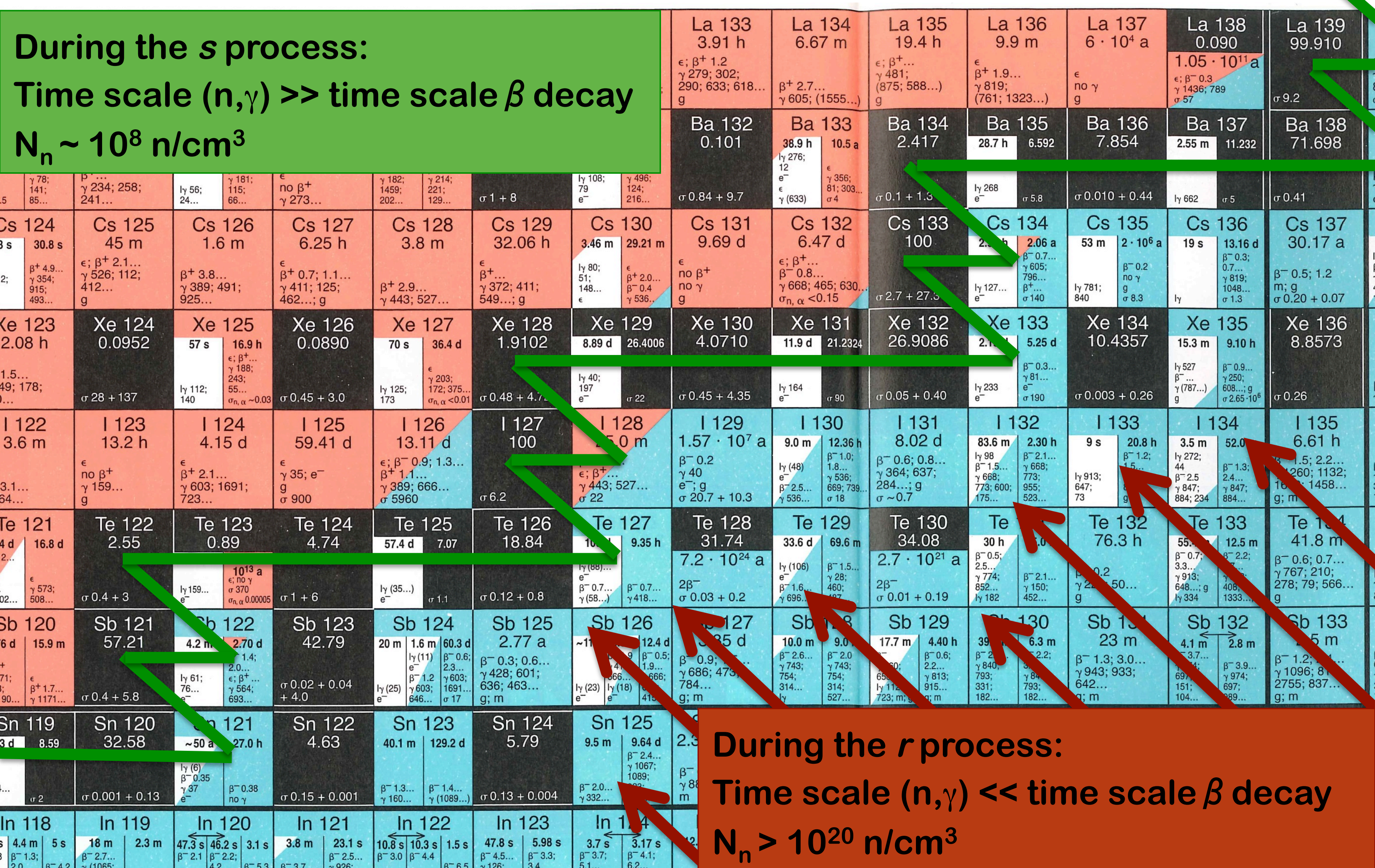
- Need to add energy to do fusion
- Nuclear reactions do not contribute anymore to the energy of a star
- High coulomb barrier prevents proton or alpha captures, because they are charged
- Have to add **neutrons** to make heavier elements!



Because of their high number of protons (>26), elements heavier than Fe have a large Coulomb barrier and can be produced only by capturing neutrons.

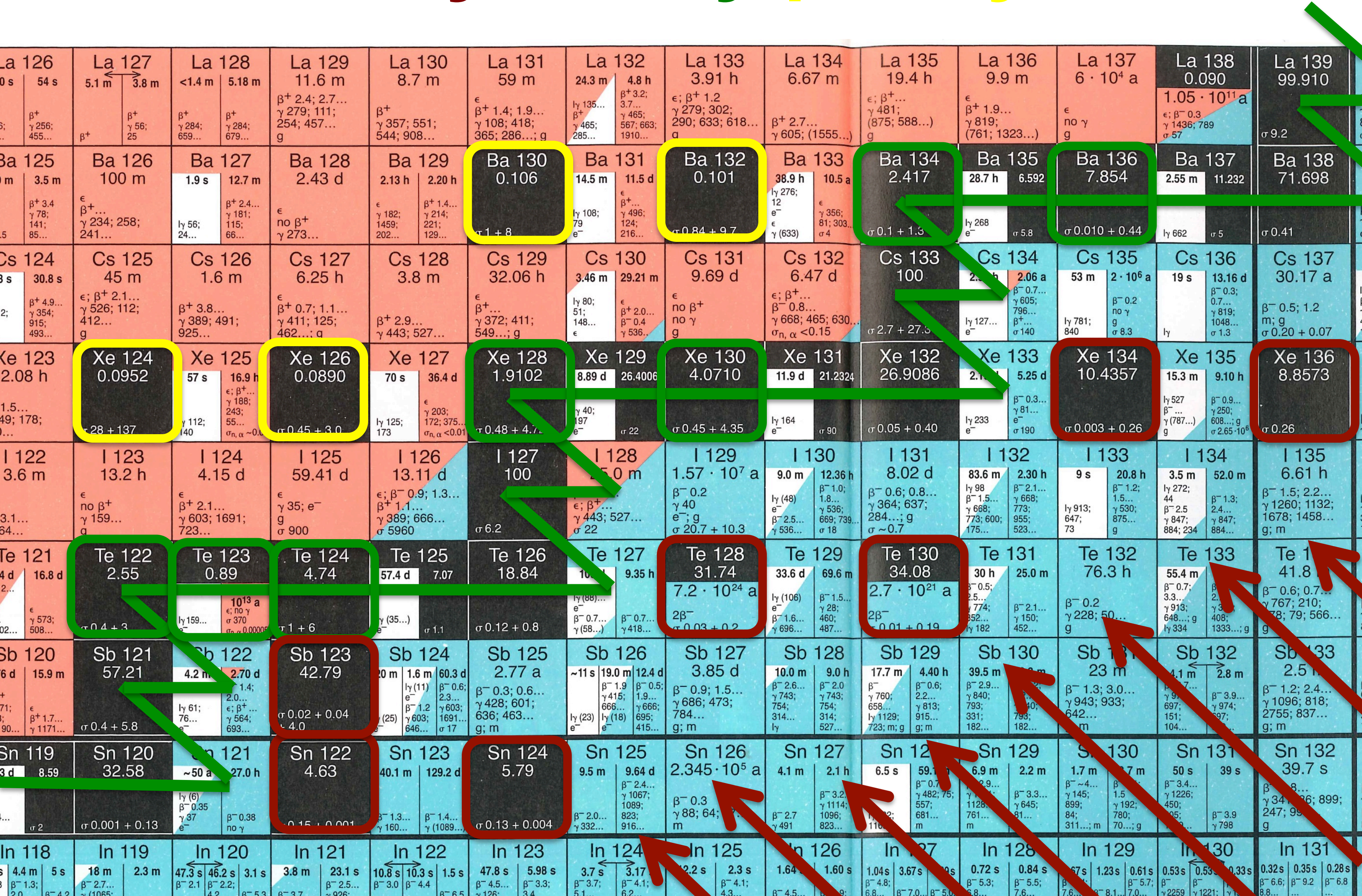
Slow and Rapid neutron captures

During the *s* process:
Time scale (n,γ) >> time scale β decay
$N_n \sim 10^8$ n/cm^3



During the *r* process:
Time scale (n,γ) << time scale β decay
$N_n > 10^{20}$ n/cm^3

r-only s-only p-only



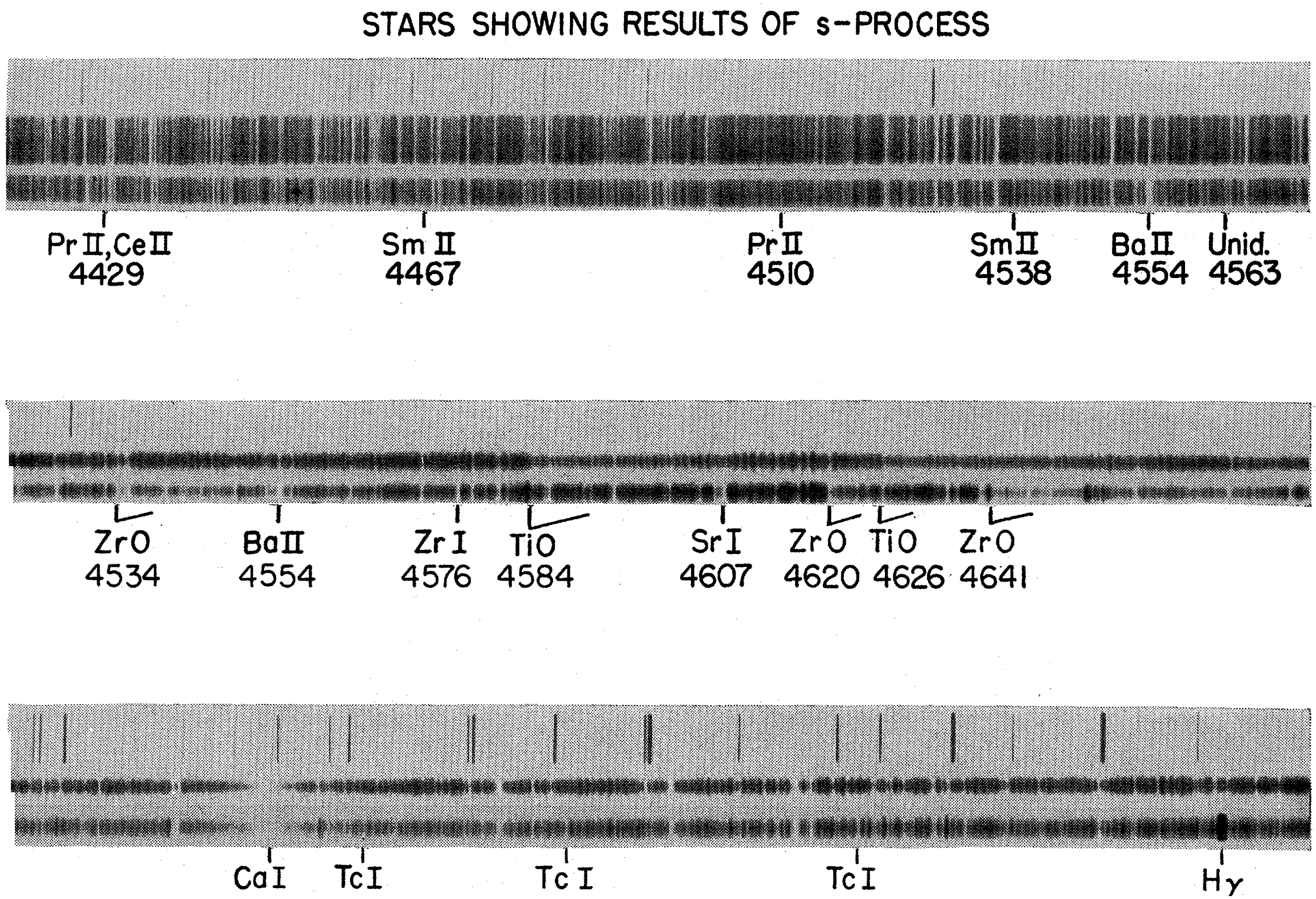
Which of these statements is wrong?

95Rh 5.02 M ϵ: 100.00%	96Rh 9.90 M ϵ: 100.00%	97Rh 30.7 M ϵ: 100.00%	98Rh 8.72 M ϵ: 100.00%	99Rh 16.1 D ϵ: 100.00%	100Rh 20.8 H ϵ: 100.00%	101Rh 3.3 Y ϵ: 100.00%	102Rh 207 D ϵ: 78.00% β-: 22.00%	103Rh STABLE 100%	104Rh 42.3 S β-: 99.55% ϵ: 0.45%	105Rh 35.36 H β-: 100.00%
94Ru 51.8 M ϵ: 100.00%	95Ru 1.643 H ϵ: 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D ϵ: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H ϵ: 100.00%	94Tc 293 M ϵ: 100.00%	95Tc 20.0 H ϵ: 100.00%	96Tc 4.28 D ϵ: 100.00%	97Tc 4.21E+6 Y ϵ: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ϵ: 1.8E-3%	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 S β-: 100.00%
92Mo STABLE 14.84%	93Mo 4.0E+3 Y ϵ: 100.00%	94Mo STABLE 9.25%	95Mo STABLE 15.92%	96Mo STABLE 16.68%	97Mo STABLE 9.55%	98Mo STABLE 24.13%	99Mo 2.7489 D β-: 100.00%	100Mo 7.3E+18 Y 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%
91Nb 6.8E+2 Y ϵ: 100.00%	92Nb 3.47E+7 Y ϵ: 100.00% β- < 0.05%	93Nb STABLE 100%	94Nb 2.03E+4 Y β-: 100.00%	95Nb 34.991 D β-: 100.00%	96Nb 23.35 H β-: 100.00%	97Nb 72.1 M β-: 100.00%	98Nb 2.86 S β-: 100.00%	99Nb 15.0 S β-: 100.00%	100Nb 1.5 S β-: 100.00%	101Nb 7.1 S β-: 100.00%
90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.53E+6 Y β-: 100.00%	94Zr STABLE 17.38%	95Zr 64.032 D β-: 100.00%	96Zr >3.9E+20 Y 2.80% 2β-	97Zr 16.744 H β-: 100.00%	98Zr 30.7 S β-: 100.00%	99Zr 2.1 S β-: 100.00%	100Zr 7.1 S β-: 100.00%
89Y STABLE 100%	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.058%	98Y 0.548 S β-: 100.00% β-n: 0.33%	99Y 1.470 S β-: 100.00% β-n: 1.90%
88Sr STABLE 82.58%	89Sr 50.57 D β-: 100.00%	90Sr 28.90 Y β-: 100.00%	91Sr 9.63 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.423 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S β-: 100.00%	96Sr 1.07 S β-: 100.00%	97Sr 429 MS β-: 100.00% β-n≤ 0.05%	98Sr 0.653 S β-: 100.00% β-n: 0.25%

Hint: Track the *s*- and *r*-process path on the nuclide chart.

1. Mo has one p-only isotope
2. Zr does not have any s-only isotopes
3. Ru has one r-only isotope
4. Zr and Mo have one r-only isotope each

Where does the *s* process happen?



Merrill 1952, Burbidge et al. 1957

Which processes produce the long-lived ($T_{1/2} > 0.1$ Myr) isotopes of Tc?

1. the *p* and the *s* processes

2. the *p* process

3. the *r* and the *p* process

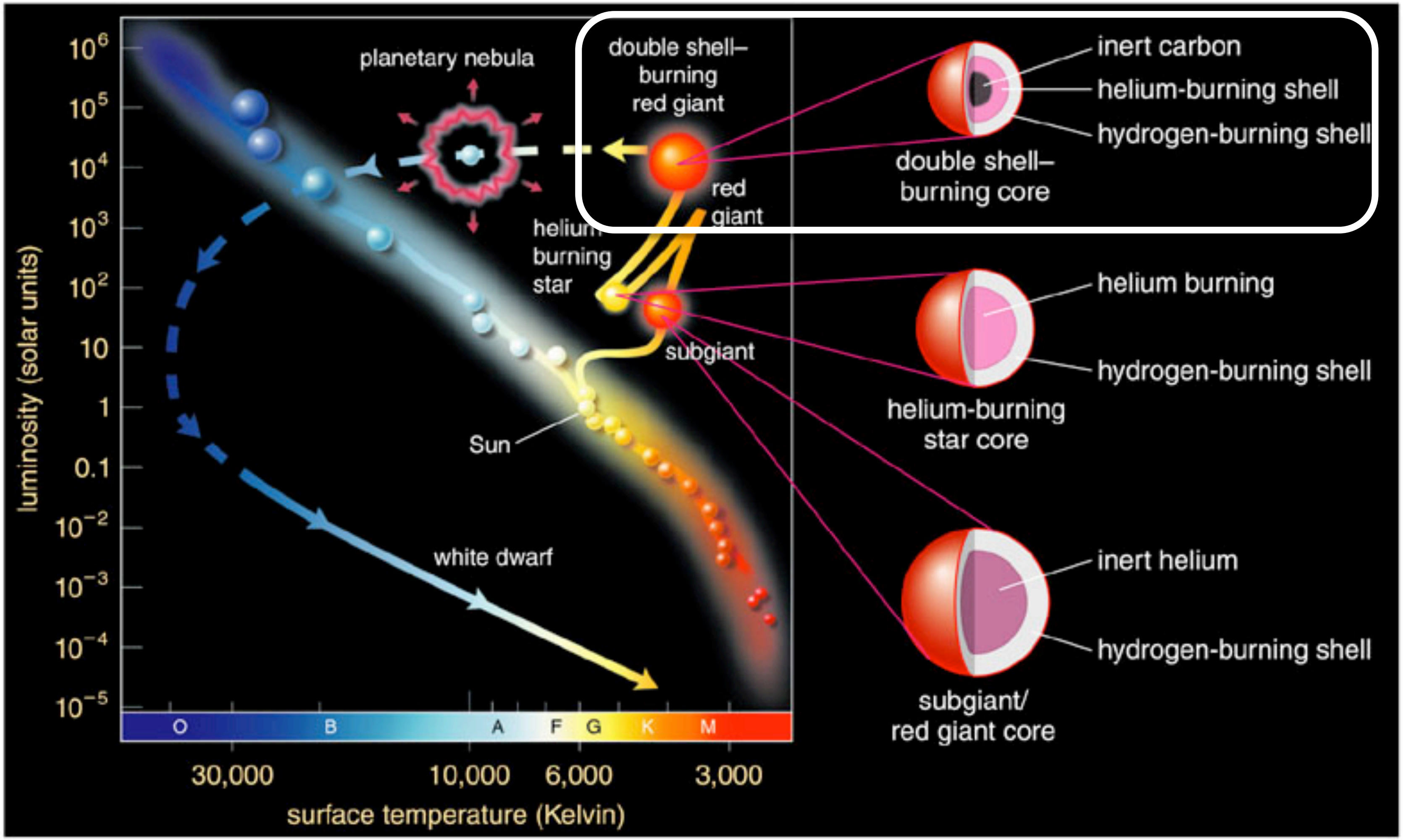
4. the *r*, *s*, and *p* processes

If the *s* process happens in the “peculiar stars”, which isotopes of Tc are we are seeing in these stars?

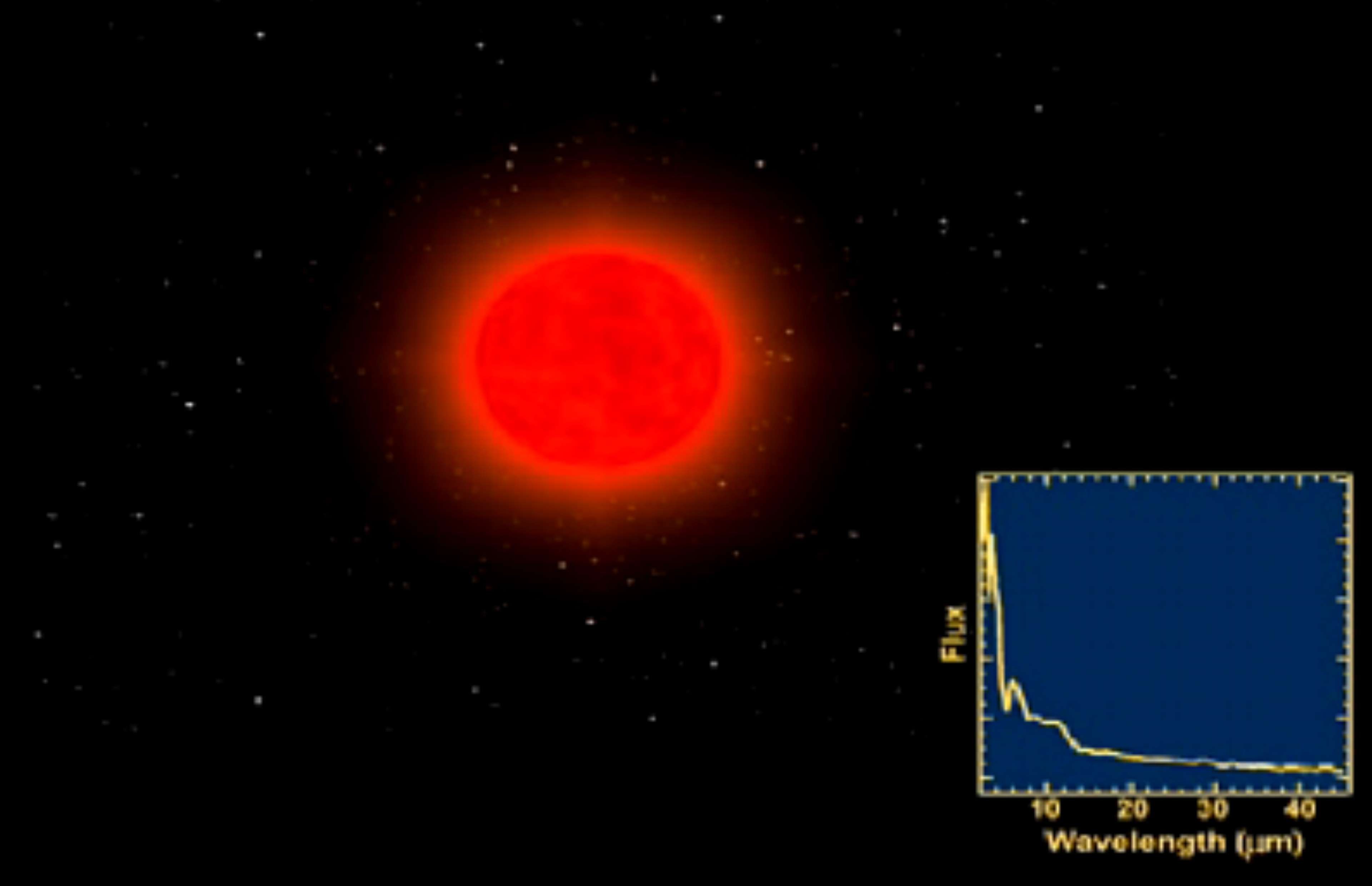
95Rh 5.02 M ϵ: 100.00%	96Rh 9.90 M ϵ: 100.00%	97Rh 30.7 M ϵ: 100.00%	98Rh 8.72 M ϵ: 100.00%	99Rh 16.1 D ϵ: 100.00%	100Rh 20.8 H ϵ: 100.00%	101Rh 3.3 Y ϵ: 100.00%	102Rh 207 D ϵ: 78.00% β-: 22.00%	103Rh STABLE 100%	104Rh 42.3 S β-: 99.55% ϵ: 0.45%	105Rh 35.36 H β-: 100.00%
94Ru 51.8 M ϵ: 100.00%	95Ru 1.643 H ϵ: 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D ϵ: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H ϵ: 100.00%	94Tc 293 M ϵ: 100.00%	95Tc 20.0 H ϵ: 100.00%	96Tc 4.28 D ϵ: 100.00%	97Tc 4.21E+6 Y ϵ: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ϵ: 1.8E-3%	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 S β-: 100.00%
92Mo STABLE 14.84%	93Mo 4.0E+3 Y ϵ: 100.00%	94Mo STABLE 9.25%	95Mo STABLE 15.92%	96Mo STABLE 16.68%	97Mo STABLE 9.55%	98Mo STABLE 24.13%	99Mo 2.7489 D β-: 100.00%	100Mo 7.3E+18 Y 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%
91Nb 6.8E+2 Y ϵ: 100.00%	92Nb 3.47E+7 Y ϵ: 100.00% β- < 0.05%	93Nb STABLE 100%	94Nb 2.03E+4 Y β-: 100.00%	95Nb 34.991 D β-: 100.00%	96Nb 23.35 H β-: 100.00%	97Nb 72.1 M β-: 100.00%	98Nb 2.86 S β-: 100.00%	99Nb 15.0 S β-: 100.00%	100Nb 1.5 S β-: 100.00%	101Nb 7.1 S β-: 100.00%
90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.53E+6 Y β-: 100.00%	94Zr STABLE 17.38%	95Zr 64.032 D β-: 100.00%	96Zr >3.9E+20 Y 2.80% 2β-	97Zr 16.744 H β-: 100.00%	98Zr 30.7 S β-: 100.00%	99Zr 2.1 S β-: 100.00%	100Zr 7.1 S β-: 100.00%
89Y STABLE 100%	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.058%	98Y 0.548 S β-: 100.00% β-n: 0.33%	99Y 1.470 S β-: 100.00% β-n: 1.90%
88Sr STABLE 82.58%	89Sr 50.57 D β-: 100.00%	90Sr 28.90 Y β-: 100.00%	91Sr 9.63 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.423 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S β-: 100.00%	96Sr 1.07 S β-: 100.00%	97Sr 429 MS β-: 100.00% β-n≤ 0.05%	98Sr 0.653 S β-: 100.00% β-n: 0.25%

1. 97 and 98
2. 99 only
3. 99 and 100
4. 98 only

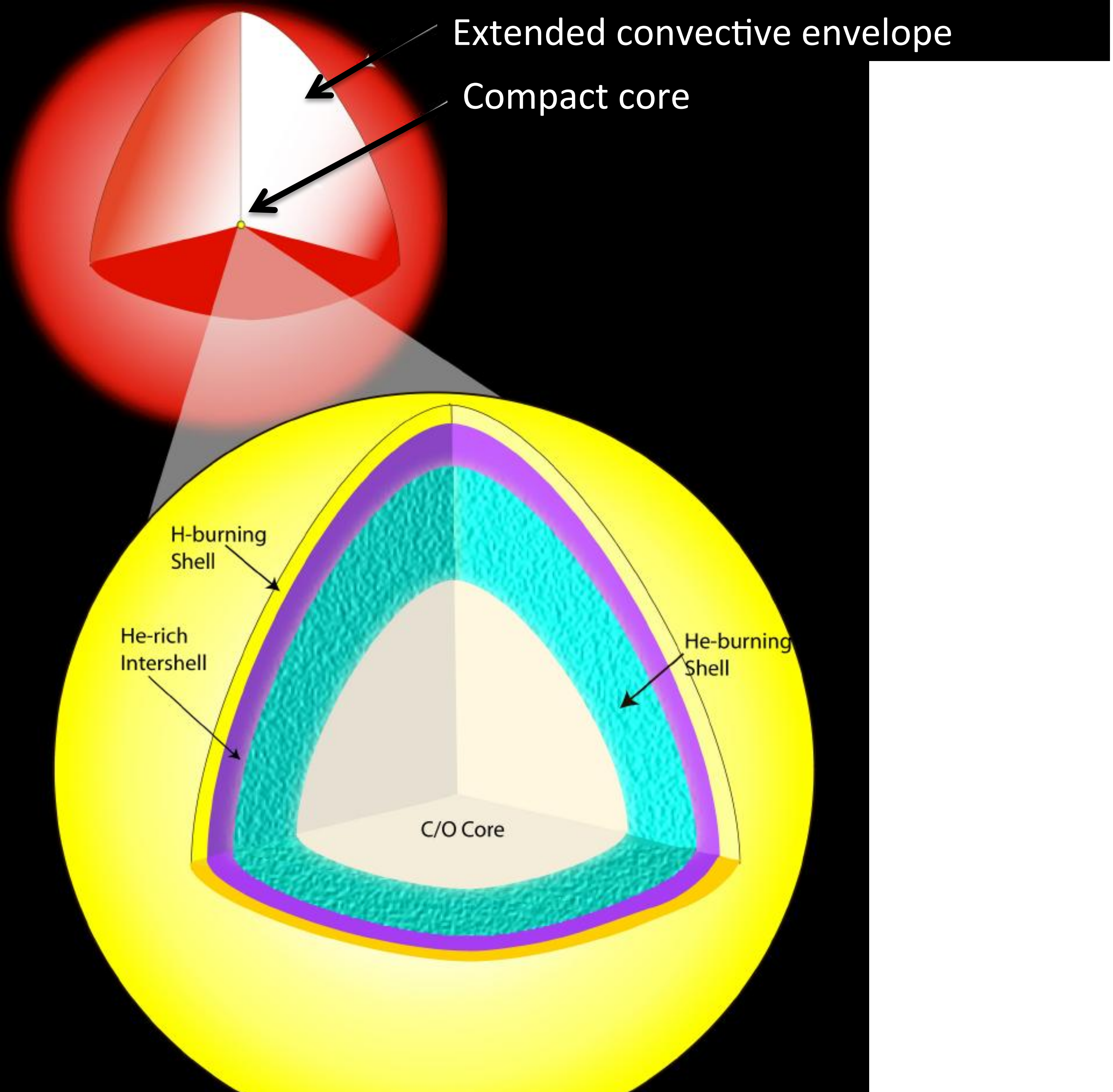
Stars < 10 the mass of the Sun…



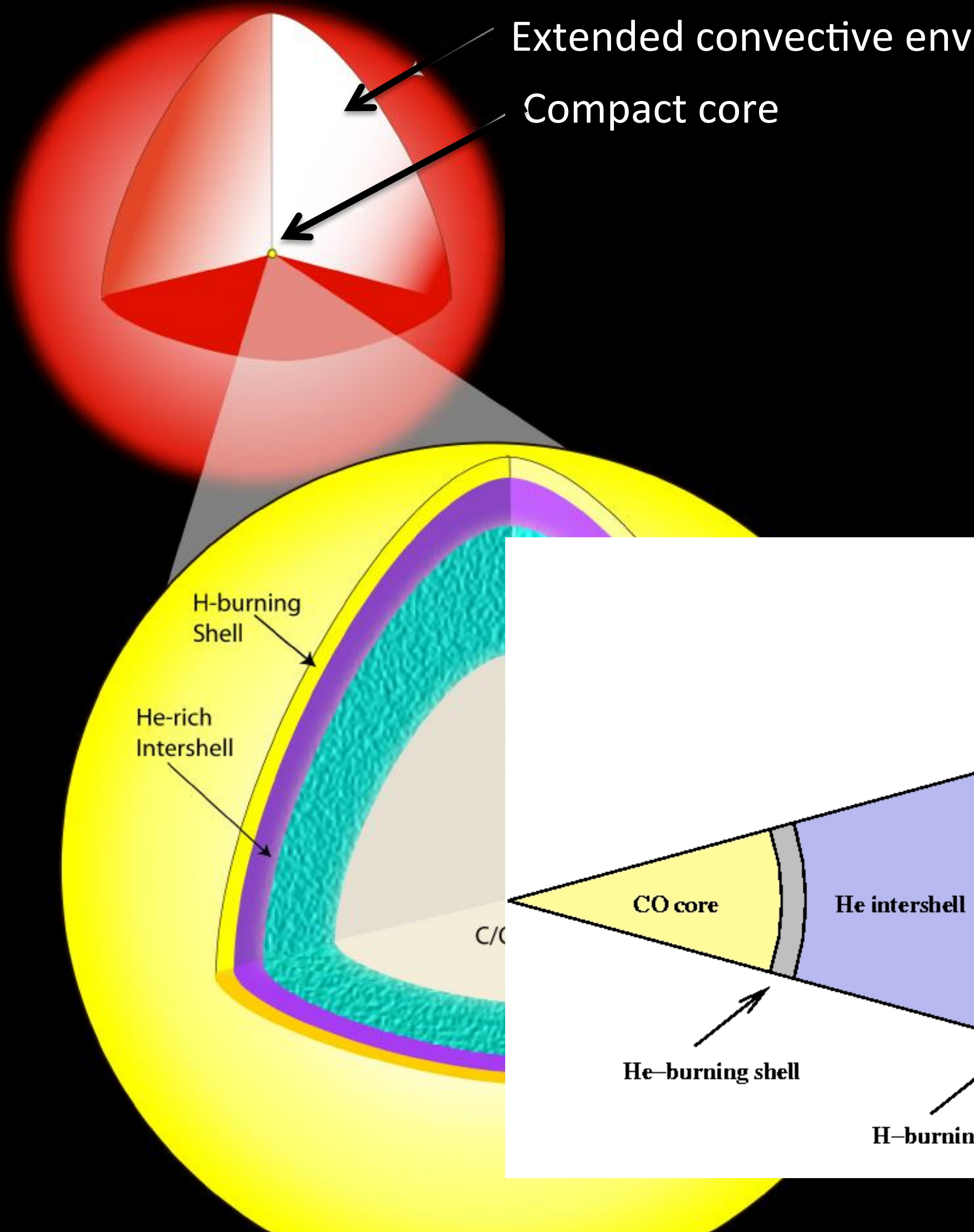
…**go through the asymptotic giant branch (AGB)** before becoming white dwarfs.

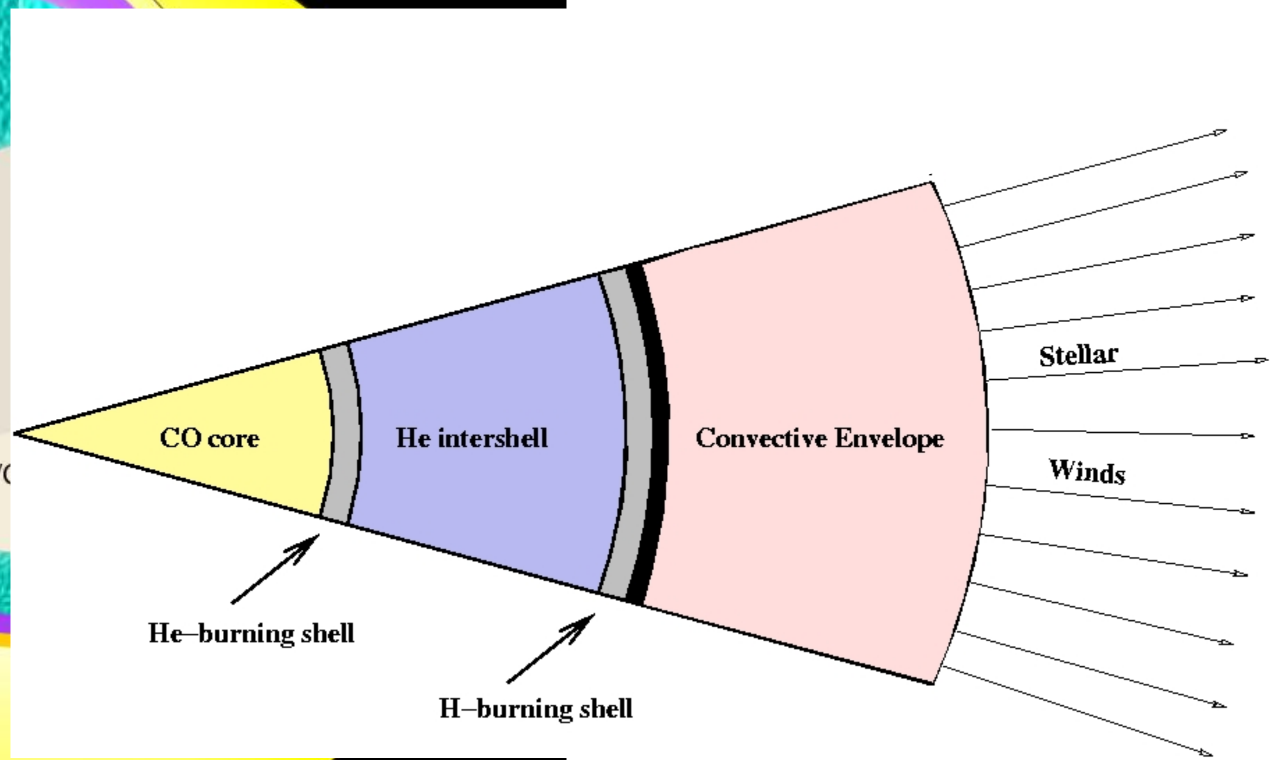


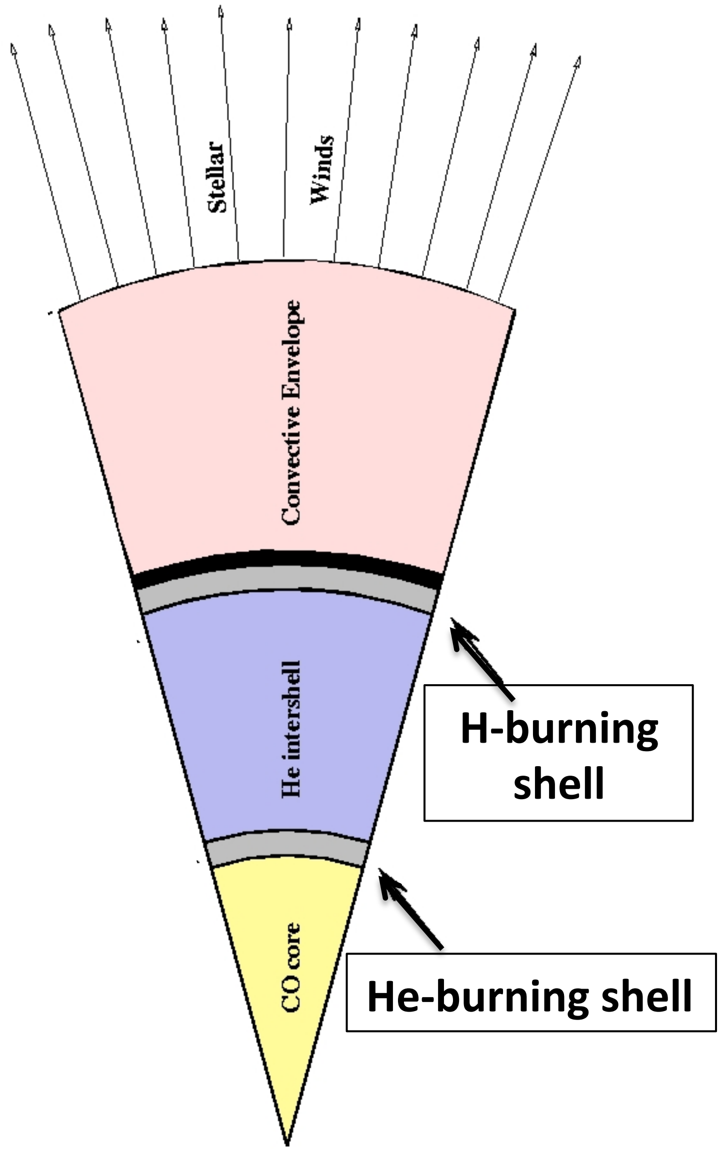
Artist impression.
Courtesy of Pedro Garcia-Lario, ESA and Anibal García-Hernandez, IAC

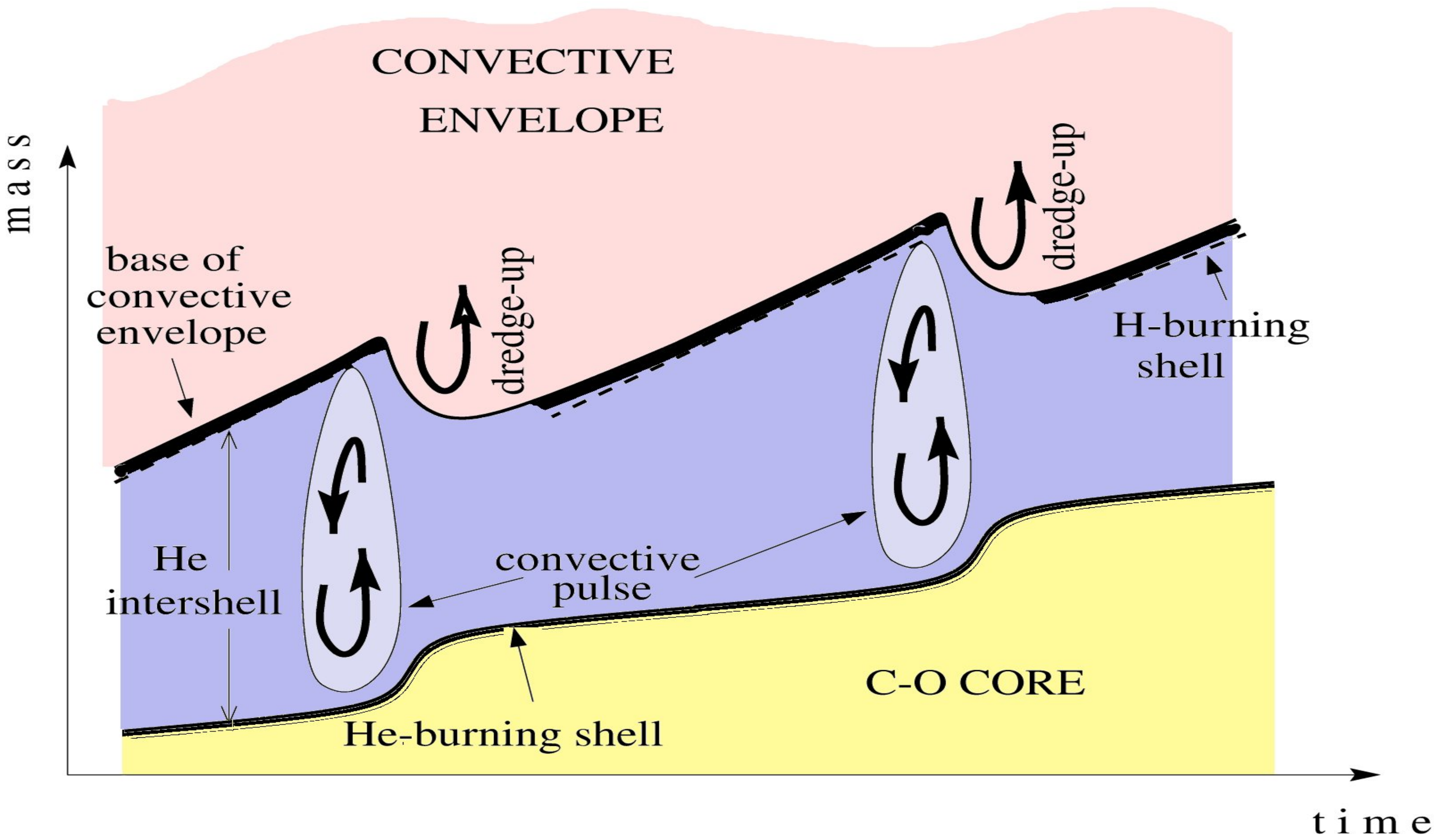

Extended convective envelope
Compact core
H-burning Shell
He-rich Intershell
He-burning Shell
C/O Core

From 3D to 2D


Extended convective envelope
Compact core
H-burning
Shell
He-rich
Intershell

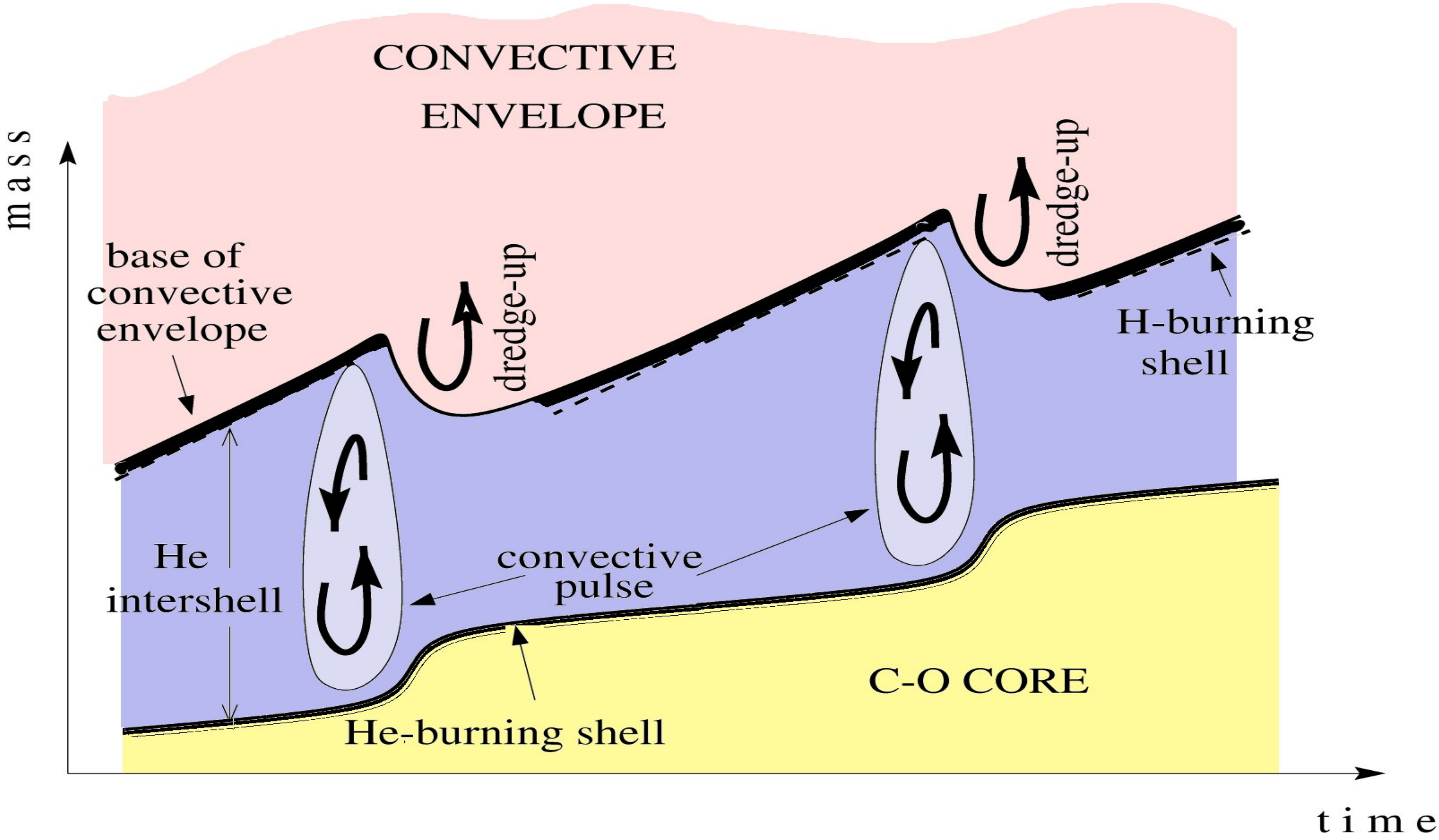

CO core
He intershell
Convective Envelope
Stellar
Winds
He–burning shell
H–burning shell


Stellar
Winds
Convective Envelope
He intershell
CO core
H-burning shell
He-burning shell

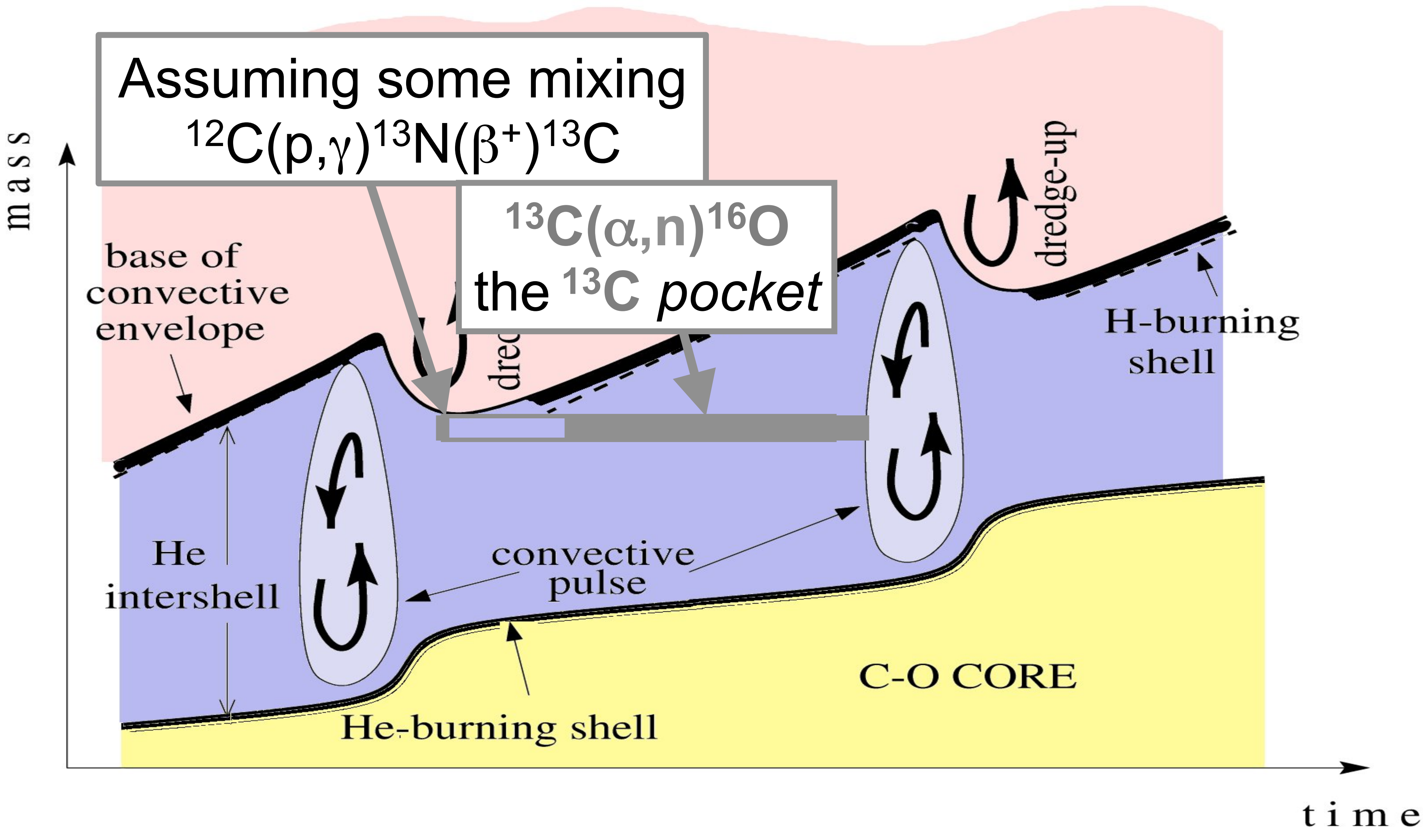


CONVECTIVE
ENVELOPE
mass
base of
convective
envelope
dredge-up
dredge-up
H-burning
shell
He
intershell
convective
pulse
C-O CORE
He-burning shell
time

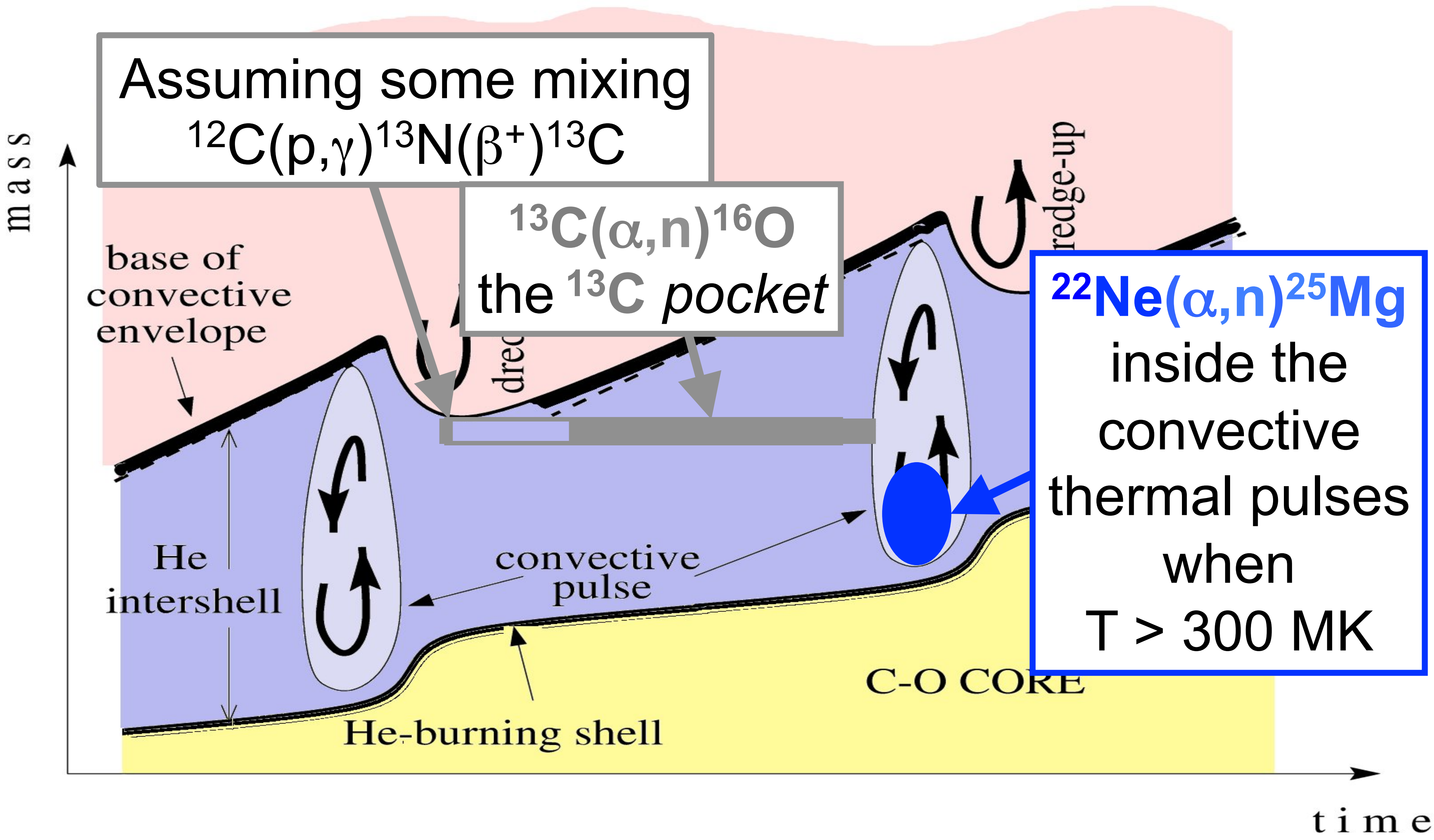
The neutron sources



The neutron sources



The neutron sources

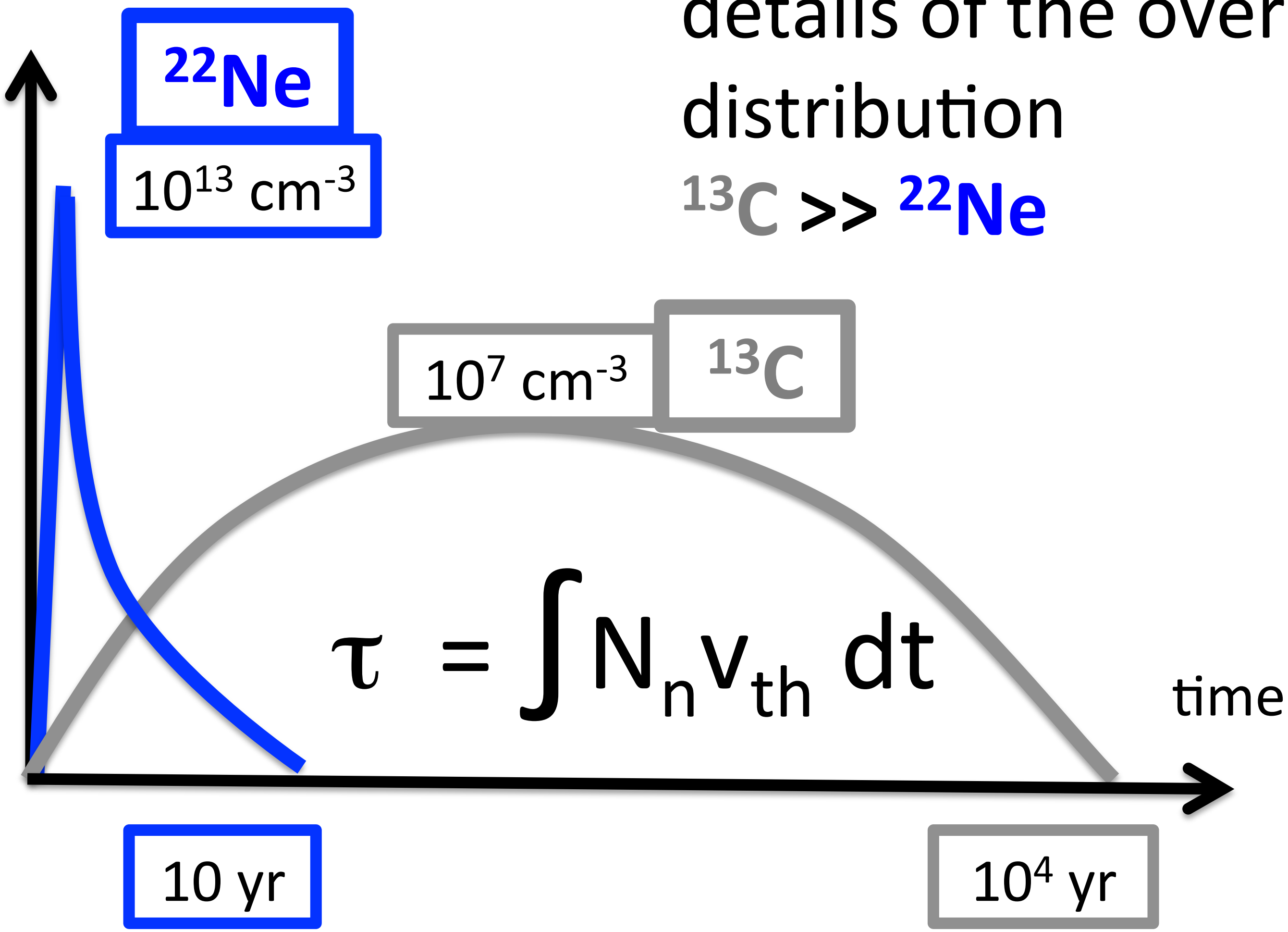


Neutron density (cm^{-3}): defines the details of the s-process path

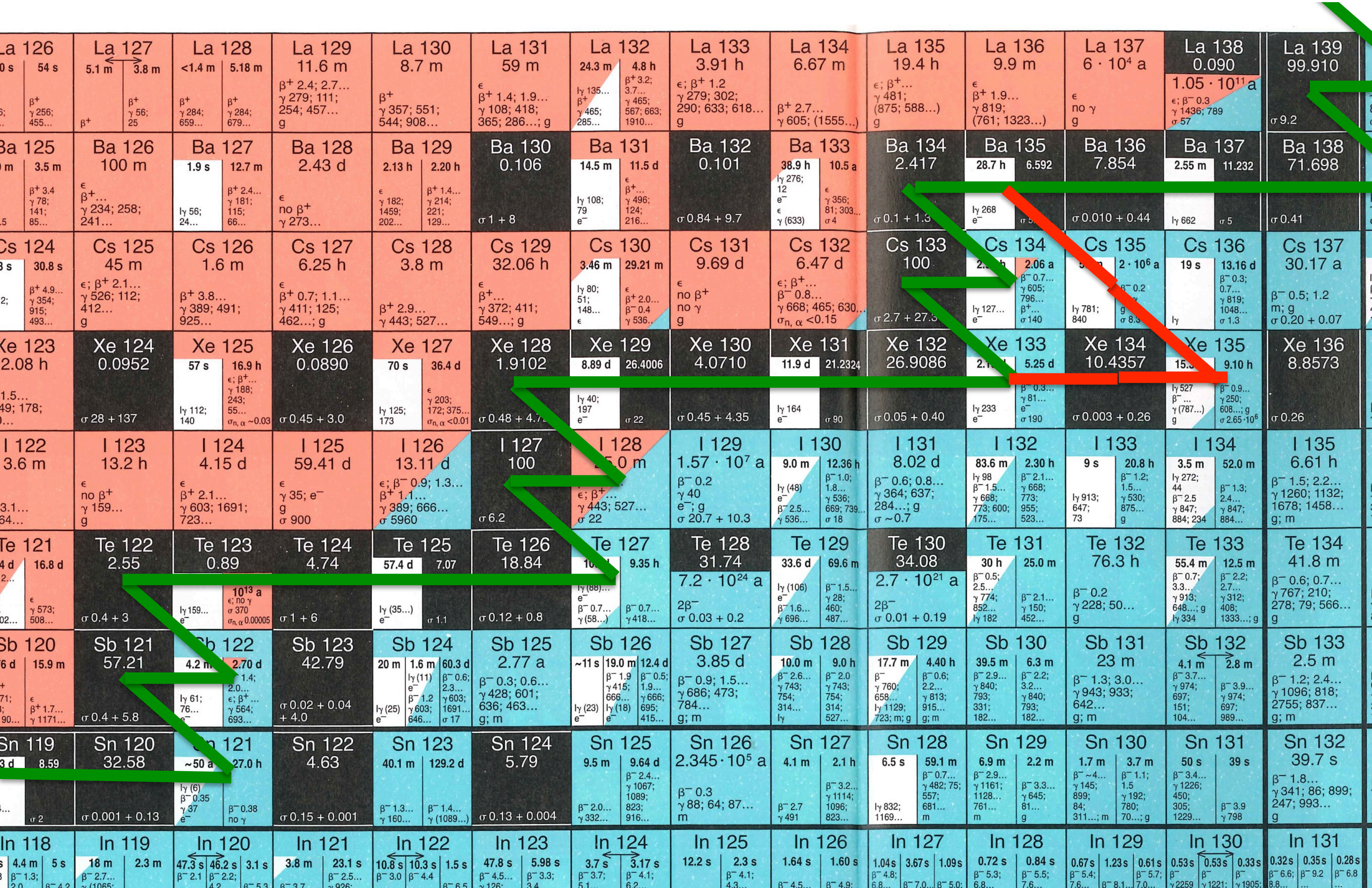
$^{22}Ne \gg {}^{13}C$

Neutron exposure τ ($mbarn^{-1}$): defines the details of the overall distribution

$^{13}C \gg {}^{22}Ne$



The **neutron density** is the key quantity the defines the final abundances around ***branching points***



Branching points can appear depending on the neutron density! If the neutron density is around 10^{11} cm^{-3} we will have a branching when half lives are greater than a few days, are there any branching points here?

95Rh 5.02 M ϵ: 100.00%	96Rh 9.90 M ϵ: 100.00%	97Rh 30.7 M ϵ: 100.00%	98Rh 8.72 M ϵ: 100.00%	99Rh 16.1 D ϵ: 100.00%	100Rh 20.8 H ϵ: 100.00%	101Rh 3.3 Y ϵ: 100.00%	102Rh 207 D ϵ: 78.00% β-: 22.00%	103Rh STABLE [illegible]	104Rh [illegible] S β-: 99.55% ϵ: 0.45%	105Rh 35.36 H β-: 100.00%
94Ru 51.8 M ϵ: 100.00%	95Ru 1.643 H ϵ: 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D ϵ: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.[illegible]%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	[illegible]3Ru [illegible]6 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H ϵ: 100.00%	94Tc 293 M ϵ: 100.00%	95Tc 20.0 H ϵ: 100.00%	96Tc 4.28 D ϵ: 100.00%	97Tc 4.21E+6 Y ϵ: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	[illegible]9Tc 2.11[illegible]E+5 Y β-: 100.0[illegible]	100Tc 15.46 S β-: 100.00% ϵ: 1.8E-3%	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 S β-: 100.00%
92Mo STABLE 14.84%	93Mo 4.0E+3 Y ϵ: 100.00%	94Mo STABLE 9.25%	95Mo STABLE 15[illegible]	96Mo STABLE [illegible]	97Mo STABLE [illegible]	98Mo STABLE [illegible]	[illegible]9Mo 2.7[illegible]9 D β-: 100.00%	100Mo 7.3E+18 Y 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%
91Nb 6.8E+2 Y ϵ: 100.00%	92Nb 3.47E+7 Y ϵ: 100.00% β- < 0.05%	93Nb STABLE 100%	94Nb 2.03E+4 Y β-: 100.00%	[illegible]5Nb 3[illegible]991 D β-: 100.[illegible]	96Nb 23.35 H β-: 100.00%	97Nb 72.1 M β-: 100.00%	98Nb 2.86 S β-: 100.00%	99Nb 15.0 S β-: 100.00%	100Nb 1.5 S β-: 100.00%	101Nb 7.1 S β-: 100.00%
90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.53E+6 Y β-: 100.00%	94Zr STABLE 17.38%	[illegible]5Zr 64[illegible]32 D β-: 100.00%	96Zr >3.9E+20 Y 2.80% 2β-	97Zr 16.744 H β-: 100.00%	98Zr 30.7 S β-: 100.00%	99Zr 2.1 S β-: 100.00%	100Zr 7.1 S β-: 100.00%
89Y STABLE [illegible]	90Y 64[illegible]53 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.058%	98Y 0.548 S β-: 100.00% β-n: 0.33%	99Y 1.470 S β-: 100.00% β-n: 1.90%
88Sr STABLE 82.58%	[illegible]9Sr 50.[illegible]7 D β-: 100.00%	90Sr 28.90 Y β-: 100.00%	91Sr 9.63 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.423 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S β-: 100.00%	96Sr 1.07 S β-: 100.00%	97Sr 429 MS β-: 100.00% β-n≤ 0.05%	98Sr 0.653 S β-: 100.00% β-n: 0.25%

Branching points can appear depending on the neutron density! If the neutron density is around 10^{11} cm^{-3} we will have a branching when half lives are greater than a few days, are there any branching points here?

95Rh 5.02 M ε: 100.00%	96Rh 9.90 M ε: 100.00%	97Rh 30.7 M ε: 100.00%	98Rh 8.72 M ε: 100.00%	99Rh 16.1 D ε: 100.00%	100Rh 20.8 H ε: 100.00%	101Rh 3.3 Y ε: 100.00%	102Rh 207 D ε: 78.00% β-: 22.00%	103Rh STABLE 100%	104Rh 42.3 S β-: 99.55% ε: 0.45%	105Rh 35.36 H β-: 100.00%
94Ru 51.8 M ε: 100.00%	95Ru 1.643 H ε: 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D ε: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H ε: 100.00%	94Tc 293 M ε: 100.00%	95Tc 20.0 H ε: 100.00%	96Tc 4.28 D ε: 100.00%	97Tc 4.21E+6 Y ε: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ε: 1.8E-3%	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 S β-: 100.00%
92Mo STABLE 14.84%	93Mo 4.0E+3 Y ε: 100.00%	94Mo STABLE 9.25%	95Mo STABLE 15.92%	96Mo STABLE 16.68%	97Mo STABLE 9.55%	98Mo STABLE 24.13%	99Mo 2.7489 D β-: 100.00%	100Mo 7.3E+18 Y 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%
91Nb 6.8E+2 Y ε: 100.00%	92Nb 3.47E+7 Y ε: 100.00% β- < 0.05%	93Nb STABLE 100%	94Nb 2.03E+4 Y β-: 100.00%	95Nb 34.991 D β-: 100.00%	96Nb 23.35 H β-: 100.00%	97Nb 72.1 M β-: 100.00%	98Nb 2.86 S β-: 100.00%	99Nb 15.0 S β-: 100.00%	100Nb 1.5 S β-: 100.00%	101Nb 7.1 S β-: 100.00%
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89Y STABLE 100%	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.058%	98Y 0.548 S β-: 100.00% β-n: 0.33%	99Y 1.470 S β-: 100.00% β-n: 1.90%
88Sr STABLE 82.58%	89Sr 50.57 D β-: 100.00%	90Sr 28.79 Y β-: 100.00%	91Sr 9.63 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.423 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S β-: 100.00%	96Sr 1.07 S β-: 100.00%	97Sr 429 MS β-: 100.00% β-n ≤ 0.05%	98Sr 0.653 S β-: 100.00% β-n: 0.25%

Careful about ^{103}Ru!

^{95}Zr is a branching point with half-life = 64 days that produces ^{96}Zr. What is the **branching factor** when the neutron density $N_n = 10^{10}$ cm^{-3}?

(use σ_{95} = 60 mbarn, v = 2 x 10^8 cm/s, and λ_β=0.693 /$T_{1/2}$ s)

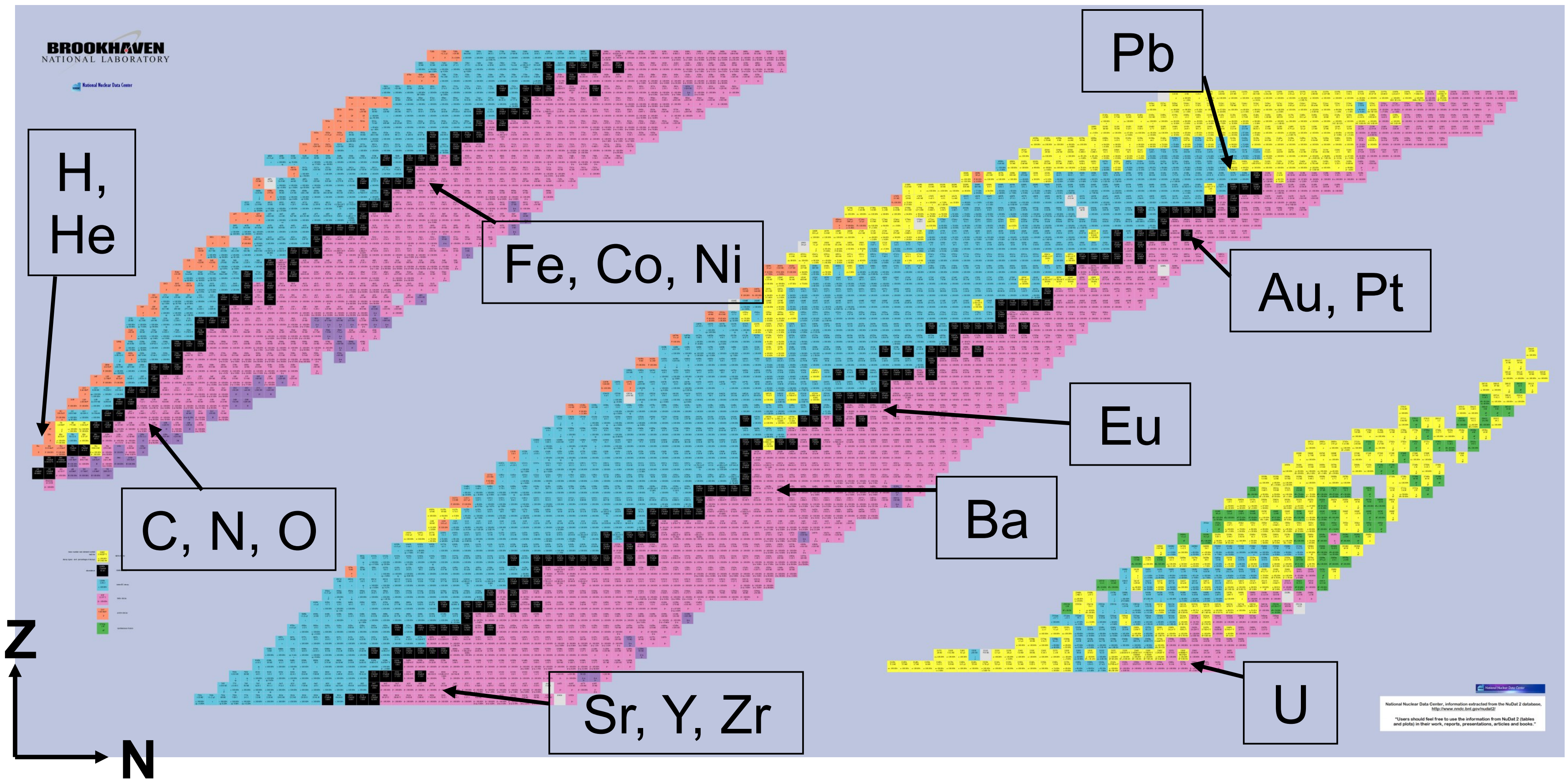
1. 1.
2. 0.8
3. 0.5
4. 0

$$f = \frac{\lambda_n}{\lambda_n + \lambda_\beta}$$

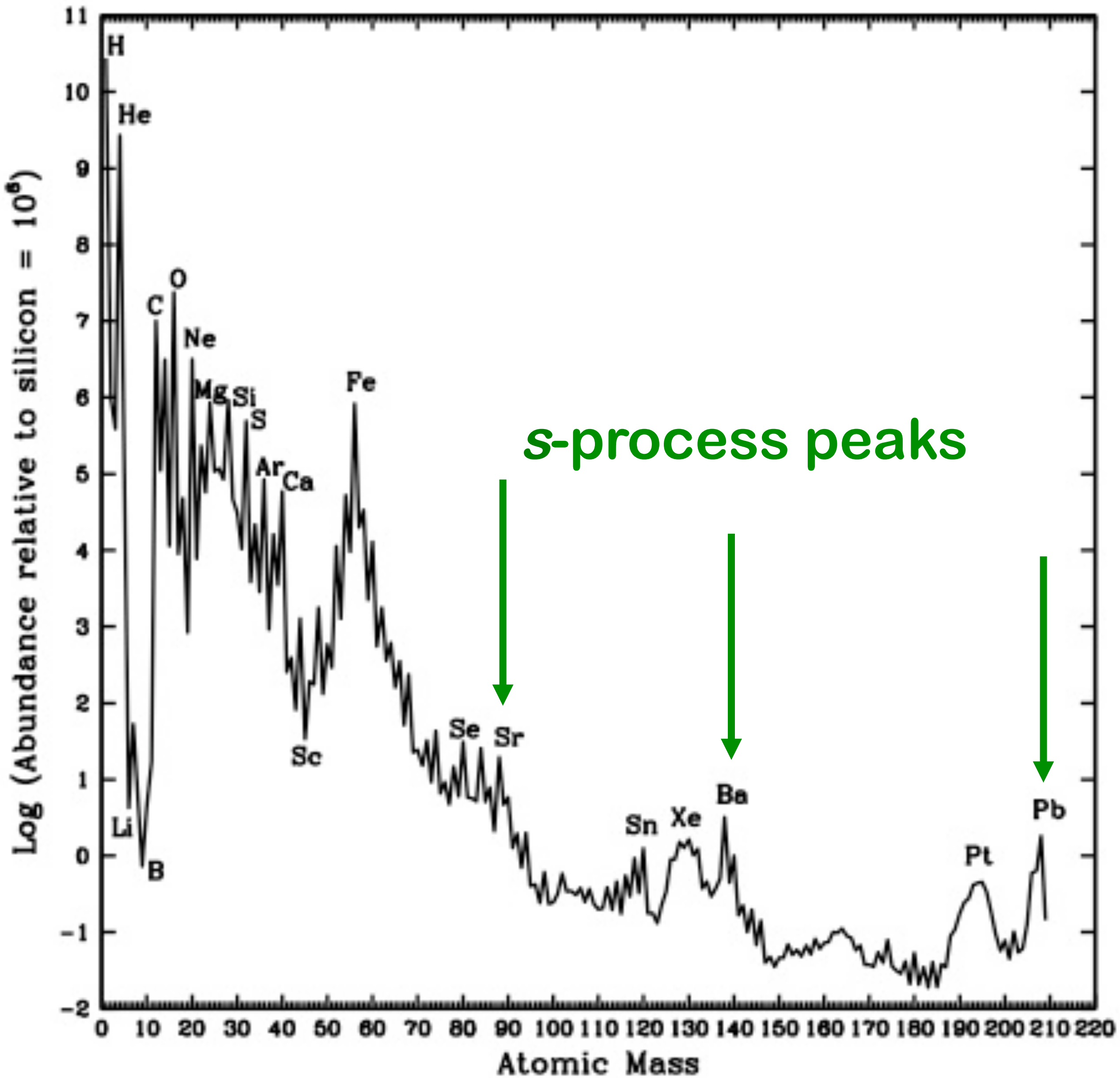
$$\lambda_n = N_n < \sigma(v) v >$$

$\lambda_\beta = ln\, 2/T_{1/2}$, where $T_{1/2}$ is the half-life in seconds

The **neutron exposure** is the key quantity the defines the relative abundances of the peaks of the overall distribution: **Which elements beyond Fe have isotopes with magic number of neutrons?**

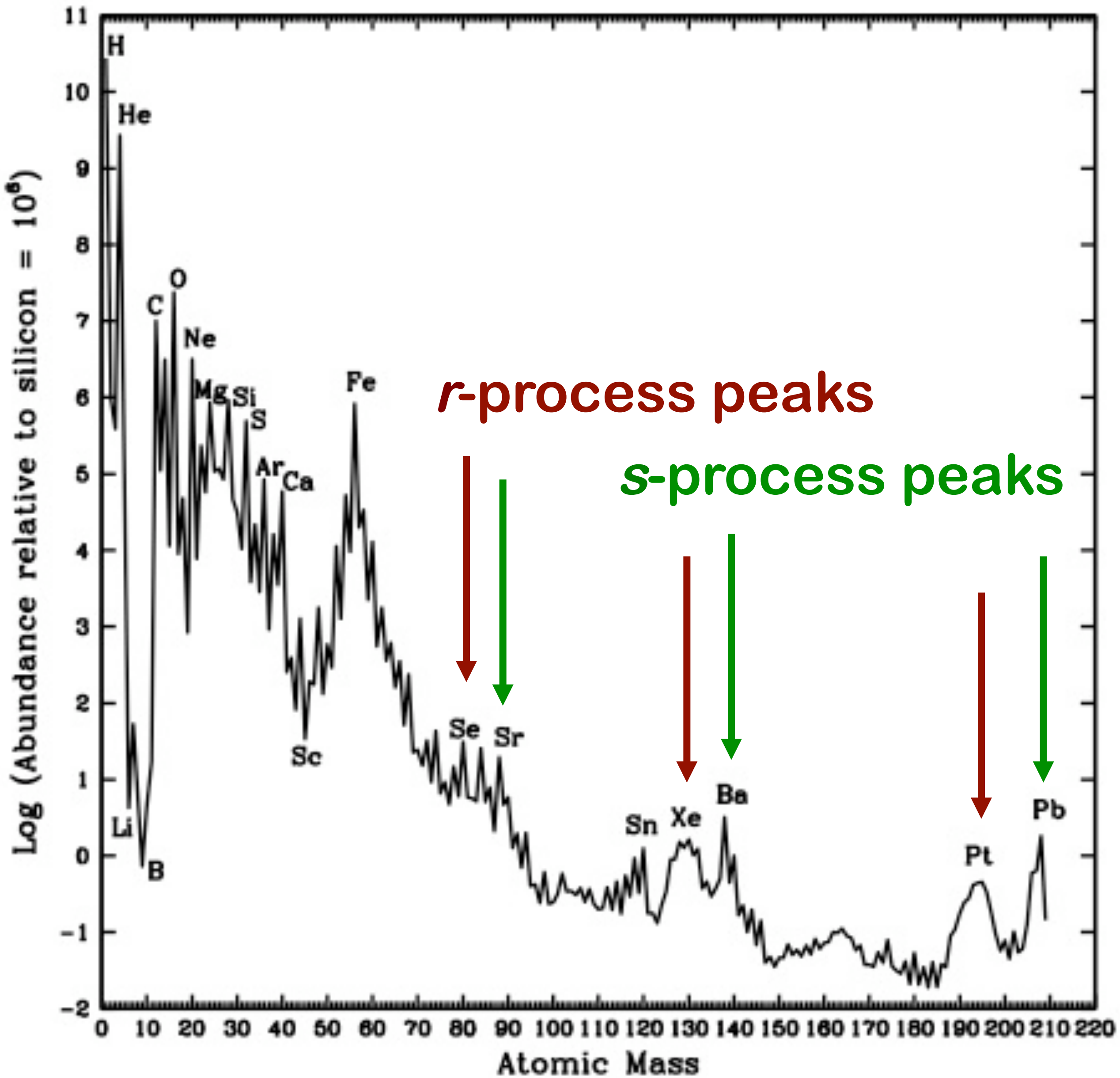


The Solar System abundances



The *s*-process peaks correspond to **stable nuclei** with neutron magic numbers N = 50, 82, 126 because the neutron capture path goes rights through them.

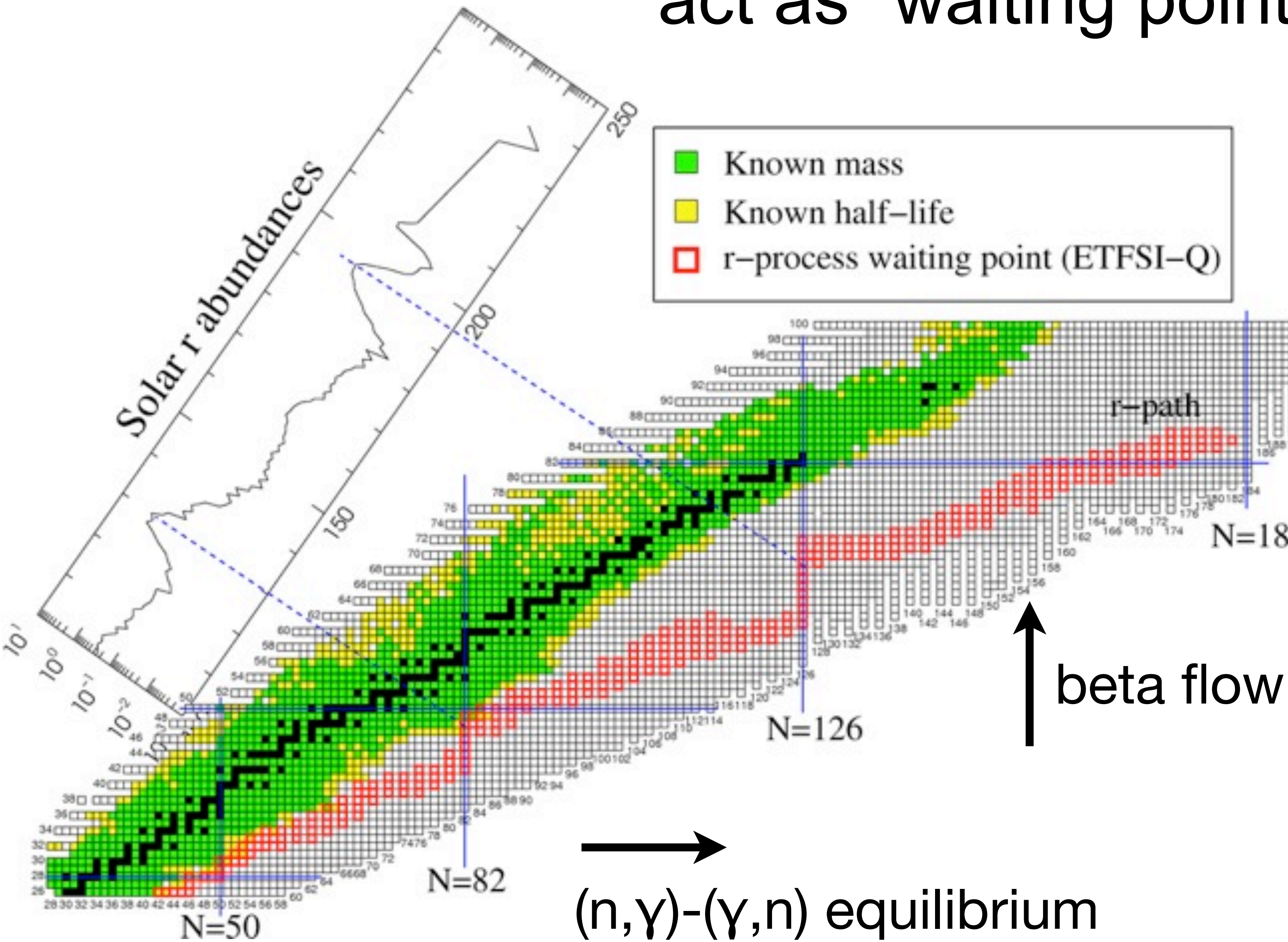
The Solar System abundances



The *s*-process peaks correspond to **stable nuclei** with neutron magic numbers

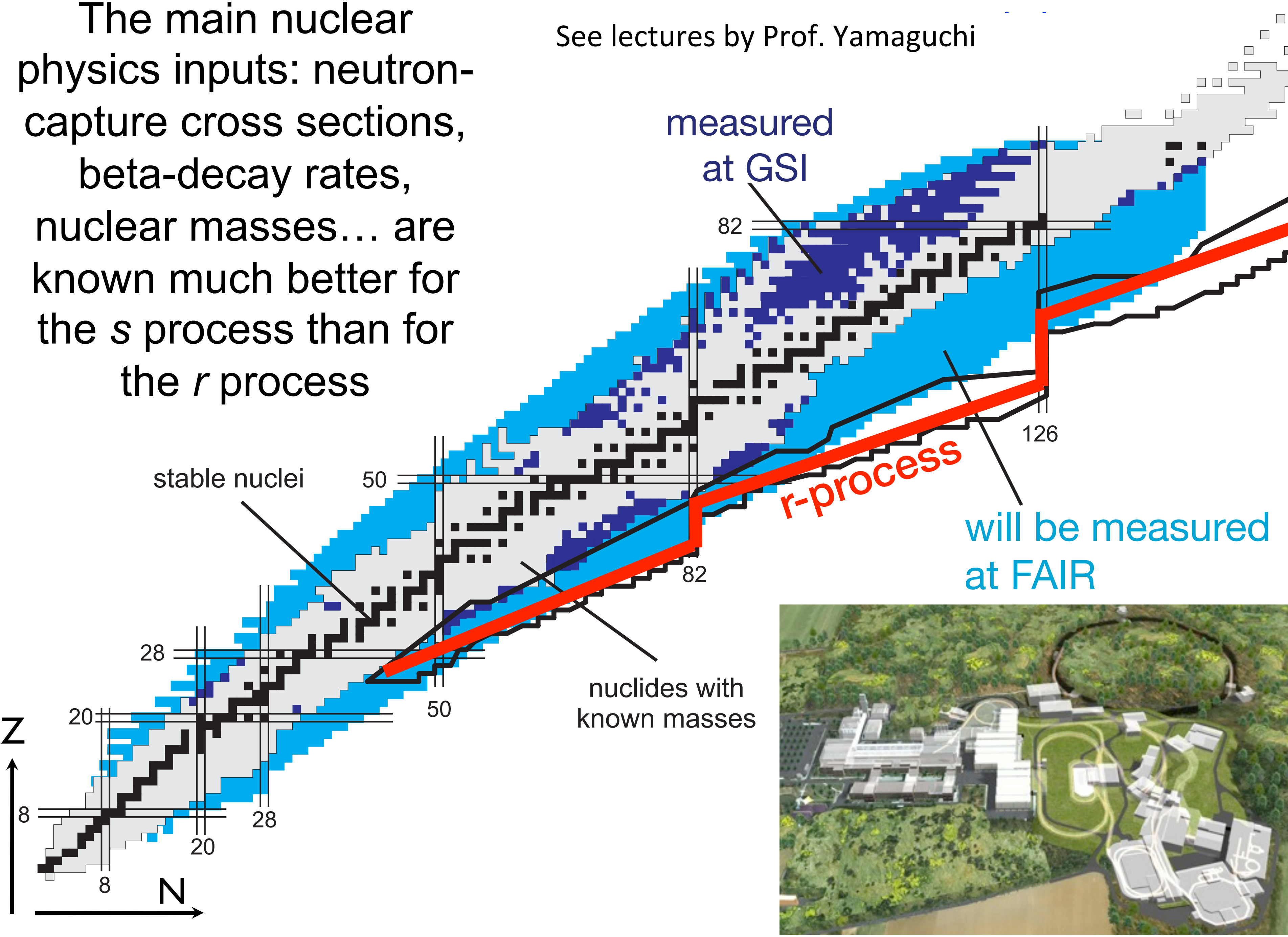
The *r*-process peaks correspond to **unstable nuclei** with neutron magic numbers

During the *r*-process **unstable magic nuclei** act as “waiting points”



The main nuclear physics inputs: neutron-capture cross sections, beta-decay rates, nuclear masses… are known much better for the *s* process than for the *r* process

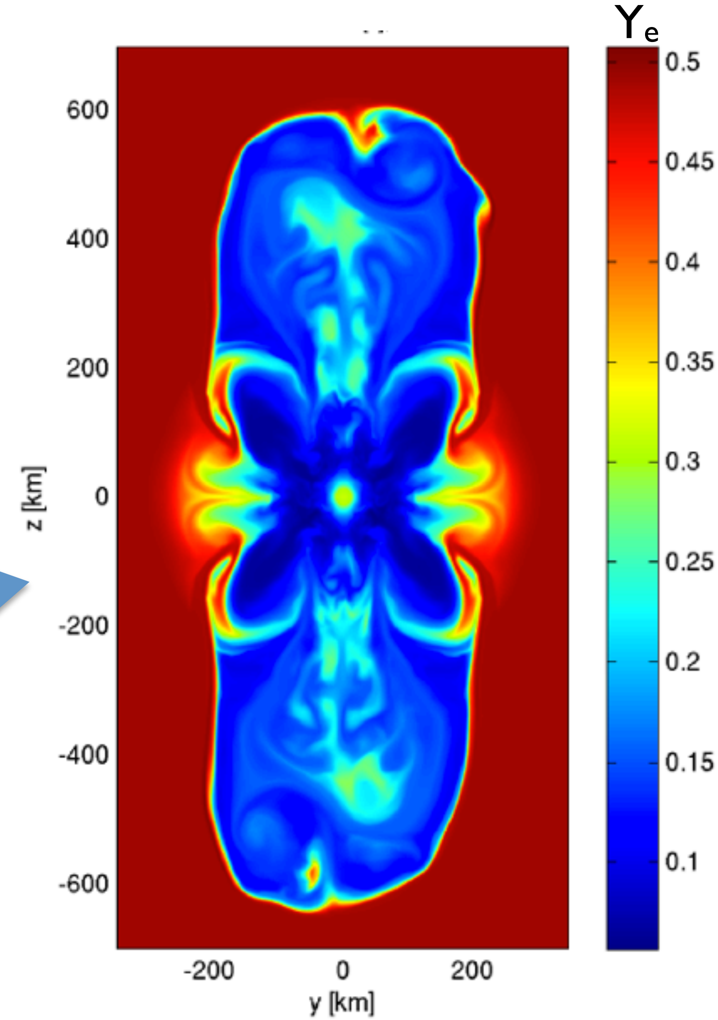
See lectures by Prof. Yamaguchi



Astrophysical sites

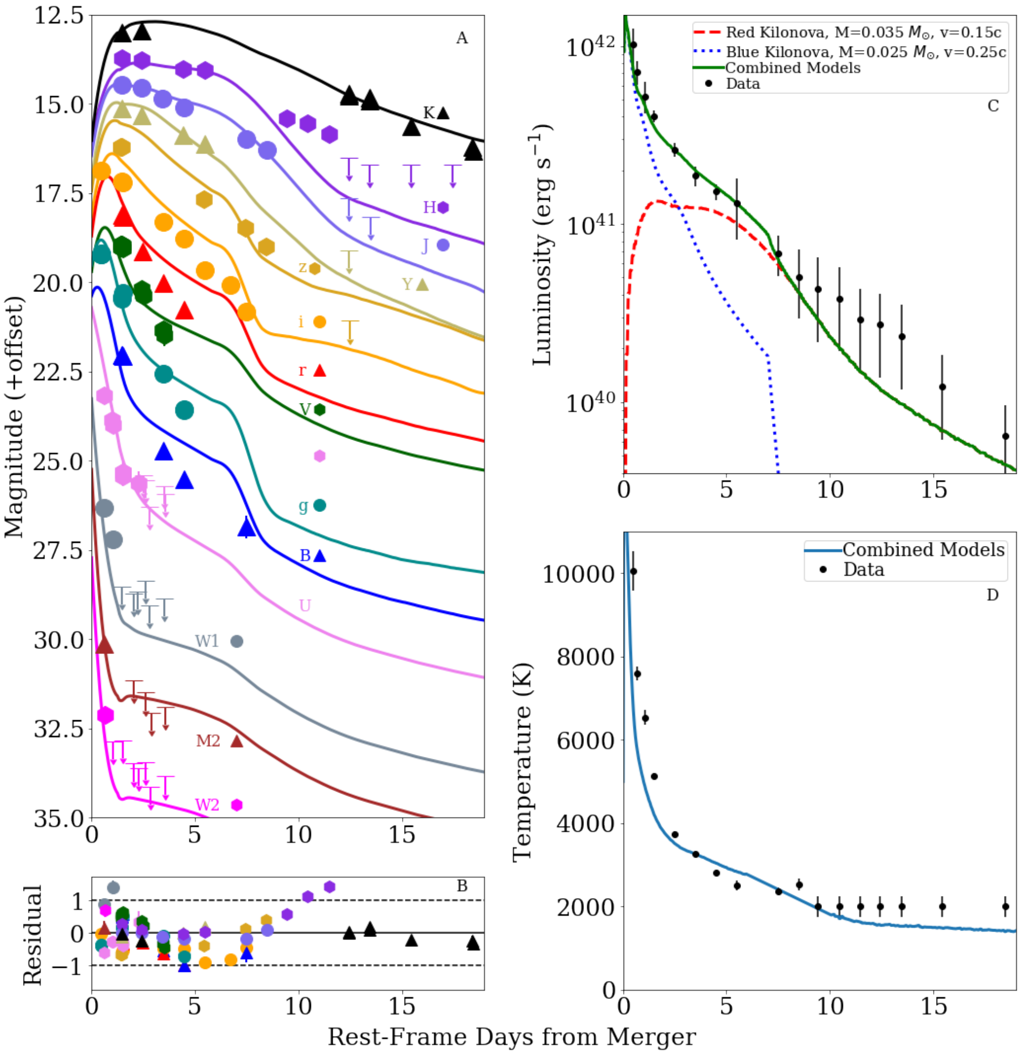
need a neutron-rich explosive environment

Neutron-rich jets in magneto-hydrodynamical supernovae: rapid rotation and strong magnetic fields, matter collimates



Neutron star mergers: dynamical and/or disk ejecta

August 2017: first direct evidence for the neutron star merger site



gravitational wave source **GW170817**

1.7 s after, short γ-ray burst detected: **GRB 170817A**

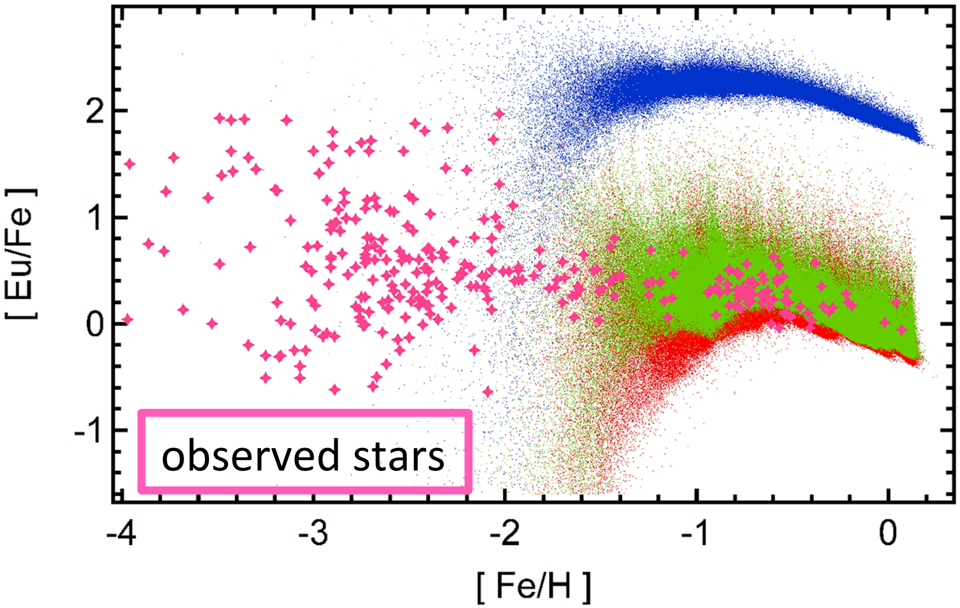
11 hours later, optical transient detected **SSS17a**

Neutron star merger

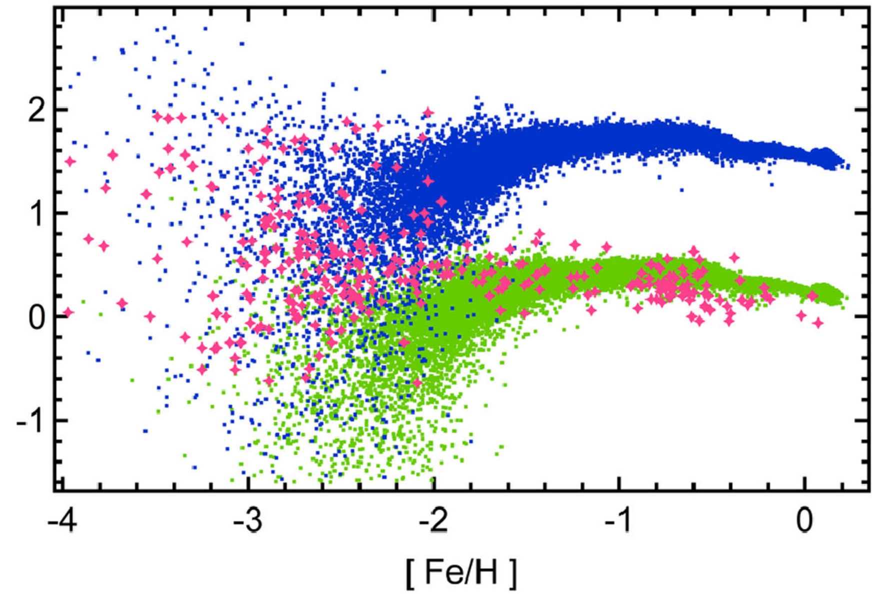
First direct observational connection

“Kilonova” probably generated by the radioactive decay of r-process products

Neutron star mergers



Jet supernovae

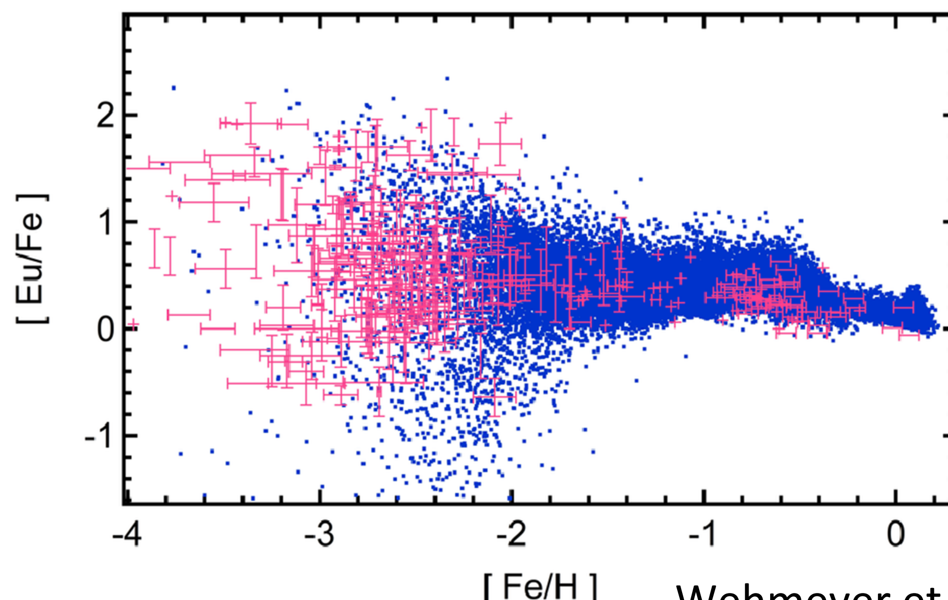


The evolution of Eu in the Galaxy

Free parameters:

- the probability of the events;
- the coalescent time for neutron star mergers.

Neutron star mergers + Jet supernovae



Wehmeyer et al. (2015)

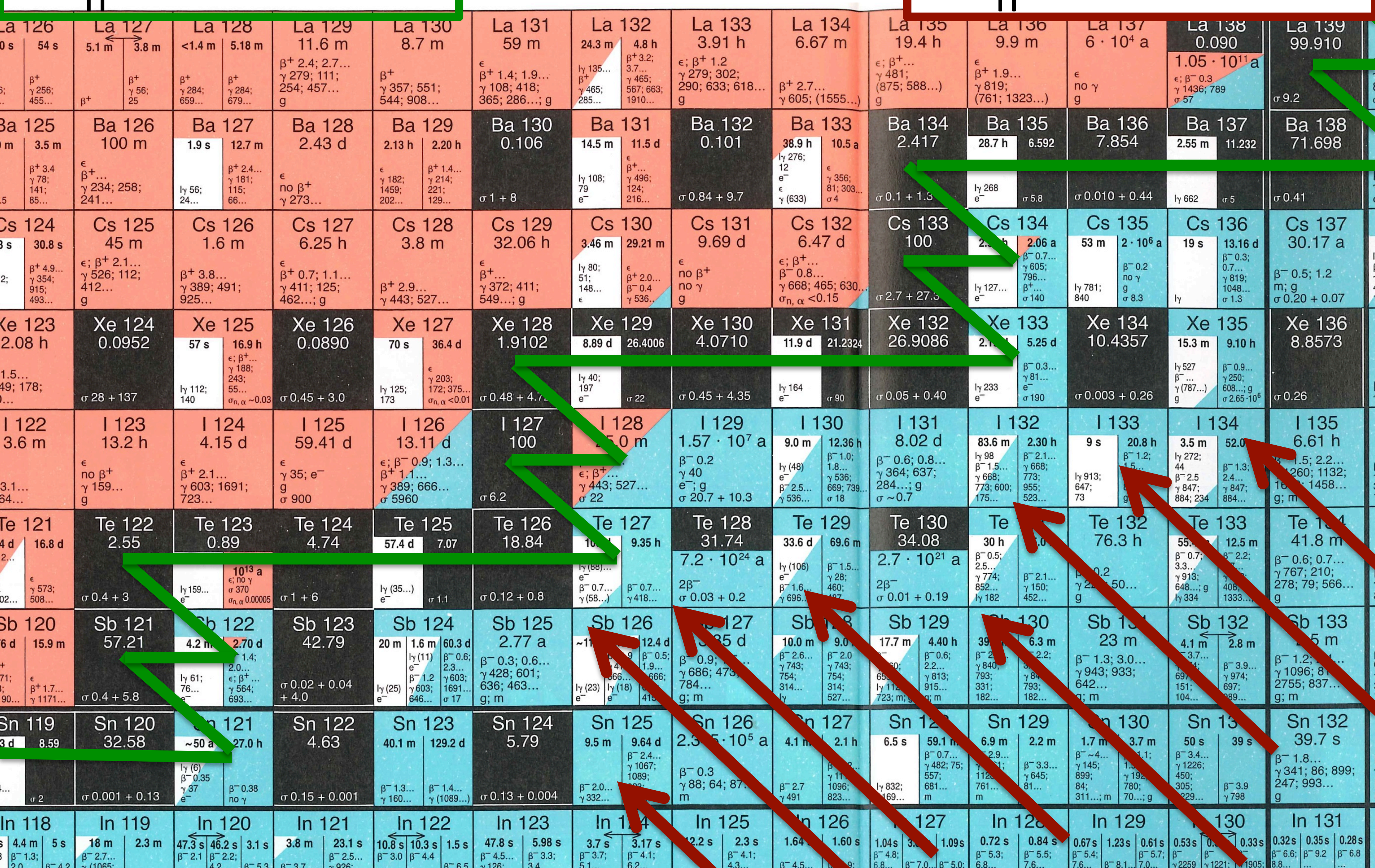
Slow s process

$N_n < 10^{13}\ cm^{-3}$

???

Rapid r process

$N_n > 10^{20}\ cm^{-3}$



Slow s process

$N_n < 10^{13}\ \mathrm{cm}^{-3}$

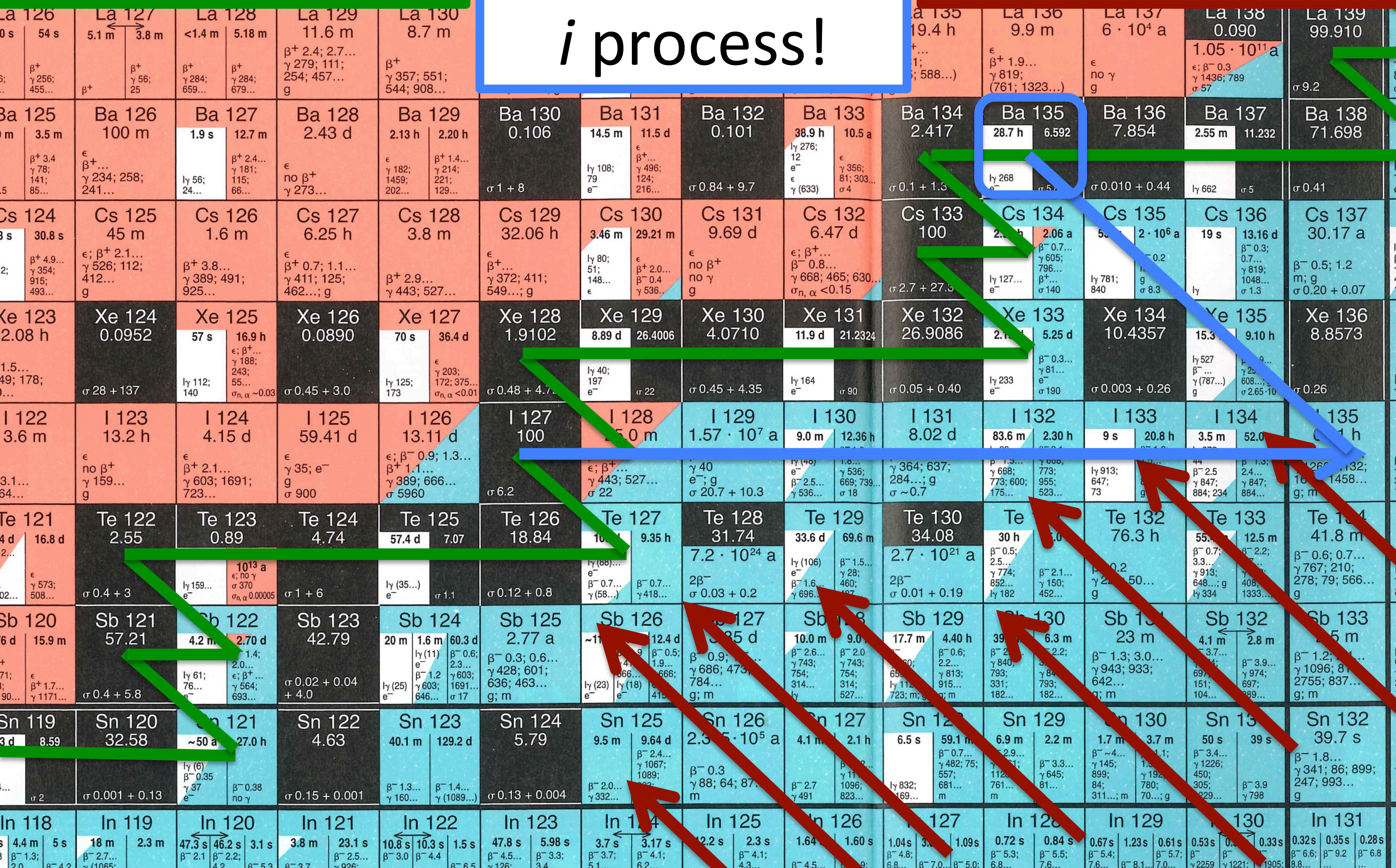
???

Intermediate

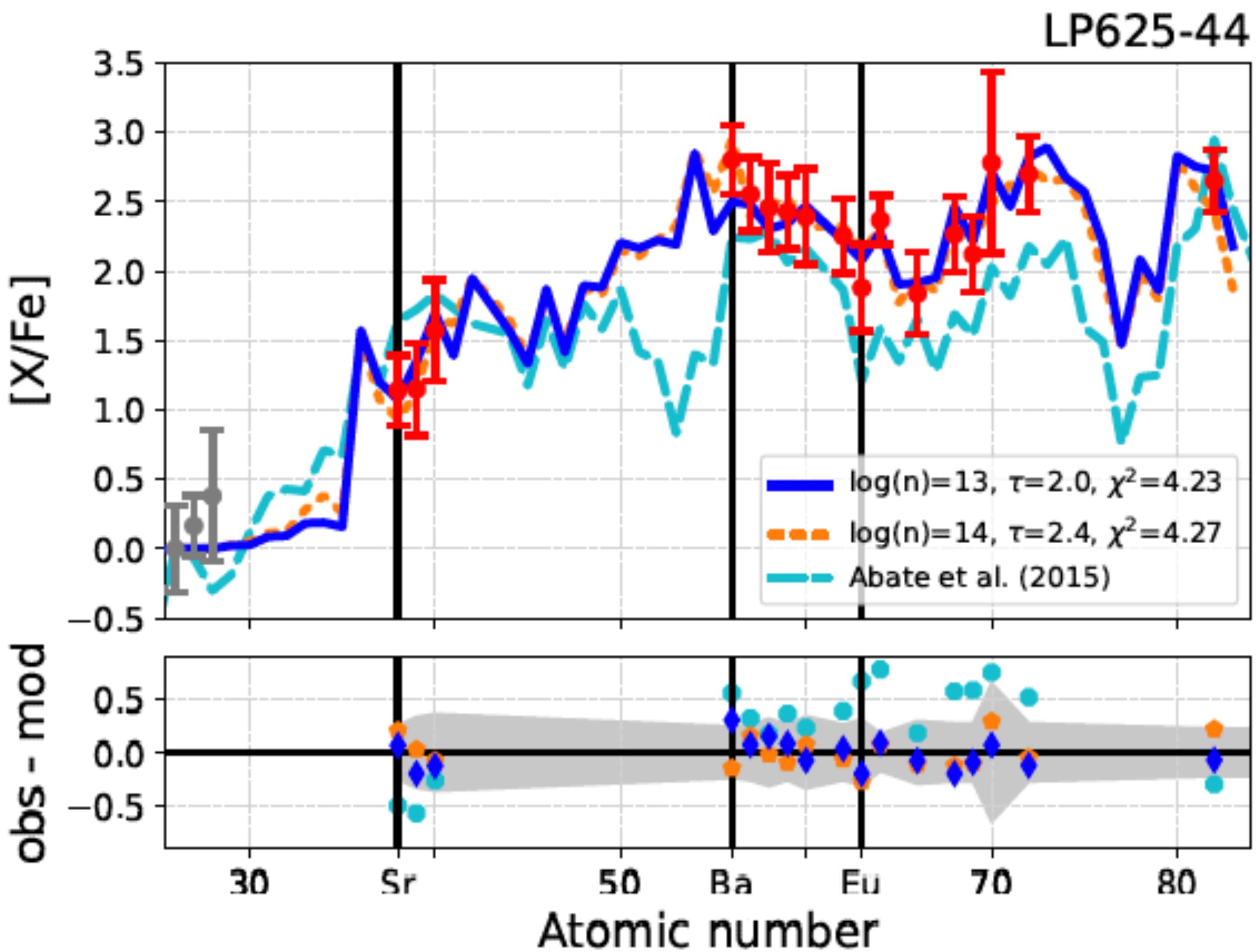
i process!

Rapid r process

$N_n > 10^{20}\ \mathrm{cm}^{-3}$



Observational evidence that it must happen in some stars…



…but we do not know which stars and how…

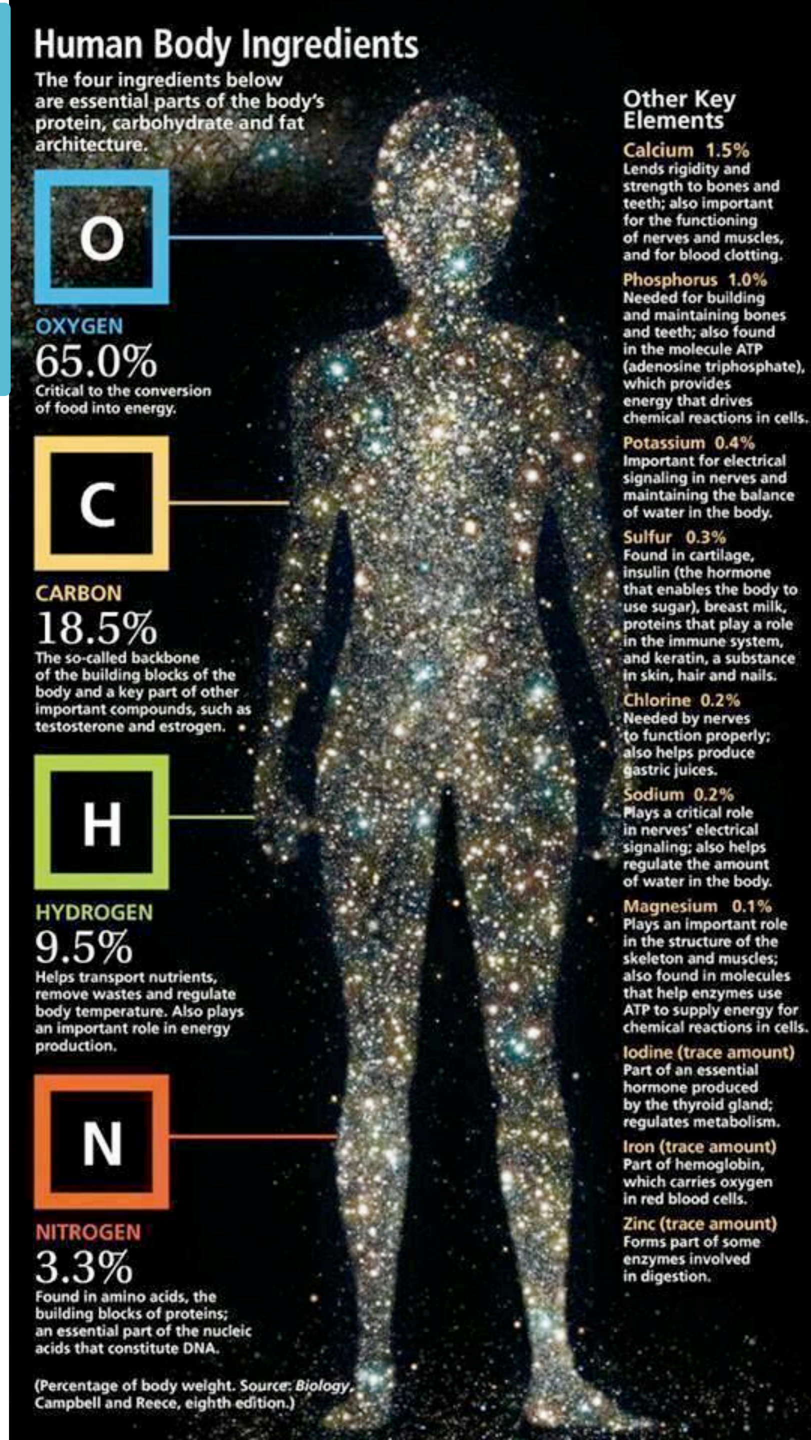
Hampel et al. (2016, 2019)

massive stars: core collapse supernovae (He burning)

low-mass stars: giant star winds (He burning)

Big Bang

every star: winds and explosions (H burning)



Ca, P, K, S, Cl, Na, Mg

massive stars: core collapse supernovae (C, Ne, O burning)

I

neutron star mergers (*r* process)

Fe, Zn

White dwarf supernovae (NSE process)

Recommended Review papers

Reports on Progress in Physics

REVIEW ARTICLE

Constraining the astrophysical origin of the p-nuclei through nuclear physics and meteoritic data

T Rauscher[1,2,3], N Dauphas[4], I Dillmann[5,6], C Fröhlich[7], Zs Fülöp[2] and Gy Gyürky[2]

Published 10 May 2013 • 2013 IOP Publishing Ltd
Reports on Progress in Physics, Volume 76, Number 6

International Journal of Modern Physics E | Vol. 25, No. 04, 1630003 (2016)
| Review Article

No Acce

The production of proton-rich isotopes beyond iron: The γ-process in stars

Marco Pignatari, Kathrin Göbel, René Reifarth and Claudia Travaglio

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 107, July 2019, Pages 109-166

Review

Current status of r-process nucleosynthesis

T. Kajino [a, b, c], W. Aoki [a], A.B. Balantekin [a, d], R. Diehl [e, f], M.A. Famiano [a, g], G.J. Mathews [a, h]

Physics of Core-Collapse Supernovae in Three Dimensions: A Sneak Preview

Annual Review of Nuclear and Particle Science

Vol. 66:341-375 (Volume publication date October 2016)
https://doi.org/10.1146/annurev-nucl-102115-044747

Hans-Thomas Janka,[1] Tobias Melson,[1,2] and Alexander Summa[1]

Publications of the Astronomical Society of Australia

Article Metrics

Volume 31 e030

The Dawes Review 2: Nucleosynthesis and Stellar Yields of Low- and Intermediate-Mass Single Stars

Amanda I. Karakas [a1] and John C. Lattanzio [a2]

DOI: https://doi.org/10.1017/pasa.2014.21 Published online by Cambridge University Press: 22 July 2014 NASA ADS Abstrac

Progress in Particle and Nuclear Physics

Volume 102, September 2018, Pages 1-47

Review

Radioactive nuclei from cosmochronology to habitability

This paper is dedicated to the memory of Gerald J. Wasserburg, who pioneered, built up, and inspired the science presented here.

M. Lugaro [a, b], U. Ott [c, d], Á. Kereszturi [a]