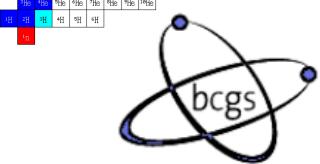
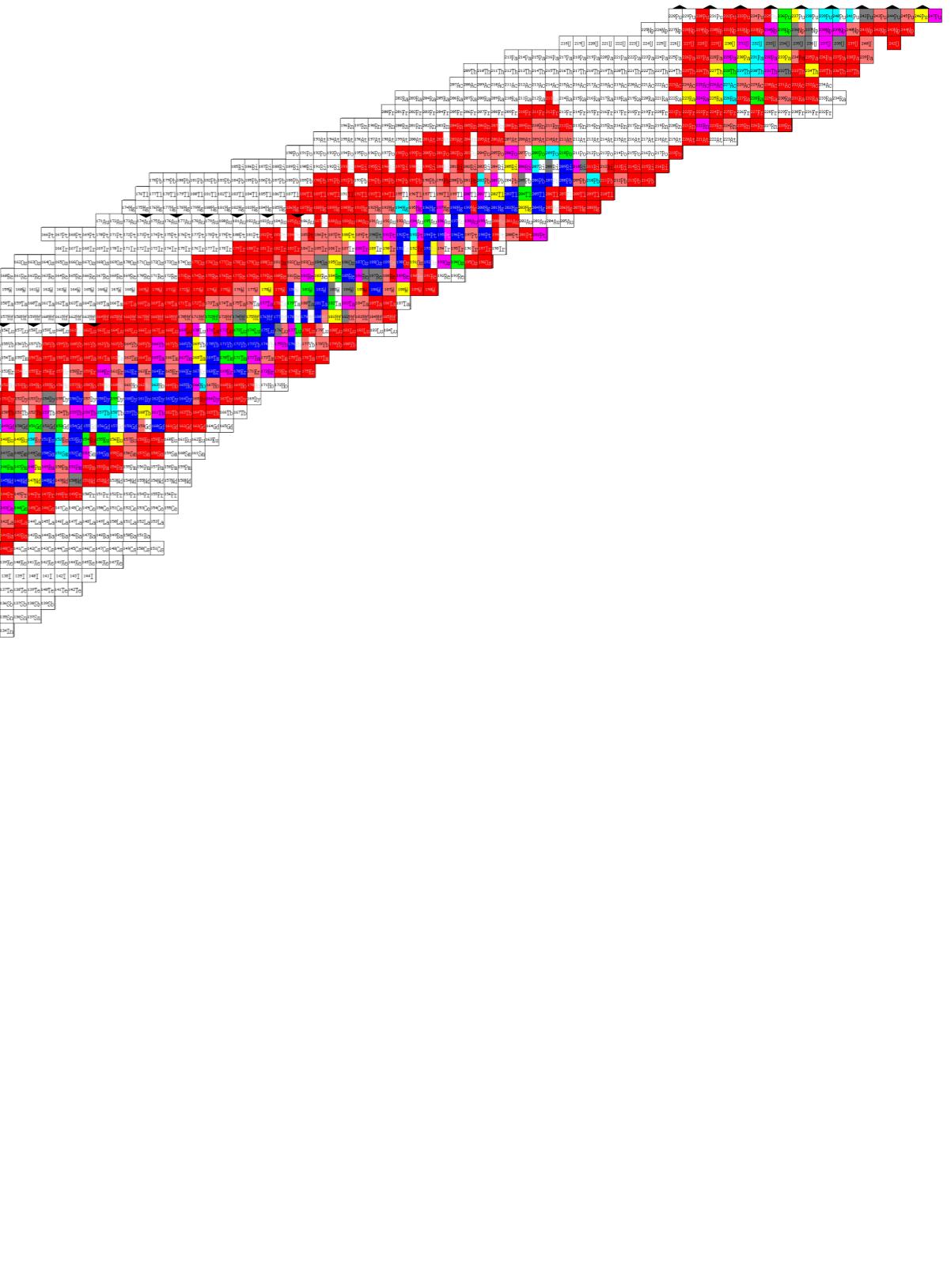


Nucleosynthesis

Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School
of Physics and Astronomy

Frequently Asked Questions

Who are you?

Instructor

John Antoniadis — office 3.015; janton@mpifr.de

Tutors

Ben Hastings — bhastings@astro.uni-bonn.de

Tasha Gautam — tgautam@mpifr-bonn.mpg.de

Where do I find more about the course?

Lectures

https://ecampus.uni-bonn.de/goto_ecampus_crs_1662948.html

Course website

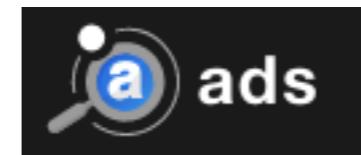
jantoniadis.github.io/nucleosynthesis

Frequently Asked Questions

How do I study for the course?

- *Self-paced* lectures on eCampus (videos, tests and at least two of the exercises)
- Exercise classes (via zoom)
- Paper presentations (check website for details)

You will need accounts for



Frequently Asked Questions

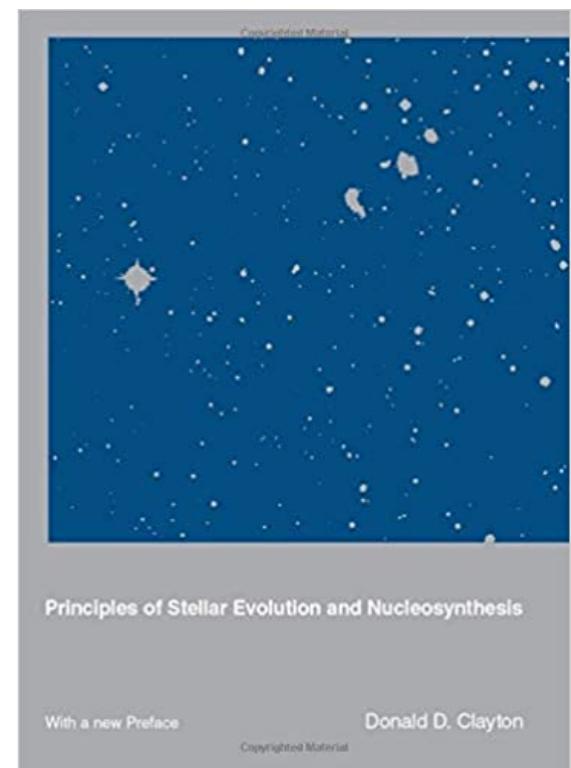
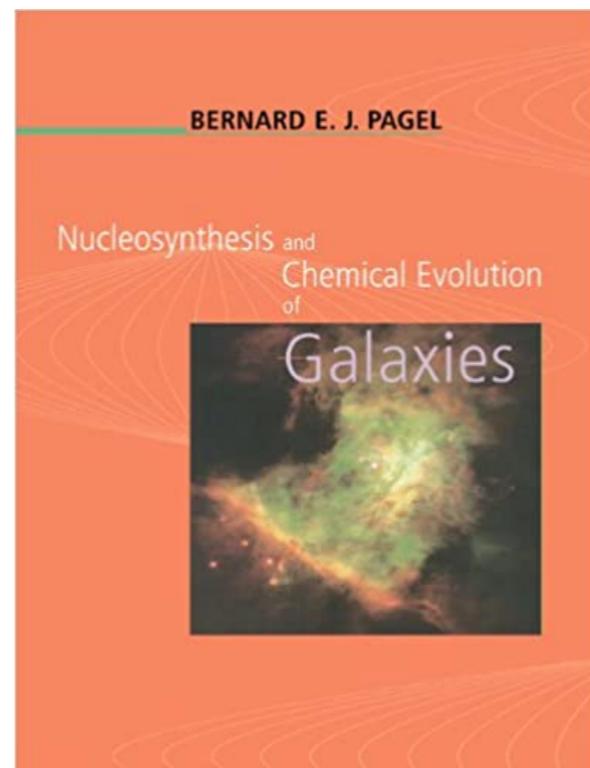
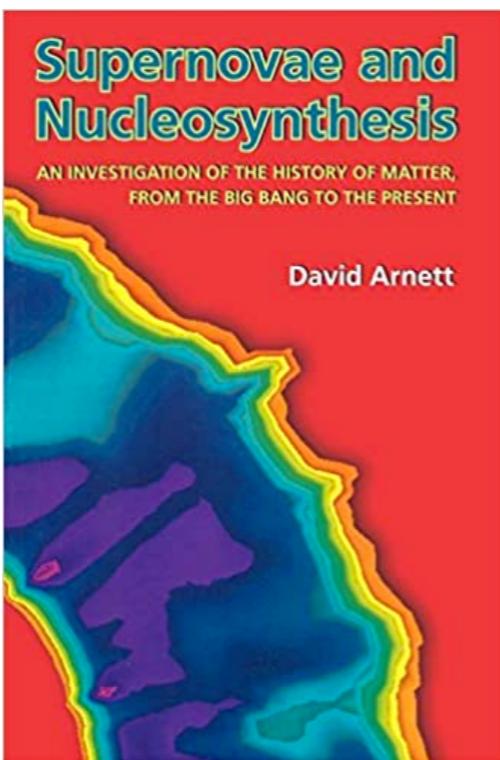
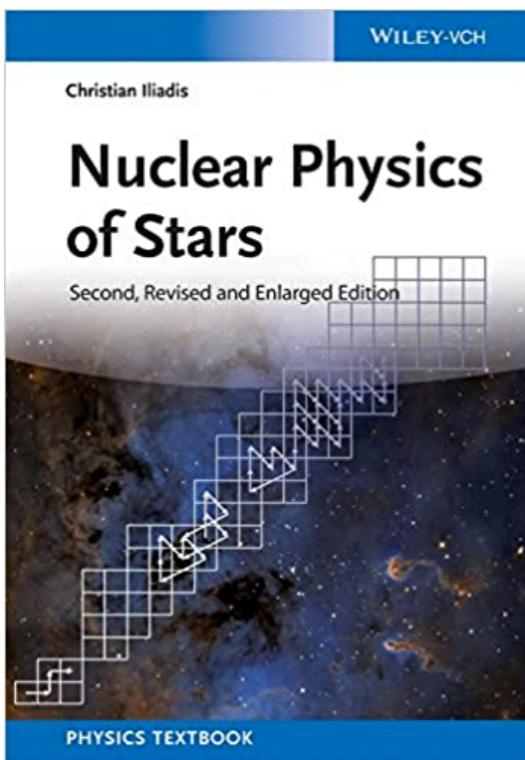
How do I study for the course?

Course material

Presentations and Videos

Lecture Notes by Prof. Norbert Langer (see website)

Lots of extra material on the website and on e-campus



Evaluation

- Completion of eModules (videos, tests + 2 exercises per problem set) **50%**
- Presentations **50%**

Questions?

Suggested Editing Time: 18. Jun 2020 - 24. Jun 2020

11. Li, Be, B
Suggested Editing Time: 25. Jun 2020 - 01. Jul 2020

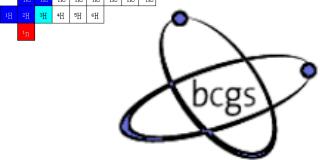
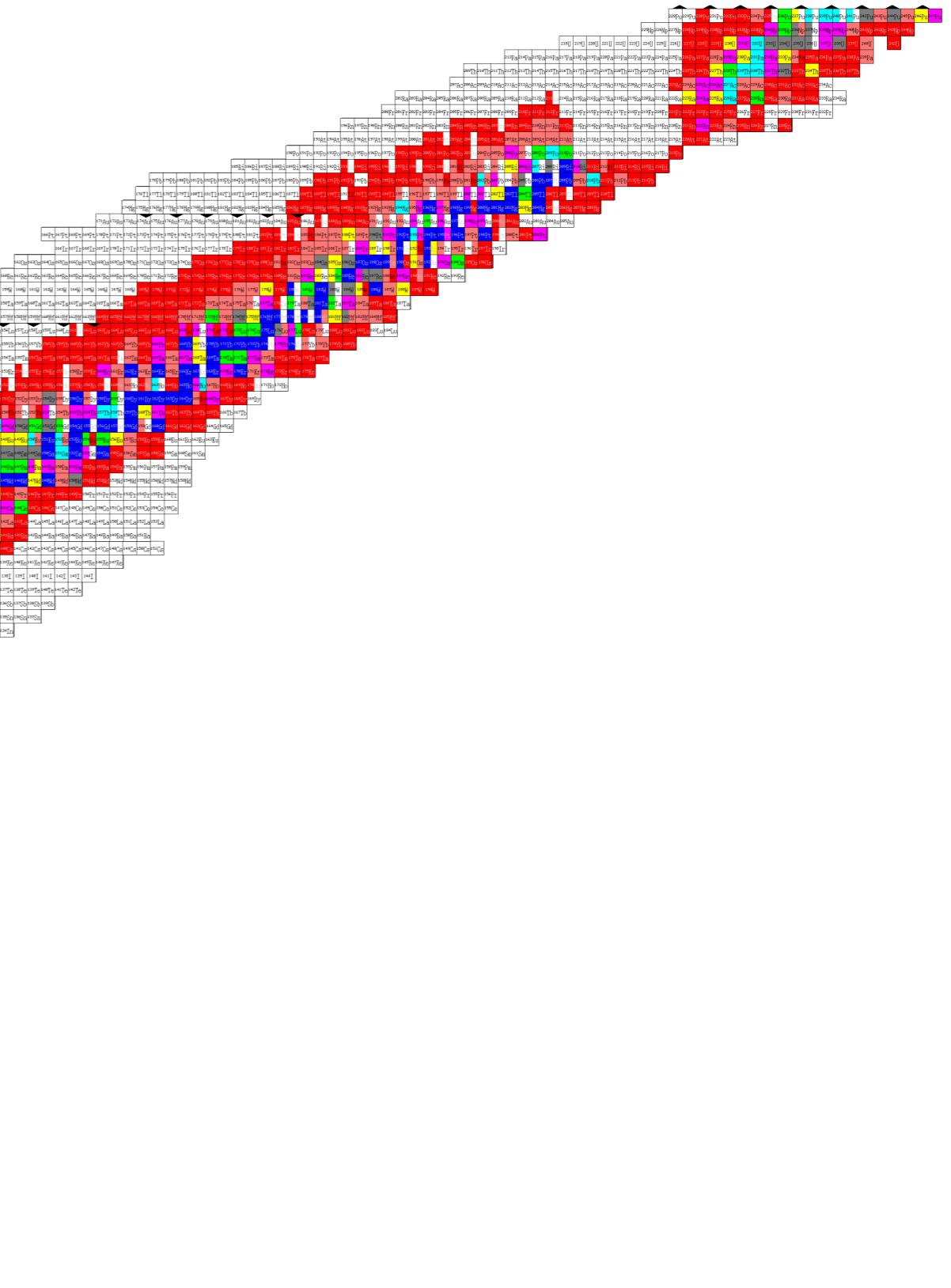
12. Galactic Chemical Evolution
Suggested Editing Time: 02. Jul 2020 - 08. Jul 2020

Astro858 forum
Use this space to discuss topics related to lectures, exercises, paper presentations, questions etc.
Articles (Unread): 1 (0)
Latest Article: Hi everyone, We are currently working... from Ioannis Antoniadis (iantonia), Today, 14:19

Three large red arrows point downwards from the module titles towards the forum section.

Nucleosynthesis

Lecture 1: Introduction & Overview



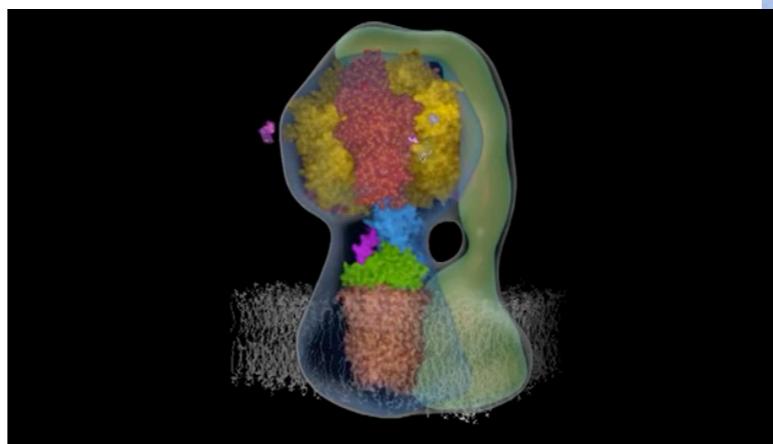
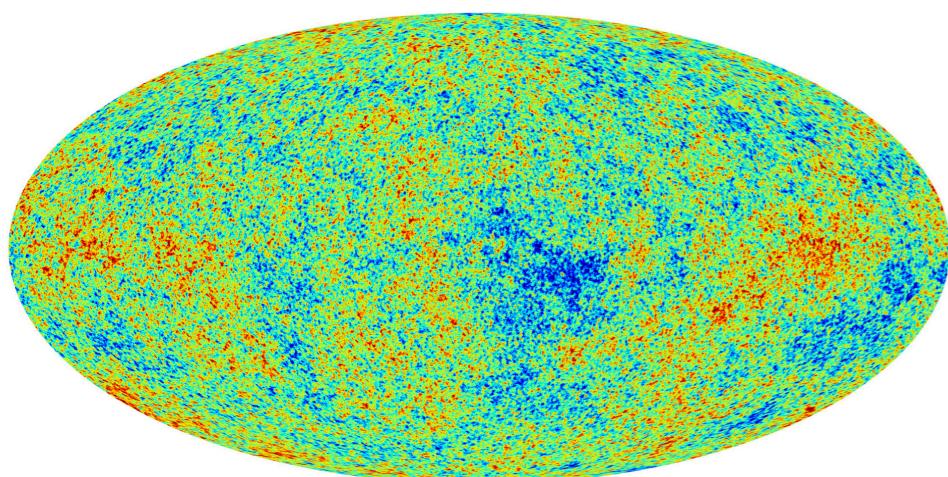
Bonn-Cologne Graduate School
of Physics and Astronomy

Overview

Goal:
**explain the evolution and “current” distribution
of isotopic abundances in the Universe**

Big Bang

Today



Overview

**Goal:
explain the evolution and “current” distribution
of isotopic abundances in the Universe**

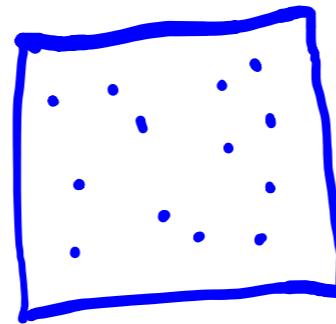
We will study the THERMONUCLEAR history of matter

- 1. Where do all the elements come from**
- 2. Why they are organised in their observed abundances**
- 3. How these abundances evolved with time**

Abundances

Definition:

How much “stuff” there is, i.e. a measure of the fraction of one element relative to all other elements in a given environment



Abundance by number:

$$Y_j = N_j / N_{\text{total}}$$

$$E_j = N_j - N_H = \log(N_j / N_H)$$

$$N_H = 12; A_H = \log(N_H) = 12$$

Abundance by mass:

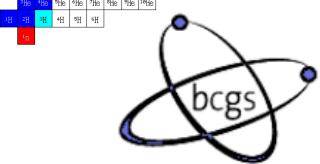
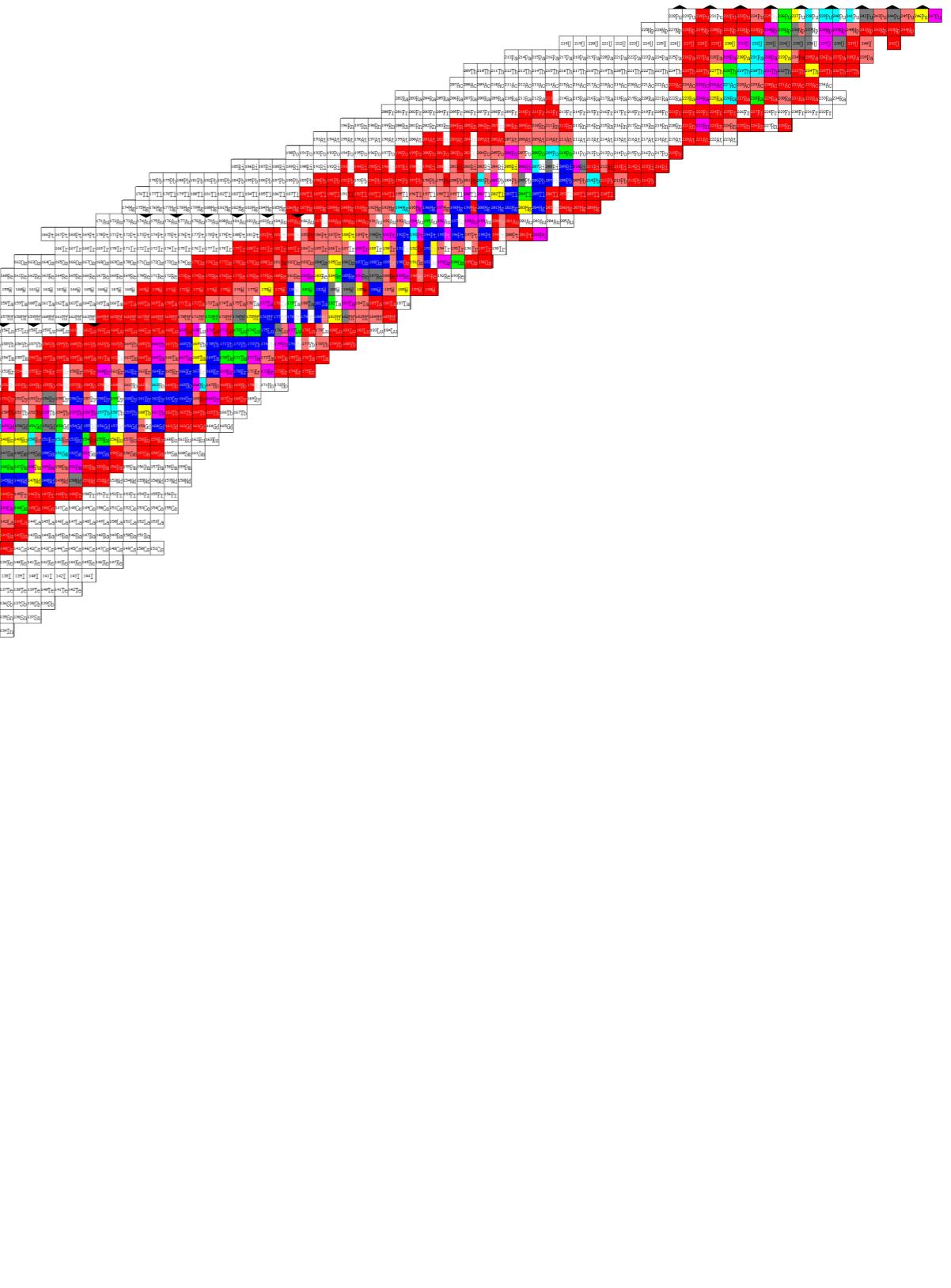
$$\text{Sun : } X_{\odot} = 0.71; Y_{\odot} = 0.275; Z_{\odot} = 0.015$$

Relative to solar:

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

Nucleosynthesis

Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School
of Physics and Astronomy

Chemical elements

1 IA 1A	1 H Hydrogen 1.008	2 IIA 2A	3 Li Lithium 6.941	4 Be Beryllium 9.012	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
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	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 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798	
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294	
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018	
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	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 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]



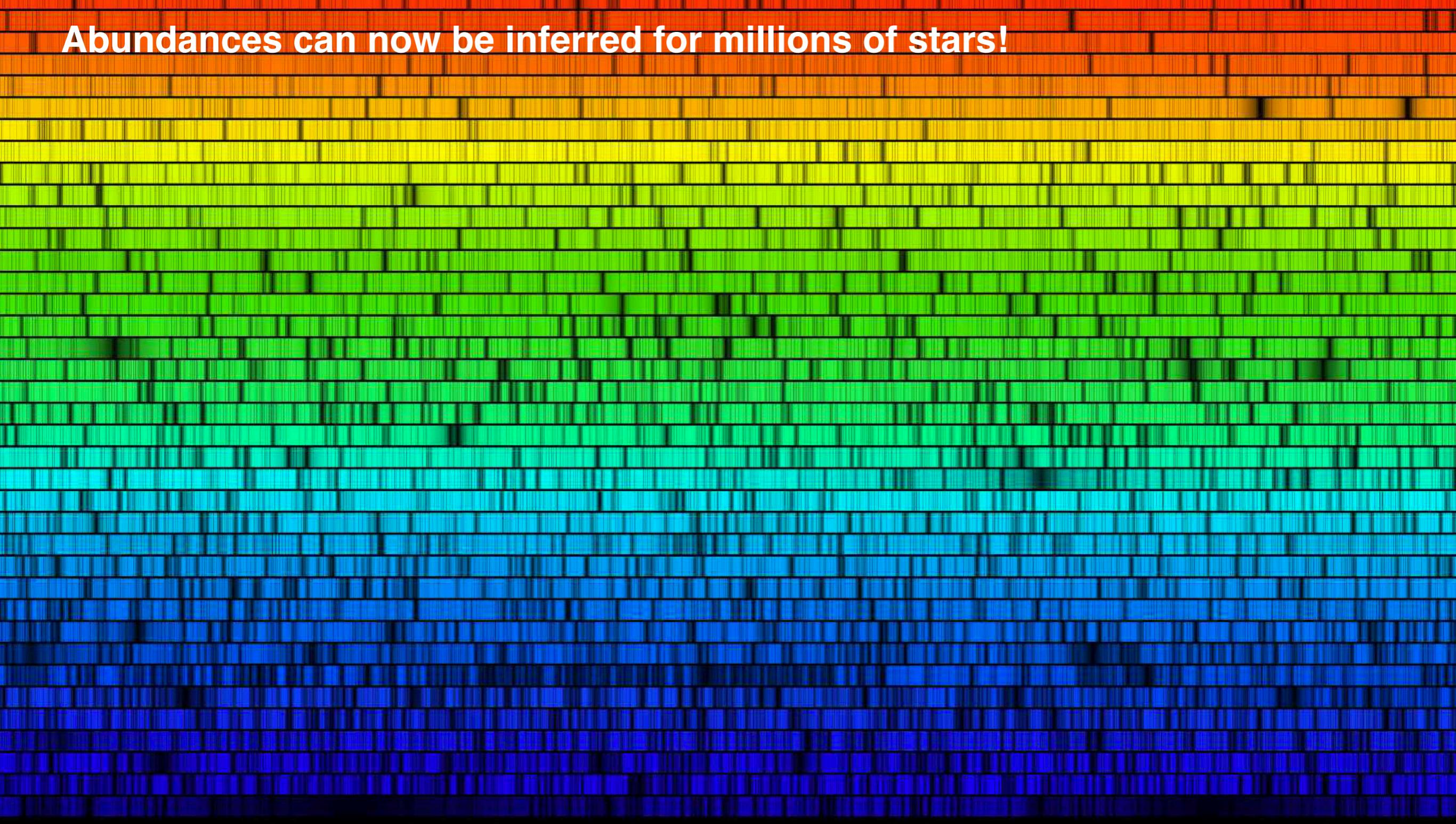
Measurement of Elemental Abundances – the Sun and the Stars

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

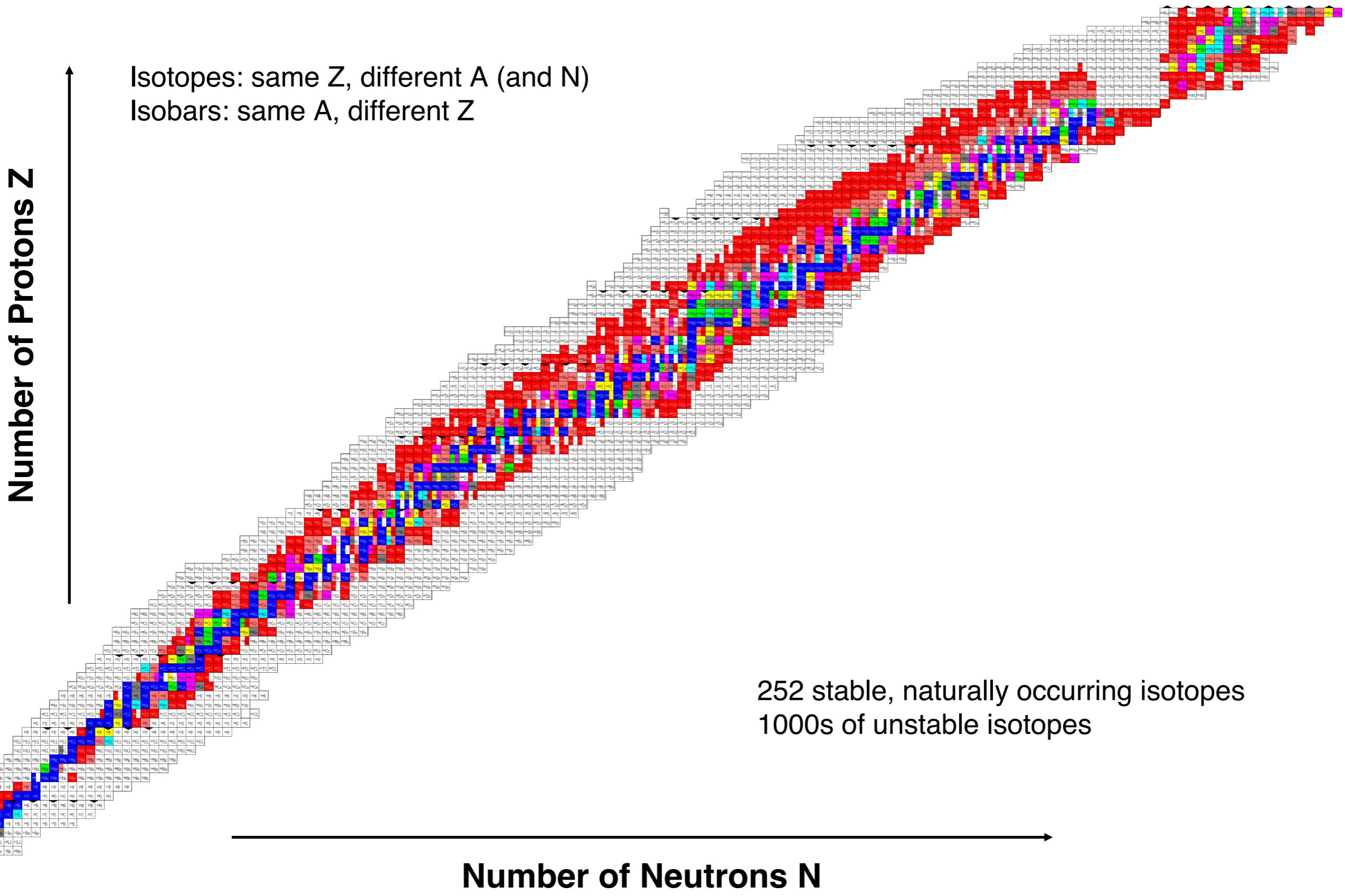
Element	Abundance (pct. of total number of atoms)	Abundance (pct. of total mass)
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.030	0.014
Sulfur	0.015	0.040

“Metals”

...but spectroscopy has limitations:

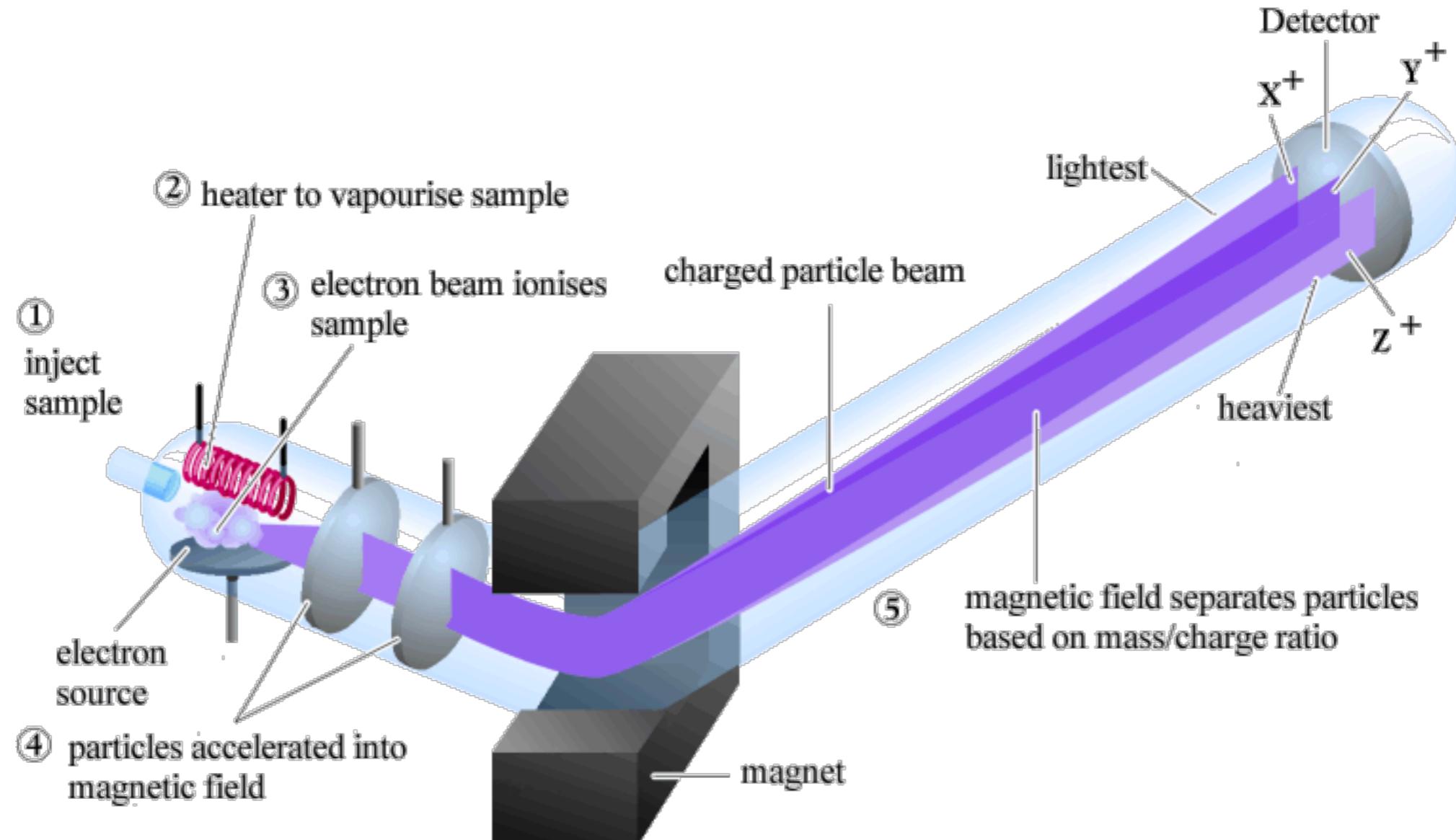
- derived abundances depend on complex models
- only *elemental* abundances: chemical properties (incl. spectra) depend on the number of electrons → atomic number, Z

Isotopes and isobars



Measurement of Isotopic Abundances

Masses of isotopes can be measured with a mass spectrometer



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

Ivuna, CI Carbonaceous Chondrite



© Natural History Museum, London.
(Image courtesy of the Natural History Museum, London.)

Extremely rare: only five known

- Silicate, sulfide and iron phases
- No evidence for geological reshaping, thought to be unprocessed
- Contain small chondrules (grains)
- Believed to be representative of the composition of the original molecular cloud that formed the solar system

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

Homogeneous solar system composition

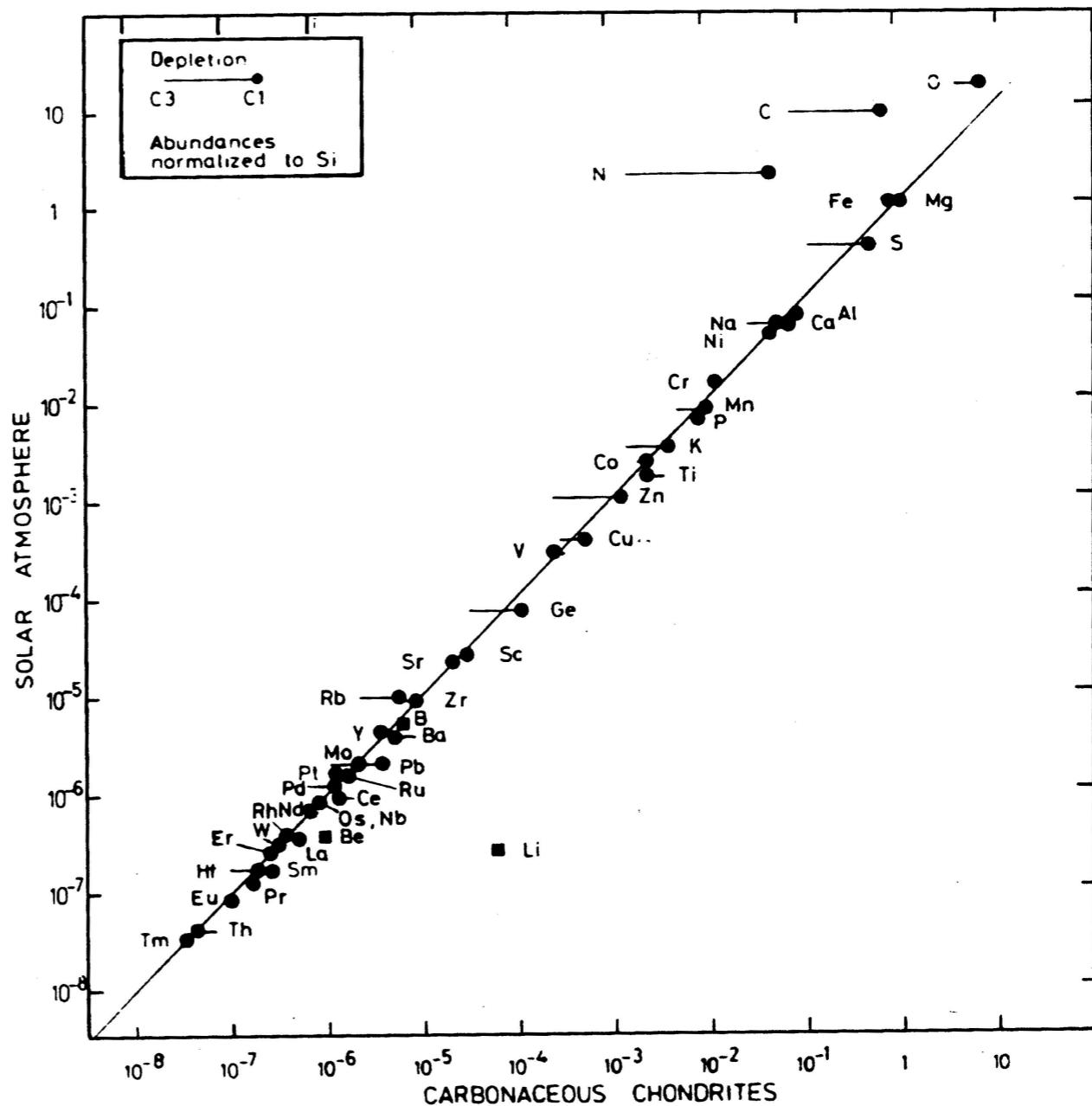


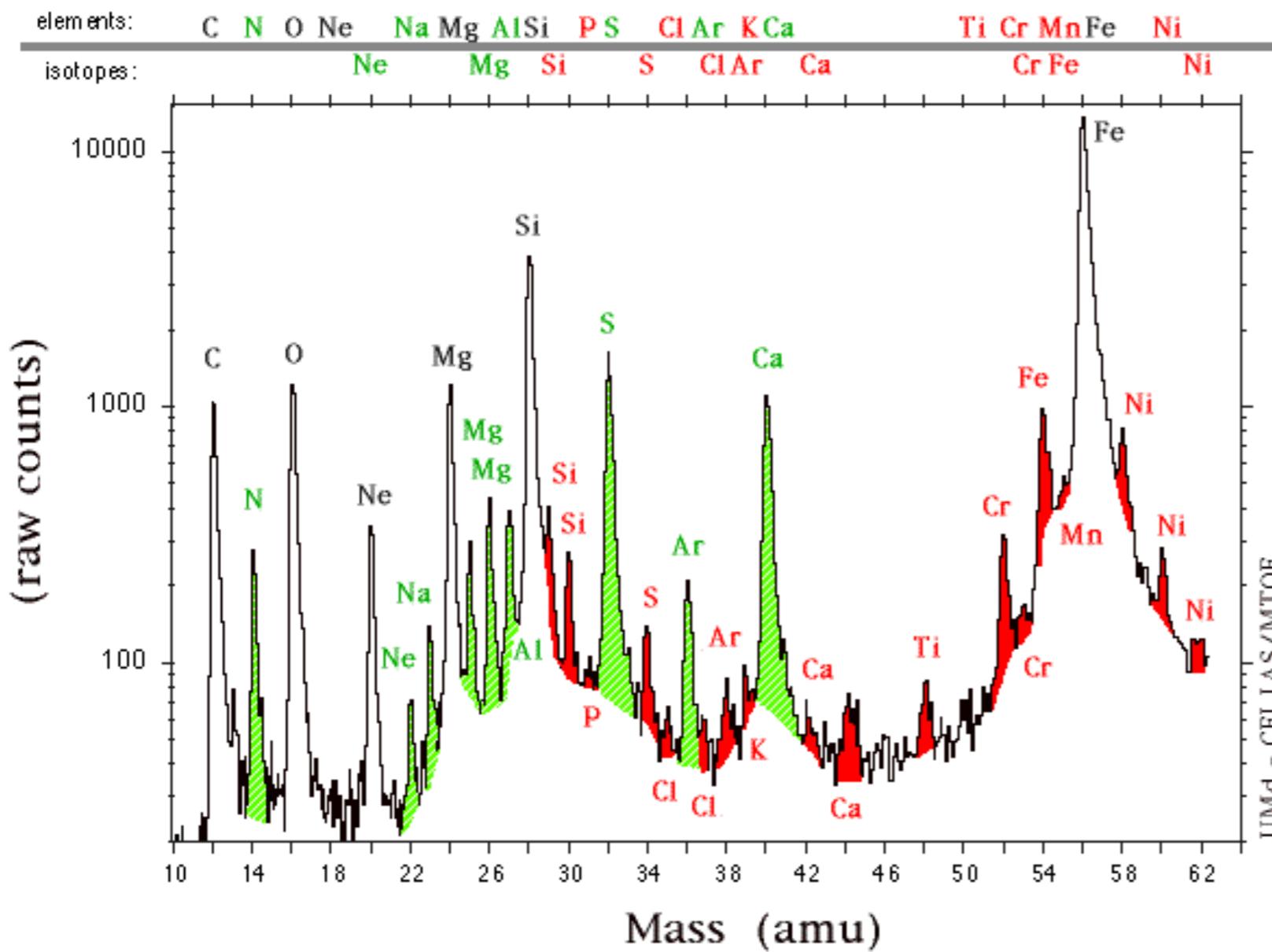
Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

...but they also contain pre-solar grains

Measurement of Isotopic Abundances

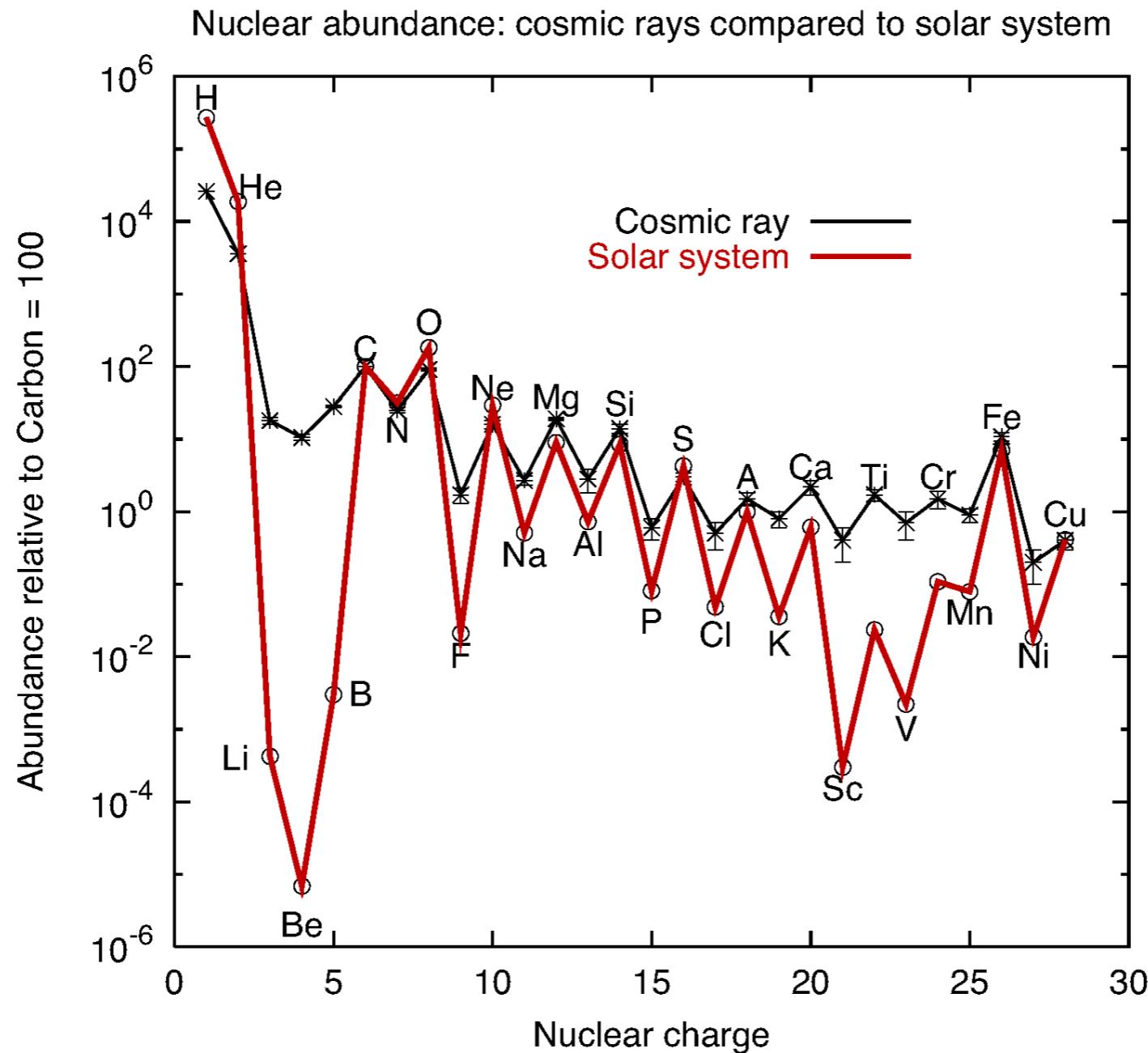
Isotope abundances in the solar system

Solar Wind Elements/Isotopes Observed by CELIAS MTOF



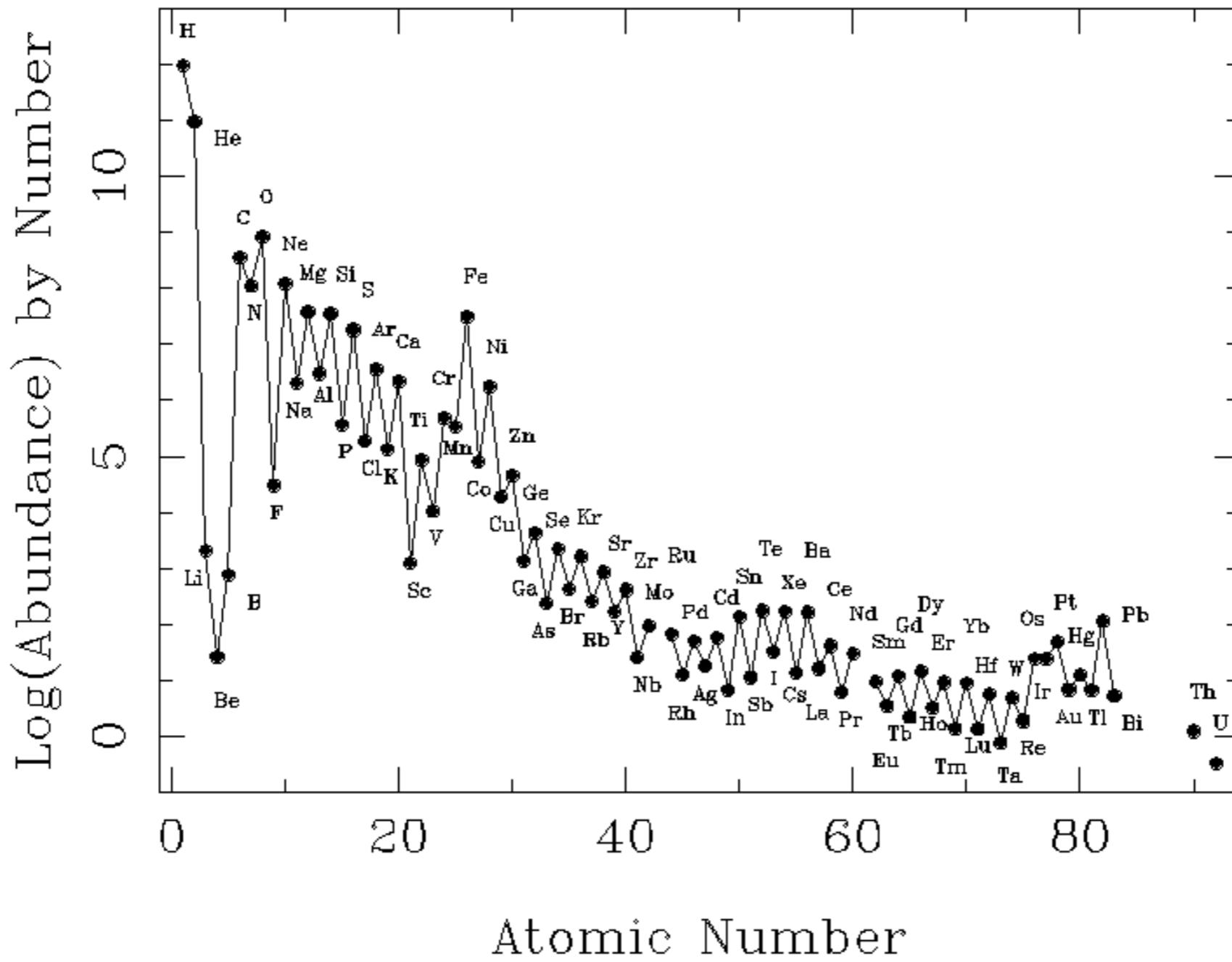
Other sources of abundances

Cosmic rays: Extra-solar material!



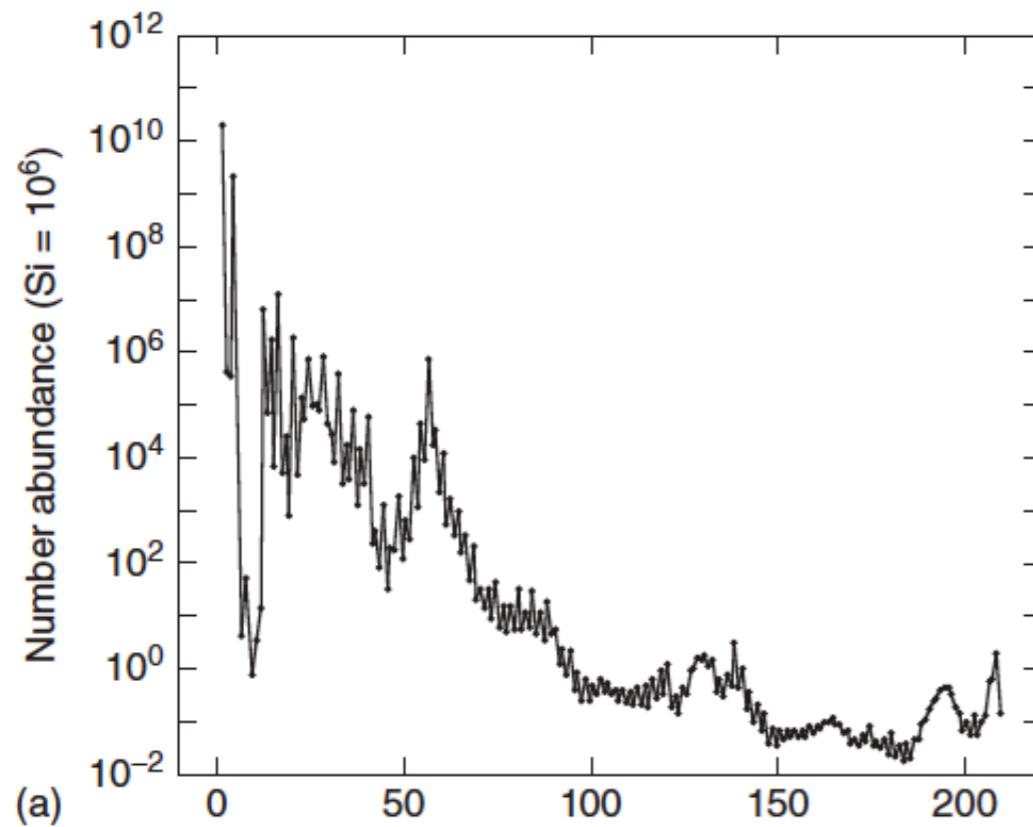
Solar System Abundance Pattern

Logarithmic SAD Abundances: $\text{Log}(\text{H}) = 12.0$



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

Solar System Abundance Pattern



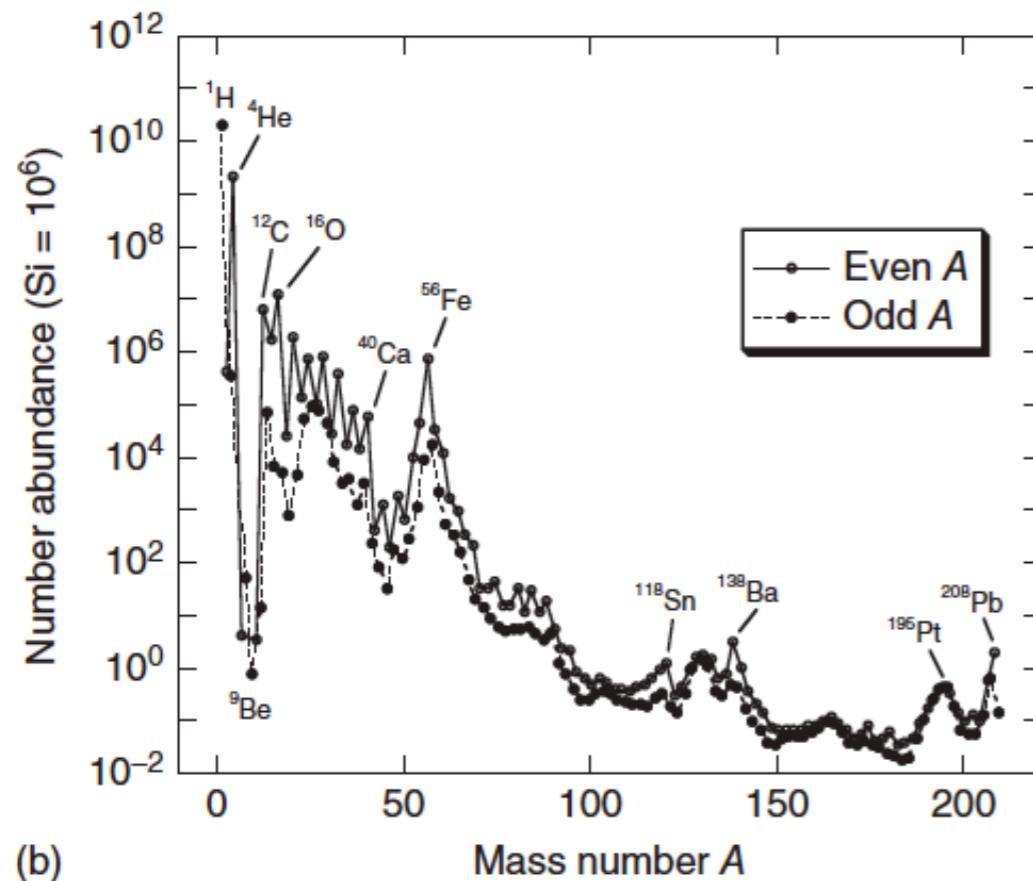
Y-axis spans more than 12 orders of magnitude!

Abundance generally decreases with A

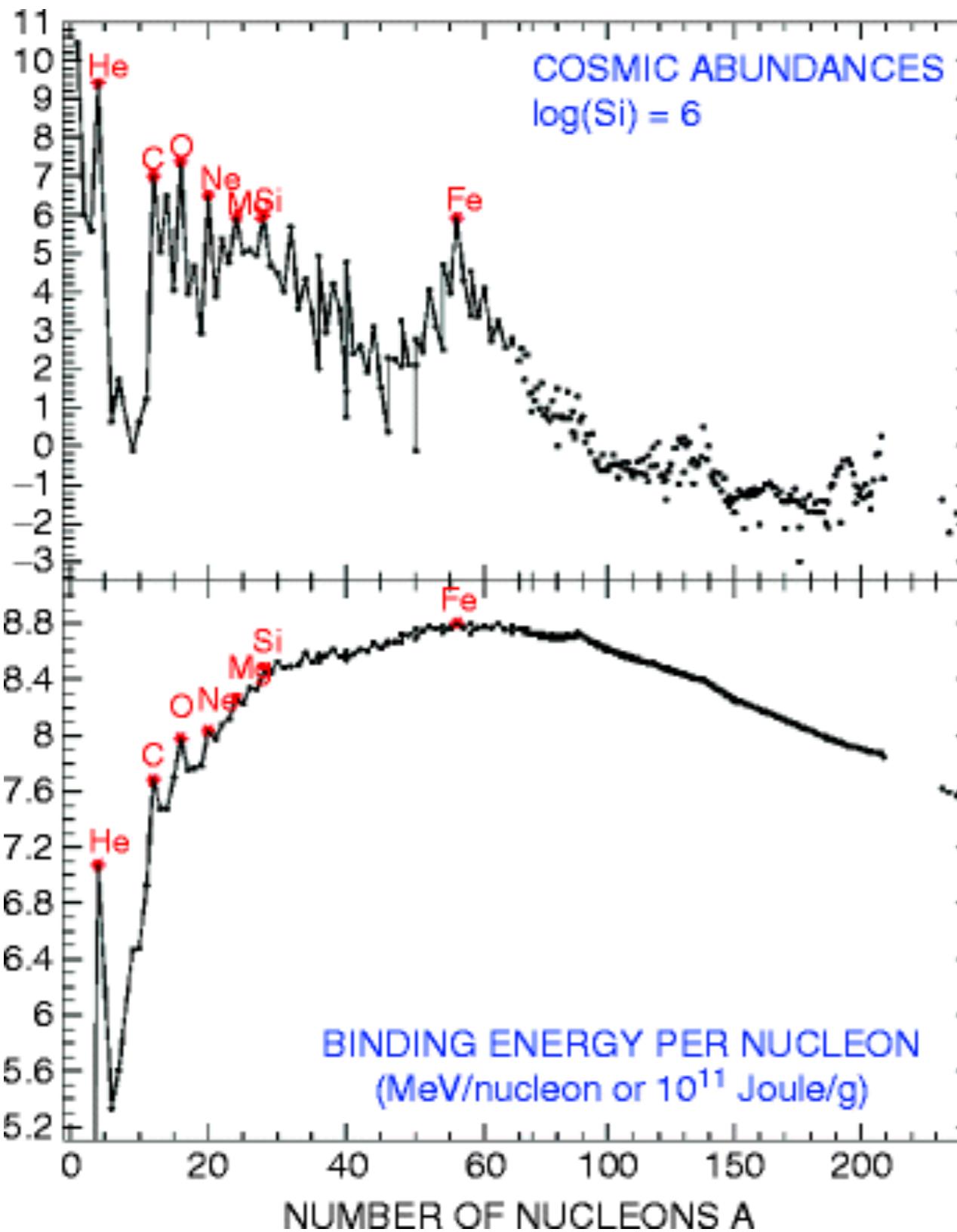
Some light elements like Li, Be and B appear to be rare

“zigzag” pattern: most odd- A nuclei are less abundant than their even- A neighbors

Local maxima: oxygen, iron, barium etc.: generally for Z or N equal to 2, 20, 28, 50, 82 and 126



Abundances and nuclear processes



Elemental abundances are correlated with nuclear properties!

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

Conclusion

Abundances are written in the language of nuclear physics

Nuclear charges inhibit nuclei from relaxing to equilibrium abundances.

What could counter charge repulsion?
High temperatures → deep gravity potentials

Where does nucleosynthesis take place?

Debate in the 40s -50s

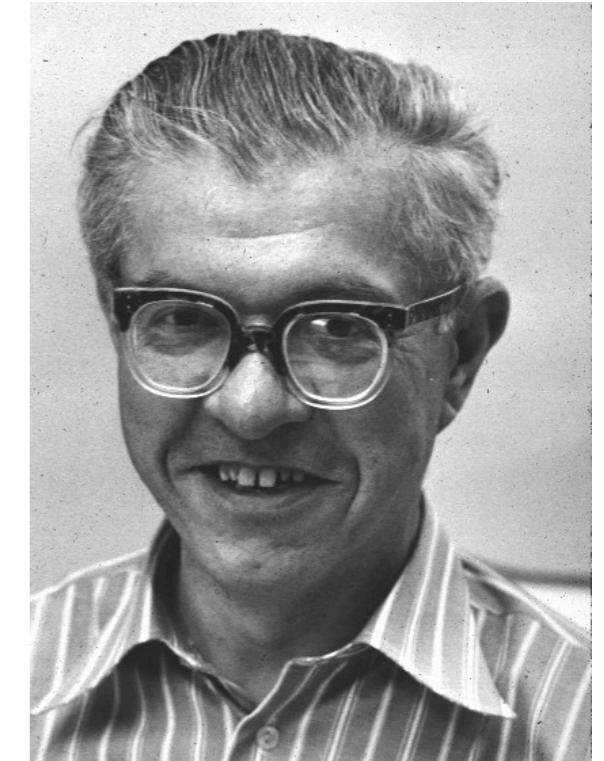
Primordial or Big-bang nucleosynthesis vs stars and supernovae



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

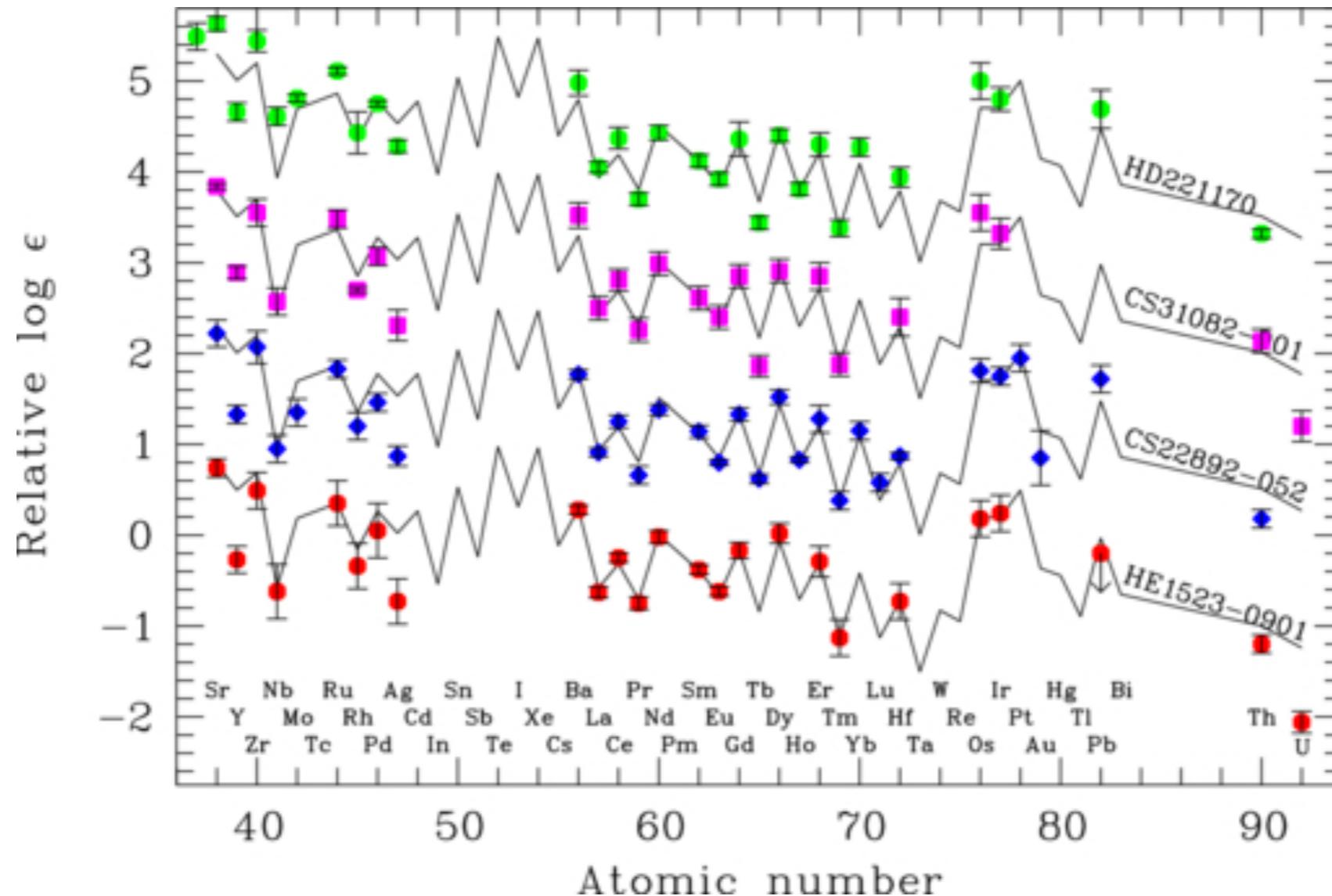


Fred Hoyle (1915–2001)

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



...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

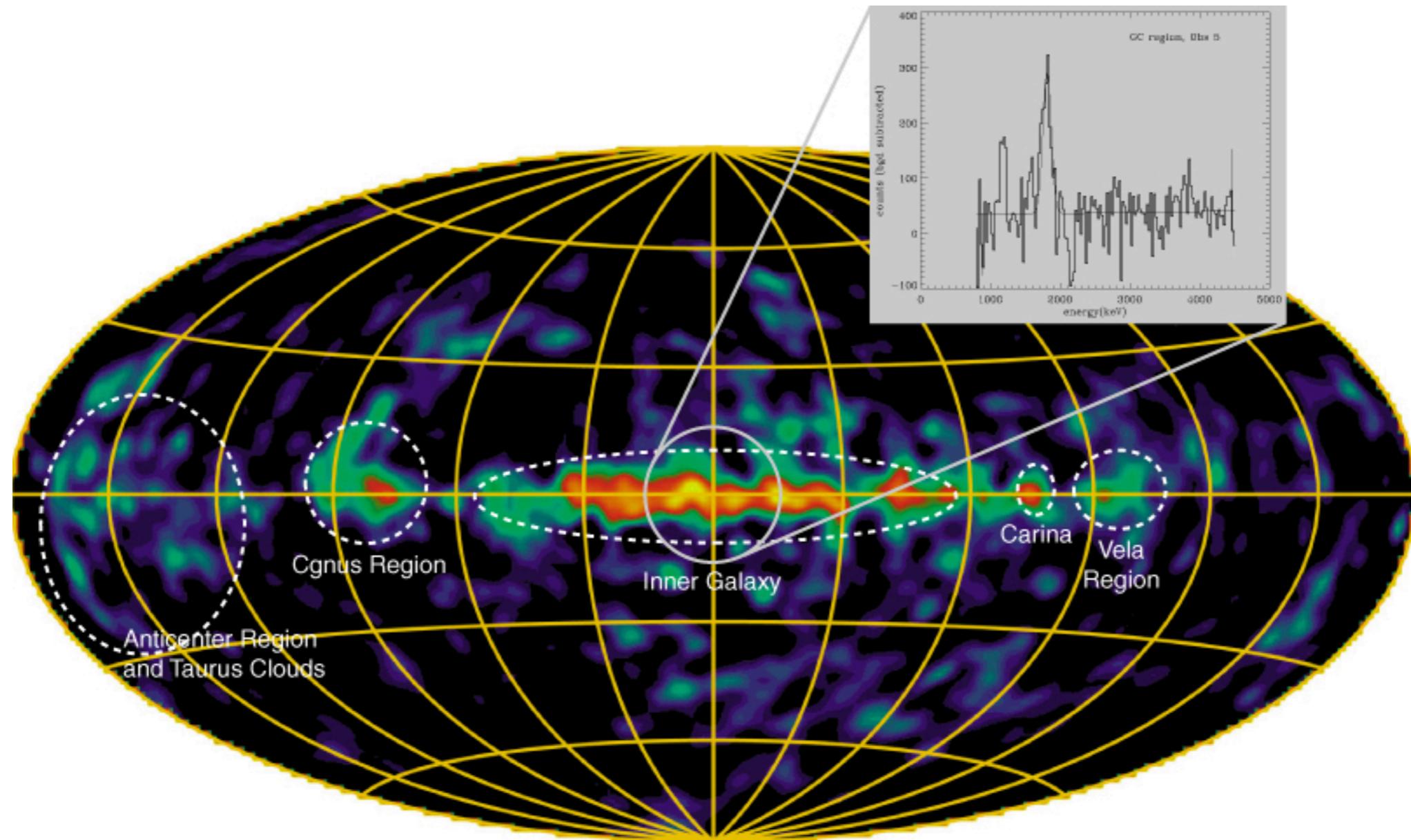
Synthesis of the Elements in Stars*

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



Modern observational evidence for nucleosynthesis

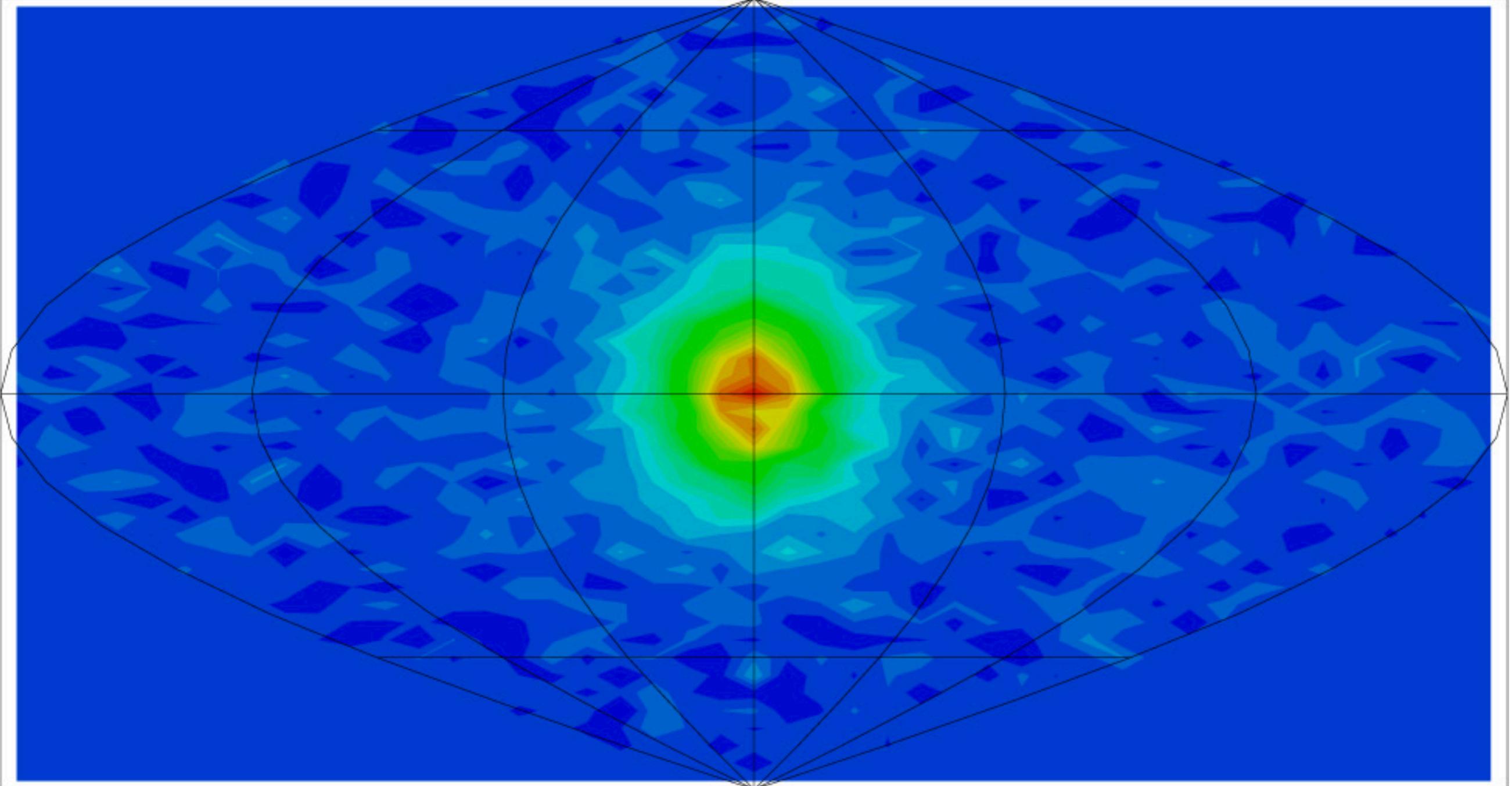
More (in)direct evidence for ongoing nucleosynthesis



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

Modern observational evidence for nucleosynthesis

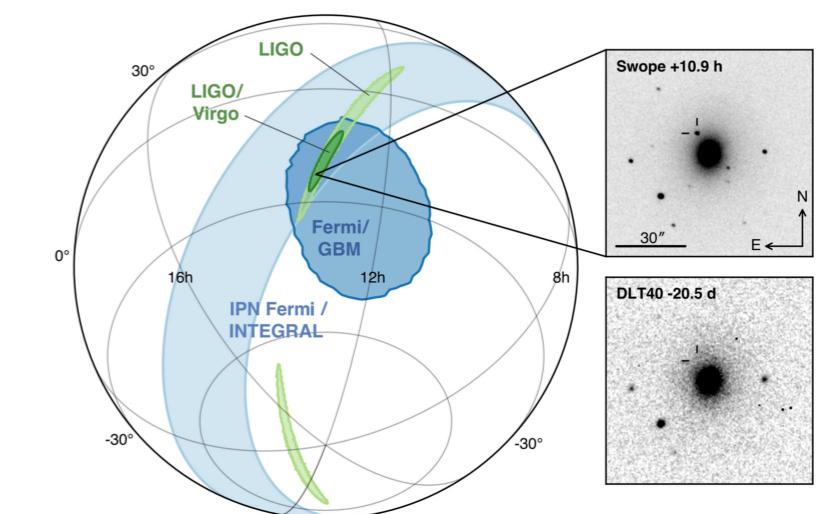
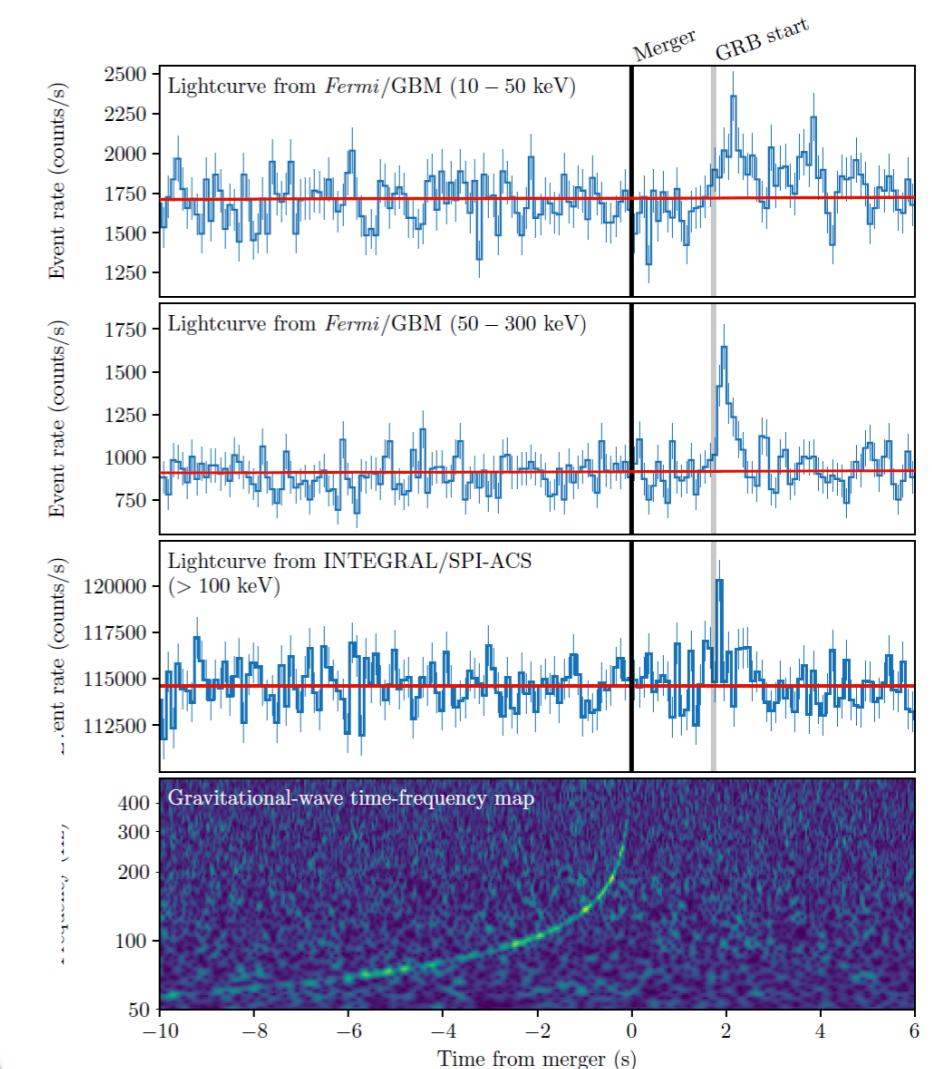
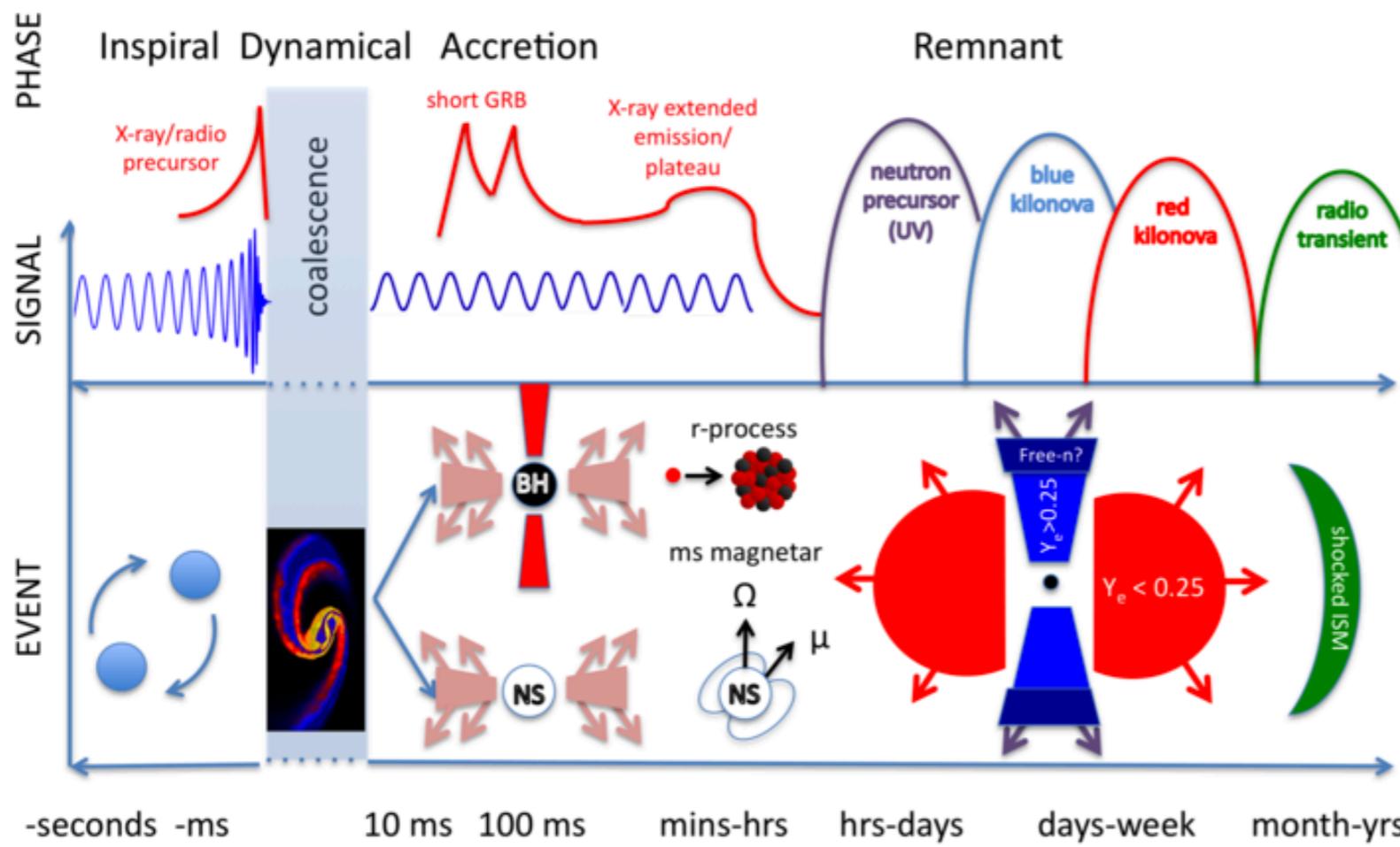
More (in)direct evidence for ongoing nucleosynthesis



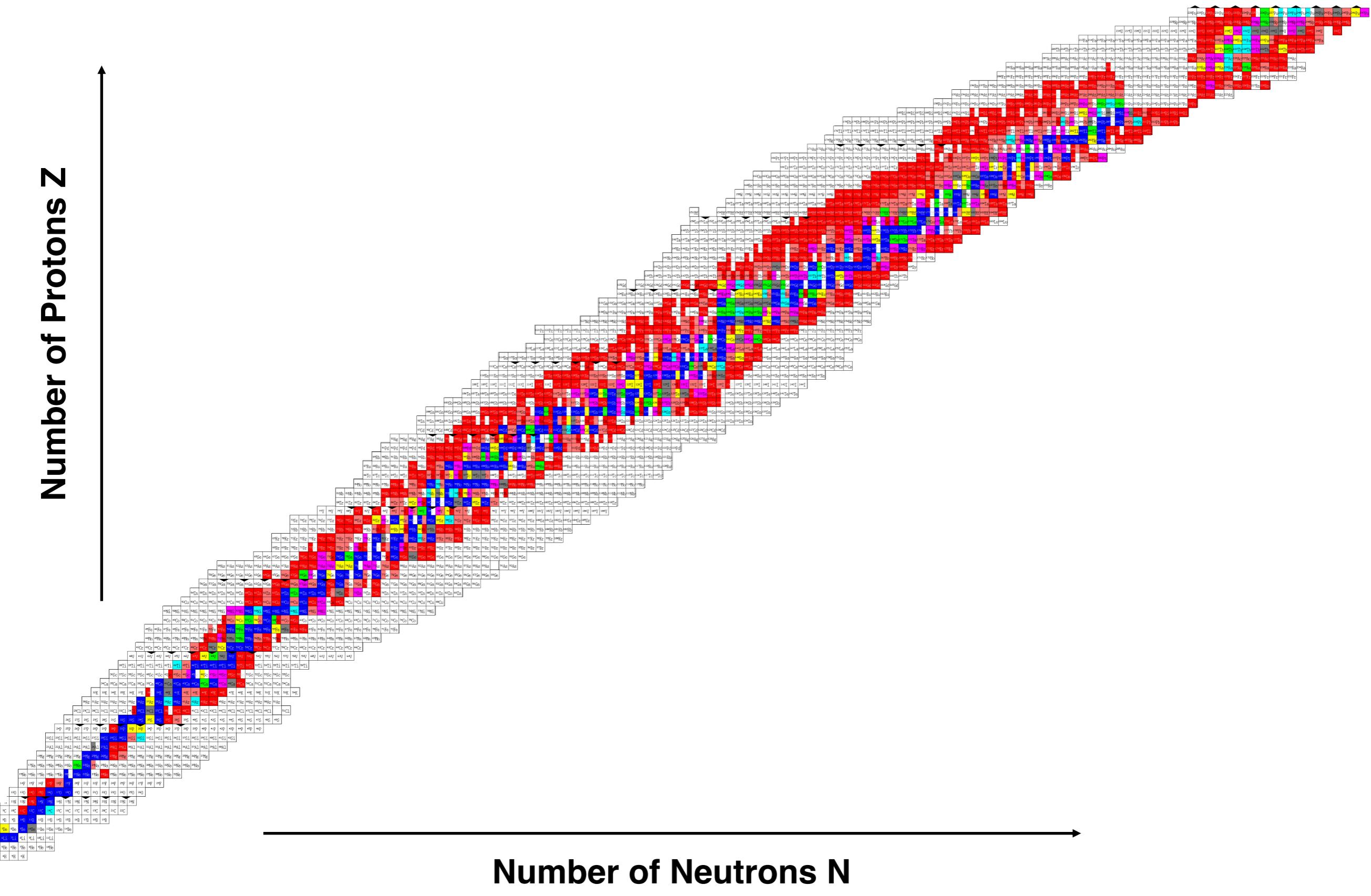
example 2: observation of solar neutrinos

Modern observational evidence for nucleosynthesis

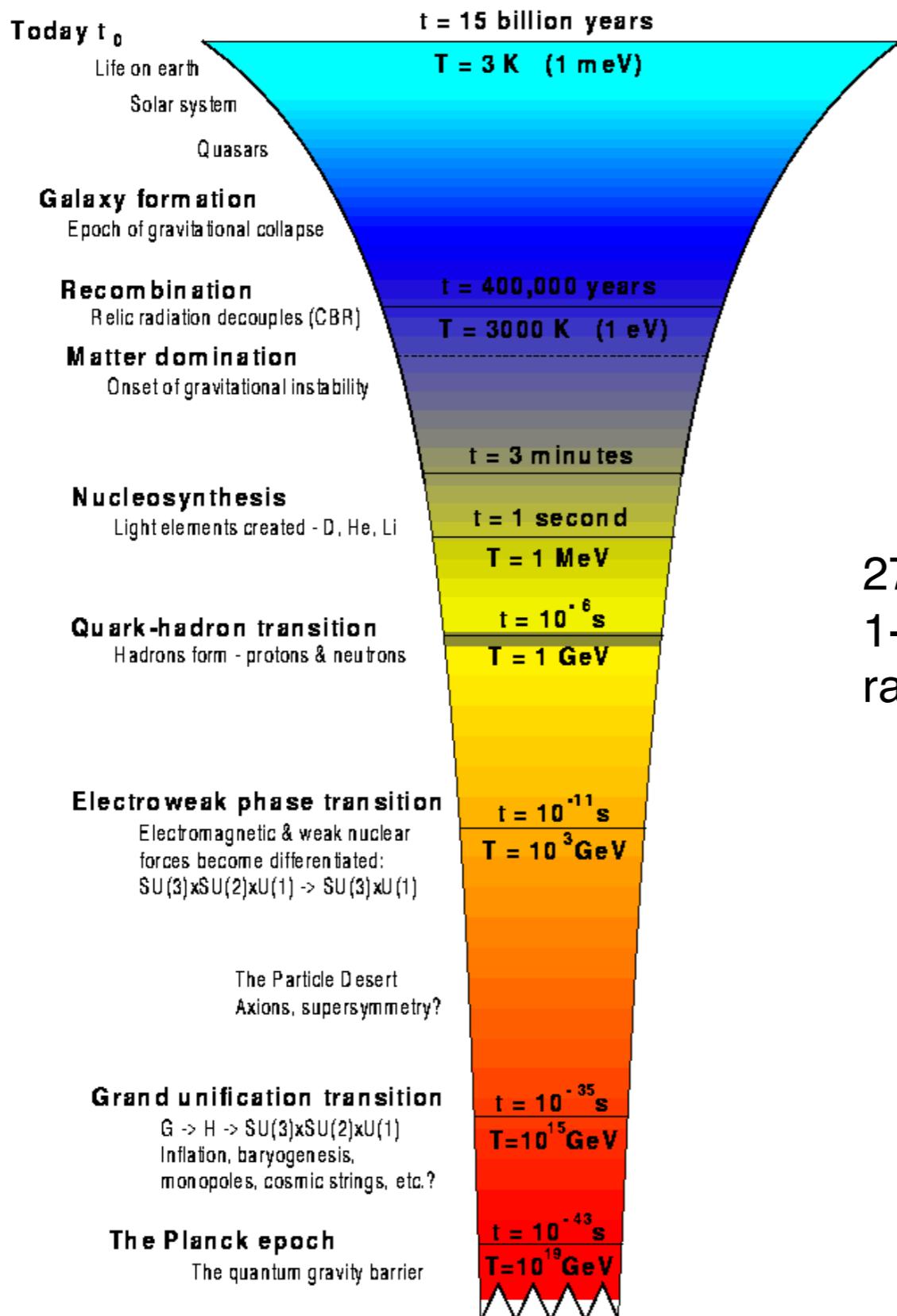
GW 170814



Lectures 2 and 3: Nuclear properties and thermonuclear reactions



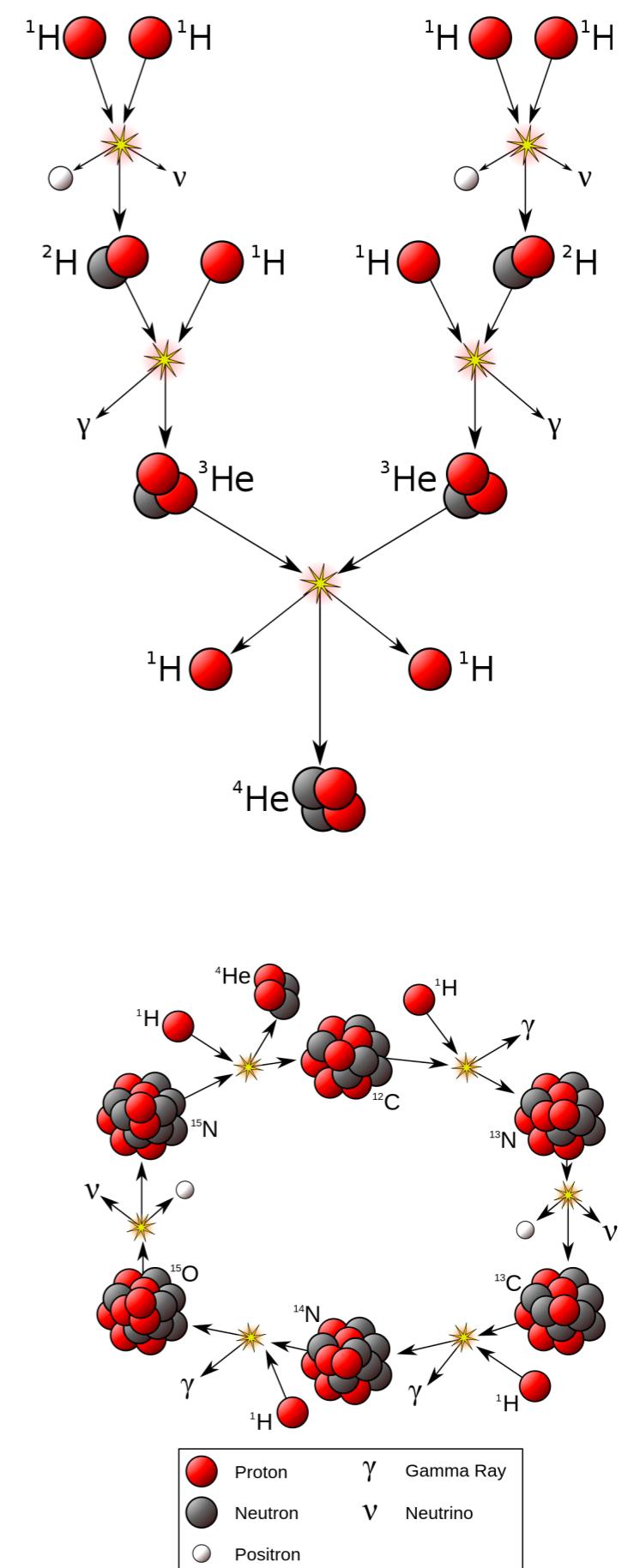
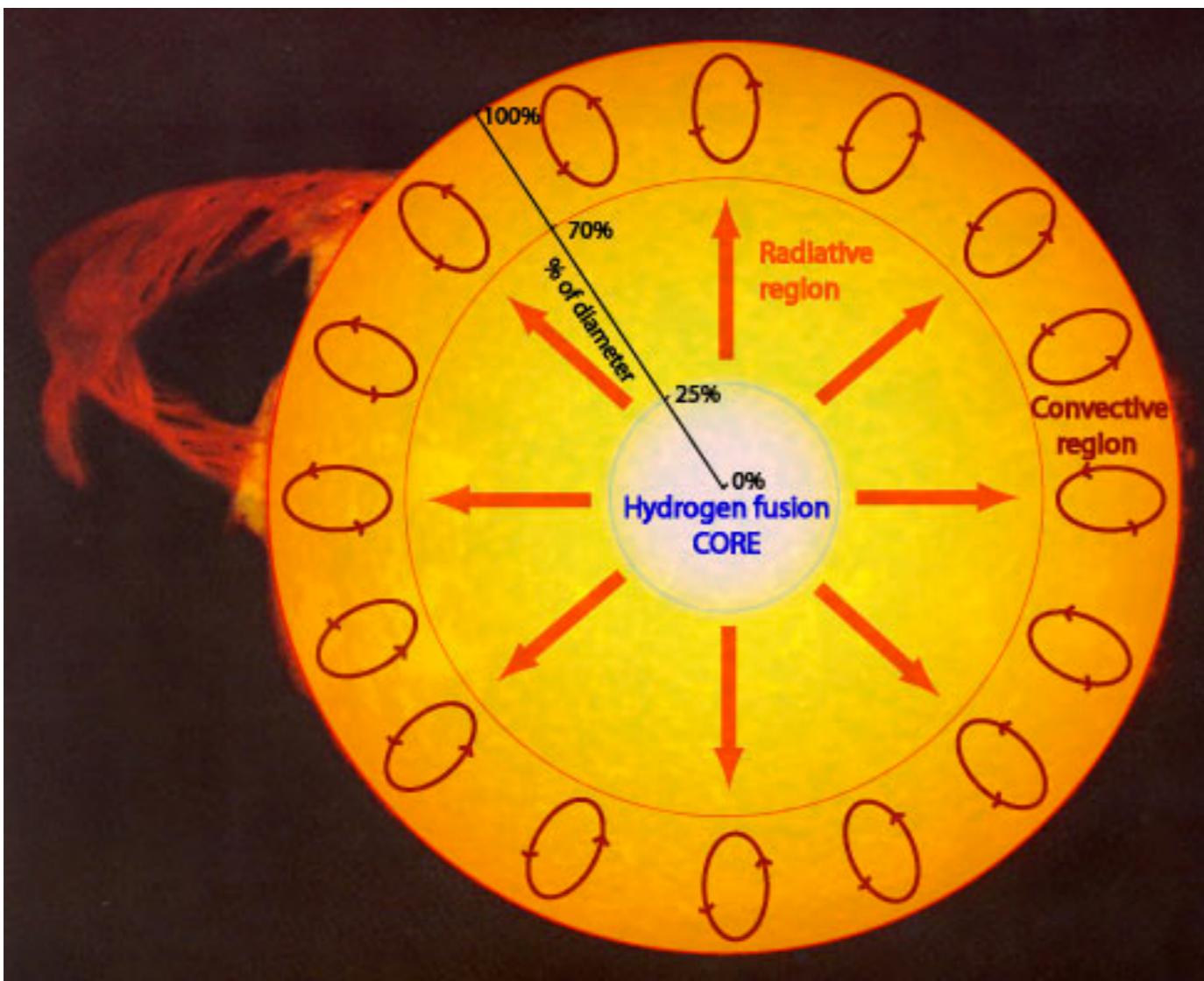
Lecture 4: Primordial nucleosynthesis



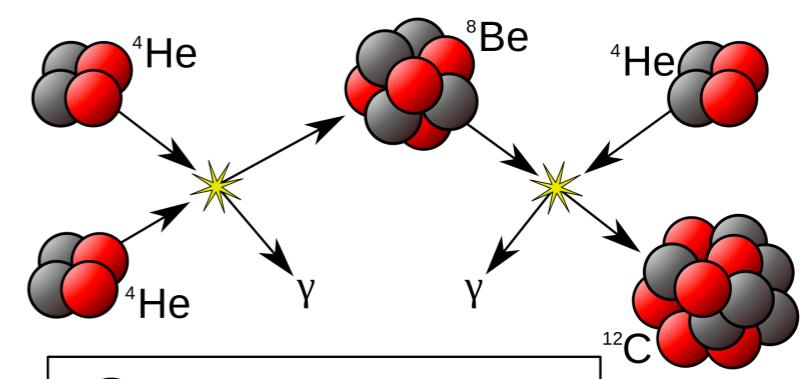
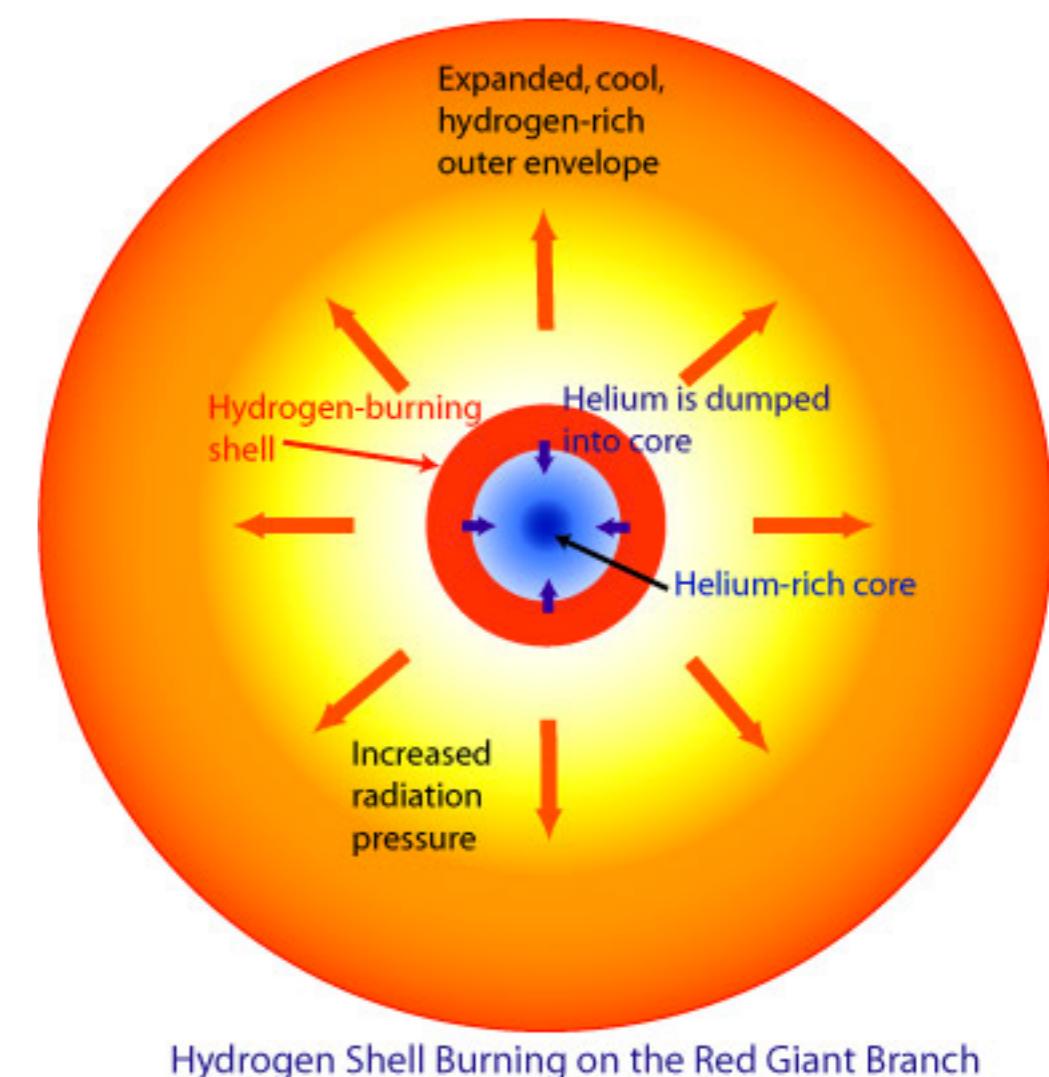
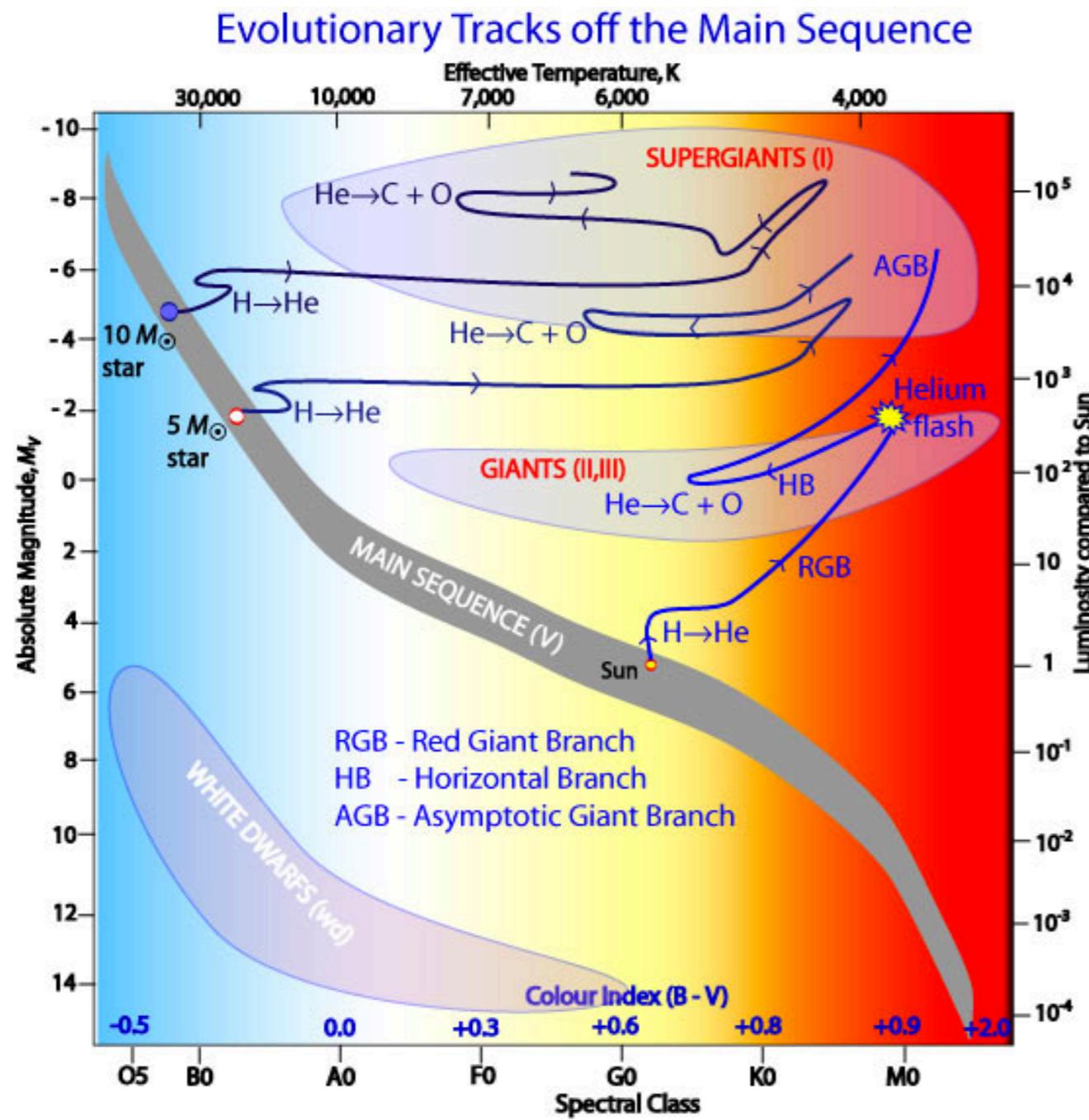
27% He requires primordial origin
1-3 sec after Big Bang: High temperatures but rapid cooling

Lectures 5 and 6: Hydrogen burning

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



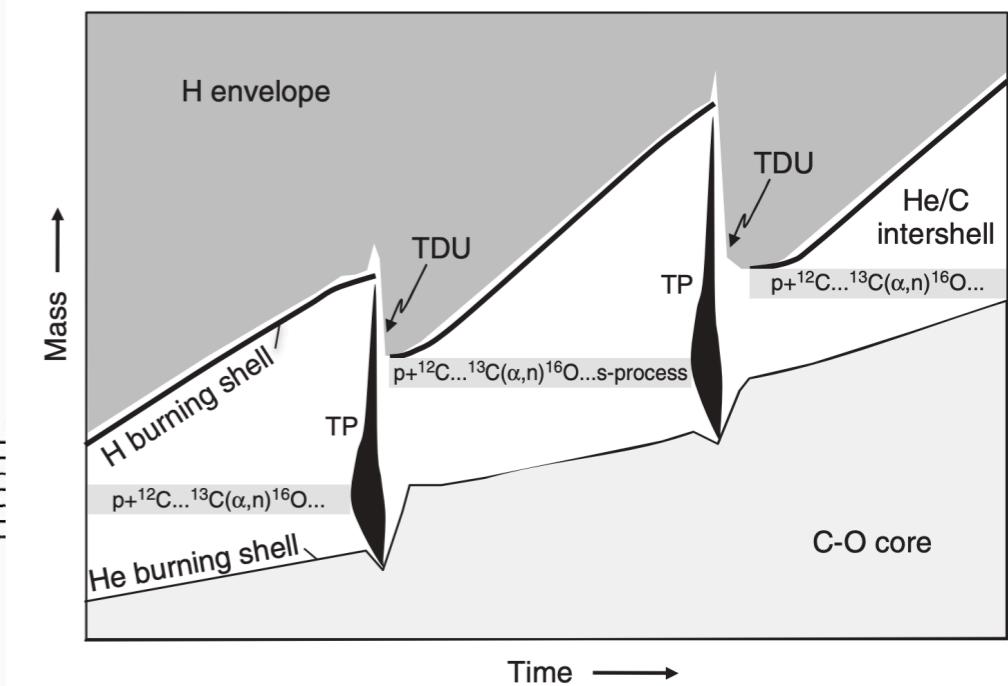
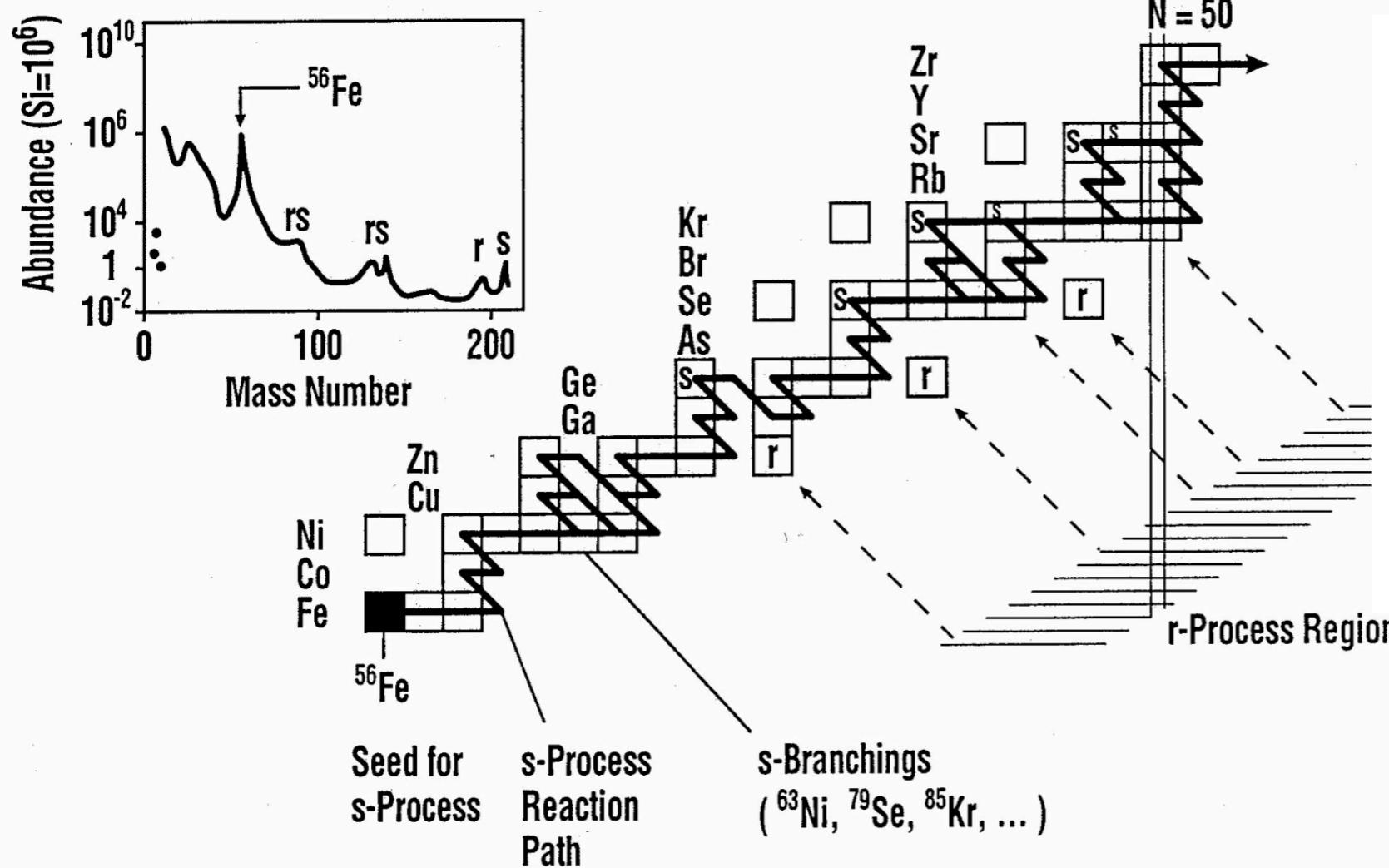
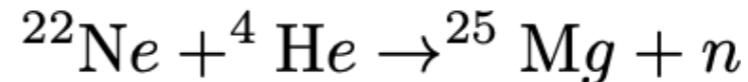
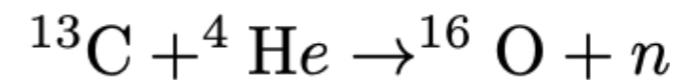
Lecture 7: Helium burning and beyond



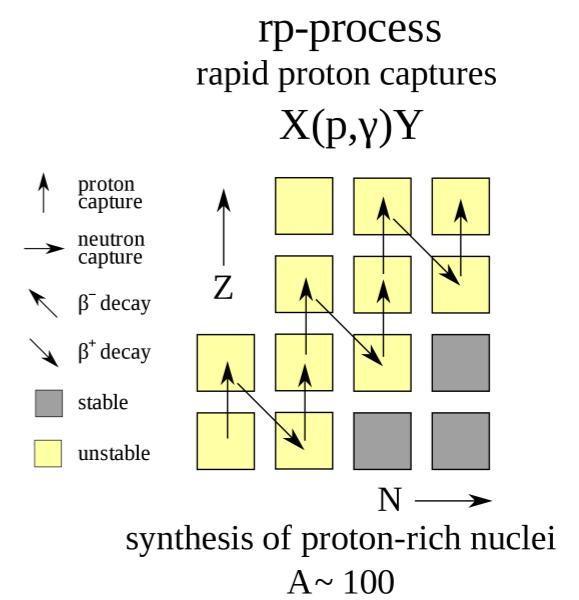
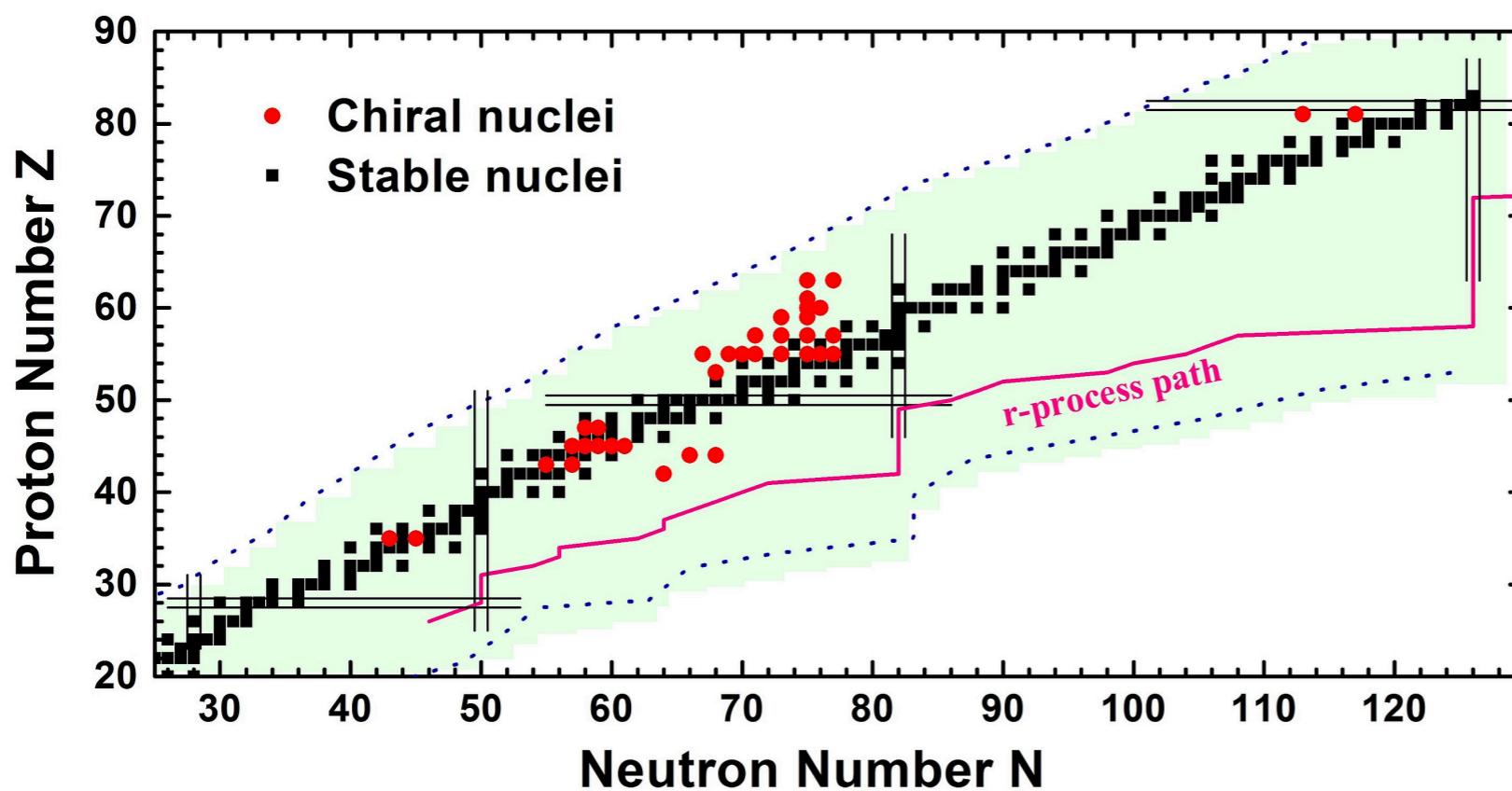
Wikipedia

Lecture 8: slow neutron captures (s-process)

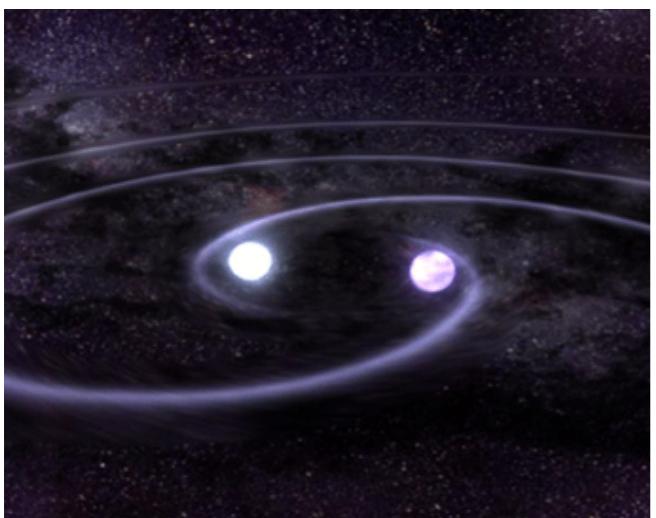
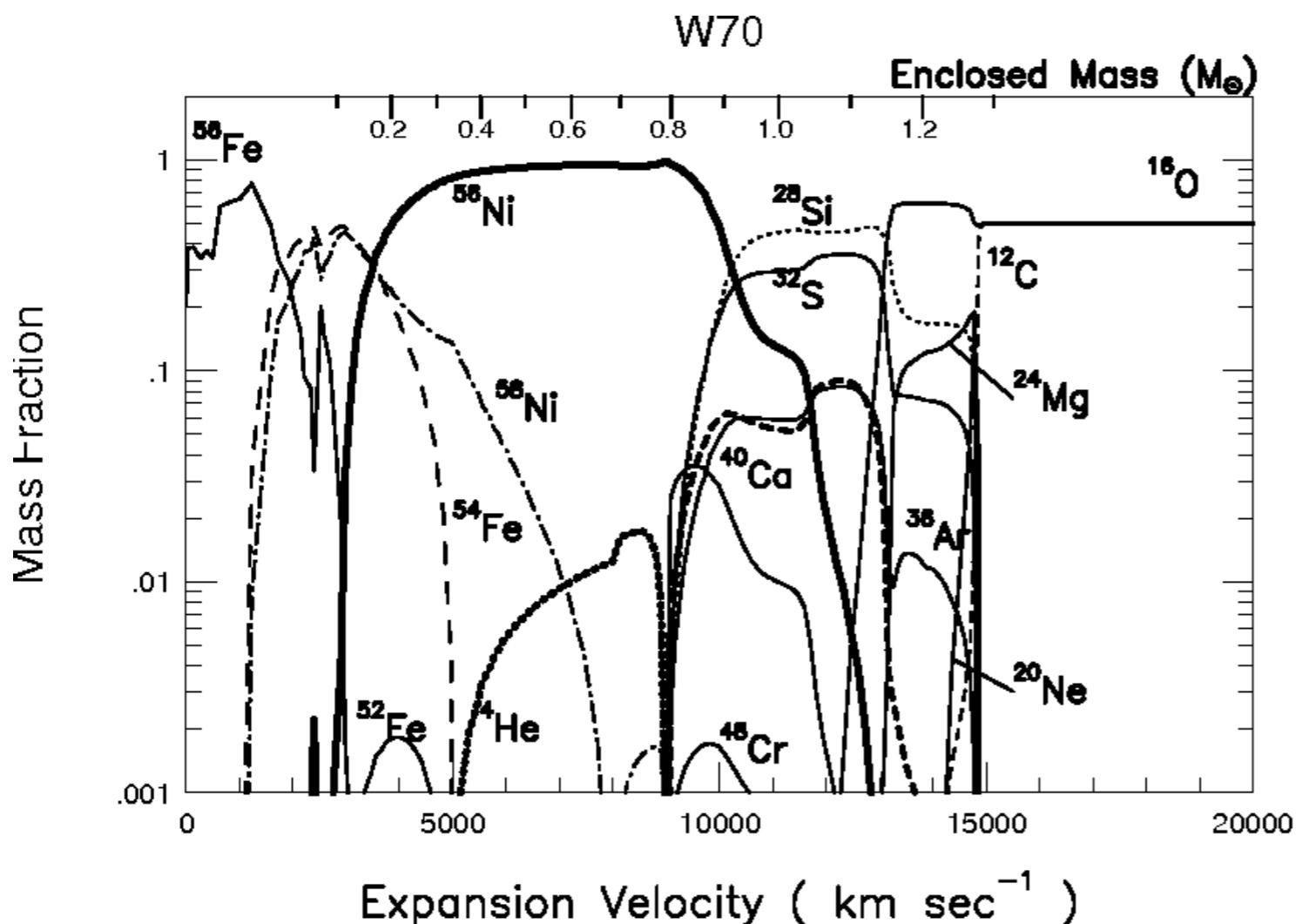
main neutron sources



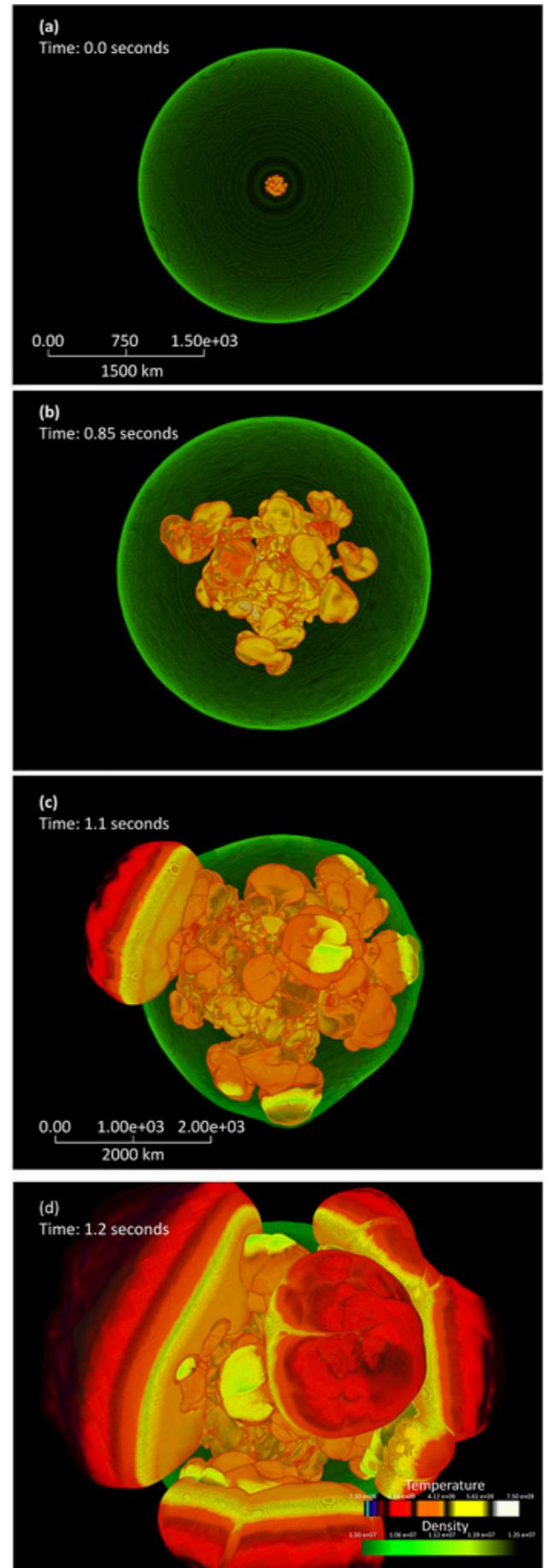
Lecture 9: explosive nucleosynthesis



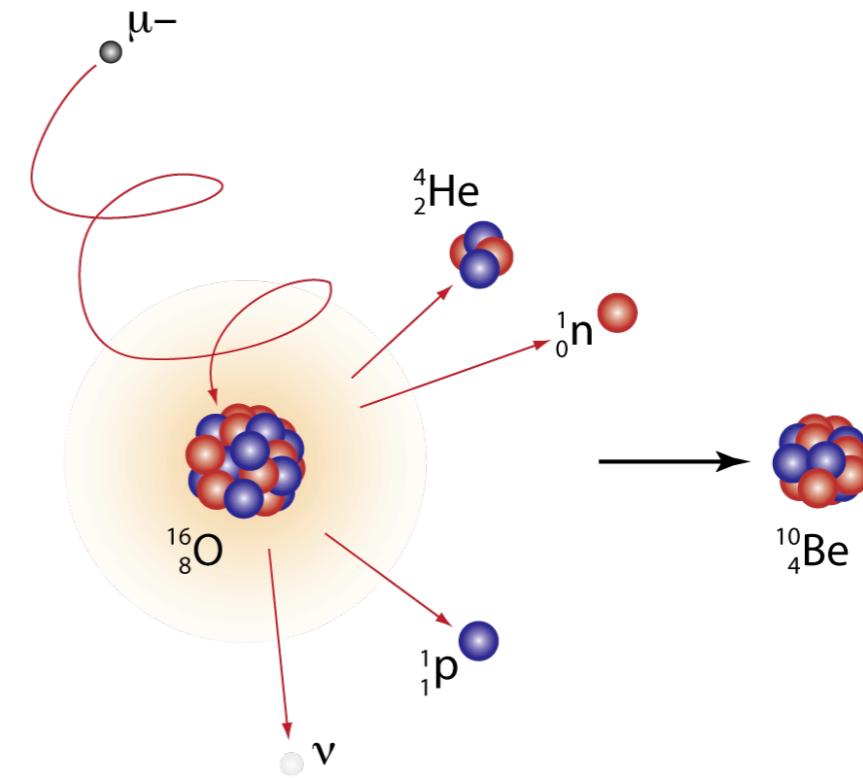
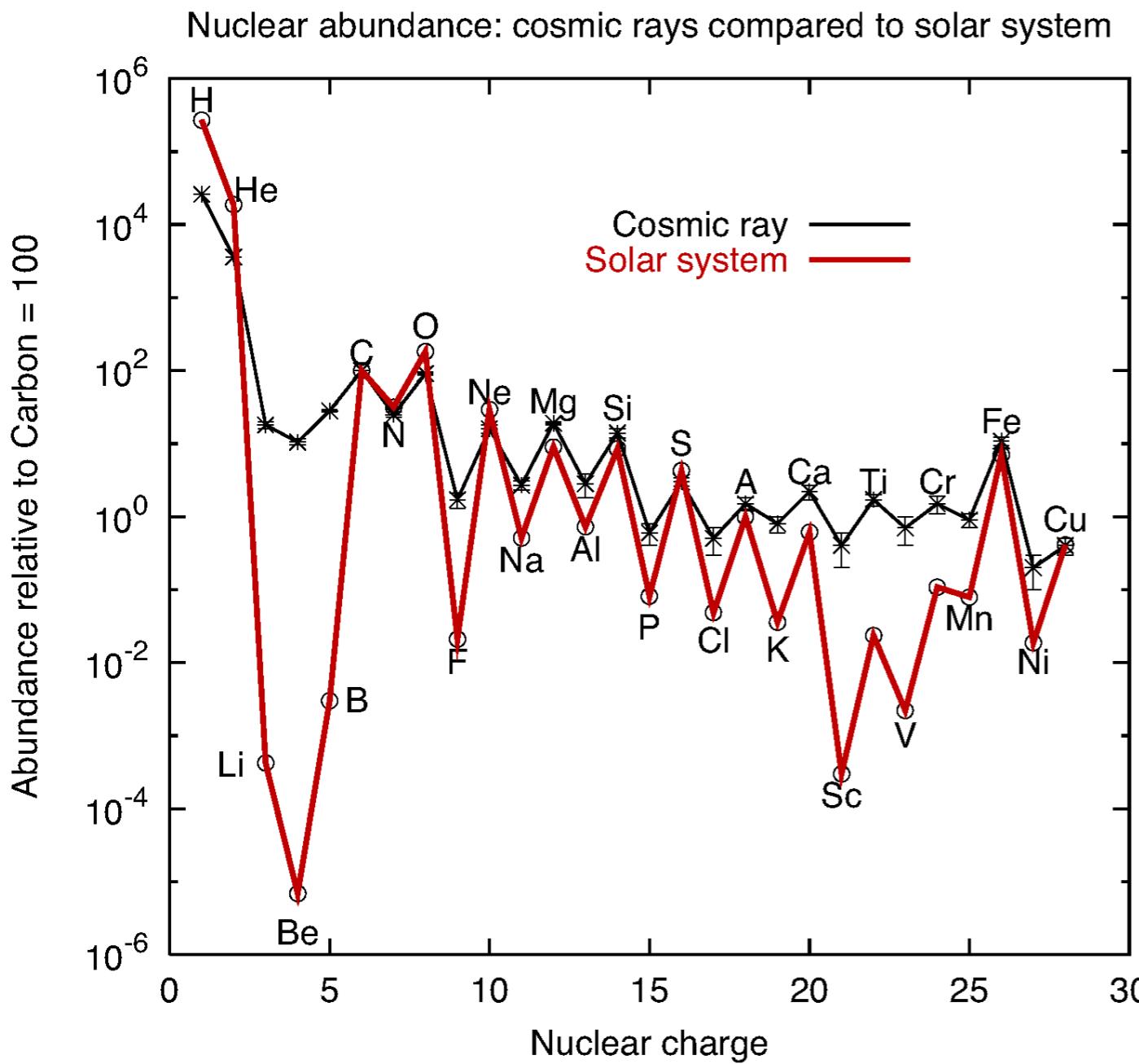
Lecture 10: Type Ia supernovae



Progenitors still debated
Responsible for most iron-peak elements



Lecture 11: CR-induced spallation



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

Lecture 12: galactic chemical evolution

Sun-like Star

