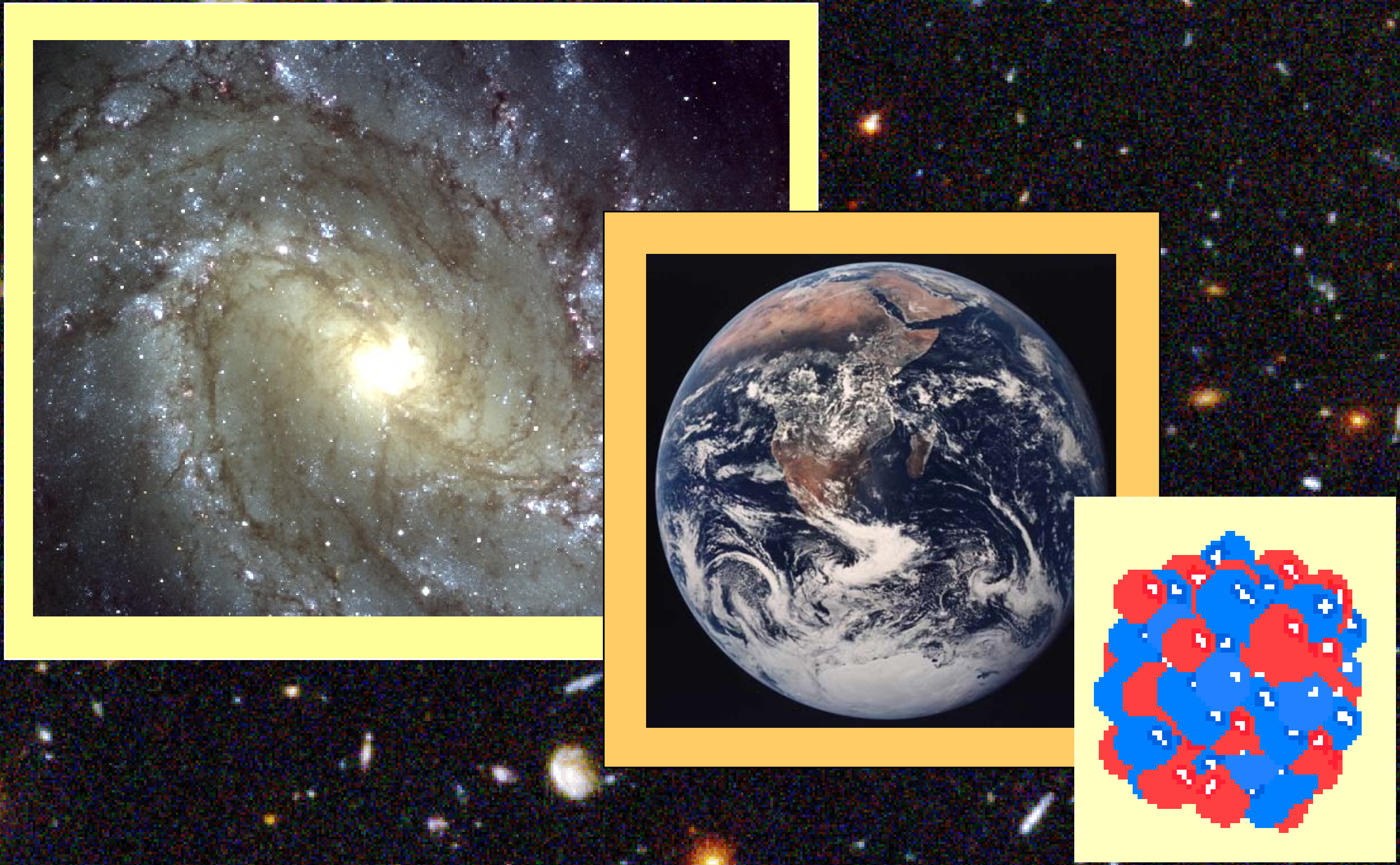
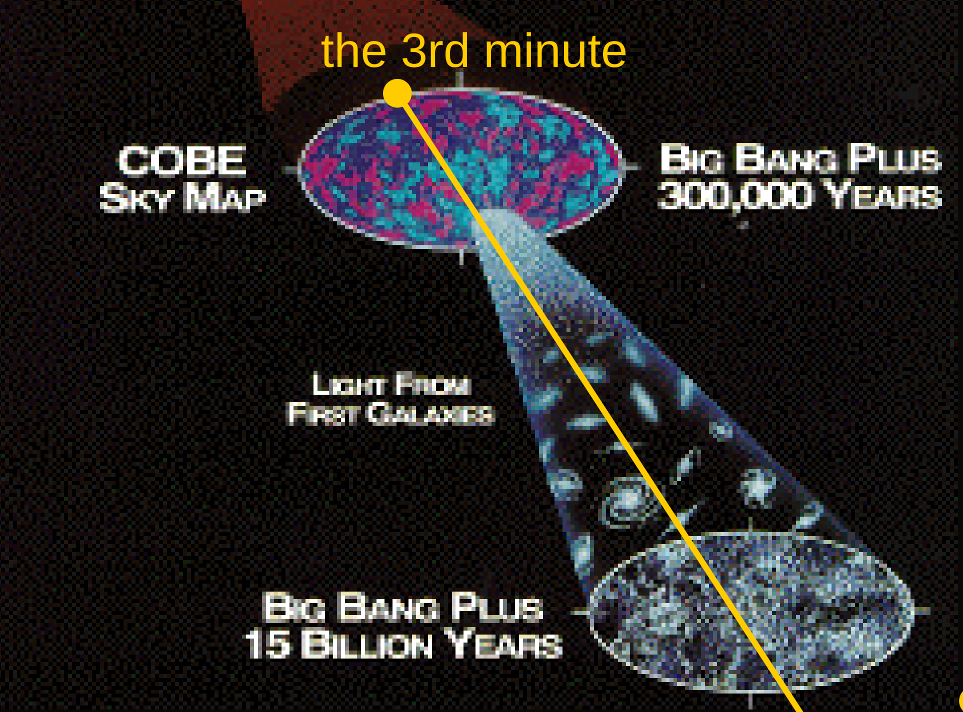
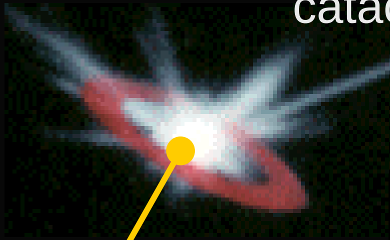
A Cosmic Connection:

Properties of Nuclei and Properties of the Cosmos

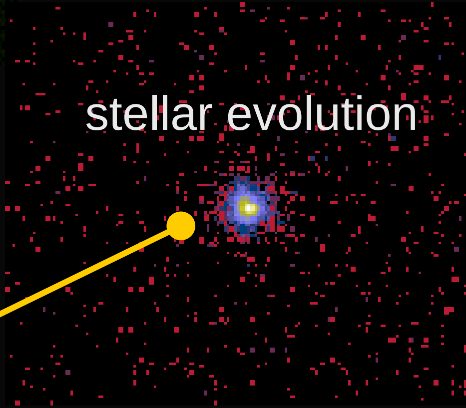




the 3rd minute

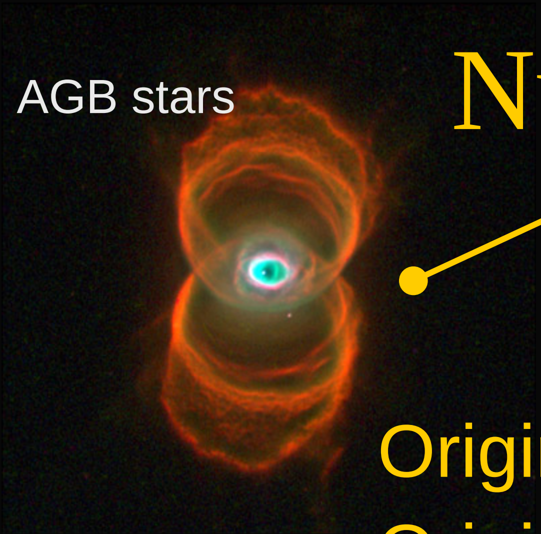


cataclysmic binaries

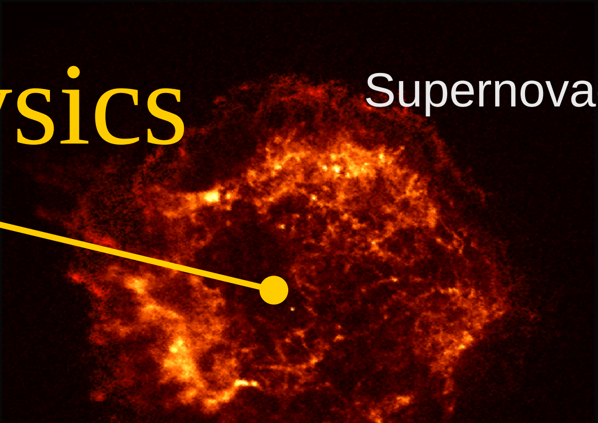


stellar evolution

Nuclear Astrophysics



AGB stars



Supernovae

Origin and fate of the elements in our universe

Origin of radiation and energy in our universe

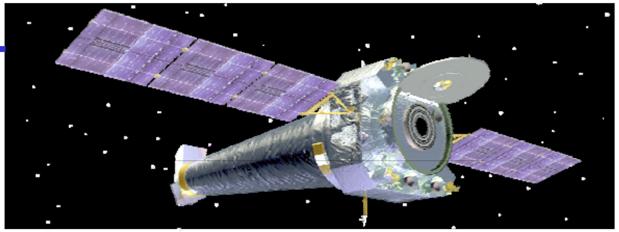
Joint Institute for Nuclear Astrophysics (JINA)

a NSF Physics Frontiers Center – **www.jinaweb.org**

- **Identify and address the critical open questions and needs of the field**
- **Form an intellectual center for the field**
- **Overcome boundaries between astrophysics and nuclear physics and between theory and experiment**
- **Attract and educate young people**

Nuclear Physics Experiments

Astronomical Observations



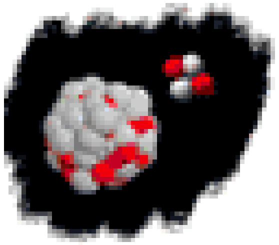
Astrophysical Models

JINA

Core institutions:
- **Notre Dame**
- **MSU**
- **U. of Chicago**

Associated:
- **ANL**
- **LANL**
- **U of Arizona**
- **UC Santa Barbara**
- **UC Santa Cruz**
- **VISTARS (Mainz,GSI)**

Nuclear Theory



http://www.jinaweb.org

I. 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 ….

72% Dark Energy (don't know what it is)
23% Cold dark matter (don't know what it is)
4.6% Nuclei and electrons (visible as stars ~0.4%) ← **Topic of this course**

Why bother with 4% ???

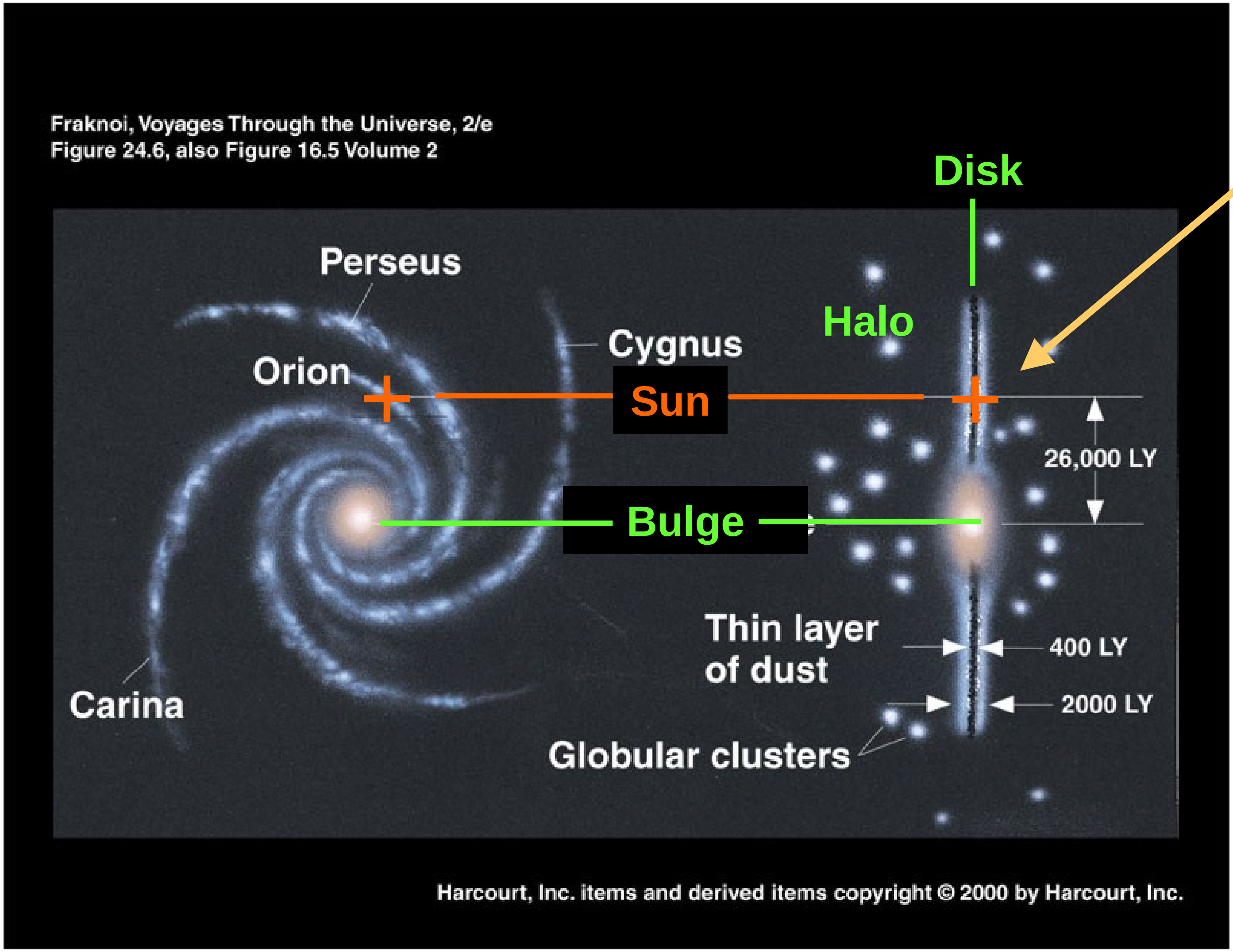
Important things are made of it:

Questions to be answered:

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

Window of the protestant church in Wixhausen, Germany

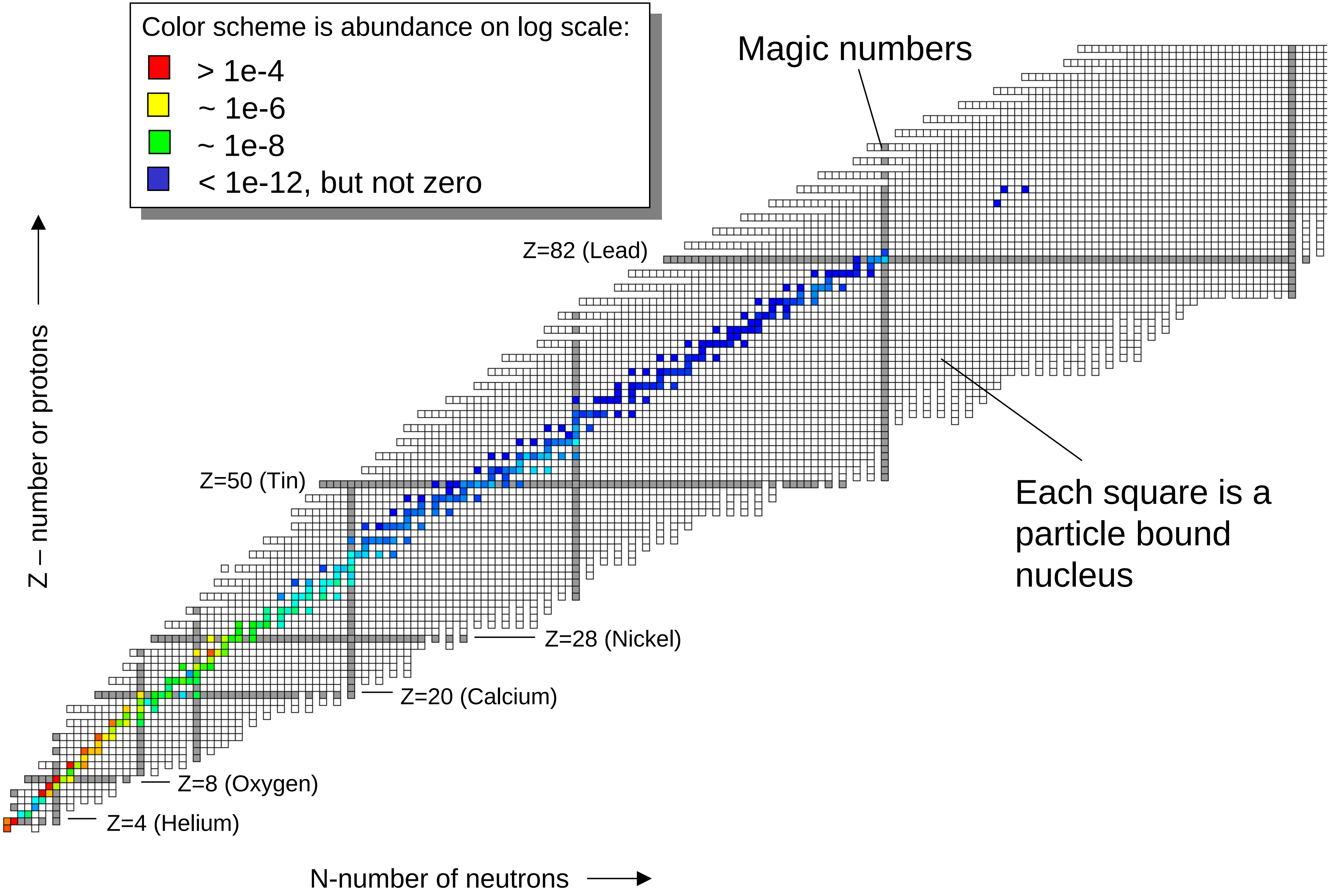
The solar abundance distribution



solar abundances:

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

Abundances of nuclei on the chart of nuclides:


Color scheme is abundance on log scale:

🟥 > 1e-4

🟨 ~ 1e-6

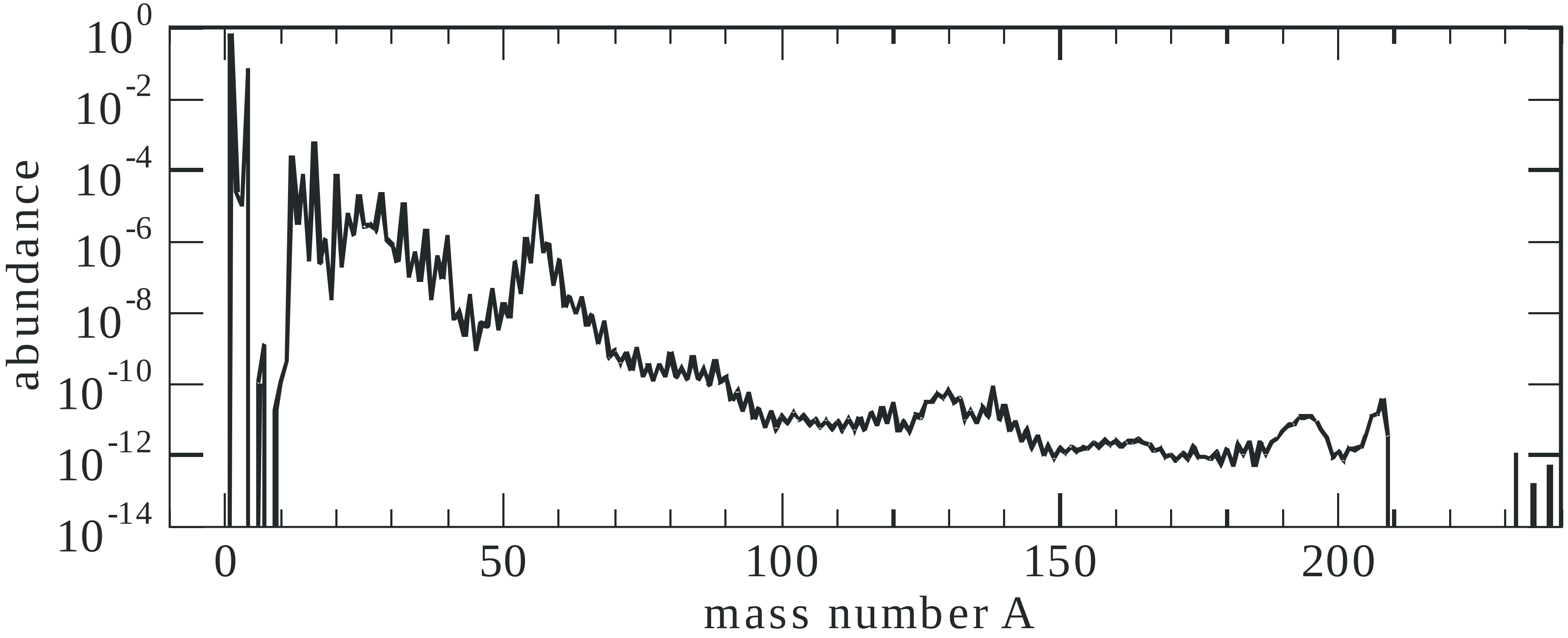
🟩 ~ 1e-8

🟦 < 1e-12, but not zero

Magic numbers

Each square is a particle bound nucleus

Abundance as a function of mass number A=Z+N:

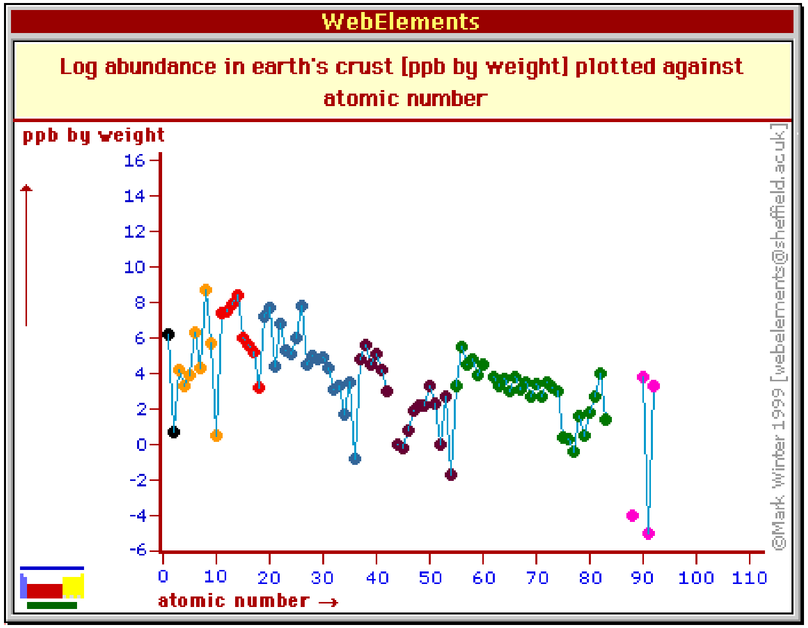


History:

1889, Frank Wigglesworth Clarke read a paper before the Philosophical Society of Washington “The Relative Abundance of the Chemical Elements”

“An attempt was made in the course of this investigation to represent the relative abundances of the elements by a curve, taking their atomic weight for one set of the ordinates. It was hoped that some sort of periodicity might be evident, but no such regularity appeared”

Current “abundance” distribution of elements in the earths crust:



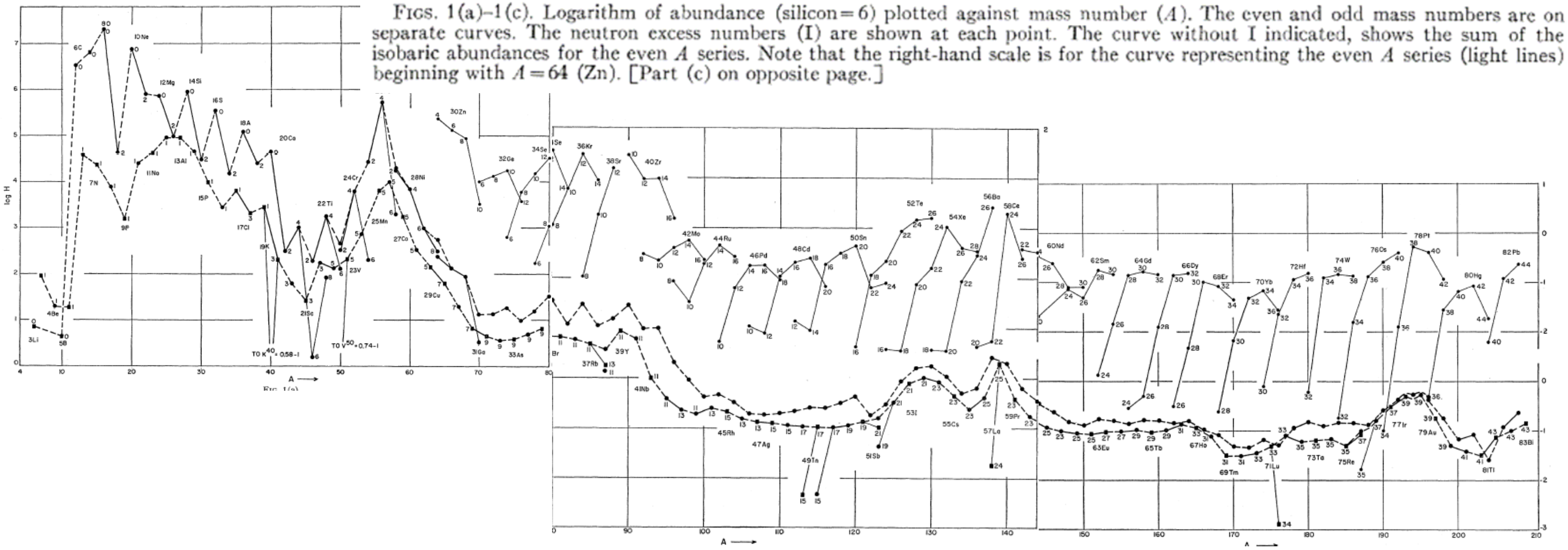
→ No correlation with periodic table of the elements (since 1870 by Medelejeev) ???

1895 Rowland: relative intensities of 39 elemental signatures in solar spectrum

1929 Russell: calibrated solar spectral data to obtain table of abundances

1937 Goldschmidt: First analysis of “primordial” abundances: meteorites, sun

1956 Suess and Urey “Abundances of the Elements”, Rev. Mod. Phys. 28 (1956) 53

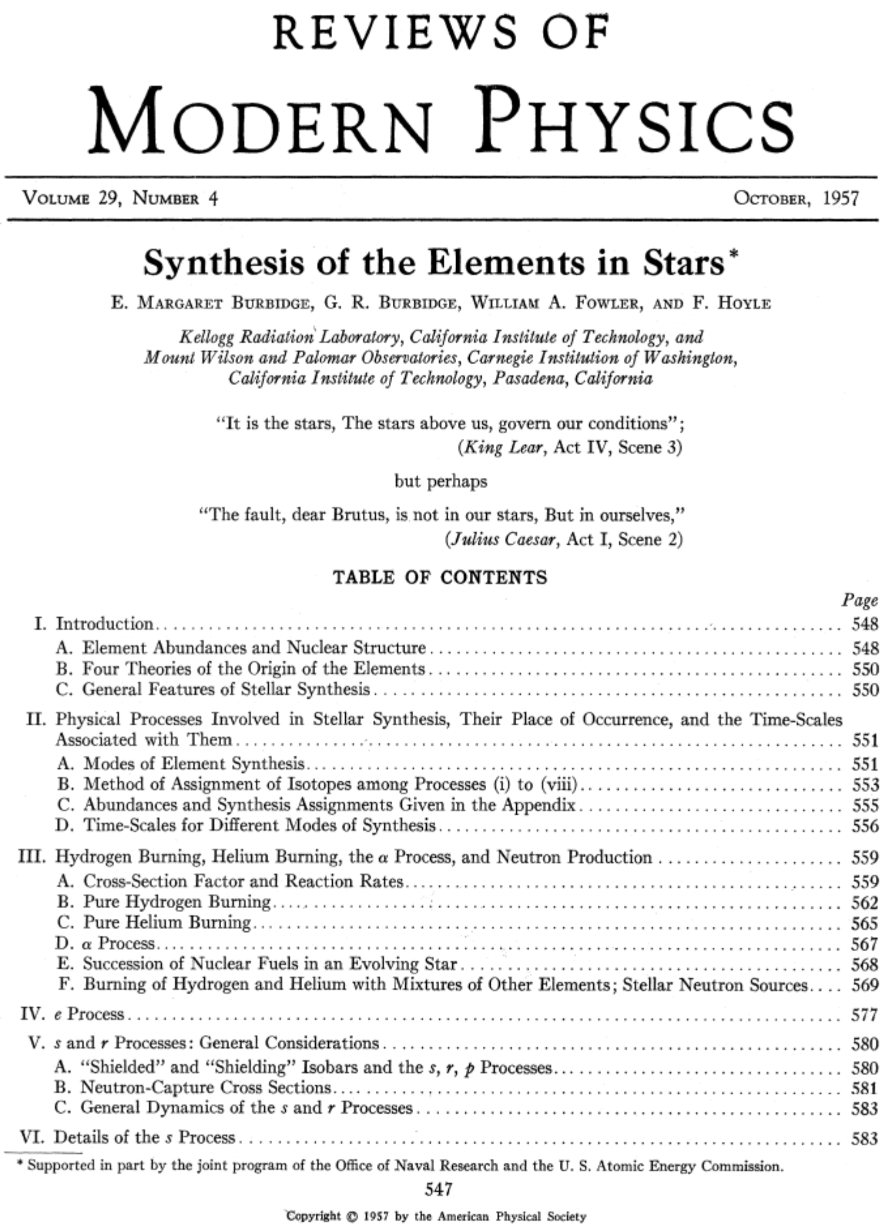


FIGS. 1(a)–1(c). Logarithm of abundance (silicon = 6) plotted against mass number (A). The even and odd mass numbers are on separate curves. The neutron excess numbers (I) are shown at each point. The curve without I indicated, shows the sum of the isobaric abundances for the even A series. Note that the right-hand scale is for the curve representing the even A series (light lines) beginning with $A = 64$ (Zn). [Part (c) on opposite page.]

> “Independent of any theory of the origin of the universe, one may try to find indications
> For the nature of the last nuclear reaction that took place …going backwards in time
> One may then try to find out how the conditions developed under which these reactions
> took place. … a cosmogenic model may then be found as an explanation of the course of events.”

> “No attempt is made to do this here. However, attention is drawn to evidence which might
> serve as a basis for future work along these lines.”

1957 Burbidge, Burbidge, Fowler, Hoyle



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

*Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California*

> "It is the stars, The stars above us, govern our conditions";
> (*King Lear*, Act IV, Scene 3)
>
> but perhaps
>
> "The fault, dear Brutus, is not in our stars, But in ourselves,"
> (*Julius Caesar*, Act I, Scene 2)

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[*] Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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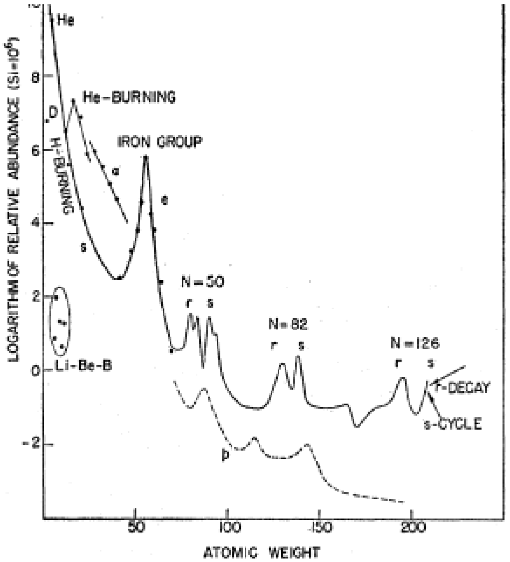
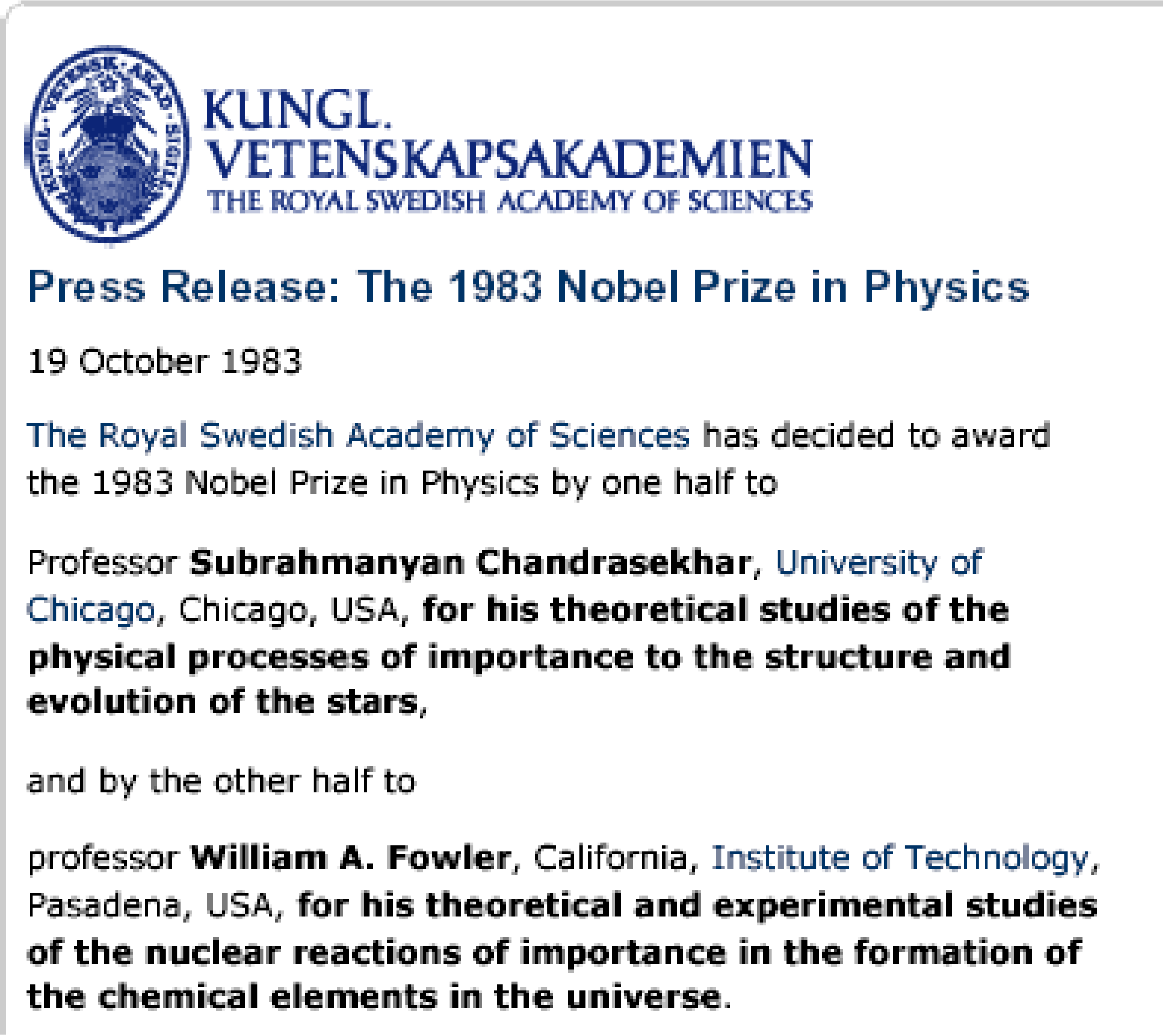


"Man inhibits a universe composed of a great variety of elements and their isotopes …"

1983 Nobel Prize in Physics for Willy Fowler:



KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Press Release: The 1983 Nobel Prize in Physics

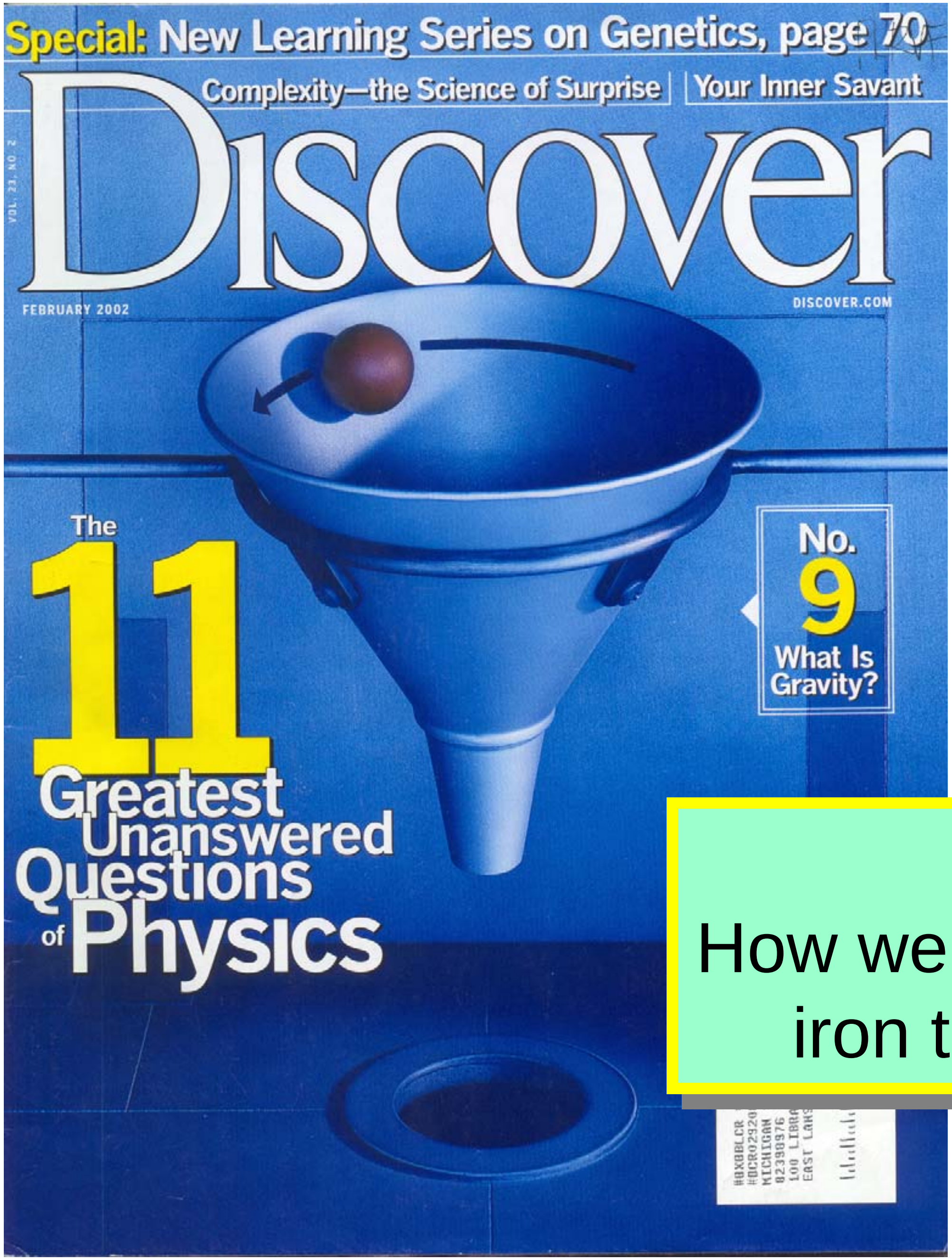
19 October 1983

The Royal Swedish Academy of Sciences has decided to award the 1983 Nobel Prize in Physics by one half to

Professor **Subrahmanyan Chandrasekhar**, University of Chicago, Chicago, USA, **for his theoretical studies of the physical processes of importance to the structure and evolution of the stars,**

and by the other half to

professor **William A. Fowler**, California, Institute of Technology, Pasadena, USA, **for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe.**



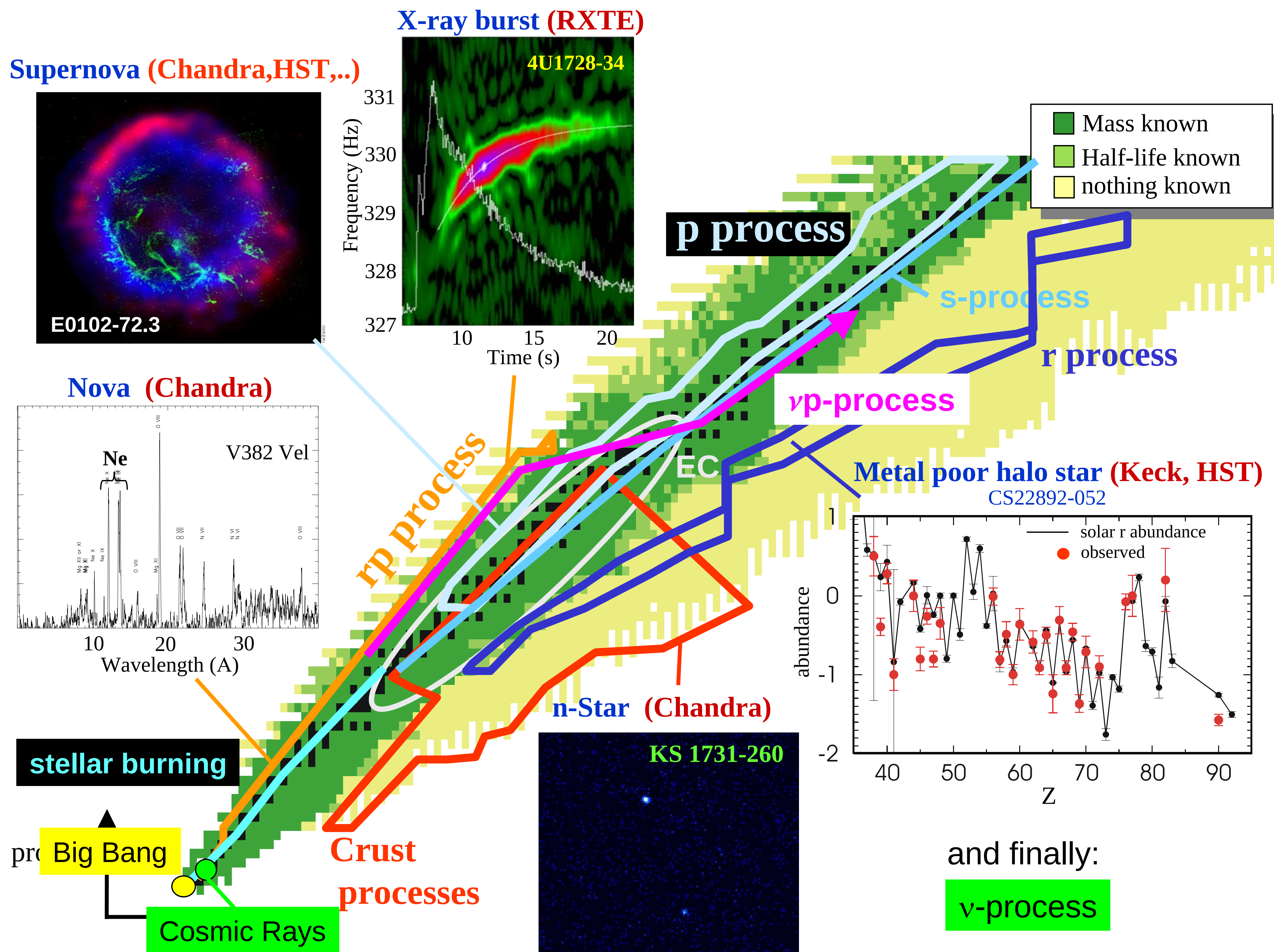
Based on National Academy of Science Report

[Committee for the Physics of the Universe (CPU)]

Question 3

How were the elements from iron to uranium made ?

→ **"Old problems"**
Still unsolved !!!



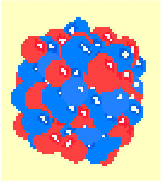
and finally:

ν-process

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
- N: Neutron Number

Determines the Element

Determines the Isotope

Of course A=Z+N

Usual notation:

Mass number A

$$^{12}\mathrm{C}$$

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 n_i = 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 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 $m_u = m_{12C} / 12 \overset{\downarrow}{=} 1 / \mathrm{N_A}$ 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

Abundance is not a fraction !

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 $n_e = \rho \mathrm{N}_{\mathrm{A}} Y_e$

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")

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: $Y_e=0$

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**

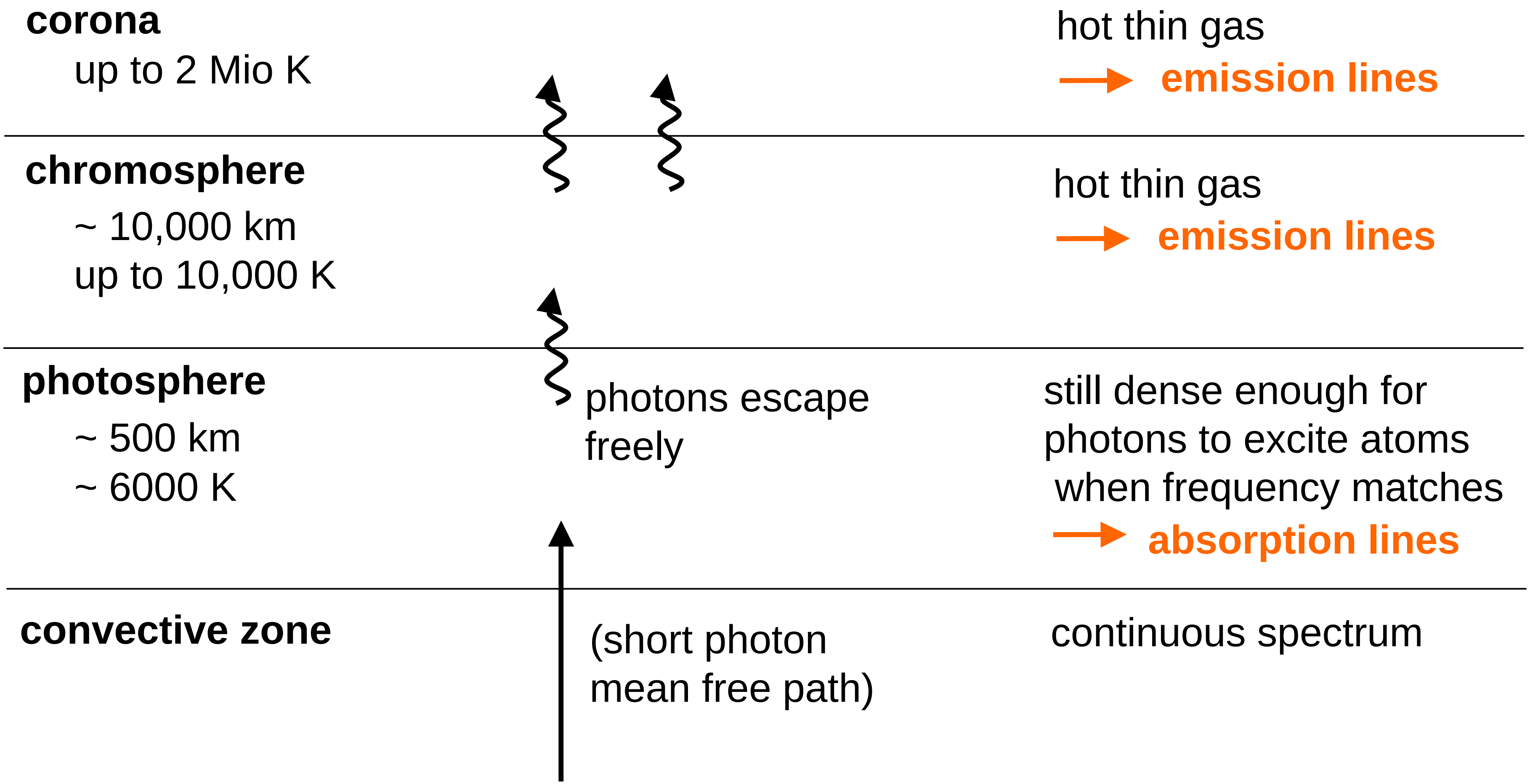
2. Solar spectra

Sun formed directly from presolar 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 presolar nebula

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



corona
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
~ 500 km
~ 6000 K

photons escape freely

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

convective zone

(short photon mean free path)

continuous spectrum

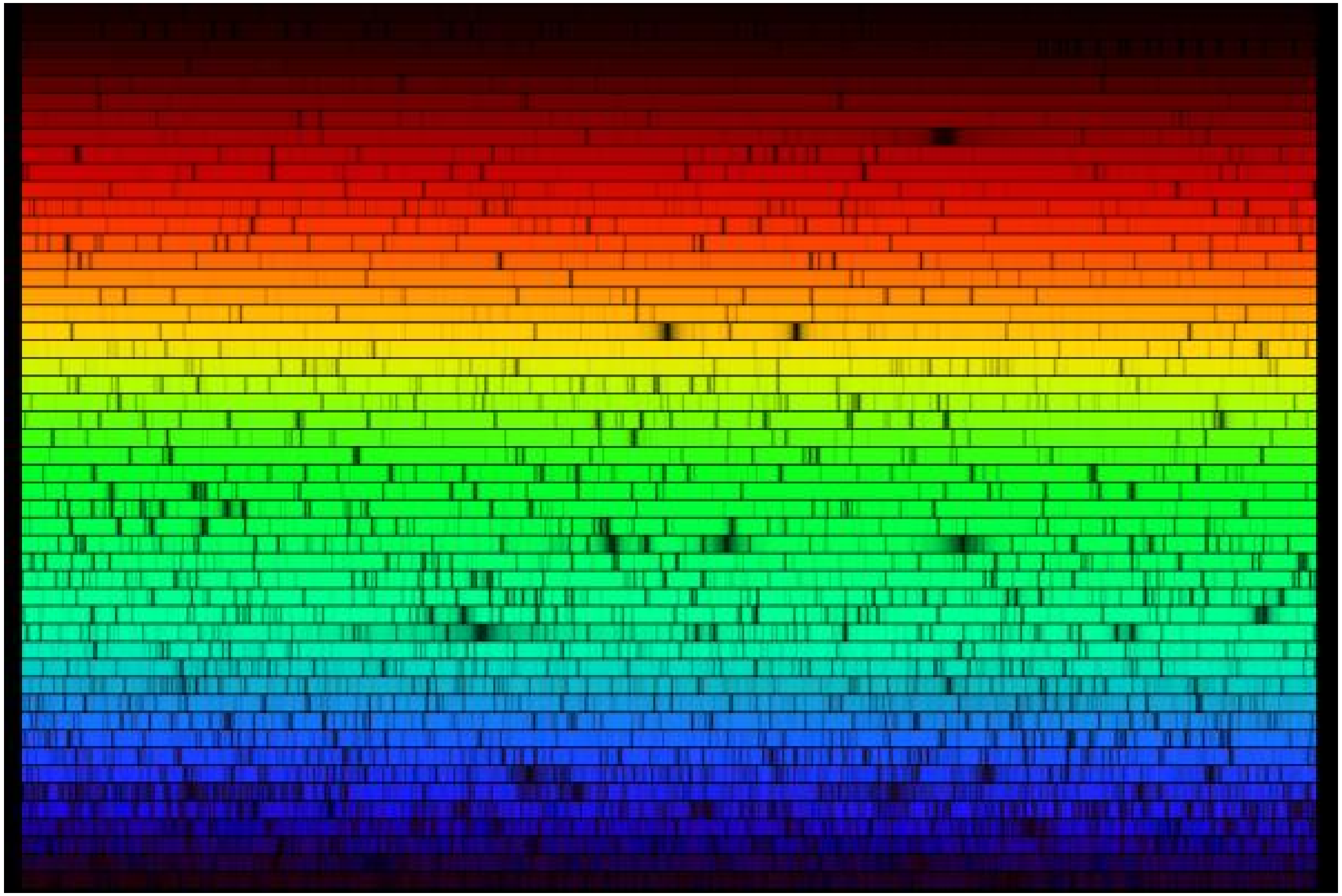
Emission lines from atomic deexcitations
Absorption lines from atomic excitations

Wavelength -> Atomic Species
Intensity -> Abundance

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

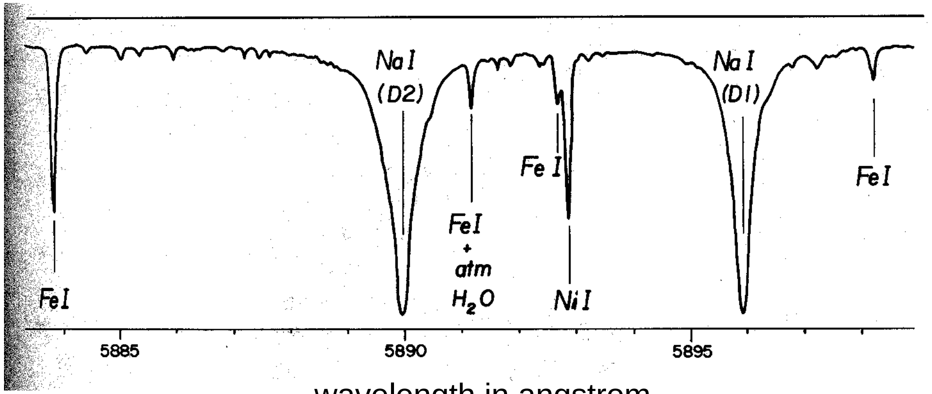


solar spectrum (Nigel Sharp, NOAO)

Example for quantitative measurement of absorption lines:

Each line originates from absorption from a specific atomic transition in a specific atom/ion:

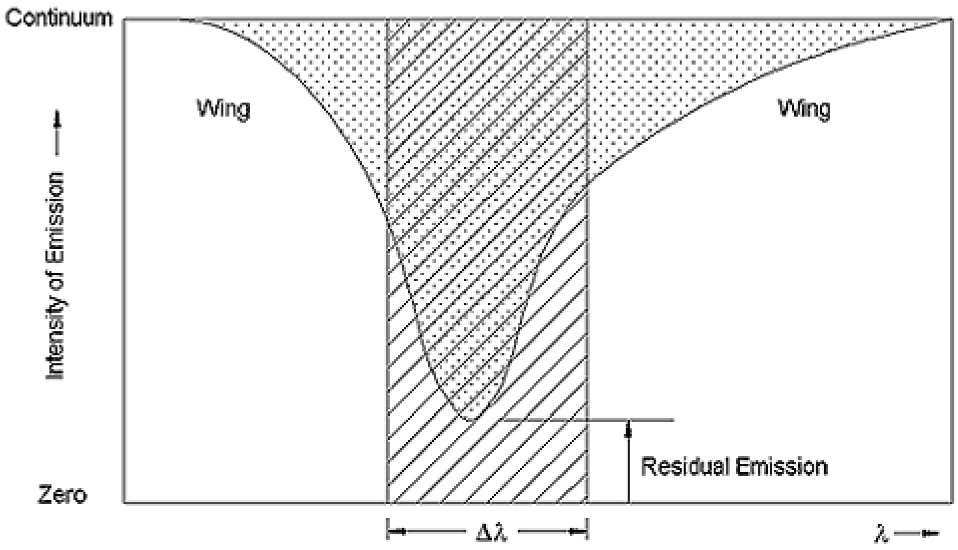
portion of the solar spectrum (from Pagel Fig 3.2.)



wavelength in angstrom

Fe I: neutral ion
FeII: singly ionized iron ion
…

Absorption, opacity, and effective line width:



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

often σn expressed as $\kappa\rho$ with ρ=mass density. κ is then called “opacity”

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 …)

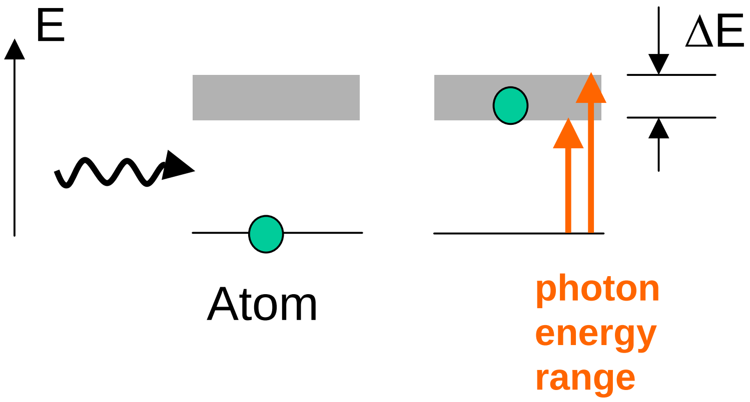
It depends on:

- **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

Heisenbergs uncertainty principle relates that to the **lifetime** τ of the excited state

$$\Delta E \cdot \tau = \hbar$$

→ 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

Example: 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:

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

This is maintained by
frequent collisions in hot gas
But not always !!!

Then the **Saha 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

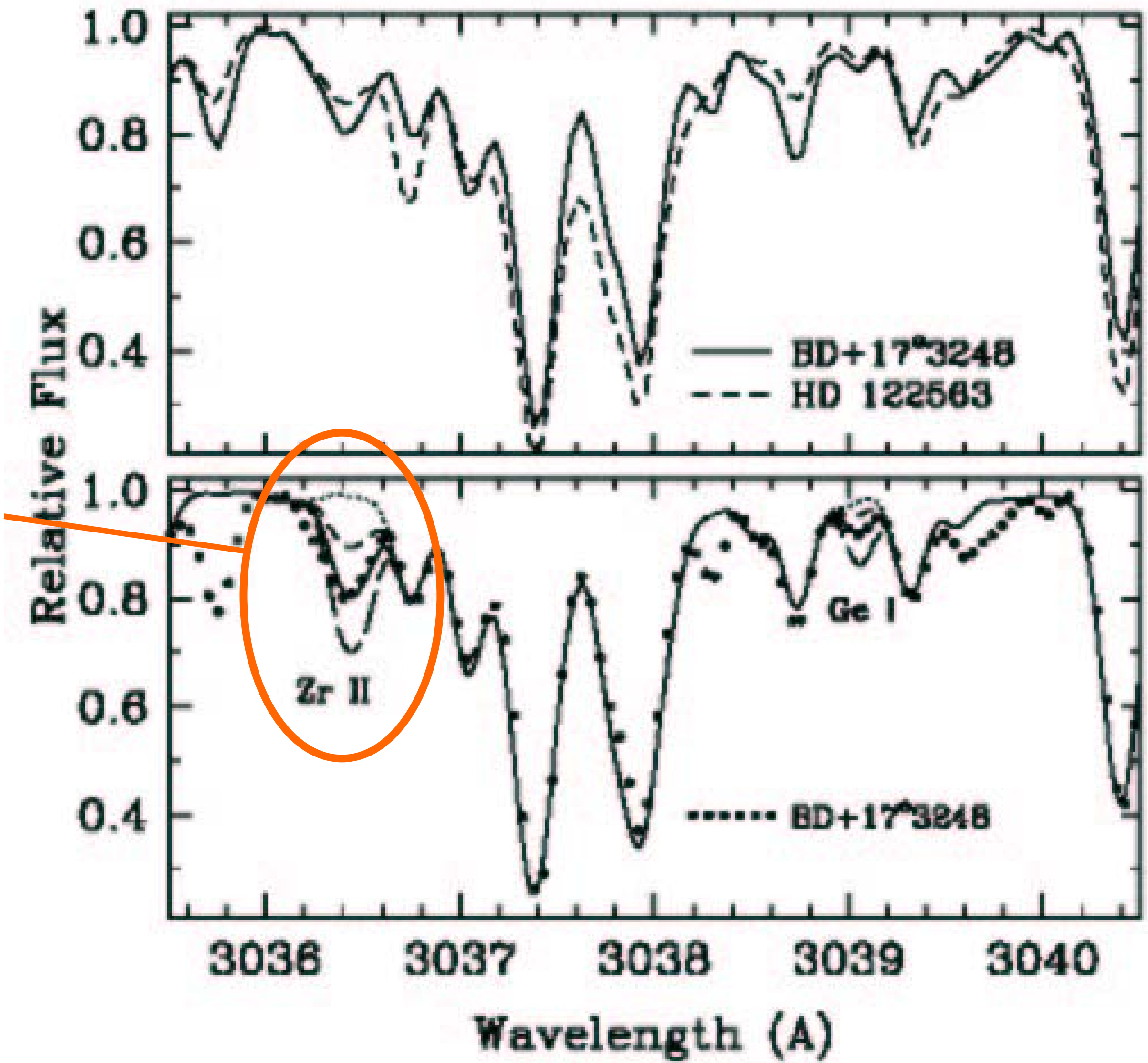
strong temperature dependence !

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

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: 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 of
England in
20 October 1868.

Solar Chromosphere
red from Hα emission
lines

3.2. Meteorites

Meteorites can provide accurate information on elemental abundances in the presolar 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.

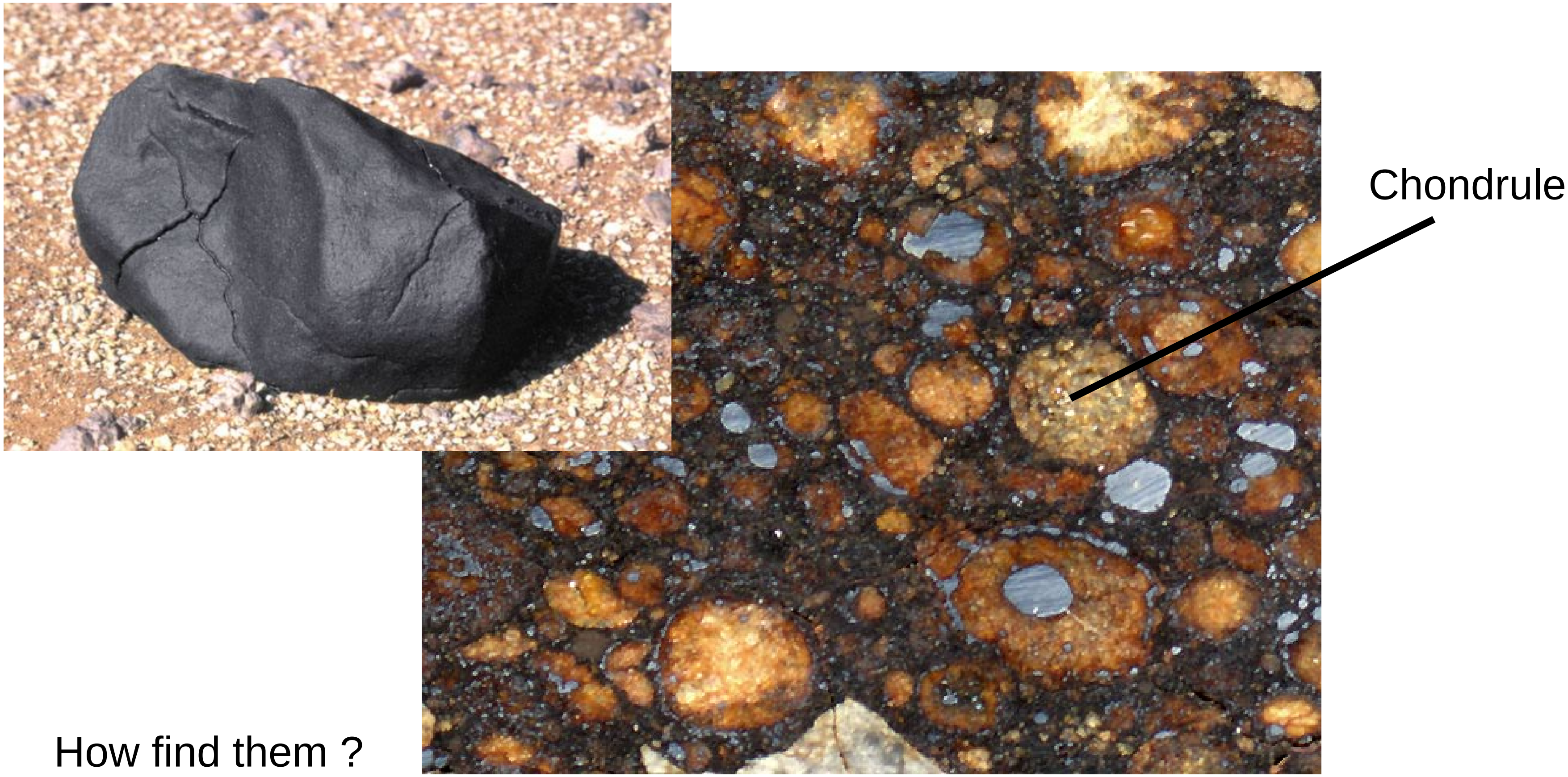
Classification of meteorites:

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 shperical inclusions in matrix
believed to have formed very early in the presolar 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 ?

Not all carbonaceous chondrites are equal

(see http://www.daviddarling.info/encyclopedia/C/carbchon.html for a nice summary)

There are CI, CM, CV, CO, CK, CR, CH, CB, and other chondites

CI Chondites (~3% of all carbonaceous chondrites)

- are considered to be the least altered meteorites available
- named after Ivuna Meteorite (Dec 16, 1938 in Ivuna, Tanzania, 705g)

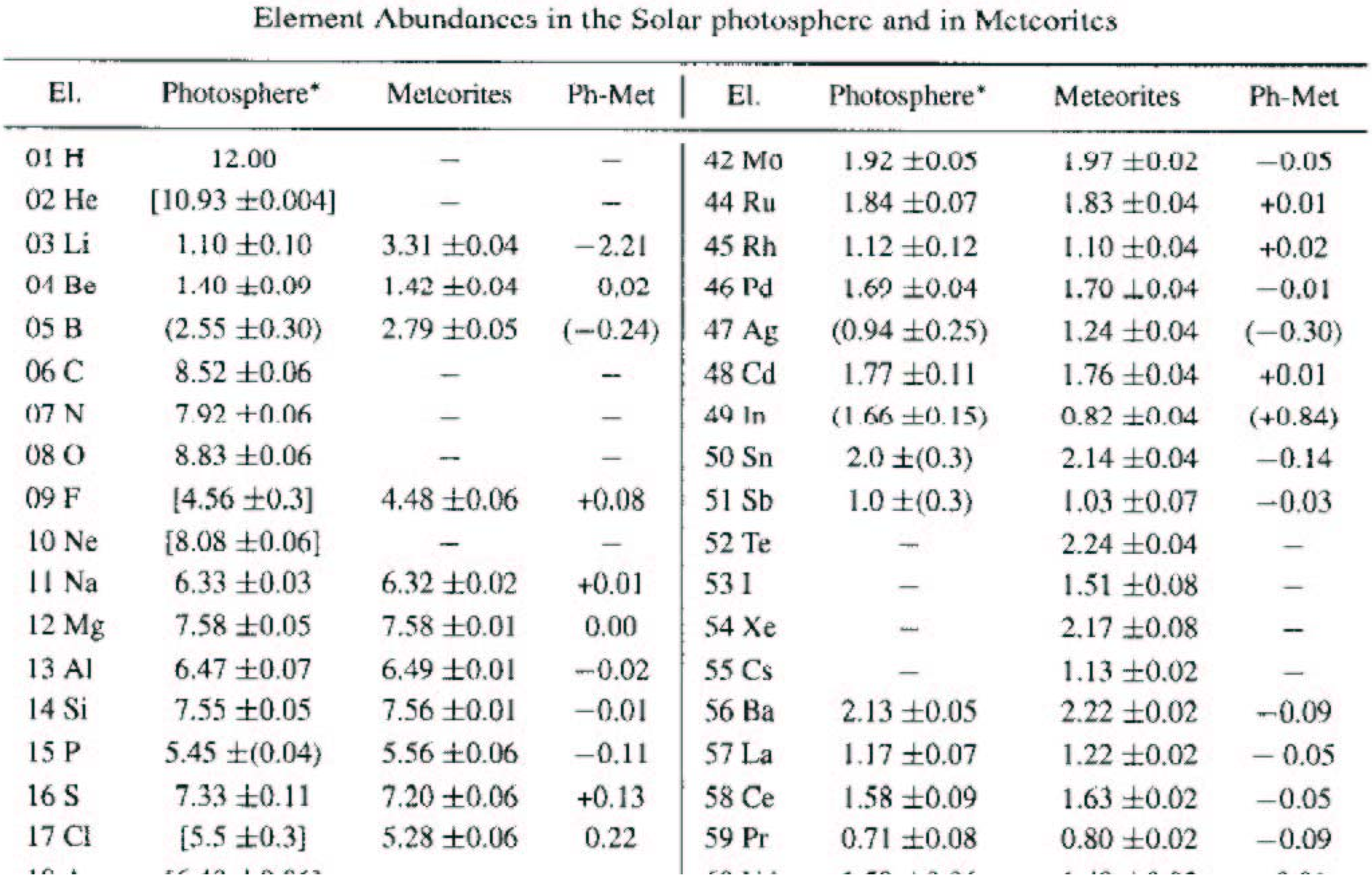
- only 5 known – only 4 suitably large (Alais, Ivuna, Orgueil, Revelstoke, Tonk)
- see Lodders et al. Ap. J. 591 (2003) 1220 for a recent analysis

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

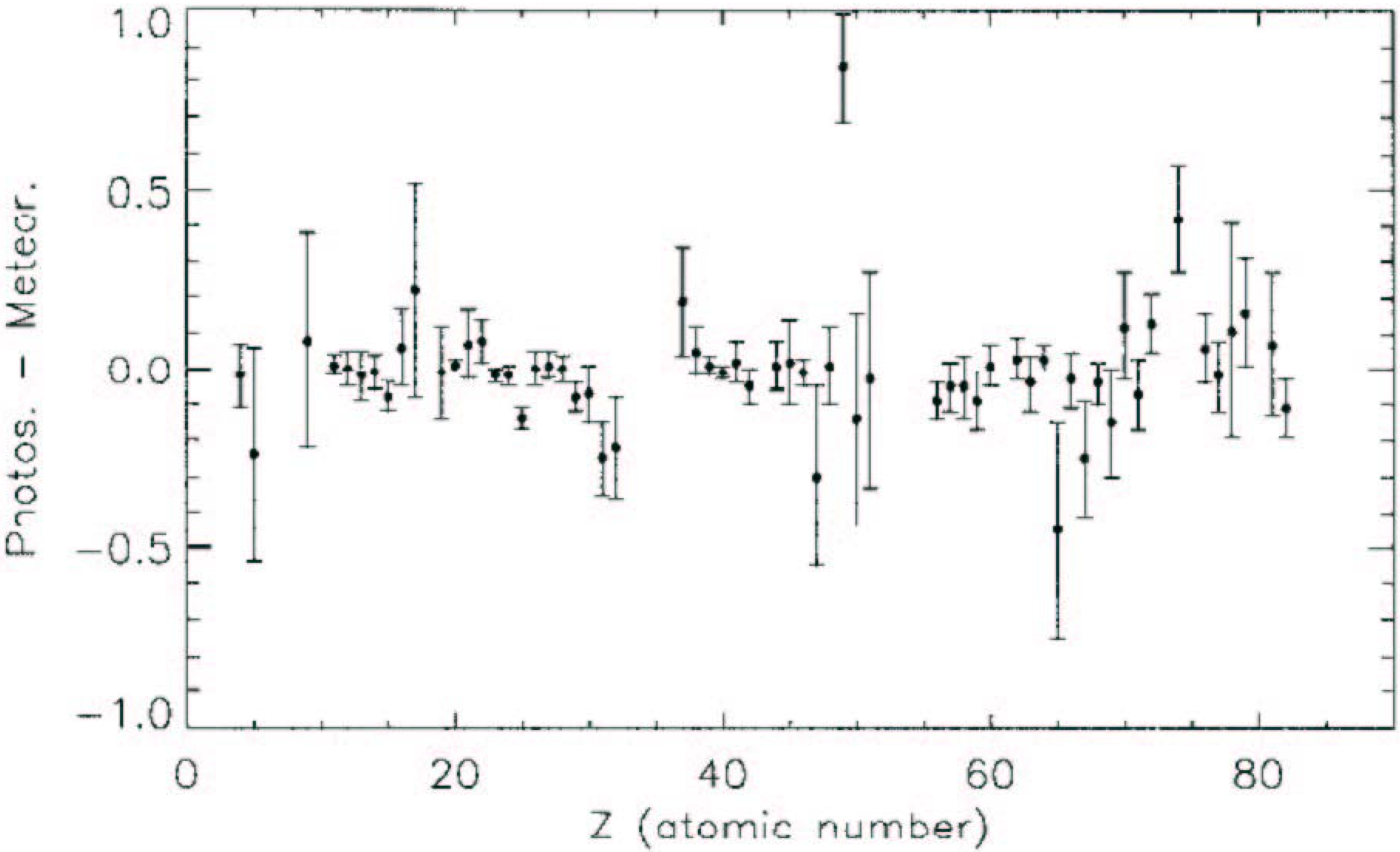


Element Abundances in the Solar photosphere and in Meteorites

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

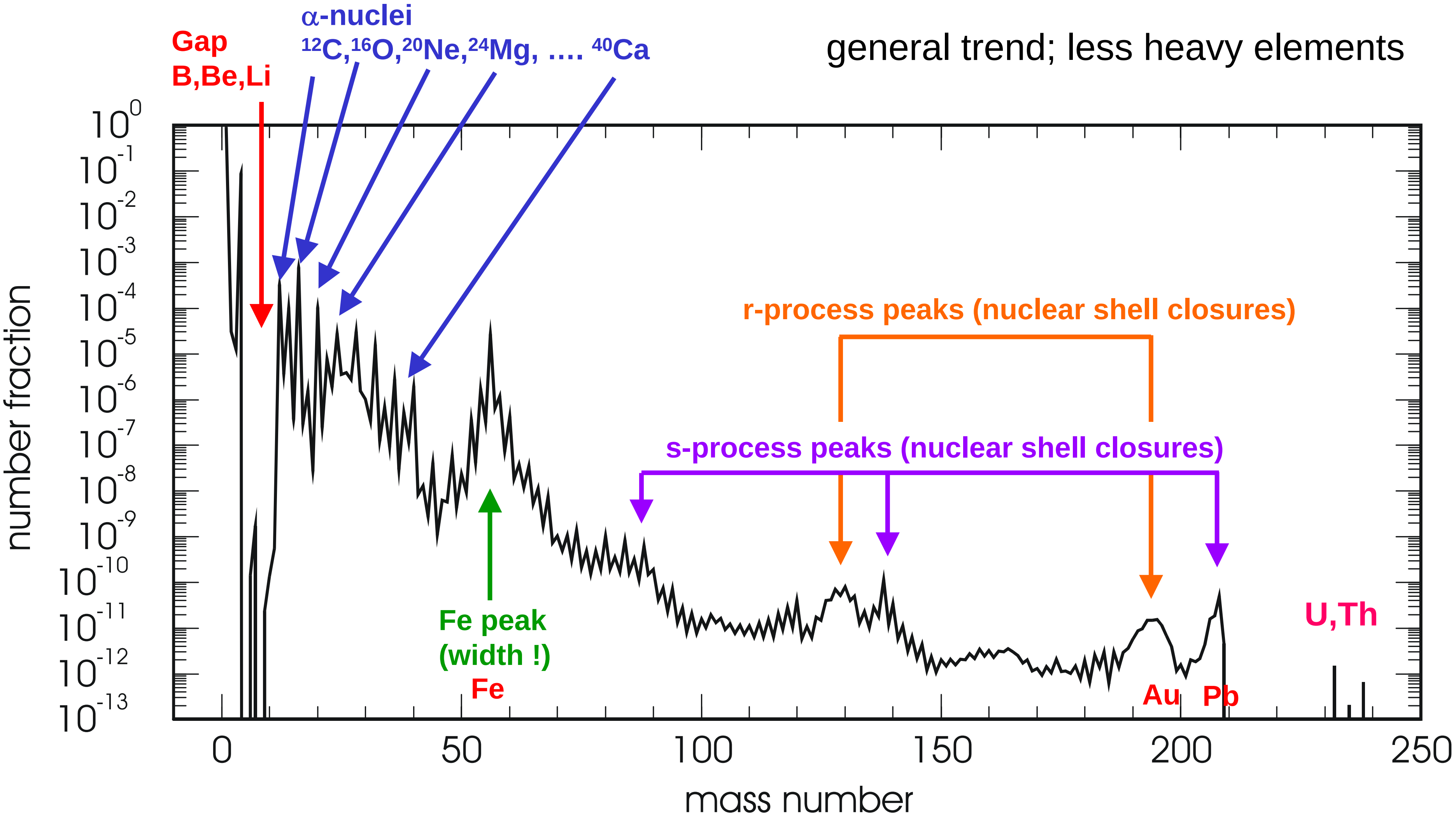
units: given is $A = \log(n/n_H) + 12$ (log of number of atoms per 10^{12} H atoms)

(often also used: number of atoms per 10^6 Si atoms) log of photosphere abundance/ meteoritic abundance



generally good agreement

Hydrogen mass fraction	X = 0.739
Helium mass fraction	Y = 0.249
Metallicity (mass fraction of everything else)	Z = 0.012
Heavy Elements (beyond Nickel) mass fraction	4E-6



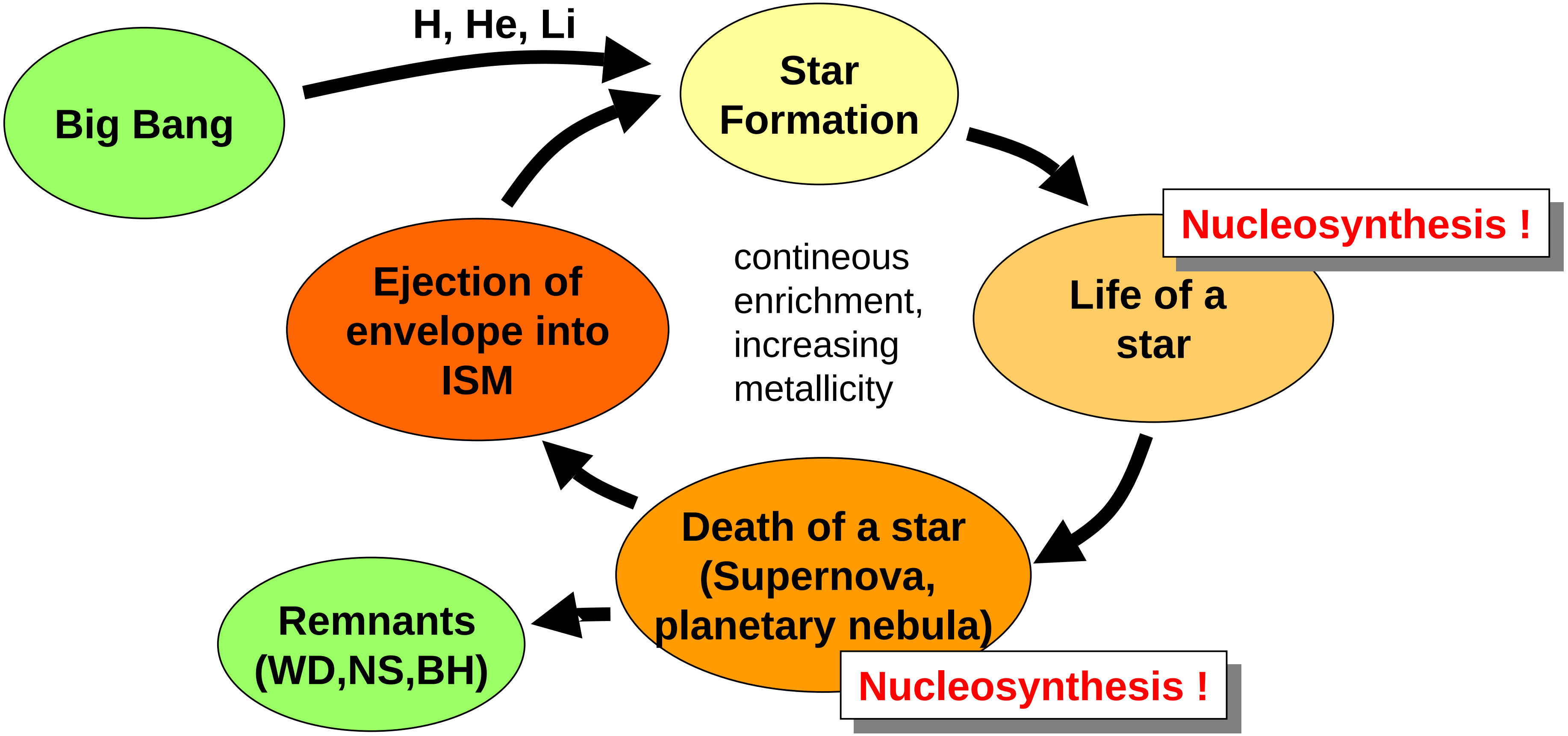
4. Abundances outside the solar neighborhood ?

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
- Presolar grains in meteorites

What do we expect ?

Nucleosynthesis is a gradual, still ongoing process:



Big Bang

H, He, Li

Star Formation

Life of a star

Nucleosynthesis !

Death of a star (Supernova, planetary nebula)

Nucleosynthesis !

Remnants (WD,NS,BH)

Ejection of envelope into ISM

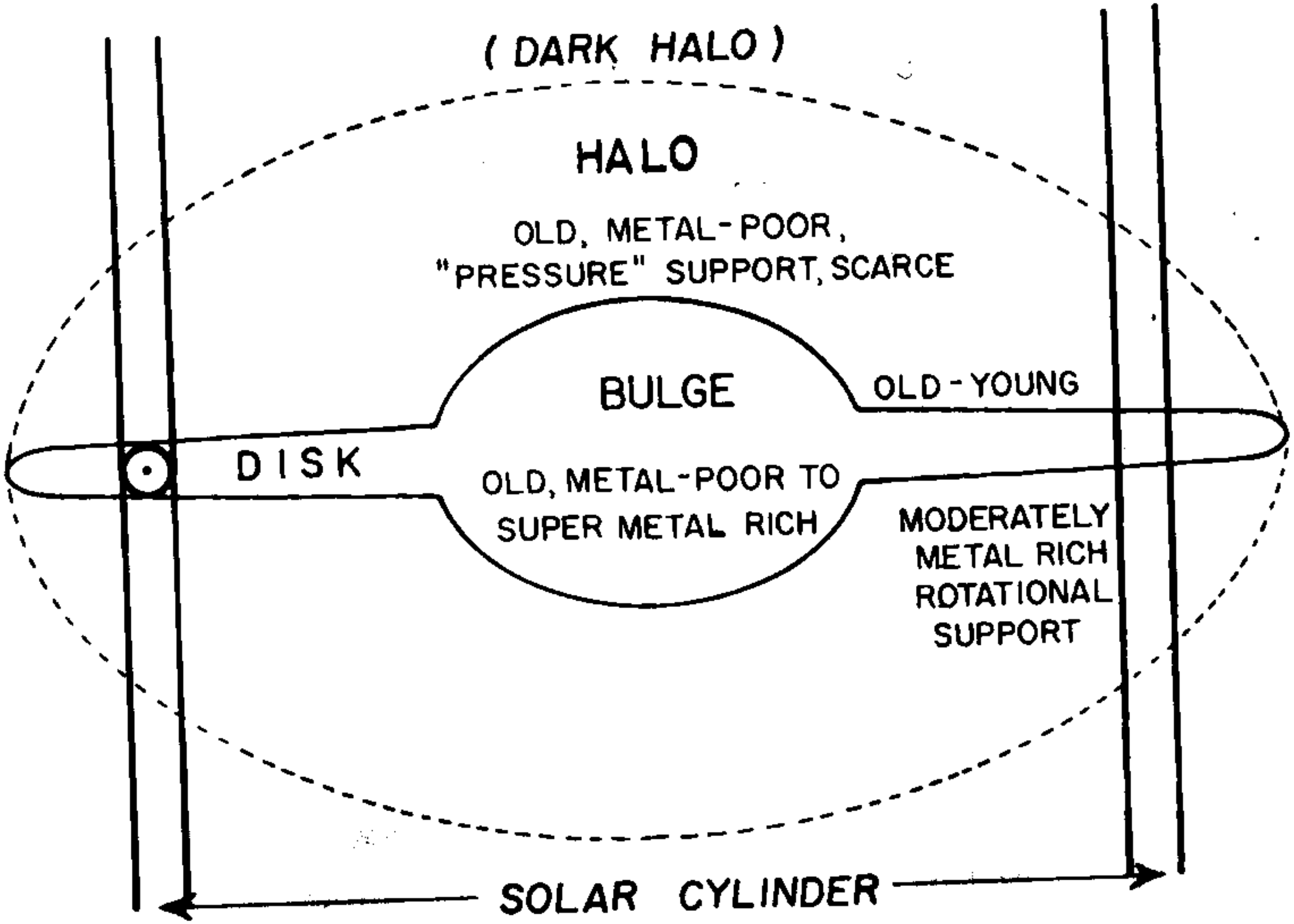
contineous enrichment, increasing metallicity

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**

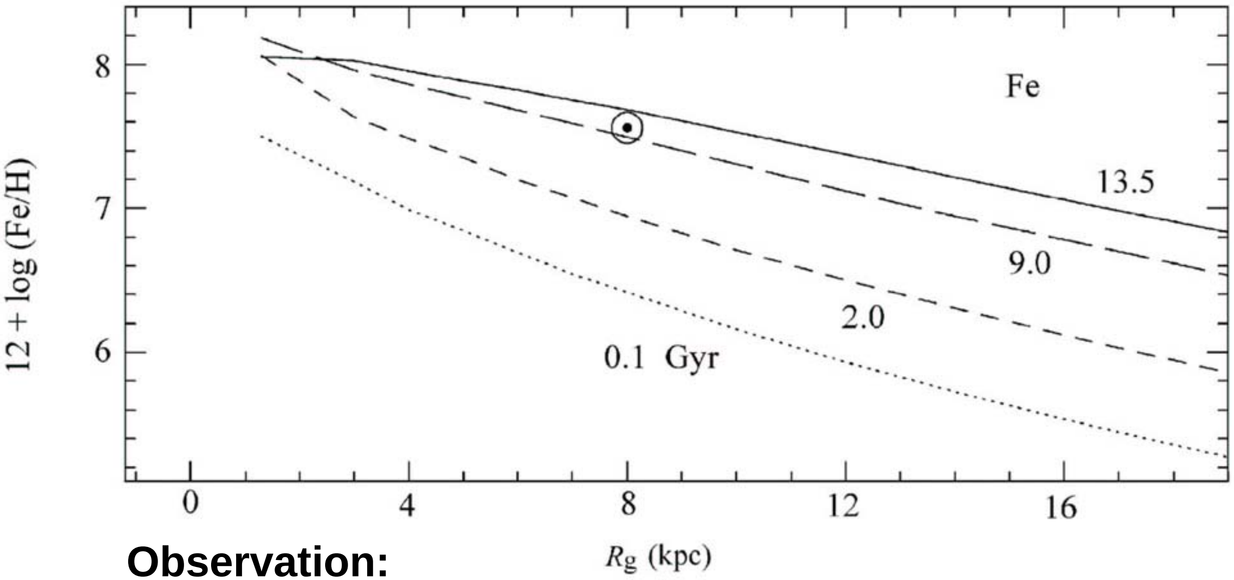
  For example star formation requires gas and dust - therefore extremely different metallicities in different parts of the Galaxy



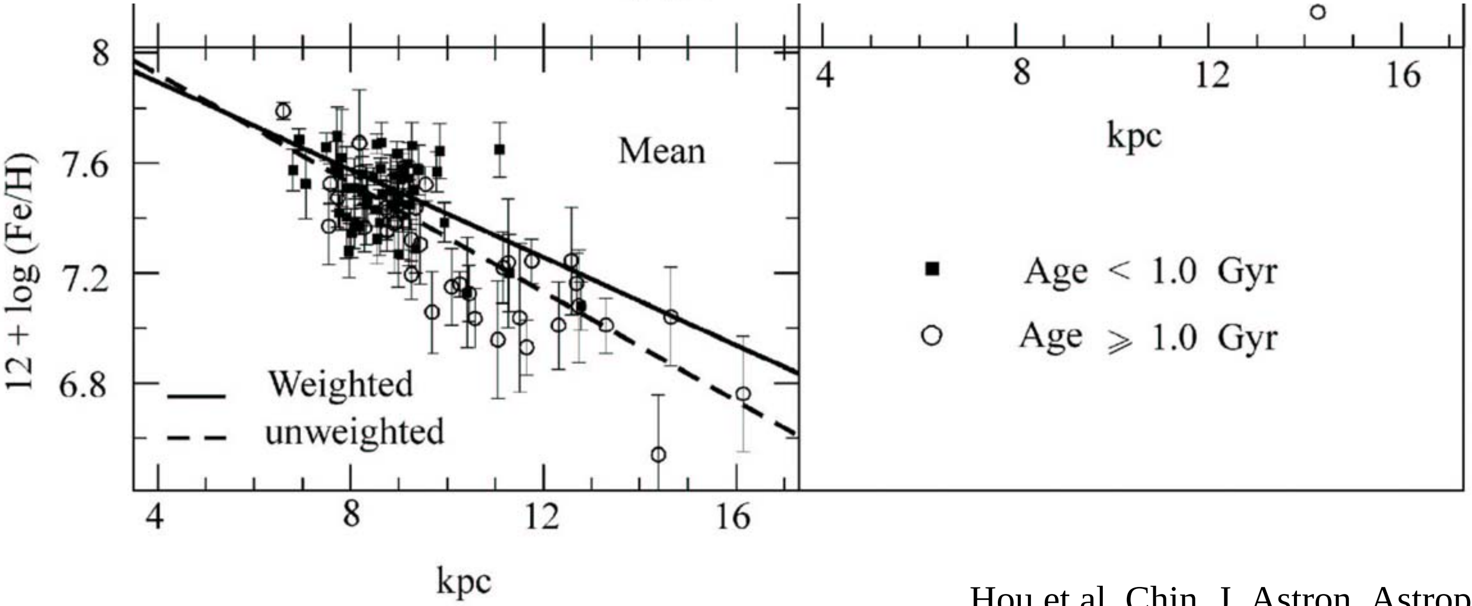
Pagel, Fig 3.31

Also, metallicity gradient in Galactic disk:

model calculation:



Observation:



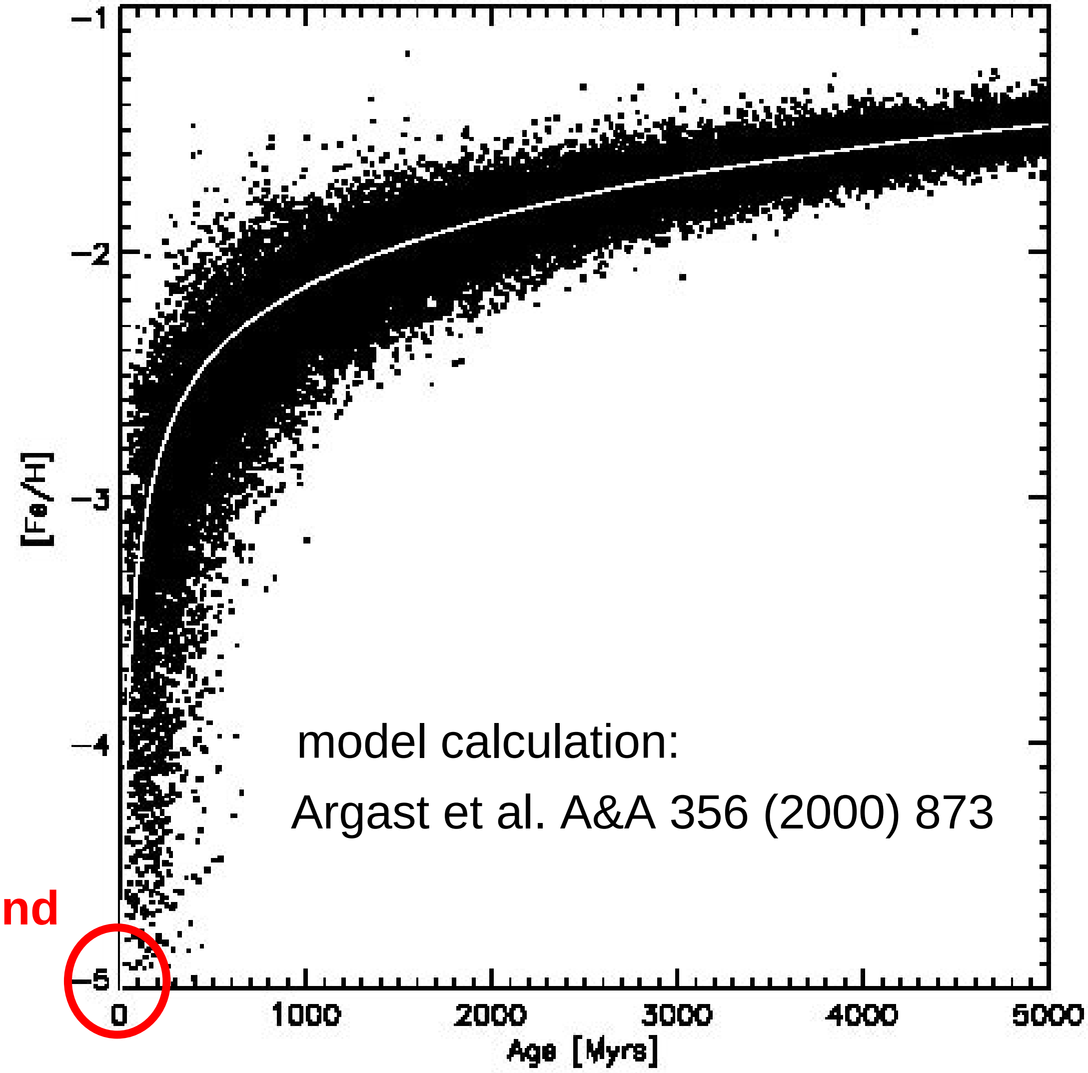
Hou et al. Chin. J. Astron. Astrophys. 2 (2002) 17

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

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

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

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



finally found

model calculation:

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

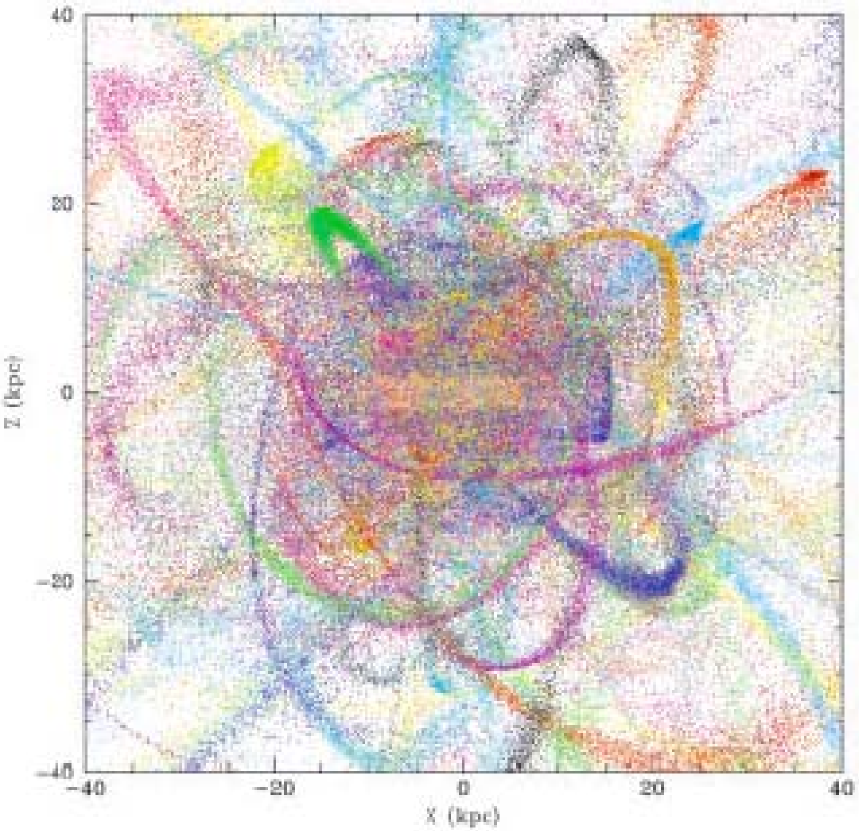
metallicity - age relation: old stars are metal poor BUT: large scatter !!!

From MSU Physics and Astronomy Department Website:

[Fe/H]=-5.1

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

• “population effect (2)” … and composition of star depends on WHERE it was born:



(Bland-Hawthorn & Freeman,
Science 287, 2000)

- Galaxy (here halo) has formed over extended Periods of time by accretion and merging with other galaxies

- This process is still ongoing at low level

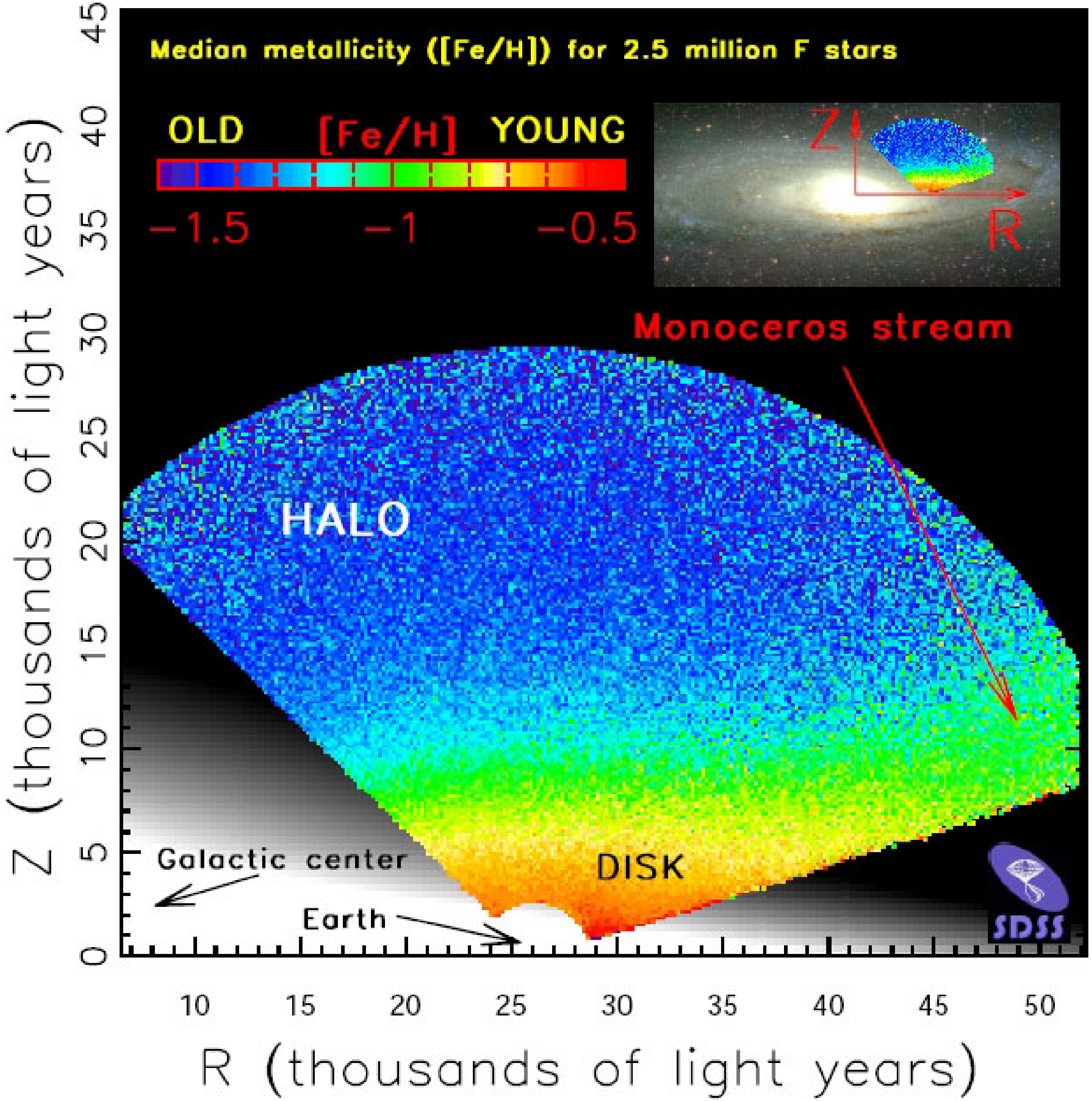
- Stellar composition is characteristic of original galaxy and can be used to disentangle components and merger history

→ Can study Galaxy formation “at home” using nuclear astrophysics

“near field cosmology”

“Future satellite missions to derive 3D space motions and heavy element (metal) abundances for a billion stars will disentangle the existing web and elucidate how galaxies like our own came into existence.”

"New Map Locates Metals in Millions of Milky Way Stars"



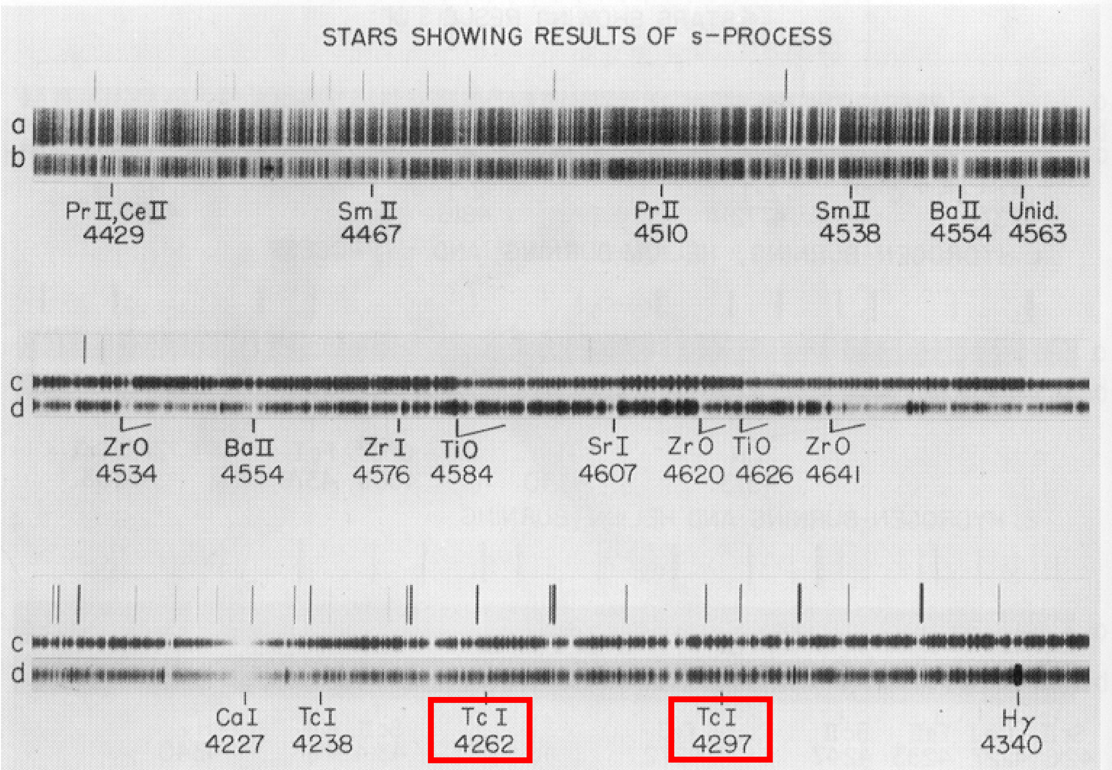
SDSS-II

- **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)

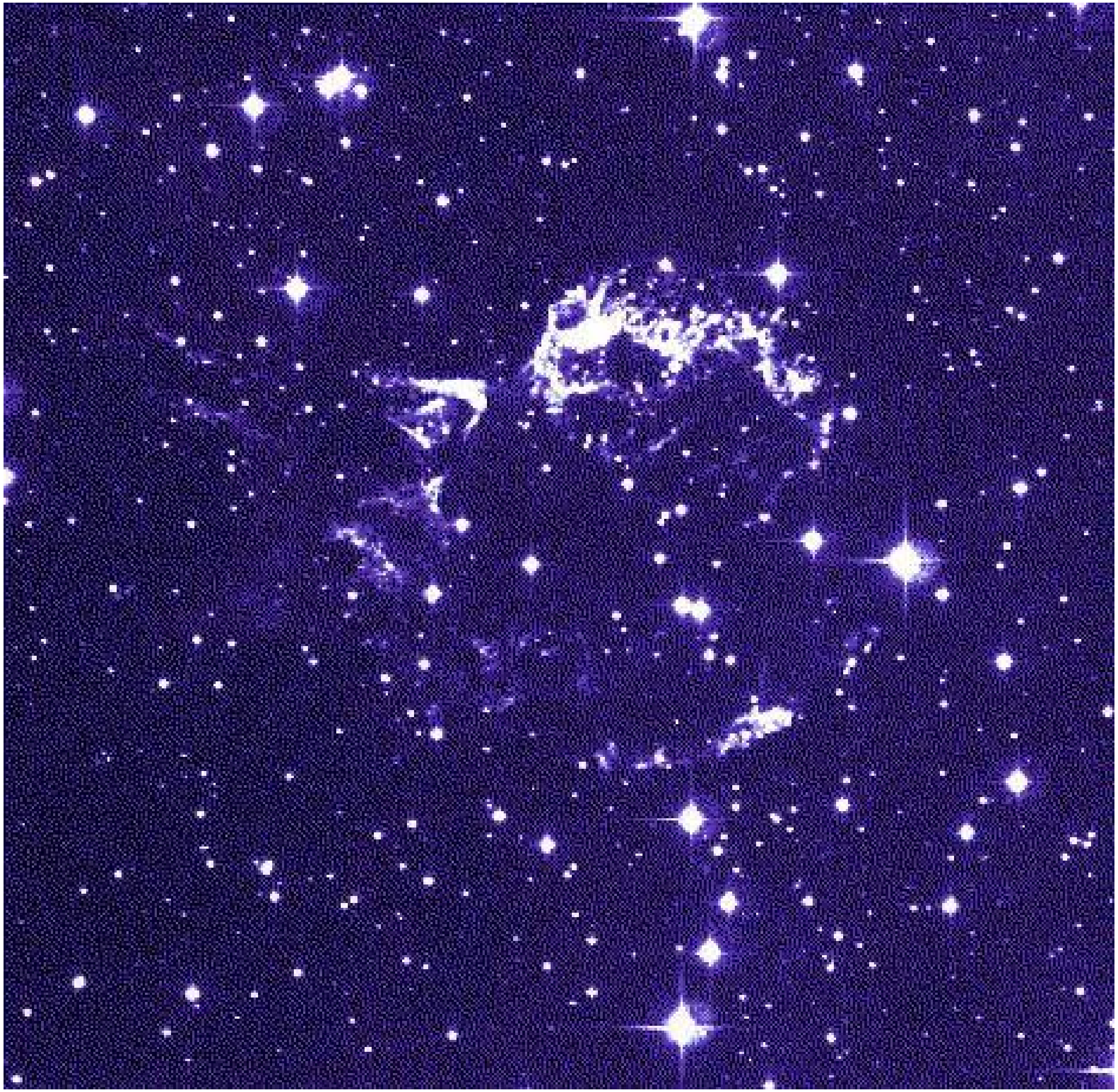


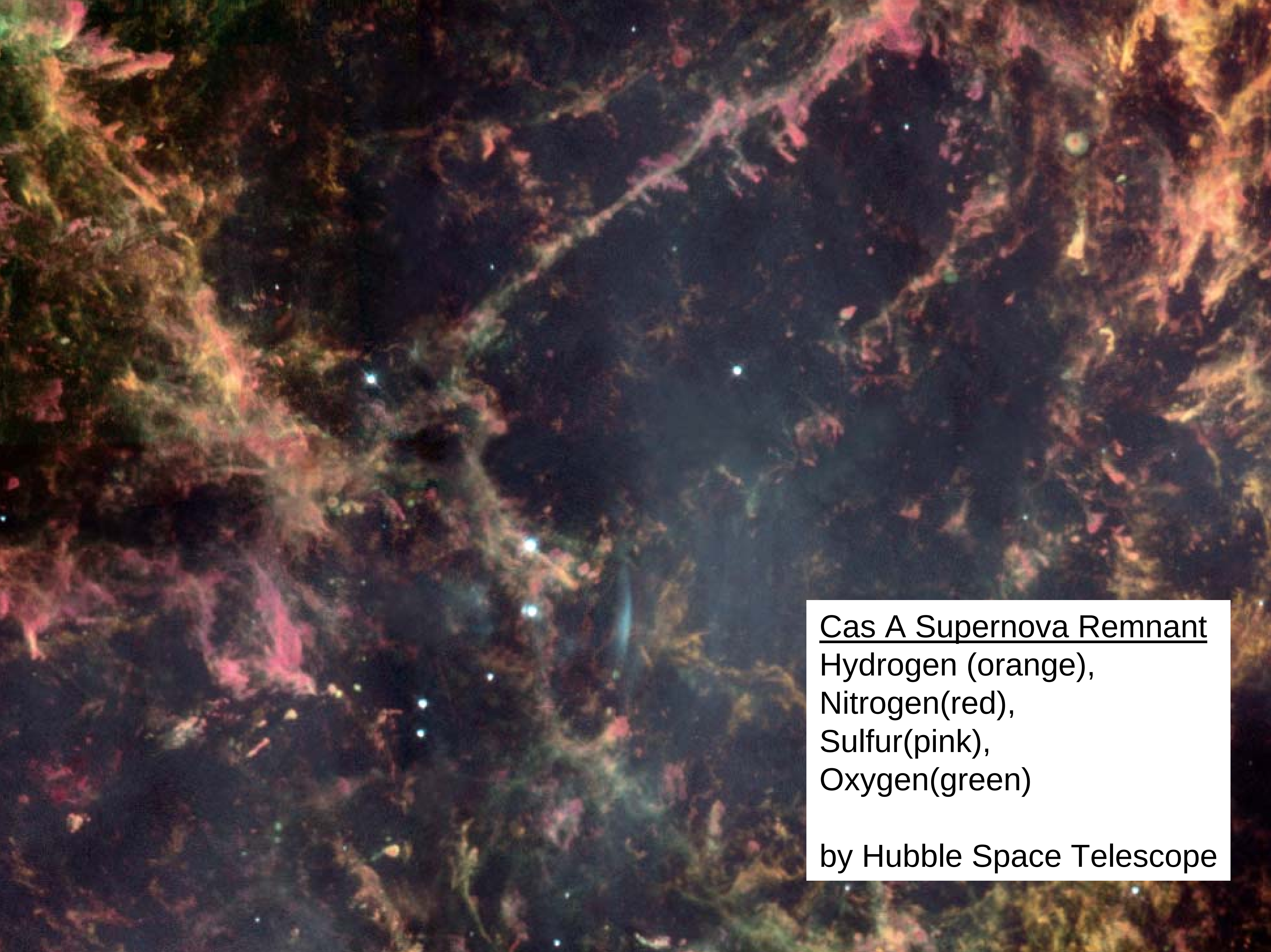
Pagel Fig 1.8

proof for ongoing nucleosynthesis in stars !

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

Cas A:





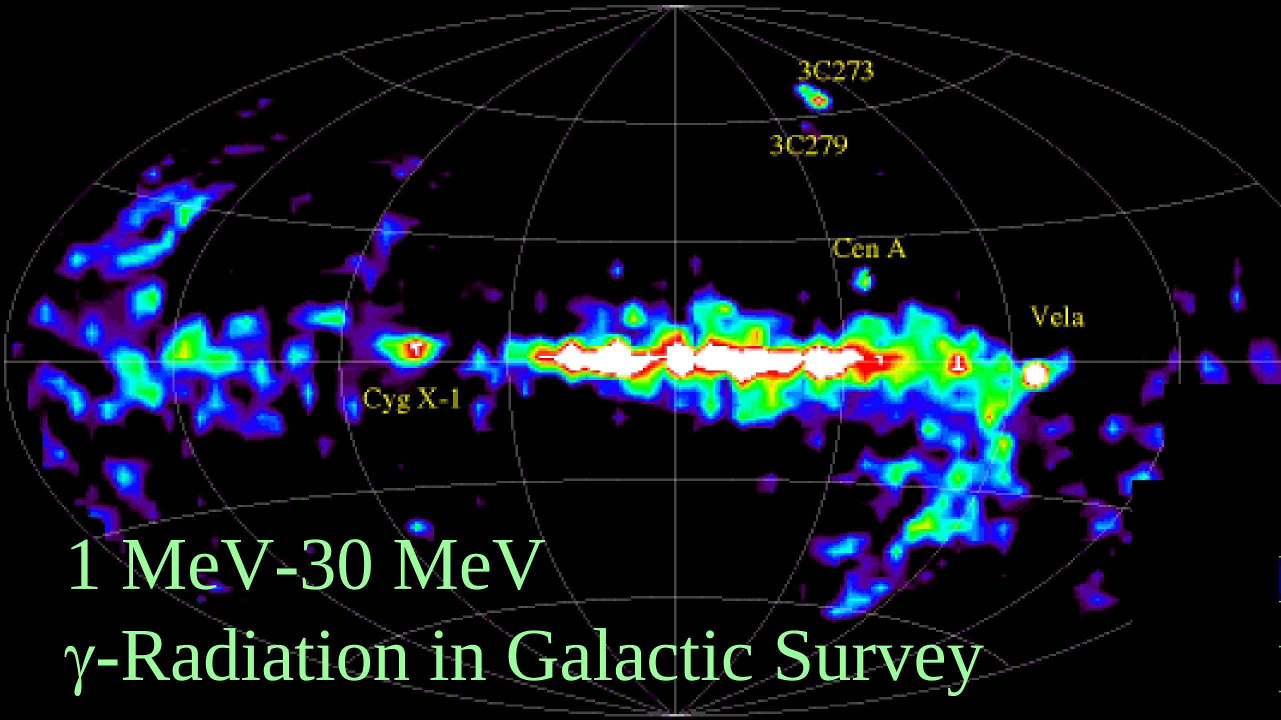
Cas A Supernova Remnant
Hydrogen (orange),
Nitrogen(red),
Sulfur(pink),
Oxygen(green)

by Hubble Space Telescope

Cas A with
Chandra X-ray observatory:

red: iron rich
blue: silicon/sulfur rich

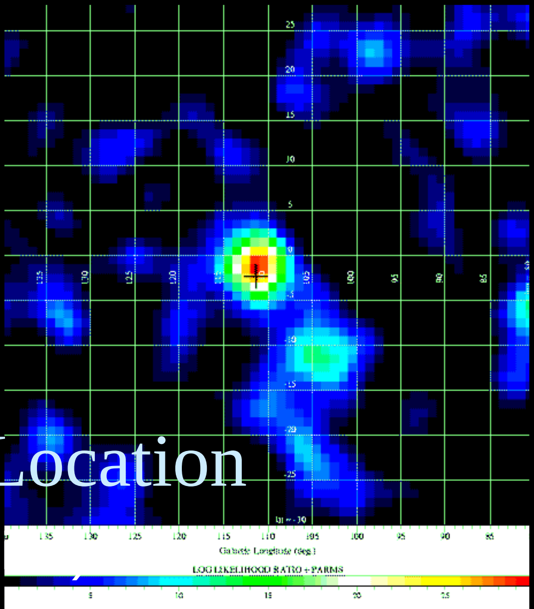
Galactic Radioactivity - detected by γ-radiation



1 MeV-30 MeV

γ-Radiation in Galactic Survey

(^{26}Al Half life: 700,0000 years, 1.809 MeV line)

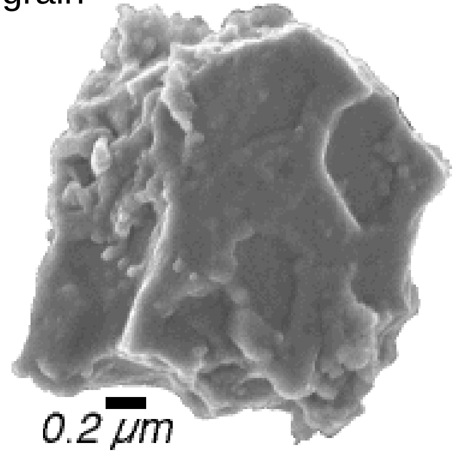


^{44}Ti in Supernova Cas-A Location

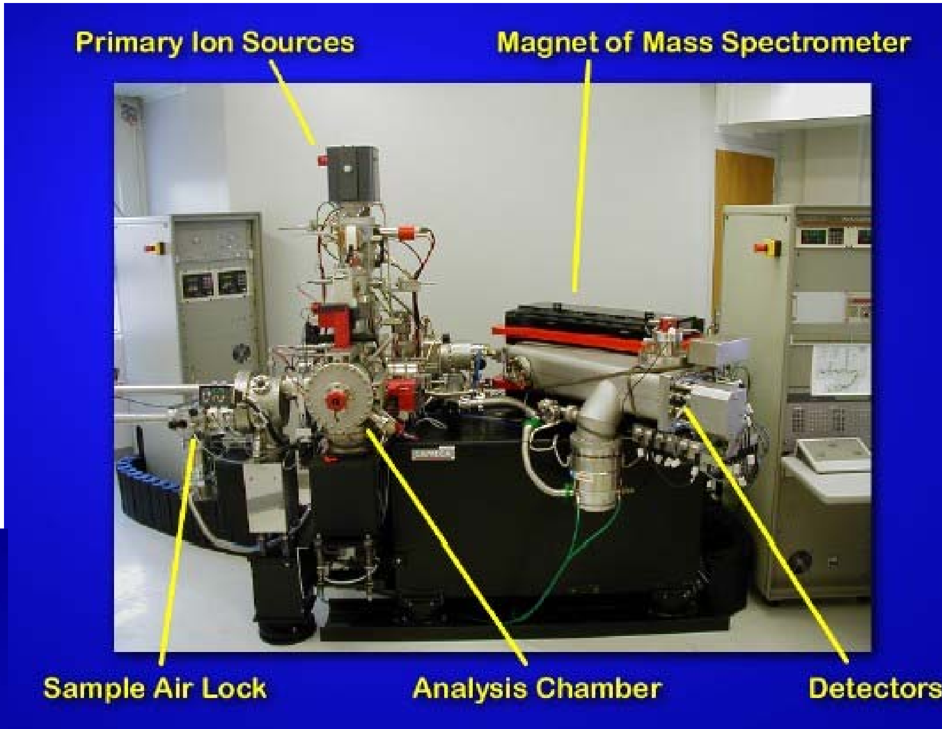
(Half life: 60 years, , 1.157 MeV l

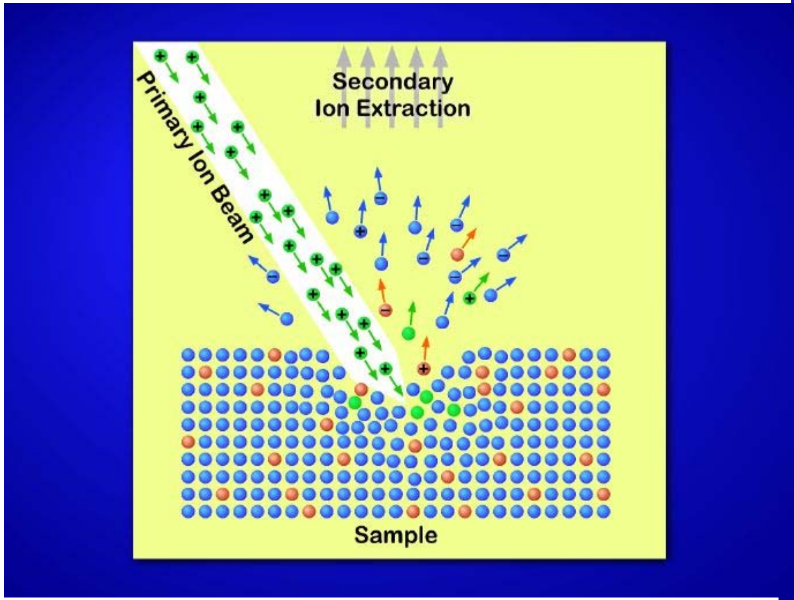
Analysis of presolar grains found in meteorites

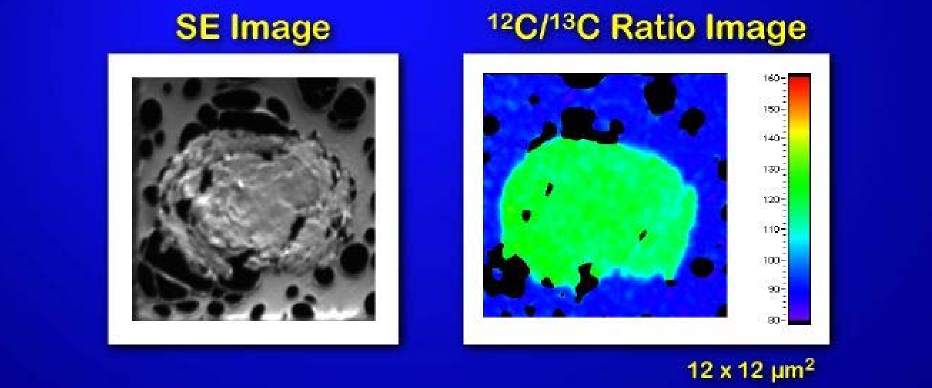
SiC grain



NanoSIMS at Washington University, St. Louis

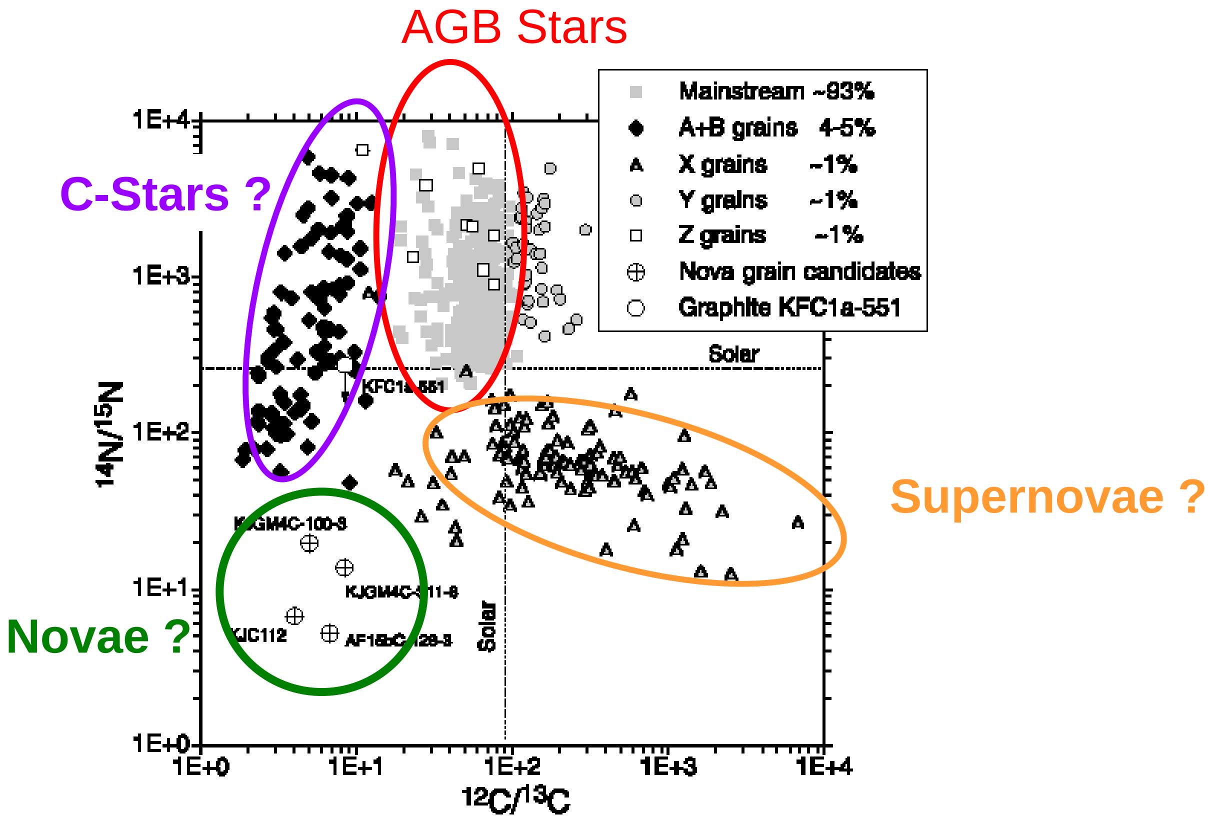






F.J. Stadermann, http://presolar.wustl.edu/nanosims/wks2003/index.html

SiC grain analysis – and the origin of the grains


AGB Stars

C-Stars ?

Supernovae ?

Novae ?

E. Zinner, Ann. Rev. Earth. Planet. Sci. 1998, 26; 147-188