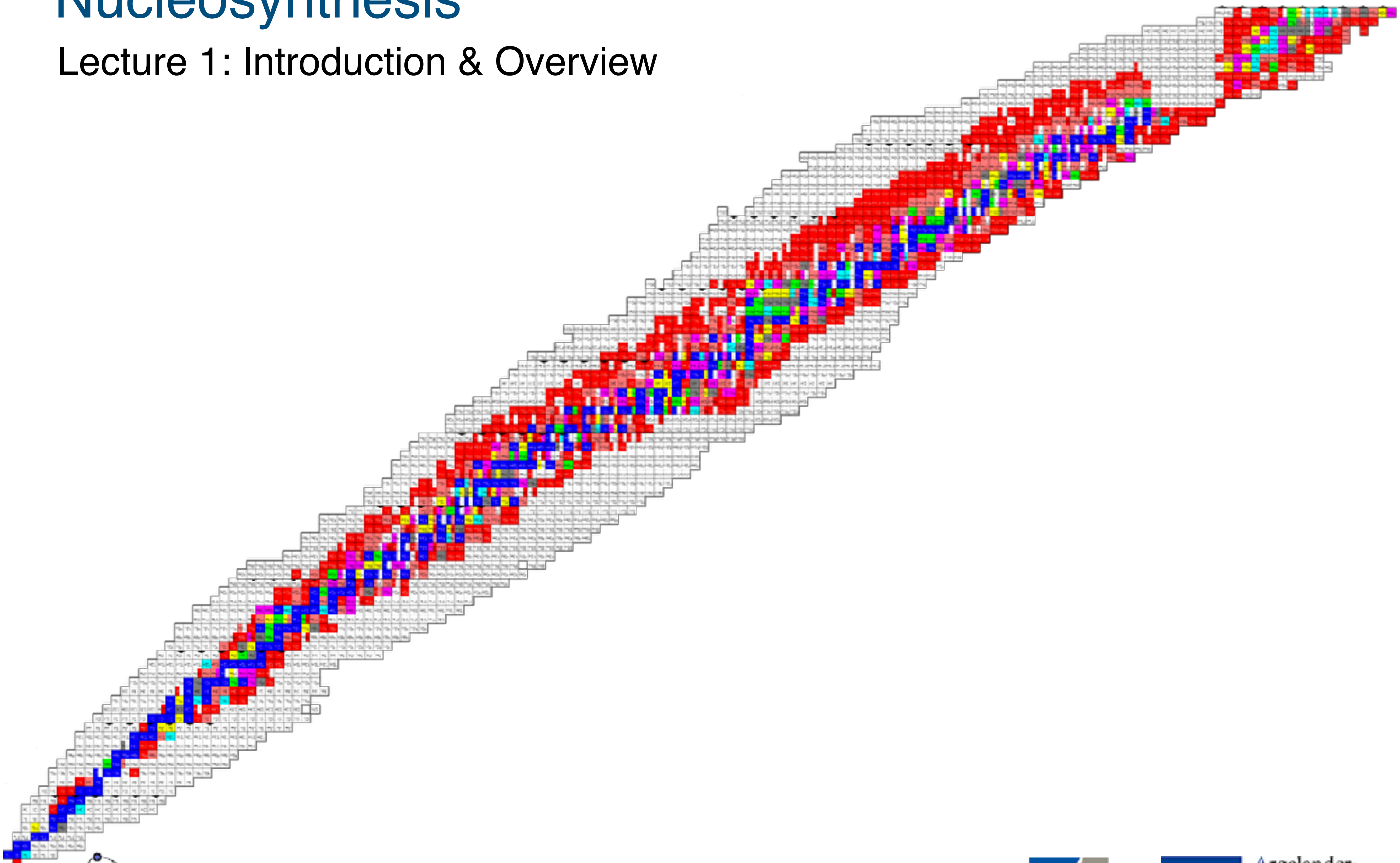
Nucleosynthesis

Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School of Physics and Astronomy

UNIVERSITÄT BONN

Argelander-Institut für Astronomie

Logistics

Nucleosynthesis

Course website	jantoniadis.github.io/nucleosynthesis
Lectures	John Antoniadis — office 3.015; janton@mpifr.de
Lab	David Aguilera Dena
	Ben Hastings
Lectures	Thursdays @ 11:15 — 13:00 April 18 to July 11 Room 0.008
Exercises	Fridays @ 10:00 — 11:00 April 19 to July 12 Room 0.006/0.008
	9:00 — 10:00 feedback on presentations (…but later)

Logistics

Nucleosynthesis

Course material

Presentations

Lecture Notes by Prof. Norbert Langer (see website)

B. E. J. Pagel *Nucleosynthesis and Chemical Evolution of Galaxies*
1997, University Press, ISBN 0 521 55958 8

D. D. Clayton *Principles of Stellar Evolution and Nucleosynthesis*
1968, University of Chicago Press, ISBN 0 226 10953 4

C. Iliadis *Nuclear Physics of Stars*
2015, Wiley, ISBN 978 3 527 33648 7

Logistics

Evaluation

- Read material beforehand and e-mail at least 3 non-trivial questions before **Tuesday @ 13:00** 25%
  email to tutors; use subject heading [Nuc]
- Lectures and Exercises (compulsory attendance) 25%
- Student presentations on nucleosynthesis papers
  check website for paper suggestions 50%

Overview

Goal: explain the distribution of isotopic abundances in the Universe

• **Lecture 1:**	Introduction & overview	**April 18**
• **Lecture 2:**	Thermonuclear reactions	**April 25**
• **Lecture 3:**	Big-bang nucleosynthesis	**May 2**
• **Lecture 4:**	Thermonuclear reactions inside stars — I (H-burning)	**May 7**
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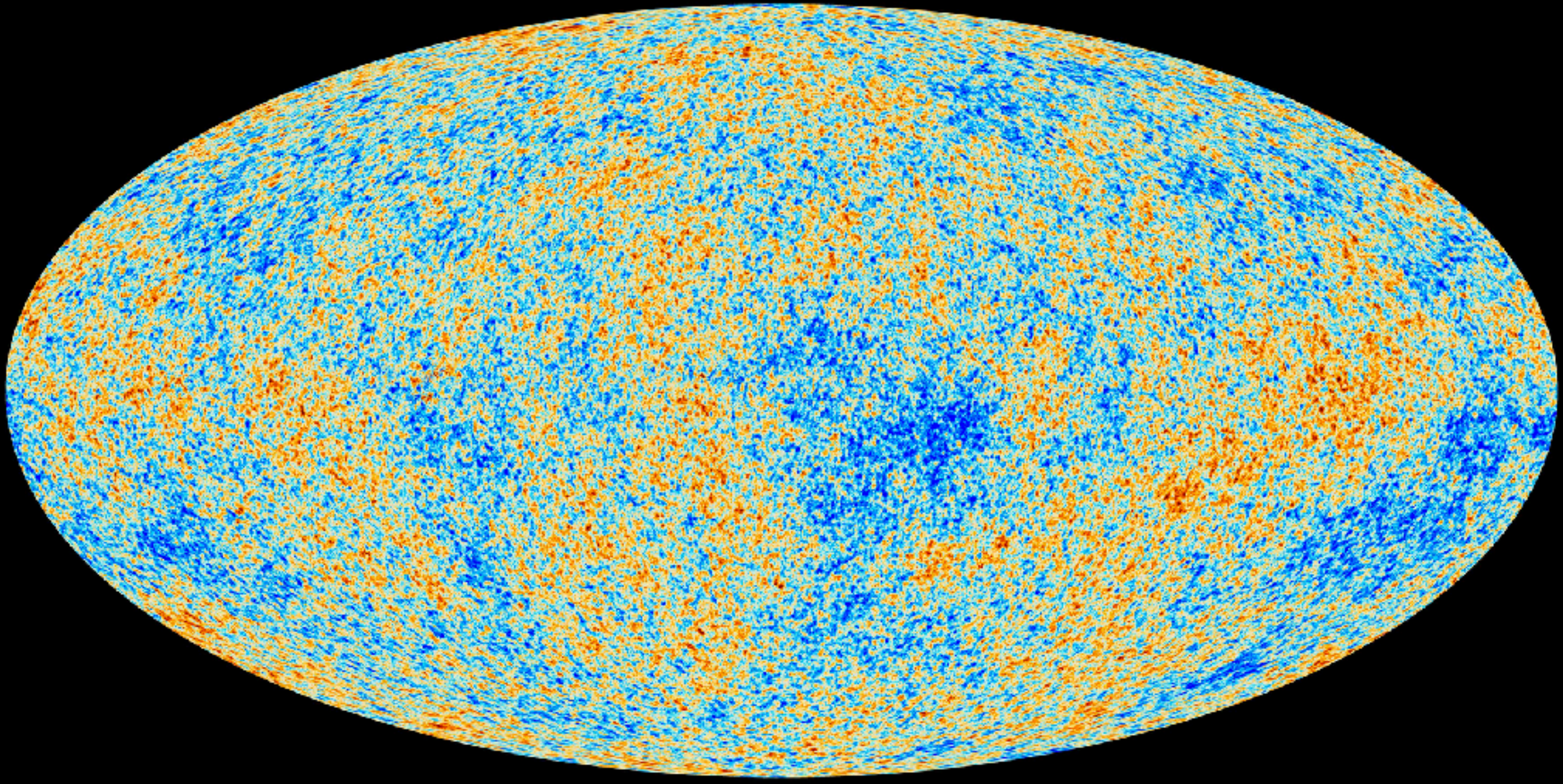
• **Lecture 9:**	Li, Be and B	**July 4**
• **Lecture 10:**	Galactic chemical evolution and relation to astrobiology	**July 11**

Paper presentations I — **June 21**

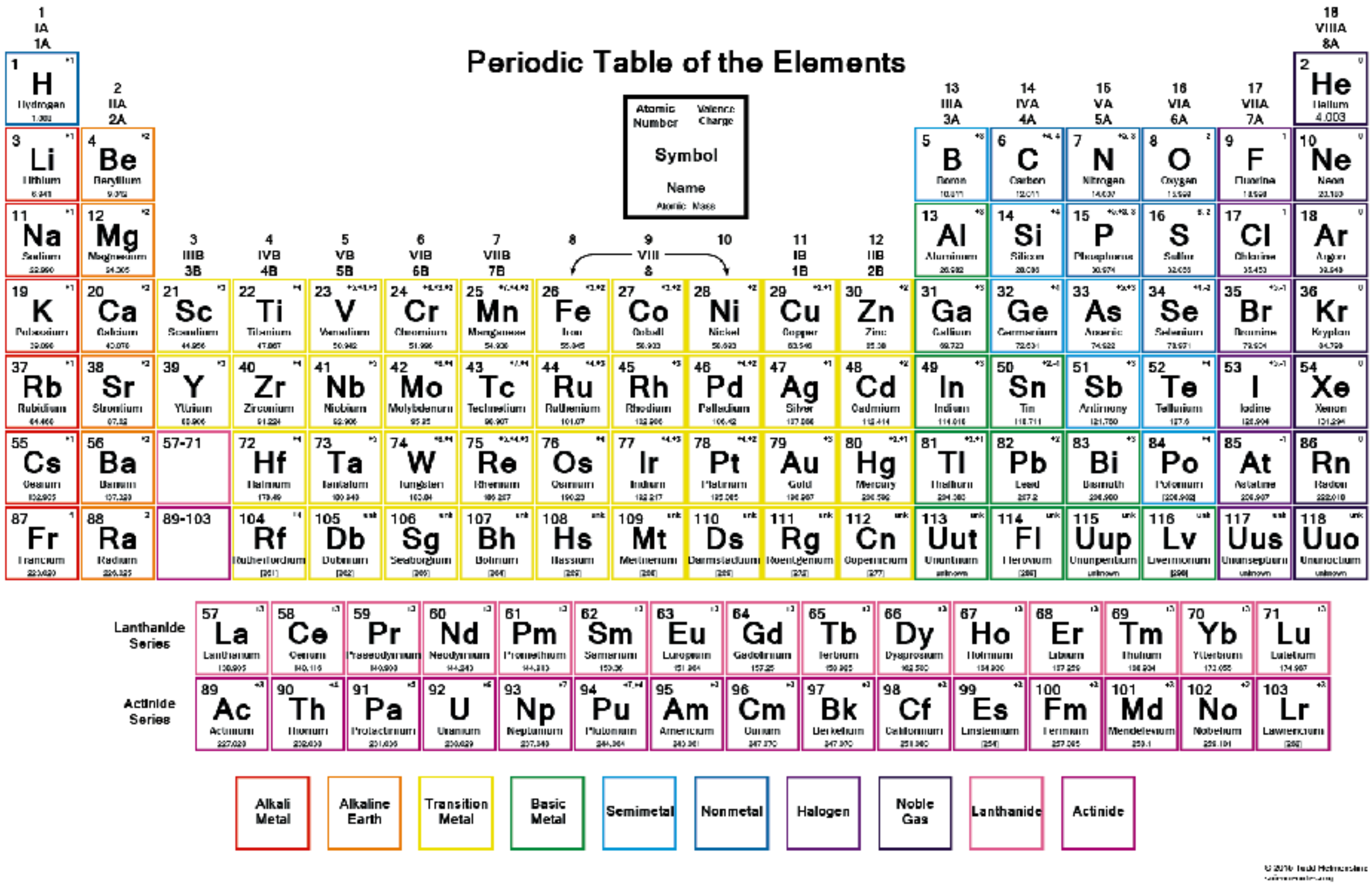
Paper presentations II — **June 27**

Overview



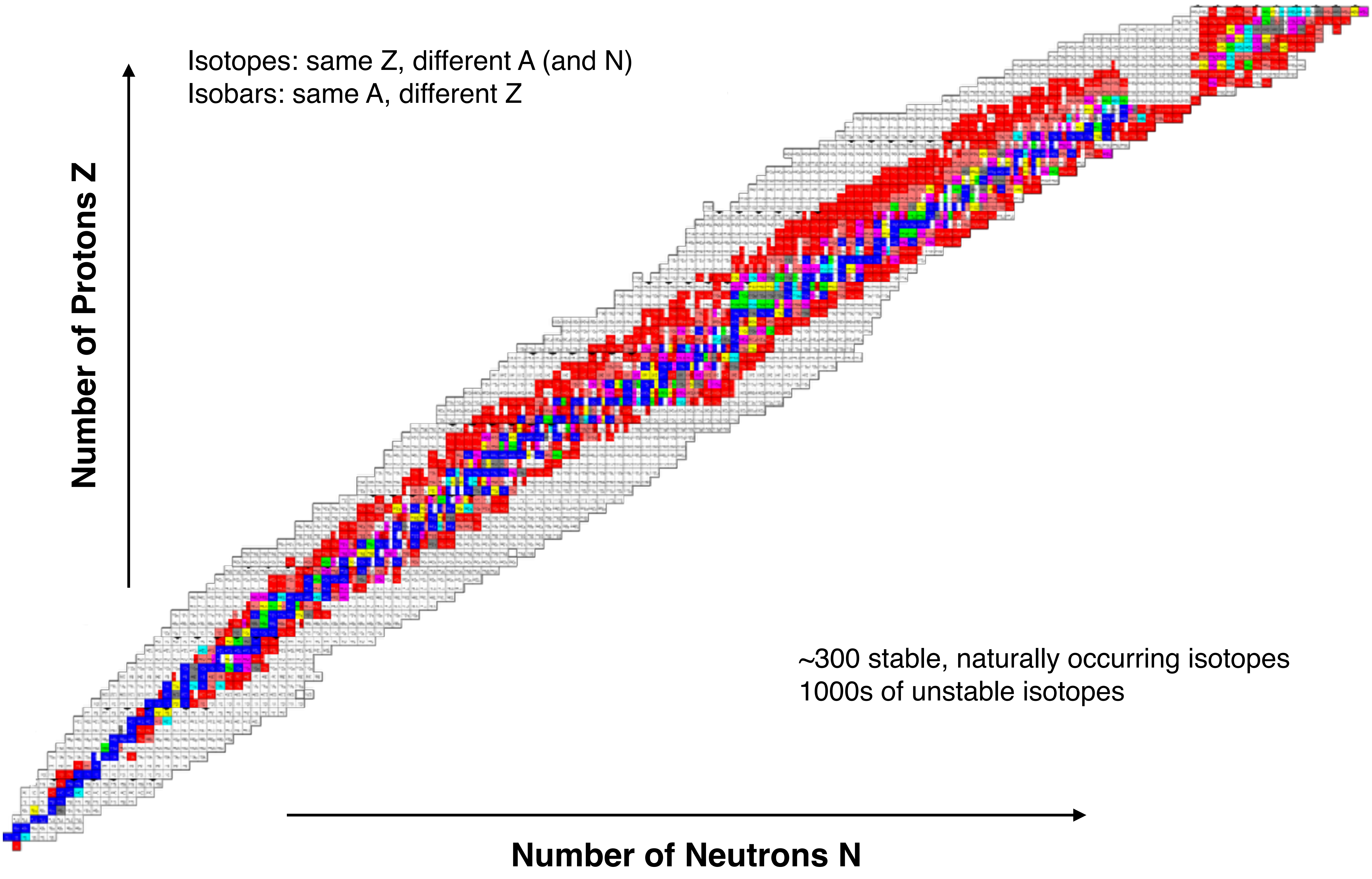
Overview

Chemical elements



Isotopes and isobars

Isotopes: same Z, different A (and N)
Isobars: same A, different Z



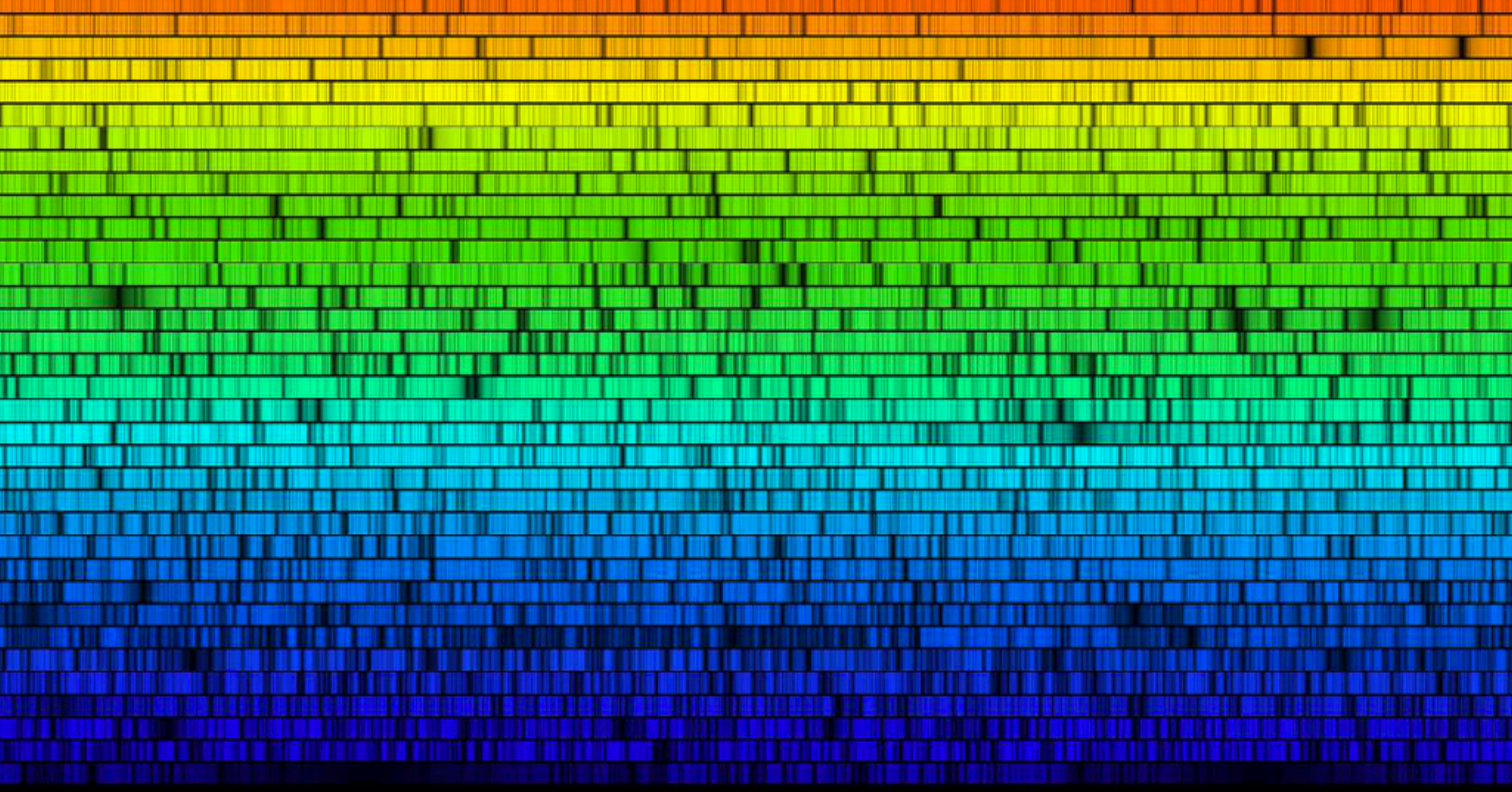
~300 stable, naturally occurring isotopes
1000s of unstable isotopes

Measurement of Elemental Abundances — the Sun

Absorption-line spectrum of the solar photosphere

Unmodified by processes in the Sun’s interior
Reflects the composition of the gas from which the sun formed

Abundances can now be inferred for millions of stars!



Measurement of Elemental Abundances — the Sun

Element	Abundance (pct. of total number of atoms)	Abundance (pct. of total mass)
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.030	0.014
Sulfur	0.015	0.040

“Metals”

Isotopic Abundances — Meteorites (e.g. C1 carbonaceous chondrites)

Homogeneous solar system composition

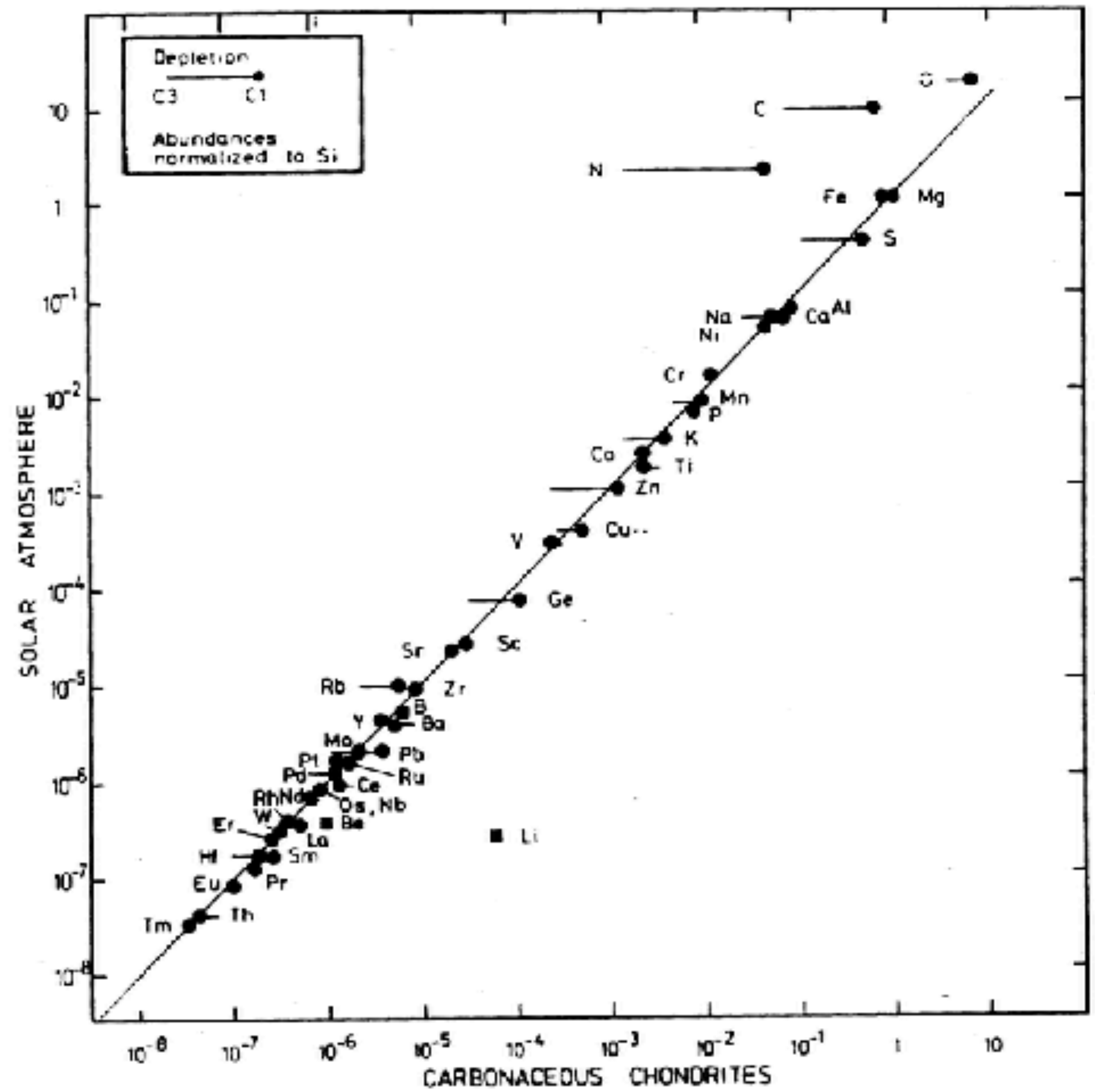
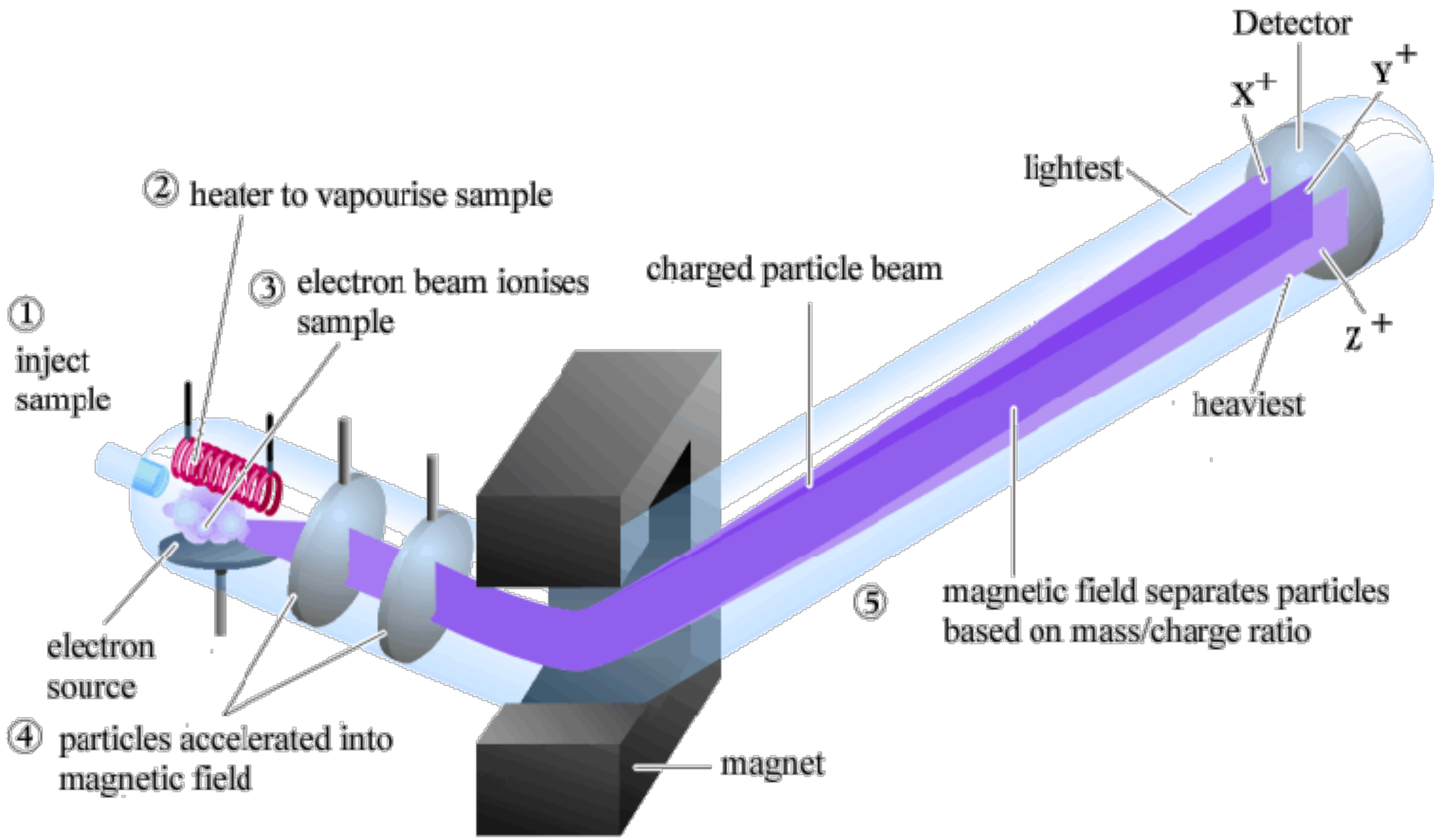


Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

…also from rocks and minerals, but element abundances differ substantially

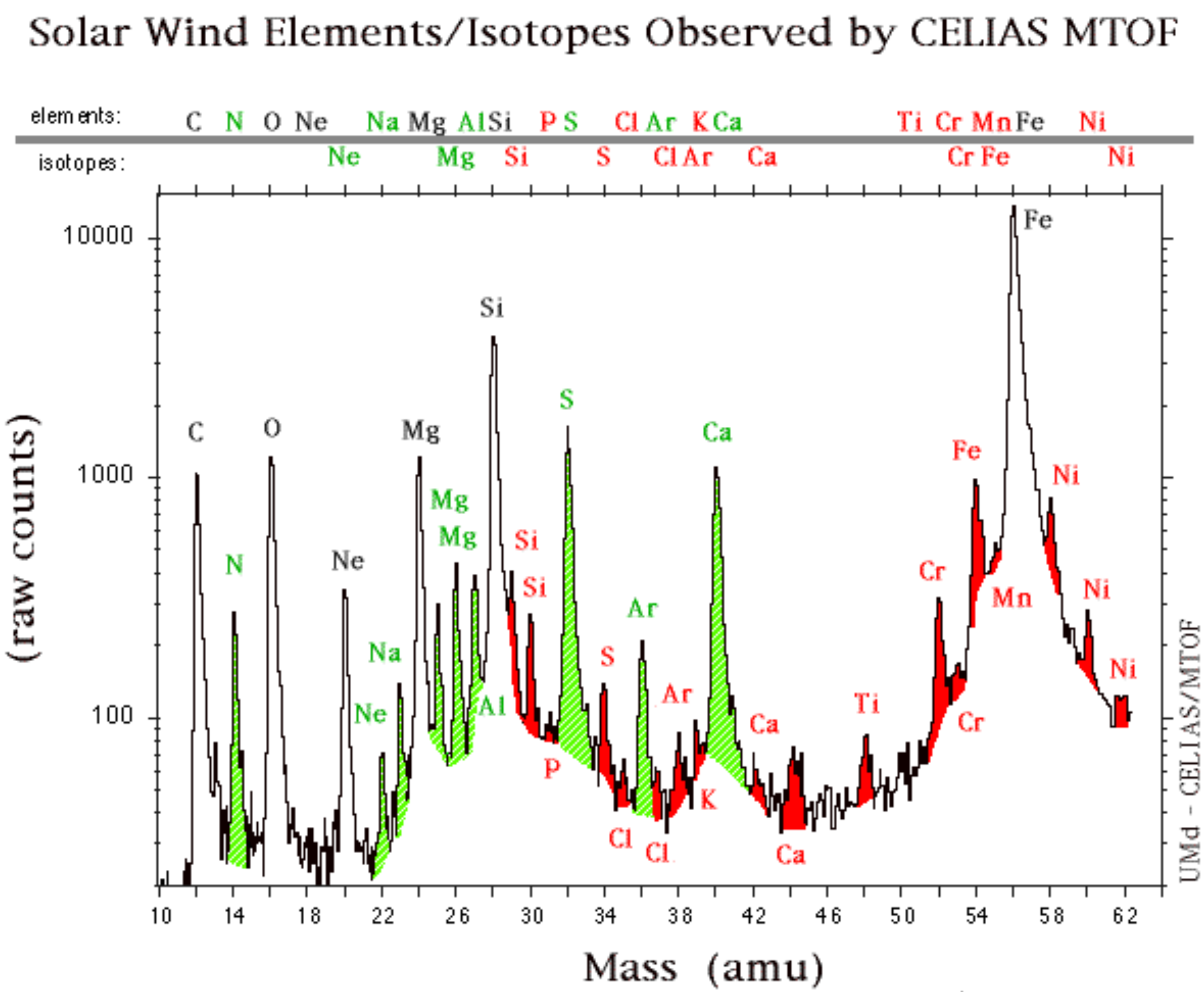
Measurement of Isotopic Abundances

Masses of isotopes can be measured with a mass spectrometer

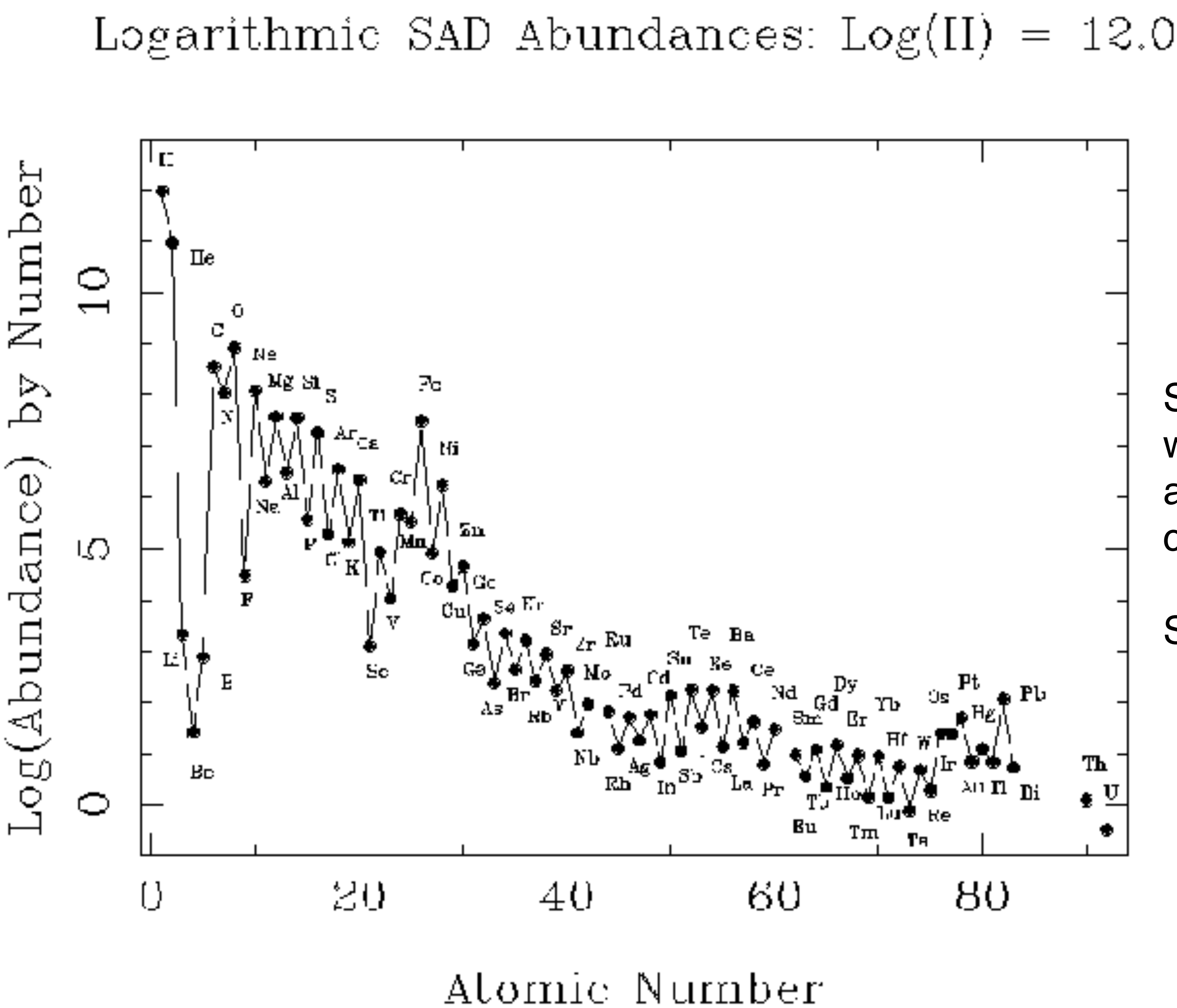


Measurement of Isotopic Abundances

Isotope abundances in the solar system



“~~Cosmic~~” Abundances



Stars in the solar neighbourhood with approx. the same age as the sun, also have very similar elemental composition

Solar Abundances = Cosmic Abundances

Goal

explain abundances of chemical elements, isotope ratios and evolution with time

Abundances

Definitions

By number

$$N_i = X_i/A_i$$

$$N_{\mathrm{H}} = 10^{12}$$

$$A_{\mathrm{H}} = \log(N_{\mathrm{H}}) = 12$$

$$E_X = A_X - A_H = \log(N_X/N_H)$$

By mass fraction

$$\mathrm{H} \rightarrow X$$

$$\mathrm{He} \rightarrow Y$$

$$\mathrm{Metals}\,(\mathrm{A} > 4) \rightarrow Z$$

$$\mathrm{Sun}: X_\odot = 0.71;\ Y_\odot = 0.275;\ Z_\odot = 0.015$$

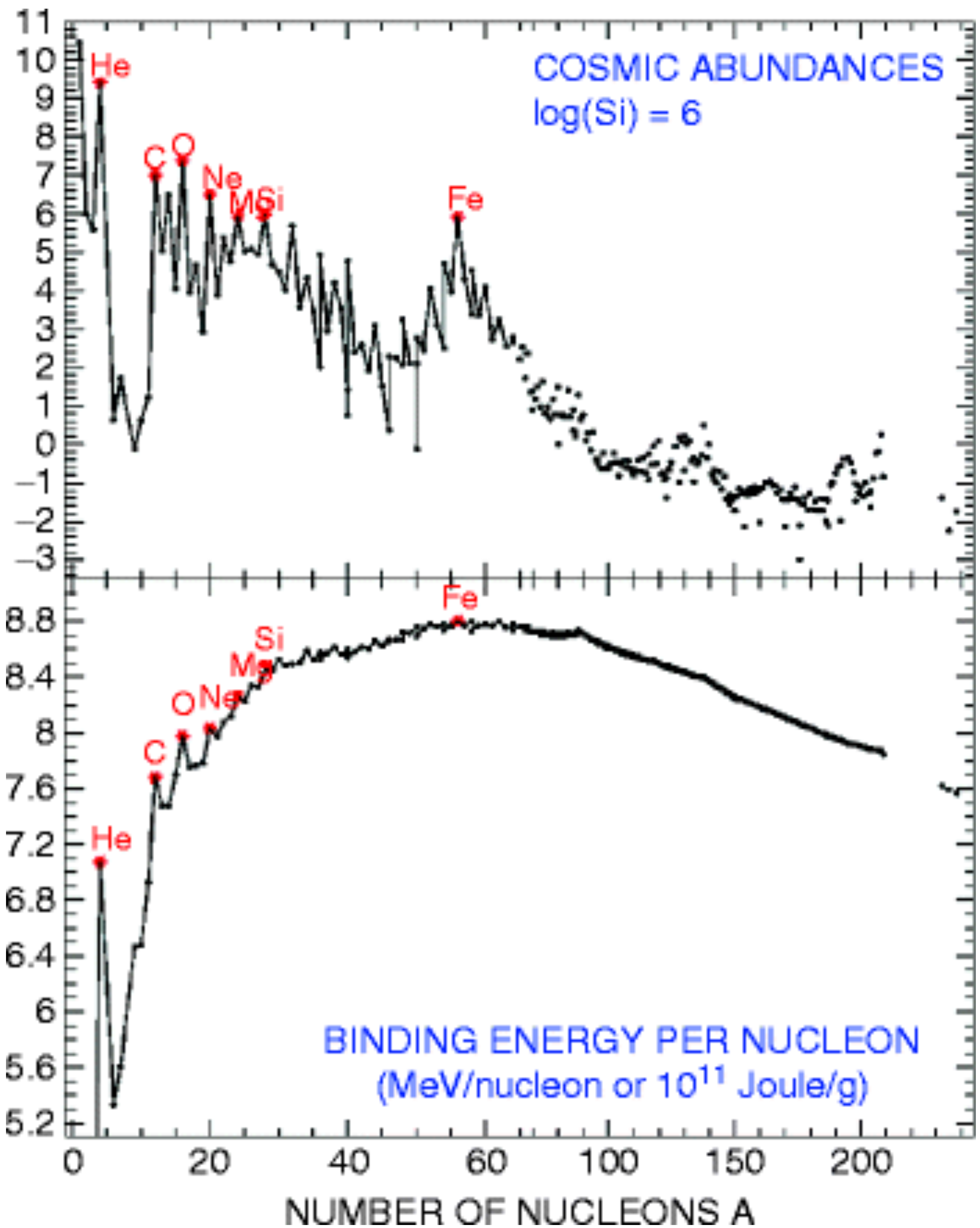
$$X + Y + Z = 1$$

$$\sum X_i = 1$$

Relative to solar $(X_i/X_j)_\odot$

$$[X_i/X_j] = log(X_i/X_j) - log(X_i/X_j)_\odot \rightarrow [X_i/X_j]_\odot = 0$$

Abundances and nuclear processes



Elemental abundances are correlated with a fundamental property of the nucleus

“Magic” nuclei or α-nuclei locally more stable and more abundant than neighbours

Conclusion
Abundances of chemical elements depend on nuclear processes

Nuclei are electrically charged, therefore high velocities (energies) are required to bring them sufficiently close, for a reaction to take place

Where does nucleosynthesis takes place?

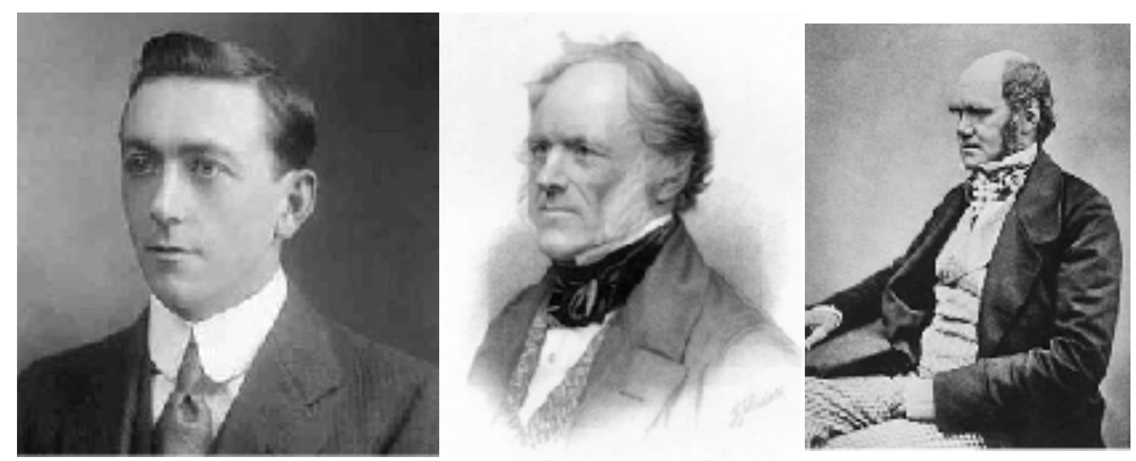
High energies = high temperatures and/or densities

Before early 30s: Can nuclear reactions take place inside the Sun and the stars?

Temperature in the center~ 10-15 million degrees K
Classically, no.

Temperatures seem too low even for proton-proton fusion, let alone other elements
However, several lines of evidence indicate that the solar system is billions of years old

Charles Darwin, Charles Lyell, Arthur Holme
Geology and evolution require billions of years



Arthur Eddington et al.
fusion must take place inside stars but not clear how (not hot enough)

Nucleosynthesis inside stars

George Gamow (1904–1968)
Quantum tunnelling effect allows fusion at much lower temperatures

Hans Albrecht Bethe (1906 — 2005)
Fusion of hydrogen via pp- and CNO- chain takes place inside the Sun

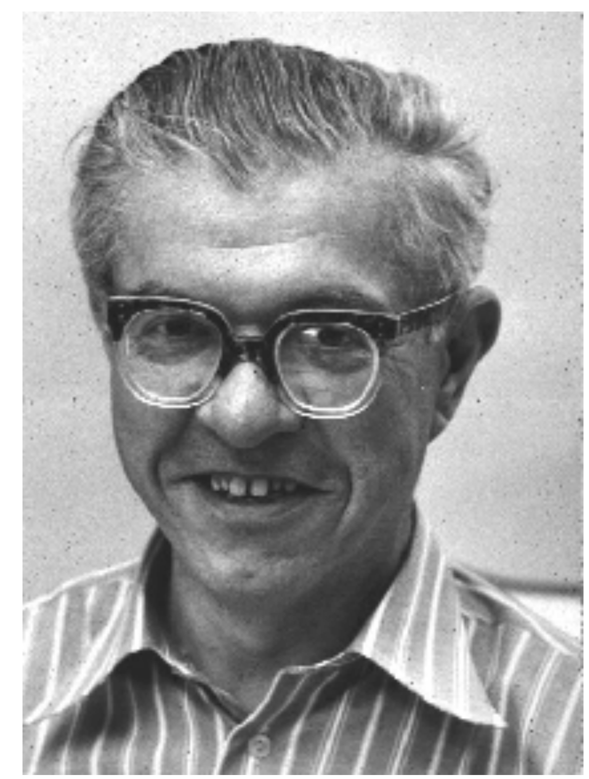
Where does nucleosynthesis take place?

Debate in the 40s: Primordial or Big-bang nucleosynthesis vs stars and supernovae

George Gamow (1904–1968)
Elements formed during the Big Bang via neutron captures successful in explaining the abundances of H and He, but not of heavier elements

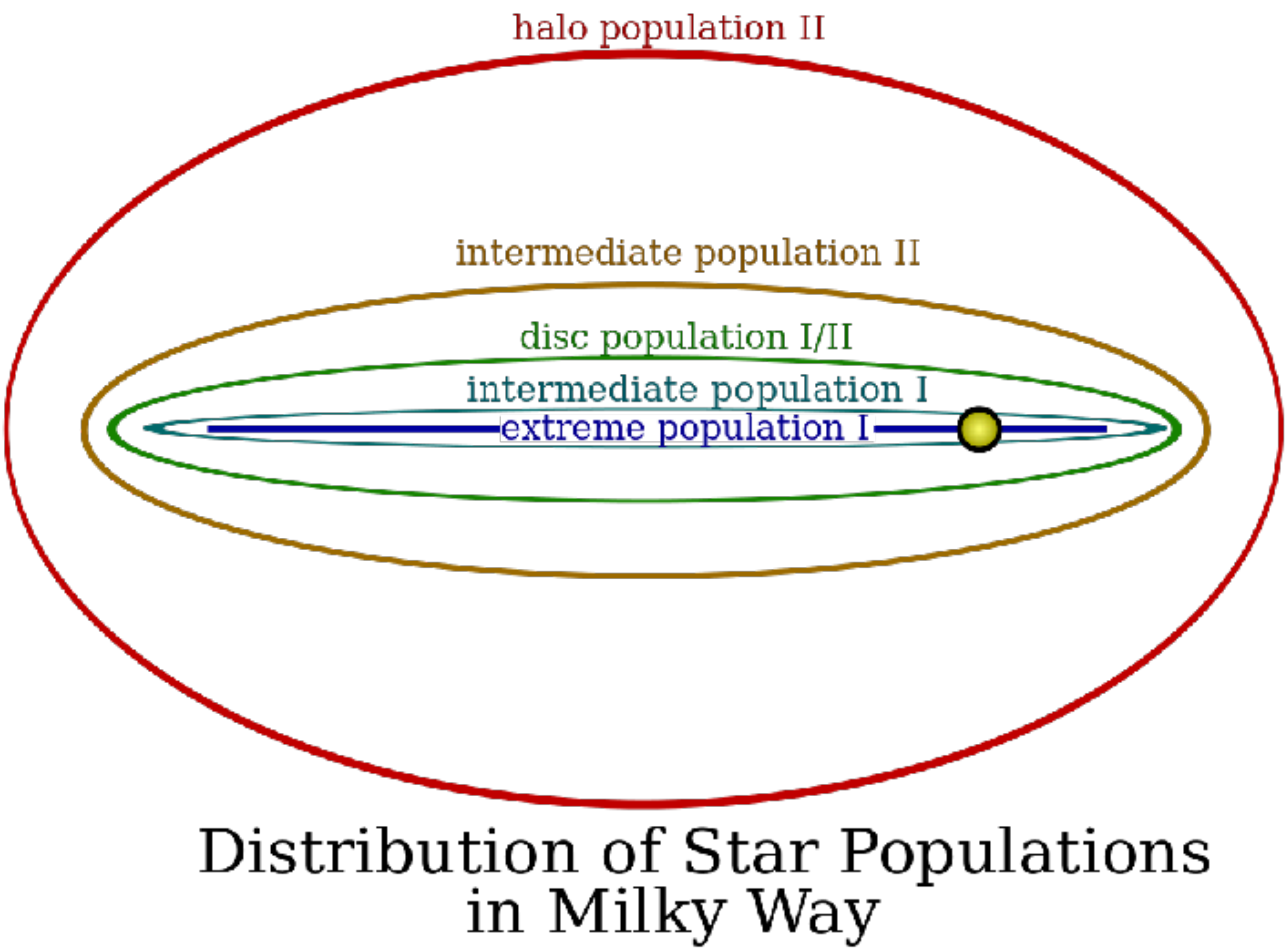
vs

Fred Hoyle (1915–2001)
Elements created in stars and supernovae



Observational evidence for nucleosynthesis

In early 50s: evidence for evolution of abundances with cosmic time
Stars near the galactic disk have higher metallicities that stars in the halo



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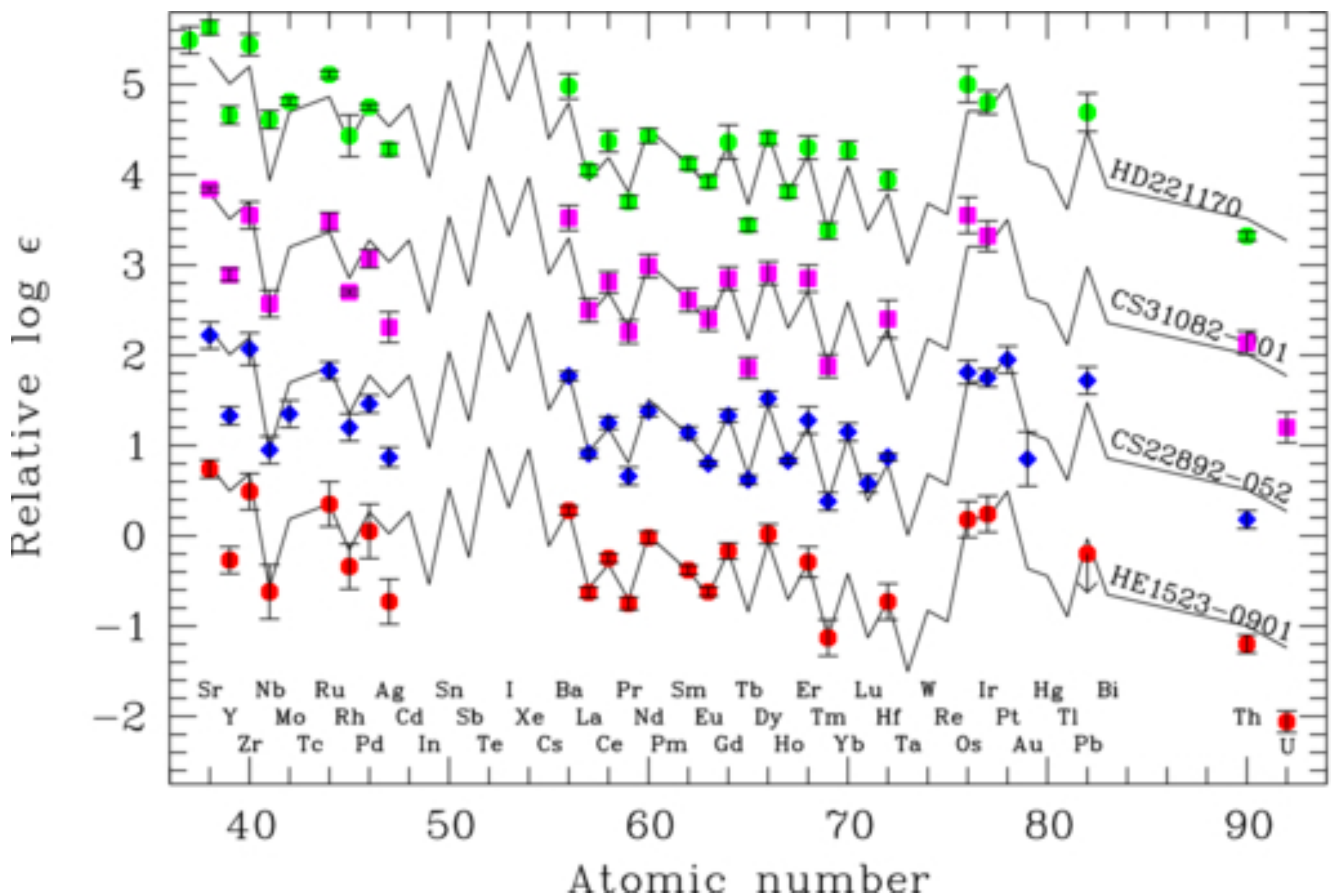
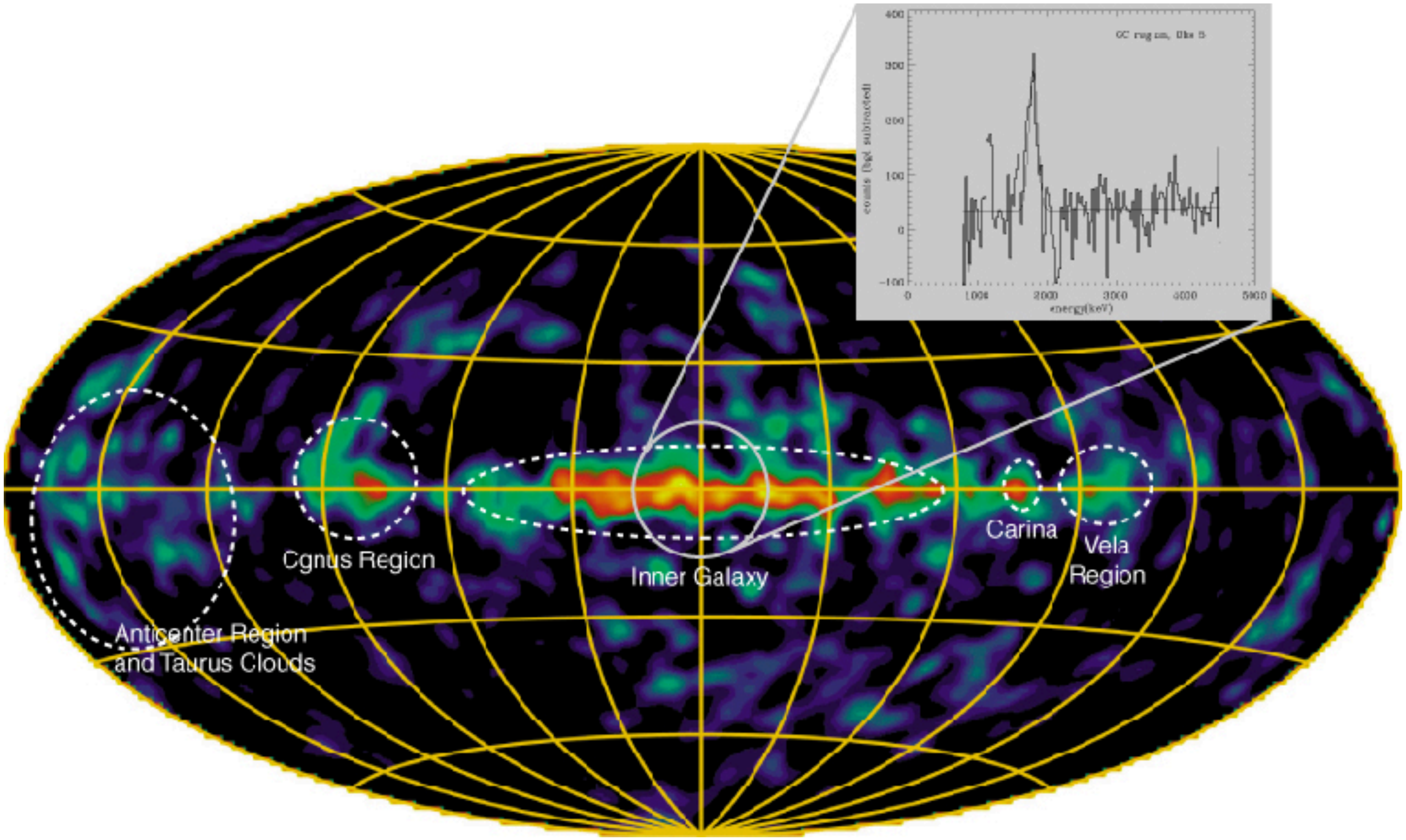


…but H and He about the same: i.e. both Gamow and Hoyle were right

Jacobson & Frebel 2014

Observational evidence for nucleosynthesis

More (in)direct evidence for ongoing nucleosynthesis

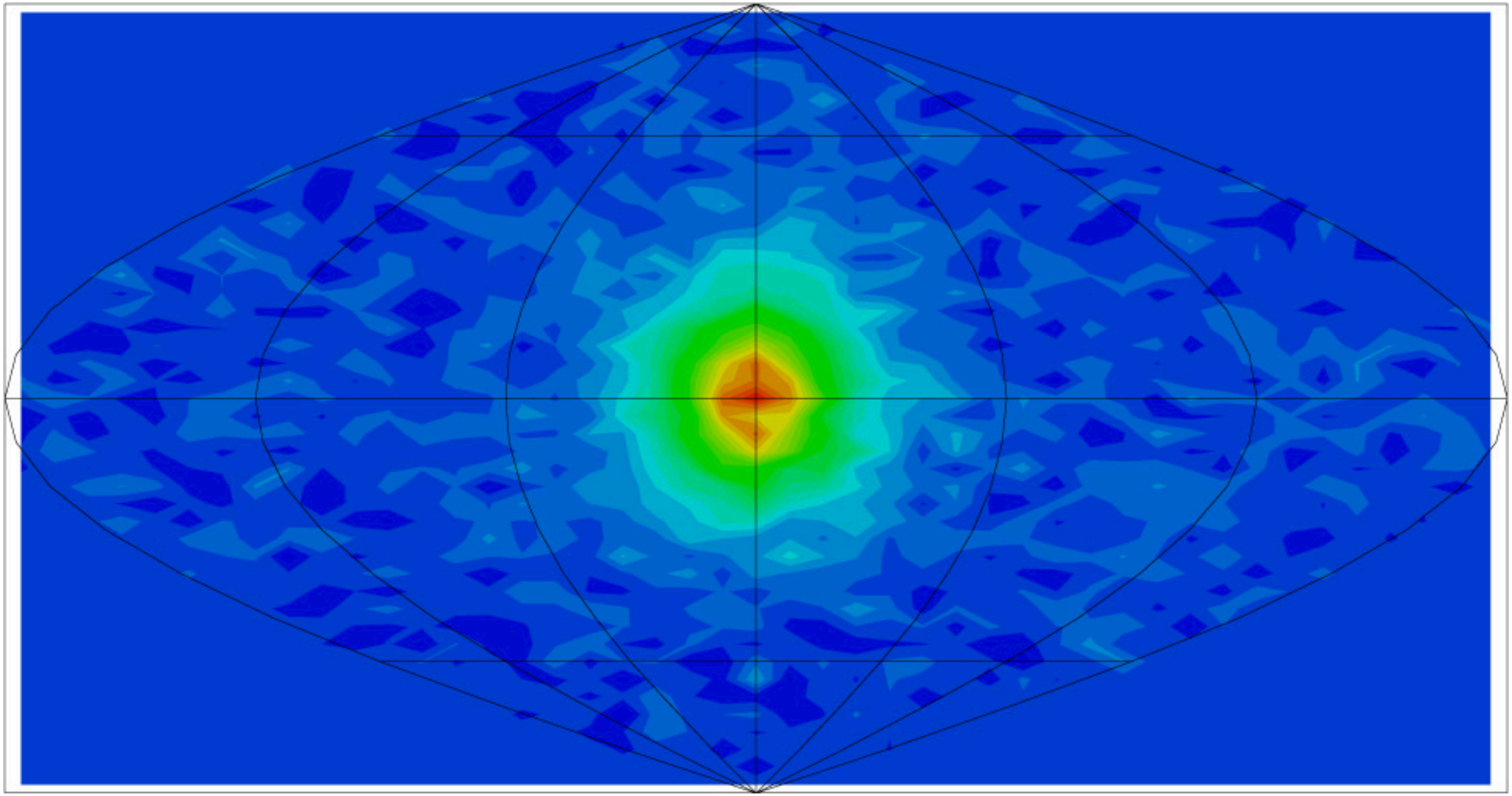


example 1:1.8 MeV line emission from the decay of ^{26}Al (lifetime of $7x10^5$ yr)

COMPTEL collaboration

Observational evidence for nucleosynthesis

More (in)direct evidence for ongoing nucleosynthesis



example 2: observation of solar neutrinos

Super-Kamiokande

Thermonuclear reactions

In late 50s: advancements in computer science, thermonuclear bombs

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

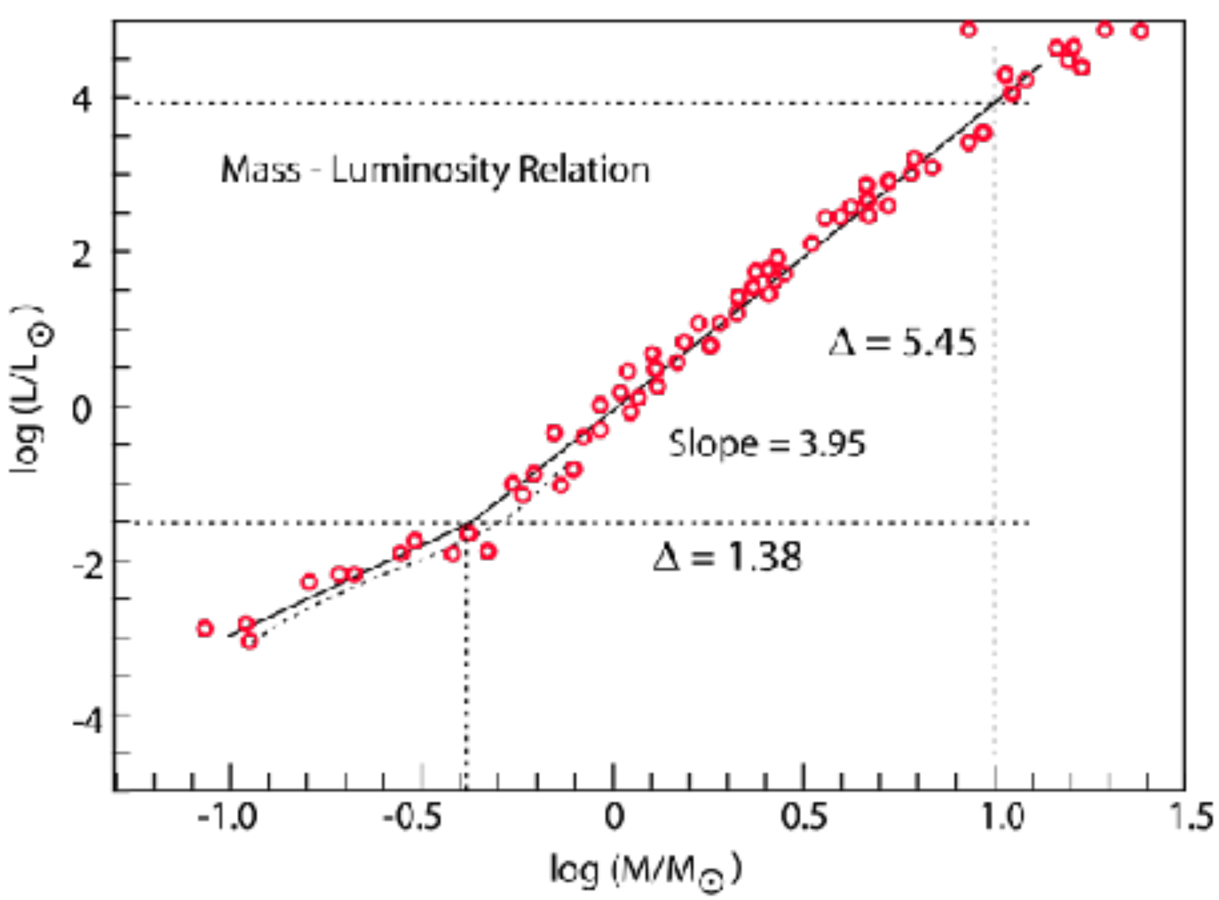
Synthesis of the Elements in Stars*

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

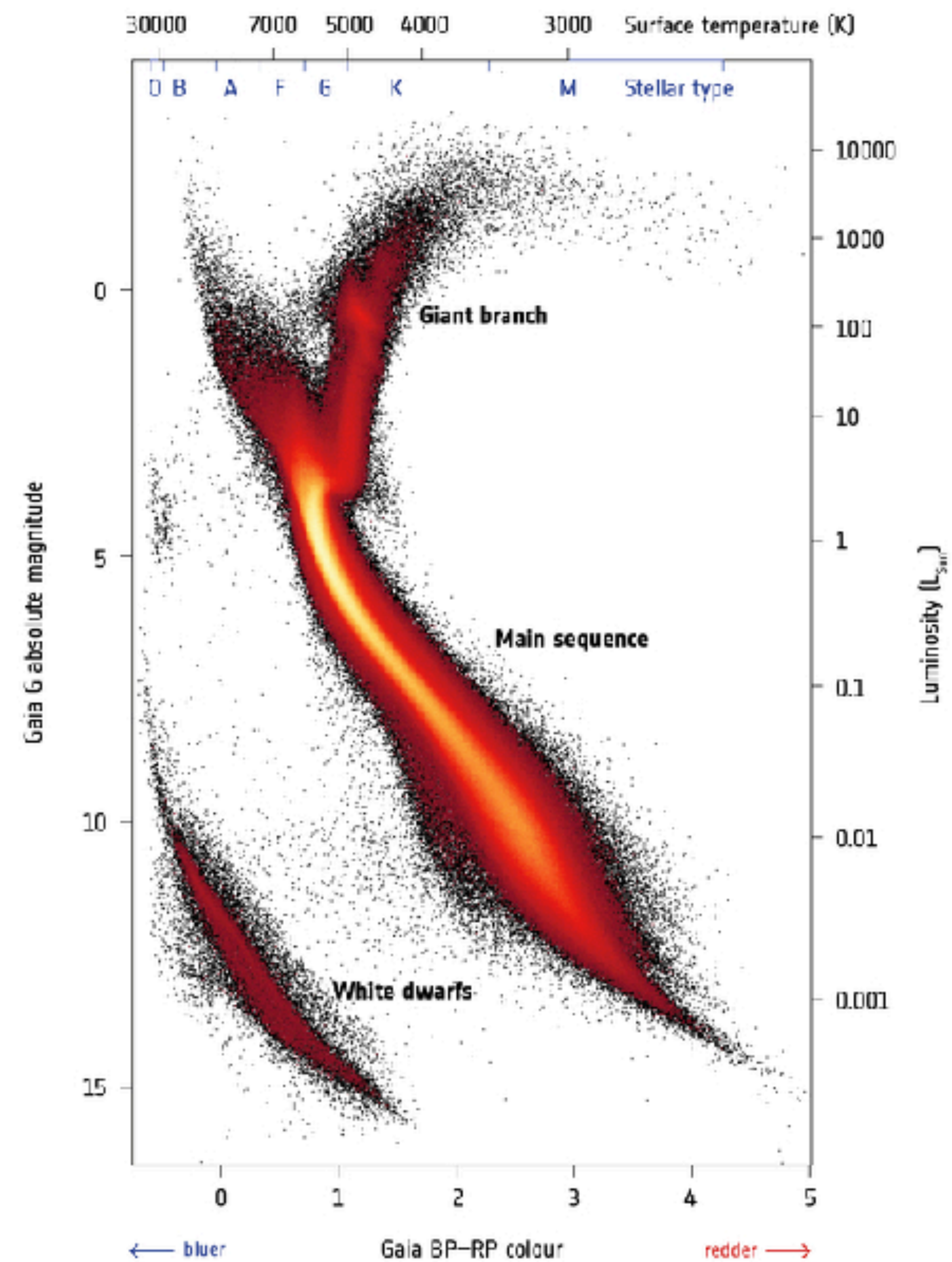
Thermonuclear reactions

Stars can have a range of masses, temperatures and internal properties.

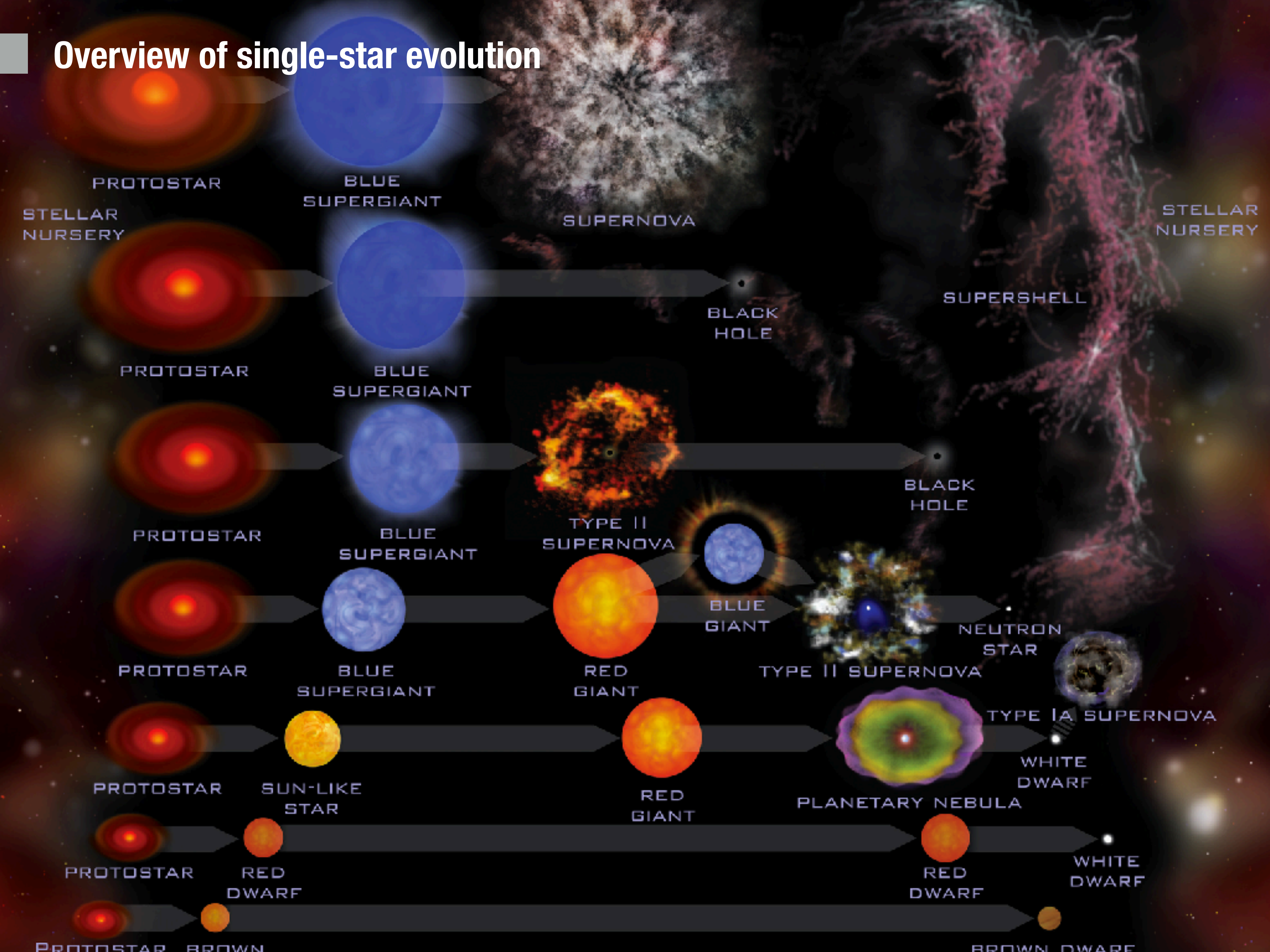
Fusion of different elements takes part at different locations of the H-R diagram



→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM



Overview of single-star evolution



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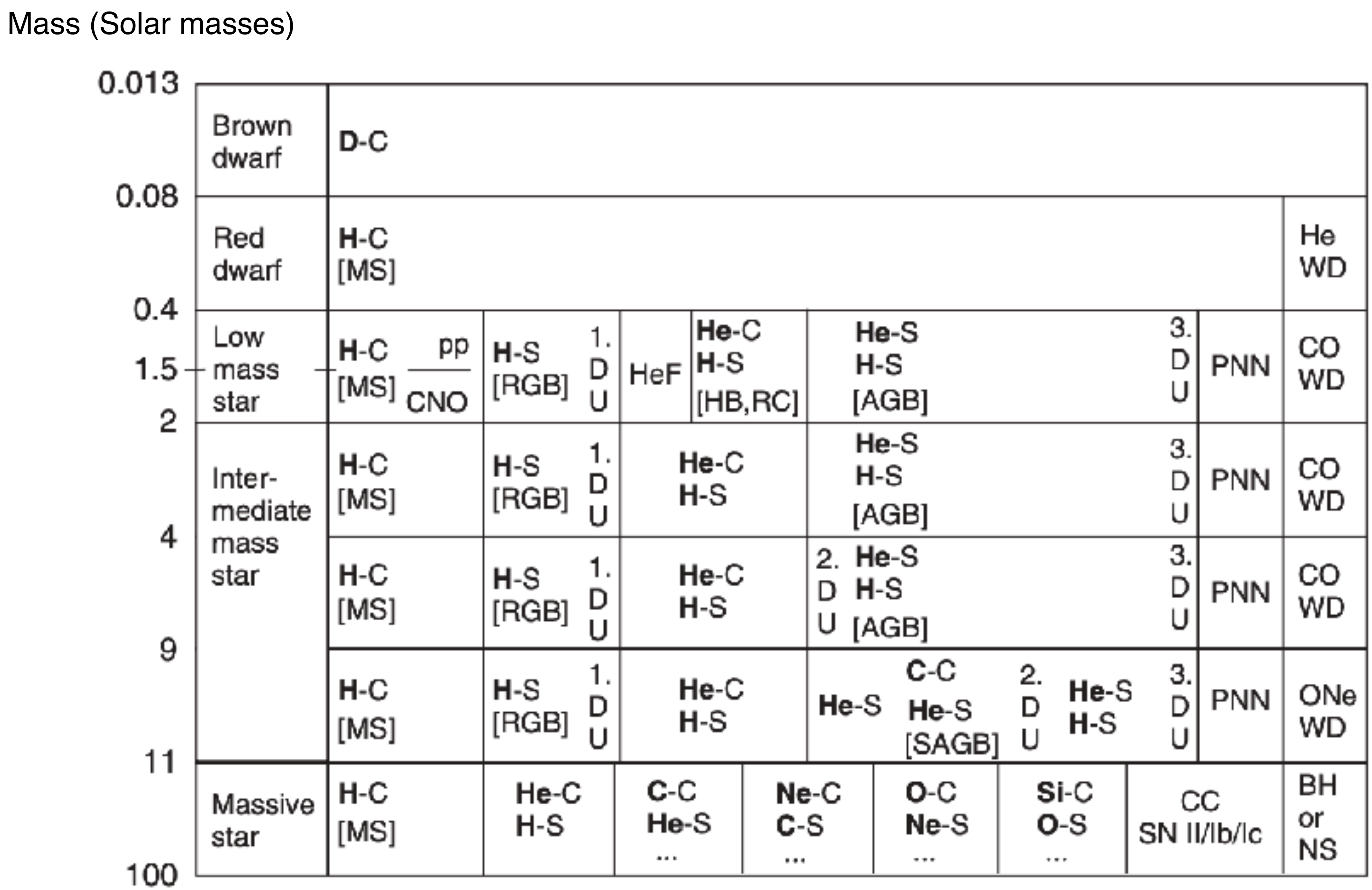
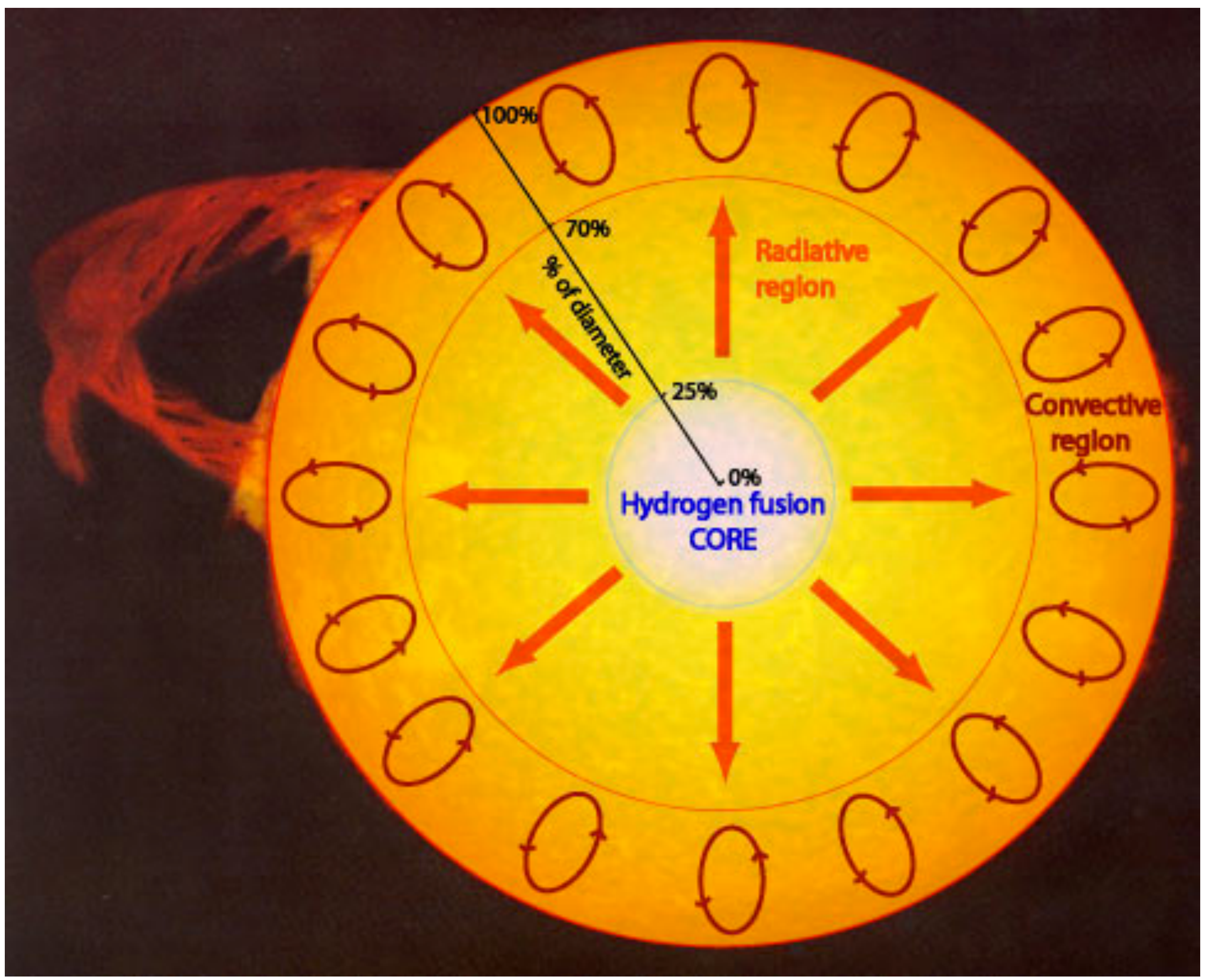
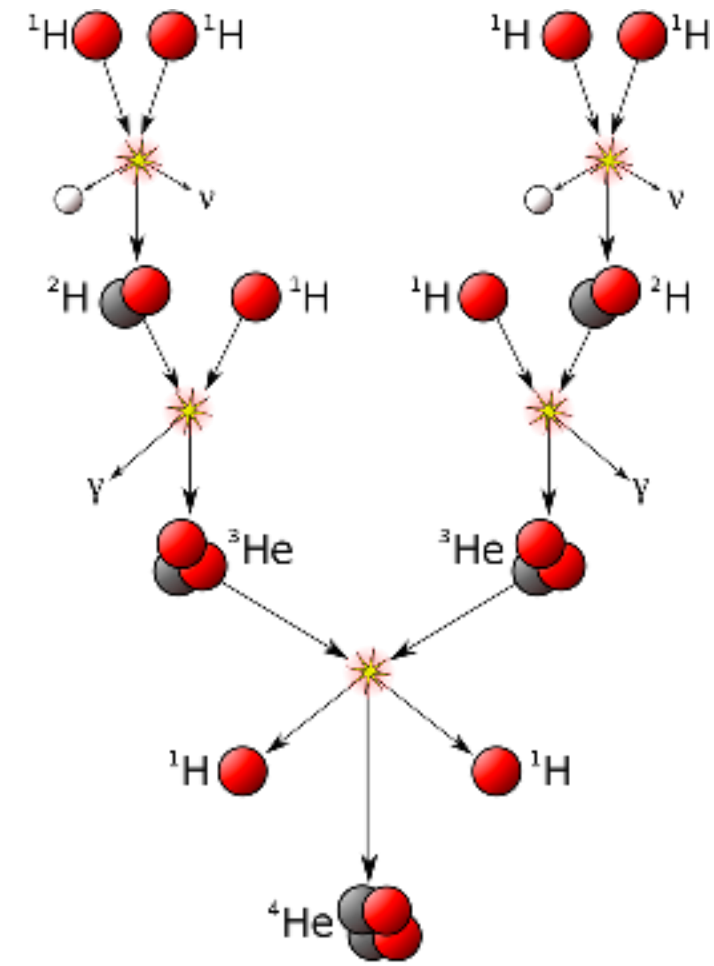


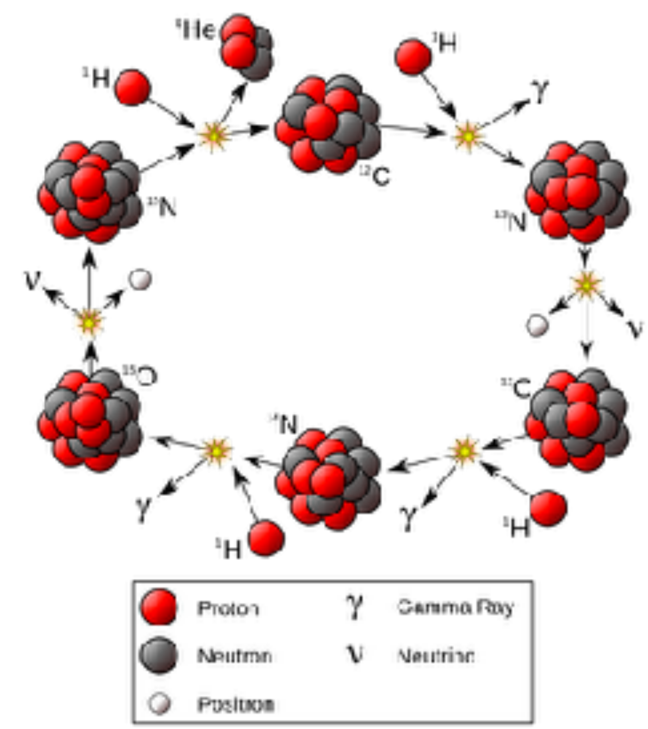
Iliadis (2015)

Hydrogen burning

Starts on the main sequence
via pp (low mass) and CNO (high mass) chains

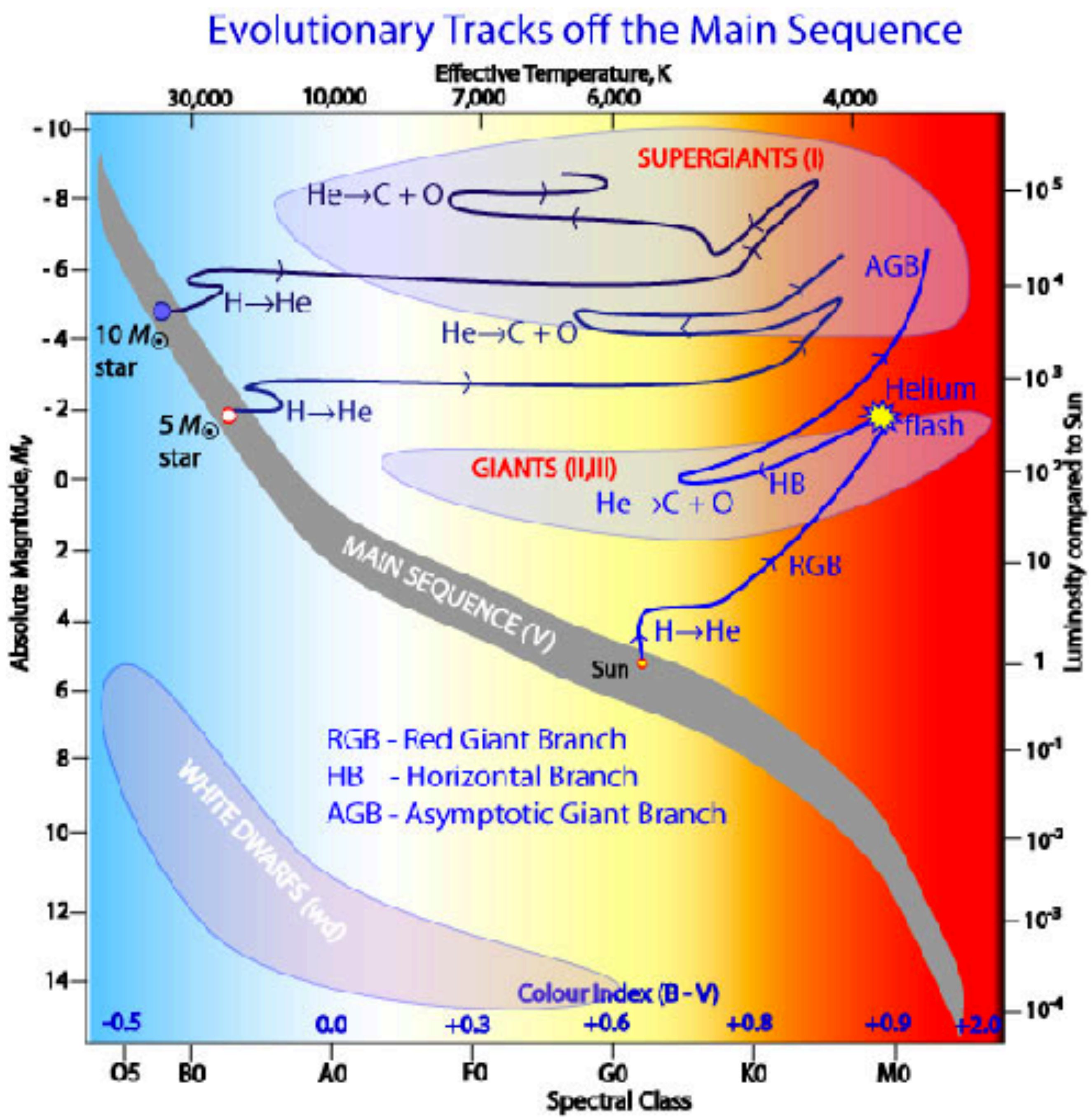


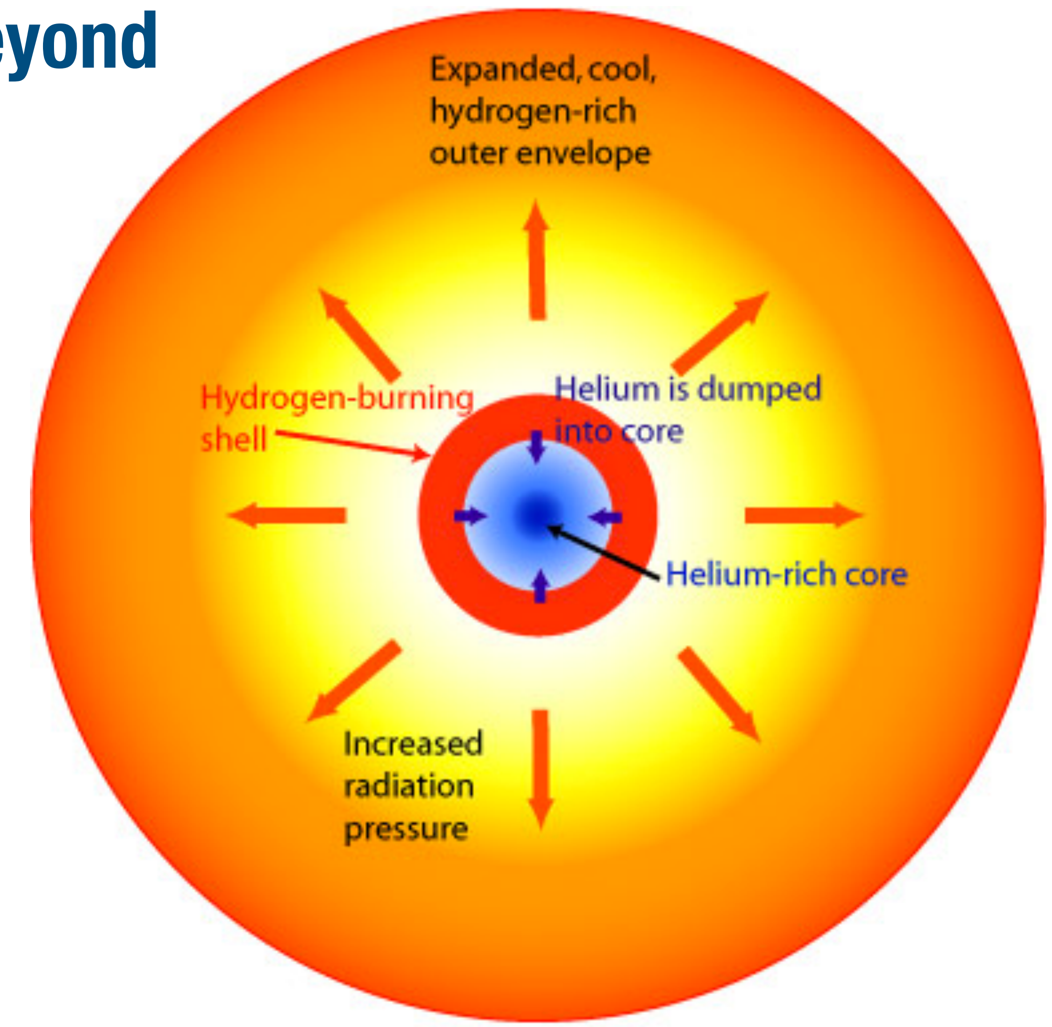




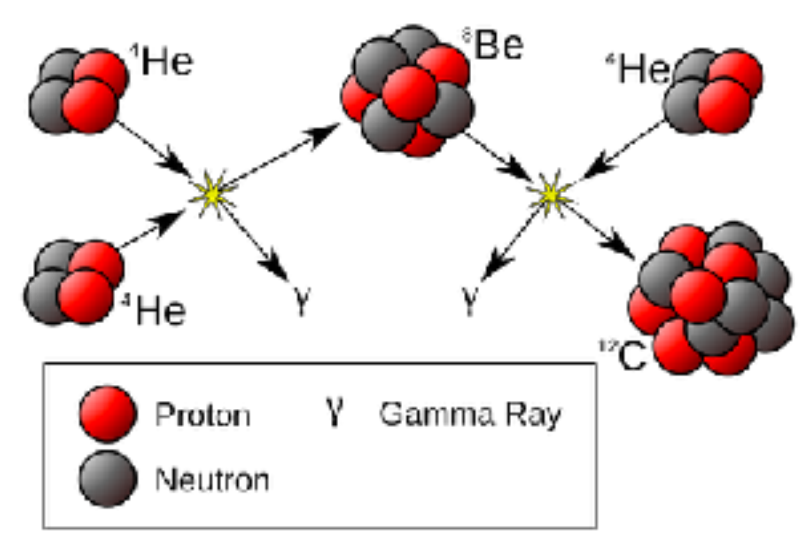
ATNF, *Wikipedia*

Helium burning on the red giant branch and beyond



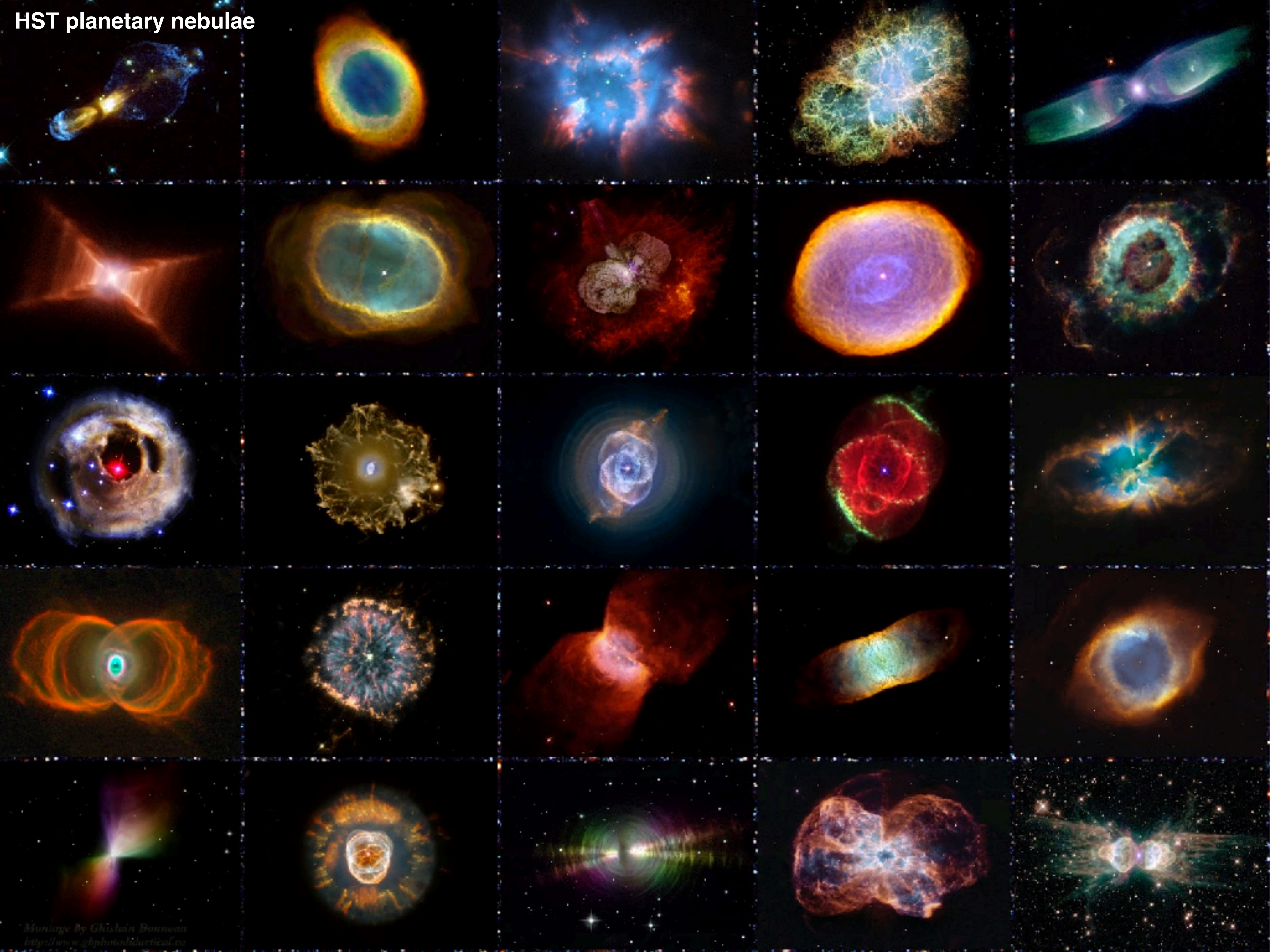


Hydrogen Shell Burning on the Red Giant Branch



Wikipedia

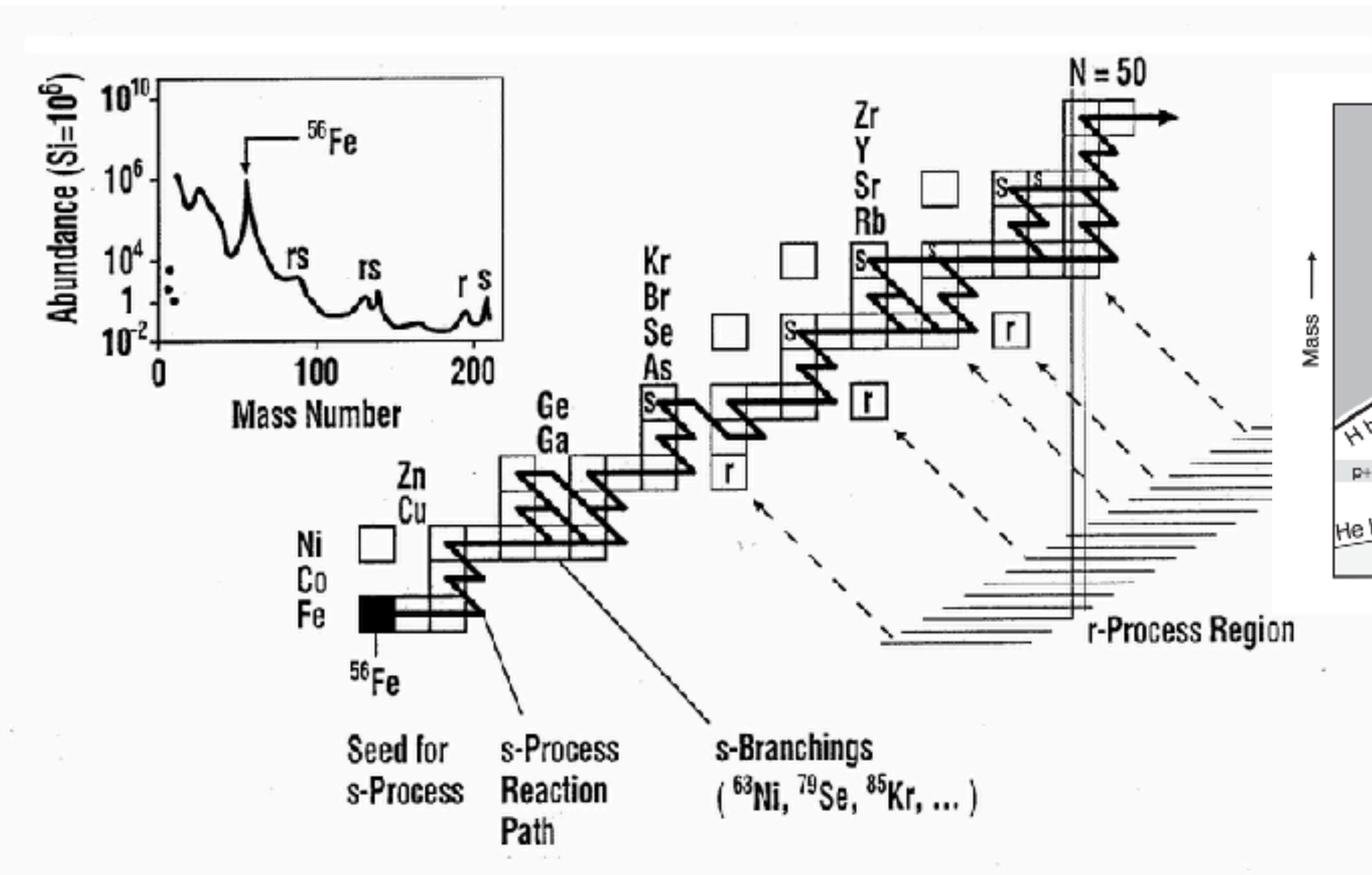
HST planetary nebulae

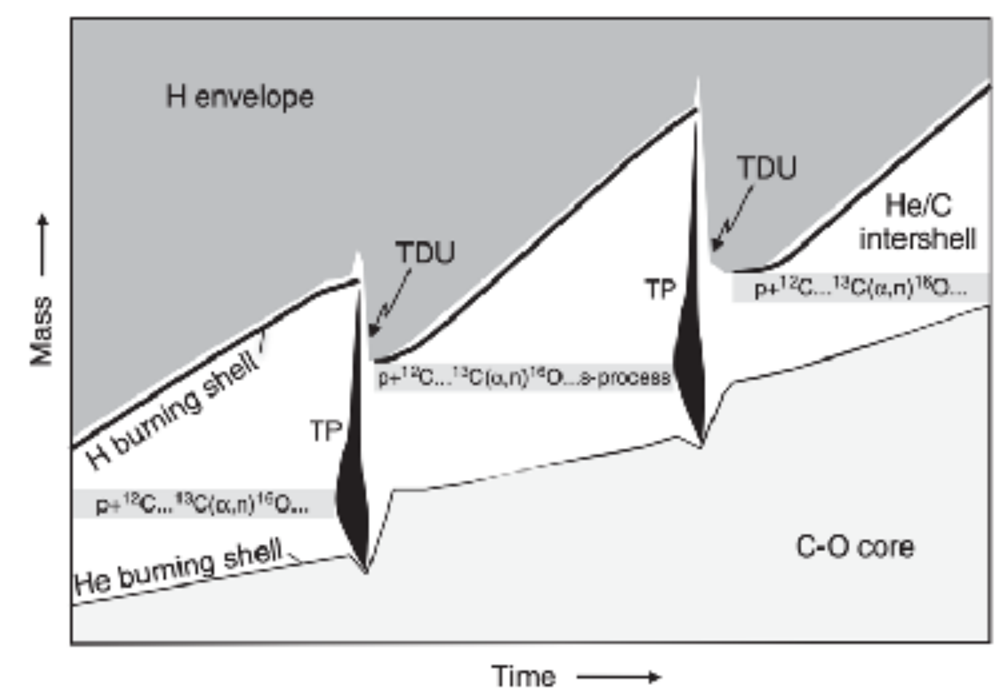


slow neutron capture on the AGB (s-process)

main neutron sources

$$^{13}\mathrm{C} + ^{4}\mathrm{He} \rightarrow ^{16}\mathrm{O} + n$$
$$^{22}\mathrm{Ne} + ^{4}\mathrm{He} \rightarrow ^{25}\mathrm{Mg} + n$$





Iliadis (2015); Kaeppeler, Franz *et al.* Rev.Mod.Phys. 83 (2011) 157 arXiv:1012.5218

Carbon burning and beyond

$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\,{}^{4}He \\
&\rightarrow {}^{20}Ne +{}^{4}He \\
&\rightarrow {}^{23}Na + p^{+} \\
&\rightarrow {}^{23}Mg + n \\
&\rightarrow {}^{24}Mg + \gamma
\end{aligned}
$$

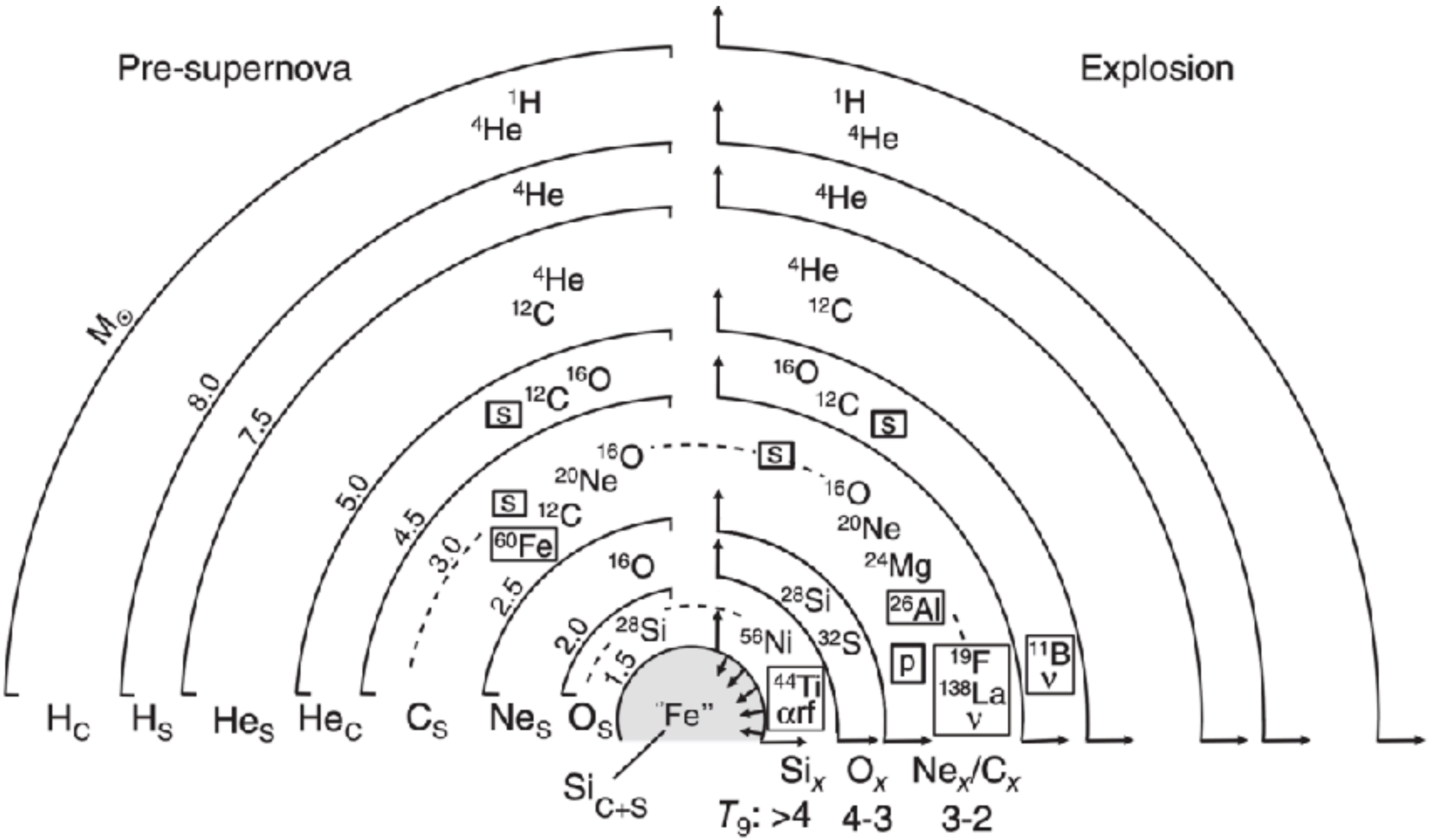
$$
\begin{aligned}
{}^{16}O + {}^{16}O &\rightarrow {}^{24}Mg + 2\,{}^{4}He \\
&\rightarrow {}^{28}Si +{}^{4}He \\
&\rightarrow {}^{31}P + p^{+} \\
&\rightarrow {}^{31}S + n \\
&\rightarrow {}^{32}S + \gamma
\end{aligned}
$$

For 8 solar mass star

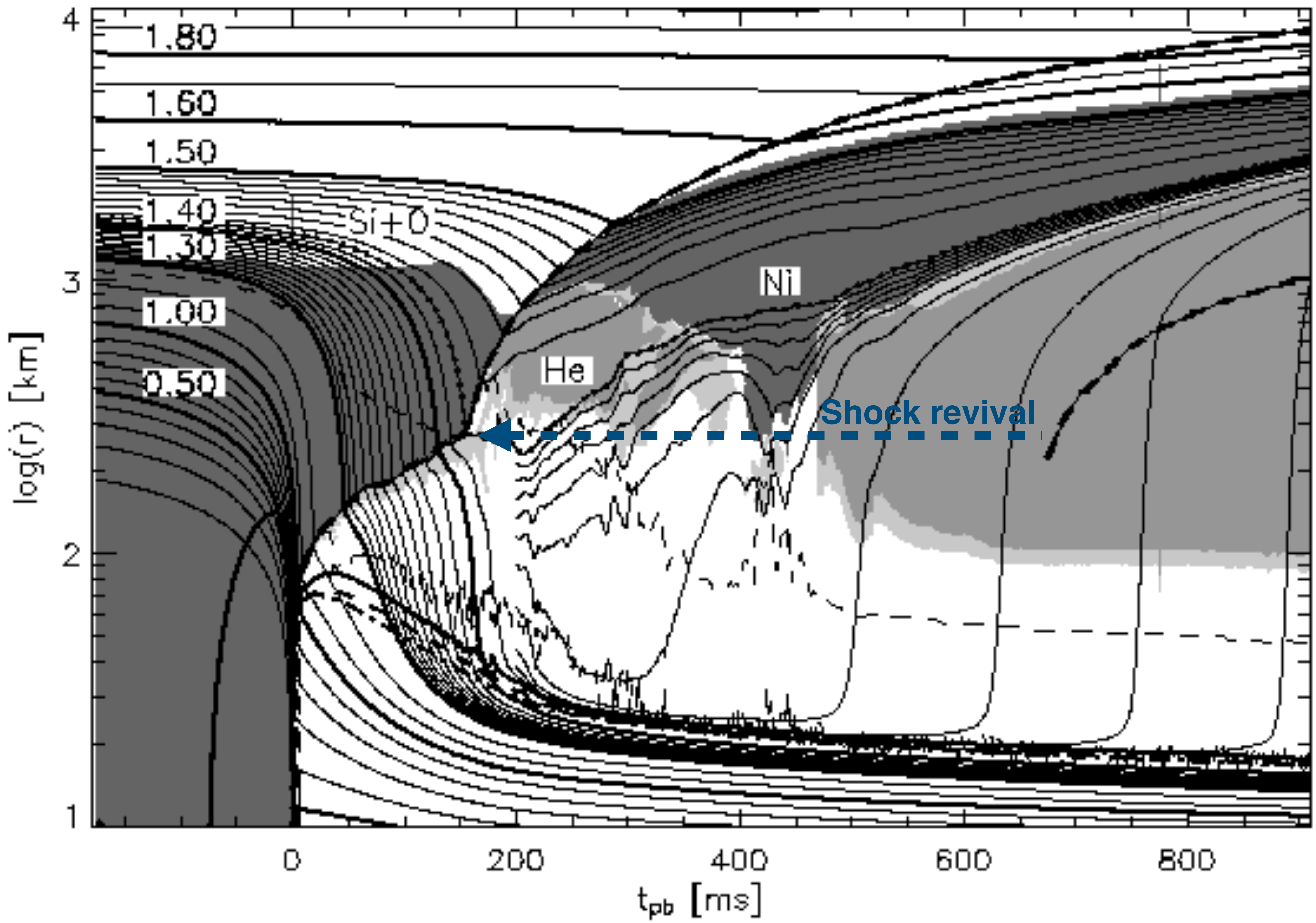
- Hydrogen: 10 Myr
- Helium: 1 Myr
- Carbon: 1000 yr
- Neon: 10 yr
- Oxygen: 1 yr
- Silicon: 1 day
- Core collapse: < 1 sec

Silicon burning occurs at extremely high temperatures: ~3 GK
Nuclei photo-disintegrate and the emitted protons and alpha particles can be captured, forming heavier nuclei.
Process near **nuclear statistical equilibrium** (~equal rate between forward and reverse reactions

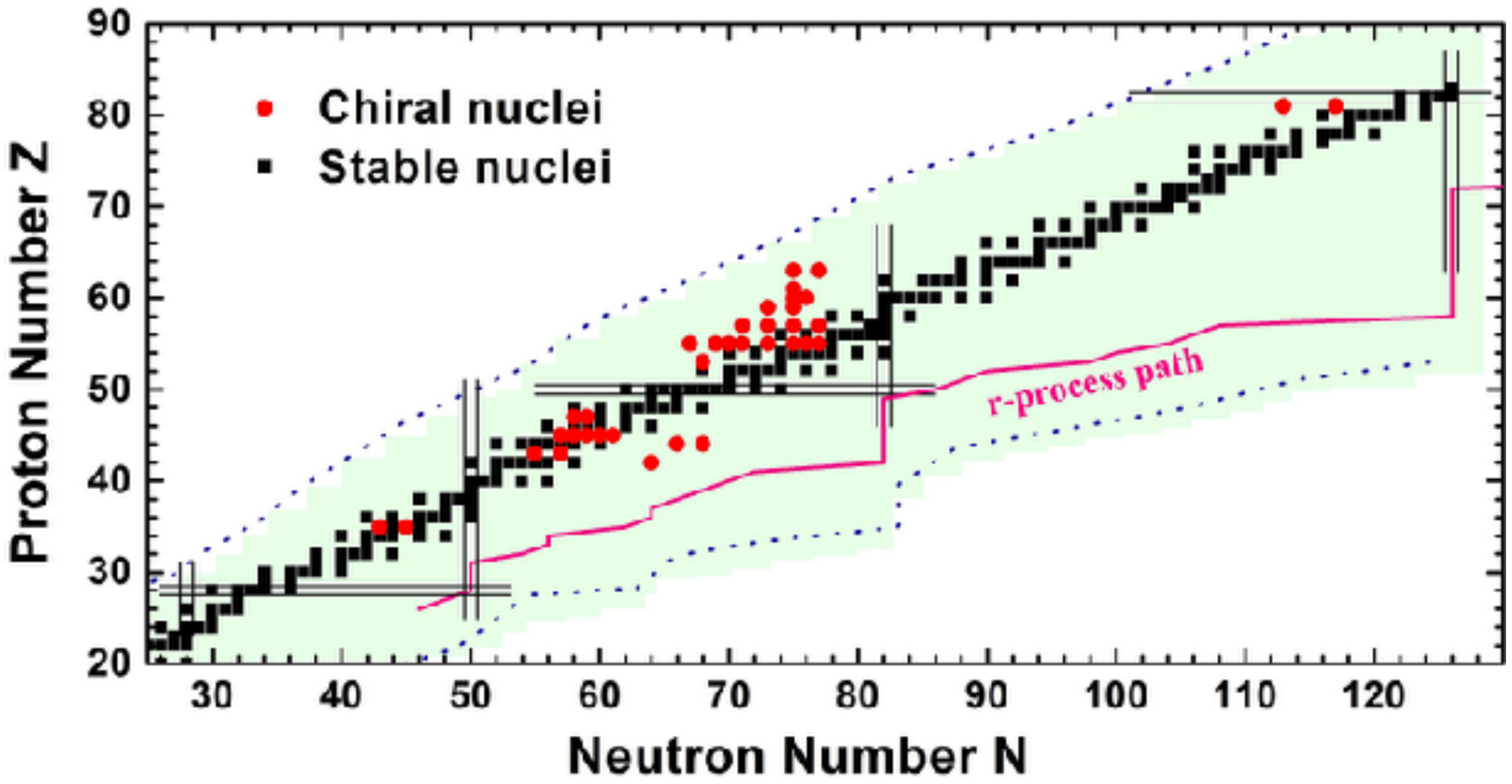
Pre-supernova structure and core-collapse

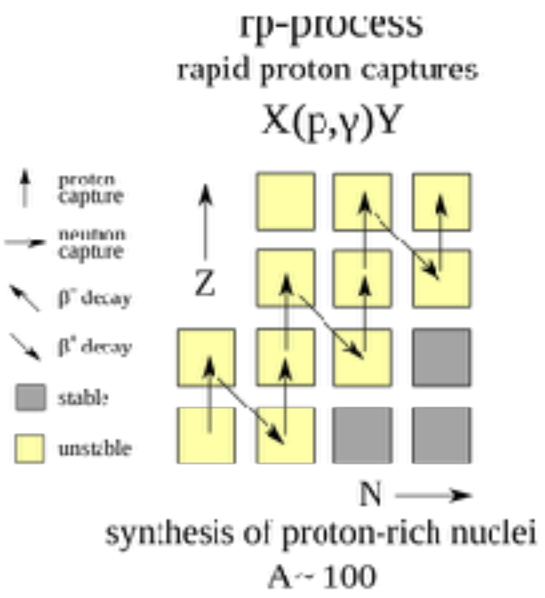


Core-collapse supernovae

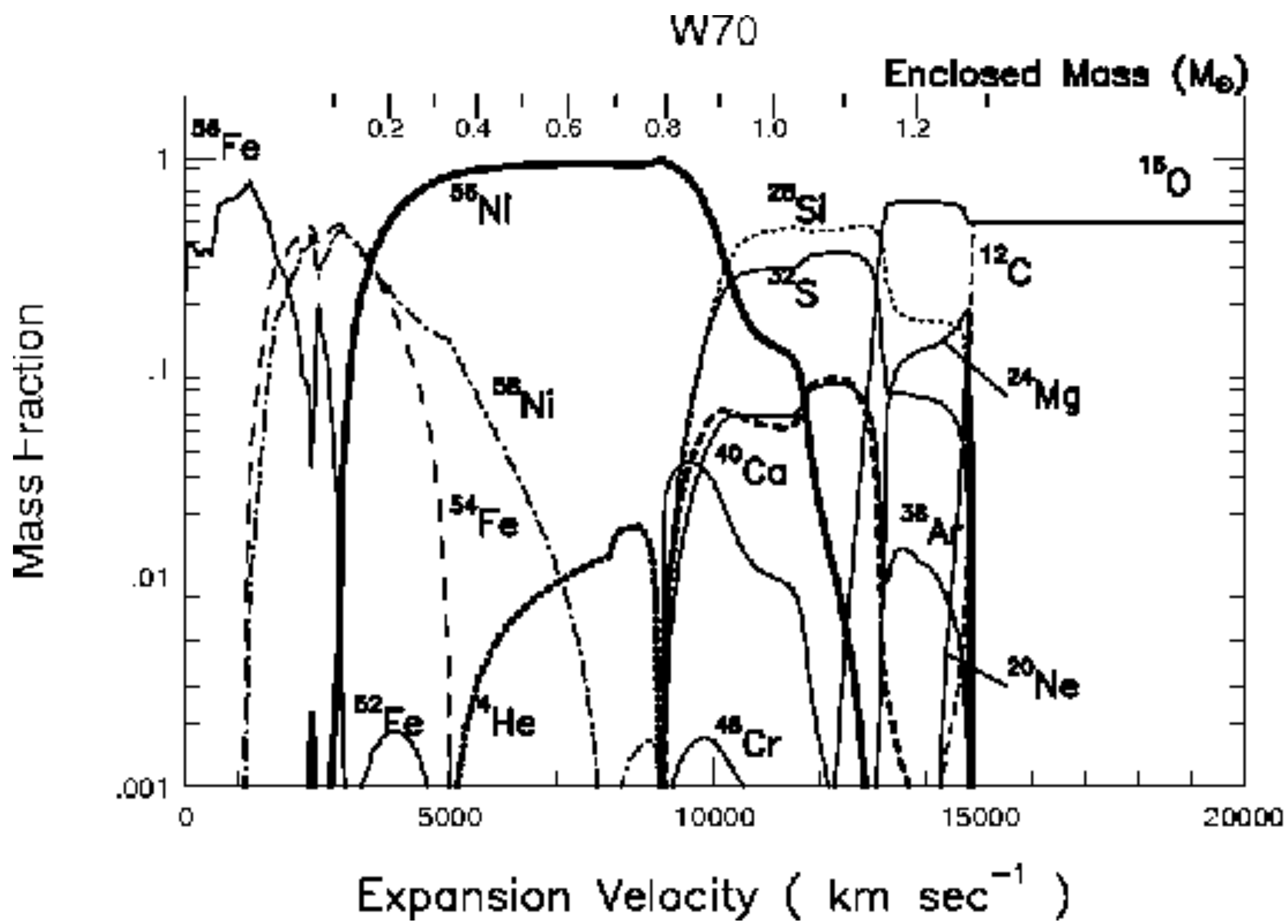


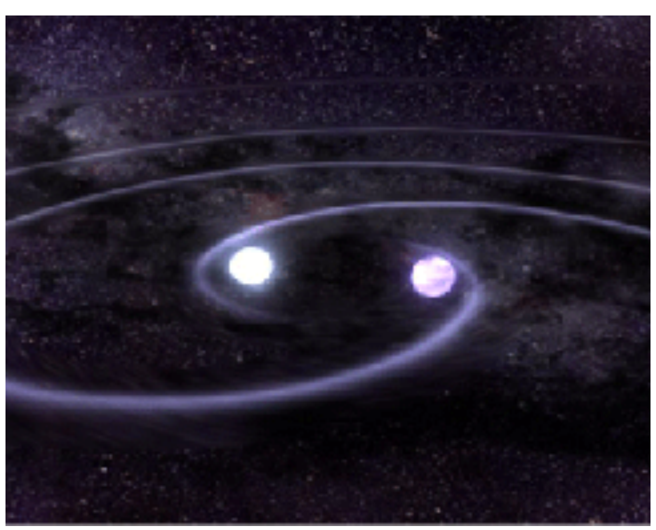
Explosive nucleosynthesis (rapid neutron capture; r-process; rp-process)



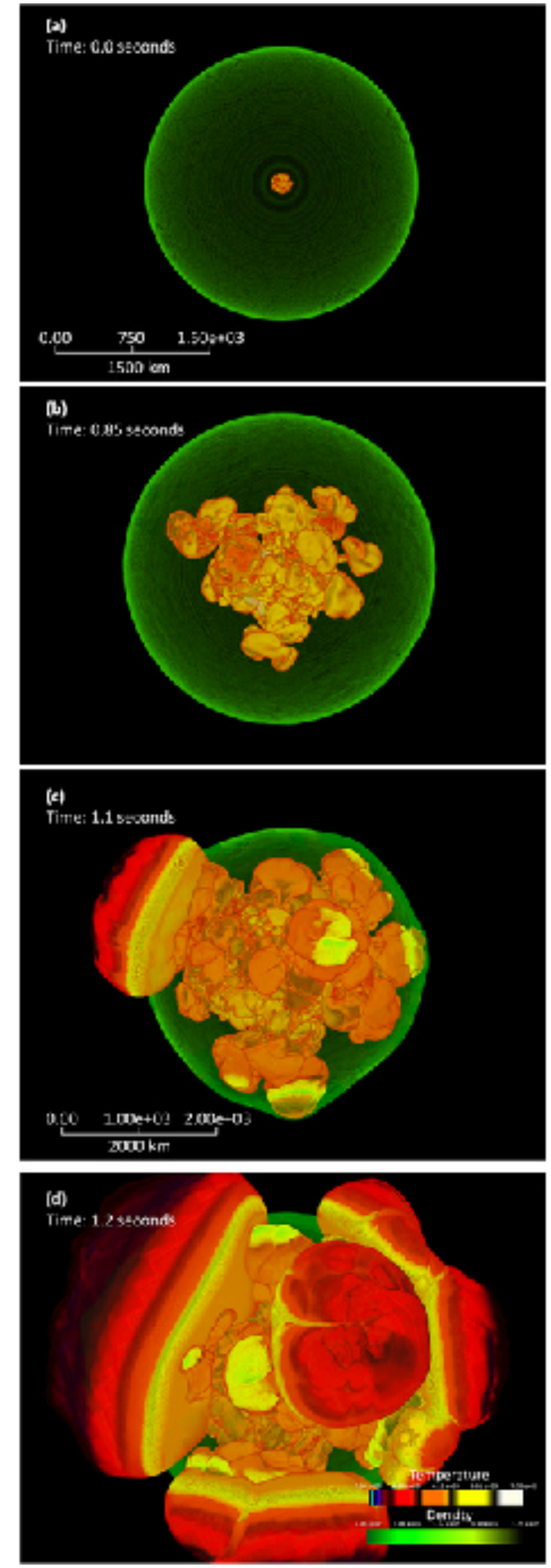


Type Ia supernovae (NSE)



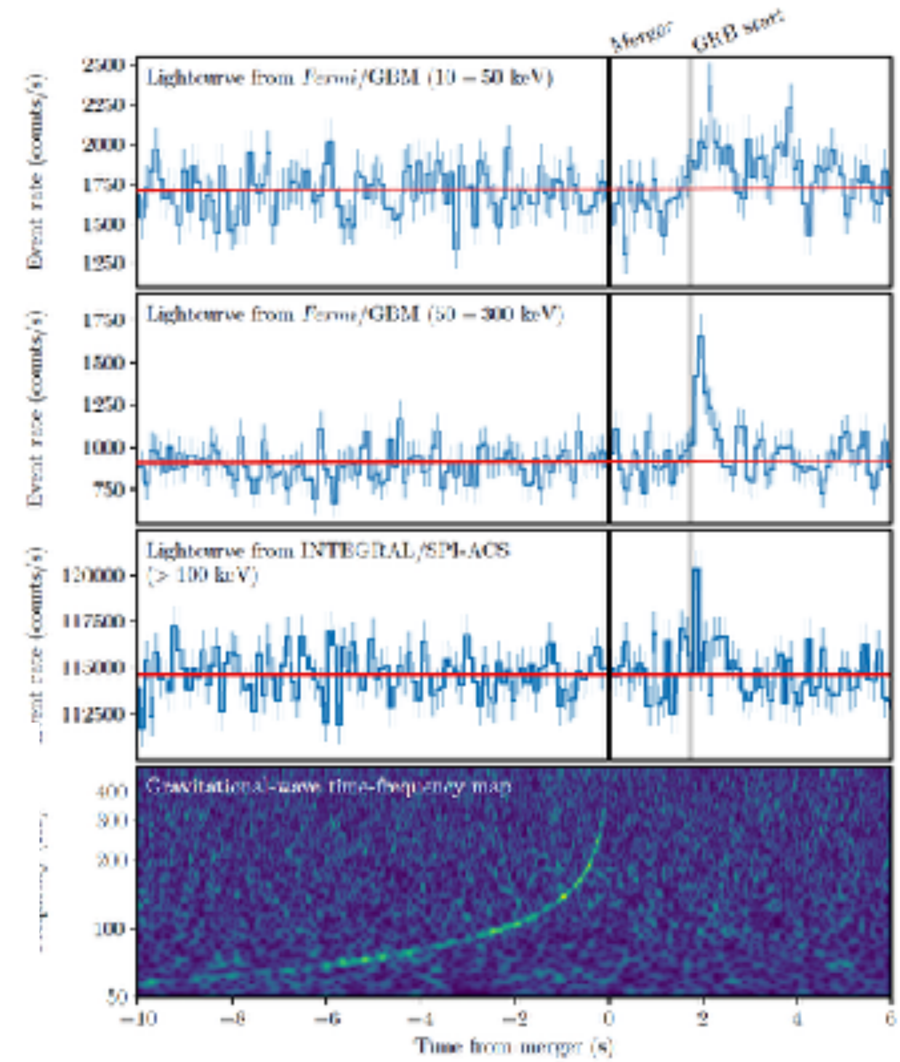


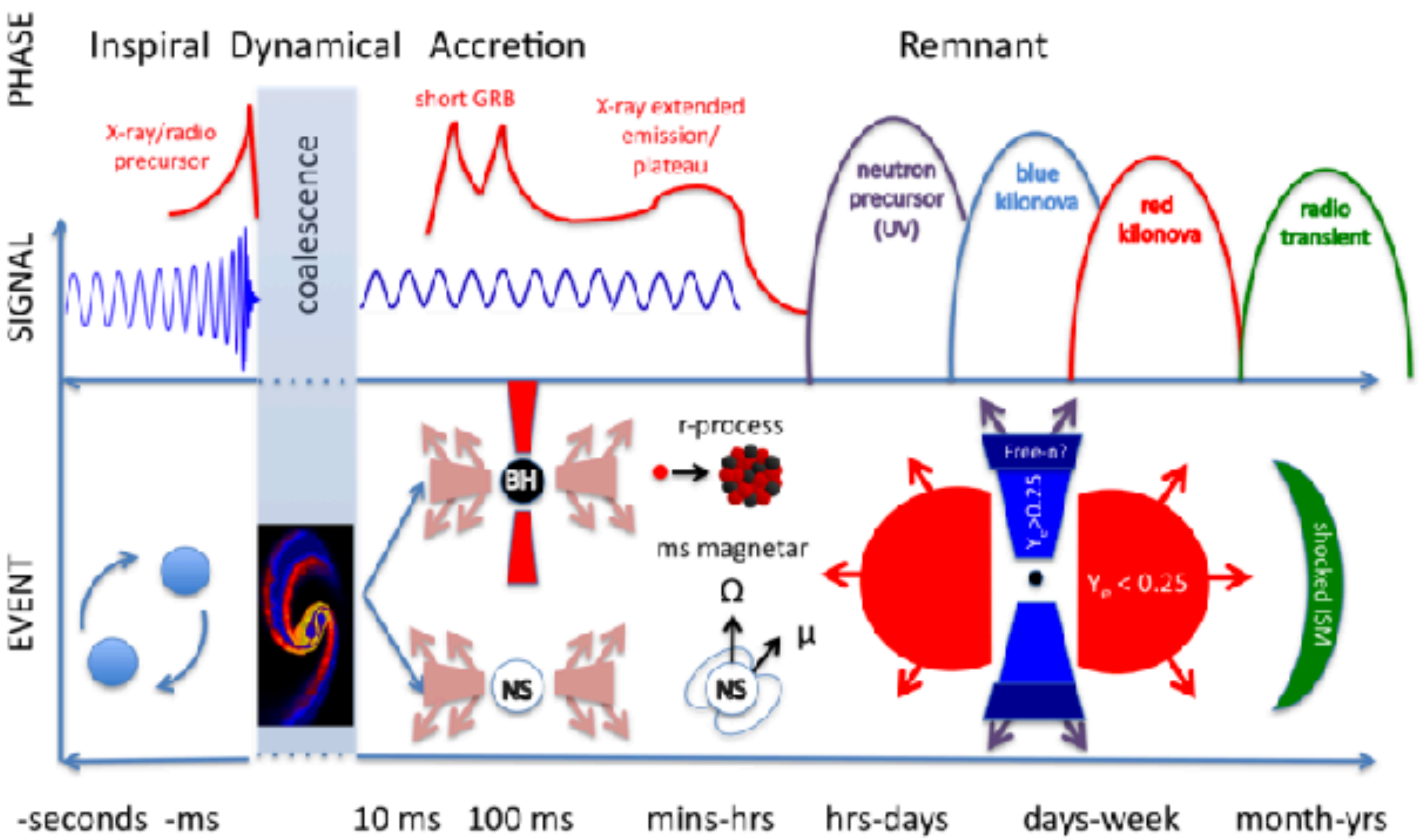
Progenitors still debated
Responsible for most iron-peak elements

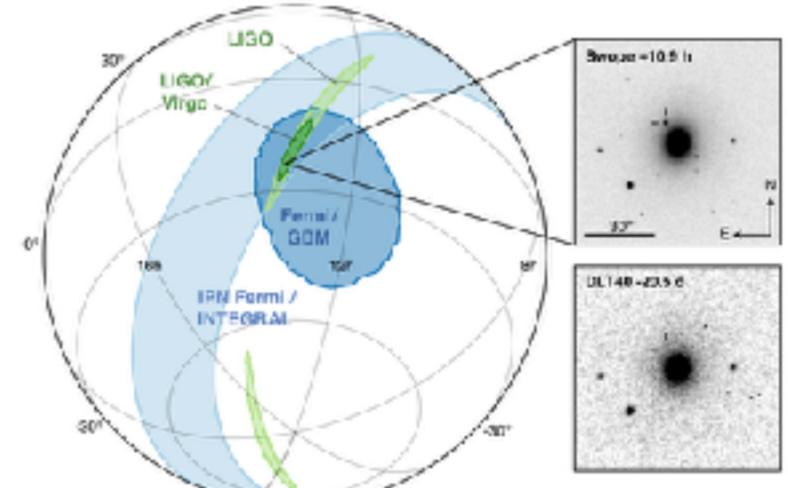


Neutron star mergers, gamma-ray bursts

GW 170814

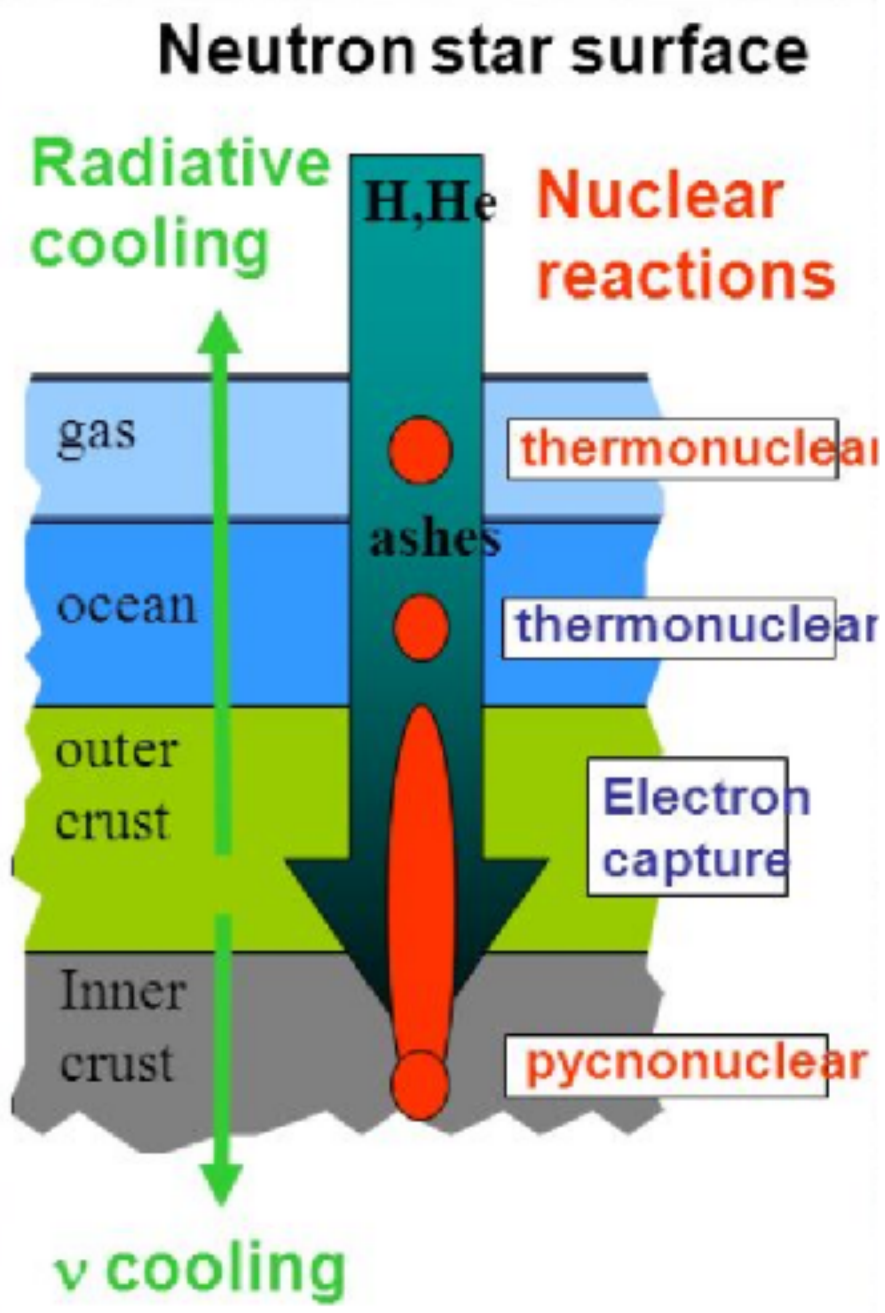




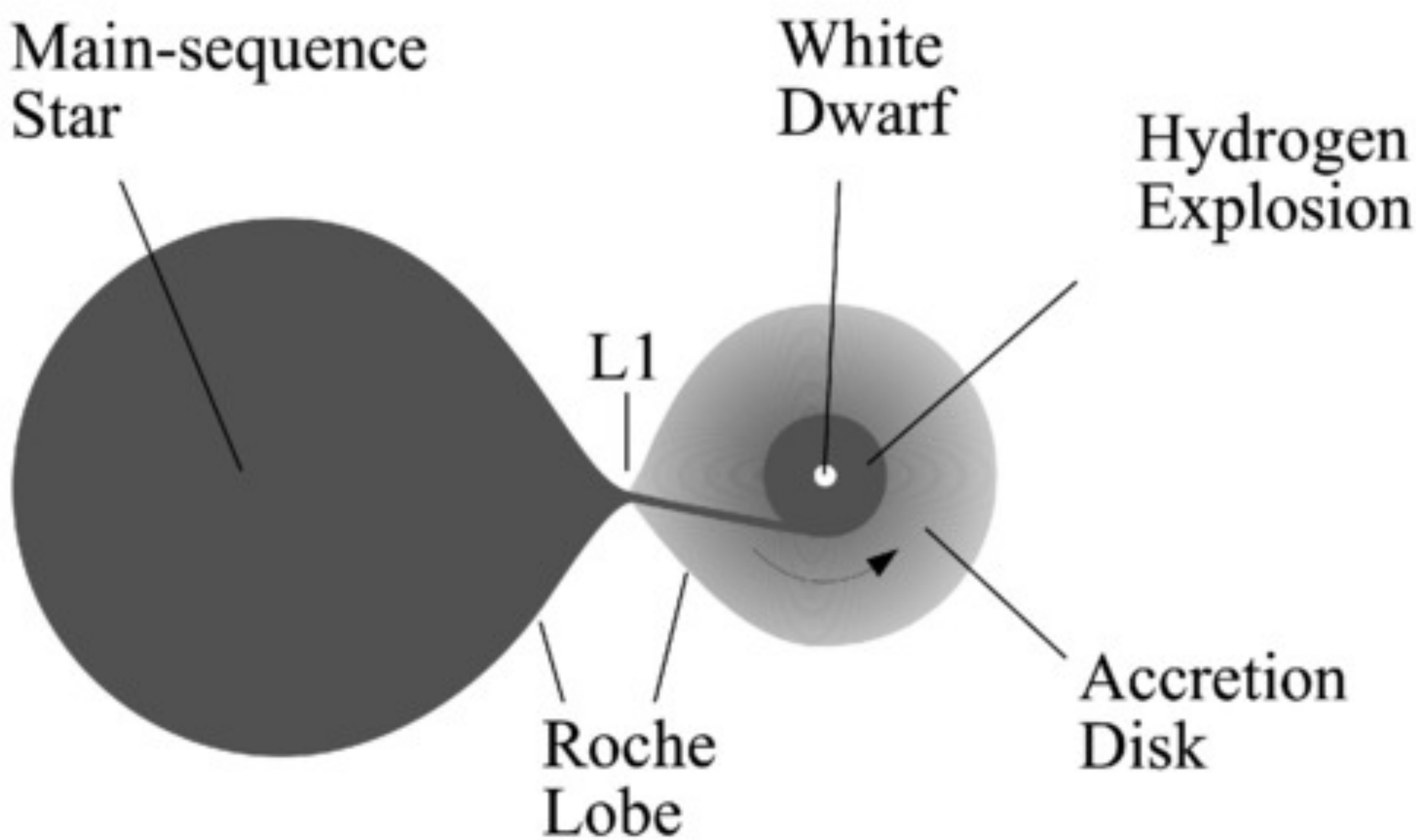


Pycno-nuclear reactions

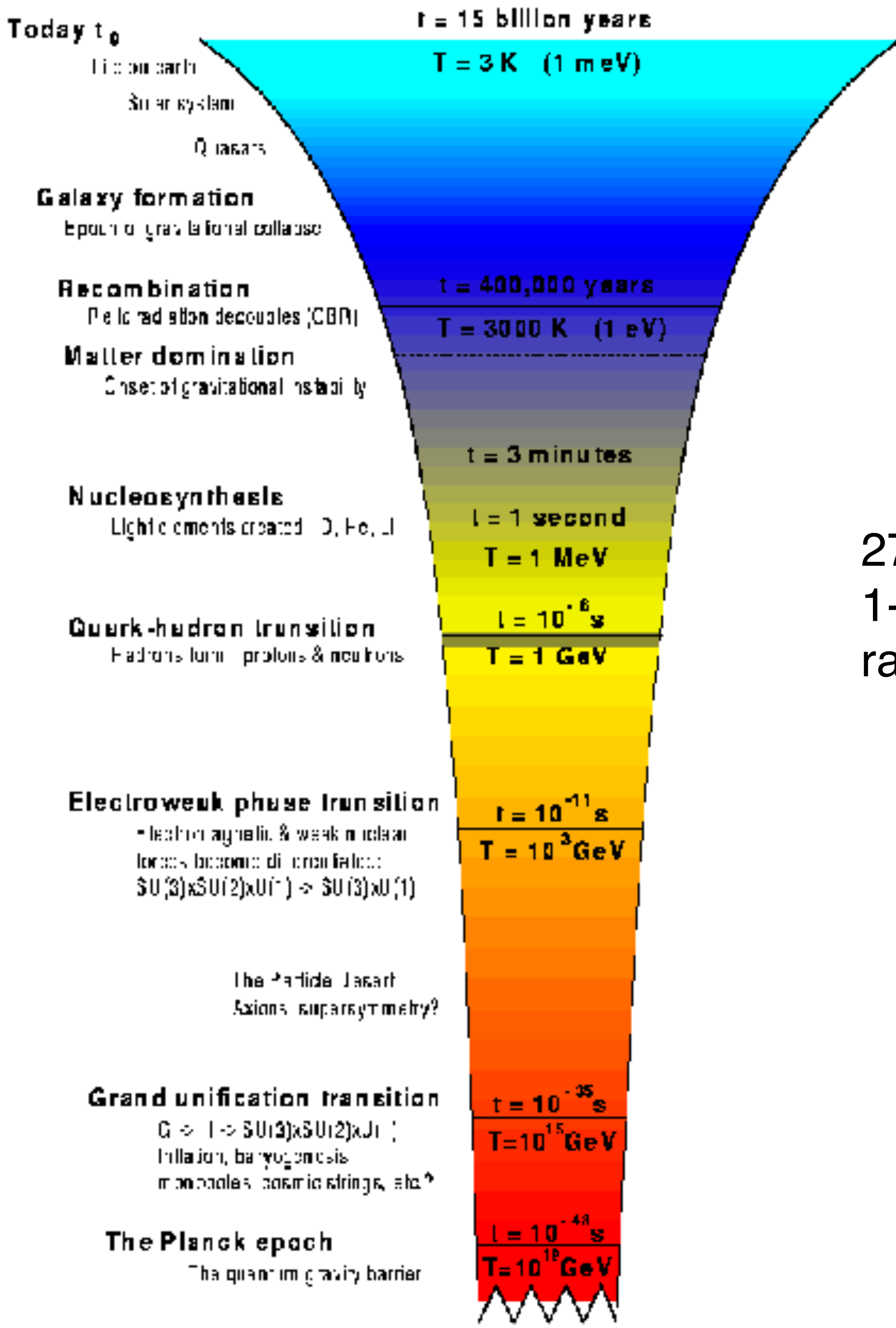
Inside neutron stars, at extremely high densities, the effective coulomb barrier is reduced by high neutron fraction, close distance and electron cloud



Binary stars: x-ray binaries, classical novae, etc

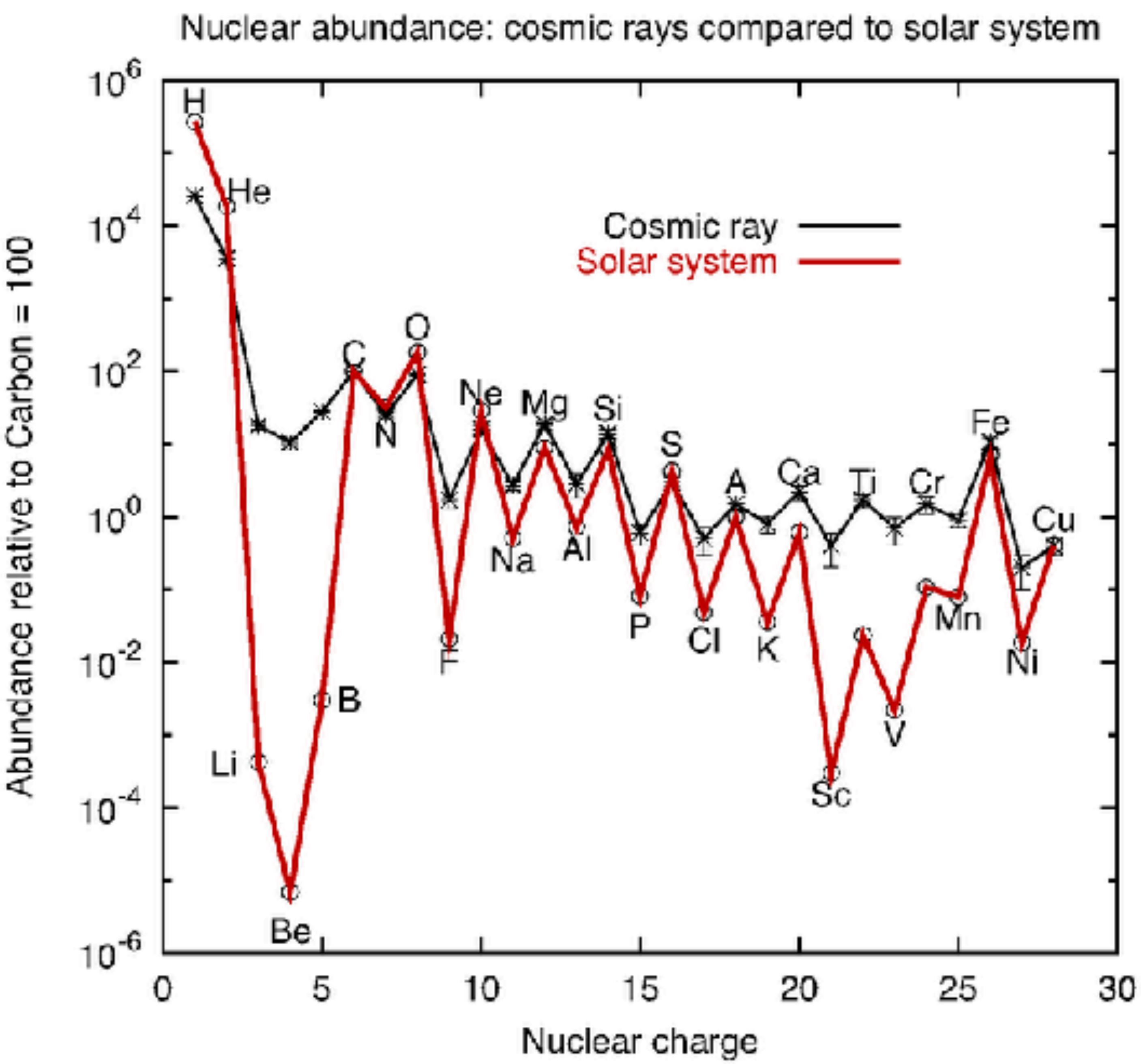


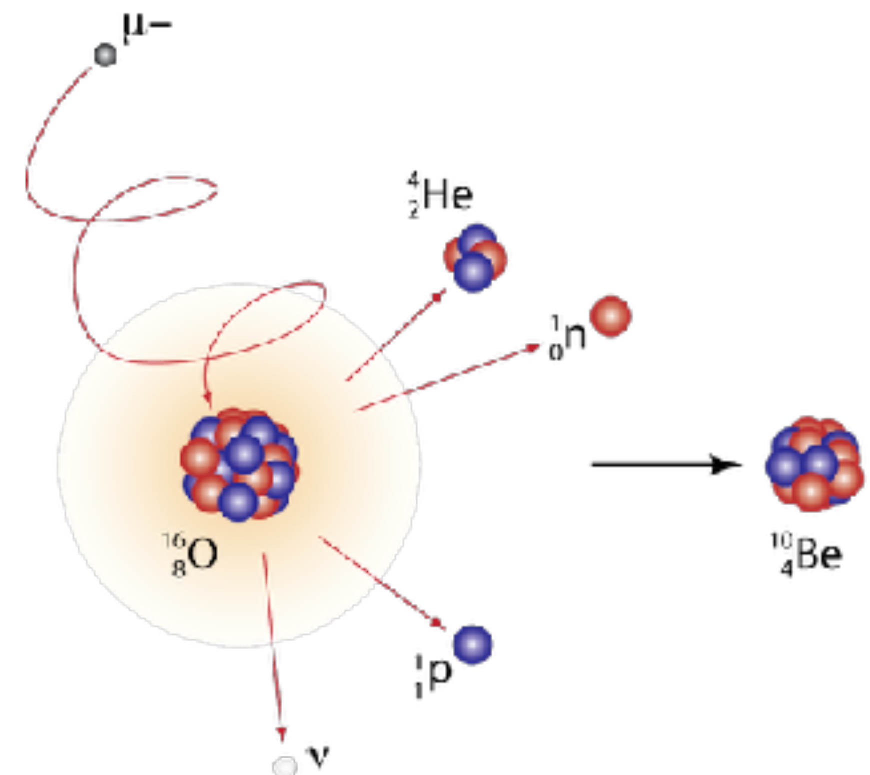
Primordial nucleosynthesis



27% He requires primordial origin
1-3 sec after Big Bang: High temperatures but rapid cooling

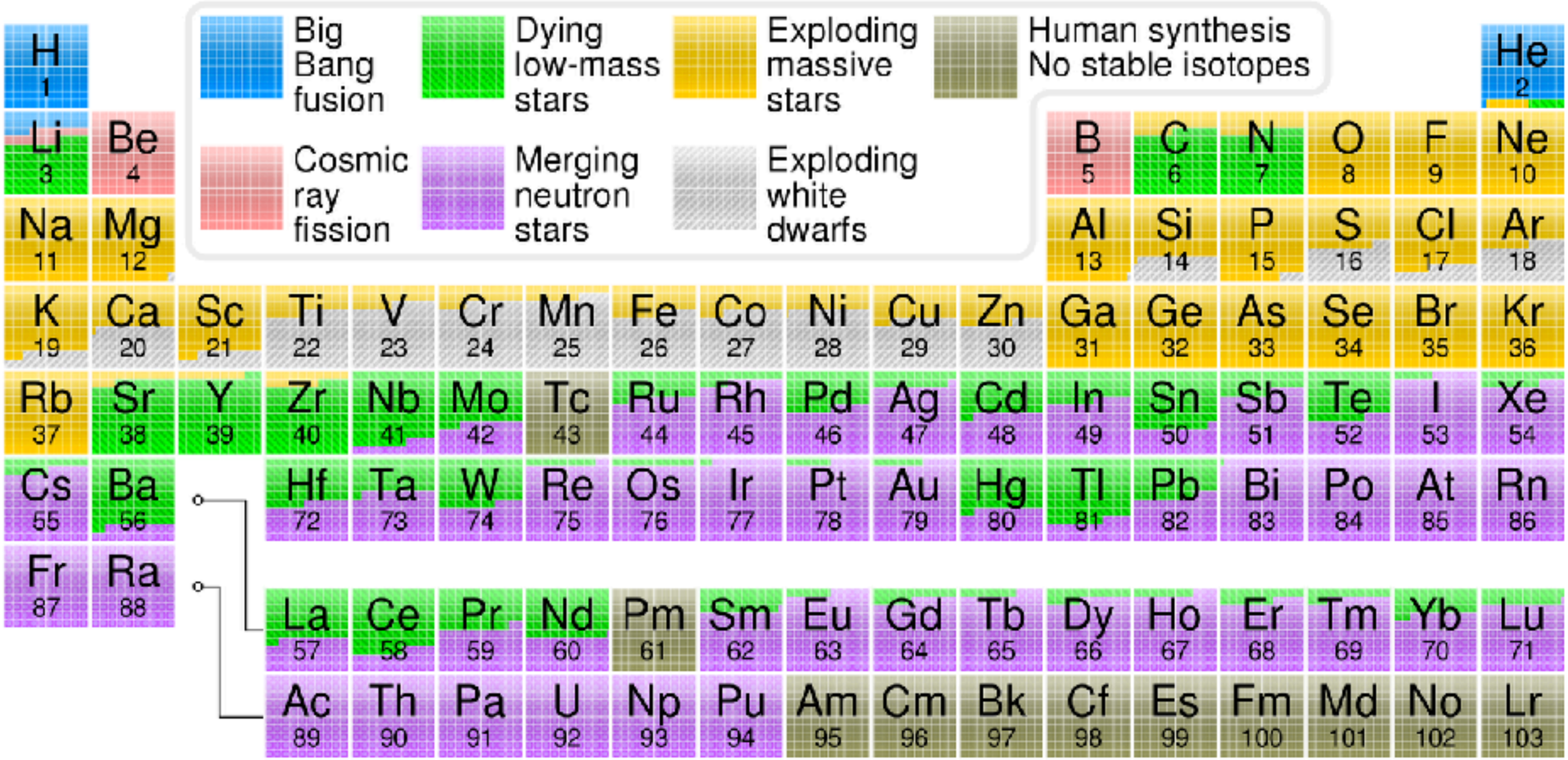
CR-induced spallation





Not enough to explain observed Li abundances in the Solar System, other processes required (explosive nucleosynthesis, novae, red giants?)

Origin of elements



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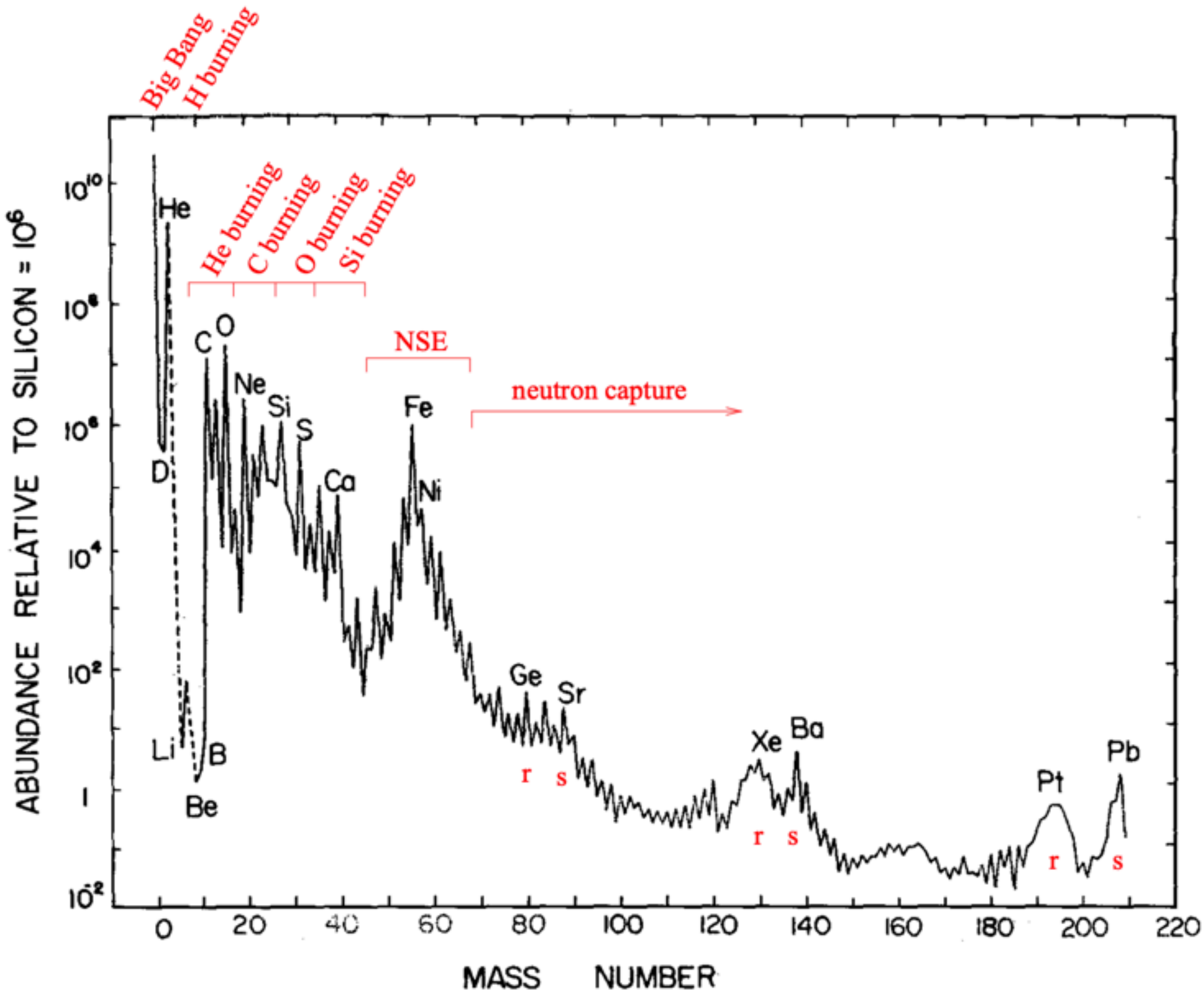
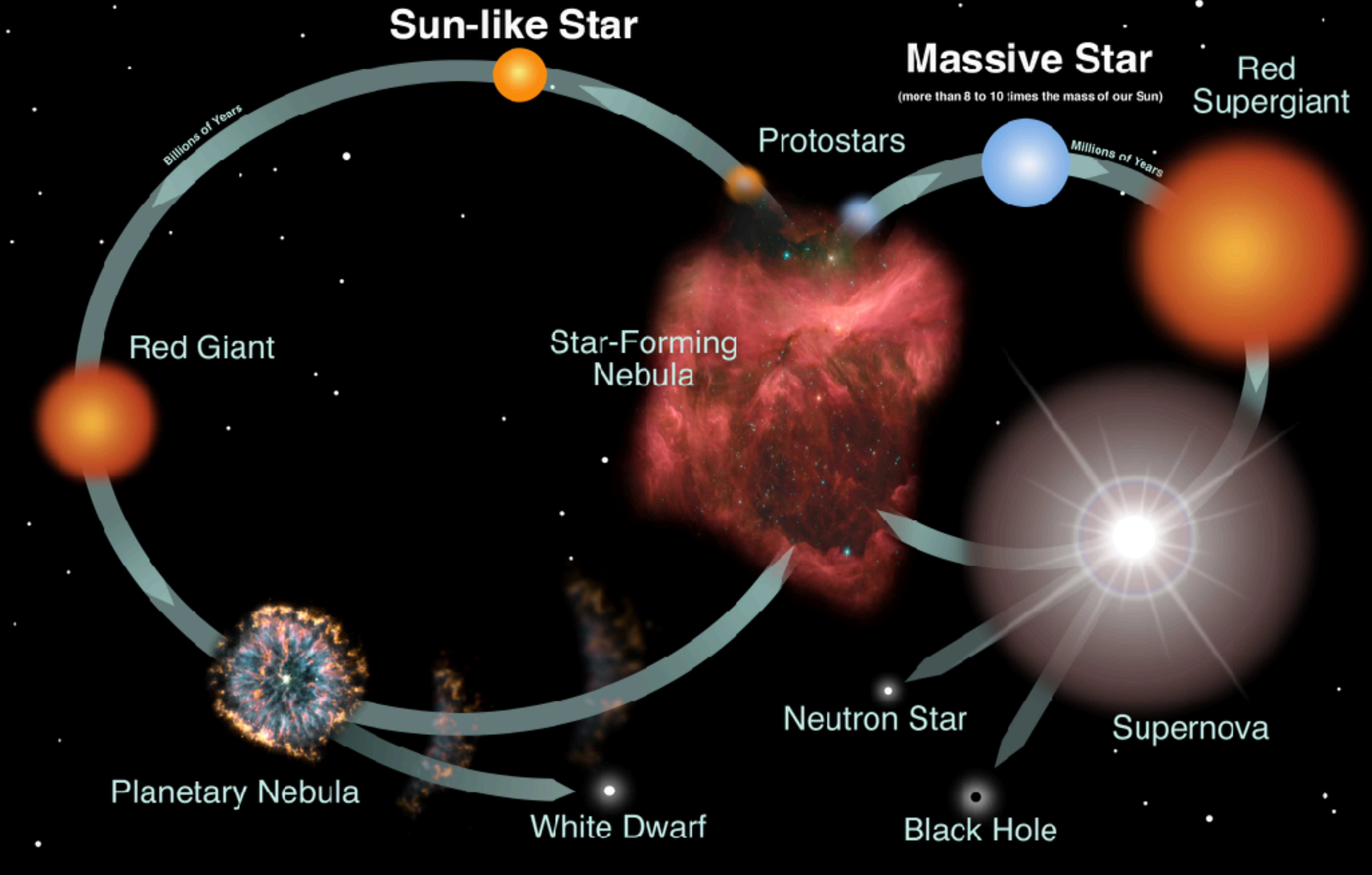


Nucleosynthesis goes on



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