Outline: Solar Abundances

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web-page: https://web-docs.gsi.de/~wolle/ and click on

1. mass fraction and abundance
2. solar abundances
3. outside the solar neighborhood
4. galactic radioactivity

Abundances – the composition of the universe

Before answering the question of the origin of the elements we want to see what elements are actually there - in other words

What is the Universe made of ? Answer: We have no clue ….

60% Dark Energy (don’t know what it is)
35% Cold dark matter (don’t know what it is)
5% Nuclei and electrons (visible as stars ~ 0.5%) ← **Topic of this course**

Why bother with 5% ???

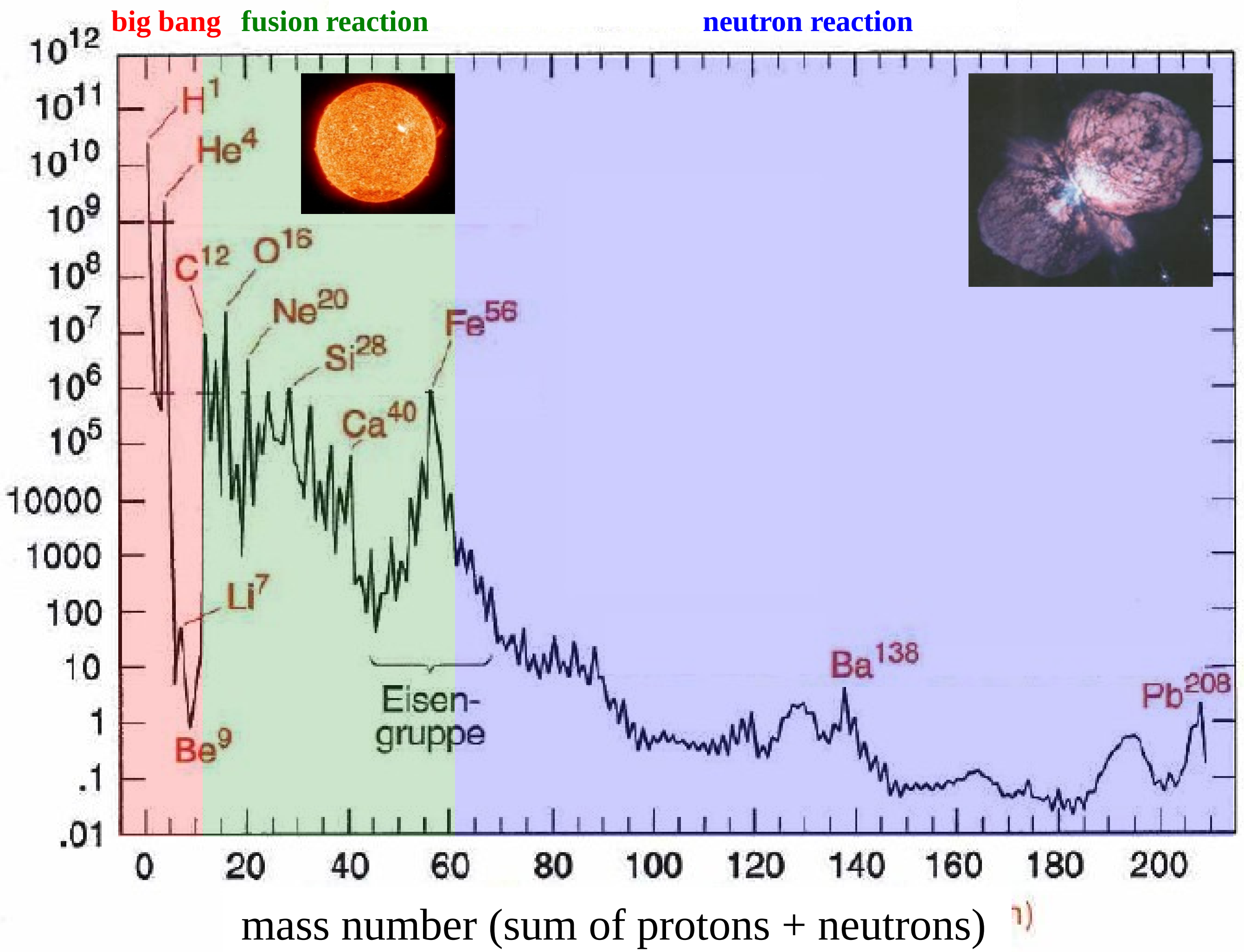
Important things are made of it:

Questions to be answered:

- What kind of nuclei (nuclides) is the universe made of ?
- How abundant is each element ? Each nuclide ?

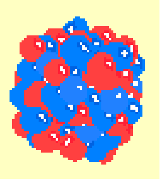
Open questions

solar abundances ($Si^{28} = 10^6$)



- Why is iron more abundant than gold?
- Why are the heavy elements existing and how are they produced?
- How can we explain the abundances in the universe?

1. The nucleus



The atomic nucleus consists of protons and neutrons

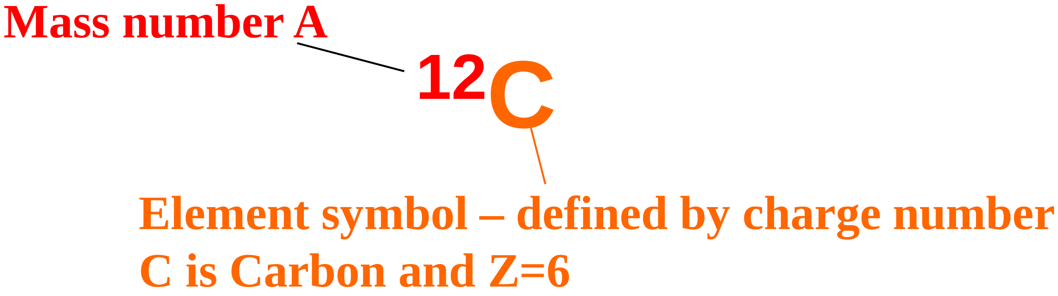
Protons and Neutrons are therefore called nucleons

A nucleus is characterized by:

- A: Mass Number = number of nucleons
- Z: Charge Number = number of protons — Determines the Element
- N: Neutron Number — Determines the Isotope

Of course A=Z+N

Usual notation:



Mass number A

^{12}C

Element symbol – defined by charge number
C is Carbon and Z=6

So this nucleus is made of 6 protons and 6 neutrons

2. Abundance of a nucleus

How can we describe the relative abundances of nuclei of different species and their evolution in a given sample (say, a star, or the Universe) ?

2.1. Number density

We could use the number density = number of nuclei of species **i** per **cm^3**

Disadvantage: tracks not only nuclear processes that create or destroy nuclei,
but also density changes, for example due to compression
or expansion of the material.

2.2 Mass fraction and abundance

Mass fraction $\boldsymbol{X_i}$ is fraction of total mass of sample that is made up by nucleus of species i

$$n_i = \frac{X_i \rho}{m_i}$$

ρ : mass density (g/cm^3)

m_i mass of nucleus of species i

(CGS only !!!)

with $m_i \approx A_i \cdot m_u$ and $m_u = m_{^{12}C}/12 \overset{\downarrow}{=} 1/\mathrm{N_A}$ as <u>atomic</u> mass unit (amu)

$$n_i = \boxed{\frac{X_i}{A_i}} \rho\, \mathrm{N_A}$$

call this abundance Y_i

note: we neglect **here** nuclear binding energy and electrons (mixing atomic and nuclear masses) - therefore strictly speaking our ρ is slightly different from the real ρ, but differences are negligible in terms of the accuracy needed for densities in astrophysics

so $\boxed{n_i = Y_i \rho N_A}$ with $\boxed{Y_i = \frac{X_i}{A_i}}$

note: abundance has no units
only valid in CGS

The abundance Y is proportional to number density but changes only if the nuclear species gets destroyed or produced. Changes in density are factored out.

2.3 Some useful quantities and relations

of course $\sum_i X_i = 1$ but, as Y=X/A < X $\sum_i Y_i < 1$

- Mean molecular weight μ_i

= average mass number = $\frac{\sum_i A_i Y_i}{\sum_i Y_i} = \frac{1}{\sum_i Y_i}$ or $\boxed{\mu_i = \frac{1}{\sum_i Y_i}}$

- Electron Abundance Y_e

As matter is electrically neutral, for each nucleus with charge number Z there are Z electrons:

$Y_e = \sum_i Z_i Y_i$ and as with nuclei, electron density $n_e = \rho \mathrm{N_A} Y_e$

can also write: $Y_e = \frac{\sum_i Z_i Y_i}{\sum_i A_i Y_i}$

prop. to number of protons

prop. to number of nucleons

So Y_e is ratio of protons to nucleons in sample
(counting all protons including the ones contained in nuclei
- not just free protons as described by the "proton abundance")

2.3 Some useful quantities and relations

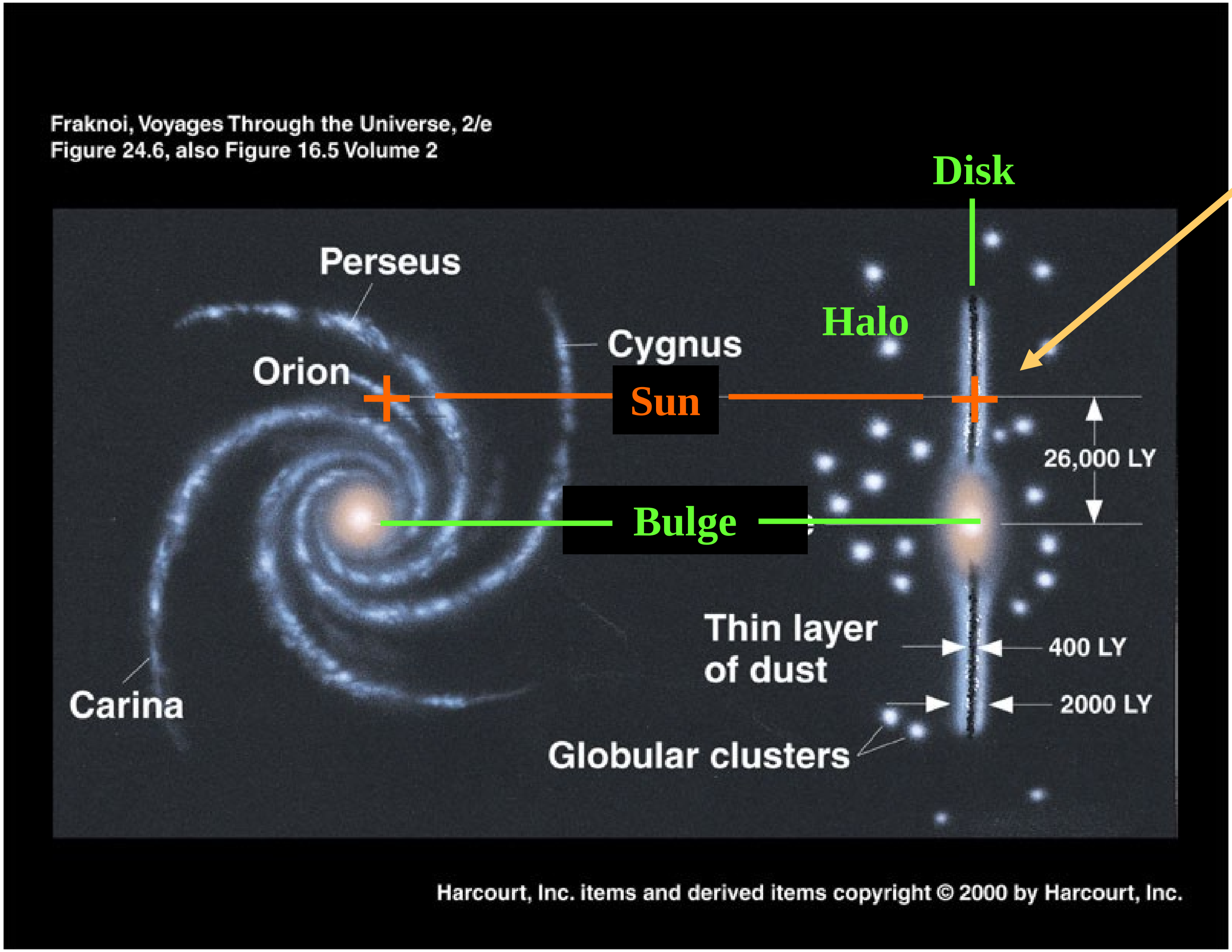
some special cases:

For 100% hydrogen: $Y_e = 1$

For equal number of protons and neutrons (N=Z nuclei): $Y_e = 0.5$

For pure neutron gas: $Y_e = 0$

3. The solar abundance distribution



solar abundances:

Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it’s formation

How can solar abundances be determined?

1. Earth material

Problem: chemical fractionation modified the local composition strongly compared to pre solar nebula and overall solar system.

for example: Quarz is 1/3 Si and 2/3 Oxygen and not much else.
This is not the composition of the solar system.

But: Isotopic compositions mostly unaffected (as chemistry is determined by number of electrons (protons), not the number of neutrons).

⟶ **main source for isotopic composition of elements**

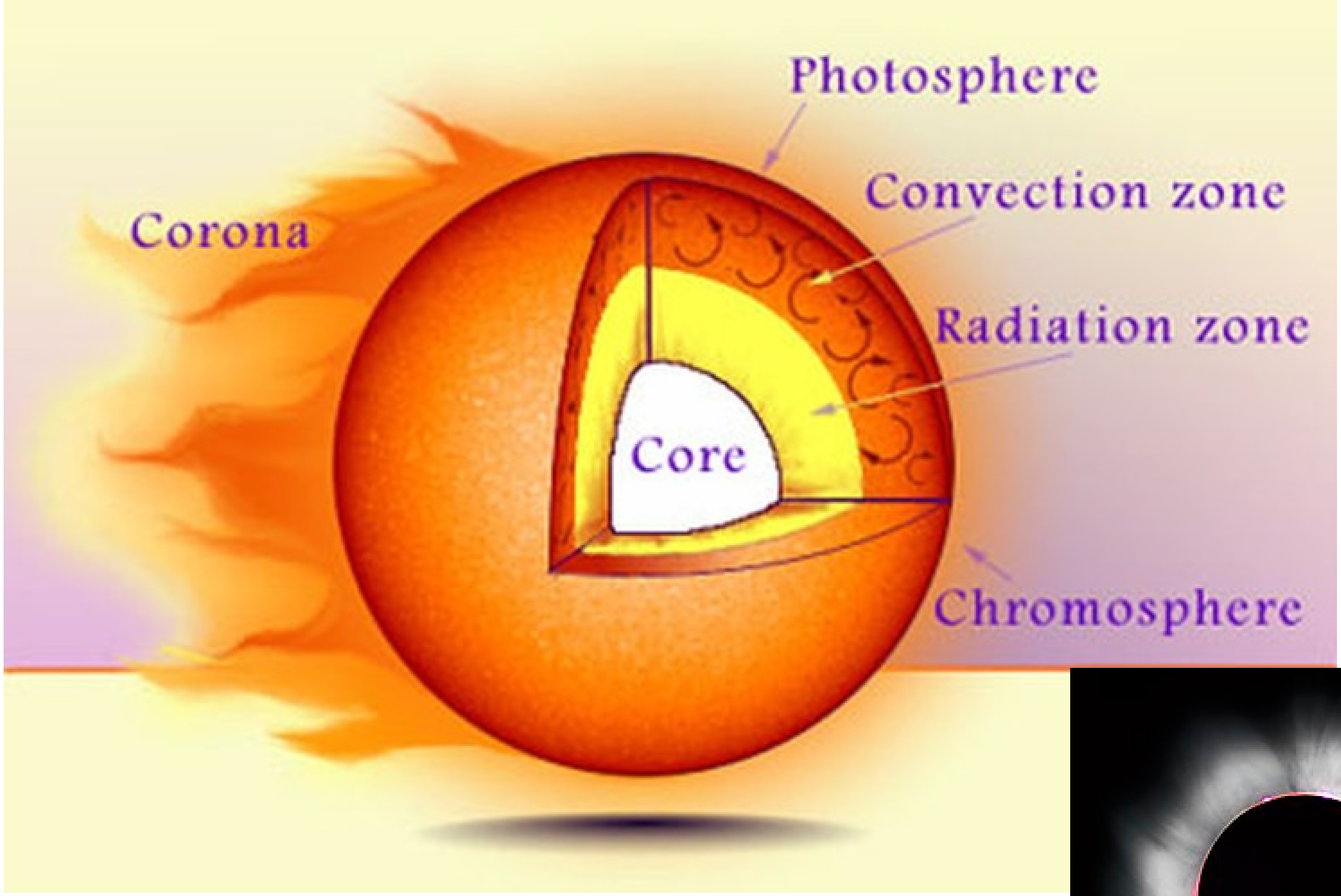
2. Solar spectra

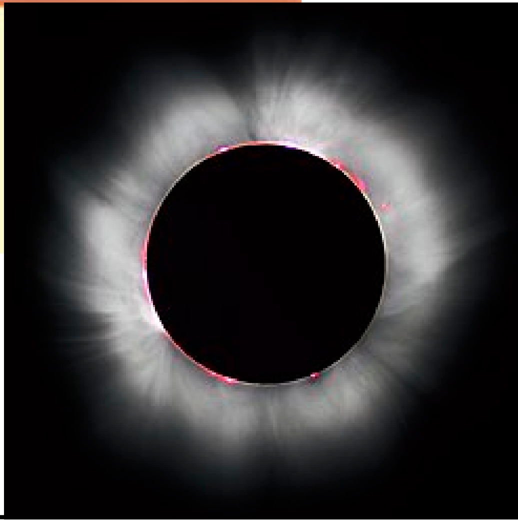
Sun formed directly from pre solar nebula - (largely) unmodified outer layers create spectral features

3. Unfractionated meteorites

Certain classes of meteorites formed from material that never experienced high pressure or temperatures and therefore was never fractionated.
These meteorites directly sample the pre solar nebula

The sun





sun´s chromosphere (red rim)
during a solar eclipse

3.1 Abundances from stellar spectra (for example the sun):

corona (nanoflares)
up to 2 Mio K

hot thin gas
→ **emission lines**

chromosphere
~ 10,000 km
up to 10,000 K

hot thin gas
→ **emission lines**

photosphere (sphere of light)
~ 500 km
~ 6000 K

photons escape freely

still dense enough for photons to excite atoms when frequency matches
→ **absorption lines**

convective zone

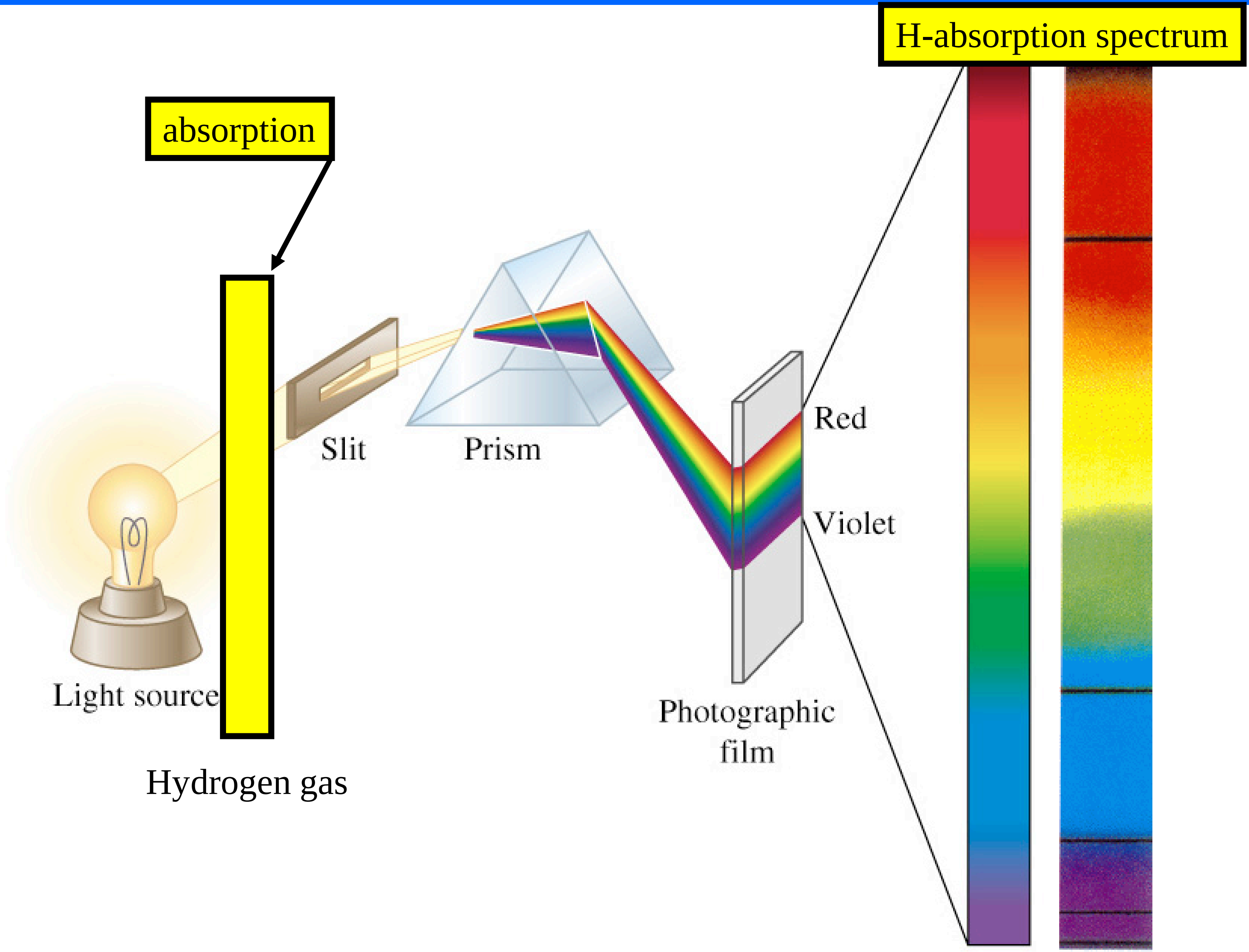
radiation transport (short photon mean free path)

continuous spectrum

Emission lines from atomic deexcitations
Absorption lines from atomic excitations

Wavelength → Atomic Species
Intensity → Abundance

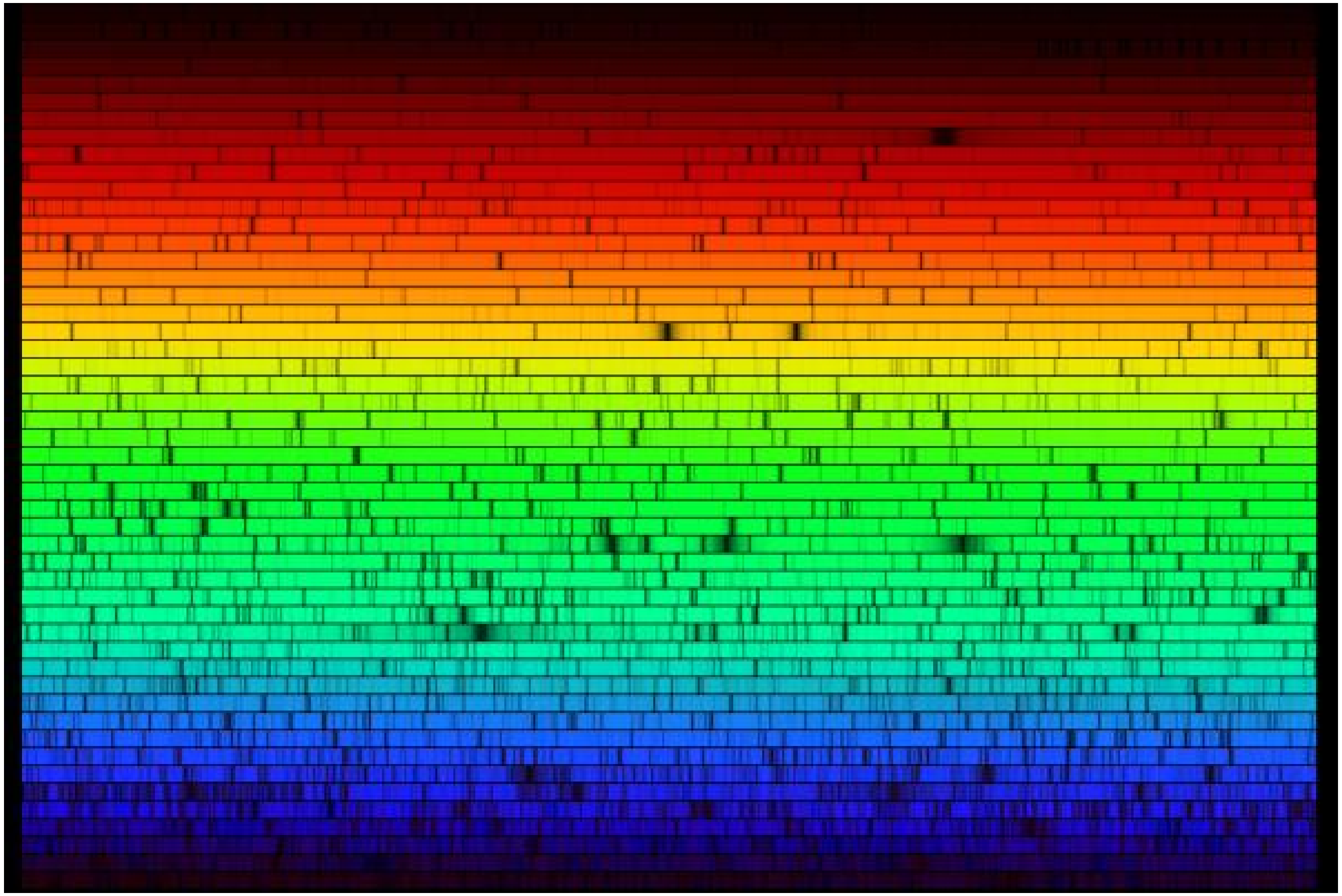
Spectral analysis absorption



3.1.1 Absorption spectra:

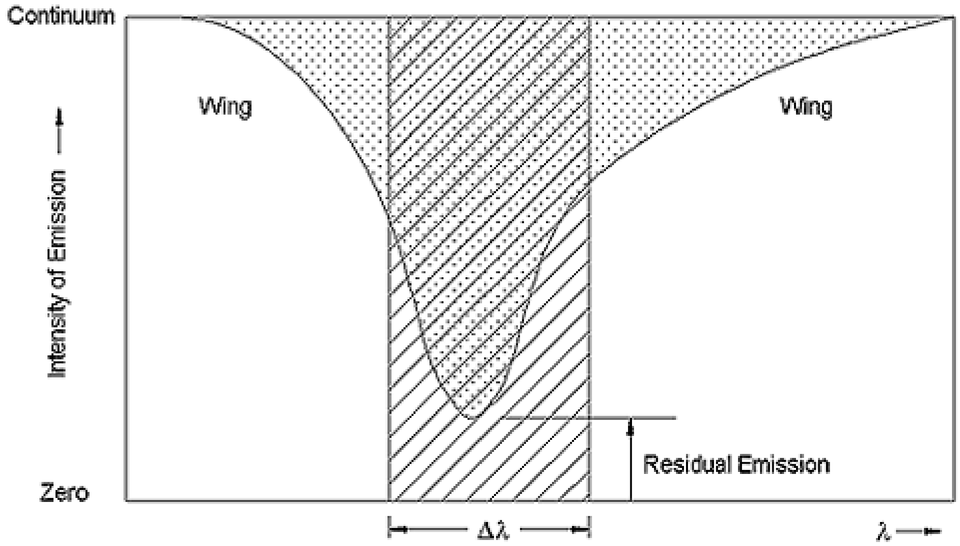
provide majority of data because:

- by far the largest number of elements can be observed
- least fractionation as right at end of convection zone - still well mixed
- well understood - good models available



solar spectrum (Nigel Sharp, NOAO)

Analysis of absorption spectra



effective line width ~ total absorbed intensity

Simple model consideration for absorption in a slab of thickness Δx:

$$I = I_0\, \mathrm{e}^{-\sigma\, n\, \Delta x}$$

I, I_0 = observed and initial intensity
σ = absorption cross section
n = number density of absorbing atom

So if one knows σ one can determine n and get the abundances

There are 2 complications:

Complication (1) Determine σ

The cross section is a measure of how likely a photon gets absorbed when an atom is bombarded with a flux of photons (more on cross section later …)

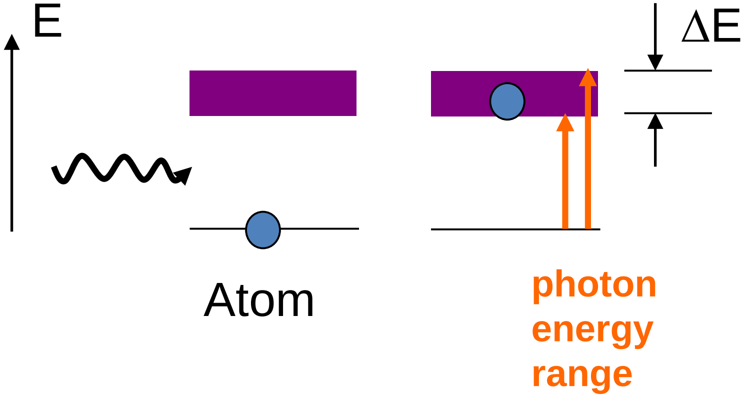
It depends on:

- **Oscillator strength**: a quantum mechanical property of the atomic transition

  Needs to be measured in the laboratory - not done with sufficient accuracy for a number of elements.

- **Line width**

  the wider the line in wavelength, the more likely a photon is absorbed (as in a classical oscillator).



excited state has an energy width ΔE. This leads to a range of photon energies that can be absorbed and to a line width

Heisenberg's uncertainty principle relates that to the **lifetime** τ of the excited state

$$\Delta E \cdot \tau = h$$

⟶ need lifetime of final state

The *lifetime of an atomic level* in the stellar environment depends on:

- **The natural lifetime** (natural width)

  lifetime that level would have if atom is left undisturbed

- **Frequency of interactions of atom with other atoms or electrons**

  Collisions with other atoms or electrons lead to deexcitation, and therefore to a shortening of the lifetime and a broadening of the line

  Varying electric fields from neighboring ions vary level energies through Stark Effect

  → depends on **pressure**

  → need local **gravity**, or **mass/radius** of star

- **Doppler broadening** through variations in atom velocity

  - thermal motion → depends on **temperature**
  - micro turbulence

Need detailed and accurate model of stellar atmosphere !

Complication (2)

Atomic transitions depend on the state of ionization !

The number density ***n*** determined through absorption lines is therefore the number density of ions in the ionization state that corresponds to the respective transition.

to determine the total abundance of an atomic species one needs the fraction of atoms in the specific state of ionization.

Notation: I = neutral atom, II = one electron removed, III = two electrons removed …..

Example: a CaII line originates from singly ionized Calcium

<u>Example:</u> determine abundance of single ionized atom through lines.

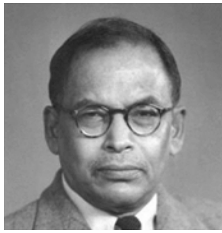
need n_+/n_0 to determine total abundance $n_+ + n_0$

n_+: number density of atoms in specific state of ionization
n_0: number density of neutral atoms

We assume local thermodynamic equilibrium **LTE**, which means that the ionization and recombination reactions are in thermal equilibrium:

$$A \longleftrightarrow A^+ + e^-$$

Then the **Saha ionization equation** yields:



$$\frac{n_+ n_e}{n_0} = \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \frac{g_+ g_e}{g_0}\, e^{-\frac{B}{kT}}$$

n_e = electron number density
m_e = electron mass
B = electron binding energy
g = statistical factors (2J+1)

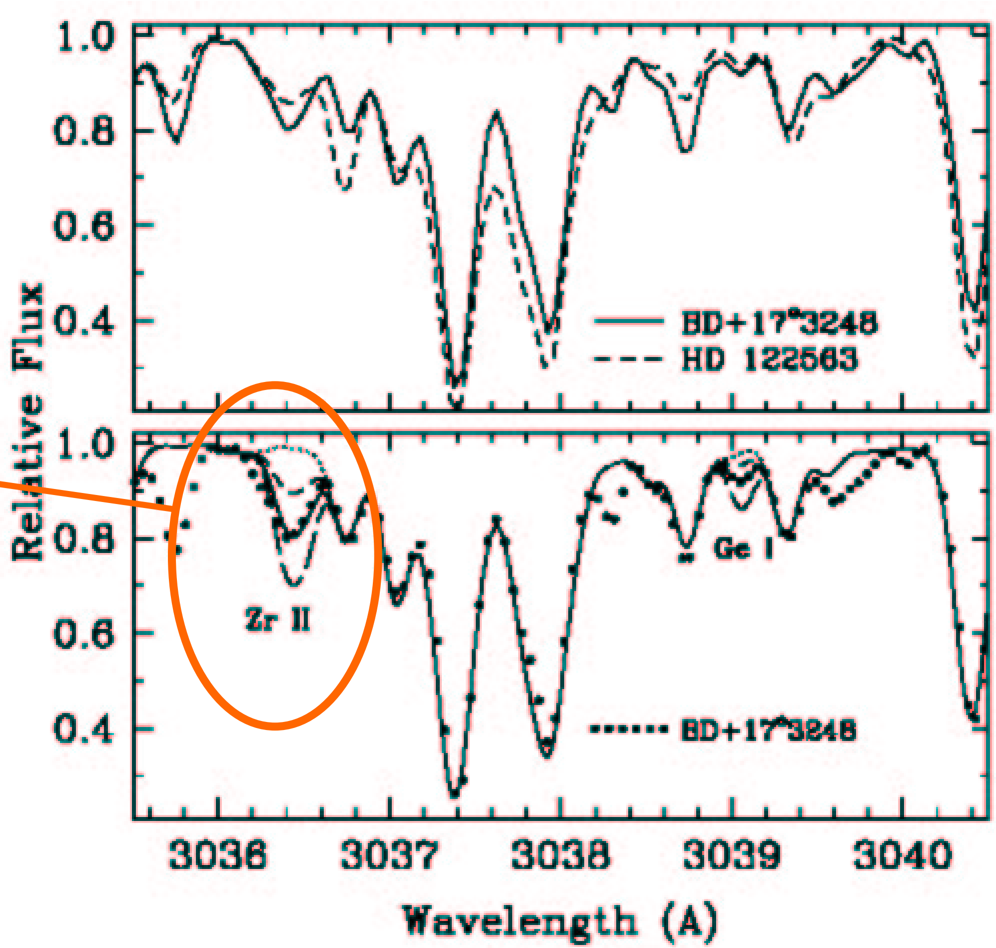
need pressure and temperature **strong temperature dependence !**

with higher and higher temperature more ionized nuclei - of course eventually a second, third, … ionization will happen.

again: one needs a detailed and accurate stellar atmosphere model

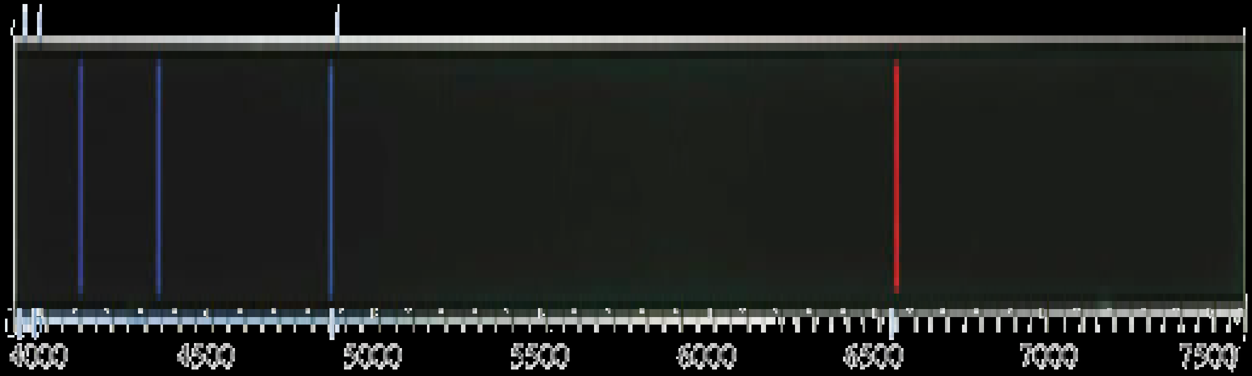
Practically, one sets up a *stellar atmosphere model*, based on star type, effective temperature etc. Then the parameters (including all abundances) of the model are fitted to best reproduce all spectral features, incl. all absorption lines (can be 100’s or more) .

Example for a r-process star (Sneden et al. ApJ 572 (2002) 861)

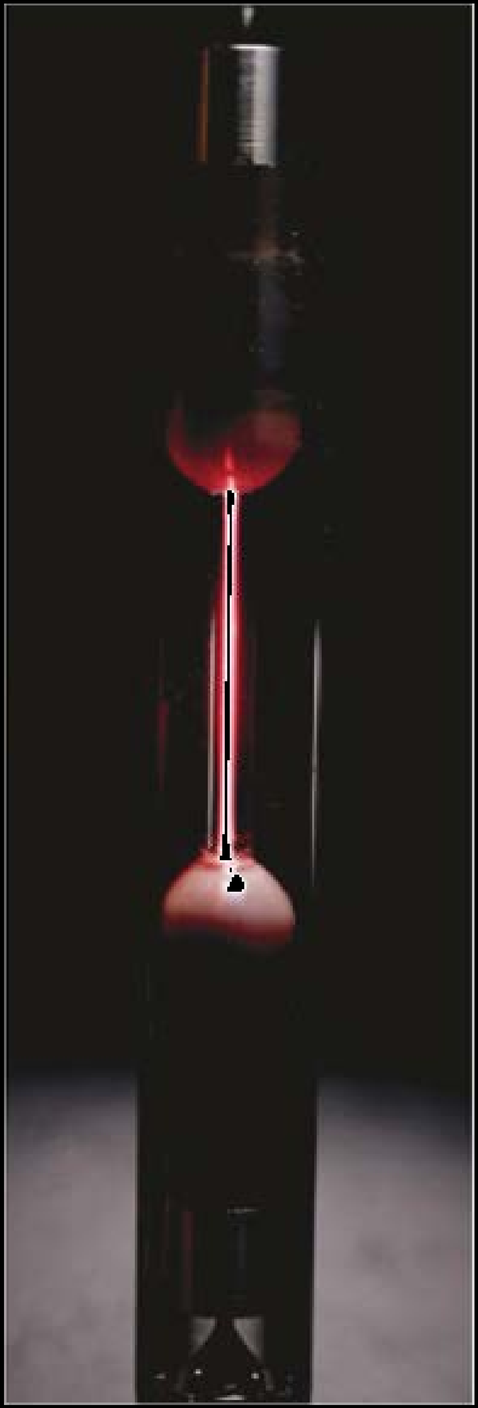


varied ZrII abundance

Hydrogen emission spectrum

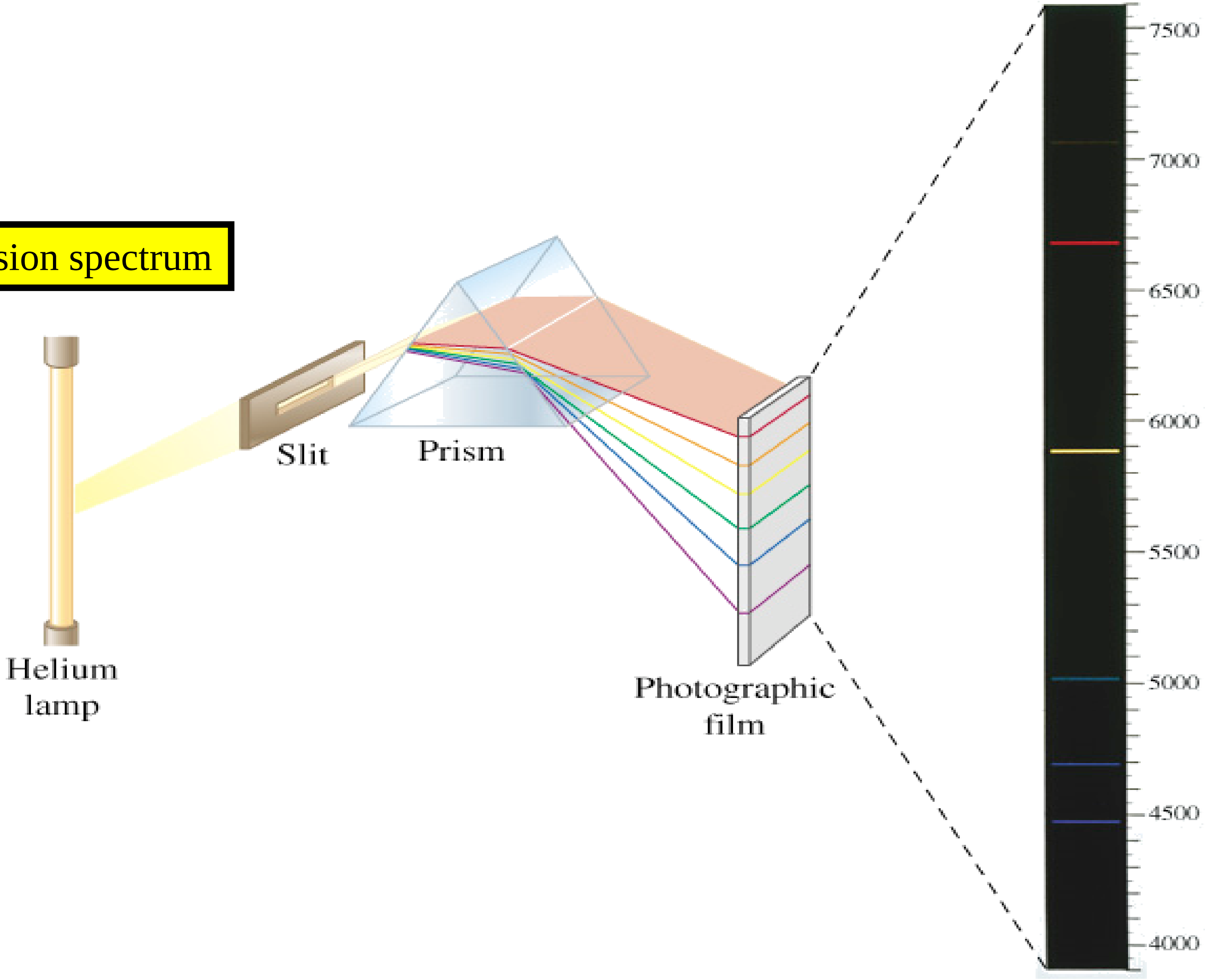


wave length nm



3.1.2 Emission spectra Helium spectral lines

Emission spectrum

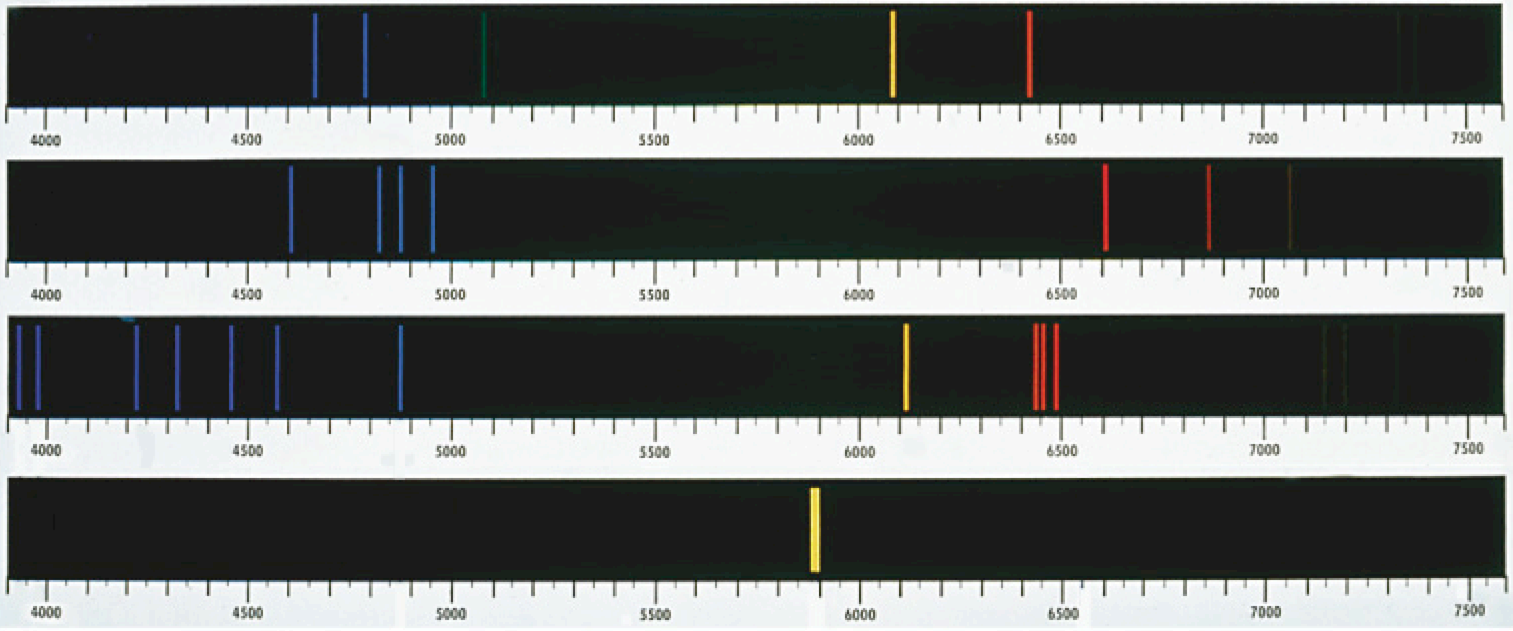


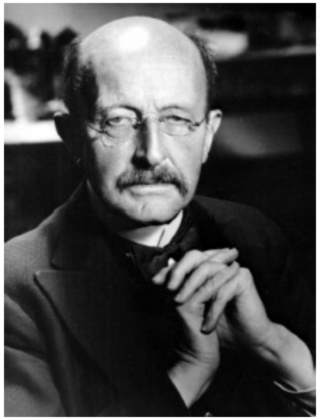
3.1.2 Emission spectra

Spectral analysis

Kirchhoff und Bunsen:

Every element has its characteristic emission band





Max Planck

3.1.2 Emission spectra

Disadvantages:

- **less understood, more complicated solar regions**
  (it is still not clear how exactly these layers are heated)
- **some fractionation/migration effects**
  for example FIP (first ionization potential): species with low first ionization potential are enhanced in respect to photosphere possibly because of fractionation between ions and neutral atoms

Therefore abundances less accurate

But there are elements that cannot be observed in the photosphere
(for example Helium is only seen in emission lines)

this is how Helium
was discovered by
Sir Joseph Lockyer
England in October 20, 1868

Solar Chromosphere
red from Hα emission
lines

3.2 Meteorites

Meteorites can provide accurate information on elemental abundances in the pre solar nebula. More precise than solar spectra if data are available …

But some gases escape and cannot be determined this way (for example hydrogen, or noble gases)

Not all meteorites are suitable - most of them are fractionated and do not provide representative solar abundance information.

One needs primitive meteorites that underwent little modification after forming.

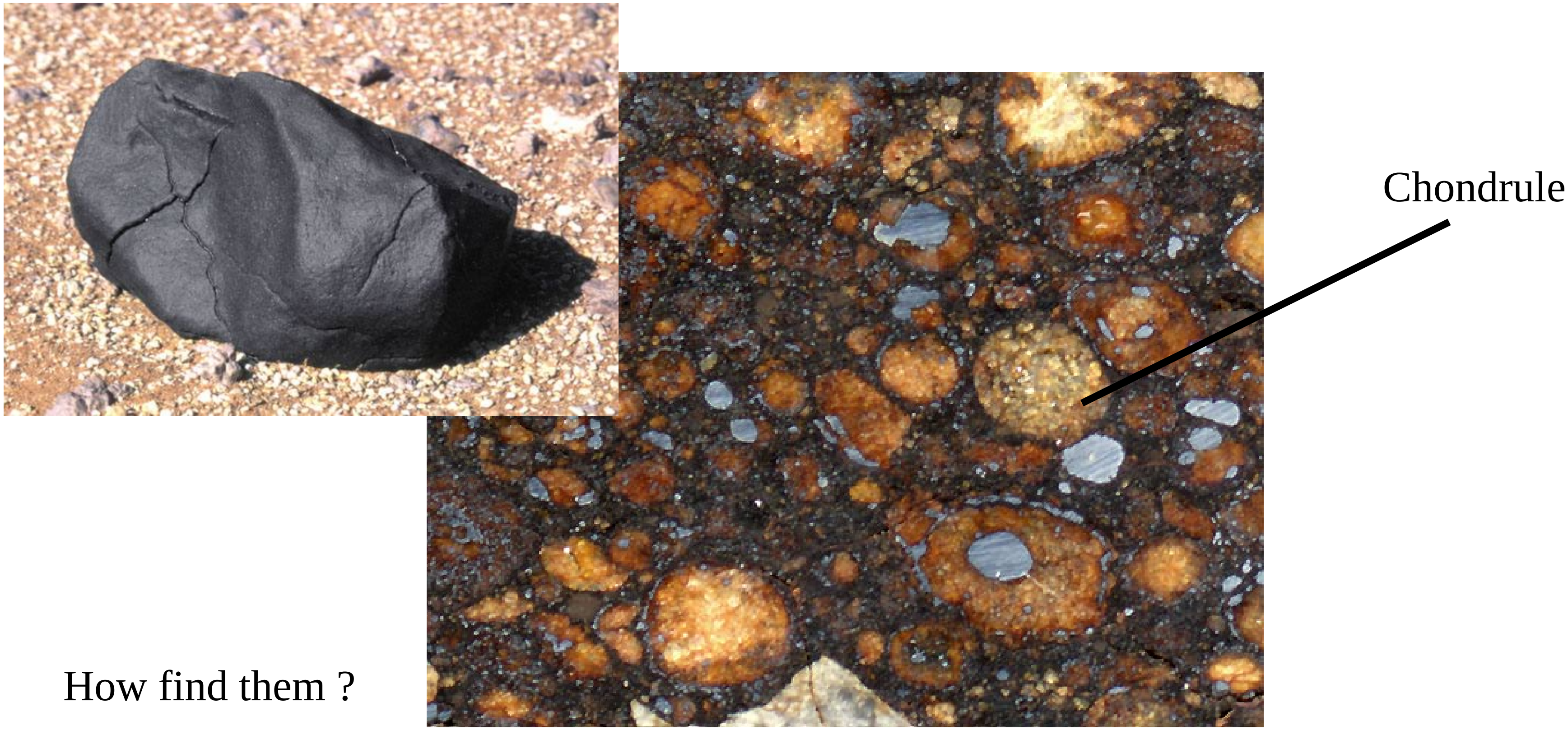
Classification of meteorites:

Group	*Subgroup*	*Frequency*
Stones	Chondrites	86%
	Achondrites	7%
Stony Irons		1.5%
Irons		5.5%

Use **carbonaceous chondrites (~ 6% of falls)**

Chondrites: Have Chondrules - small ~1mm size spherical inclusions in matrix
believed to have formed very early in the pre solar nebula
accreted together and remained largely unchanged since then

Carbonaceous Chondrites have lots of organic compounds that indicate very little heating (some were never heated above 50 degrees)



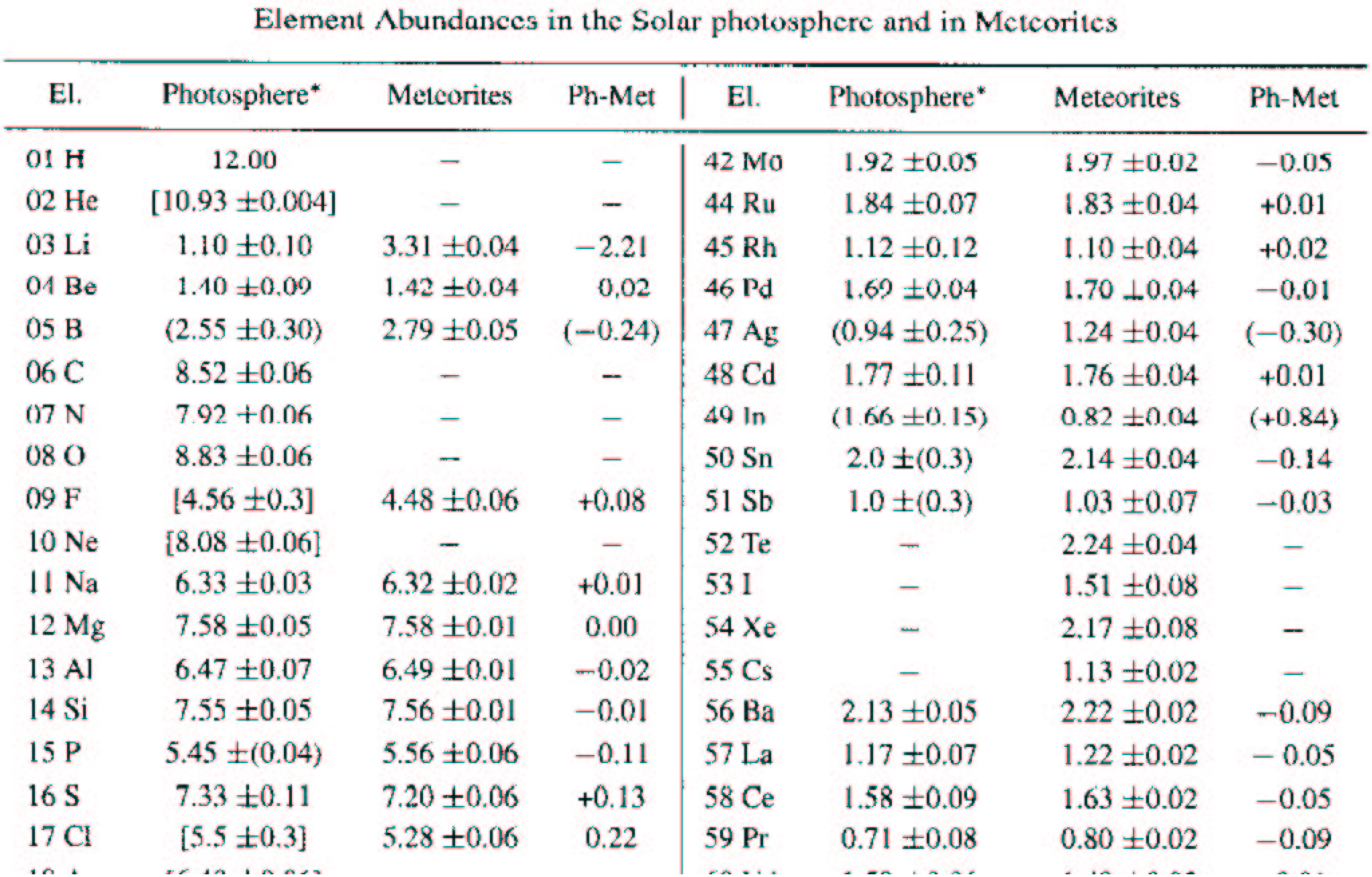
How find them ?

more on meteorites

http://www.saharamet.com
http://www.meteorite.fr

3.3 Results for solar abundance distribution

Part of Tab. 1, Grevesse & Sauval, Space Sci. Rev. 85 (1998) 161

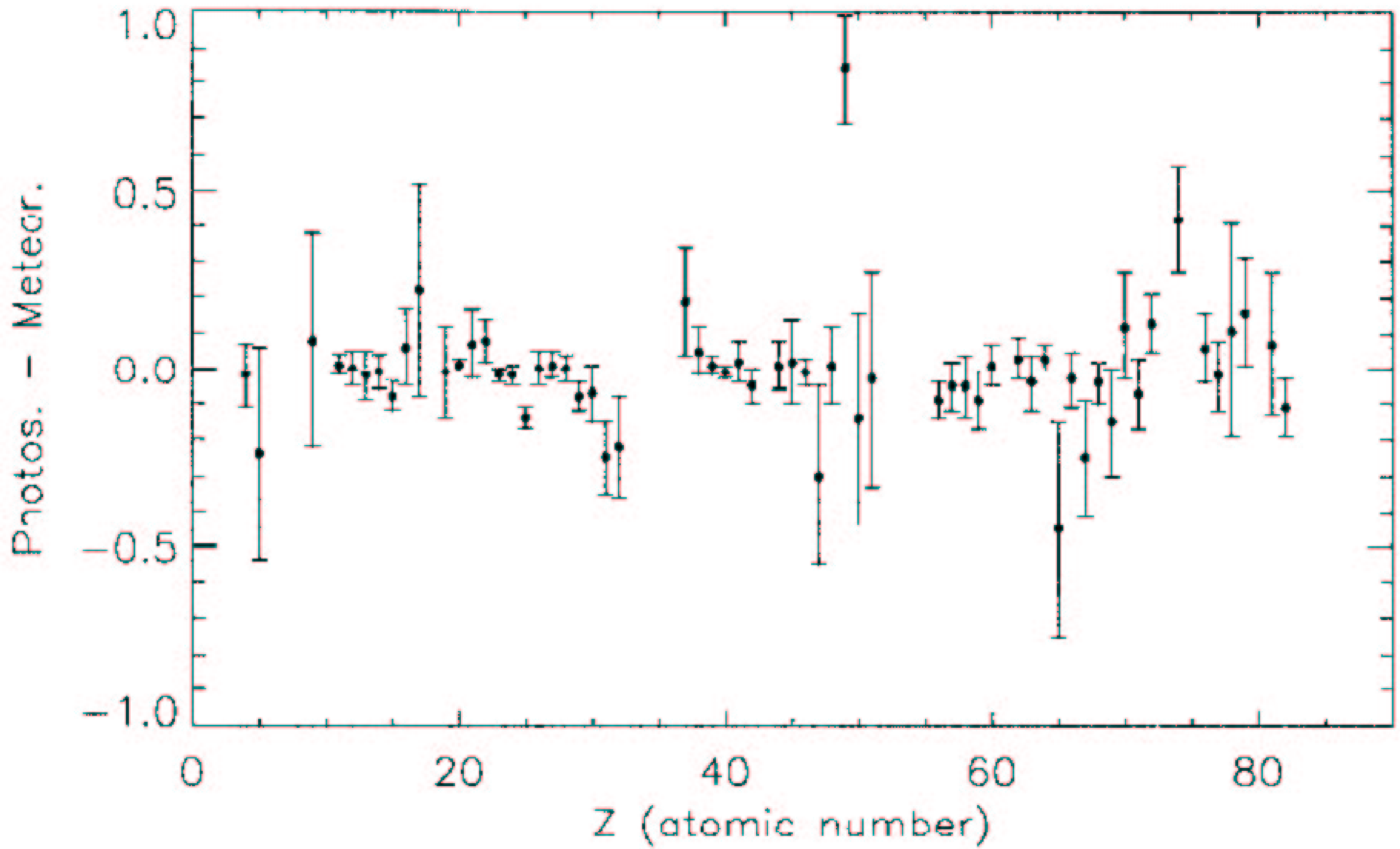


Element Abundances in the Solar photosphere and in Meteorites

El.	Photosphere*	Meteorites	Ph-Met	El.	Photosphere*	Meteorites	Ph-Met
01 H	12.00	–	–	42 Mo	1.92 ±0.05	1.97 ±0.02	−0.05
02 He	[10.93 ±0.004]	–	–	44 Ru	1.84 ±0.07	1.83 ±0.04	+0.01
03 Li	1.10 ±0.10	3.31 ±0.04	−2.21	45 Rh	1.12 ±0.12	1.10 ±0.04	+0.02
04 Be	1.40 ±0.09	1.42 ±0.04	0.02	46 Pd	1.69 ±0.04	1.70 ±0.04	−0.01
05 B	(2.55 ±0.30)	2.79 ±0.05	(−0.24)	47 Ag	(0.94 ±0.25)	1.24 ±0.04	(−0.30)
06 C	8.52 ±0.06	–	–	48 Cd	1.77 ±0.11	1.76 ±0.04	+0.01
07 N	7.92 ±0.06	–	–	49 In	(1.66 ±0.15)	0.82 ±0.04	(+0.84)
08 O	8.83 ±0.06	–	–	50 Sn	2.0 ±(0.3)	2.14 ±0.04	−0.14
09 F	[4.56 ±0.3]	4.48 ±0.06	+0.08	51 Sb	1.0 ±(0.3)	1.03 ±0.07	−0.03
10 Ne	[8.08 ±0.06]	–	–	52 Te	–	2.24 ±0.04	–
11 Na	6.33 ±0.03	6.32 ±0.02	+0.01	53 I	–	1.51 ±0.08	–
12 Mg	7.58 ±0.05	7.58 ±0.01	0.00	54 Xe	–	2.17 ±0.08	–
13 Al	6.47 ±0.07	6.49 ±0.01	−0.02	55 Cs	–	1.13 ±0.02	–
14 Si	7.55 ±0.05	7.56 ±0.01	−0.01	56 Ba	2.13 ±0.05	2.22 ±0.02	−0.09
15 P	5.45 ±(0.04)	5.56 ±0.06	−0.11	57 La	1.17 ±0.07	1.22 ±0.02	− 0.05
16 S	7.33 ±0.11	7.20 ±0.06	+0.13	58 Ce	1.58 ±0.09	1.63 ±0.02	−0.05
17 Cl	[5.5 ±0.3]	5.28 ±0.06	0.22	59 Pr	0.71 ±0.08	0.80 ±0.02	−0.09

units: given is $A = \log(n/n_H) + 12$ (log of number of atoms per 10^{12} H atoms)
(often also used: number of atoms per 10^6 Si atoms)

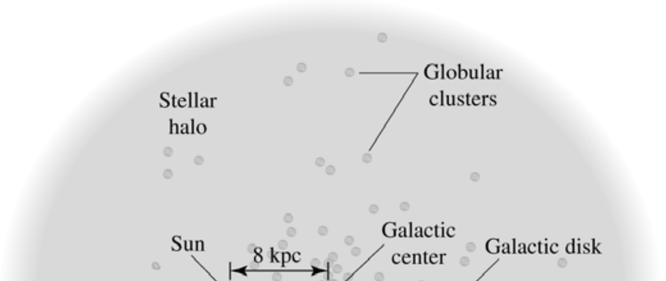
log of photosphere abundance/ meteoritic abundance

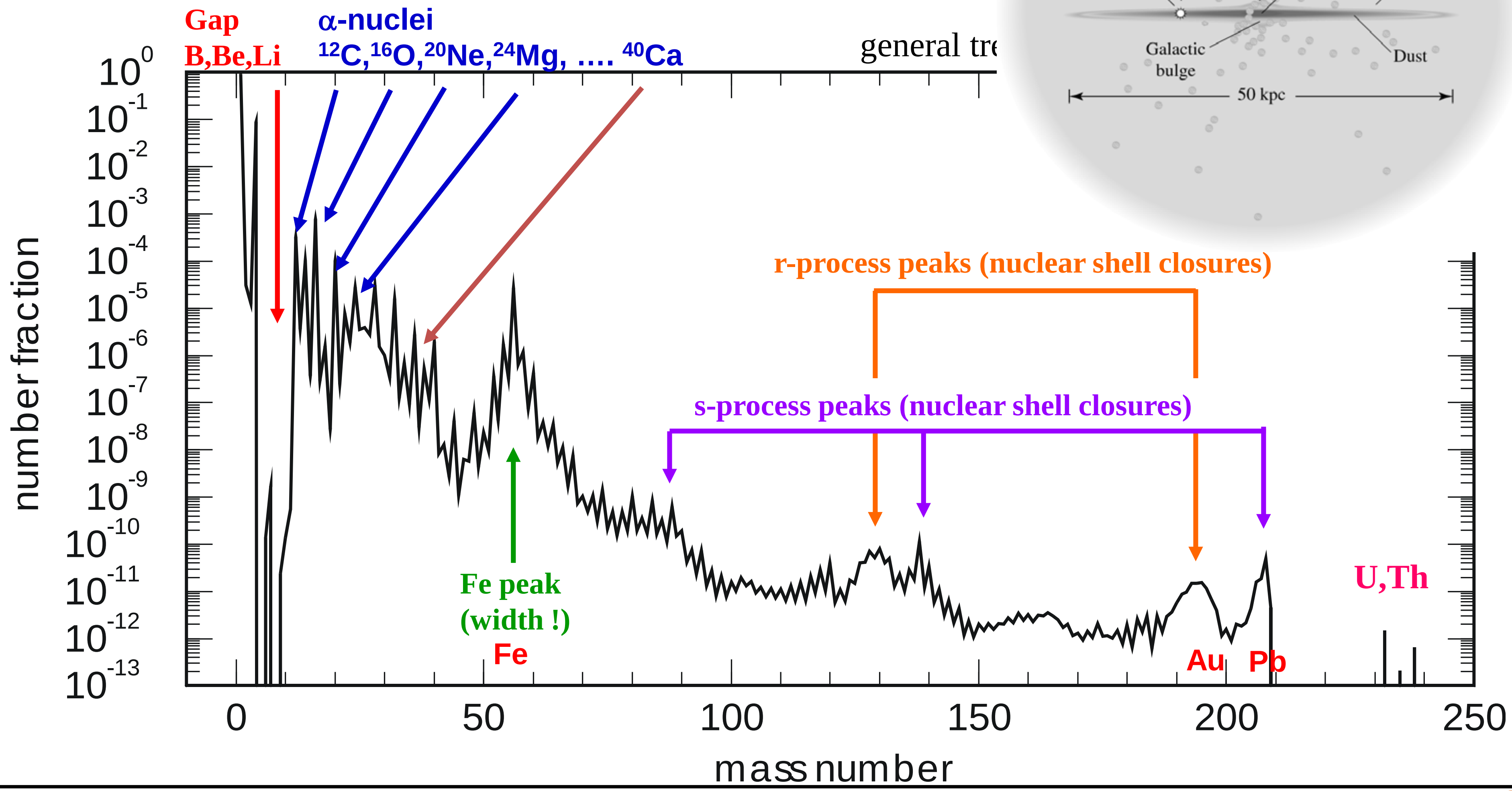


generally good agreement

Solar abundance distribution

Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6





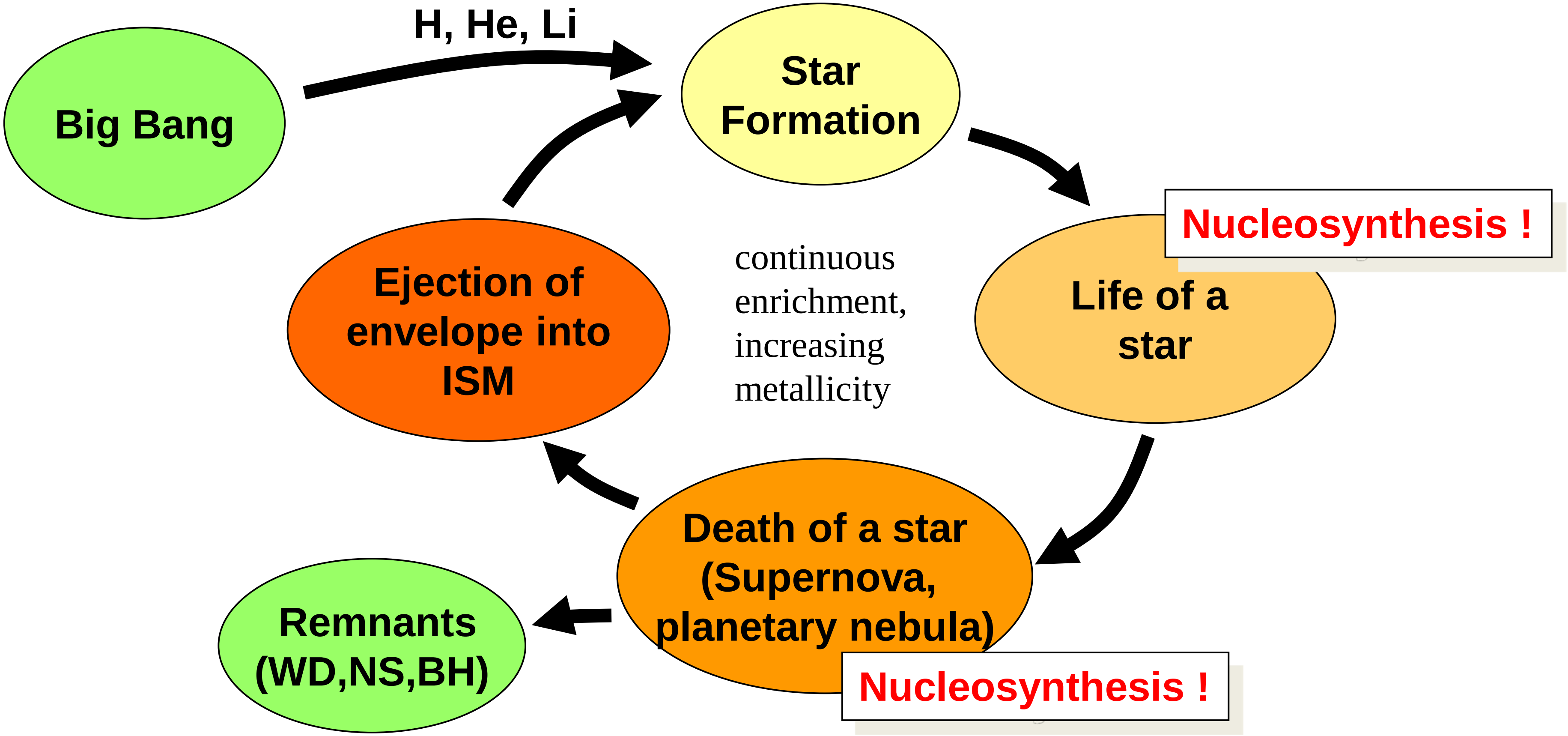
4. Abundances outside the solar neighborhood?

Abundances outside the solar system can be determined through:

- Stellar absorption spectra of other stars than the sun
- Interstellar absorption spectra
- Emission lines from Nebulae (Supernova remnants, Planetary nebulae, …)
- γ-ray detection from the decay of radioactive nuclei
- Cosmic Rays

What do we expect ?

Nucleosynthesis is a gradual, still ongoing process:



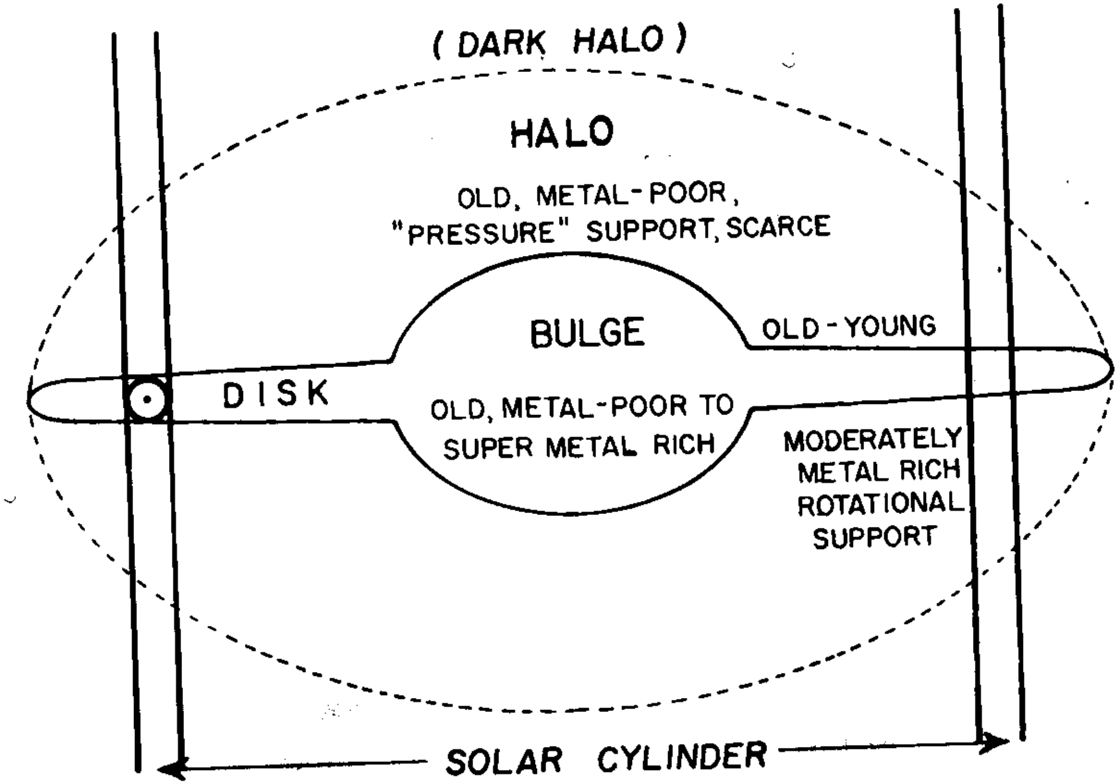
continuous enrichment, increasing metallicity

BH: Black Hole
NS: Neutron Star
WD: White Dwarf Star
ISM Interstellar Medium

Therefore the composition of the universe is NOT homogeneous !

- **Efficiency of nucleosynthesis cycle depends on local environment**

  For example star formation requires gas and dust - therefore extremely different metallicities in different parts of the Galaxy



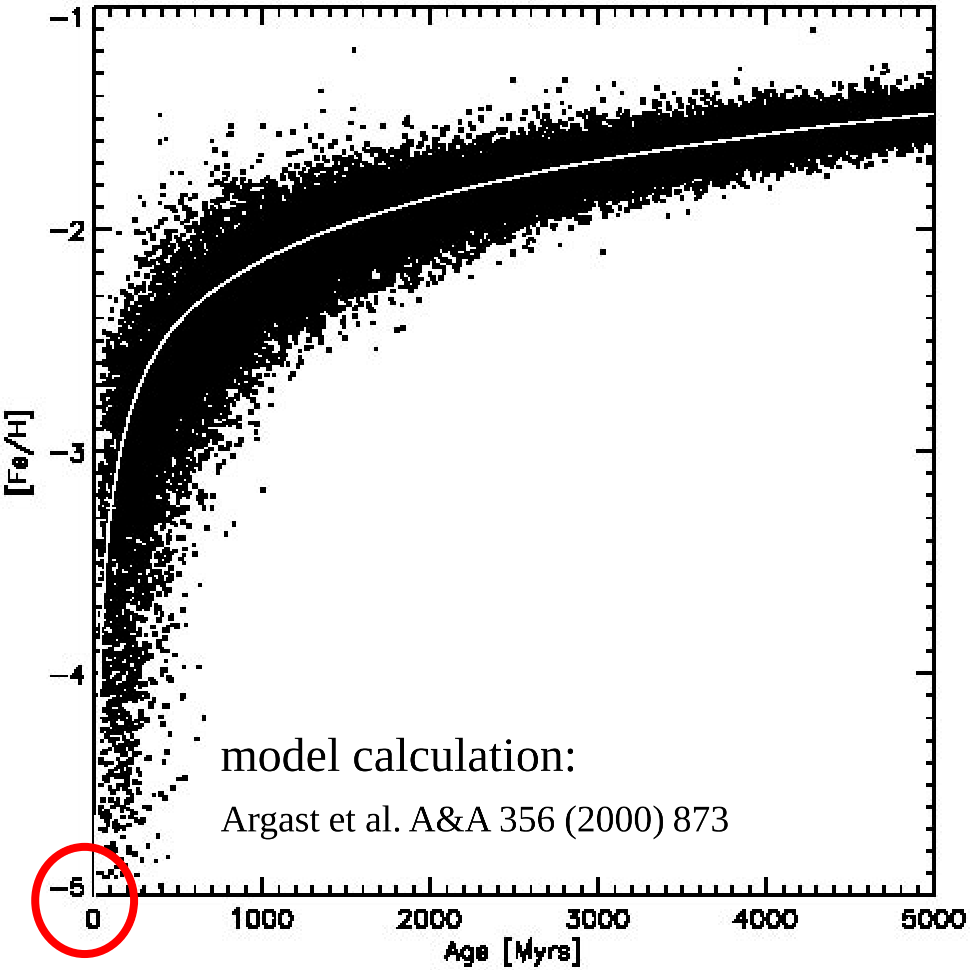
Pagel, Fig 3.31

- **“population effect” - enrichment contineous over time (see prev. slide) so metallicity of a star depends on when it was born**

$$[Fe/H] = \log \frac{(Fe/H)}{(Fe/H)_{solar}}$$

Classical picture:
Pop I: metal rich like sun
Pop II: metal poor [Fe/H] < -2
Pop III: first stars (not seen)

but today situation is much more complicated - many mixed case …



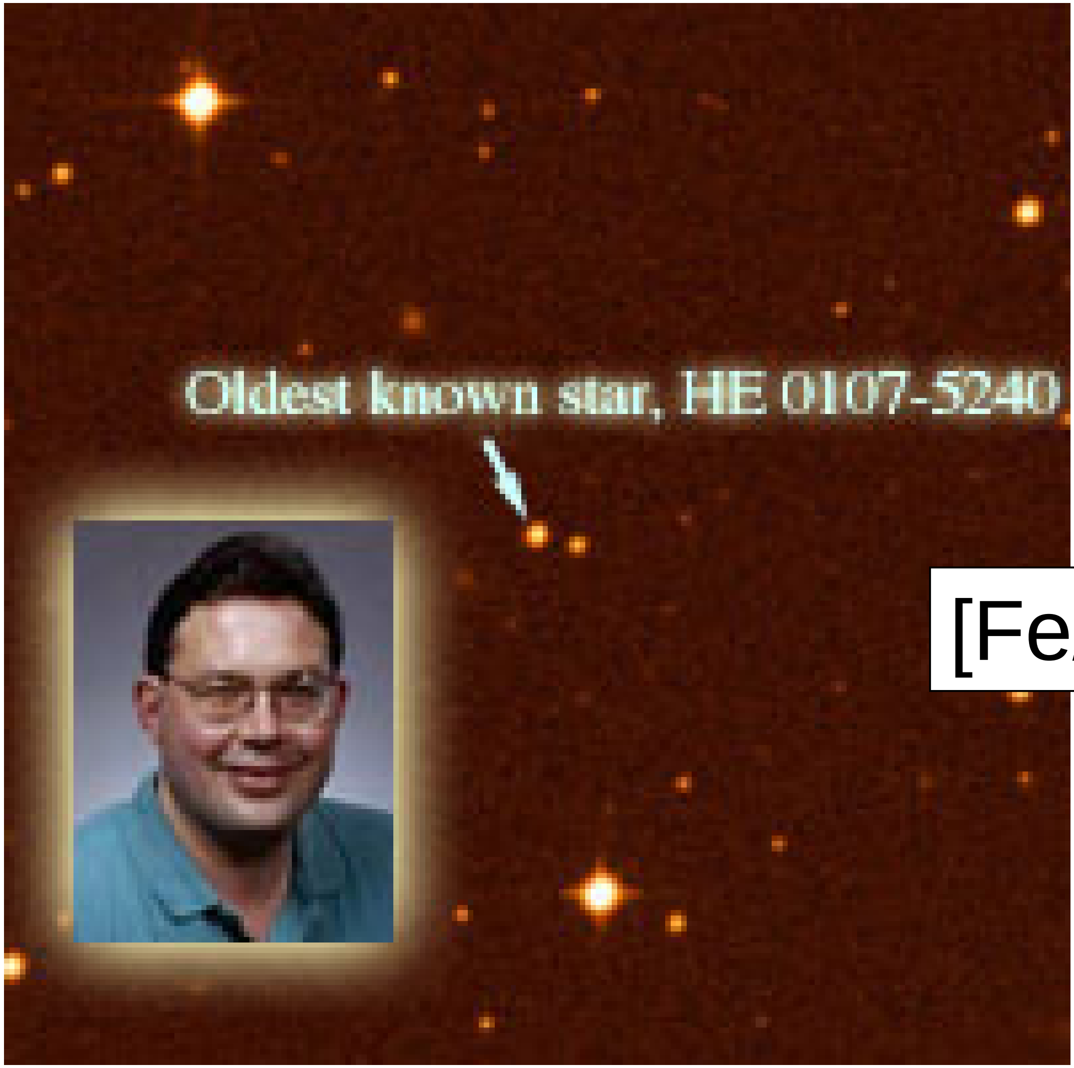
model calculation:

Argast et al. A&A 356 (2000) 873

finally found

metallicity - age relation: old stars are metal poor   BUT: large scatter !!!

From MSU Physics and Astronomy Department Website:



[Fe/H]=-5.1

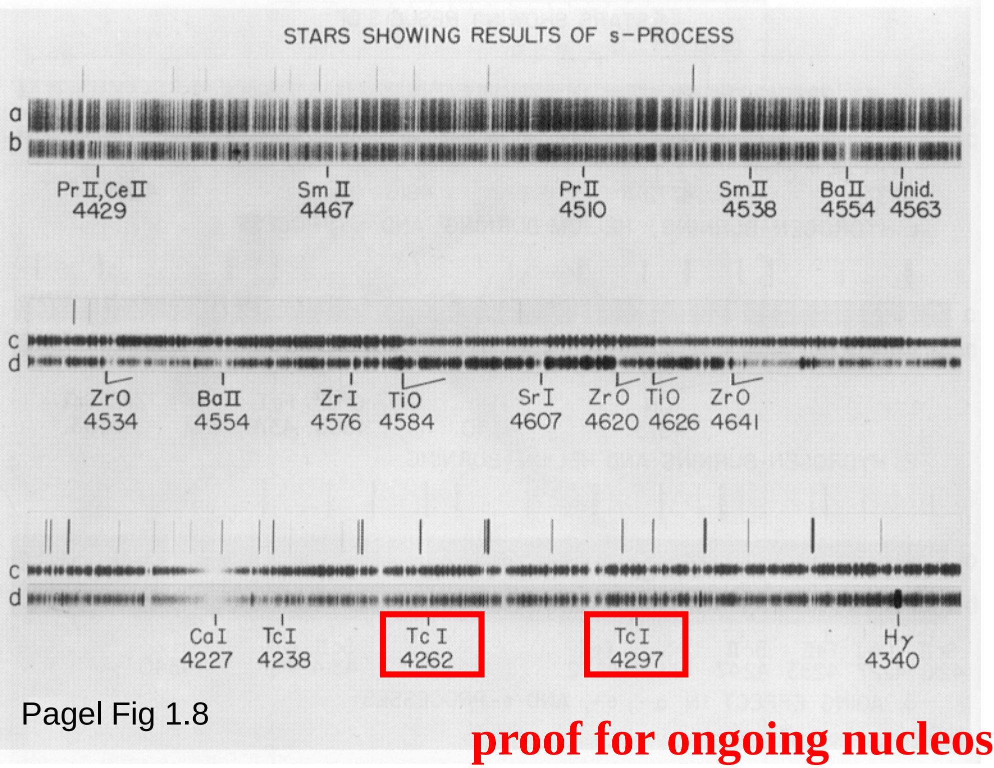
found in halo (little star formation, lots of old, metal poor stars)

- **very different abundance distribution when one looks directly at or near nucleosynthesis sites (before mixing with ISM)**

Examples:

(a) Stars where, unlike in the sun, nucleosynthesis products from the interior are mixed into the photosphere

for example discovery of Tc in stars. Tc has no stable isotope and decays with a half-life of 4 Mio years (Merrill 1952)

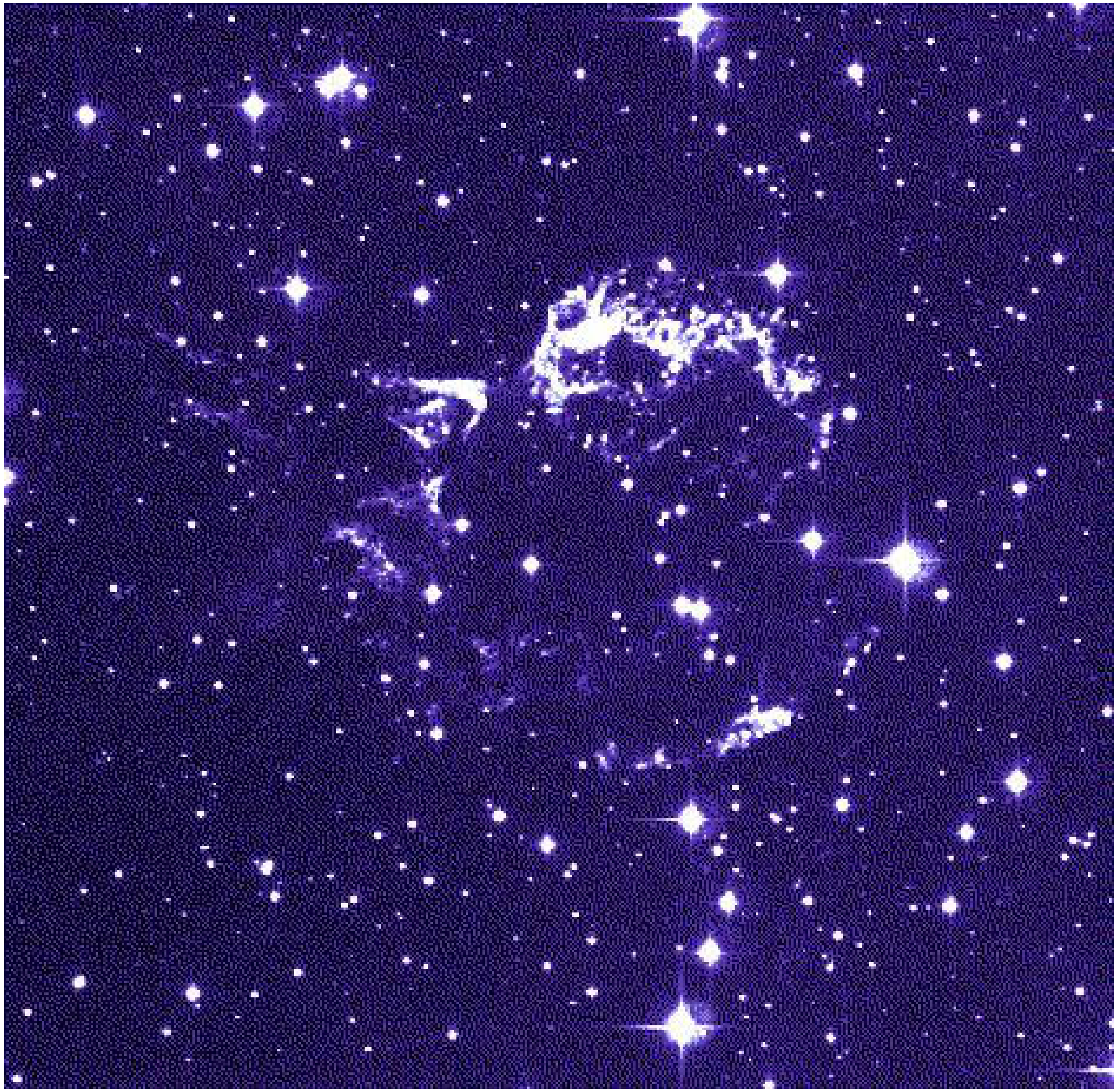


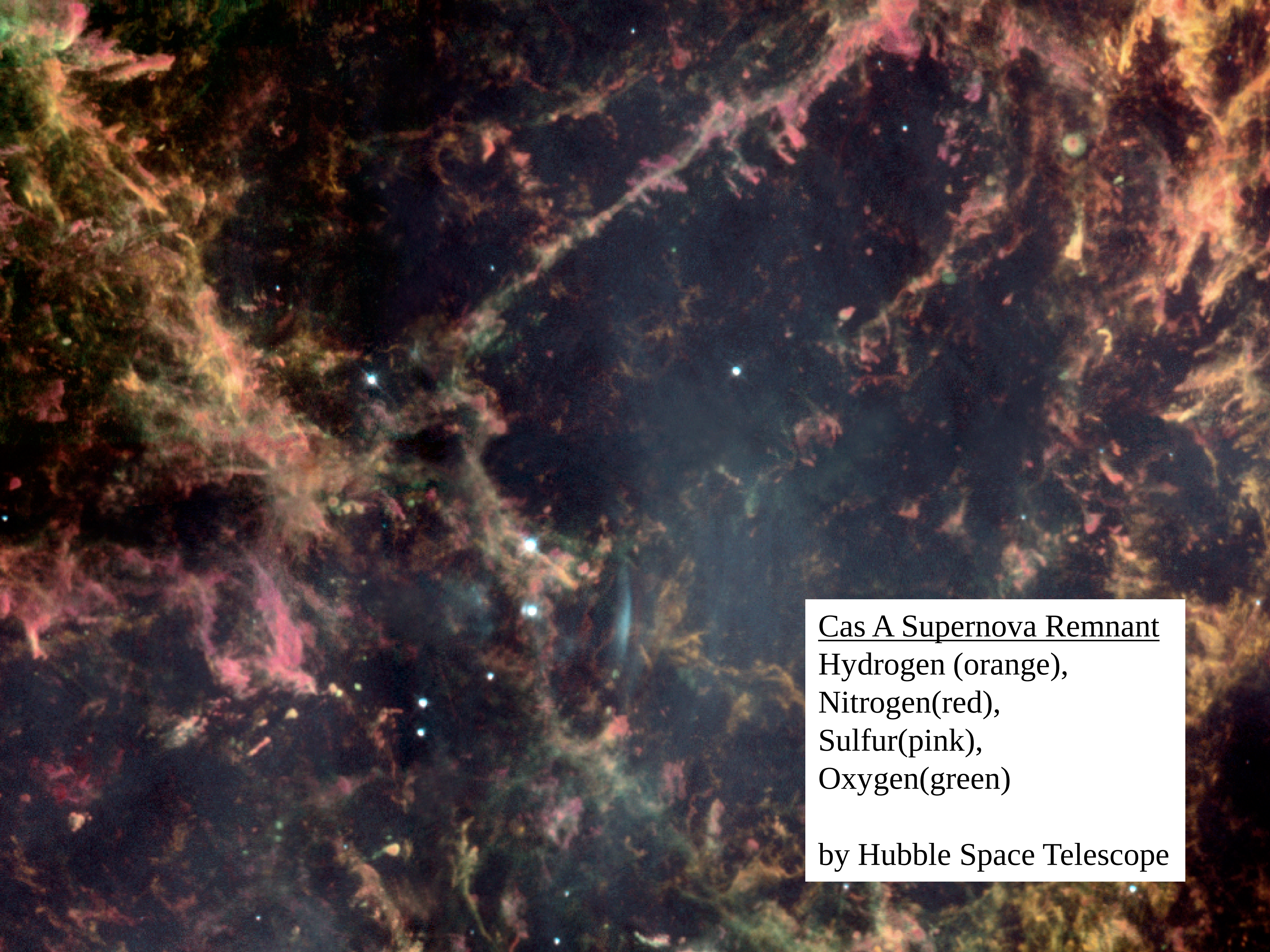
Pagel Fig 1.8

proof for ongoing nucleosynthesis in stars !

(b) Supernova remnants - where freshly synthesized elements got ejected

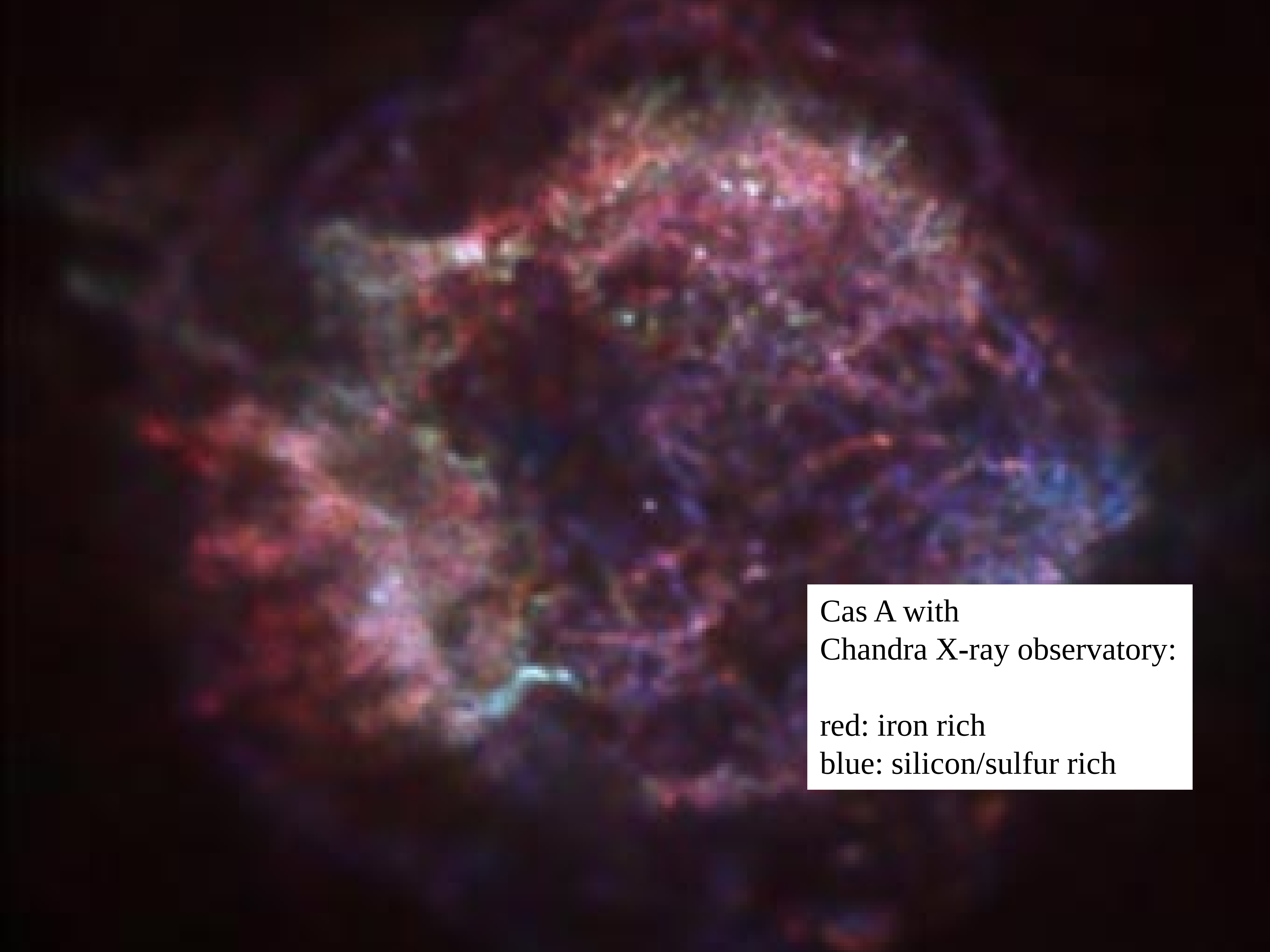
Cas A:





Cas A Supernova Remnant
Hydrogen (orange),
Nitrogen(red),
Sulfur(pink),
Oxygen(green)

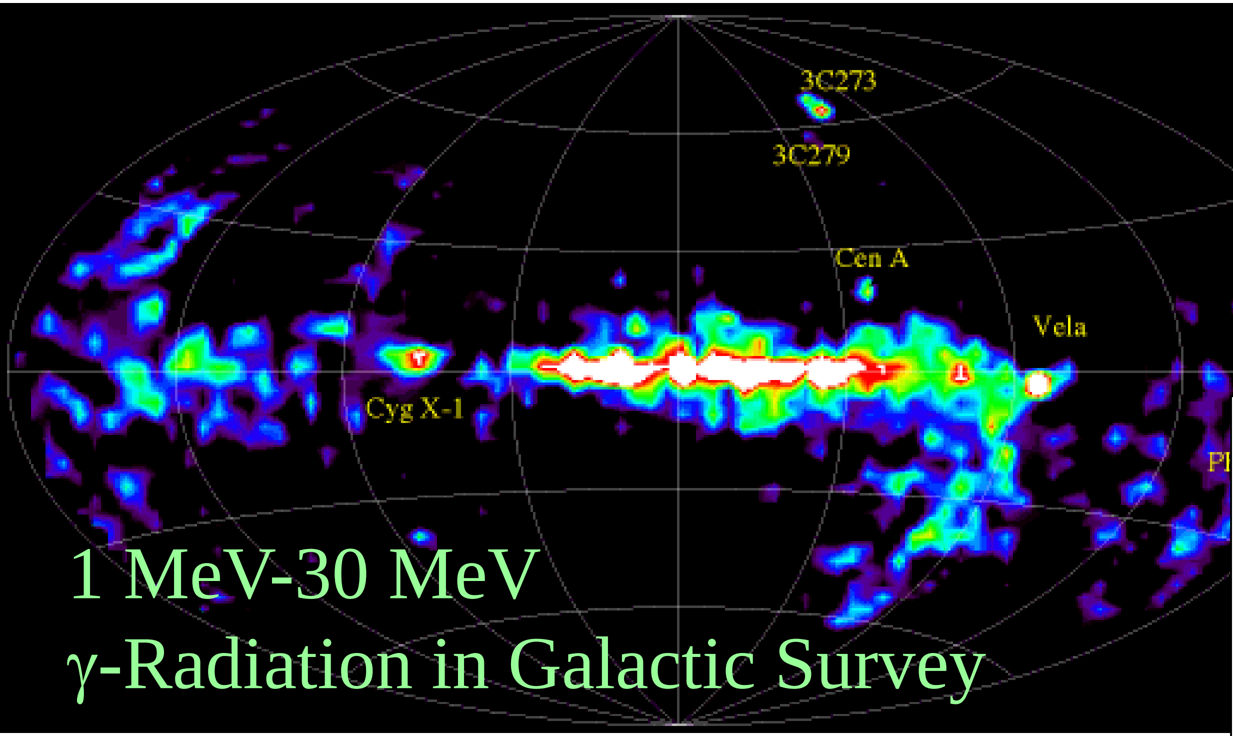
by Hubble Space Telescope



Cas A with
Chandra X-ray observatory:

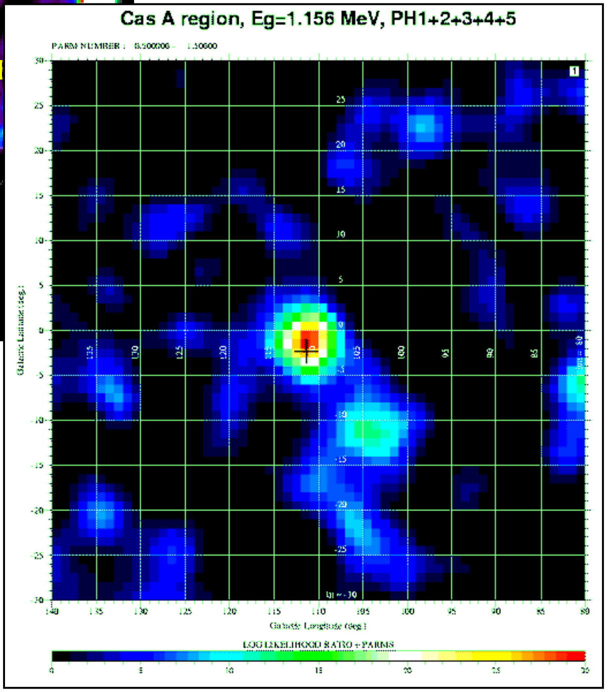
red: iron rich
blue: silicon/sulfur rich

Galactic radioactivity – detected by γ-radiation



1 MeV-30 MeV
γ-Radiation in Galactic Survey

(^{26}Al Half life: 700,0000 years)



^{44}Ti in Supernova Cas-A Location

Half life: 60 years)