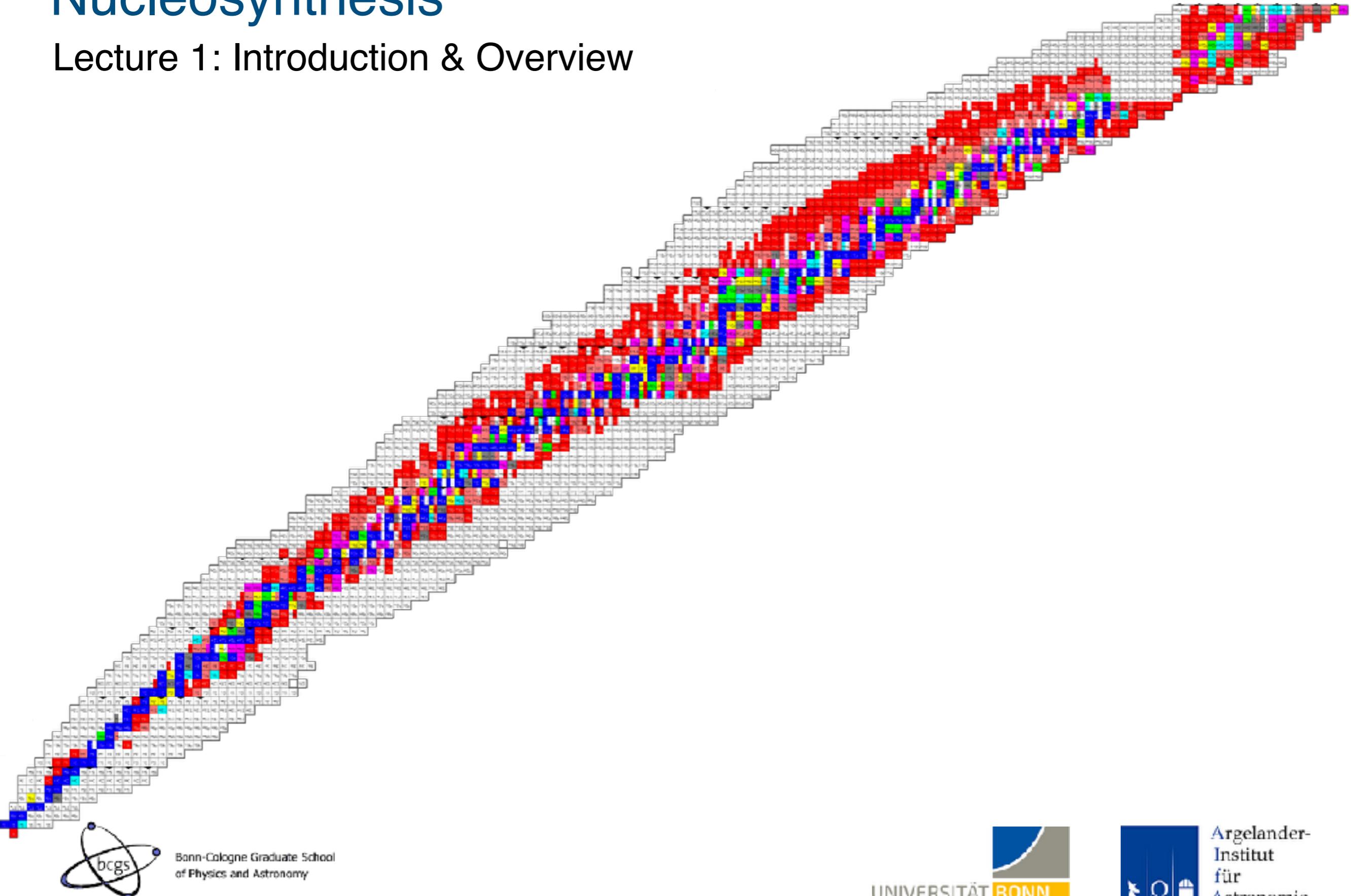


# Nucleosynthesis

## Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School  
of Physics and Astronomy



Argelander-  
Institut  
für  
Astronomie

# Nucleosynthesis

Course website [jantoniadis.github.io/nucleosynthesis](https://jantoniadis.github.io/nucleosynthesis)

Lectures                    John Antoniadis – office 3.015; [janton@mpifr.de](mailto:janton@mpifr.de)  
Exercises                David Aguilera Dena - [davidad@astro.uni-bonn.de](mailto:davidad@astro.uni-bonn.de)  
                            Ben Hastings - [bhastings@astro-uni-bonn.de](mailto: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

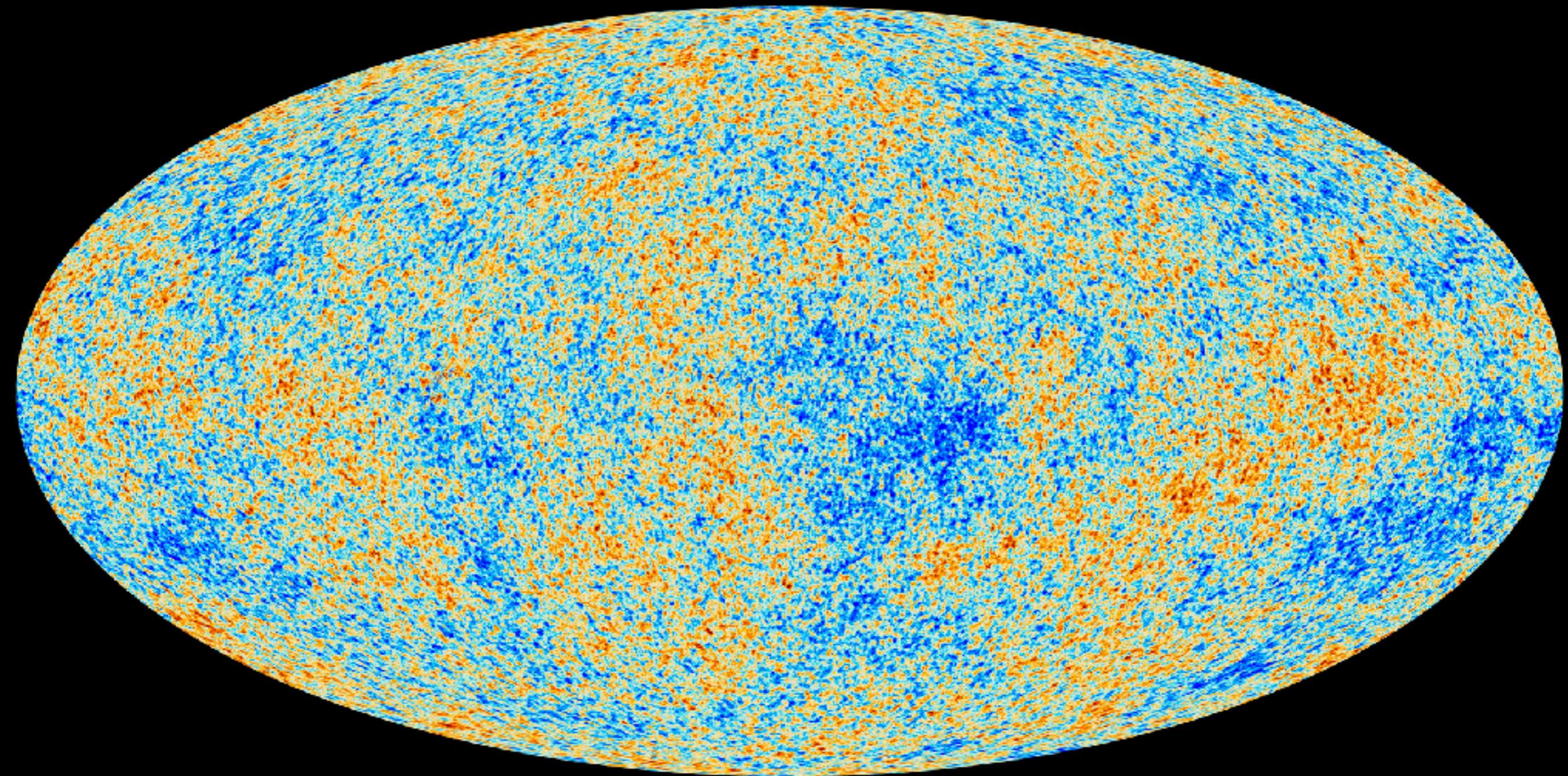
- Read material beforehand and e-mail at least 3 non-trivial questions before **Tuesday @ 13:00**  
**email to tutors; use subject heading [Nuc]** **25%**
- Lectures and Exercises (compulsory attendance) **25%**
- Student presentations on nucleosynthesis papers  
check website for paper suggestions **50%**

## Overview

### Goal: explain the distribution of isotopic abundances in the Universe

• <b>Lecture 1:</b> Introduction & overview	<b>April 18</b>
• <b>Lecture 2:</b> Thermonuclear reactions	<b>April 25</b>
• <b>Lecture 3:</b> Big-bang nucleosynthesis	<b>May 2</b>
• <b>Lecture 4:</b> Thermonuclear reactions inside stars – I (H-burning)	<b>May 7</b>
• <b>Lecture 5:</b> Thermonuclear reactions inside stars – II (advanced burning)	<b>May 16</b>
• <b>Lecture 6:</b> Neutron-capture and supernovae – I	<b>May 23</b>
• <b>Lecture 7:</b> Neutron-capture and supernovae – II	<b>June 6</b>
• <b>Lecture 8:</b> Thermonuclear supernovae	<b>June 13</b>
• <b>Lecture 9:</b> Li, Be and B	<b>July 4</b>
• <b>Lecture 10:</b> Galactic chemical evolution and relation to astrobiology	<b>July 11</b>
<b>Paper presentations I</b>	<b>June 21</b>
<b>Paper presentations II</b>	<b>June 27</b>

# Overview



# Overview



# Chemical elements

1 IA 1A	<b>H</b> 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 <b>Na</b> Sodium 22.990	12 <b>Mg</b> 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 <b>K</b> Potassium 39.090	20 <b>Ca</b> Calcium 40.070	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.867	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.980	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.720	32 <b>Ge</b> Germanium 72.031	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.971	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.798	
37 <b>Rb</b> Rubidium 64.466	38 <b>Sr</b> Strontium 69.983	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.925	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.86	48 <b>Cd</b> Cadmium 112.414	49 <b>In</b> Indium 114.016	50 <b>Sn</b> Tin 118.711	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.296	
55 <b>Cs</b> Cesium 132.905	56 <b>Ba</b> Barium 137.329	57-71	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.949	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.217	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.065	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 204.592	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.900	84 <b>Po</b> Polonium 209.903	85 <b>At</b> Astatine 209.907	86 <b>Rn</b> Radon 222.010	
87 <b>Fr</b> Francium 223.020	88 <b>Ra</b> Radium 226.025	89-103	104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (265)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (269)	109 <b>Mt</b> Mertensium (266)	110 <b>Ds</b> Darmstadtium (268)	111 <b>Rg</b> Roentgenium (270)	112 <b>Cn</b> Copernicium (272)	113 <b>Uut</b> Ununtrium unknown	114 <b>Fl</b> Florium unknown	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium unknown	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown	

Periodic Table of the Elements

Atomic Number	Valence Charge
Symbol	Name
Atomic Mass	

Lanthanide Series

57 <b>La</b> Lanthanum 130.905	58 <b>Ce</b> Cerium 140.119	59 <b>Pr</b> Praseodymium 141.003	60 <b>Nd</b> Neodymium 144.243	61 <b>Pm</b> Promethium 147.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 159.265	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.920	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 169.924	70 <b>Yb</b> Ytterbium 173.052	71 <b>Lu</b> Lutetium 174.967
89 <b>Ac</b> Actinium 227.020	90 <b>Th</b> Thorium 232.039	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 239.029	94 <b>Pu</b> Plutonium 244.036	95 <b>Am</b> Americium 243.031	96 <b>Cm</b> Curium 247.370	97 <b>Bk</b> Berkelium 247.370	98 <b>Cf</b> Californium 251.360	99 <b>Es</b> Lanthanum 257.026	100 <b>Fm</b> Fermium 257.026	101 <b>Md</b> Mendelevium 259.1	102 <b>No</b> Nobelium 259.101	103 <b>Lr</b> Lawrencium (260)

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

Nonmetal

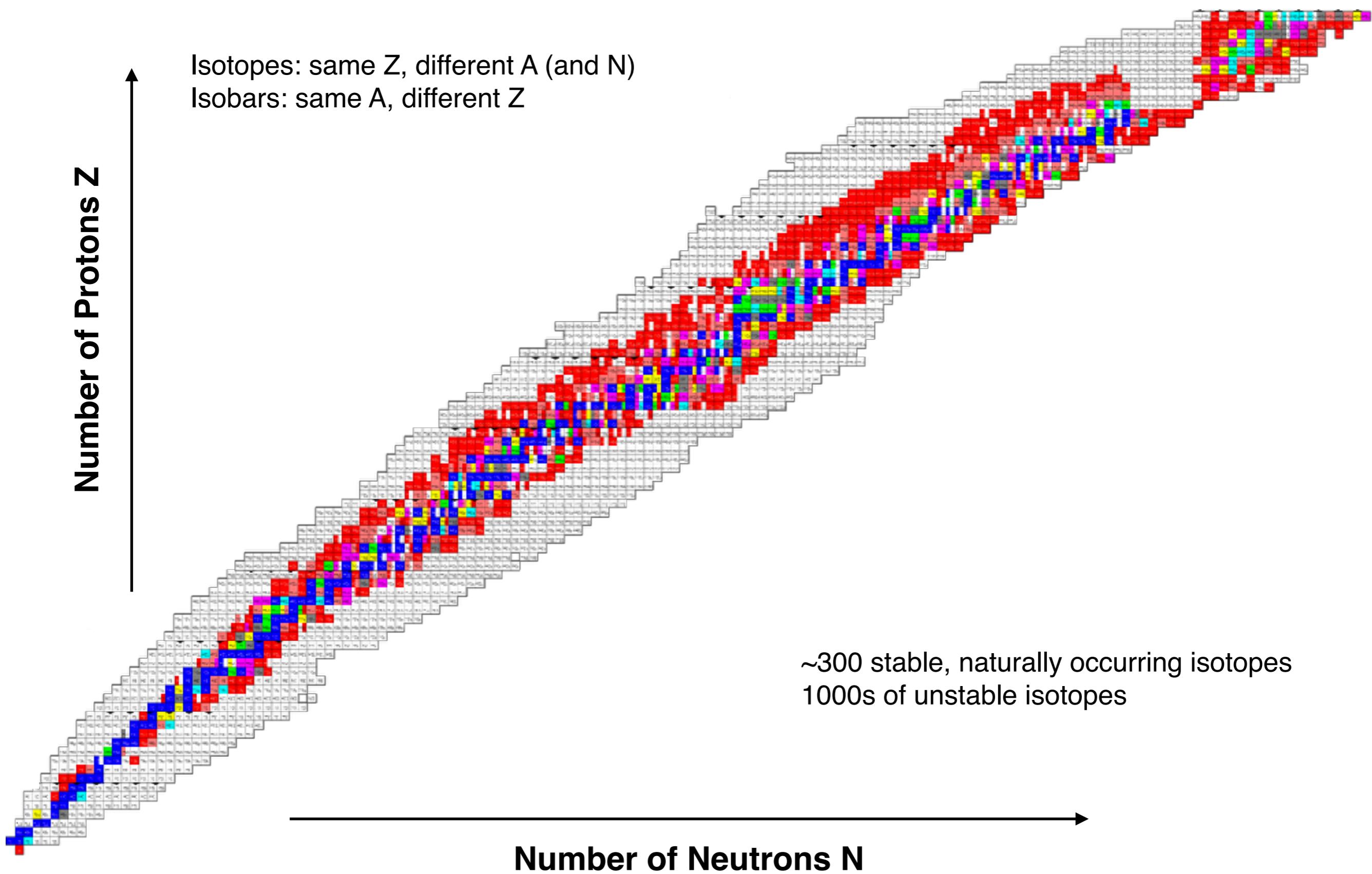
Halogen

Noble Gas

Lanthanide

Actinide

# Isotopes and isobars



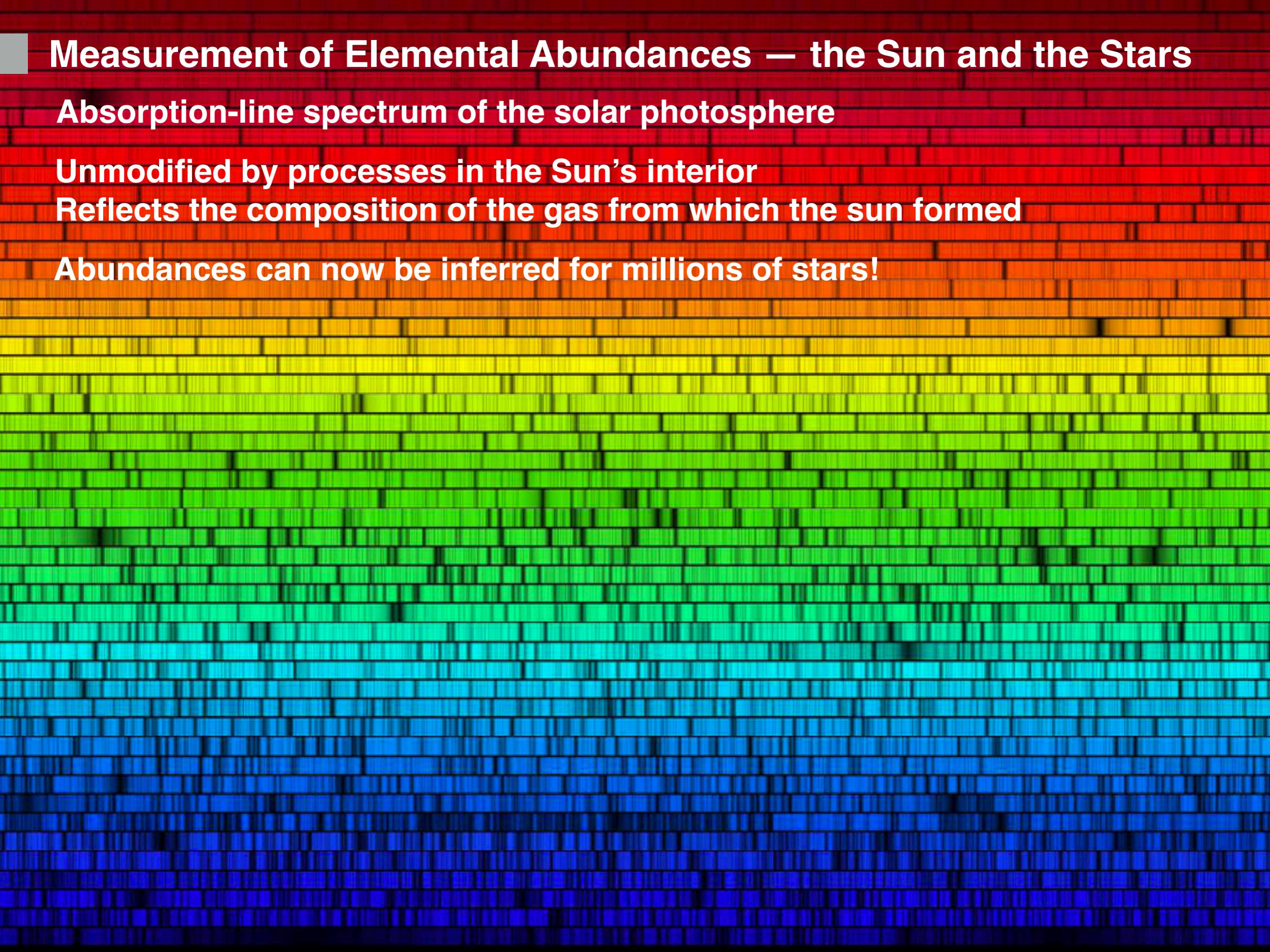
# Measurement of Elemental Abundances – the Sun and the Stars

**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

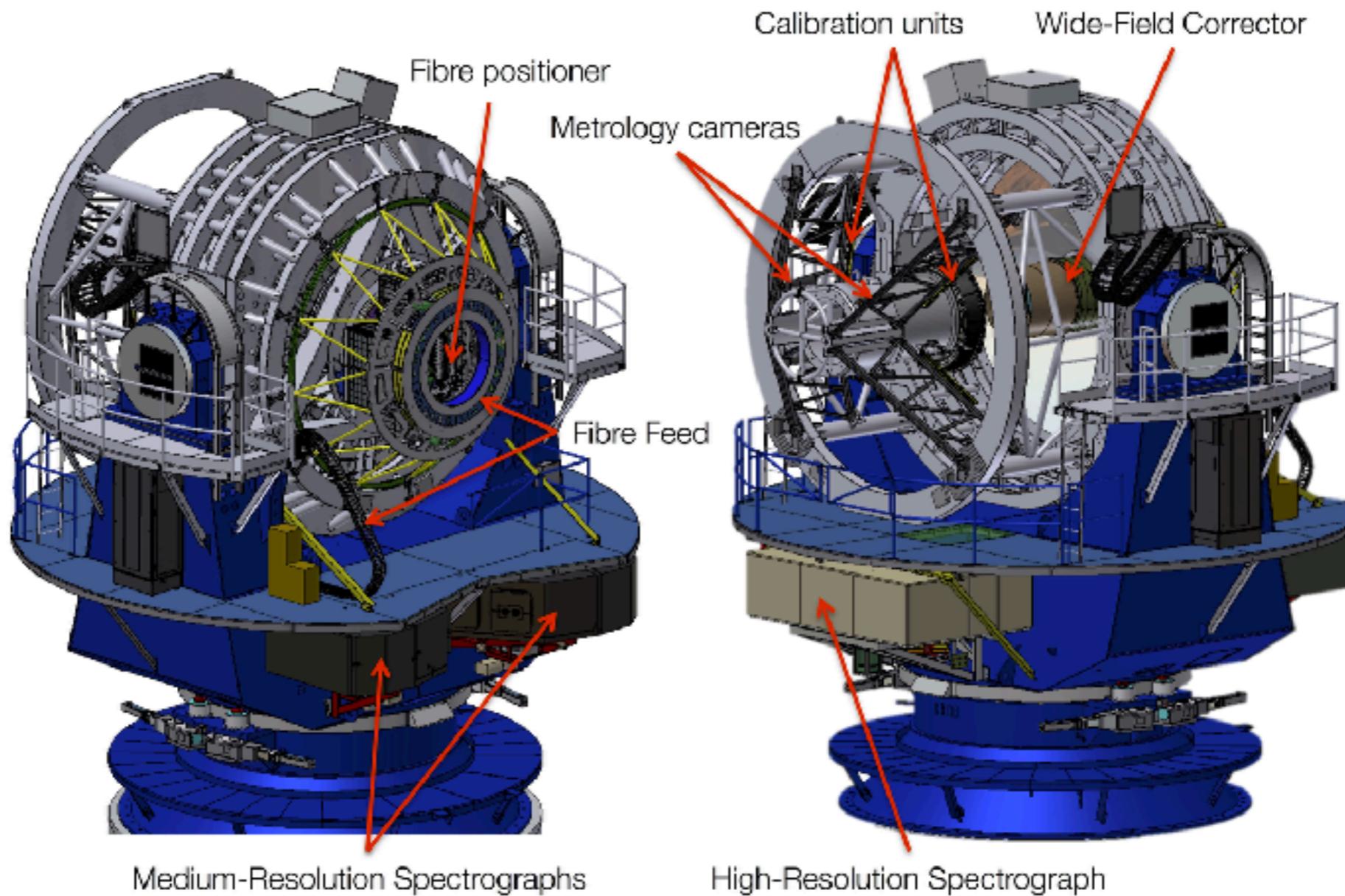
**“Metals”**

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

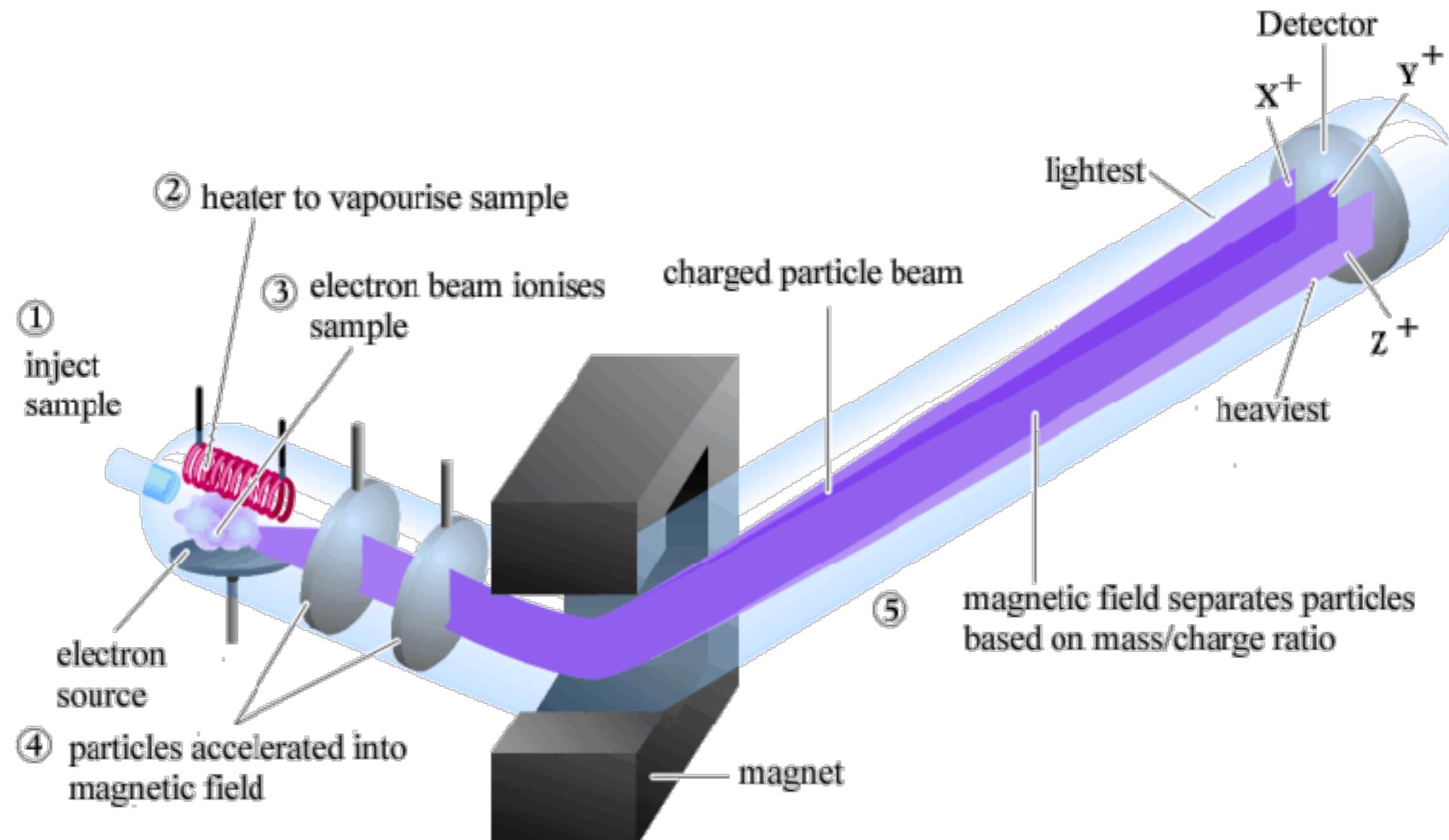
the 4MOST fibre-fed spectrograph for the 4m VISTA telescope

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

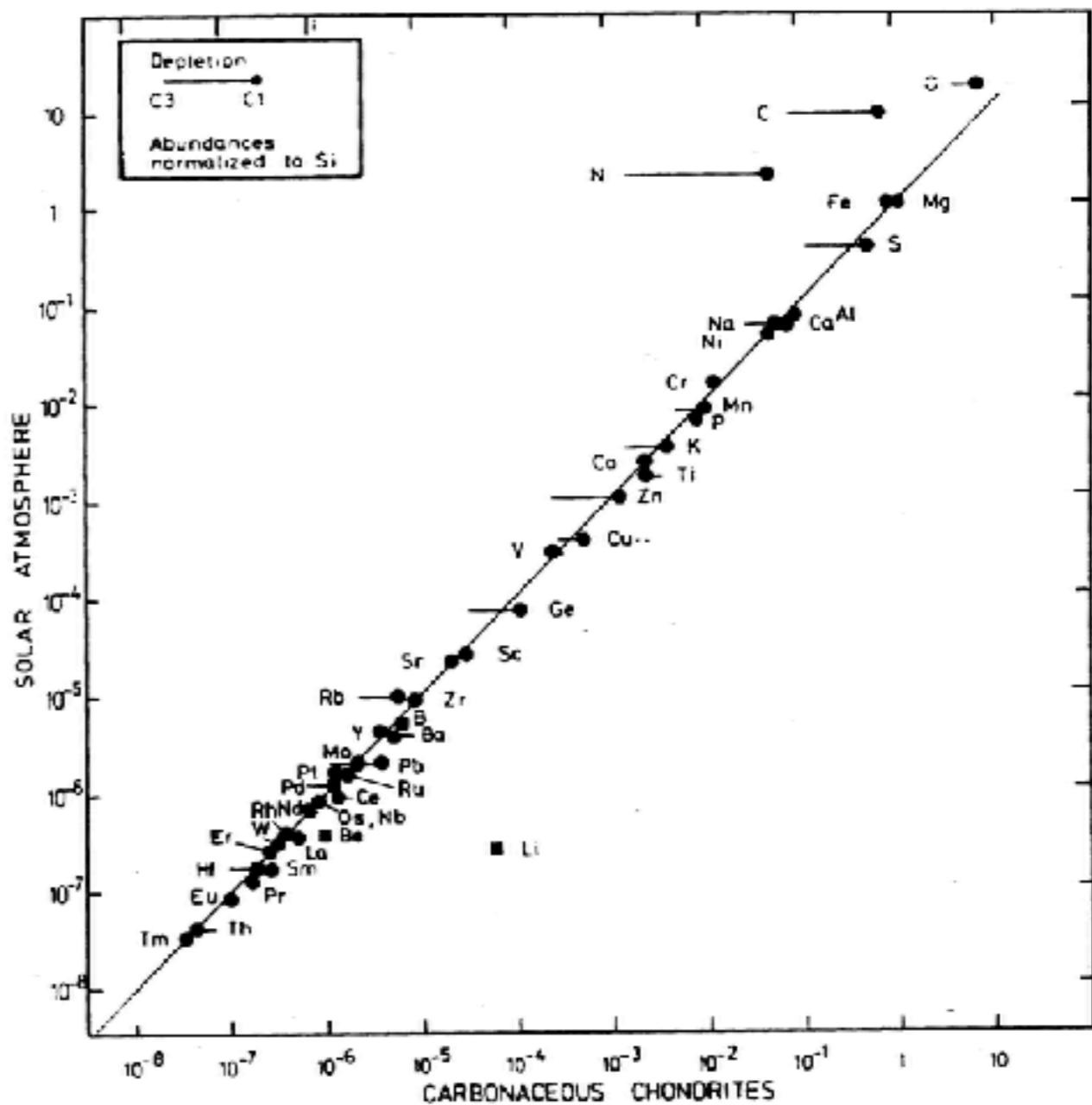


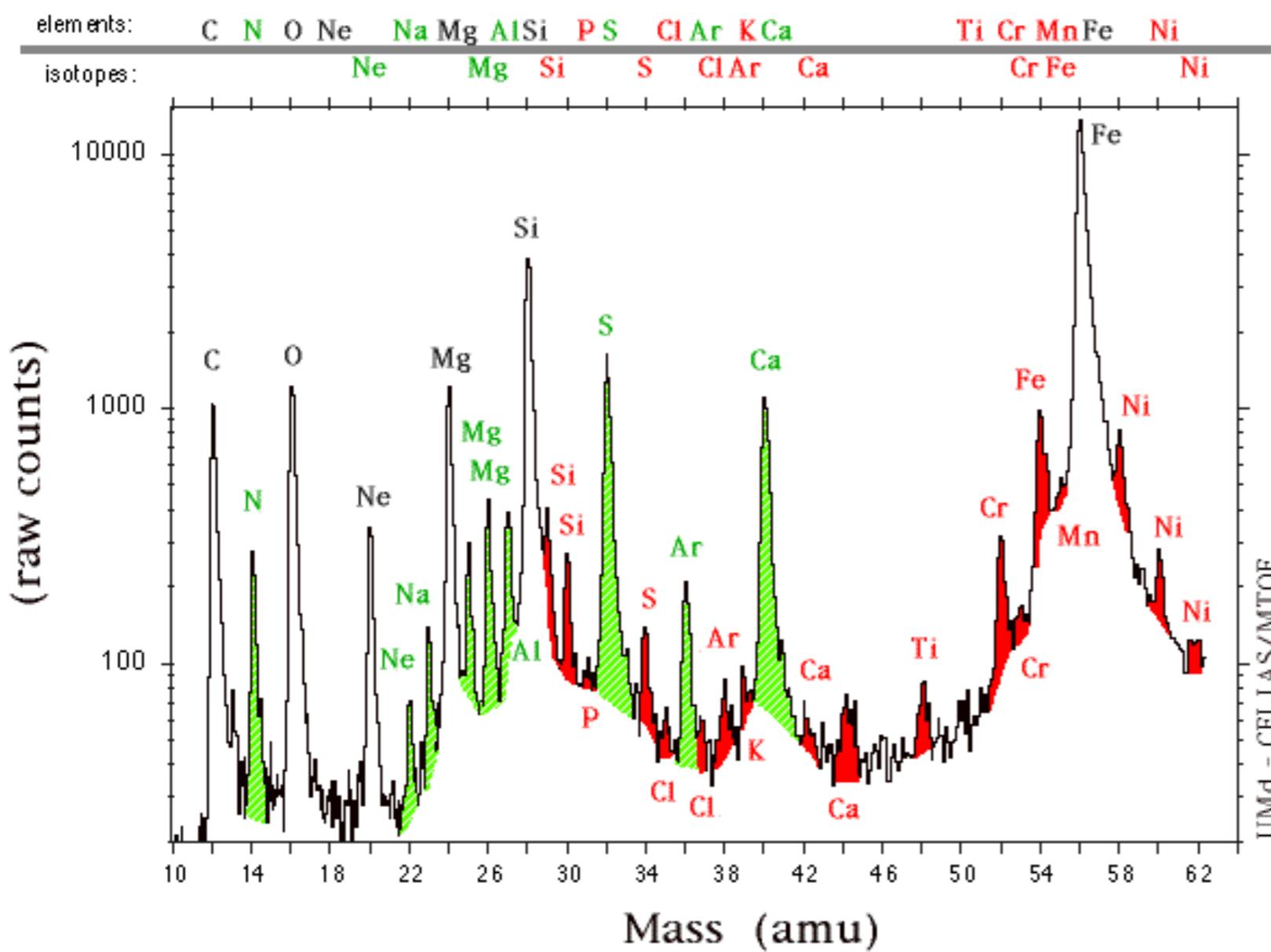
Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

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

# Measurement of Isotopic Abundances

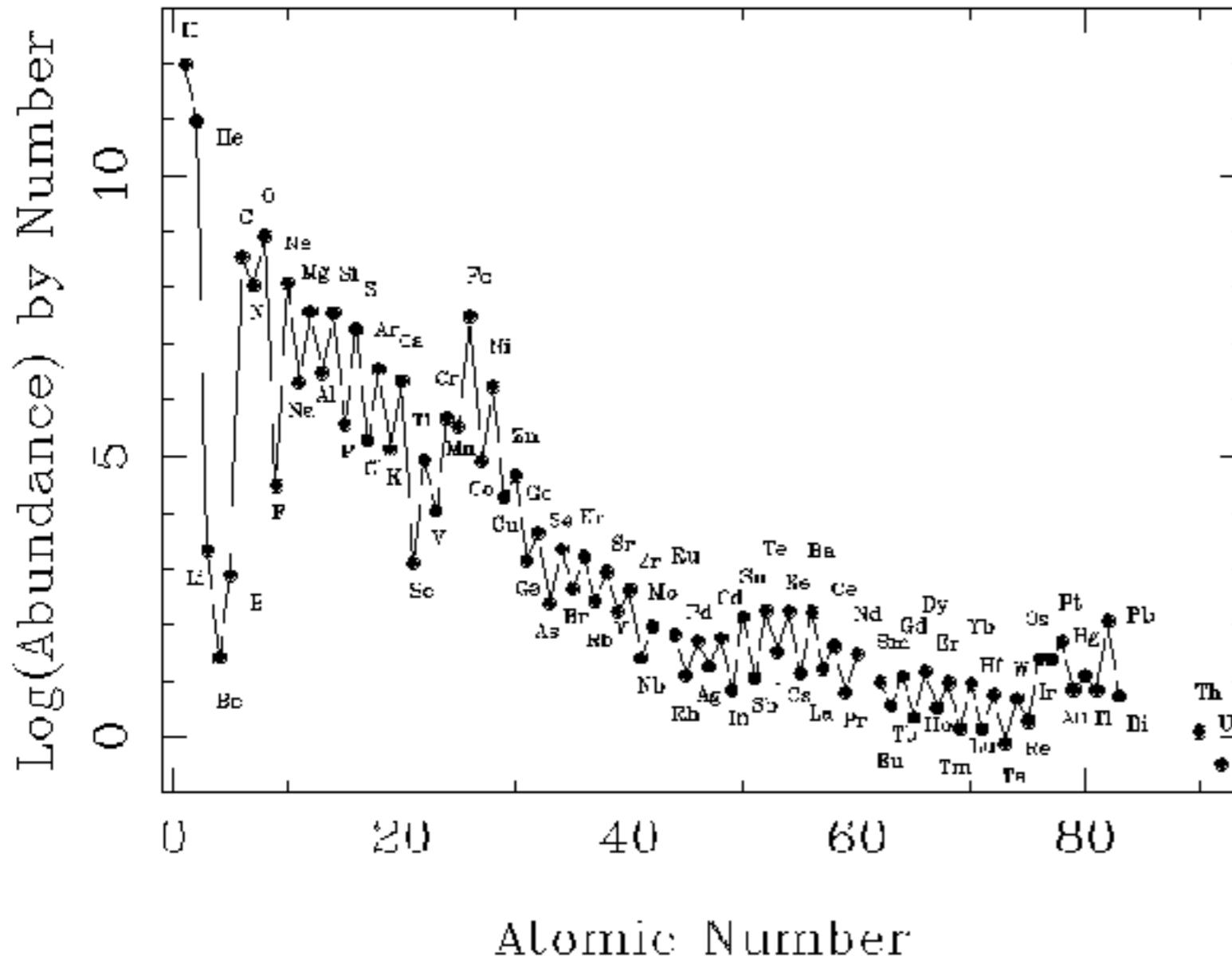
## Isotope abundances in the solar system

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

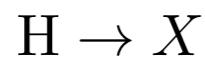
$$N_i = X_i/A_i$$

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

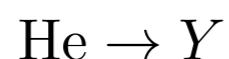
$$A_{\text{H}} = \log(N_{\text{H}}) = 12$$

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

### By mass fraction



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



$$X + Y + Z = 1$$



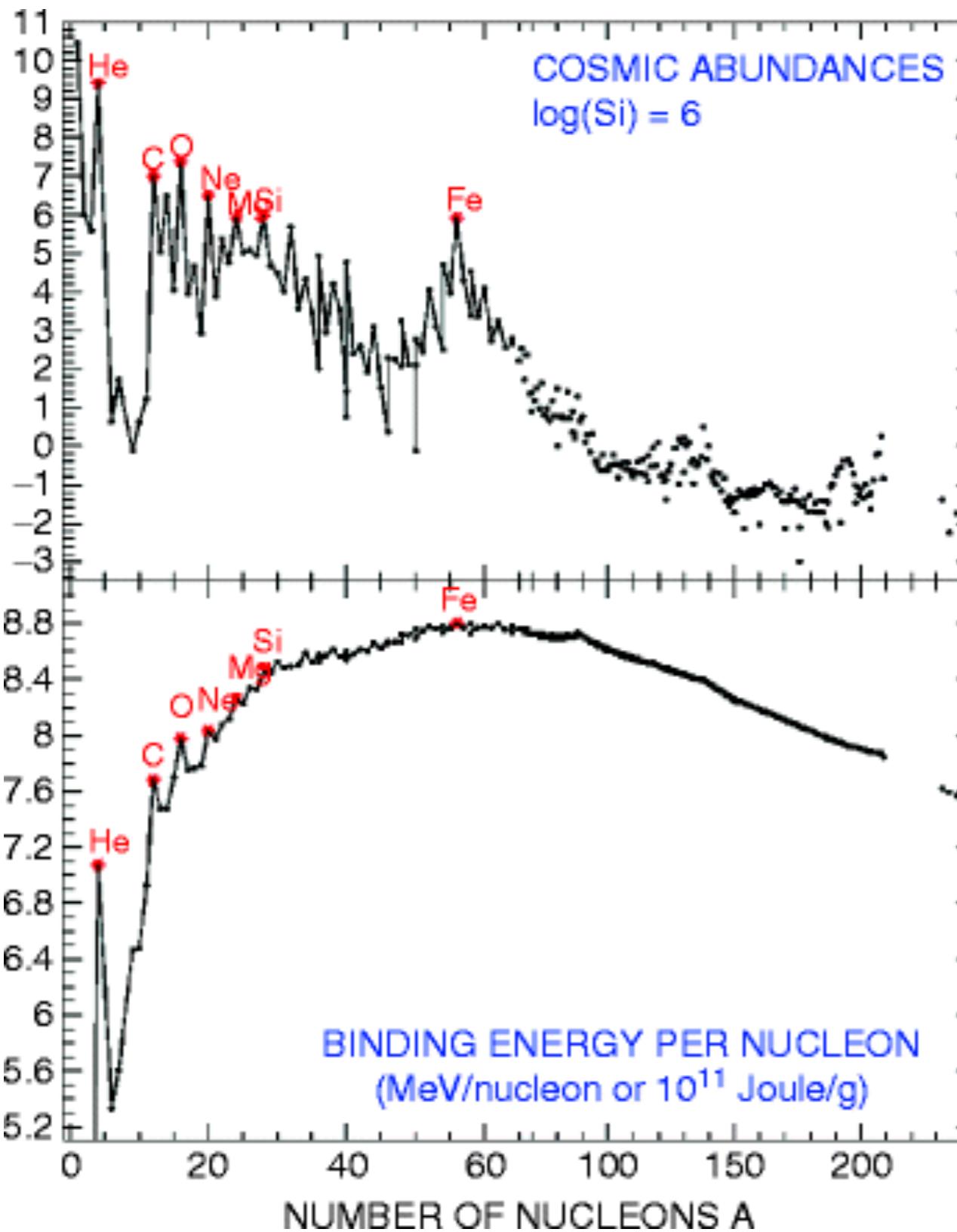
$$\sum X_i = 1$$

### 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  $\alpha$ -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

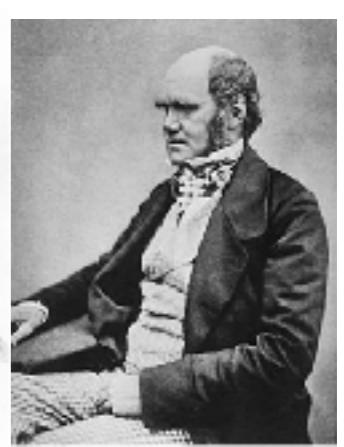
Classically, no.

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



**Francis William Aston, Arthur Eddington in 1920**

The mass of  $\alpha$ -particles is slightly less than 4 times the mass of hydrogen

This can be a source of energy generation in the Sun

# Nucleosynthesis inside stars



**George Gamow**

Quantum tunnelling effect allows fusion at much lower temperatures



**Cockcroft & Walton**

First experimental fusion demonstration:  $p + Li \rightarrow 2\alpha$



**Hans Albrecht Bethe, Atkinson and others**

Fusion of hydrogen via pp- and CNO- chain takes place inside the Sun

# Where does nucleosynthesis take place?

Debate in the 40s -50s

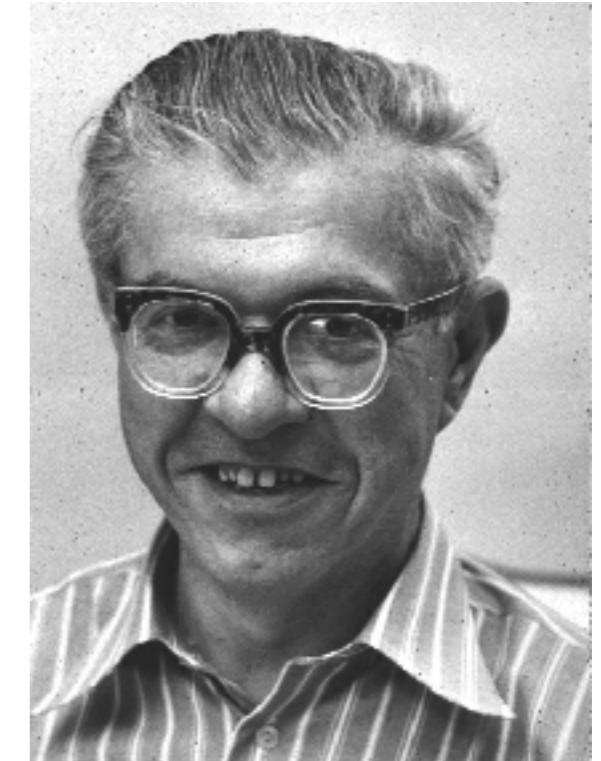
Primordial or Big-bang nucleosynthesis vs stars and supernovae



**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**

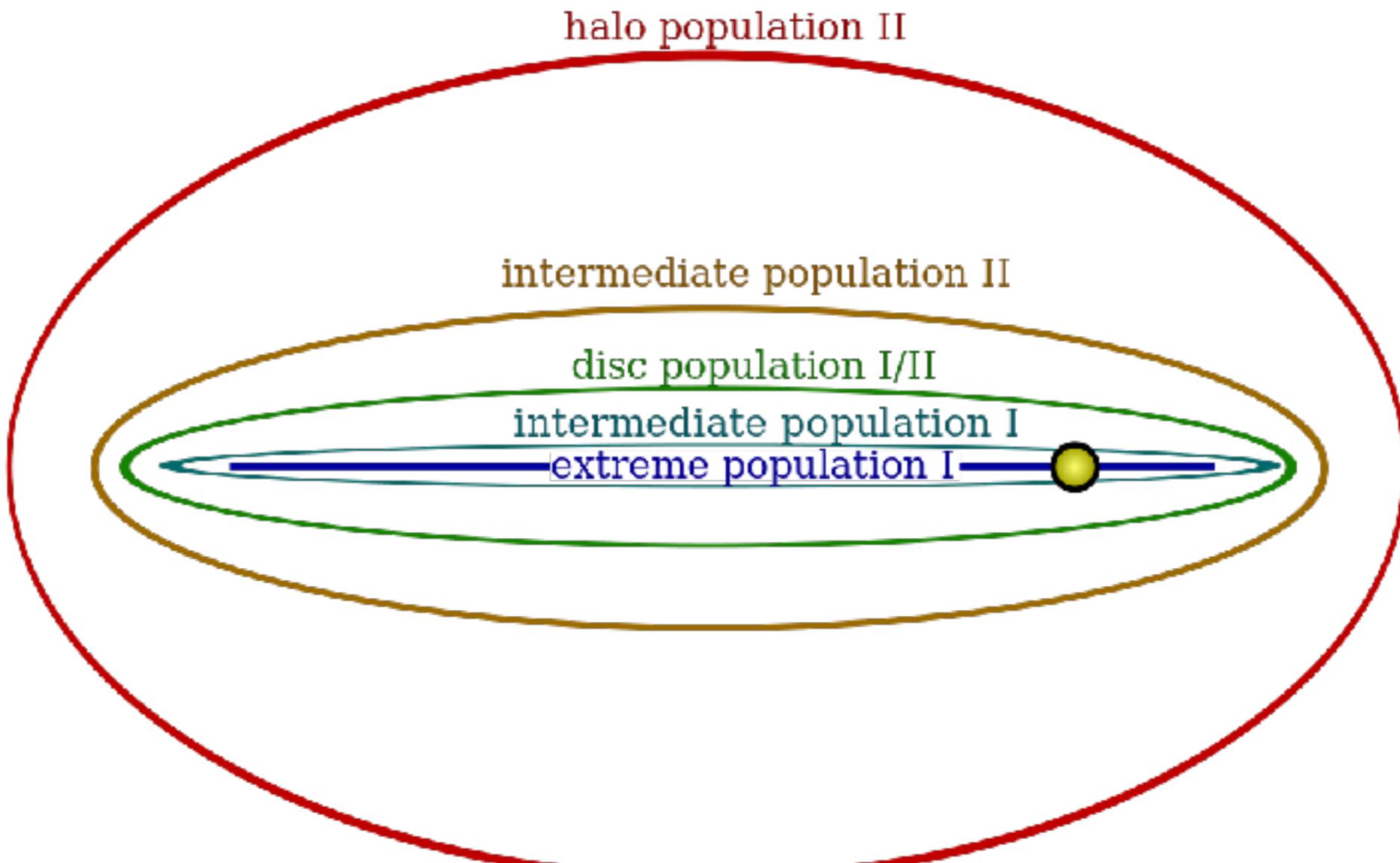


**Fred Hoyle (1915–2001)**

Elements created in stars and supernovae

# Observational evidence for nucleosynthesis

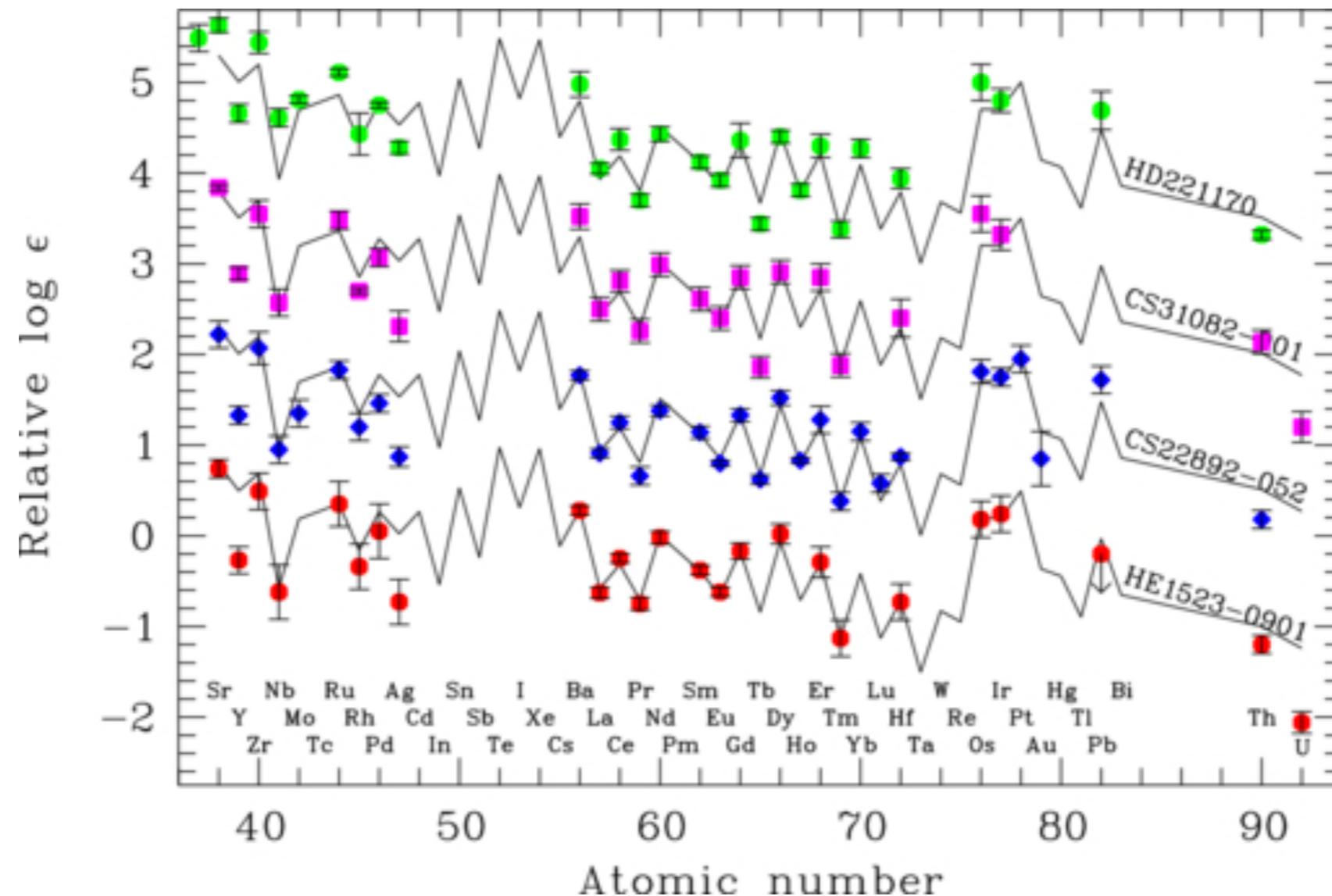
In early 50s: evidence for evolution of abundances with cosmic time  
Stars near the galactic disk have higher metallicities than stars in the halo



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

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VOLUME 29, NUMBER 4

OCTOBER, 1957

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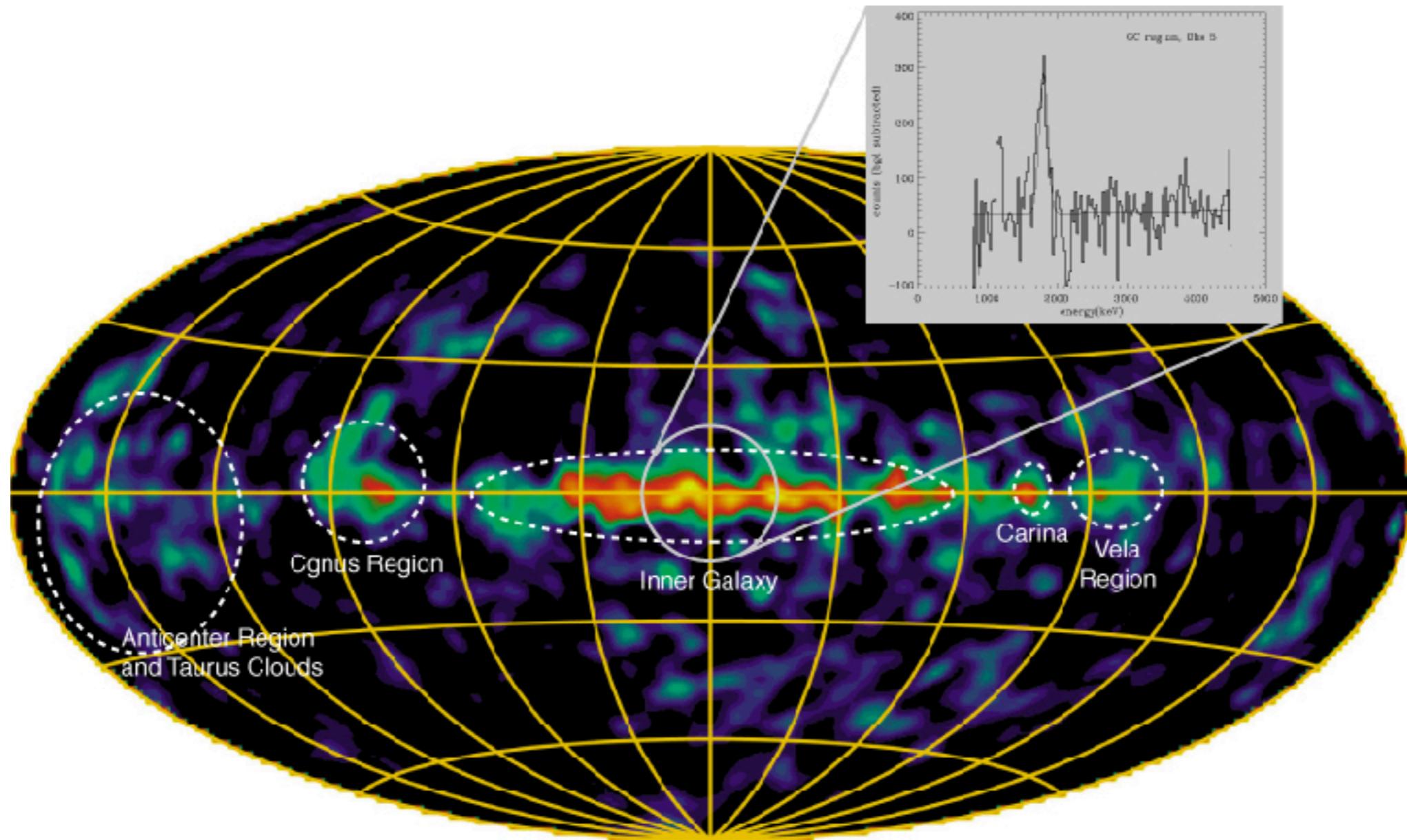
**Synthesis of the Elements in Stars\***

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



# Modern observational evidence for nucleosynthesis

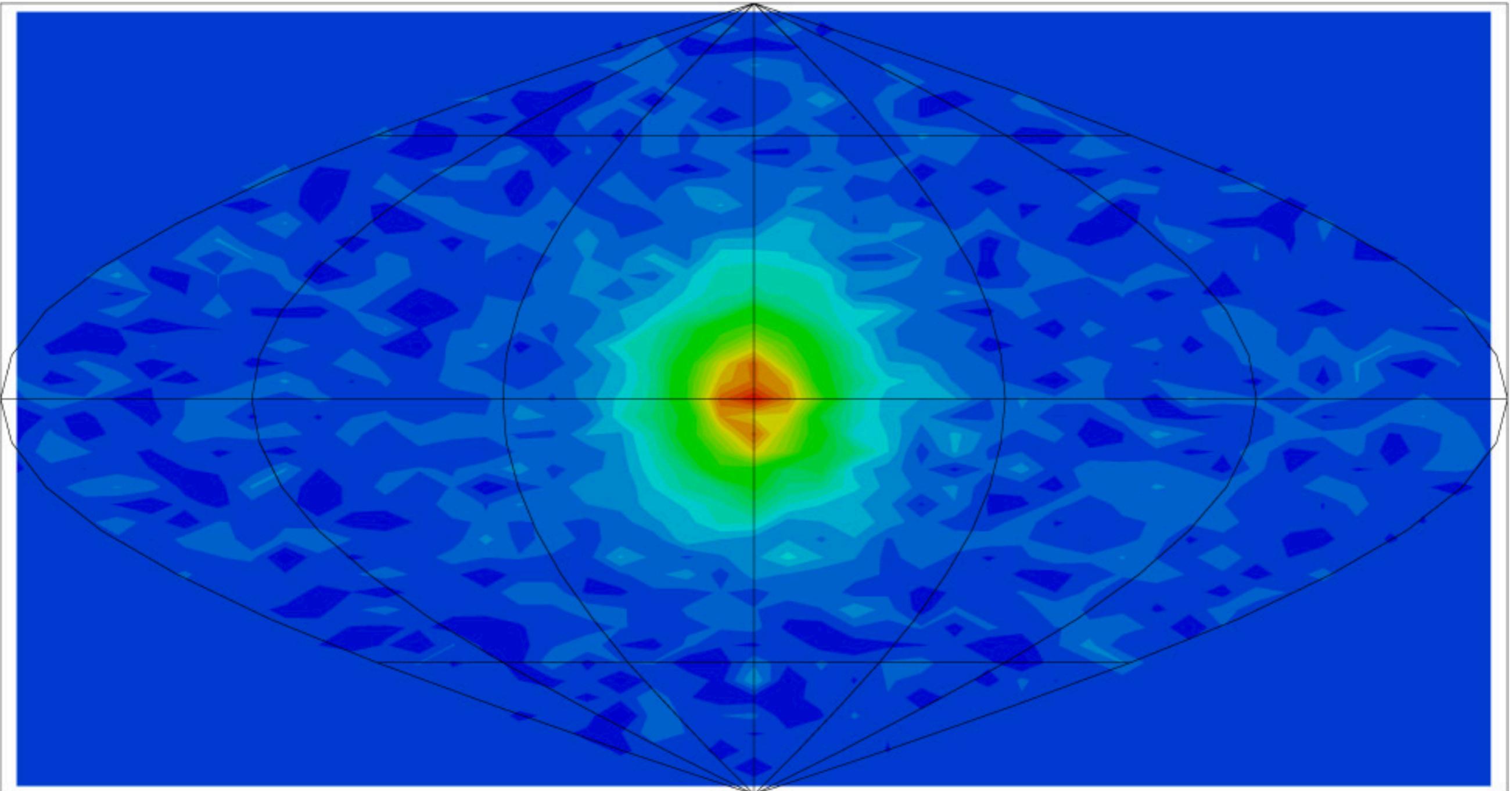
## More (in)direct evidence for ongoing nucleosynthesis



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

# Modern observational evidence for nucleosynthesis

More (in)direct evidence for ongoing nucleosynthesis



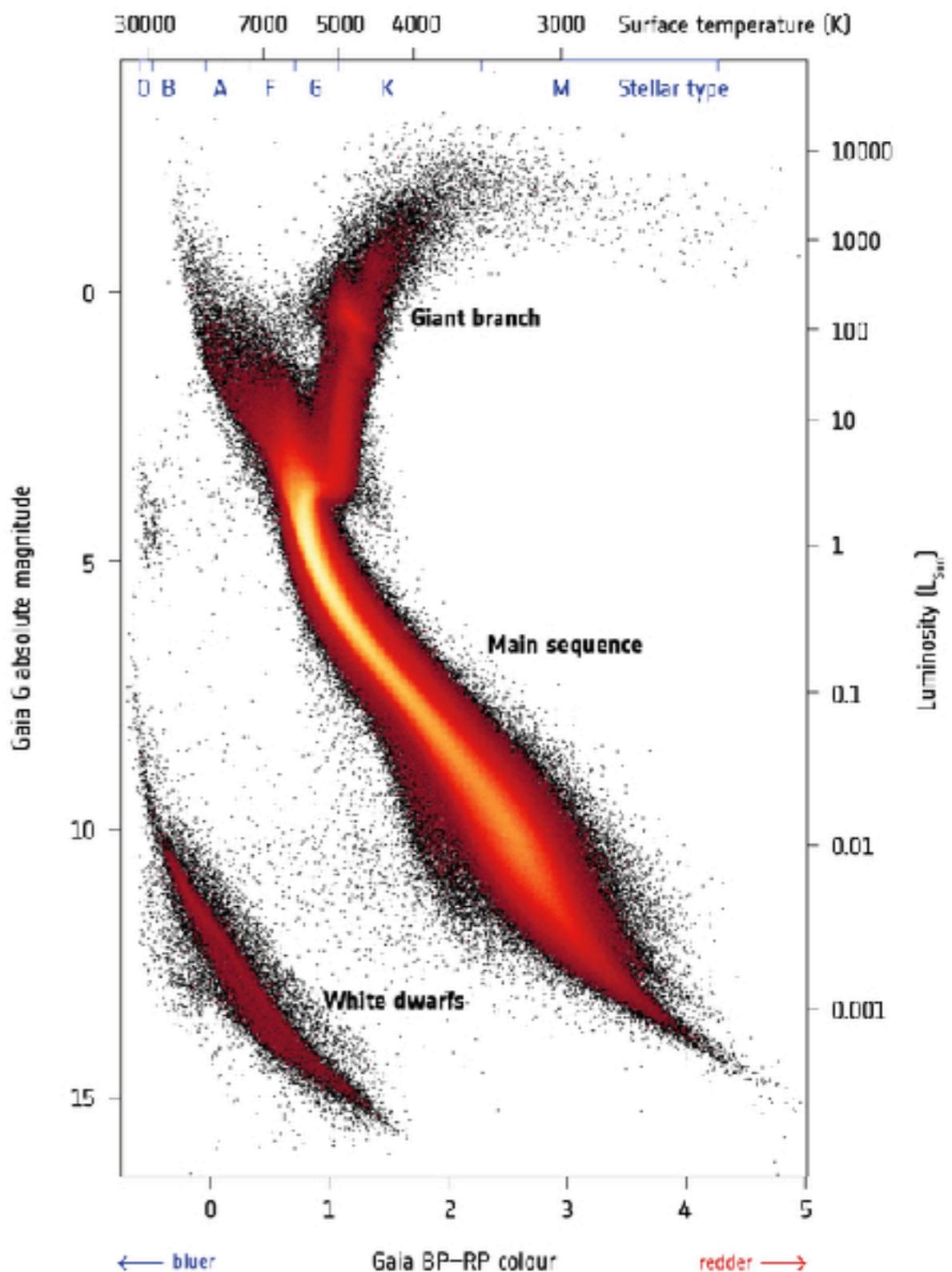
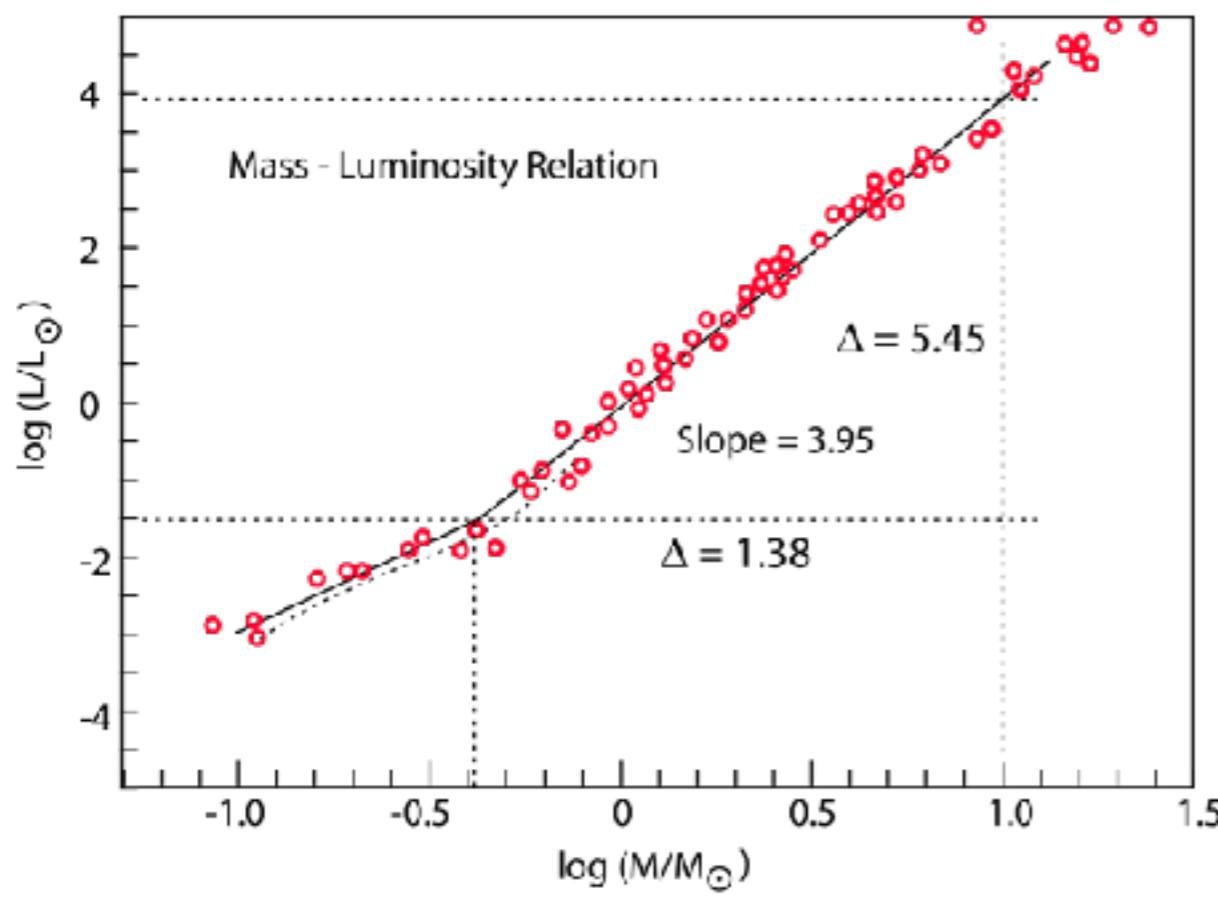
example 2: observation of solar neutrinos

# Thermonuclear reactions

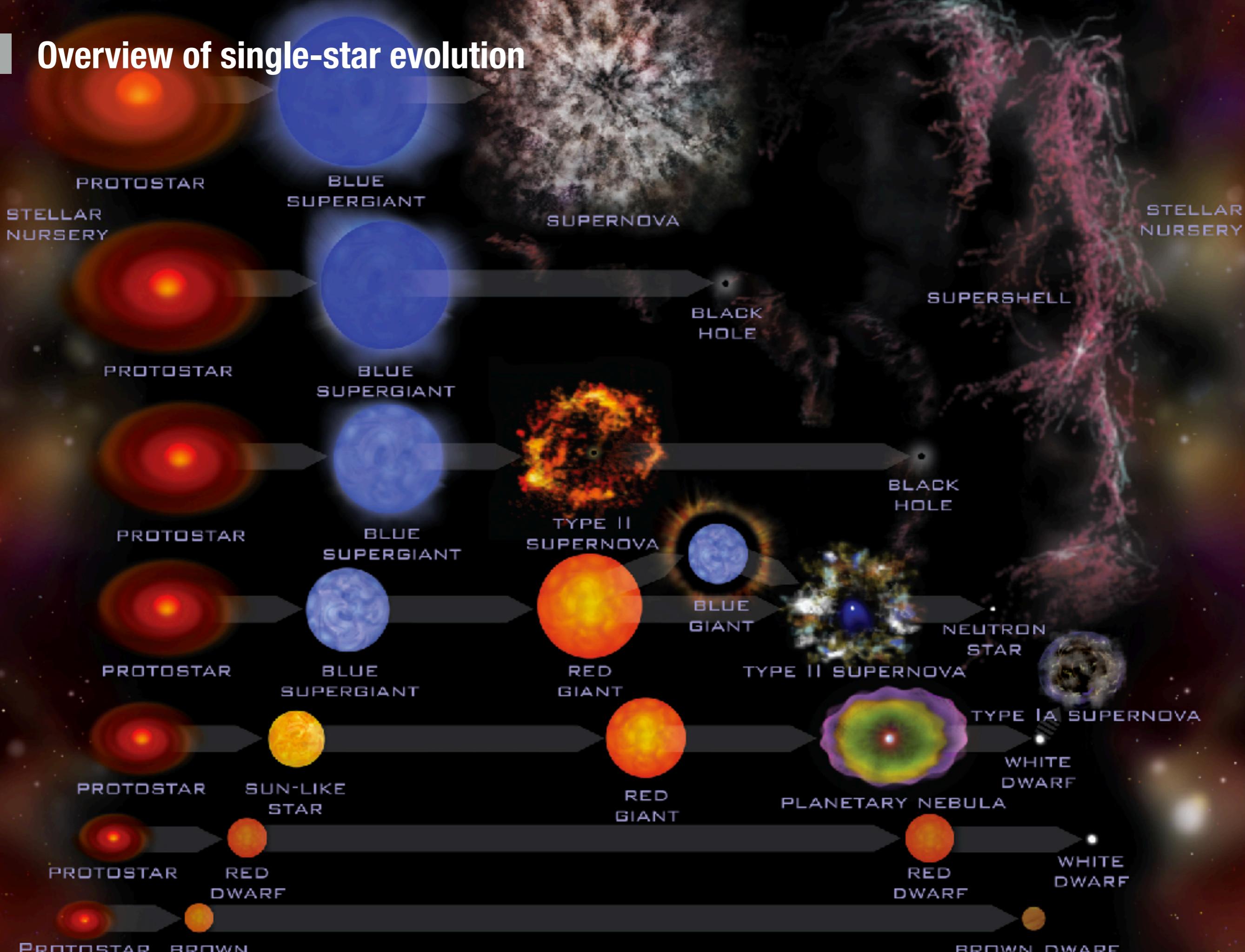
→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

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



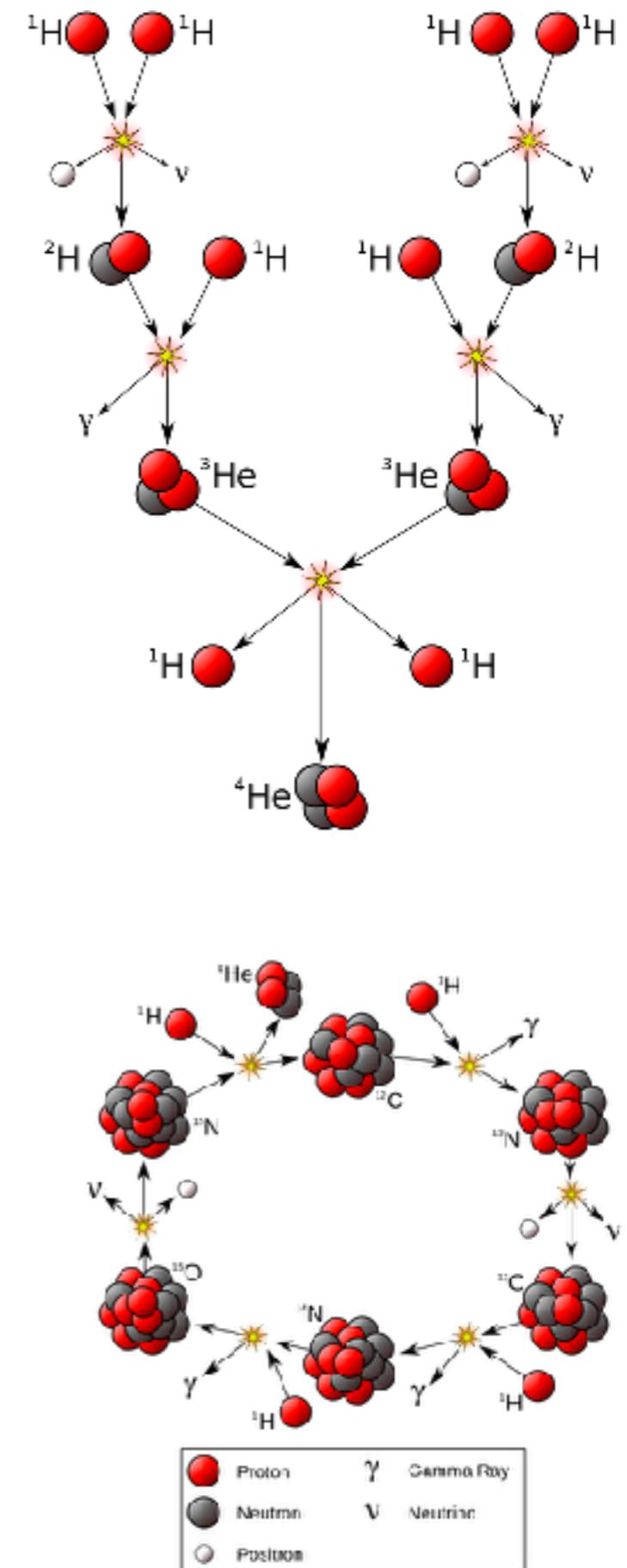
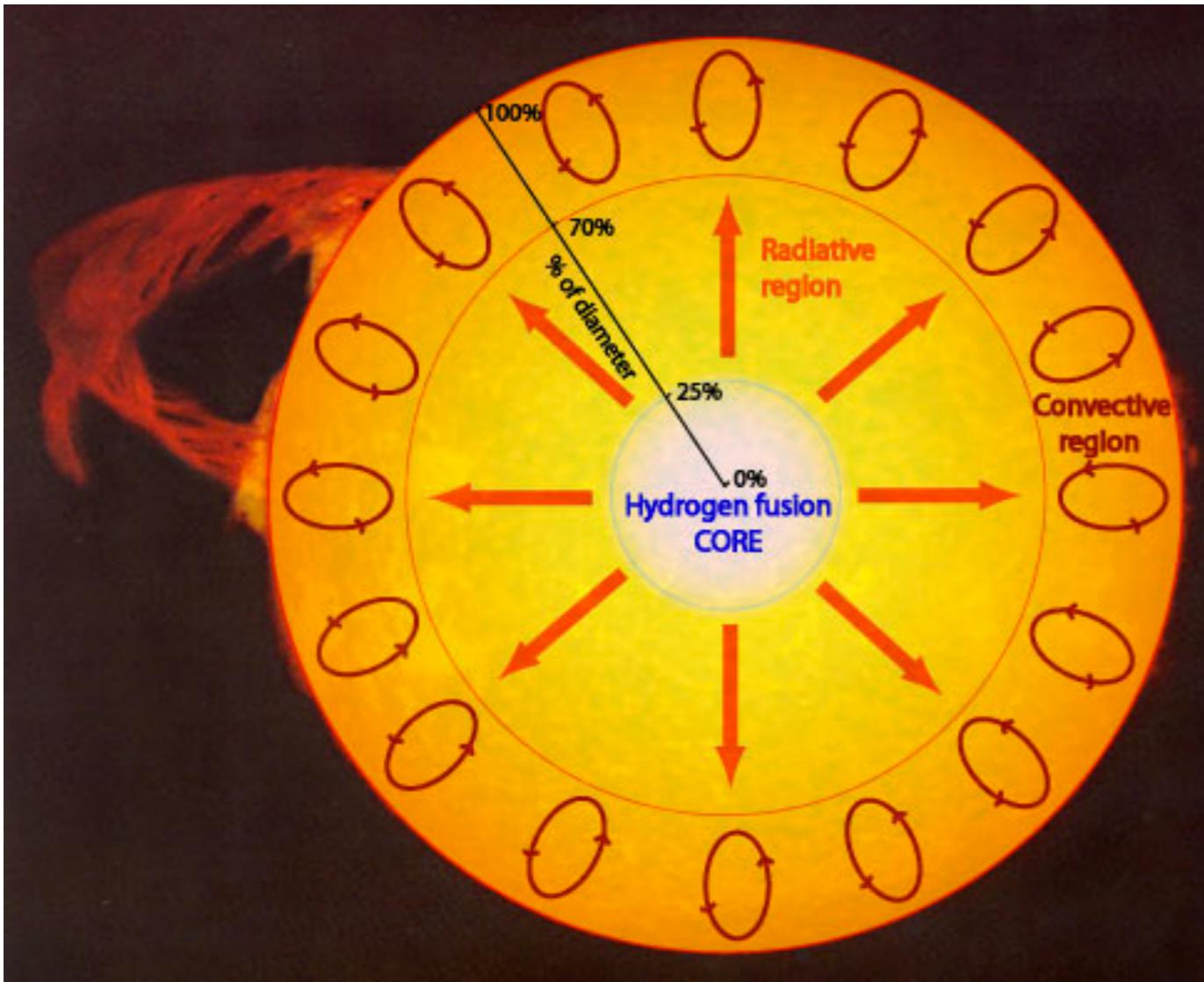
# Overview of single-star evolution

Mass (Solar masses)

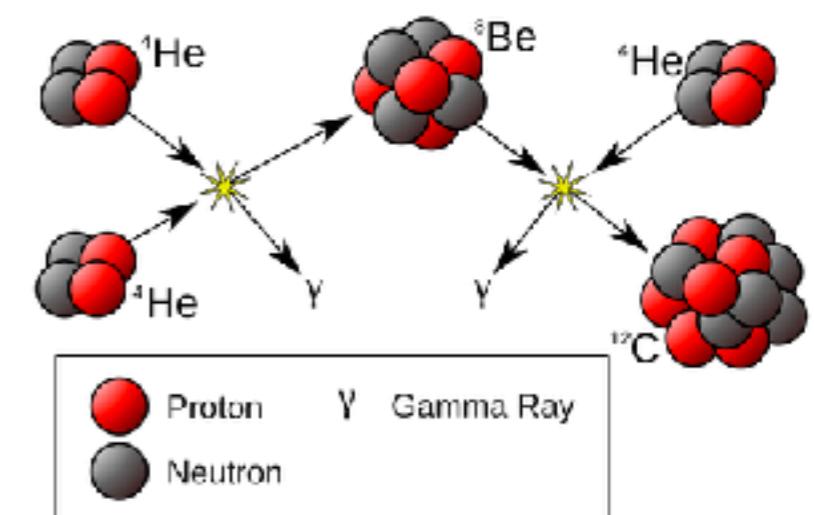
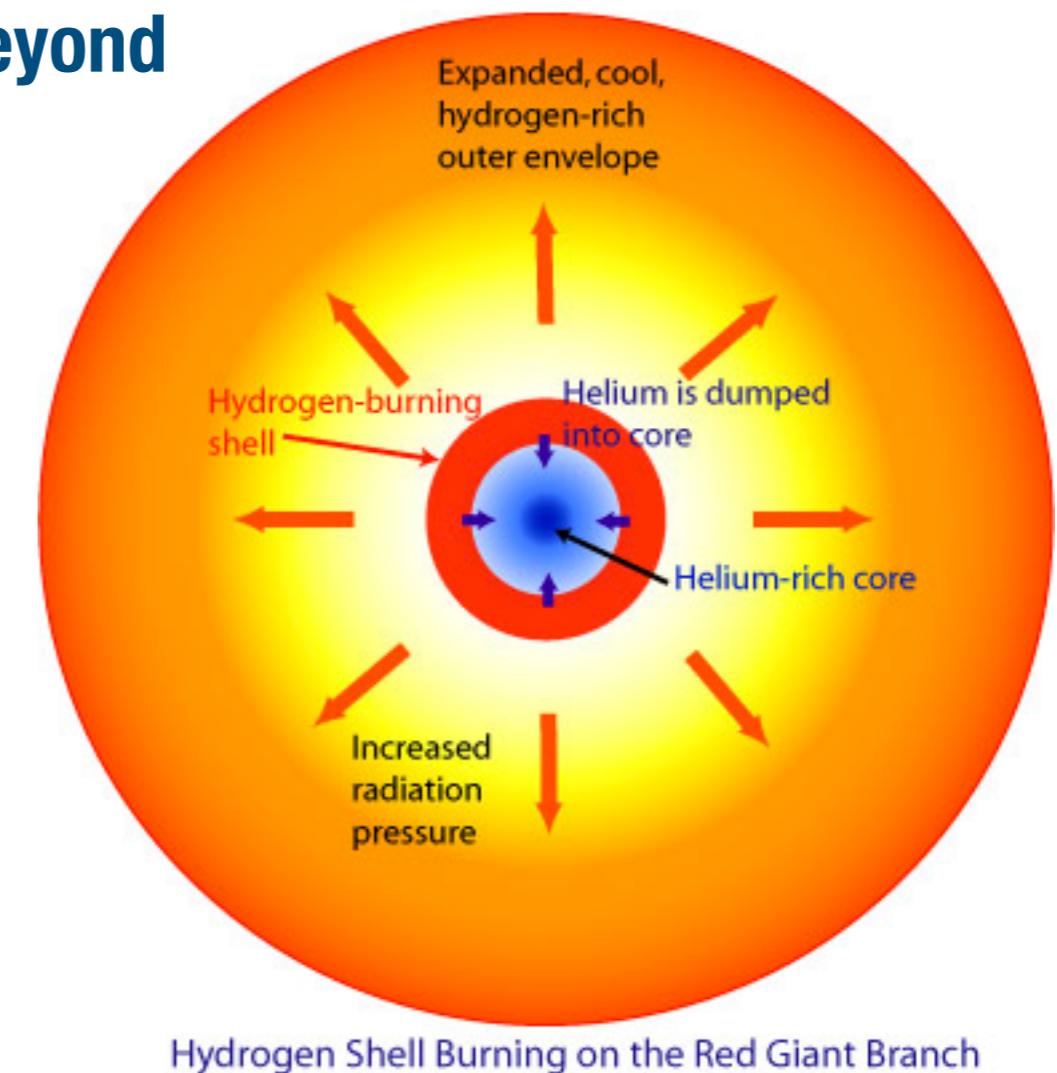
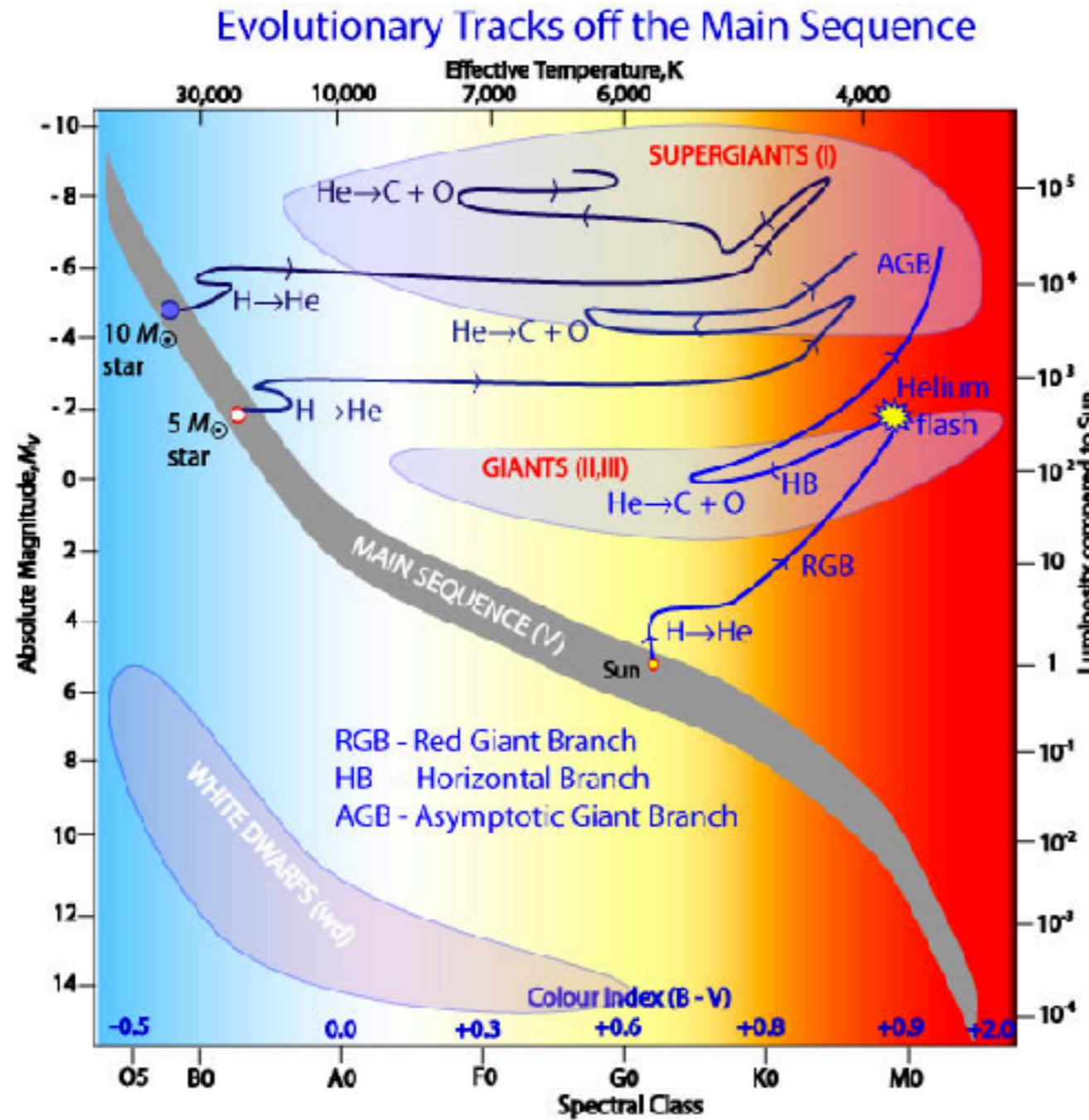
Brown dwarf	D-C									
Red dwarf	H-C [MS]									
Low mass star	H-C [MS]	pp CNO	H-S [RGB]	1. D U	HeF	He-C H-S [HB,RC]	He-S H-S [AGB]	3. D U	PNN	He WD
Intermediate mass star	H-C [MS]		H-S [RGB]	1. D U		He-C H-S	He-S H-S [AGB]	3. D U	PNN	CO WD
	H-C [MS]		H-S [RGB]	1. D U		He-C H-S	2. He-S D H-S U [AGB]	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

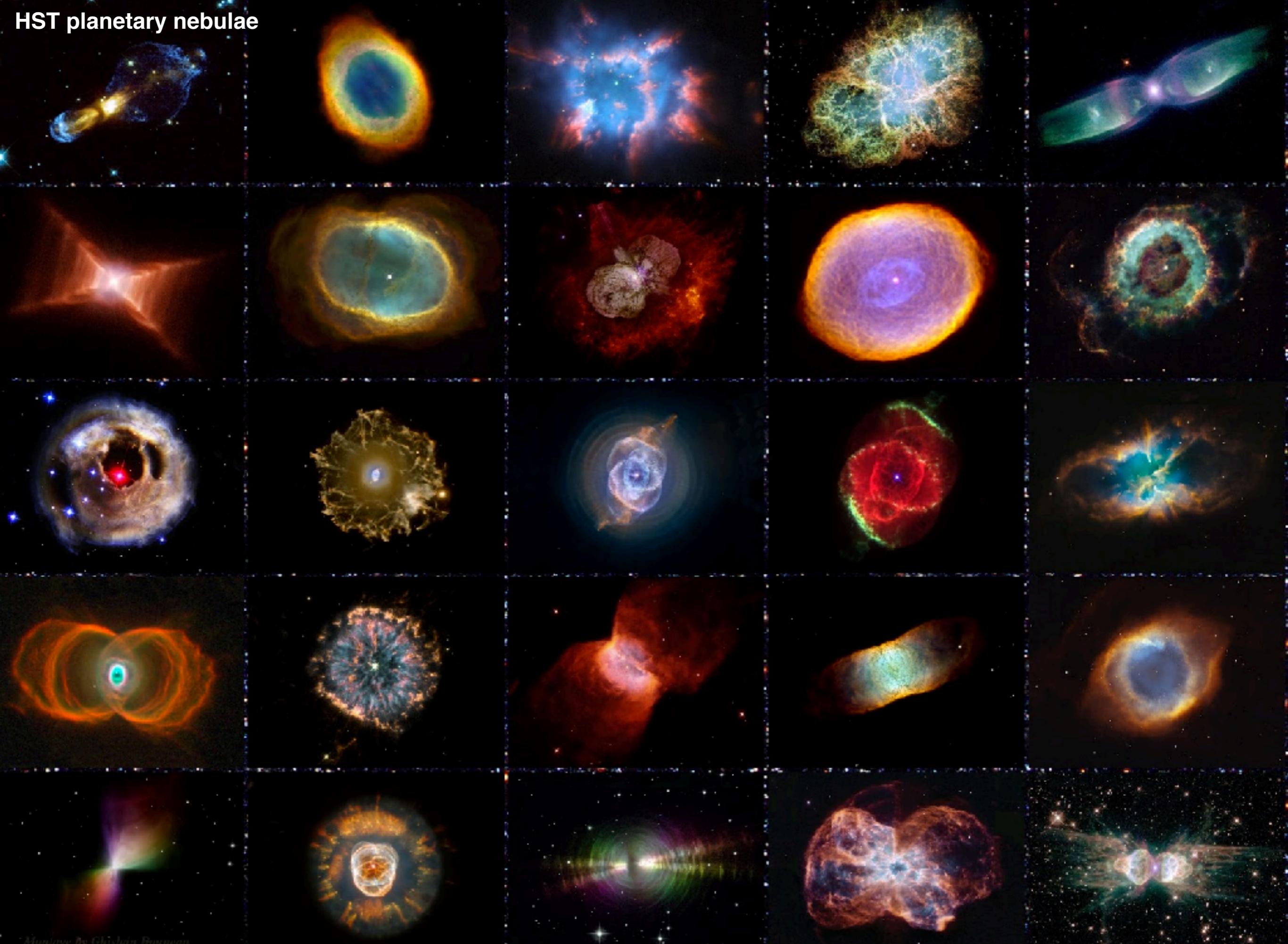
Starts on the main sequence  
via pp (low mass) and CNO (high mass) chains



# Helium burning on the red giant branch and beyond

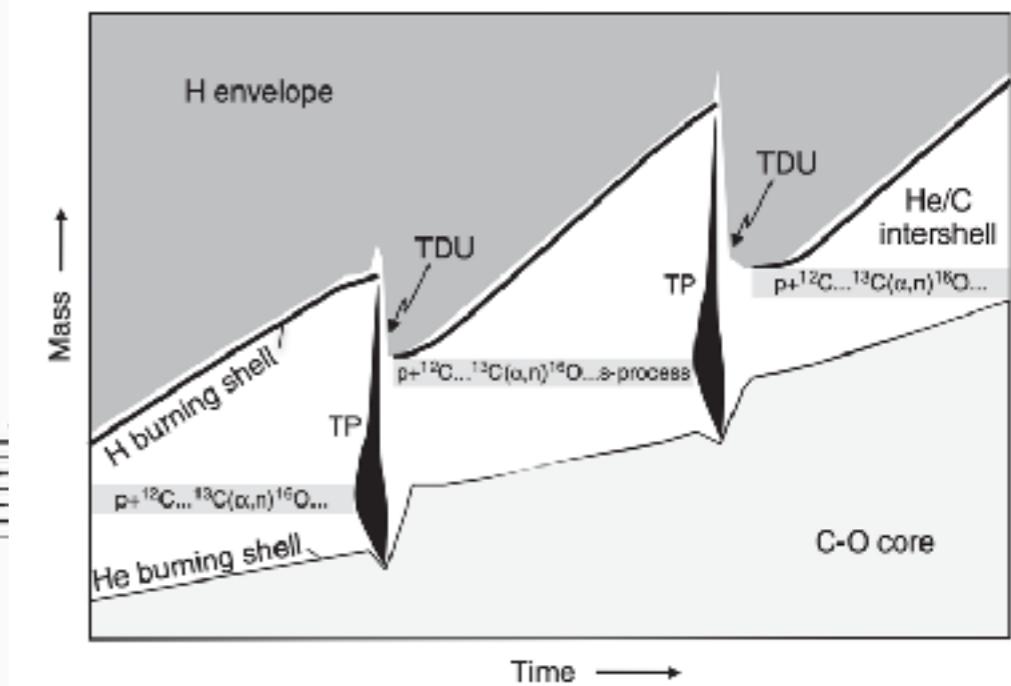
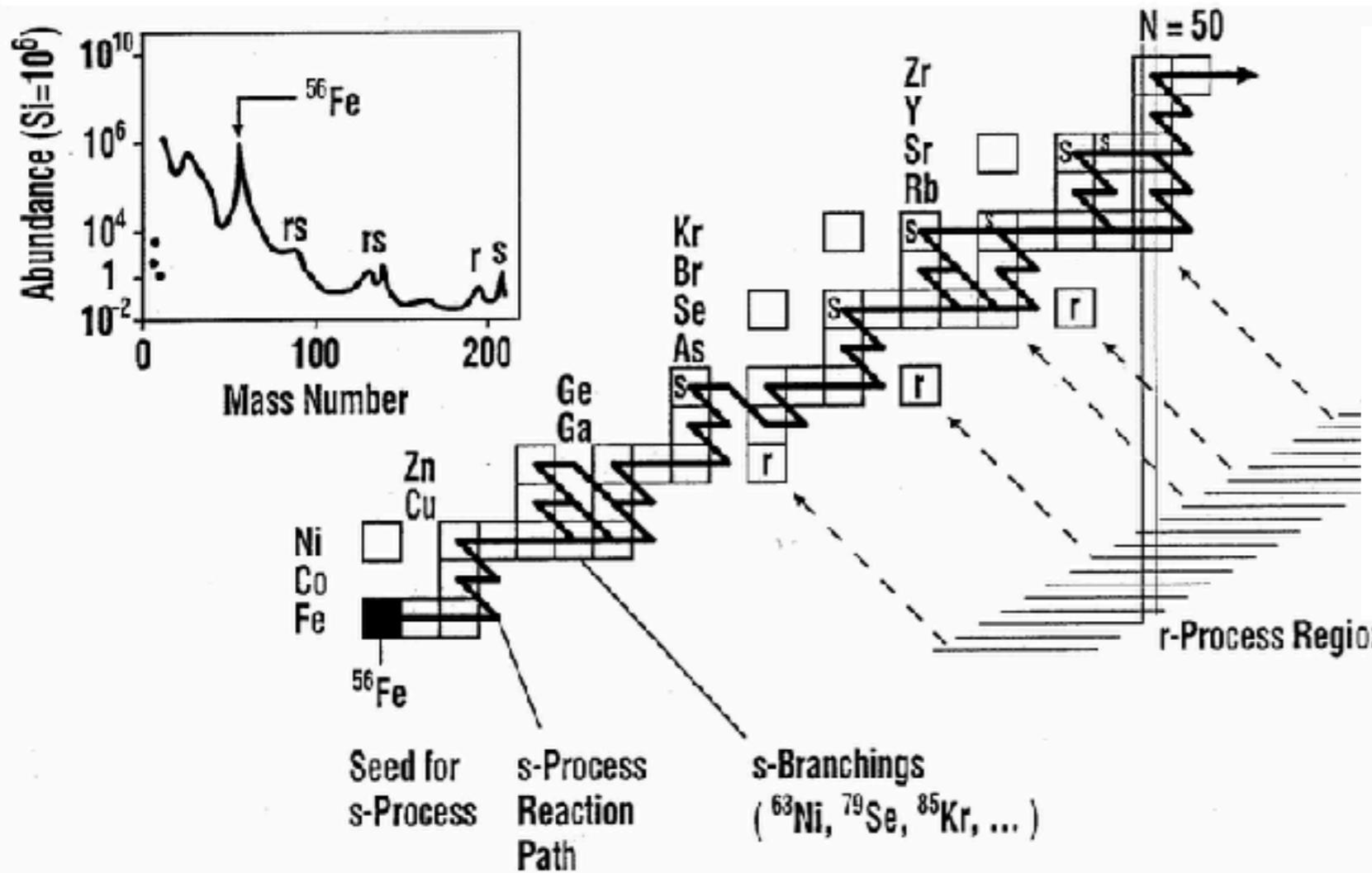
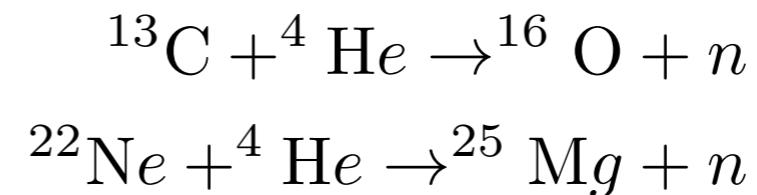


# HST planetary nebulae

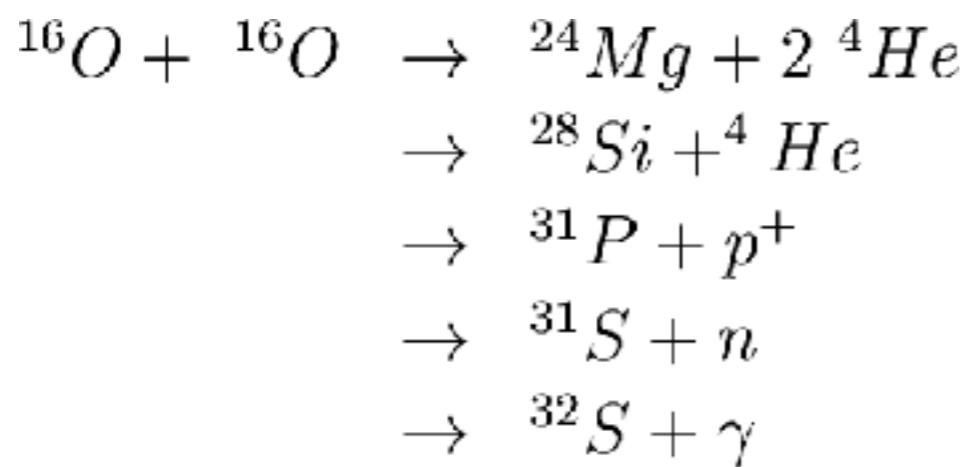
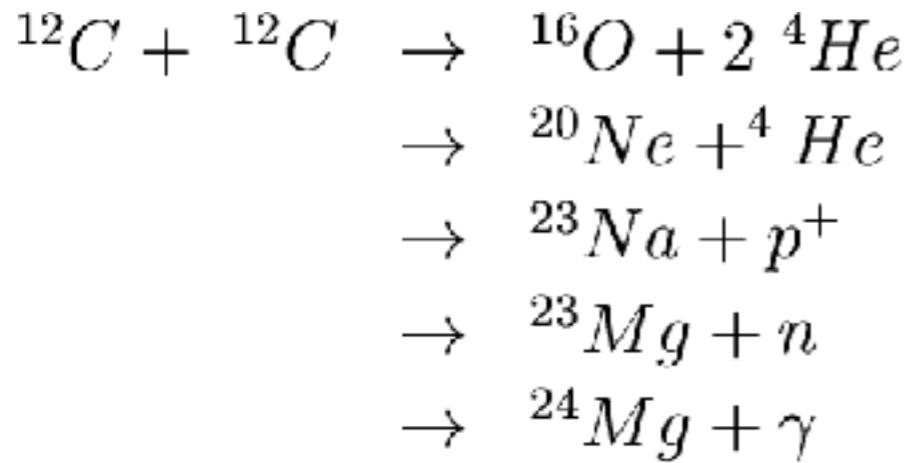


# slow neutron capture on the AGB (s-process)

main neutron sources



# Carbon burning and beyond



-----  
For 8 solar mass star

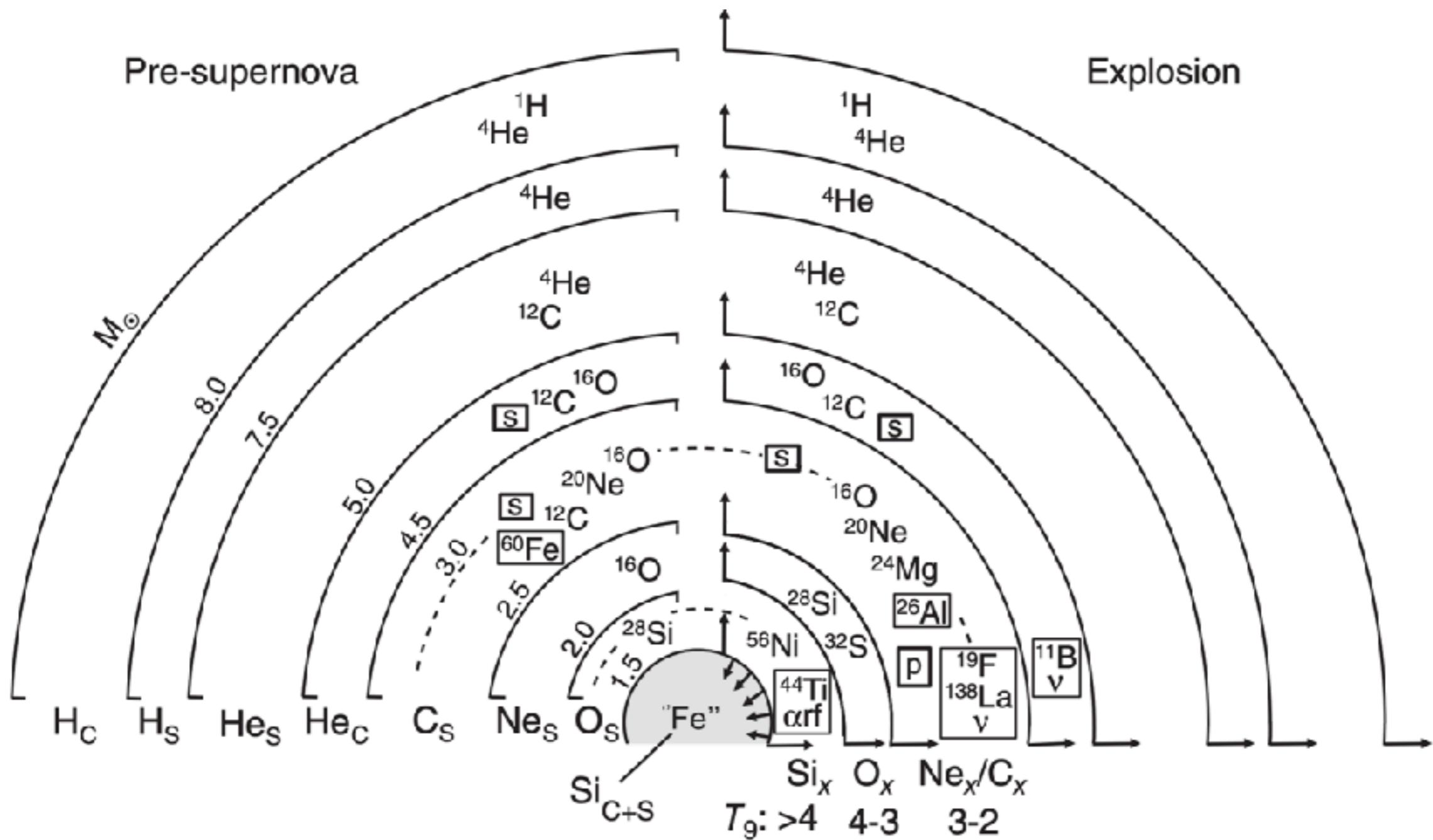
- Hydrogen: 10 Myr
- Helium: 1 Myr
- Carbon: 1000 yr
- Neon: 10 yr
- Oxygen: 1 yr
- Silicon: 1 day
- Core collapse: < 1 sec

Silicon burning occurs at extremely high temperatures: ~3 GK

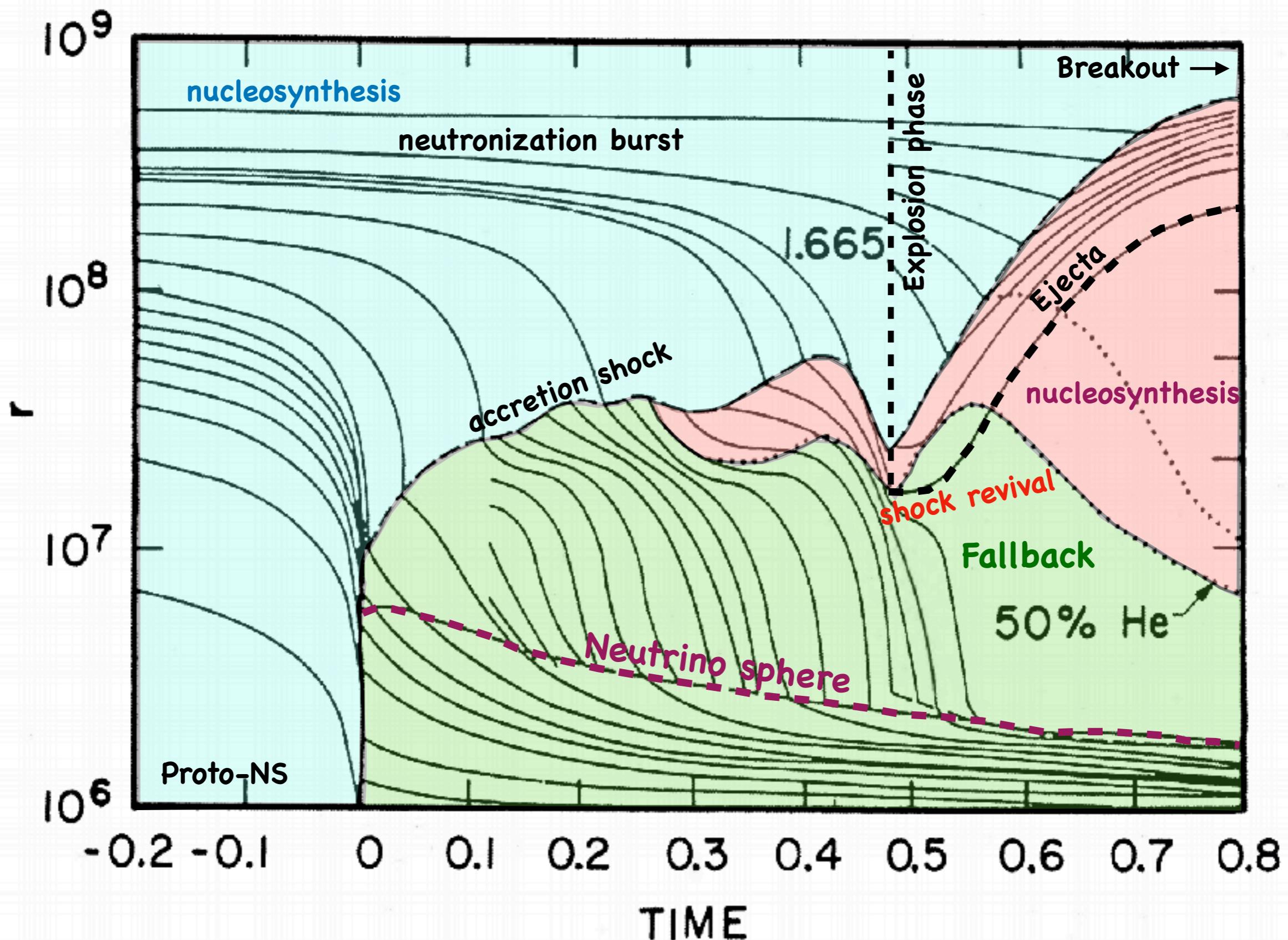
Nuclei photo-disintegrate and the emitted protons and alpha particles can be captured, forming heavier nuclei.

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

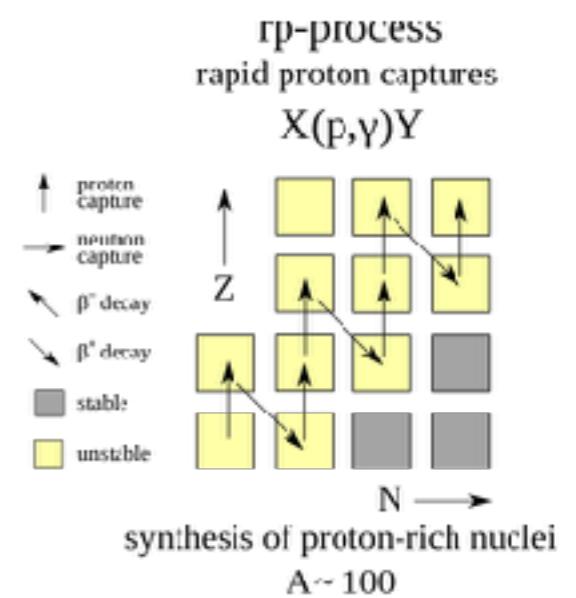
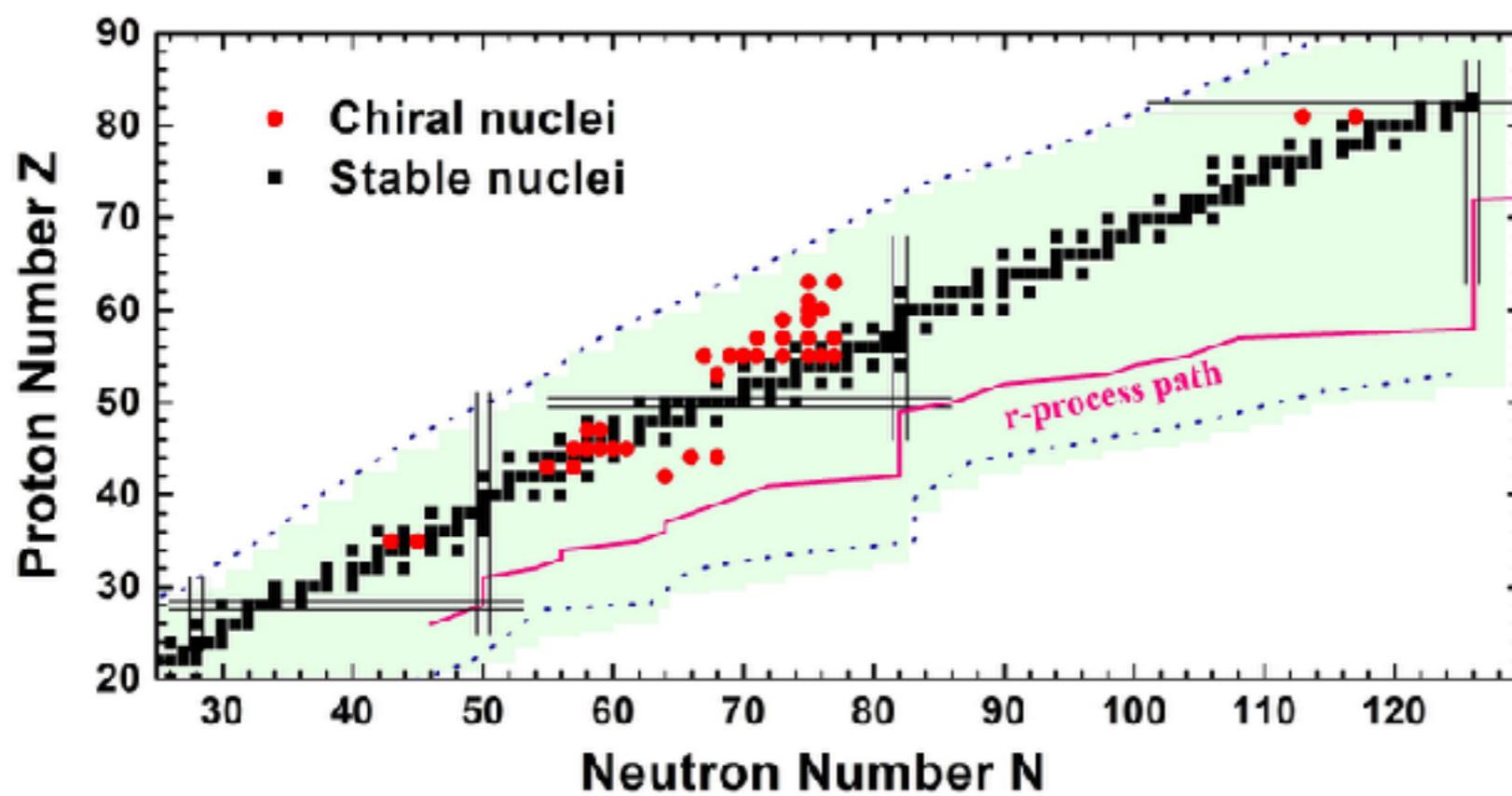
# Pre-supernova structure and core-collapse



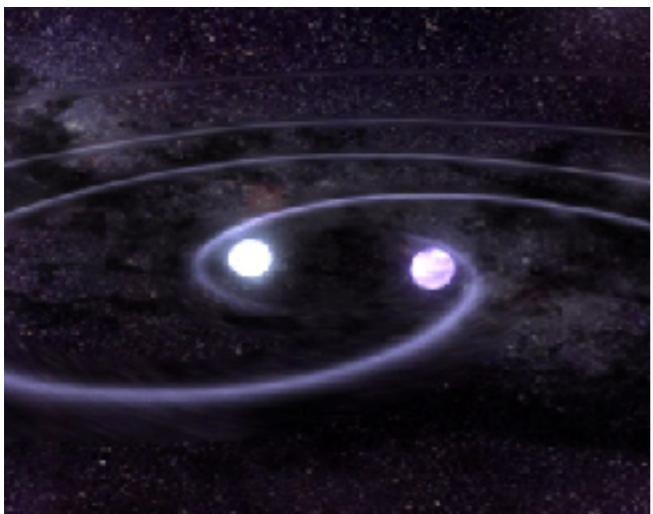
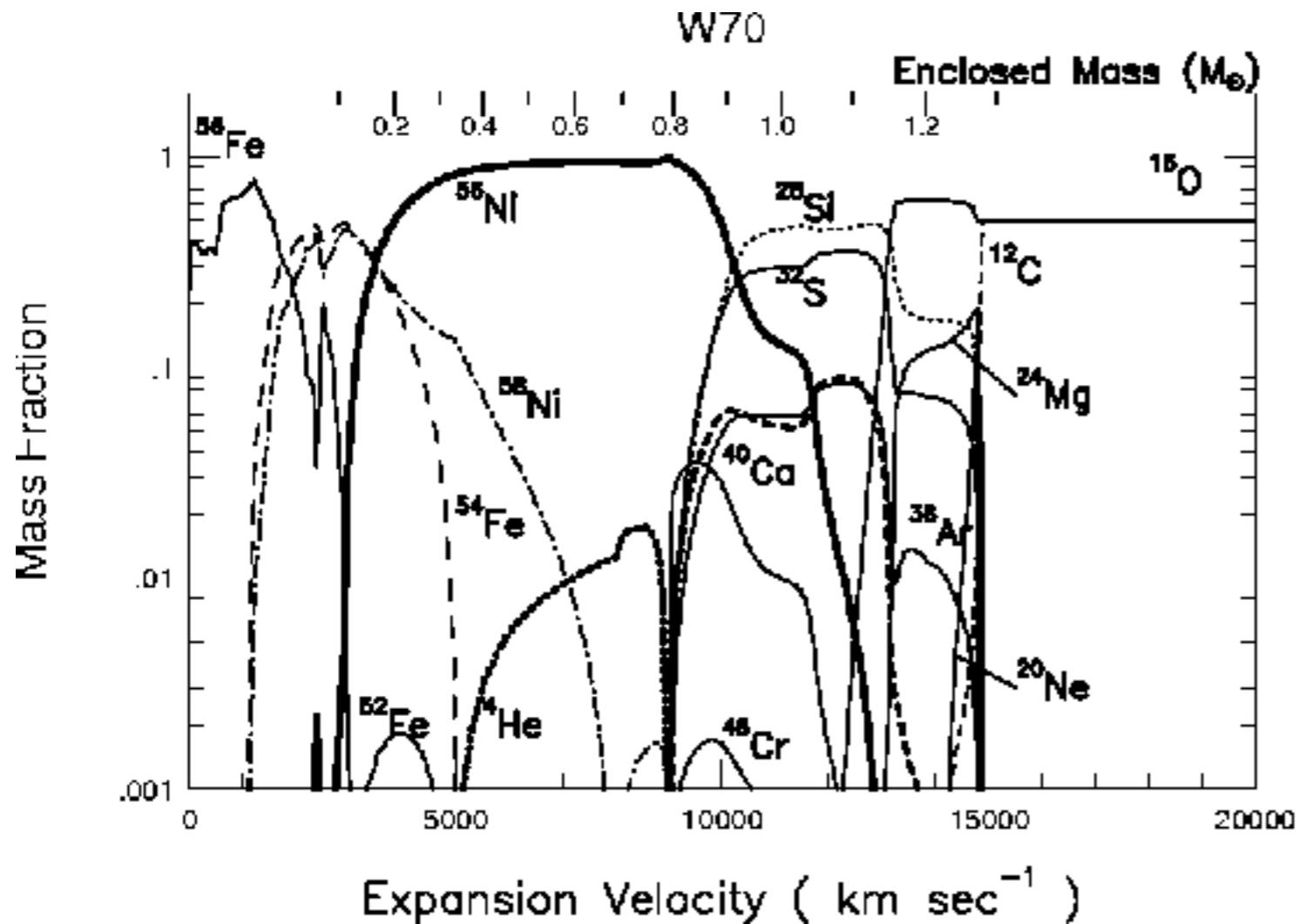
# Core-collapse supernovae



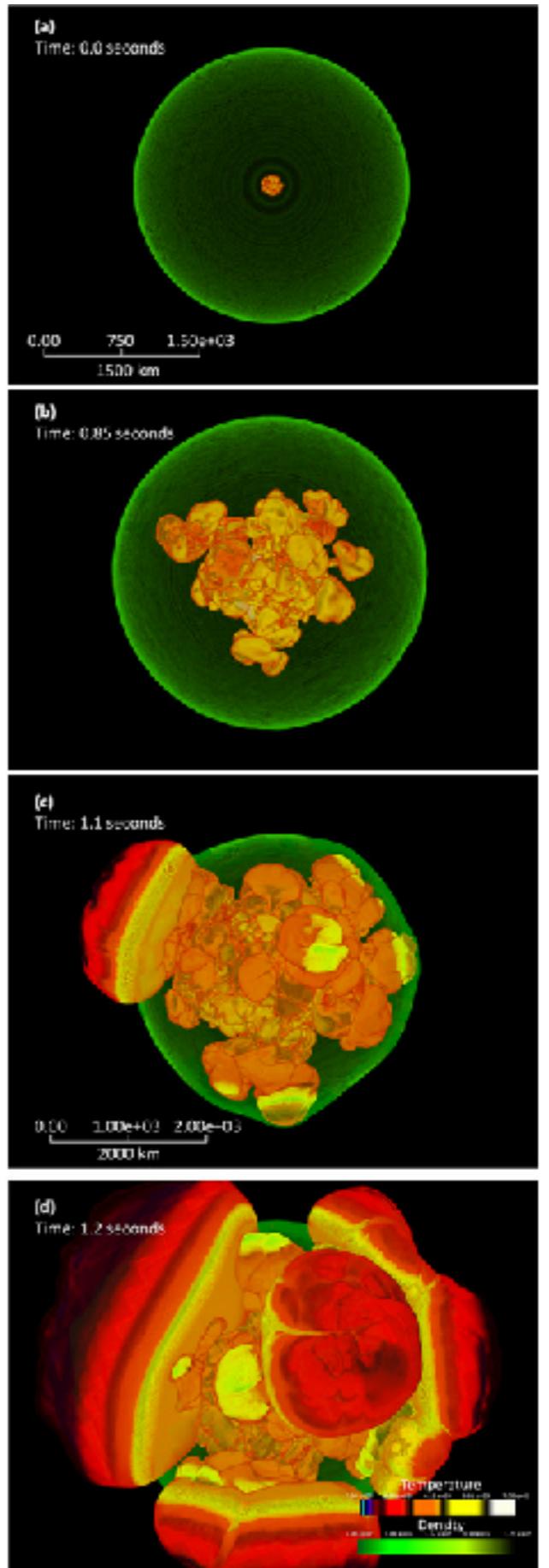
# Explosive nucleosynthesis (rapid neutron capture; r-process; rp-process)



# Type Ia supernovae (NSE)

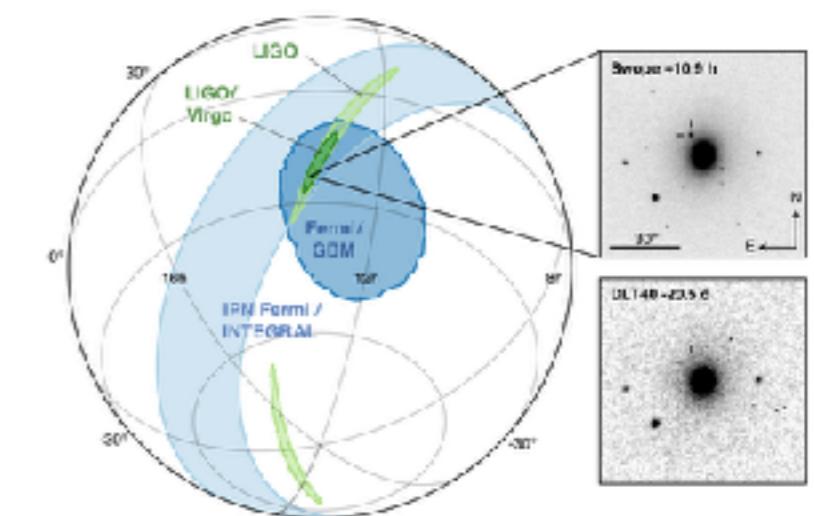
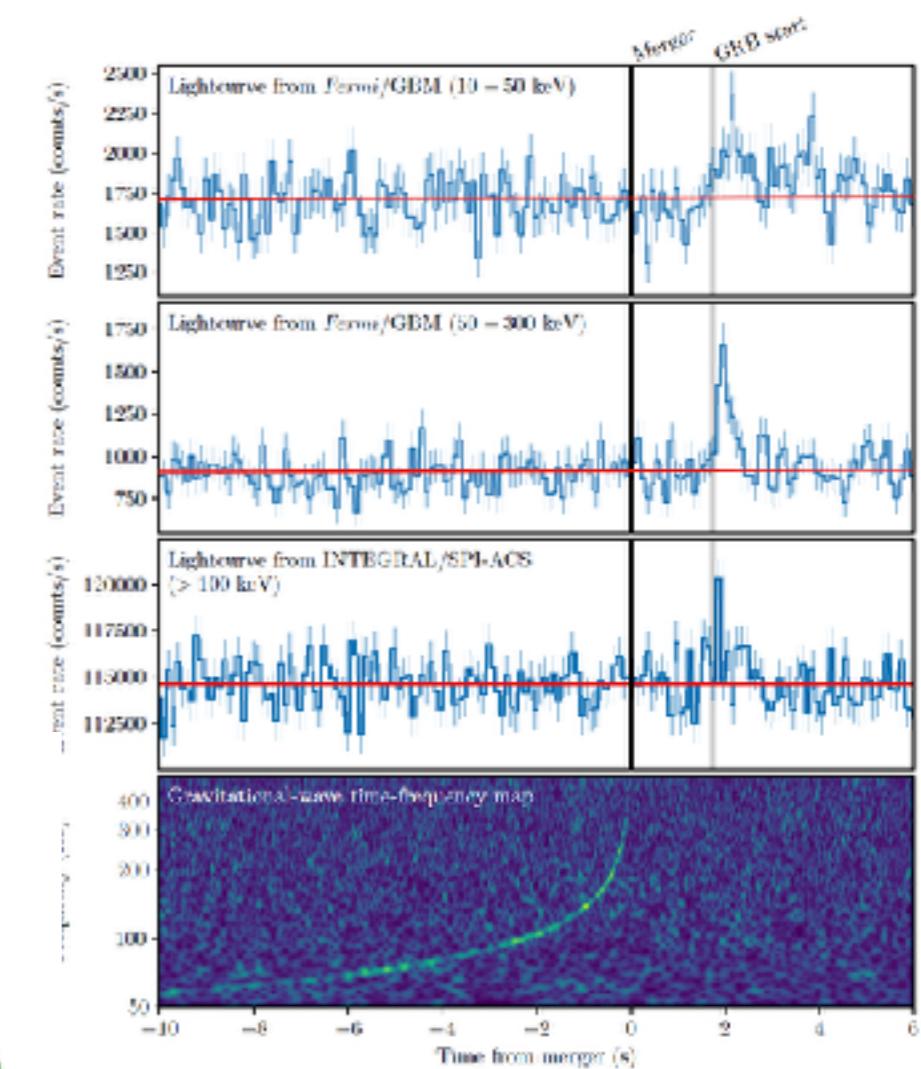
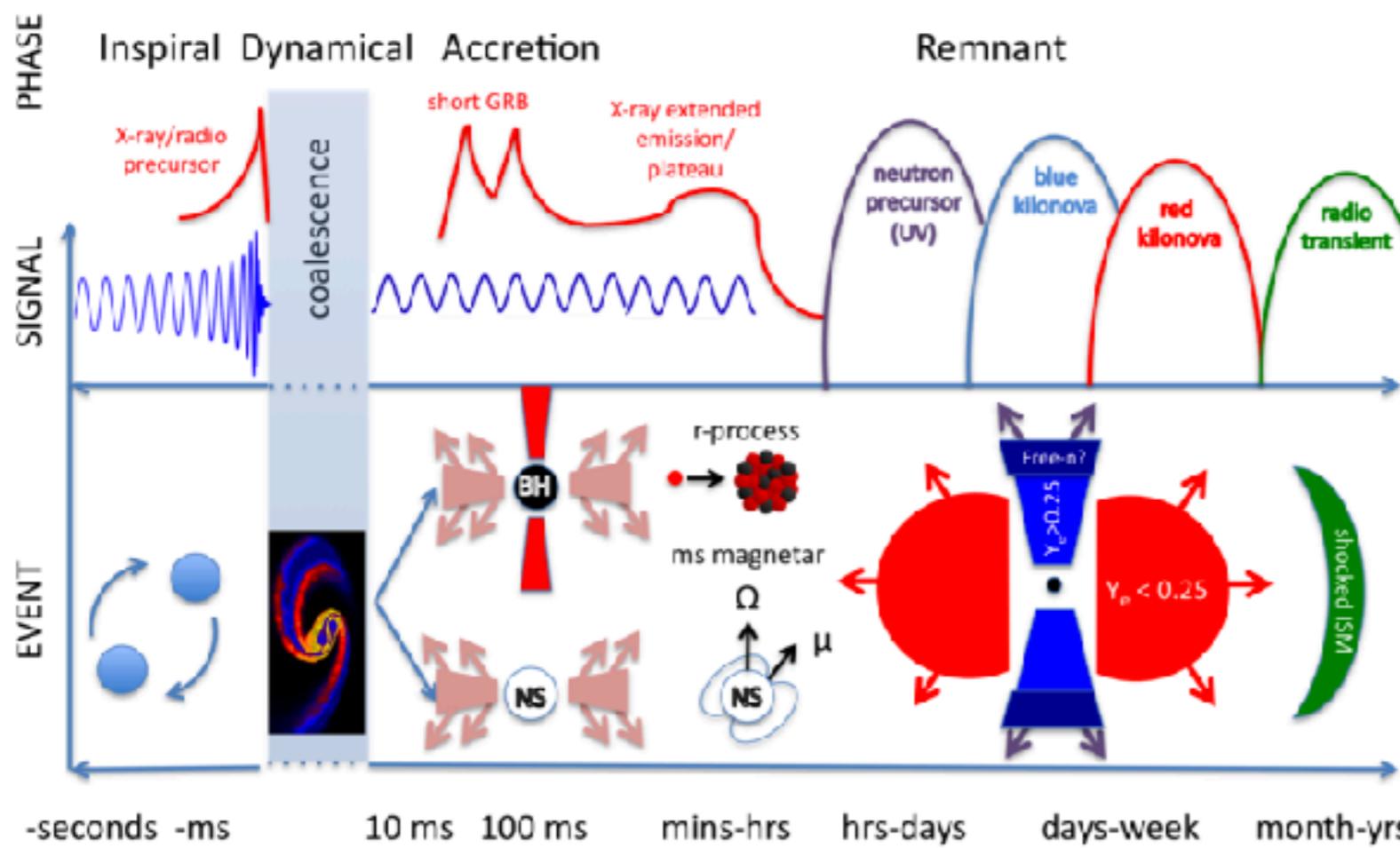


Progenitors still debated  
Responsible for most iron-peak elements



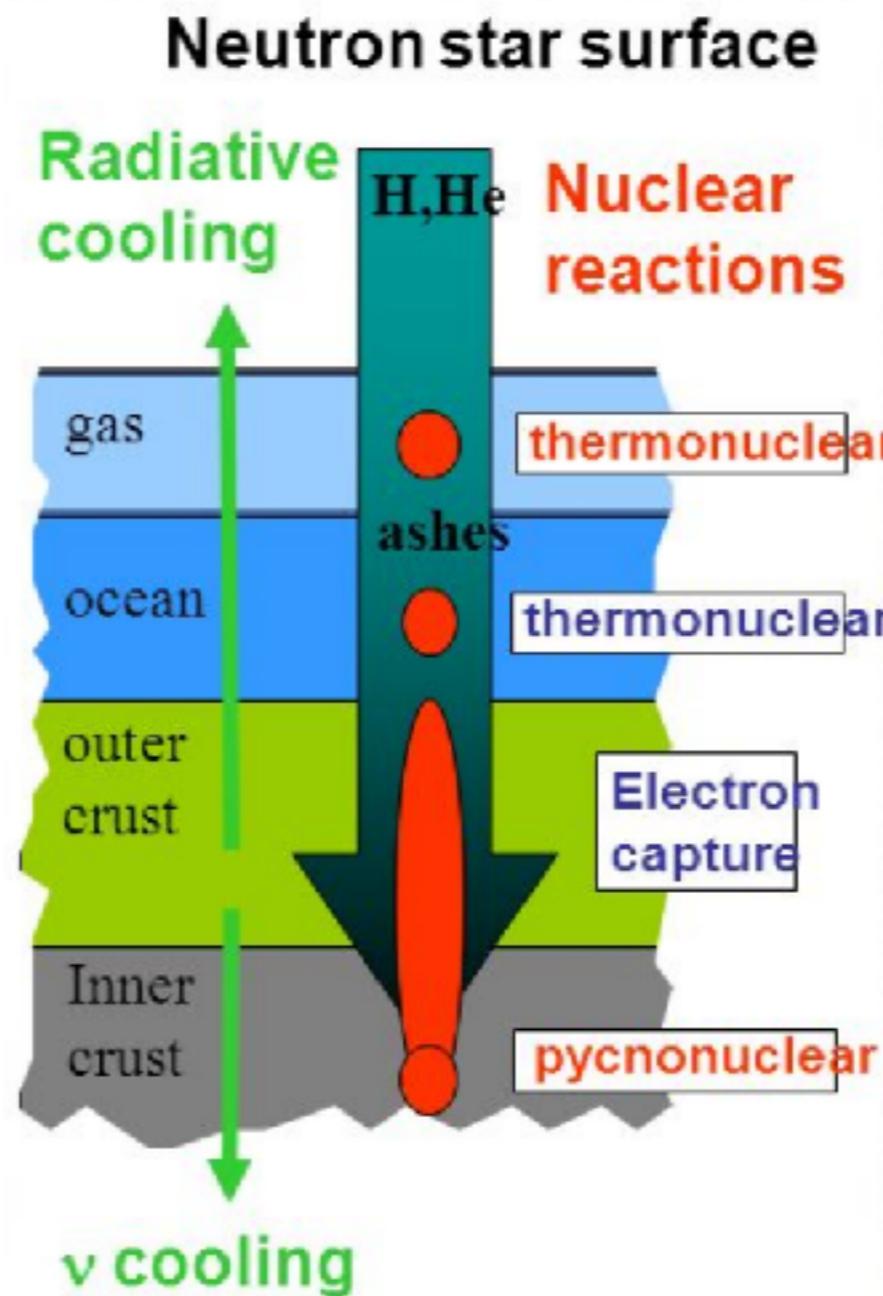
# Neutron star mergers, gamma-ray bursts

GW 170814

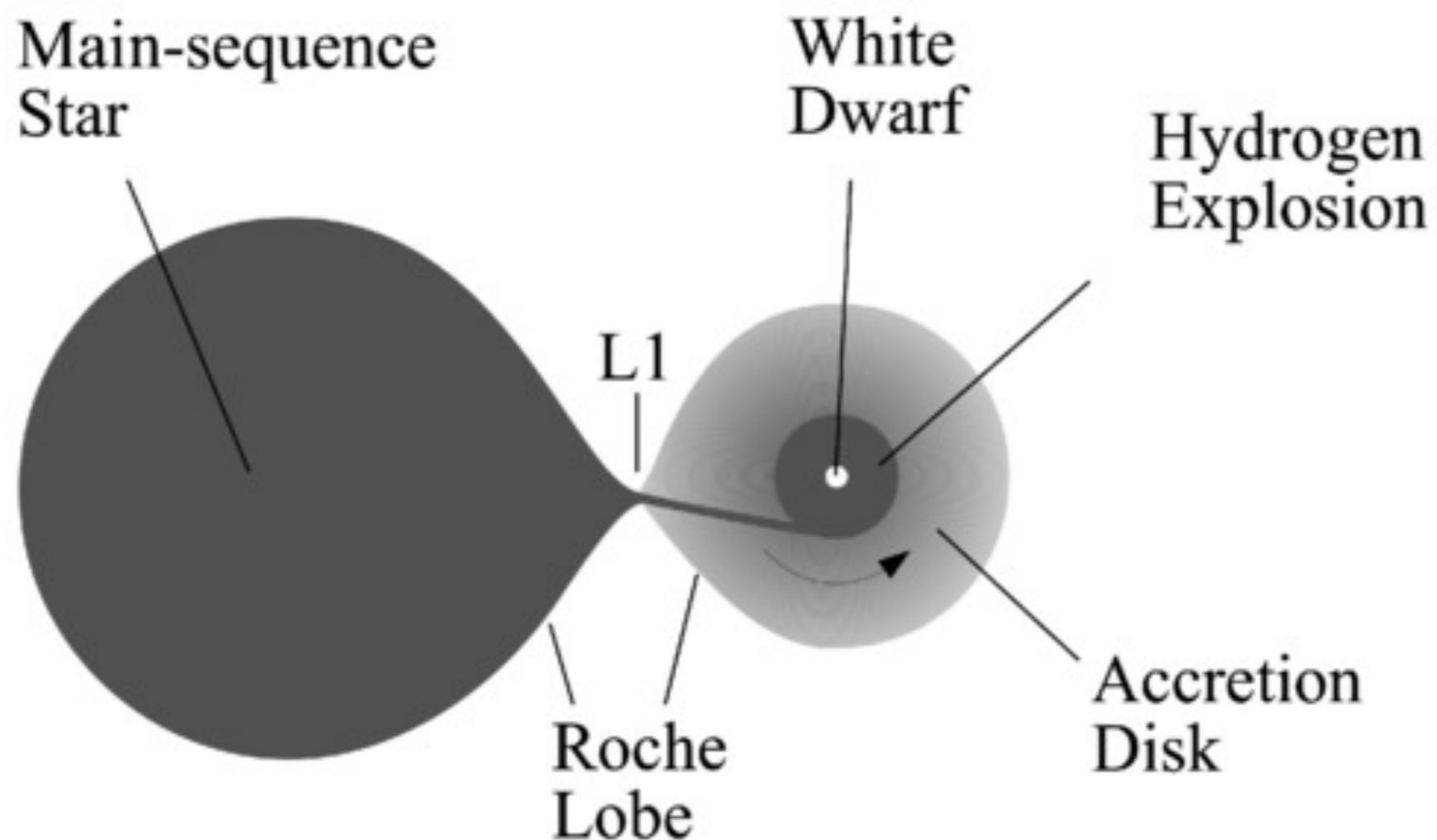


# Pycno-nuclear reactions

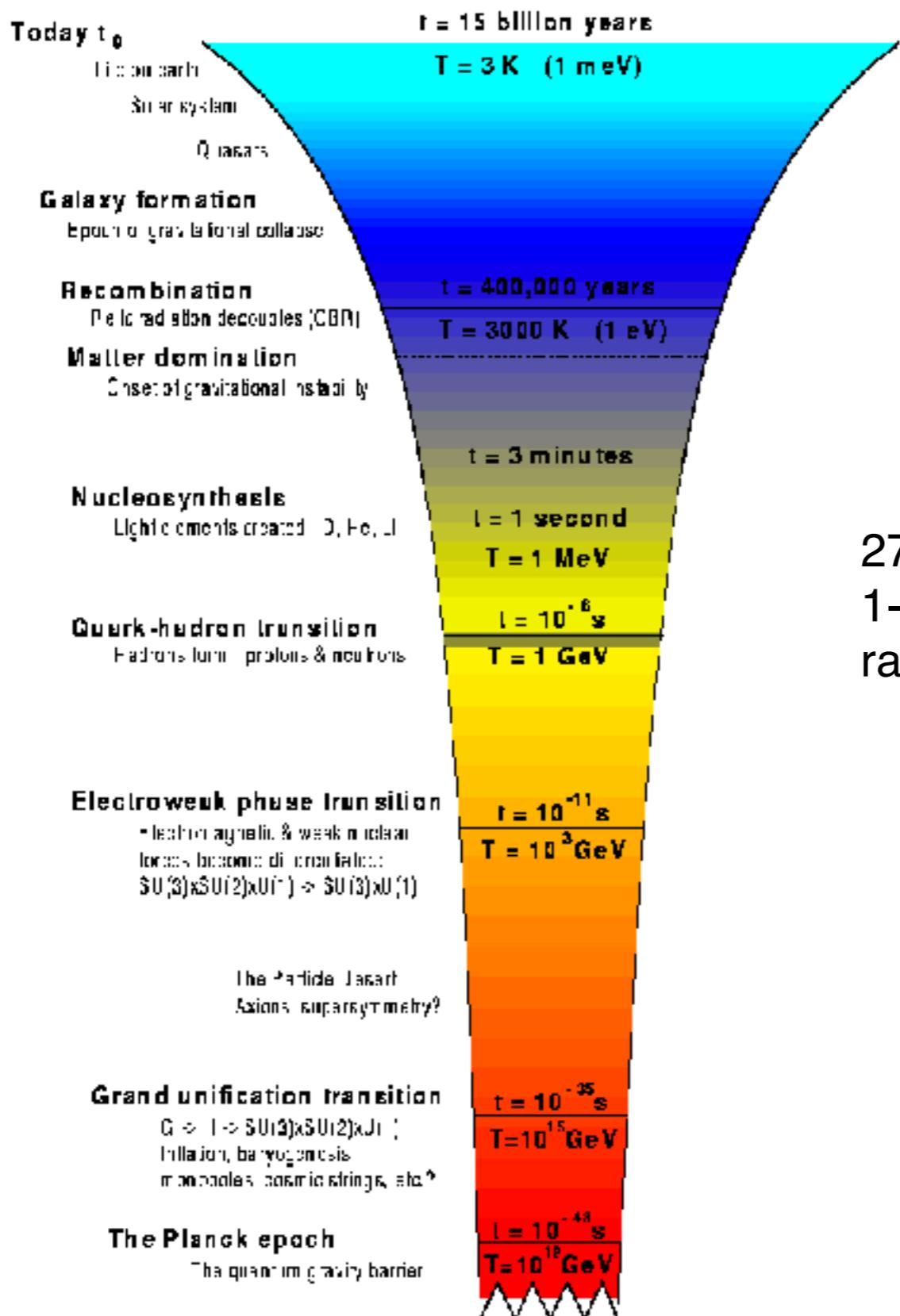
Inside neutron stars, at extremely high densities, the effective coulomb barrier is reduced by high neutron fraction, close distance and electron cloud



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

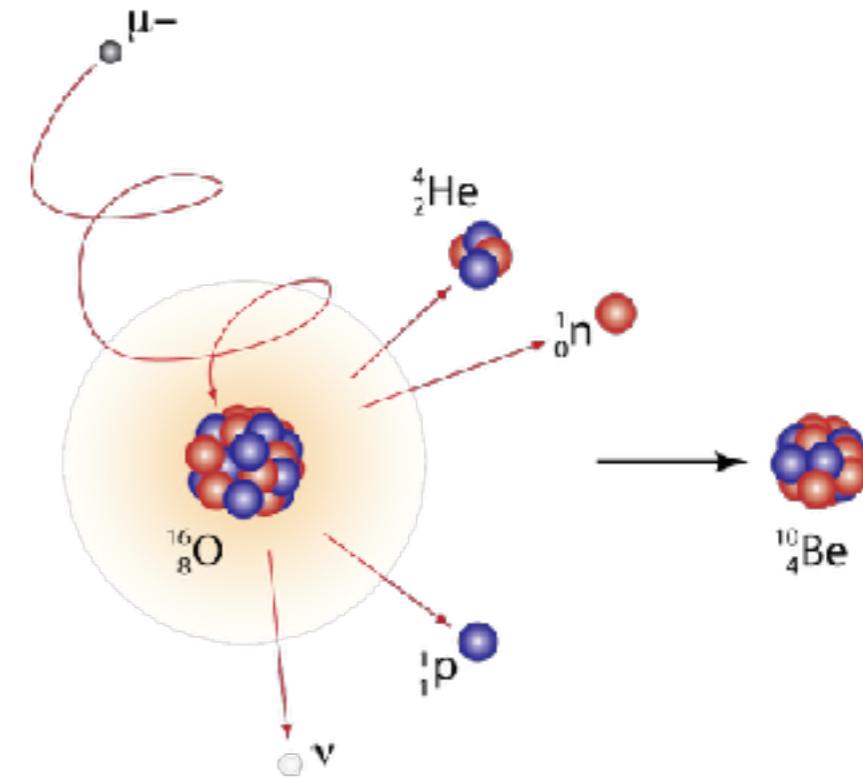
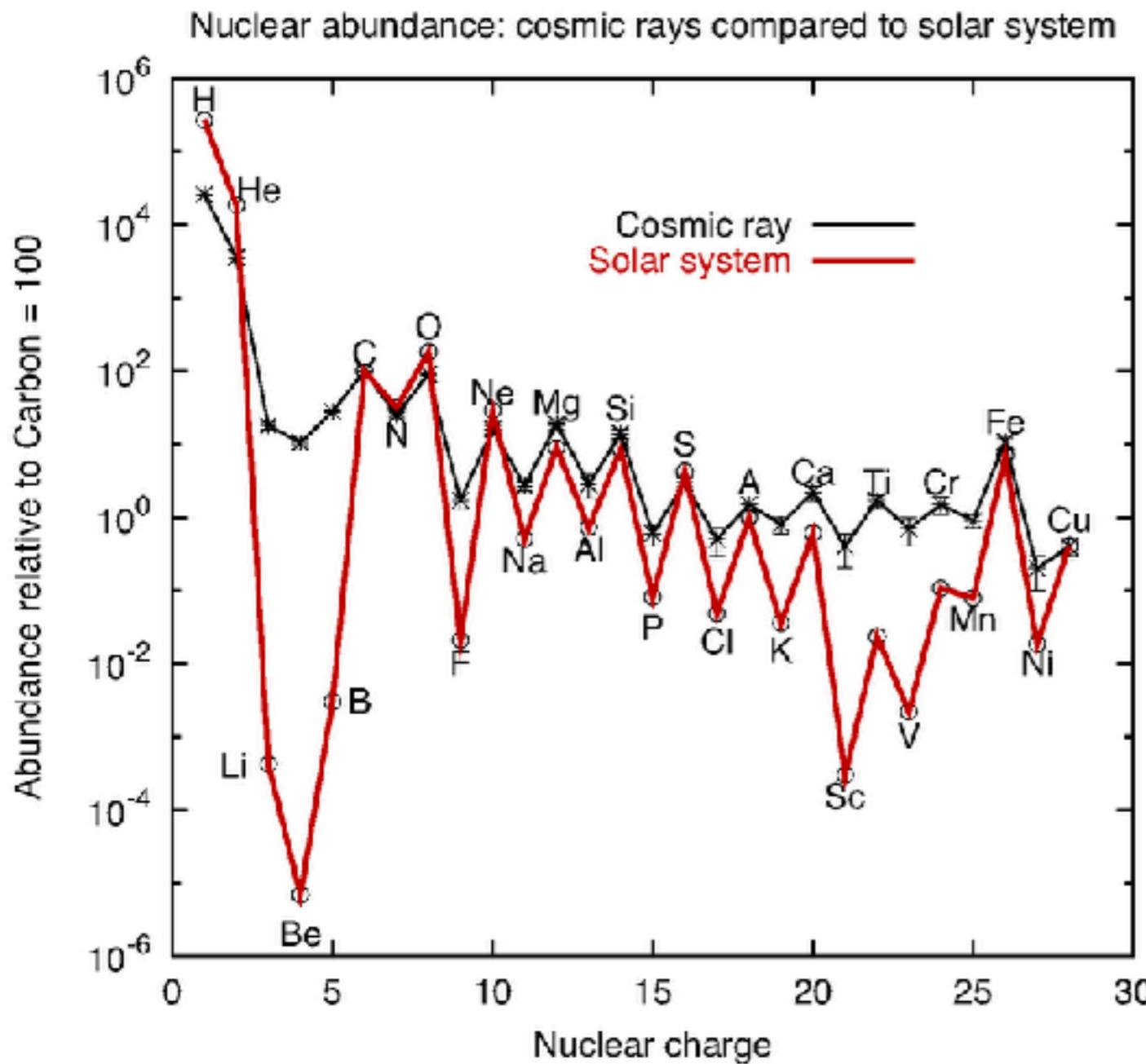


# Primordial nucleosynthesis



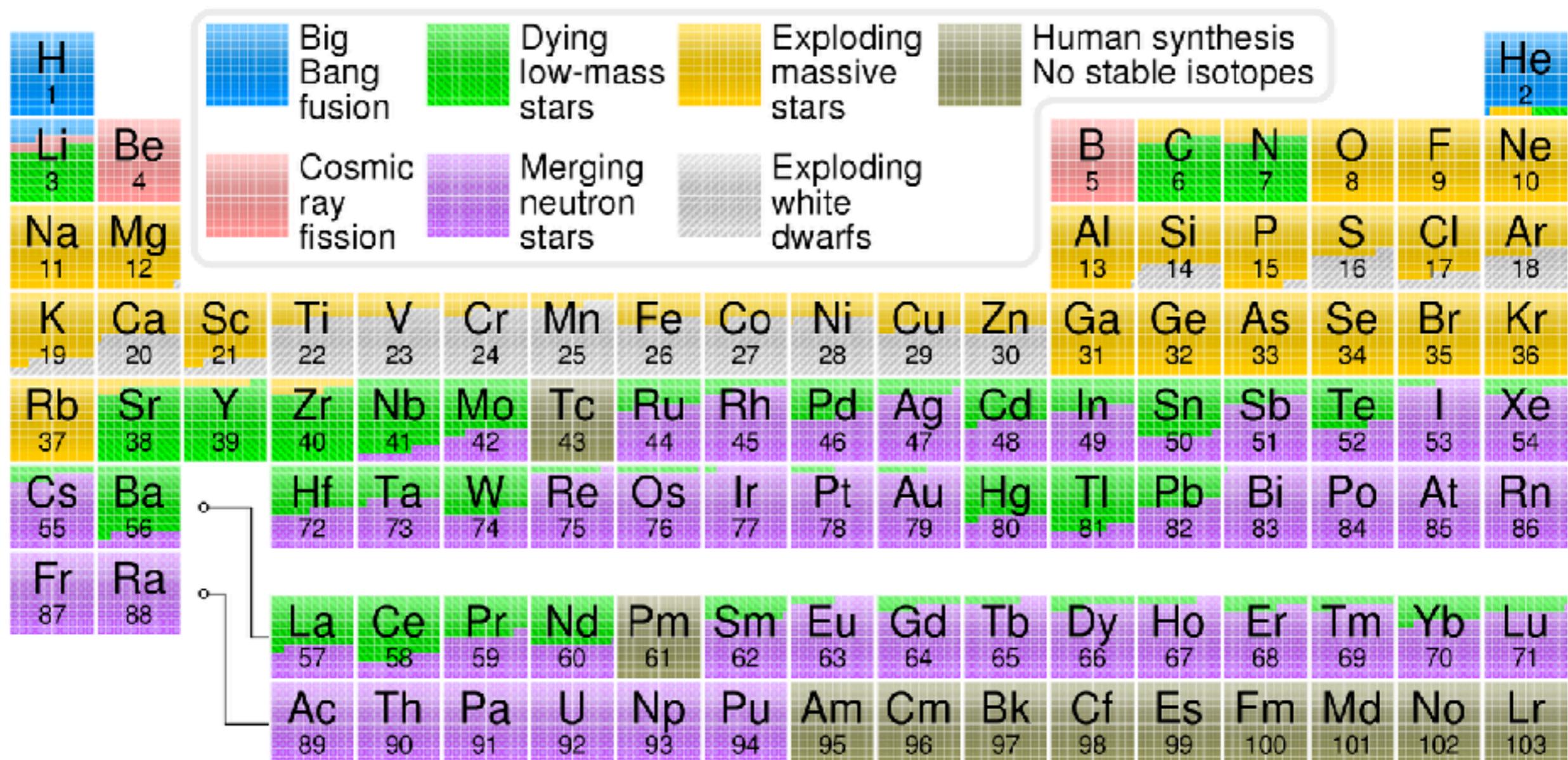
27% He requires primordial origin  
1-3 sec after Big Bang: High temperatures but rapid cooling

# CR-induced spallation

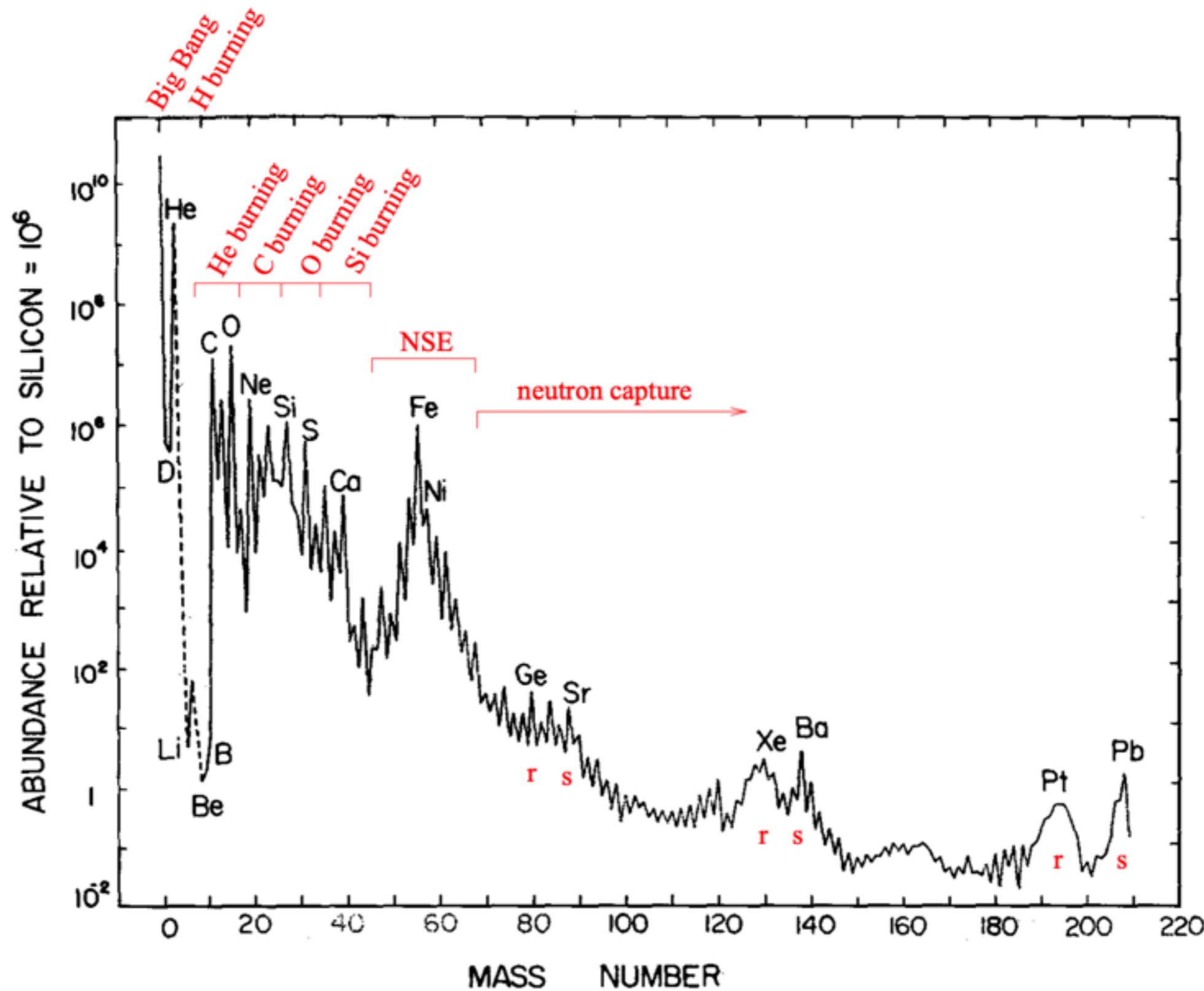


Not enough to explain observed Li abundances in the Solar System, other processes required (explosive nucleosynthesis, novae, red giants?)

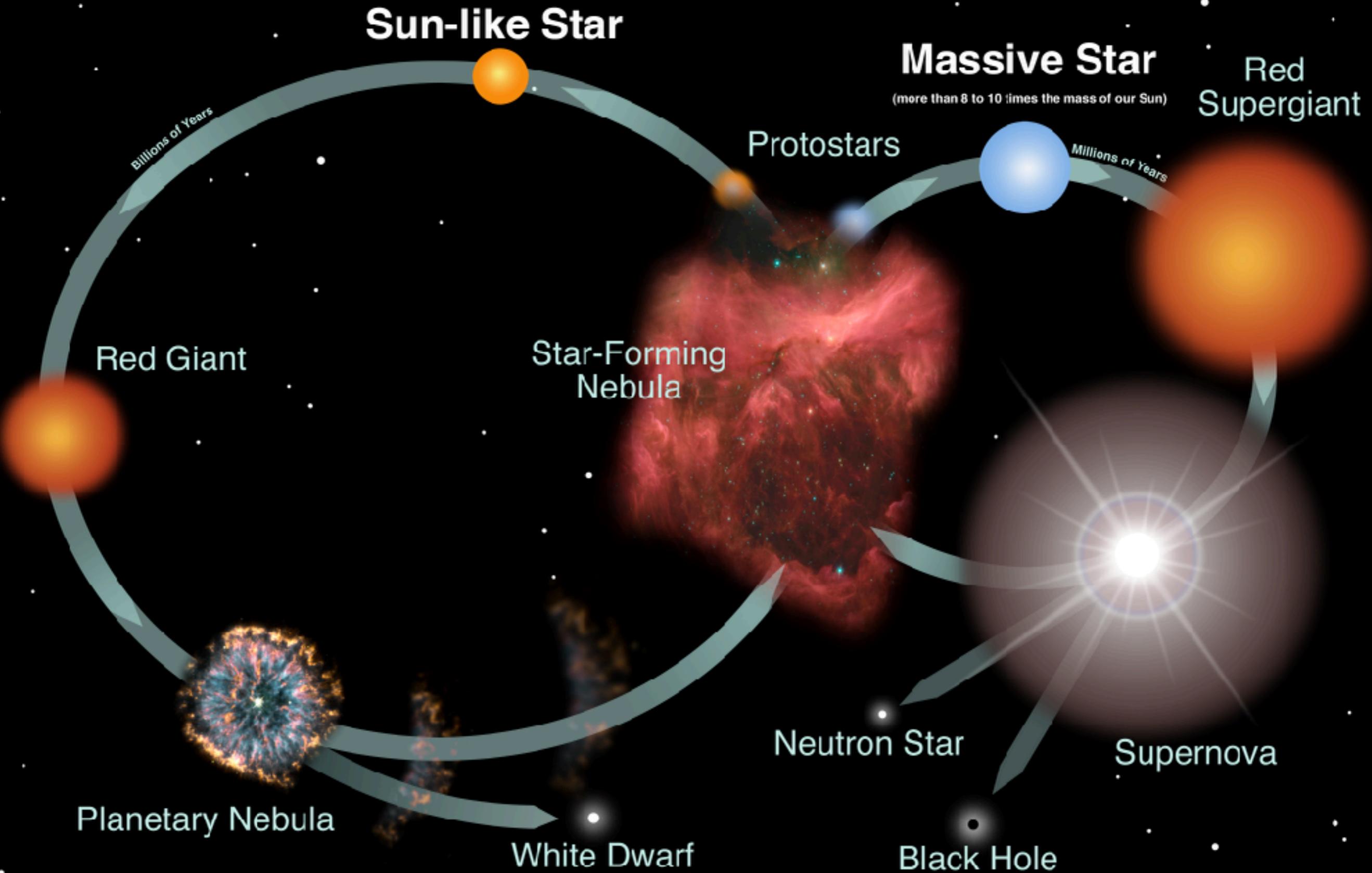
# Origin of elements



# Origin of elements



## Nucleosynthesis goes on



# Overview

- **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