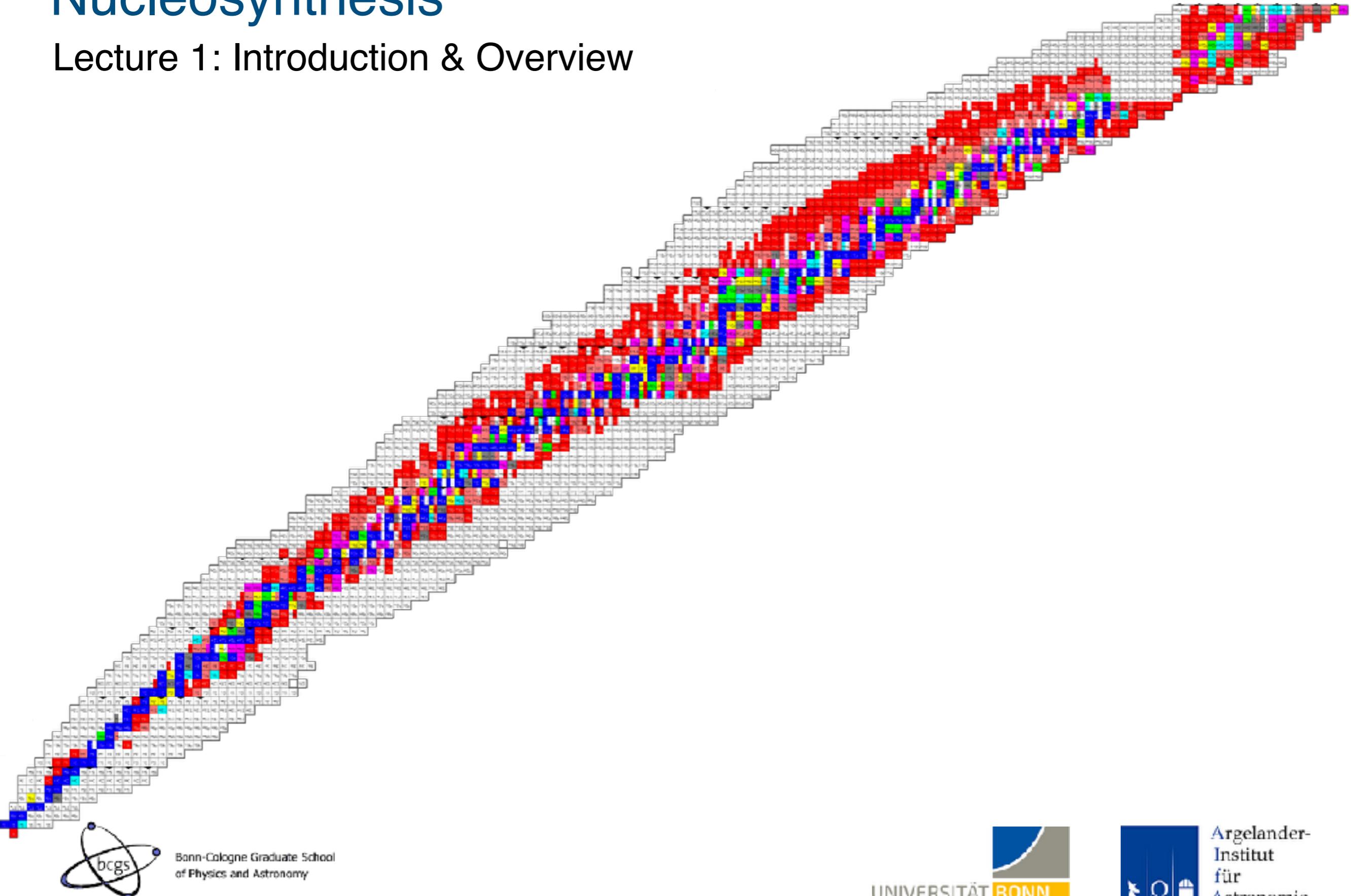


Nucleosynthesis

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
Exercises David Aguilera Dena - davidad@astro.uni-bonn.de
 Ben Hastings - bhastings@astro-uni-bonn.de

Lectures Thursdays @ 11:15 – 13:00 April 18 to July 11 Room 0.008

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

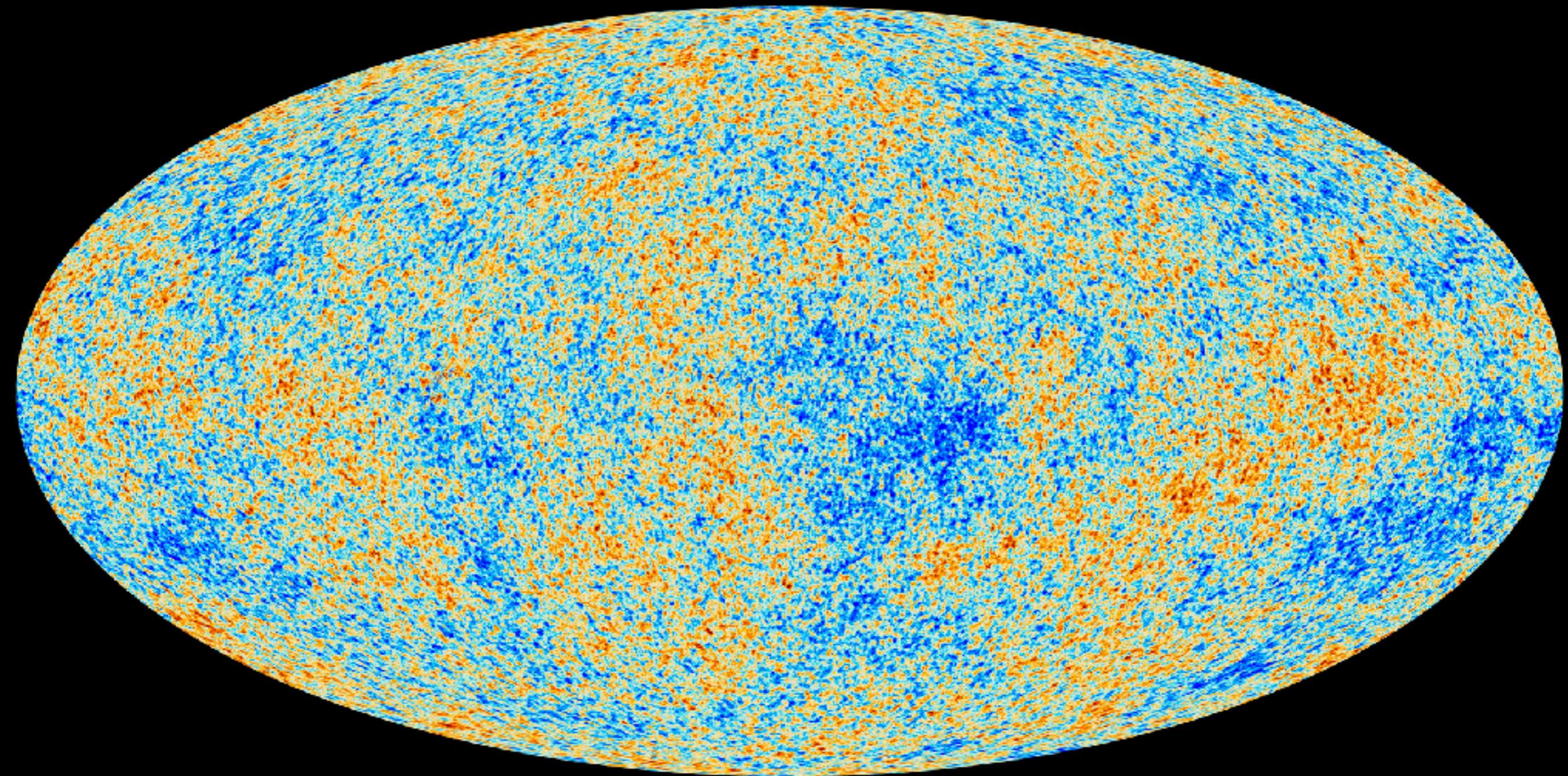
- Read material beforehand and e-mail at least 3 non-trivial questions before **Tuesday @ 13:00** **email to tutors; use subject heading [Nuc]** **25%**
- Lectures and Exercises (compulsory attendance) **25%**
- Student presentations on nucleosynthesis papers
check website for paper suggestions **50%**

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 114.016 | 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 209.907 | 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 (288) | 111 Rg Roentgenium (287) | 112 Cn Copernicium (287) | 113 Uut Ununtrium unknown | 114 Fl Florium unknown | 115 Uup Ununpentium unknown | 116 Lv Livermorium unknown | 117 Uus Ununseptium unknown | 118 Uuo Ununoctium unknown | |

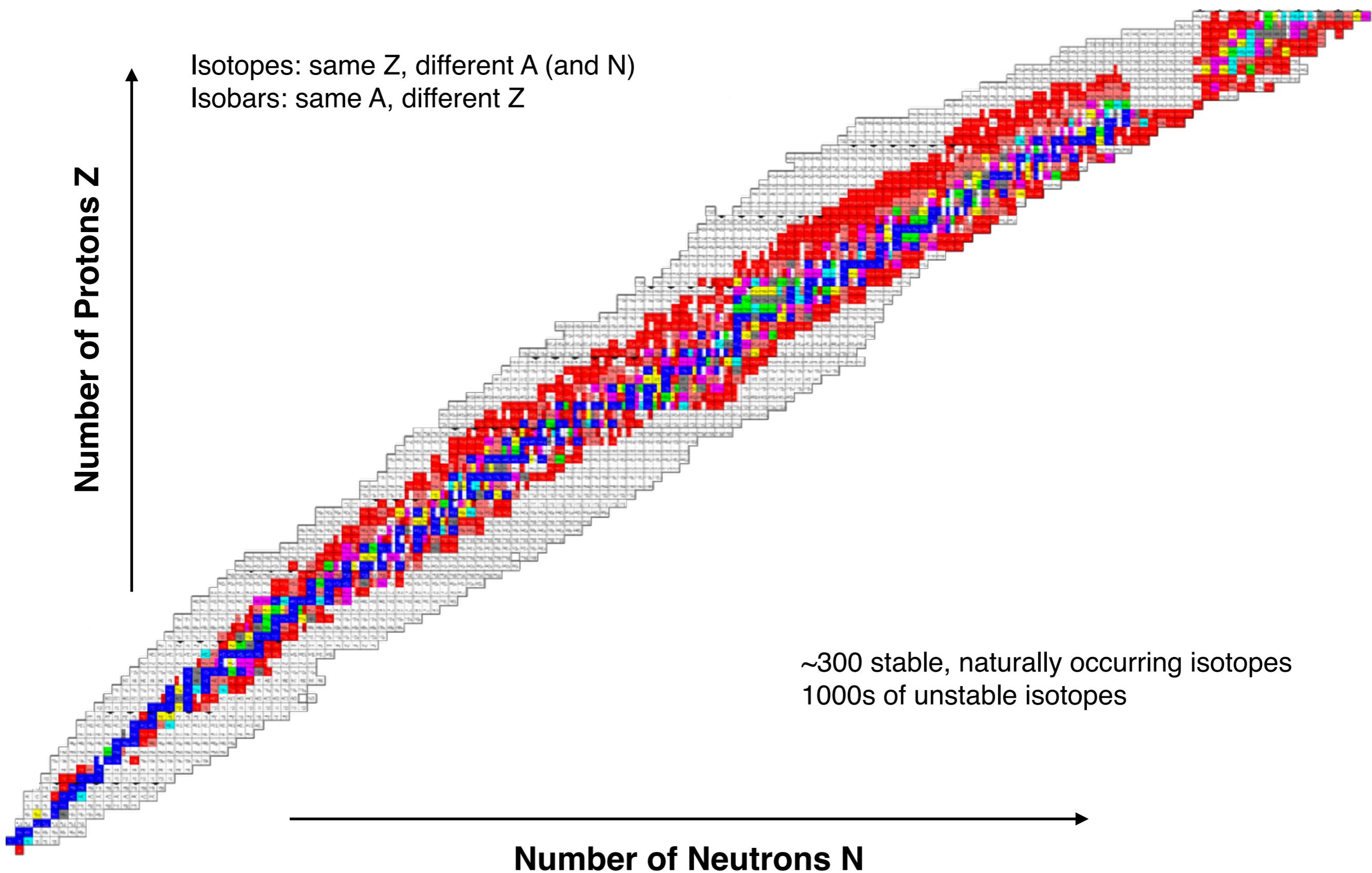
Periodic Table of the Elements

| | |
|---------------|----------------|
| 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 243.024 | 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



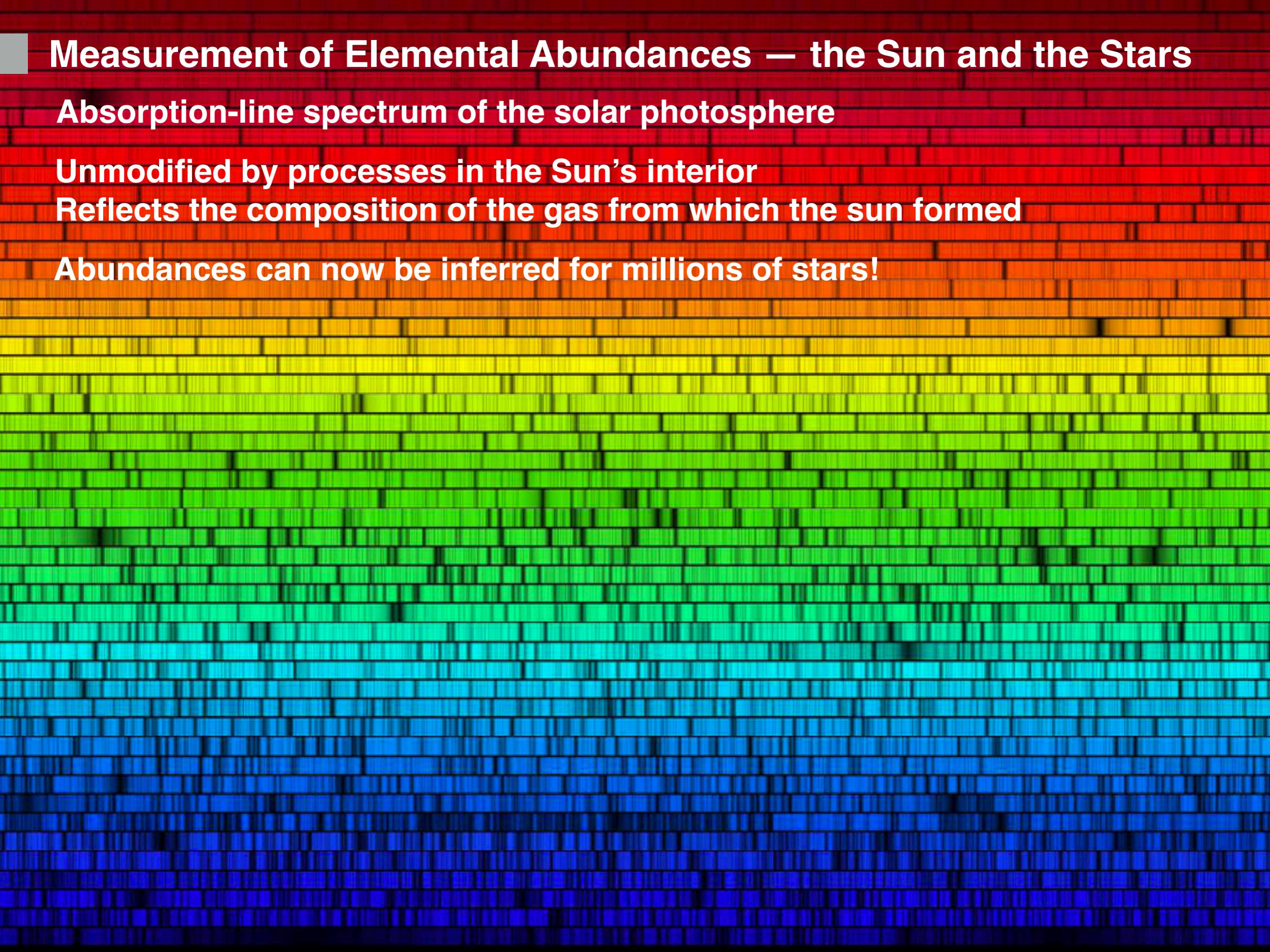
Measurement of Elemental Abundances – the Sun and the Stars

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 and the Stars

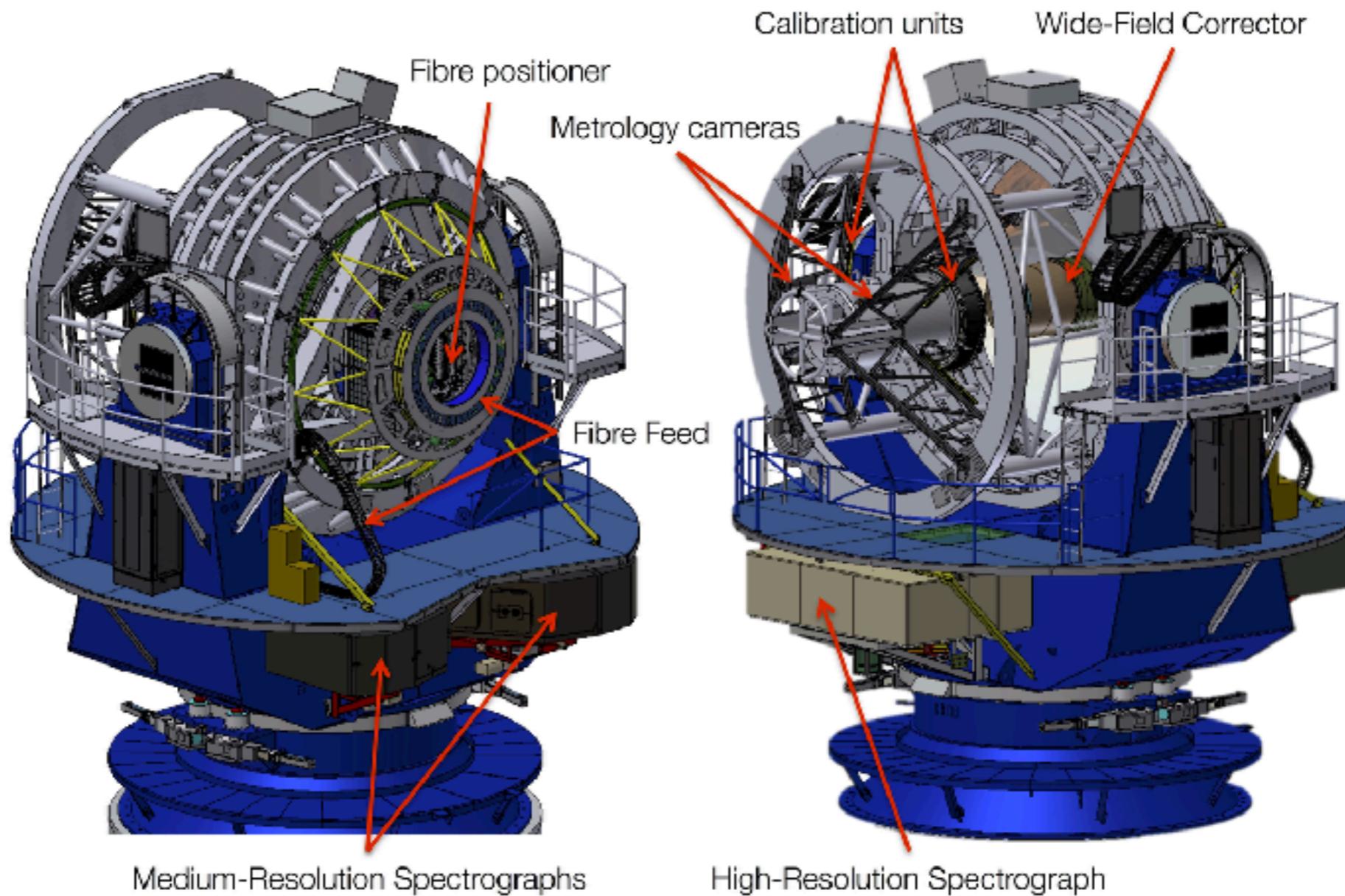
“Metals”

| 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 |

Measurement of Elemental Abundances — the Sun

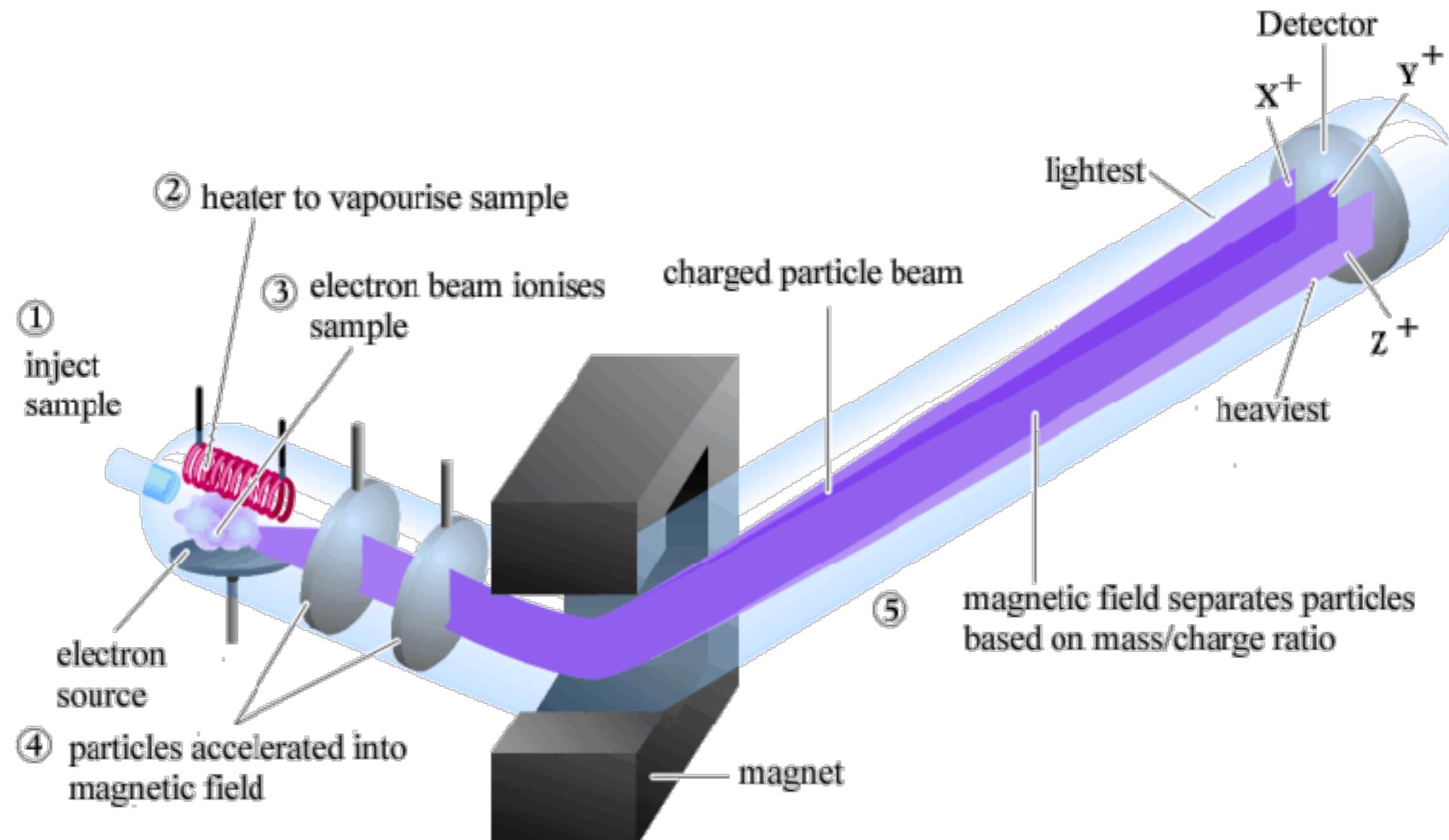
the 4MOST fibre-fed spectrograph for the 4m VISTA telescope

simultaneous spectra of 2500 stars down to mag 22



Measurement of Isotopic Abundances

Masses of isotopes can be measured with a mass spectrometer



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

Homogeneous solar system composition

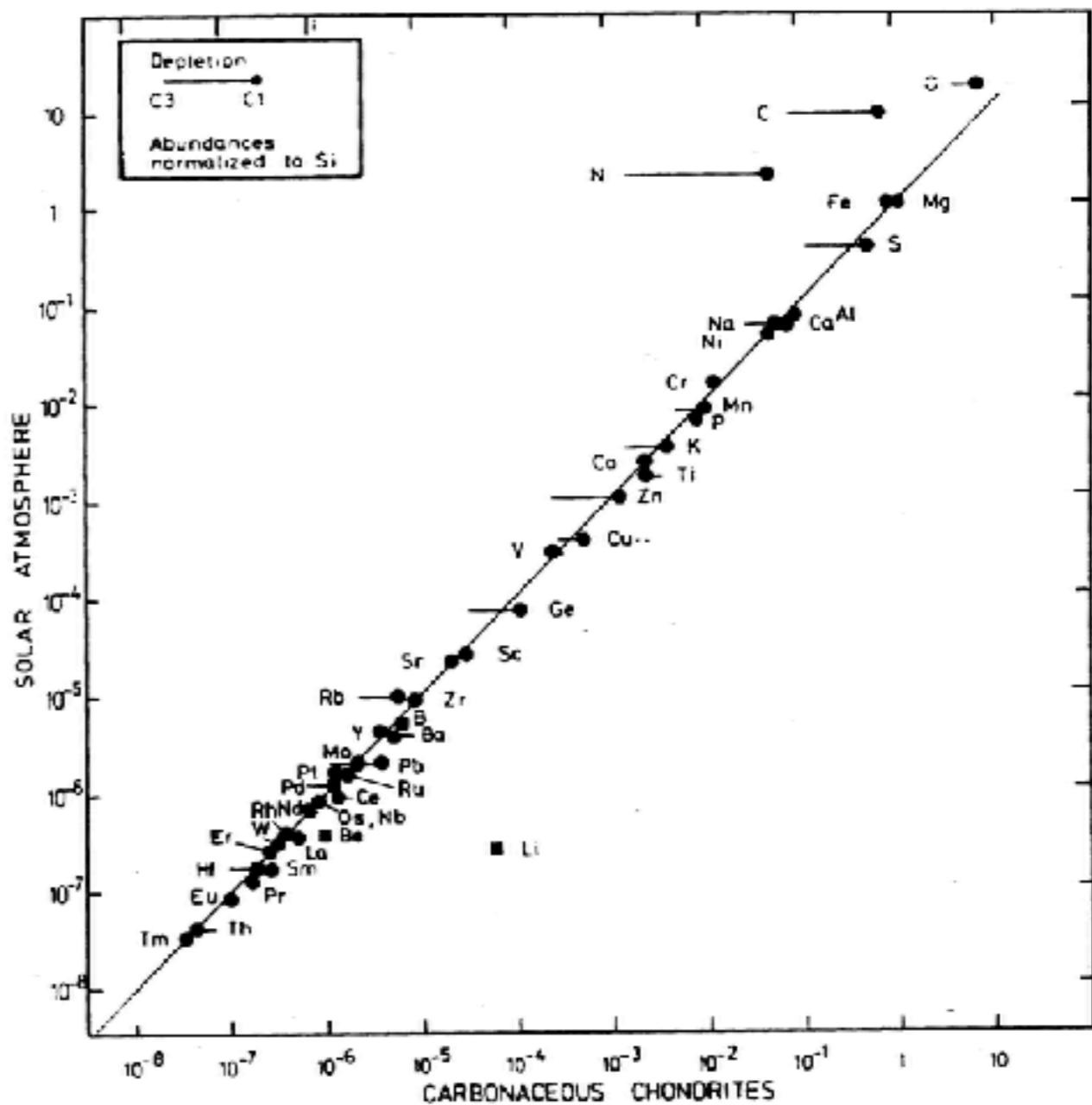


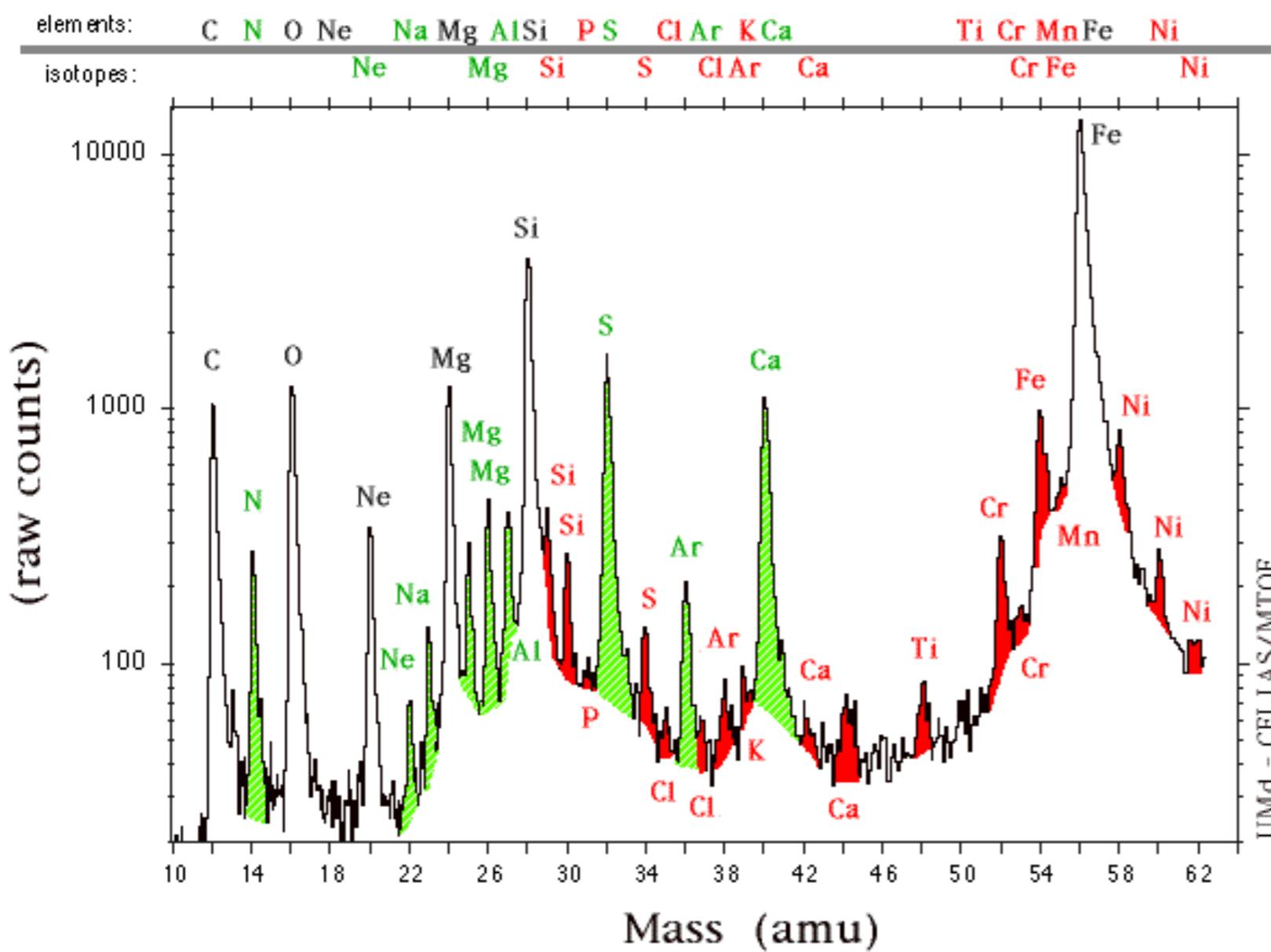
Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

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

Measurement of Isotopic Abundances

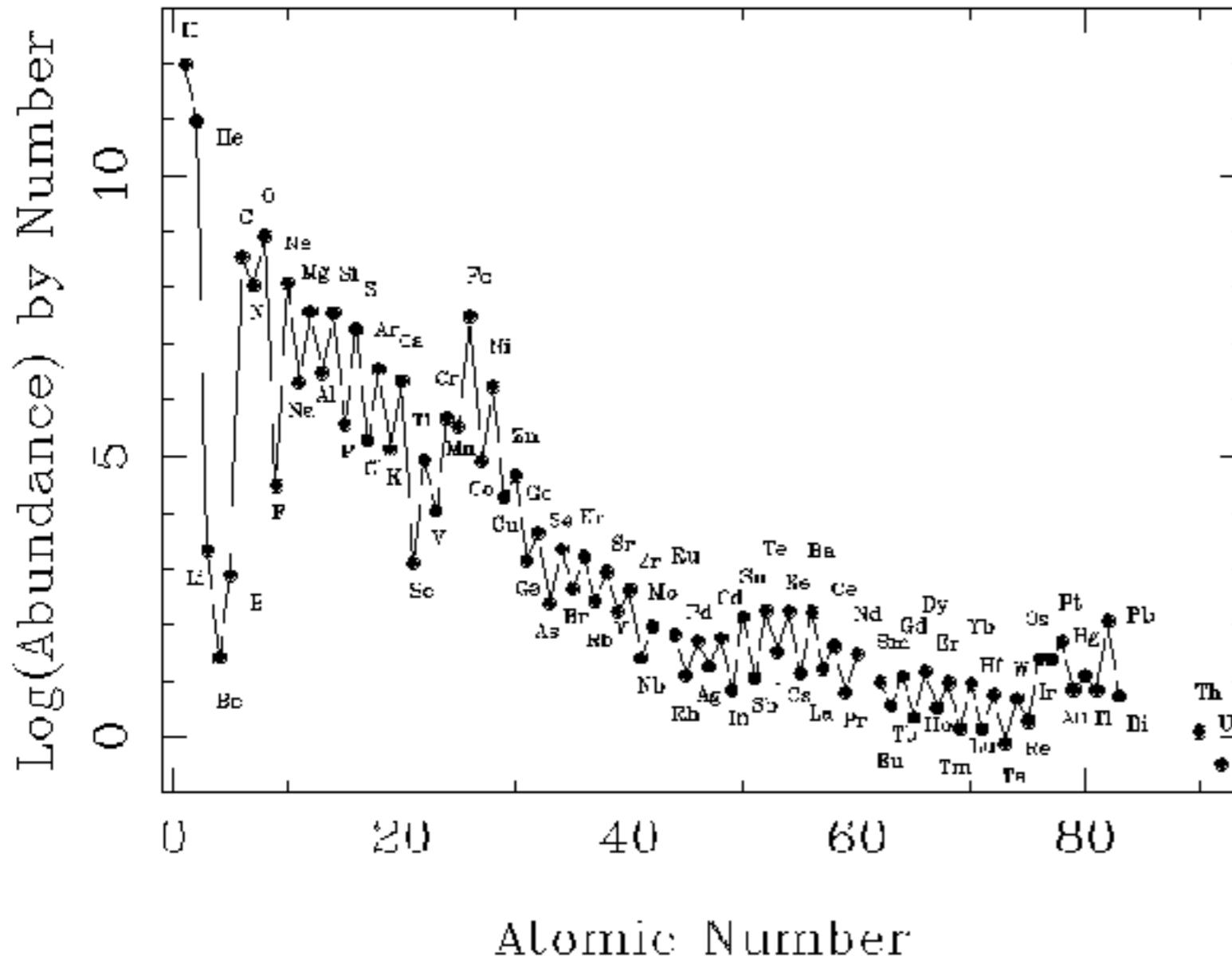
Isotope abundances in the solar system

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

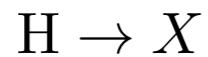
$$N_i = X_i/A_i$$

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

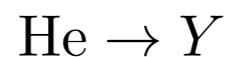
$$A_{\text{H}} = \log(N_{\text{H}}) = 12$$

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

By mass fraction



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



$$X + Y + Z = 1$$



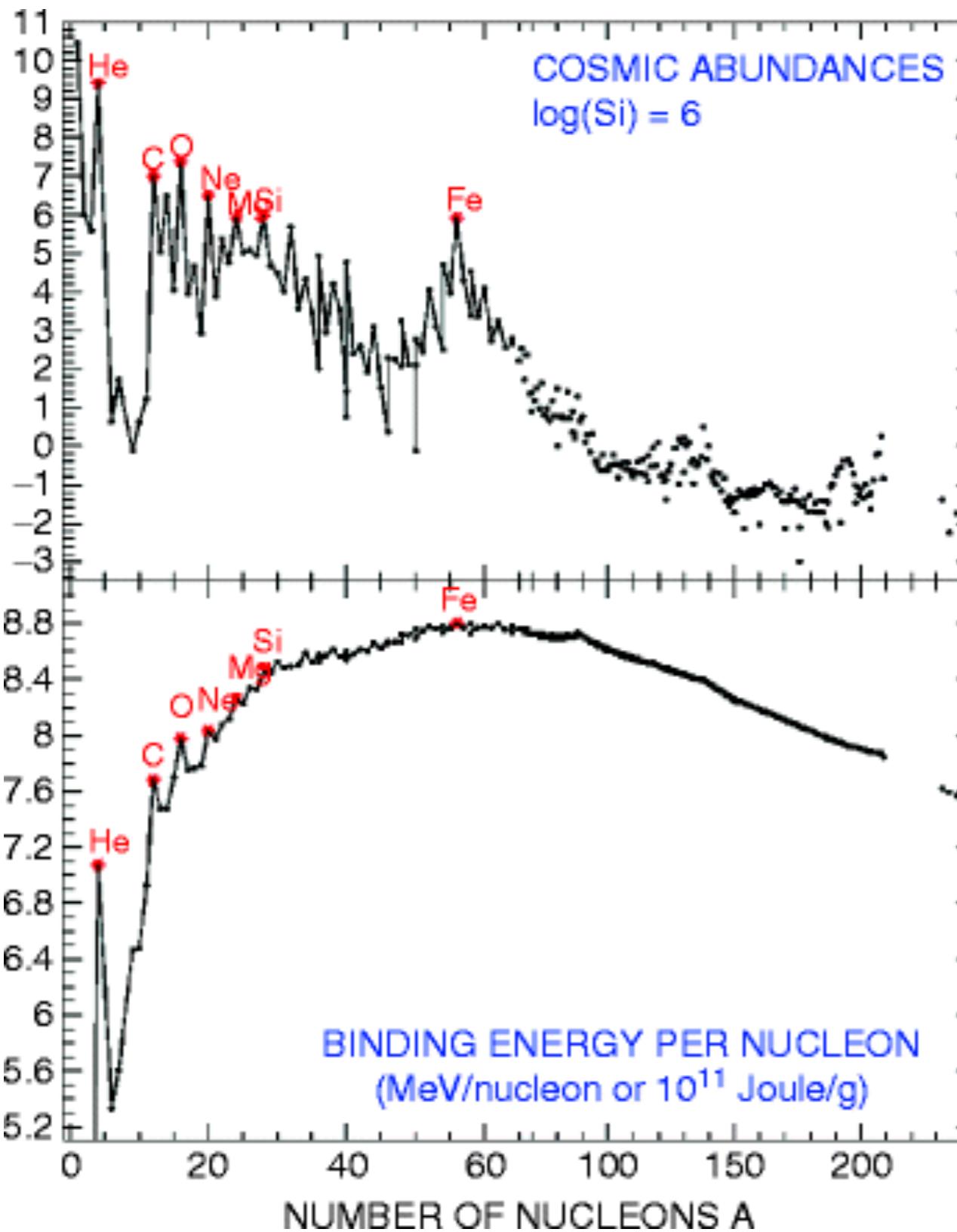
$$\sum X_i = 1$$

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

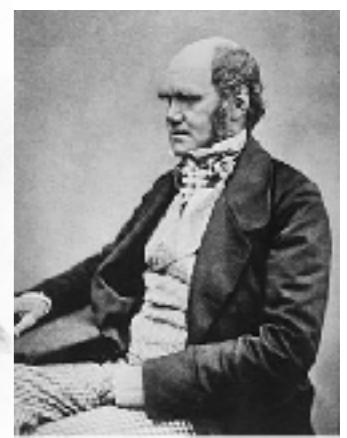
Before early 30s: Can nuclear reactions take place inside the Sun and the stars?

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?

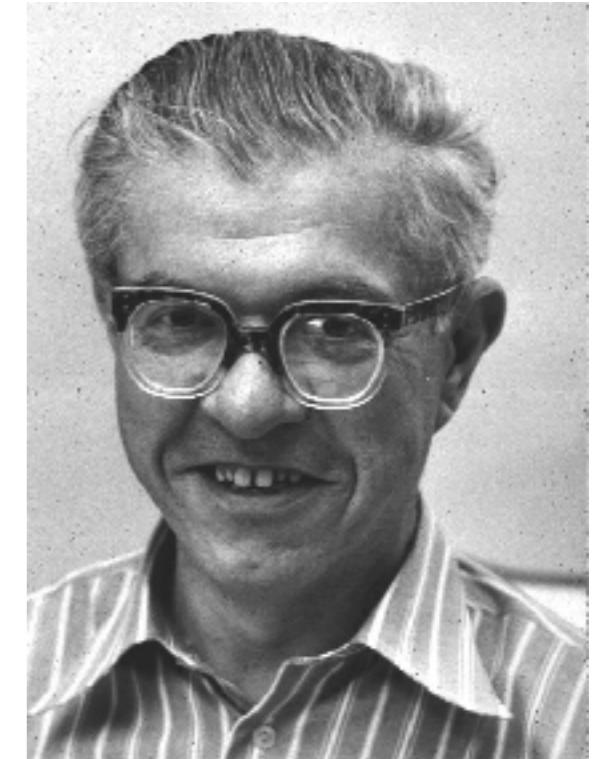
Debate in the 40s: Primordial or Big-bang nucleosynthesis vs stars and supernovae



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

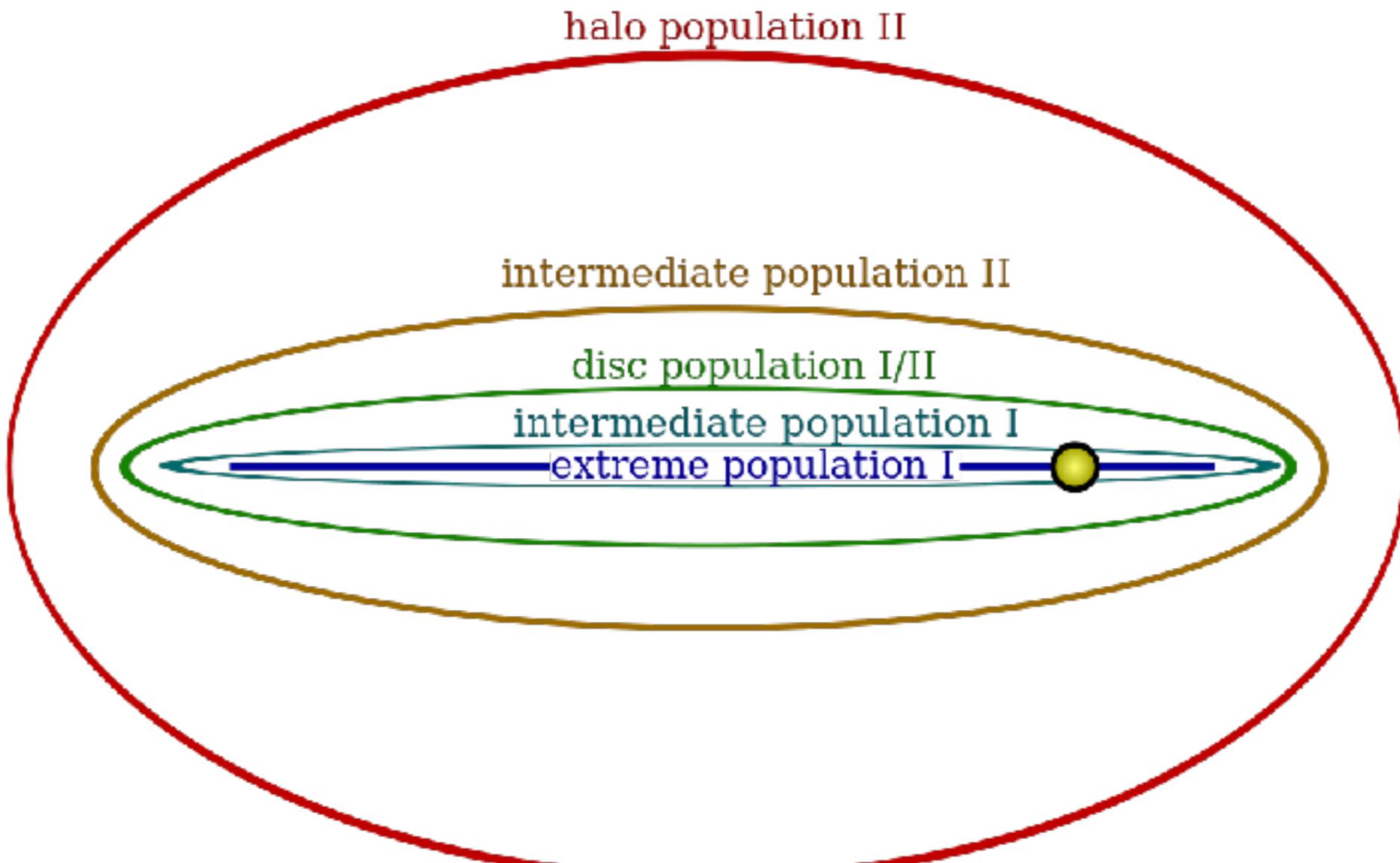


Fred Hoyle (1915–2001)

Elements created in stars and supernovae

Observational evidence for nucleosynthesis

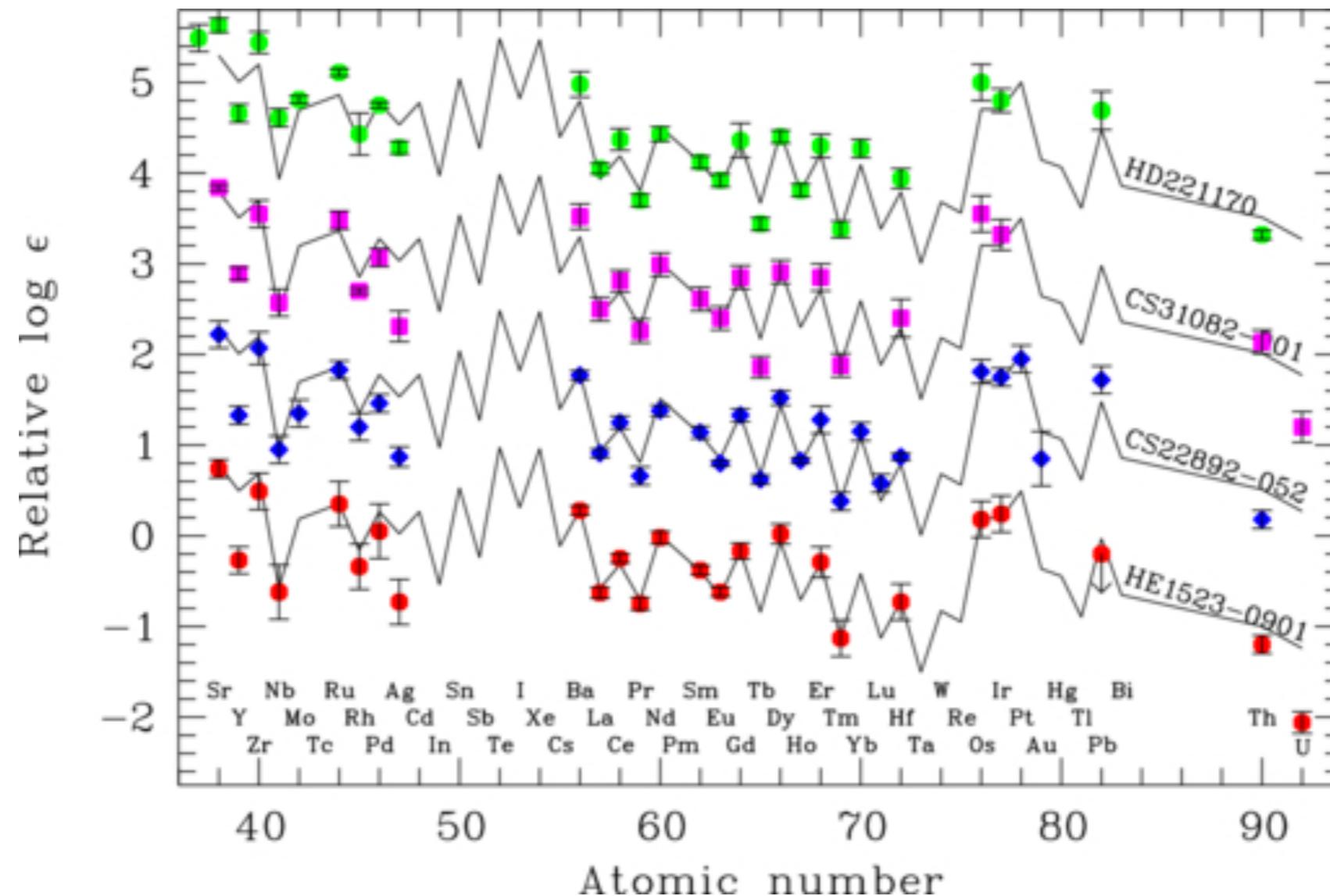
In early 50s: evidence for evolution of abundances with cosmic time
Stars near the galactic disk have higher metallicities than stars in the halo



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

Thermonuclear reactions

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



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

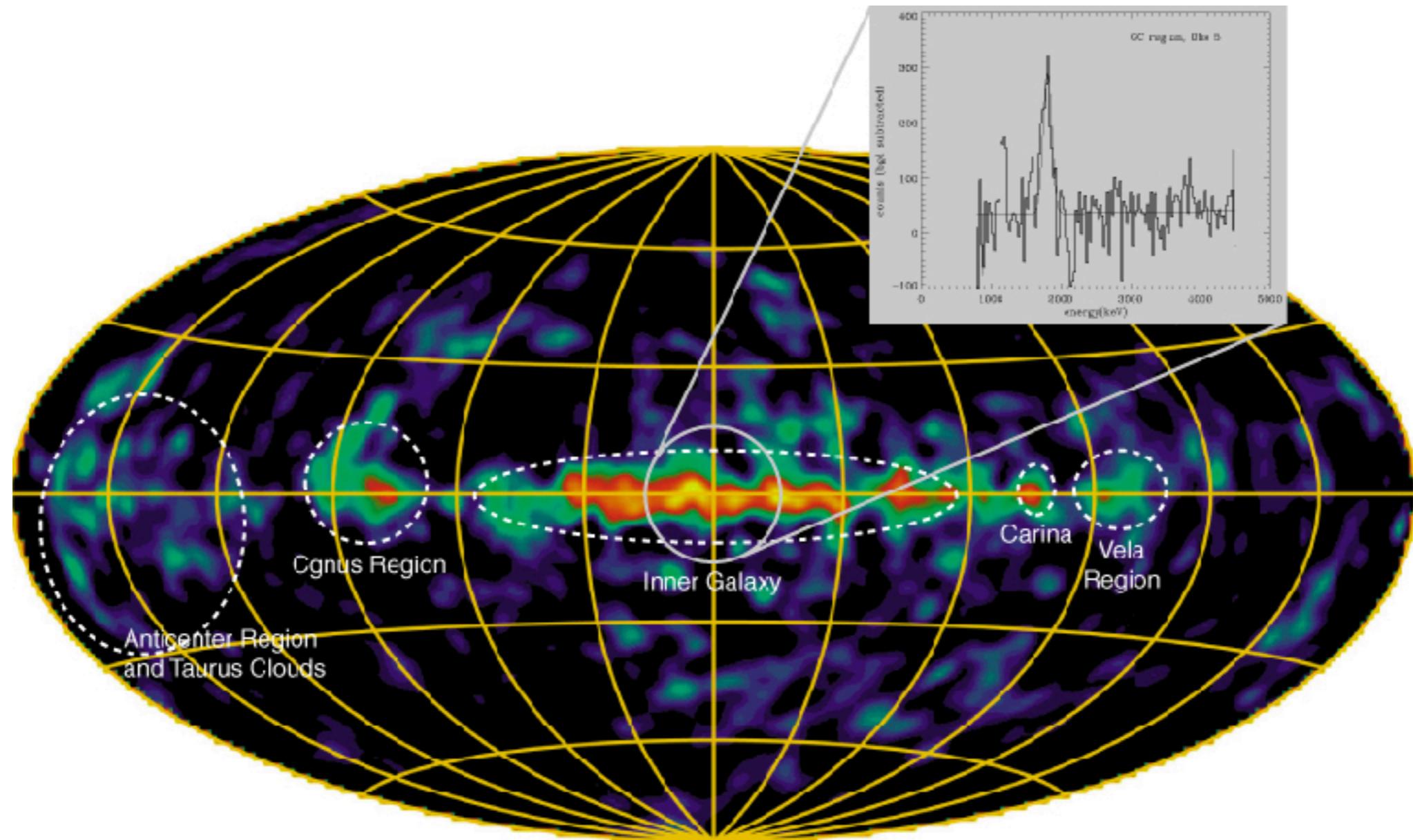
Synthesis of the Elements in Stars*

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



Modern observational evidence for nucleosynthesis

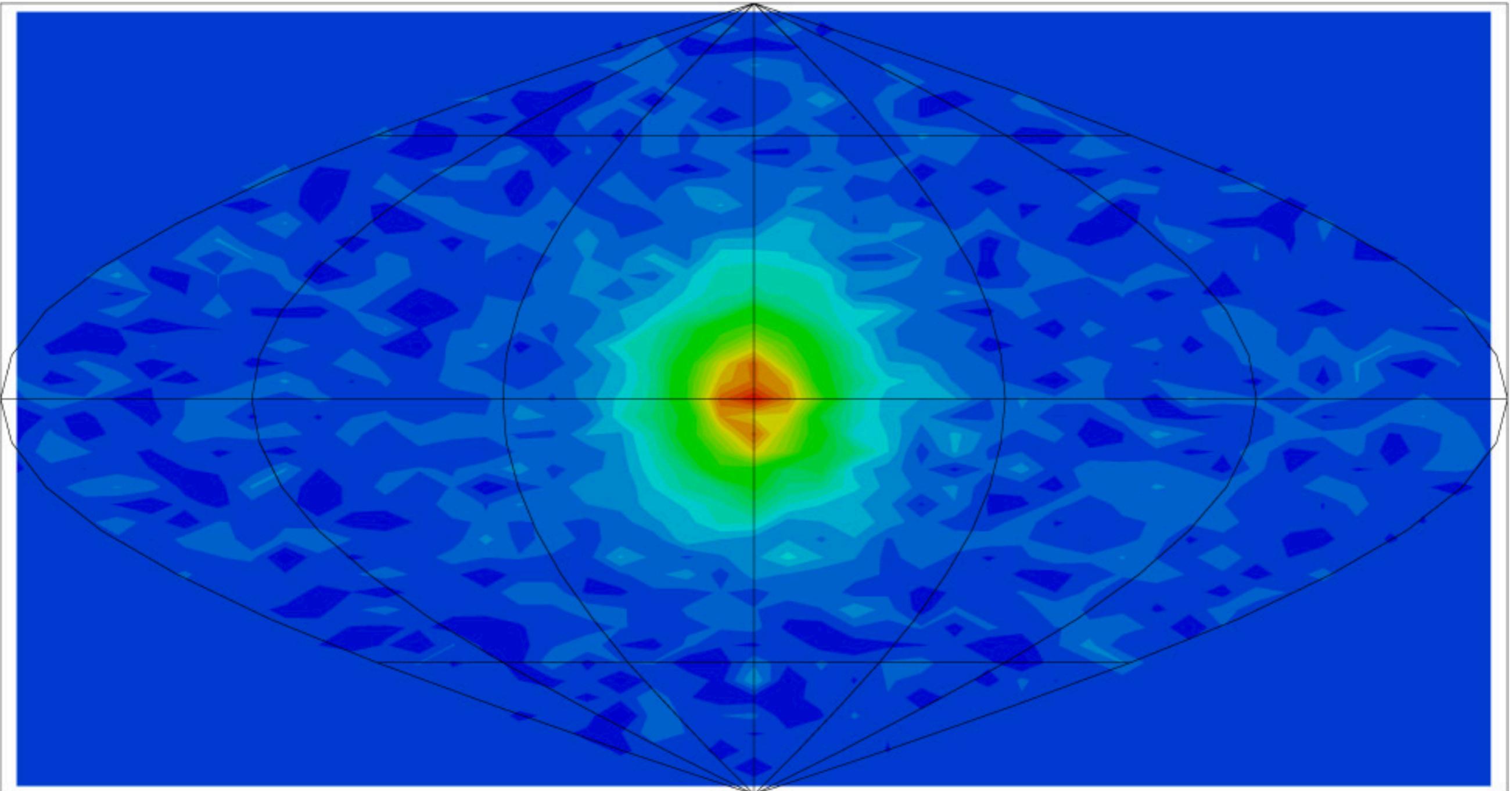
More (in)direct evidence for ongoing nucleosynthesis



example 1.809 MeV line emission from the decay of ^{26}Al (lifetime of 7×10^5 yr)

Modern observational evidence for nucleosynthesis

More (in)direct evidence for ongoing nucleosynthesis



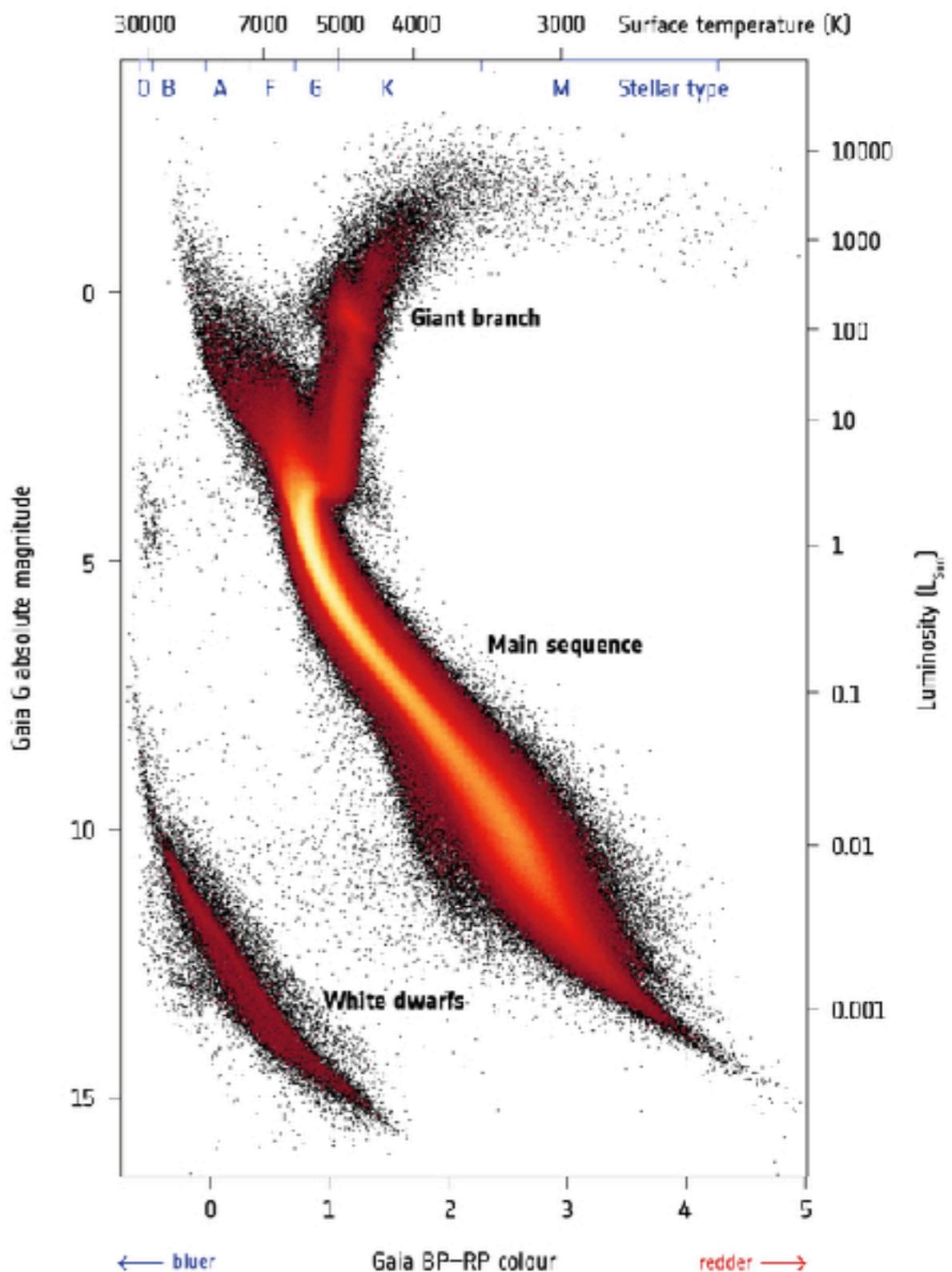
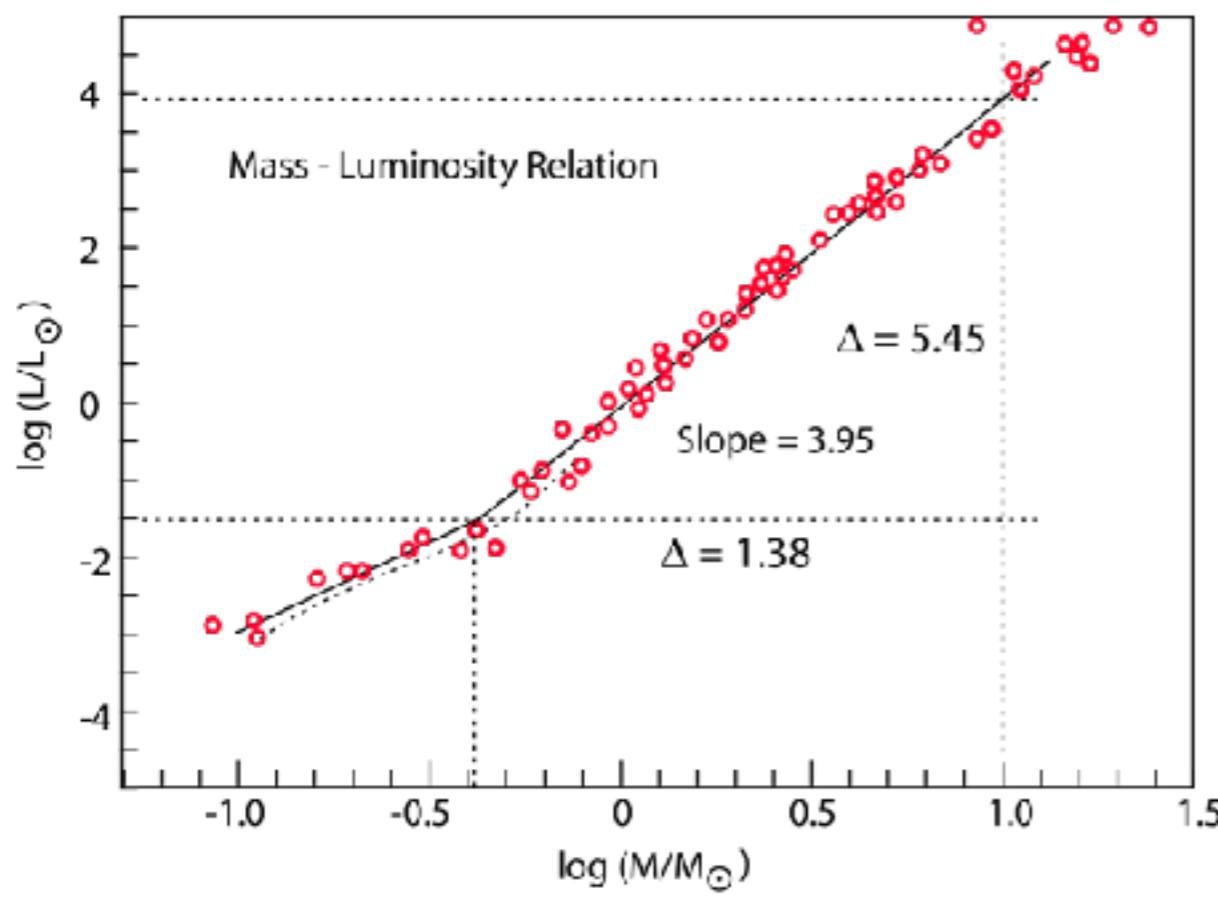
example 2: observation of solar neutrinos

Thermonuclear reactions

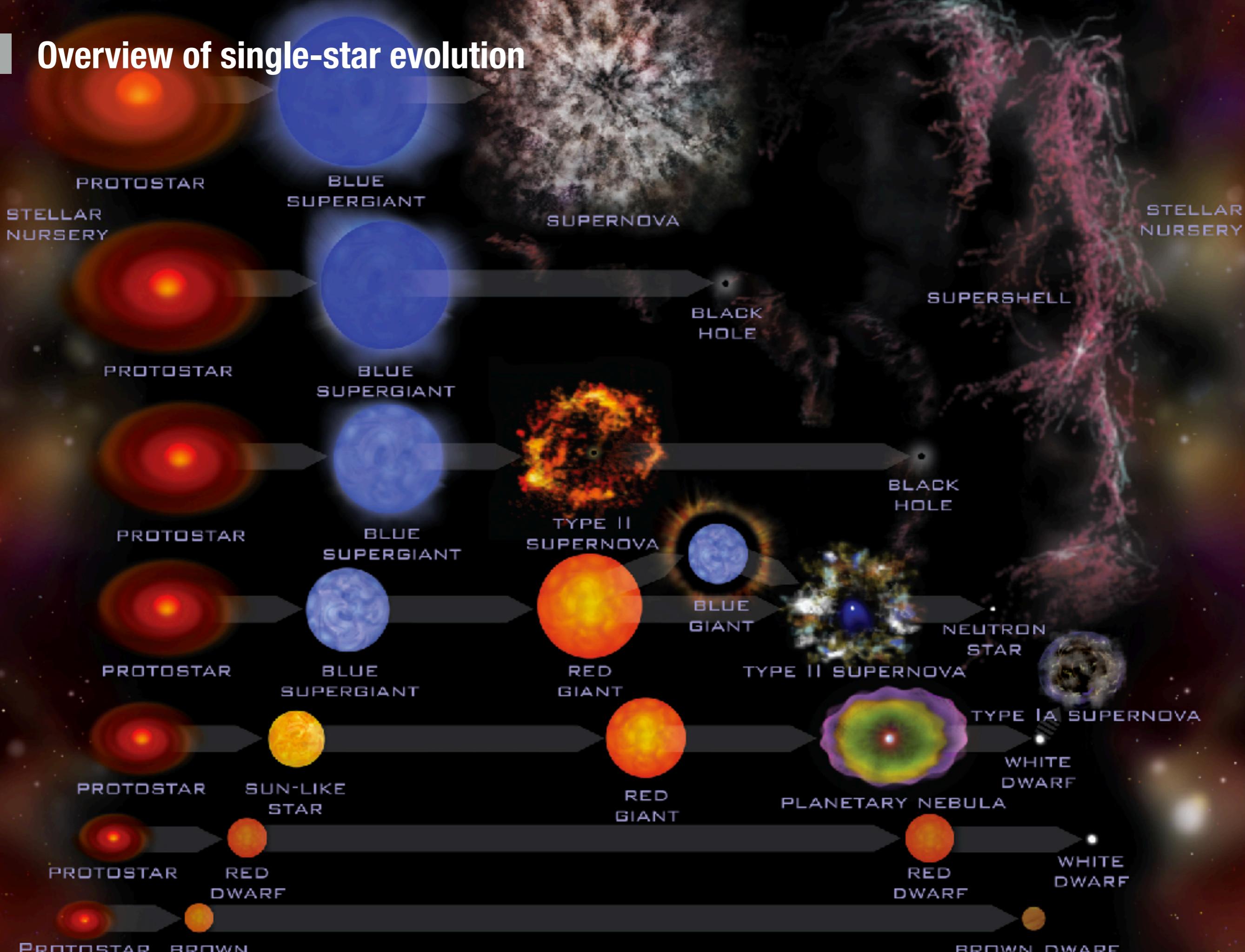
→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

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



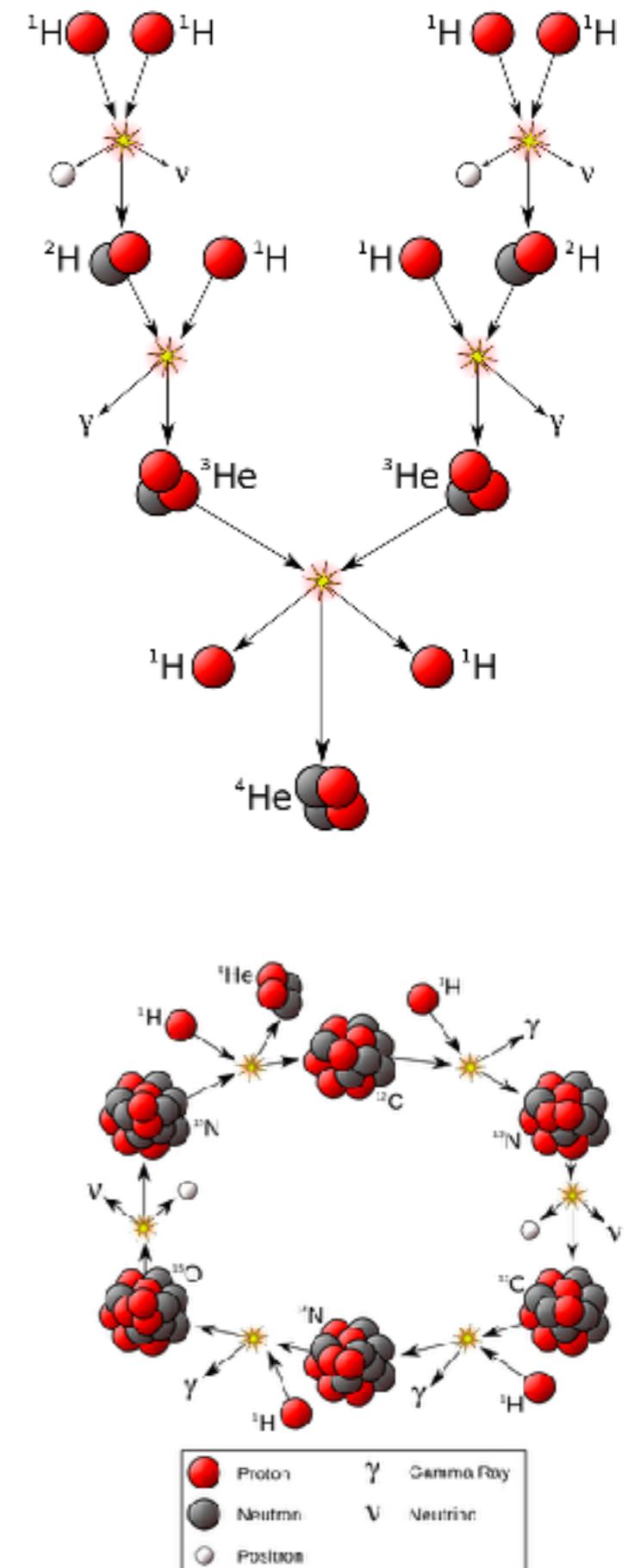
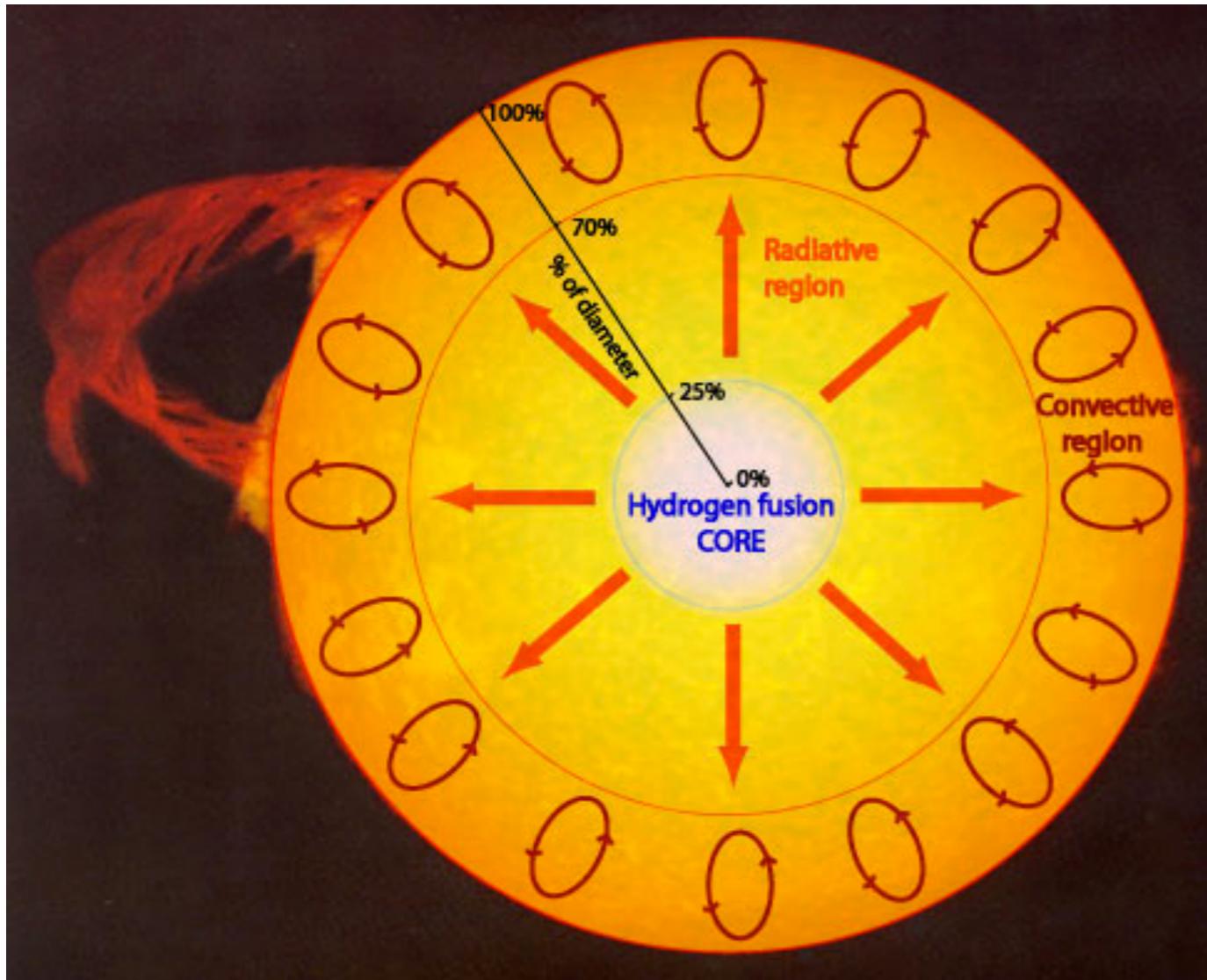
Overview of single-star evolution

Mass (Solar masses)

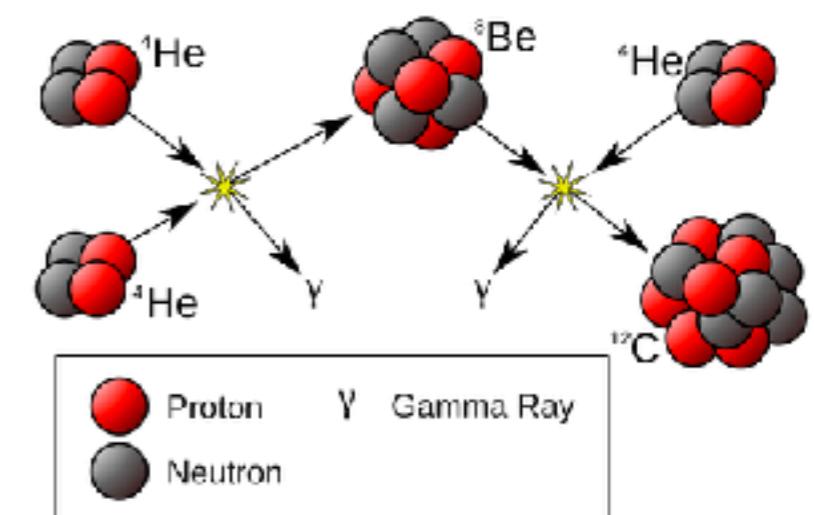
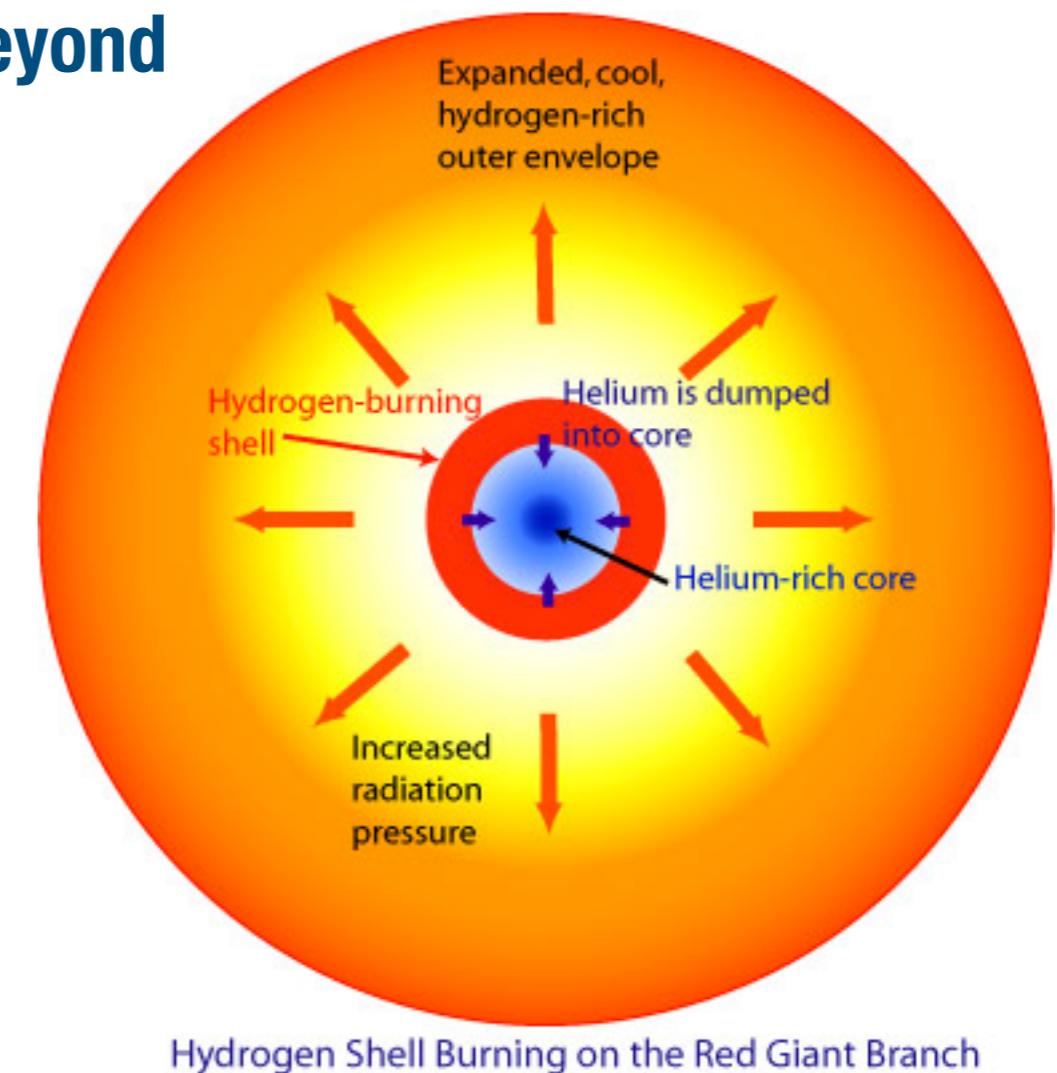
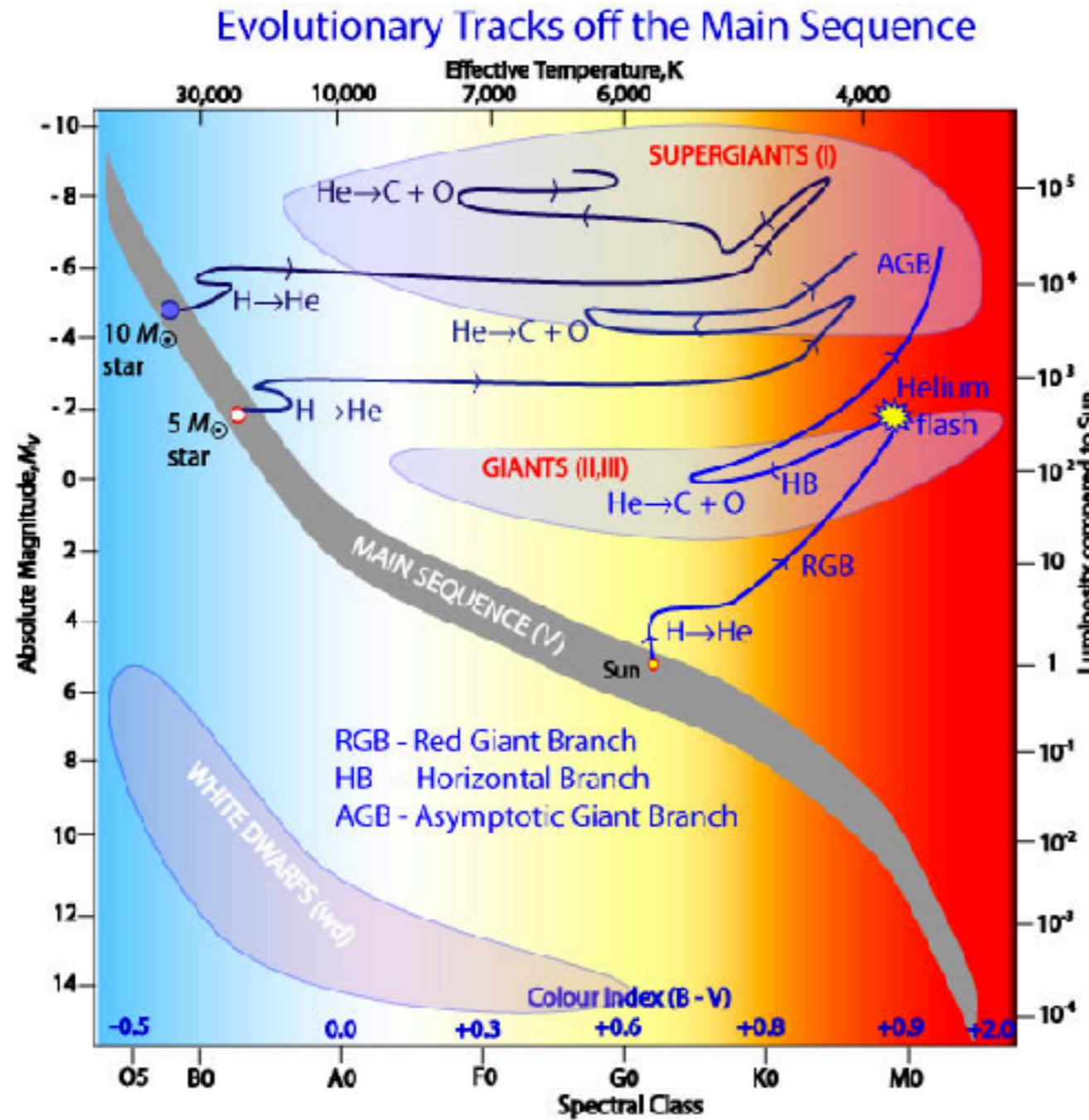
| | | | | | | | | | | |
|------------------------|-------------|-----------|--------------|--------------------|--------------------|------------------------|-------------------------------|-------------------|-------------|----------------|
| Brown dwarf | D-C | | | | | | | | | |
| Red dwarf | H-C [MS] | | | | | | | | | |
| 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

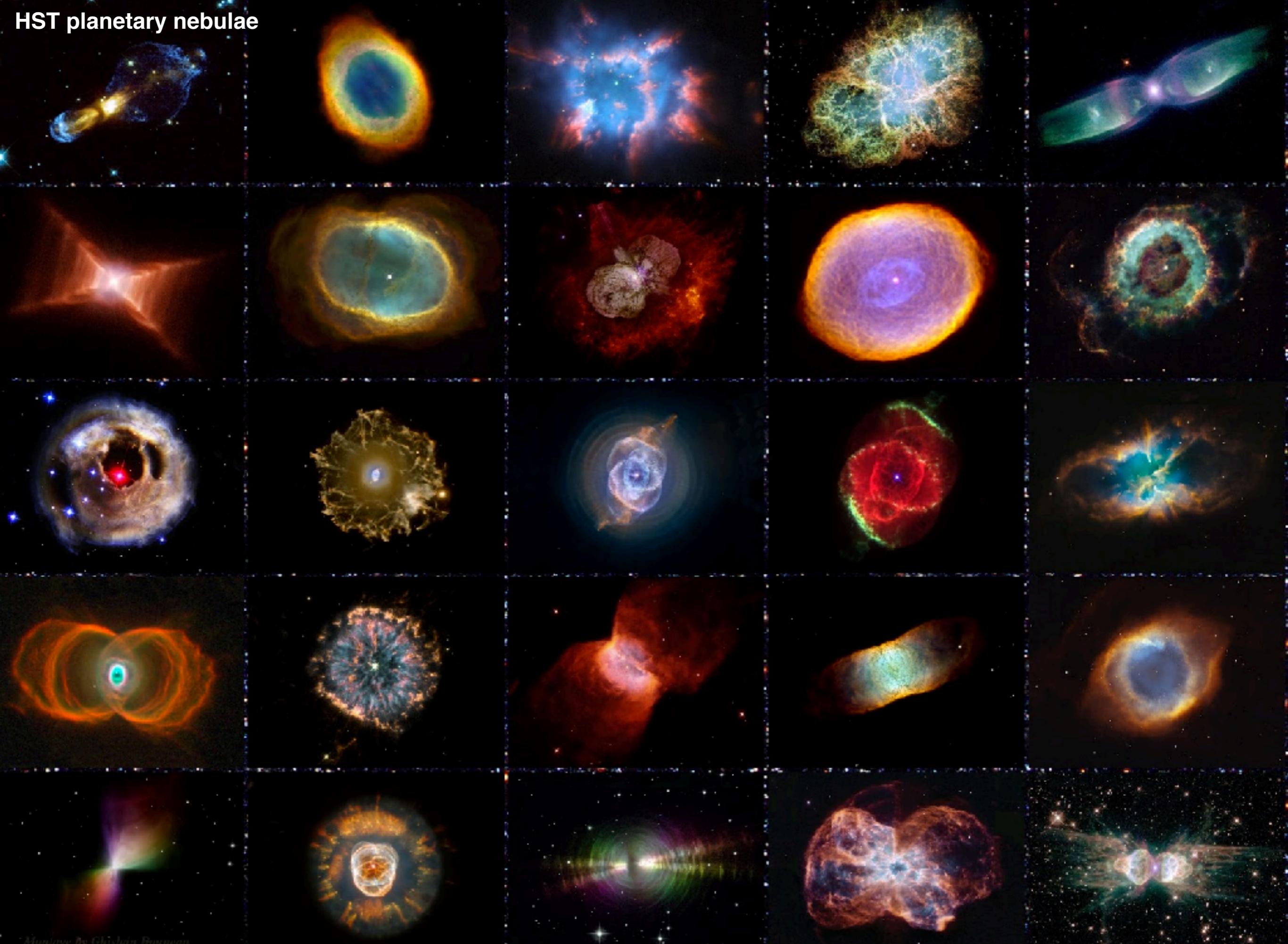
Starts on the main sequence
via pp (low mass) and CNO (high mass) chains



Helium burning on the red giant branch and beyond

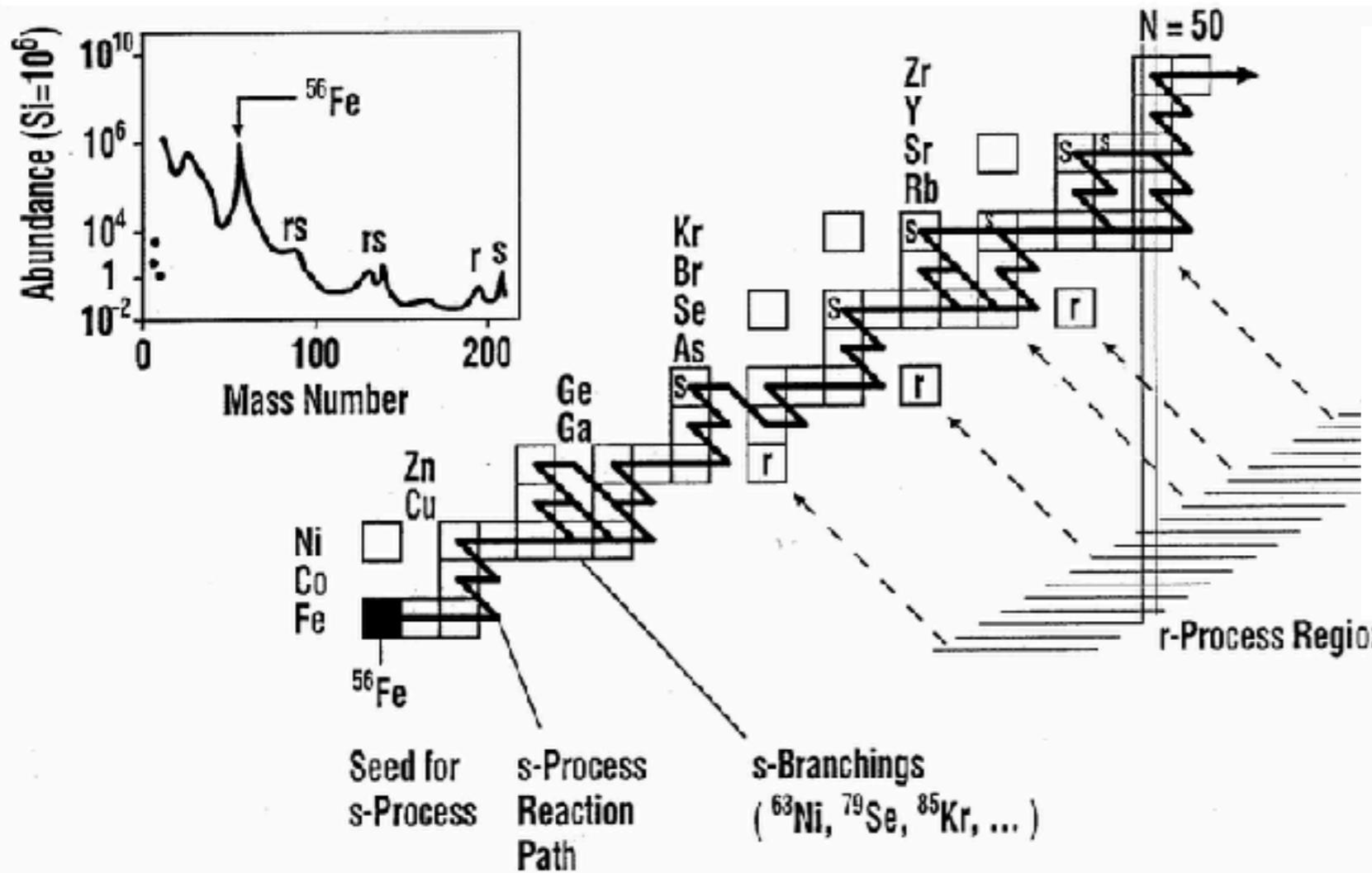
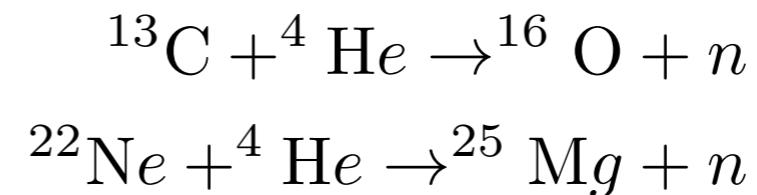


HST planetary nebulae

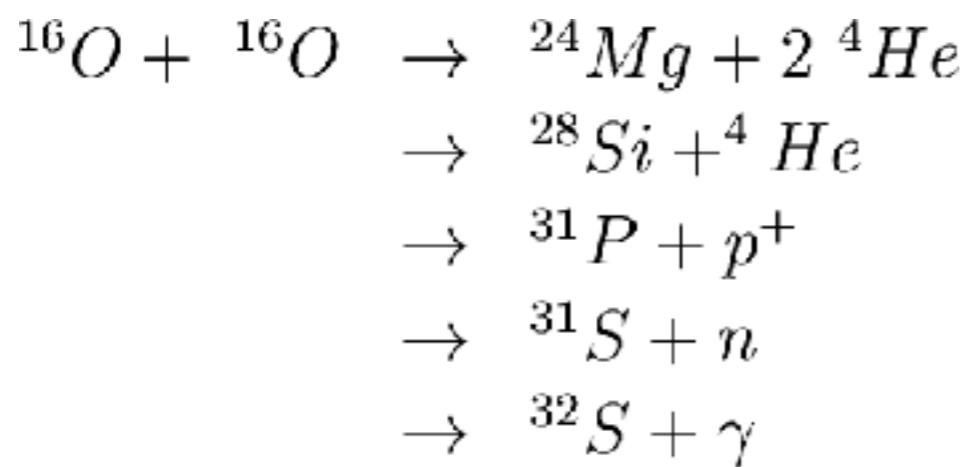
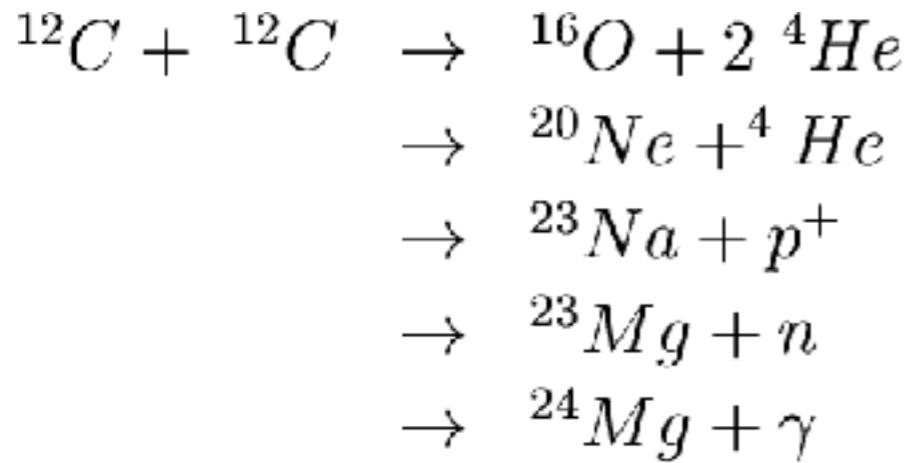


slow neutron capture on the AGB (s-process)

main neutron sources



Carbon burning and beyond



For 8 solar mass star

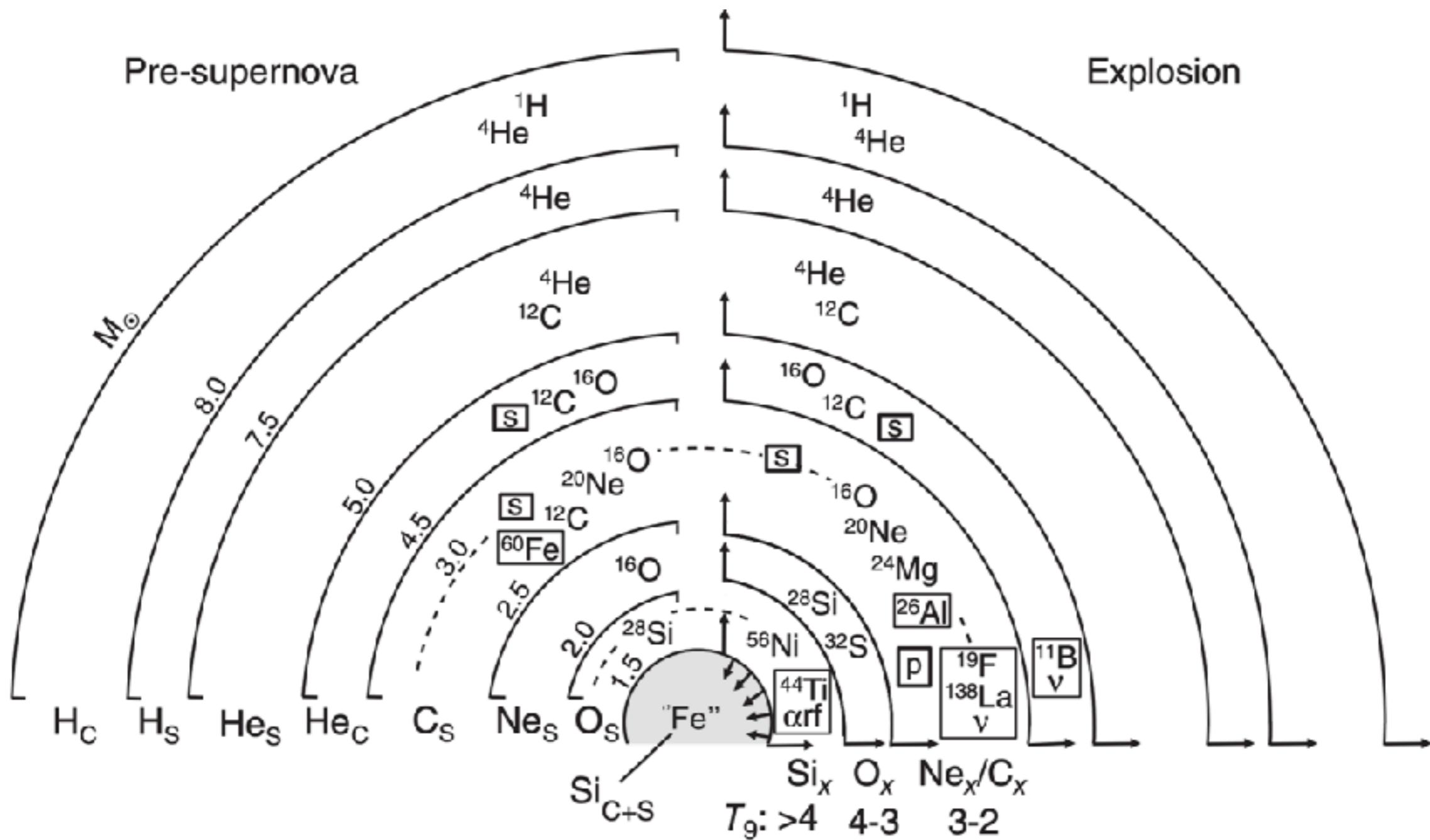
- Hydrogen: 10 Myr
- Helium: 1 Myr
- Carbon: 1000 yr
- Neon: 10 yr
- Oxygen: 1 yr
- Silicon: 1 day
- Core collapse: < 1 sec

Silicon burning occurs at extremely high temperatures: ~3 GK

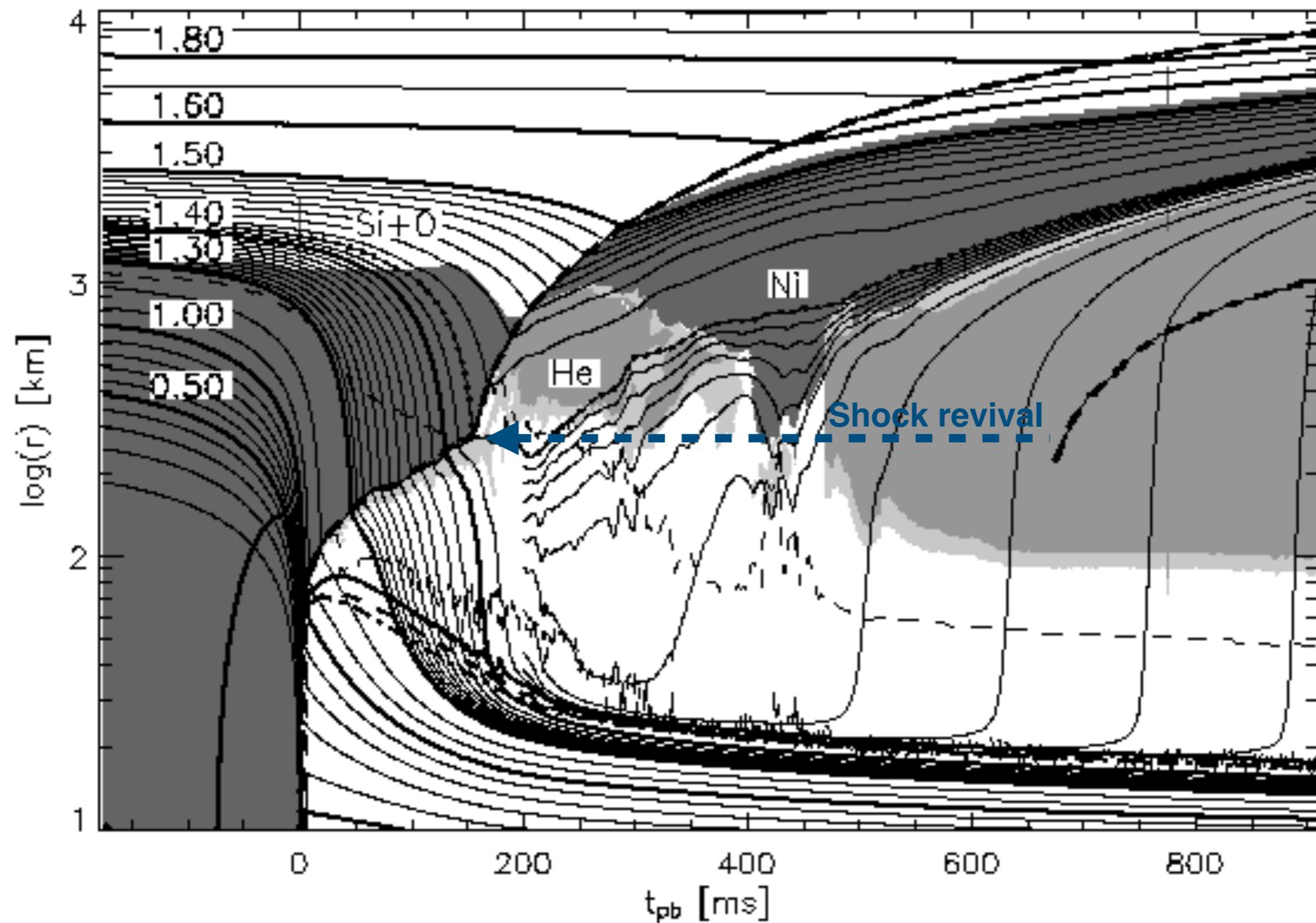
Nuclei photo-disintegrate and the emitted protons and alpha particles can be captured, forming heavier nuclei.

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

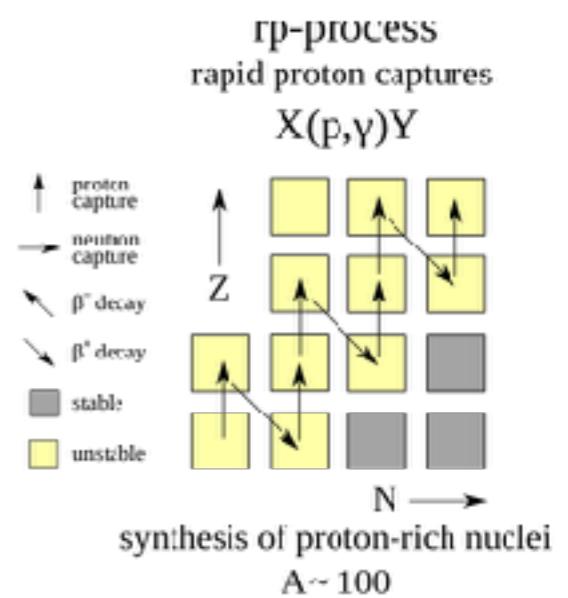
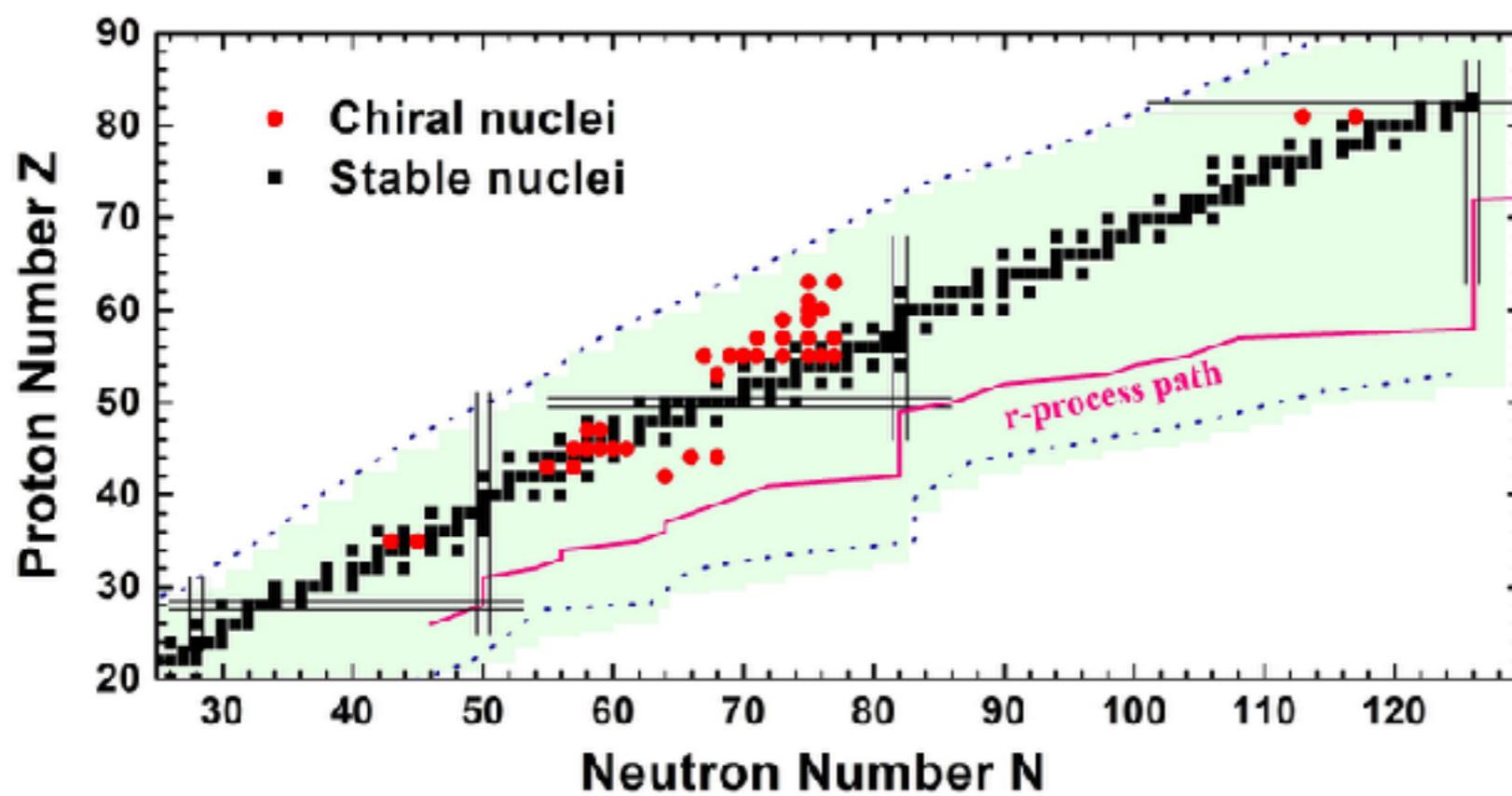
Pre-supernova structure and core-collapse



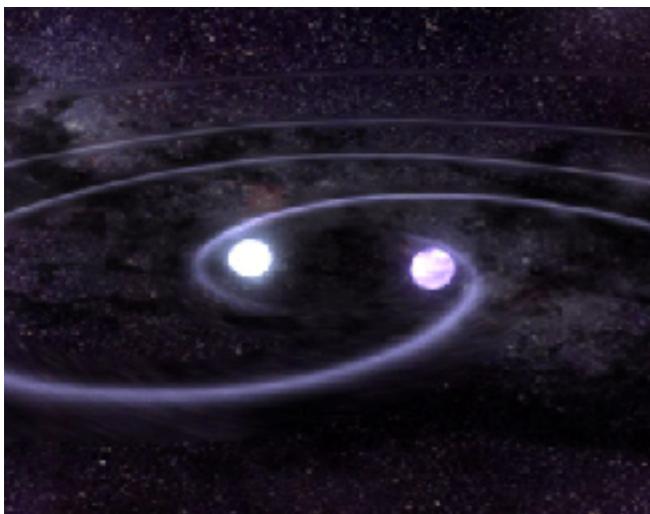
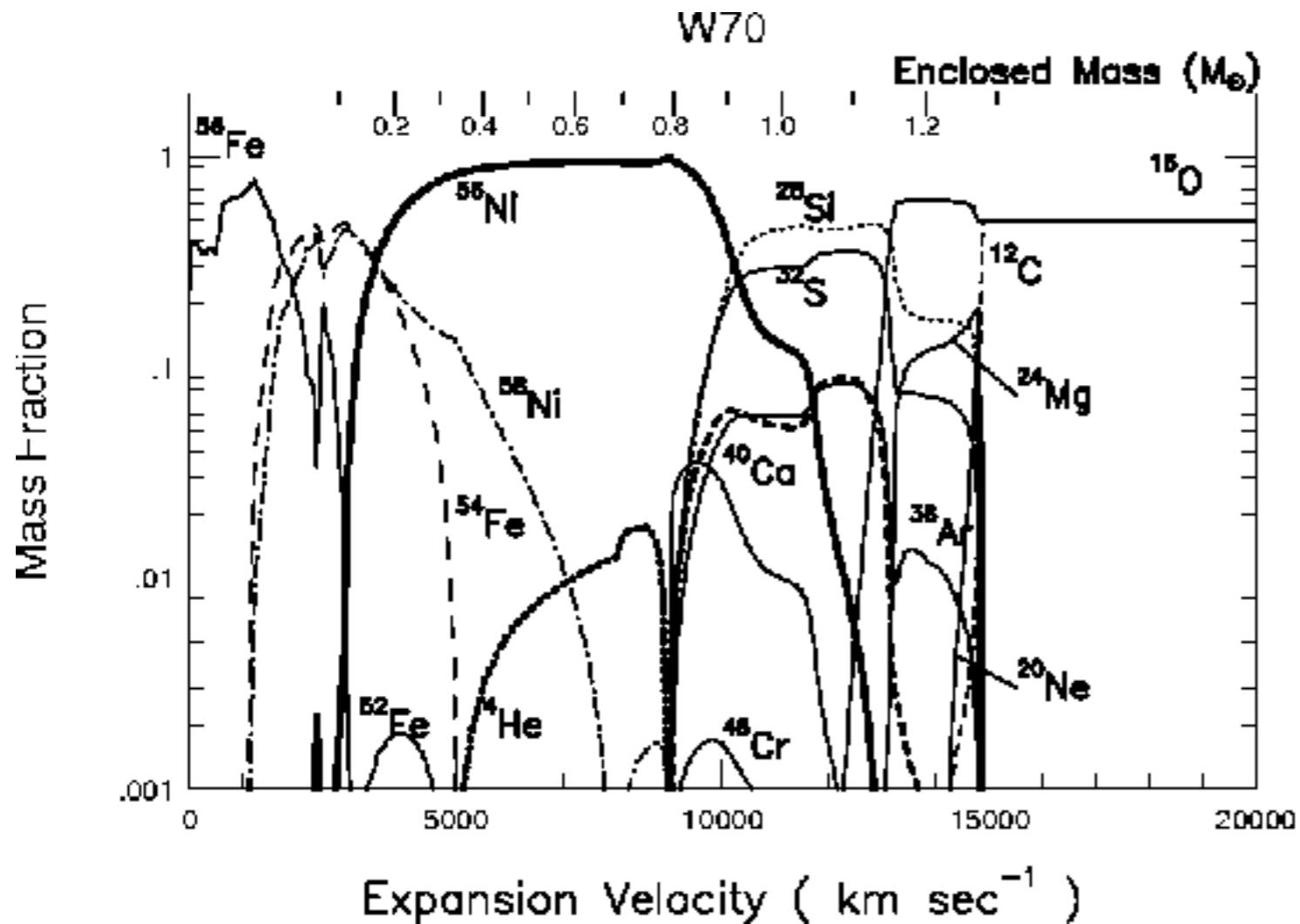
Core-collapse supernovae



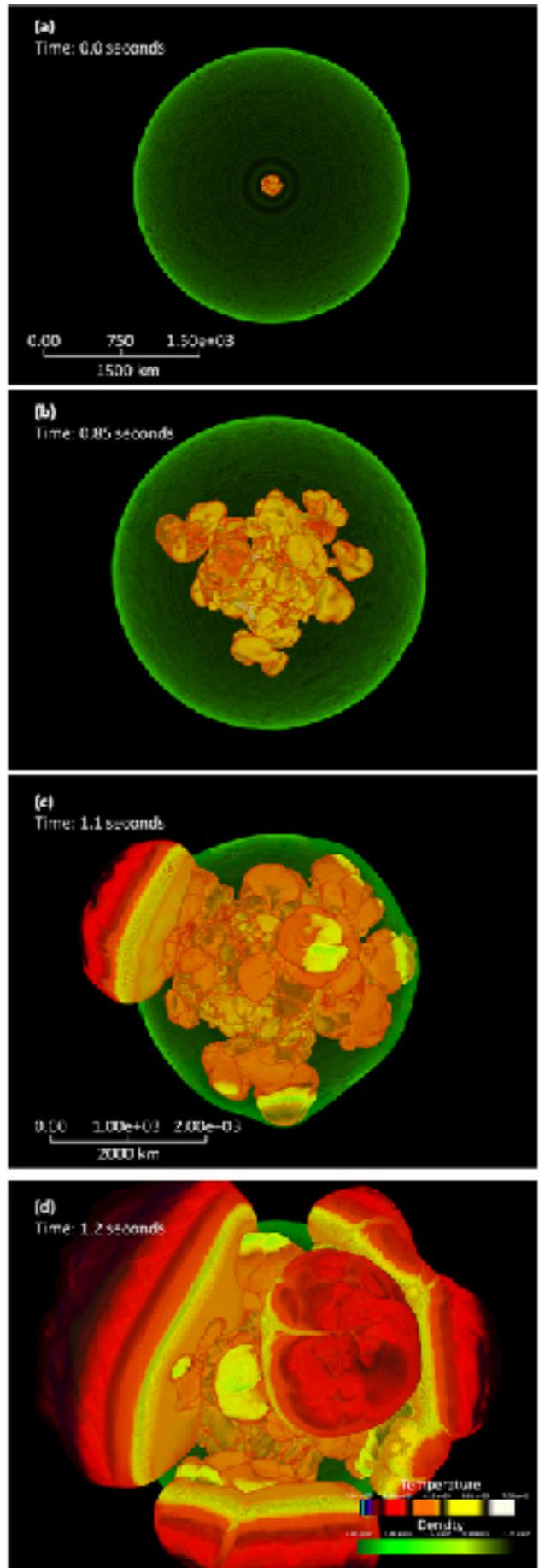
Explosive nucleosynthesis (rapid neutron capture; r-process; rp-process)



Type Ia supernovae (NSE)

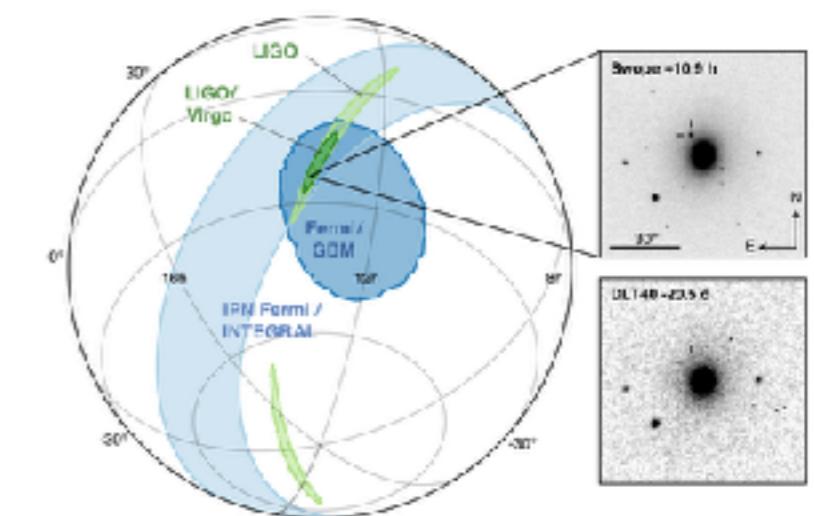
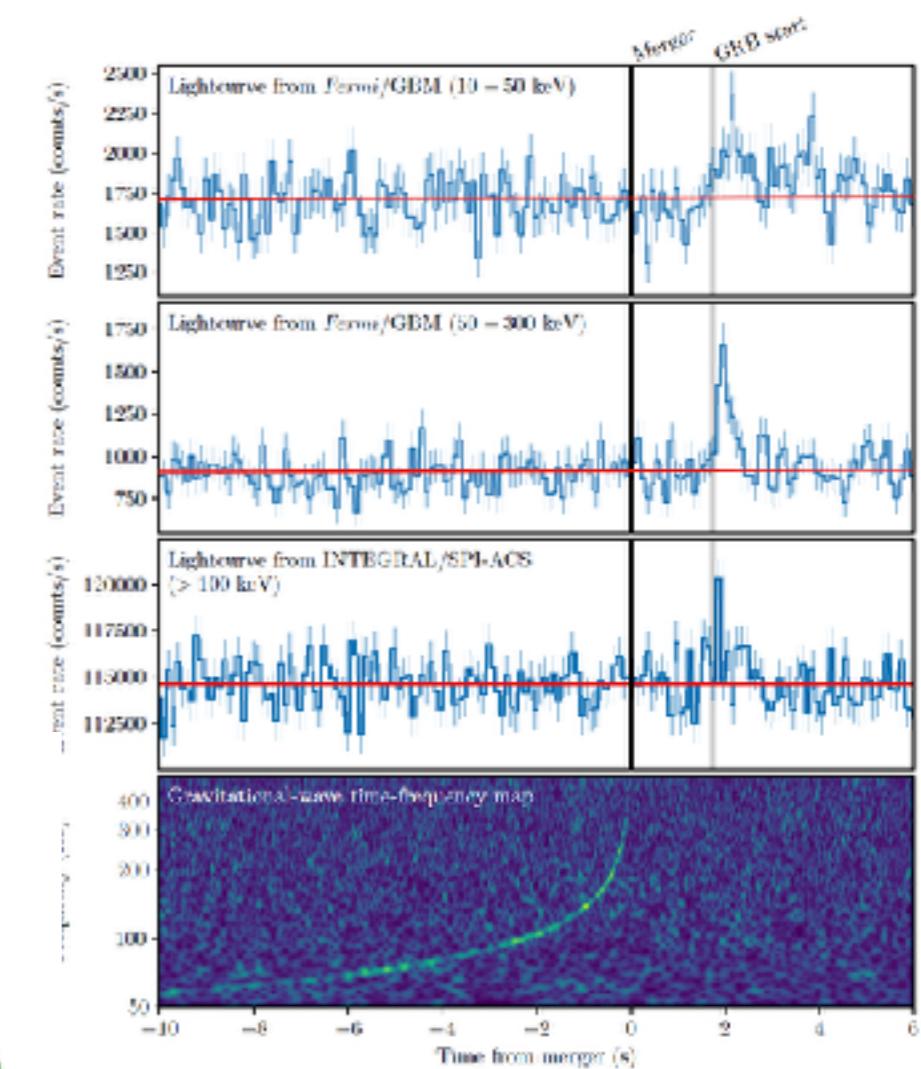
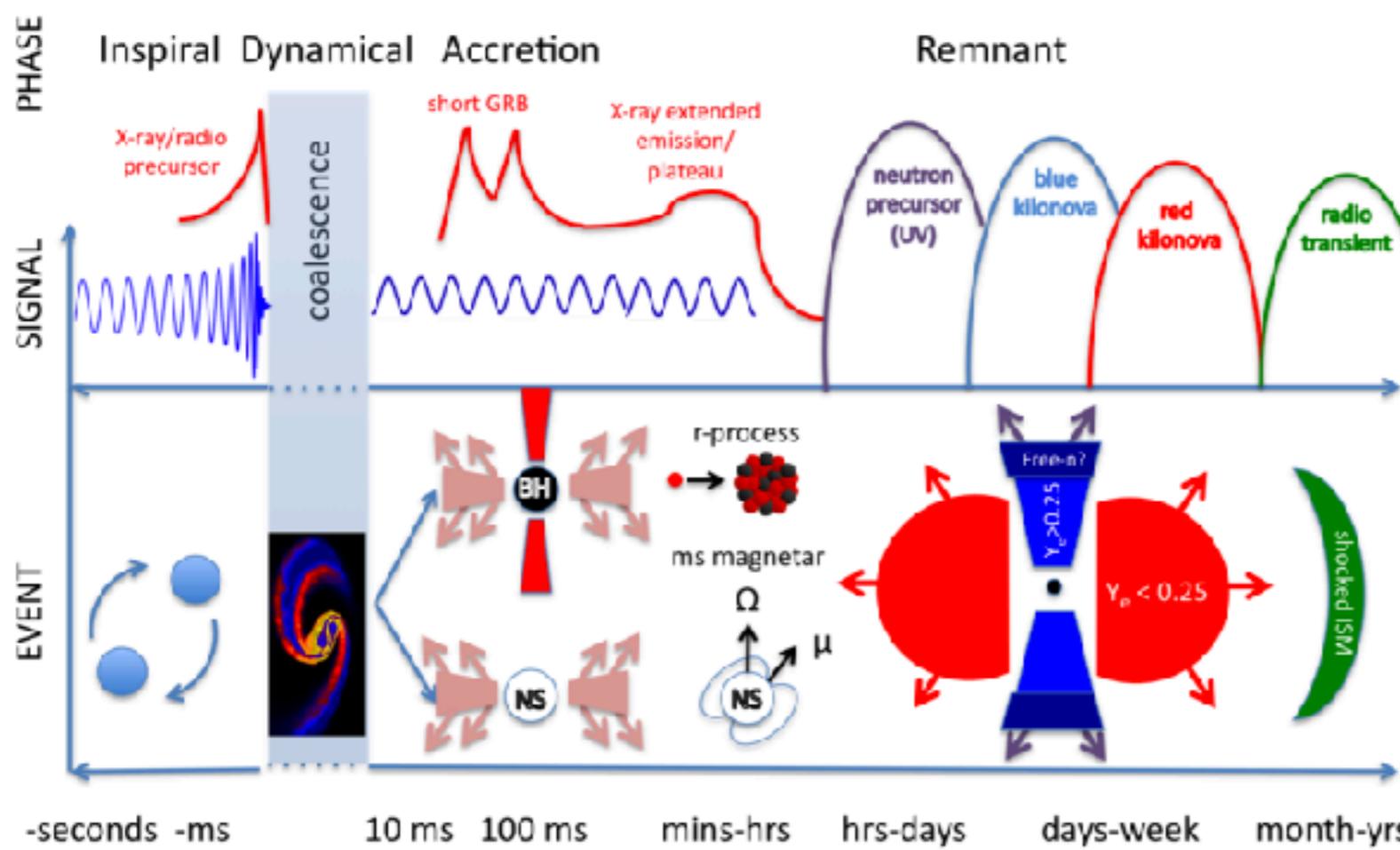


Progenitors still debated
Responsible for most iron-peak elements



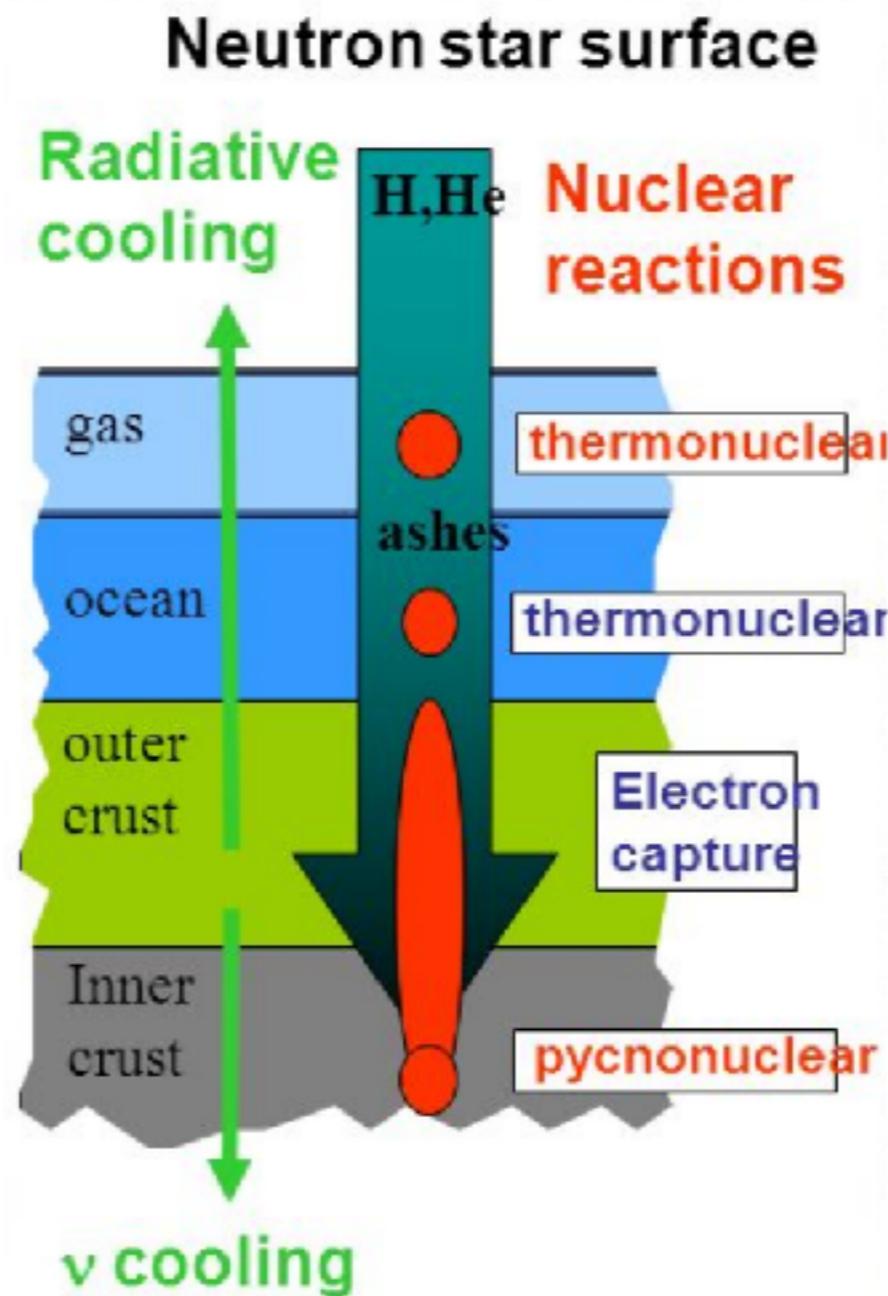
Neutron star mergers, gamma-ray bursts

GW 170814

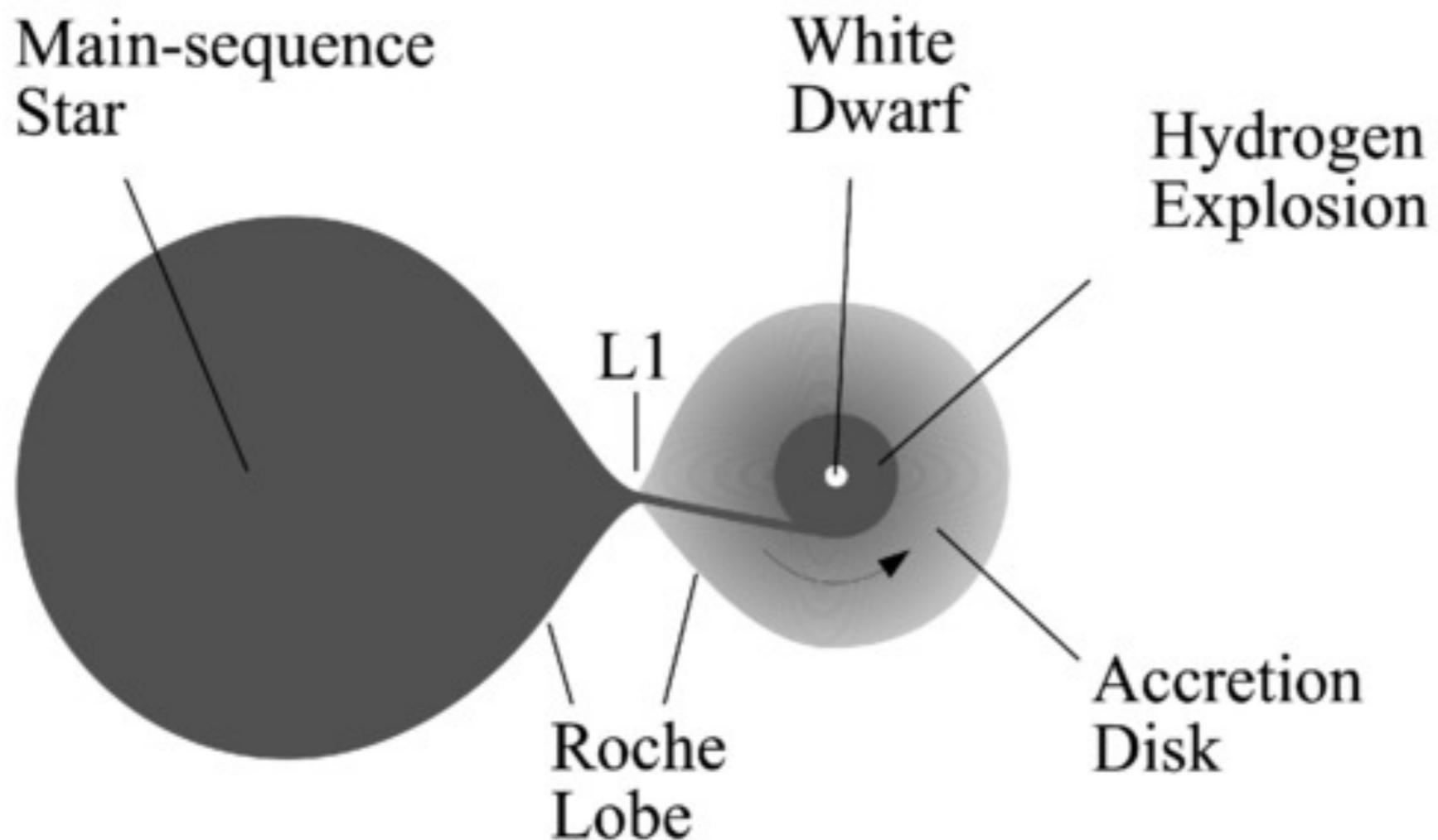


Pycno-nuclear reactions

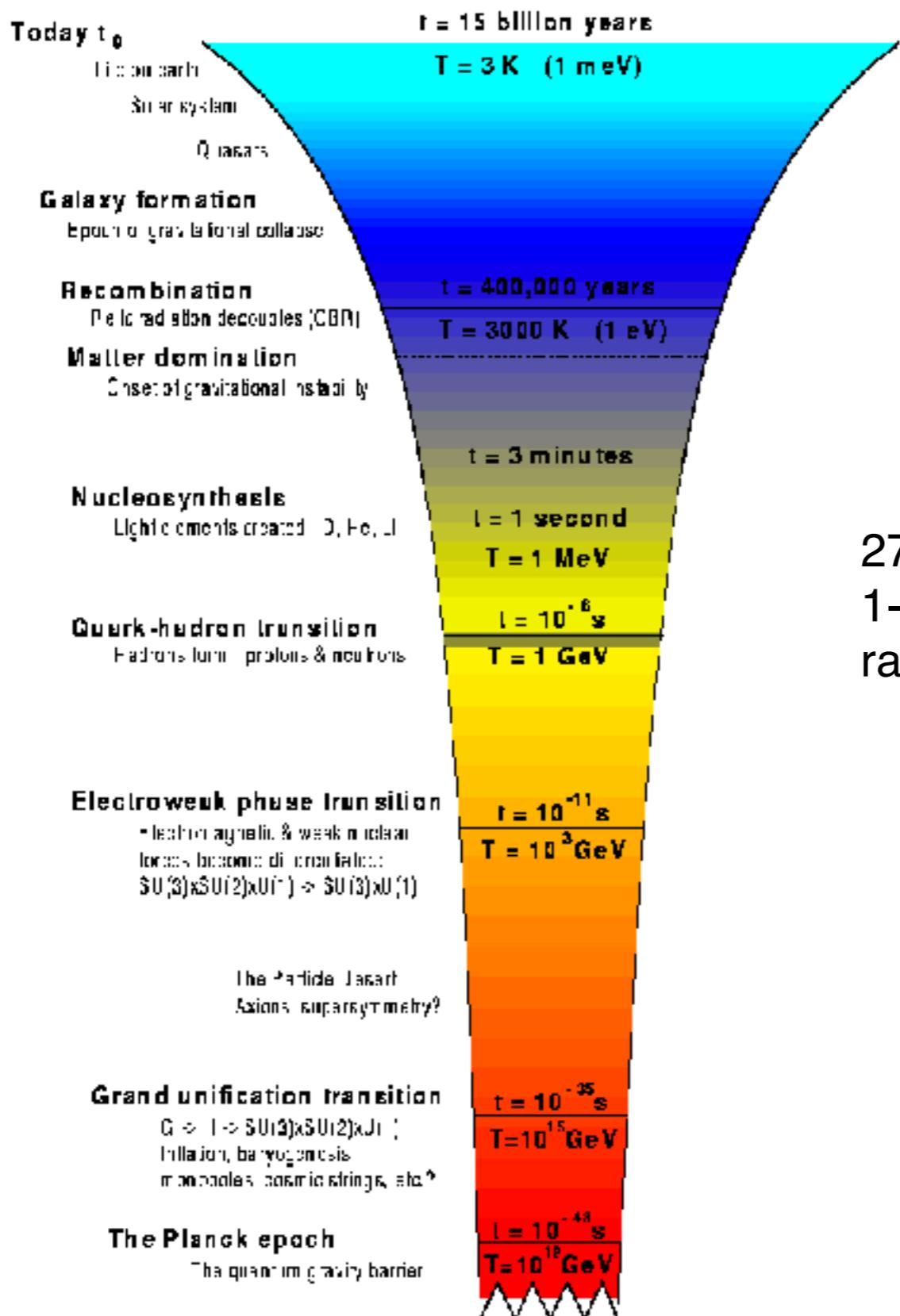
Inside neutron stars, at extremely high densities, the effective coulomb barrier is reduced by high neutron fraction, close distance and electron cloud



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

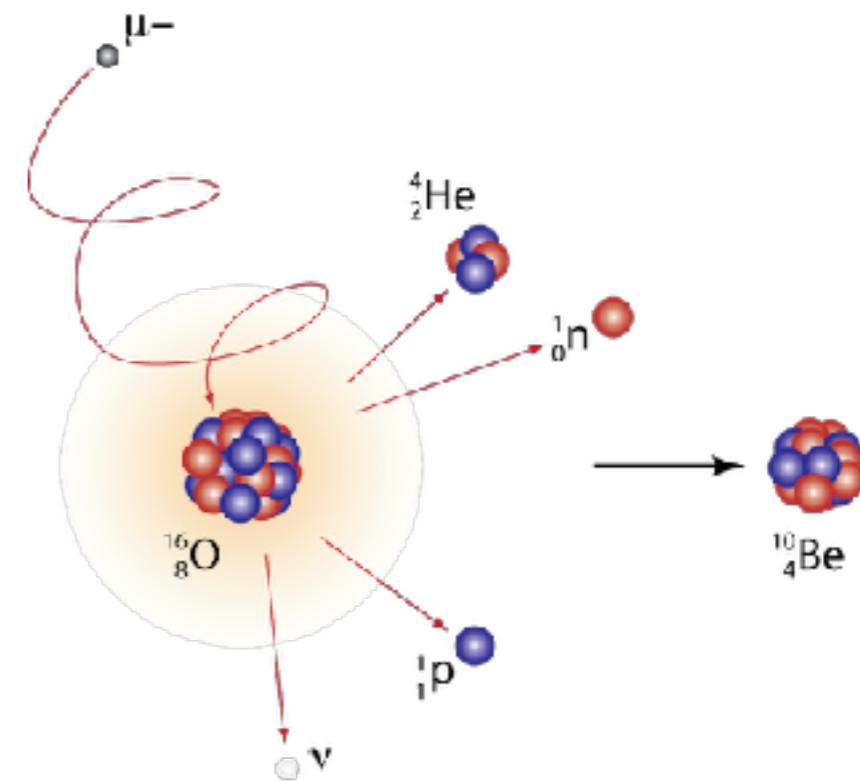
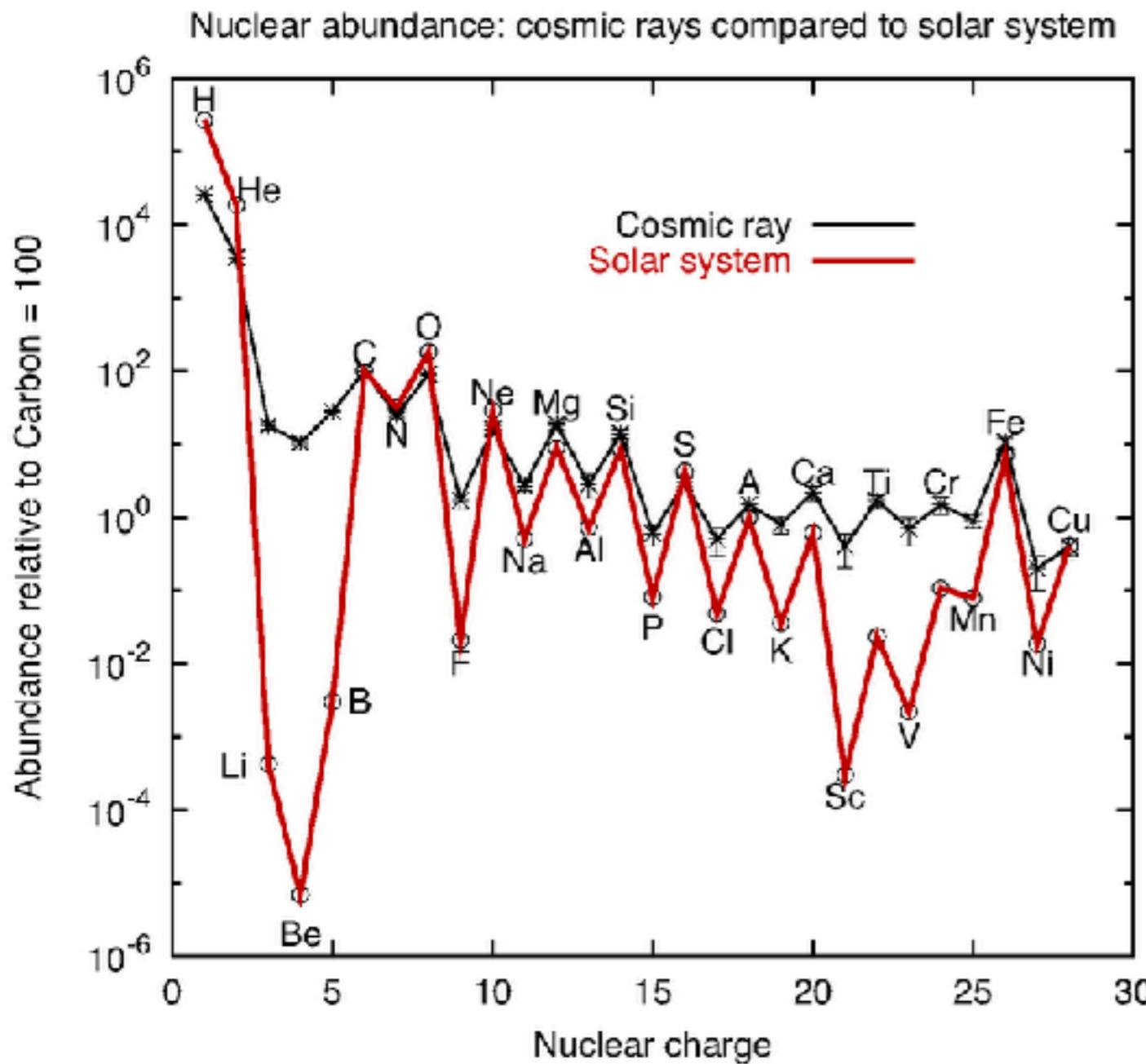


Primordial nucleosynthesis



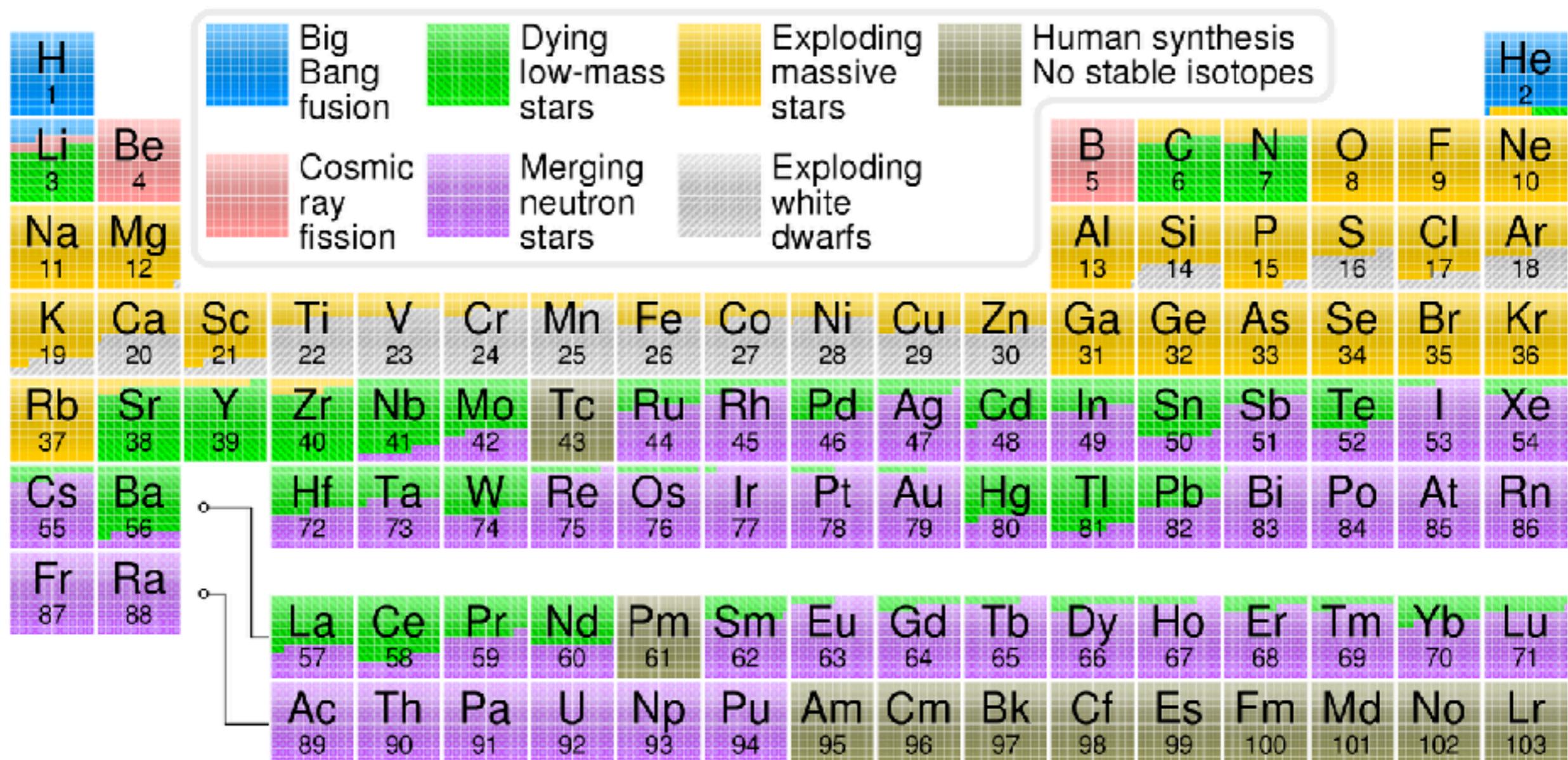
27% He requires primordial origin
1-3 sec after Big Bang: High temperatures but rapid cooling

CR-induced spallation

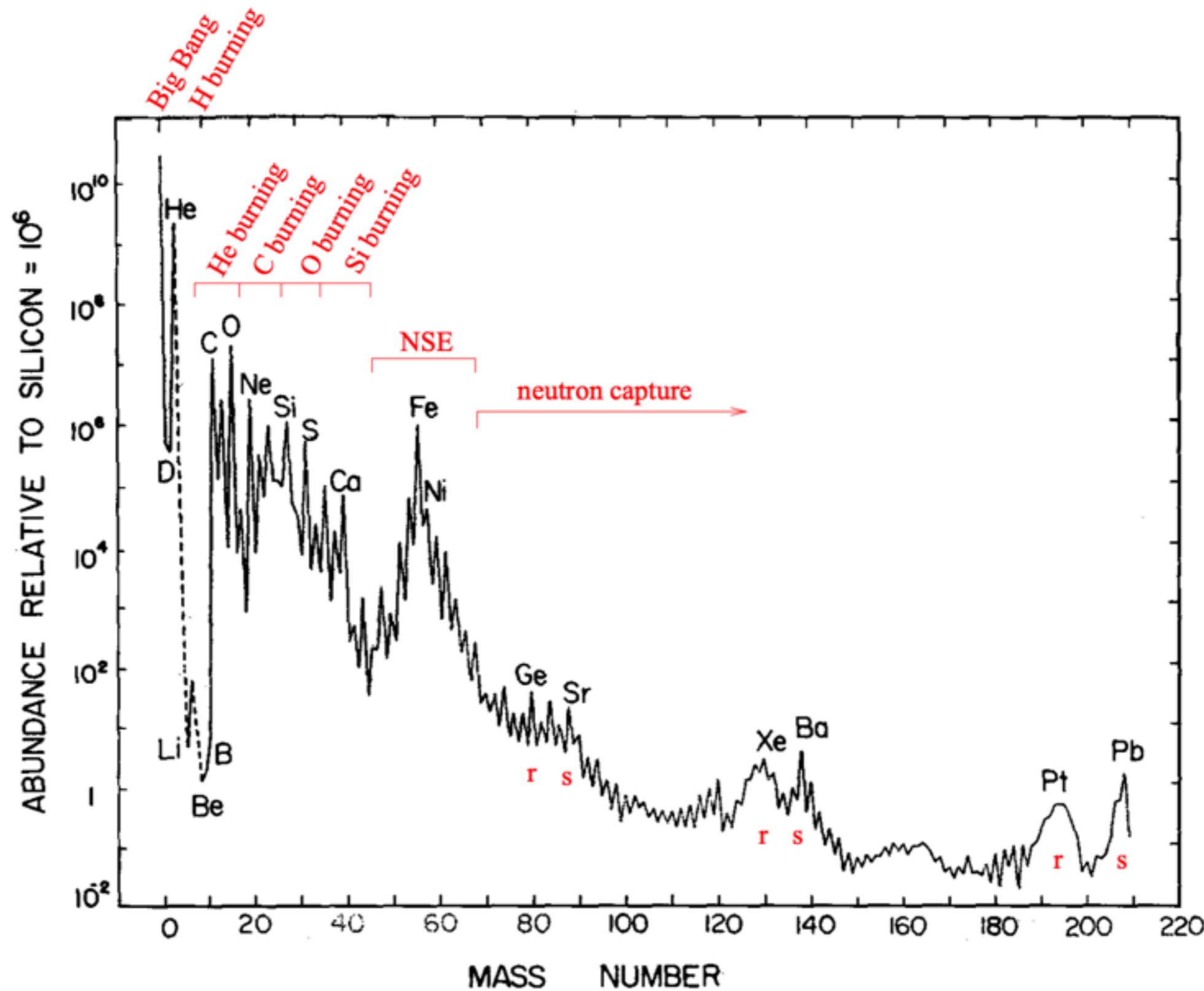


Not enough to explain observed Li abundances in the Solar System, other processes required (explosive nucleosynthesis, novae, red giants?)

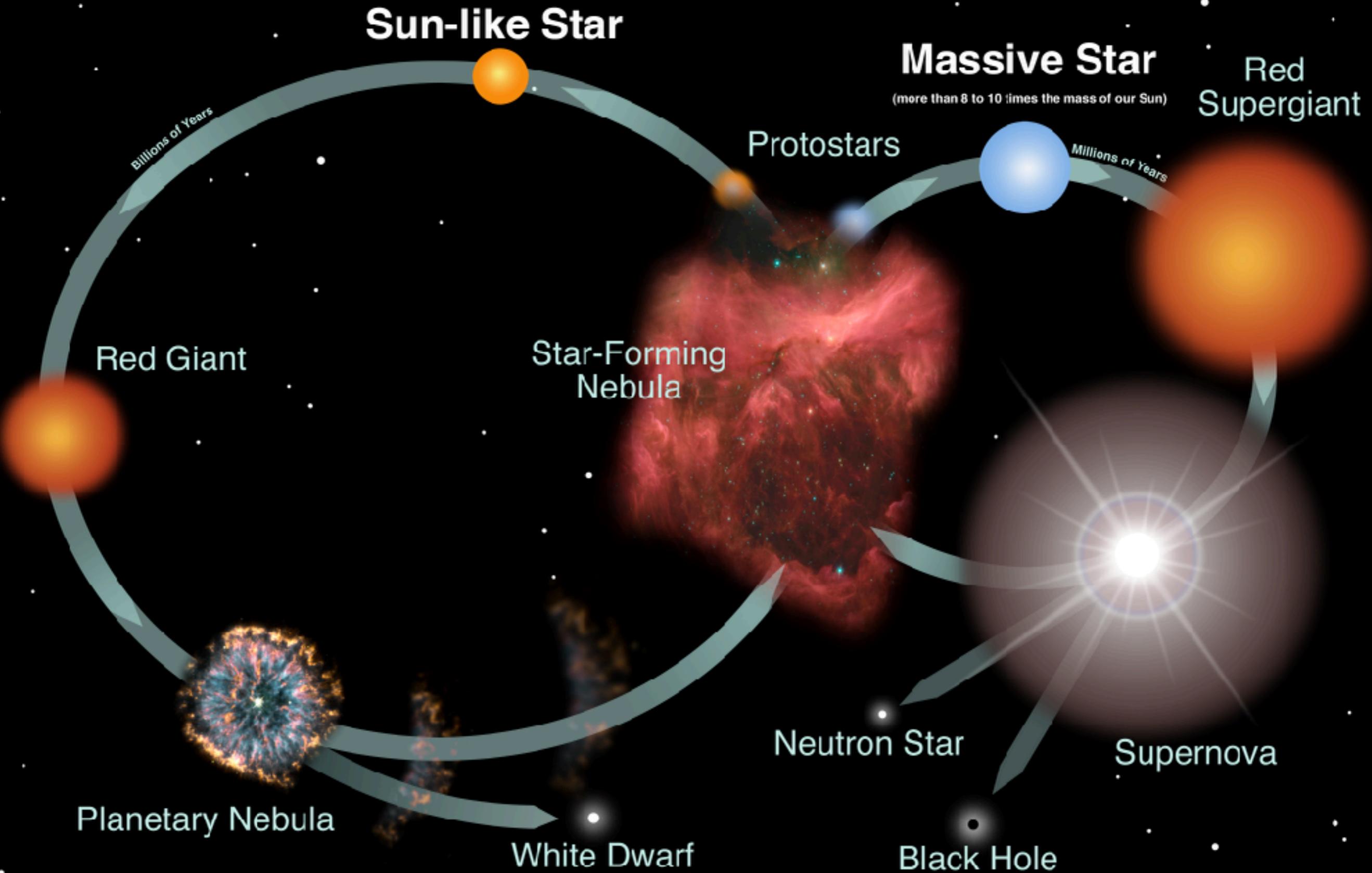
Origin of elements



Origin of elements



Nucleosynthesis goes on



Overview

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|--|-----------------|
| • 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 |