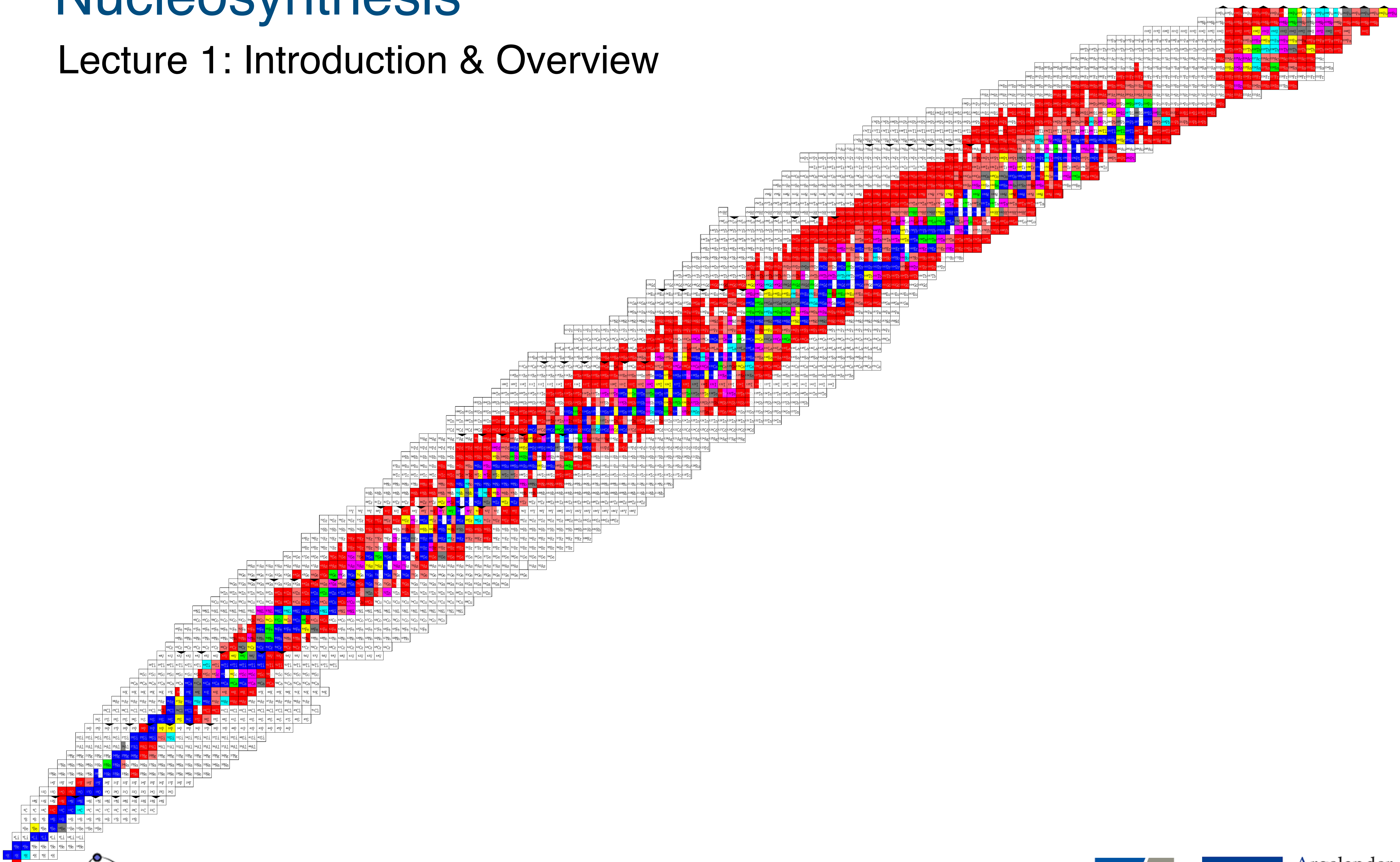
Nucleosynthesis

Lecture 1: Introduction & Overview



Bonn-Cologne Graduate School of Physics and Astronomy

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Argelander-Institut für Astronomie

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

UNIVERSITÄT BONN ads

Frequently Asked Questions

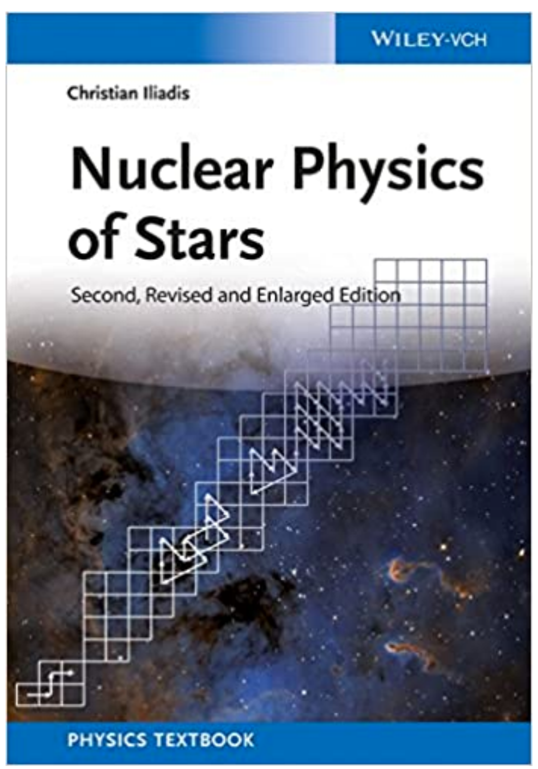
How do I study for the course?

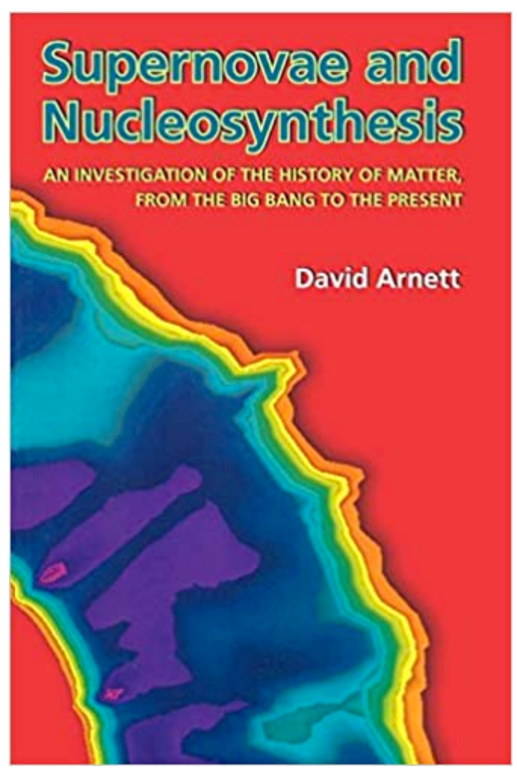
Course material

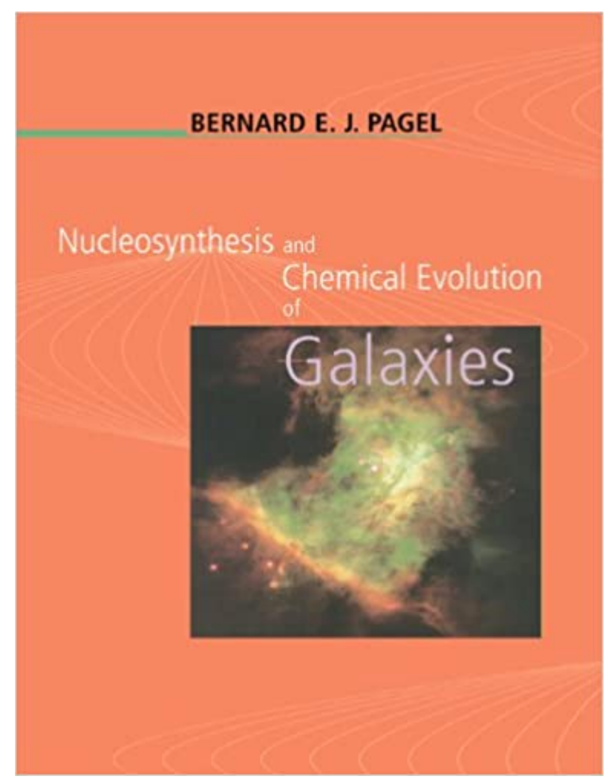
Presentations and Videos

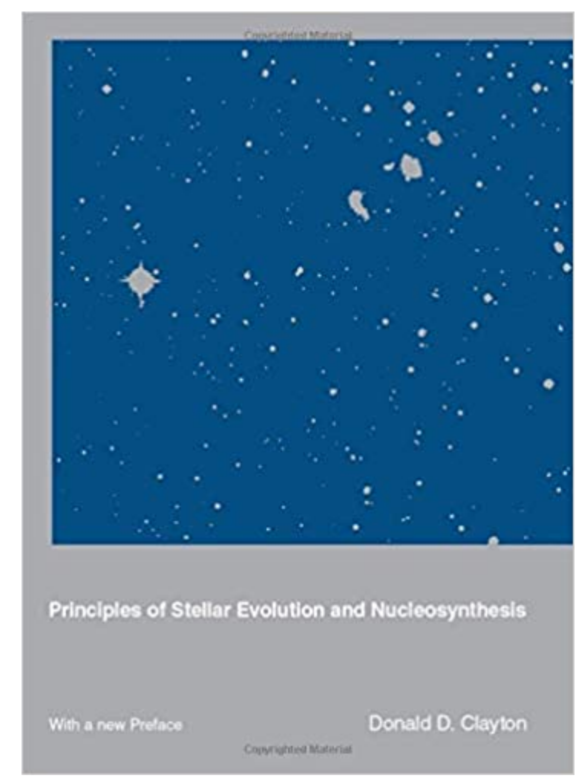
Lecture Notes by Prof. Norbert Langer (see website)

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







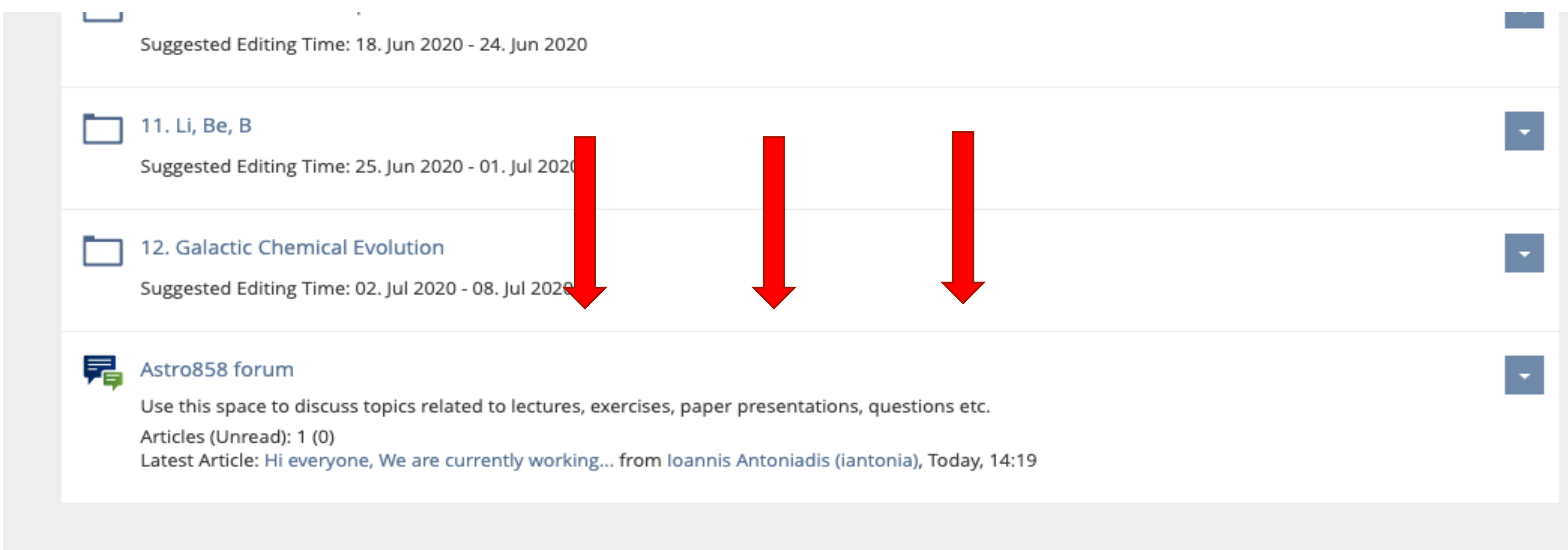


Credit

Evaluation

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

Questions?



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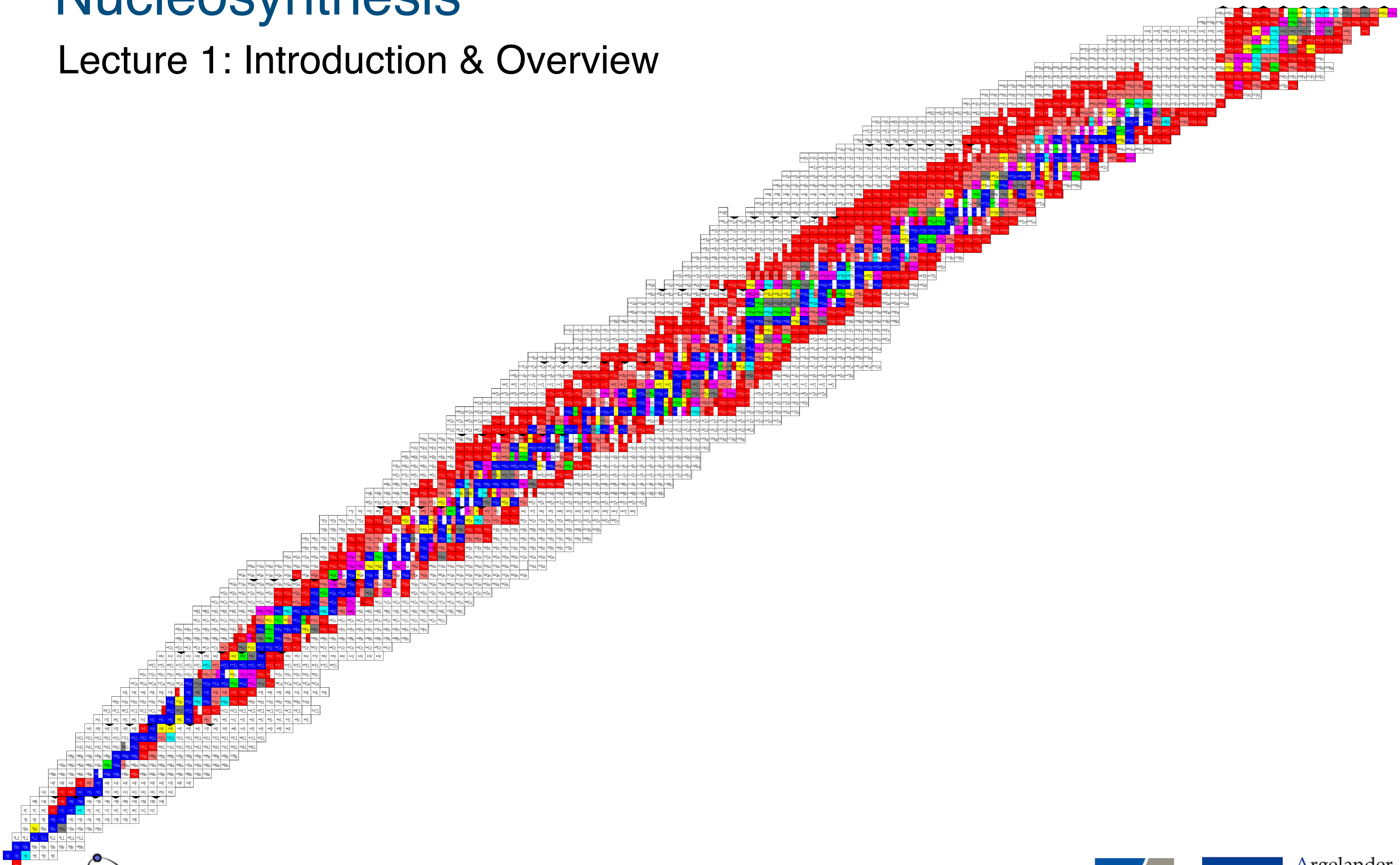

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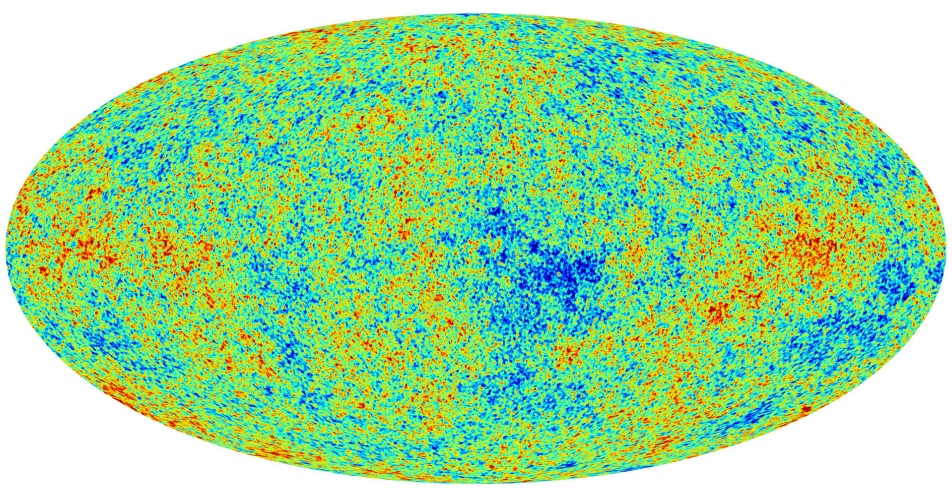
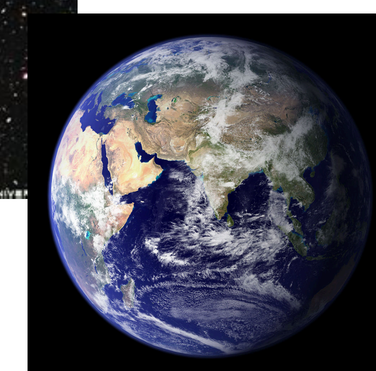
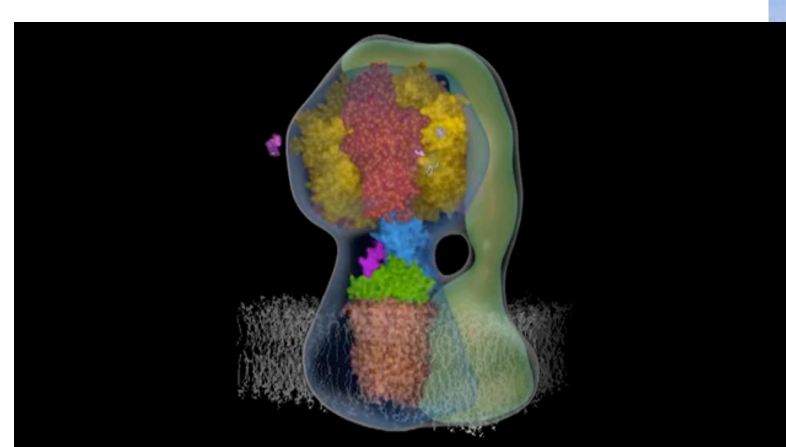
Overview

Goal:
explain the evolution and "current" distribution of isotopic abundances in the Universe

Big Bang → **Today**







Overview

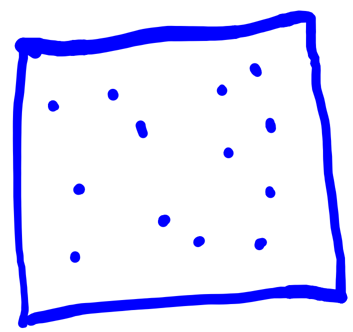
Goal:
explain the evolution and “current” distribution of isotopic abundances in the Universe

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: $Y_j = N_j/N_{\rm total}$

$$E_{\rm j} = N_{\rm j} - N_{\rm H} = \log(N_{\rm j}/N_{\rm H})$$

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

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

Relative to solar: $[X_i/X_j] = log(X_i/X_j) - log(X_i/X_j)_\odot \rightarrow [X_i/X_j]_\odot = 0$

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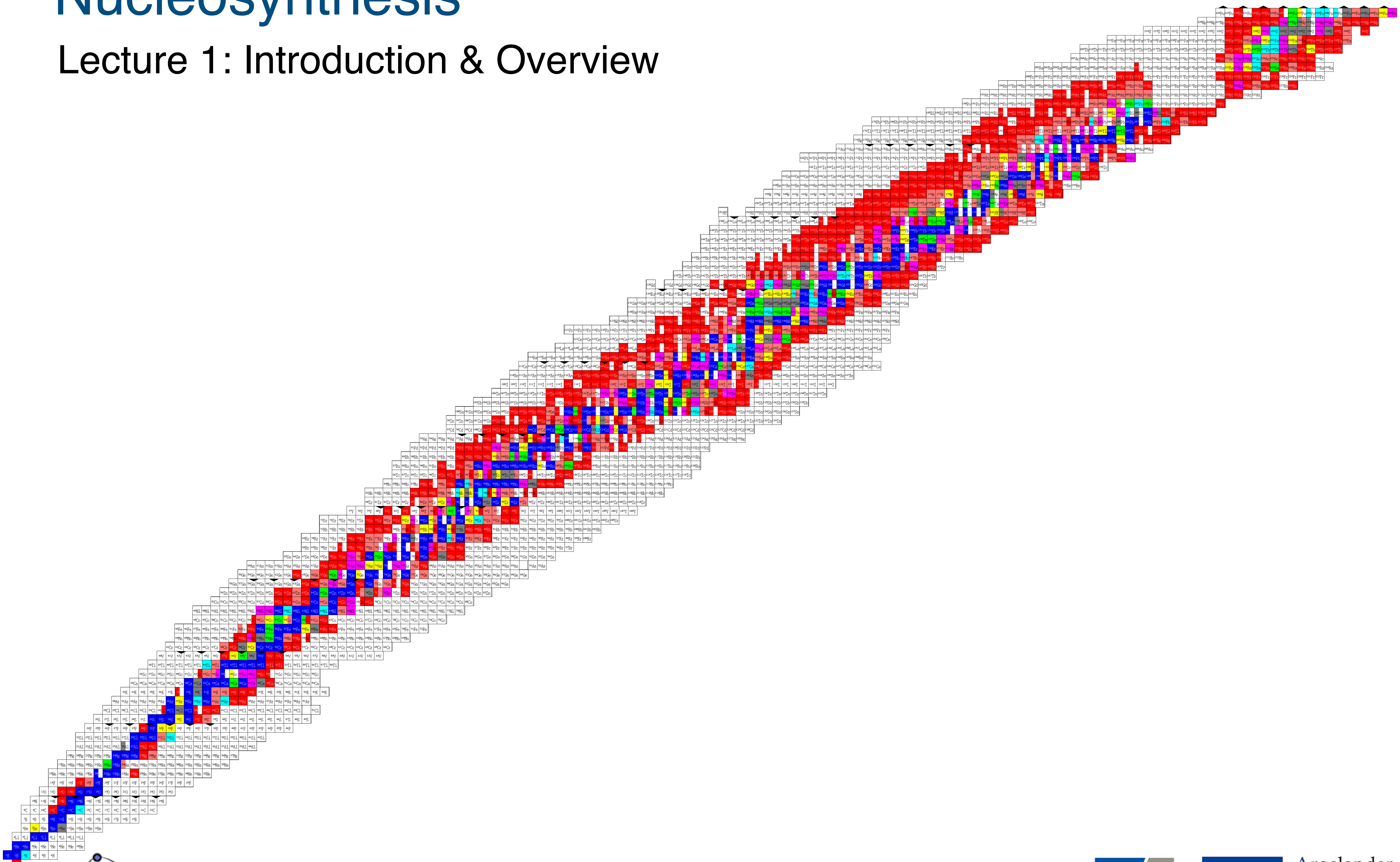

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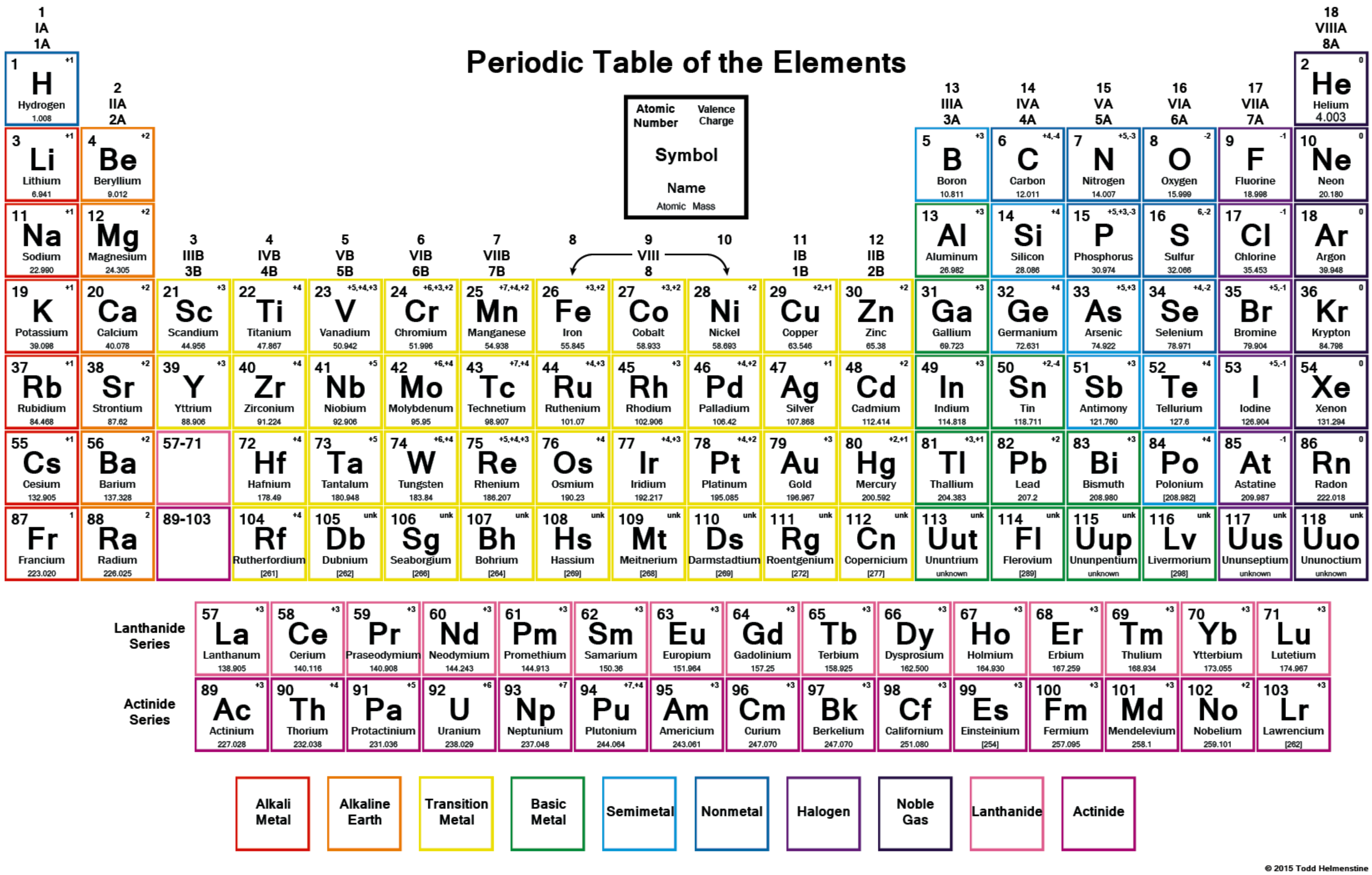
Chemical elements

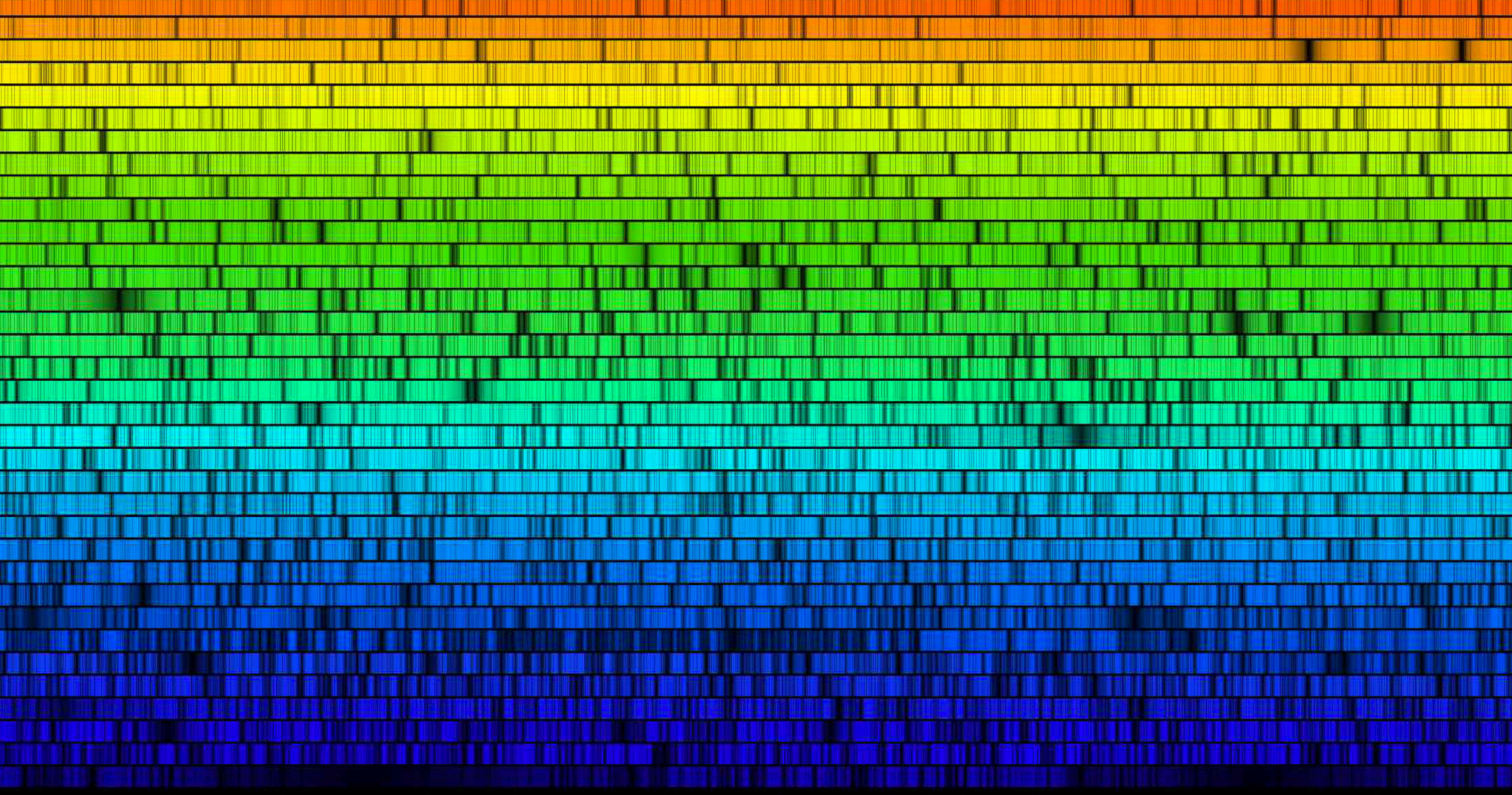


Measurement of Elemental Abundances — the Sun and the Stars

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

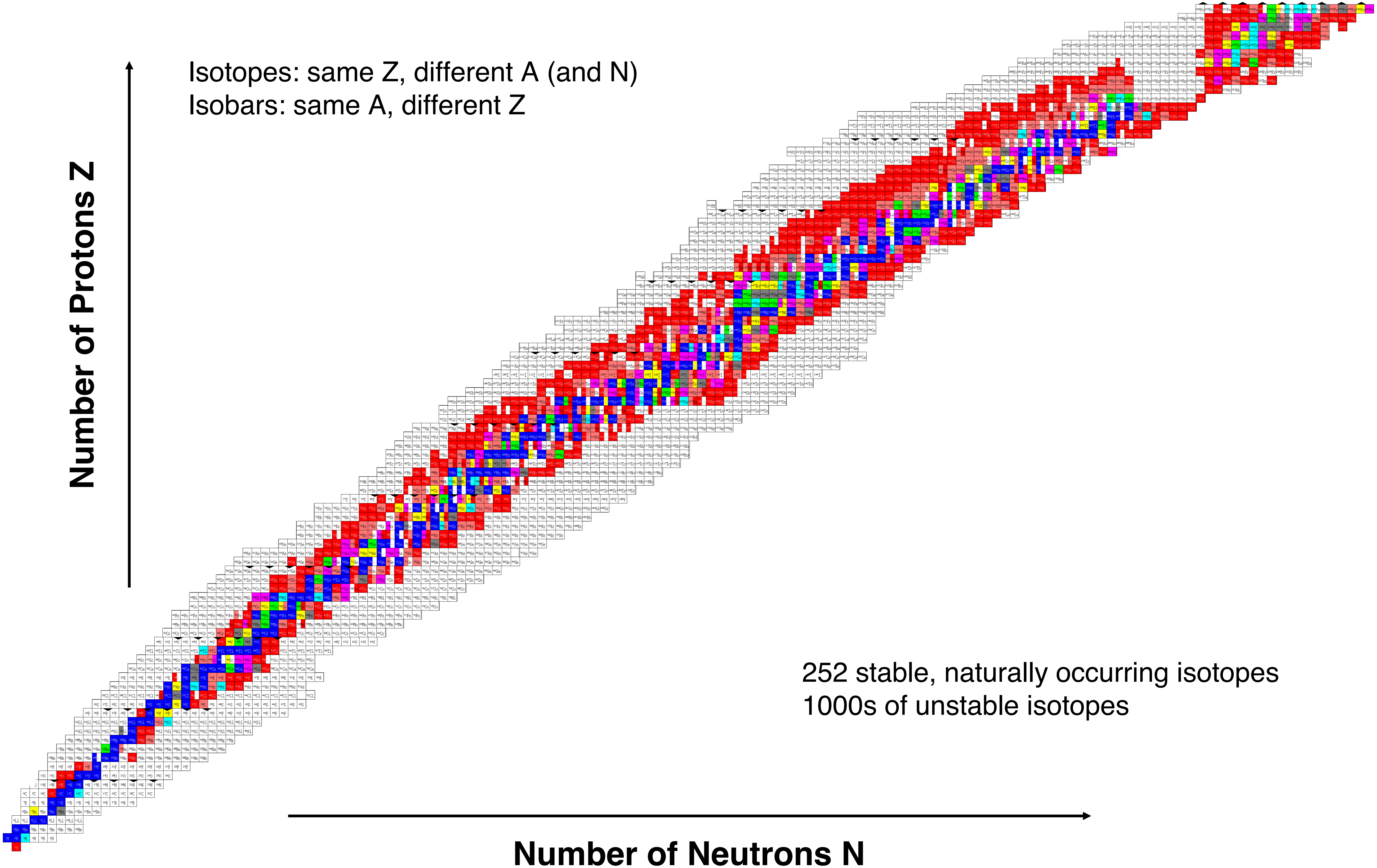
"Metals"

…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

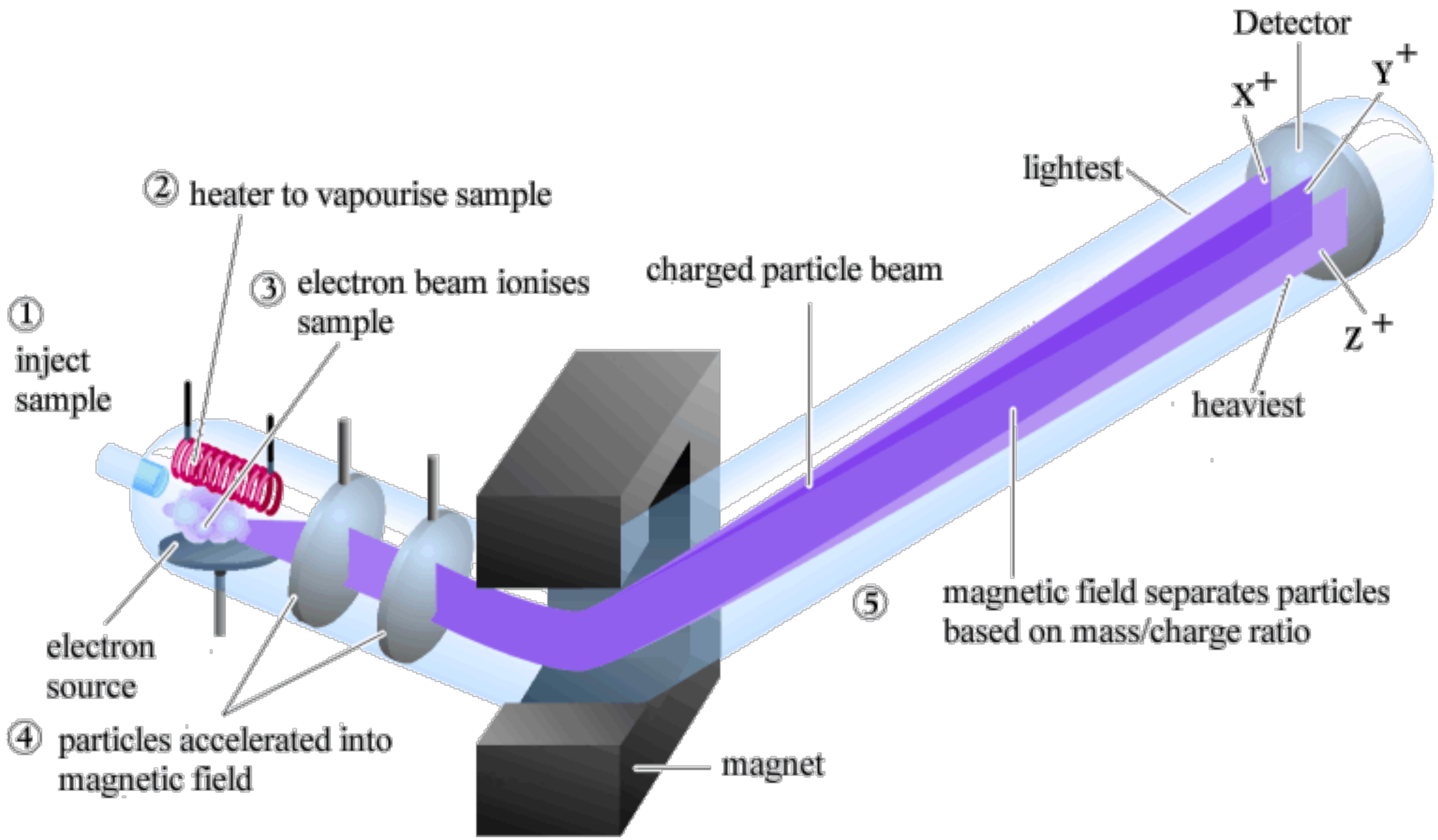
Isotopes: same Z, different A (and N)
Isobars: same A, different Z



252 stable, naturally occurring isotopes
1000s of unstable isotopes

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

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 could that formed the solar system**

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

Homogeneous solar system composition

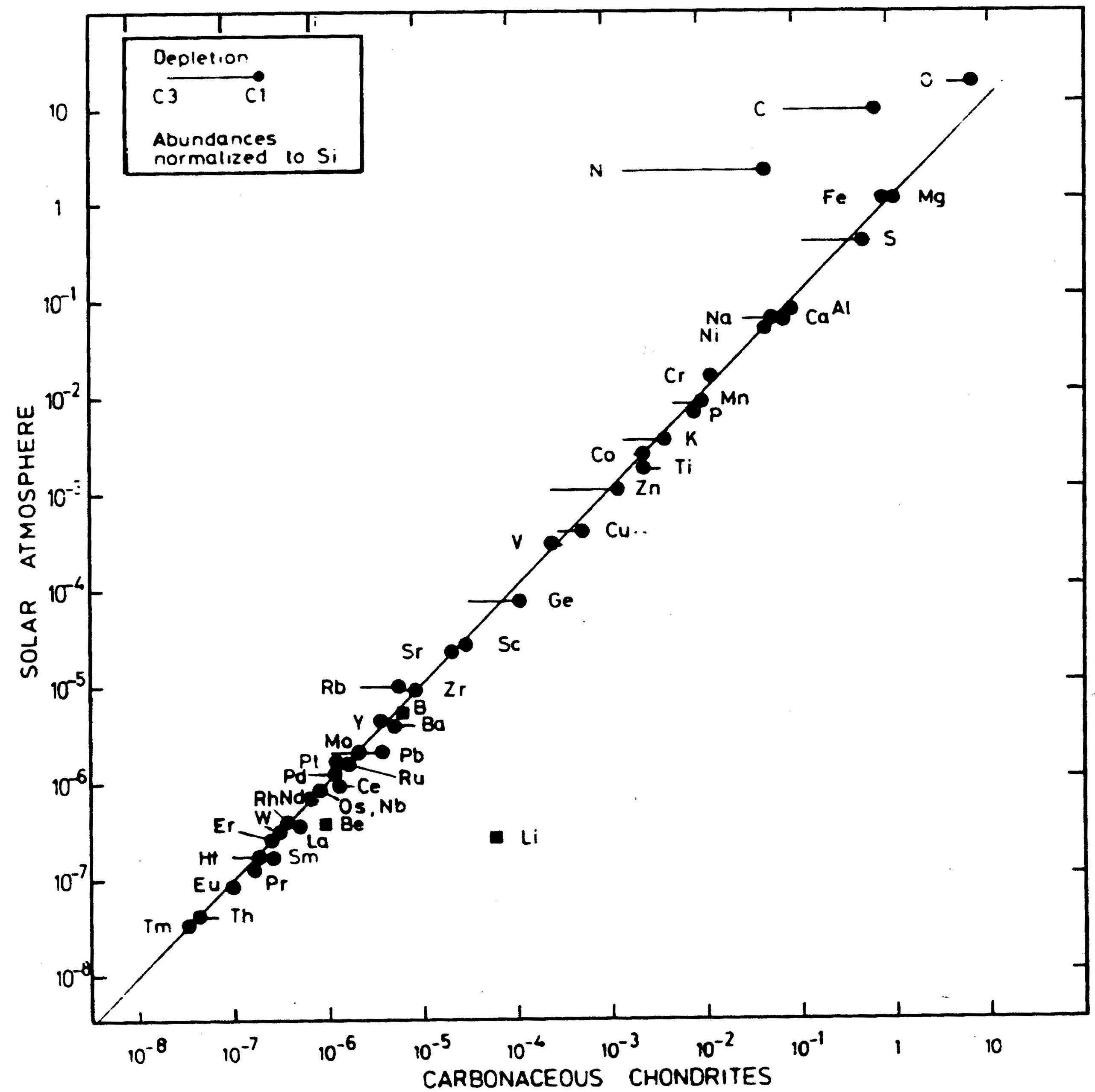
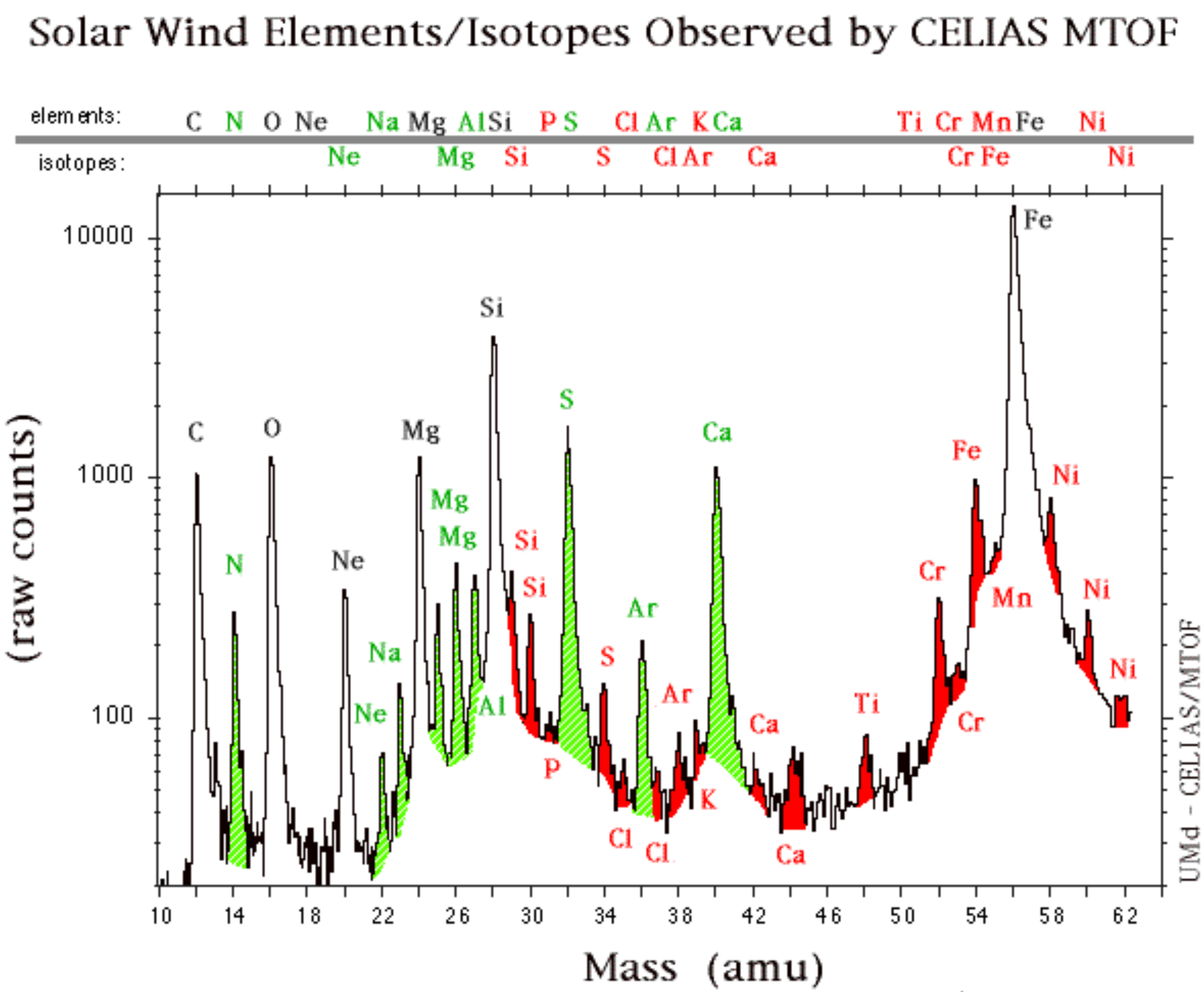


Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

…but they also contrain pre-solar grains

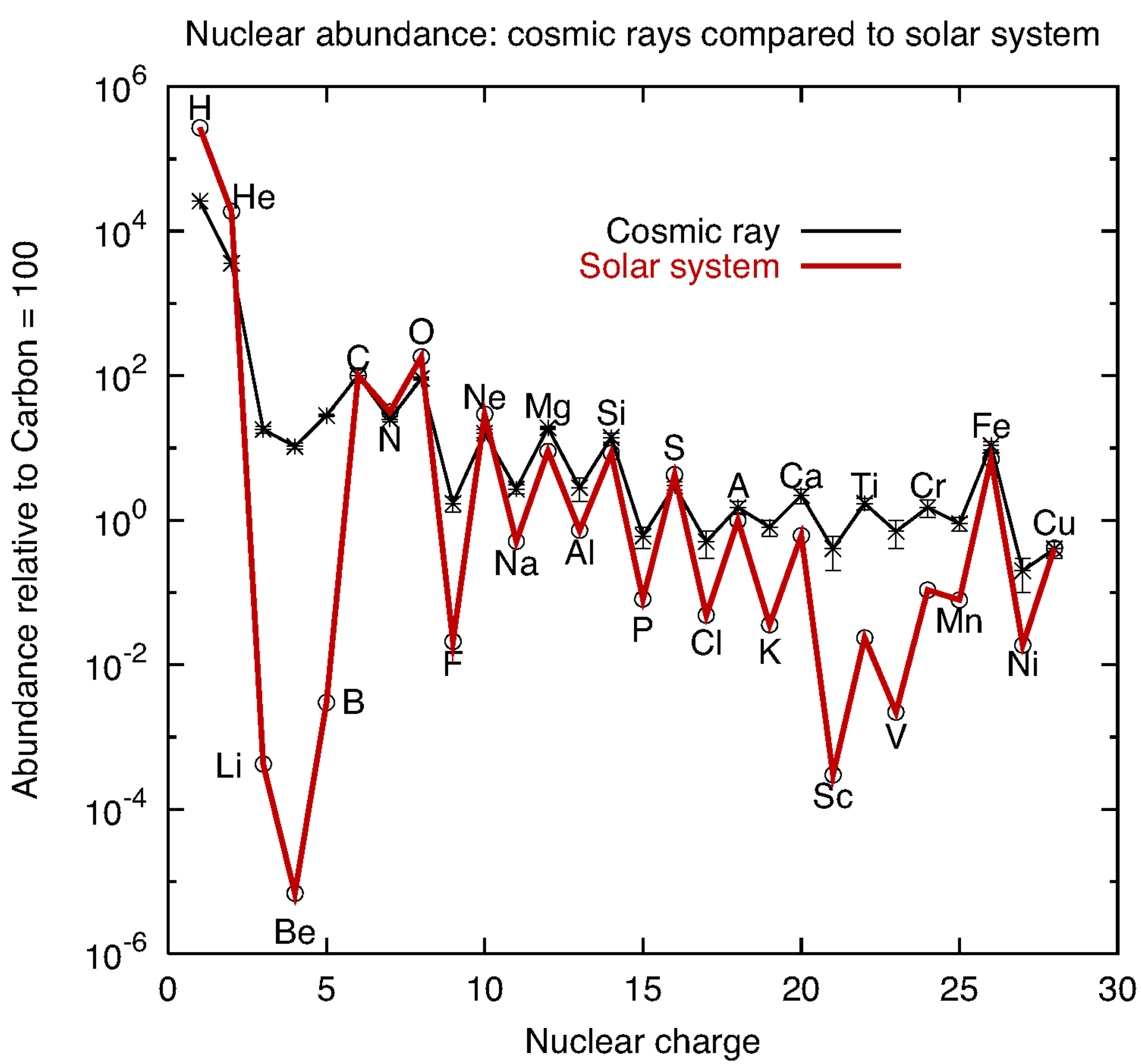
Measurement of Isotopic Abundances

Isotope abundances in the solar system

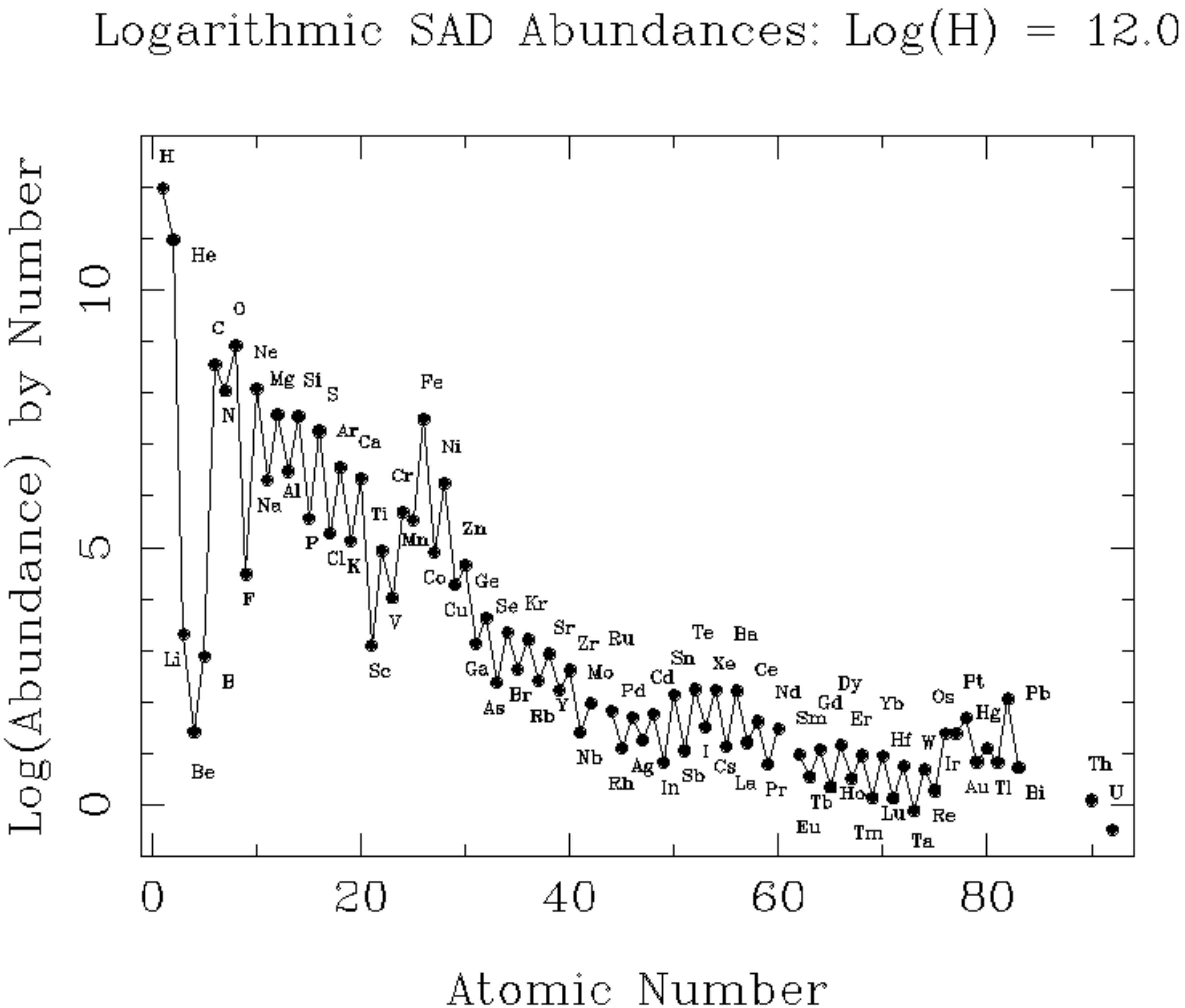


Other sources of abundances

Cosmic rays: Extra-solar material!

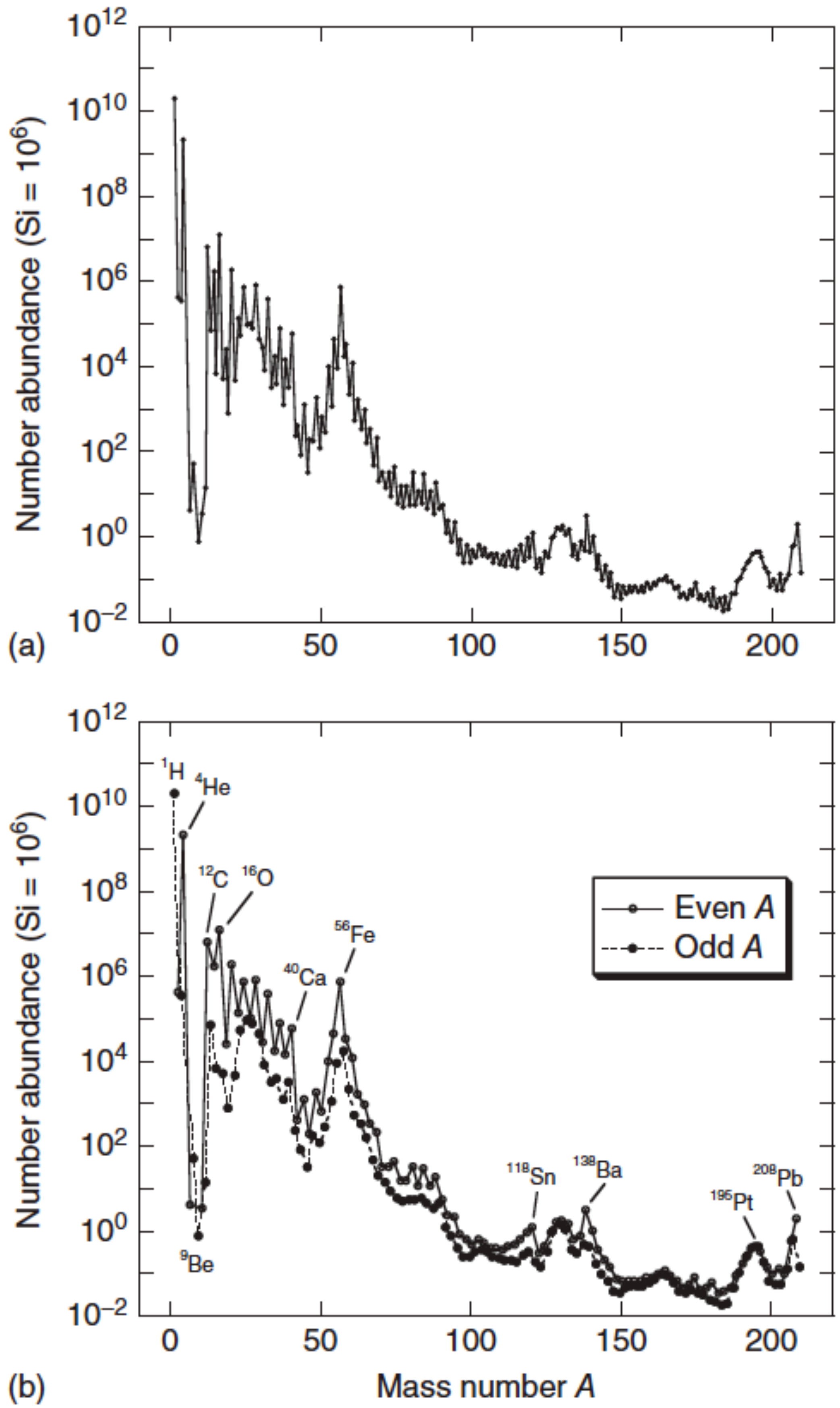


Solar System Abundance Pattern



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

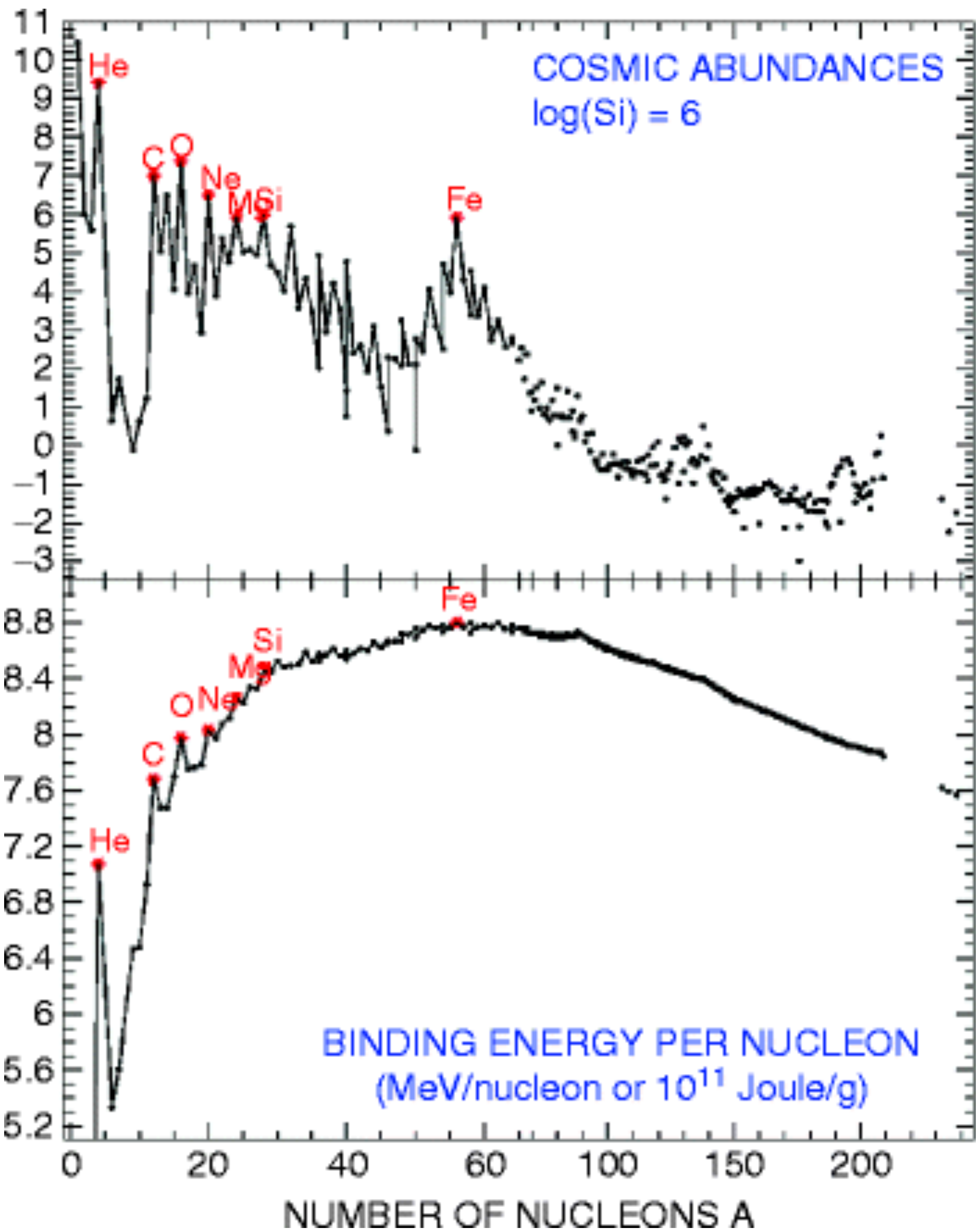
Some light elements like Li, Be and B appear to be rare

“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

Figure from ILIADIS

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

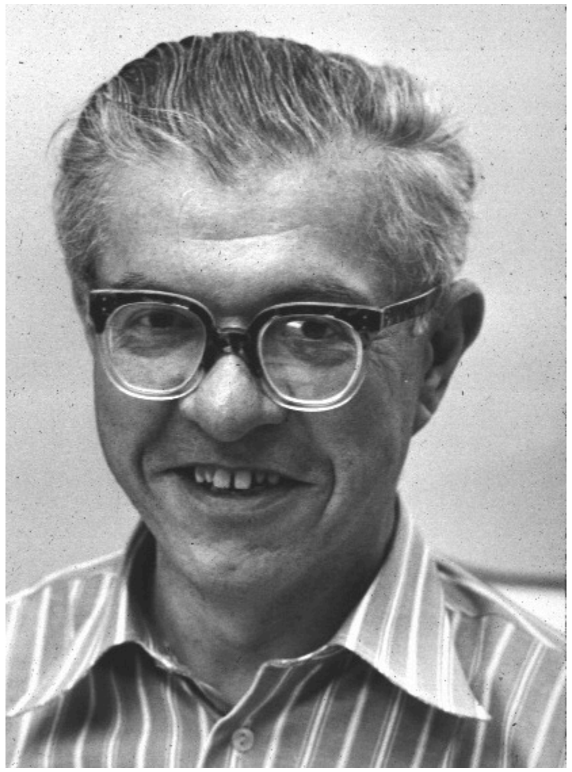
Where does nucleosynthesis take place?

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

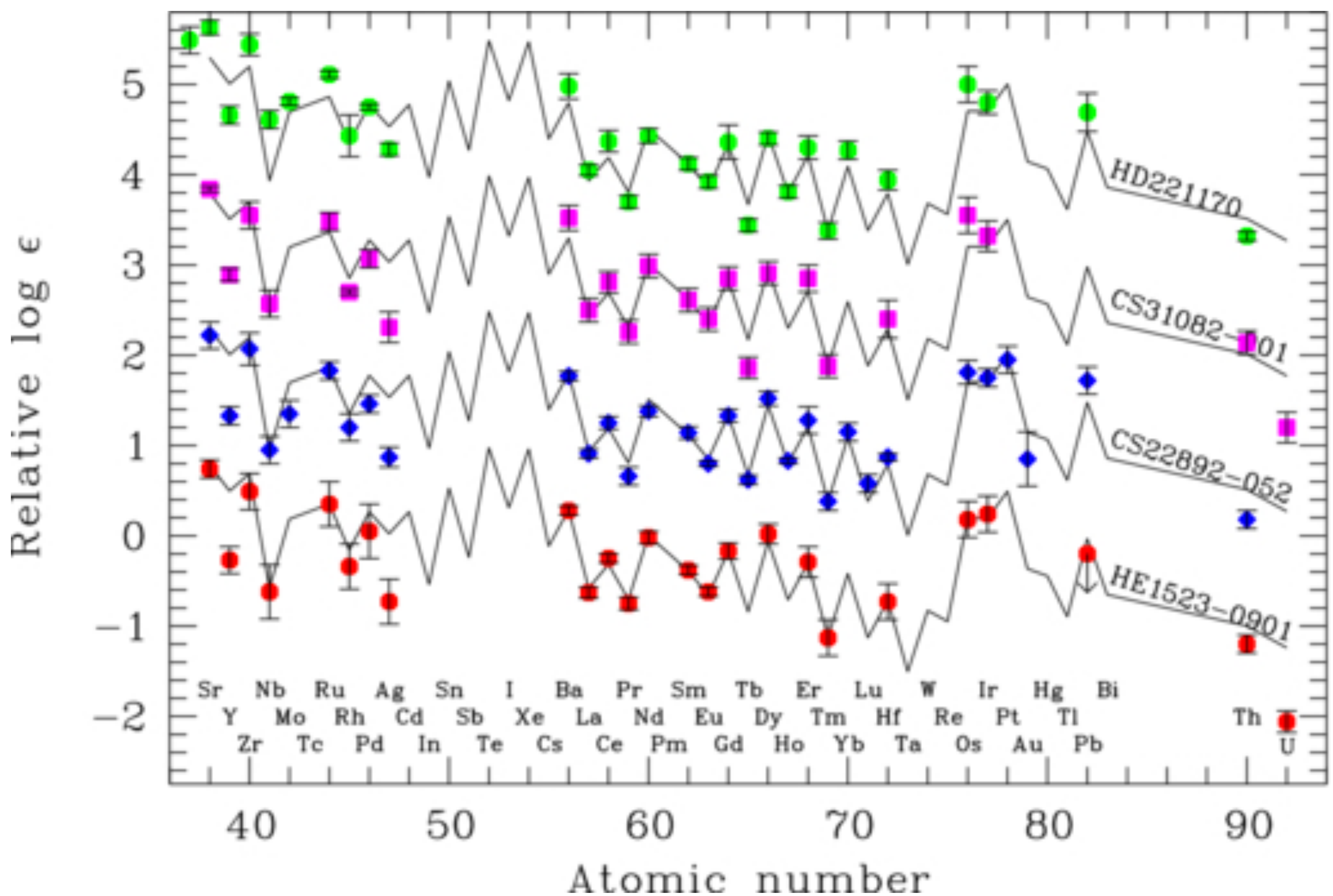
Fred Hoyle (1915–2001)
Elements created in stars and supernovae



Observational evidence for nucleosynthesis

In early 50s: evidence for evolution of abundances with cosmic time

Stars near the galactic disk have higher metallicities that stars in the halo



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

Jacobson & Frebel 2014

Thermonuclear reactions

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

REVIEWS OF MODERN PHYSICS

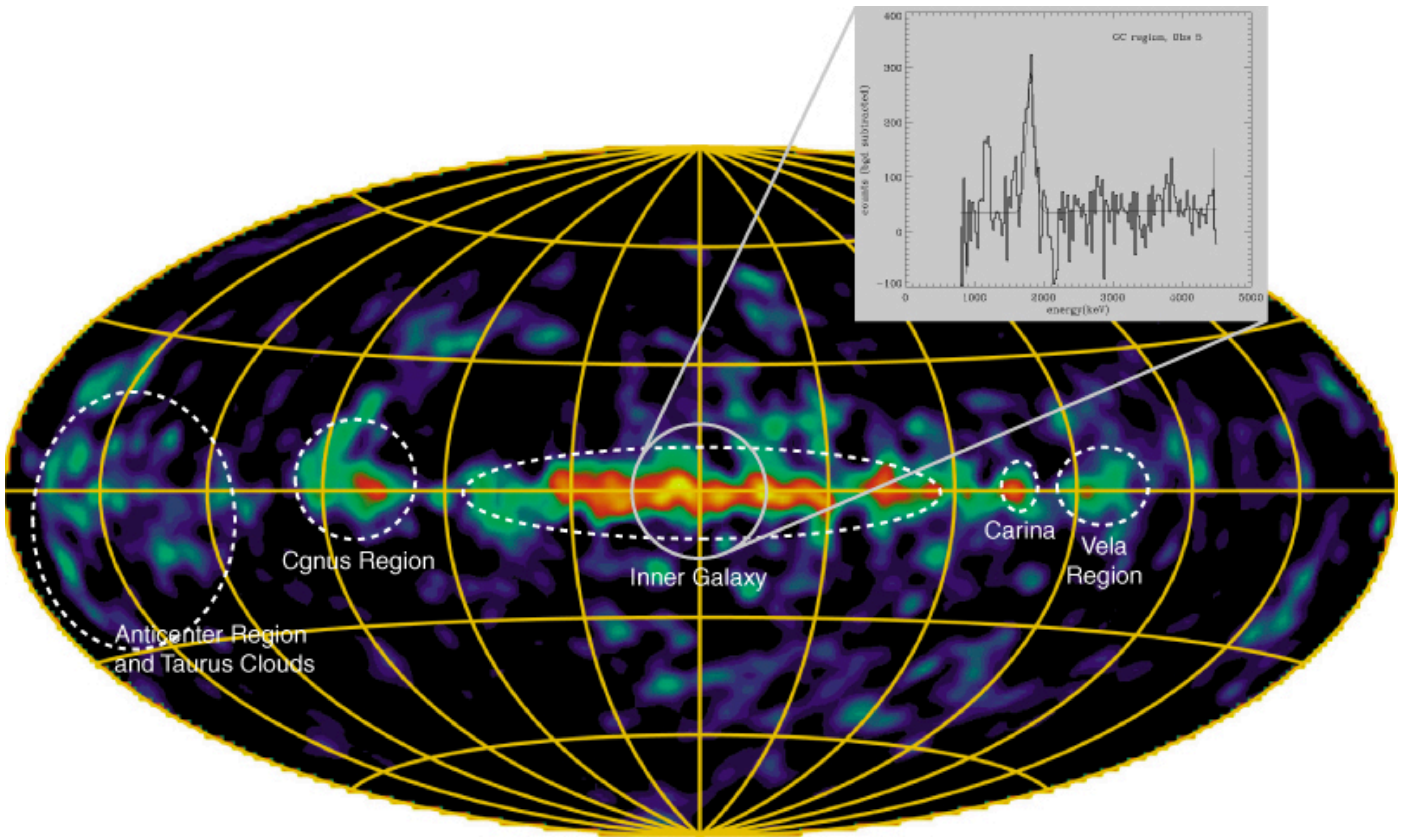
VOLUME 29, NUMBER 4 OCTOBER, 1957

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

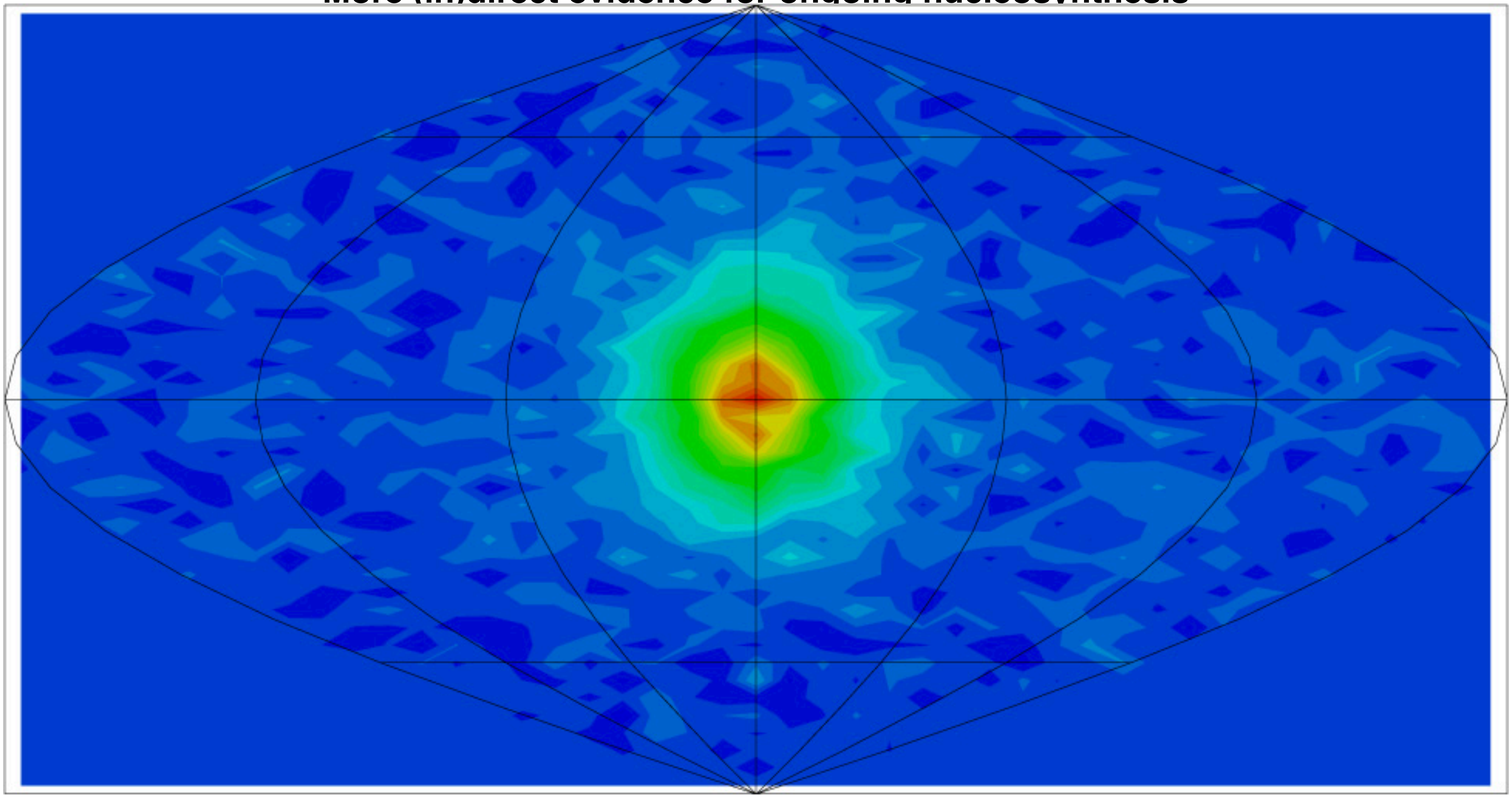


example 1.809 MeV line emission from the decay of ^{26}Al (lifetime of 7×10^5 yr)

COMPTEL collaboration

Modern observational evidence for nucleosynthesis

More (in)direct evidence for ongoing nucleosynthesis

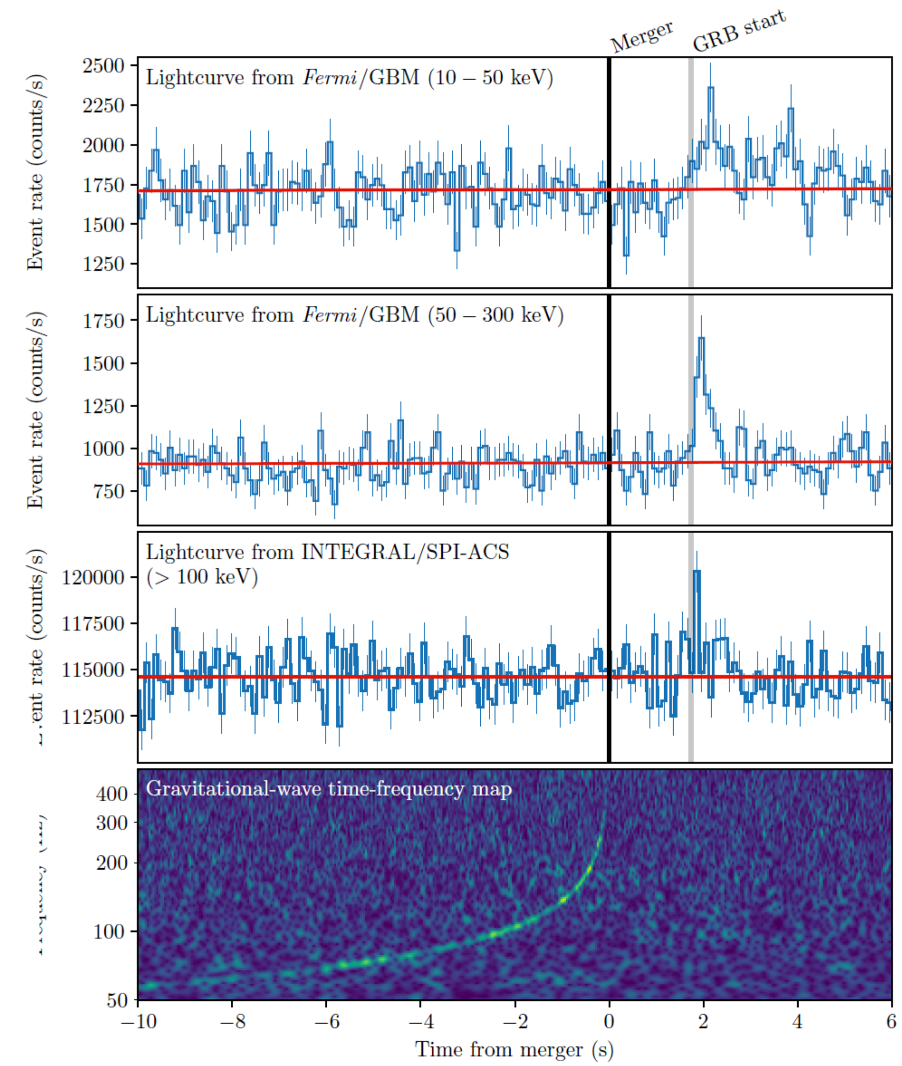


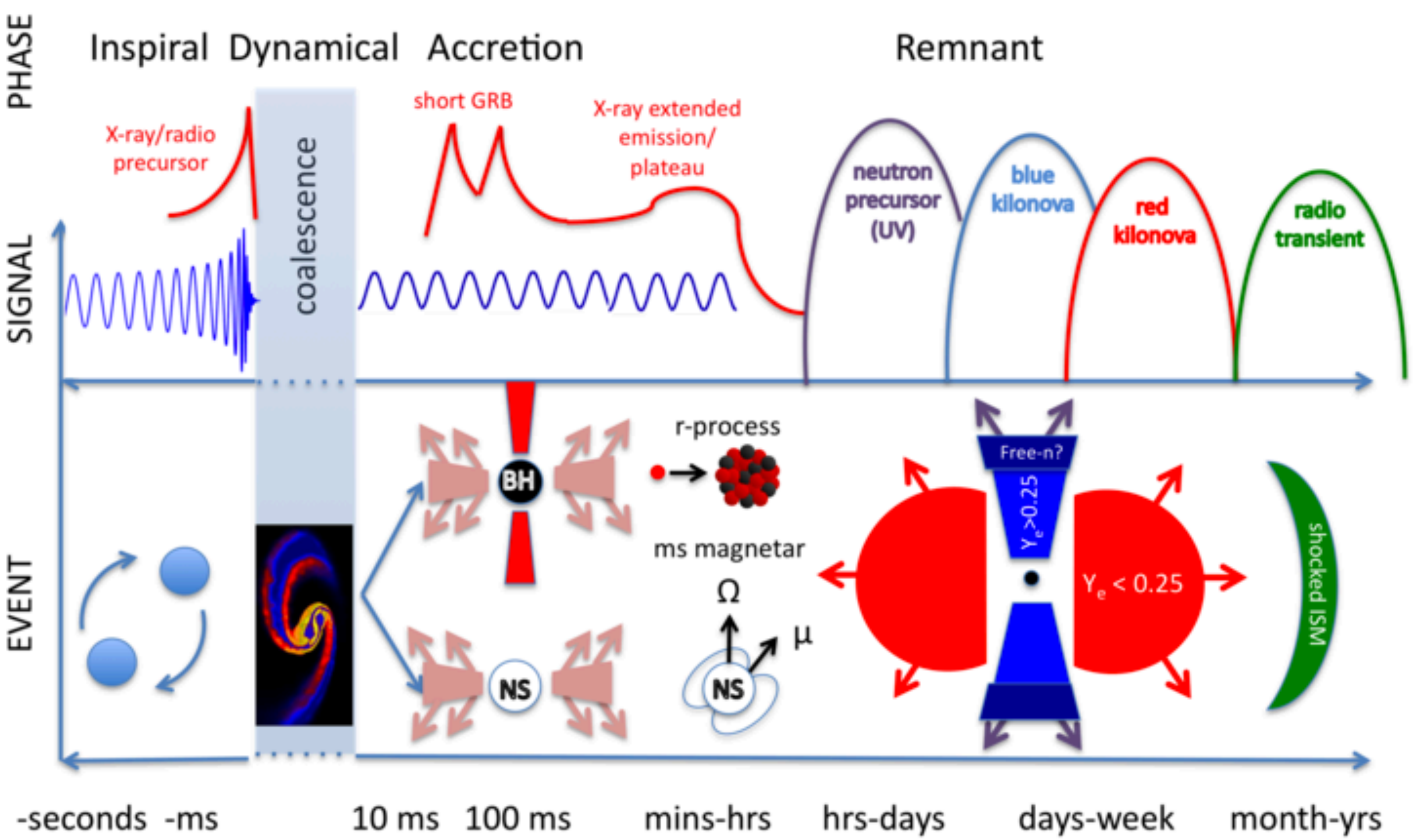
example 2: observation of solar neutrinos

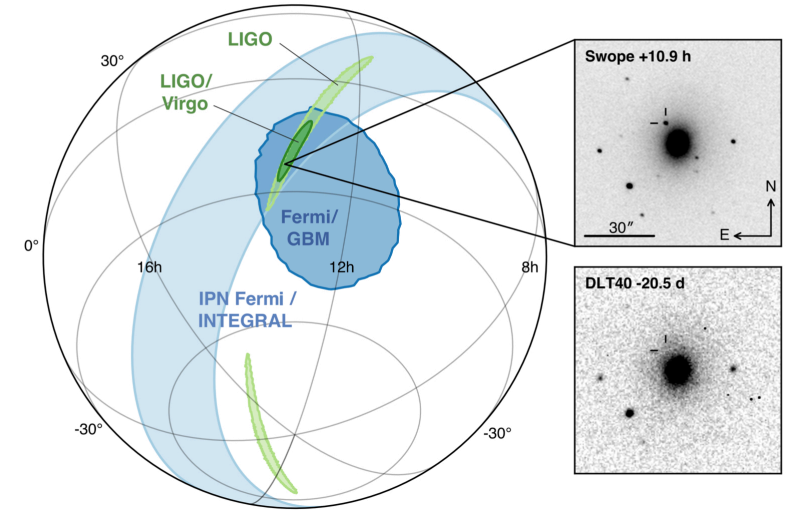
Super-Kamiokande

Modern observational evidence for nucleosynthesis

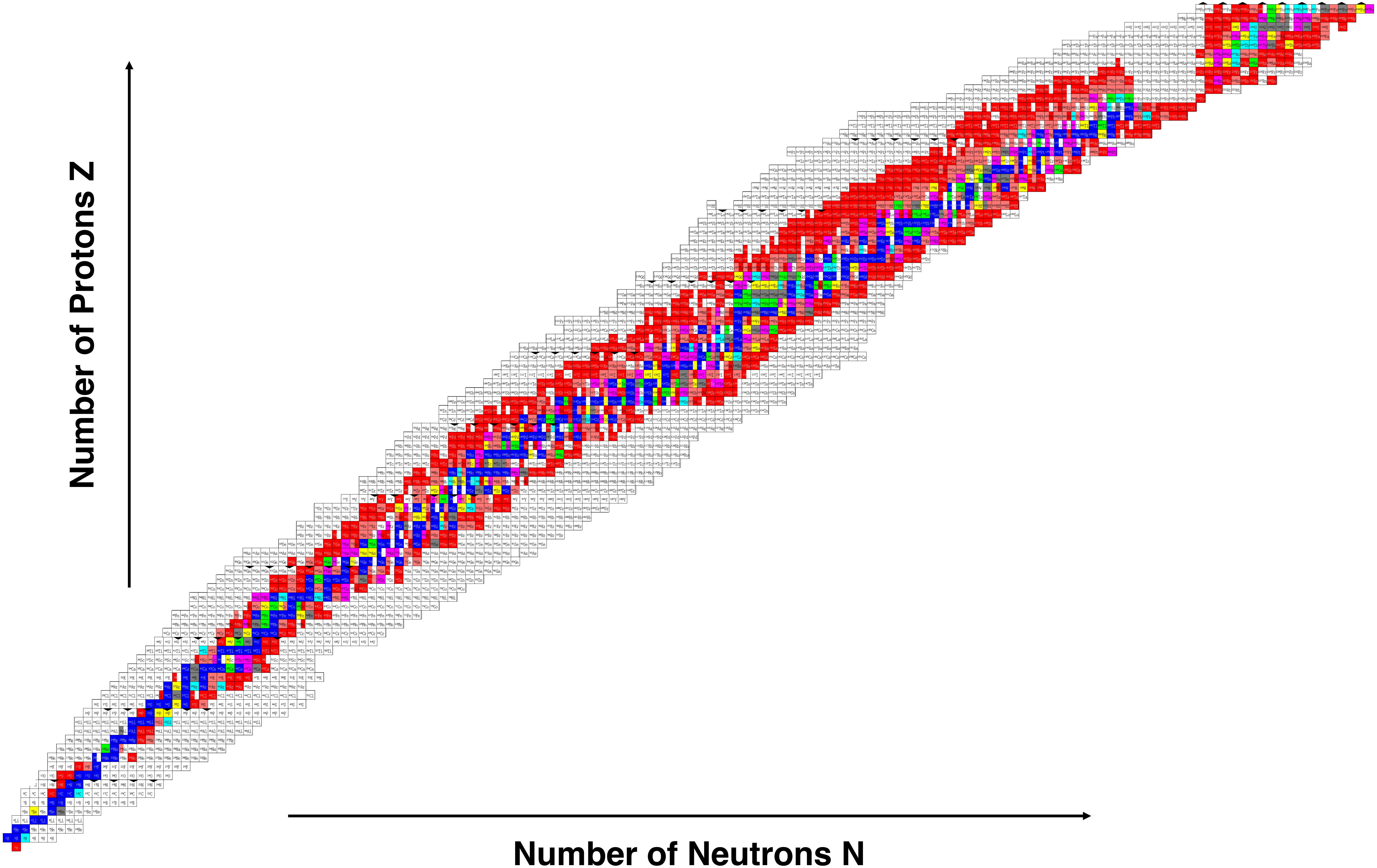
GW 170814



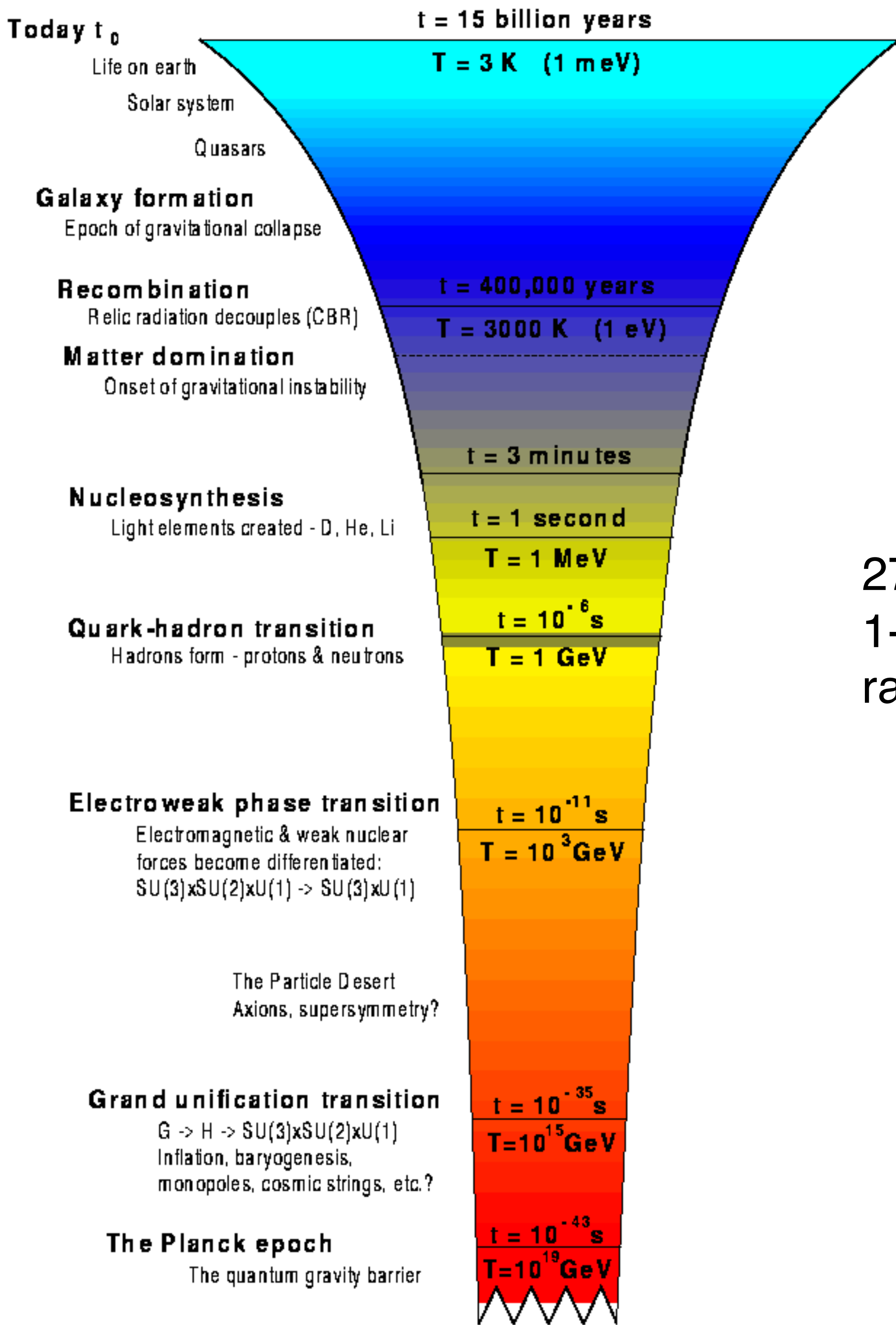




Lectures 2 and 3: Nuclear properties and thermonuclear reactions



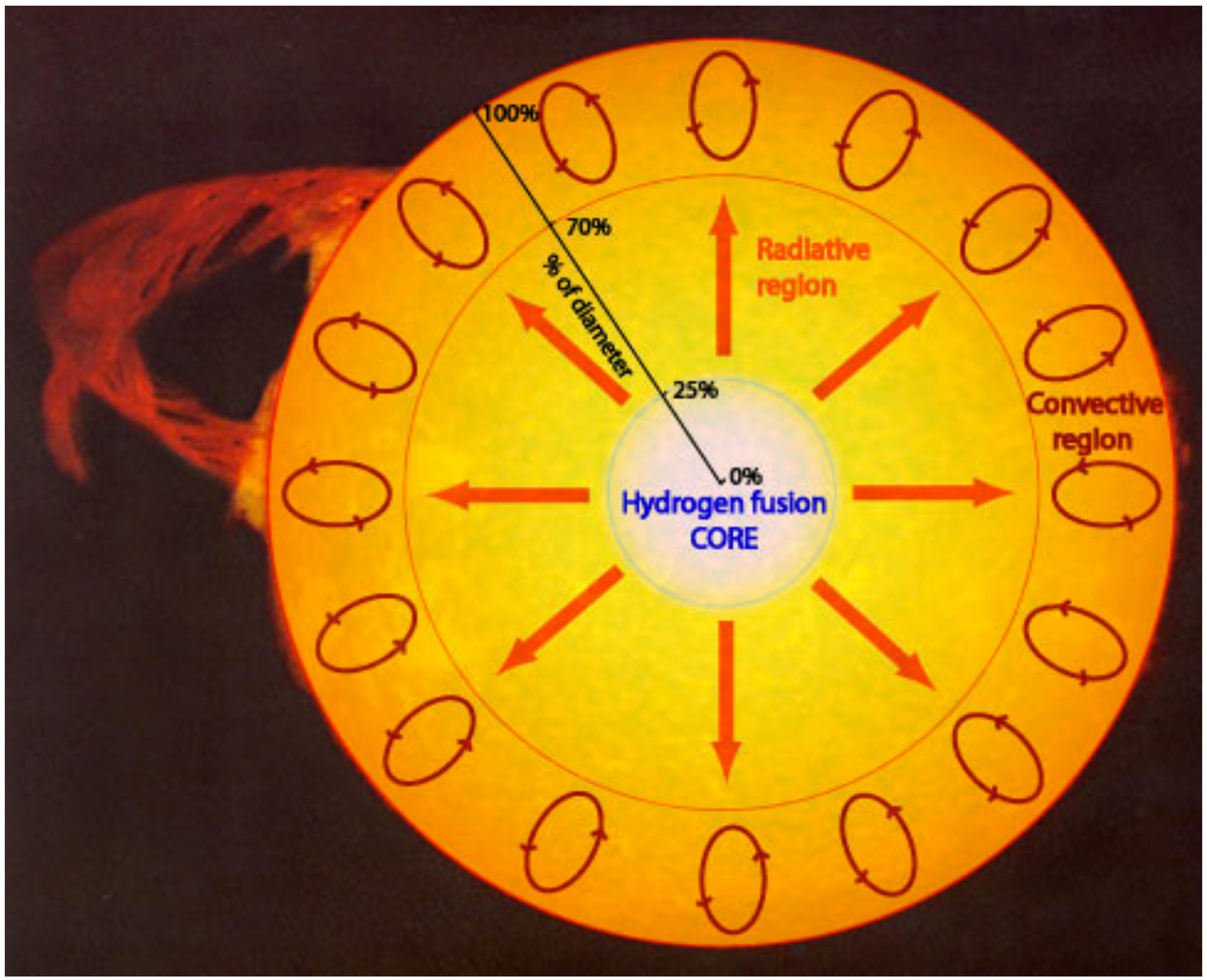
Lecture 4: Primordial nucleosynthesis

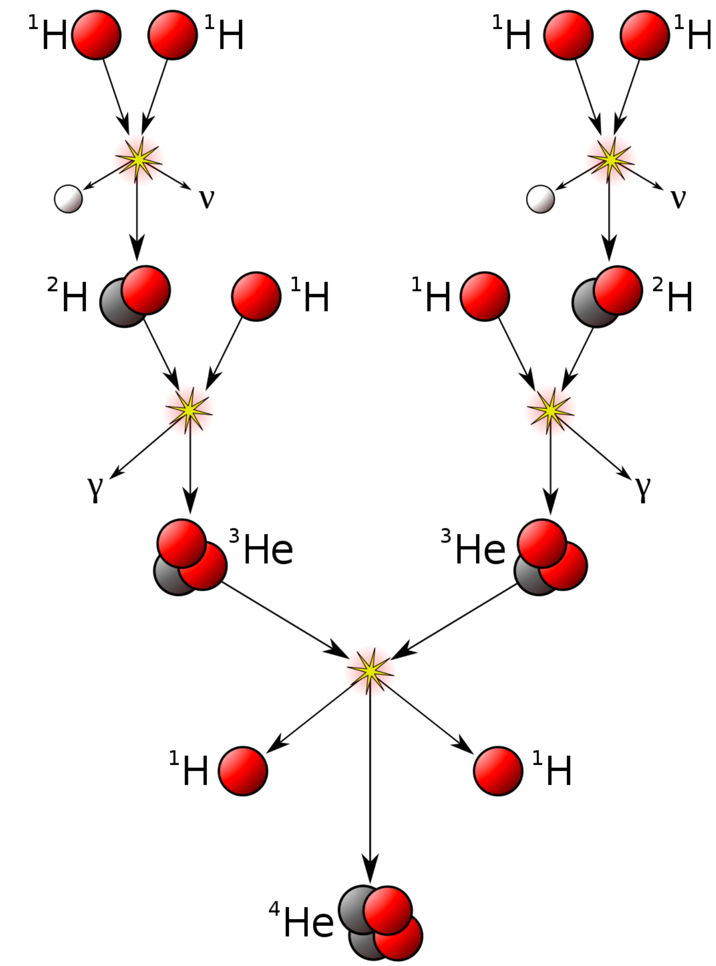


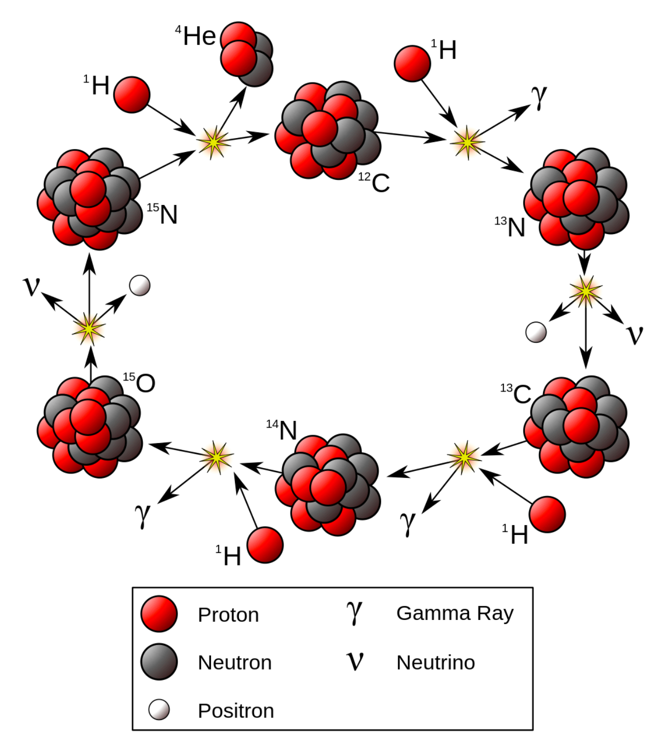
27% He requires primordial origin
1-3 sec after Big Bang: High temperatures but rapid cooling

Lectures 5 and 6: Hydrogen burning

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

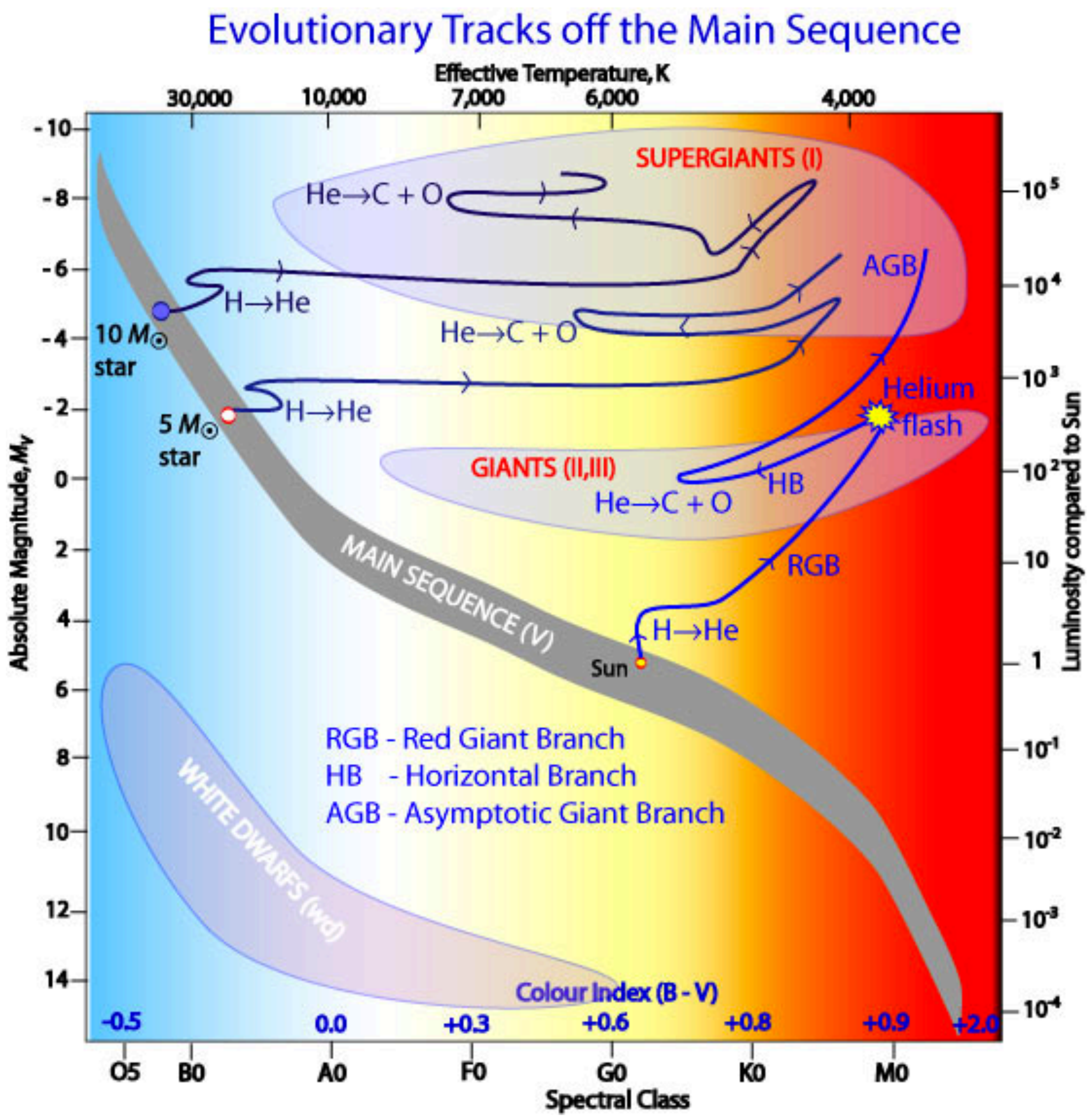


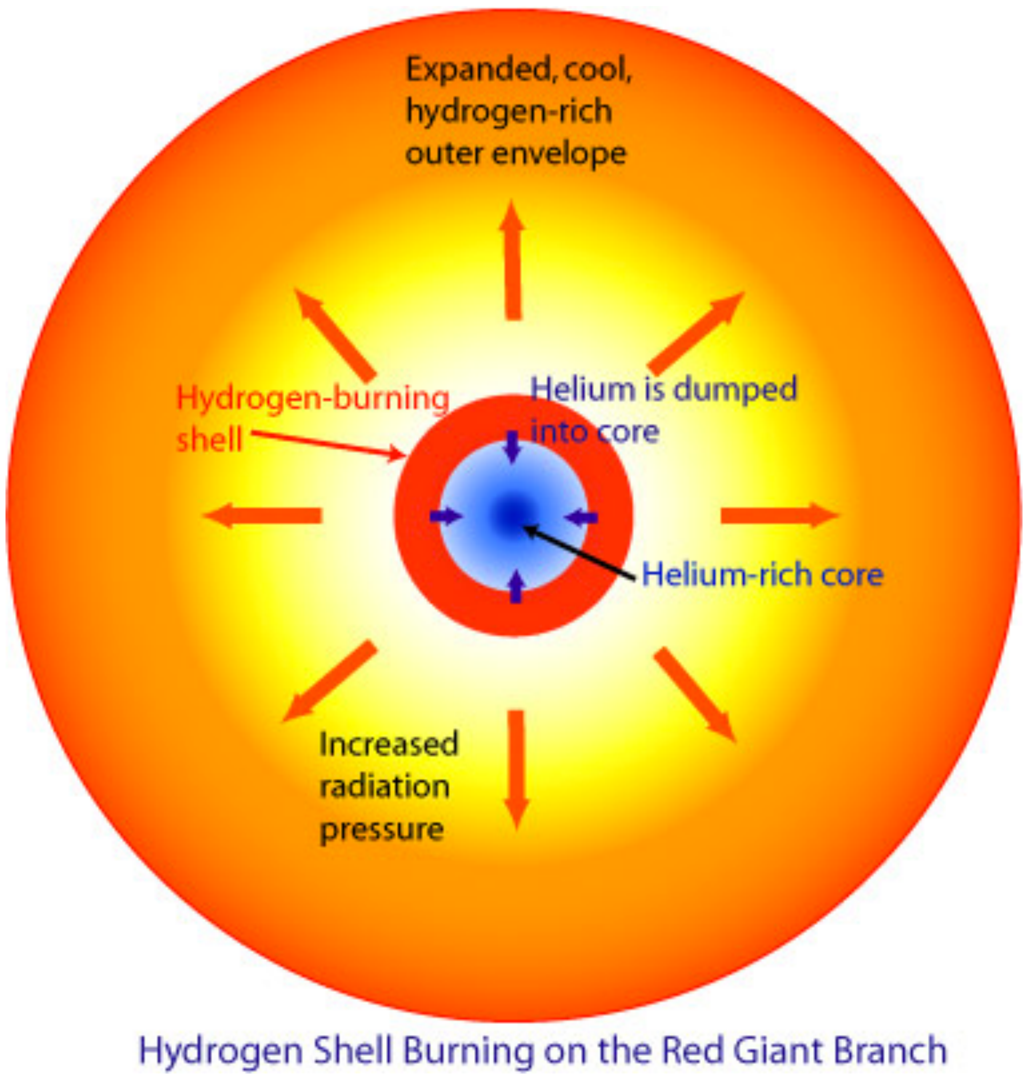


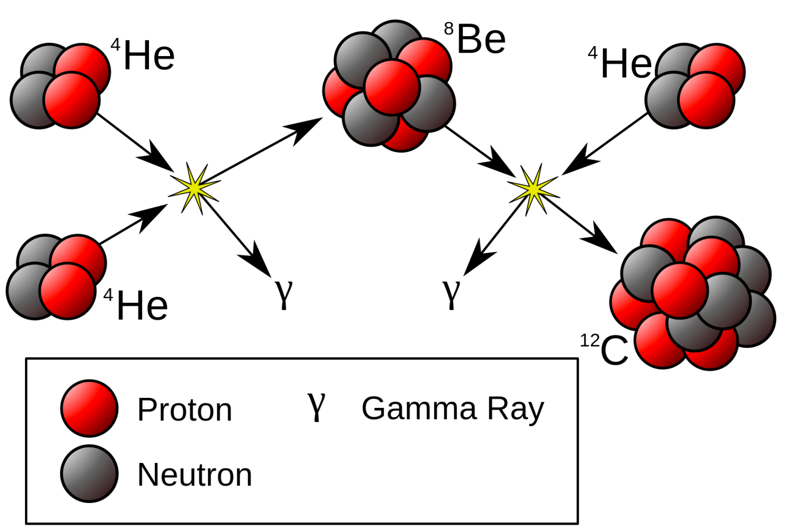


ATNF, *Wikipedia*

Lecture 7: Helium burning and beyond





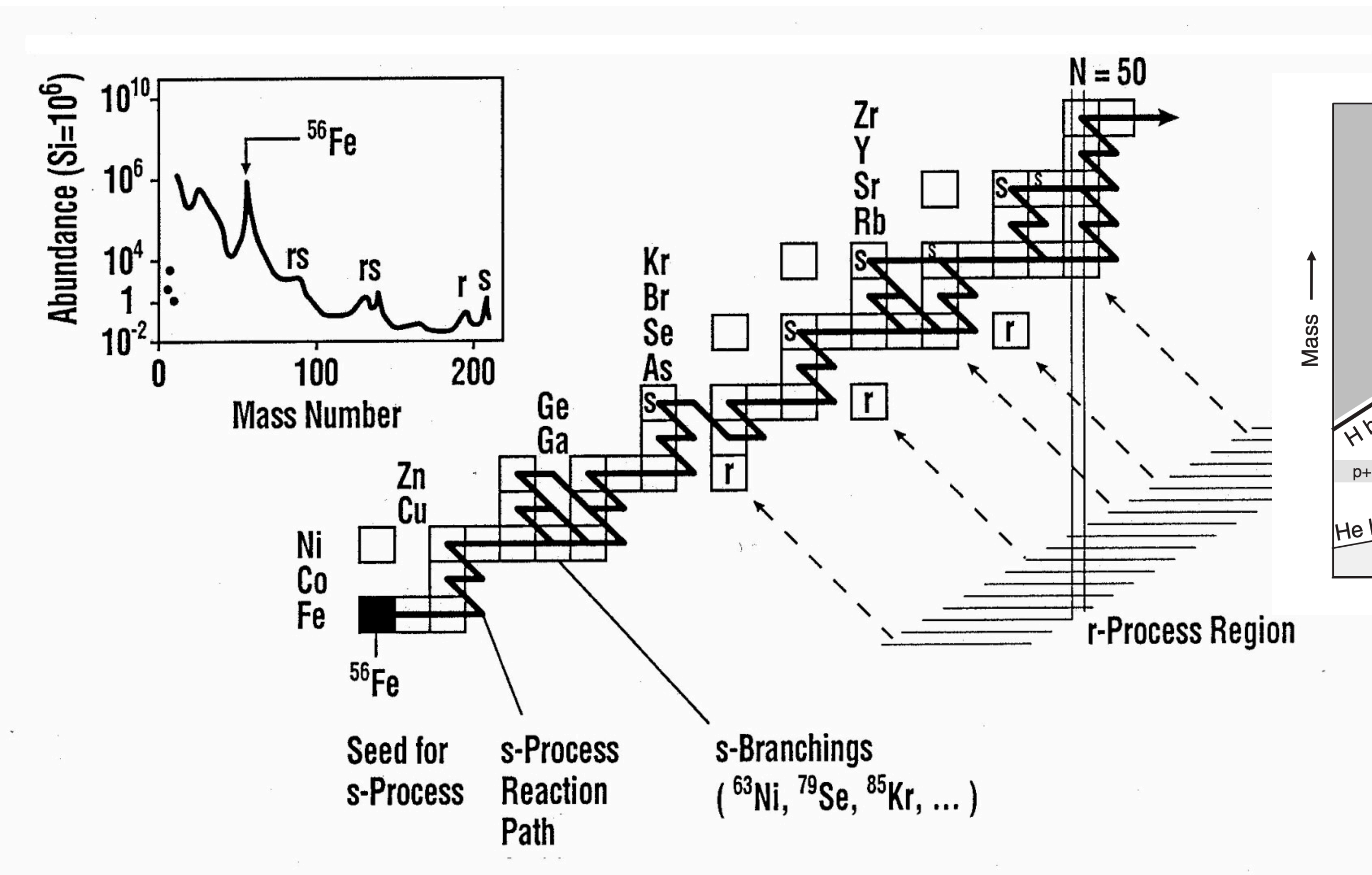


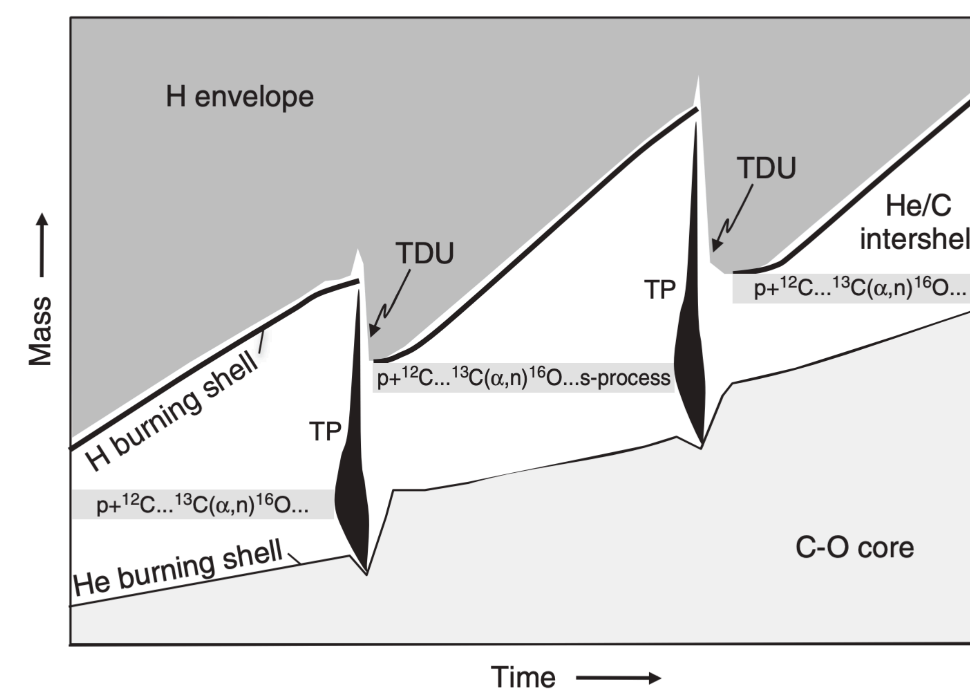
Wikipedia

Lecture 8: slow neutron captures (s-process)

main neutron sources

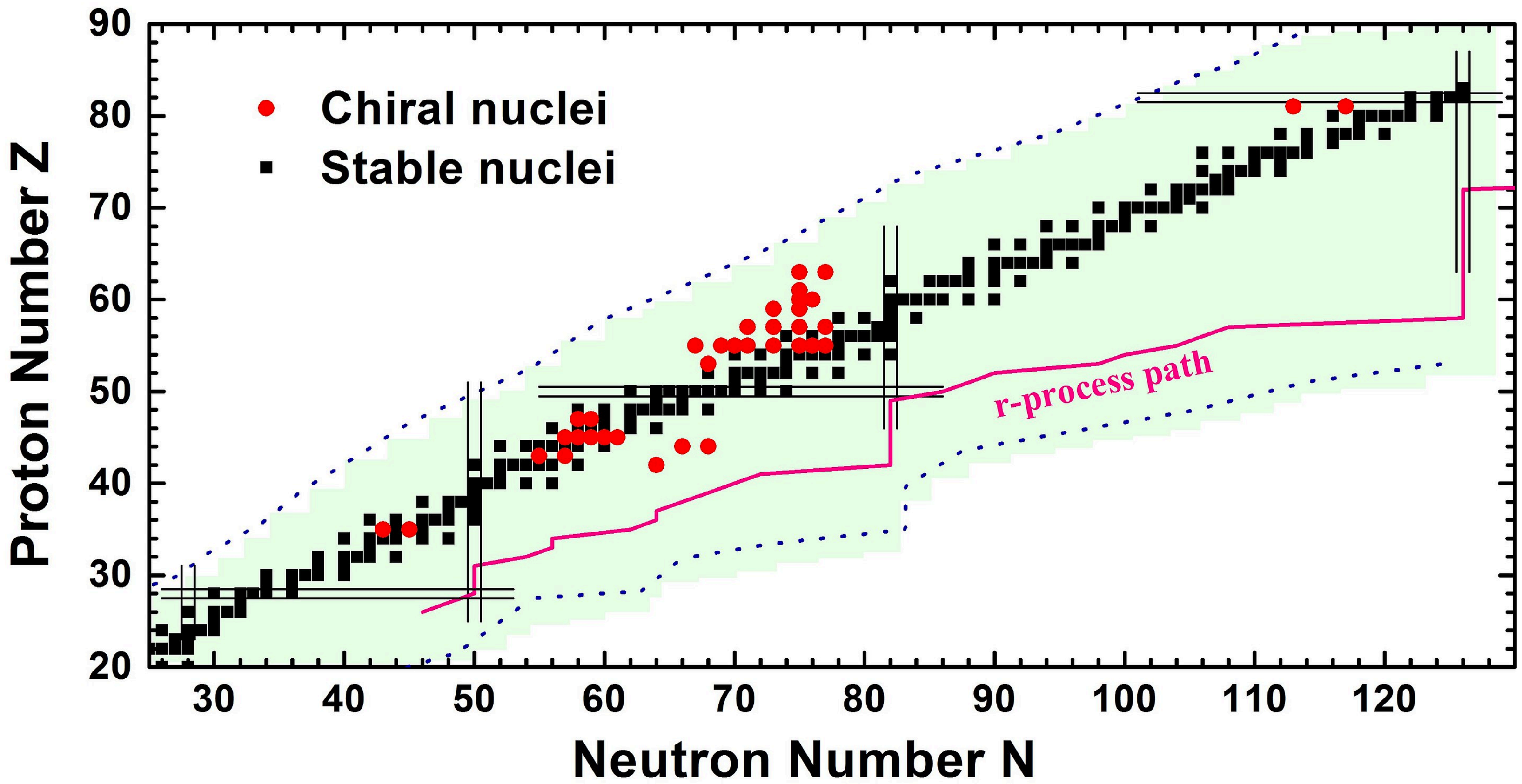
$$^{13}\mathrm{C} + ^{4}\mathrm{He} \rightarrow ^{16}\mathrm{O} + n$$
$$^{22}\mathrm{Ne} + ^{4}\mathrm{He} \rightarrow ^{25}\mathrm{Mg} + n$$

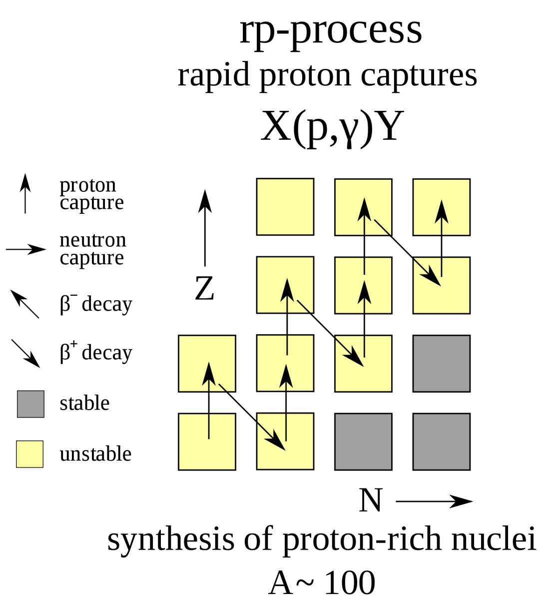




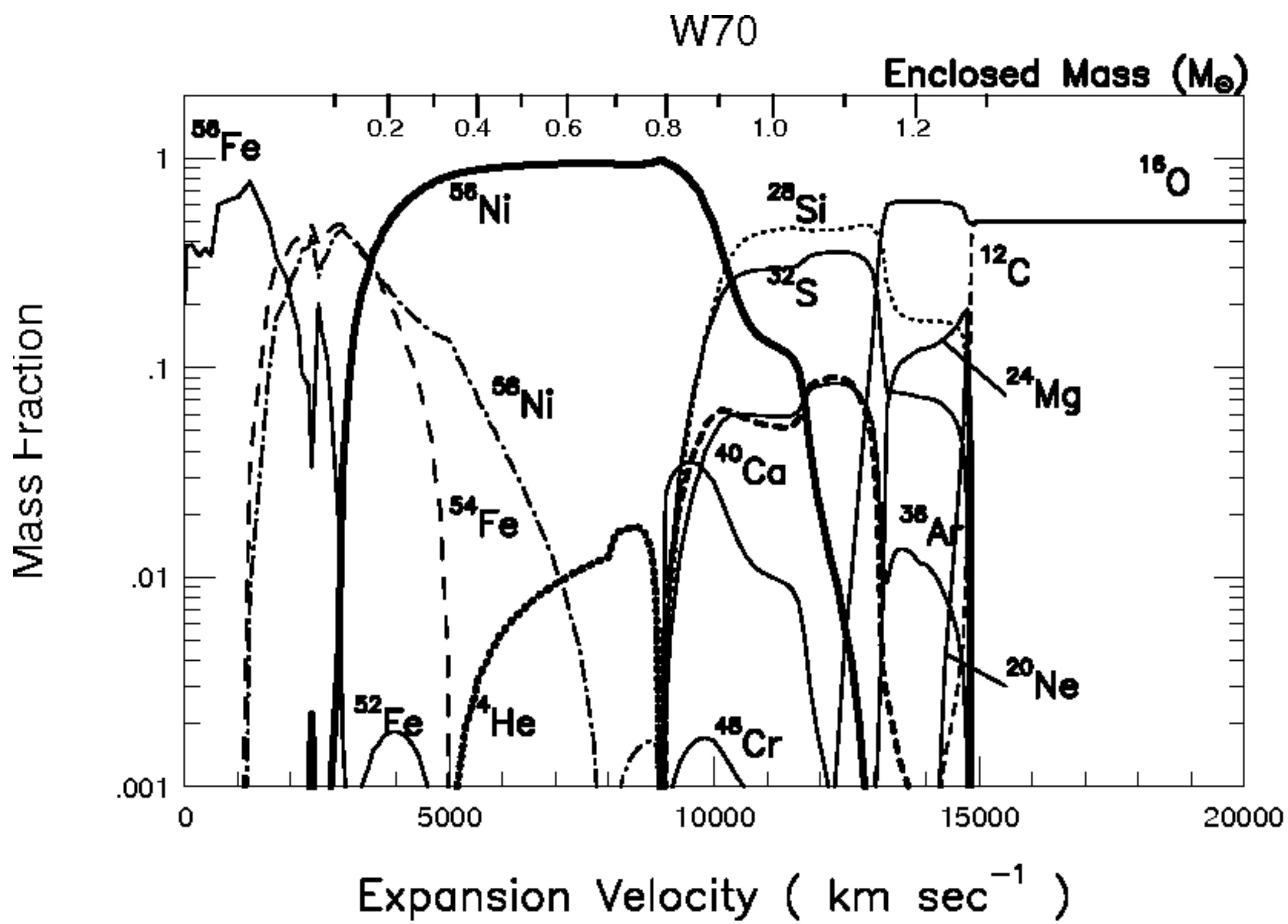
Iliadis (2015); [Kaeppeler, Franz](#) et al. Rev.Mod.Phys. 83 (2011) 157 arXiv:1012.5218

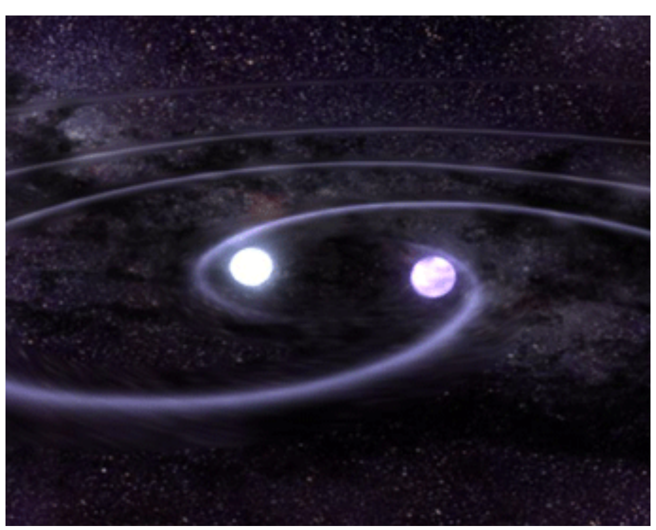
Lecture 9: explosive nucleosynthesis

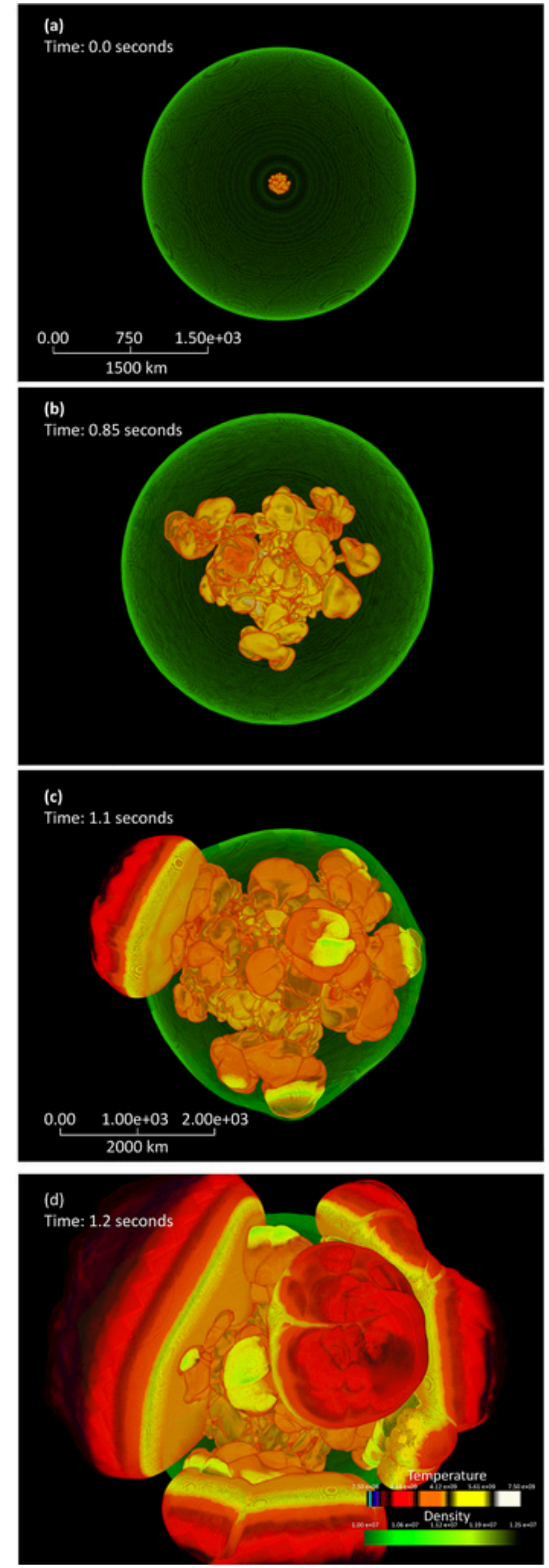




Lecture 10: Type Ia supernovae

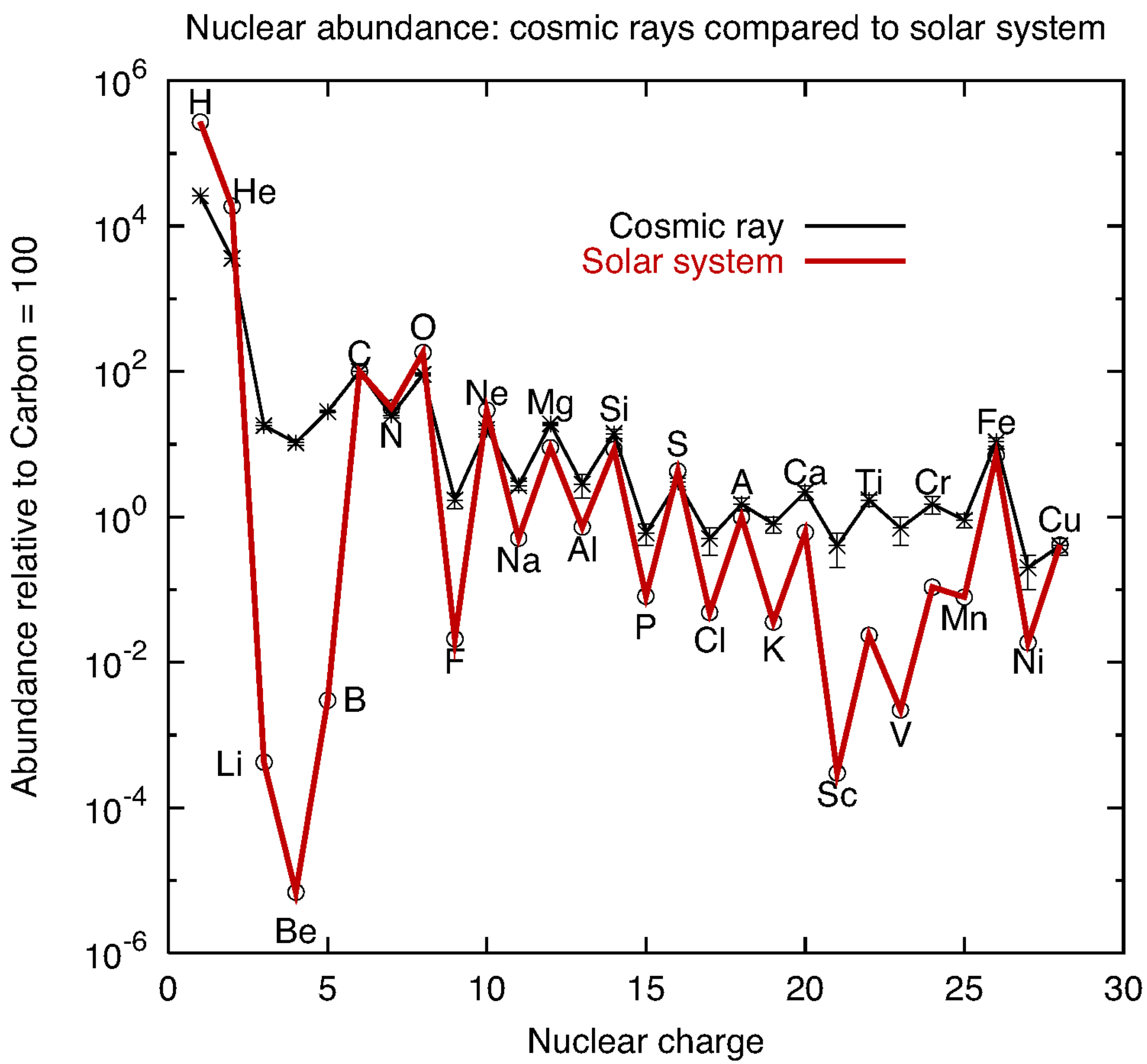


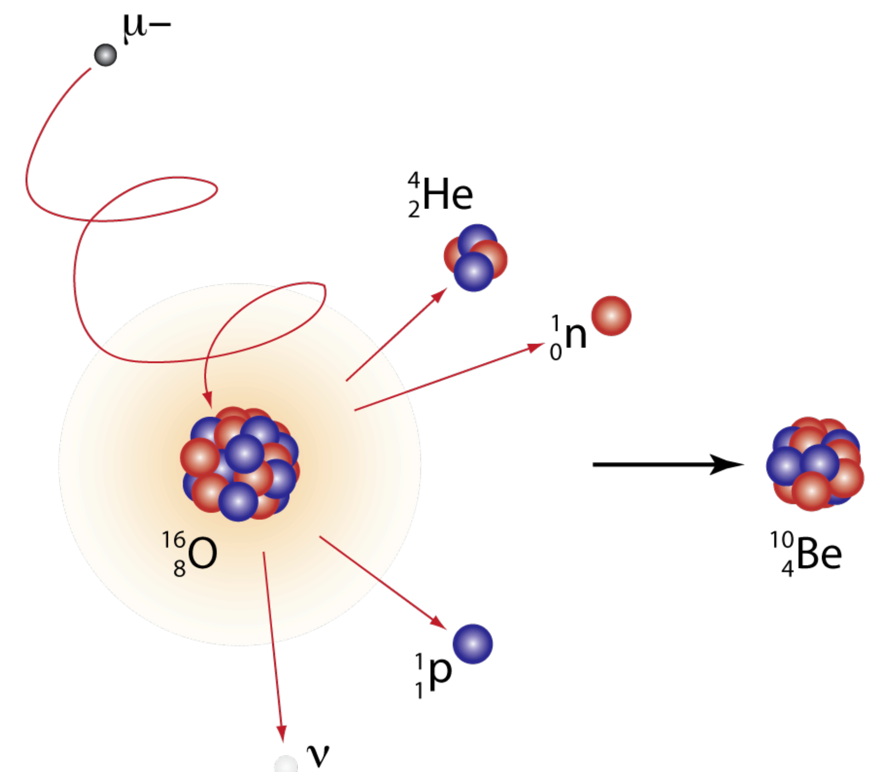




Progenitors still debated
Responsible for most iron-peak elements

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