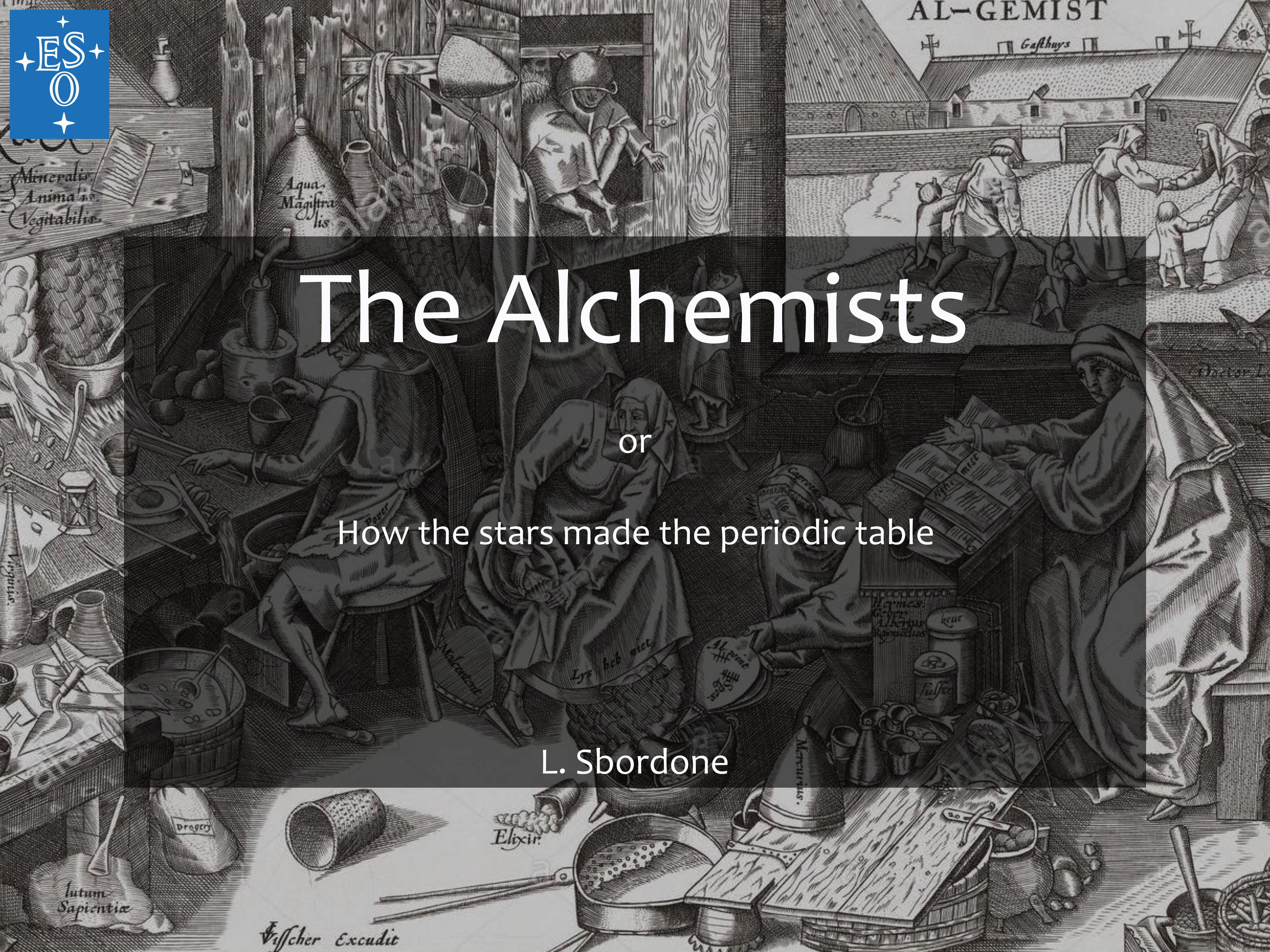

AL-GEMIST
Gasthuys
Mineralis
Animalis
Vegitabilis
Aqua Magistralis
Calis Bende
Pieter Pover
Lys heb niet
Elixir
Drogery
lutum Sapientiæ
Mercurius
Visscher Excudit



The Alchemists

or

How the stars made the periodic table

L. Sbordone

And so it began

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

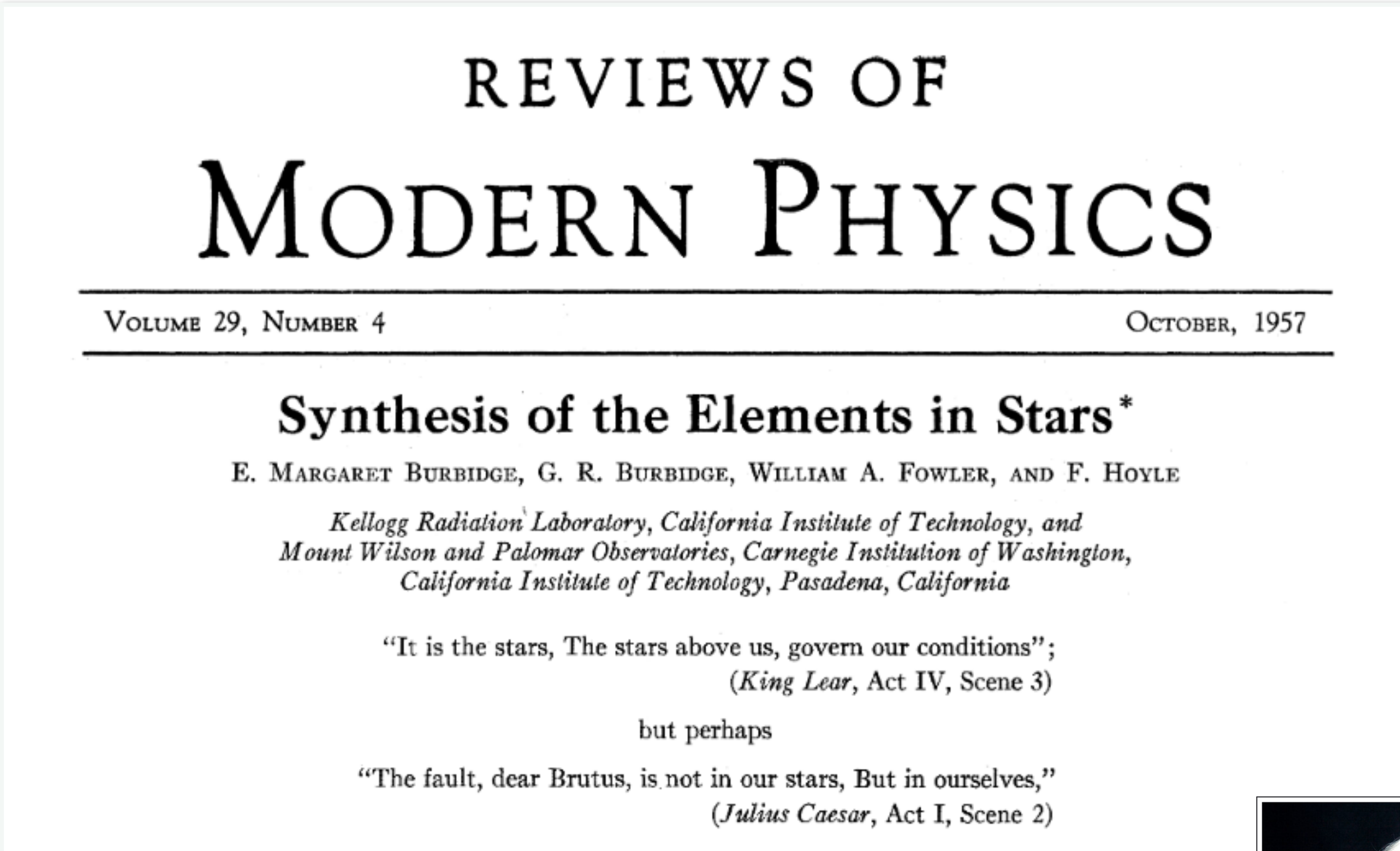
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Defines α-process, p-capture, s- and r-neutron capture, statistical equilibrium nucleosynthesis.

62 years later we are largely still there.

Burbidge, Burbidge, Fowler & Hoyle 1957, a.k.a. "B^{2}FH"

And so it began



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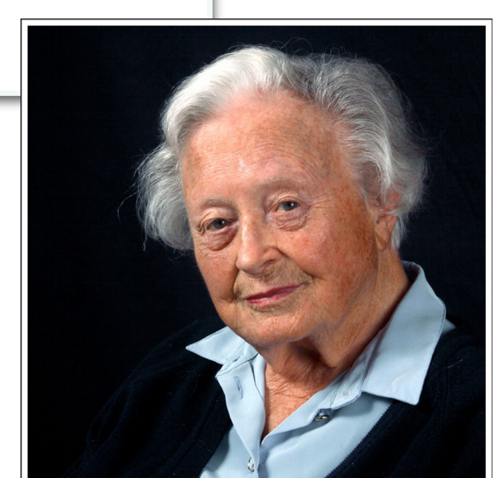

Margaret Burbidge turned 100 this year!

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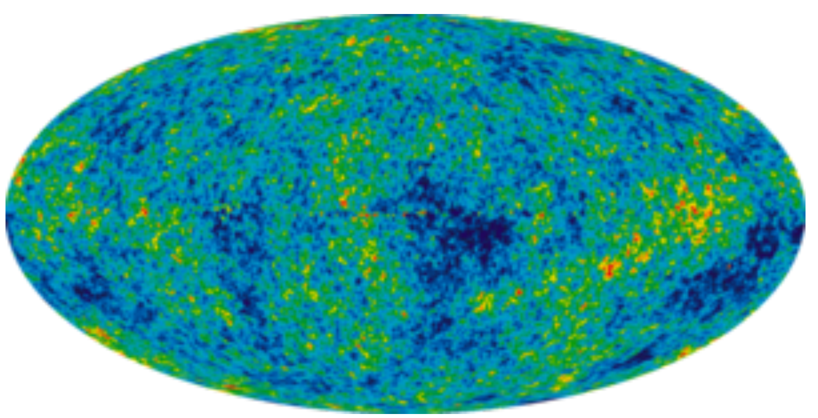
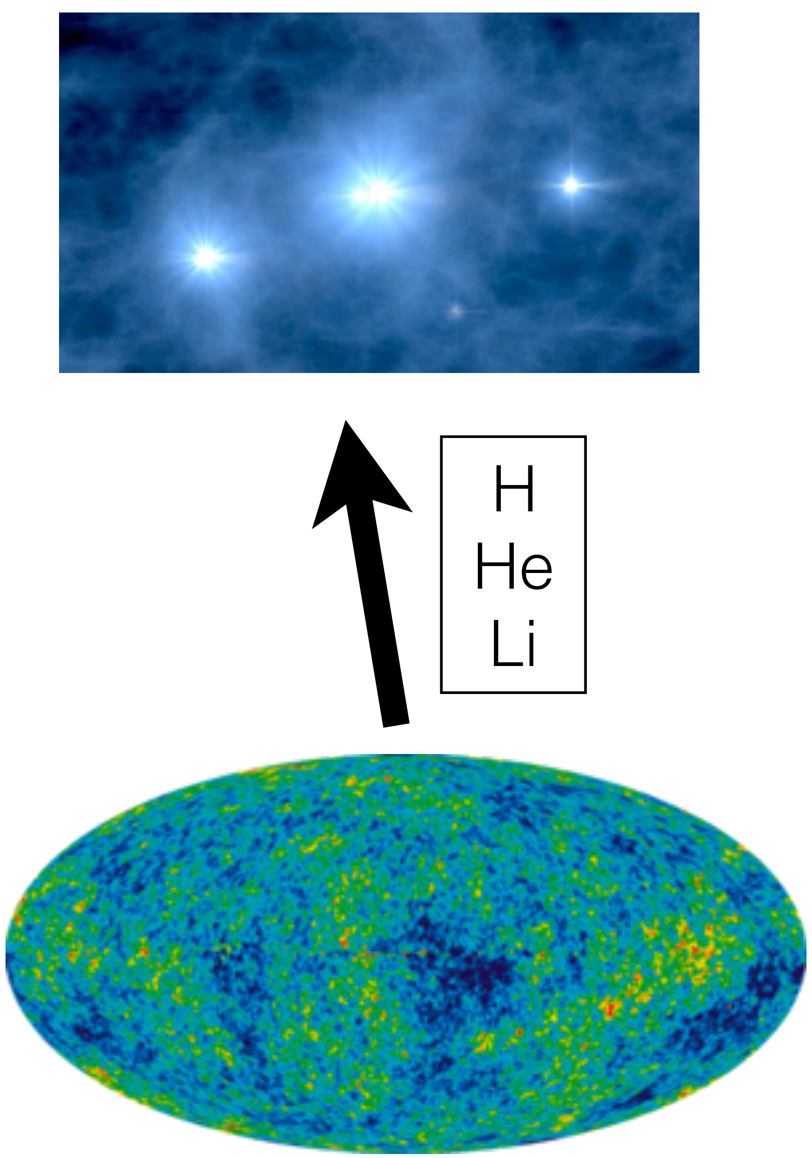
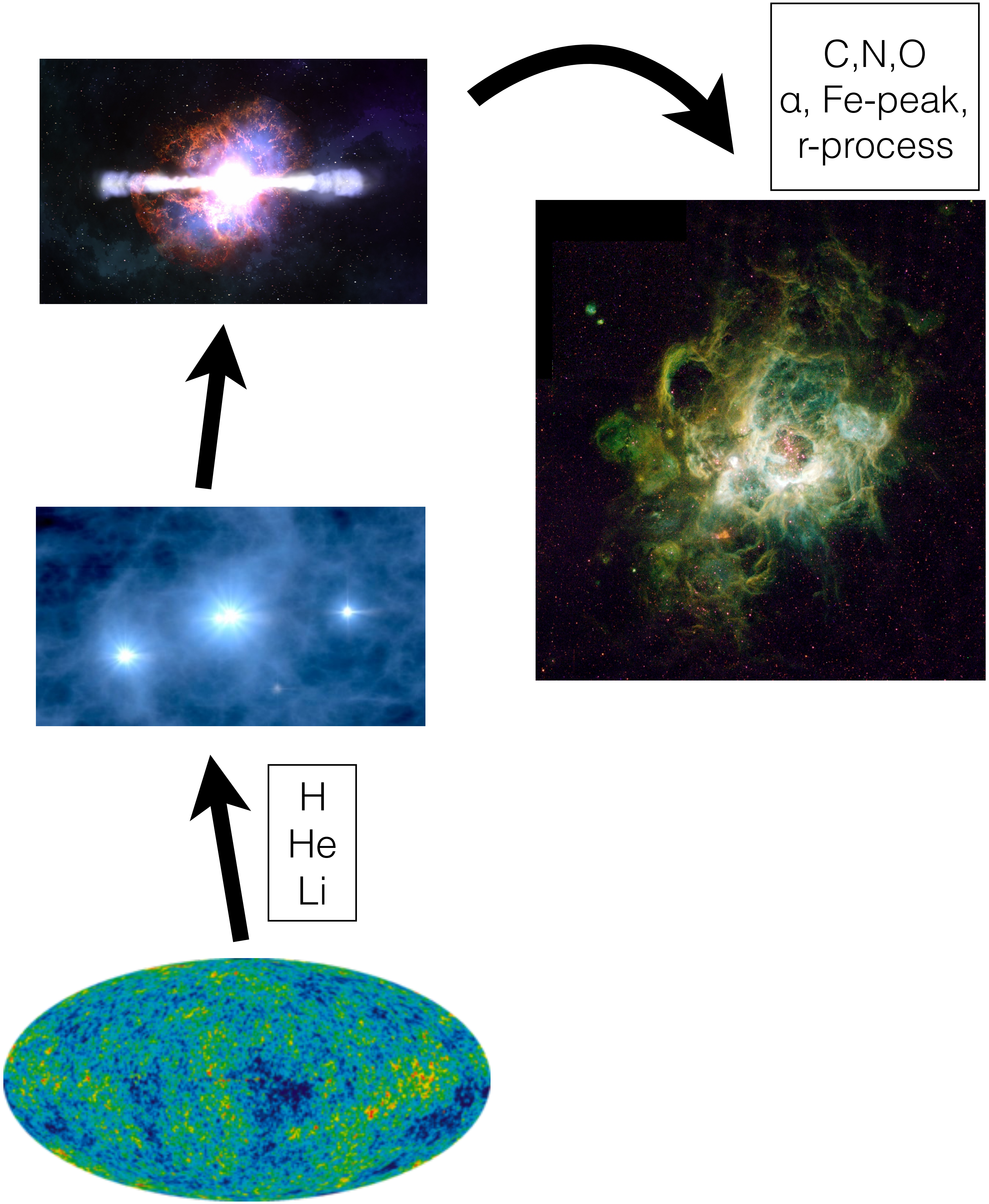
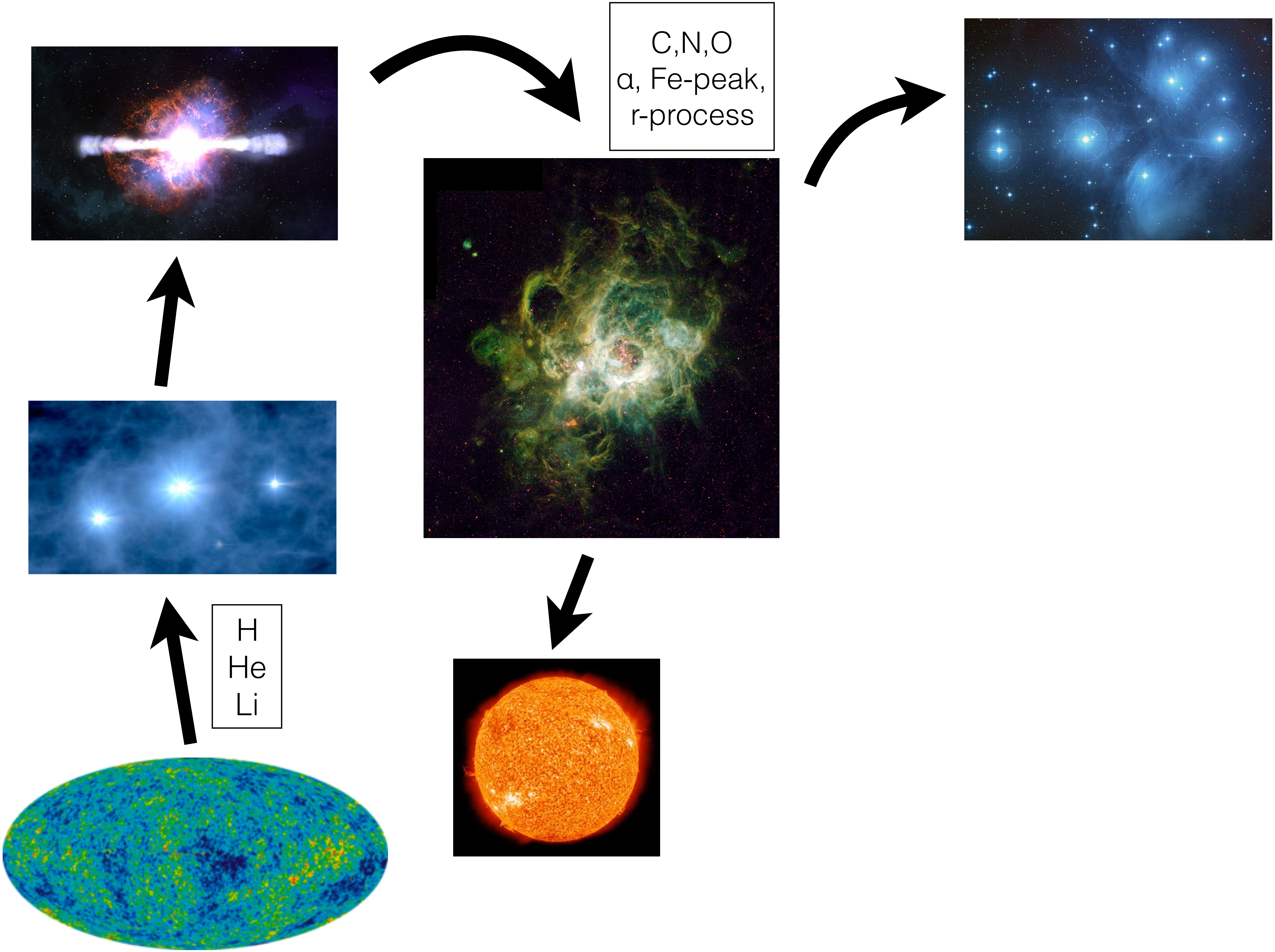



H
He
Li


C,N,O
α, Fe-peak,
r-process
H
He
Li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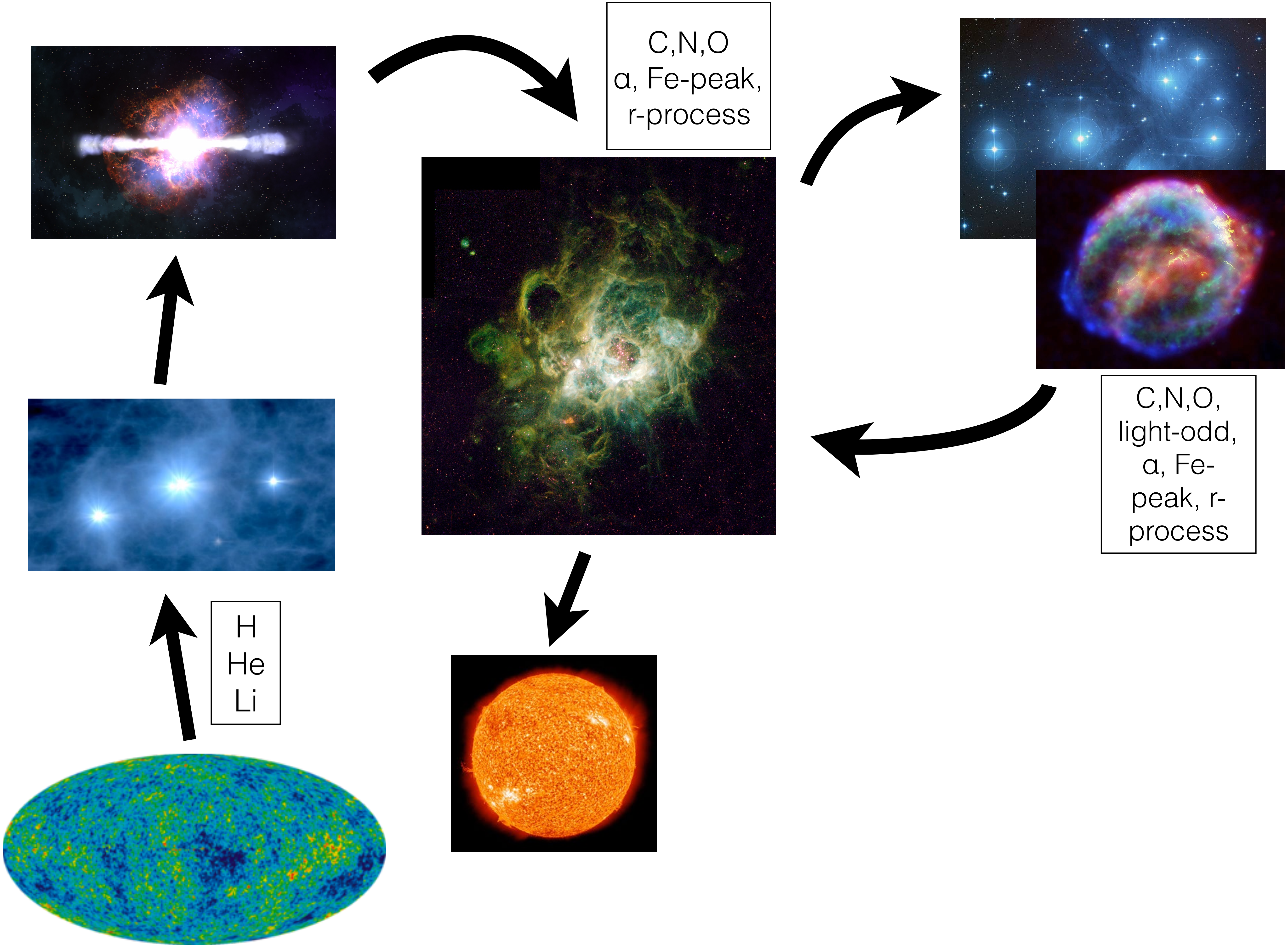
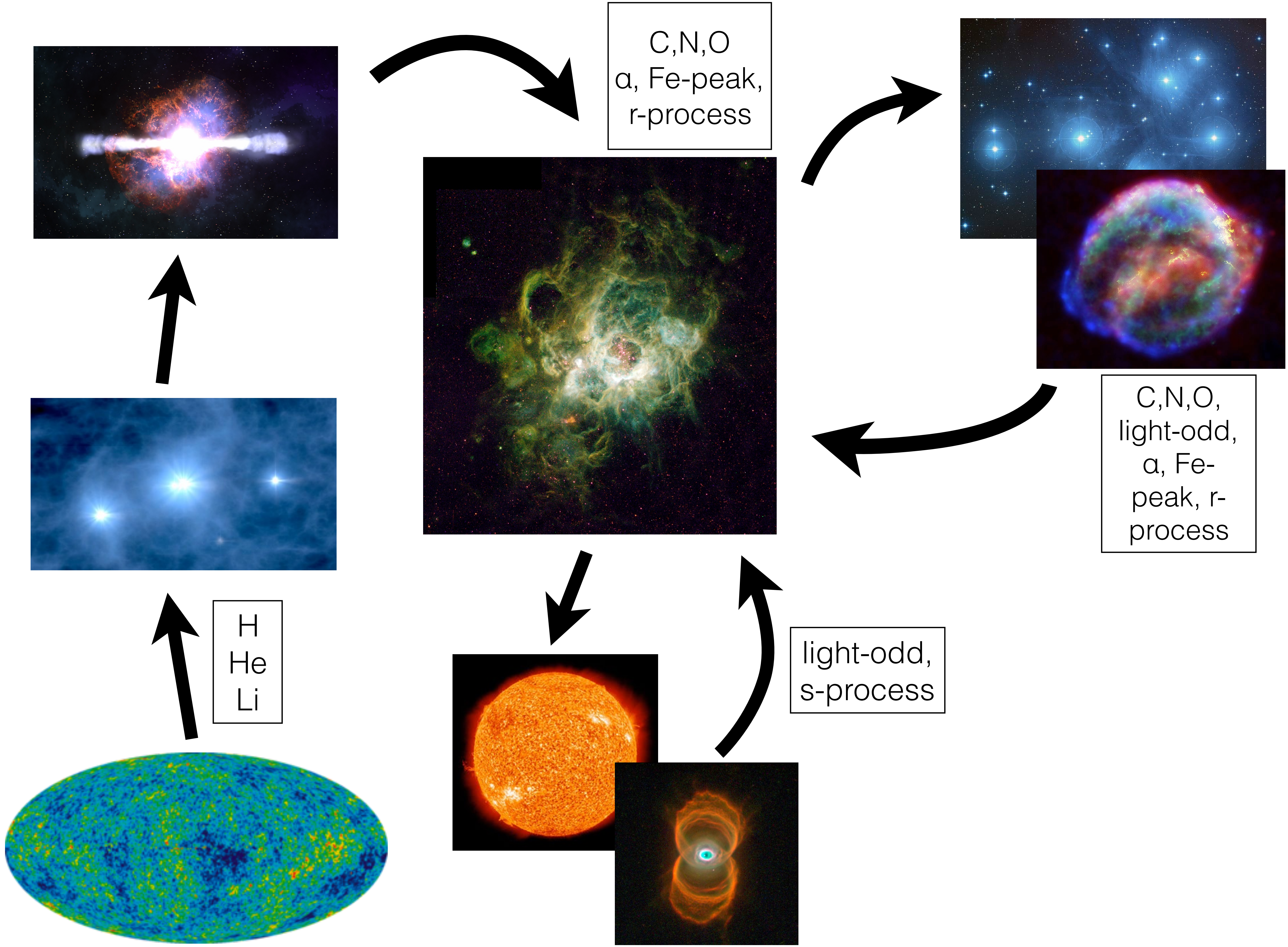
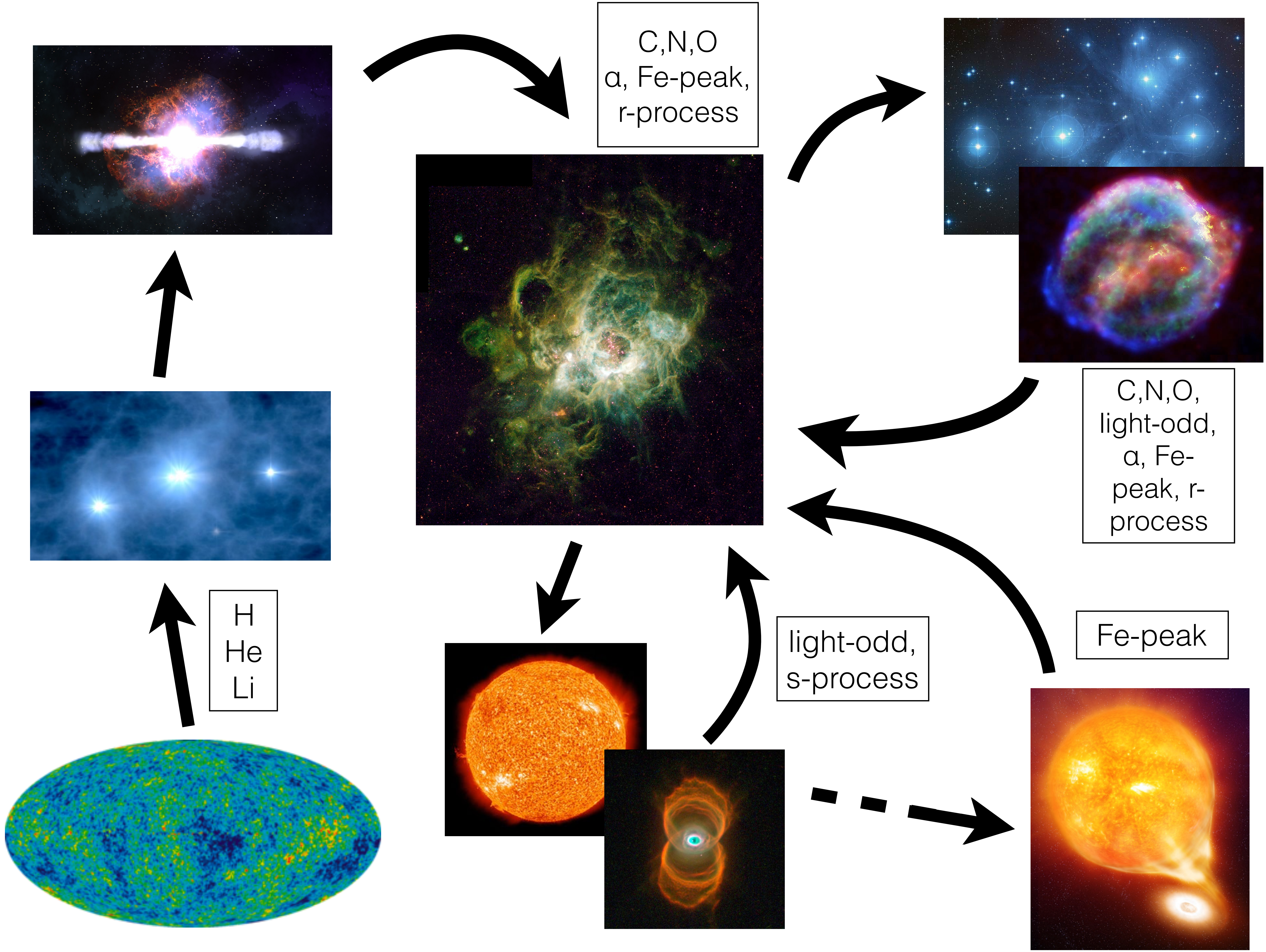

C,N,O
α, Fe-peak,
r-process
C,N,O,
light-odd,
α, Fe-
peak, r-
process
H
He
Li


C,N,O
α, Fe-peak,
r-process
C,N,O,
light-odd,
α, Fe-
peak, r-
process
light-odd,
s-process
H
He
Li



C,N,O
α, Fe-peak,
r-process
C,N,O,
light-odd,
α, Fe-
peak, r-
process
H
He
Li
light-odd,
s-process
Fe-peak

General concepts: nucleosynthesis

- **H, He, Li** were synthesized in the high-temperature phase of early universe (**BB Nucleosynthesis**, 3 to 20 min after BB)…
- … but almost 100% of everything else was synthesized in **stars**.
- Stellar nucleosynthesis products are reintroduced in ISM **at the end of the star life**. New stars will be then born **enriched** of the product of previous generations.
- What matters is not what the star **makes**, but what **it can eject**.
- Different elements produced by different **processes**, active in stars of different **masses**, thus enriching the ISM **on different timescales**.
- Enrichment **feeds back** on itself: increasing heavy-elements content affects **star formation, stellar evolution, and nucleosynthetic yields**

General concepts: abundance analysis

- Stars mostly preserve the surface composition they were **born with.**
- Stars are relatively **simple**, stable and constrained objects: their **atmosphere** can be modeled, its **abundances** determined.
- Their **evolution** is also modeled, so we know their **age:** chemical **evolution** of stellar populations can be reconstructed…
- … allowing to probe the **environment** in which the star was formed, at the time it was formed.
- A 0.8 $M_\odot$ star born right after the BB is still a dwarf now…

Putting them together…

- Stellar (ISM / IGM) abundances bear the imprint of the chemical evolution **in the environment** and **up to the birth time** of the star.
- They are **dense** in information: 25-30 elements (+isotopes) measurable, probing vastly different physical conditions and stellar masses
- They constrain **SF history** & **efficiency, SN rates, yield retention** capability of the galaxy…
- They constrain **stellar astrophysics** (SN physics, thermal pulse conditions, convection depth in giants…) and…
- … they do it for objects **no longer observable** (zero-metal SN), or processes that leave **no further trace** (multiple populations in GC)
- They allow **chemical tagging**, associating stellar populations on the basis of their chemical similarity
- They couple with **kinematics**, allowing to detect and characterize the evolution of galaxies (radial disk migration, tidal accretion, secular bar formation…)

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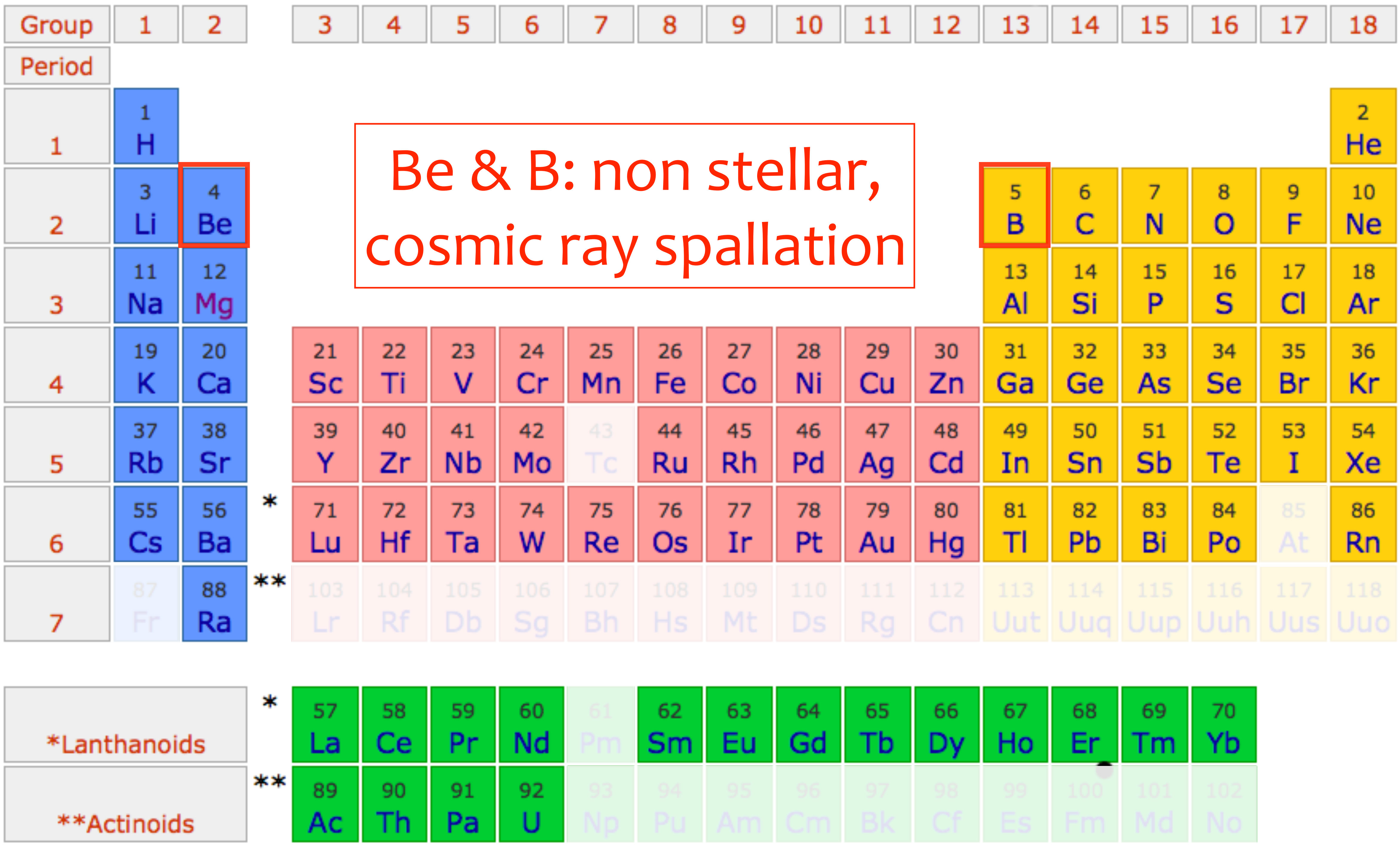

Be & B: non stellar,
cosmic ray spallation
Group 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Period
1 1 H 2 He
2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
4 19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
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CNO: hydrostatic burning, massive stars - SN II

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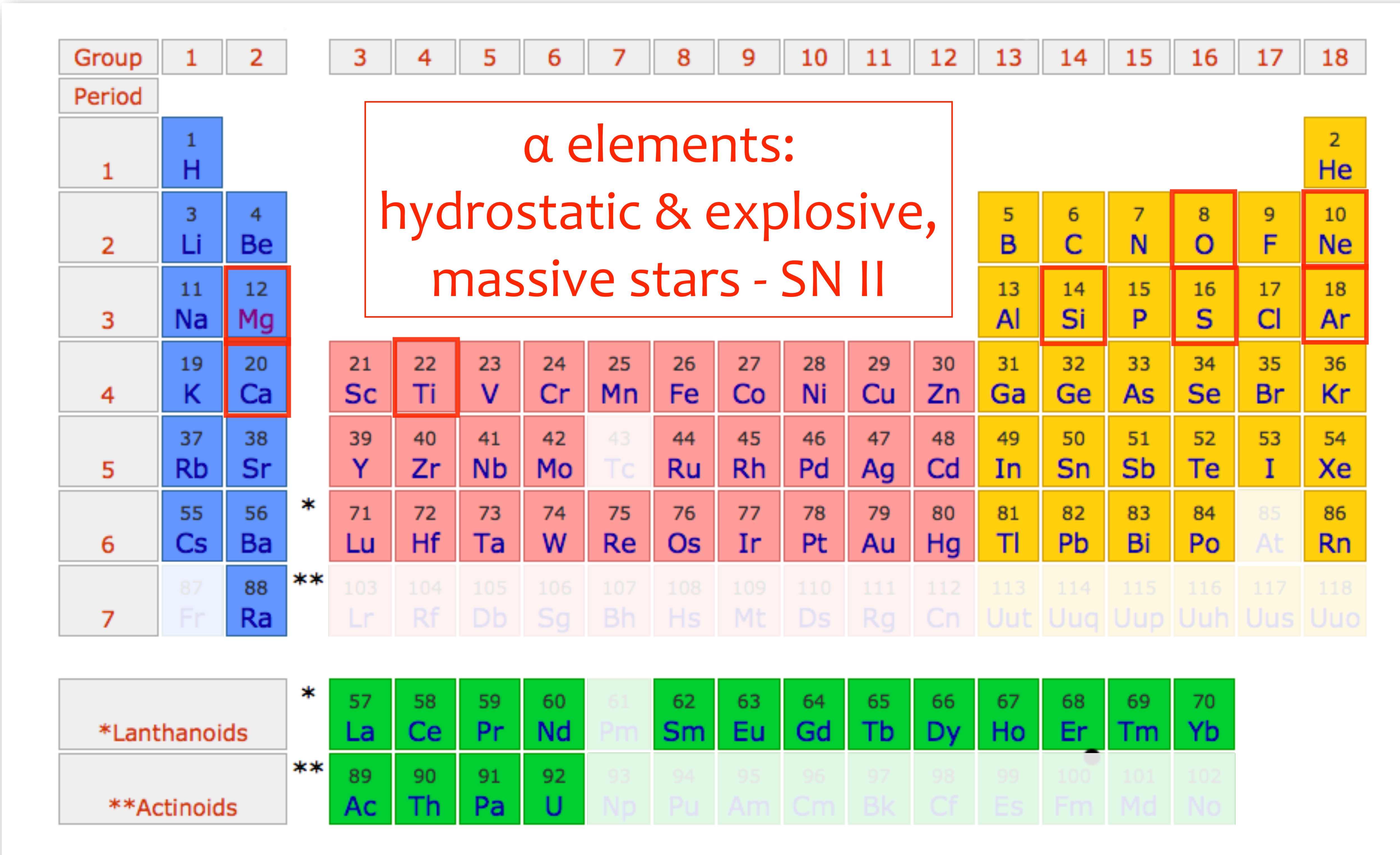
α elements:
hydrostatic & explosive,
massive stars - SN II
Group 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Period
1 H 2 He
2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
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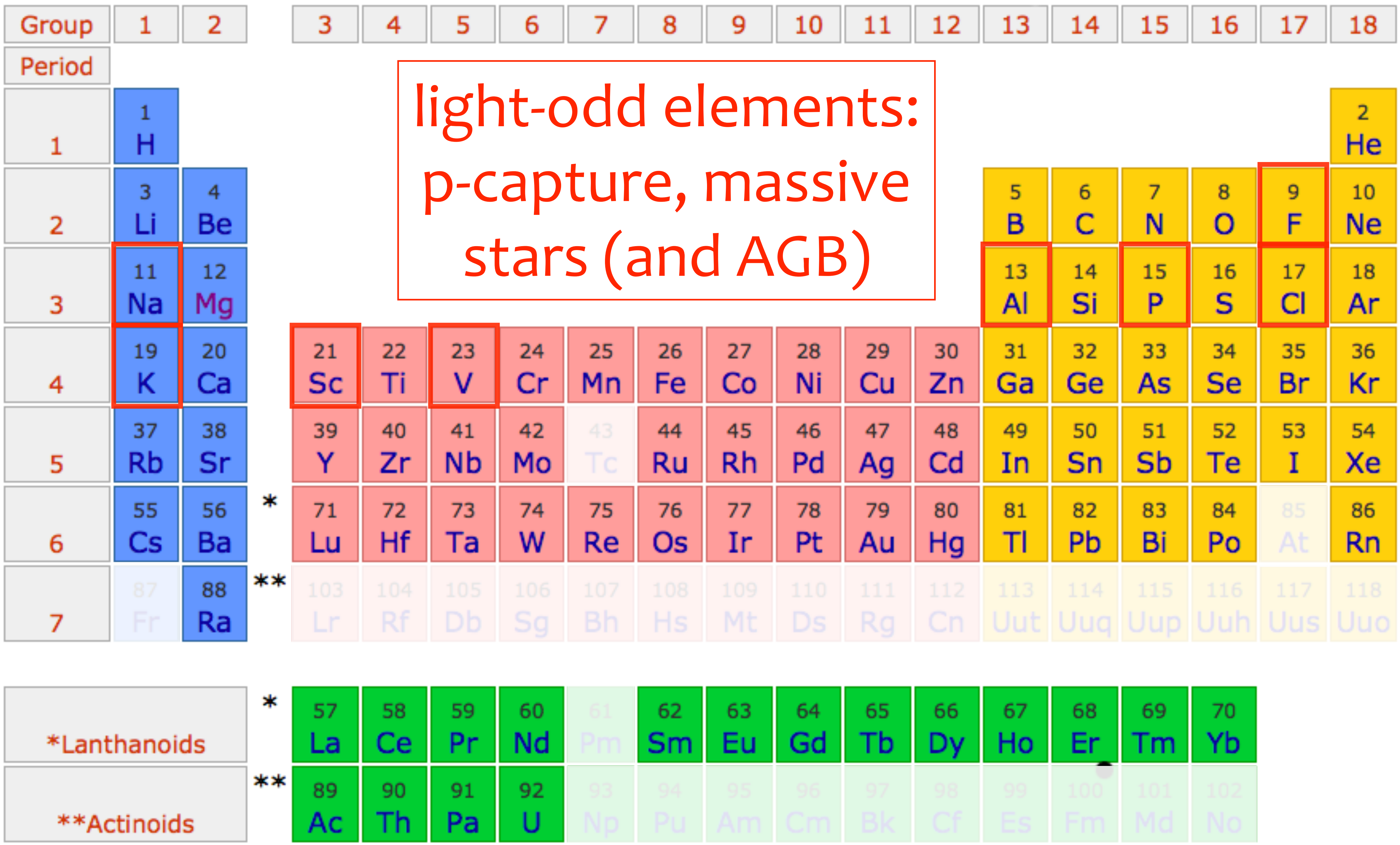

light-odd elements:
p-capture, massive
stars (and AGB)
Group 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Period
1 1 H 2 He
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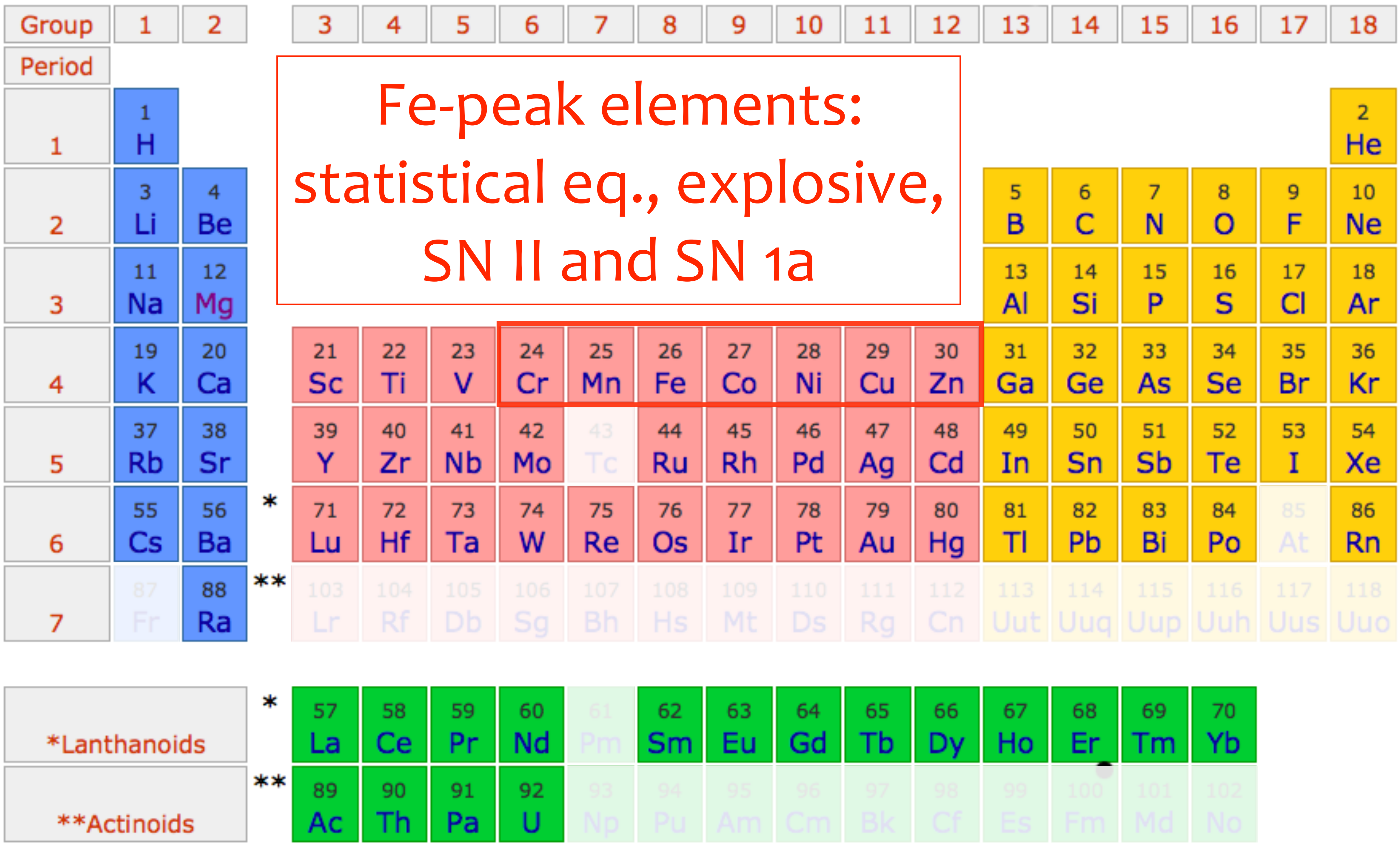
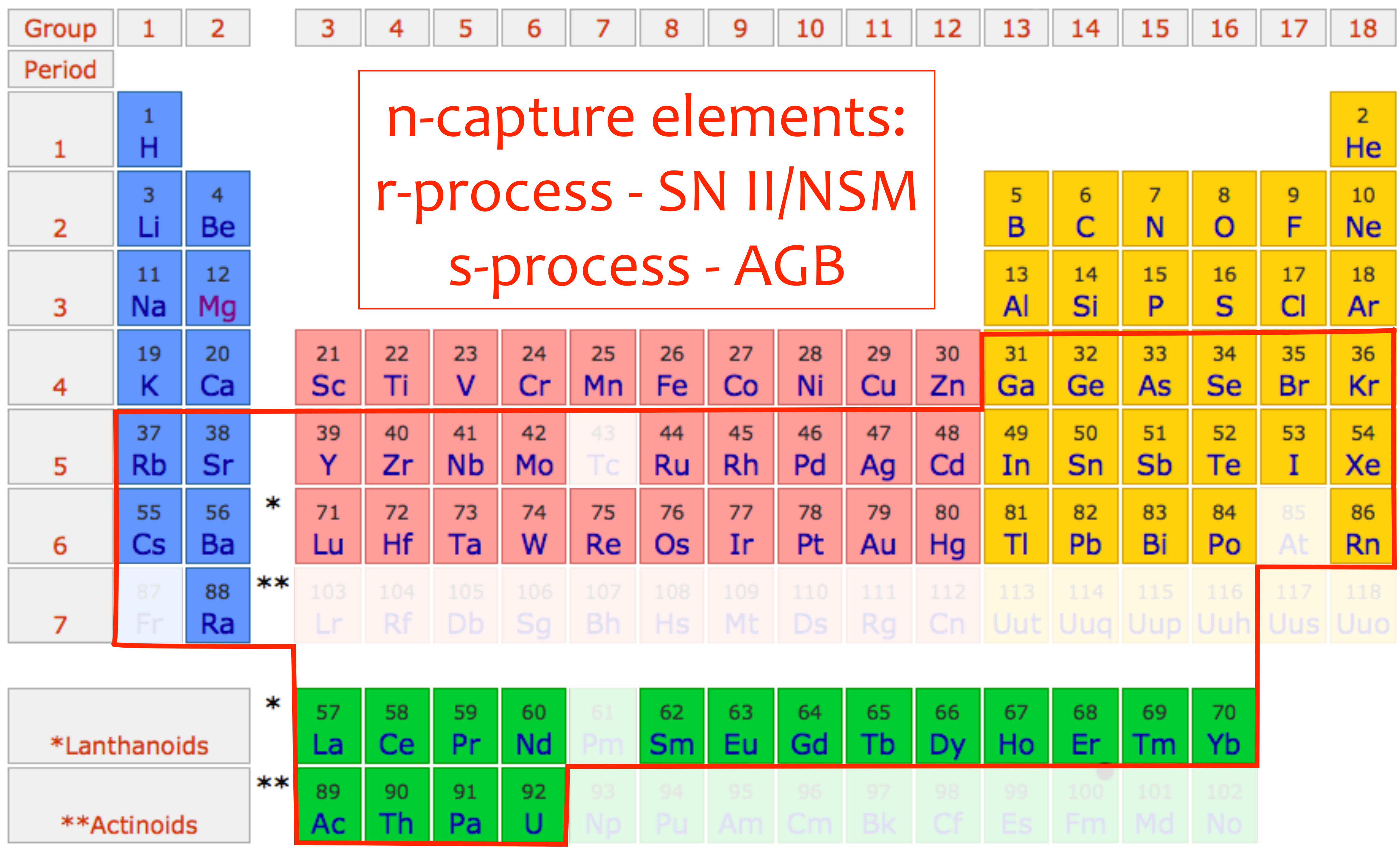
Fe-peak elements: statistical eq., explosive, SN II and SN 1a




n-capture elements:
r-process - SN II/NSM
s-process - AGB
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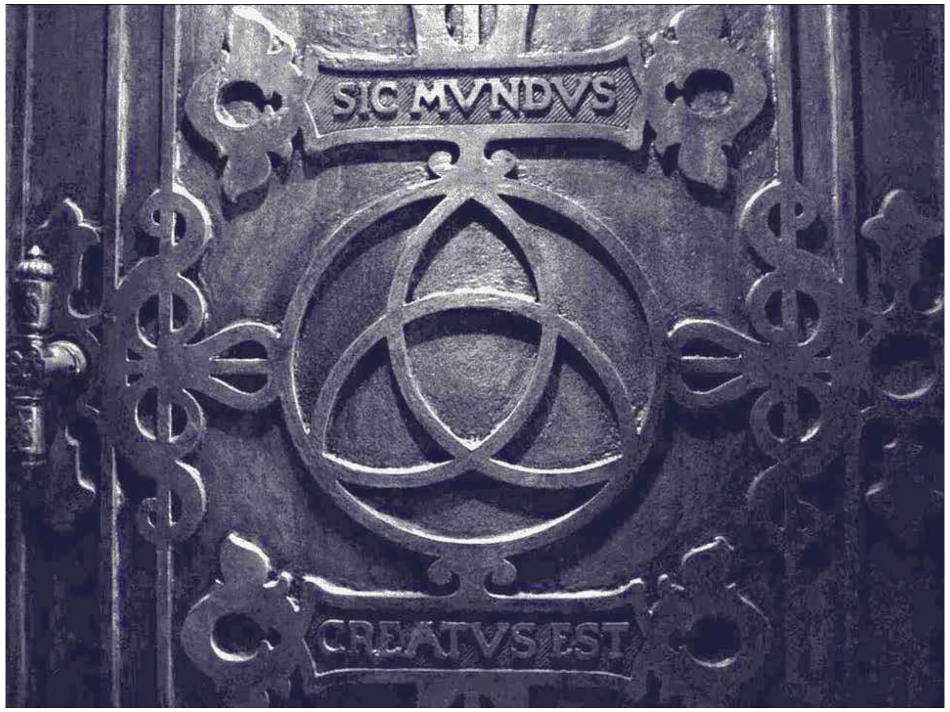
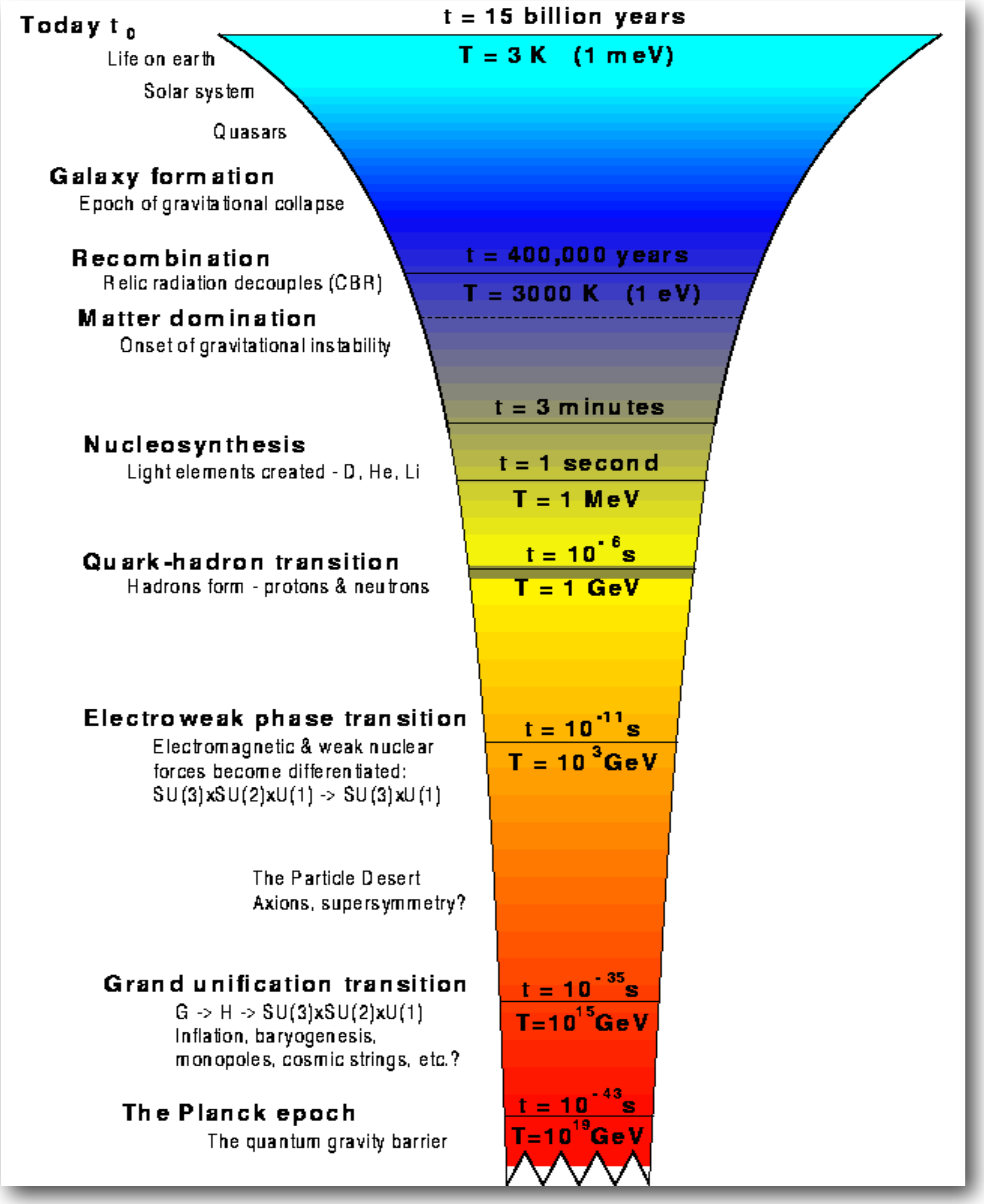
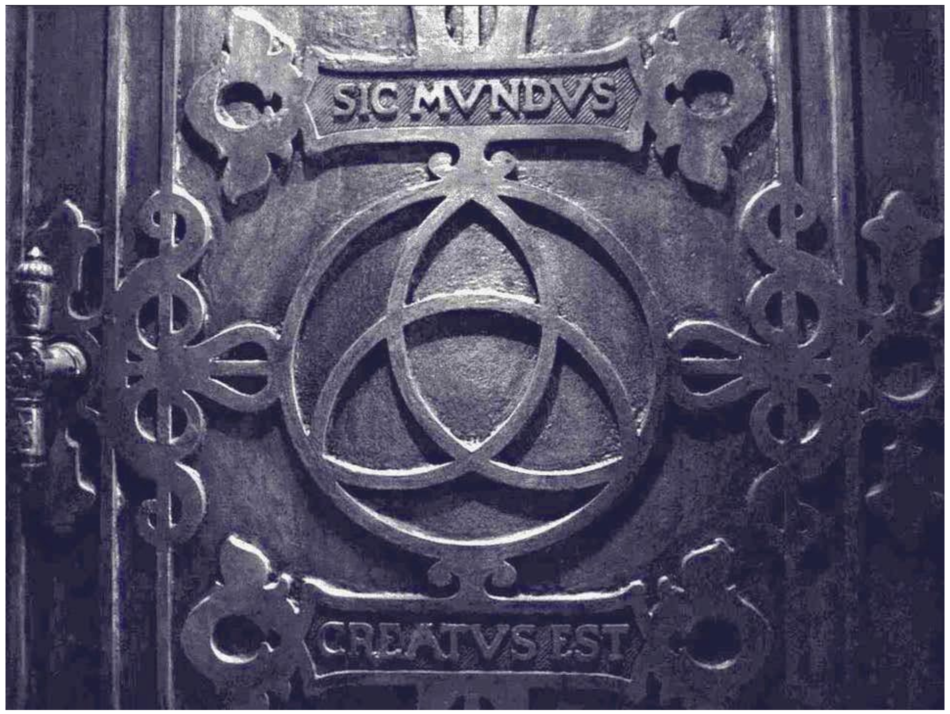
Sic Mundus Creatus Est: BB Nucleosynthesis



- H, He, and Li are the only elements synthesized in BB nucleosynthesis.
- lasts 3 to 20 minutes after the BB



Sic Mundus Creatus Est: BB Nucleosynthesis



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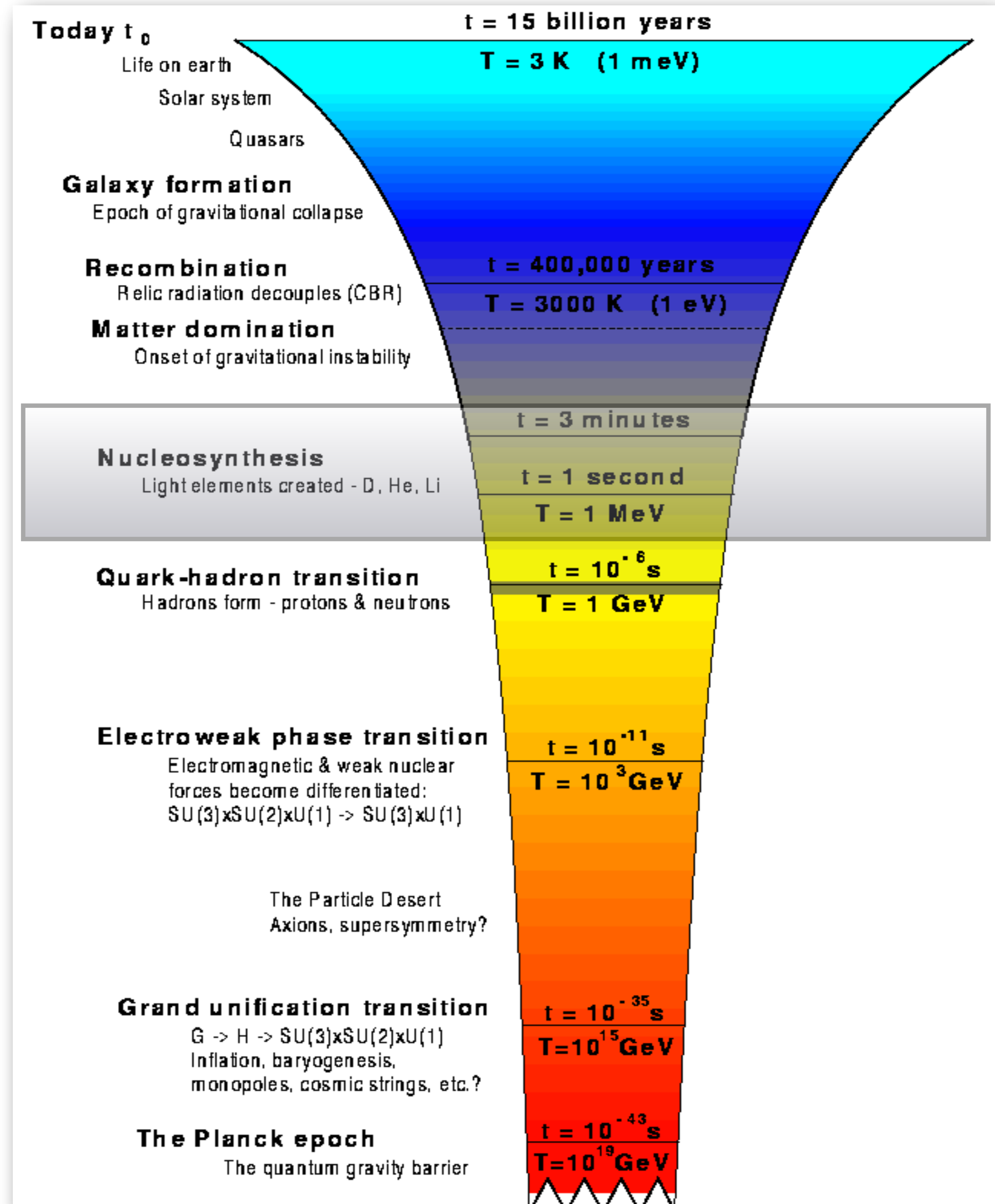
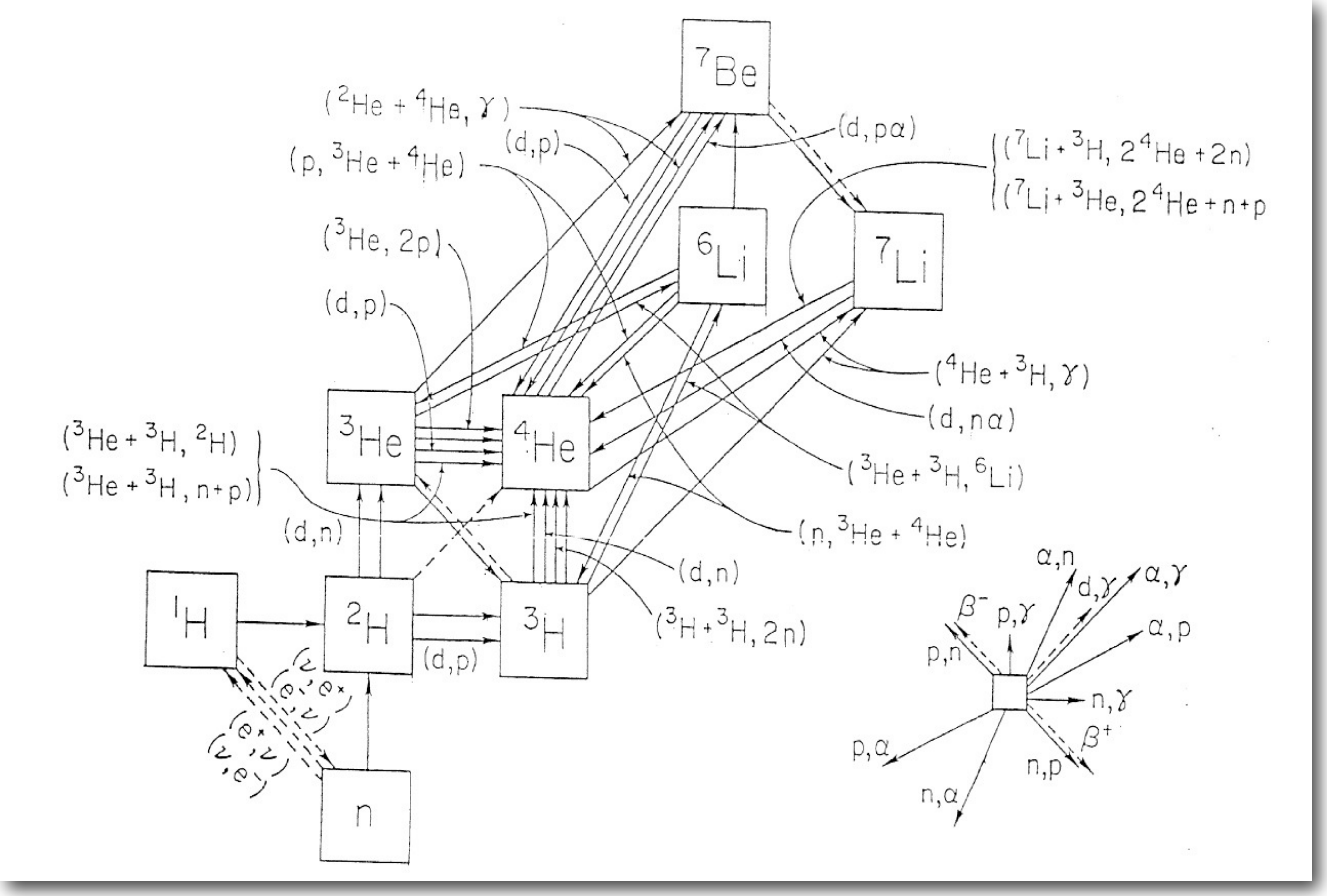
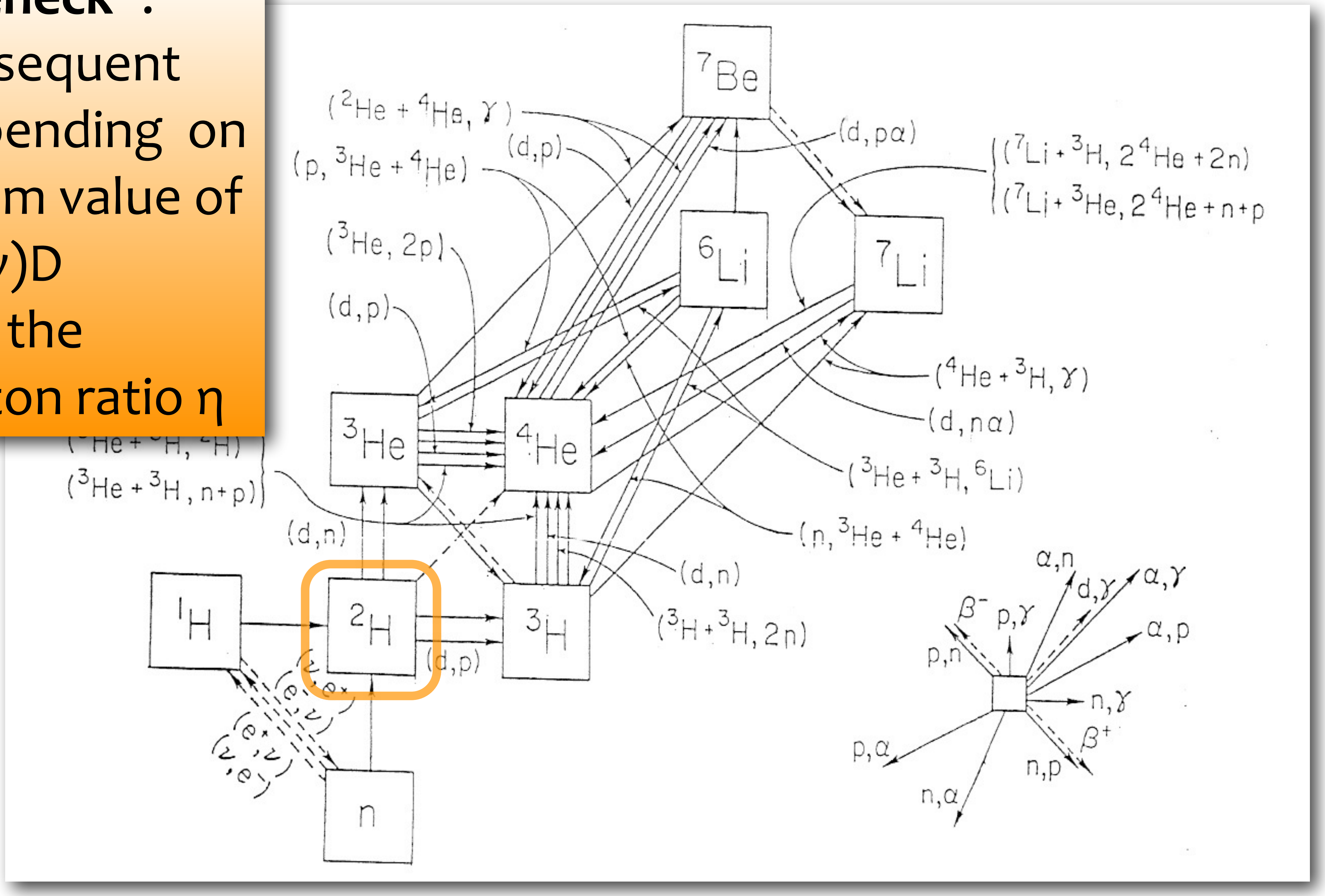


Cosmological Nucleosynthesis

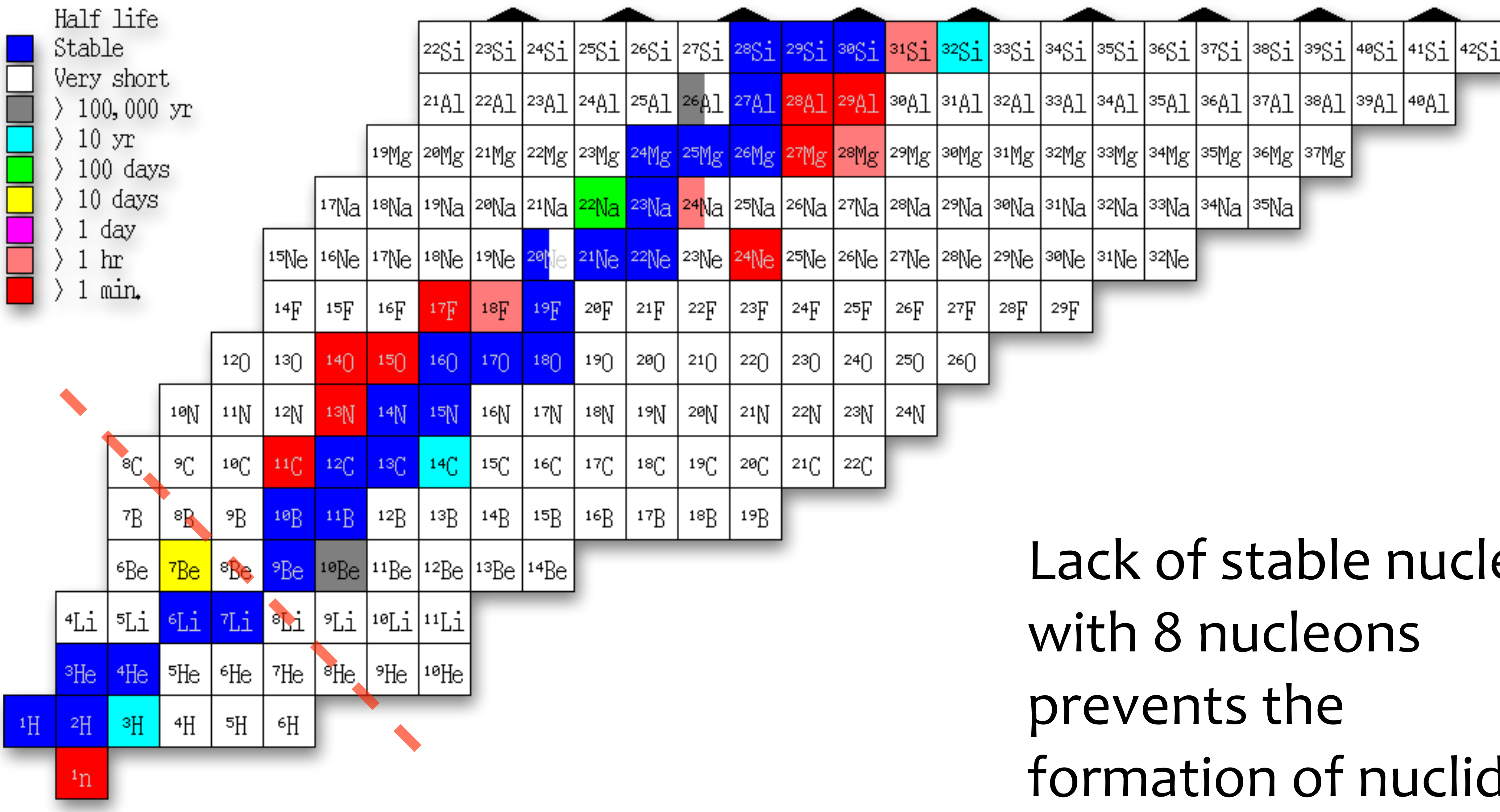


Cosmological Nucleosynthesis

“D Bottleneck”:
all the subsequent synthesis depending on the equilibrium value of H(H,γ)D
i.e. on the Baryon/Photon ratio η



Cosmological nucleosynthesis

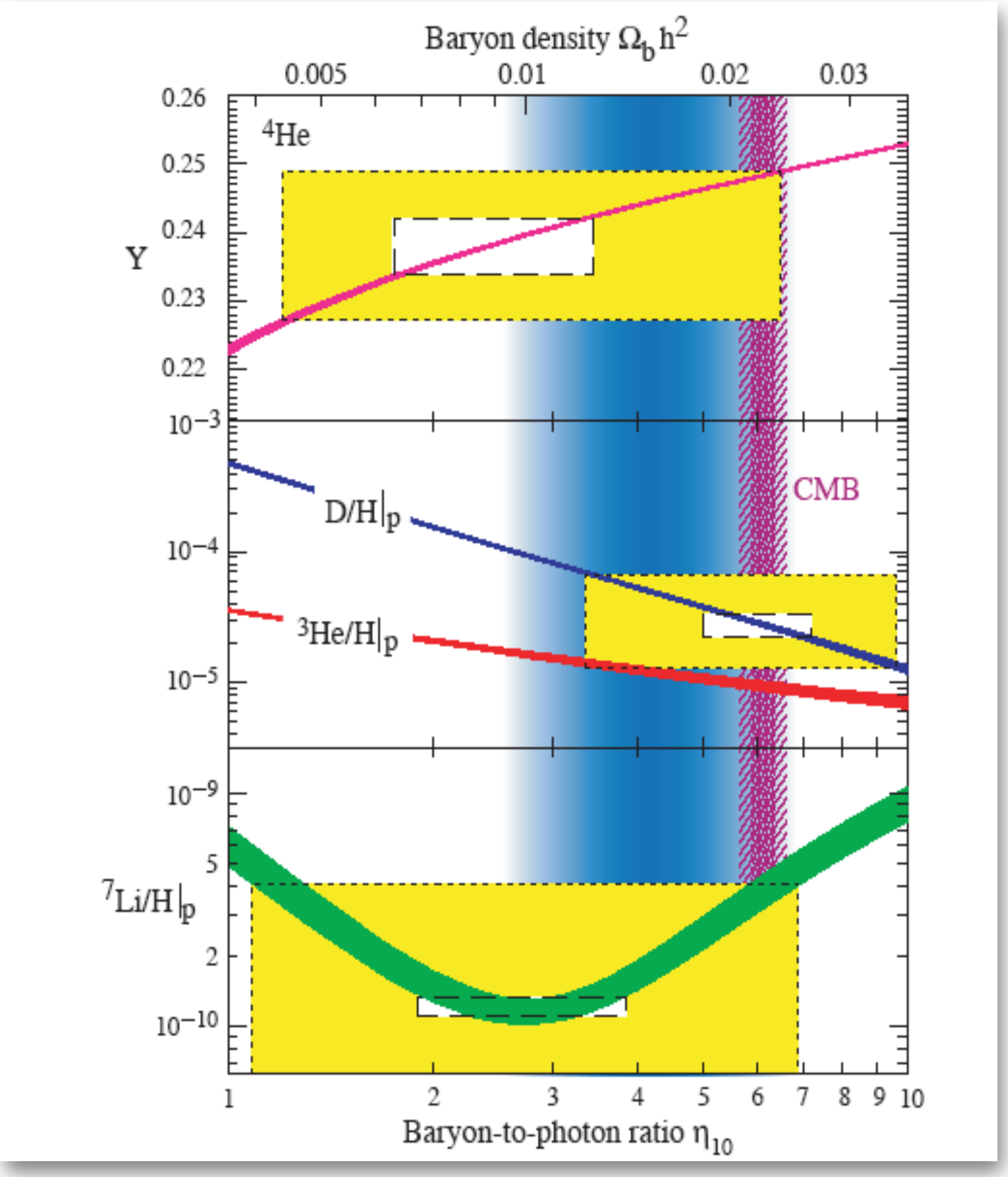


Lack of stable nuclei with 8 nucleons prevents the formation of nuclides from ^{9}Be upwards

Cosmological nucleosynthesis

...as a consequence, all abundances of BBN products, **if not altered afterwards**, allow the measurement of the BB photon-baryon ratio!

Cosmological nucleosynthesis



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CNO: hydrostatic burning,
massive stars - SN II
low-mass (AGB)

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The important stuff: C, N, O

- Almost all "metallicity" is in fact C+N+O:

$$\log\left(\frac{N(O)}{N(H)}\right)_{\odot} = -3.24 \qquad \log\left(\frac{N(C+N+O)}{N(H)}\right)_{\odot} = -3.01$$

$$\log\left(\frac{N(Fe)}{N(H)}\right)_{\odot} = -4.5$$

- Produced through hydrostatic He burning, through the "triple alpha" reaction, plus p-captures for N:

$$^{4}He + ^{4}He \rightleftarrows ^{8}Be \qquad ^{8}Be + ^{4}He \rightarrow ^{12}C + \gamma$$

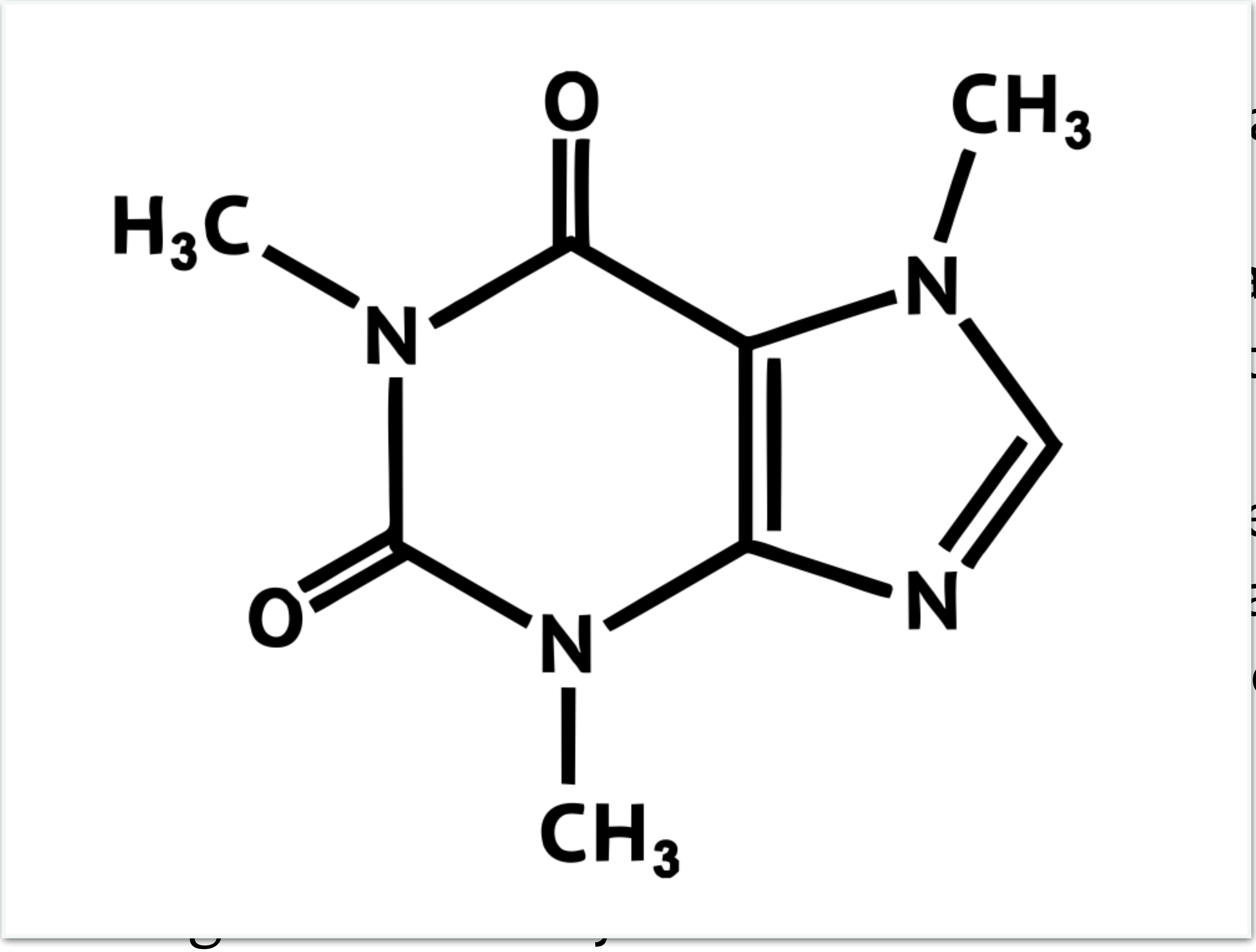
$$^{12}C + ^{4}He \rightarrow ^{16}O + \gamma \qquad ^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$$

$$^{13}C(p,\gamma)^{14}N$$

C, N, O

- produced in almost every star reaching He-flash and core He burning (HB)...
- ... but **released** in significant amounts **by massive stars**, and by **low mass stars** when produced in intershell burning (AGB)
- C, N, O typically **enhanced** in the photospheres of low gravity giants due to dredge-up of processed material
- Their origin in massive stars makes them **among the earliest yields** released in the primordial Universe…
- … possibly allowing/facilitating **low mass star formation,** and organic chemistry

C, N, O



- ash and core He
- **assive stars**, and tershell burning
- es of low gravity al
- **ong the earliest**
- **star formation,**

C, N, O

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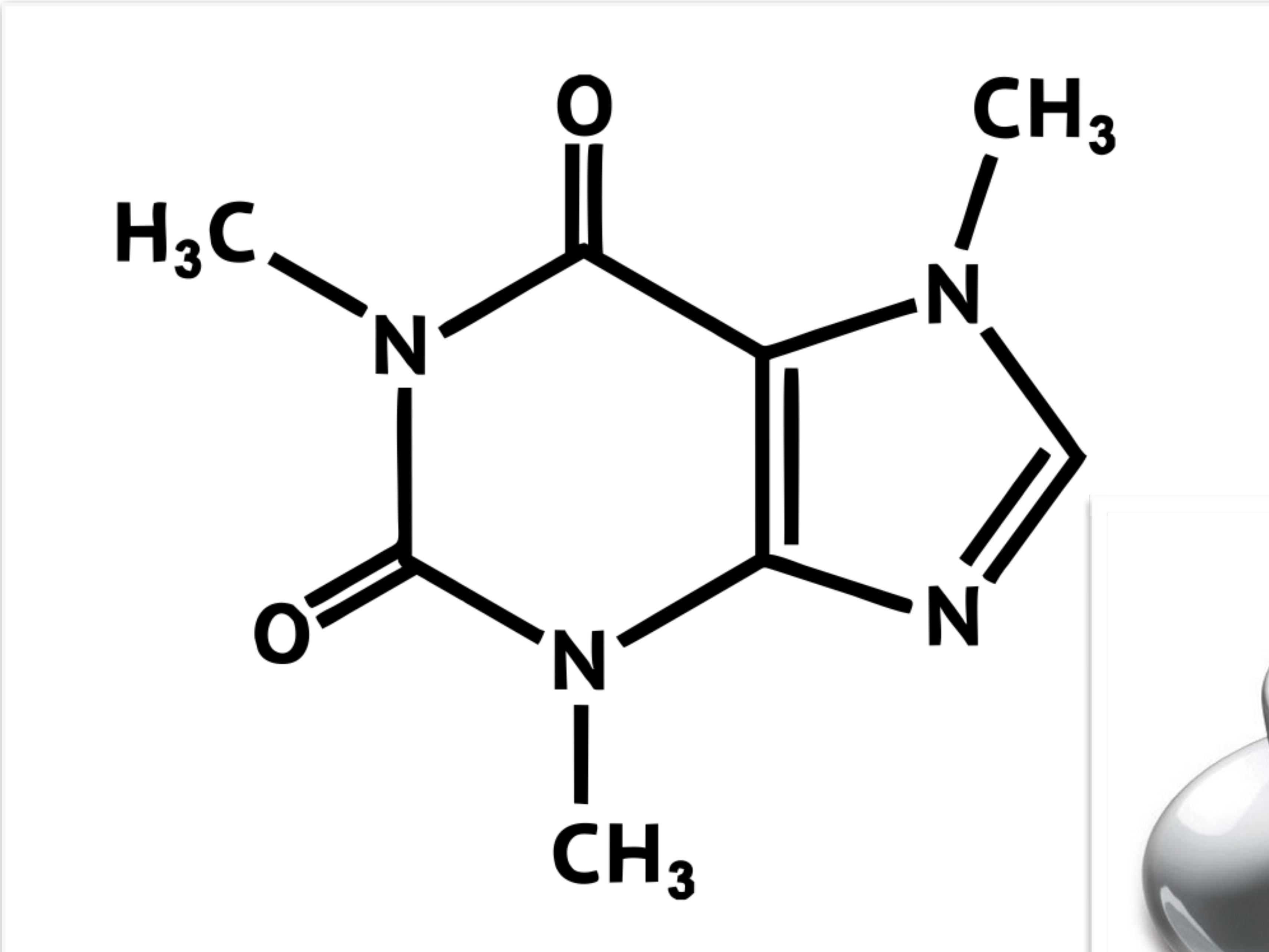

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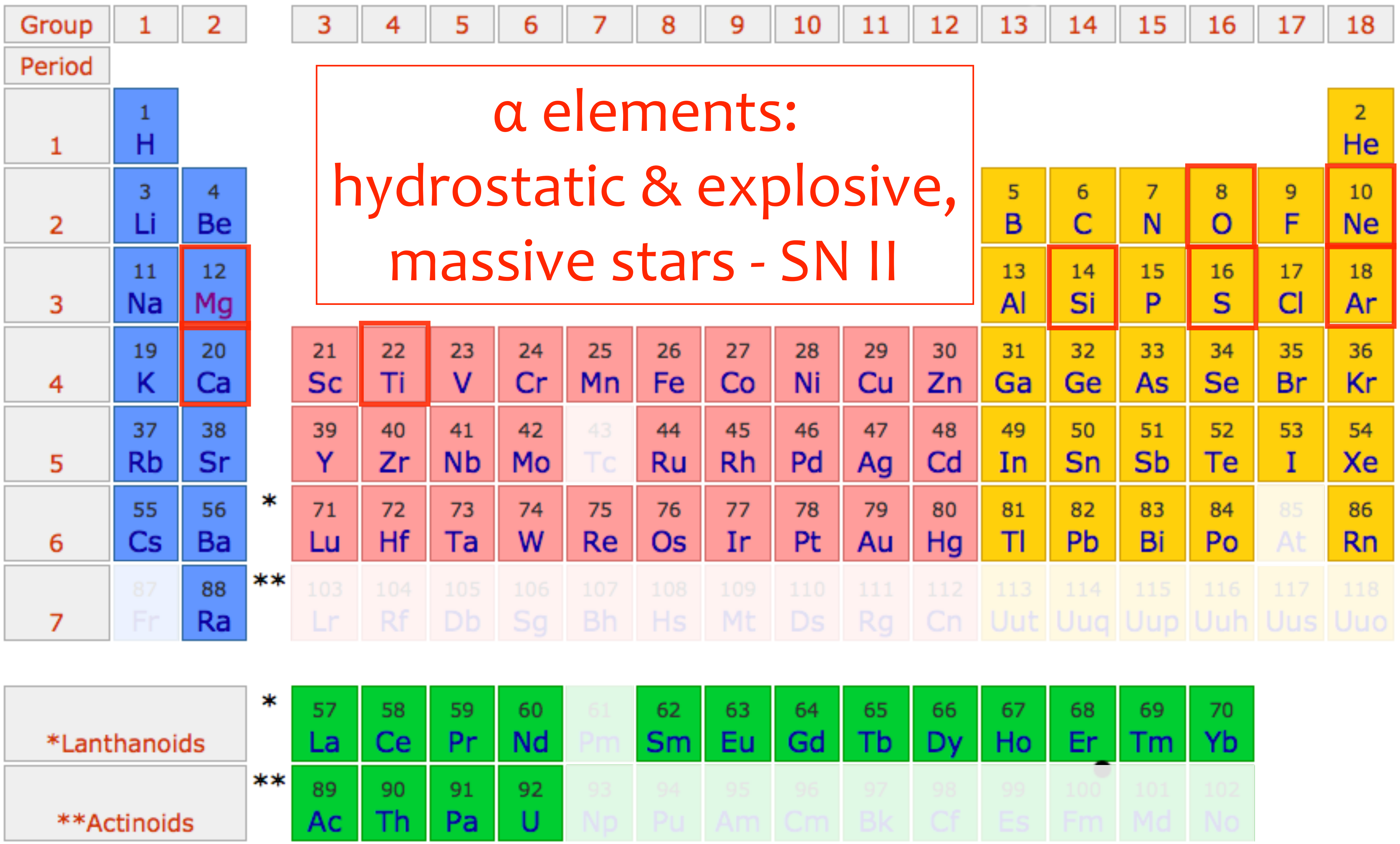
α elements:
hydrostatic & explosive,
massive stars - SN II
Group 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Period
1 1 H 2 He
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What you stand on: α-elements

- **even**-atomic-number elements between **O** and **Ti** (Z=8 to 22) are mostly produced by **α-capture**
- Burning up to Ne is usually hydrostatic even in moderate mass stars…
- … but in fact most of the hydrostatic Ne is photodissociated during SN explosion and synthesized again as explosive product
- above Mg α-elements are essentially explosion products
- released by **massive, short lived** stars, enrich ISM **early** in the hostory of the Universe

$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$$
$$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma$$
$$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma$$
$$^{24}Mg + {}^{4}He \rightarrow {}^{28}Si + \gamma$$
$$\ldots$$

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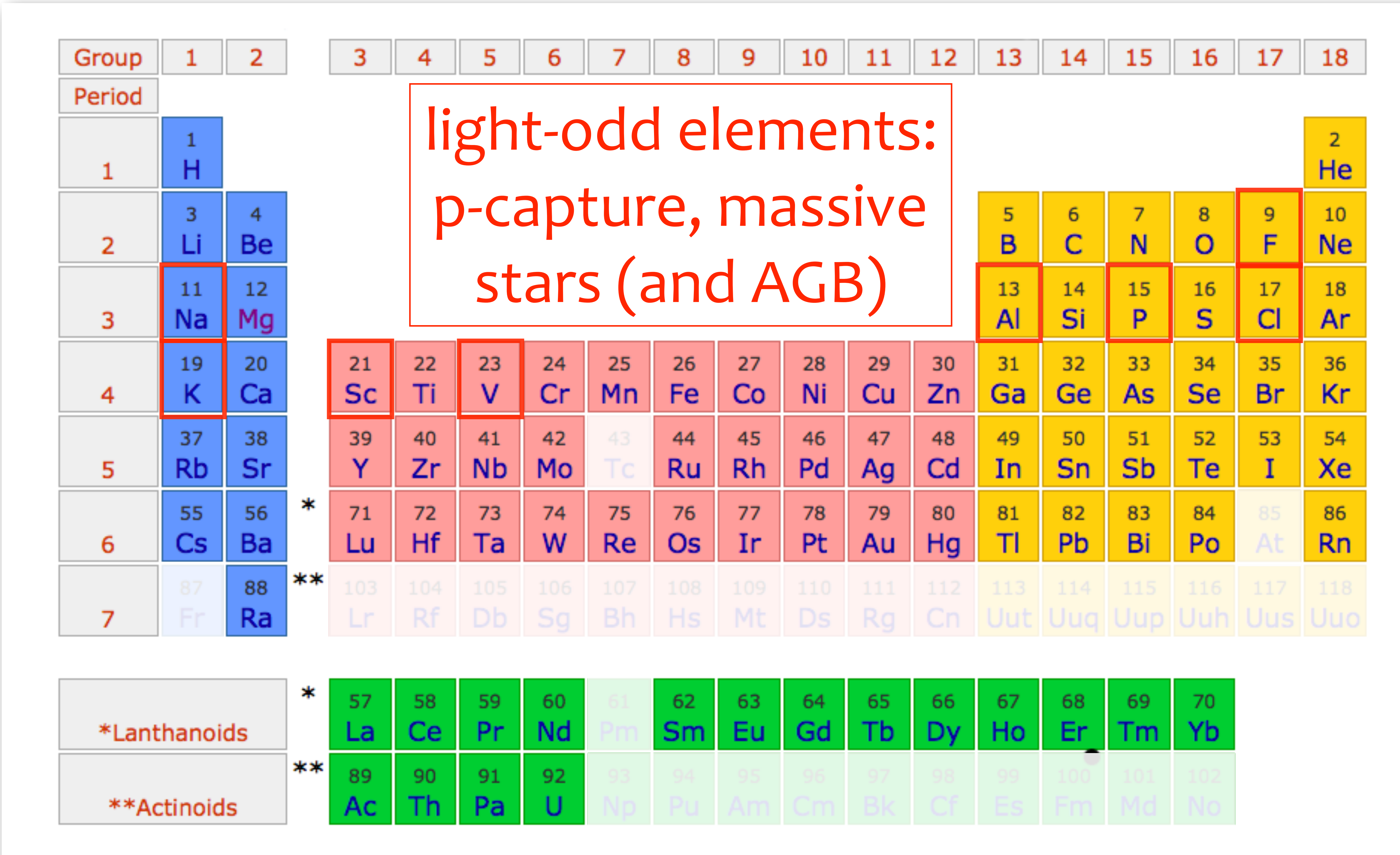
light-odd elements:
p-capture, massive
stars (and AGB)
Group
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Period
1 H 2 He
2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
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Salt of Life: light p-capture elements

- odd-atomic-number nuclei are (mostly) produced by capture of a proton on a lighter, even-atomic-number one.
- p-captures happen every time sufficient (~10^6-10^7 K) temperatures are reached, the issue is the delivery to ISM
- most light-odd elements likely come from SN II, but also AGB (intermediate mass?) production is likely (see globular clusters)
- Lower odd-N nucleus stability and α-capture starting from higher abundance in even elements produce the **even-odd effect.**

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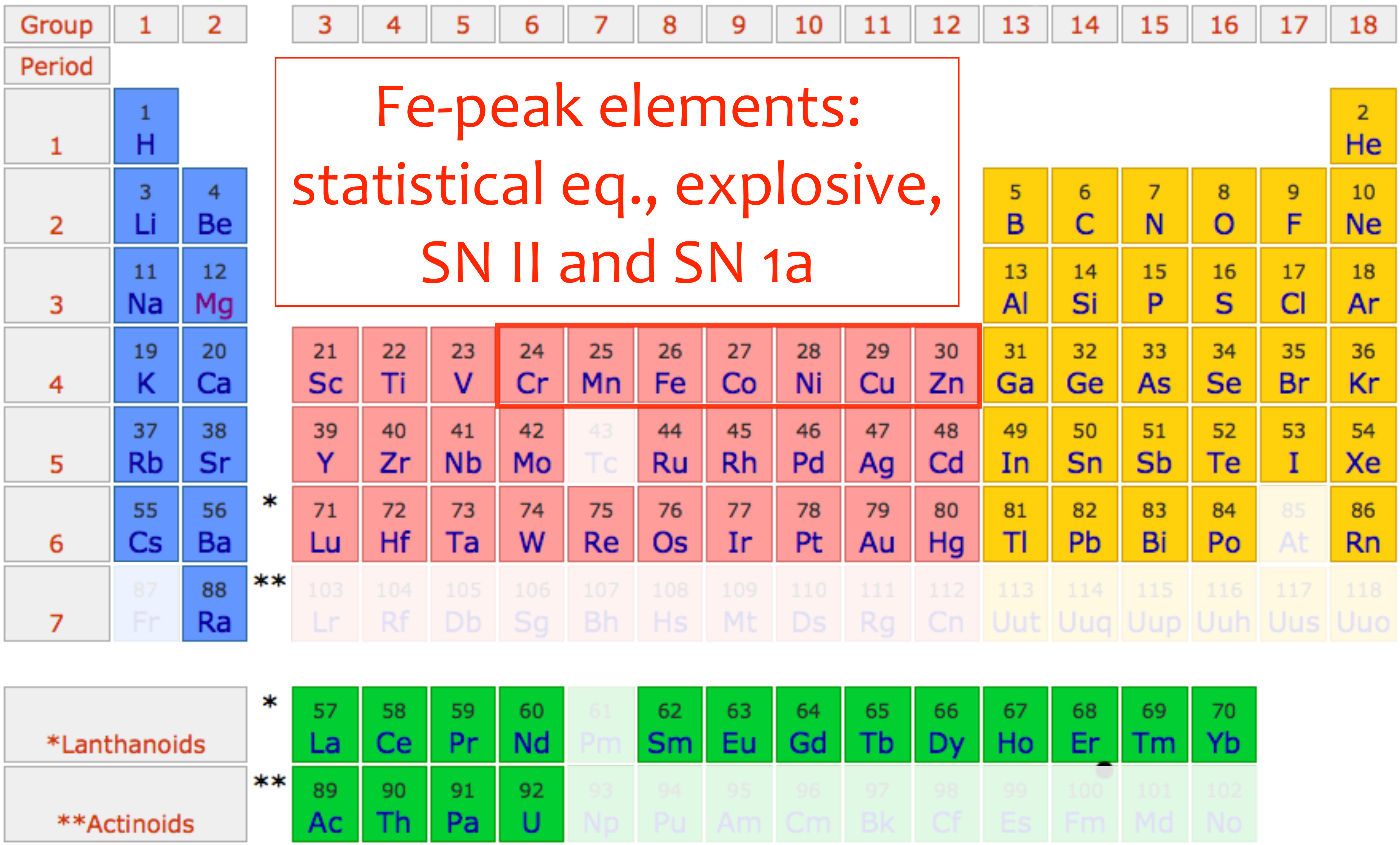
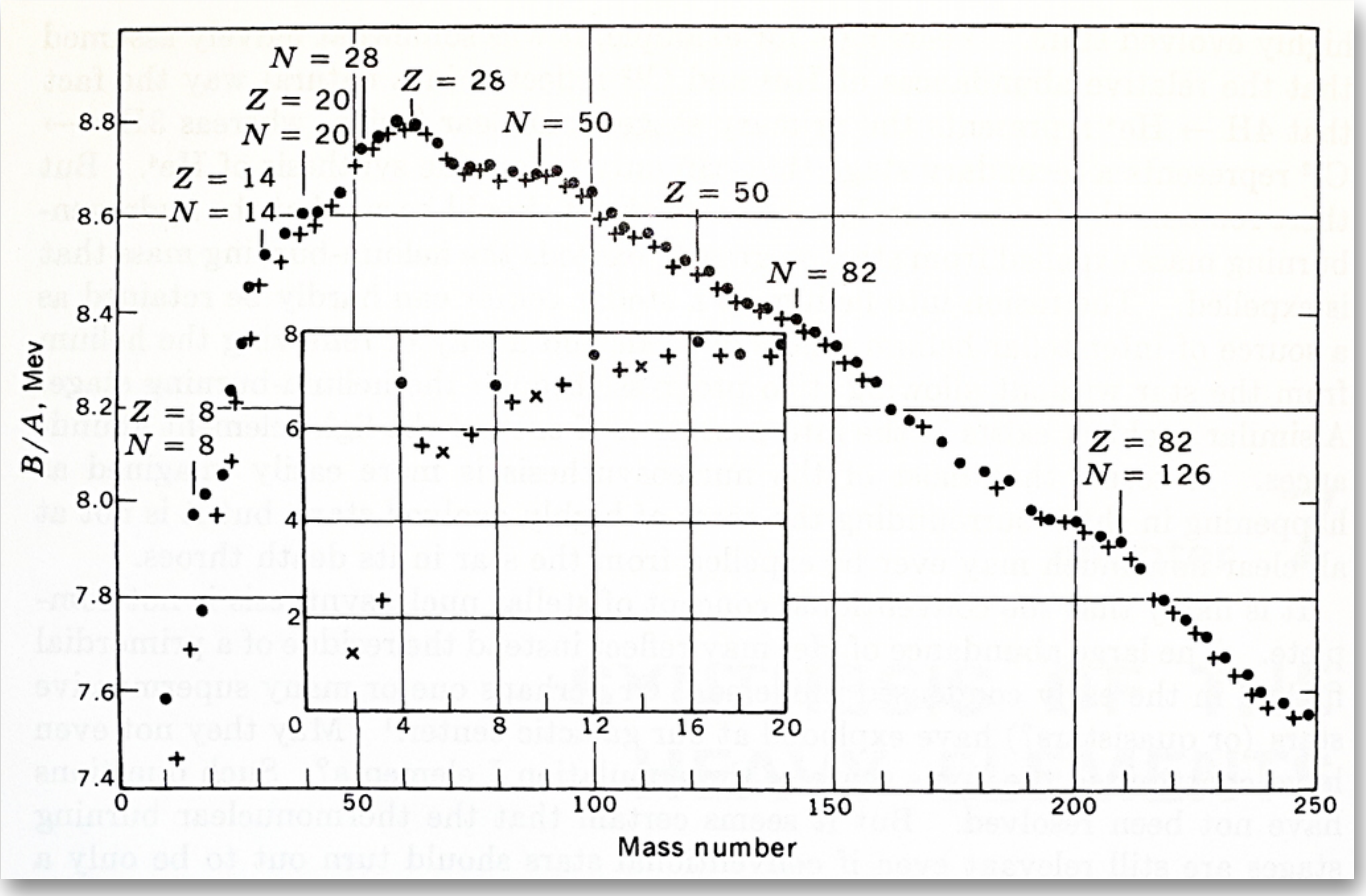
Fe-peak elements: statistical eq., explosive, SN II and SN 1a



Heavy Metal: Iron peak elements

- elements between Z=24 (Cr) and Z=30 (Zn) are usually called "iron peak" elements as a reference to the peak in the nuclear binding energy at ^{56}Fe
- no fusion reaction is exothermic past Fe, fissions become exothermic instead

- around the peak the abundances are determined by statistical equilibrium of n- and p- captures through "nuclear Saha equations"



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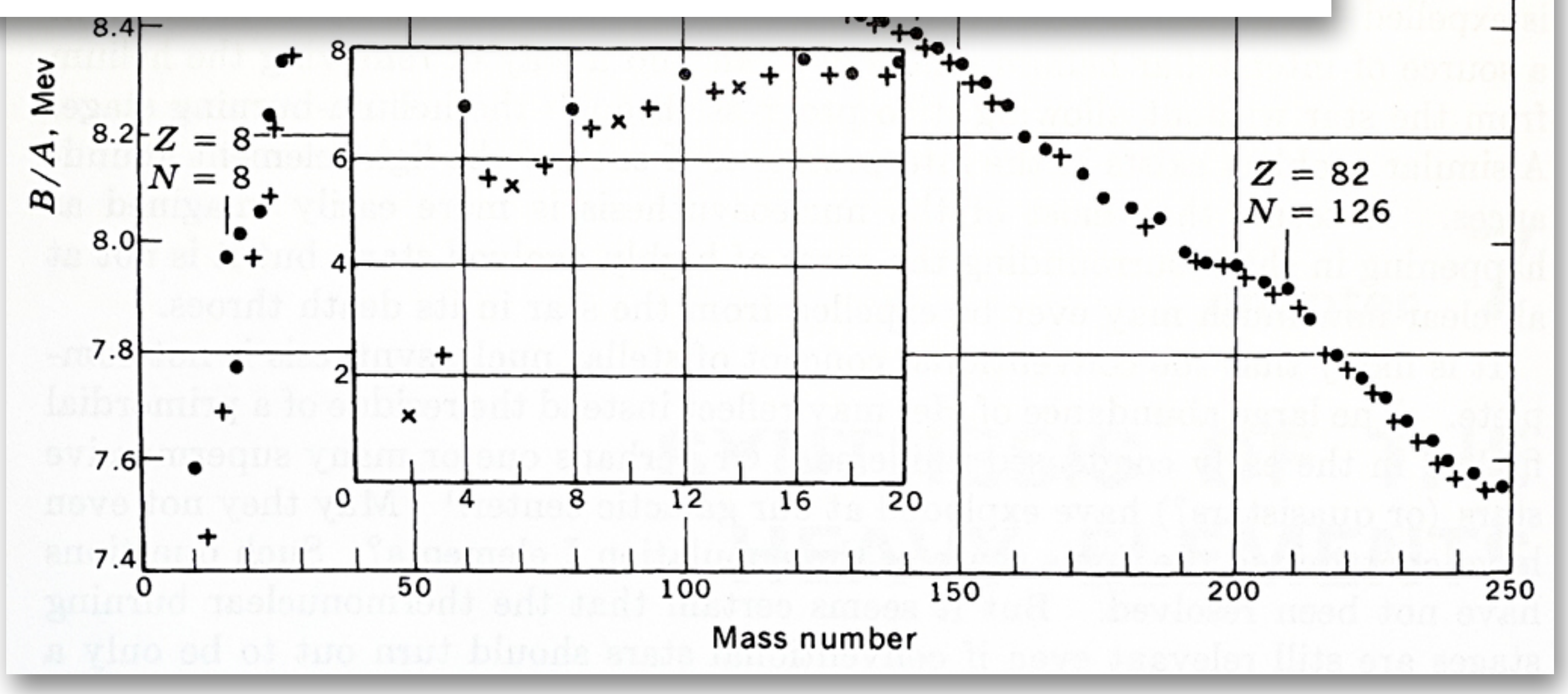
$$\frac{N\left(A-1,Z\right)n_n}{N\left(A,Z\right)} = \frac{2G\left(A-1,Z\right)}{G\left(A,Z\right)}\frac{\left(2\pi\mu kT\right)^{3/2}}{h^3}\mathrm{e}^{-\frac{Q_n}{kT}}$$

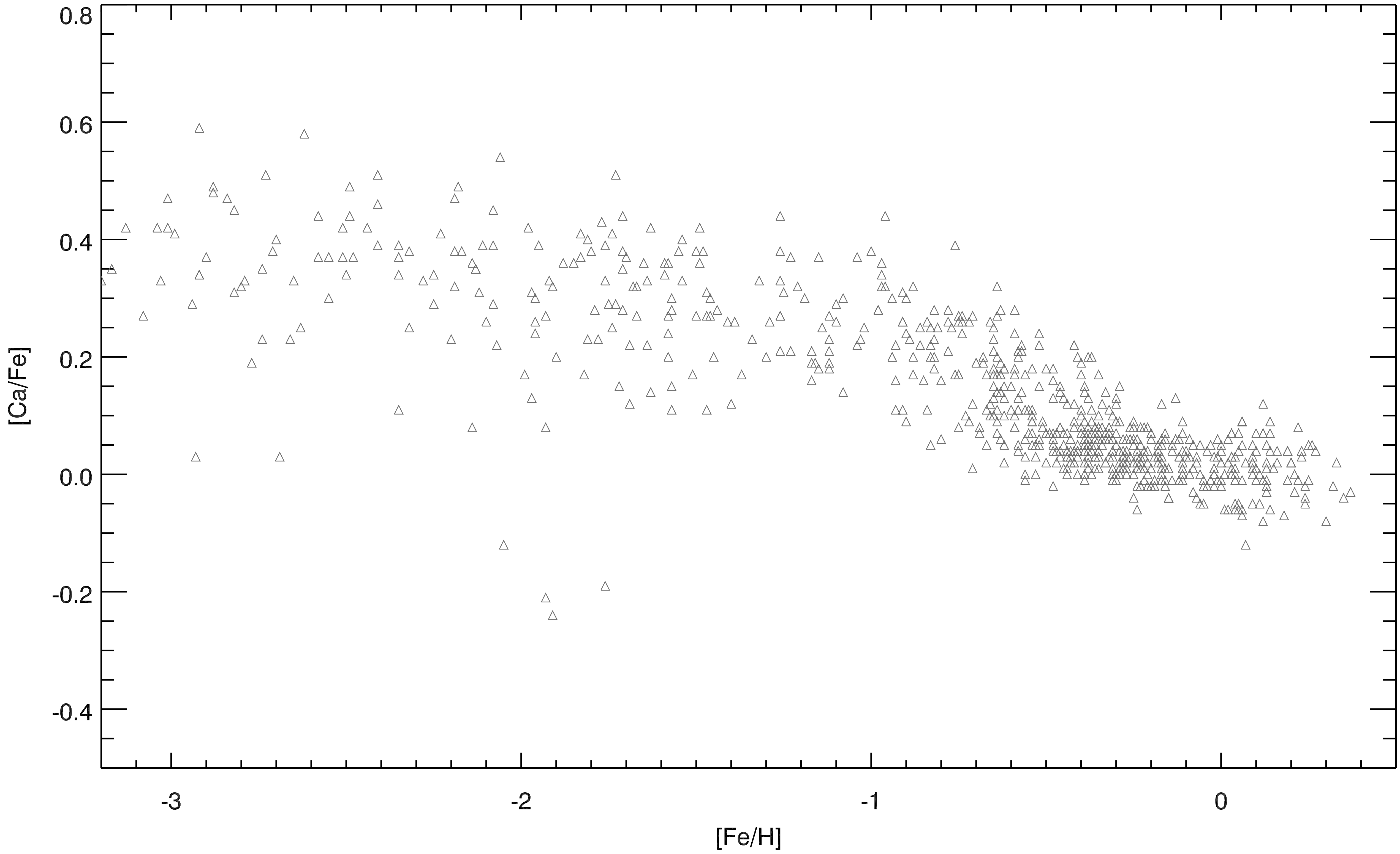
- aro… a b… determined by statistical equilibrium of n- and p- captures through "nuclear Saha equations"



Iron peak elements

- Fe-peak elements are produced **both by SN II and SN 1a.**
- **Explosive environments** are required due to the very high temperature (~3*10^9K) and (almost) endothermic nature of reactions
- Again, **delivery is important:** Sn 1a are totally destroyed, thus efficiently delivering large fractions of Fe-peak to the ISM…
- … while SN II are producing most Fe-peak in the inner core, where i) they get photodisintegrated and ii) they remain under the fall-back, locked in the compact remain…
- …but explosive nucleosynthesis dumps large amounts of energy into producing **many solar masses of ^{56}Ni,** whose decay into ^{56}Fe powers most of the SN light curve.
- Having both **prompt** and **delayed** sources, Fe-peak elements show a complex interplay of abundance with α-elements

… that α-enhancement thing…



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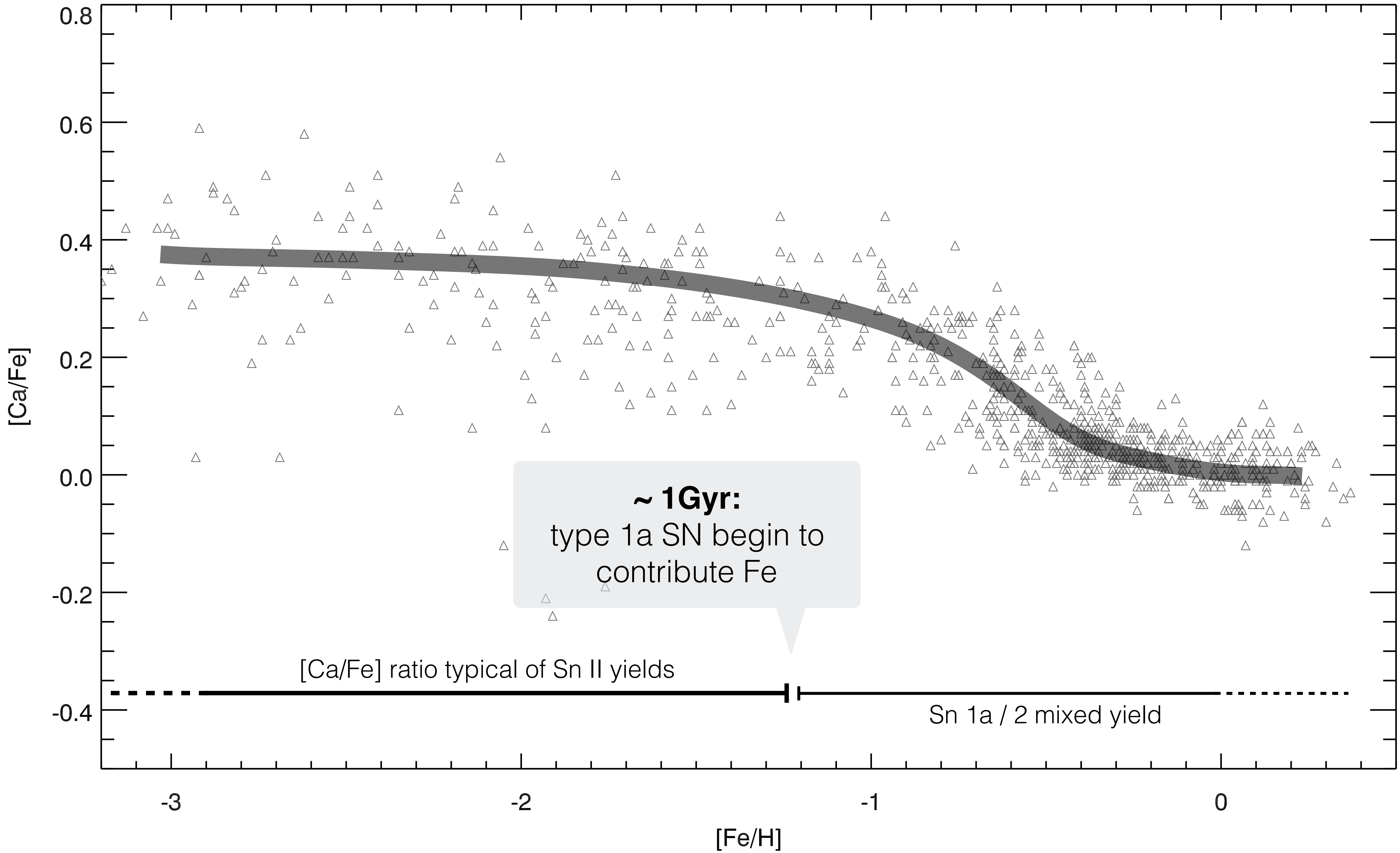

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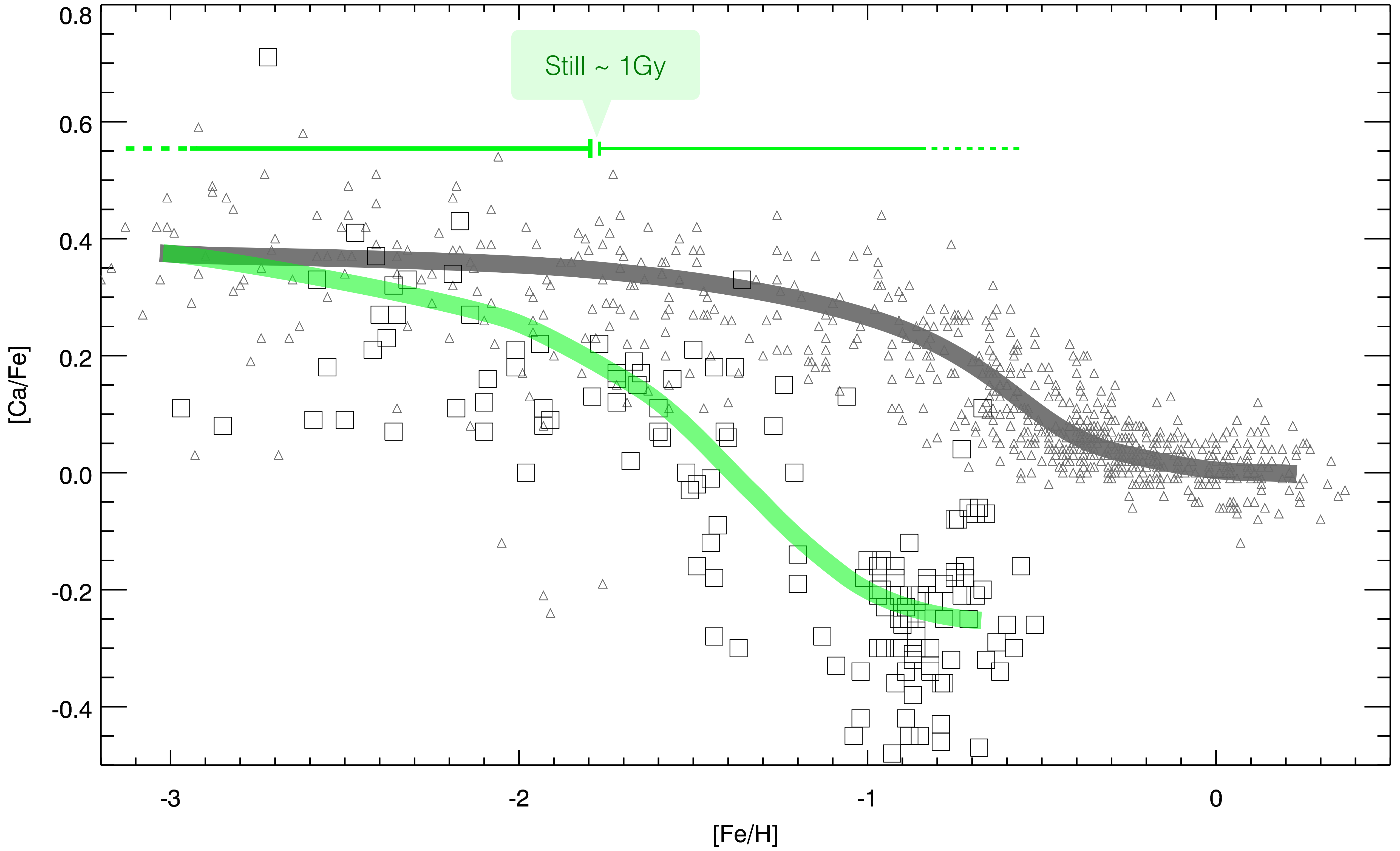

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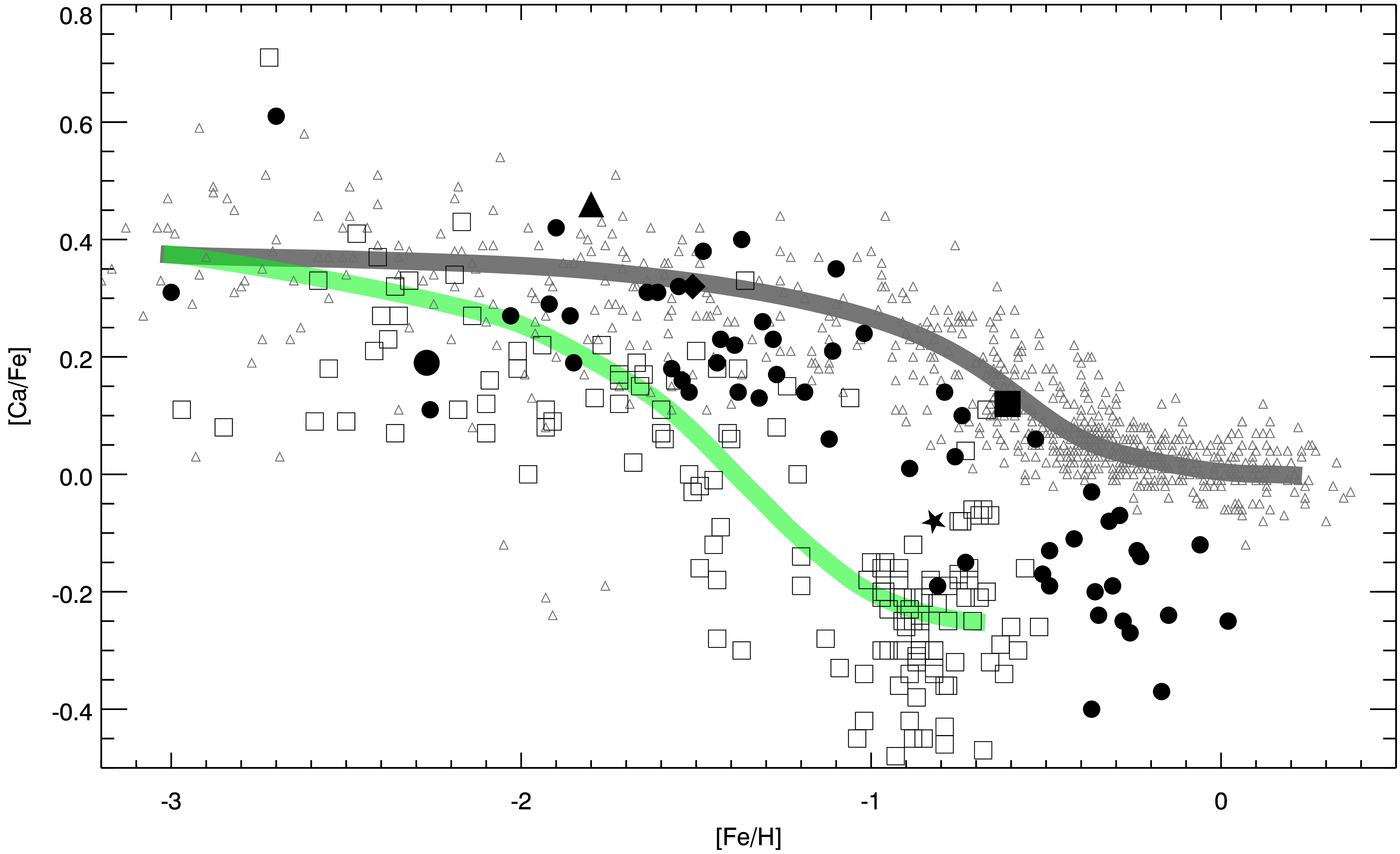

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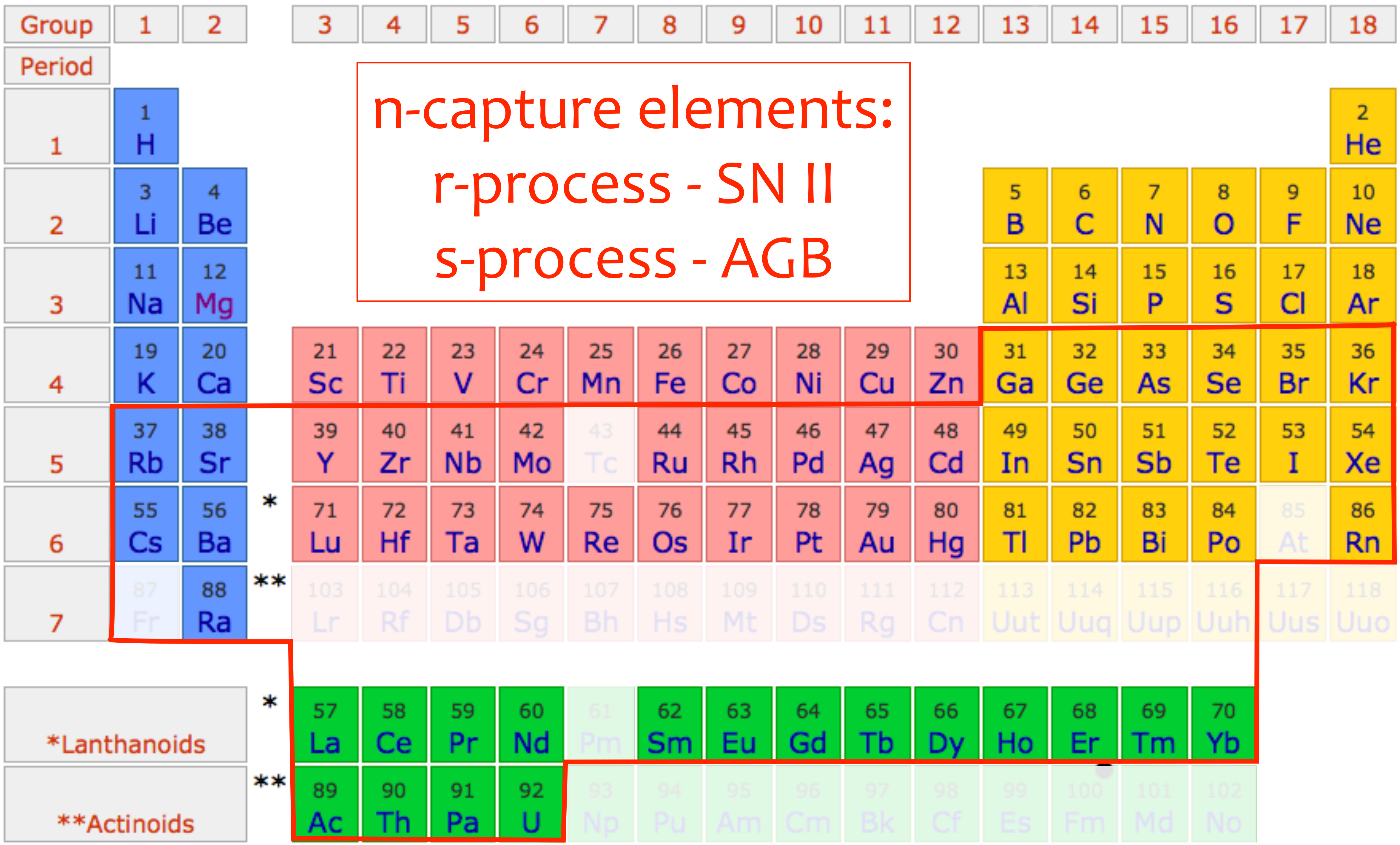

n-capture elements:
r-process - SN II
s-process - AGB
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Godzilla stuff: n-capture elements

(those that are either really expensive, or you hear about only when a nuclear plant blows off, or both)

- Statistical equilibrium calculation foresee **extremely low abundances** for elements past Zn, so non-equilibrium mechanism is required
- Due to insensitivity to Coulomb barrier, **n-capture is efficient** also at low energies for heavy nuclei.
- PROBLEM: you need a high density of neutrons, i.e. you need a **neutron source**.

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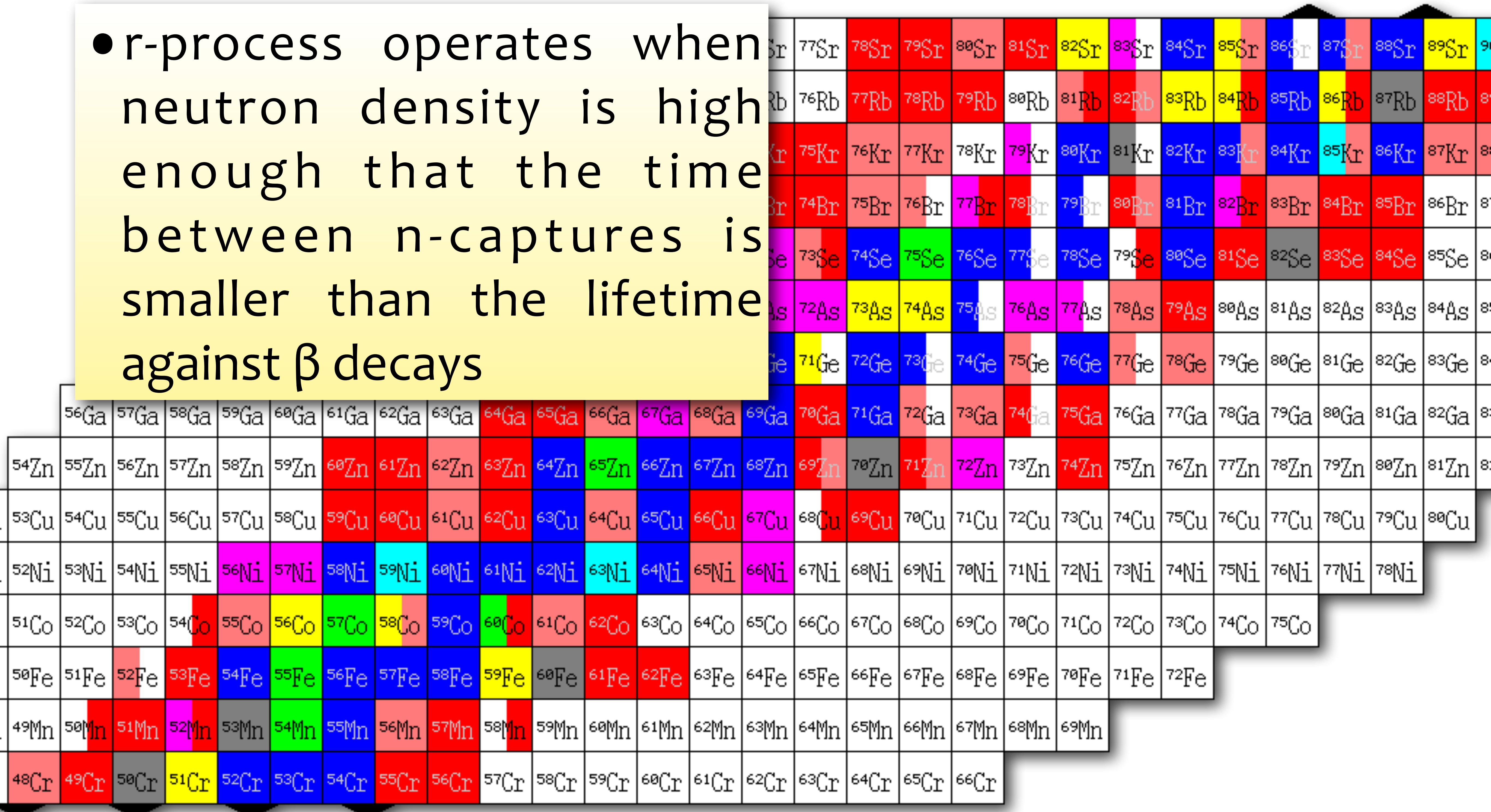
Godzilla stuff: n-capture elements

- Two domains, divided by the ratio between the **timescale of n-capture vs. timescale of β-decays.**
- n-captures are **faster: r-process** (rapid), many neutron captures happen before any can β-decay: $T>10^9$K $n_n>10^{22}cm^{-3}$. Timescale for capture is below the second.
- β-decays are faster: **s-process** (slow), every n captured decays before another happens. Timescale of capture is years, $T\sim3*10^8$K, $n_n\sim3*10^8cm^{-3}$.

Rapid capture: r-process

- r-process operates when neutron density is high enough that the time between n-captures is smaller than the lifetime against β decays



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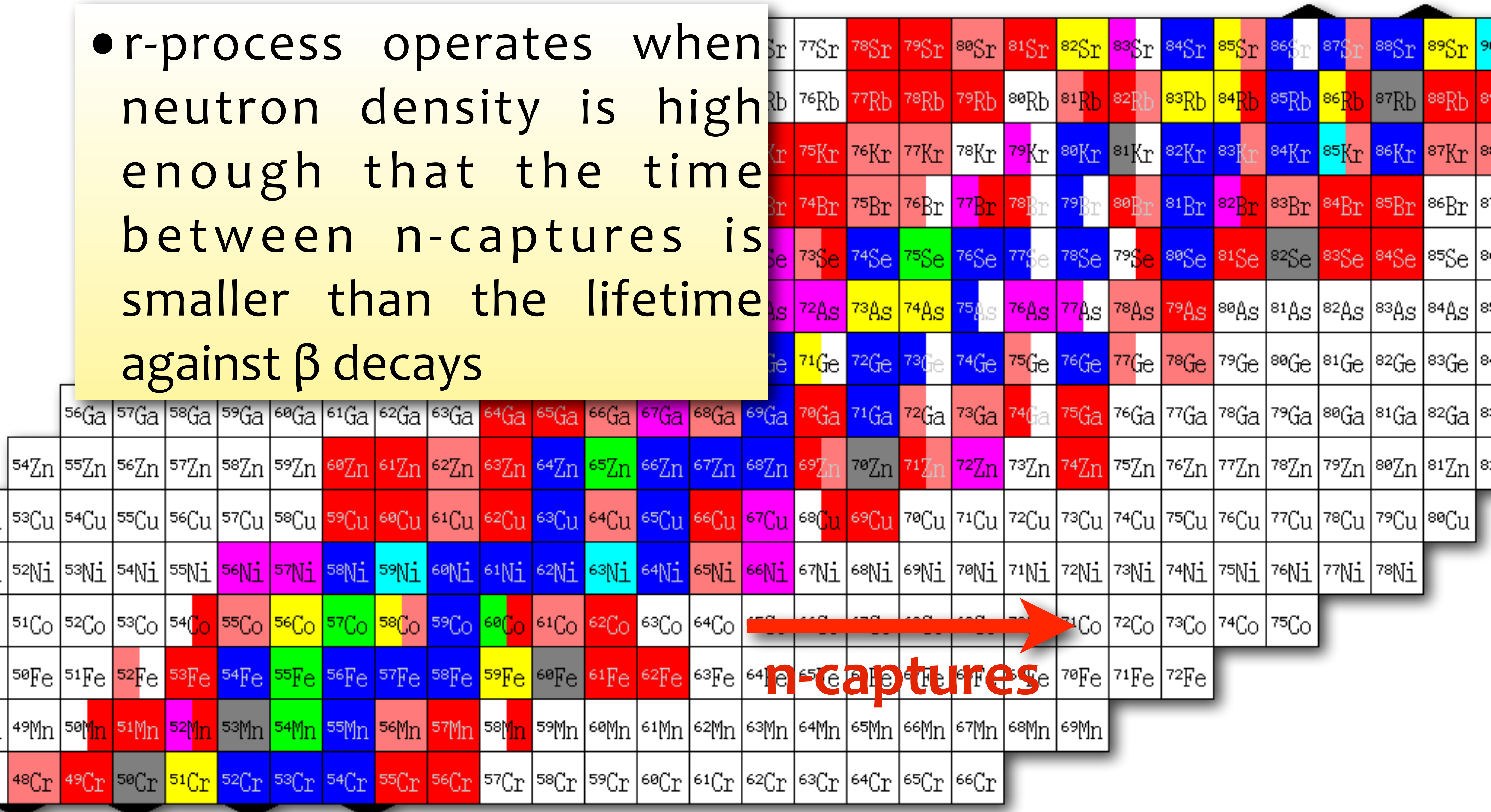

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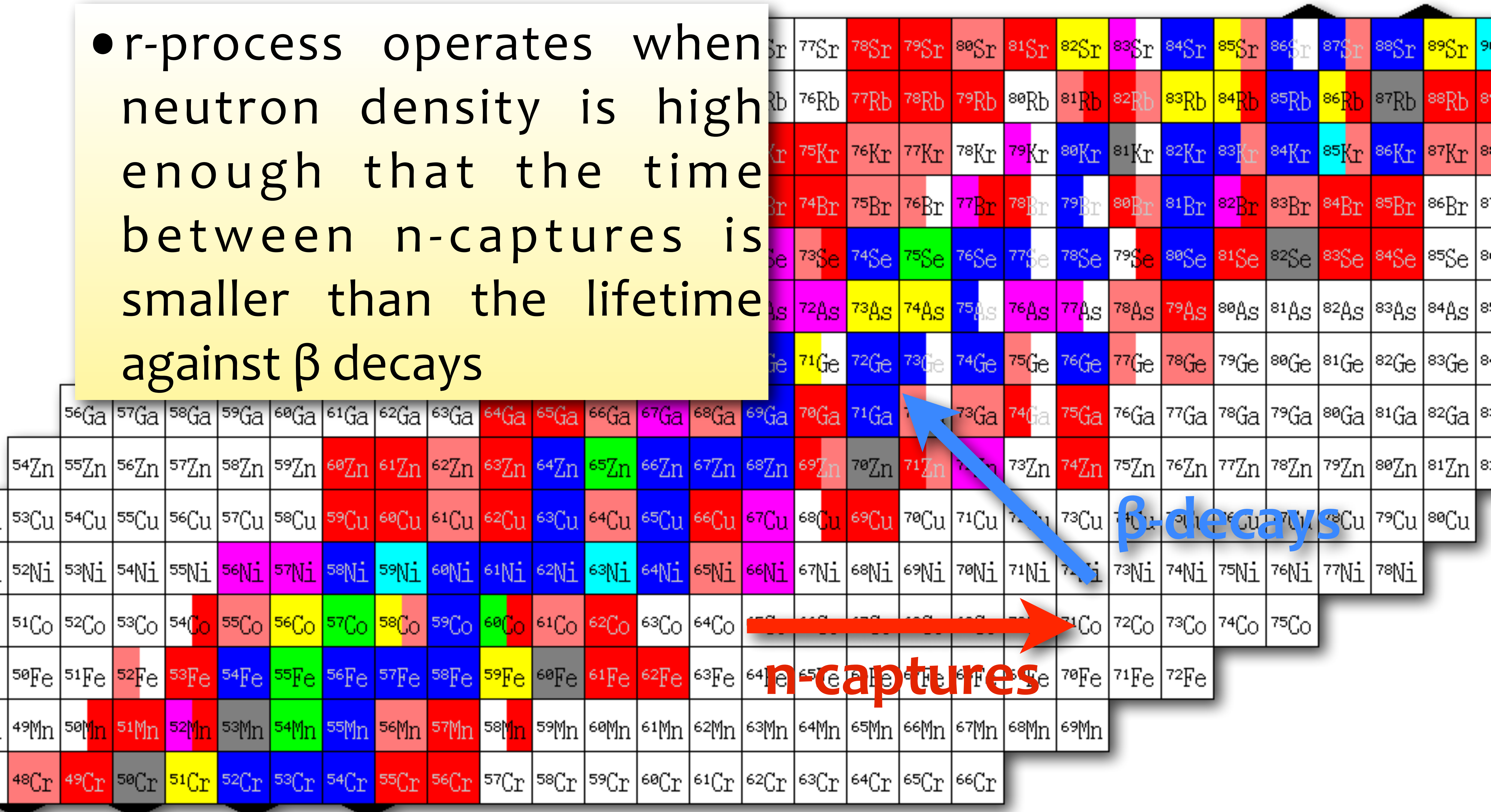
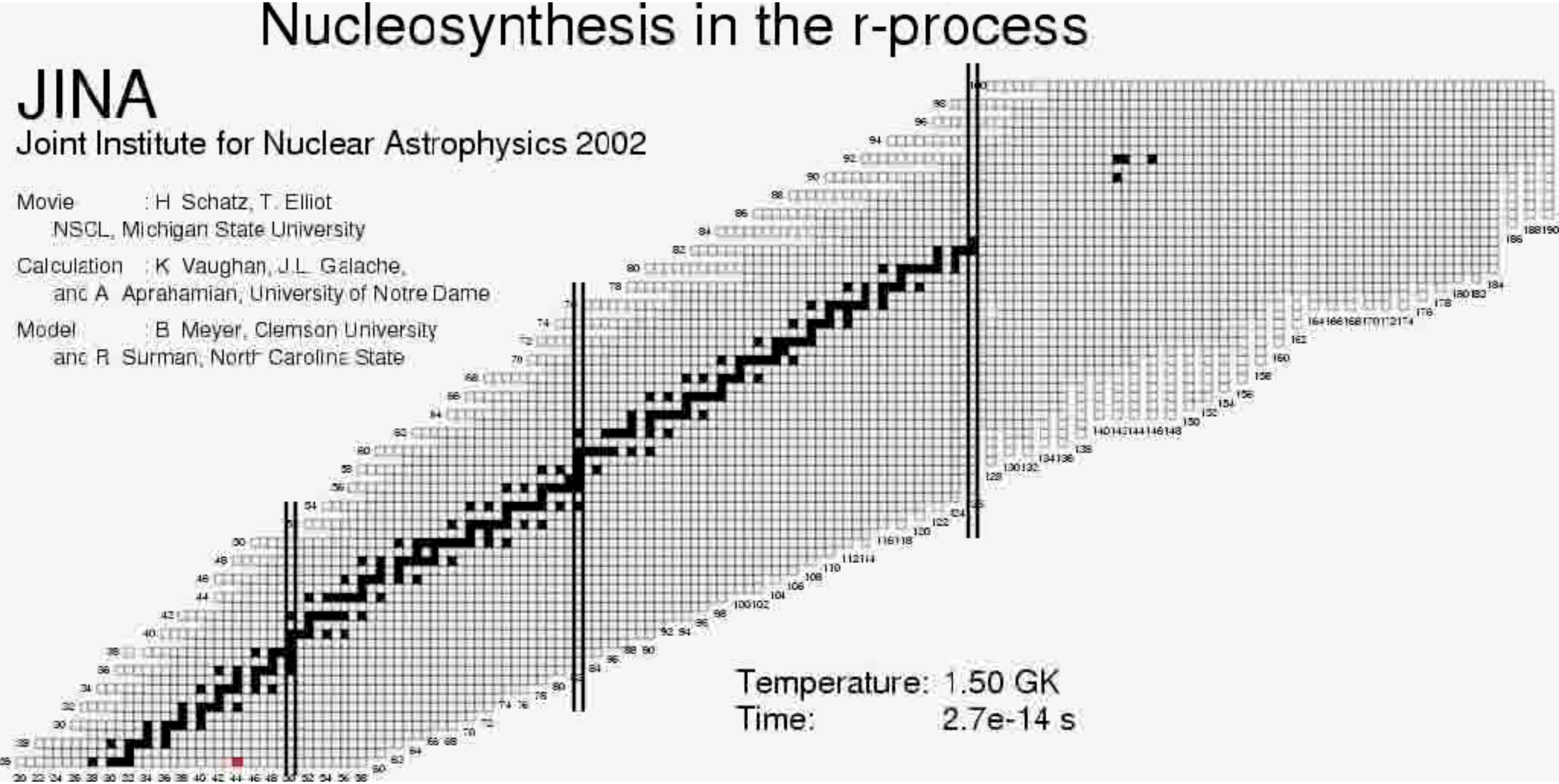


r-process LIVE!!



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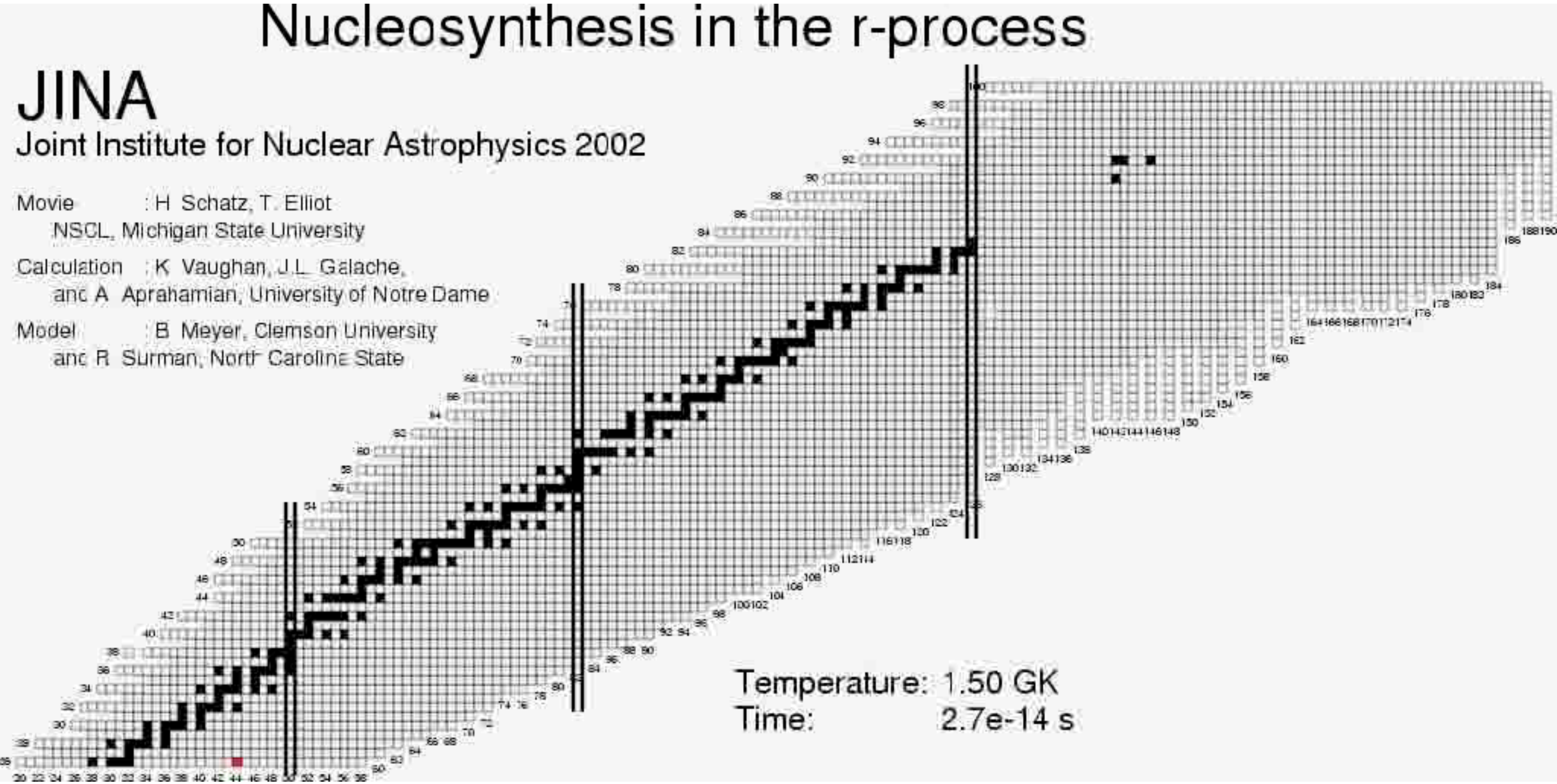
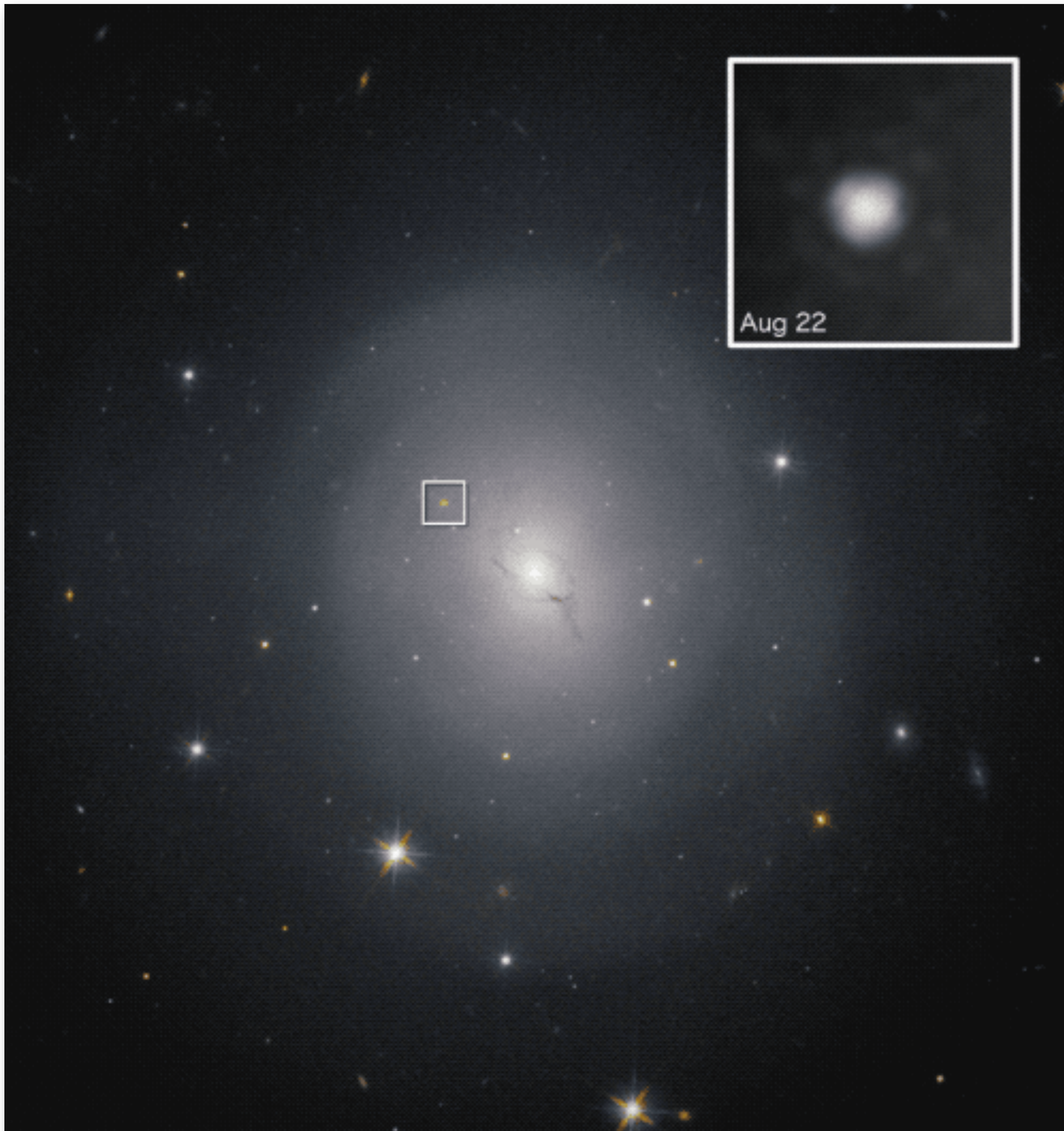


r-process is cool…

- r-process forms isotopes “below” the “stability valley” than subsequently β-decay again into stable ones <u>always coming from higher-A, lower-Z</u>
- most β-decay half life times ~hours, days: is a very fast process, instantaneous by astrophysical standards
- very high neutron density is required
- happens during SNII explosions, n produced by low-Z burnings…
- … or (more likely?) NS-NS mergers

r-process is cool…



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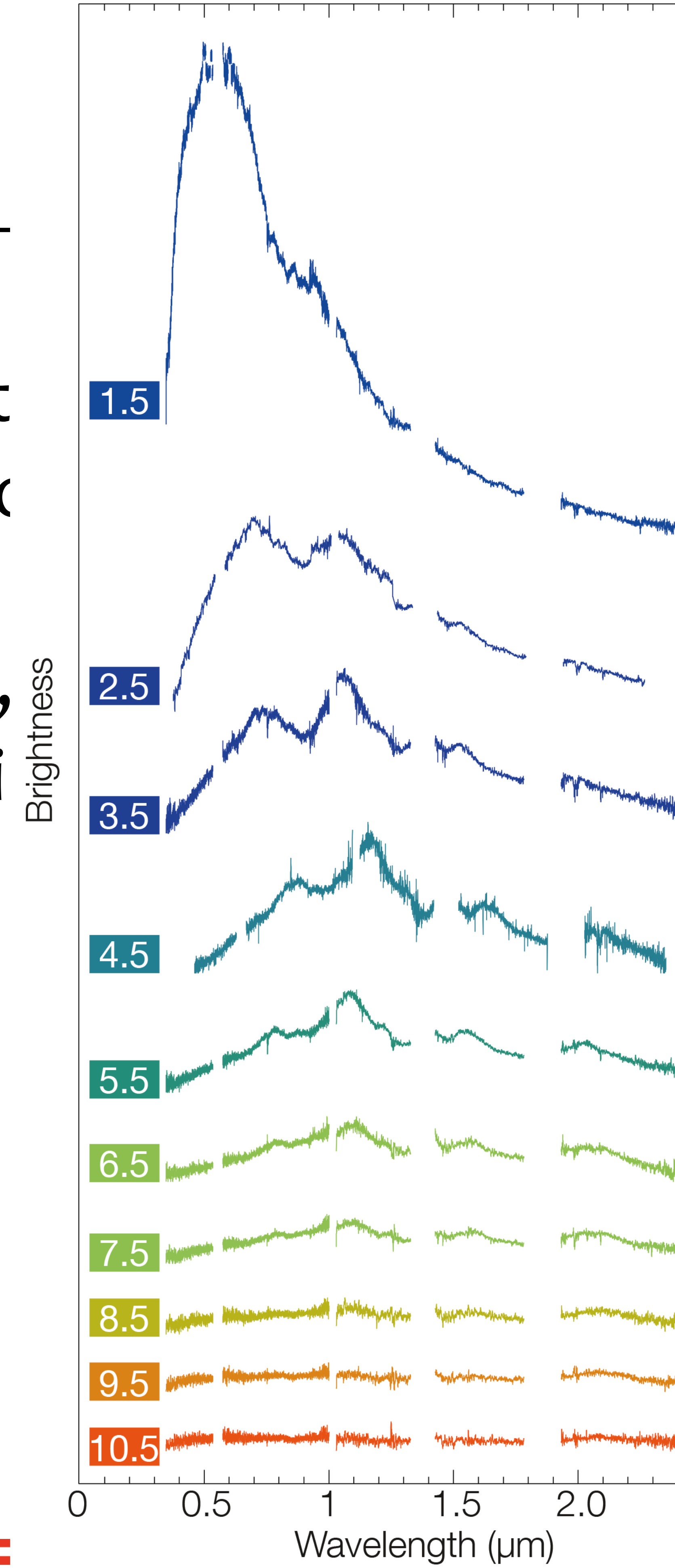
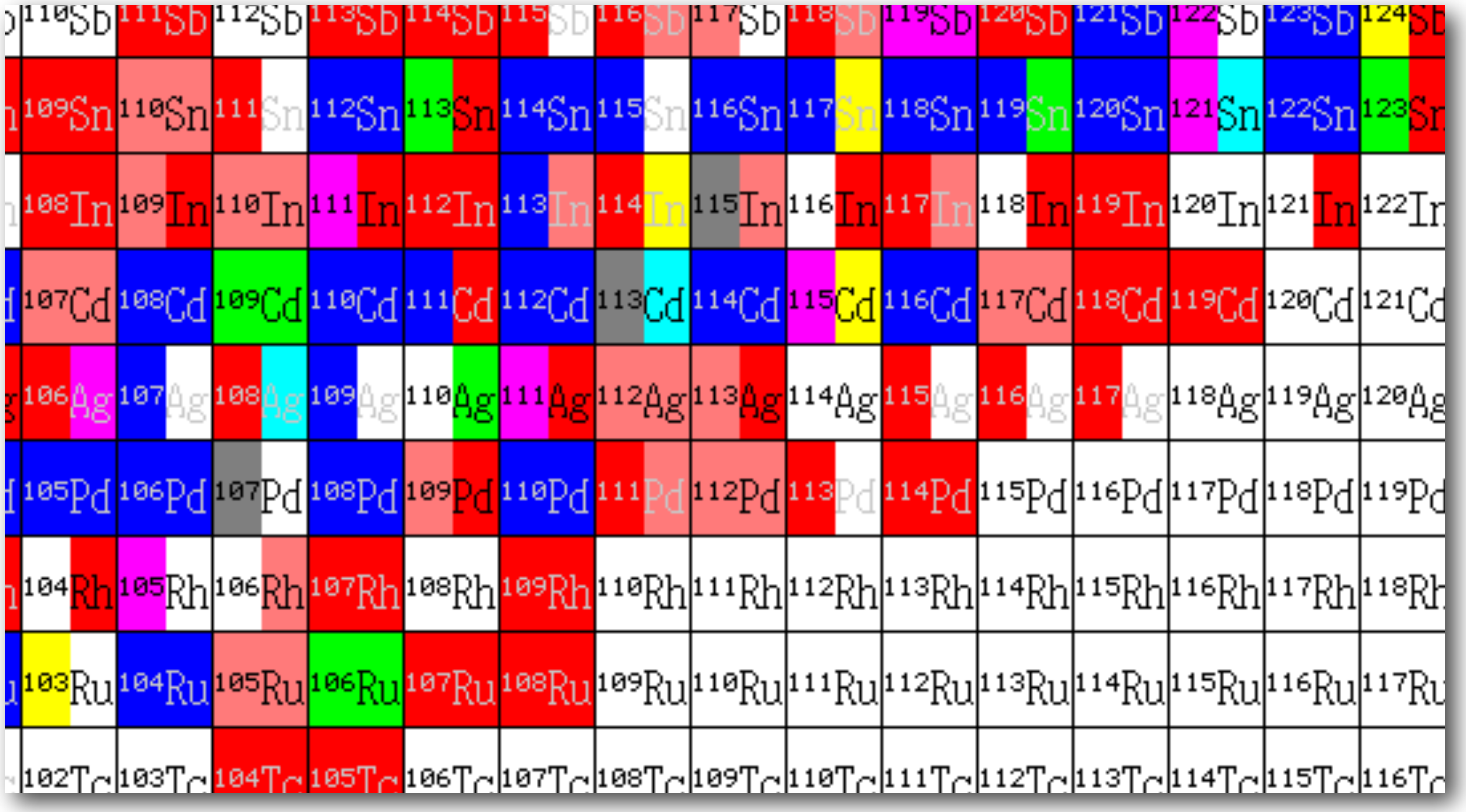
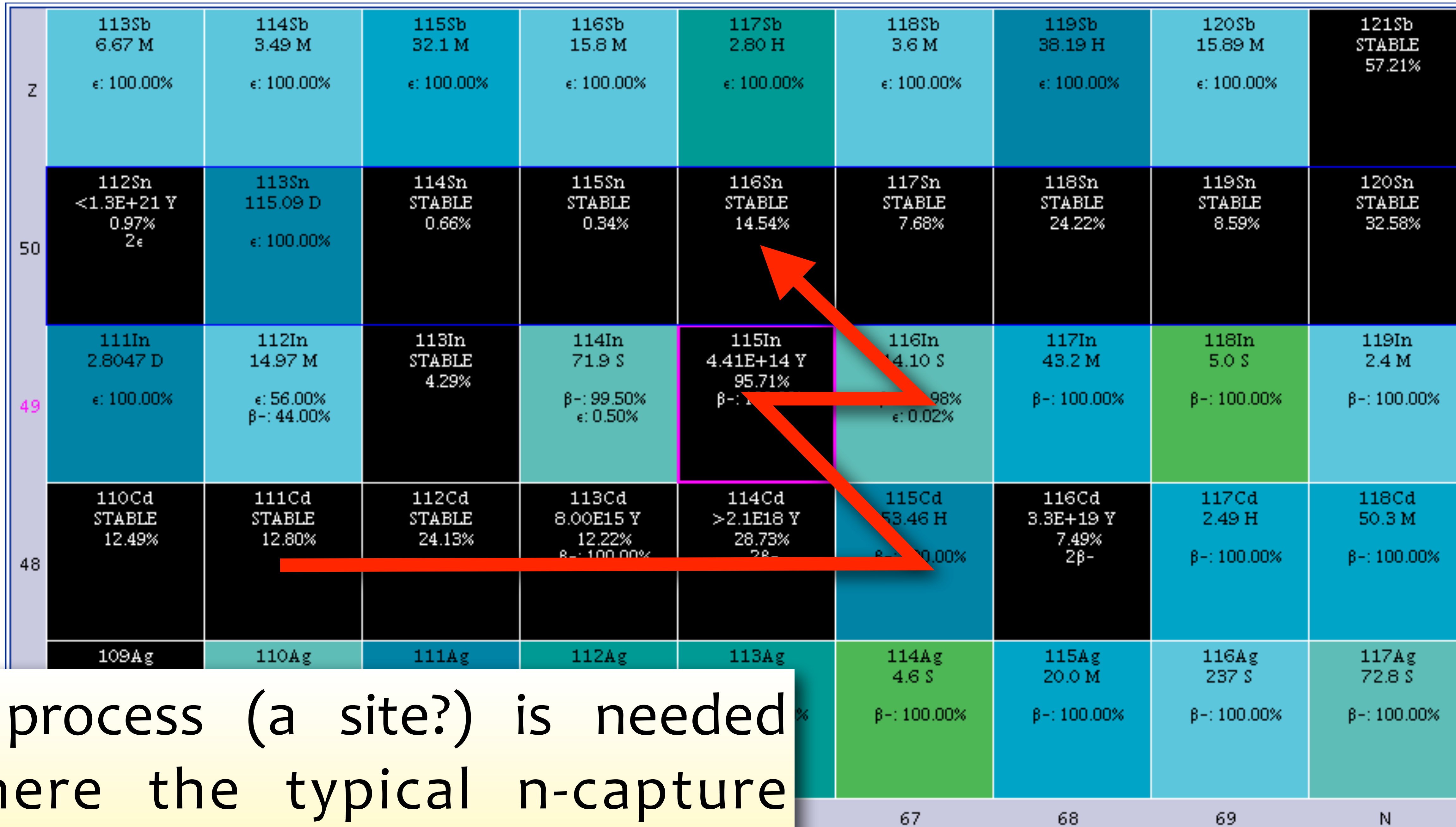


… but it’s not enough: shielding.



- Some stable isotopes, such as ^{116}Sn, cannot be produced by r-process because the β-decay path is blocked by a stable isotope (^{116}Cd), and yet it is found in stars.

… but it’s not enough: shielding.



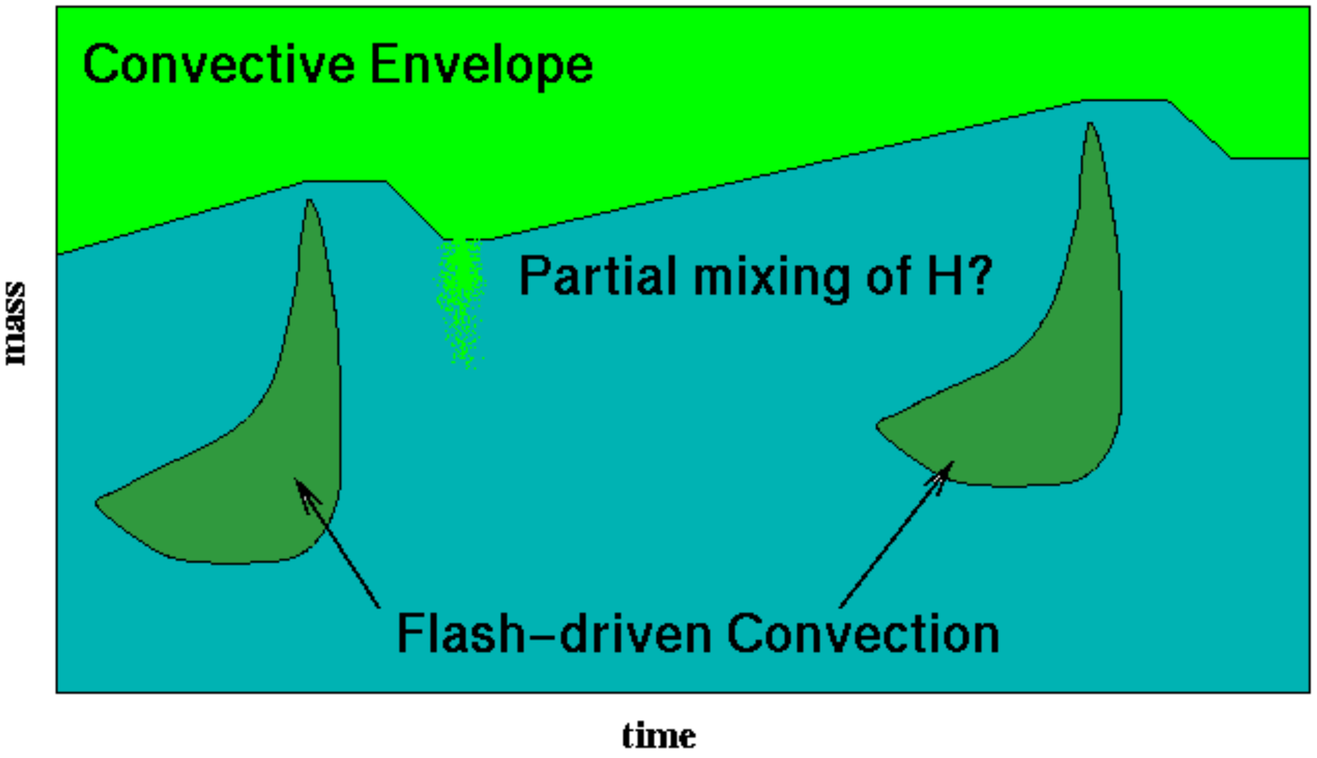
- A process (a site?) is needed where the typical n-capture timescale is much longer than the β decay timescale

the slow neutron capture: s-process

- if neutron density is low enough, or neutron source is turned on and off periodically over timescales of ~100-1000+ years, n-capture moves along the stability valley
- SN explosions are too fast
- Where can we imagine a neutron source that turns on and shuts off?

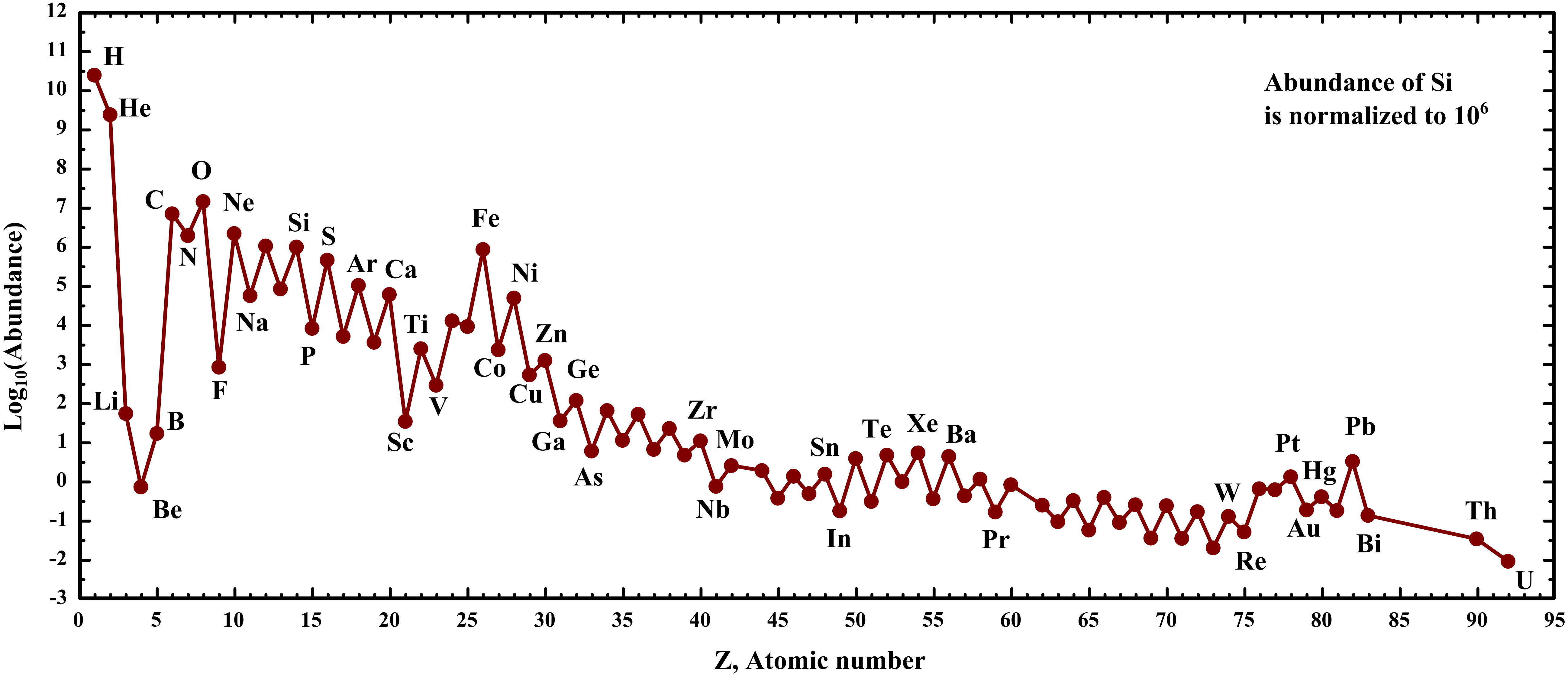
- Most likely, in AGB stars, where 13C mixed in the inter-pulse phase burns through

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



All together now

The solar composition



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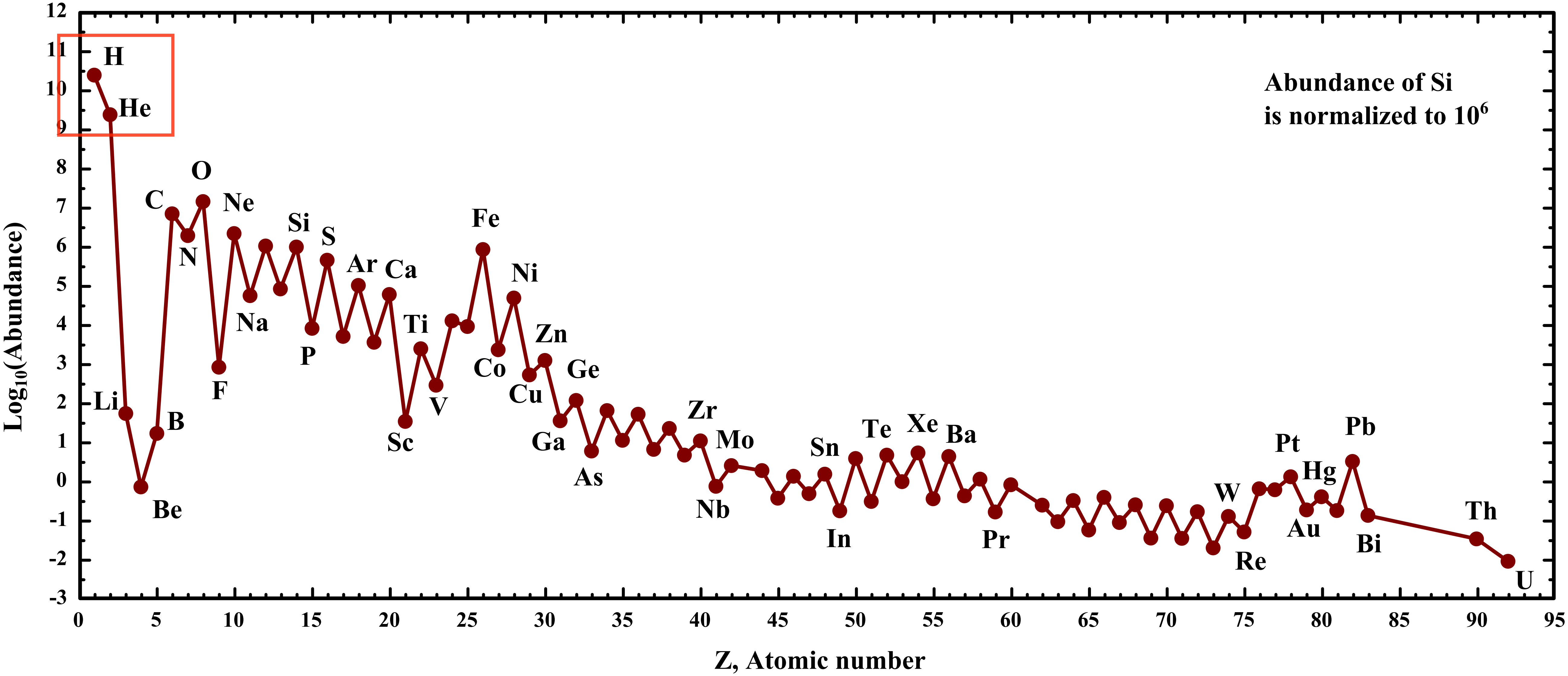

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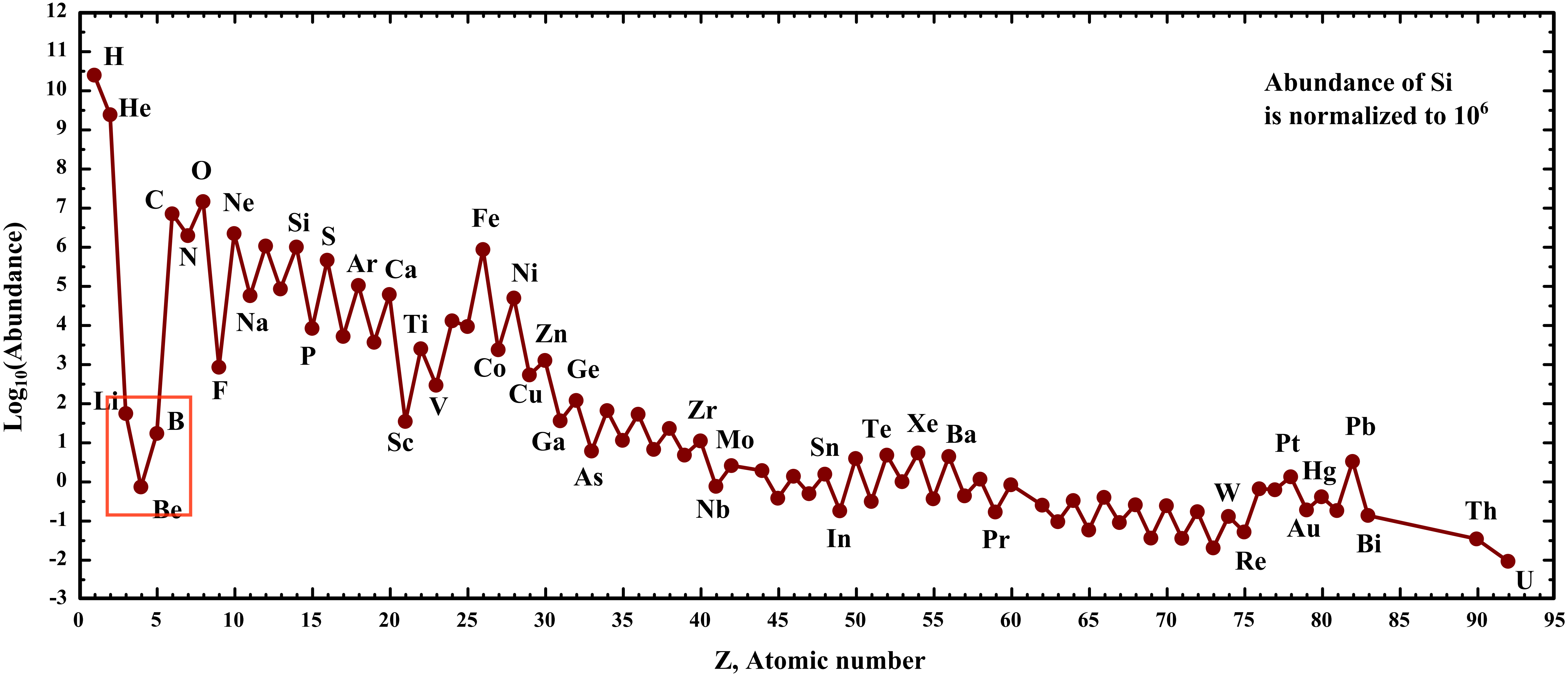

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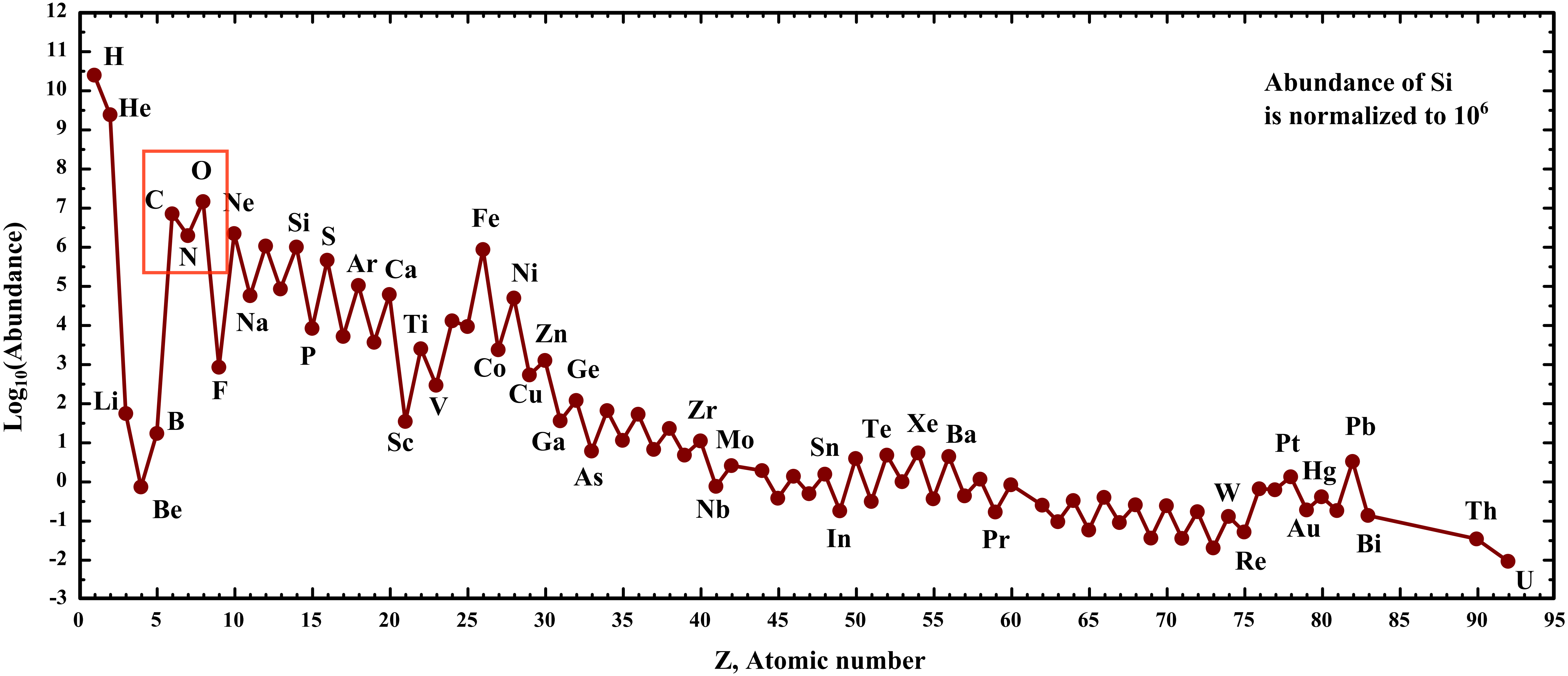

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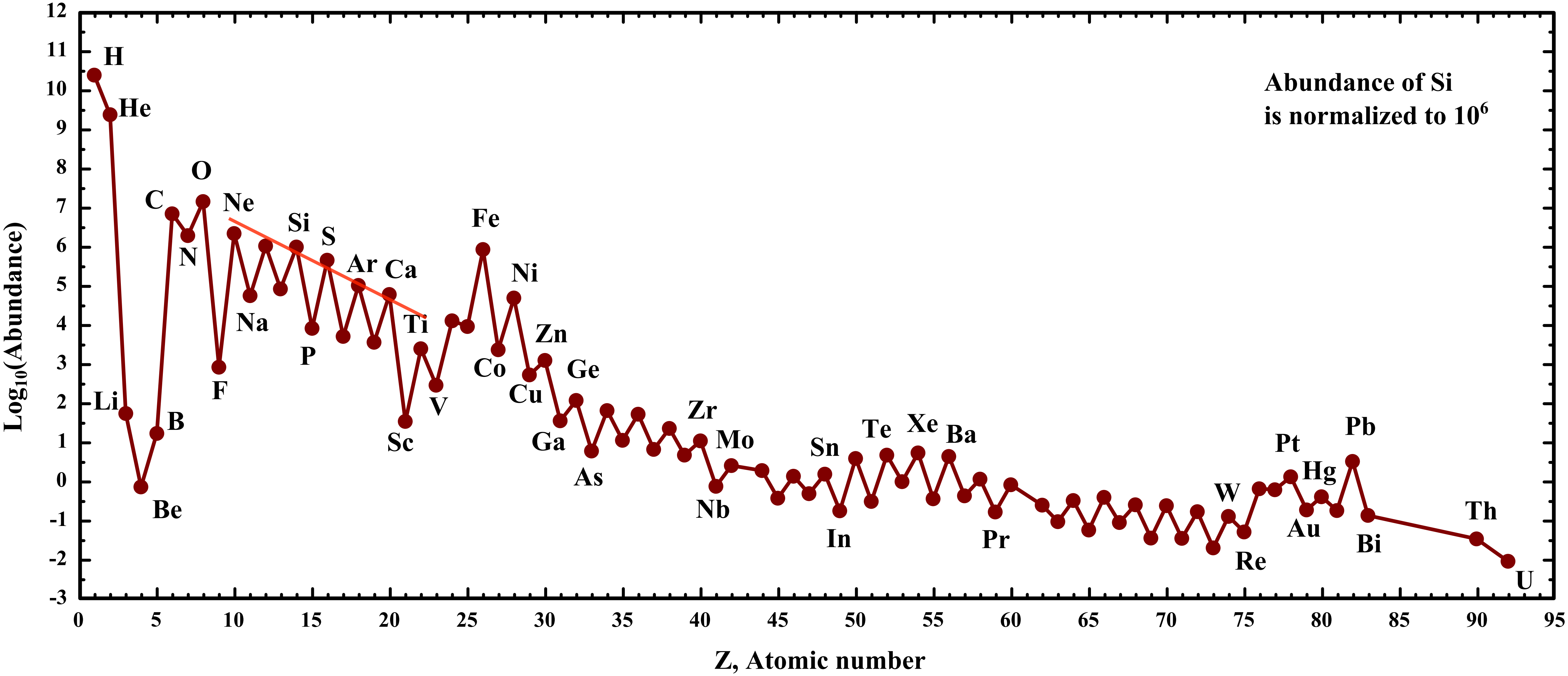

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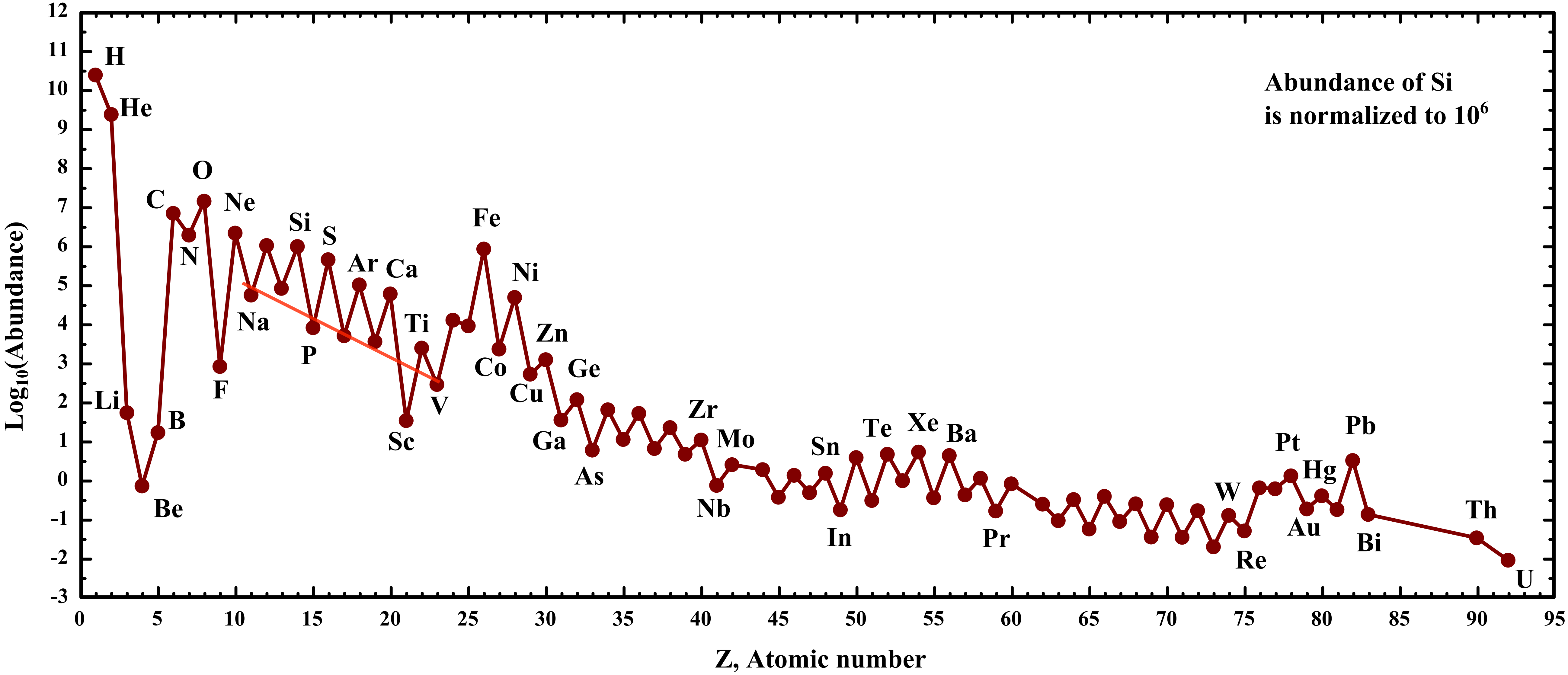

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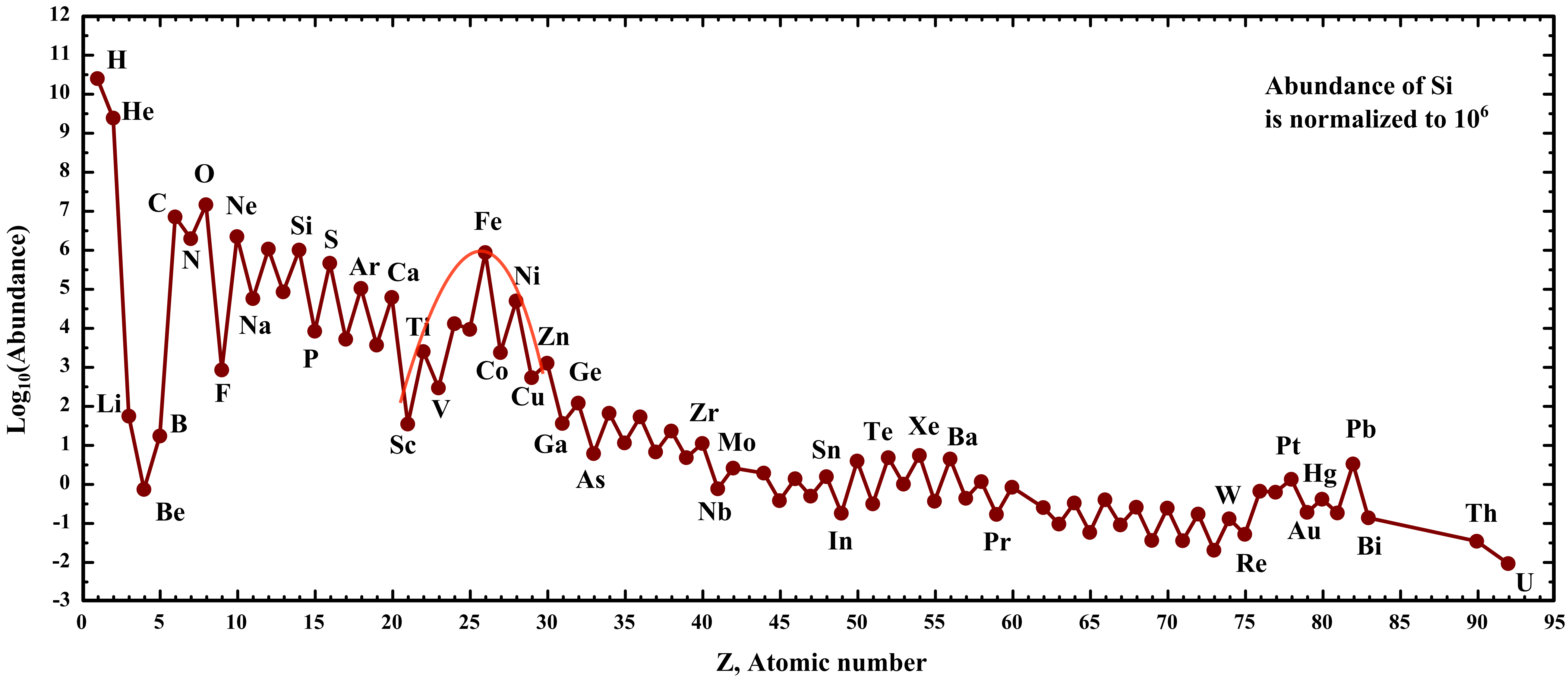

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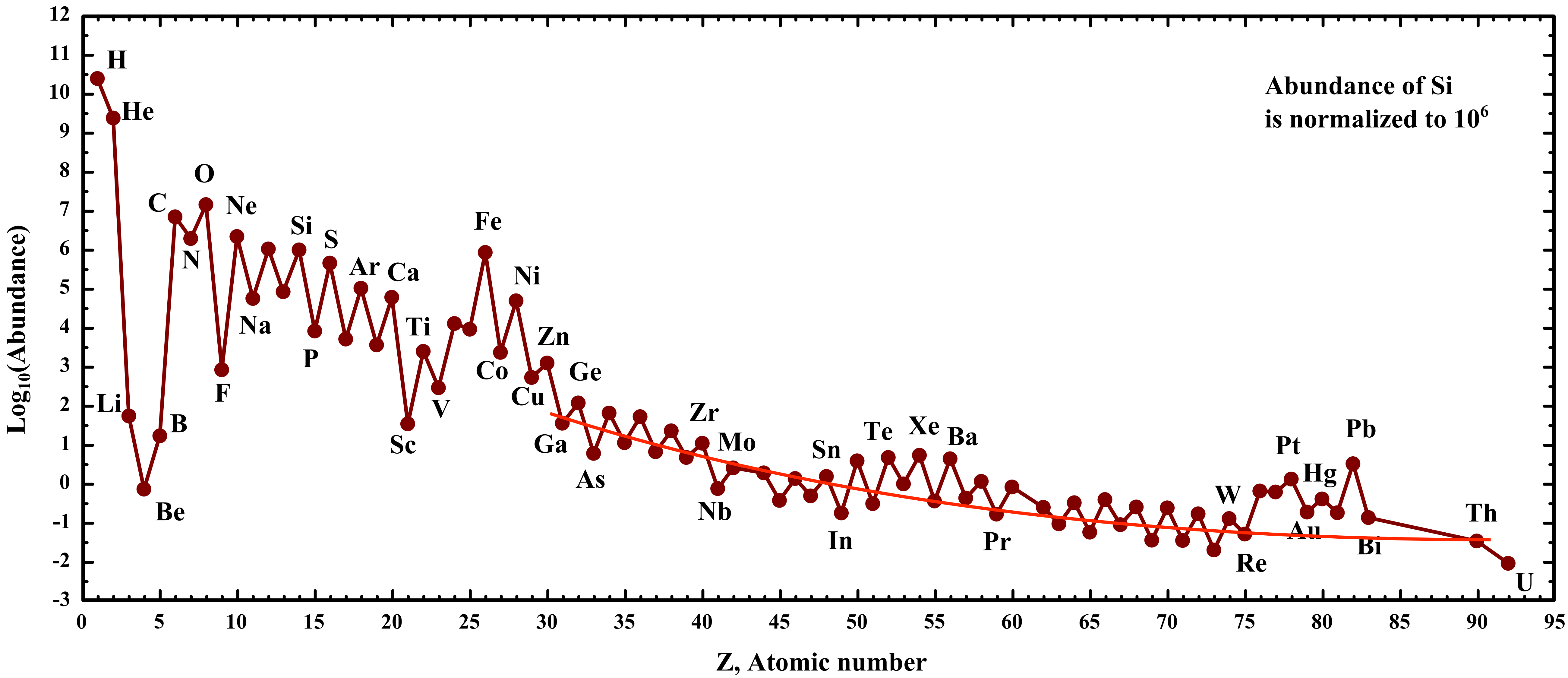

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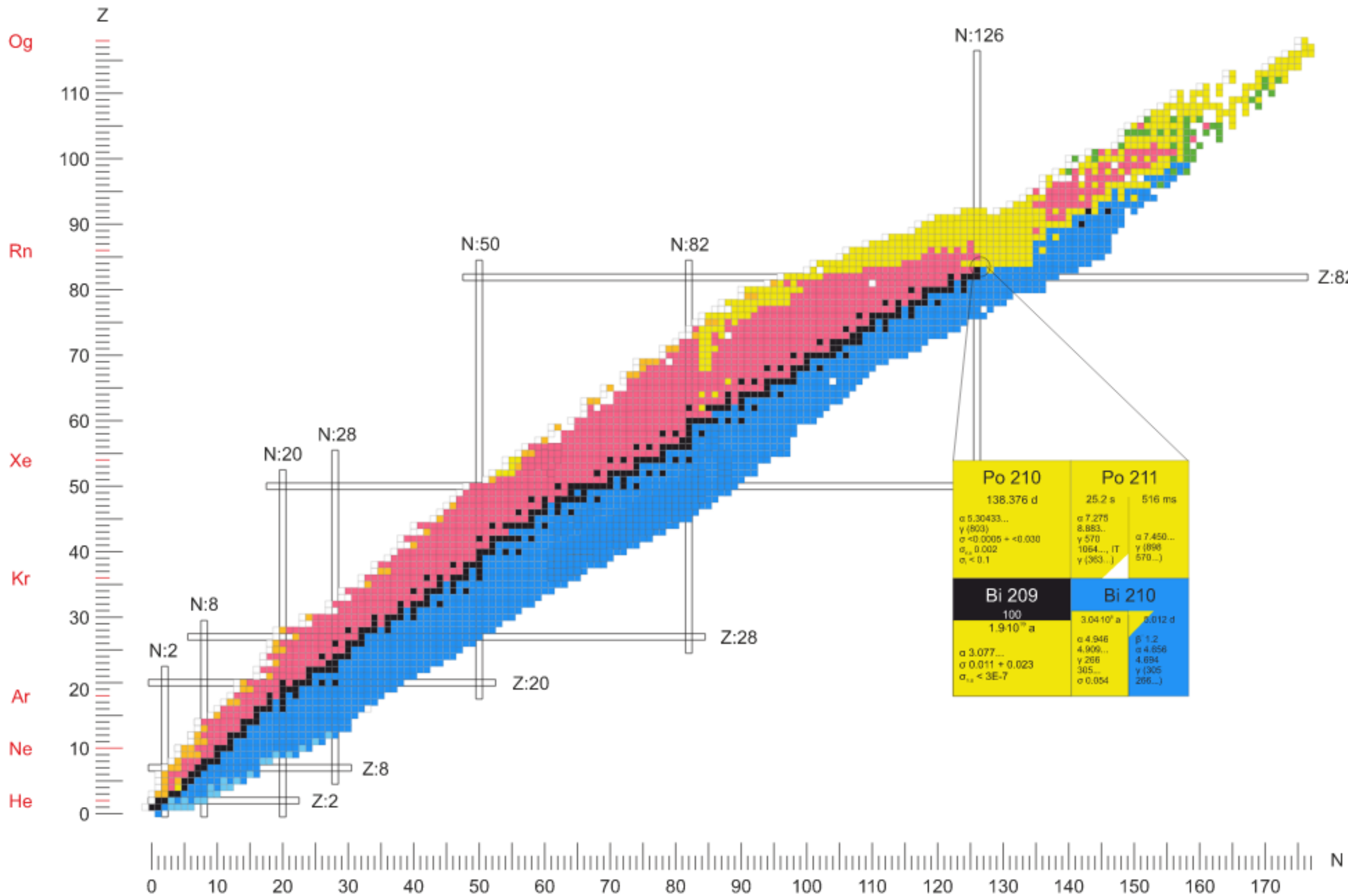

Closing remarks

- Stellar nucleosynthesis is a complex network of processes
- chemical patterns are the result of the interplay between stellar yields, environment, the timescales of galactic buildup, and its dynamical evolution
- This produces broadly similar trends, but also a large amount of fine grained information…
- … which is revealing as it is ambiguous.
- Generalizations are necessary, but dangerous: blunt concepts ("metallicity") have to be treated with caution.

Thank you! (again)