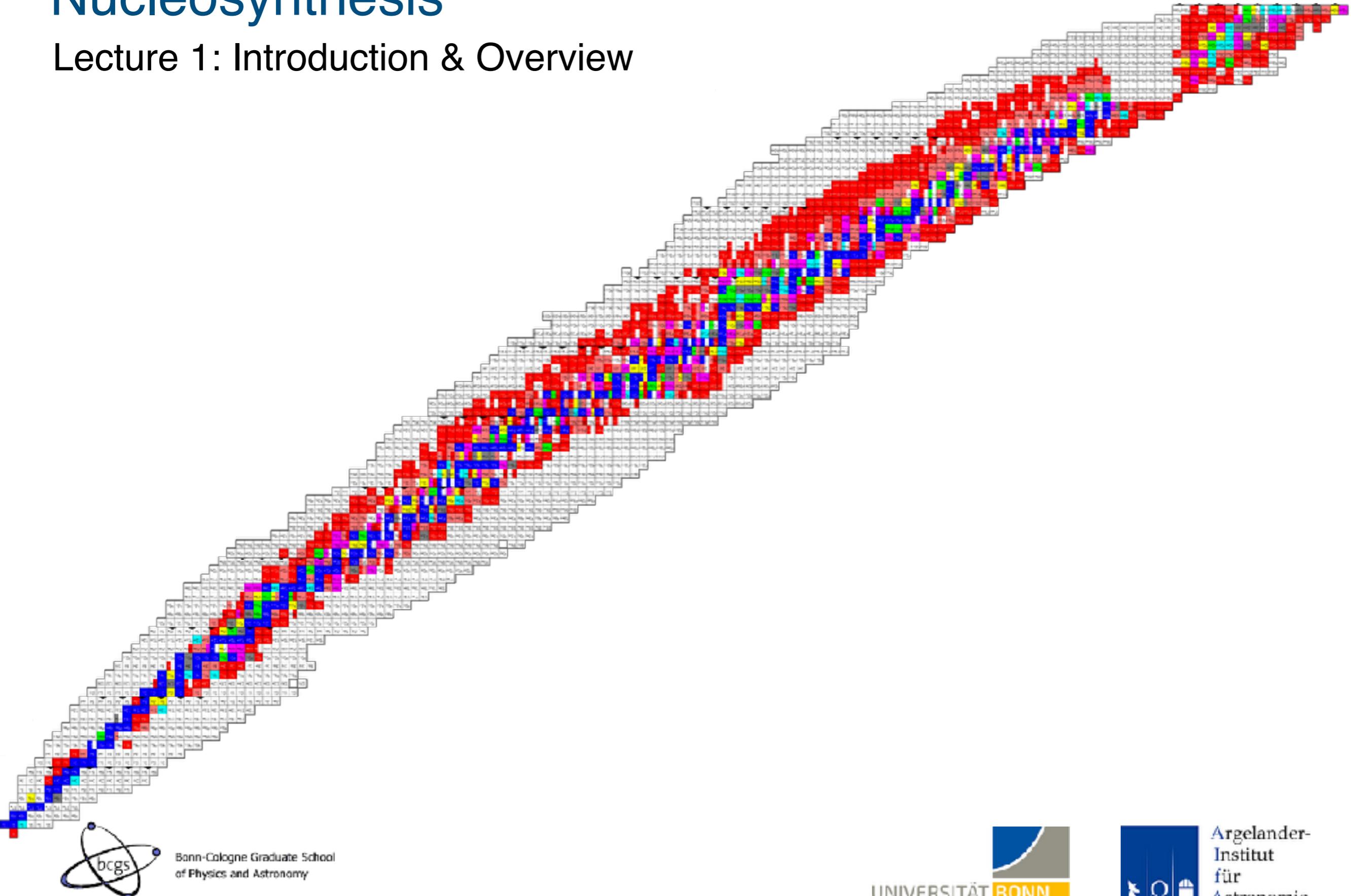


Nucleosynthesis

Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School
of Physics and Astronomy



Argelander-
Institut
für
Astronomie

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)

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

Evaluation

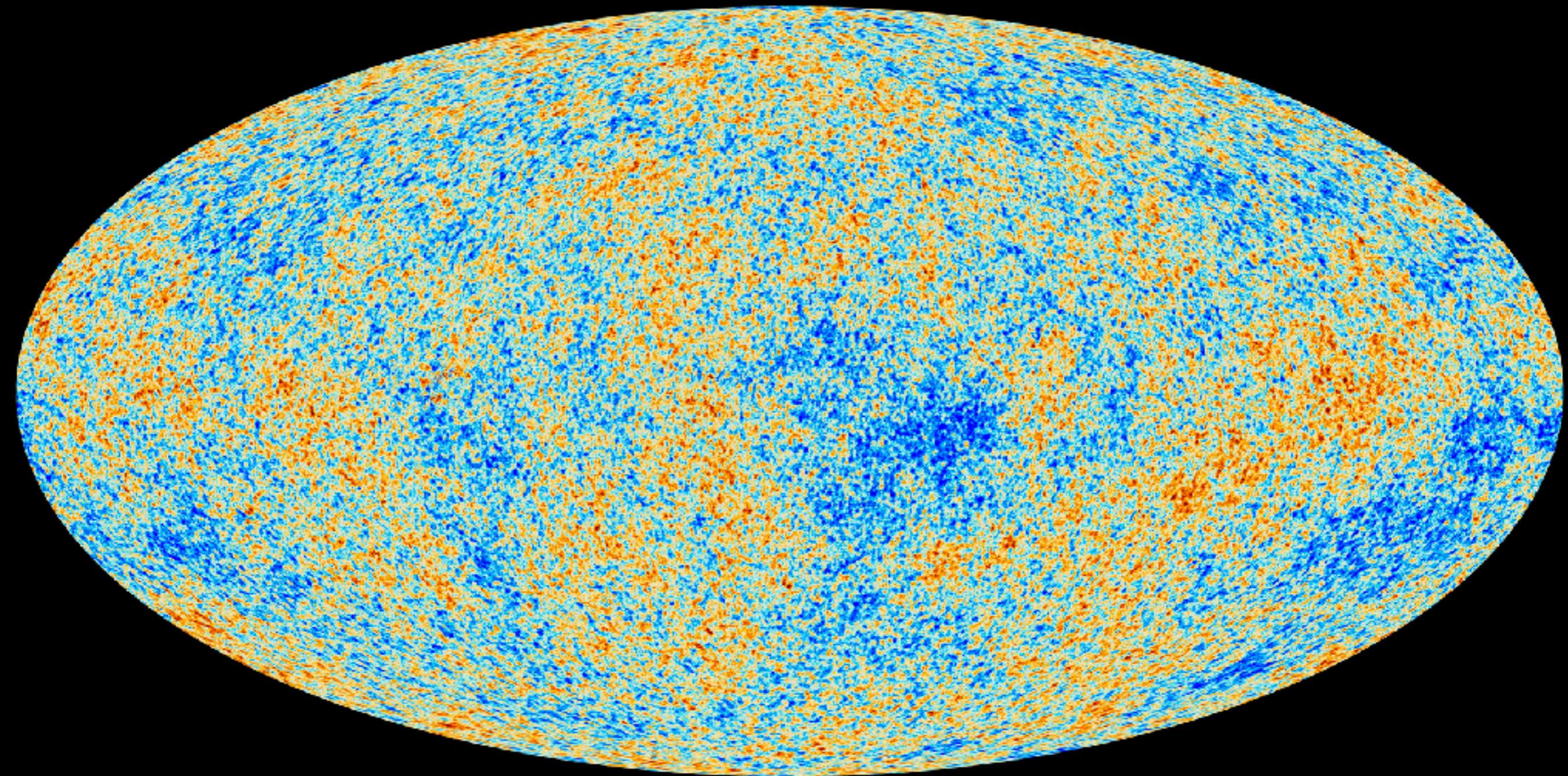
- Read material beforehand and e-mail at least 3 non-trivial questions before **Tuesday @ 13:00**
email to tutors; use subject heading [Nuc] **25%**
- Lectures and Exercises (compulsory attendance) **25%**
- Student presentations on nucleosynthesis papers
check website for paper suggestions **50%**

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
• Lecture 5: Thermonuclear reactions inside stars – II (advanced burning)	May 16
• Lecture 6: Neutron-capture and supernovae – I	May 23
• Lecture 7: Neutron-capture and supernovae – II	June 6
• Lecture 8: Thermonuclear supernovae	June 13
• 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

1 IA 1A	H Hydrogen 1.001	2 IIA 2A	3 Li Lithium 6.941	4 Be Beryllium 9.032	5 VB 5B	6 VIB 6B	7 VIIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.085	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.949	
19 K Potassium 39.090	20 Ca Calcium 40.070	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.980	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.720	32 Ge Germanium 72.031	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 64.466	38 Sr Strontium 69.983	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.925	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.866	48 Cd Cadmium 112.414	49 In Indium 114.816	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.296	
55 Cs Cesium 132.905	56 Ba Barium 137.329	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.949	74 W Tungsten 183.84	75 Re Rhenium 186.217	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.065	79 Au Gold 196.967	80 Hg Mercury 204.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.900	84 Po Polonium 209.903	85 At Astatine 216.907	86 Rn Radon 222.010	
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (265)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Mertensium (266)	110 Ds Darmstadtium (268)	111 Rg Roentgenium (270)	112 Cn Copernicium (272)	113 Uut Ununtrium unknown	114 Fl Florium unknown	115 Uup Ununpentium unknown	116 Lv Livermorium unknown	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown	

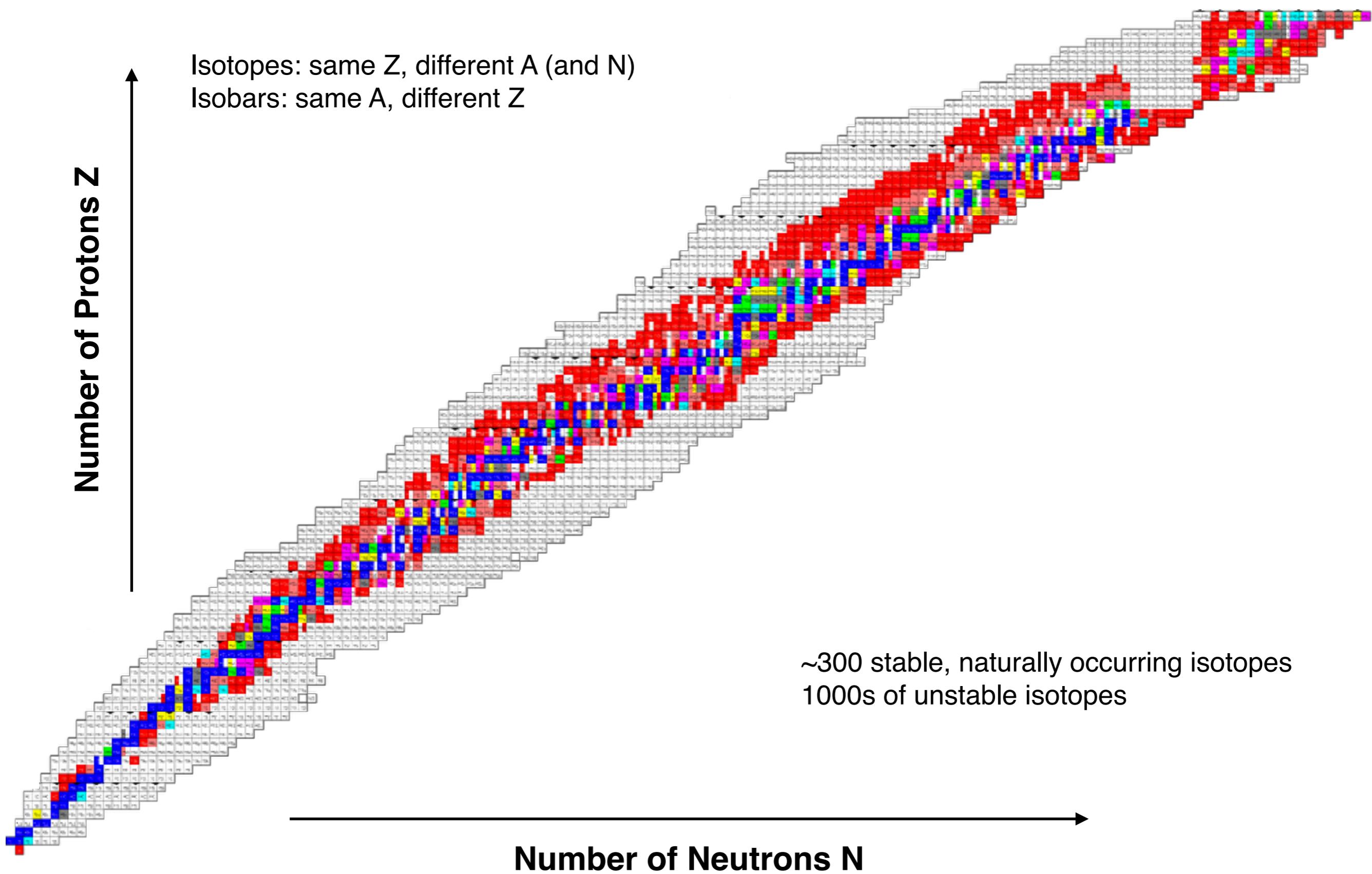
Periodic Table of the Elements

Atomic Number	Valence Charge
	Symbol
	Name
	Atomic Mass

Lanthanide Series	57 La Lanthanum 130.905	58 Ce Cerium 140.119	59 Pr Praseodymium 140.909	60 Nd Neodymium 144.242	61 Pm Promethium 147.919	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 159.265	66 Dy Dysprosium 162.580	67 Ho Holmium 164.920	68 Er Erbium 167.259	69 Tm Thulium 169.924	70 Yb Ytterbium 173.052	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.020	90 Th Thorium 232.039	91 Pa Protactinium 231.026	92 U Uranium 238.029	93 Np Neptunium 239.029	94 Pu Plutonium 243.026	95 Am Americium 243.021	96 Cm Curium 247.270	97 Bk Berkelium 247.270	98 Cf Californium 251.020	99 Es Einsteinium 257.020	100 Fm Fermium 257.025	101 Md Mendelevium 259.1	102 No Nobelium 259.101	103 Lr Lawrencium 259.0



Isotopes and isobars



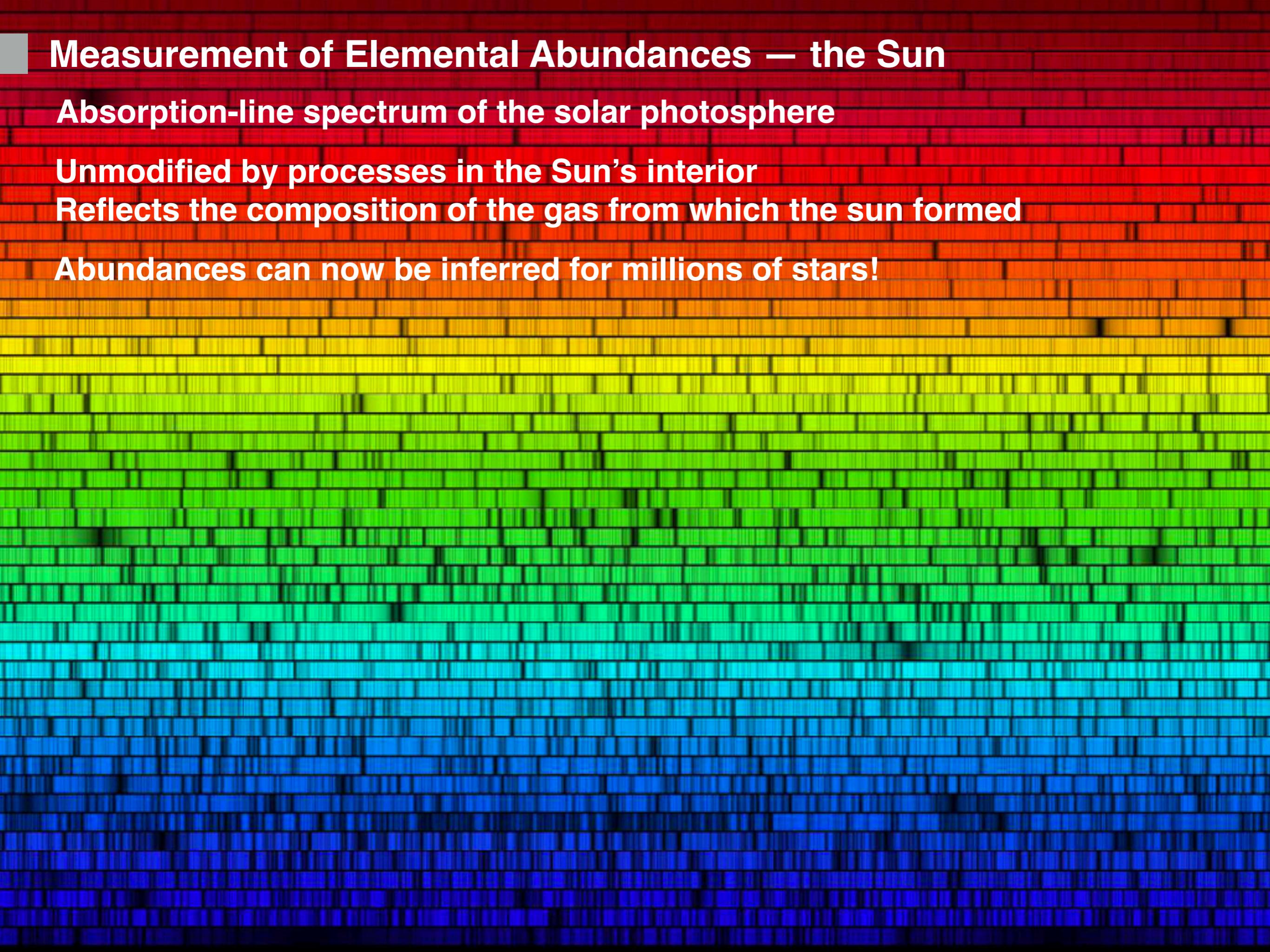
Measurement of Elemental Abundances – the Sun

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

“Metals”

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

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

Homogeneous solar system composition

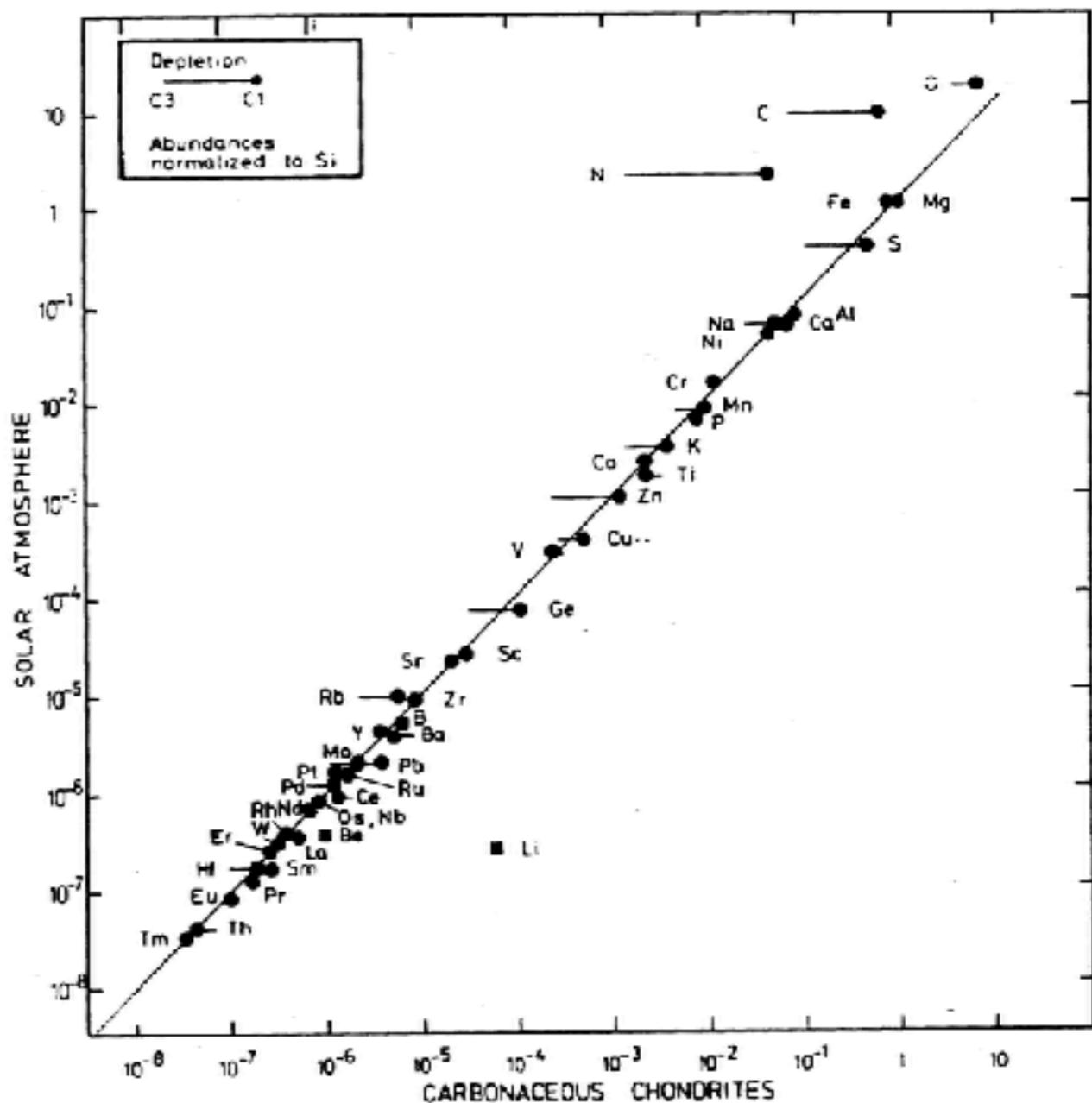
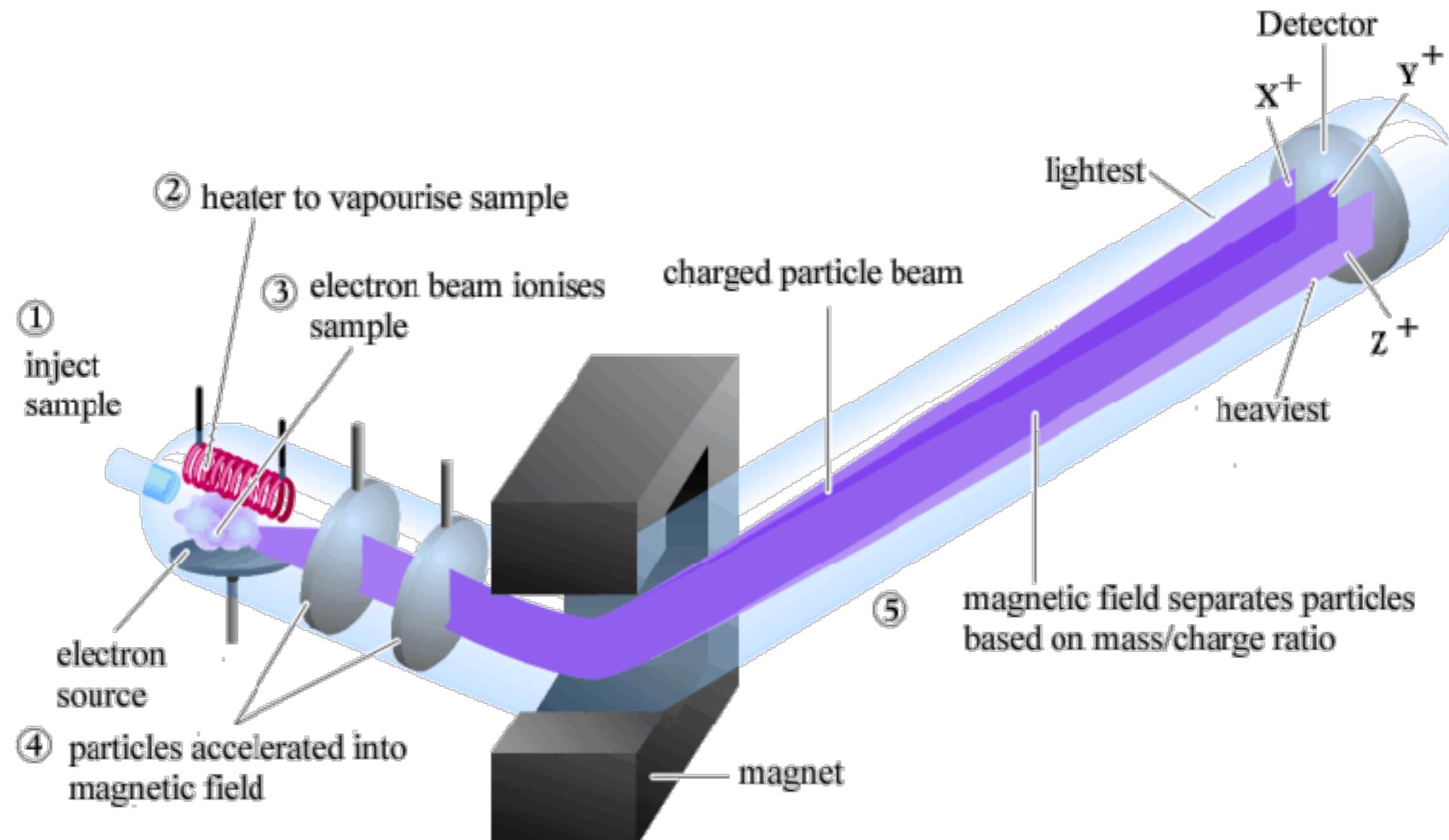


Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

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

Measurement of Isotopic Abundances

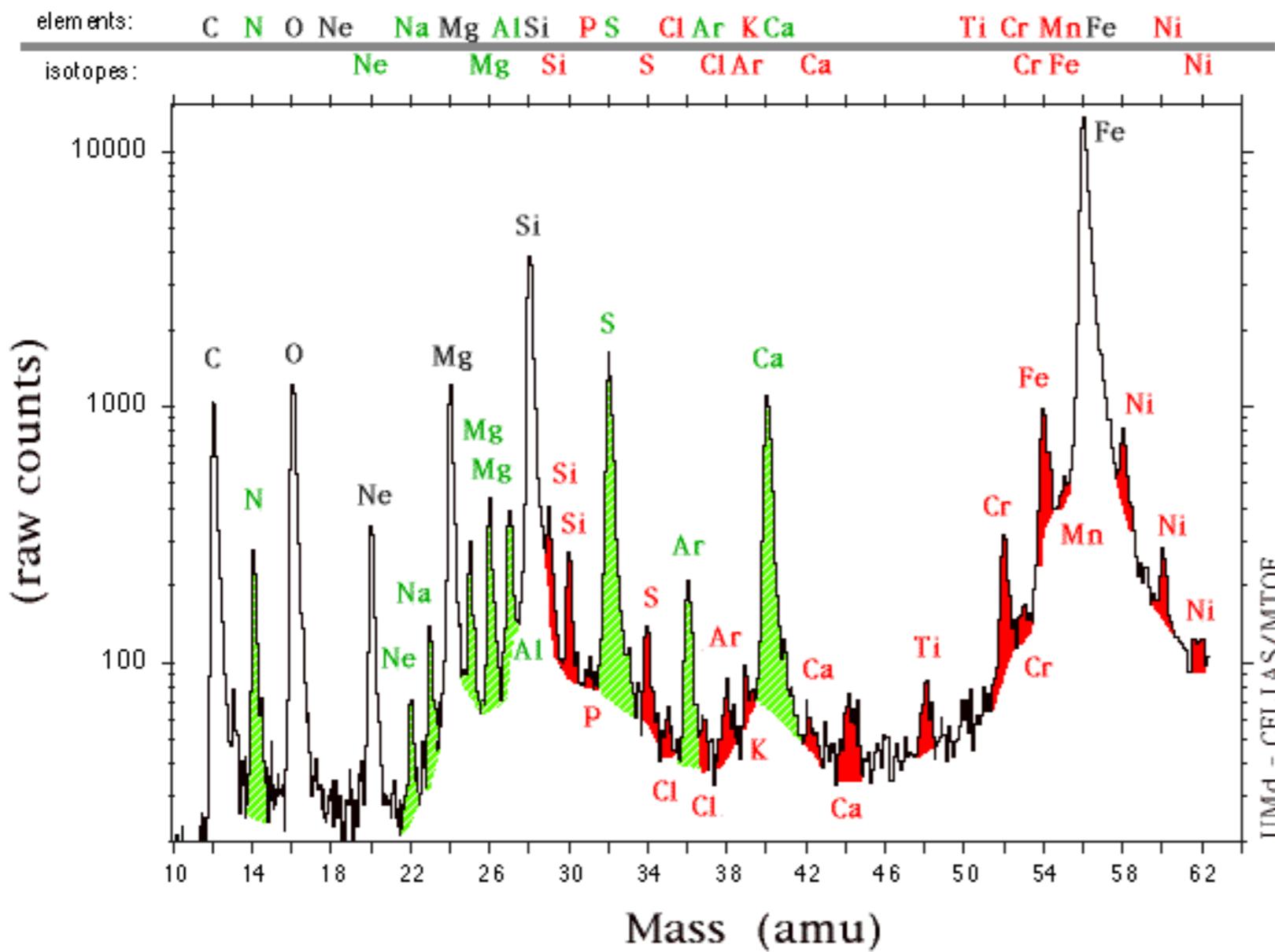
Masses of isotopes can be measured with a mass spectrometer



Measurement of Isotopic Abundances

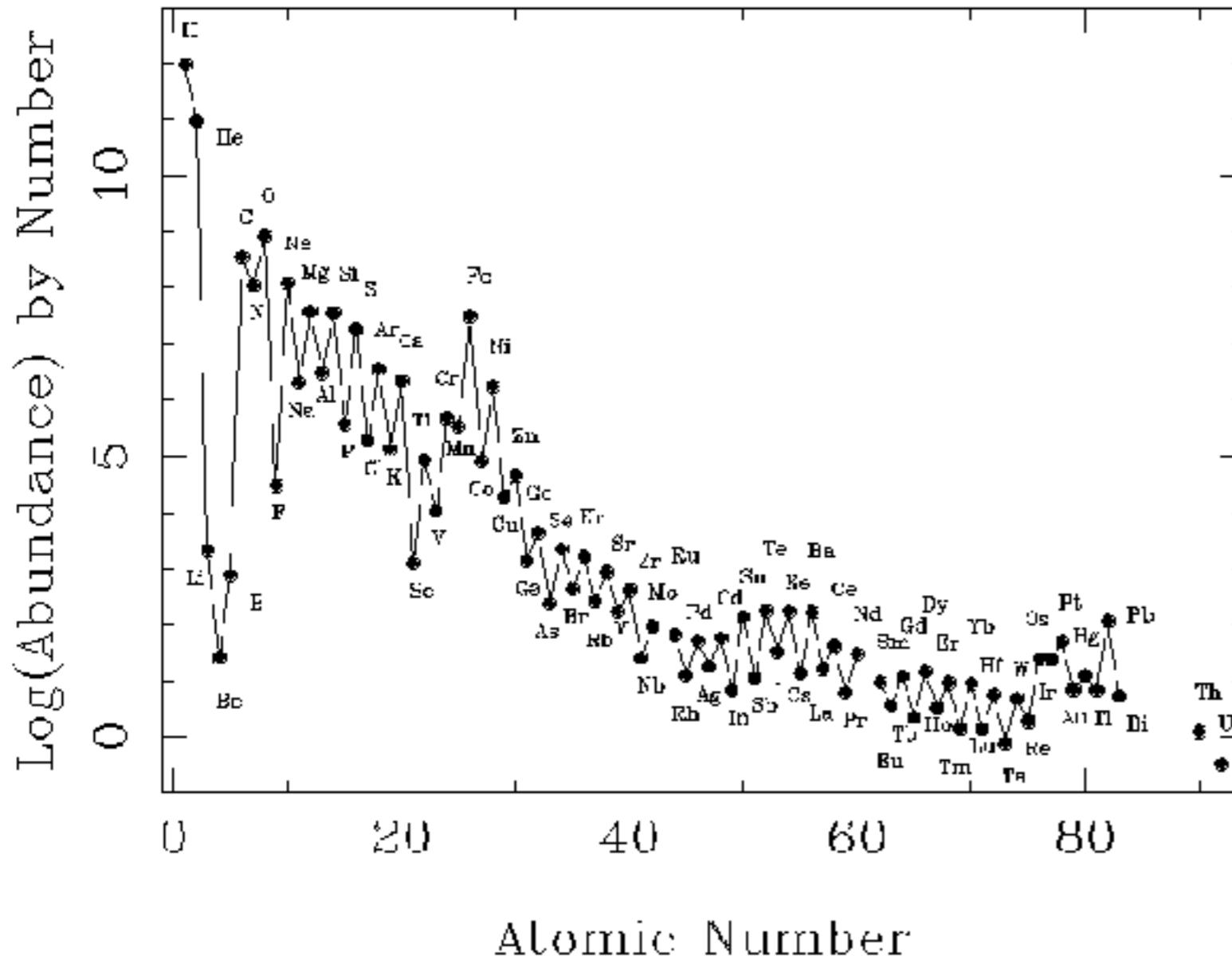
Isotope abundances in the solar system

Solar Wind Elements/Isotopes Observed by CELIAS MTOF



~~“Cosmic” Abundances~~

Logarithmic SAD Abundances: Log(H) = 12.0



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

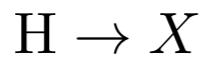
$$N_i = X_i/A_i$$

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

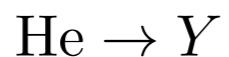
$$A_{\text{H}} = \log(N_{\text{H}}) = 12$$

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

By mass fraction



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



$$X + Y + Z = 1$$

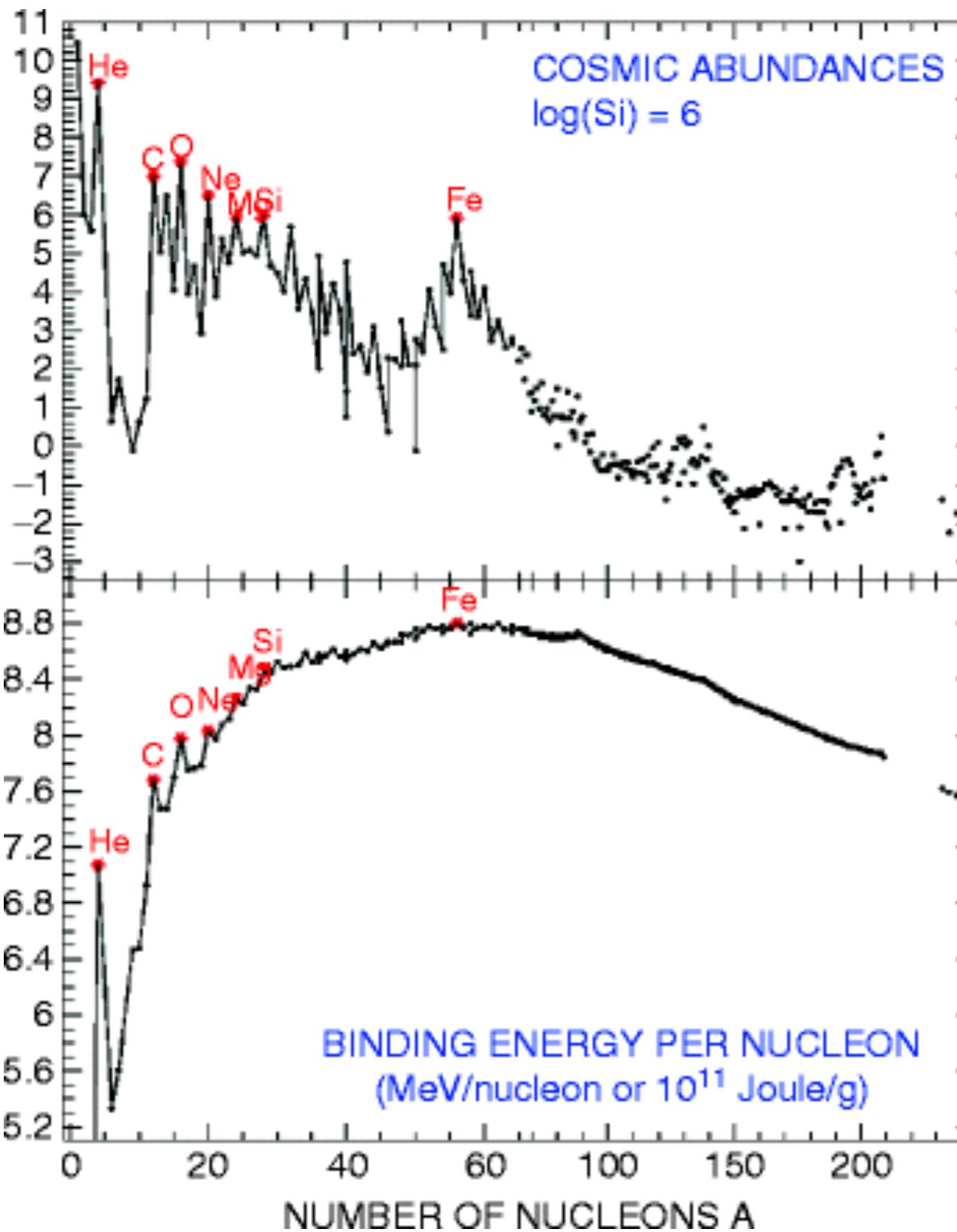


$$\sum X_i = 1$$

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 a -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

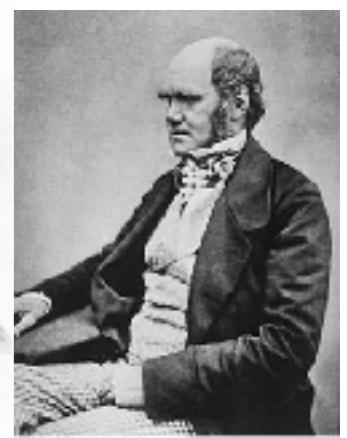
Before early 30s: Can nuclear reactions take place inside the Sun and the stars?

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?

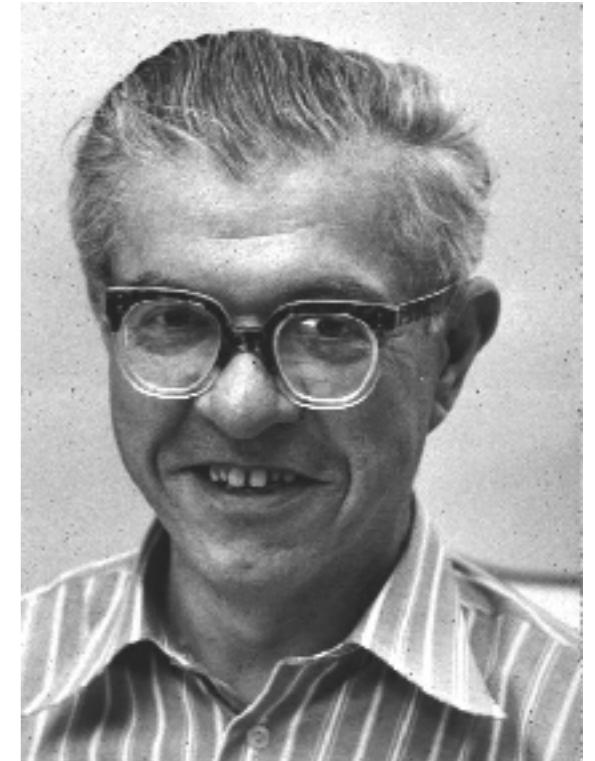
Debate in the 40s: Primordial or Big-bang nucleosynthesis vs stars and supernovae



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

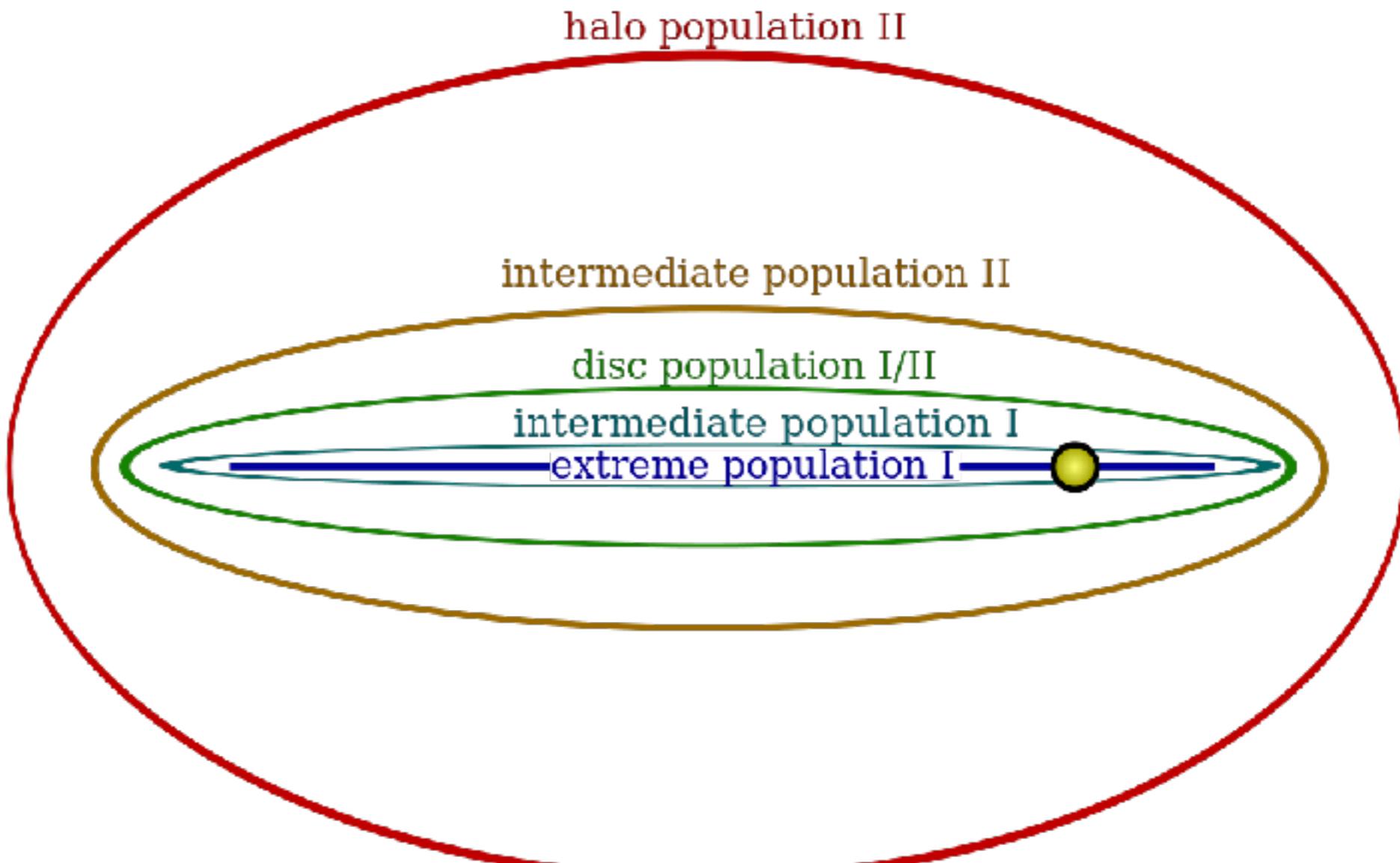


Fred Hoyle (1915–2001)

Elements created in stars and supernovae

Observational evidence for nucleosynthesis

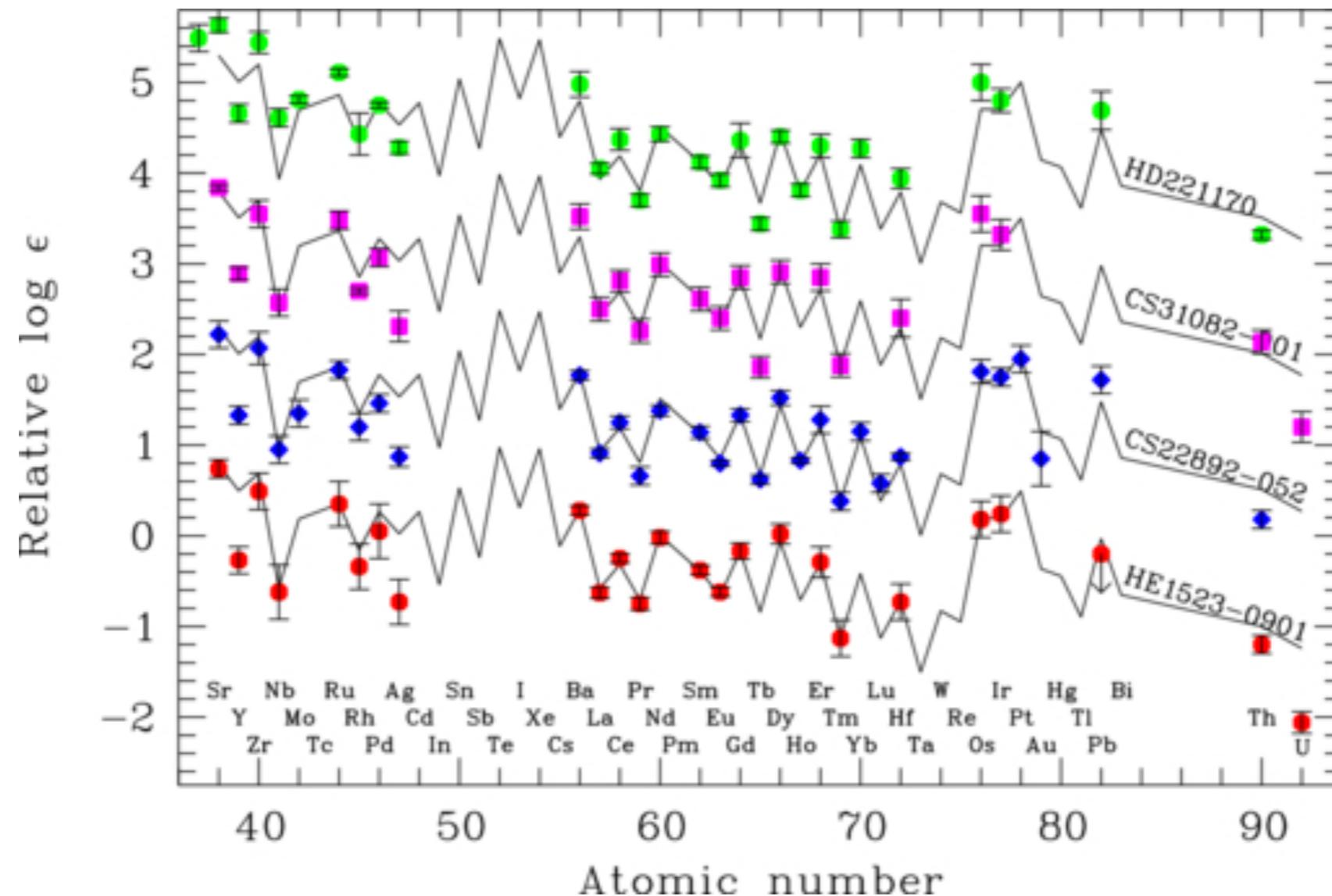
In early 50s: evidence for evolution of abundances with cosmic time
Stars near the galactic disk have higher metallicities than stars in the halo



Distribution of Star Populations
in Milky Way

Observational evidence for nucleosynthesis

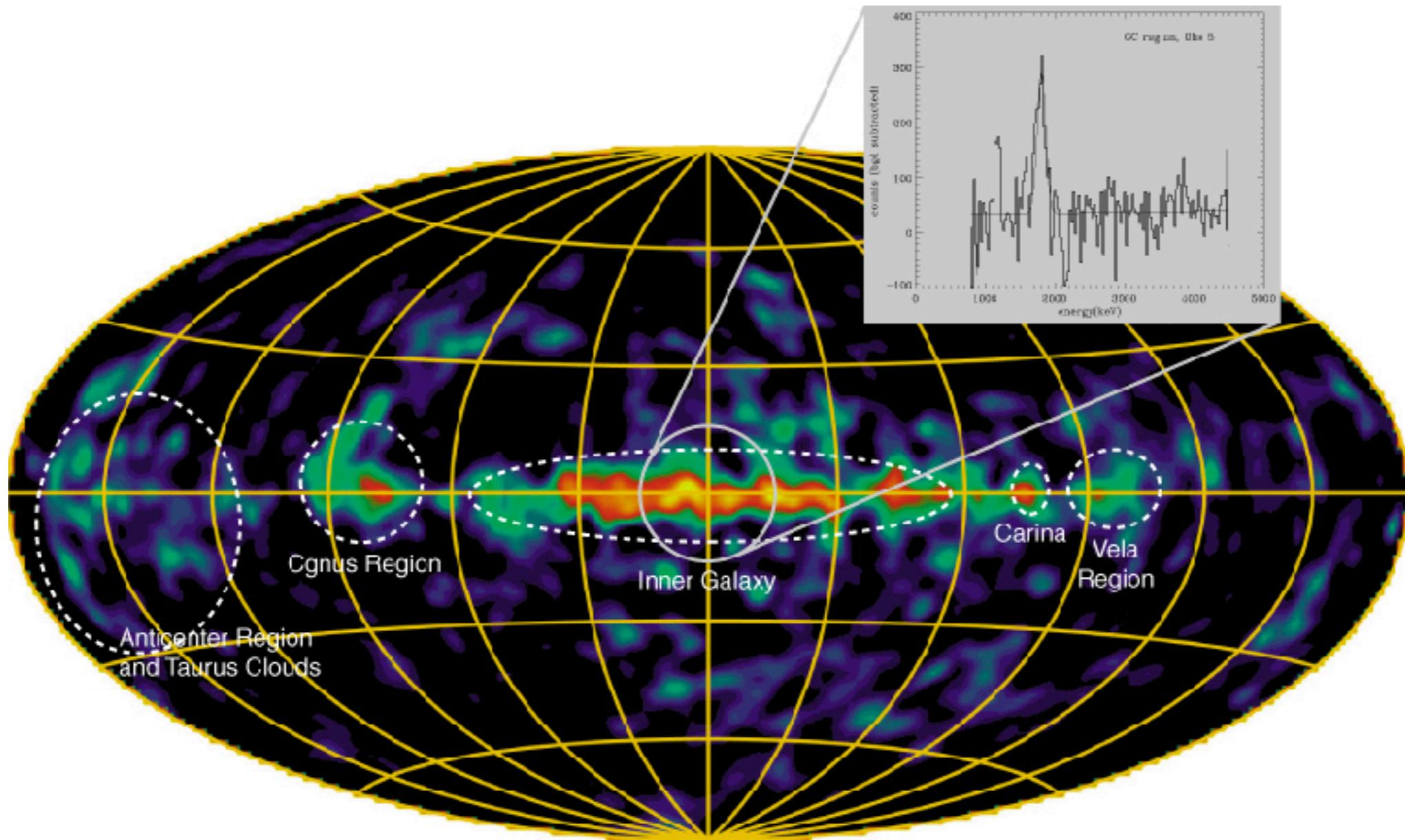
In early 50s: evidence for evolution of abundances with cosmic time
Stars near the galactic disk have higher metallicities than stars in the halo



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

Observational evidence for nucleosynthesis

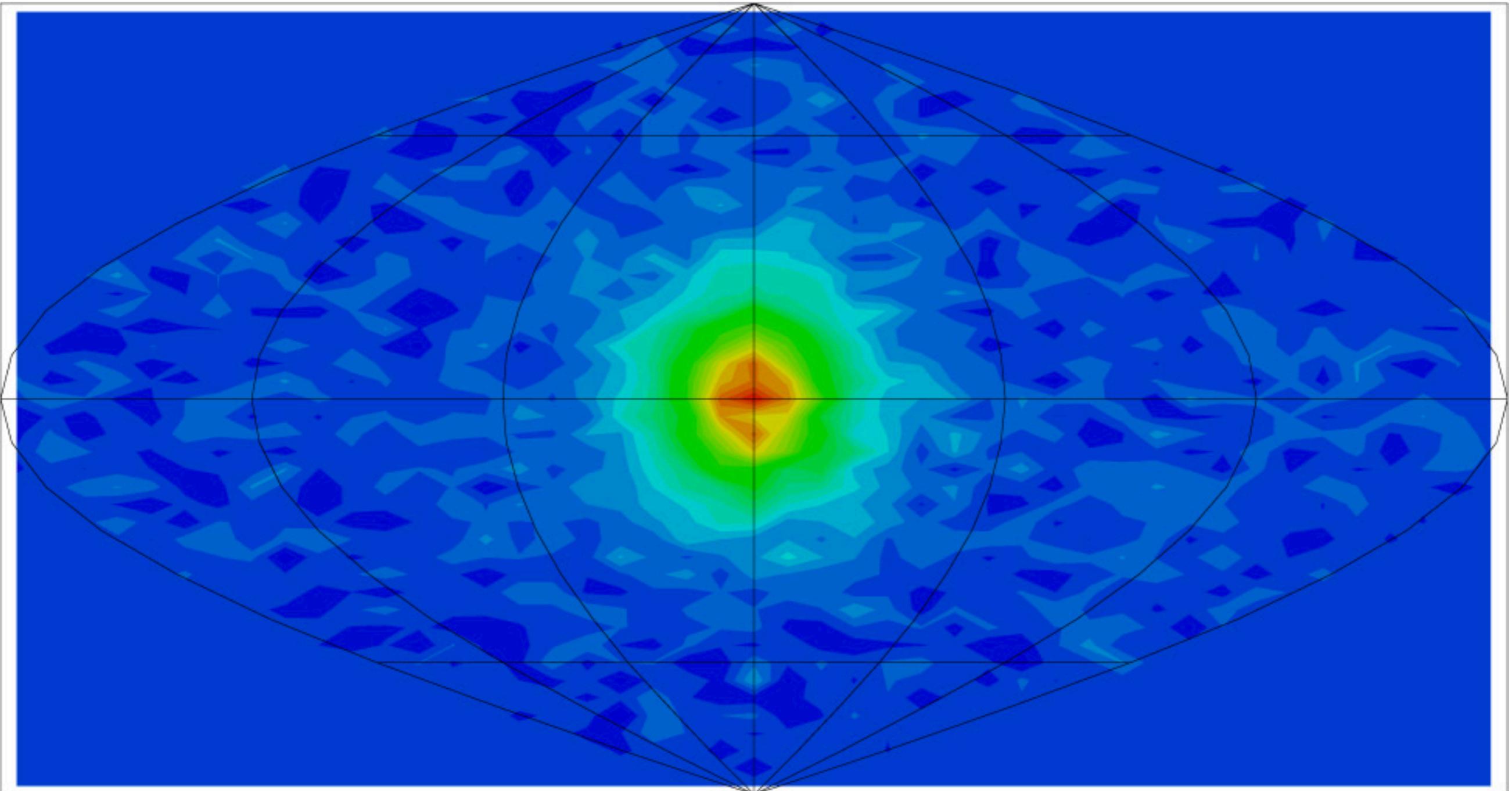
More (in)direct evidence for ongoing nucleosynthesis



example 1: 1.8 MeV line emission from the decay of ^{26}Al (lifetime of 7×10^5 yr)

Observational evidence for nucleosynthesis

More (in)direct evidence for ongoing nucleosynthesis



example 2: observation of solar neutrinos

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

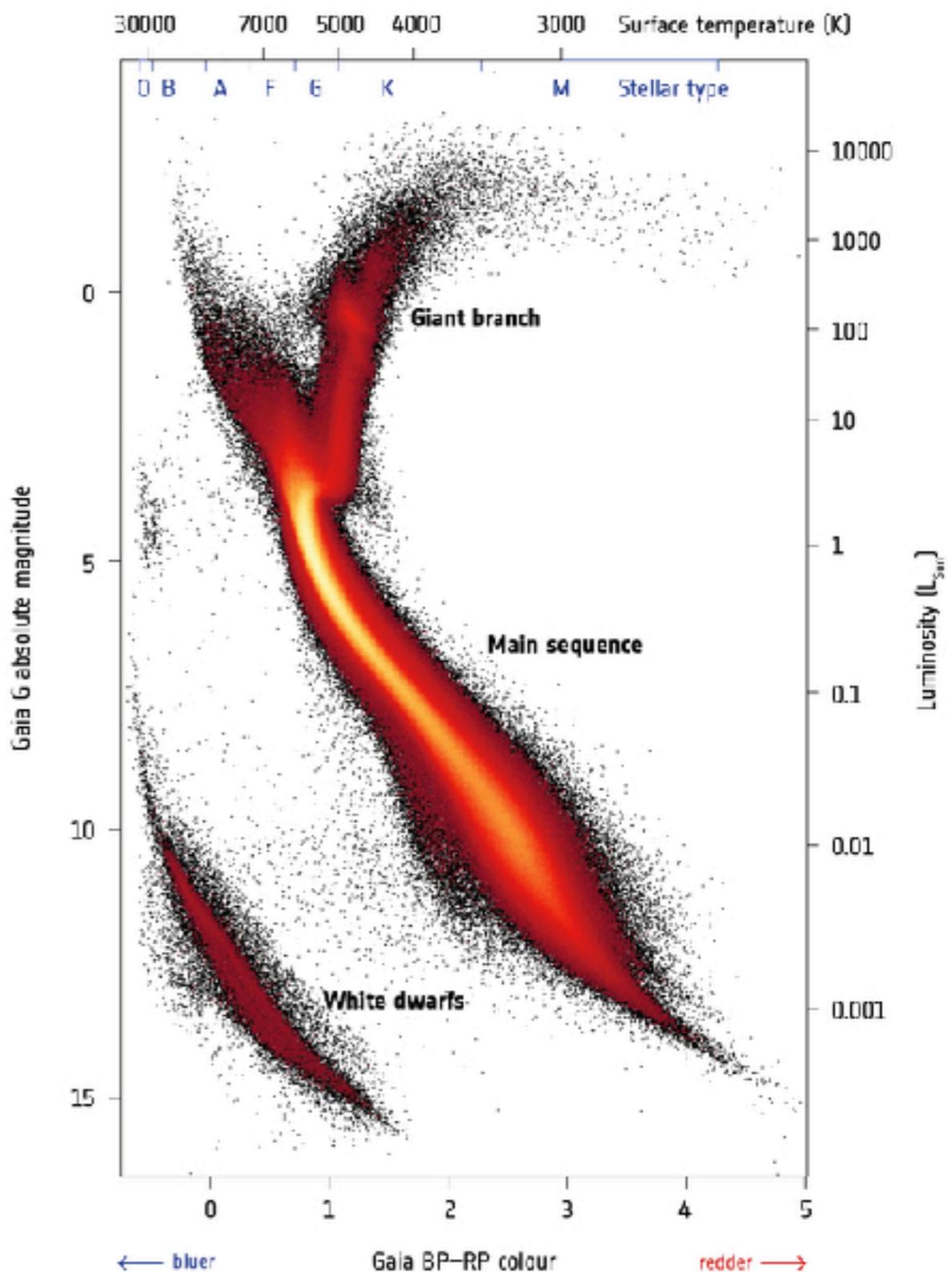
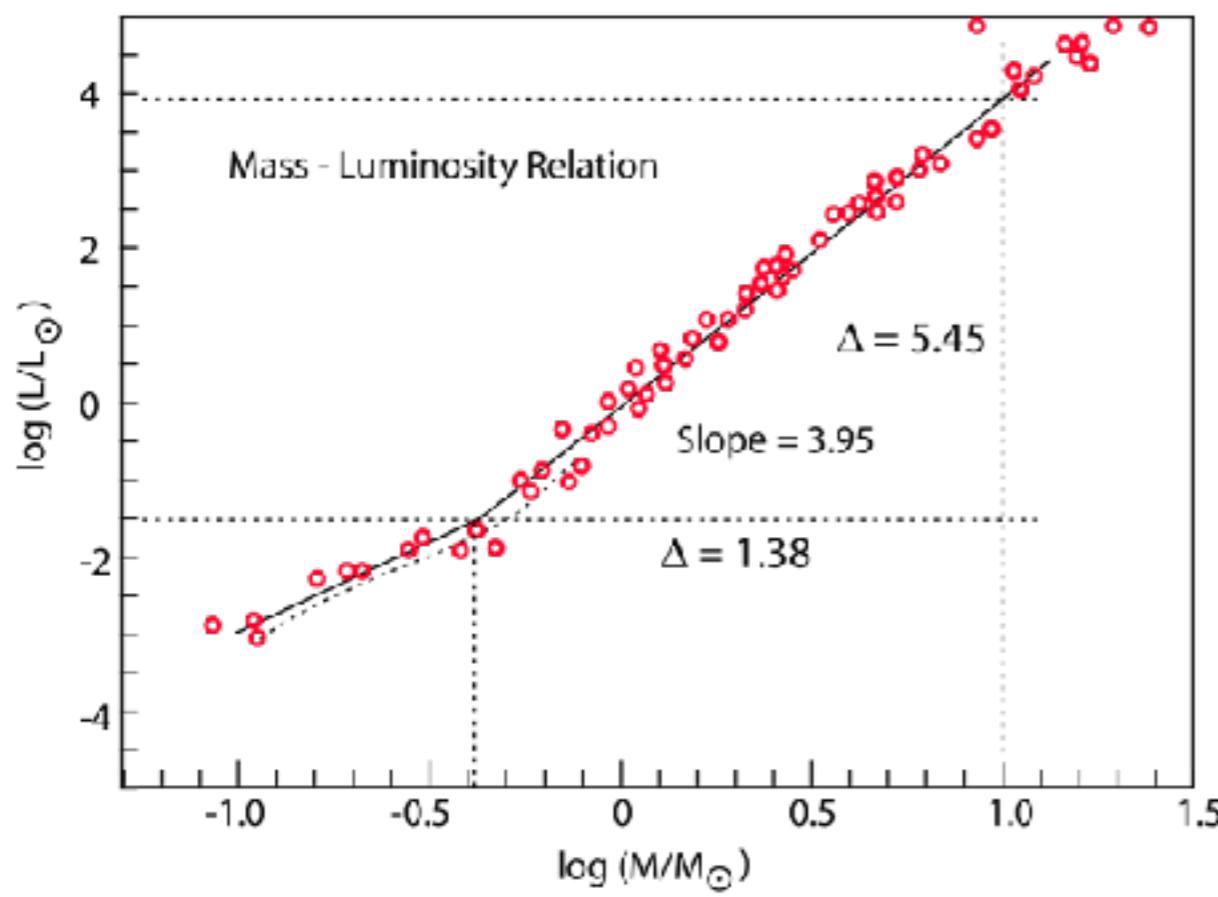


Thermonuclear reactions

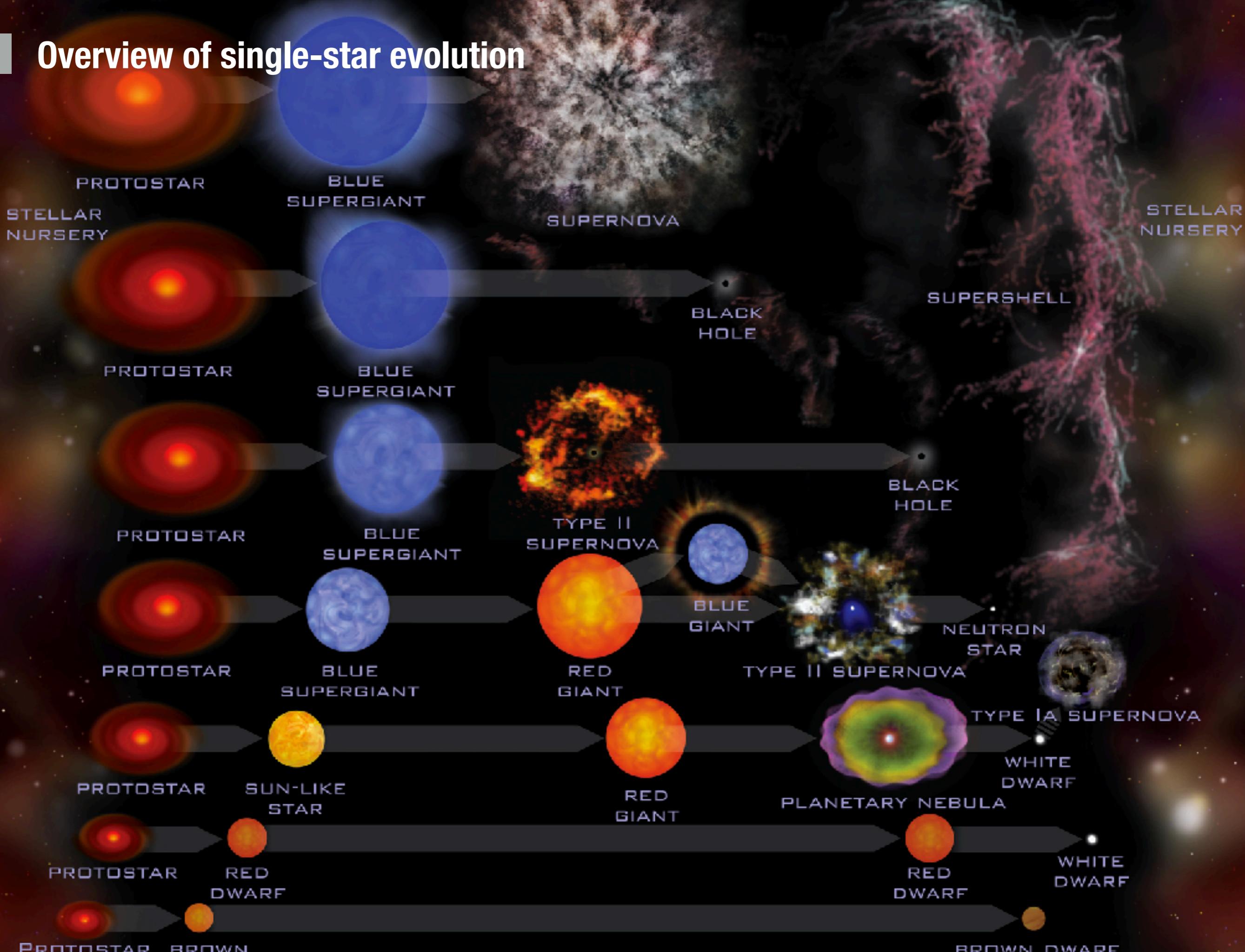
→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

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



Overview of single-star evolution



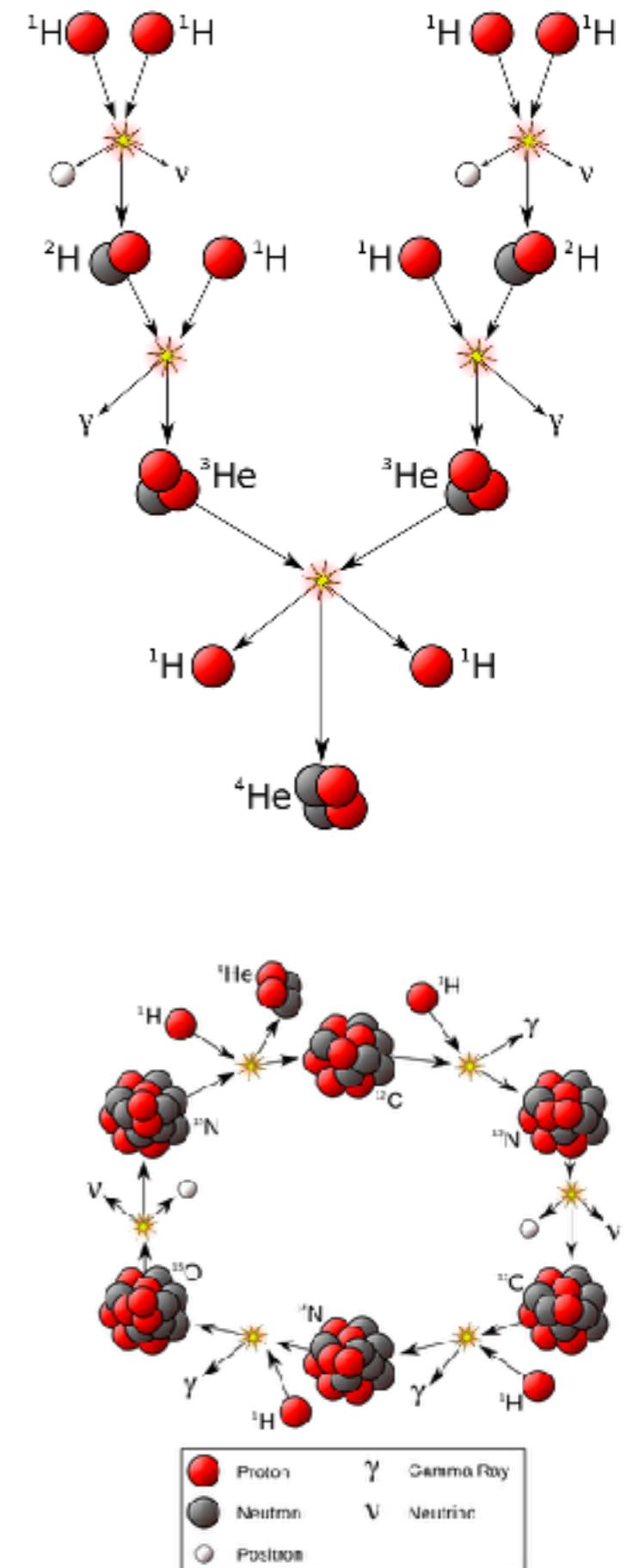
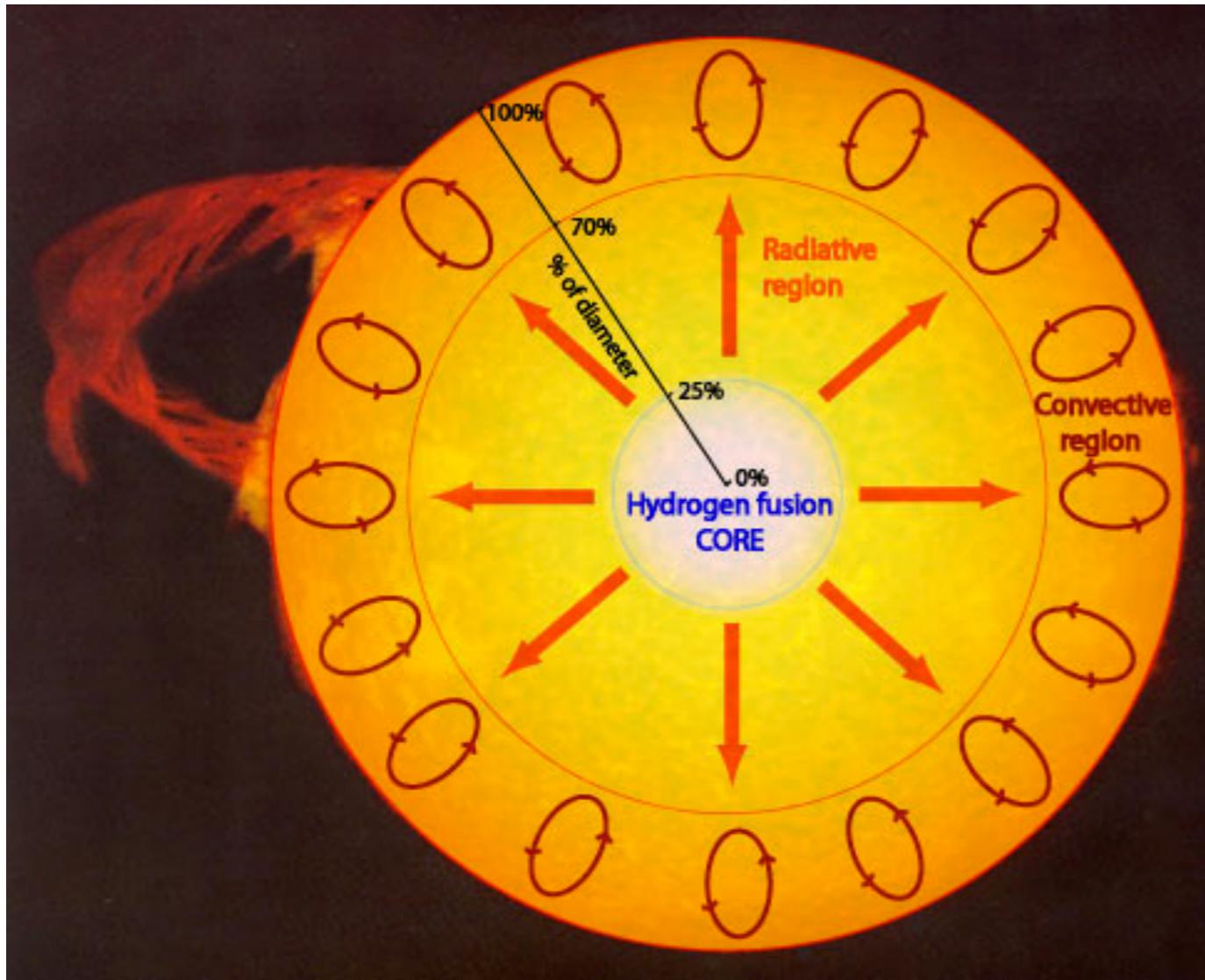
Overview of single-star evolution

Mass (Solar masses)

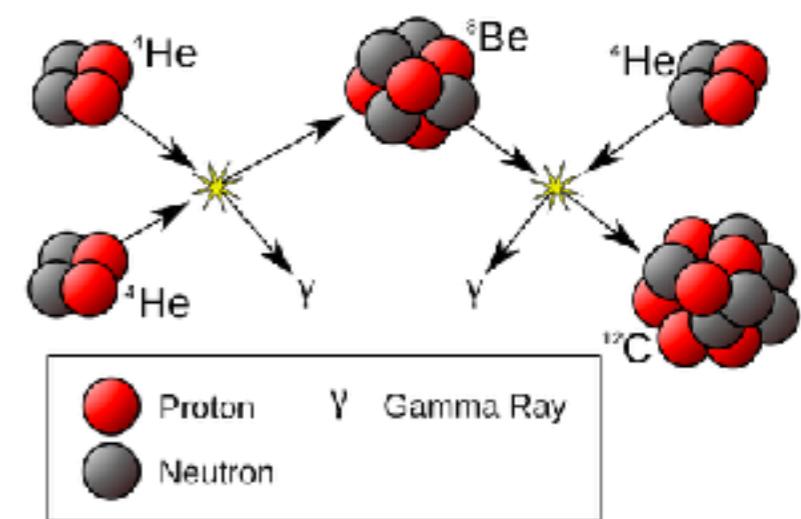
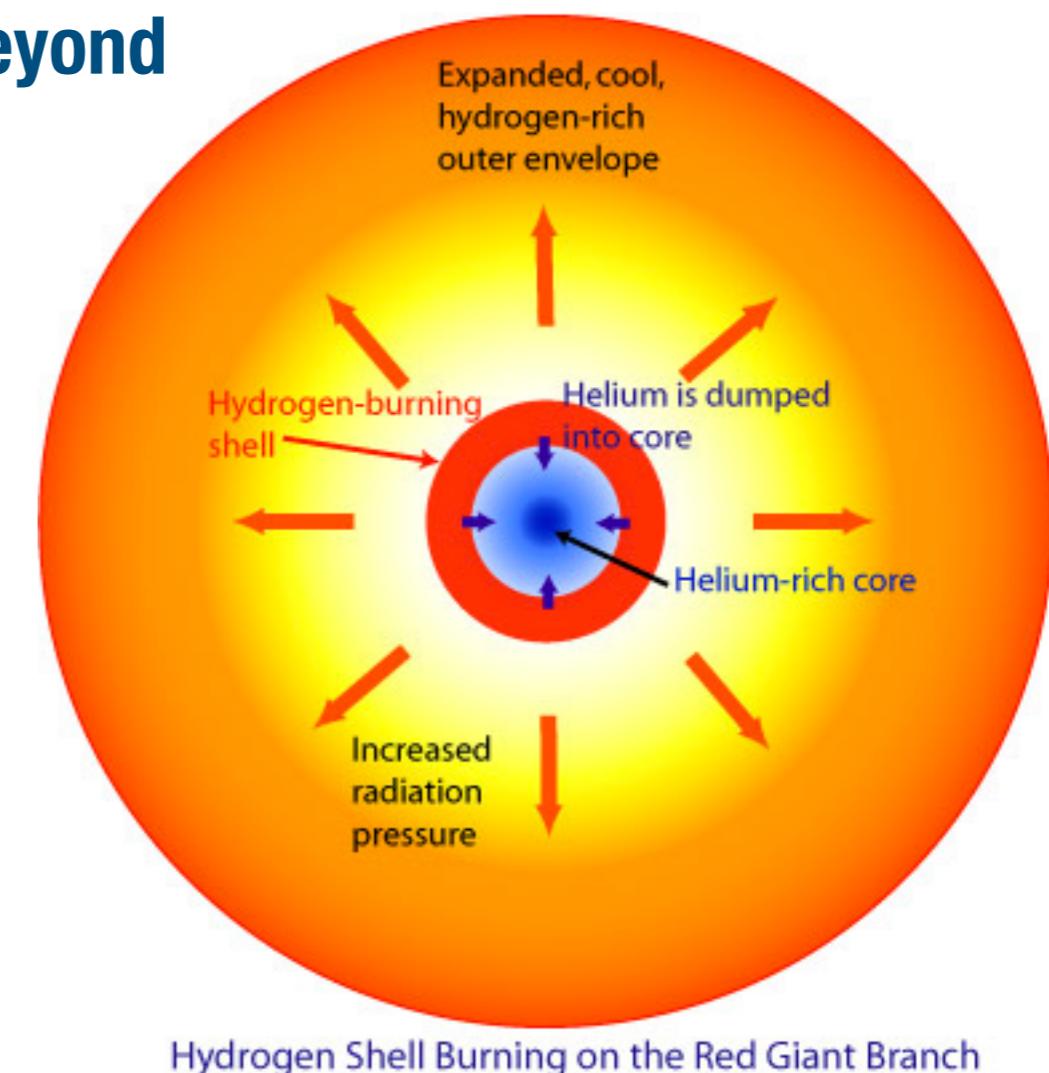
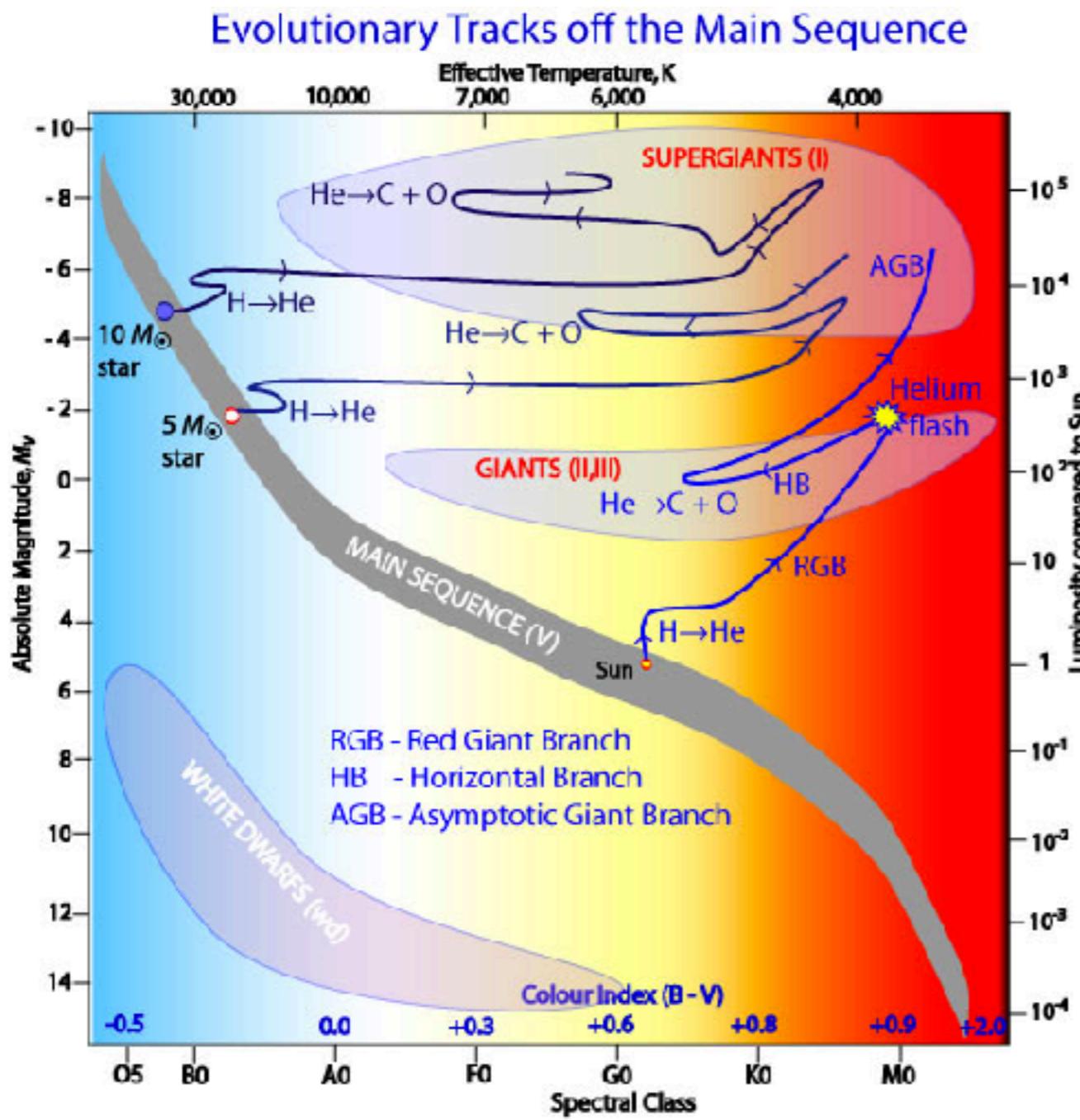
Brown dwarf	D-C									
Red dwarf	H-C [MS]									
Low mass star	H-C [MS]	pp CNO	H-S [RGB]	1. D U	HeF	He-C H-S [HB,RC]	He-S H-S [AGB]	3. D U	PNN	He WD
Intermediate mass star	H-C [MS]		H-S [RGB]	1. D U		He-C H-S	He-S H-S [AGB]	3. D U	PNN	CO WD
	H-C [MS]		H-S [RGB]	1. D U		He-C H-S	2. He-S D H-S U [AGB]	3. D U	PNN	CO WD
	H-C [MS]		H-S [RGB]	1. D U		He-C H-S	He-S C-C He-S [SAGB]	2. D U	He-S PNN	ONe WD
Massive star	H-C [MS]		He-C H-S	C-C He-S ...	Ne-C C-S ...	O-C Ne-S ...	Si-C O-S ...	CC SN II/Ib/Ic		BH or NS

Hydrogen burning

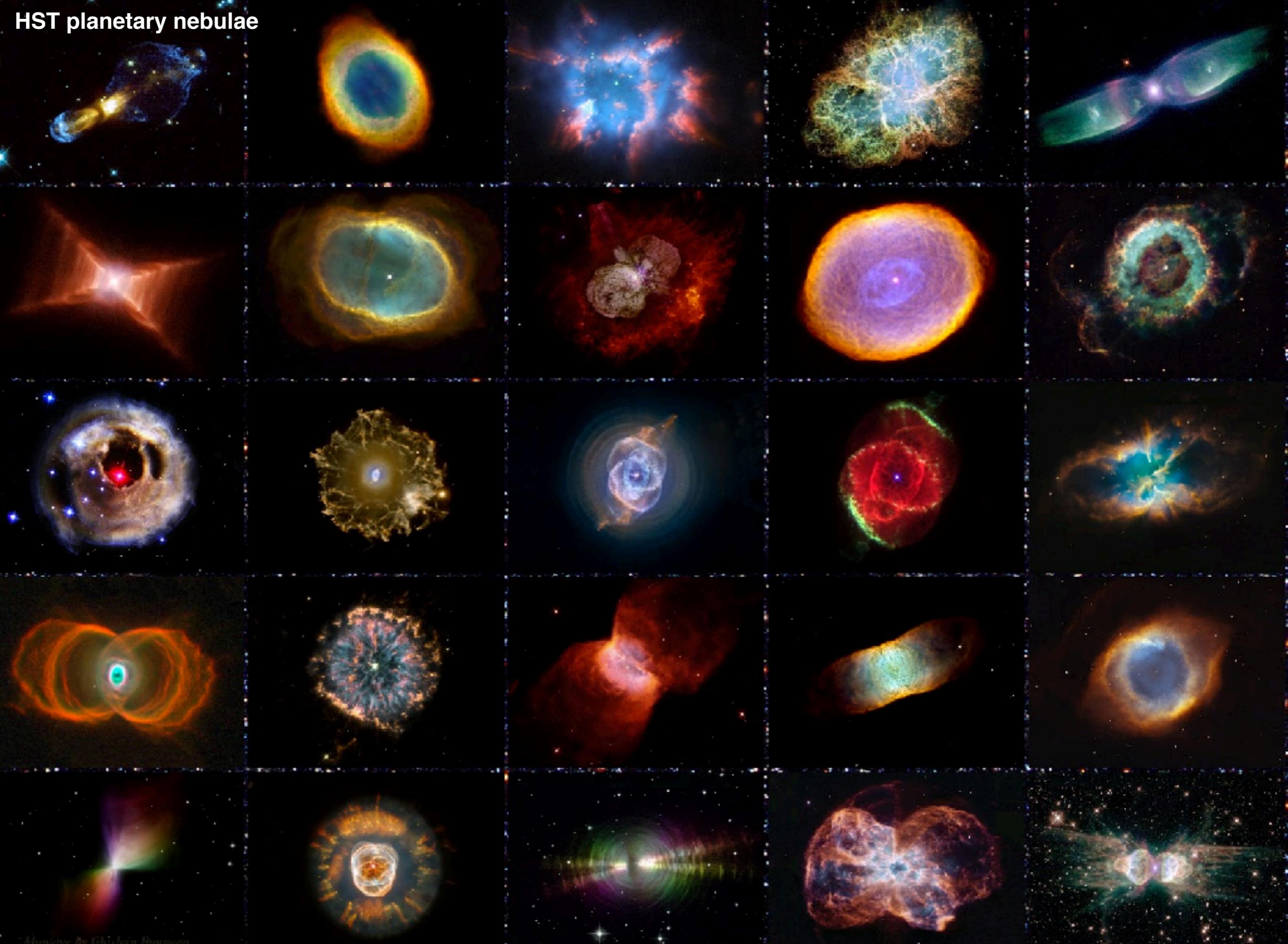
Starts on the main sequence
via pp (low mass) and CNO (high mass) chains



Helium burning on the red giant branch and beyond

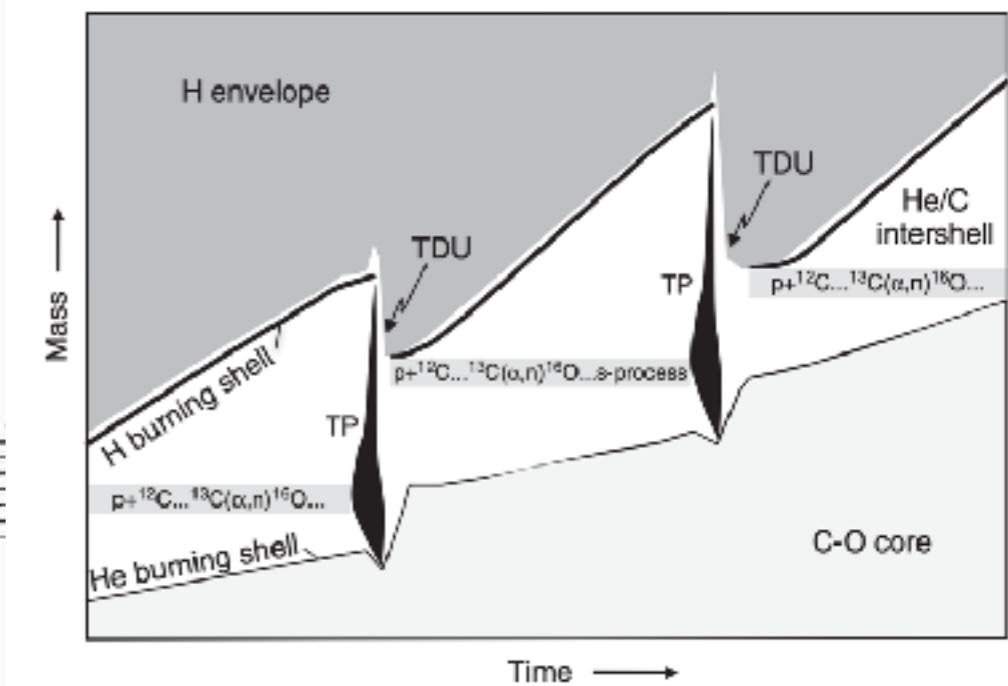
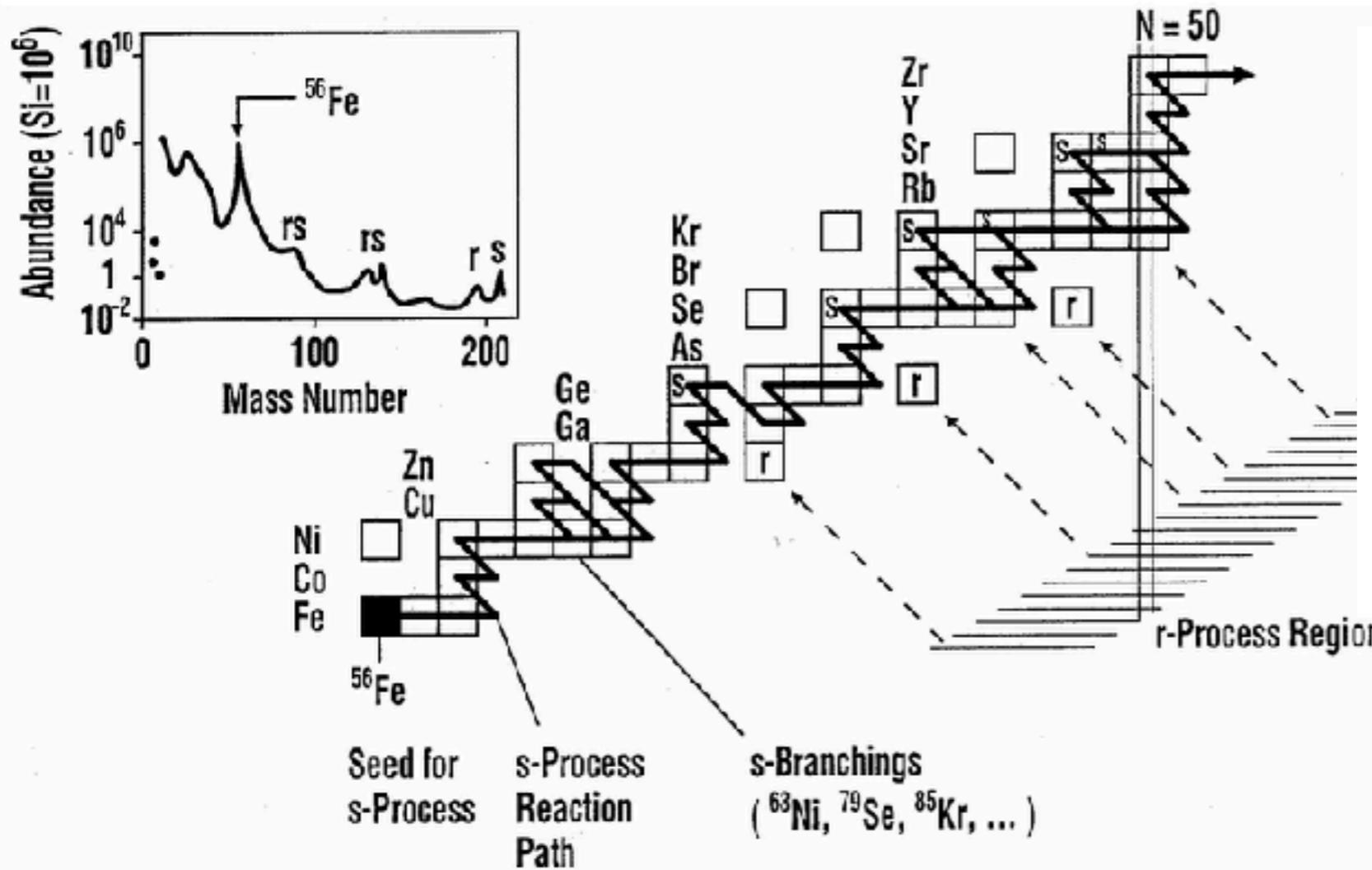
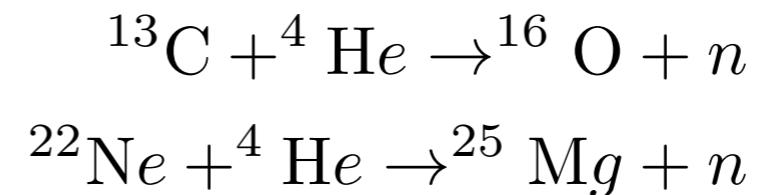


HST planetary nebulae

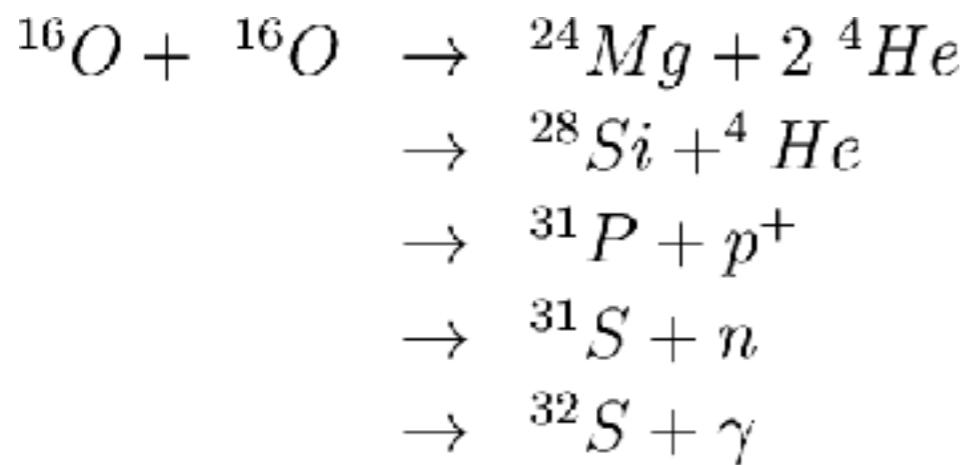
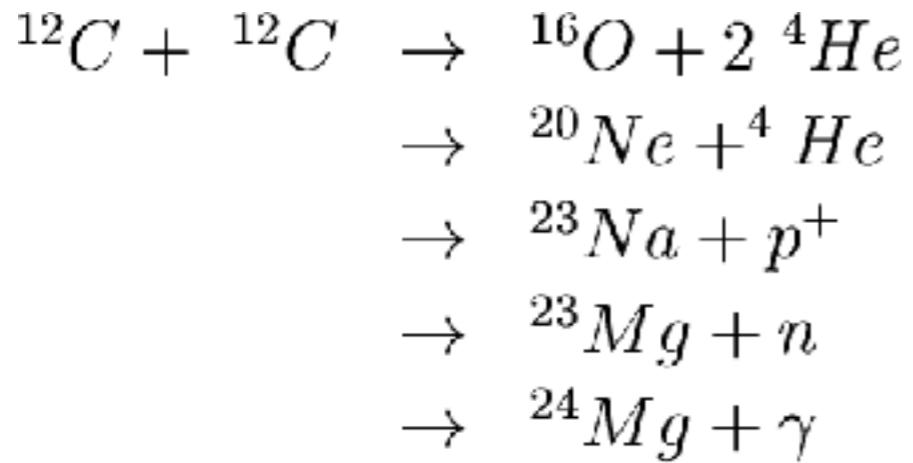


slow neutron capture on the AGB (s-process)

main neutron sources



Carbon burning and beyond



For 8 solar mass star

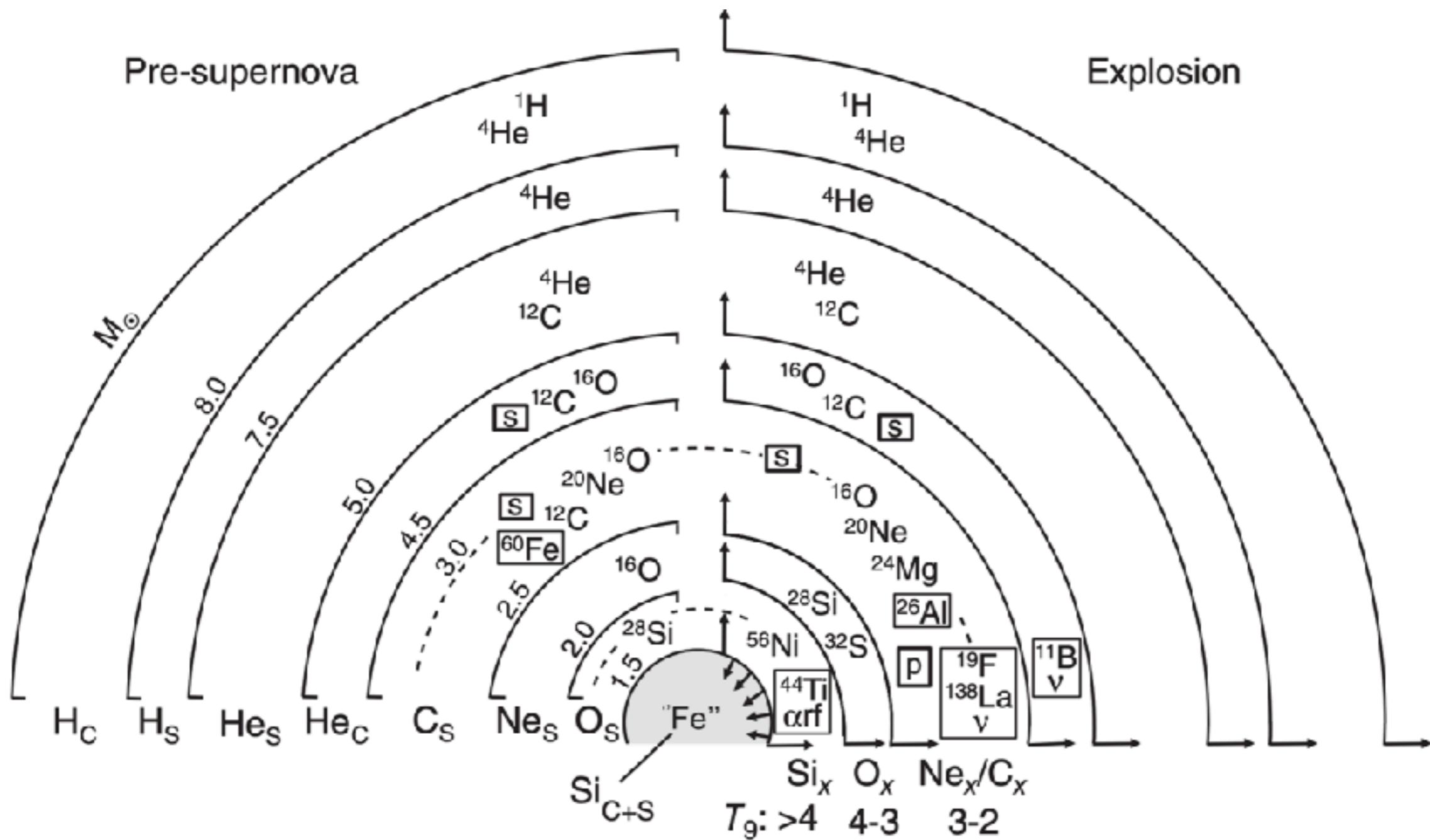
- Hydrogen: 10 Myr
- Helium: 1 Myr
- Carbon: 1000 yr
- Neon: 10 yr
- Oxygen: 1 yr
- Silicon: 1 day
- Core collapse: < 1 sec

Silicon burning occurs at extremely high temperatures: ~3 GK

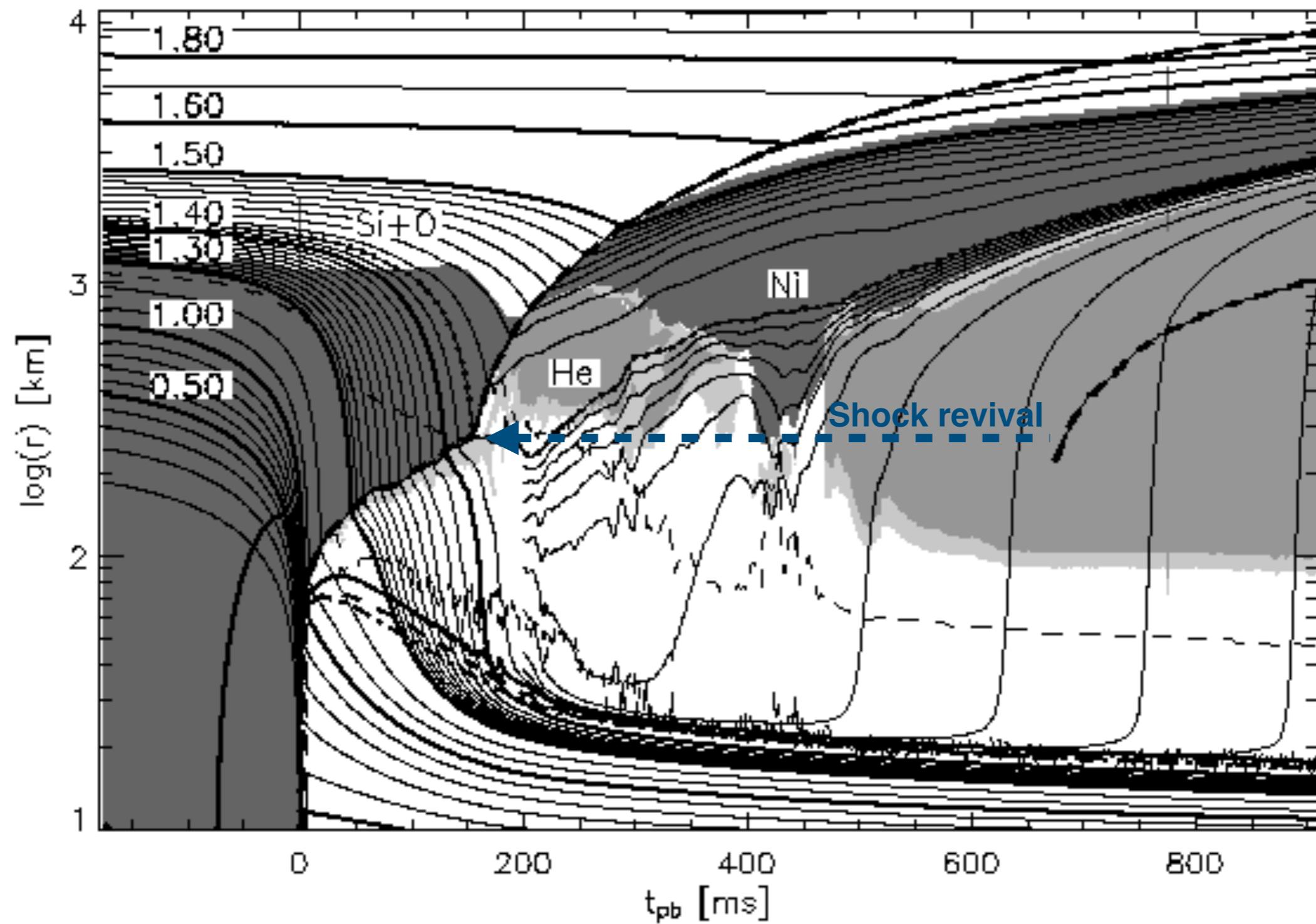
Nuclei photo-disintegrate and the emitted protons and alpha particles can be captured, forming heavier nuclei.

Process near **nuclear statistical equilibrium** (~equal rate between forward and reverse reactions)

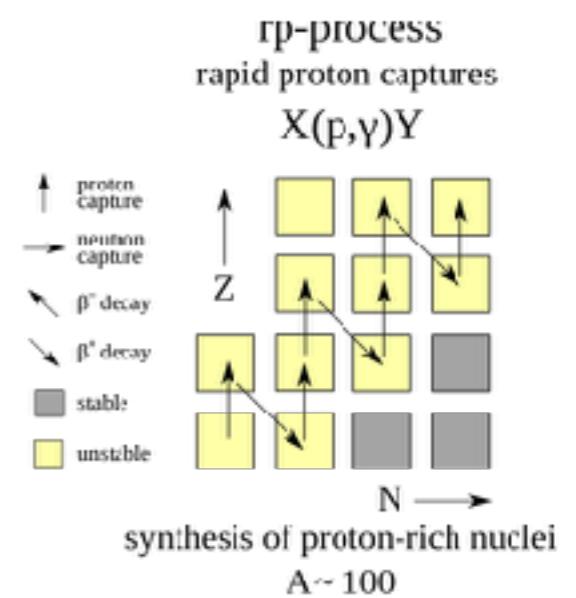
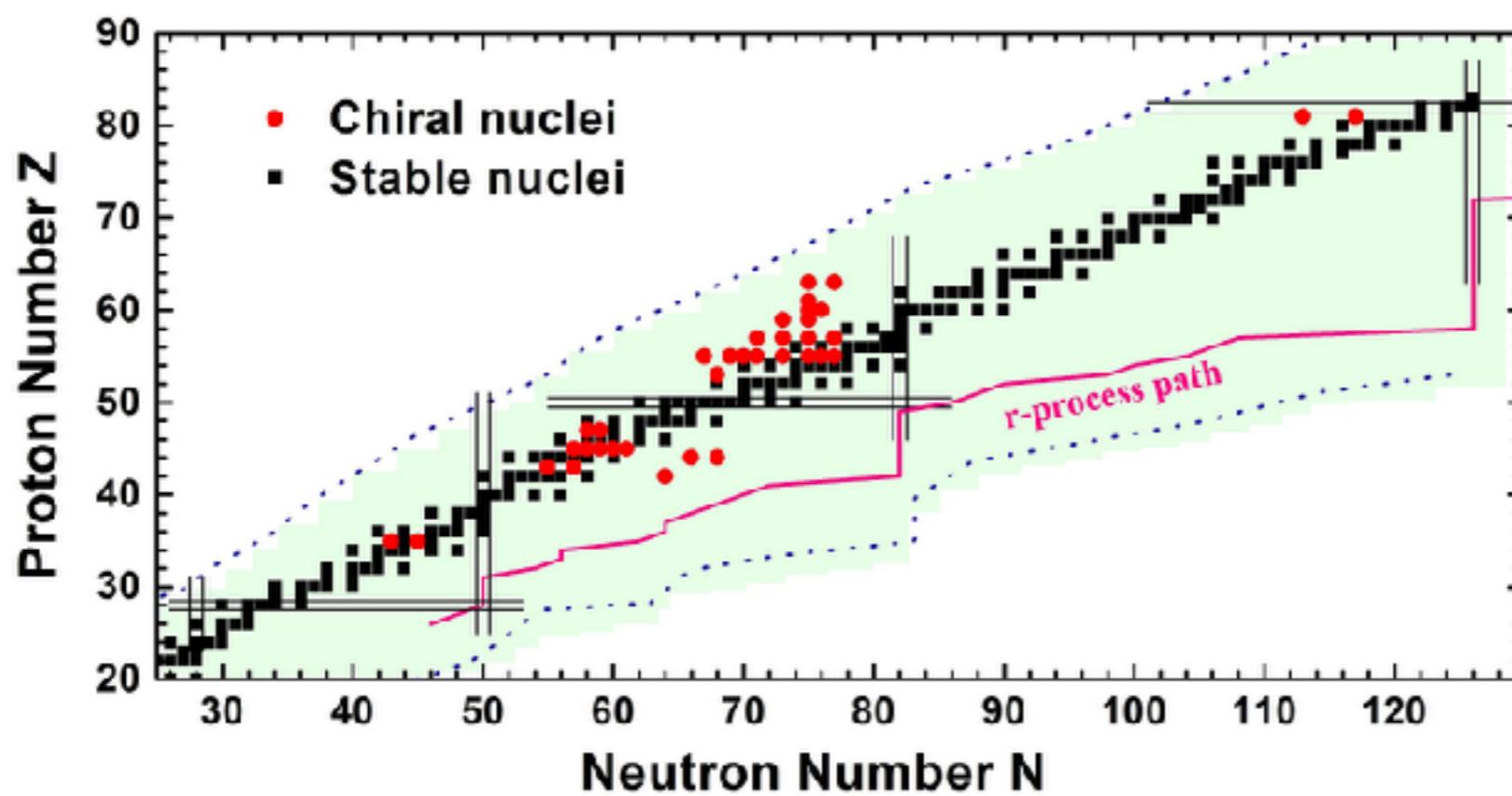
Pre-supernova structure and core-collapse



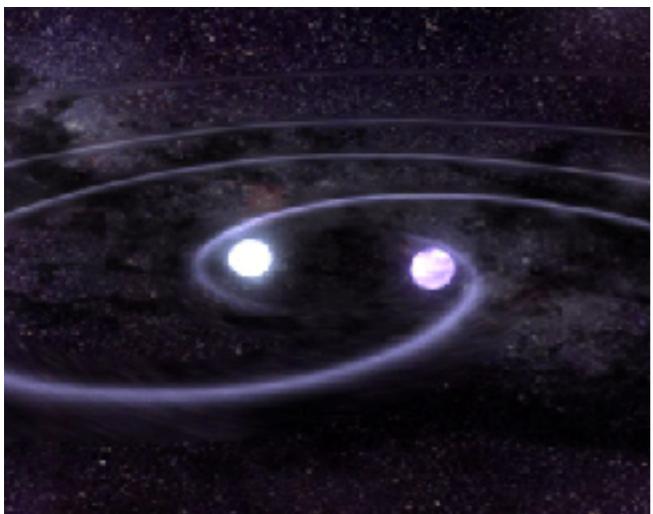
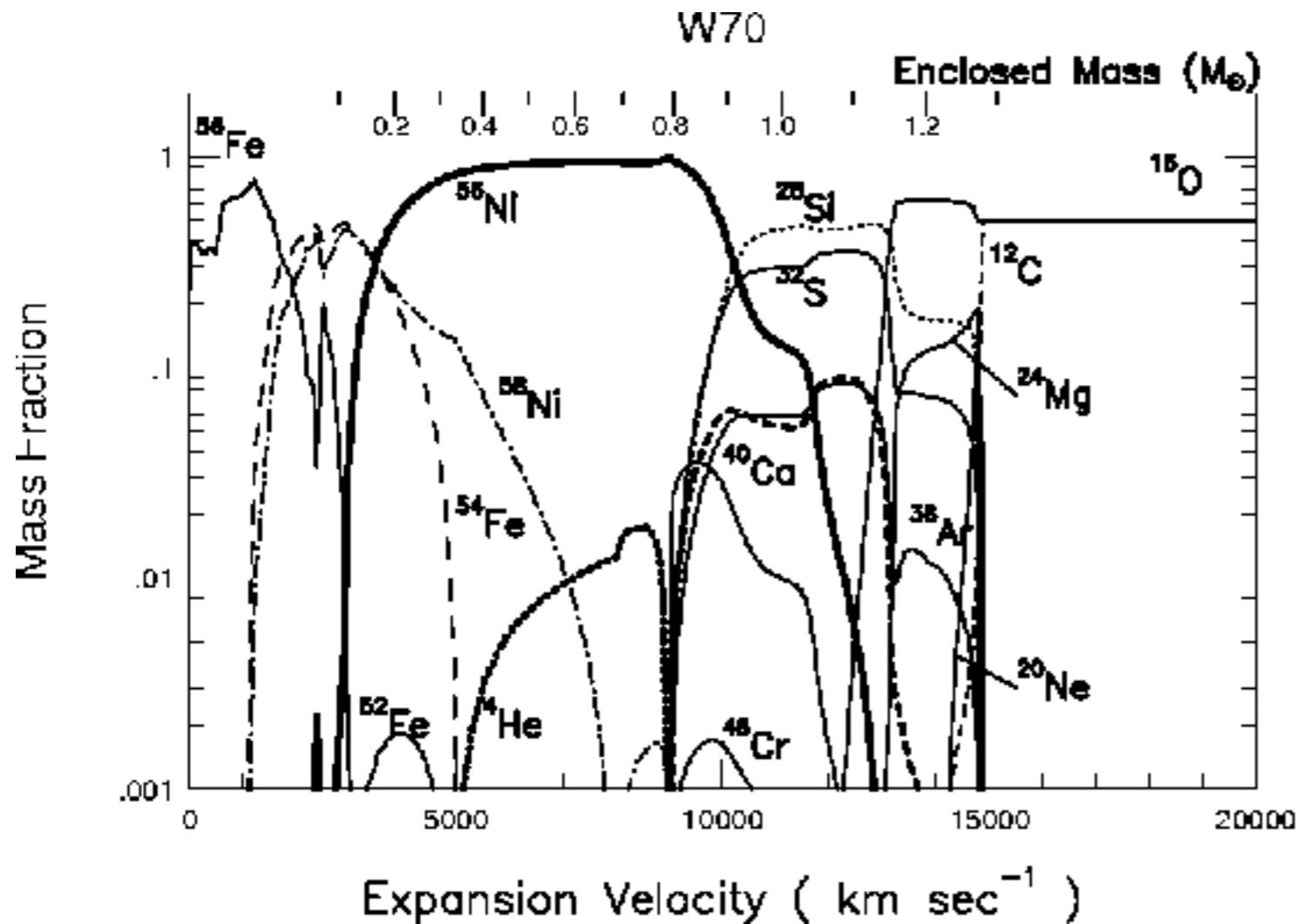
Core-collapse supernovae



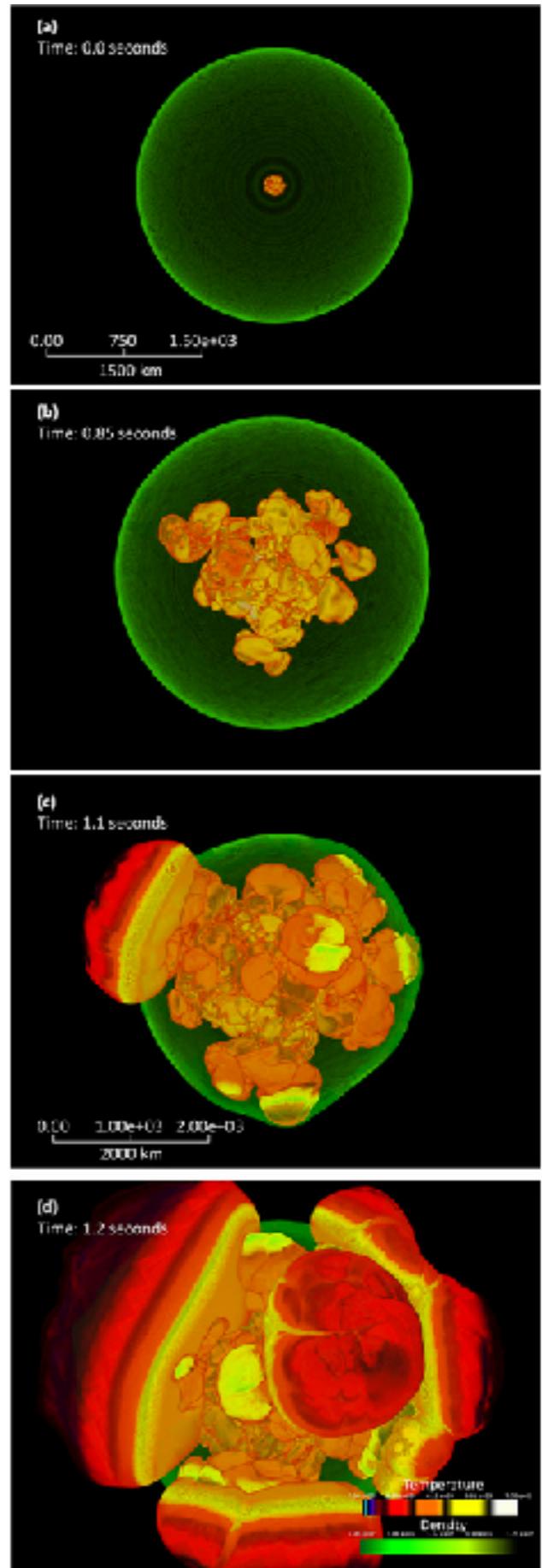
Explosive nucleosynthesis (rapid neutron capture; r-process; rp-process)



Type Ia supernovae (NSE)

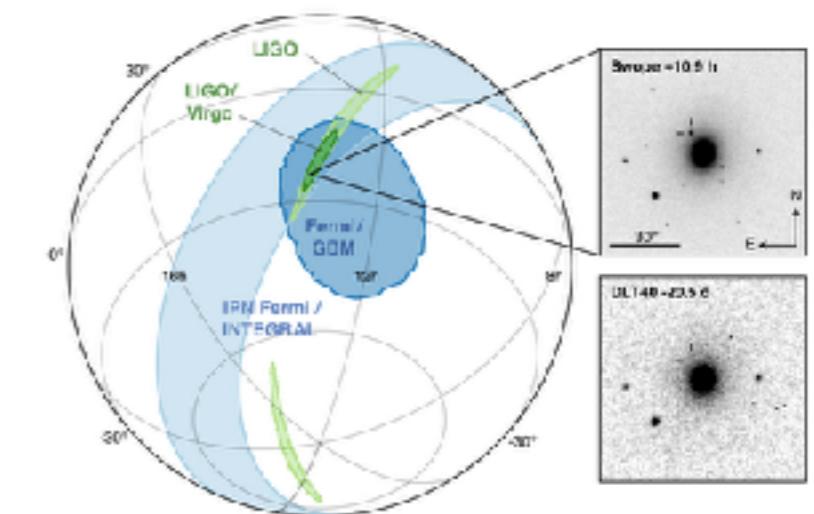
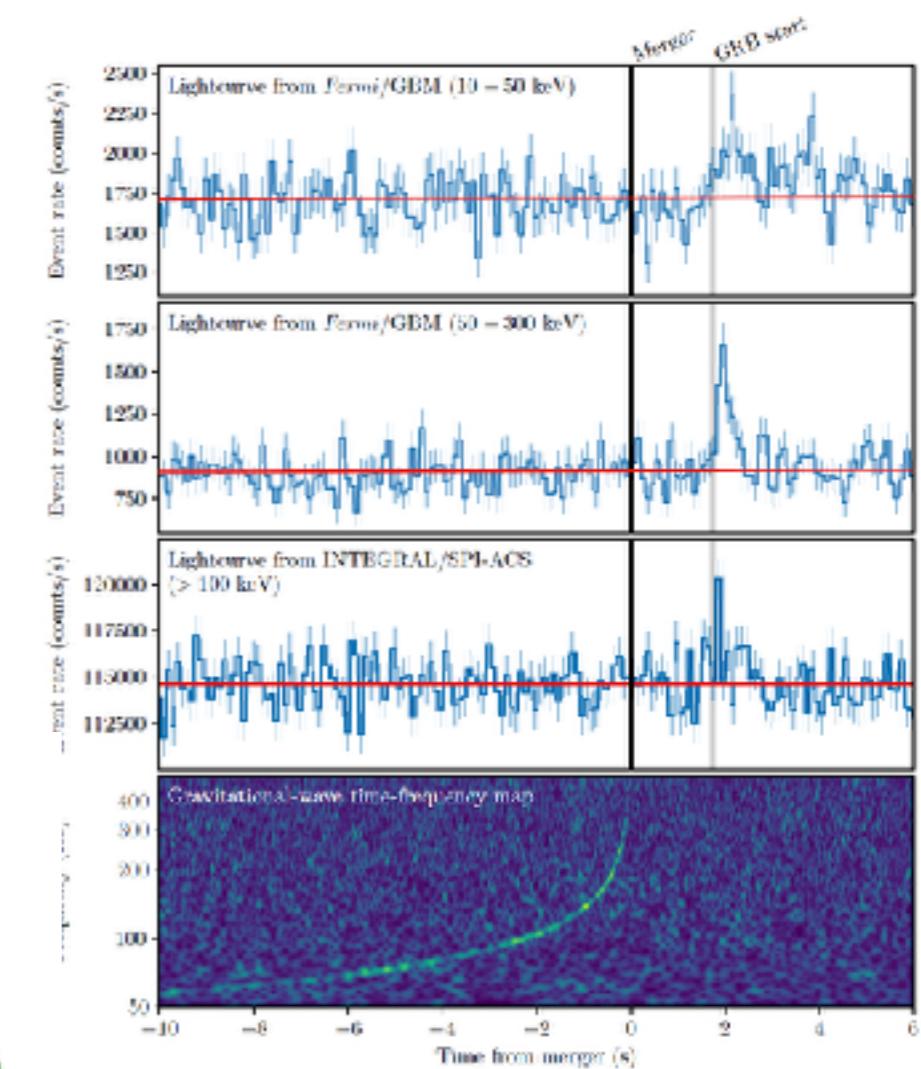
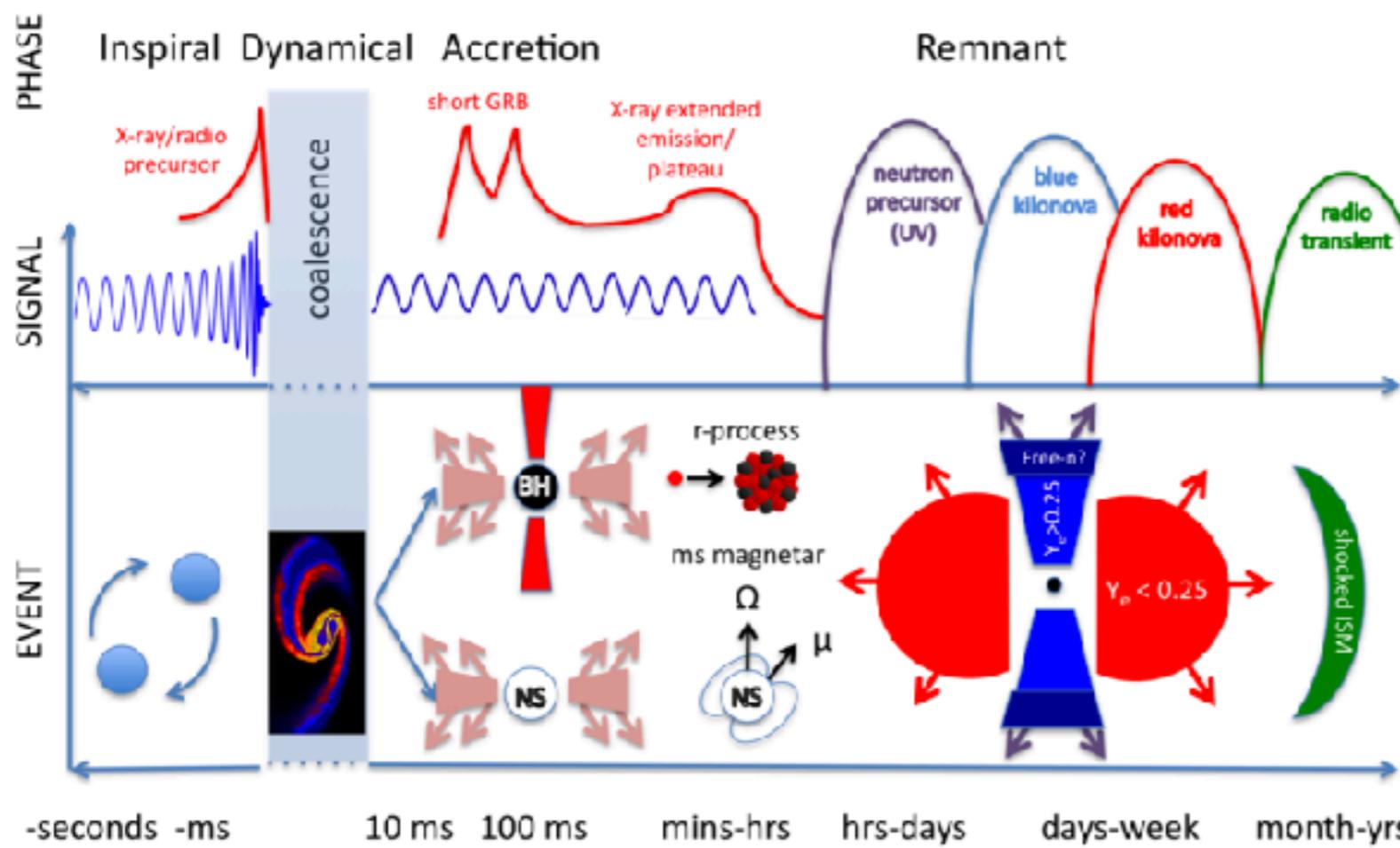


Progenitors still debated
Responsible for most iron-peak elements



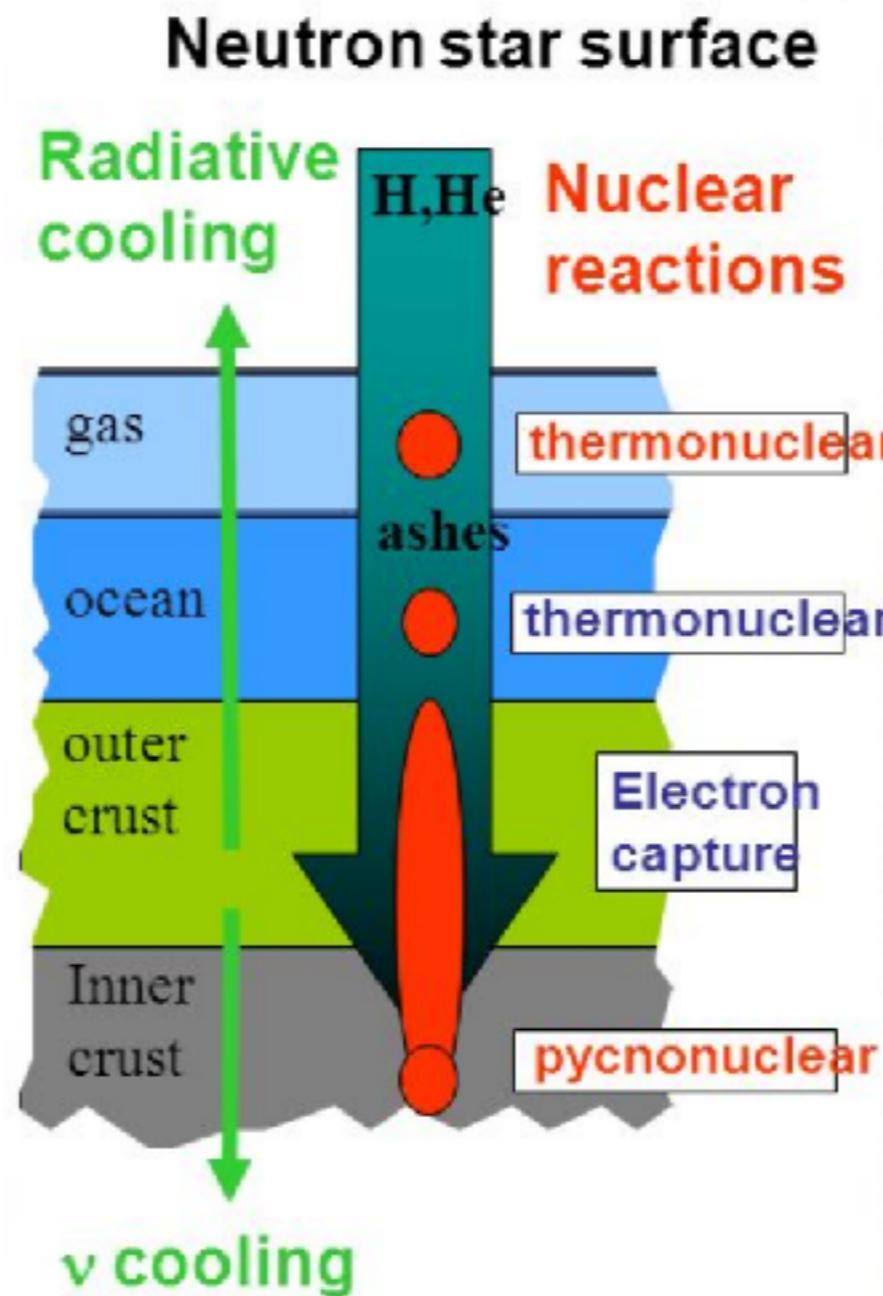
Neutron star mergers, gamma-ray bursts

GW 170814

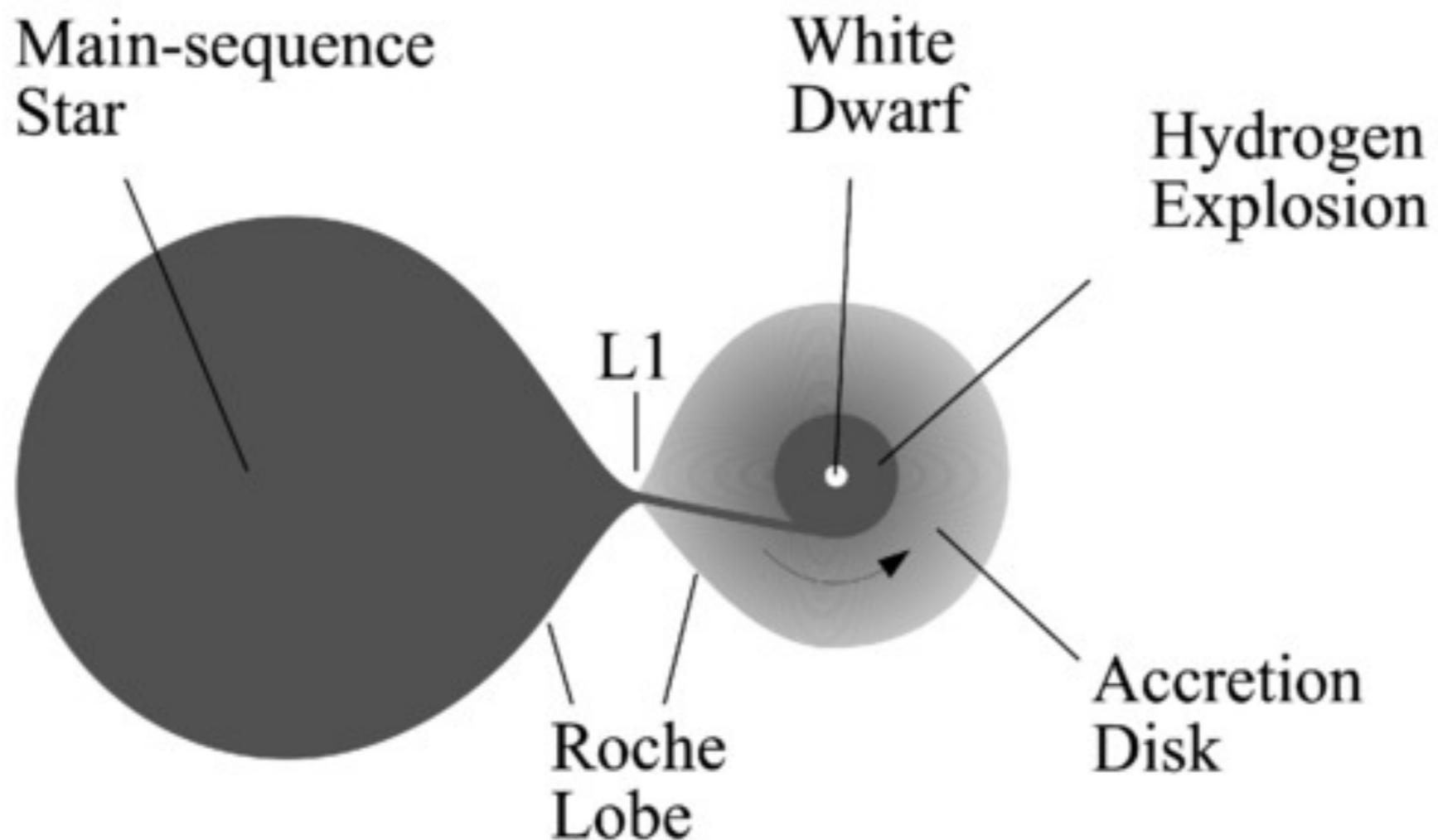


Pycno-nuclear reactions

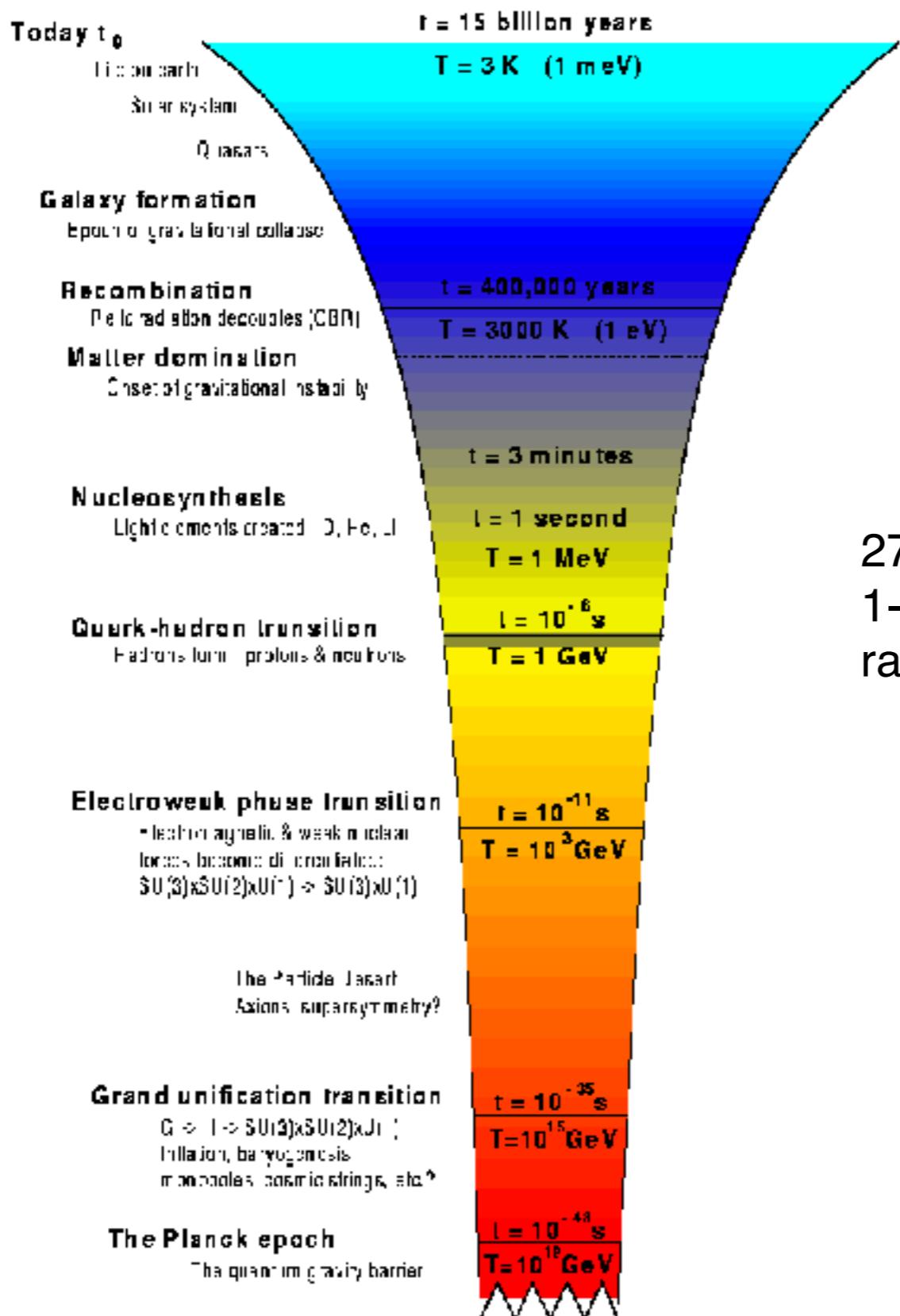
Inside neutron stars, at extremely high densities, the effective coulomb barrier is reduced by high neutron fraction, close distance and electron cloud



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

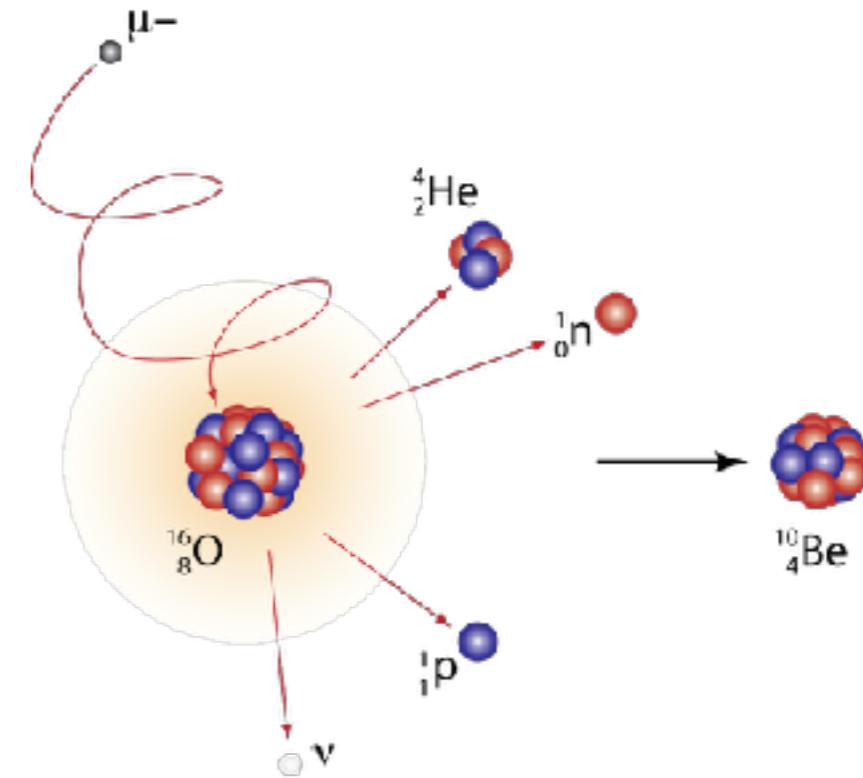
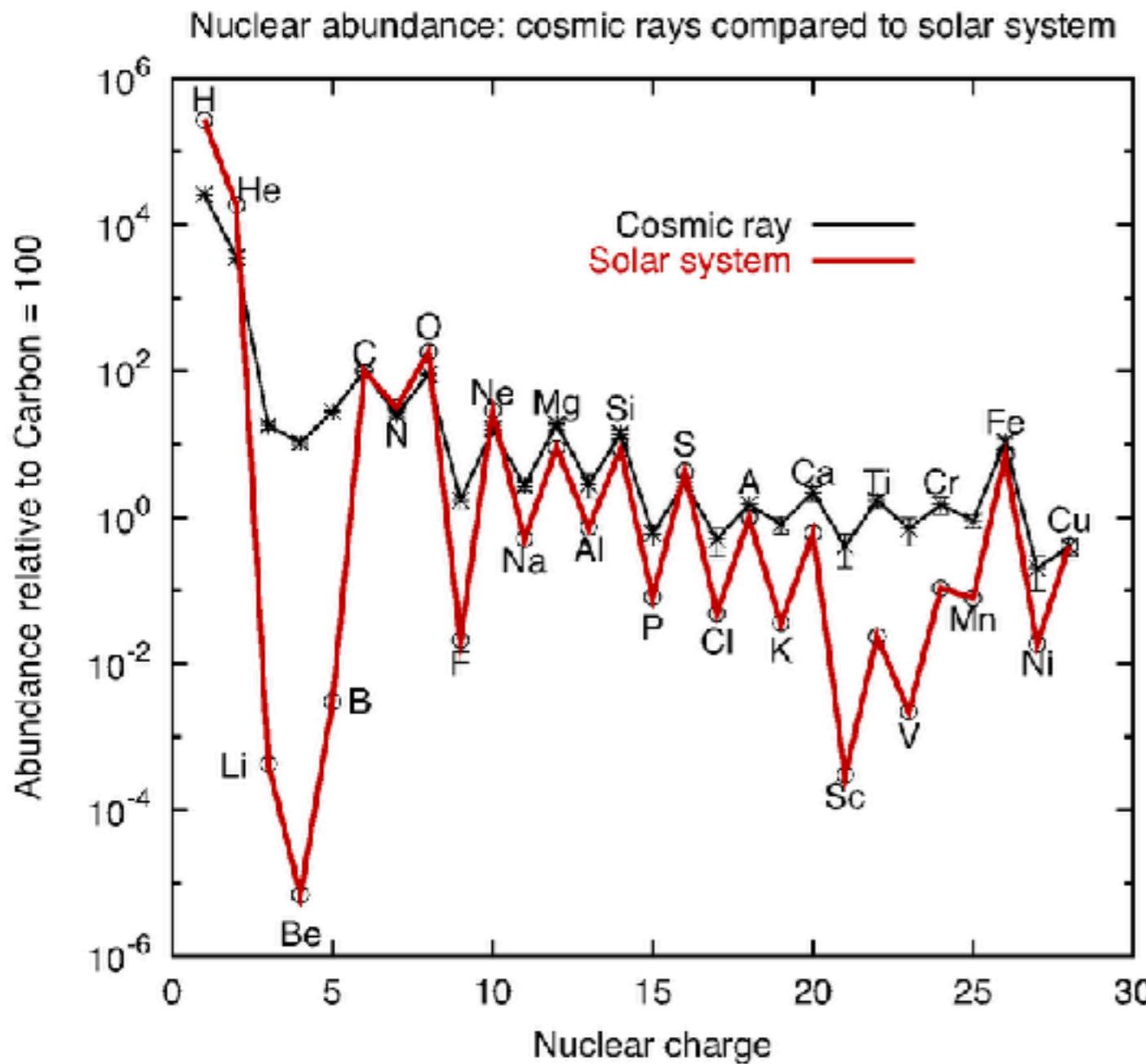


Primordial nucleosynthesis



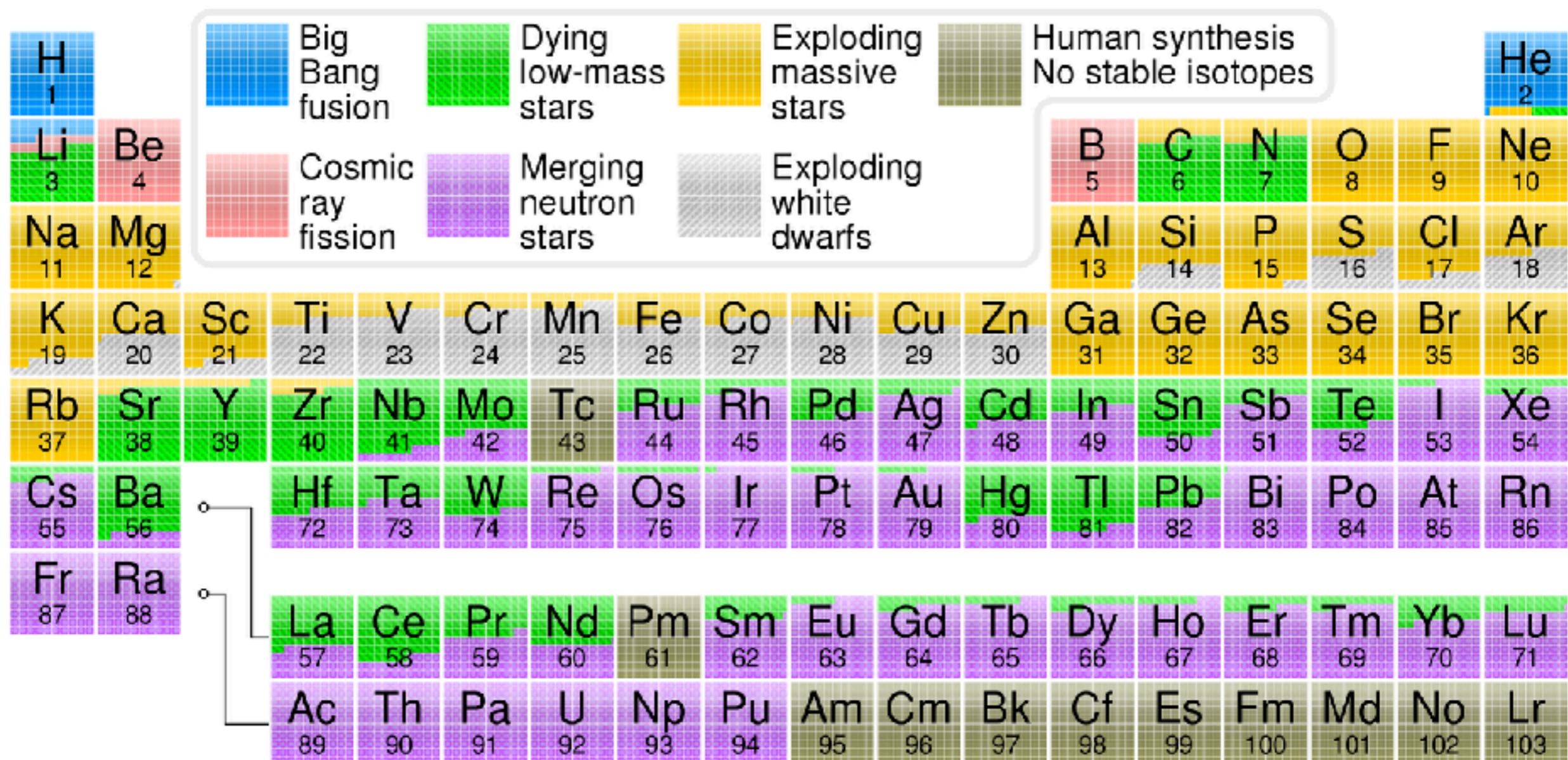
27% He requires primordial origin
1-3 sec after Big Bang: High temperatures but rapid cooling

CR-induced spallation

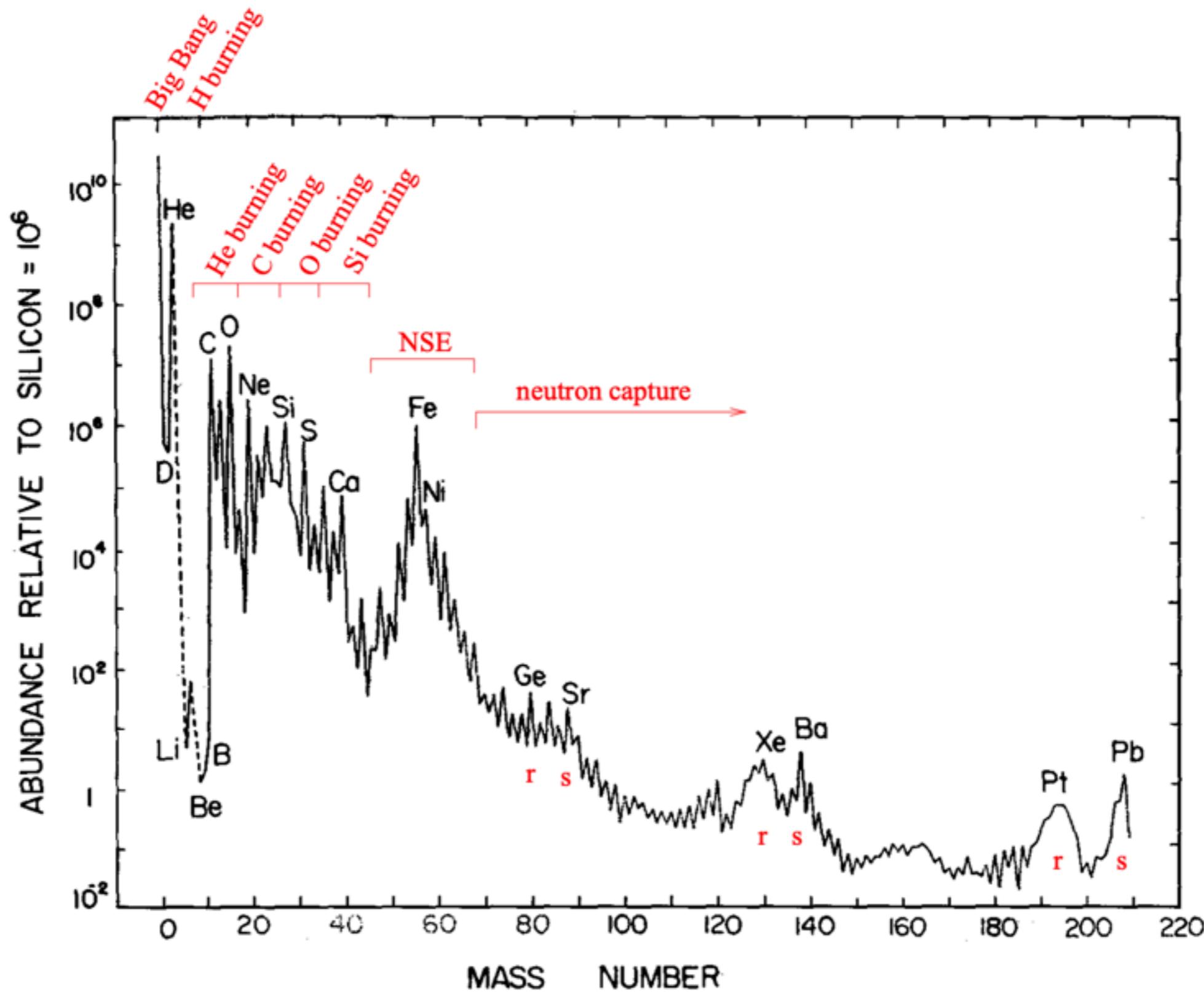


Not enough to explain observed Li abundances in the Solar System, other processes required (explosive nucleosynthesis, novae, red giants?)

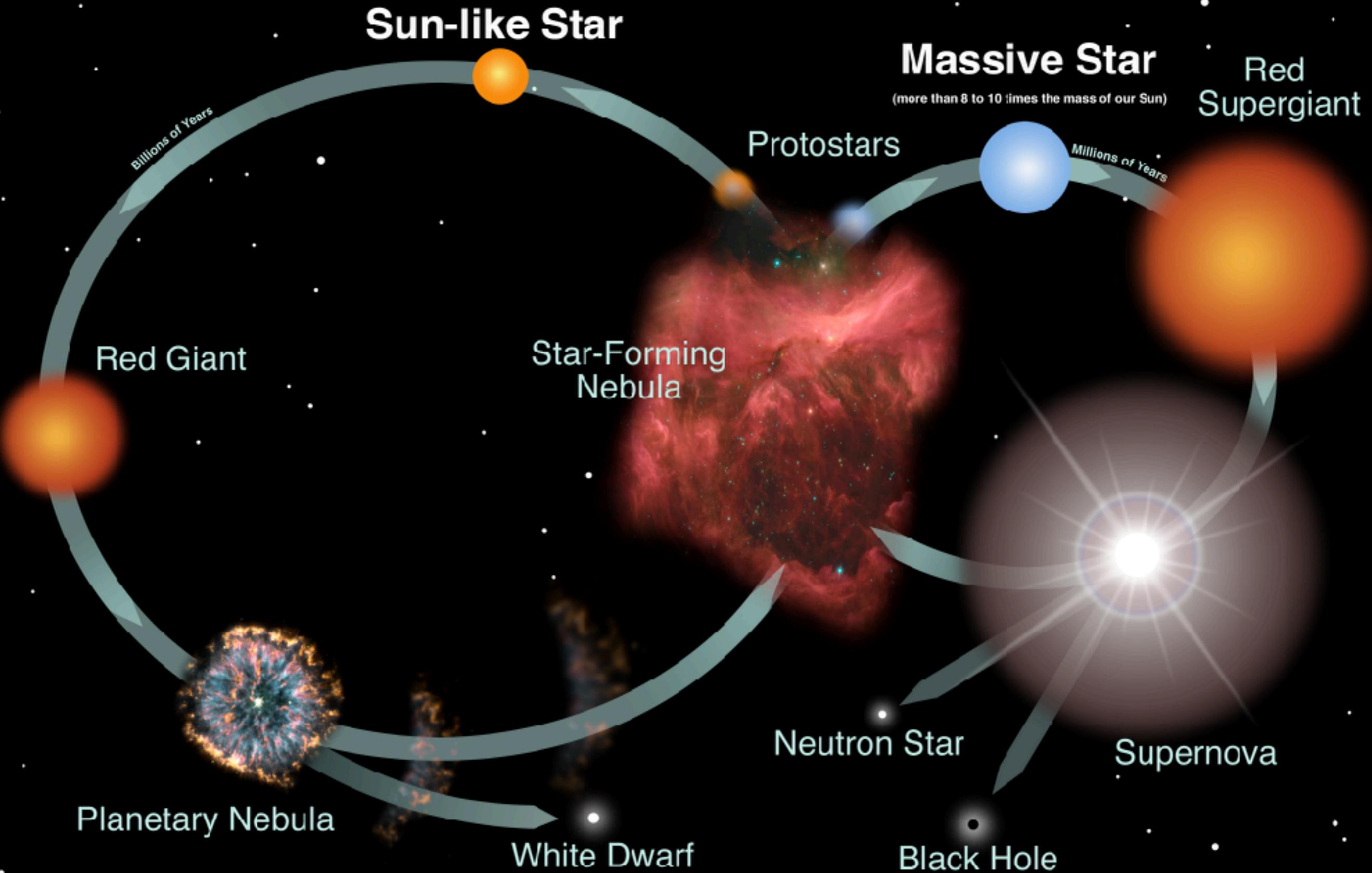
Origin of elements



Origin of elements



Nucleosynthesis goes on



Overview

- **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
 - **Lecture 5:** Thermonuclear reactions inside stars — II (advanced burning) May 16
 - **Lecture 6:** Neutron-capture and supernovae — I May 23
 - **Lecture 7:** Neutron-capture and supernovae — II June 6
 - **Lecture 8:** Thermonuclear supernovae June 13
 - **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