Lecture 2

IMF and
Solar Abundances

A) Initial Mass Function and Typical Supernova Masses

The initial mass function (IMF) is defined as that number of stars that have ever formed per unit area of the Galactic disk (pc^{-2}) per unit logarithmic (base 10) interval (earlier was per volume pc^{-3})

$$\text{IMF} = \xi(\log M)$$

The product $\xi(\log M_1) \times (\Delta \log M)$ is thus the number of stars in the mass interval $\Delta \log M$ around $\log M_1$ ever formed per unit area (pc^{-2}) in our Galaxy between.

An interval of ± 0.3 around $\log M_1$ thus corresponds to a range in masses $M_1 / 2$ to $2\, M_1$.

For low mass stars, $\tau_{MS} > \tau_{Gal}$ (i.e. $M < 0.8\, M_{\odot}$), the IMF equals the present day mass function (PDMF). For higher mass stars an uncetain correction must be applied.

There are many IMFs in the literature. Here to get some simple results that only depend on the slope of the IMF above 10 solar masses, we will use the one from Salpeter (1955), which remains appropriate for massive stars, as well as one taken from Shapiro and Teukolsky's textbook (Chap 1.3, page 9) for a more extended mass interval. This latter IMF is an amalgamation of Bahcall and Soneira (ApJS, 44, 73, (1980)) and Miller and Scalo (ApJS, 41, 513, (1979))

$$\log\,\xi(\log M) = 1.41 - 0.9\log M - 0.28(\log M^2)$$

A related quantity is the slope of the IMF

$$\Gamma = \frac{d\log\xi}{d\log M} = -0.9 - 0.56\log M$$

Salpeter, in his classic treatment took Γ=const. =-1.35

Salpeter (1955)
(7 pages large type)

[4668 citations as of 3/29/15]

$$dN = \xi(\log M)\, d(\log_{10} M)\, \frac{dt}{T_0}$$

where T_0 is the age of the galaxy and dN is the number of stars in the mass range $d\log M$ created per cubic pc in time dt

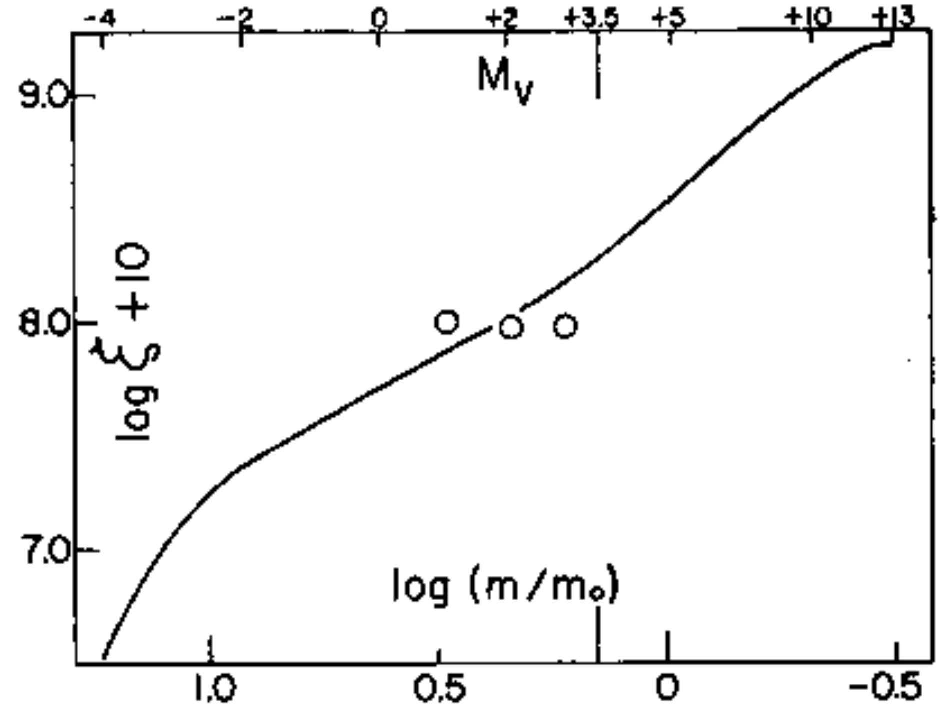


FIG. 2.—The logarithm of the "original mass function," ξ, plotted against the mass, 𝔐, in solar units.

For $\log\left(\frac{M}{M_\odot}\right)$ between -0.4 and +1.0 M between 0.4 and 10

$$\xi(\log \mathrm{M}) \approx 0.03\left(\frac{M}{M_\odot}\right)^{-1.35}$$

Kroupa (2002, *Science*)

general	$dN = \xi(m)\,dm = \xi_{\rm L}(m)dlm$		
	$\xi_{\rm L}(m) = (m\ln 10)\,\xi(m)$		*gen*
Scalo's IMF index (*8*)	$\Gamma(m) \equiv \frac{d}{dlm}\left(\log_{10}\xi_{\rm L}(lm)\right)$		*Gam*
	$\Gamma = -x = 1+\gamma = 1-\alpha$		*ind*
	e.g. for power-law form:	$\xi_{\rm L} = A\,m^{\Gamma} = A\,m^{-x}$ $\xi = A'\,m^{\alpha} = A'\,m^{-\gamma}$ $A' = A/\ln 10$	
Salpeter(1955) (*3*)	$\xi_{\rm L}(lm) = A\,m^{\Gamma}$	$\Gamma = -1.35\ (\alpha = 2.35)$	*S*
	$A = 0.03\,{\rm pc}^{-3}\log_{10}^{-1}M_\odot;\quad 0.4 \le m/M_\odot \le 10$		
Miller-Scalo(1979) (*7*)	$\xi_{\rm L}(lm) = A\exp\left[-\frac{(lm-lm_o)^2}{2\,\sigma_{lm}^2}\right]$	$\Gamma(lm) = -\frac{(lm-lm_o)}{\sigma_{lm}^2}\log_{10}e$	*MS*
thick long-dash-dotted line	$A = 106\,{\rm pc}^{-2}\log_{10}^{-1}M_\odot;\quad lm_o = -1.02;\quad \sigma_{lm} = 0.68$		
Larson(1998) (*69*)	$\xi_{\rm L}(lm) = A\,m^{-1.35}\exp\left[-\frac{m_o}{m}\right]$	$\Gamma(lm) = -1.35 + \frac{m_o}{m}$	*La*
thin short-dashed line	$A = -;\quad m_o = 0.3\,M_\odot$		
Larson(1998) (*69*)	$\xi_{\rm L}(lm) = A\left[1+\frac{m}{m_o}\right]^{-1.35}$	$\Gamma(lm) = -1.35\,(1+\frac{m_o}{m})^{-1}$	*Lb*
thin long-dashed line	$A = -;\quad m_o = 1\,M_\odot$		
Chabrier(2001) (*93, 13*)	$\xi(m) = A\,m^{-\delta}\exp\left[-\left(\frac{m_o}{m}\right)^{\beta}\right]$	$\Gamma(lm) = 1-\delta+\beta\left(\frac{m_o}{m}\right)^{\beta}$	*Ch*
thick short-dash-dotted line	$A = 3.0\,{\rm pc}^{-3}\,M_\odot^{-1};\quad m_o = 716.4\,M_\odot;\quad \delta = 3.3;\quad \beta = 0.25$		

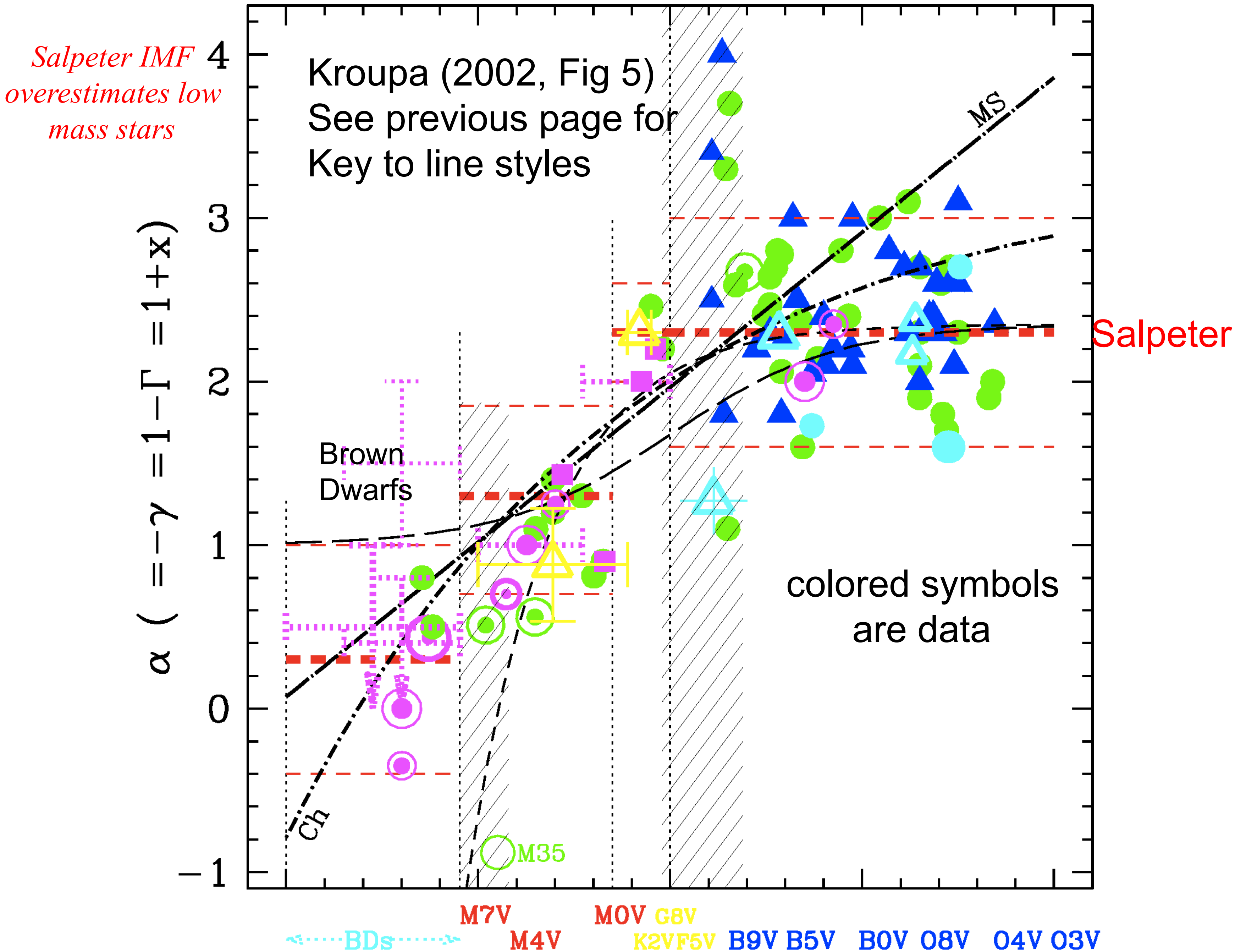
fig:apl

The multi-part power-law IMF:

$$\xi(m) = k\begin{cases} \left(\frac{m}{m_1}\right)^{-\alpha_0} & ,\ m_0 < m \le m_1 \quad ,\ n=0 \\ \left(\frac{m}{m_1}\right)^{-\alpha_1} & ,\ m_1 < m \le m_2 \quad ,\ n=1 \\ \left[\prod_{i=2}^{n\ge 2}\left(\frac{m_i}{m_{i-1}}\right)^{-\alpha_{i-1}}\right]\left(\frac{m}{m_n}\right)^{-\alpha_n} & ,\ m_n < m \le m_{n+1} \quad ,\ n\ge 2 \end{cases} \tag{4}$$

The average, or Galactic-field, single-star IMF has $k = 0.877 \pm 0.045$ stars/(pc^3 $M_\odot$) for scaling to the solar neighborhood with

$$\begin{array}{llll} \alpha_0 = +0.3\pm 0.7 & ,\ 0.01 \le m/M_\odot < 0.08 & ,\ n=0 \\ \alpha_1 = +1.3\pm 0.5 & ,\ 0.08 \le m/M_\odot < 0.50 & ,\ n=1 \\ \alpha_2 = +2.3\pm 0.3 & ,\ 0.5 \le m/M_\odot < 1 & ,\ n=2 \\ \alpha_3 = {}^{+2.7\pm 0.3}_{+2.3\pm 0.3} & ,\ 1 \le m/M_\odot & ,\ n=3. \end{array} \tag{5}$$


Salpeter IMF overestimates low mass stars
Kroupa (2002, Fig 5)
See previous page for
Key to line styles
Brown Dwarfs
colored symbols are data
Salpeter
MS
Ch
M35
α (= −γ = 1−Γ = 1+x)
4
3
2
1
0
−1
M7V
M4V
M0V
G8V
K2V F5V
B9V
B5V
B0V
O8V
O4V
O3V
BDs

Examples of how to use the IMF

Suppose you want to know the fraction by number of all stars ever born having mass $\geq$ M (Here M_U equals the most massive star is taken to be 100 $M_\odot$; M_L, the least massive star, is taken to be 0.1)

$$F_n(M) = \frac{\int_{M}^{M_U} \xi(\log M)\, d\log M}{\int_{M_L}^{M_U} \xi(\log M)\, d\log M} = 1/2$$

We use the Shapiro-Teukolsky IMF here because the Salpeter IMF is not good below about 0.5 solar mass. The answer is 0.3 solar masses. Half of the stars ever born were above 0.3 solar masses and half were below

Examples of how to use the IMF

How about the total fraction of mass ever incorporated into stars with masses greater than M?

$$X_m(M) = \frac{\int_{M}^{M_U} M \, \xi(\log M) \, d\log M}{\int_{M_L}^{M^U} M \, \xi(\log M) \, d\log M}$$

This quantity is 0.5 for a larger value of M, 1.3 $M_\odot$.
Half the mass went into stars lighter than 1.3, half into heavier stars.

For simplicity in what follows use a Salpeter IMF, take Γ=-1.35, then $\varsigma(\log M)=C_0 M^\Gamma$ and

$$\varsigma(\log M)\ d\log M = C' M^\Gamma \frac{dM}{M} = C' \frac{dM}{M^{1-\Gamma}} = C' \frac{dM}{M^{2.35}}$$

What is the number fraction greater than M?

$$F_n(M) = \frac{\int_M^{M_U} \frac{dM}{M^{1-\Gamma}}}{\int_{M_L}^{M_U} \frac{dM}{M^{1-\Gamma}}} = \frac{M_U^\Gamma - M^\Gamma}{M_U^\Gamma - M_L^\Gamma}$$

For $\Gamma = -1.35$ for example and $M_U = 100$, and $M_L = 0.1$, the number fraction greater than 10 $M_\odot$ is 0.2% and the number fraction greater than 25 $M_\odot$ is 0.06%. Simi-

The mass weighted average tells us the fraction of the mass incorporated into stars above some value

$$X_m(M) = \frac{\int_{M}^{M_U} \frac{(M)dM}{M^{1-\Gamma}}}{\int_{M_L}^{M_U} \frac{(M)dM}{M^{1-\Gamma}}}$$

$$= \frac{M_U^{\Gamma+1} - M^{\Gamma+1}}{M_U^{\Gamma+1} - M_L^{\Gamma+1}}$$

This gives 12% for 10 $M_\odot$, and 6.1% for 25 $M_\odot$.

According to Miller + Scalo (1979)
ApJ Sup, 41, 513

$M/M_\odot$	Fraction by # Stars Ever Born	Fraction by Mass Into Stars Ever Formed
0.1	100%	100%
0.16	78%	95%
0.25	56%	89%
0.40	38	79
0.63	24	69
1.0	14	58
1.6	7.8	45
2.5	4.0	32
4	1.9	22
6.3	0.81%	14
10	0.32%	8.5 (SNae ↓)
16	0.12%	4.5
25	0.038%	2.0
40	0.009%	0.71%

Current star formation rate

3 to $7 \times 10^{-9}\ M_\odot\ pc^{-2}\ yr^{-1}$ solar neighborhood

2 solar masses/Gyr/pc^2
45 solar masses/pc^2
current values - Berteli and Nasi (2001)

The average supernova by number is then

$$\int_{M_L}^{<M_{SN}>} \frac{dM}{M^{1-\Gamma}} = \int_{<M_{SN}>}^{M_U} \frac{dM}{M^{1-\Gamma}}$$

$$M_L^\Gamma - <M_{SN}>^\Gamma = <M_{SN}>^\Gamma - M_U^\Gamma$$

$$<M_{SN}> = (\frac{1}{2})^{1/\Gamma} M_L$$

$$= 13.4 M_\odot$$

$$\int \frac{dM}{M^{1-\Gamma}} = \int M^{\Gamma-1}\, dM = \frac{M^\Gamma}{\Gamma}$$

where M_U^Γ is negligibly small and $M_L =$ 8 $M_\odot$. If $M_L =$ **9** $M_\odot$, then the average is 15 $M_\odot$. Suppose above 35 $M_\odot$ don't get a Type II supernova, but instead a black hole or a SN Ib, then

$$8^\Gamma - <M_{SN}>^\Gamma = <M_{SN}> - 35^\Gamma$$

$$2 <M_{SN}>^\Gamma = 8^\Gamma + 35^\Gamma$$

$$<M_{SN}> = 12.2\ M_\odot$$

So, probably 15 $M_\odot$ is typical. SN 1987A was ~~20 - 22~~ $M_\odot$. ~18

The typical *nucleosynthesis* supernova is not the numerical average, but the average

For homework evaluate using Smartt's limit of 20 weighted by the mass ejected in heavy elements. That is

$$\int_{10}^{M} \frac{dM}{M^{-\Gamma}} Z_{\rm ej} = \int_{M}^{M_U} \frac{dM}{M^{-\Gamma}} Z_{\rm ej}$$

where $Z_{\rm ej}$ is the fraction of a star's mass ejected in the form of heavy elements. A 40 $M_\odot$ supernova ejects about 11 $M_\odot$of heavy elements (neglecting mass loss); an 11 $M_\odot$ supernova ejects almost none. Woosley and Weaver (*Ann NY Acad.*, 336, 347, (1986)) find $Z_{\rm ej} \approx 0.4 - 4.2(M_\odot/M)$ for $M \gtrsim 11$ $M_\odot$. The result depends upon M_U and the choice of Γ, but is typically ∼ 25 $M_\odot$. This motivates our particular interest in stars of this main sequence mass.

The mass of heavy elements divided by the mass of the the star is approximately the "metallicity" of the supernova. This ranges from 0 0at 10.5 $M_\odot$ to 0.3 for 40 $M_\odot$ (neglecting mass loss which may become important over about 30 $M_\odot$.) Let u define a "production factor", P_i which is the ratio of the mass fraction of a given species, i, in the ejecta divided by the corresponding mass fraction in the sun. Typically $P_i \sim 10$. This suggests that the Population I abundances in the Galaxy could be created if $\sim 10\%$ of the matter in the ISM from which Population I formed had been processed through stars heavier than 10 $M_\odot$. This is approximately the case. Note the distinction however, that the mass of Population I material in the Galaxy may be considerably less than its total gravitational, or even baryonic mass.

Chiosi + Maeder
ARAA 24, (1986)

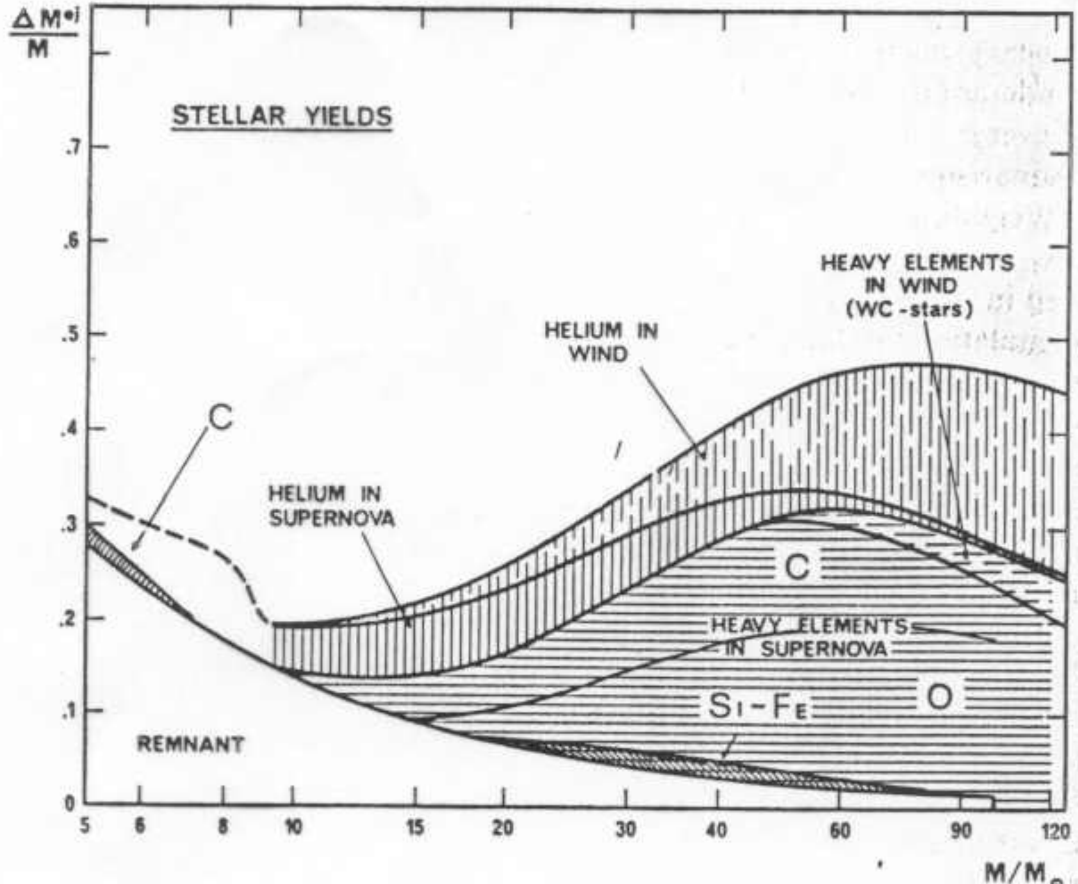
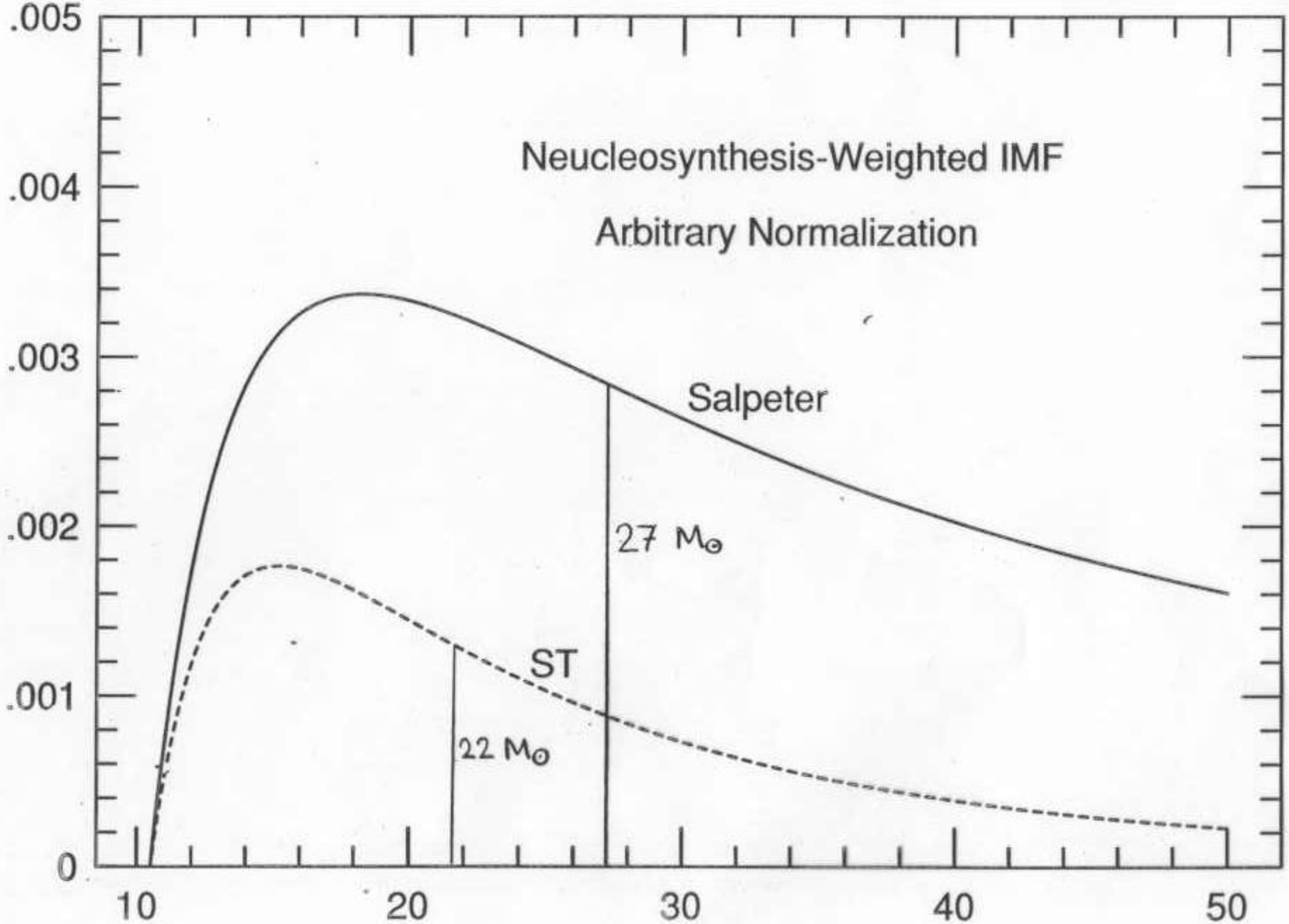


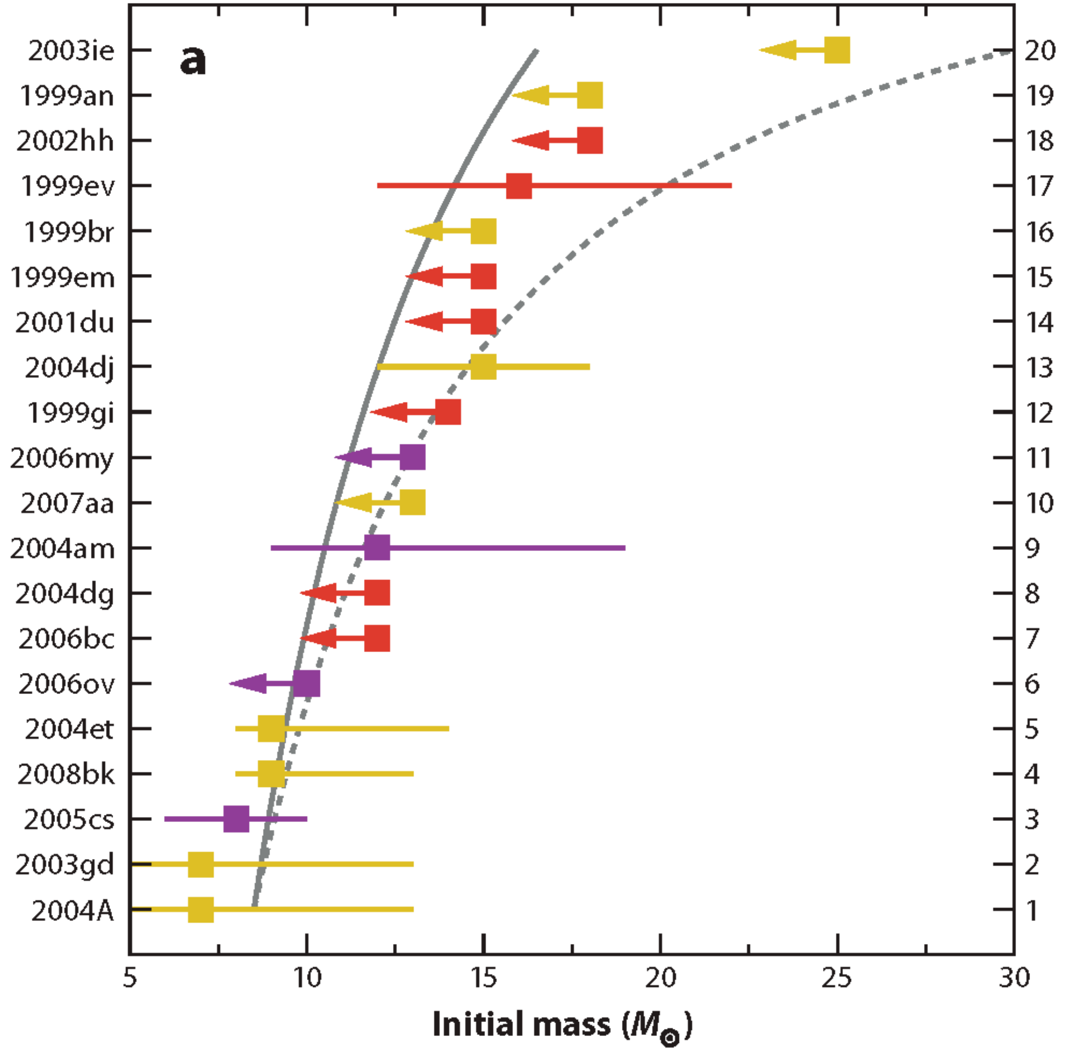
Figure 6 Mass fraction of new helium and new heavy elements ejected as a function of the initial stellar mass. Contributions from stellar winds of OB stars, supergiants, and WR stars are totaled and distinguished from the contribution from supernova explosions. The distribution of heavy elements in the supernova ejecta is based on the classic value for the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate (see text). The contribution to ^{12}C by intermediate-mass stars is derived from Renzini & Voli (214) and is limited to their case A.



Neucleosynthesis-Weighted IMF
Arbitrary Normalization
Salpeter
ST
27 M⊙
22 M⊙
.005
.004
.003
.002
.001
0
10
20
30
40
50

Modern Limits on the Mass Range of Supernovae

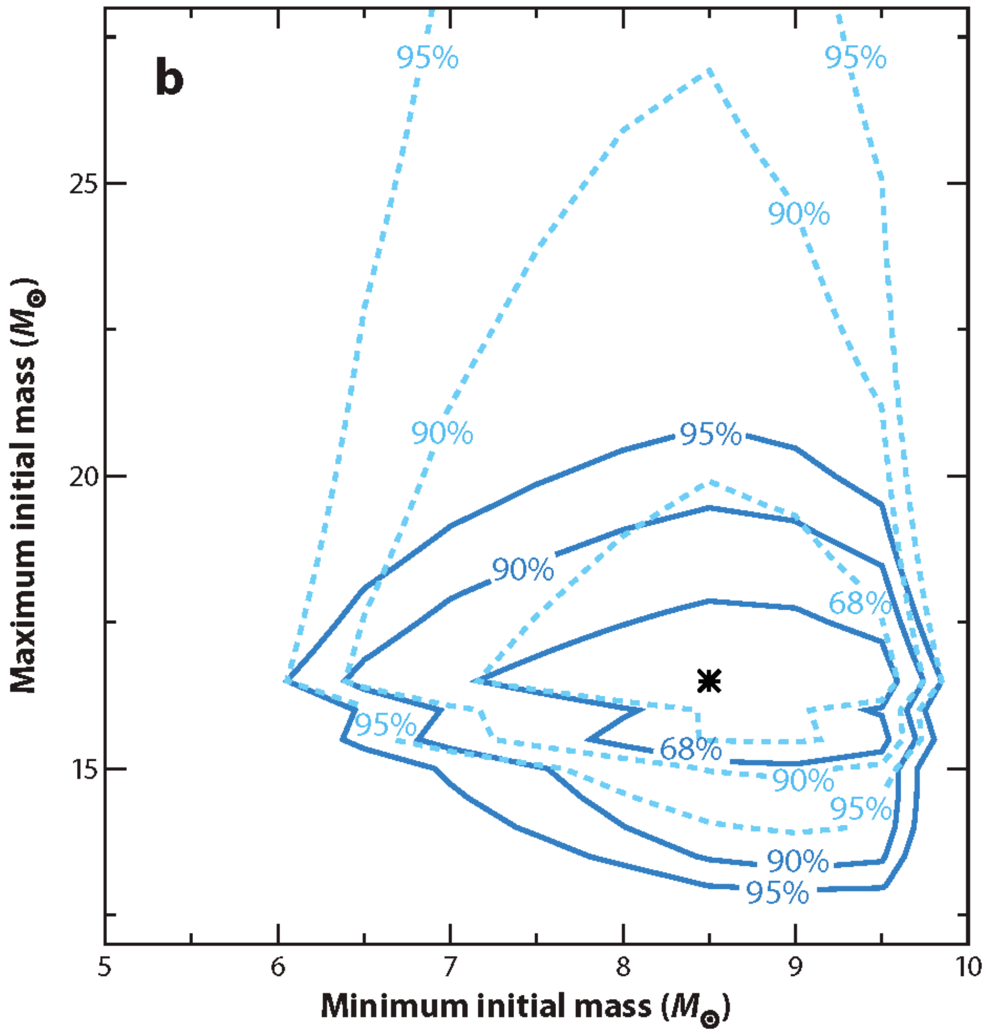
Presupernova stars – Type IIp and II-L



Smartt, 2009
ARAA

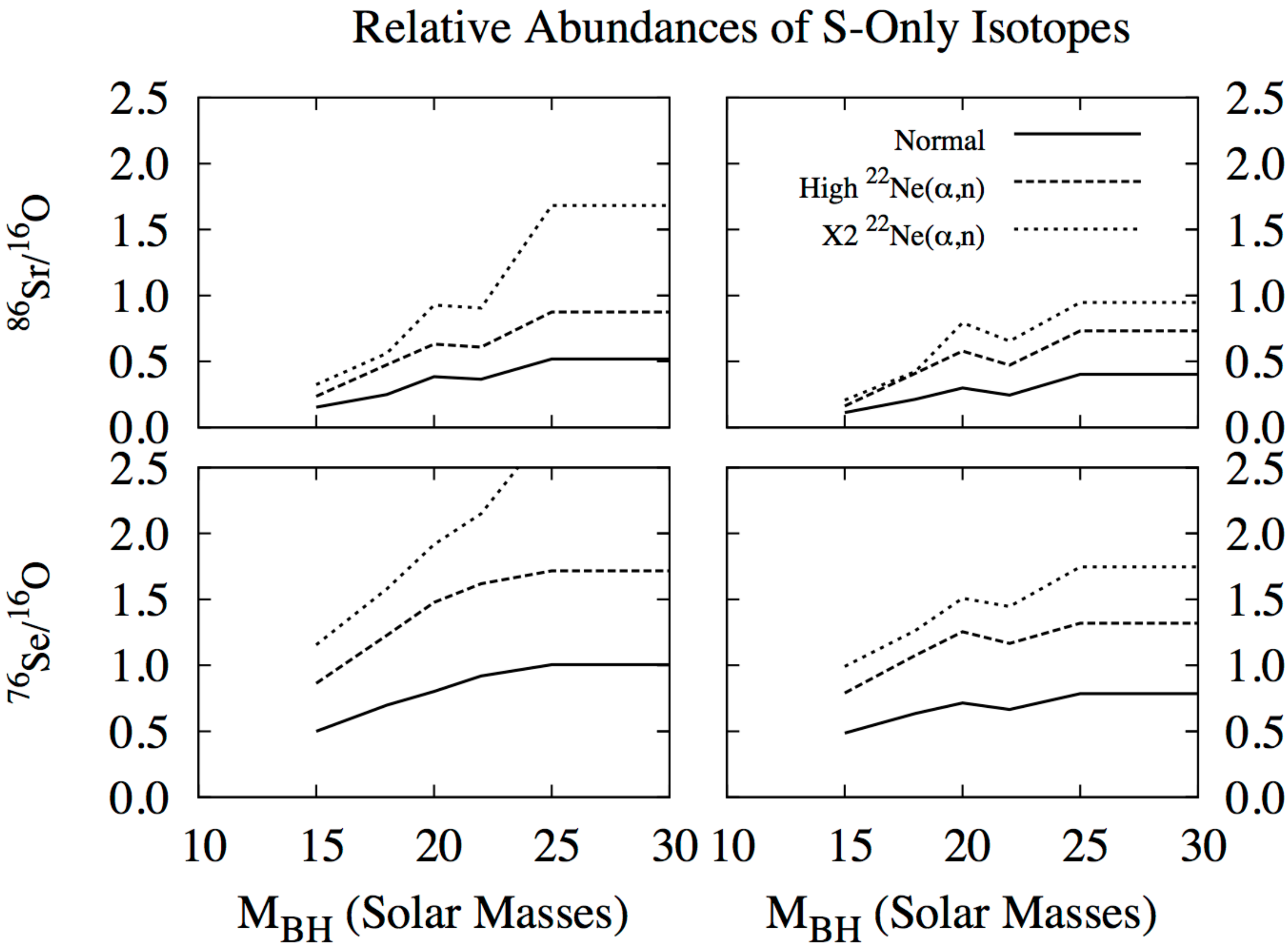
The solid line is for a Salpeter IMF with a maximum mass of 16.5 solar masses. The dashed line is a Salpeter IMF with a maximum of 35 solar masses

Minimum mass supernova



Smartt 2009
ARAA
Fig. 6b

Based on the previous figure. Solid lines use observed preSN only. Dashed lines include upper limits.



Relative Abundances of S-Only Isotopes
Normal
High $^{22}Ne(\alpha,n)$
X2 $^{22}Ne(\alpha,n)$
$^{86}Sr/^{16}O$
$^{87}Sr/^{16}O$
$^{76}Se/^{16}O$
$^{70}Ge/^{16}O$
M_{BH} (Solar Masses)
M_{BH} (Solar Masses)

Upper mass limit: theoretical predictions (for solar metallicty)

Ledoux (1941)	radial pulsation, e- opacity, H	100 $M_\odot$
Schwarzchild & Härm (1959)	radial pulsation, e- opacity, H and He, evolution	65-95 $M_\odot$
Stothers & Simon (1970)	radial pulsation, e- and atomic	80-120 $M_\odot$
Larson & Starrfield (1971)	pressure in HII region	50-60 $M_\odot$
Cox & Tabor (1976)	e- and atomic opacity Los Alamos	80-100 $M_\odot$
Klapp et al. (1987)	e- and atomic opacity Los Alamos	440 $M_\odot$
Stothers (1992)	e- and atomic opacity Rogers-Iglesias	120-150 $M_\odot$

Upper mass limit: observation

R136	Feitzinger et al. (1980)	250-1000 $M_\odot$
Eta Car	various	120-150 $M_\odot$
R136a1	Massey & Hunter (1998)	136-155 $M_\odot$
Pistol Star	Figer et al. (1998)	140-180 $M_\odot$
Eta Car	Damineli et al. (2000)	~70+? $M_\odot$
LBV 1806-20	Eikenberry et al. (2004)	150-1000 $M_\odot$
LBV 1806-20	Figer et al. (2004)	130 (binary?) $M_\odot$
HDE 269810	Walborn et al. (2004)	150 $M_\odot$
WR20a (binary)	Bonanos et al. (2004) Rauw et al. (2004)	82+83 $M_\odot$

each +- 5 Msu

What is the most massive star (nowadays)?

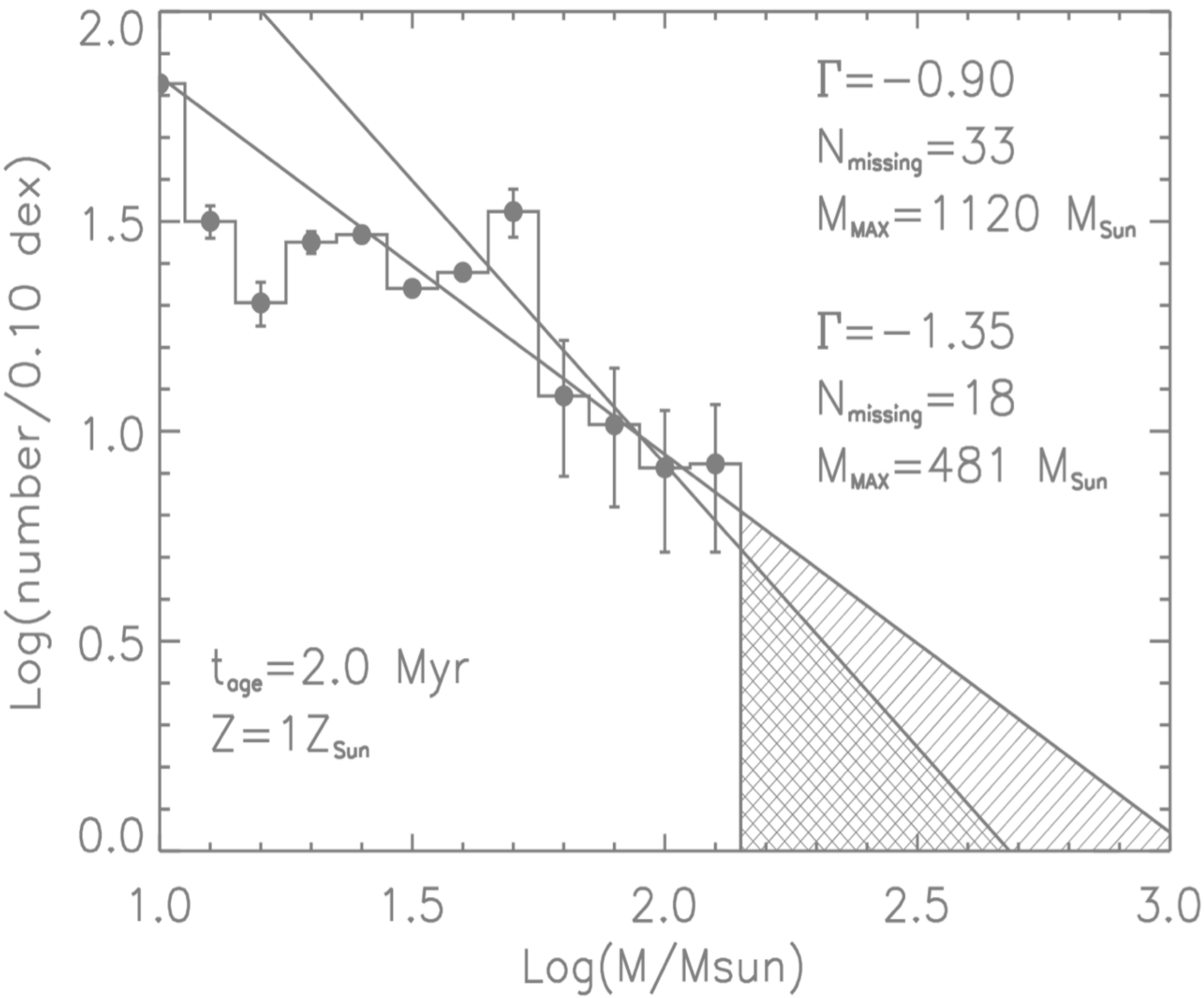
The Arches Supercluster

Massive enough and young enough to contain stars of 500 solar masses if extrapolate Salpeter IMF

No star above 130 Msun found. Limit is stated to be 150 Msun.

Figer, Nature, 434, 192 (2005)
Kim, Figer, Kudritzki and Najarro ApJ, 653L, 113 (2006)

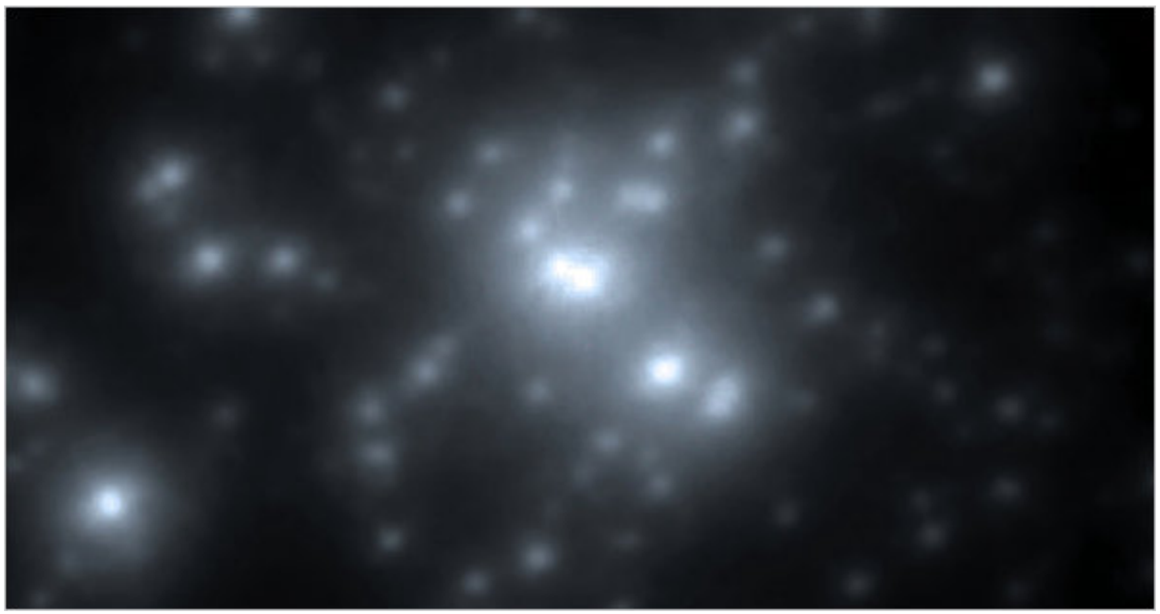
Initial mass function



A star of up to 320 solar masses was reported during summer 2010 in the Tarantula Nebula in the LMC

http://news.discovery.com/space/massive-star-cluster.html

(Crowther et al, MNRAS, 408, 73(2010))



R136A1

(controversial, maybe a binary??)

Paper not as strong a conclusion as press release

B. Solar and Stellar Abundances

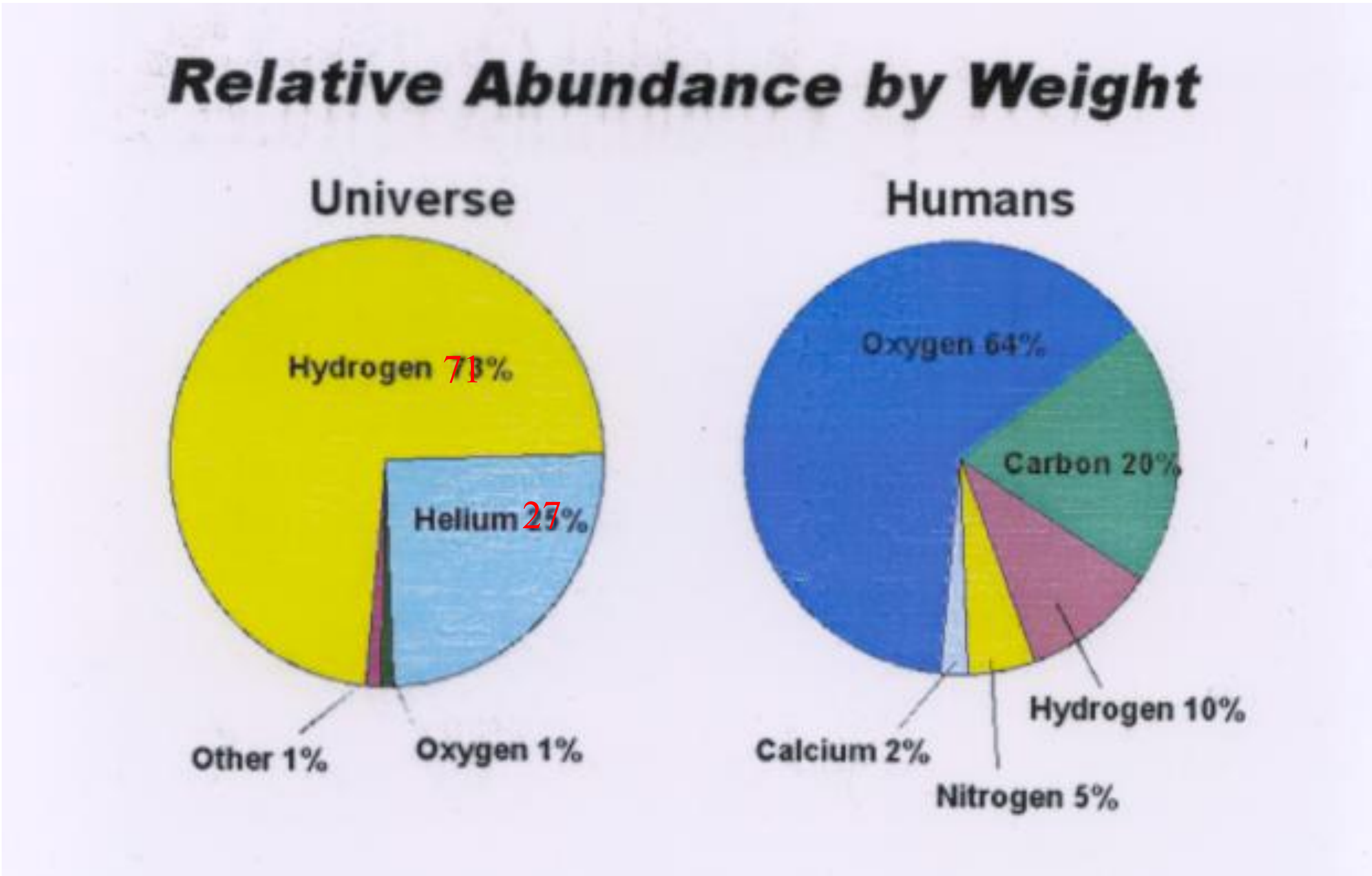
Any study of nucleosynthesis must have one of its key objectives an comprehensive, physically motivated explanation for the pattern of abundances that we find in nature -- in the solar system (i.e., the sun) and in other locations in the cosmos (other stars, the ISM, cosmic rays, IGM, and other galaxies)

Key to that is accurate information on that pattern in the sun.

For solar abundances there are three main sources:

- The Earth - good for isotopic composition only
- The solar spectrum
- Meteorites, especially primitive ones

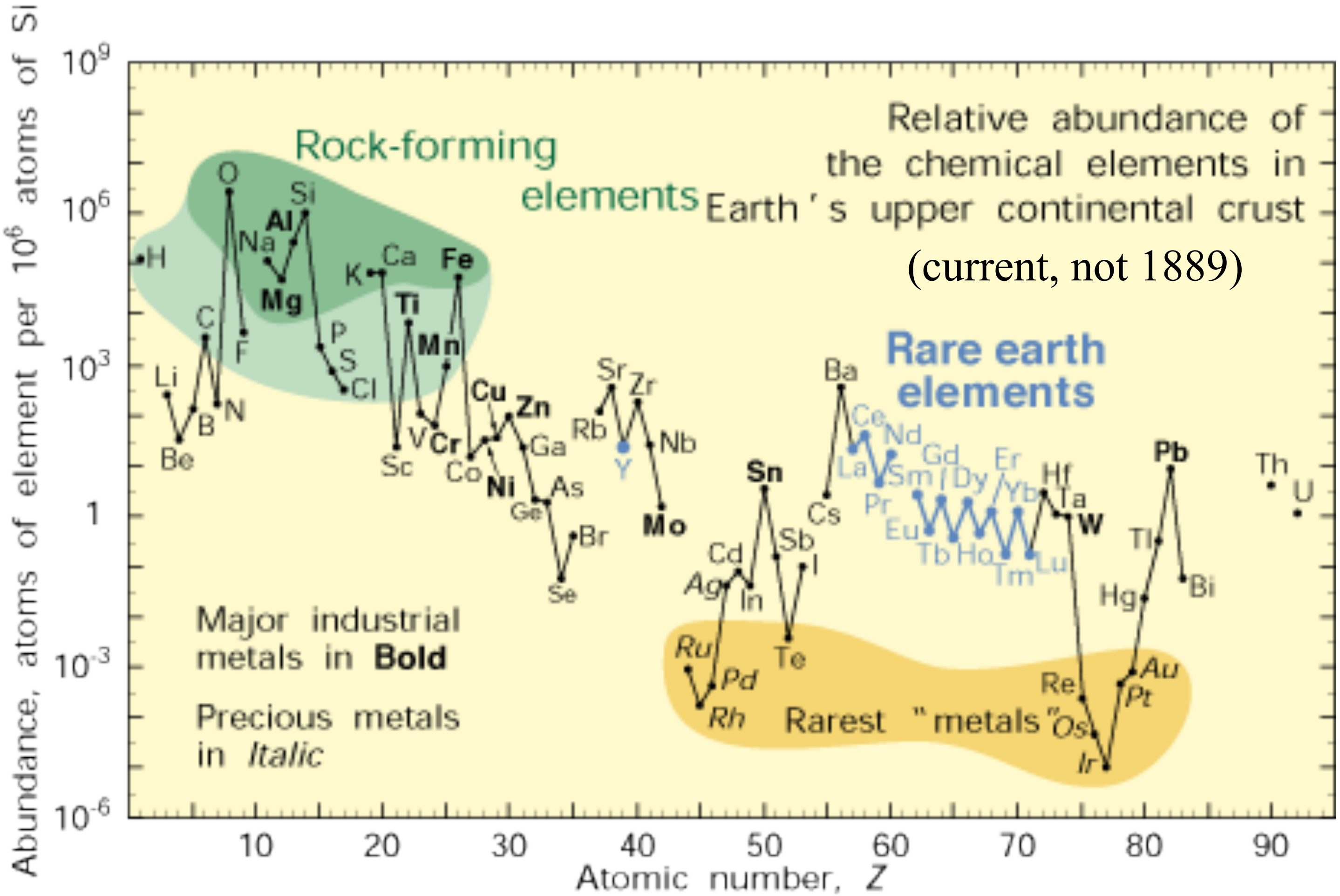
In contrast to …….



Where did these elements come from?

History:

1889, Frank W. Clarke read a paper before the Philosophical Society of Washington "The Relative Abundance of the Chemical Elements"



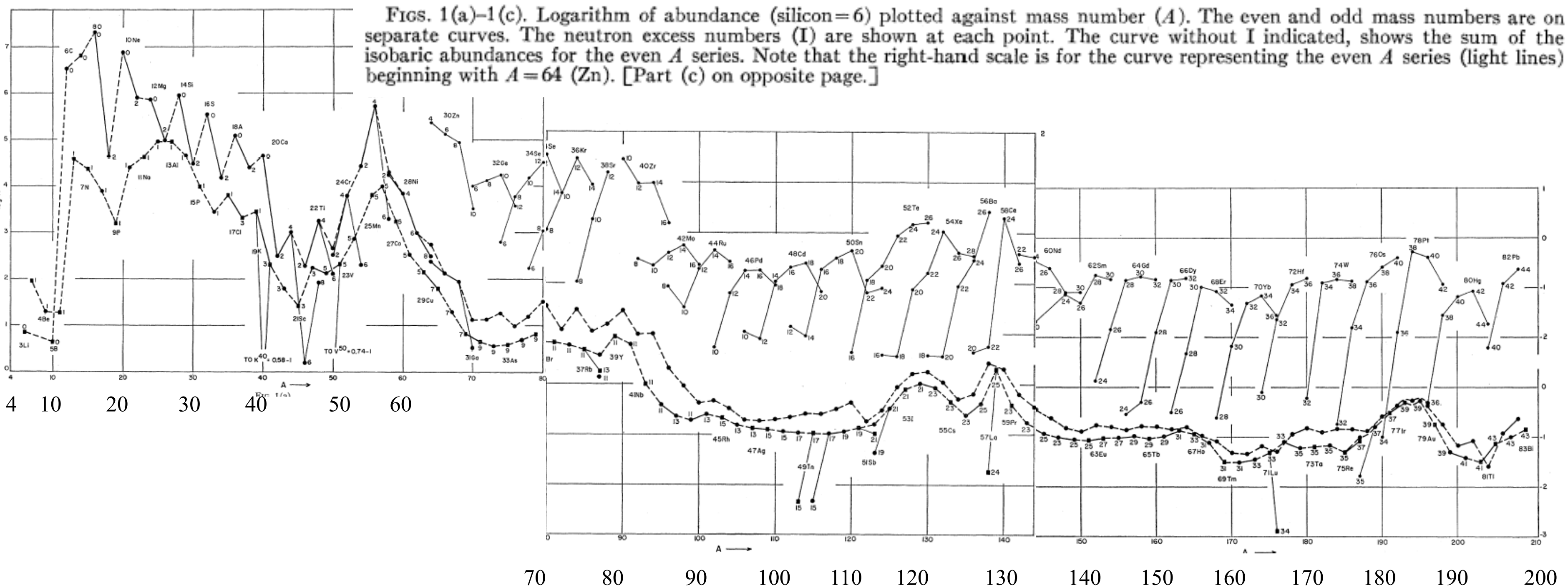
Current "abundance" distribution of elements in the earths crust:

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.]

Suess and Urey tabulated results from many prior works plus their own. Noted systematics correlated with nuclear properties. E.g. smoothness of the odd-A isotopic abundance plot.

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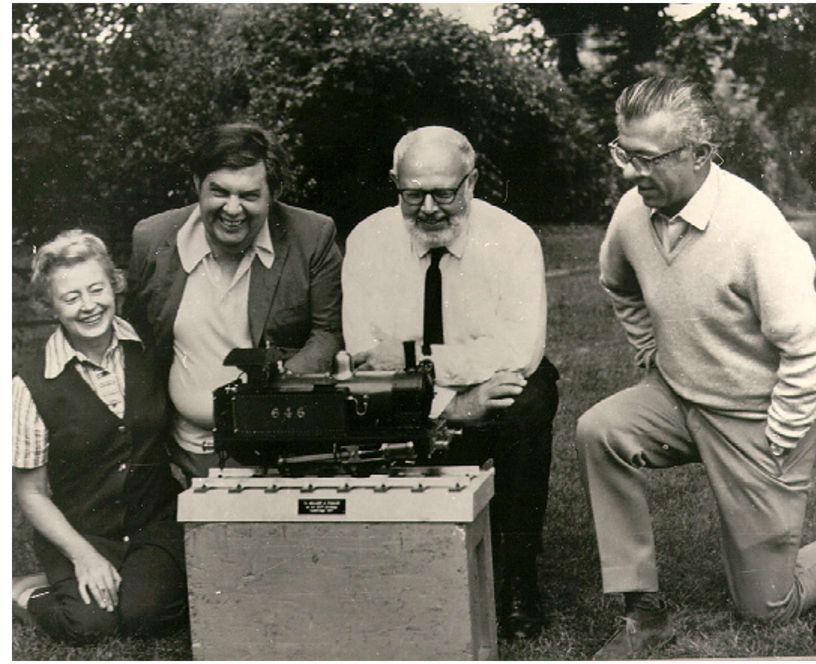
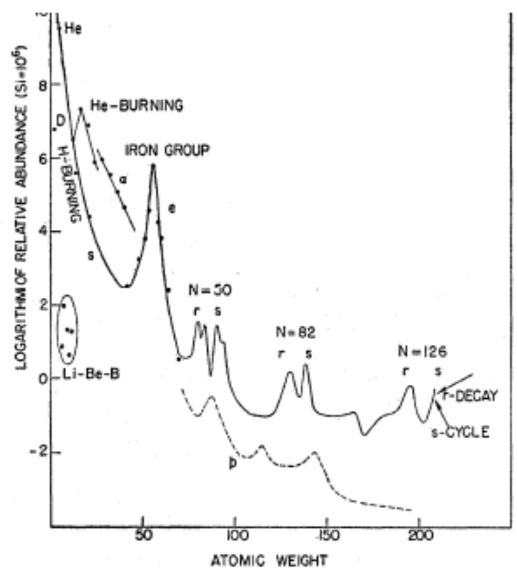
* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.





H. Schatz

Since that time many surveys by e.g.,

Cameron (1970,1973)

Anders and Ebihara (1982); Grevesse (1984)

Anders and Grevesse (1989) - largely still in use

Grevesse and Sauval (1998)

Lodders (2003, 2009) – assigned reading

Asplund, Grevesse and Sauval (2009; ARAA)

see class website

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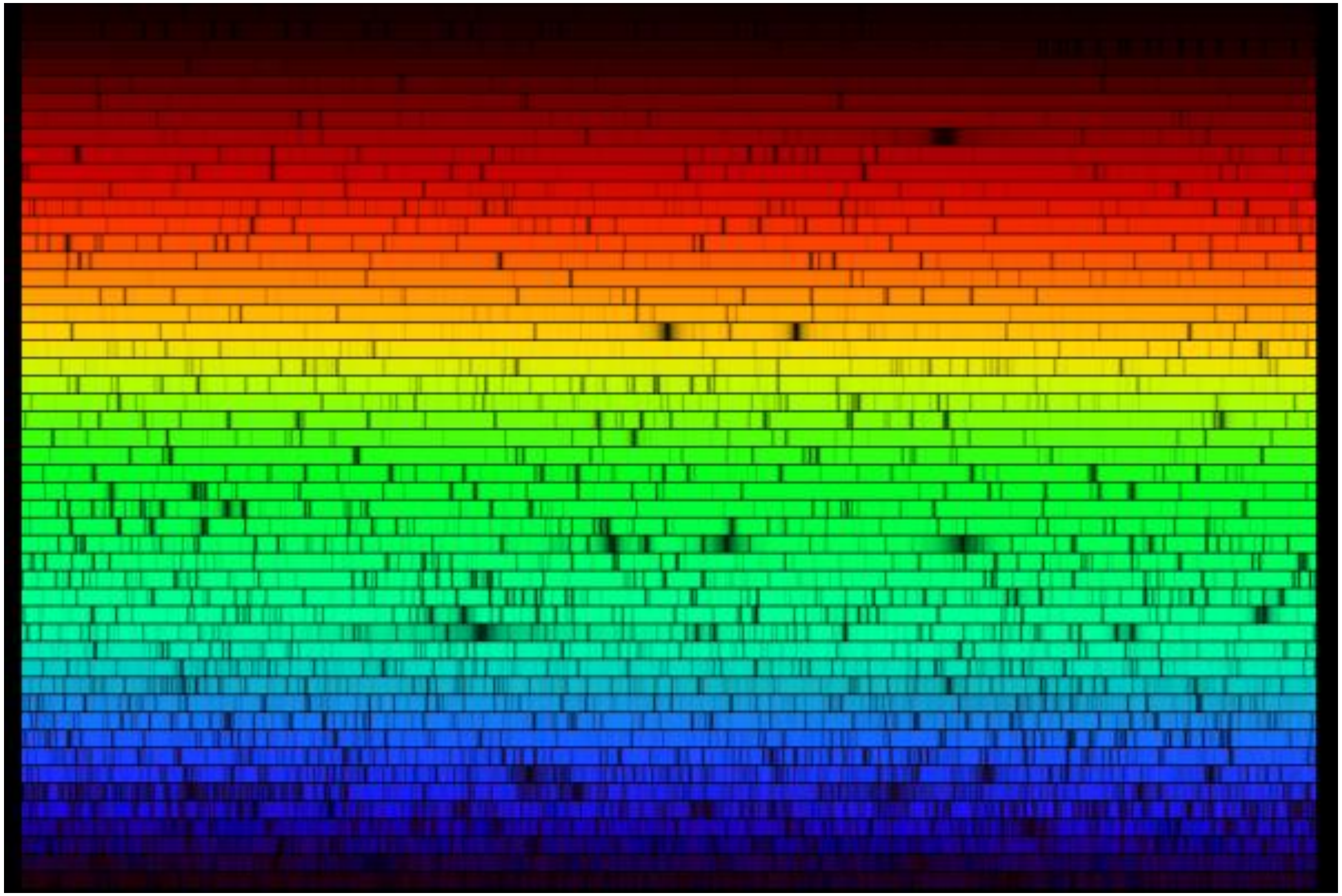
Absorption Spectra:

provide majority of data for elemental abundances 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)

Complications

- **Oscillator strengths**:

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

- **Line width**

  Depends on atomic properties but also thermal and turbulent broadening. Need an atmospheric model.

- **Line blending**

- **Ionization State**

- **Model for the solar atmosphere**

  Turbulent convection. Possible non-LTE effects.
  3D models differ from 1 D models. See Asplund, Grevesse, and Sauval (2007) on class website.

H. Schatz

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 $H\alpha$ emission lines

Meteorites

H. Schatz

Meteorites can provide accurate information on elemental abundances in the presolar nebula. More precise than solar spectra if data in some cases. Principal source for isotopic information.

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

Not all meteorites are suitable - most of them are fractionated and do not provide representative solar abundance information. Chondrites are meteorites that show little evidence for melting and differentiation.

Classification of meteorites:

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

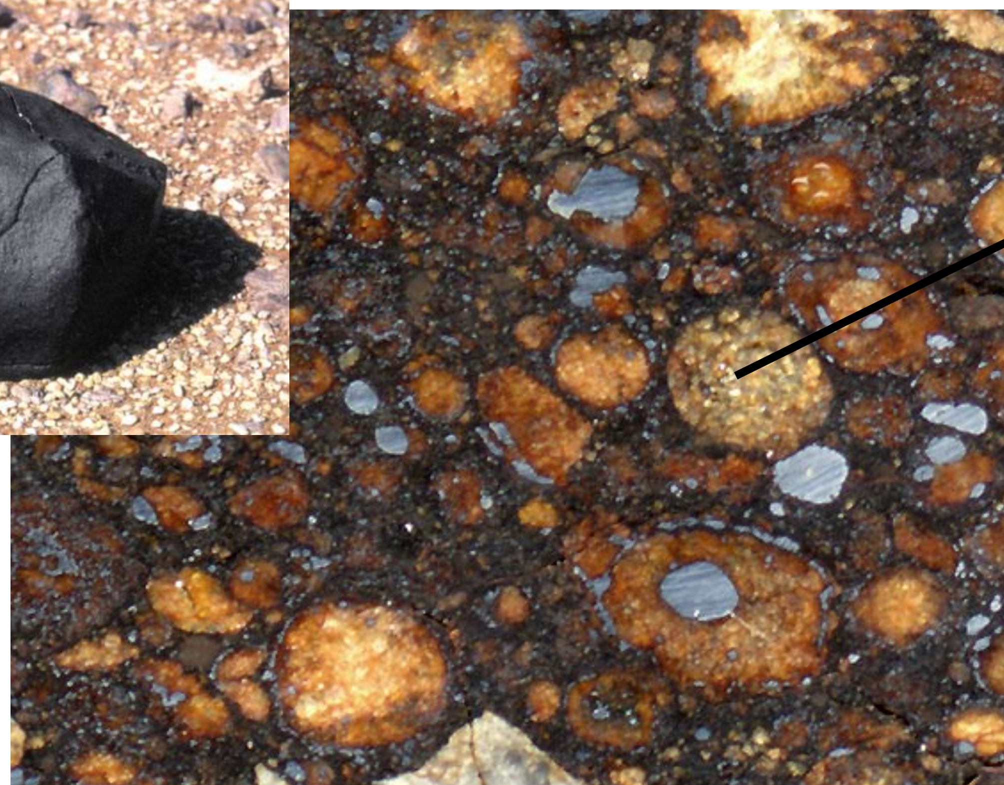
Carbonaceous chondrites are 4.6% of meteor falls.

H Schatz

Use **carbonaceous chondrites** (~5% 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)



http://www.psrd.hawaii.edu/May06/meteoriteOrganics.html

"Some carbonaceous chondrites smell. They contain volatile compounds that slowly give off chemicals with a distinctive organic aroma. Most types of carbonaceous chondrites (and there are lots of types) contain only about 2% organic compounds, but these are very important for understanding how organic compounds might have formed in the solar system. They even contain complex compounds such as amino acids, the building blocks of proteins."

There are various subclasses of carbonaceous chondrites. The C-I's and C-M's are general thought to be the most primitive because they contain water and organic material.

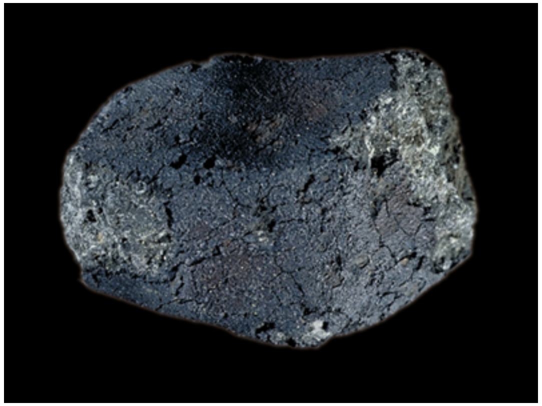
The CM meteorite Murchison, has over 70 extraterrestrial amino acids and other compounds including carboxylic acids, hydroxy carboxylic acids, sulphonic and phosphoric acids, aliphatic, aromatic, and polar hydrocarbons, fullerenes, heterocycles, carbonyl compounds, alcohols, amines, and amides.

Five CI chondrites have been observed to fall: Ivuna, Orgueil, Alais, Tonk, and Revelstoke. Several others have been found by Japanese expeditions in Antarctica. They are very fragile and subject to weathering. They do not survive long on the earth's surface after they fall. CI carbonaceous chondrites lack the "condrules" that most other chondites have.

To understand the uncertainties involved in the determination of the various abundances read Lodders et al (2009) paper and if you have time skim Asplund et al (2009)

The tables on the following pages summarize mostly Asplund et al’s (2009) view of the current elemental abundances and their uncertainties in the sun and in meteorites.

The Orgueil meteorite is especially popular for abundance analyses. It is a very primitive (and rare) carbonaceous chondrite that fell in France in 1864. Over 13 kg of material was recovered.



http://www.meteoritestudies.com/protected_ORGUEIL.HTM

In Asplund's list of *solar photospheric* abundances (neglecting Li and noble gases):

Very uncertain elements (uncertainty > 0.2 dex)

boron, fluorine, chlorine, indium, thallium

Unseen in the sun (must take from meteorites)

Arsenic, selenium, bromine, technetium (Z = 43, unstable), cadmium, antimony, tellurium, iodine, cesium, tantalum, rhenium, platinum, mercury, bismuth, promethium (Z = 61, unstable), and all elements heavier than lead (Z = 82), except for thorium.

In meteorites

Where not affected by evaporation, most good to 0.04 dex except mercury (0.08 dex)

Table 1: Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Sect. 3.9).

	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	$[10.93 \pm 0.01]$	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	$[7.93 \pm 0.10]$	-1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	$[2.24 \pm 0.06]$	-1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	$[6.40 \pm 0.13]$	-0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02

20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.05	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		-0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	$[3.25 \pm 0.06]$	-2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		-0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

Scanning the table one notes:

a) H and H have escaped from the meteorites

b) Li is depleted in the sun, presumably by nuclear reactions in the convection zone

c) C, N, and to a lesser extent O, are also depleted in the meteorites

d) The noble gases have been lost, Ne, Ar, etc

e) Agreement is pretty good for the rest – where the element has been measured in both the sun and meteorites

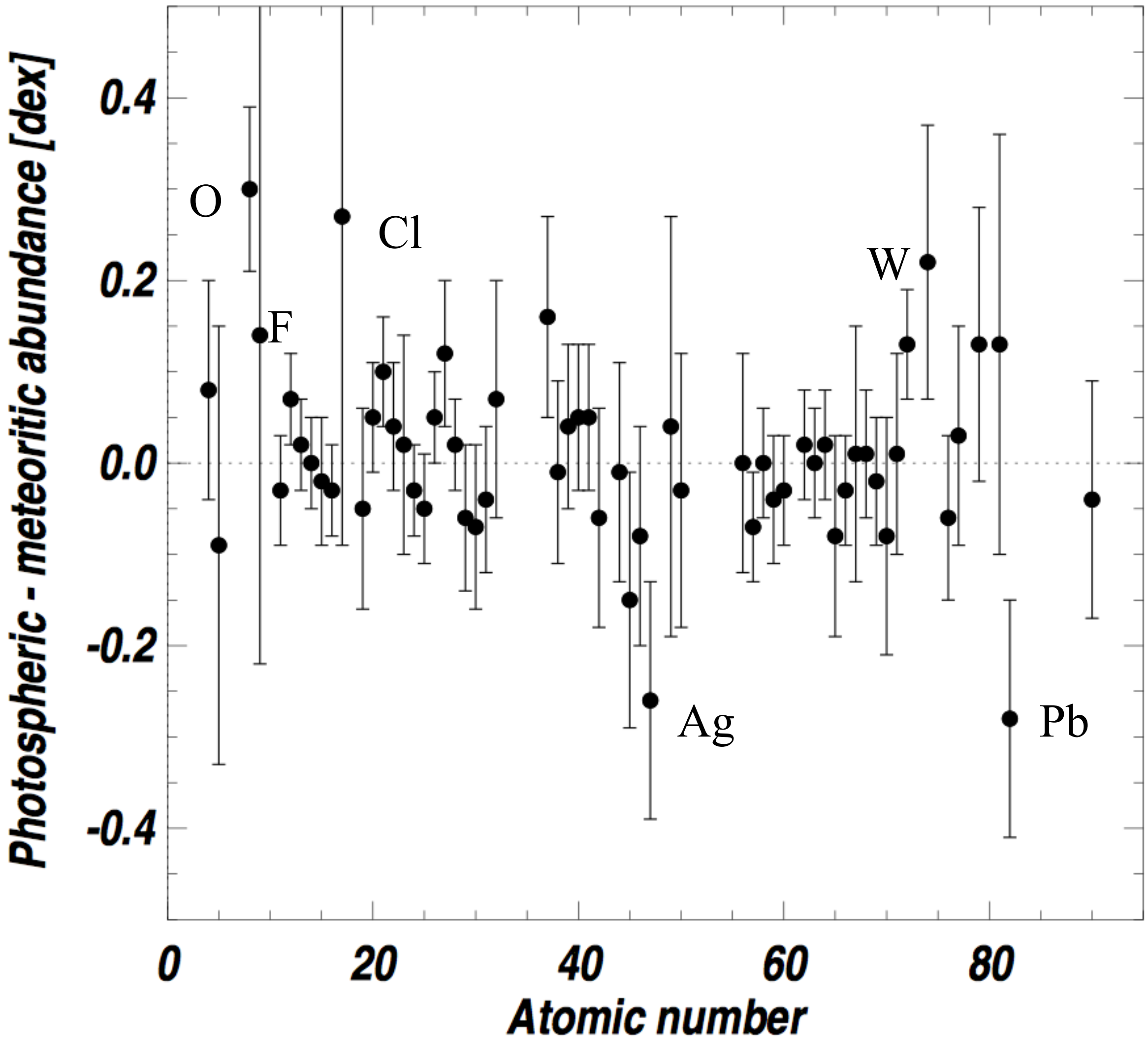


Figure 7: Difference between the logarithmic abundances determined from the solar photosphere and the CI carbonaceous chondrites as a function of atomic number. With a few exceptions the agreement is excellent. Note that due to depletion in the Sun and meteorites, the data points for Li, C, N and the noble gases fall outside the range of the figure.

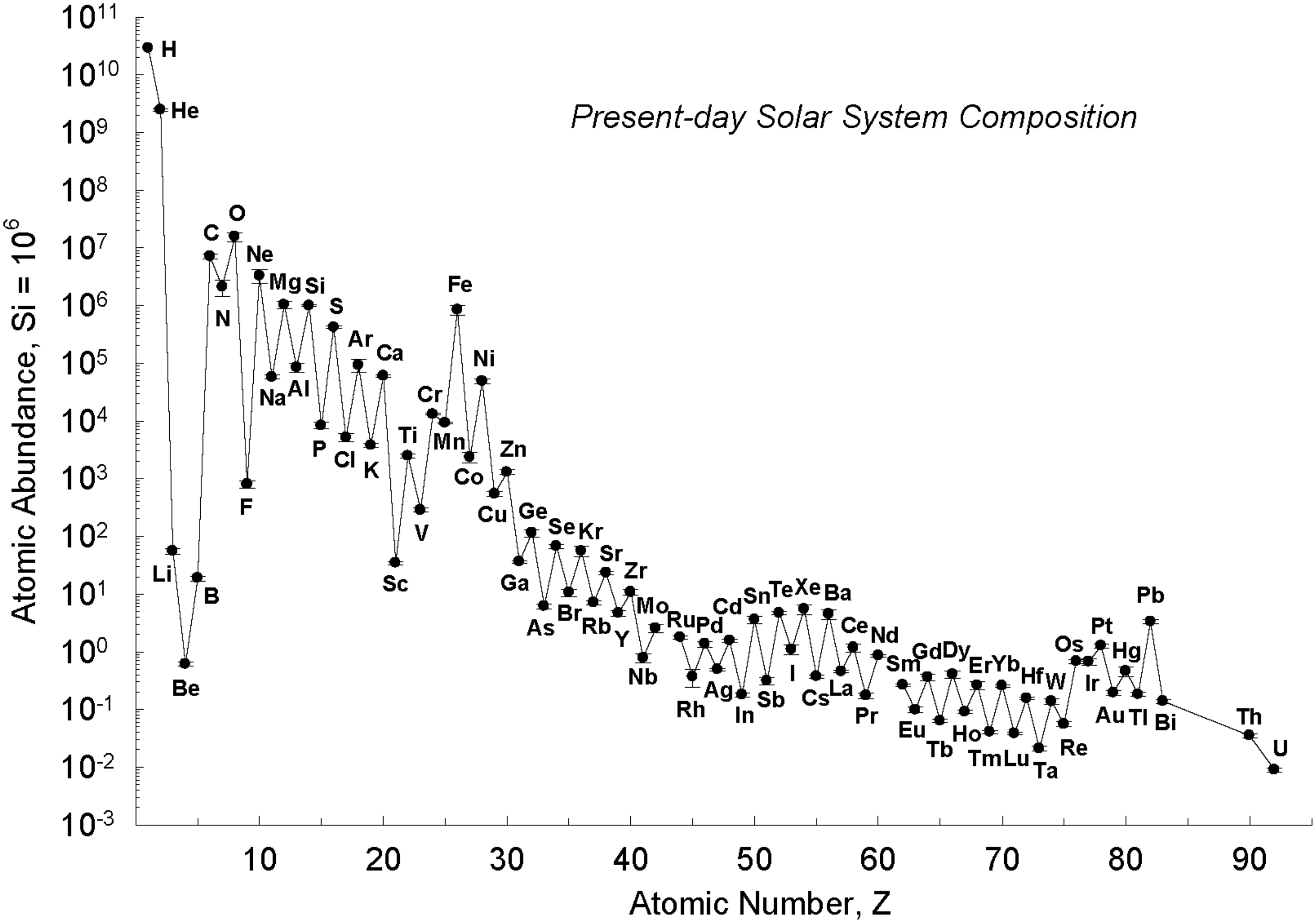
Asplund et al (2009; ARAA)

Asplund et al (2009, ARAA)

Table 4: The mass fractions of hydrogen (X), helium (Y) and metals (Z) for a number of widely-used compilations of the solar chemical composition.

Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Proto-solar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

[a] The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).


Present-day Solar System Composition
Atomic Abundance, Si = 10^6
Atomic Number, Z
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
20
30
40
50
60
70
80
90
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Isotopes with even and odd A plotted separately
Lodders (2009) Fig 7. The curve for odd Z is smoother.

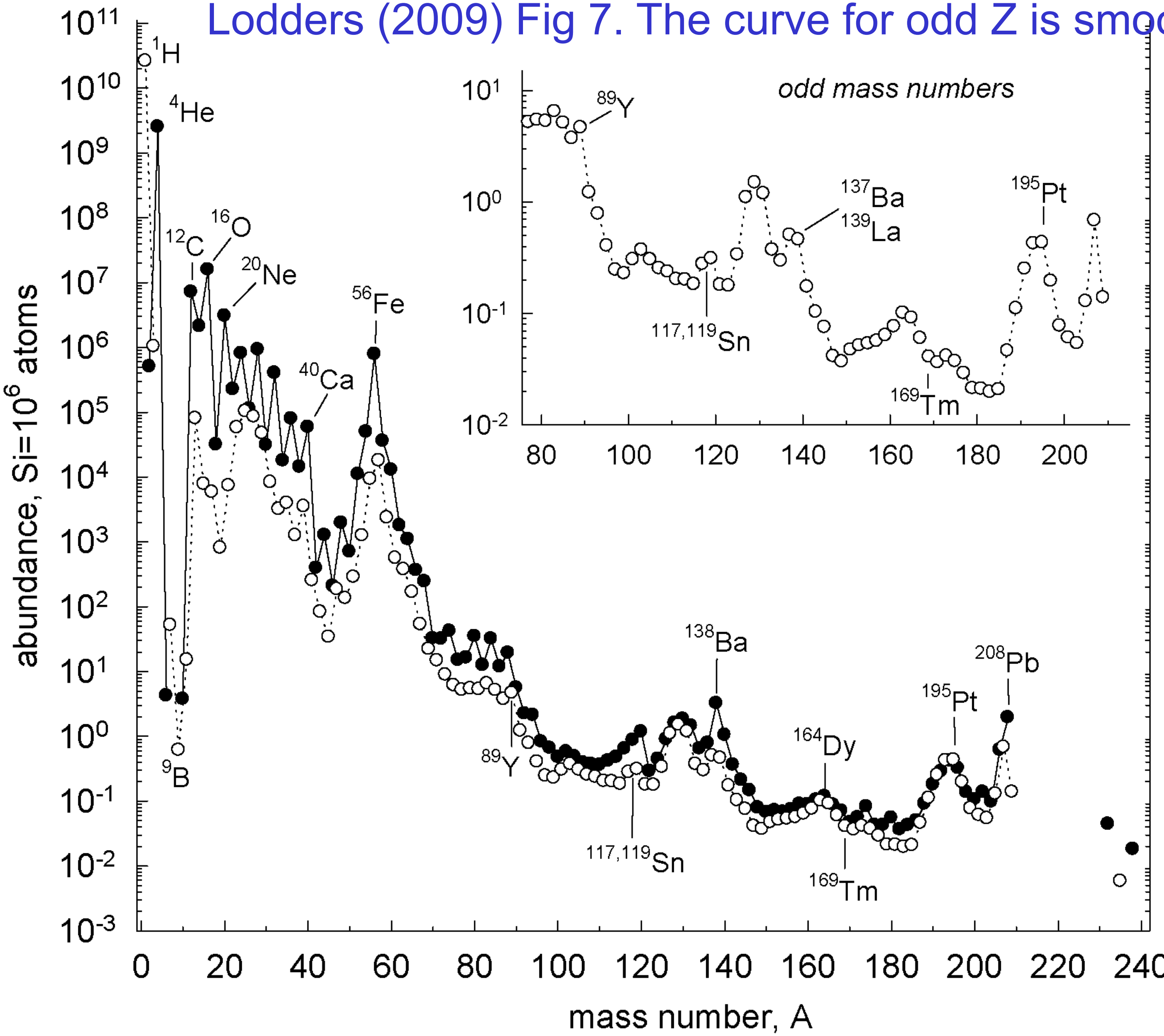


Table 3: Representative isotopic abundance fractions in the solar system. Most of the isotopic values are taken from Rosman & Taylor (1998) with updates for some elements, as discussed in Sect. 3.10.

Z	A	%	Z	A	%	Z	A	%	Z	A	%	Z	A	%
H	1	99.998	S	32	94.93	Fe	57	2.119	Kr	82	11.655	Pd	105	22.33
	2	0.002		33	0.76		58	0.282		83	11.546		106	27.33
				34	4.29					84	56.903		108	26.46
He	3	0.0166		36	0.02	Co	59	100.0		86	17.208		110	11.72
	4	99.9834												
			Cl	35	75.78	Ni	58	68.0769	Rb	85	70.844	Ag	107	51.839
Li	6	7.59		37	24.22		60	26.2231		87	29.156		109	48.161
	7	92.41					61	1.1399						
			Ar	36	84.5946		62	3.6345	Sr	84	0.5580	Cd	106	1.25
Be	9	100.0		38	15.3808		64	0.9256		86	9.8678		108	0.89
				40	0.0246					87	6.8961		110	12.49
B	10	19.9				Cu	63	69.17		88	82.6781		111	12.80
	11	80.1	K	39	93.132		65	30.83					112	24.13
				40	0.147				Y	89	100.0		113	12.22
C	12	98.8938		41	6.721	Zn	64	48.63					114	28.73
	13	1.1062					66	27.90	Zr	90	51.45		116	7.49
			Ca	40	96.941		67	4.10		91	11.22			
N	14	99.771		42	0.647		68	18.75		92	17.15	In	113	4.29
	15	0.229		43	0.135		70	0.62		94	17.38		115	95.71
				44	2.086					96	2.80			
O	16	99.7621		46	0.004	Ga	69	60.108				Sn	112	0.97
	17	0.0379		48	0.187		71	39.892	Nb	93	100.0		114	0.66
	18	0.2000											115	0.34
			Sc	45	100.0	Ge	70	20.84	Mo	92	14.525		116	14.54
F	19	100.0					72	27.54		94	9.151		117	7.68
			Ti	46	8.25		73	7.73		95	15.838		118	24.22
Ne	20	92.9431		47	7.44		74	36.28		96	16.672		119	8.59
	21	0.2228		48	73.72		76	7.61		97	9.599		120	32.58
	22	6.8341		49	5.41					98	24.391		122	4.63
				50	5.18	As	75	100.0		100	9.824		124	5.79

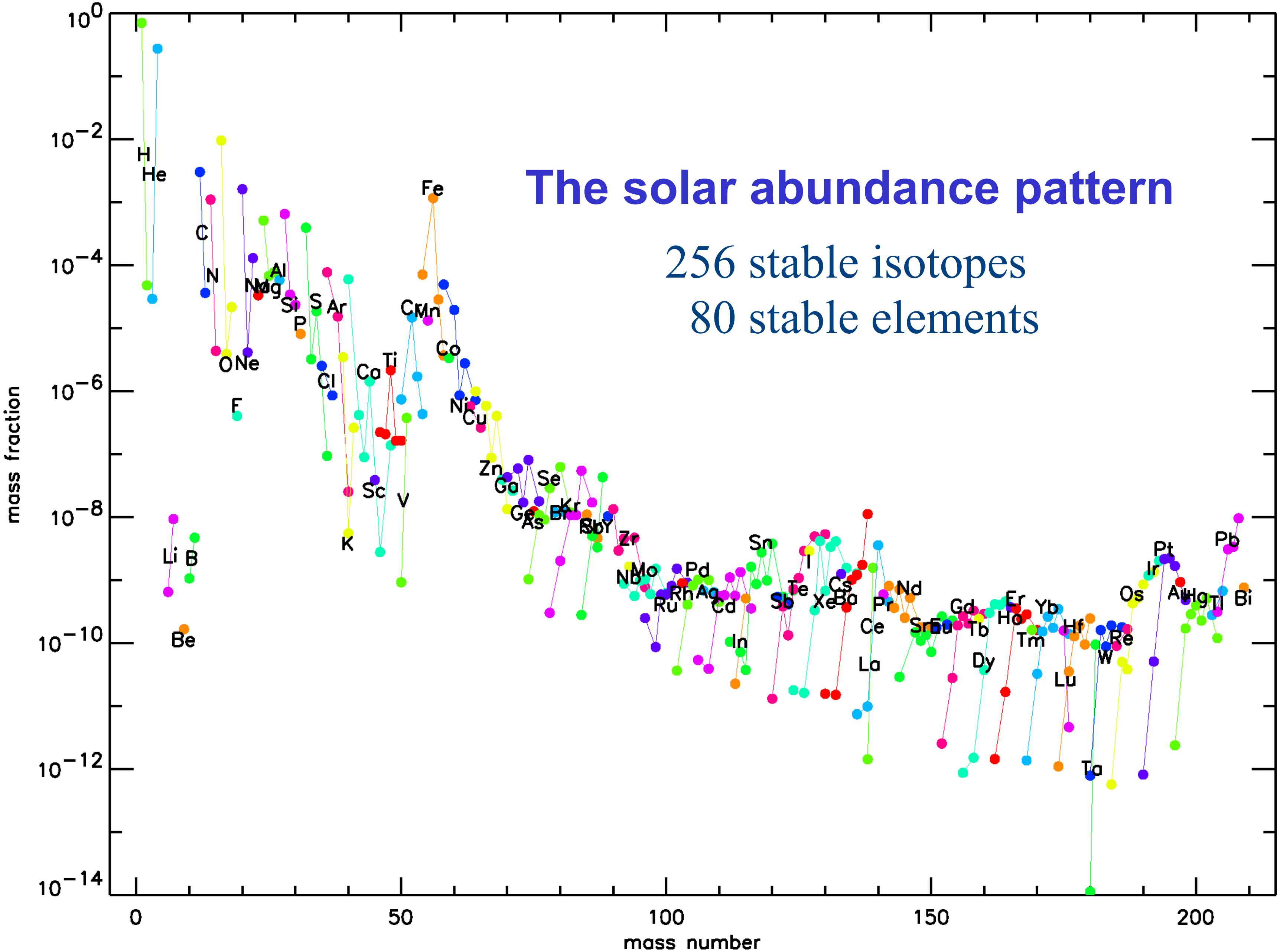
1 part in 1000 would be a big isotopic anomaly for most elements.

Lodders (2009) translated into mass fractions – see class website for more

h1	7.11E-01	si28	7.02E-04	ti47	2.34E-07	zn66	6.48E-07
h2	2.75E-05	si29	3.69E-05	ti48	2.37E-06	zn67	9.67E-08
he3	3.42E-05	si30	2.51E-05	ti49	1.78E-07	zn68	4.49E-07
he4	2.73E-01	p31	6.99E-06	ti50	1.74E-07	zn70	1.52E-08
li6	6.90E-10	s32	3.48E-04	v50	9.71E-10	ga69	4.12E-08
li7	9.80E-09	s33	2.83E-06	v51	3.95E-07	ga71	2.81E-08
be9	1.49E-10	s34	1.64E-05	cr50	7.72E-07	ge70	4.63E-08
b10	1.01E-09	s36	7.00E-08	cr52	1.54E-05	ge72	6.20E-08
b11	4.51E-09	cl35	3.72E-06	cr53	1.79E-06	ge73	1.75E-08
c12	2.32E-03	cl37	1.25E-06	cr54	4.54E-07	ge74	8.28E-08
c13	2.82E-05	ar36	7.67E-05	mn55	1.37E-05	ge76	1.76E-08
n14	8.05E-04	ar38	1.47E-05	fe54	7.27E-05	as75	1.24E-08
n15	3.17E-06	ar40	2.42E-08	fe56	1.18E-03	se74	1.20E-09
o16	6.83E-03	k39	3.71E-06	fe57	2.78E-05	se76	1.30E-08
o17	2.70E-06	k40	5.99E-09	fe58	3.76E-06	se77	1.07E-08
o18	1.54E-05	k41	2.81E-07	co59	3.76E-06	se78	3.40E-08
f19	4.15E-07	ca40	6.36E-05	ni58	5.26E-05	se80	7.27E-08
ne20	1.66E-03	ca42	4.45E-07	ni60	2.09E-05	se82	1.31E-08
ne21	4.18E-06	ca43	9.52E-08	ni61	9.26E-07	br79	1.16E-08
ne22	1.34E-04	ca44	1.50E-06	ni62	3.00E-06	br81	1.16E-08
na23	3.61E-05	ca46	3.01E-09	ni64	7.89E-07	Etc.	
mg24	5.28E-04	ca48	1.47E-07	cu63	6.40E-07		
mg25	6.97E-05	sc45	4.21E-08	cu65	2.94E-07		
mg26	7.97E-05	ti46	2.55E-07	zn64	1.09E-06.		

The solar abundance pattern

256 stable isotopes
80 stable elements



Abundances outside the solar neighborhood ?

Abundances outside the solar system through:

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

Asplund et al (2009)

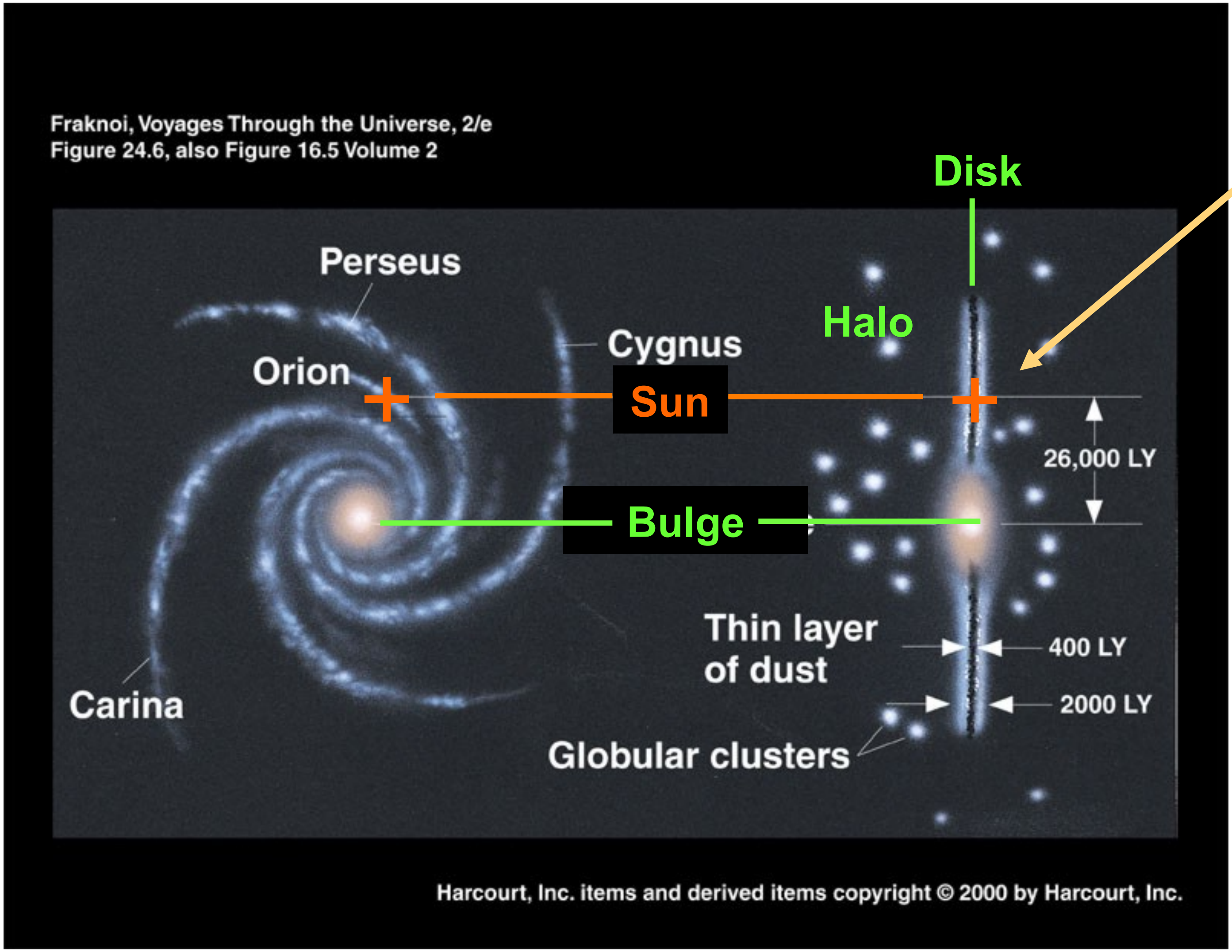
Table 5: Comparison of the proto-solar abundances from the present work and Grevesse & Sauval (1998) with those in nearby B stars and H II regions. The solar values given here include the effects of diffusion (Turcotte & Wimmer-Schweingruber 2002) as discussed in Sect. 3.11. The H II numbers include the estimated elemental fractions tied up in dust; the dust corrections for Mg, Si and Fe are very large and thus too uncertain to provide meaningful values here. Also given in the last column is the predicted Galactic chemical enrichment (GCE) over the past 4.56 Gyr.

Elem.	Sun[a]	Sun[b]	B stars[c]	H II[d]	GCE[e]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.02	10.96 ± 0.01	0.01
C	8.56 ± 0.06	8.47 ± 0.05	8.35 ± 0.03	8.66 ± 0.06	0.06
N	7.96 ± 0.06	7.87 ± 0.05	7.76 ± 0.05	7.85 ± 0.06	0.08
O	8.87 ± 0.06	8.73 ± 0.05	8.76 ± 0.03	8.80 ± 0.04	0.04
Ne	8.12 ± 0.06	7.97 ± 0.10	8.08 ± 0.03	8.00 ± 0.08	0.04
Mg	7.62 ± 0.05	7.64 ± 0.04	7.56 ± 0.05		0.04
Si	7.59 ± 0.05	7.55 ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± 0.11	7.16 ± 0.03	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.54 ± 0.04	7.44 ± 0.04		0.14

[a] Grevesse & Sauval (1998) [b] Present work [c] Przybilla, Nieva & Butler (2008), Morel et al. (2006), Lanz et al. (2008) [d] Esteban et al. (2005, 2004), García-Rojas & Esteban (2007) [e] Chiappini, Romano & Matteucci (2003).

[b]Metals increased by 0.04 dex to account for diffusio

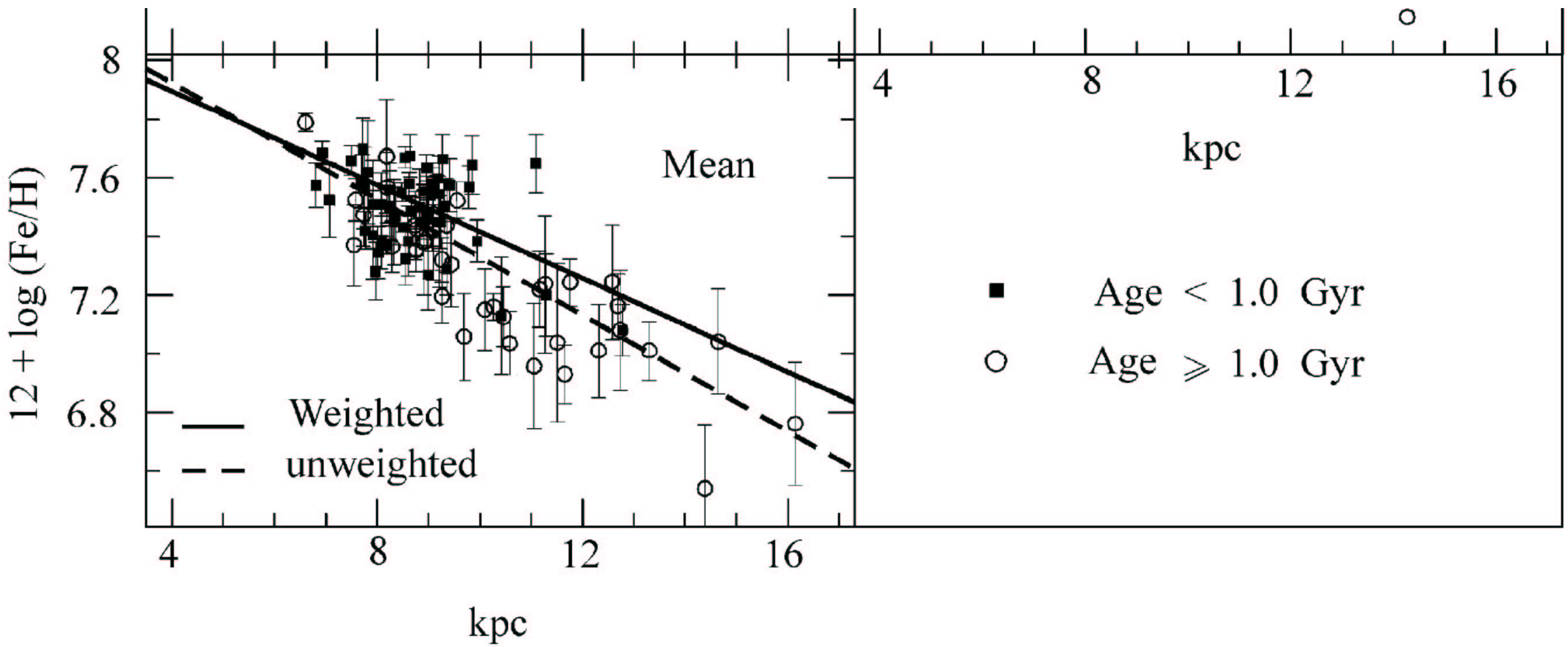
The solar abundance distribution - should reflect the composition of the ISM when and where the sun was born



solar abundances:

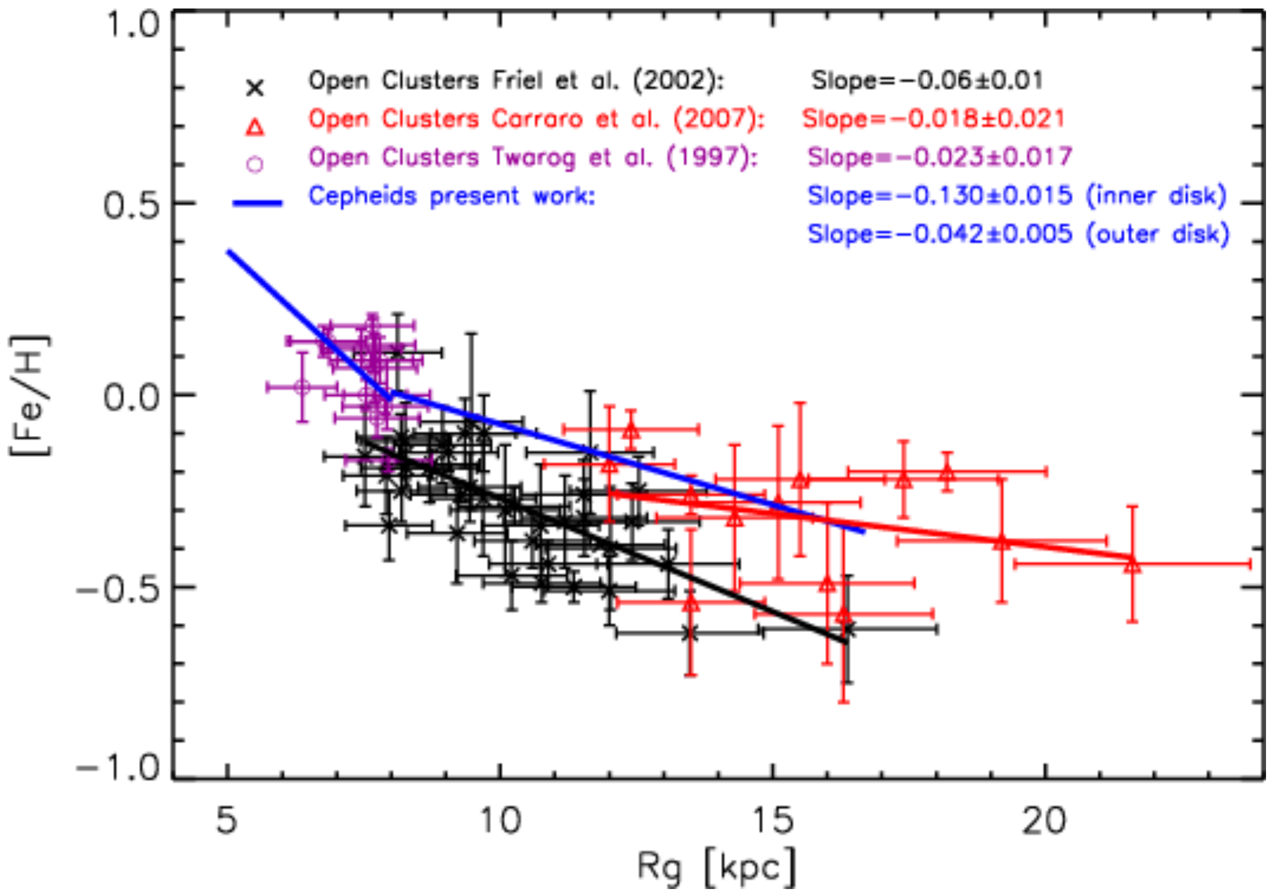
Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it's formation

Observed metallicity gradient in Galactic disk:



Many other works on this subject
See e.g. Luck et al, 132, 902, AJ (2006)
radial Fe gradient = - 0.068 +_ 0.003 dex/kpc
from 54 Cepheids

Hou et al. Chin. J. Astron. Astrophys. 2 (2002) 17
data from 89 open clusters
radial iron gradient = -0.099 +_ 0.008 dex/kpc



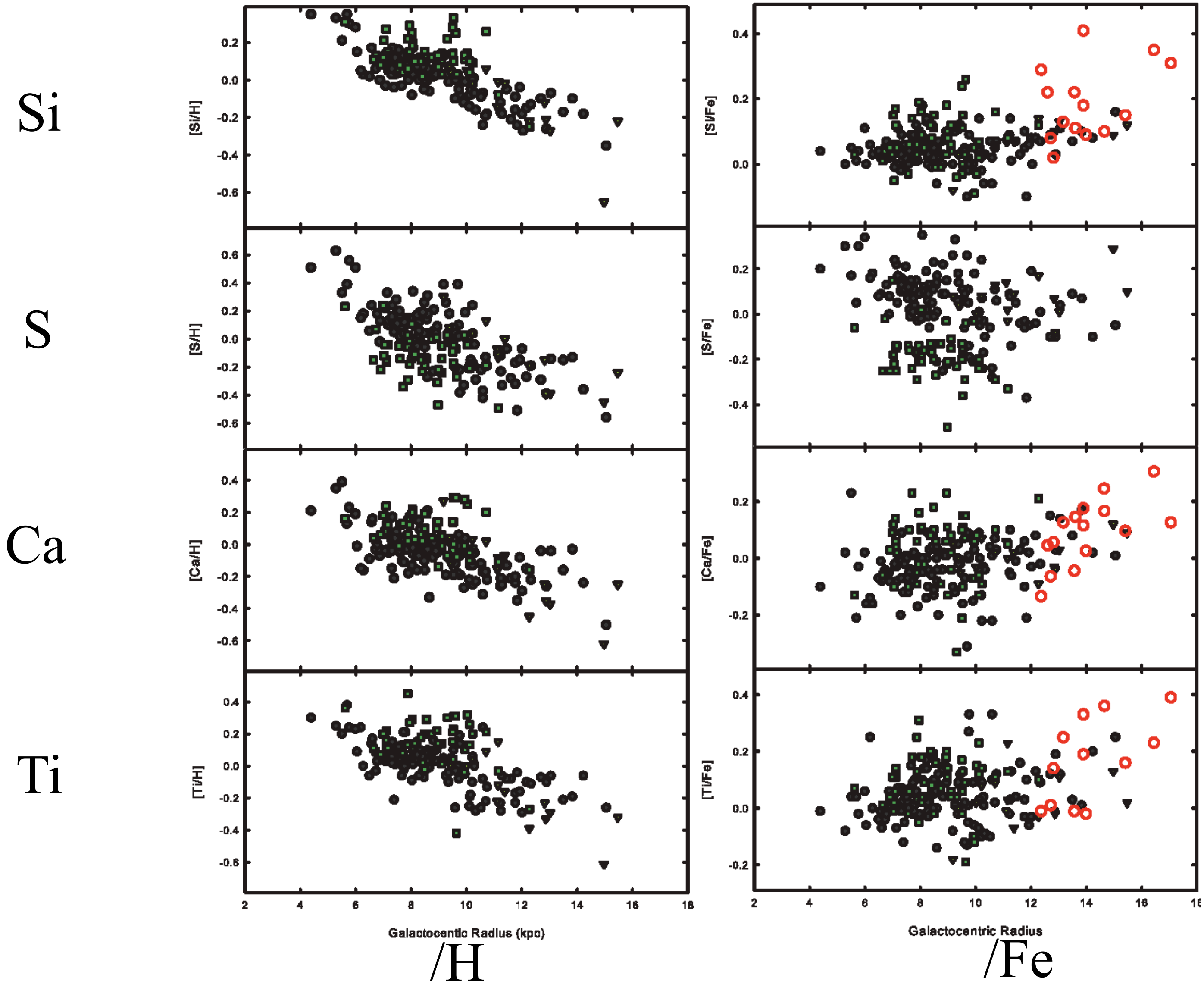
but see also Najarro et al (ApJ, 691, 1816 (2009)) who find solar iron near the Galactic center.

From Pedicelli et al. (A&A, 504, 81, (2009)) studied abundances in Cepheid variables. Tabulated data from others for open clusters.

For entire region 5 – 17 kpc, Fe gradient is -0.051+- 0.004 dex/kpc but it is ~3 times steeper in the inner galaxy. Spans a factor of 3 in Fe abundance.

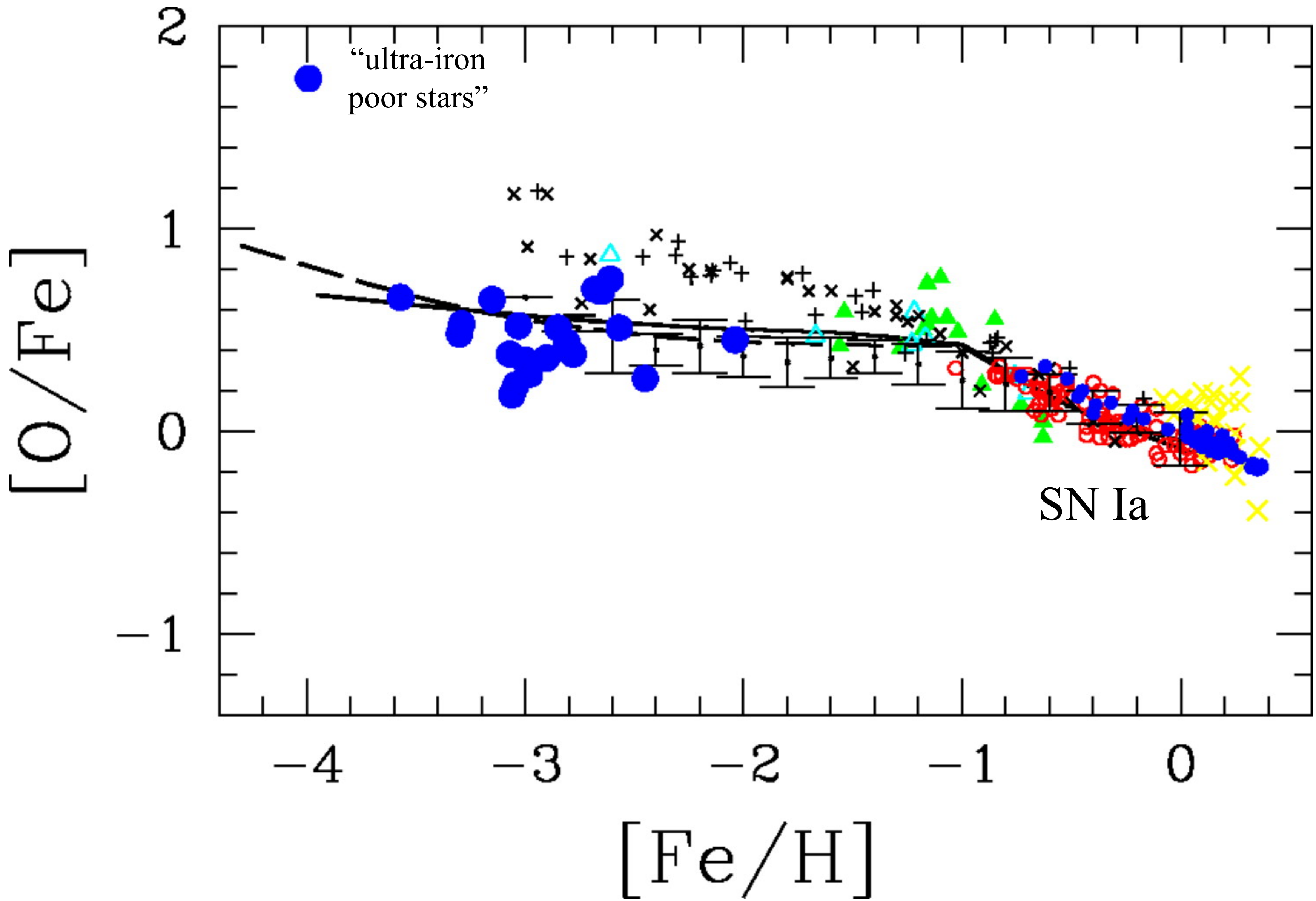
Abundance Patterns with Radius

From Luck et al.

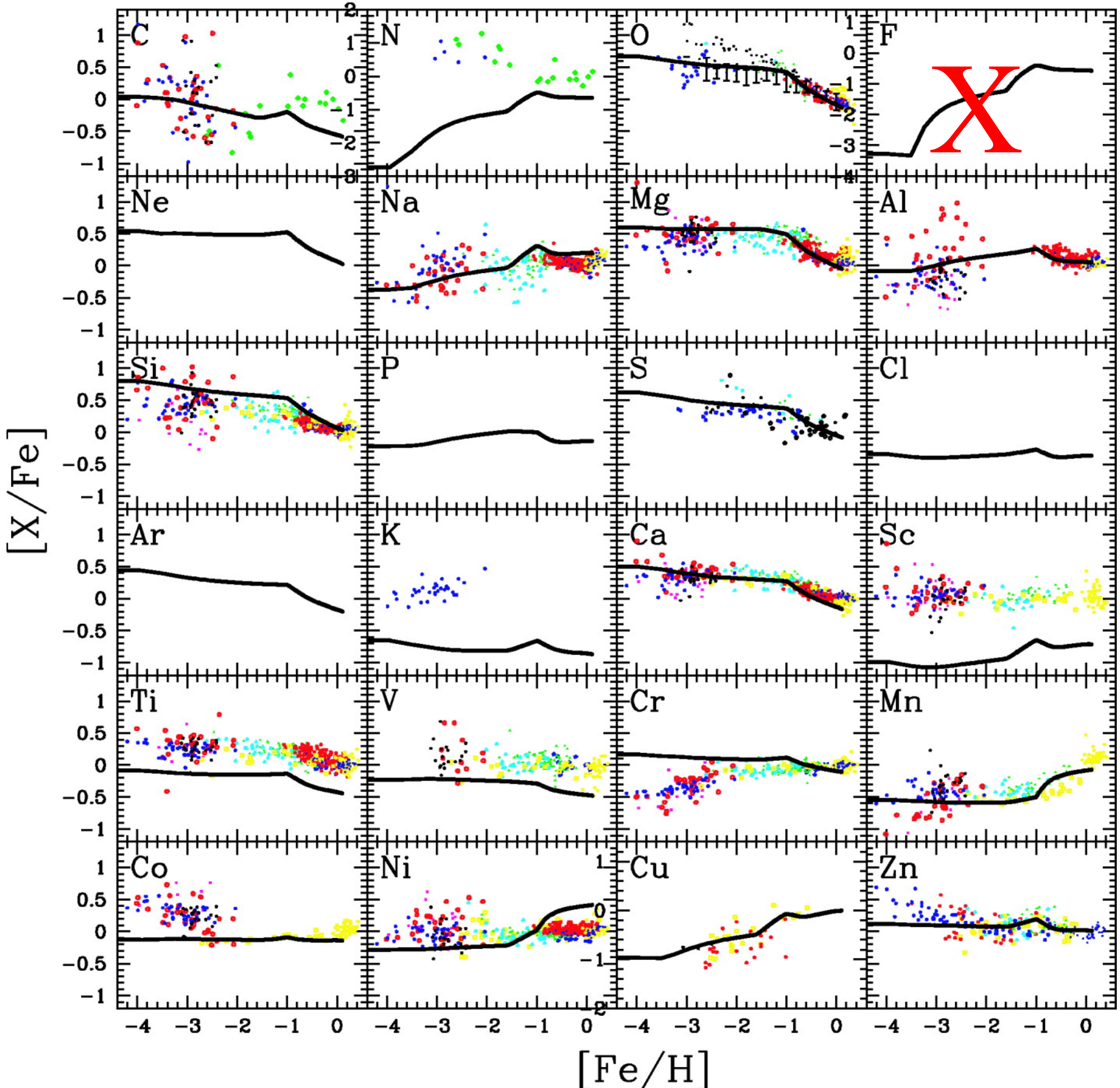


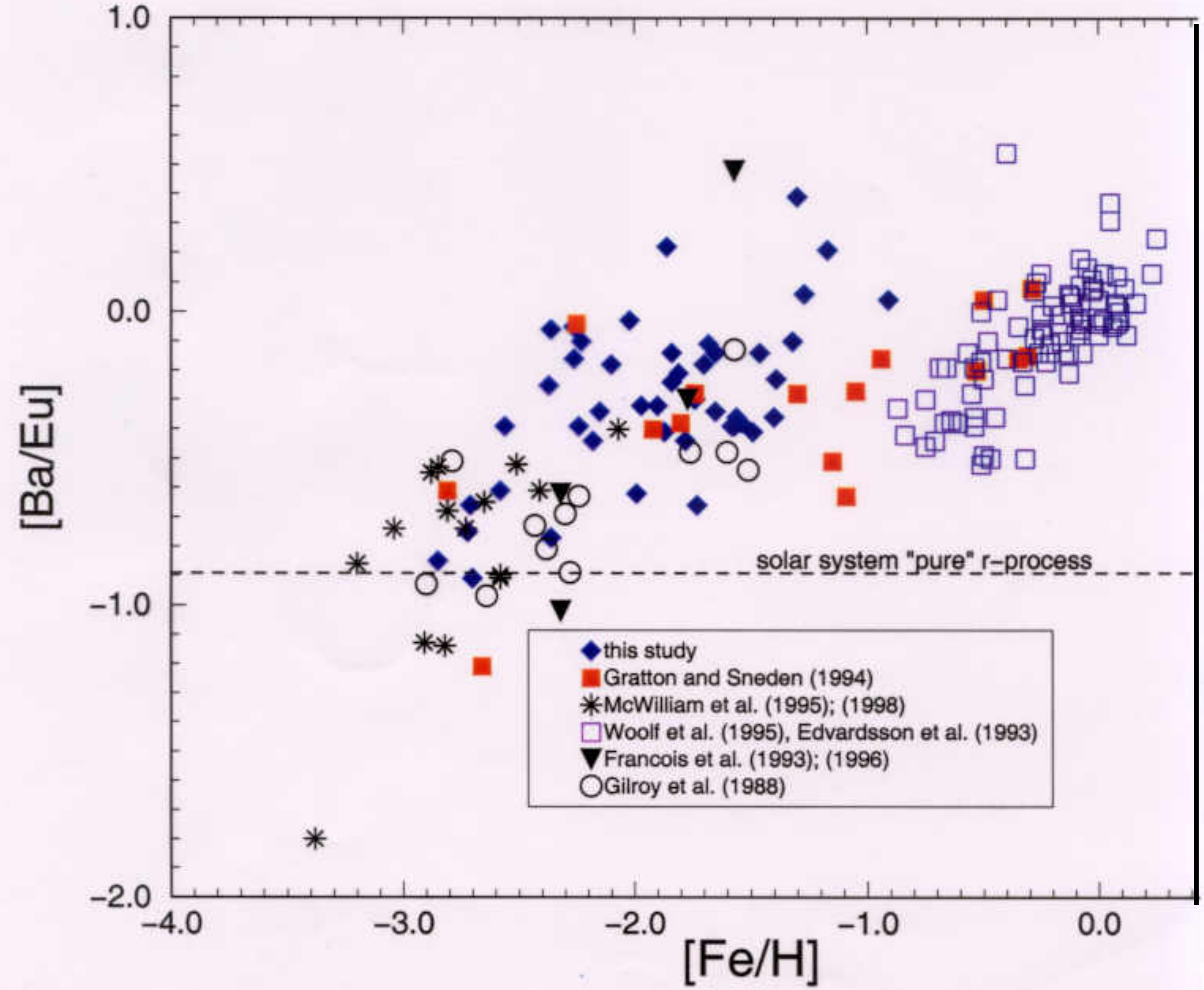
Variation with metallicity

Kobayashi et al, *ApJ*, **653**, 1145, (2006)



Kobayashi et al, *ApJ*, **653**, 1145, (2006)





1.0
0.0
−1.0
−2.0
−4.0
−3.0
−2.0
−1.0
0.0
[Ba/Eu]
[Fe/H]
solar system "pure" r−process
this study
Gratton and Sneden (1994)
McWilliam et al. (1995); (1998)
Woolf et al. (1995), Edvardsson et al. (1993)
Francois et al. (1993); (1996)
Gilroy et al. (1988)

CS 22892-052

Sneden et al, ApJ, 591, 936 (2003)

[Fe/H] ~ -3.1

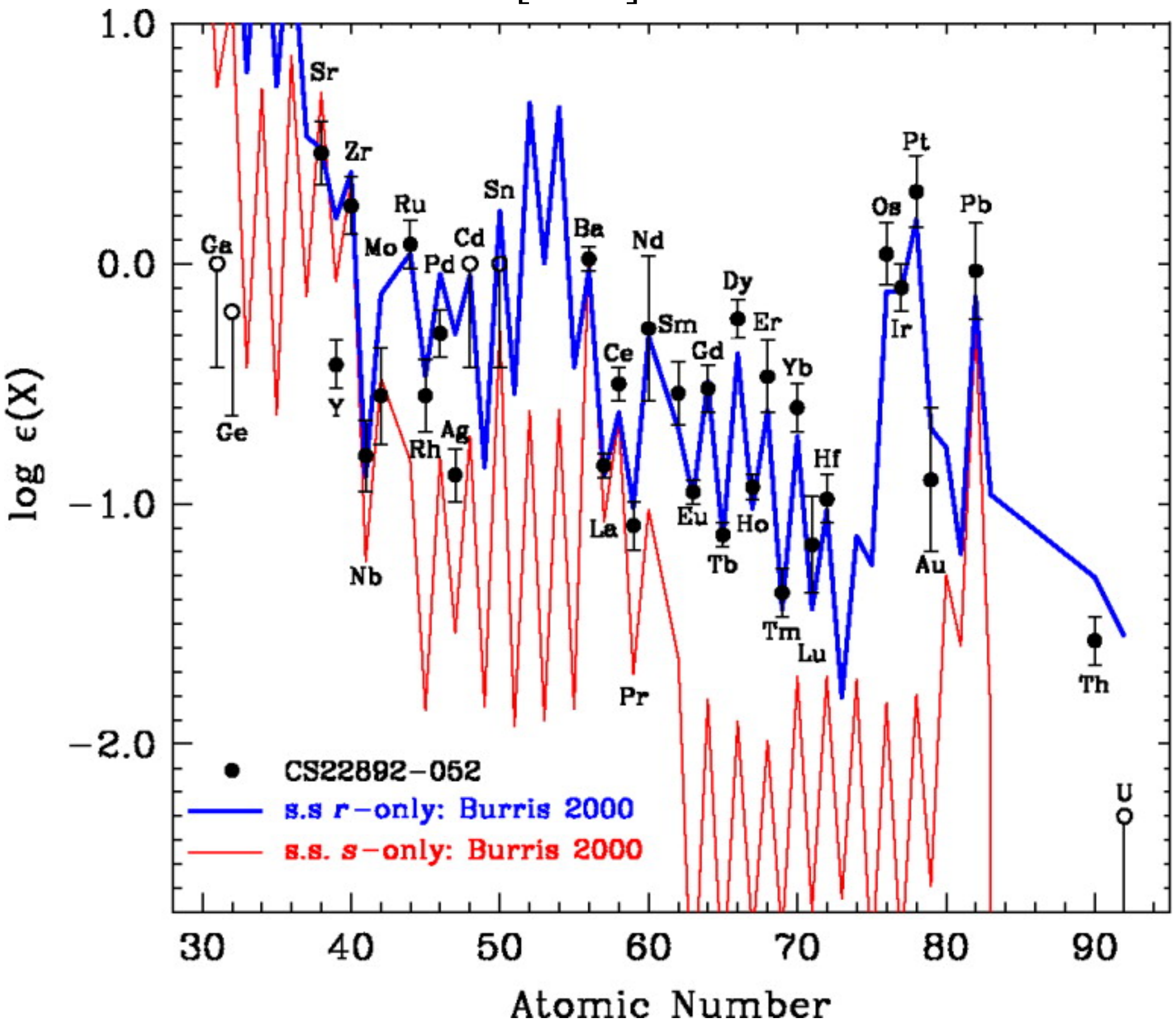


TABLE 1
ELEMENTAL ABUNDANCES IN DLA-B/FJ0812+32

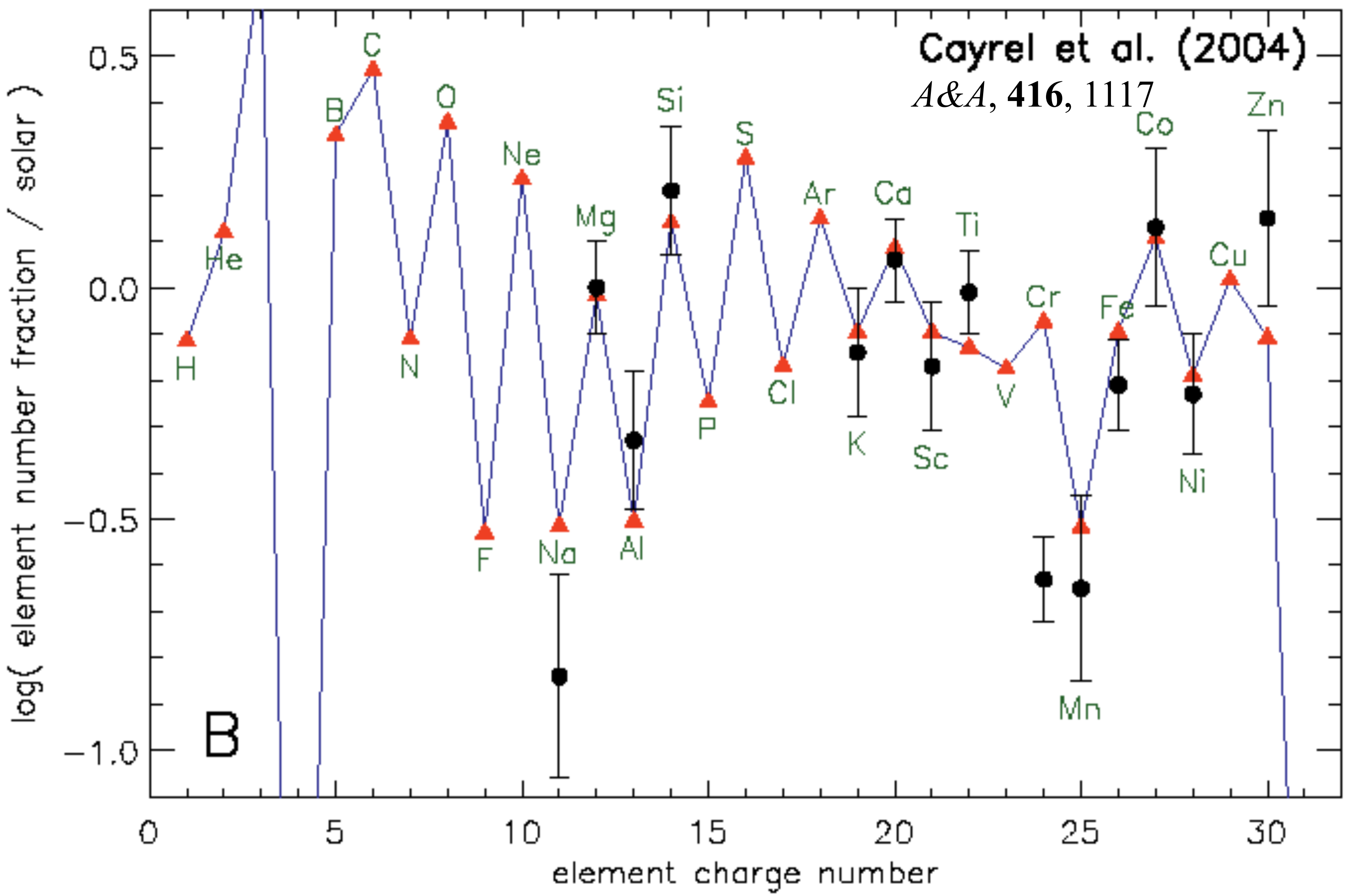
El (1)	[X/H][a] (2)	σ_N[b] (3)	δ_{DC} (90% c.l.)[c] (4)	[X/S][d] (5)
B	−0.57	0.085	0.1 (0.05)	+0.3
N	>−2.24	0.058	0.0 (0.1)	>−1.47
O	−0.54	0.101	0.1 (0.05)	+0.33
Mg	−0.78	0.053	0.3 (0.1)	+0.29
Al	>−2.00	0.054	>0.5	>−0.73
Si	−0.91	0.053	0.3 (0.1)	+0.16
P	<−1.06	0.000	<0.3	<+0.01
S	−0.87	0.050	0.1 (0.05)	0.0
Cl	−1.55	0.000	>0.0	>−0.78
Ti	−1.87	0.112	>0.7	>−0.4
Cr	−1.61	0.032	>0.7	>−0.14
Mn	<−1.85	0.000	0.7 (0.1)	<−0.38
Fe	−1.69	0.017	>0.7	>−0.22
Co	<−1.48	0.000	>0.7	>−0.01
Ni	−1.73	0.007	>0.7	>−0.26
Cu	<−1.11	0.000	>0.7	<+0.36
Zn	−0.91	0.022	0.2 (0.1)	+0.06
Ga	<−1.45	0.000	0.7 (0.1)	<+0.02
Ge	−0.92	0.035	0.3 (0.1)	+0.15
As	<0.26	0.000	0.0	<+1.03
Kr	<−0.44	0.000	0.0 (0.1)	<+0.33
Sn	<−0.27	0.000	0.0 (0.1)	<+0.5
Pb	<−0.10	0.000	0.0 (0.1)	<+0.67

NOTE.—Measurements taken by PHW03.
[a] Gas-phase abundance on a logarithmic scale relative to solar, where $N(\text{H I}) = 10^{21.35}$ cm^{-2}.
[b] Statistical error on gas-phase abundances.
[c] Dust corrections and uncertainties estimated from depletions patterns observed in Galactic gas.
[d] Dust-corrected abundances on a logarithmic scale relative to S.

Abundances in a damped Ly-alpha system at redshift 2.626. 20 elements.

Metallicity ~ 1/3 solar

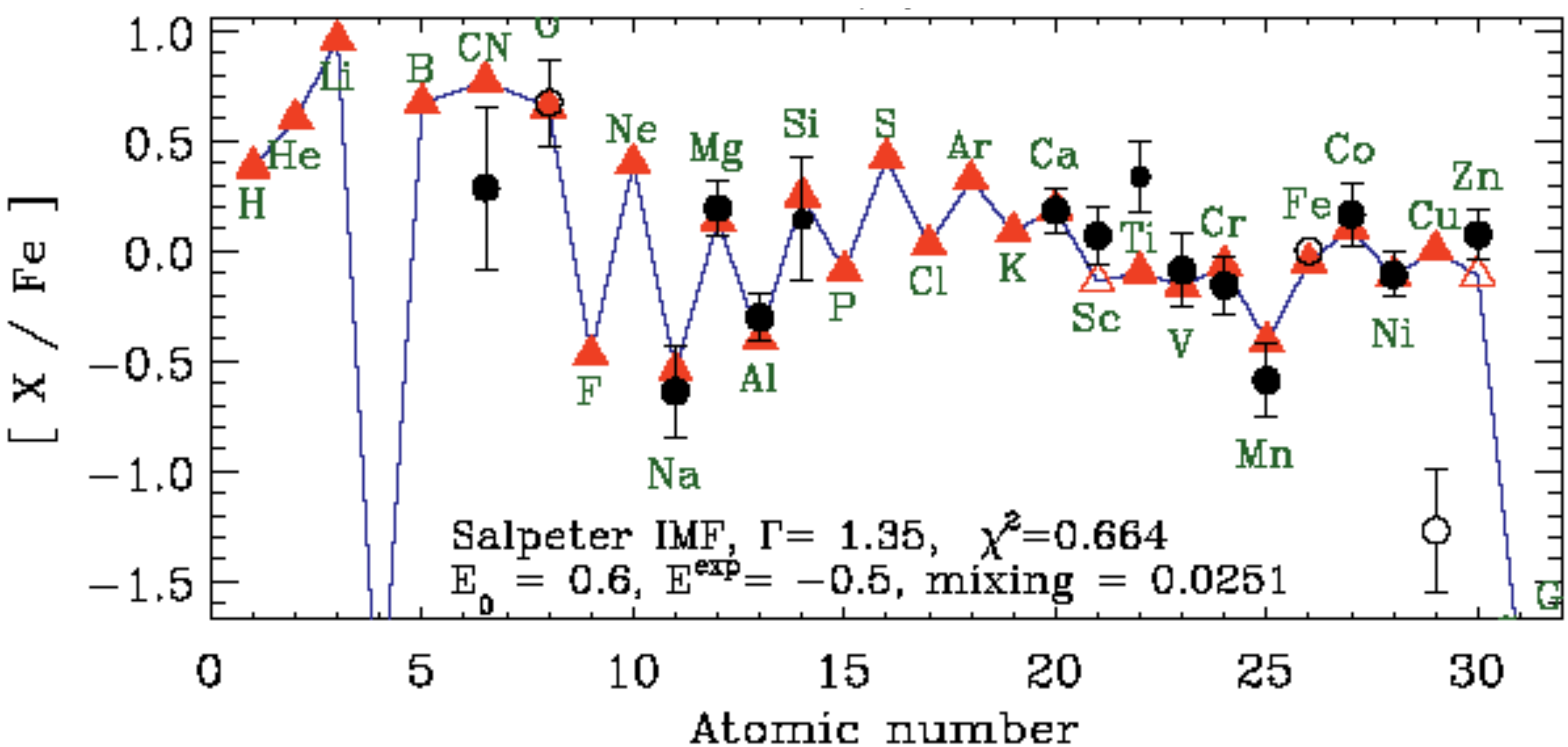
Fenner, Prochaska, and Gibson, ApJ, 606, 116, (2004)



Best fit, 0.9 B, Γ= -1.35, mix = 0.0158, 10 - 100 solar masses (Heger and Woosley 2010)

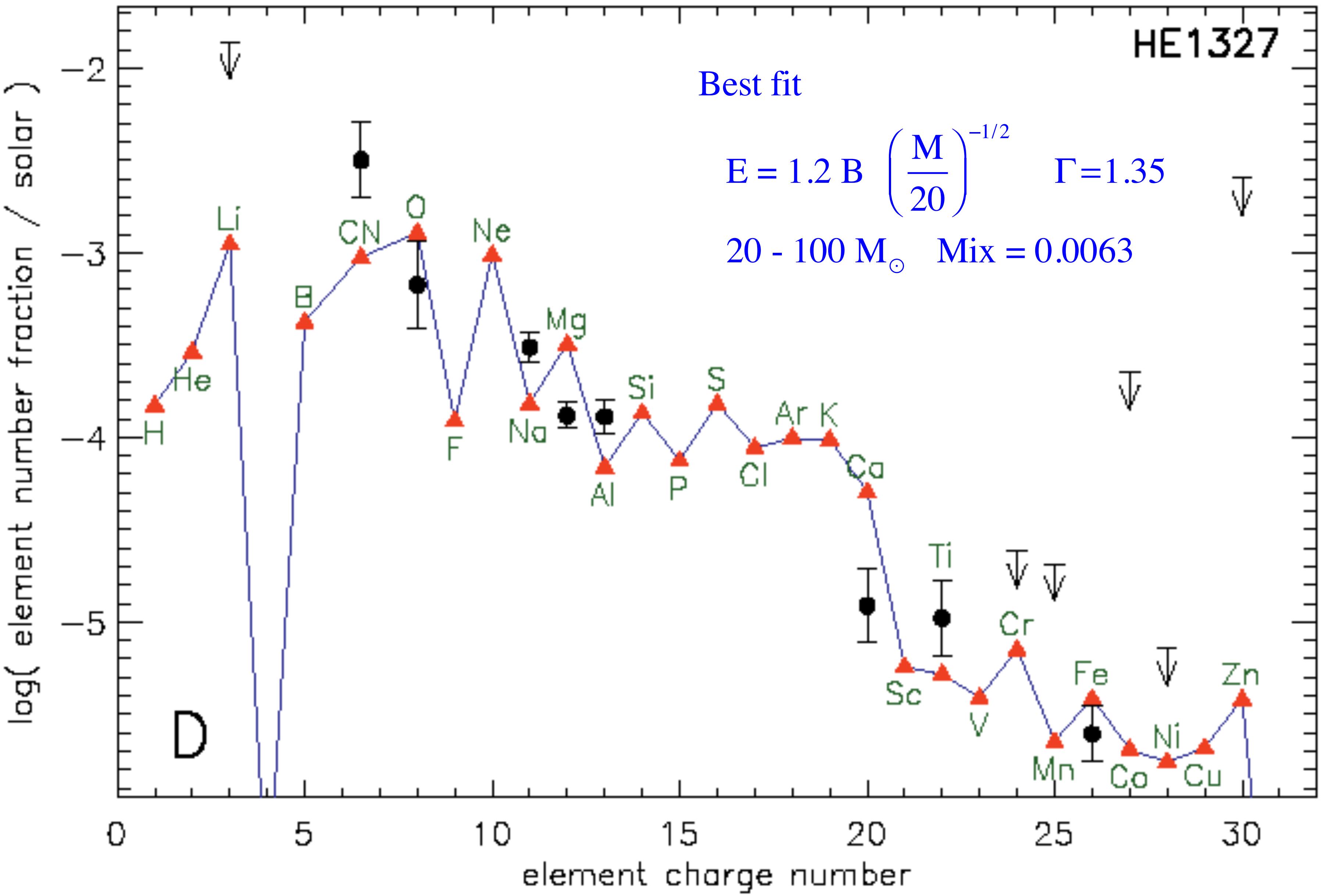
Data are for 35 giants with -4.1 < [Fe/H] < -2.7

Integrated yield of 126 masses 11 - 100 $M_\odot$ (1200 SN models), with Z= 0, Heger and Woosley (2008, ApJ 2010) compared with low Z observations by Lai et al (*ApJ*, 681, 1524, (2008)). Odd-even effect due to sensitivity of neutron excess to metallicity and secondary nature of the s-process.

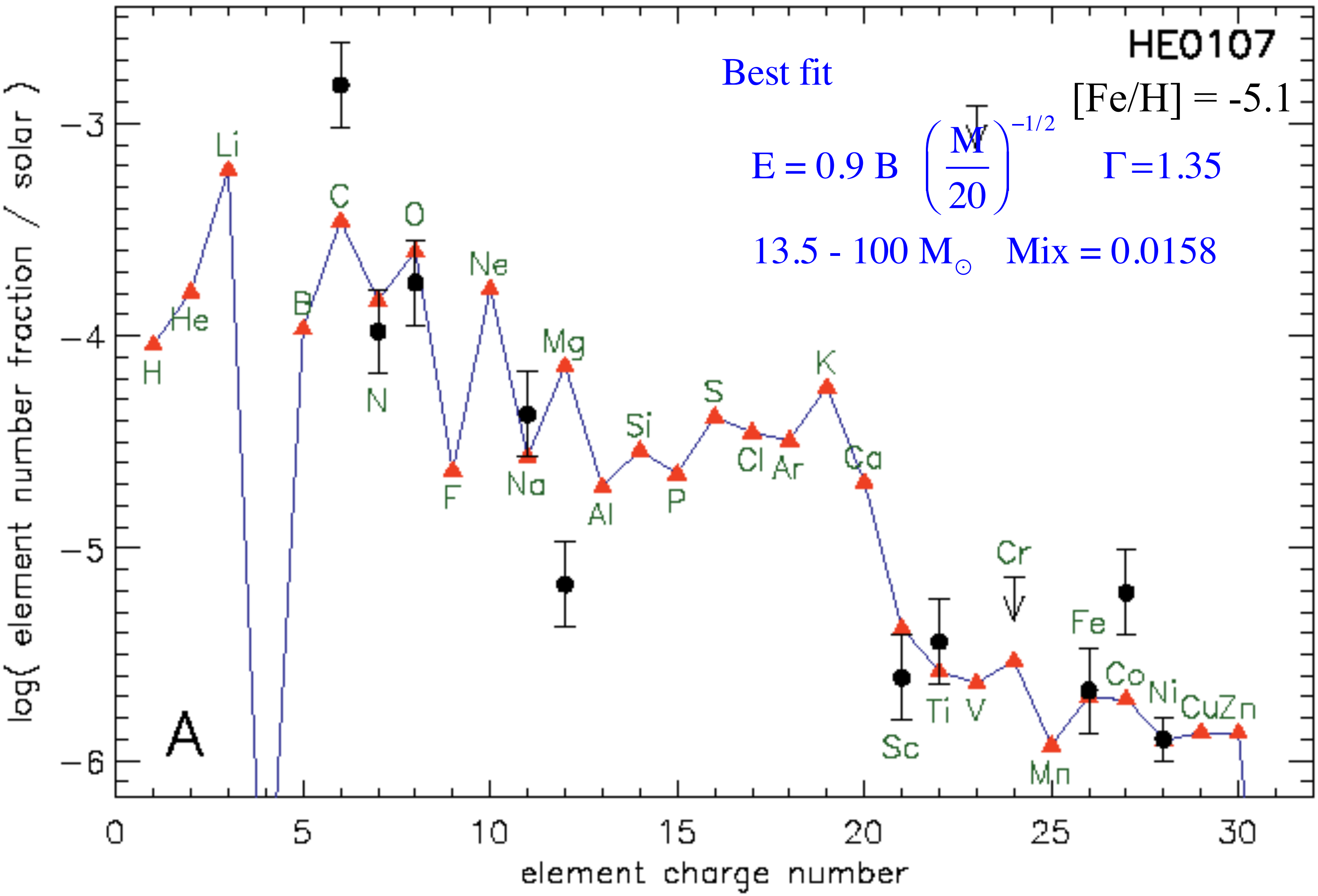


28 metal poor stars in the Milky Way Galaxy
-4 < [Fe/H] < -2; 13 are < -.26

Frebel et al, *ApJ*, **638**, 17, (2006)
Aoki et al, *ApJ*, **639**, 896, (2006)



Christlieb et al 2007



Abundances of cosmic rays arriving at Earth

http://www.srl.caltech.edu/ACE/

Advanced Composition Explorer (1997 - 1998)