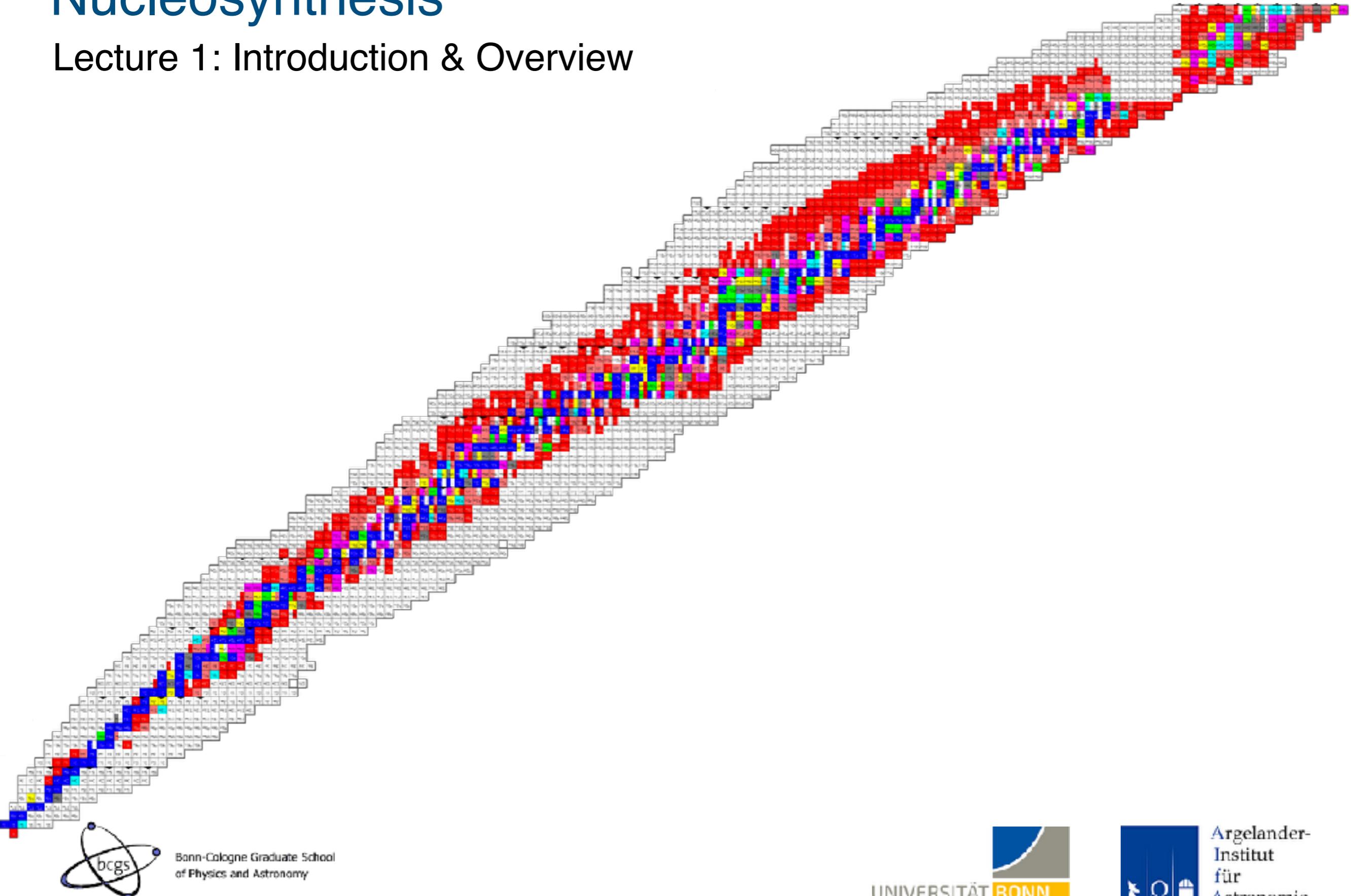


# Nucleosynthesis

## Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School  
of Physics and Astronomy



Argelander-  
Institut  
für  
Astronomie

## Nucleosynthesis

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

Exercises                         Fridays      @ 10:00 – 11:00 April 26 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

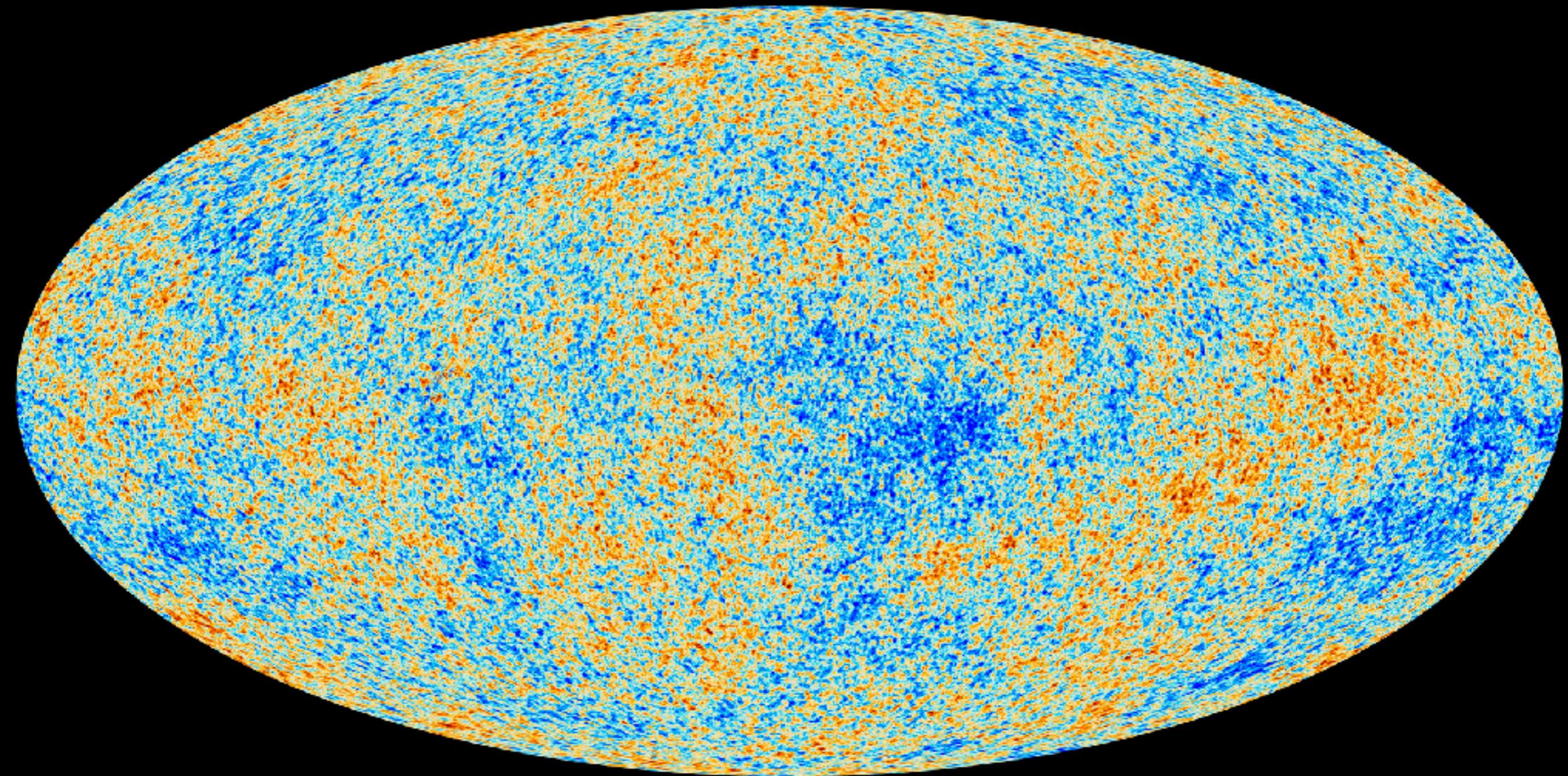
- Read material beforehand and e-mail at least 3 non-trivial questions before **Tuesday @ 13:00**  
**email to tutors; use subject heading [Nuc]** **25%**
- Lectures and Exercises (compulsory attendance) **25%**
- Student presentations on nucleosynthesis papers  
check website for paper suggestions **50%**

## Overview

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

|  |                 |
|--|-----------------|
| • <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>  |
| <br>   |                 |
| <b>Paper presentations I</b>   | <b>June 21</b>  |
| <b>Paper presentations II</b>  | <b>June 27</b>  |

# Overview



# Overview



# Chemical elements

|  |  |                                       |  |  |   |   |  |   |   |  |  |   |  |   |  |   |  |                   |
|--|--|---------------------------------------|--|--|---|---|--|---|---|--|--|---|--|---|--|---|--|-------------------|
| 1<br>IA<br>1A                          | <b>H</b><br>Hydrogen<br>1.001          | 2<br>IIA<br>2A                        | 3<br>Li<br>Lithium<br>6.941                | 4<br>Be<br>Beryllium<br>9.032          | 5<br>VB<br>5B                           | 6<br>VIB<br>6B                          | 7<br>VIIIB<br>7B                       | 8                                       | 9<br>VIII<br>8                            | 10                                       | 11<br>IB<br>1B                           | 12<br>IIB<br>2B                           | 13<br>IIIA<br>3A                       | 14<br>IVA<br>4A                             | 15<br>VA<br>5A                             | 16<br>VIA<br>6A                             | 17<br>VIIA<br>7A                           | 18<br>VIIIA<br>8A |
| 11<br><b>Na</b><br>Sodium<br>22.990    | 12<br><b>Mg</b><br>Magnesium<br>24.305 | 3<br>IIIB<br>3B                       | 4<br>IVB<br>4B                             | 5<br>VB<br>5B                          | 6<br>VIB<br>6B                          | 7<br>VIIIB<br>7B                        | 8                                      | 9<br>VIII<br>8                          | 10  | 11<br>IB<br>1B                           | 12<br>IIB<br>2B                          | 13<br>Al<br>Aluminum<br>26.982            | 14<br>Si<br>Silicon<br>28.085          | 15<br>P<br>Phosphorus<br>30.974             | 16<br>S<br>Sulfur<br>32.065                | 17<br>Cl<br>Chlorine<br>35.453              | 18<br>Ar<br>Argon<br>39.949                |                   |
| 19<br><b>K</b><br>Potassium<br>39.090  | 20<br><b>Ca</b><br>Calcium<br>40.070   | 21<br><b>Sc</b><br>Scandium<br>44.956 | 22<br><b>Ti</b><br>Titanium<br>47.867      | 23<br><b>V</b><br>Vanadium<br>50.942   | 24<br><b>Cr</b><br>Chromium<br>51.980   | 25<br><b>Mn</b><br>Manganese<br>54.938  | 26<br><b>Fe</b><br>Iron<br>55.845      | 27<br><b>Co</b><br>Cobalt<br>58.933     | 28<br><b>Ni</b><br>Nickel<br>58.693       | 29<br><b>Cu</b><br>Copper<br>63.546      | 30<br><b>Zn</b><br>Zinc<br>65.38         | 31<br><b>Ga</b><br>Gallium<br>69.720      | 32<br><b>Ge</b><br>Germanium<br>72.031 | 33<br><b>As</b><br>Arsenic<br>74.922        | 34<br><b>Se</b><br>Selenium<br>78.971      | 35<br><b>Br</b><br>Bromine<br>79.904        | 36<br><b>Kr</b><br>Krypton<br>83.798       |                   |
| 37<br><b>Rb</b><br>Rubidium<br>64.466  | 38<br><b>Sr</b><br>Strontium<br>69.983 | 39<br><b>Y</b><br>Yttrium<br>88.906   | 40<br><b>Zr</b><br>Zirconium<br>91.224     | 41<br><b>Nb</b><br>Niobium<br>92.906   | 42<br><b>Mo</b><br>Molybdenum<br>95.925 | 43<br><b>Tc</b><br>Technetium<br>98.907 | 44<br><b>Ru</b><br>Ruthenium<br>101.07 | 45<br><b>Rh</b><br>Rhodium<br>102.906   | 46<br><b>Pd</b><br>Palladium<br>106.42    | 47<br><b>Ag</b><br>Silver<br>107.86      | 48<br><b>Cd</b><br>Cadmium<br>112.414    | 49<br><b>In</b><br>Indium<br>114.016      | 50<br><b>Sn</b><br>Tin<br>118.711      | 51<br><b>Sb</b><br>Antimony<br>121.760      | 52<br><b>Te</b><br>Tellurium<br>127.6      | 53<br><b>I</b><br>Iodine<br>126.904         | 54<br><b>Xe</b><br>Xenon<br>131.296        |                   |
| 55<br><b>Cs</b><br>Cesium<br>132.905   | 56<br><b>Ba</b><br>Barium<br>137.329   | 57-71                                 | 72<br><b>Hf</b><br>Hafnium<br>178.49       | 73<br><b>Ta</b><br>Tantalum<br>180.949 | 74<br><b>W</b><br>Tungsten<br>183.84    | 75<br><b>Re</b><br>Rhenium<br>186.217   | 76<br><b>Os</b><br>Osmium<br>190.23    | 77<br><b>Ir</b><br>Iridium<br>192.217   | 78<br><b>Pt</b><br>Platinum<br>195.065    | 79<br><b>Au</b><br>Gold<br>196.967       | 80<br><b>Hg</b><br>Mercury<br>204.592    | 81<br><b>Tl</b><br>Thallium<br>204.383    | 82<br><b>Pb</b><br>Lead<br>207.2       | 83<br><b>Bi</b><br>Bismuth<br>208.900       | 84<br><b>Po</b><br>Polonium<br>209.903     | 85<br><b>At</b><br>Astatine<br>209.907      | 86<br><b>Rn</b><br>Radon<br>222.010        |                   |
| 87<br><b>Fr</b><br>Francium<br>223.020 | 88<br><b>Ra</b><br>Radium<br>226.025   | 89-103                                | 104<br><b>Rf</b><br>Rutherfordium<br>(261) | 105<br><b>Db</b><br>Dubnium<br>(262)   | 106<br><b>Sg</b><br>Seaborgium<br>(265) | 107<br><b>Bh</b><br>Bohrium<br>(264)    | 108<br><b>Hs</b><br>Hassium<br>(269)   | 109<br><b>Mt</b><br>Mertensium<br>(266) | 110<br><b>Ds</b><br>Darmstadtium<br>(268) | 111<br><b>Rg</b><br>Roentgenium<br>(270) | 112<br><b>Cn</b><br>Copernicium<br>(272) | 113<br><b>Uut</b><br>Ununtrium<br>unknown | 114<br><b>Fl</b><br>Florium<br>unknown | 115<br><b>Uup</b><br>Ununpentium<br>unknown | 116<br><b>Lv</b><br>Livermorium<br>unknown | 117<br><b>Uus</b><br>Ununseptium<br>unknown | 118<br><b>Uuo</b><br>Ununoctium<br>unknown |                   |

Periodic Table of the Elements

|               |                |
|---------------|----------------|
| Atomic Number | Valence Charge |
| Symbol        | Name           |
| Atomic Mass   |                |

Lanthanide Series

|   |                                       |  |   |  |   |   |   |   |   |   |  |  |   |   |
|---|---------------------------------------|--|---|--|---|---|---|---|---|---|--|--|---|---|
| 57<br><b>La</b><br>Lanthanum<br>130.905 | 58<br><b>Ce</b><br>Cerium<br>140.110  | 59<br><b>Pr</b><br>Praseodymium<br>141.003 | 60<br><b>Nd</b><br>Neodymium<br>144.243 | 61<br><b>Pm</b><br>Promethium<br>147.913 | 62<br><b>Sm</b><br>Samarium<br>150.26   | 63<br><b>Eu</b><br>Europium<br>151.964  | 64<br><b>Gd</b><br>Gadolinium<br>157.25 | 65<br><b>Tb</b><br>Terbium<br>159.265   | 66<br><b>Dy</b><br>Dysprosium<br>162.500  | 67<br><b>Ho</b><br>Holmium<br>164.920   | 68<br><b>Er</b><br>Erbium<br>167.259   | 69<br><b>Tm</b><br>Thulium<br>169.924    | 70<br><b>Yb</b><br>Ytterbium<br>173.052 | 71<br><b>Lu</b><br>Lutetium<br>174.967  |
| 89<br><b>Ac</b><br>Actinium<br>227.020  | 90<br><b>Th</b><br>Thorium<br>232.030 | 91<br><b>Pa</b><br>Protactinium<br>231.020 | 92<br><b>U</b><br>Uranium<br>238.029    | 93<br><b>Np</b><br>Neptunium<br>239.029  | 94<br><b>Pu</b><br>Plutonium<br>244.024 | 95<br><b>Am</b><br>Americium<br>243.021 | 96<br><b>Cm</b><br>Curium<br>247.270    | 97<br><b>Bk</b><br>Berkelium<br>247.270 | 98<br><b>Cf</b><br>Californium<br>251.020 | 99<br><b>Es</b><br>Lanthanum<br>257.020 | 100<br><b>Fm</b><br>Fermium<br>257.025 | 101<br><b>Md</b><br>Mendelevium<br>259.1 | 102<br><b>No</b><br>Nobelium<br>259.101 | 103<br><b>Lr</b><br>Lawrencium<br>(260) |

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

Nonmetal

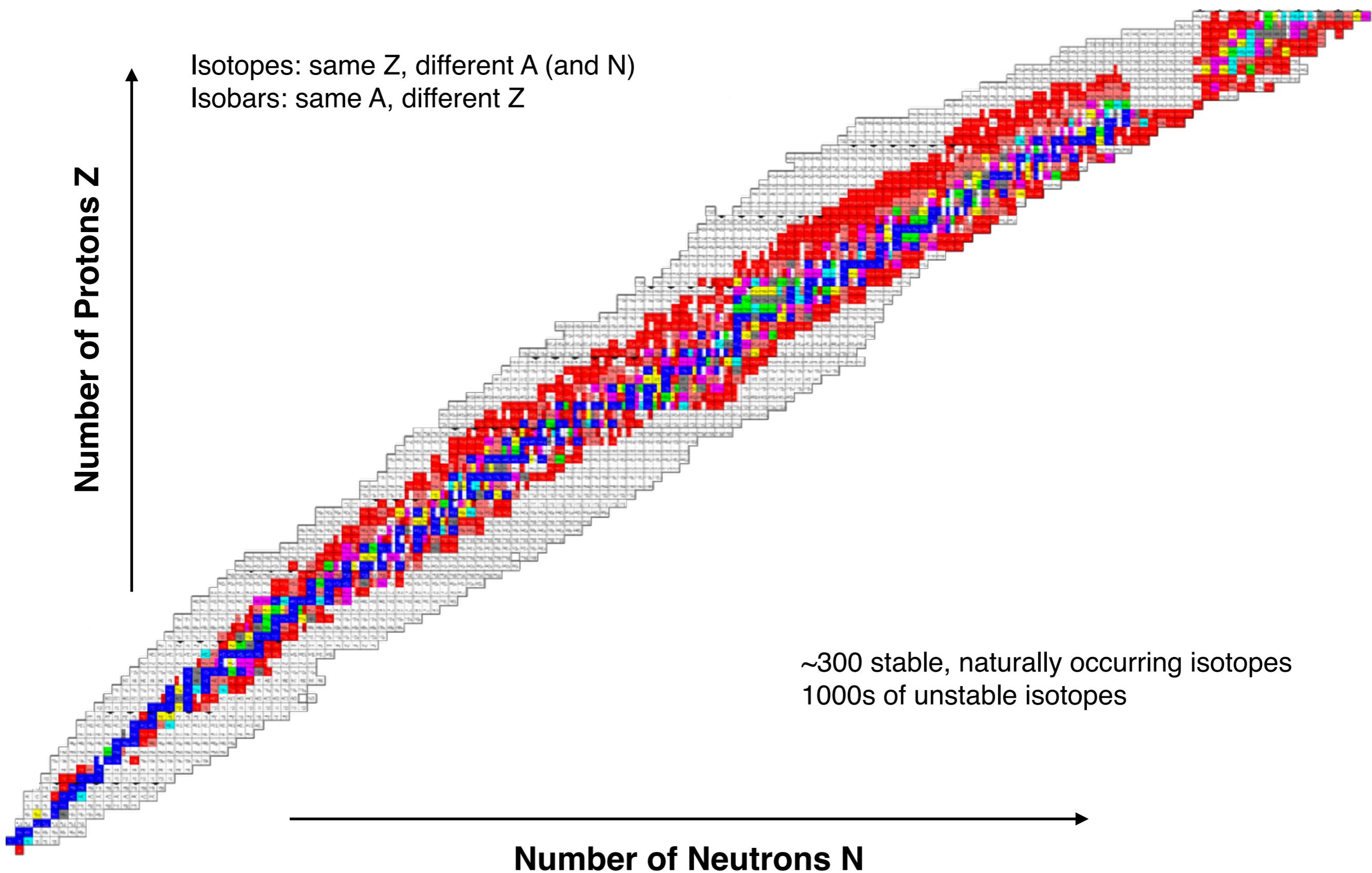
Halogen

Noble Gas

Lanthanide

Actinide

# Isotopes and isobars



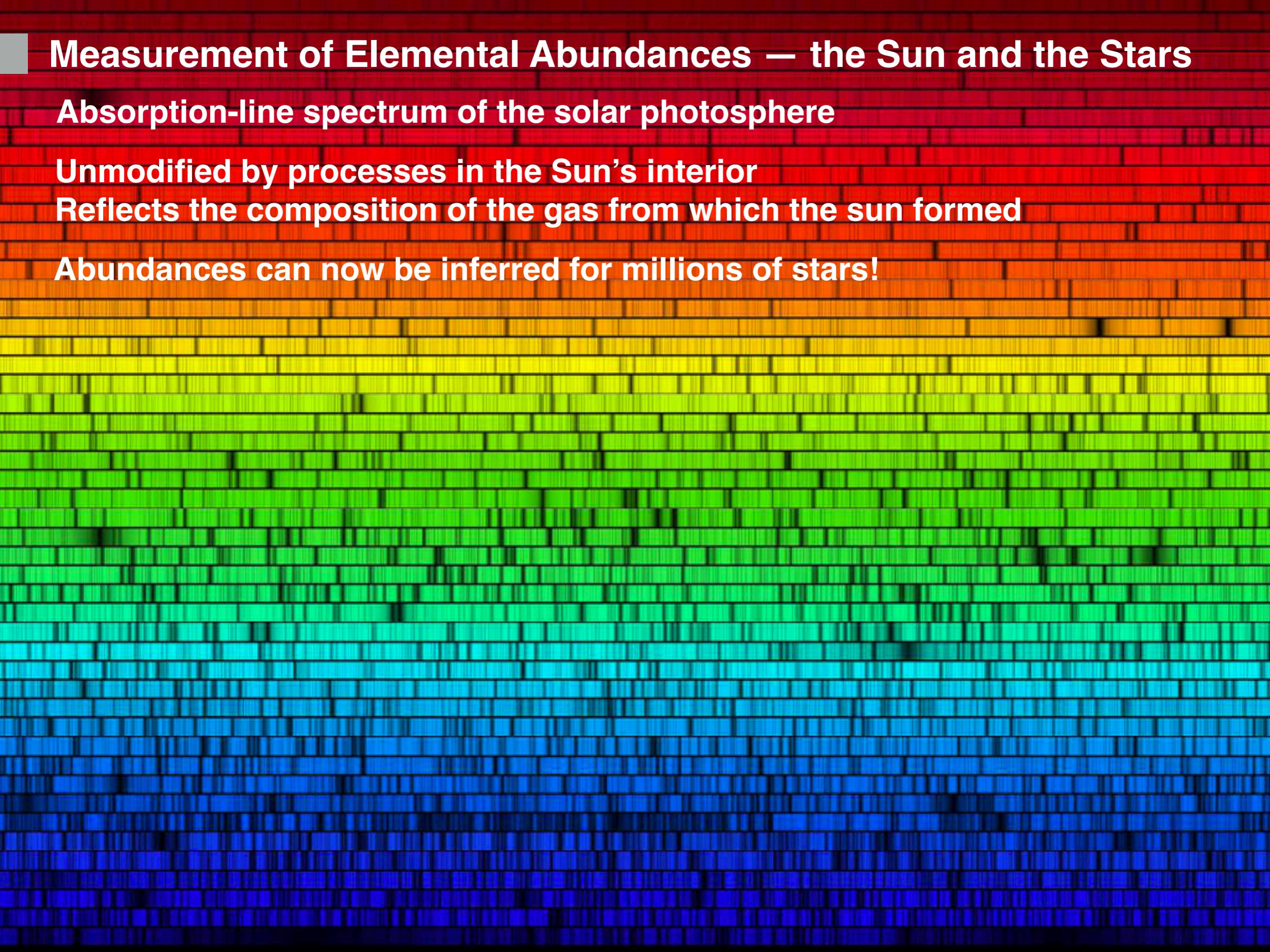
# Measurement of Elemental Abundances – the Sun and the Stars

**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

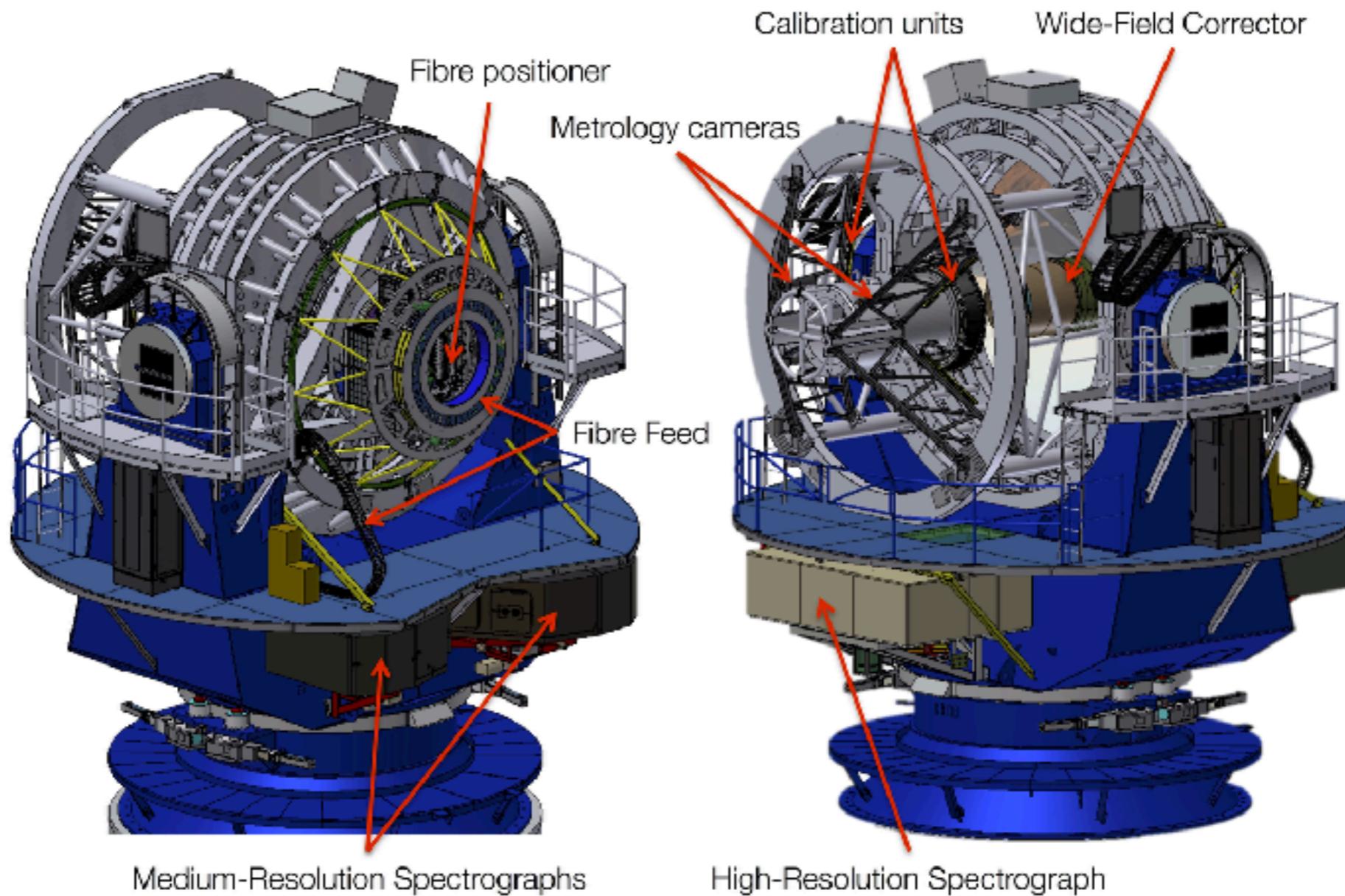
**“Metals”**

| Element   | Abundance (pct.<br>of total number<br>of atoms) | Abundance<br>(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

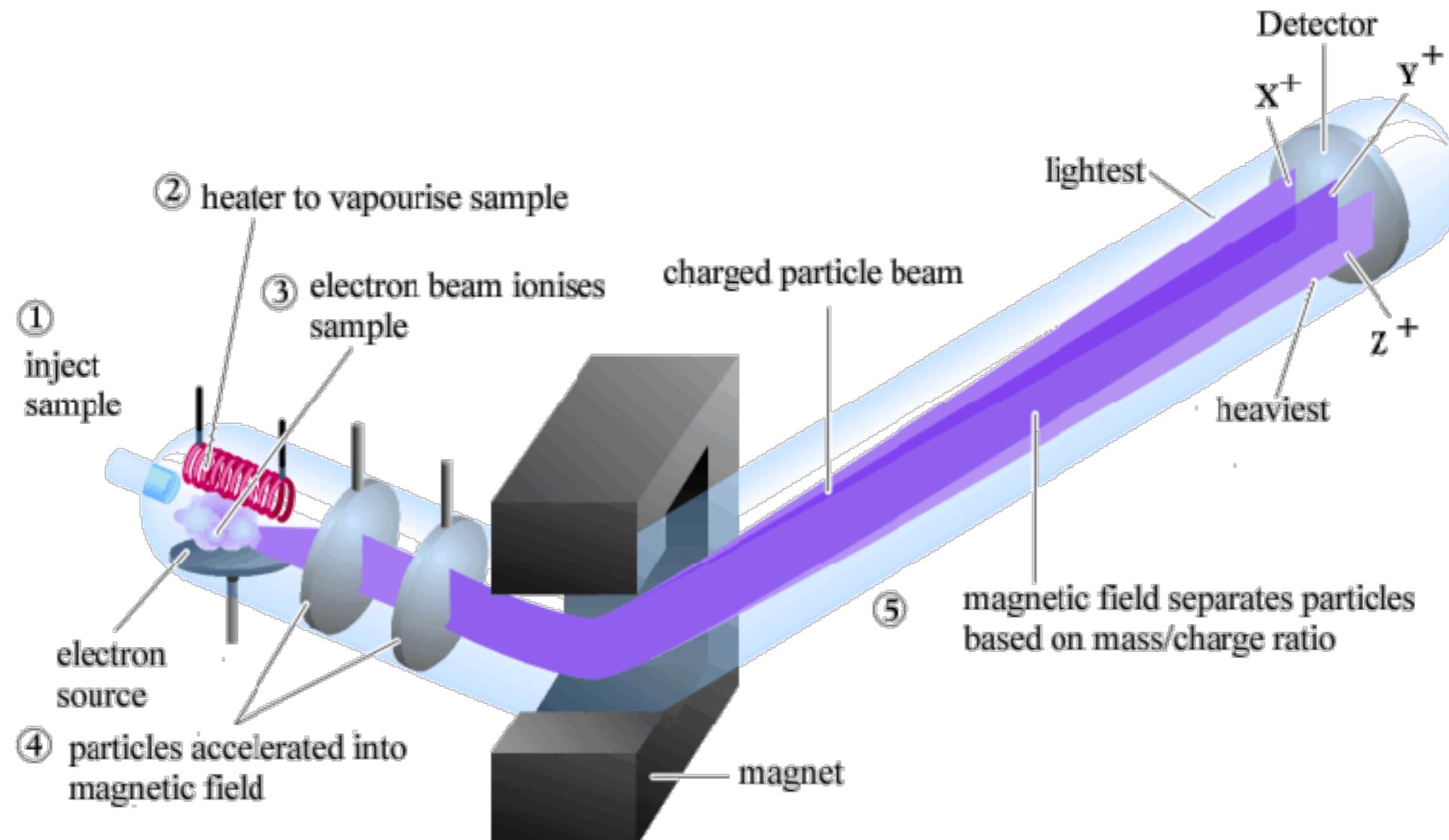
the 4MOST fibre-fed spectrograph for the 4m VISTA telescope

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

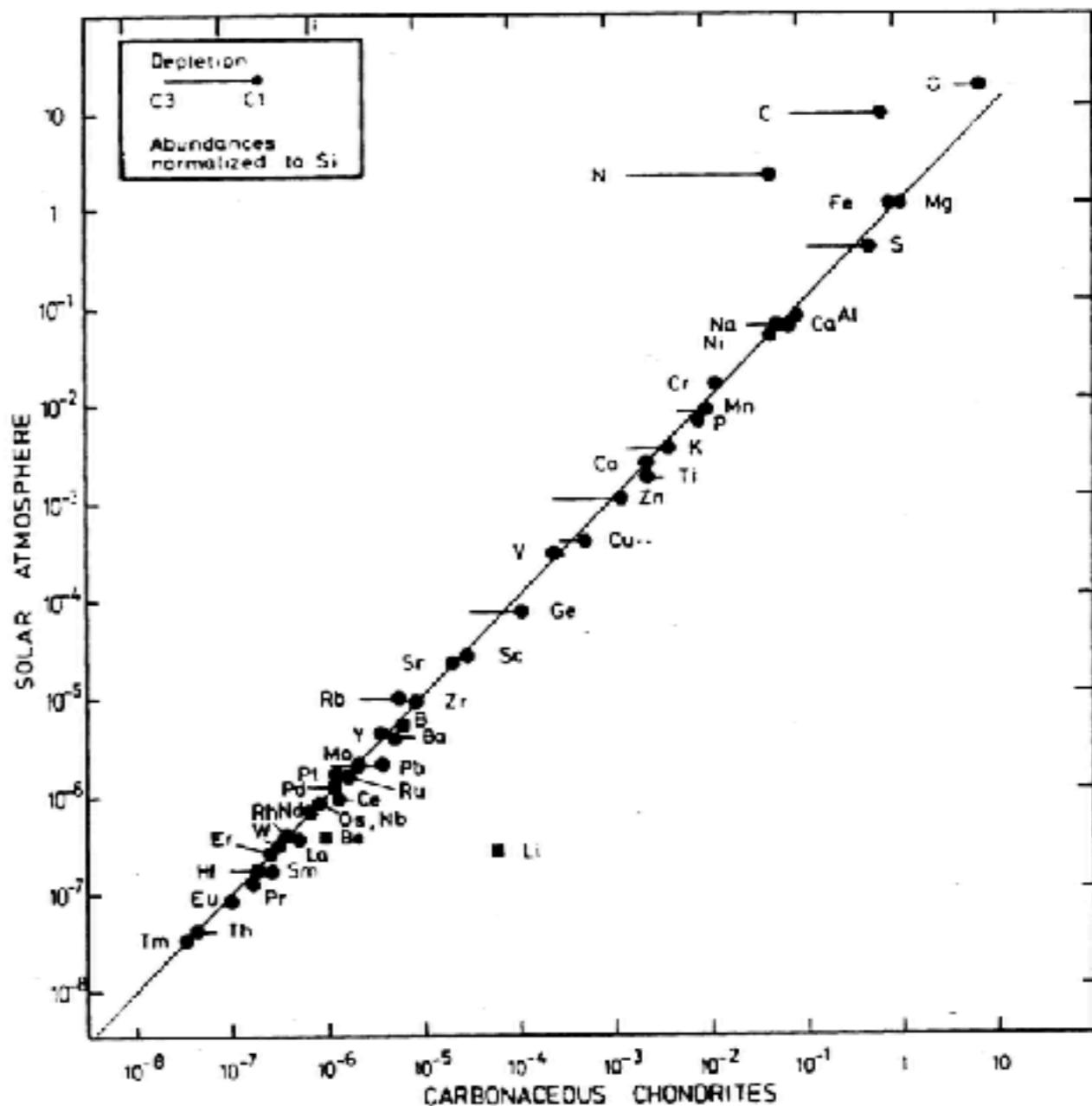


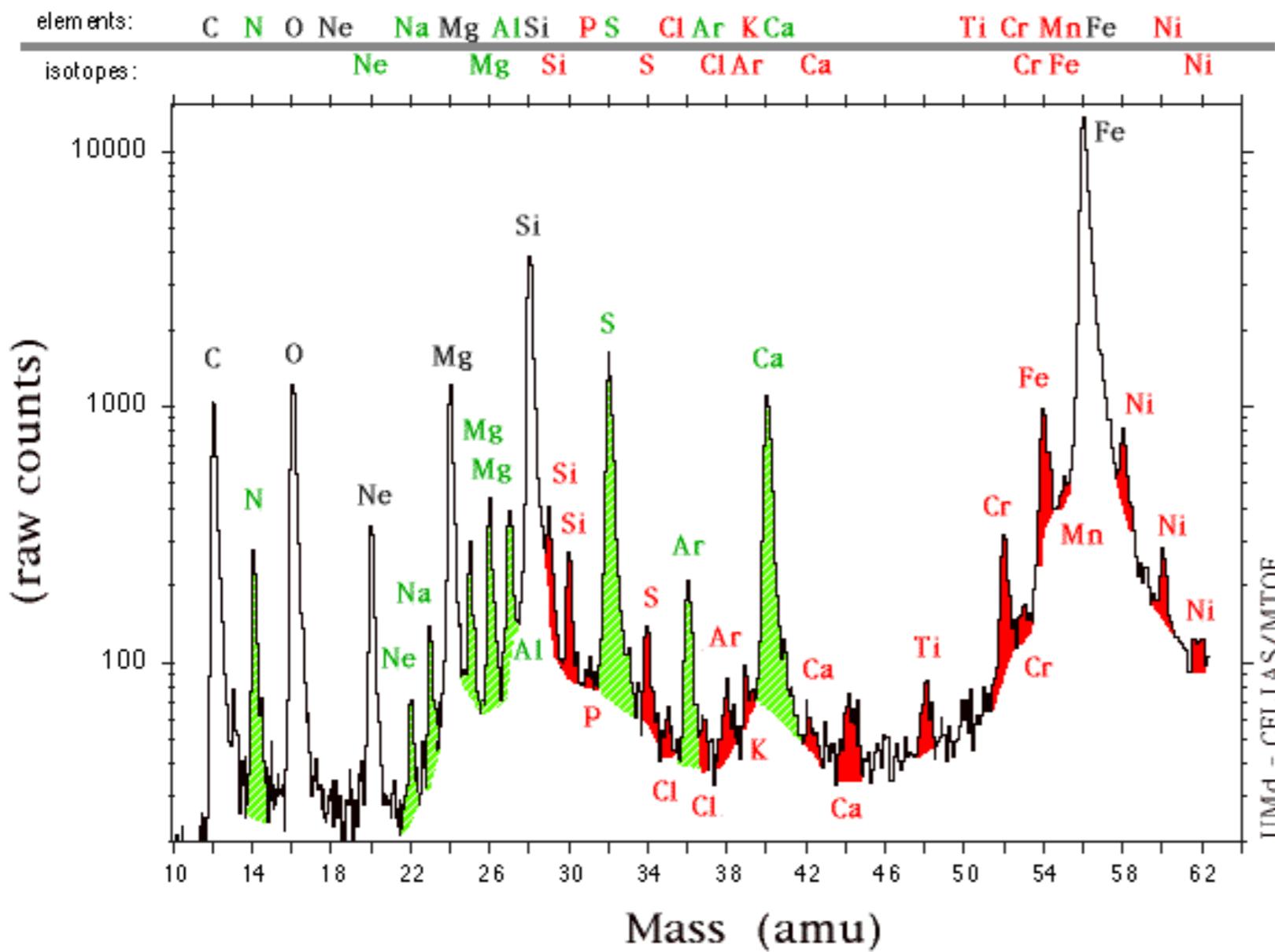
Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

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

# Measurement of Isotopic Abundances

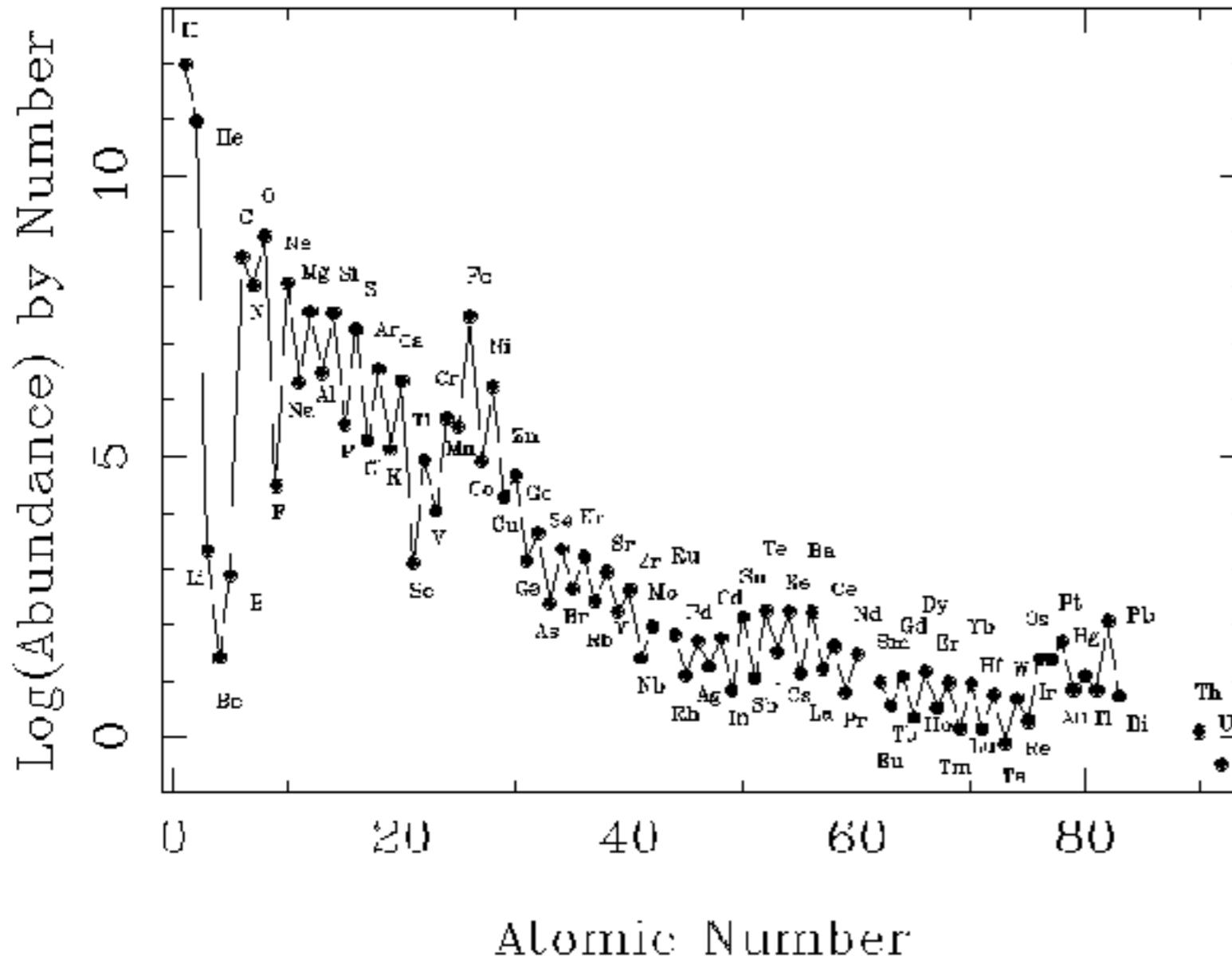
## Isotope abundances in the solar system

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

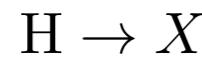
$$N_i = X_i/A_i$$

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

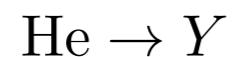
$$A_{\text{H}} = \log(N_{\text{H}}) = 12$$

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

### By mass fraction



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



$$X + Y + Z = 1$$



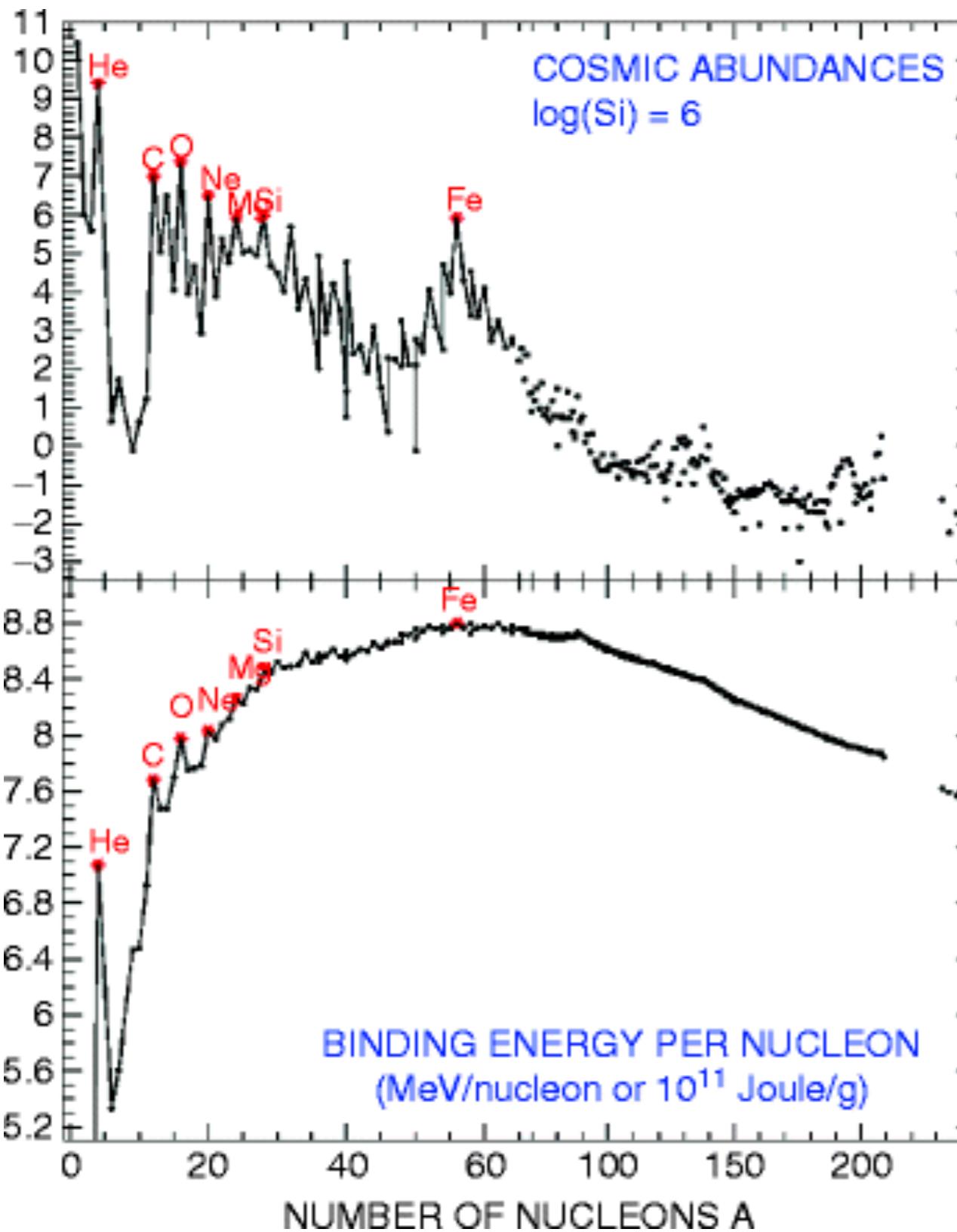
$$\sum X_i = 1$$

### 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**

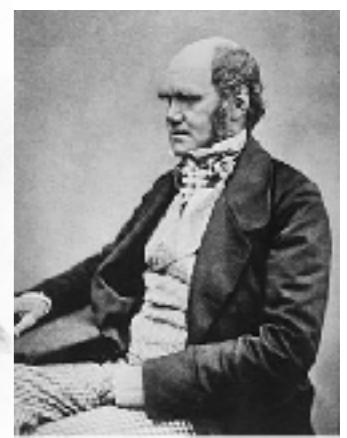
**Before early 30s: Can nuclear reactions take place inside the Sun and the stars?**

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

**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?

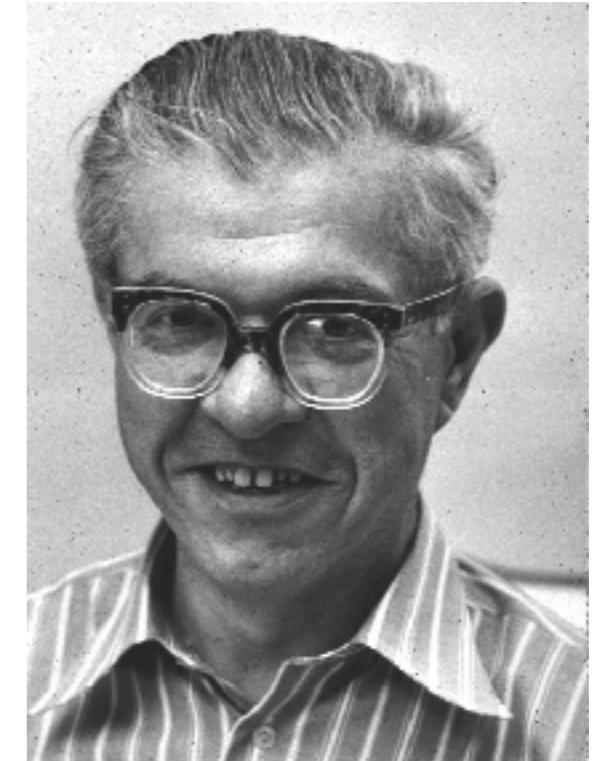
Debate in the 40s: Primordial or Big-bang nucleosynthesis vs stars and supernovae



**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**

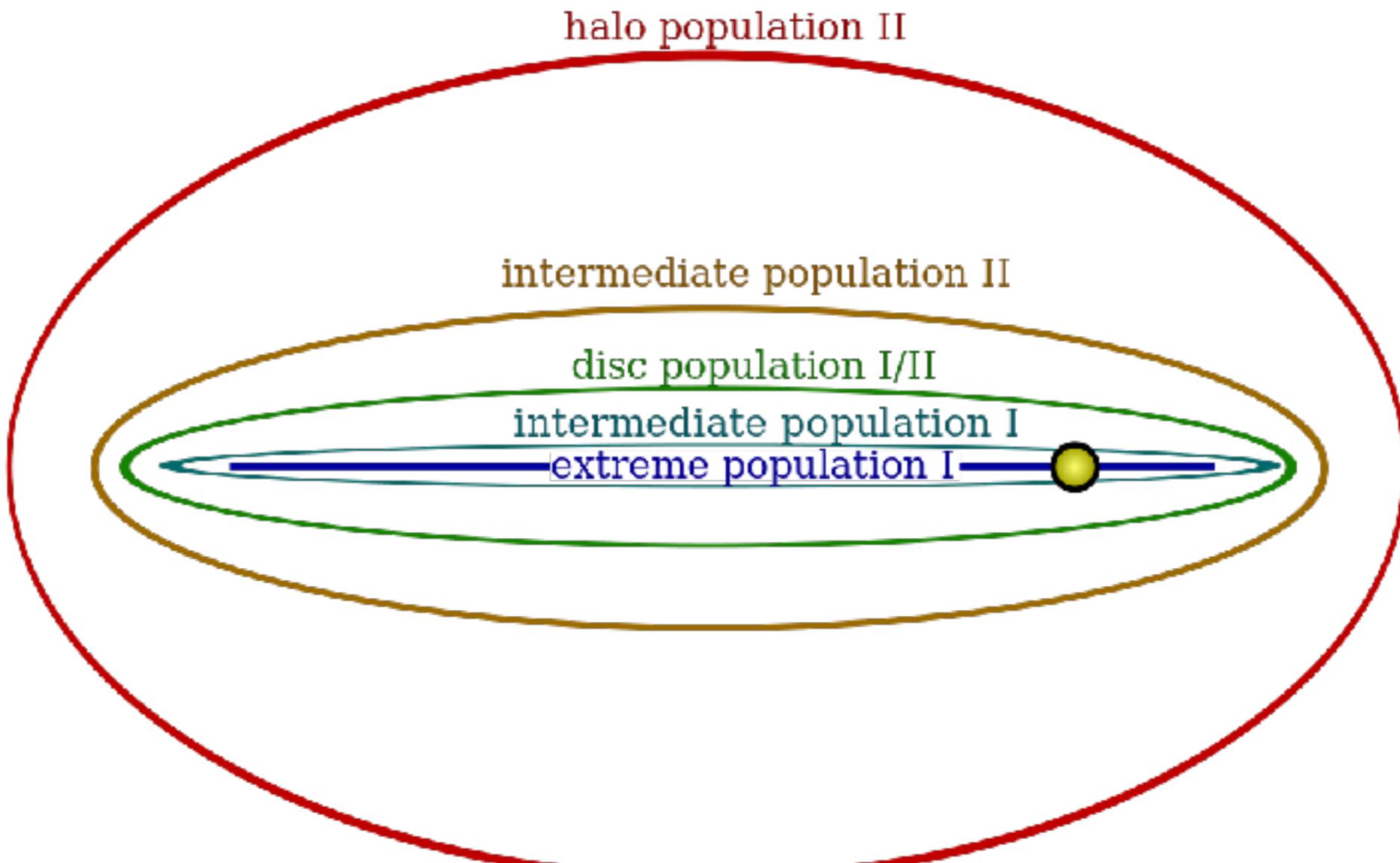


**Fred Hoyle (1915–2001)**

Elements created in stars and supernovae

## Observational evidence for nucleosynthesis

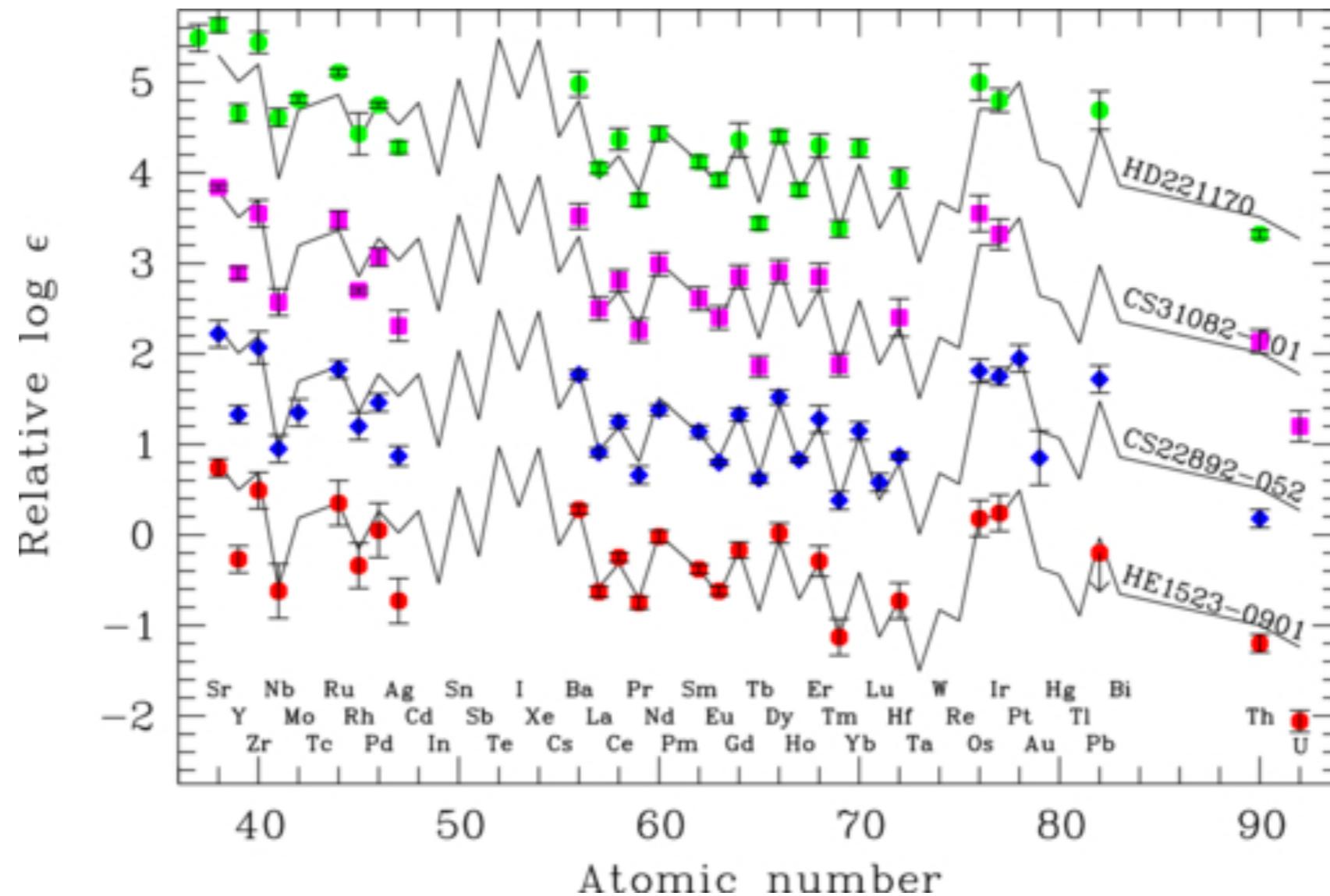
In early 50s: evidence for evolution of abundances with cosmic time  
Stars near the galactic disk have higher metallicities than stars in the halo



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

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VOLUME 29, NUMBER 4

OCTOBER, 1957

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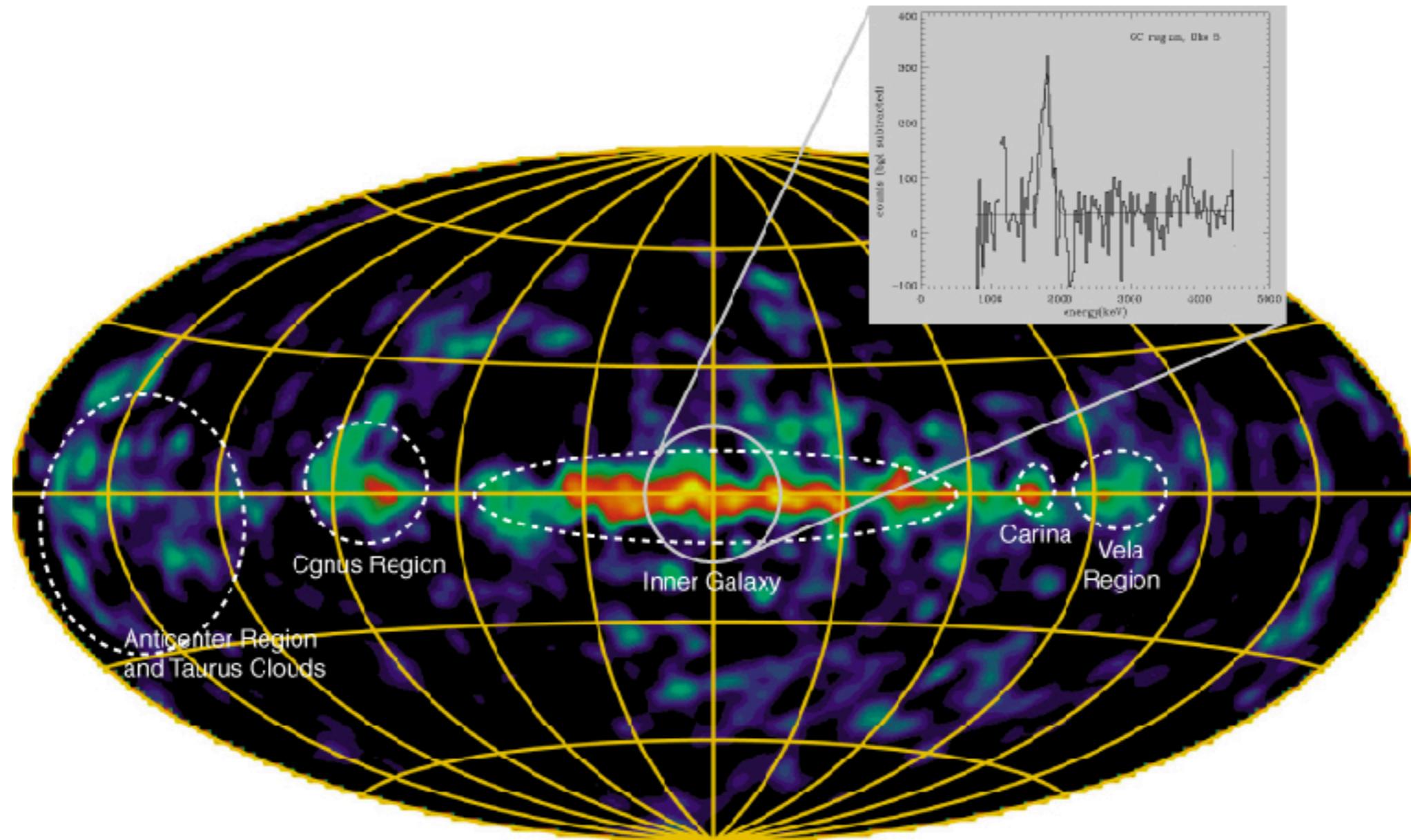
**Synthesis of the Elements in Stars\***

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



# Modern observational evidence for nucleosynthesis

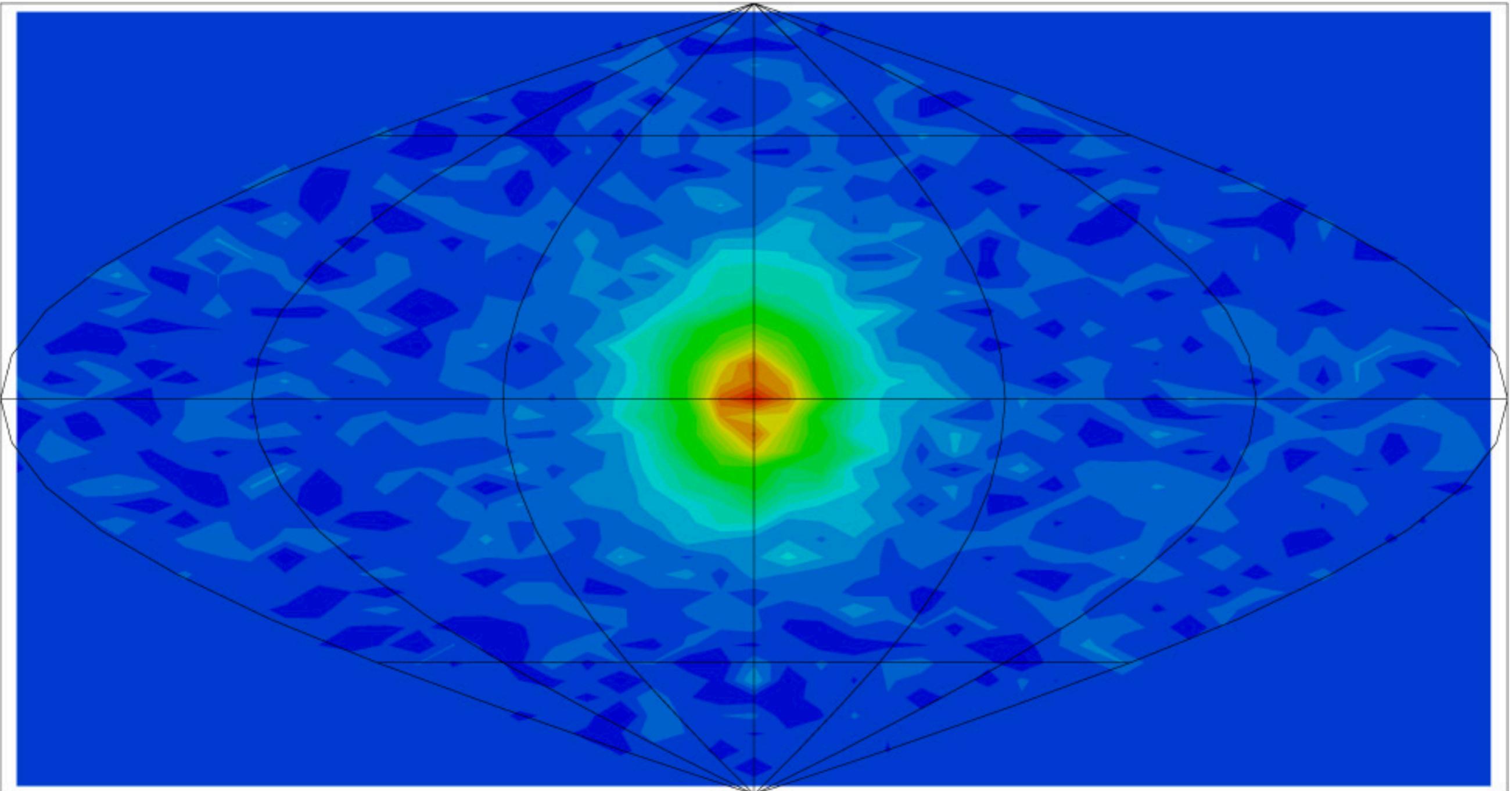
## More (in)direct evidence for ongoing nucleosynthesis



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



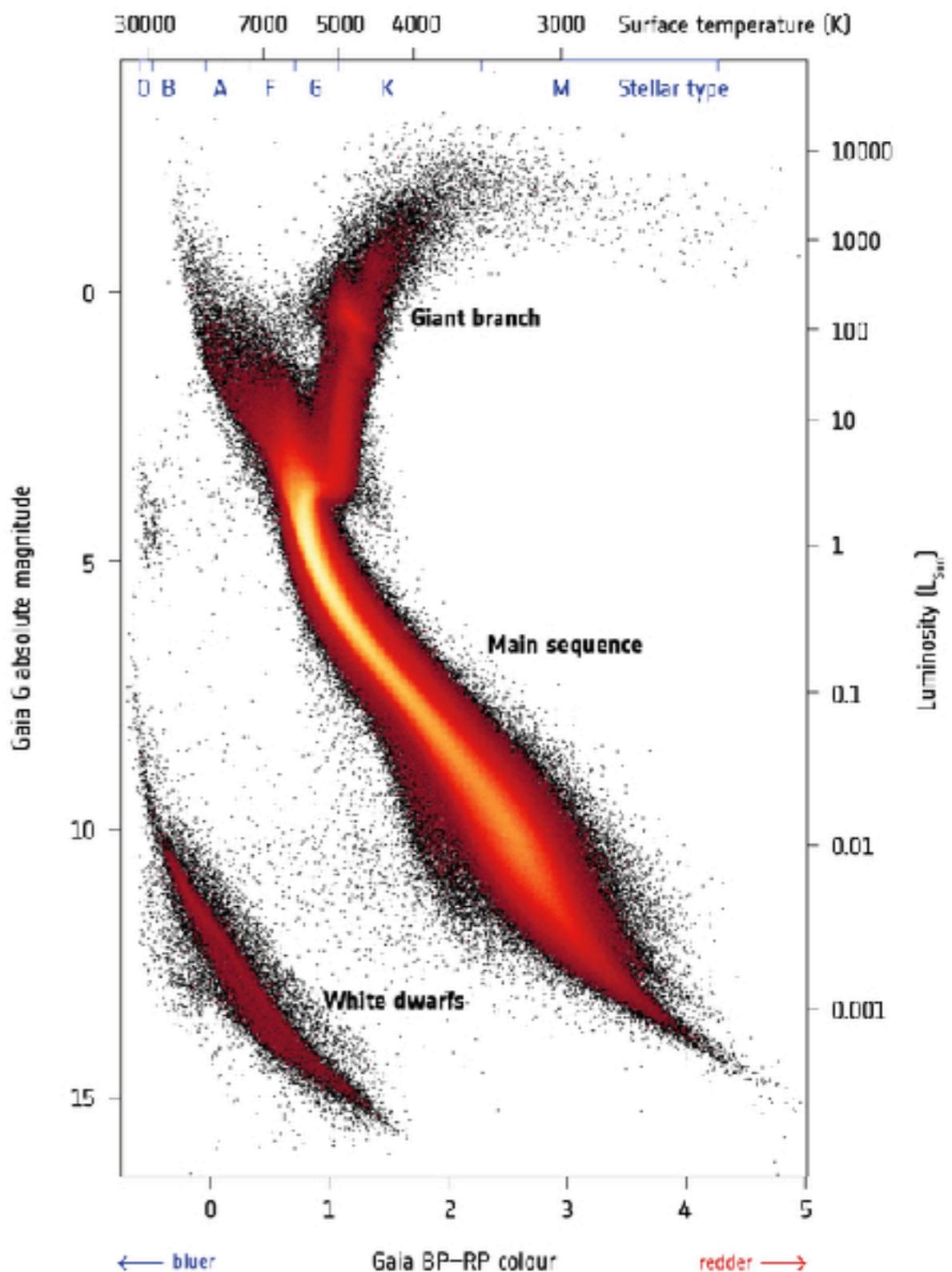
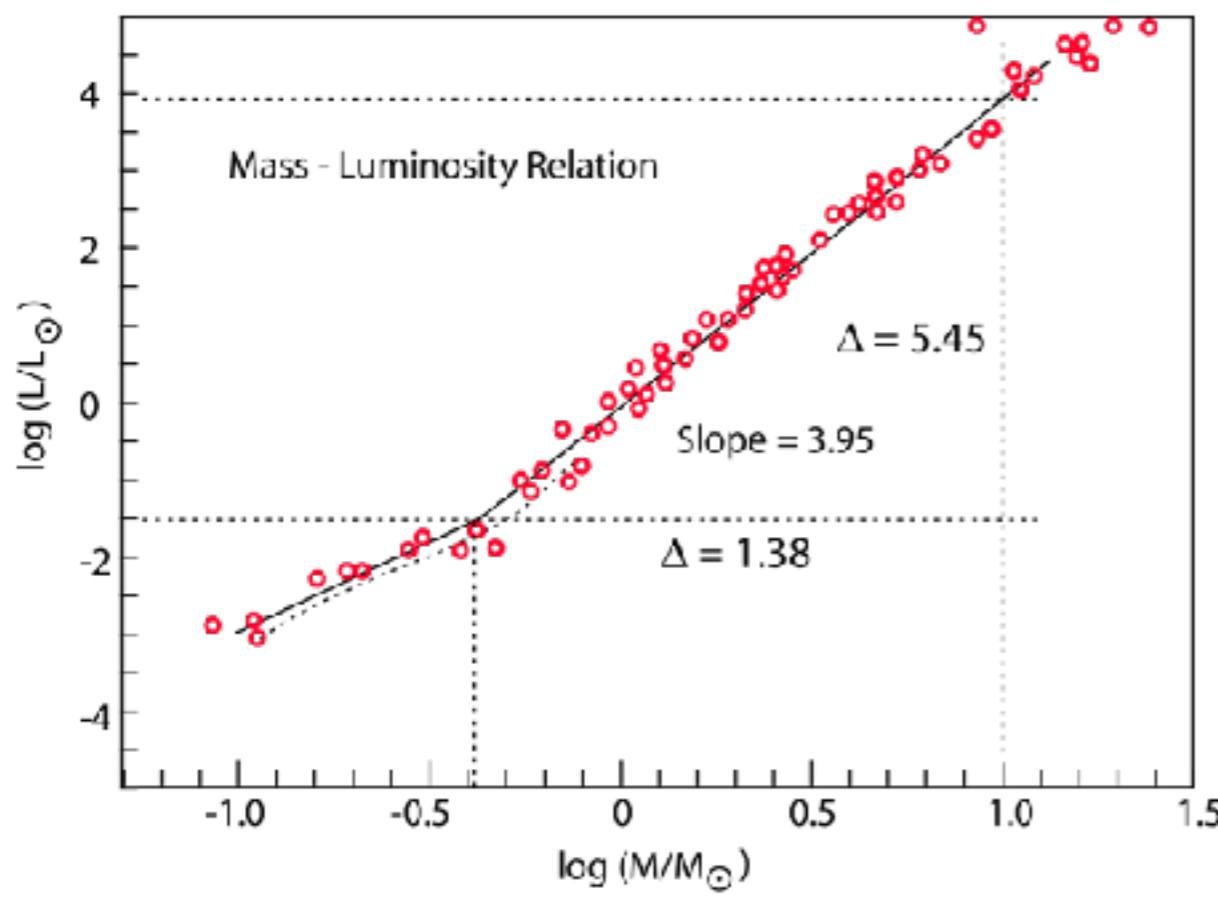
example 2: observation of solar neutrinos

# Thermonuclear reactions

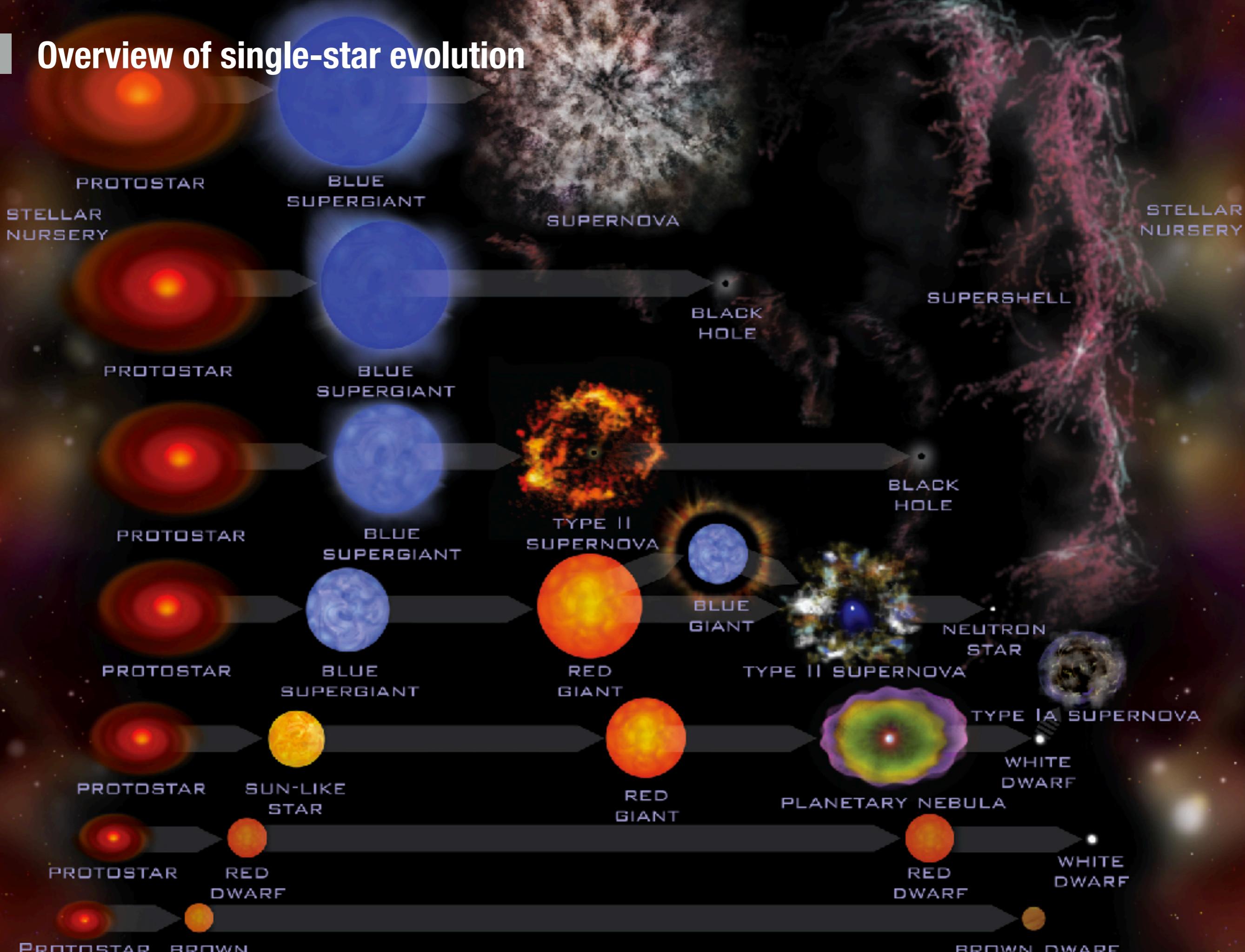
→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

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



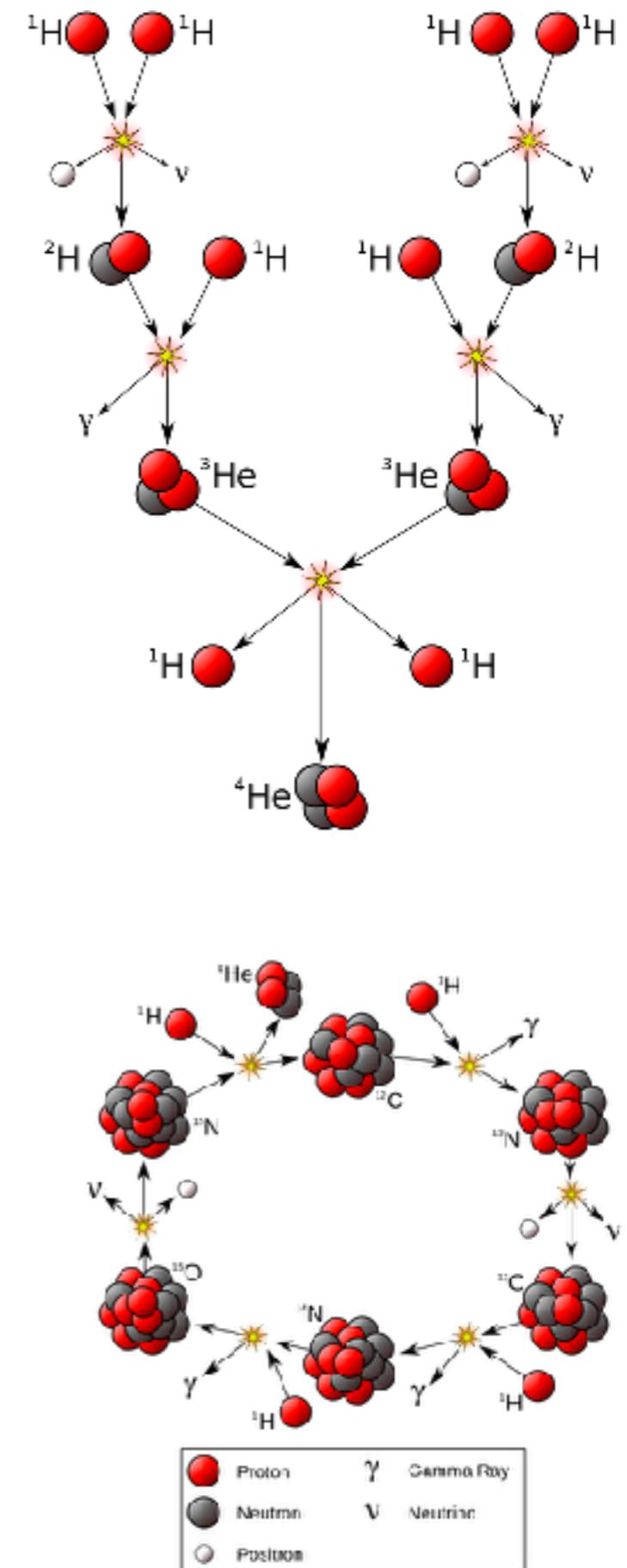
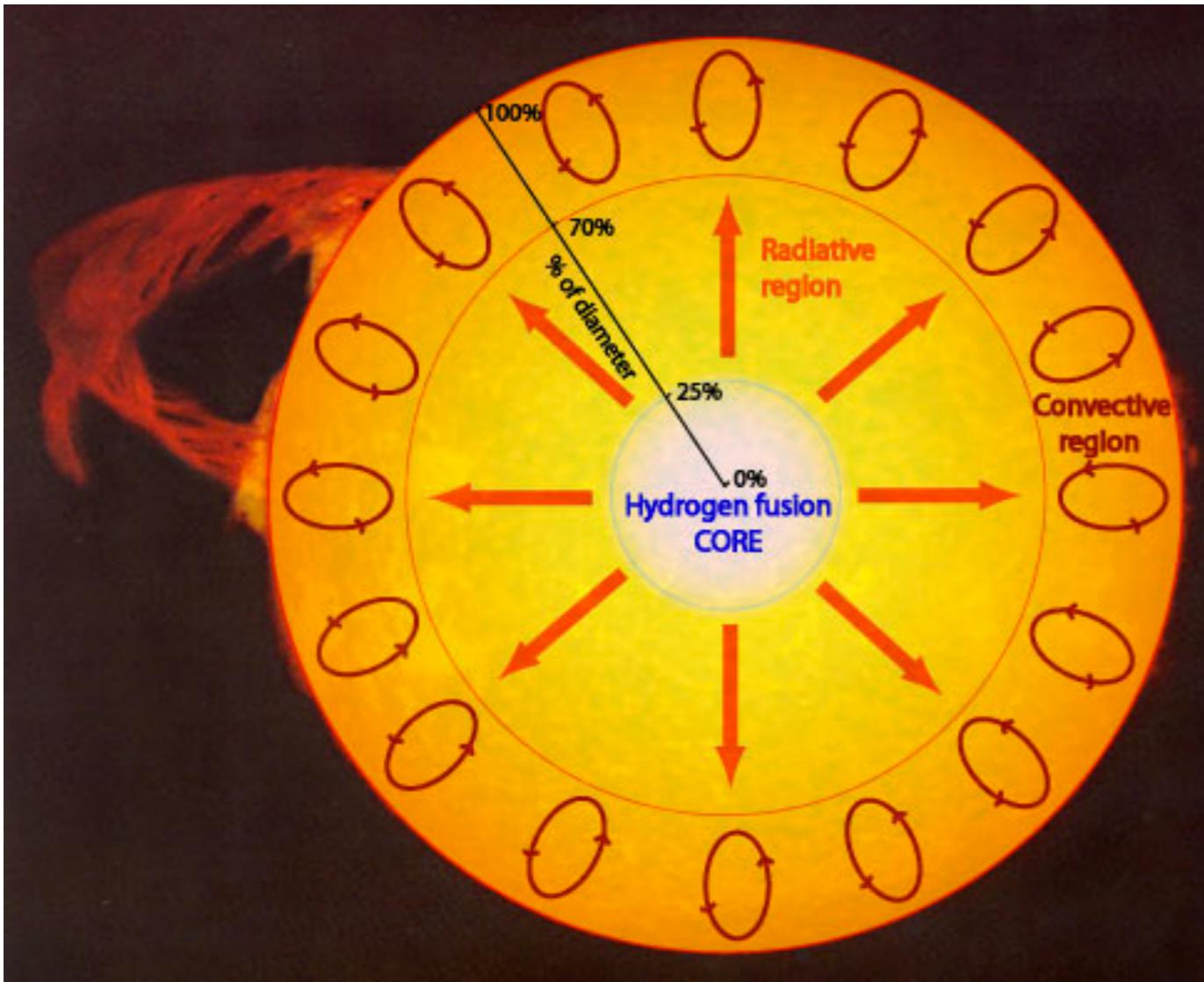
# Overview of single-star evolution

Mass (Solar masses)

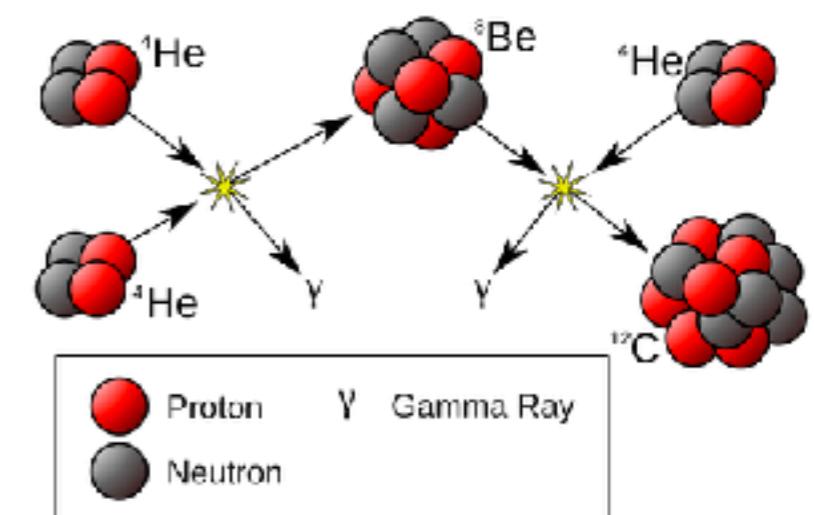
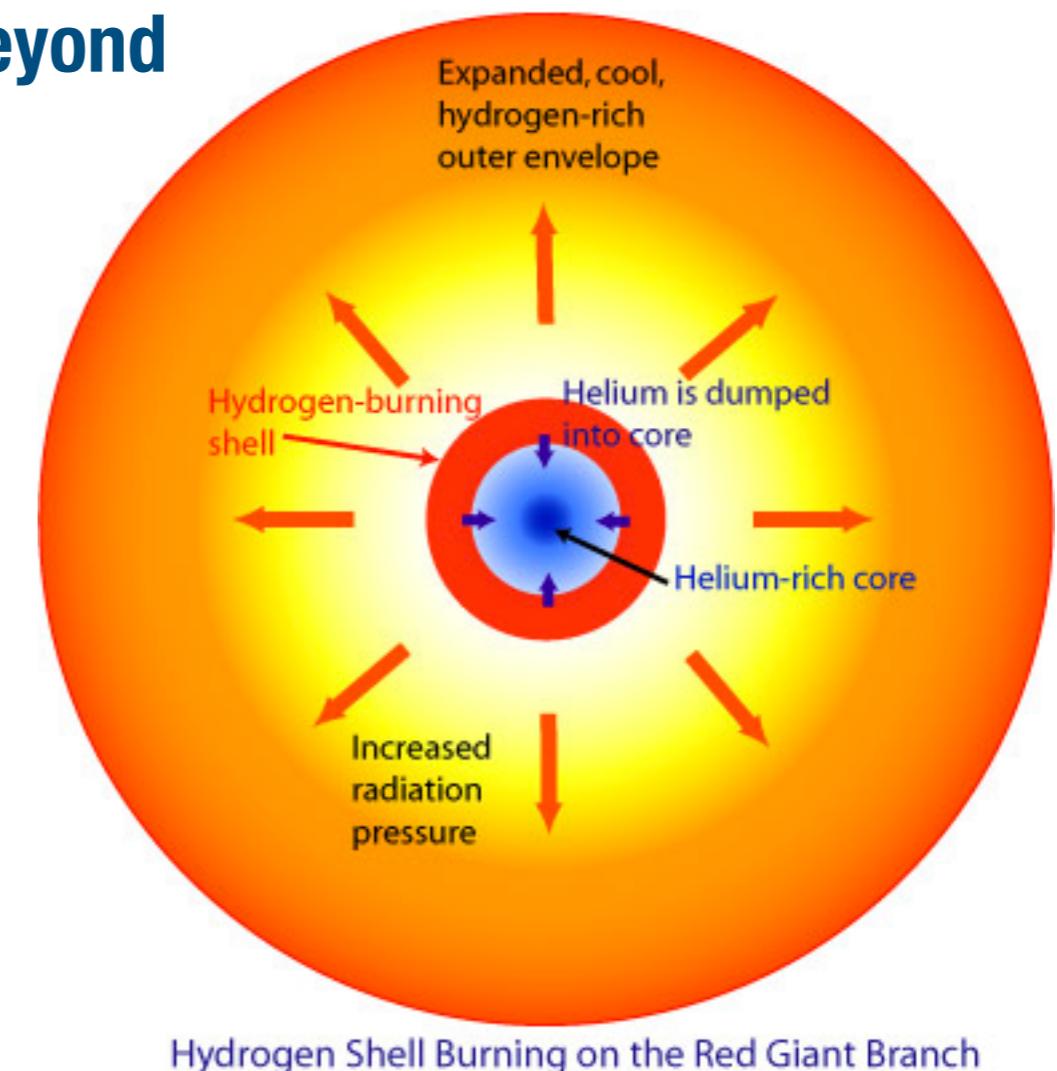
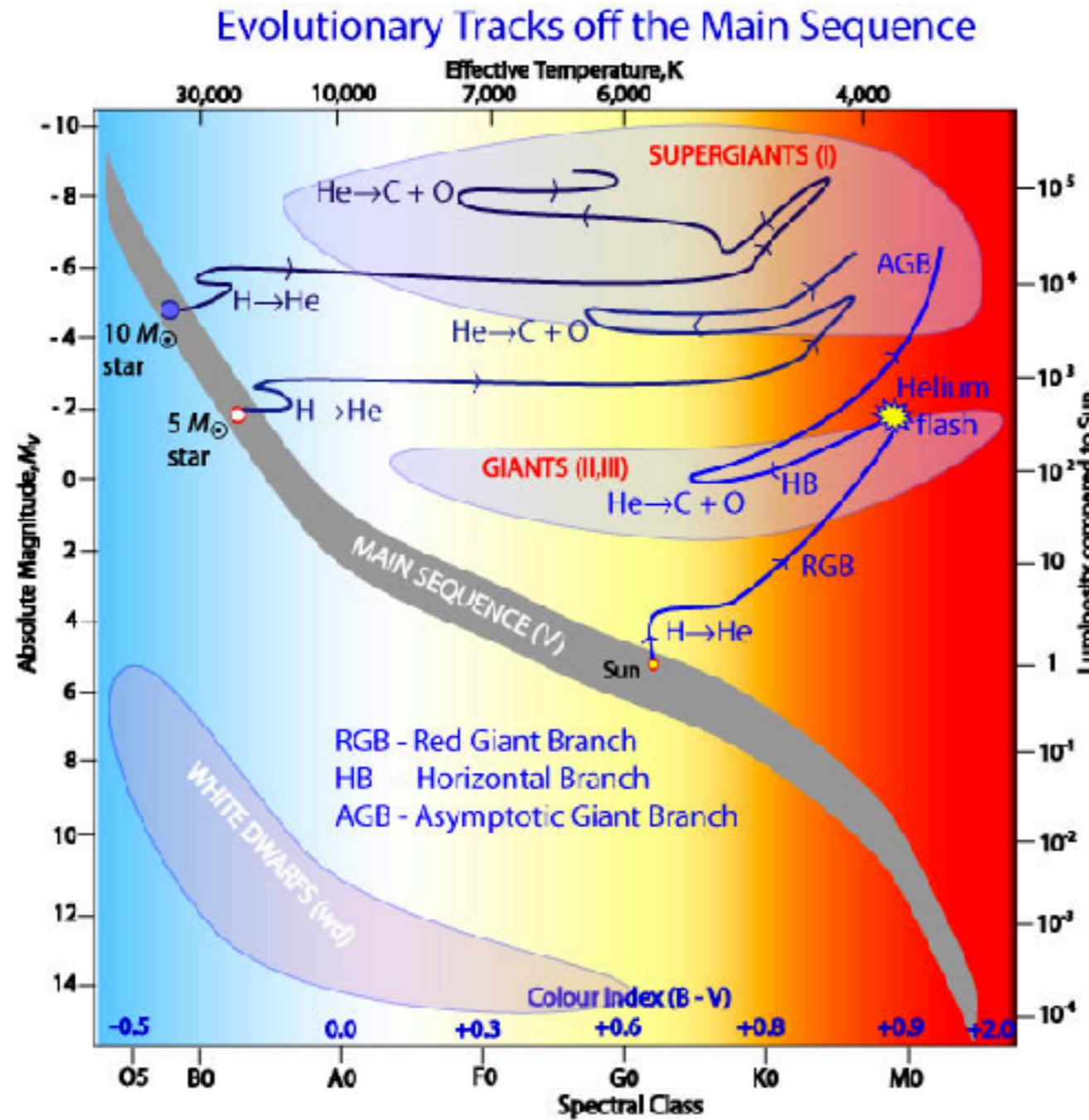
|                        |             |           |              |                    |                    |                        |                               |                   |             |                |
|------------------------|-------------|-----------|--------------|--------------------|--------------------|------------------------|------------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

# Hydrogen burning

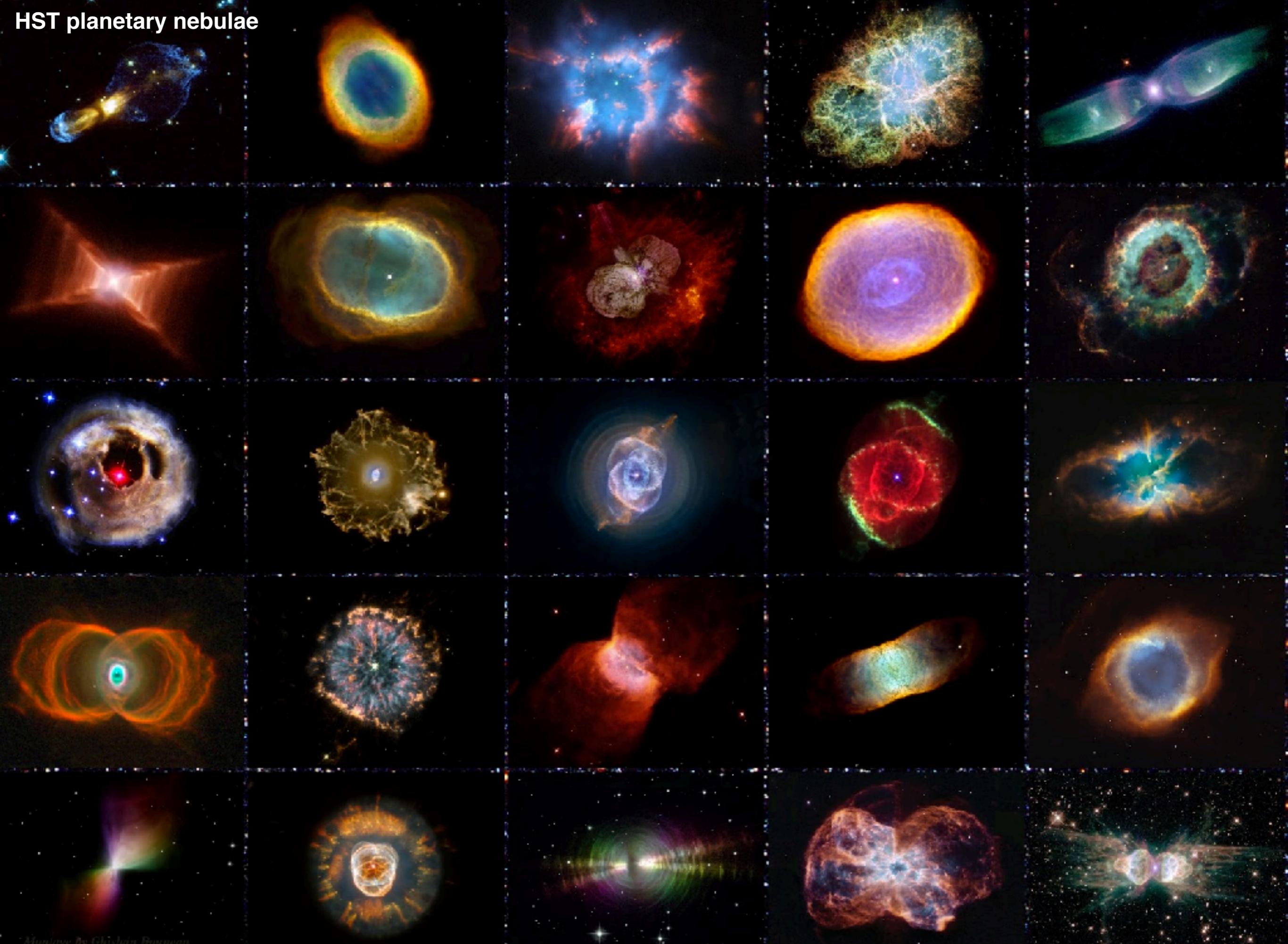
Starts on the main sequence  
via pp (low mass) and CNO (high mass) chains



# Helium burning on the red giant branch and beyond

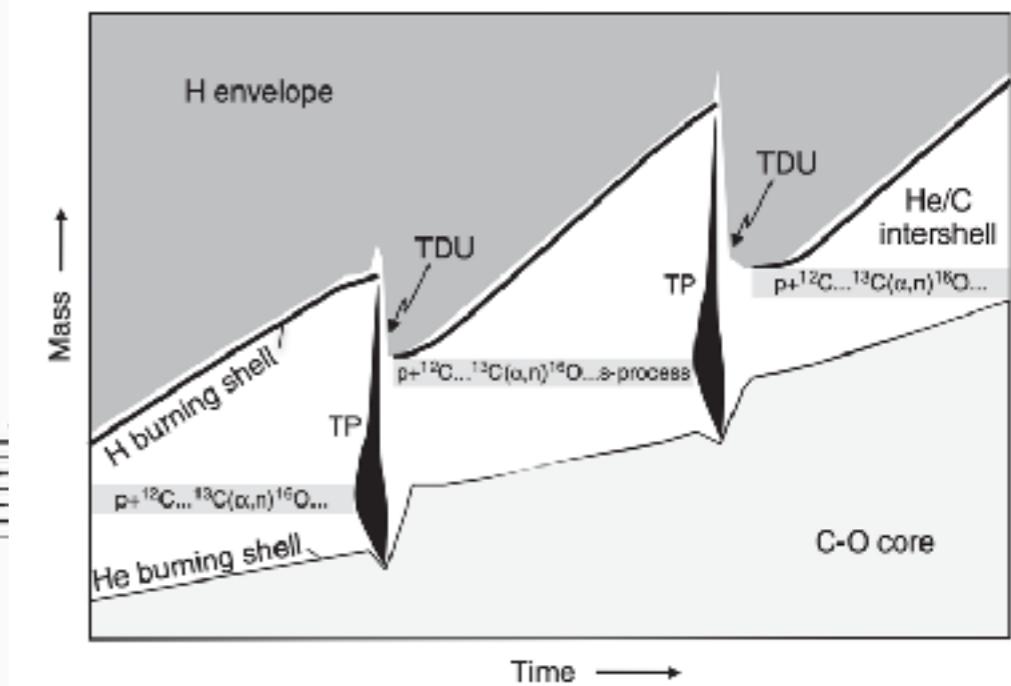
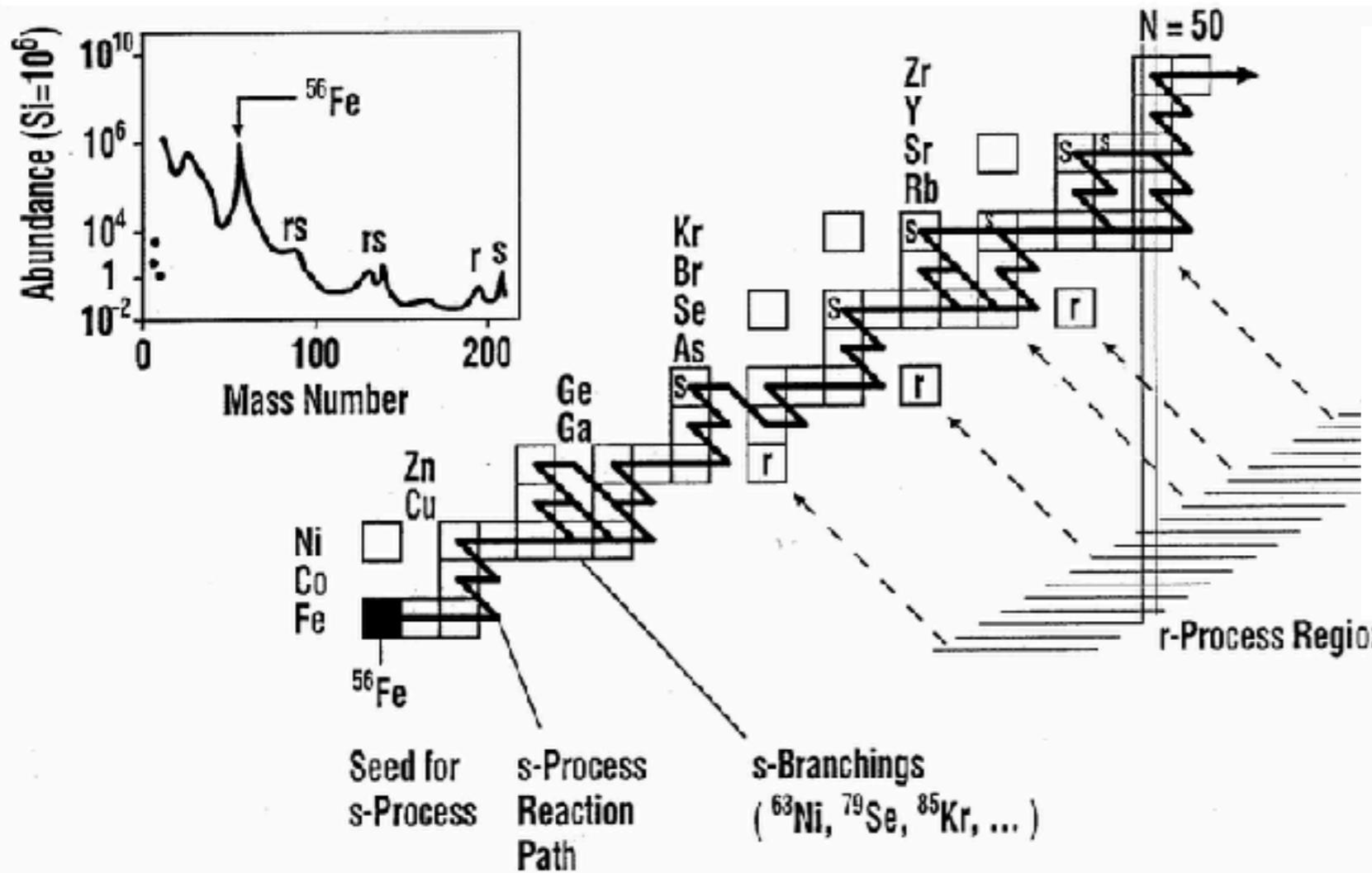
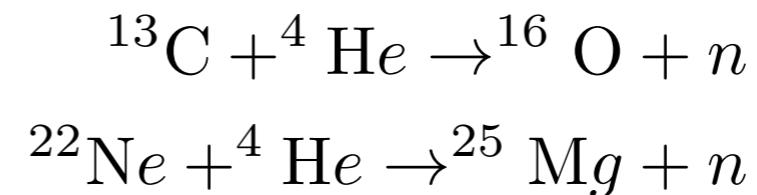


# HST planetary nebulae

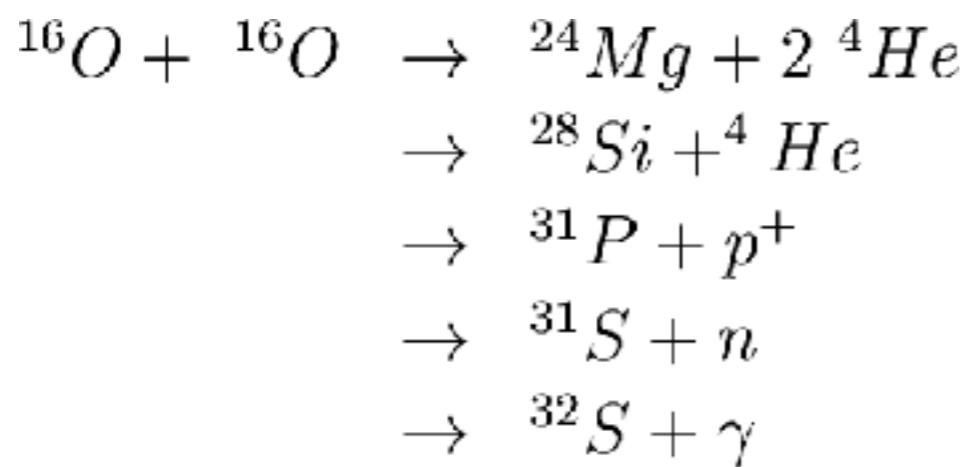
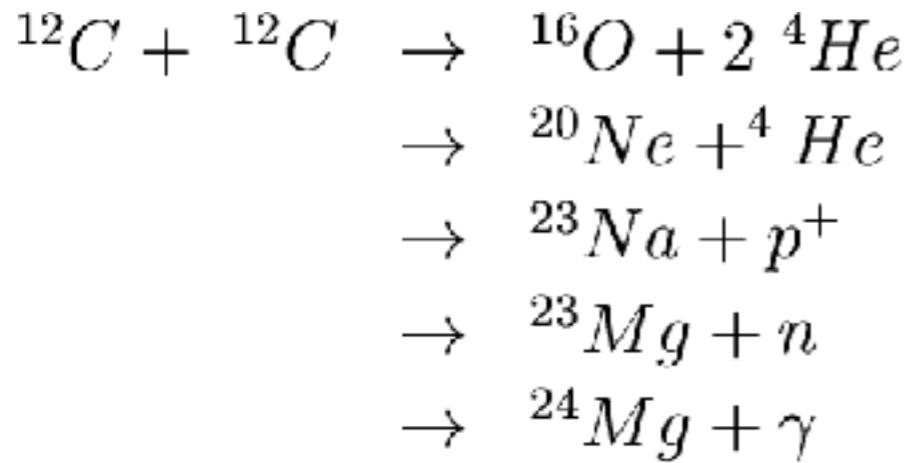


# slow neutron capture on the AGB (s-process)

main neutron sources



# Carbon burning and beyond



-----  
For 8 solar mass star

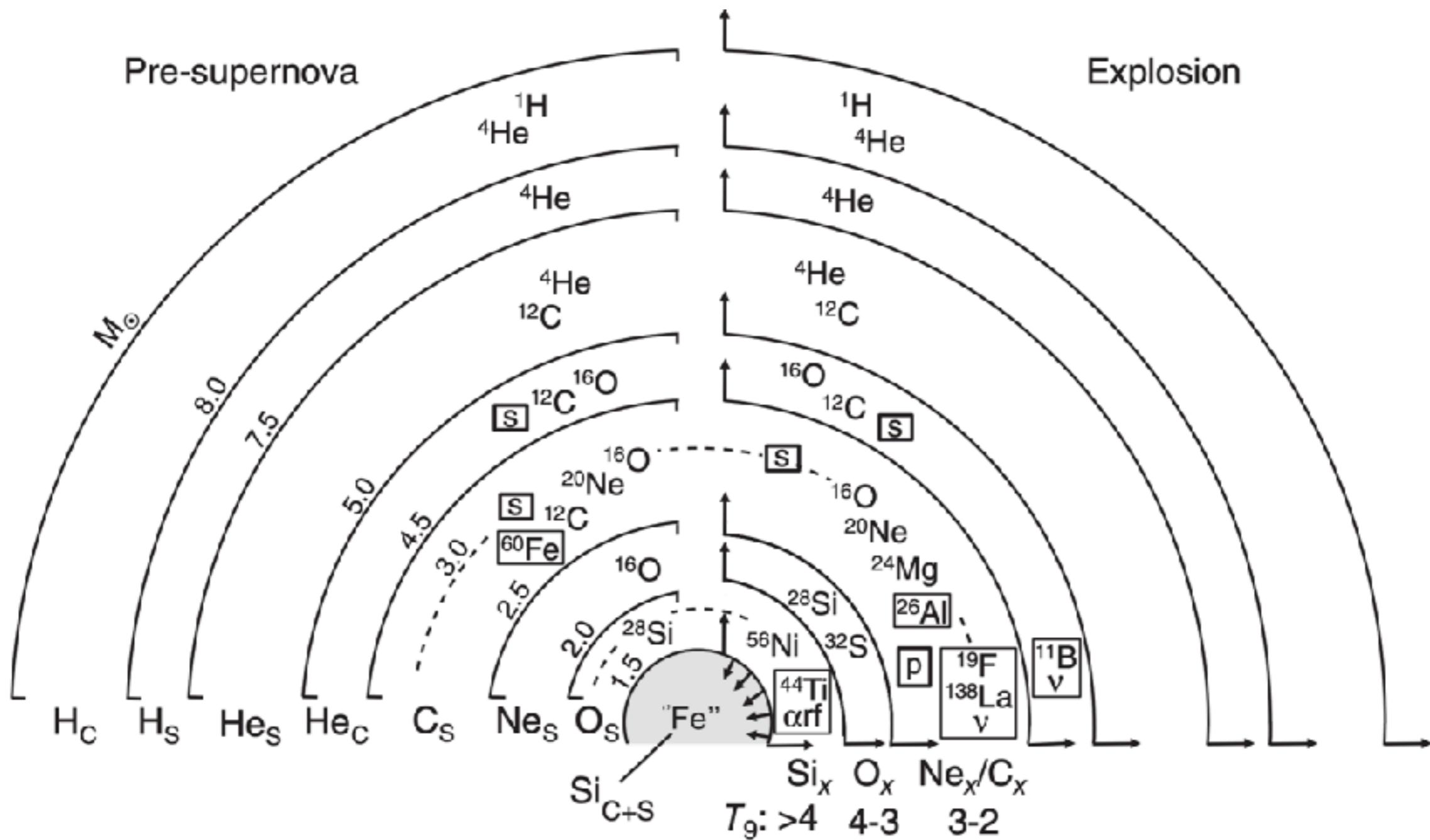
- Hydrogen: 10 Myr
- Helium: 1 Myr
- Carbon: 1000 yr
- Neon: 10 yr
- Oxygen: 1 yr
- Silicon: 1 day
- Core collapse: < 1 sec

Silicon burning occurs at extremely high temperatures: ~3 GK

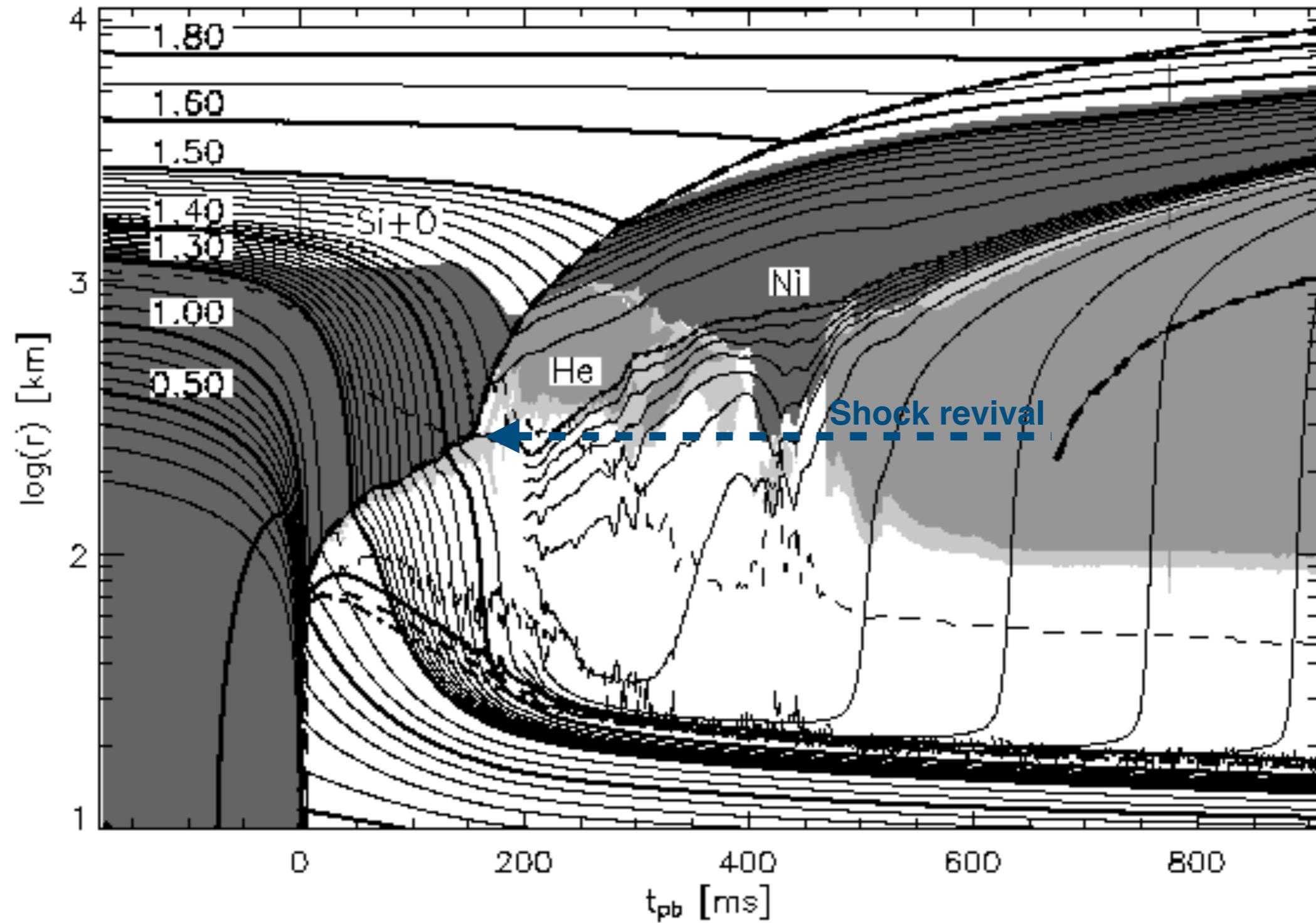
Nuclei photo-disintegrate and the emitted protons and alpha particles can be captured, forming heavier nuclei.

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

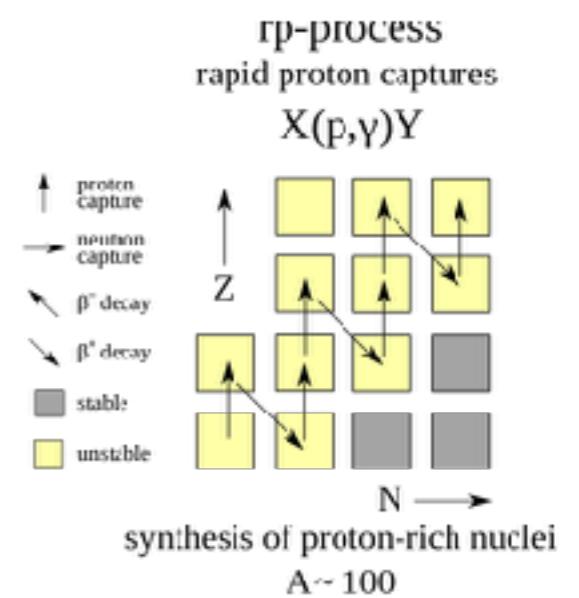
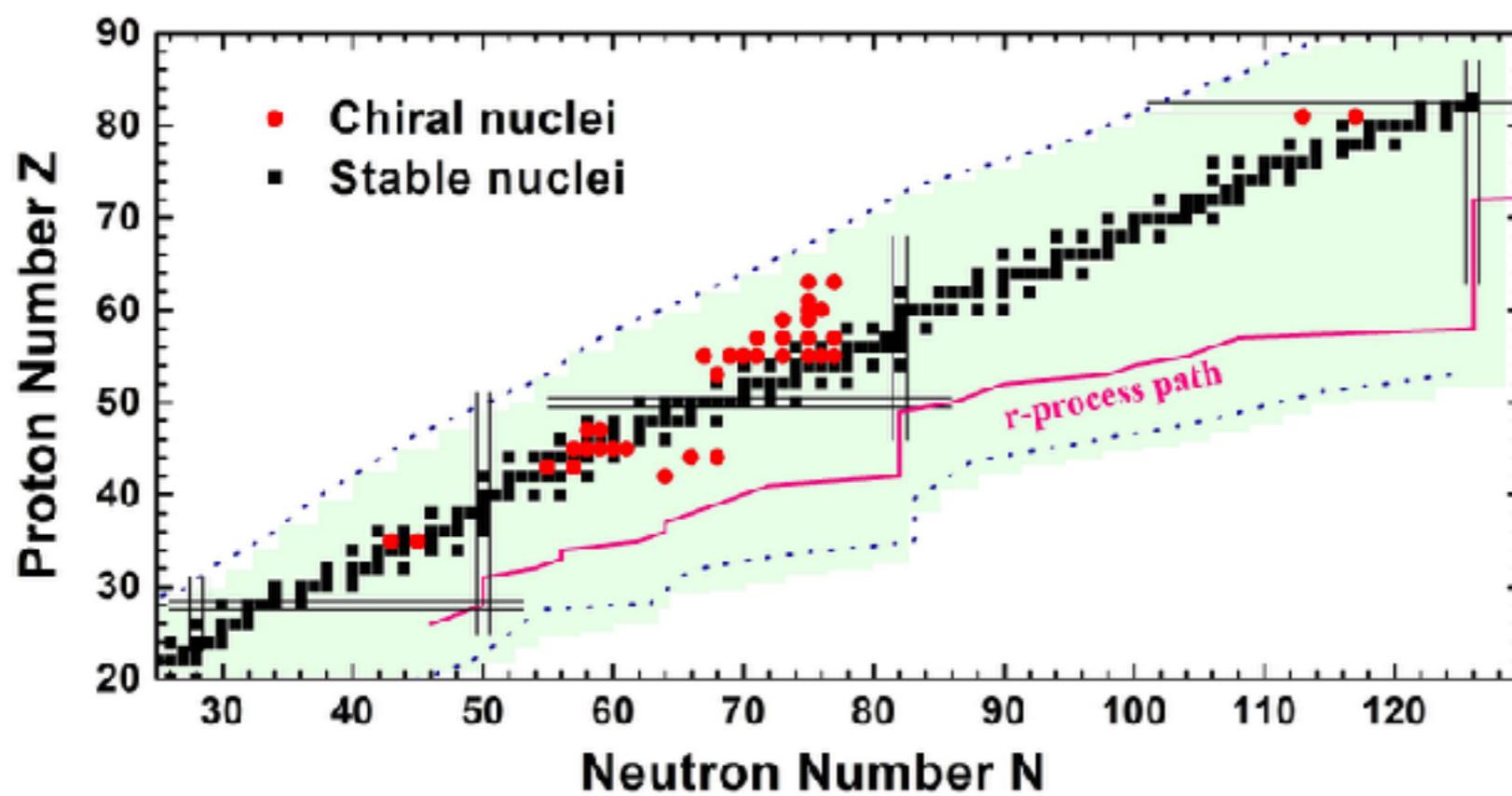
# Pre-supernova structure and core-collapse



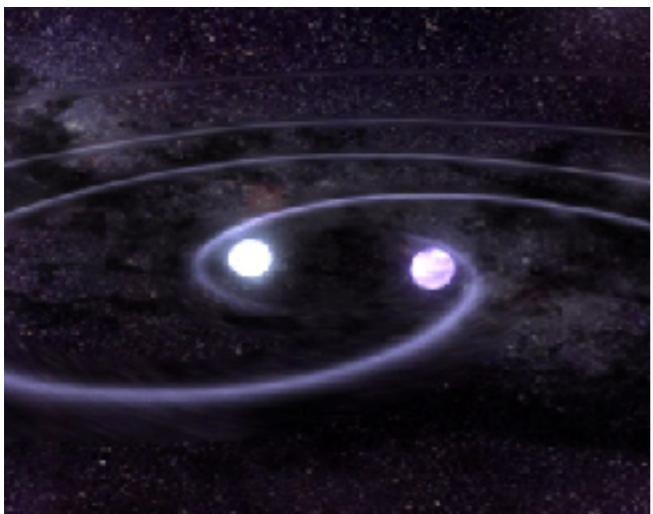
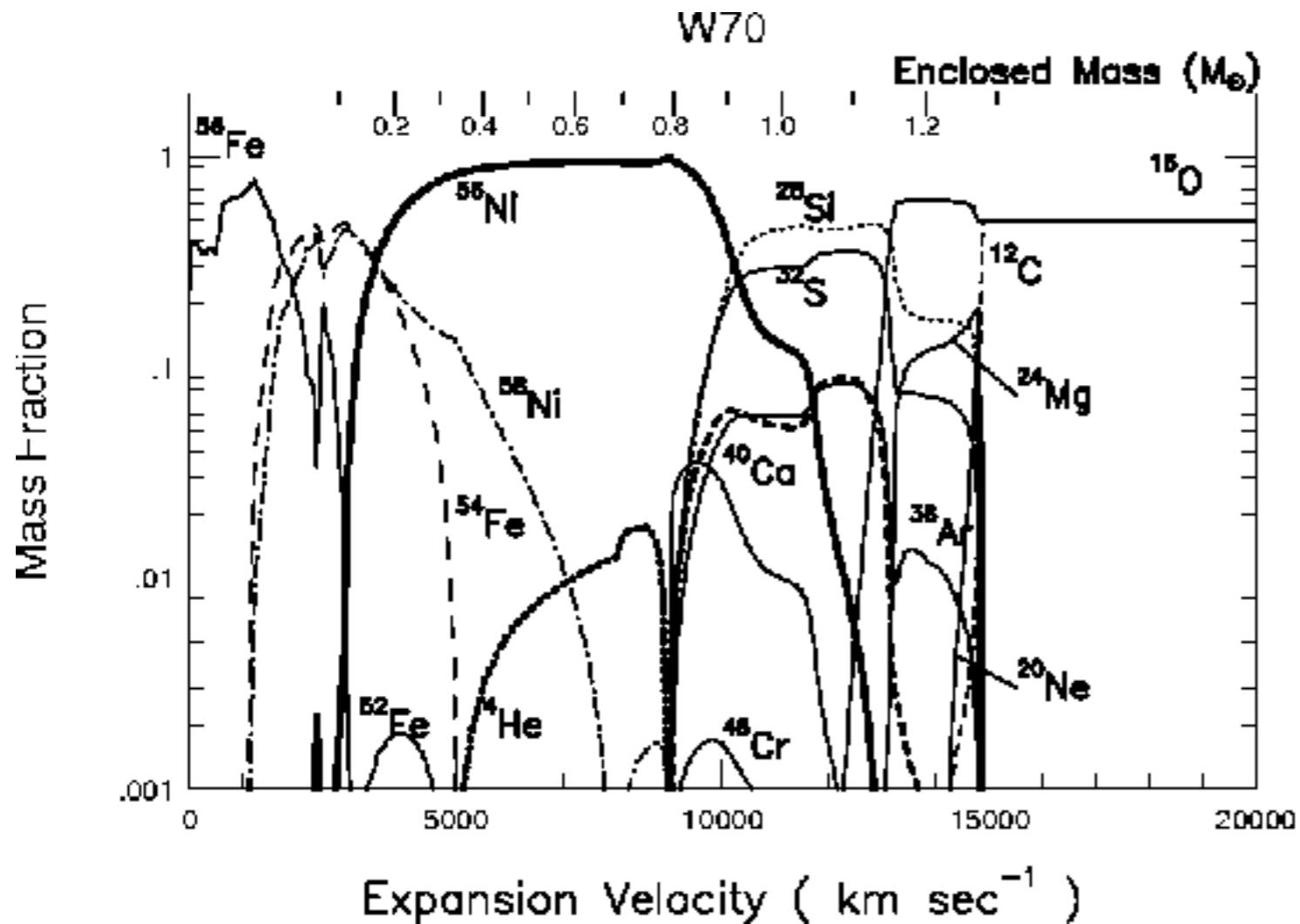
# Core-collapse supernovae



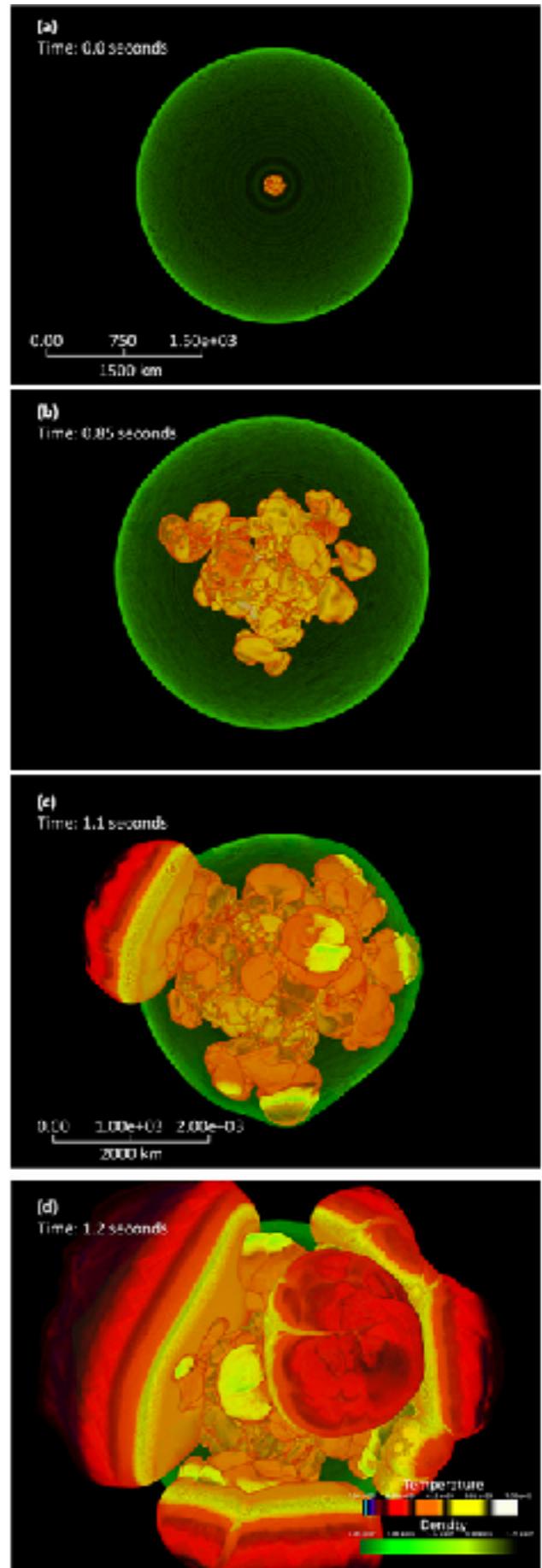
# Explosive nucleosynthesis (rapid neutron capture; r-process; rp-process)



# Type Ia supernovae (NSE)

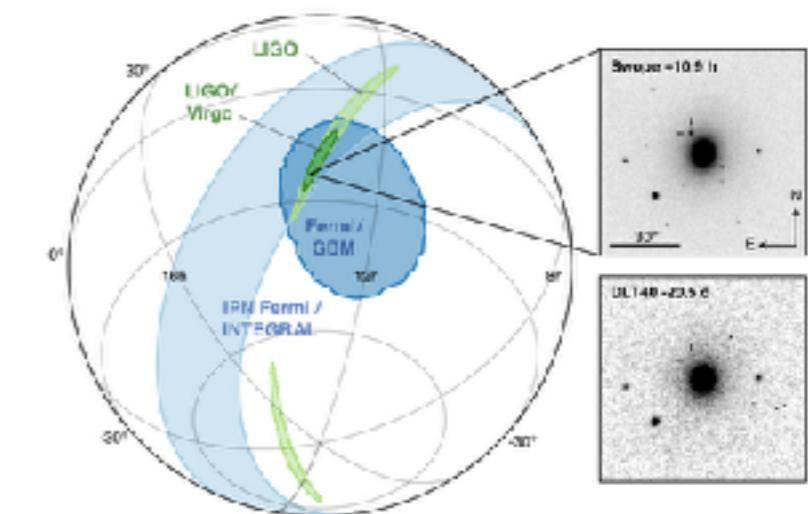
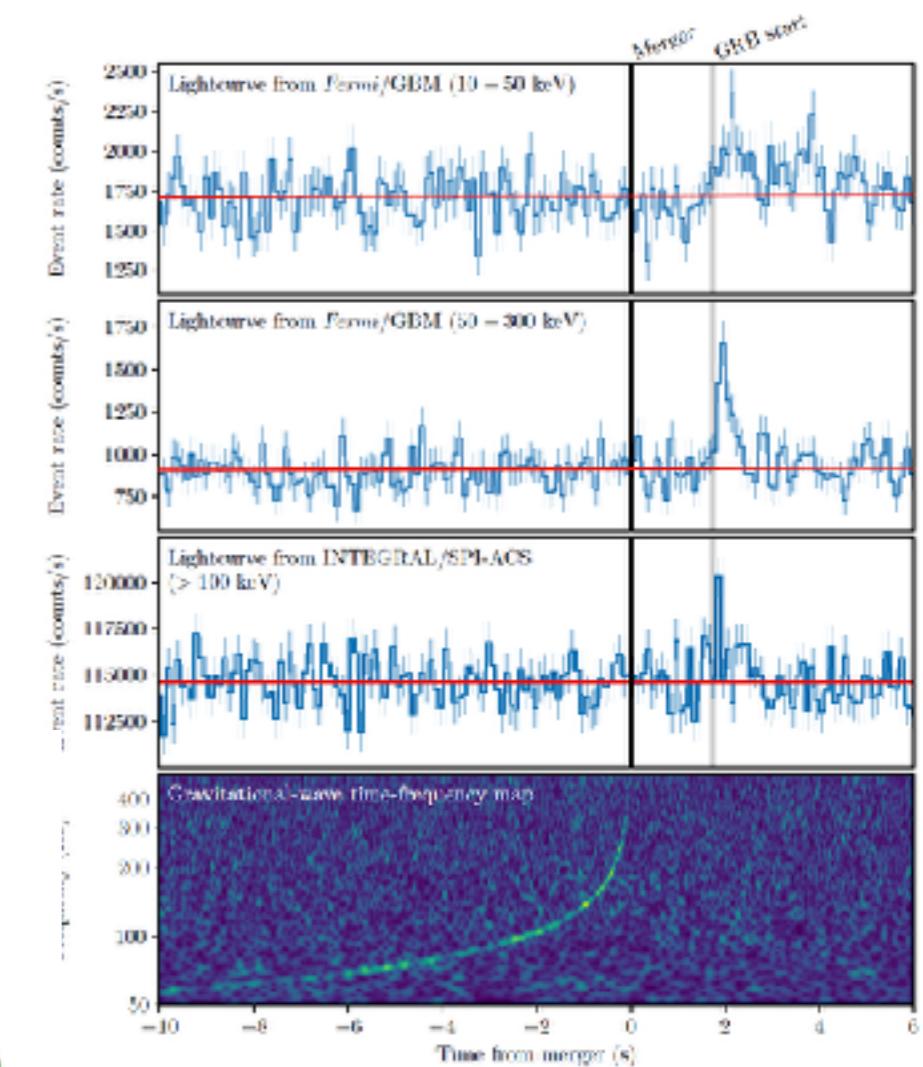
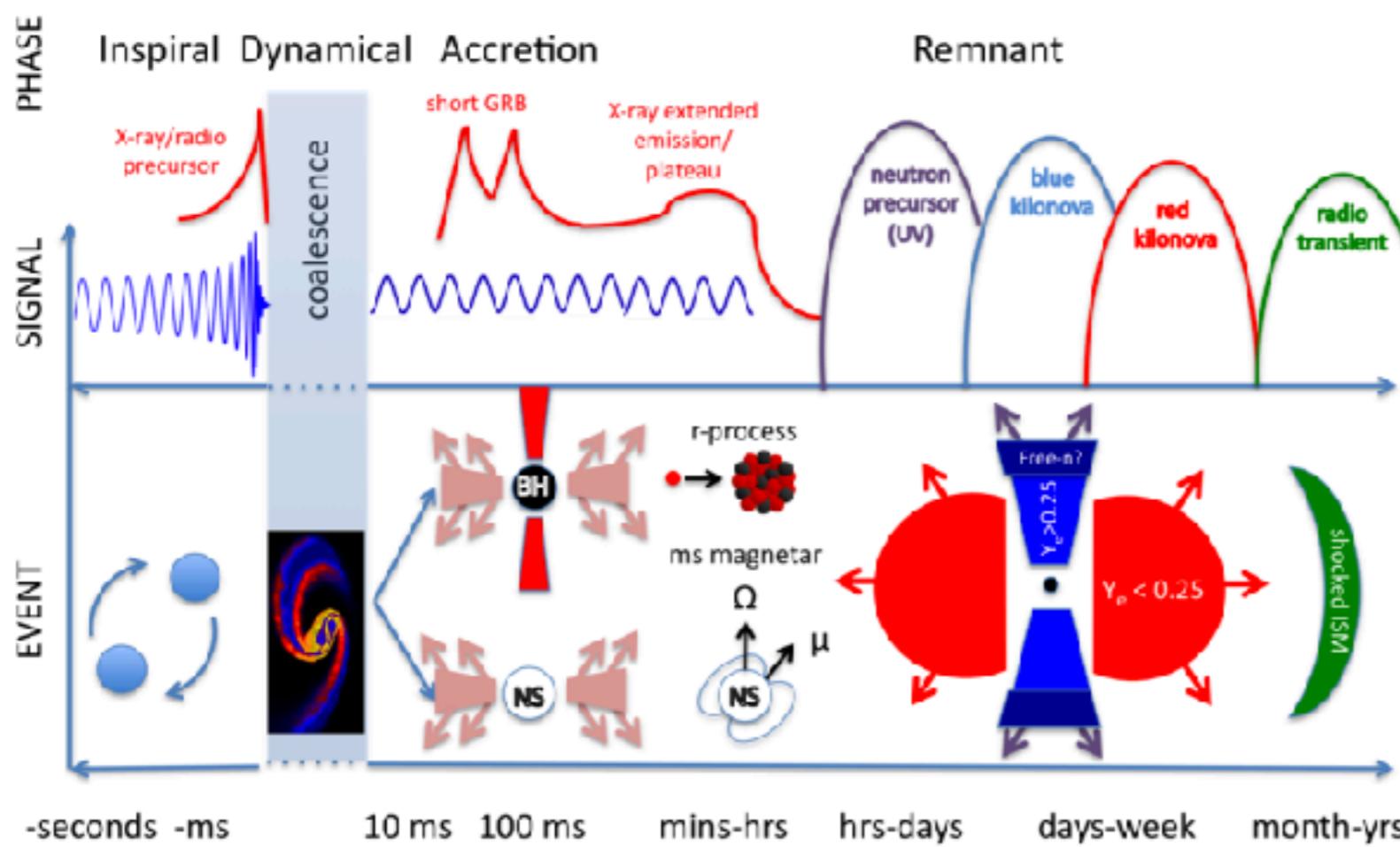


Progenitors still debated  
Responsible for most iron-peak elements



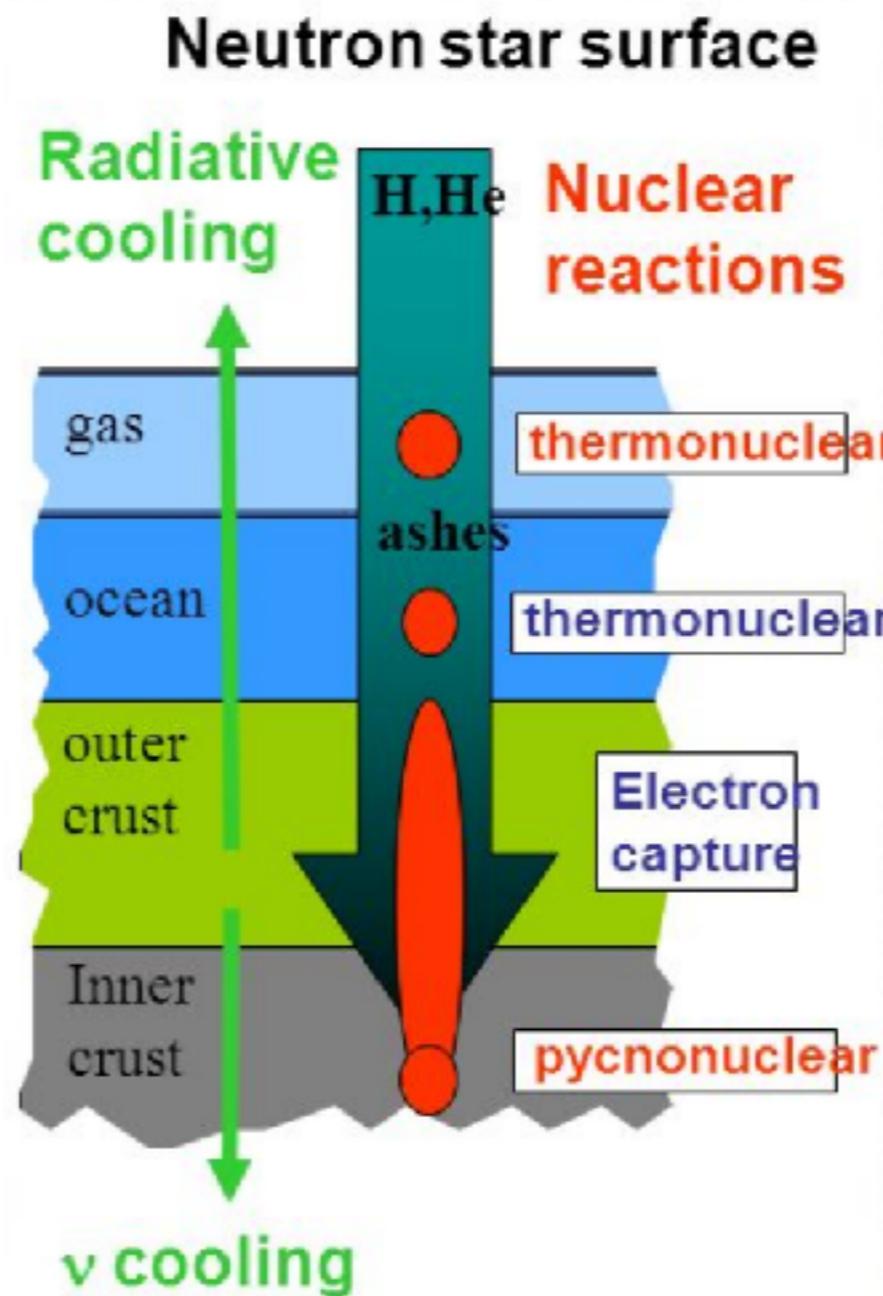
# Neutron star mergers, gamma-ray bursts

GW 170814

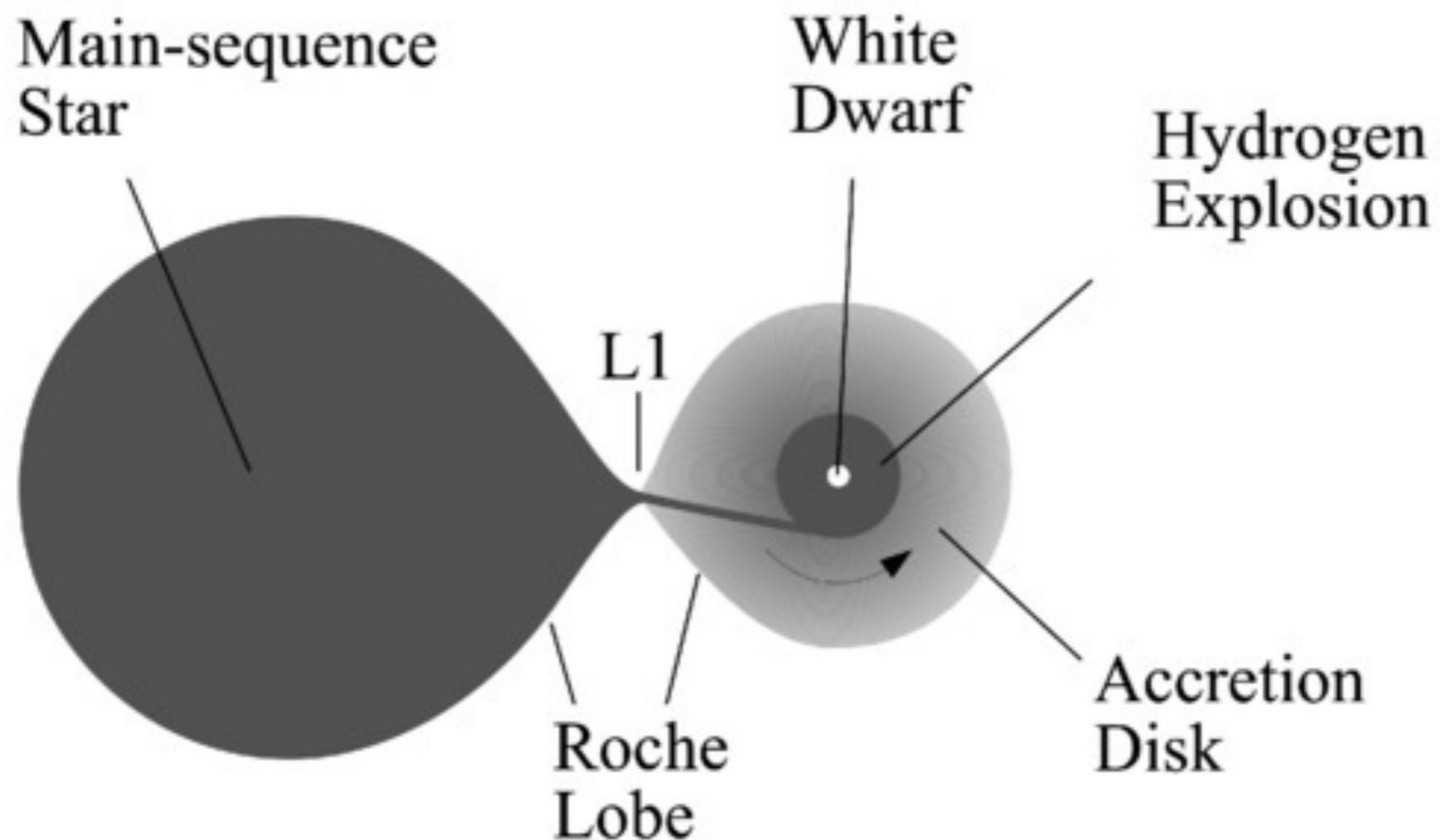


# Pycno-nuclear reactions

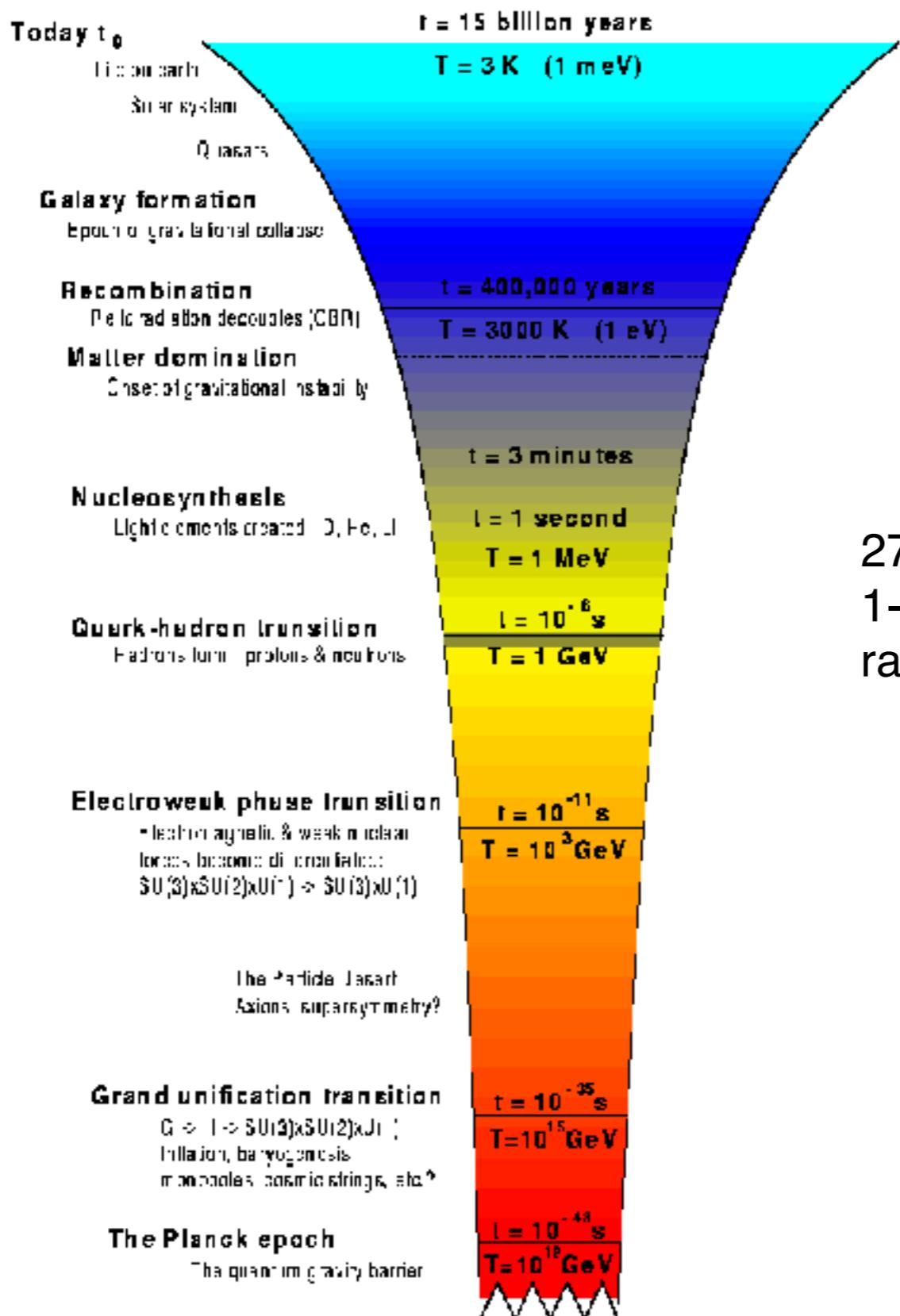
Inside neutron stars, at extremely high densities, the effective coulomb barrier is reduced by high neutron fraction, close distance and electron cloud



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

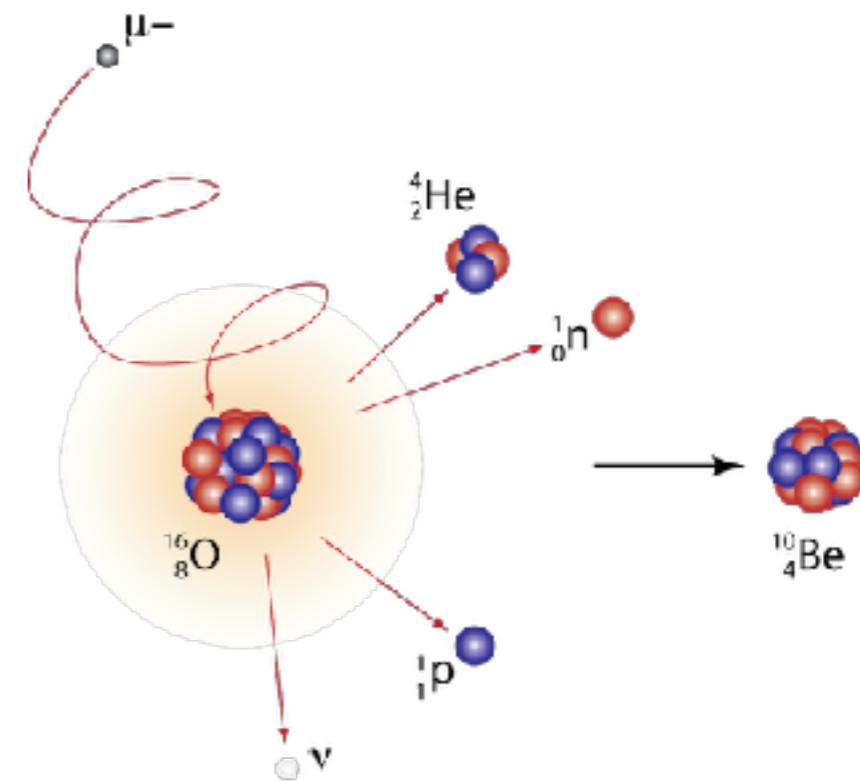
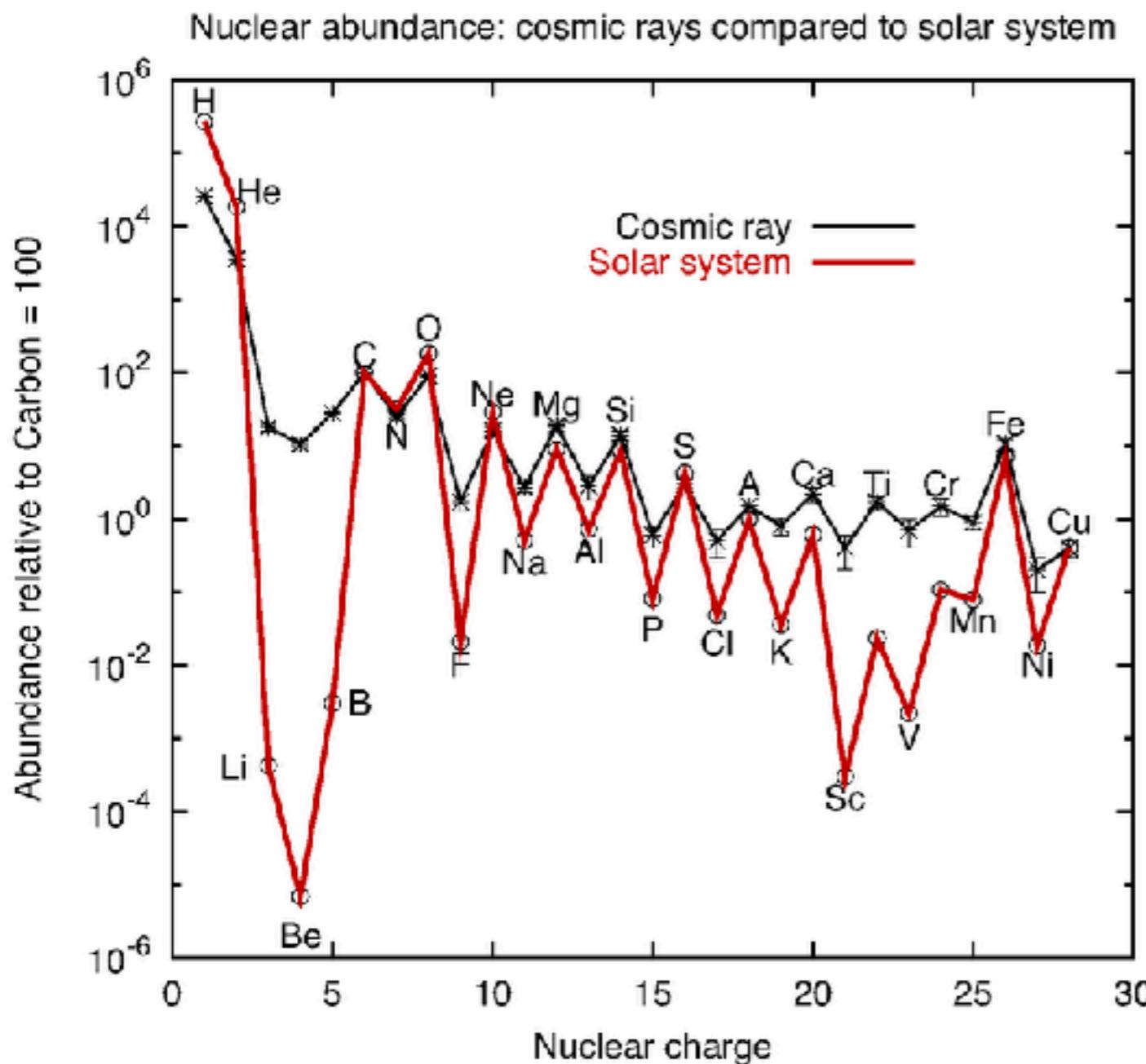


# Primordial nucleosynthesis



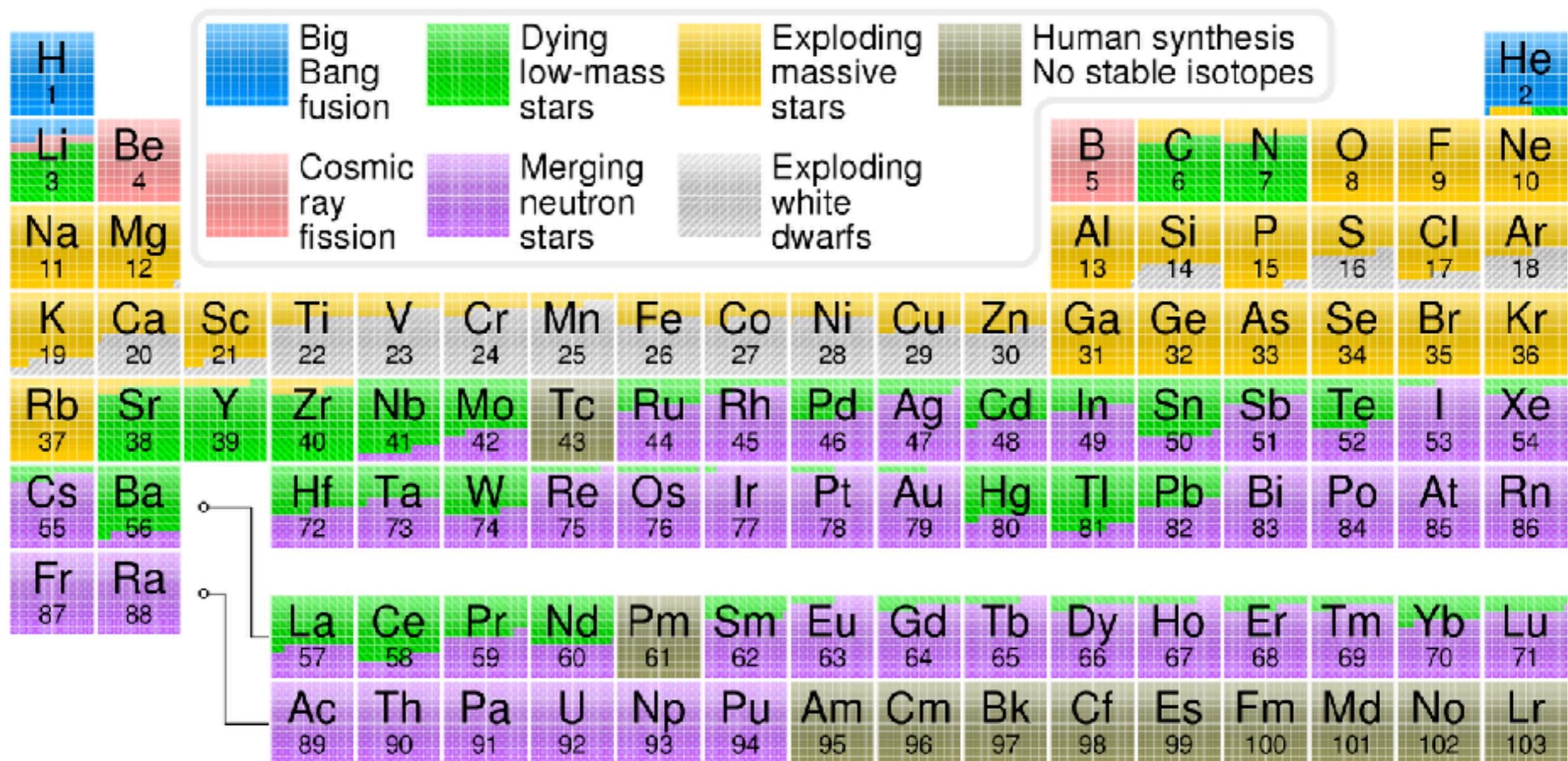
27% He requires primordial origin  
1-3 sec after Big Bang: High temperatures but rapid cooling

# CR-induced spallation

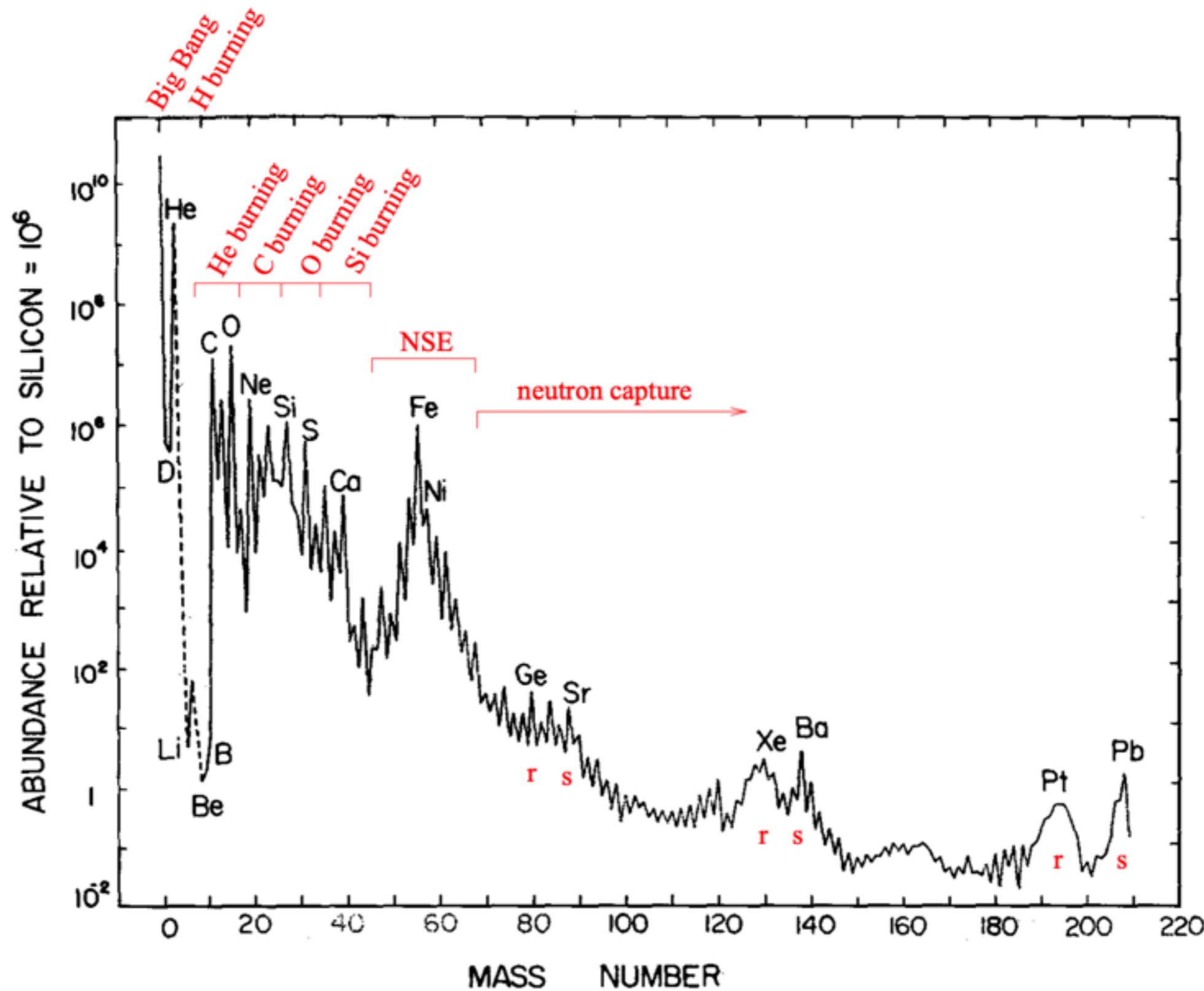


Not enough to explain observed Li abundances in the Solar System, other processes required (explosive nucleosynthesis, novae, red giants?)

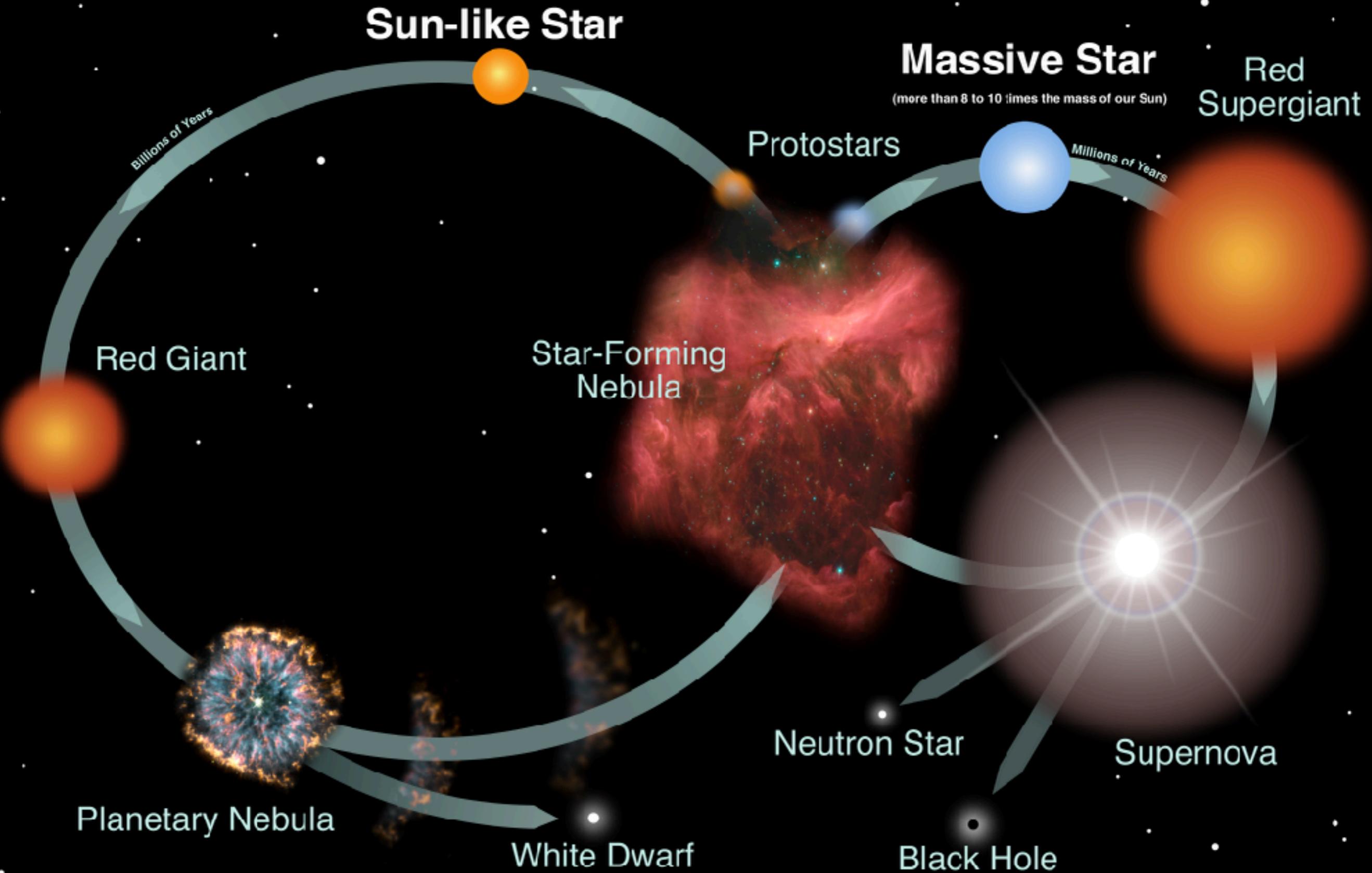
# Origin of elements



# Origin of elements



## Nucleosynthesis goes on



# Overview

|  |                 |
|--|-----------------|
| • <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>  |
| <br>   |                 |
| <b>Paper presentations I</b>   | <b>June 21</b>  |
| <b>Paper presentations II</b>  | <b>June 27</b>  |