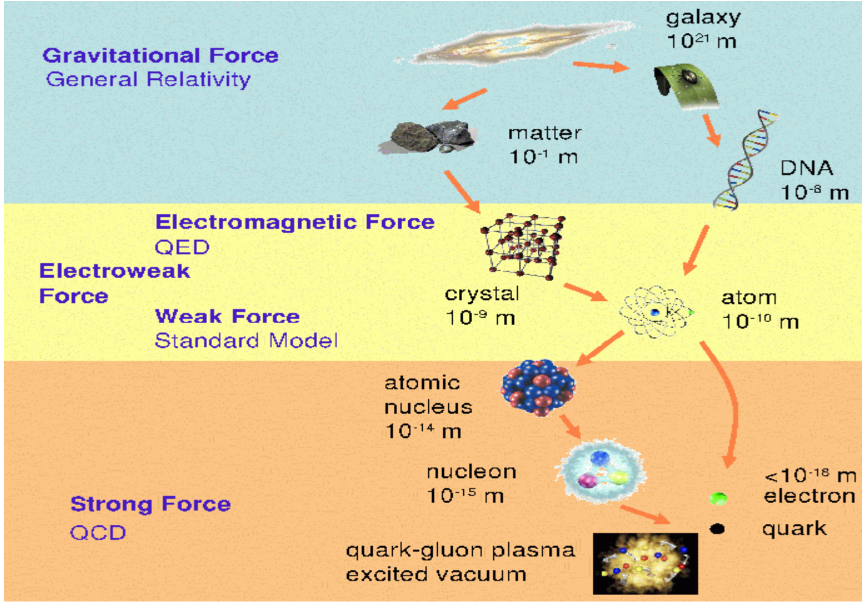
Structure of Matter and Forces

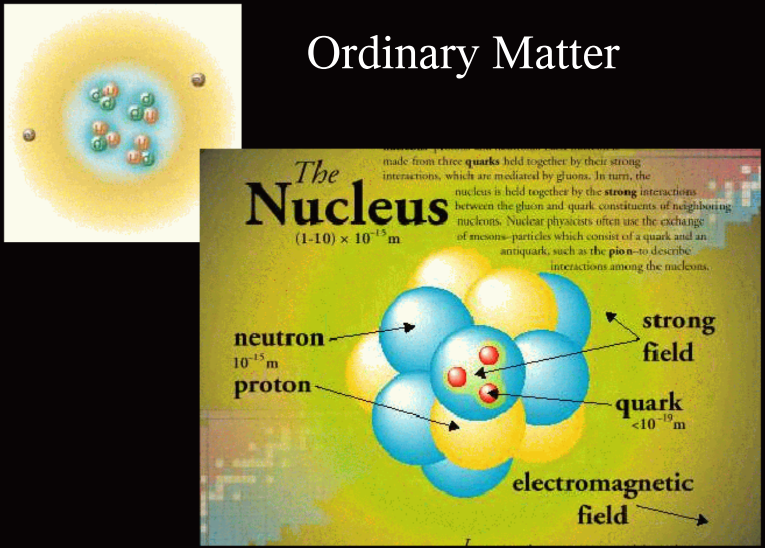


Nuclear Physics and Methods of Abundance Determination

- What is the Universe made of ?
- Some basic definitions and terminology
- How do we determine abundances ?

(Recap of “Intro do Astrophysics” and
Overview of “Nuclear Physics”)

Ordinary Matter


made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.

Ingredients of the Universe

What is the Universe made of ?

60% Dark Energy (would really like to know)
38% Cold dark matter (don’t know but there is hope)
2%   Nuclei and electrons (visible as stars and gas)

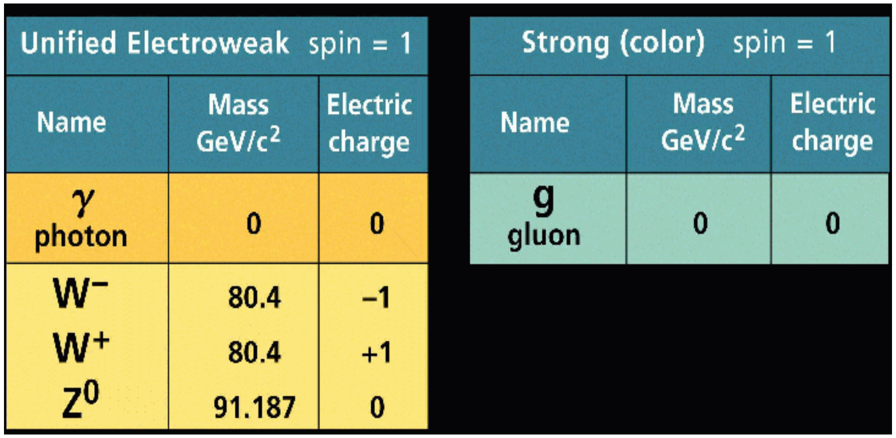
Why bother?

Scientific answer: Elements probe the physics conditions and, thus, tell us about conditions of the stars and the Universe when they are formed.
Emotional answer: Where do we come from?

Key Questions:

- What kind of nuclei is the universe made of ?
- How abundant is each element/isotope ?

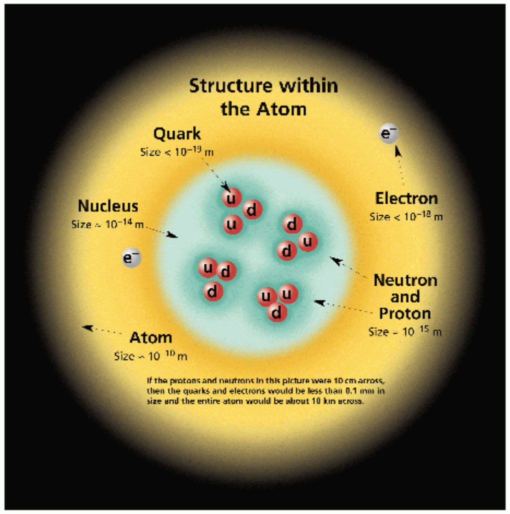
Bosons as 'carriers of forces' (spin=0,1,...)



Unified Electroweak spin = 1		
Name	**Mass GeV/c²**	**Electric charge**
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c²**	**Electric charge**
g gluon	0	0

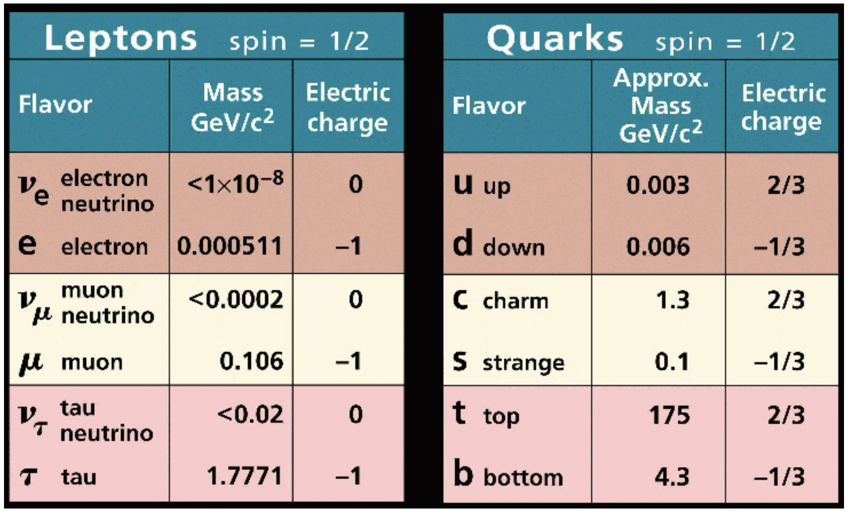
Structure of Atoms



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Fermions as matter constituents

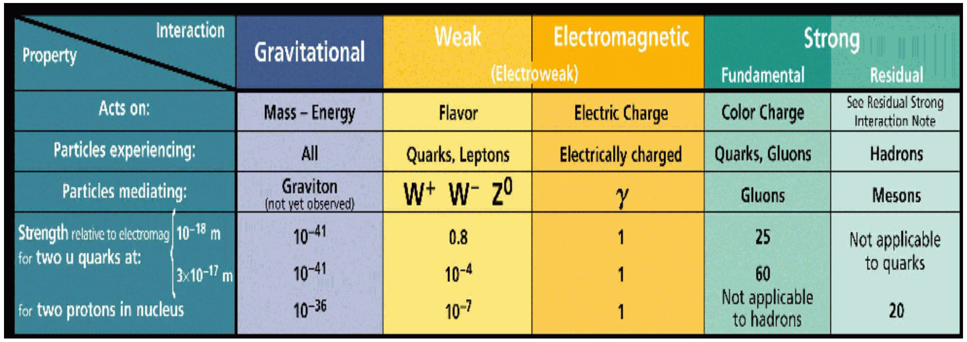
(spin=1/2,3/2, ...)



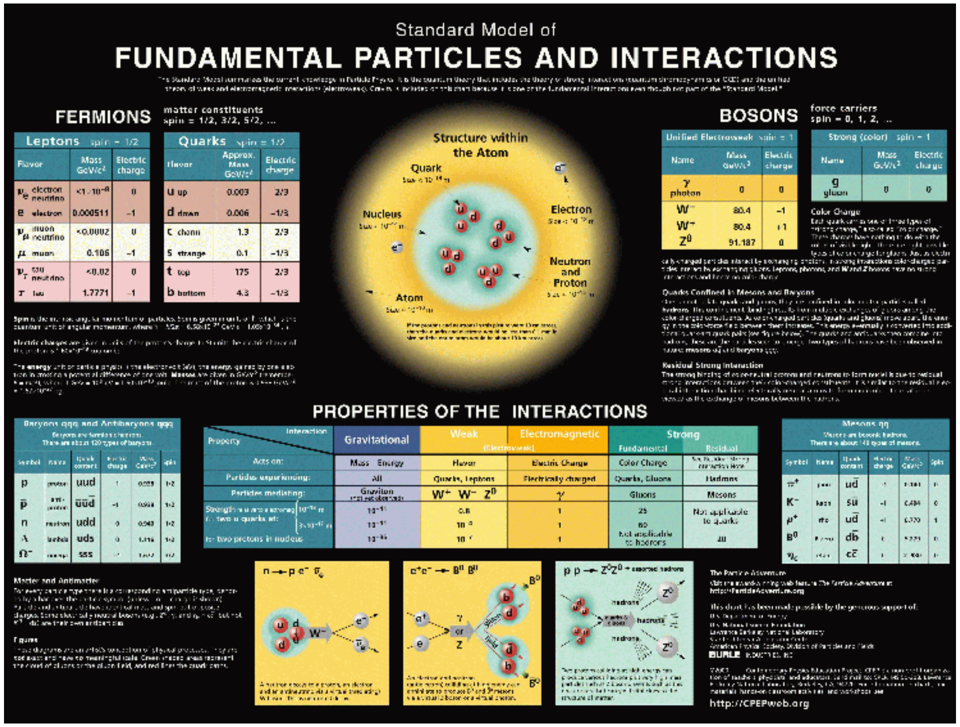
Leptons spin = 1/2		
Flavor	**Mass GeV/c²**	**Electric charge**
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	**Approx. Mass GeV/c²**	**Electric charge**
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Properties of the Interactions



Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
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c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Structure within the Atom

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Quarks Confined in Mesons and Baryons

Residual Strong Interaction

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong Fundamental	Strong Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
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for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Mesons $q\bar{q}$

Matter and Antimatter

Figures

$n \to p\, e^-\, \bar{\nu}_e$

$e^+e^- \to B^0\, \bar{B}^0$

$p\, p \to Z^0 Z^0$ + assorted hadrons

The Particle Adventure

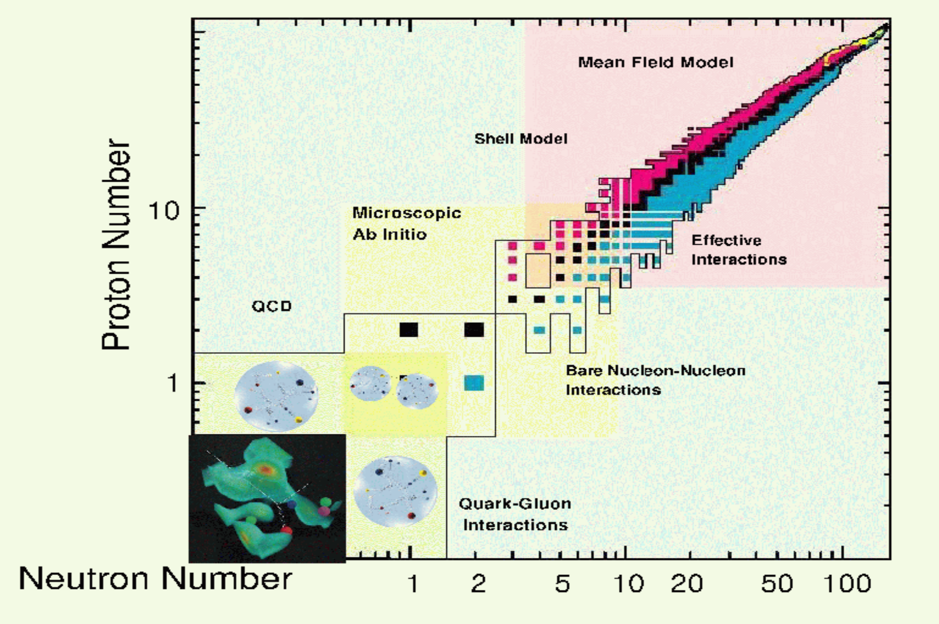
http://CPEPweb.org

Mesons are Quark Anti-Quark Particles

(about 140 stable bosonic hadrons)

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Domains of Nuclear Theories & Limitations



Barions (qqq) and Antibarions ($\bar{q}\bar{q}\bar{q}$)

(about 120 types of baryons)

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mass fractions

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/cm³)

m_i mass of nucleus of species i

(CGS only !!! because definition of mol)

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

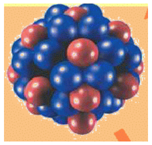
$$n_i = \boxed{\frac{X_i}{A_i}} \rho \, \mathrm{N_A}$$

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

note: Abundance has no units

Abundances in the Cosmos: 1. The nucleus

Constituencies: Protons and Neutrons



Basic Quantities :

- A: Mass Number = number of nucleons
- Z: Charge Number = number of protons
- N: Neutron Number

A=Z+N - binding energy

Usual notation:

Mass number A

$^{12}\mathrm{C}$

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

Useful Relations

of course $\sum_i X_i = 1$

- 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”)

Definitions for Abundances

Particle density of isotope i:
n_i number of particles$/cm^{-3}$

Particle abundance

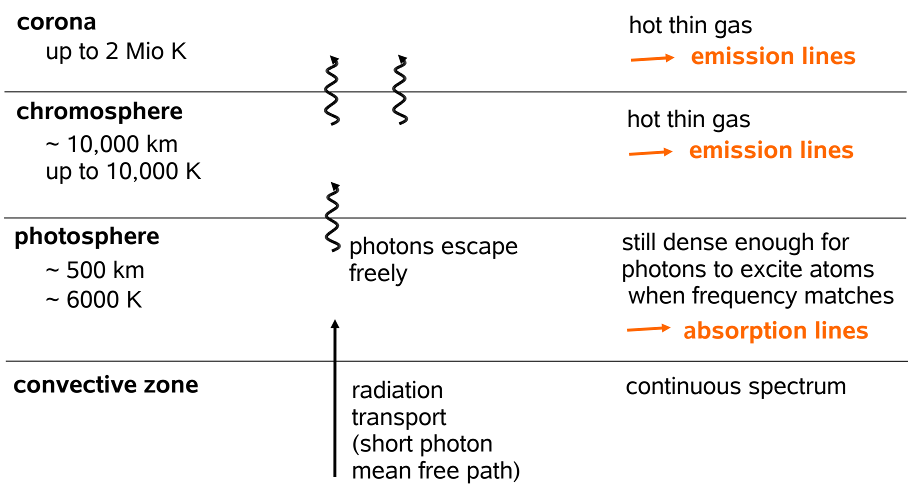
$$X_i = \frac{n_i}{\sum_{all\ isotopes\ j} n_j}$$

Remark: Often given logarithmic and normalized to hydrogen H

Relative abundance ϵ_i

$$\epsilon_i = log_{10} X_i + 12$$

Abundances from stellar spectra (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**

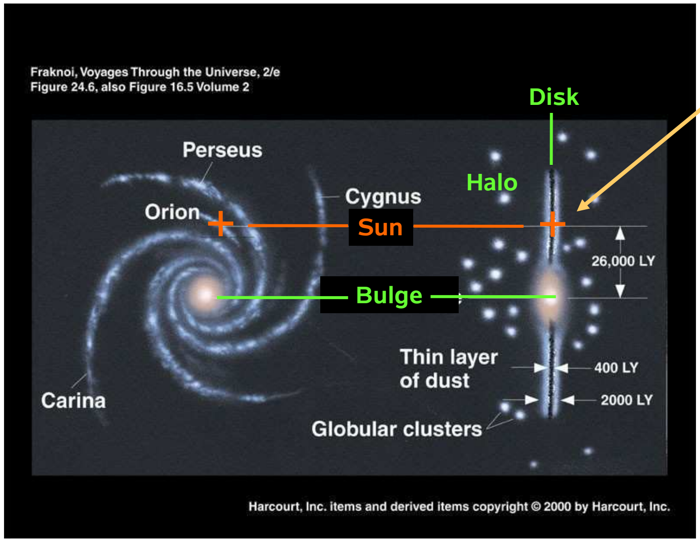
convective zone

radiation transport (short photon mean free path)

continuous spectrum

Emission lines from atomic de-excitations
Absorption lines from atomic excitations
} Wavelength -> Atomic Species
Intensity -> Abundance

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 to Identify Chemical Elements and Molecules in Stars

- Each element and chemical compound has its own unique energy levels.
- Each element and chemical compound has its own unique pattern of emission and absorption lines
- Look for the pattern in the spectra of stars. If the pattern is present, the element is present.

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).

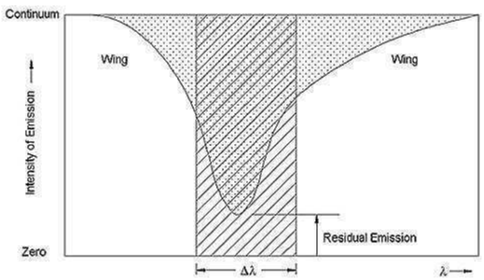
→ **main source for isotopic composition of elements**

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



effective line width ~ total absorbed intensity

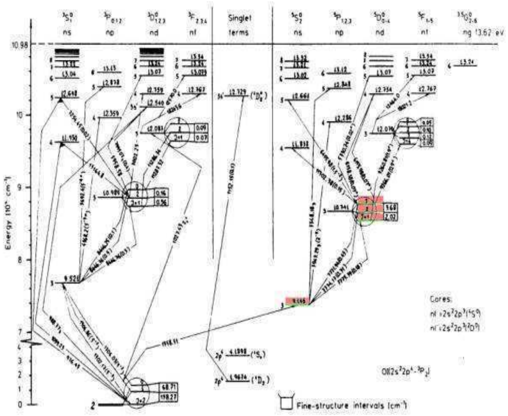
Simple model consideration for absorption in a slab of thickness Δx:

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

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

Example: Grotrian Diagram of OI



Complication (1) <u>Determine σ</u>

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 …)

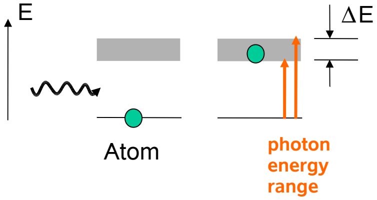
It depends on:

- **<u>Oscillator strength</u>**: 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.

- **<u>Line width</u>**

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



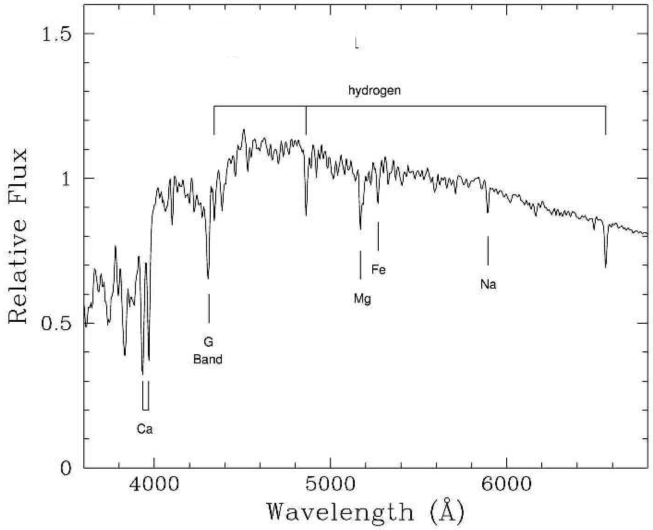
excited state has an energy width ΔE. This leads to a range of photon energies that can be absorbed and to a line width

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

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

→ need lifetime of final state

Absorption Spectra for Stars



An Excursion to Statistical Physics I

Occupation numbers: Atomic and molecular level population.

General: (Non Local Thermodynamical Equilibrium NLTE:)
Example: Time independent Statistical Equations limited to hot plasma's:

$$\boxed{n_i(\Sigma_{b-b}(R_{ij}+C_{ij}+(R_{ik}+C_{ik}))=n_k(R_{ki}+C_{ki})+\Sigma_{b-b}n_jn_e(R_{ji}+C_{ji})}$$

with R and C the radiative and collisional transition probability between bound states i and j, n_e the electron density, and n_i the number density of atoms in state i.

$$\boxed{R=R(\mathbf{r},\mathbf{v},J_\nu,T,\rho,n_{i,ion}),\quad C=C(\mathbf{r},\mathbf{v},T,\rho,n_{i,ion})}$$

Problems:
a) Solution depends on the knowledge and accuracy of all transitions.
b) System of very large dimensions $N_{total}=N_{grid}*N\nu*N_{elements}*N_{levels}*N_{ions}$

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

- **<u>The natural lifetime</u>** (natural width)

  lifetime that level would have if atom is left undisturbed

- **<u>Frequency of Interactions of atom with other atoms or electrons</u>**

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

  Varying <u>electric fields</u> from neighboring ions vary level energies through Stark Effect

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

- **<u>Doppler broadening</u>** through variations in atom velocity
  - thermal motion → depends on **temperature**
  - micro turbulence

Need detailed and accurate model of stellar atmosphere !

An Excursion to Statistical Physics II

Equilibrium equivation for concentrations in the initial and final state $[A_i], [A_f]$

$$\boxed{\Sigma[A_i]=\Sigma[A_f]}$$

The results only depends on the weight g of the quantum states, and the energy difference between i and f, and statistical properties such as T, the matter density ρ and the composition.

Examples:
Chemical Equilibrium:

$$\boxed{C+O=CO}$$

Excitation Equilibrium (2-components, Boltzman-Equation):

$$\boxed{\frac{n_i}{n_j}=(g_j/g_i)e^{\frac{E_{ij}}{k_BT}}}$$

Ionization Equilibrium (3 components, Saha-Equation):

$$\boxed{\frac{n_j}{n_{j+1}n_e}=(g_j/g_{j+1}(\underline{\frac{h^2}{2\pi\ m_e\ k_b\ T}})^{1.5})e^{\frac{E_{ion}}{k_BT}}}$$

Remark: The red, underlined term is the statistical weight of an electron in phase space.

<u>Complication (2)</u>

Atomic transitions depend on the <u>excitation and ionization</u> !

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

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.

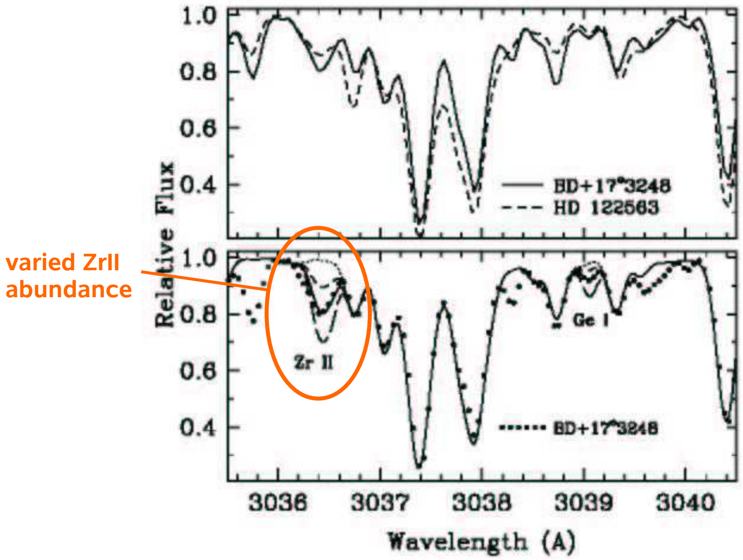
One needs primitive meteorites that underwent little modification after forming.

Classification of meteorites:

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

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)



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 ?

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

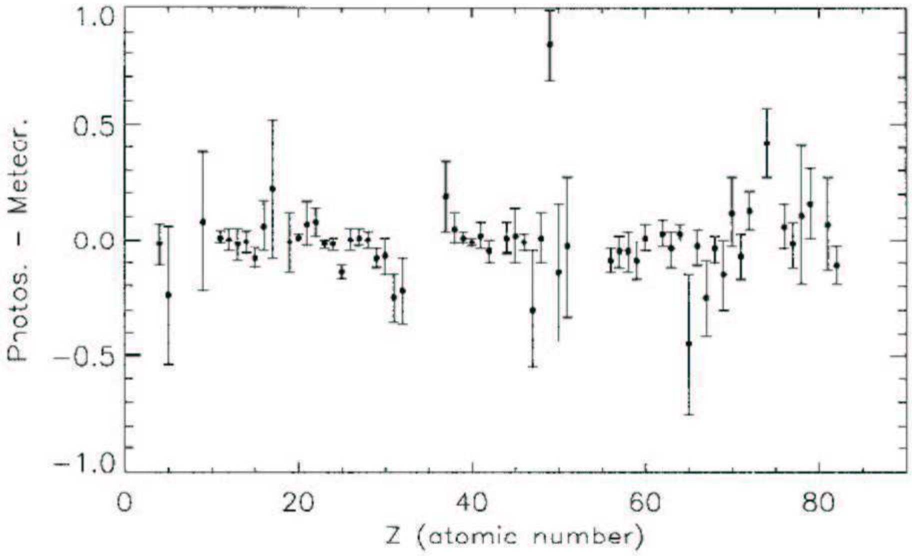
Therefore abundances less accurate

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

log of photosphere abundance/ meteoritic abundance

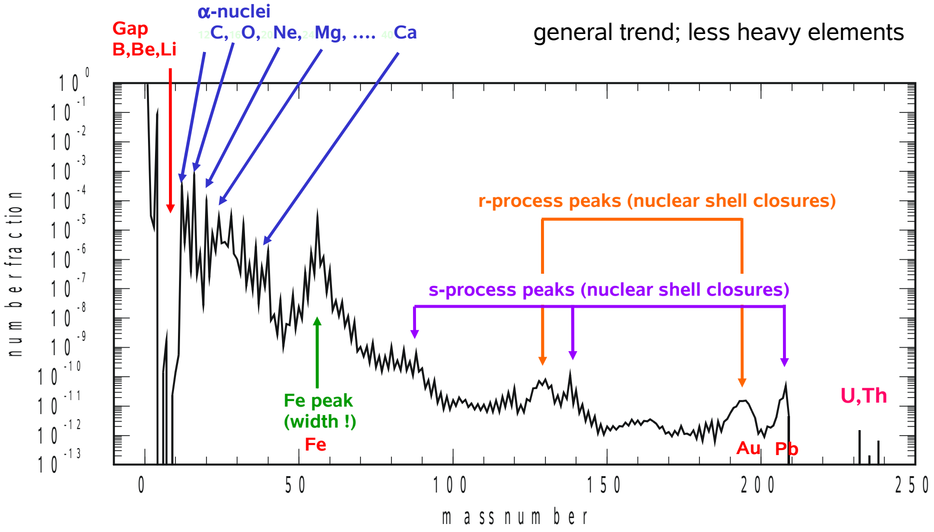


generally good agreement

Meteorites Land on the Earth All the Time

Most meteorites are found in Antarctica where they are easy to see in the snow.

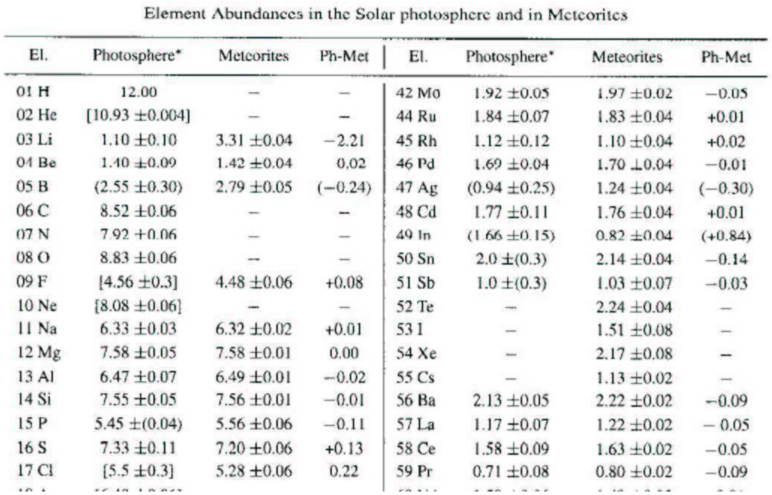
Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6



general trend; less heavy elements

3.3. Results for solar abundance distribution

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

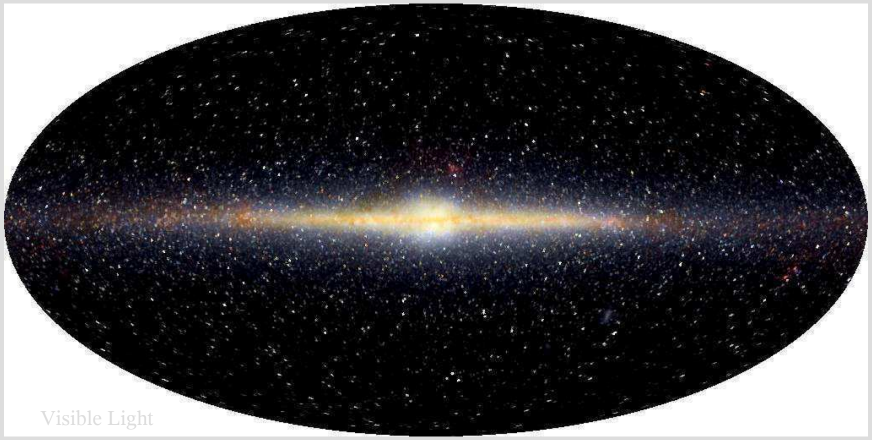


Element Abundances in the Solar photosphere and in Meteorites

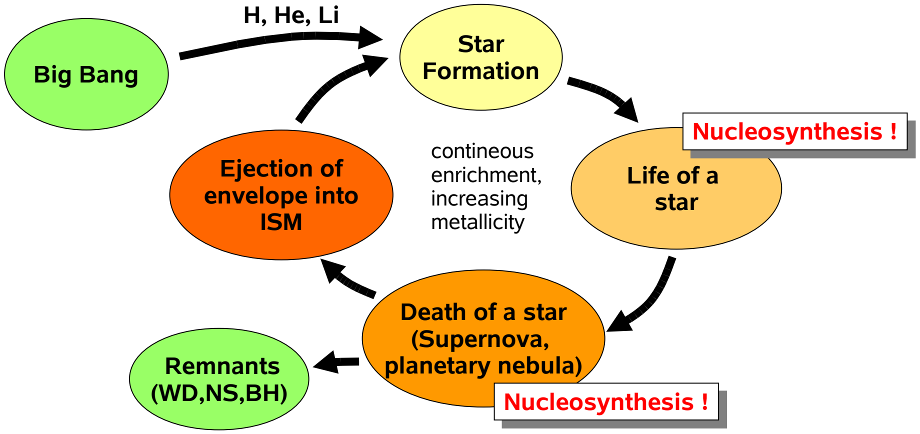
El.	Photosphere*	Meteorites	Ph-Met	El.	Photosphere*	Meteorites	Ph-Met
01 H	12.00	–	–	42 Mo	1.92 ±0.05	1.97 ±0.02	−0.05
02 He	[10.93 ±0.004]	–	–	44 Ru	1.84 ±0.07	1.83 ±0.04	+0.01
03 Li	1.10 ±0.10	3.31 ±0.04	−2.21	45 Rh	1.12 ±0.12	1.10 ±0.04	+0.02
04 Be	1.40 ±0.09	1.42 ±0.04	0.02	46 Pd	1.69 ±0.04	1.70 ±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)

The Milky Way

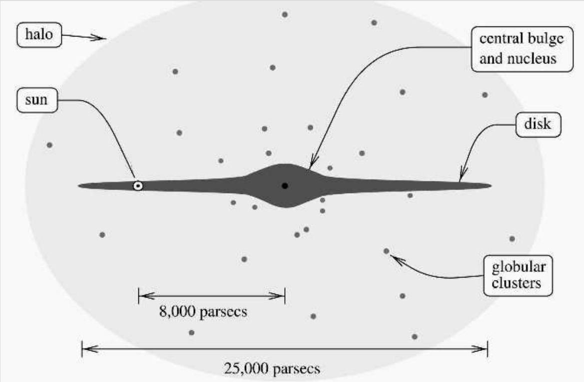


Nucleosynthesis is a gradual, still ongoing process:



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

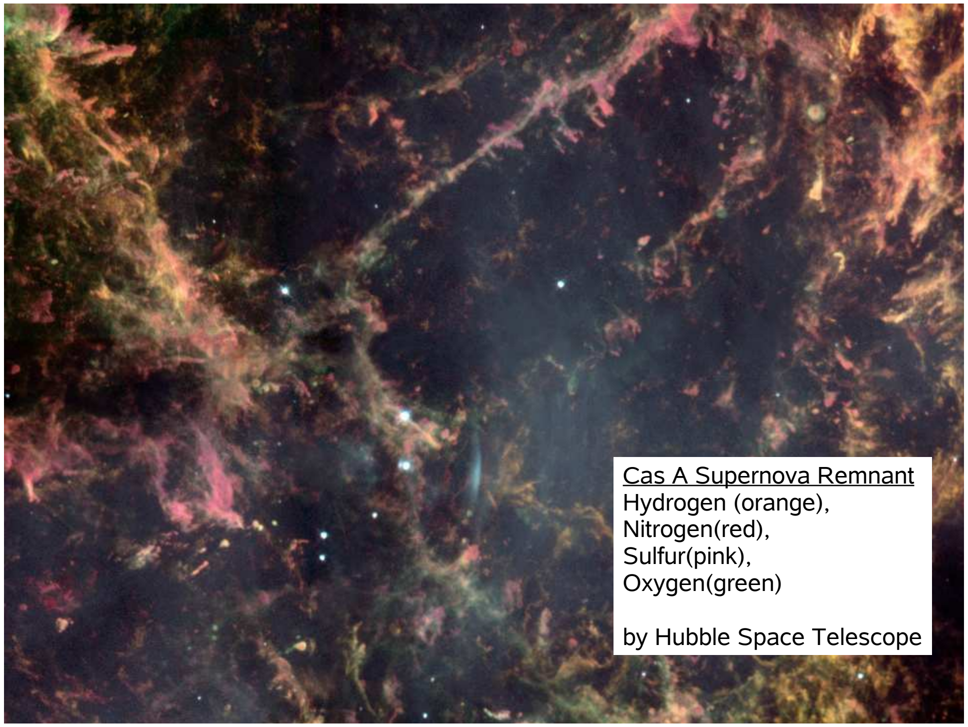
Side View of the Galaxy



M104, a Galaxy with an Unusually Prominent Halo

The Spiral Galaxy NGC 1232

- The youngest, hottest, most luminous stars are concentrated in the spiral arms, making the spiral arms bright and blue.
- The central bulge has fewer young stars and is redder.



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

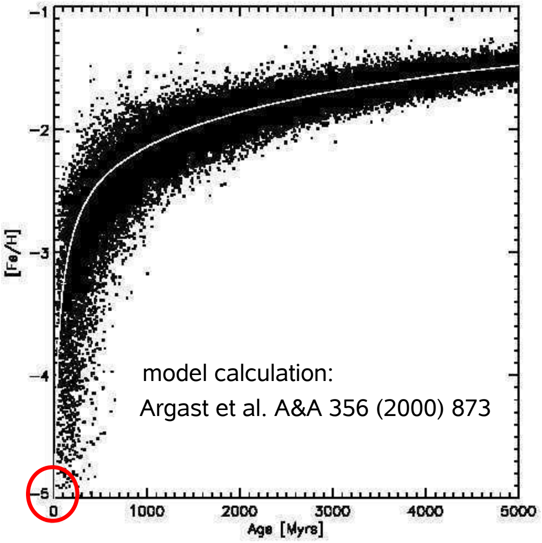
by Hubble Space Telescope

Metallicity Gradients provide the Abundance Evolution

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

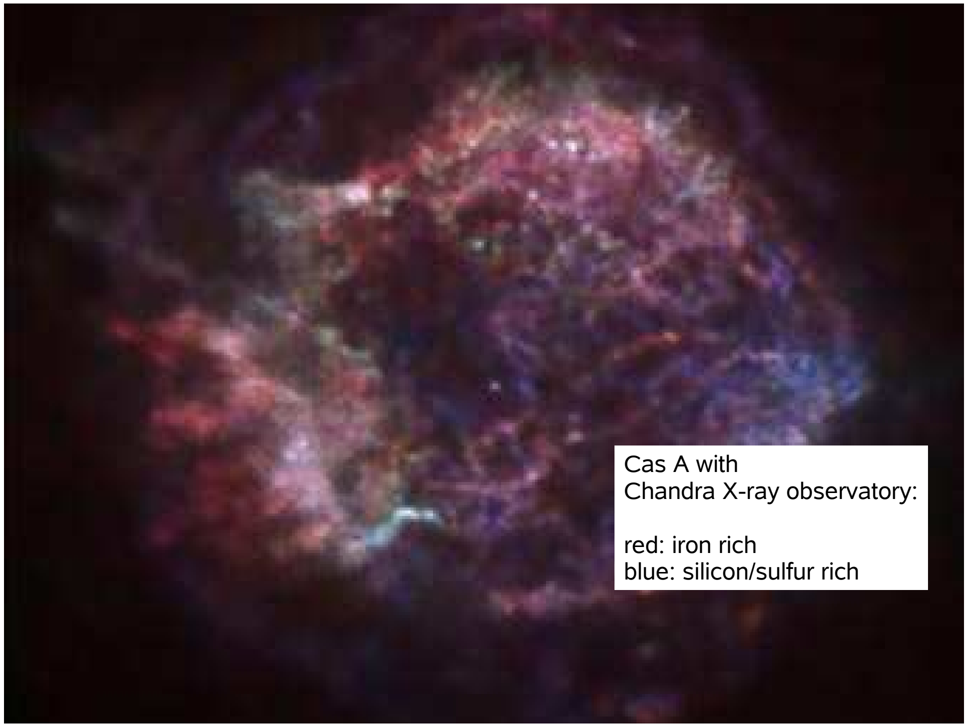
Classical picture:
Pop I: metal rich like sun
Pop II: metal poor [Fe/H]<-2
PopIII: first stars (not seen)

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



model calculation:
Argast et al. A&A 356 (2000) 873

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



Cas A with
Chandra X-ray observatory:

red: iron rich
blue: silicon/sulfur rich

Supernova remnants - where freshly synthesized elements got ejected

Cas A: