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Lecture V: Abundance Evolution of Galaxies and the Cosmos

- ☐ **Stellar Nucleosynthesis as a Function of Mass and Timescale**
 - ☐ the “observed” abundance history
 - ☐ constraints on early stellar populations

**Summer School in Nuclear Physics
Laurence Berkeley National Laboratory
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Abundances: Tracers of the Star Formation Histories of Galaxies

To the extent that the history of the Galaxy is to be found written in the compositions of its components (stars, gas, ..), its abundance history can be used to probe its dynamical and star formation history.

How might we unravel this history?

Since distinctive abundance patterns are characteristic of nucleosynthesis occurring in stars of different masses (and **lifetimes), constraints on the nucleosynthesis and early star formation histories of the Cosmos may be contained in the spectra of halo population stars, galaxies, and QSO absorption line systems.**

How might we unravel this history?

Since distinctive abundance patterns are characteristic of nucleosynthesis occurring in stars of different masses (and lifetimes), constraints on early star formation and nucleosynthesis histories may be contained in the spectra of halo population stars, galaxies, and QSO absorption line systems.

Critical Issues

- ☐ What was the primordial composition of the Galaxy?
- ☐ What was the nature of the first star(s)?
- ☐ Were the earliest stars responsible for reionization?
- ☐ What were the star formation histories of the halo, bulge, and disk of our Galaxy?
- ☐ To what extent do we expect other like galaxies to behave in like manner?
- ☐ Do “normal stars” (stellar populations) suffice to explain all observed abundance features in our Galaxy and elsewhere?

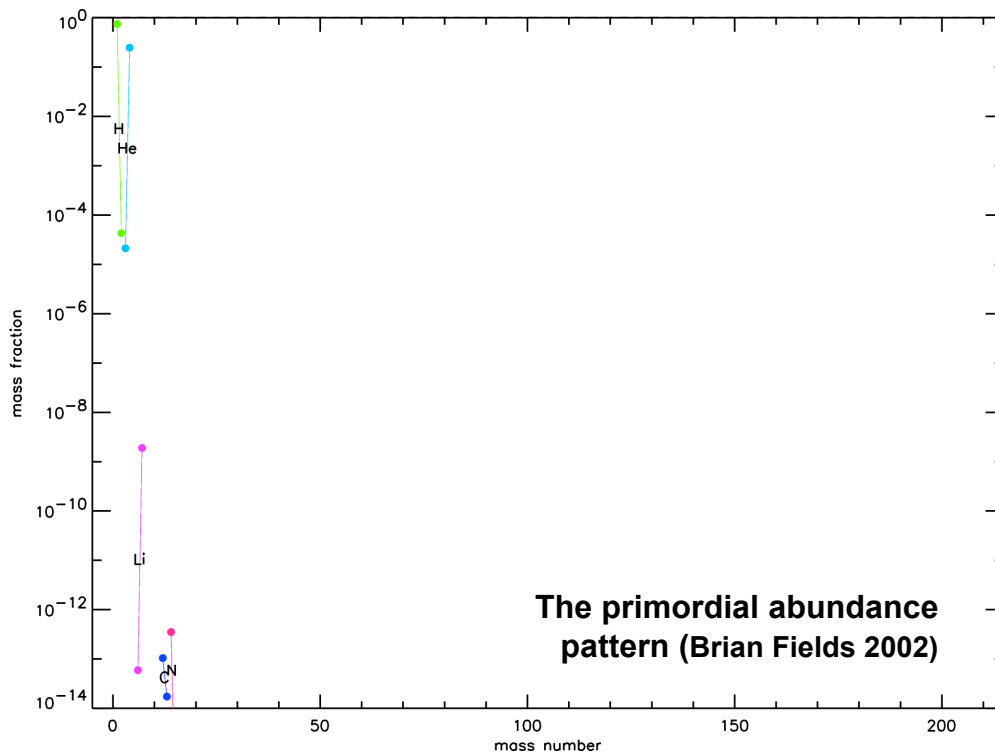
Some Critical Issues

- ☐ Do “normal stars” (stellar populations) suffice to explain all observed abundance features in our Galaxy and elsewhere?
- ☐ What constitutes a normal stellar population?
 - ☐ Salpeter (1959) initial mass function (IMF)
 - ☐ stellar mass range $0.5 \leq M \leq 300 M_{\odot}$
 - ☐ standard stellar and supernova synthesis

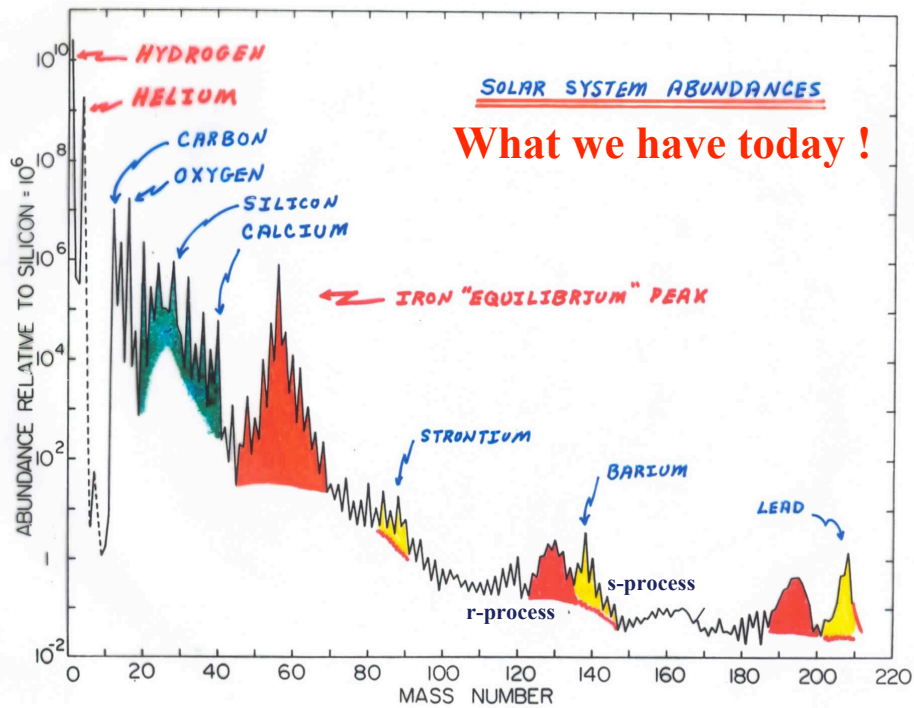
Nucleosynthesis and the “Cosmic” Abundances of the Elements

- ☐ The Universe emerged from the cosmological Big Bang with a composition consisting of hydrogen, helium, ^2D , ^3He , and ^7Li .
- ☐ Galaxies and the first stars within them were born with this primordial composition.
- ☐ The heavy elements with which we are familiar - from carbon to iron to uranium - are the products of nuclear processes associated with the evolution of stars and supernovae of Types Ia and II.

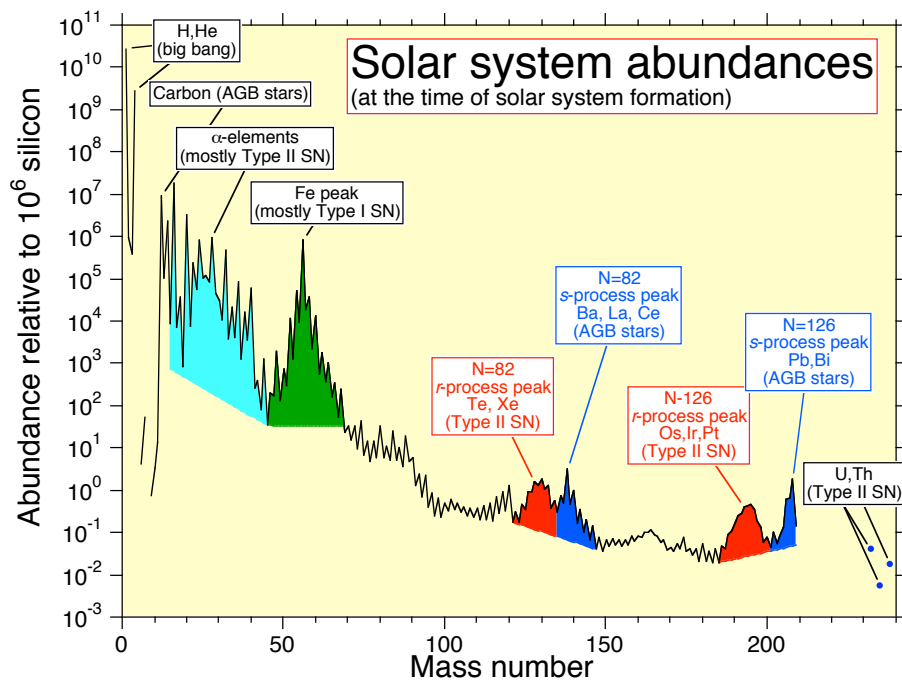
What the Big Bang Made



Cosmic Abundances



Cosmic Abundances

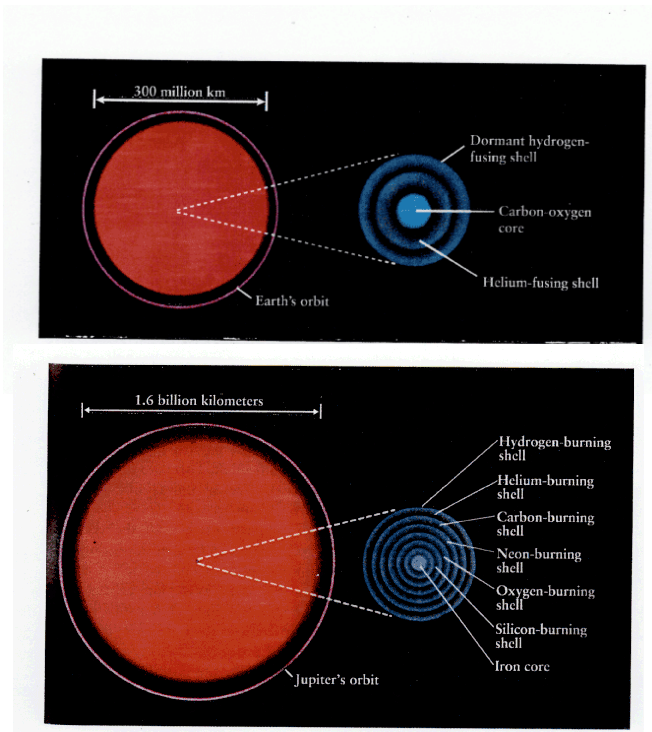


Elements heavier than helium are of Galactic origin!

Nucleosynthesis Sites

- ❑ **Massive stars ($M > 10 M_{\odot}$) and SNe II:** synthesis of the nuclear species from oxygen through zinc, and of the r-process heavy elements
- ❑ **Red Giant Stars ($1 < M < 10 M_{\odot}$):** synthesis of carbon and s-process elements
- ❑ **SNe Ia:** synthesis of the 1/2-2/3 of the iron peak nuclei not produced by SNe II

Stellar and Supernova Nucleosynthesis



Picture credit: HST



AGB Star - Planetary Nebula

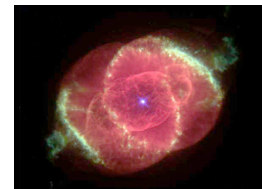
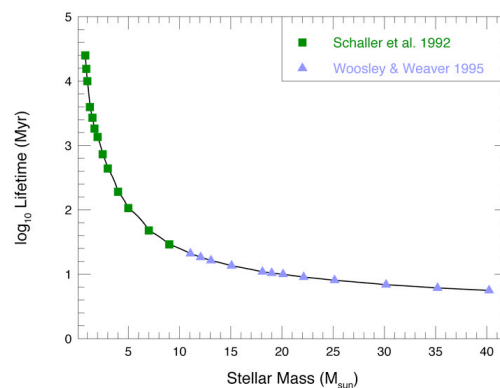


Massive Star - SNI

Nucleosynthesis Timescales

Stellar Lifetimes $\Rightarrow$ "Production Timescales"

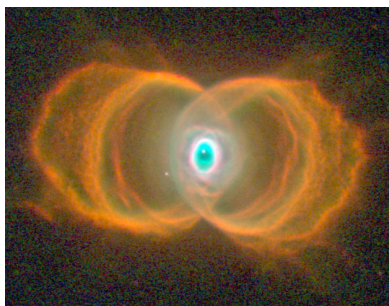
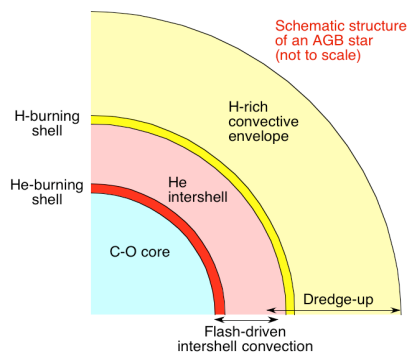
- ☐ Massive stars and SNe II $\tau < 10^8$ years
- ☐ AGB stars $\tau > 10^9$ years
- ☐ SNe Ia $\tau > 1-2 \times 10^9$ years



Synthesis of Nuclei Through Iron

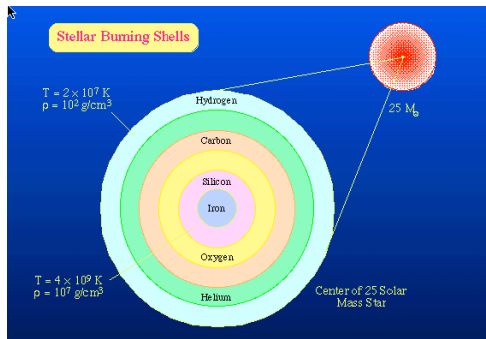
- ❑ Nuclei from **oxygen to iron** are formed in stages of nuclear burning in the cores of massive stars ($M > 10 M_{\odot}$) and in the explosive ejection of matter in the associated SNe II. (**$\approx 1/3$ of the Fe**)
- ❑ Low/intermediate mass stars ($1 < M < 10 M_{\odot}$) are the primary site for **carbon** production.
- ❑ Supernovae Ia, thermonuclear explosions of CO white dwarfs in binary systems, produce 1/2 to 2/3 of the of the **iron-peak nuclei**.

Nucleosynthesis in Red Giant Stars

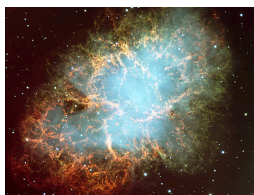


- ❑ Asymptotic giant stars are an advanced stage of evolution of all low mass stars $1 < M_{*} < 10 M_{\odot}$
- ❑ Thermal pulses in their helium burning shells provide an environment for the production of both ^{12}C and many isotopes of **heavy nuclei (s-process products)**.
- ❑ These products are returned to the interstellar gas via winds and planetary nebula ejection.

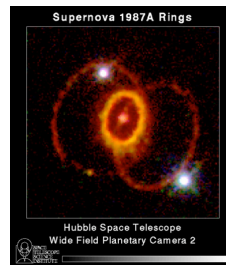
Type II Supernovae: Theory



Courtesy Mike Guidry: guidry@utk.edu



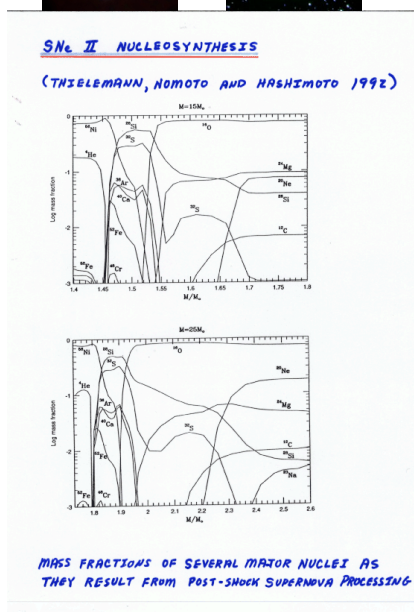
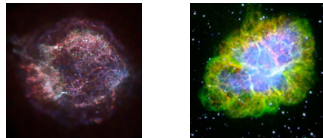
SNe1054: Crab Nebula



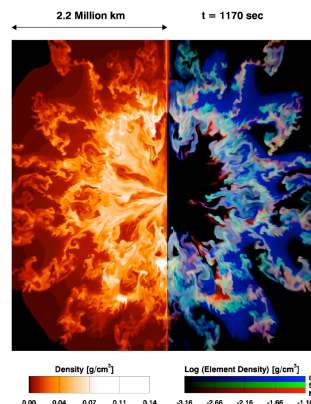
SNe1987A Hubble Image

- ❑ "Standard model" (Hoyle & Fowler 1960):
 - ❑ SNe II are the product of the evolution of massive stars $10 < M < 100 M_{\odot}$.
- ❑ Evolution to criticality:
 - ❑ A succession of nuclear burning stages yield a layered compositional structure and a core dominated by ^{56}Fe .
 - ❑ Collapse of the ^{56}Fe core yields a neutron star.
 - ❑ The gravitational energy is released in the form of neutrinos, which interact with the overlying matter and drive explosion.
- ❑ Remnants: Neutron star and black hole remnants are both possible SNe II remnants.
- ❑ Nucleosynthesis contributions: elements from oxygen to iron (formed as ^{56}Ni) and neutron capture products from krypton through uranium and thorium. ($\tau_{\text{nucleosynthesis}} < 10^8 \text{ yrs}$)

Massive Stars and Type II Supernovae

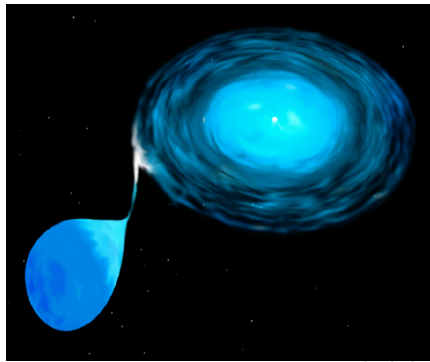


- ❑ Massive stars ($M > 10 M_{\odot}$) evolve through a sequence of burning stages to the formation of an iron core surrounded by shells of, respectively, silicon, oxygen, neon, carbon, and helium.
- ❑ The r-process heavy elements are also believed to be formed in these events.



(Kifonidis et al. 2000)

Type Ia Supernovae: Theory



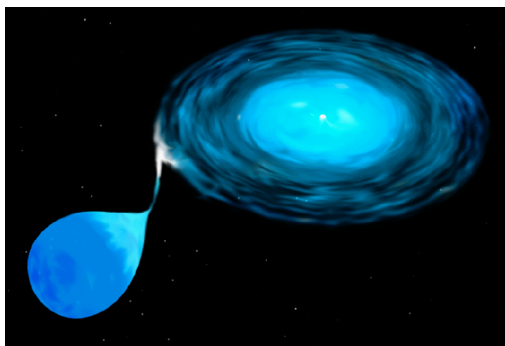
NASA STScI



High-Z Supernova Search Team, HST

- ❑ “Standard model” (Hoyle & Fowler 1960):
 - ❑ SNe Ia are thermonuclear explosions of C+O white dwarf stars.
- ❑ Evolution to criticality:
 - ❑ Accretion from a binary companion leads to growth of the WD to the critical (Chandrasekhar) mass (1.4 solar masses).
- ❑ After ~1000 years of slow thermonuclear “cooking”, a violent explosion is triggered at or near the center.
- ❑ Complete incineration occurs within two seconds, leaving no compact remnant.
- ❑ Nucleosynthesis contributions: 1/2 to 2/3 iron-peak nuclei. ($\tau_{\text{nucleosynthesis}} > 10^9$ yrs)
- ❑ Their light curves are powered by the radioactive decay of ^{56}Ni . Their peak luminosities: $L_{\text{max}} \propto M(^{56}\text{Ni})$.

The “Standard Model” for Type Ia SNe



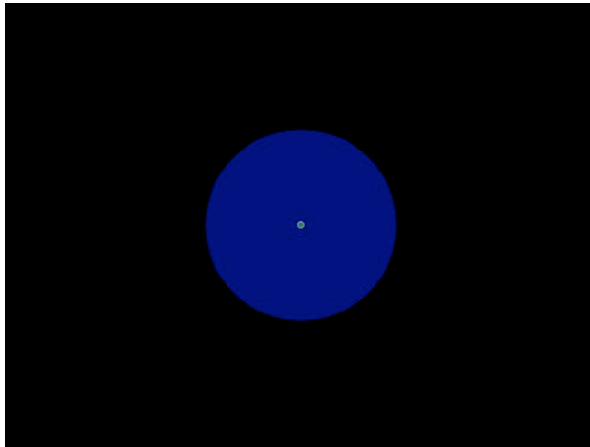
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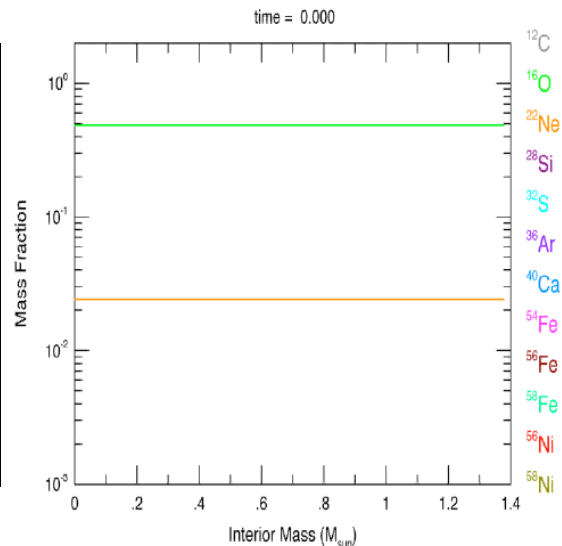
High-Z Supernova Search Team, HST

- ❑ Type Ia supernovae are the consequence of thermonuclear explosions in the cores of white dwarfs in binary systems.
- ❑ Accretion brings the white dwarf to the Chandrasekhar limiting mass ($\sim 1.4 M_{\odot}$) and a thermonuclear runaway ensues.
- ❑ Complete incineration follows on a timescale ~ 2 seconds $\Rightarrow$ no compact remnant.
- ❑ SN Ia production of ^{56}Ni - and thus supernova luminosity - are critical to their use as “standardized candles” and probes of cosmology.

Supernova Ia Nucleosynthesis



Off-center Deflagration Simulation
(Calder et al. 2003)

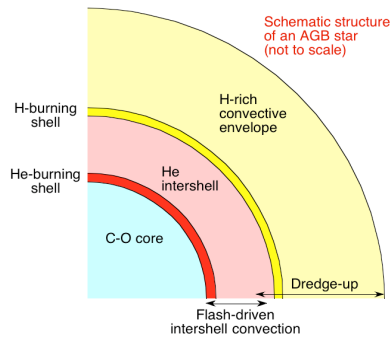
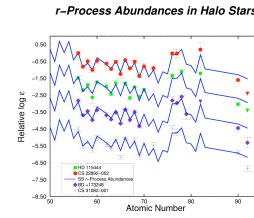
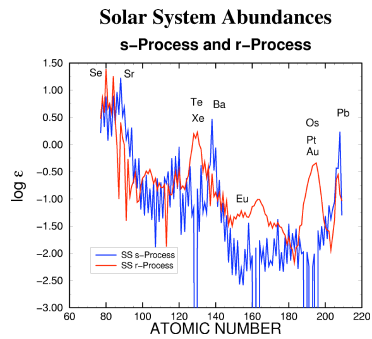


Evolution of Core Composition
(Timmes, Brown, Truran 2003)

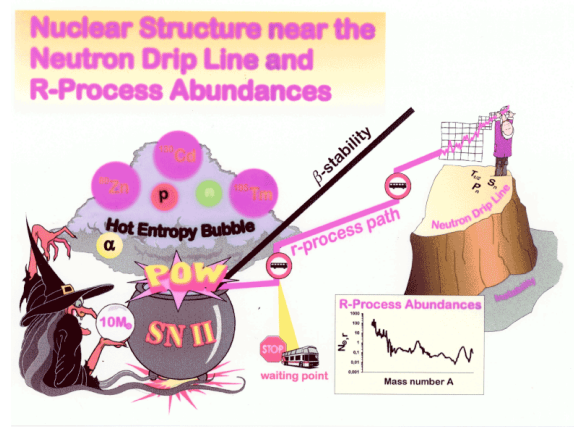
Synthesis of Nuclei Beyond Iron

- ❑ Nuclei heavier than iron ($A > 60$) are understood to be formed in neutron capture processes.
- ❑ The helium shells of red giant stars ($\approx 1-10$) provide the **s-process** environment, with the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction providing neutrons.
- ❑ Supernovae II provide the setting for the **r-process**.
- ❑ Note again the different production timescales for the two neutron capture processes – 10^9 versus 10^8 years.

r-Process and s-Process Synthesis

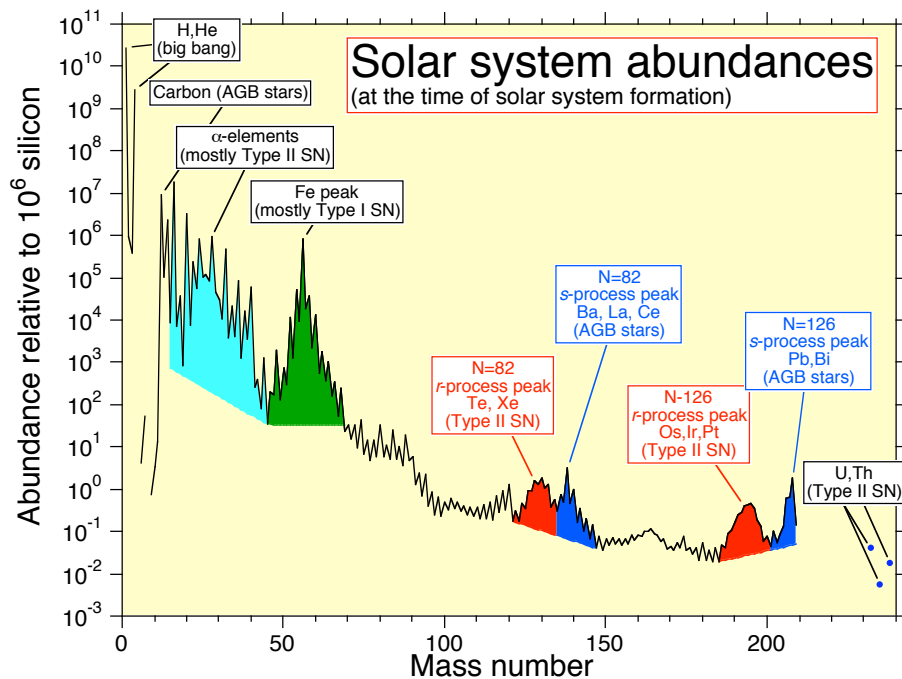


s-process in red giants



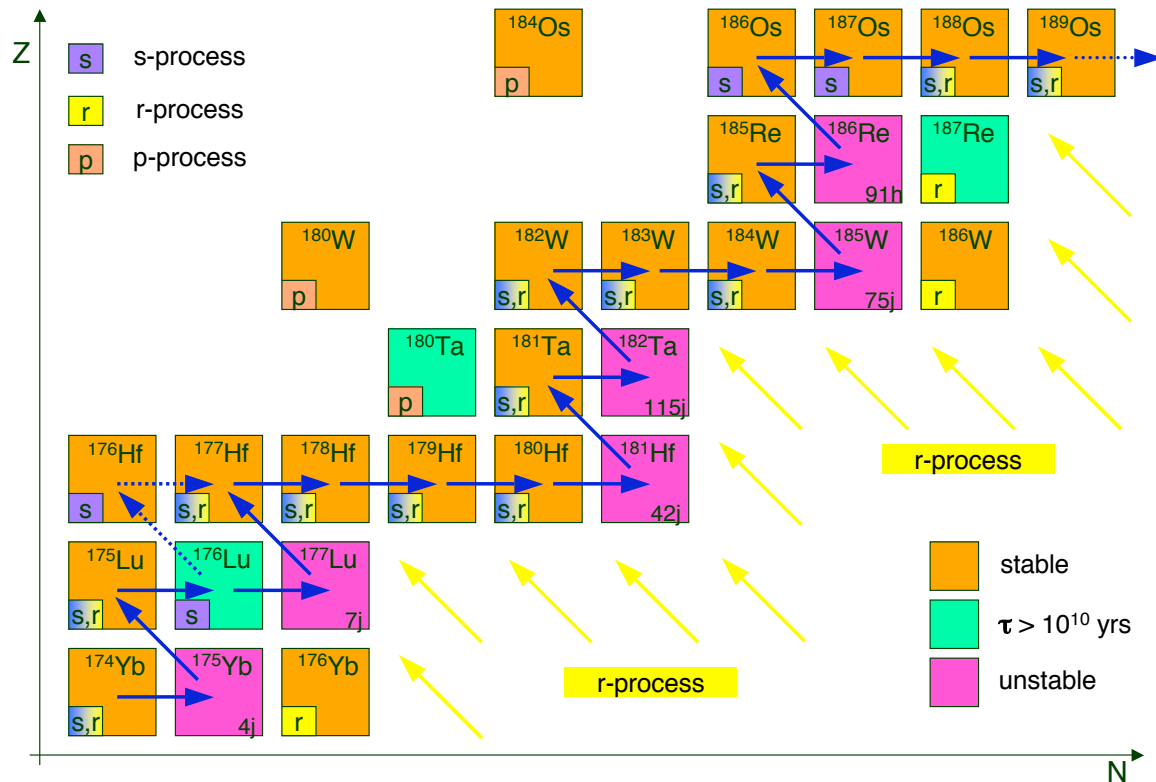
r-process in supernovae

Cosmic Abundances



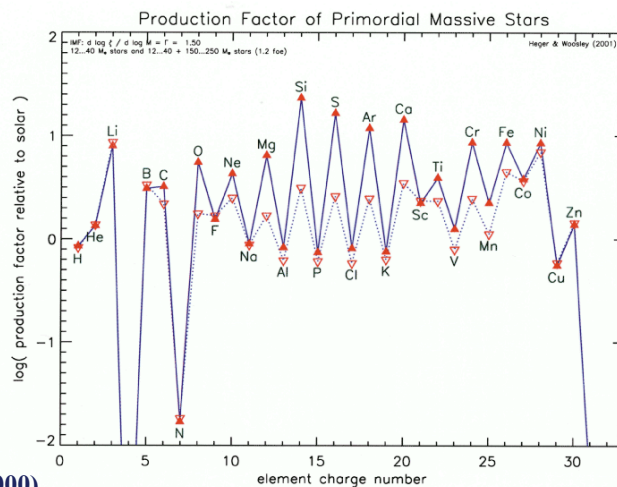
Elements heavier than helium are of Galactic origin!

« s » Process

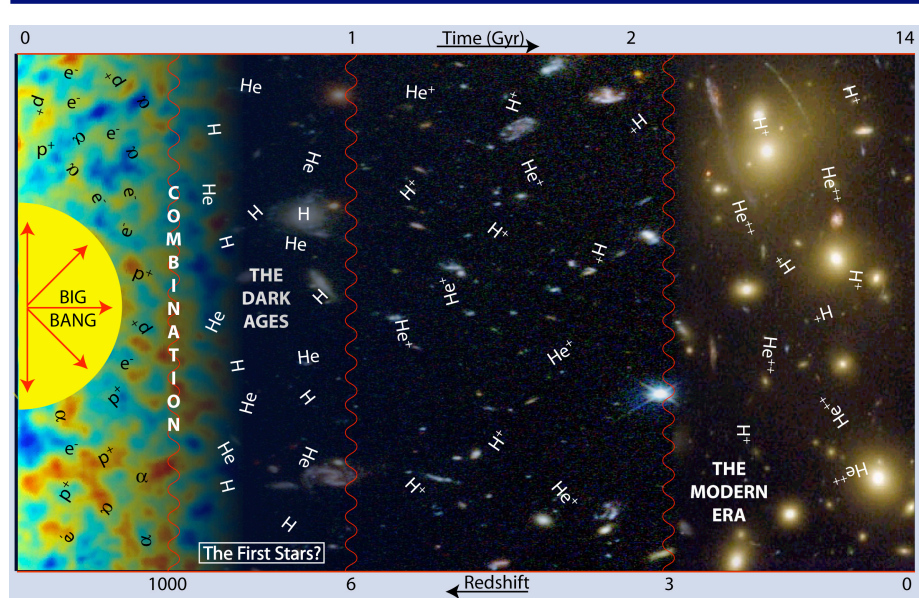


Very Massive Primordial Stars

- Very massive stars ($\sim 100\text{-}300 M_{\odot}$) can be stable at low metallicities.
- These “pair instability” supernovae eject nuclei from oxygen to iron.
- Nucleosynthesis signatures include a pronounced odd-even variation.



Nuclear Astrophysics: Perspective



The Dark Ages: Between recombination and formation of the first stars.

The Cosmic Dawn: Reionization of H at $z \sim 6$ by stars in galaxies

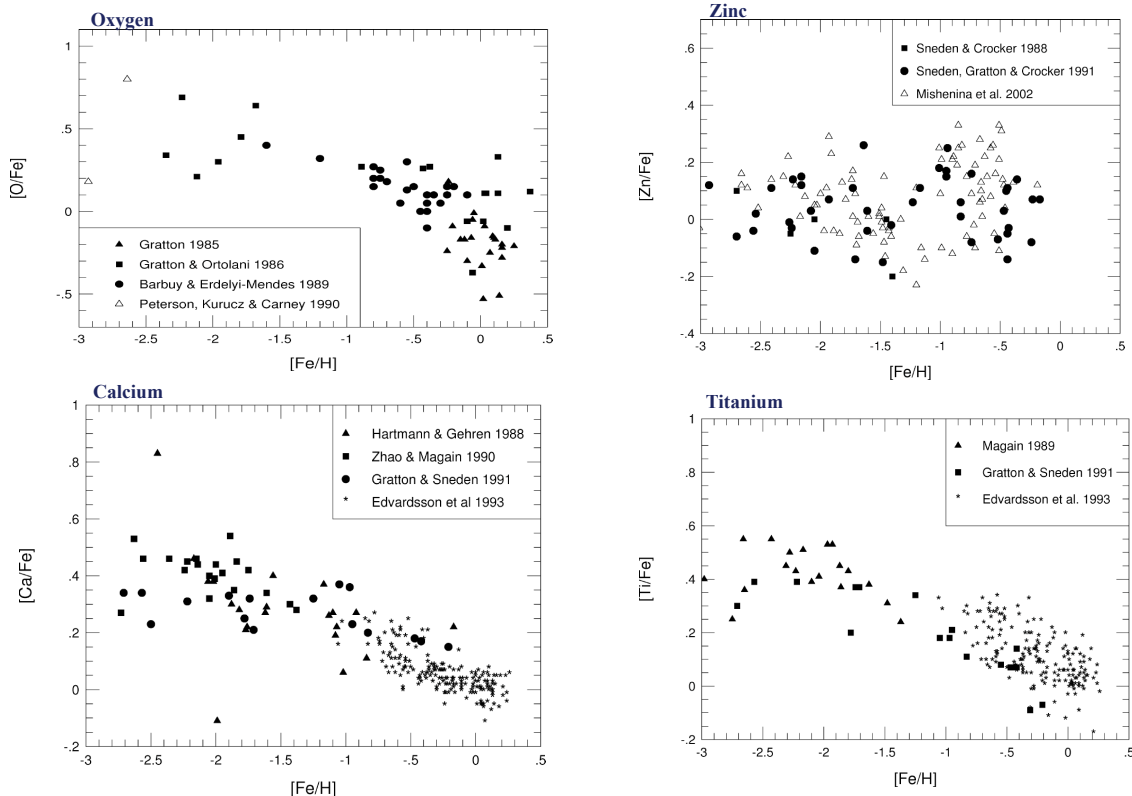
Probing Early Nucleosynthesis

- ❑ Studies of Population II stars and Damped Lyman Alpha systems have a common goal:
 - ❑ the study of early evolutionary phases of star formation and nucleosynthesis
- ❑ but two different approaches:
 - ❑ Pop II - analysis of the fossil imprint
 - ❑ DLAs - scrutiny of high red shift systems

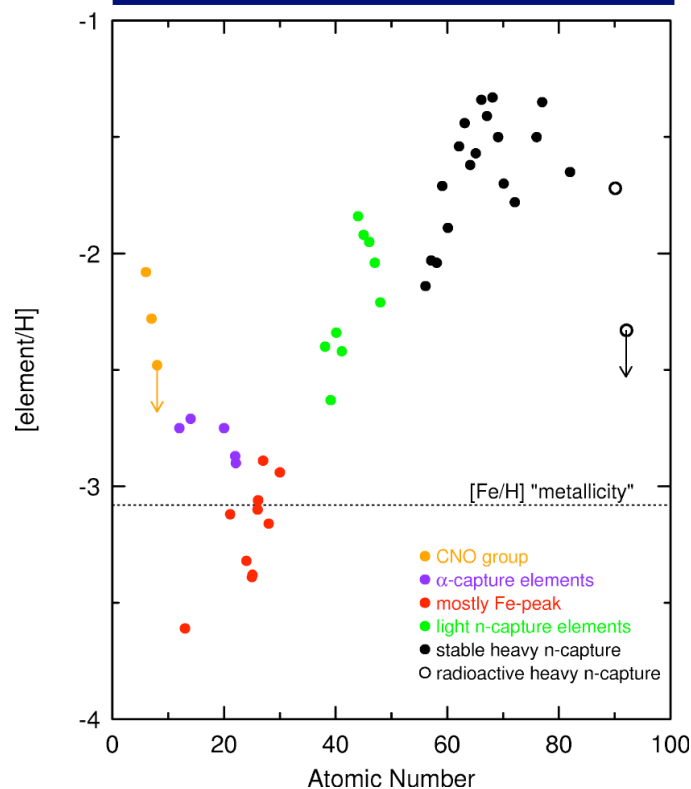
Abundance Trends & Chemical Evolution

- ❑ Extremely metal-deficient stars of $[\text{Fe}/\text{H}] \sim -2$ to -3 are characterized by both high $(\text{Ne-Ca})/\text{Fe}$ and O/Fe ratios and an r-process heavy element pattern
 - ❑ $\Rightarrow$ SNe II production ($\tau \leq 10^8$ years)
- ❑ Signatures of an increasing s-process contamination first appear at an $[\text{Fe}/\text{H}] \approx -2.5$ to -2.0
 - ❑ $\Rightarrow$ first input from AGB stars ($\tau \approx 10^9$ years)
- ❑ Evidence for entry of SNe Ia ejecta first appears at $[\text{Fe}/\text{H}] \approx -1.5$ to -1.0 , as evidenced in the $[\text{O}/\text{Fe}]$ and $[(\text{Ne-Ca})/\text{Fe}]$ histories
 - ❑ $\Rightarrow$ input from SNe Ia on timescales $> 1-2 \times 10^9$ years

Halo Abundance Trends for $-3 \leq [\text{Fe}/\text{H}] \leq 1$



Abundance Summary for CS 22892-052



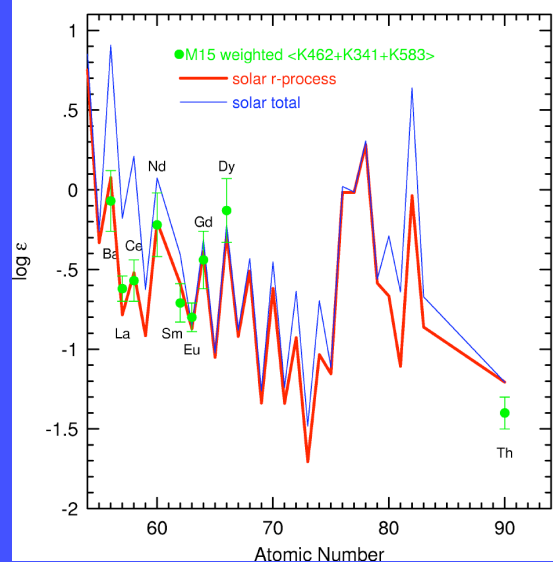
Halo Abundance Trends: Globular Clusters

Globular Cluster Abundances Trends: The α -Elements							
Cluster	Ref	[Fe/H]	[O/Fe]	[Mg/Fe]	[Si/Fe]	[Ca/Fe]	[Ti/Fe]
M71	4	-0.81		+ .38	+ .28	+ .24	
M71	2	-0.80	+ .40	+ .15	+ .58	+ .30	
NGC 362	1	-0.87			+ .65	+ .30	
NGC 3201	1	-0.95			+ .15	+ .13	
NGC 3201	4	-1.82		+ .23	+ .19	+ .18	
47 Tuc	1	-1.09			+ .44	+ .53	
47 Tuc	4	-0.83			+ .40	+ .13	+ .15
M4	3	-1.20			+ .65	+ .59	+ .20
M4	4	-1.32			+ .80	+ .46	+ .24
M4	10	-1.18	+ .25	+ .44	+ .55	+ .26	
M5	1	-1.09			+ .37	+ .30	
M5	4	-1.47			+ .39	+ .56	+ .39
M5	7	-1.17	+ .35		+ .20	+ .19	+ .29
M10	1	-1.28			+ .38	+ .31	
M10	4	-1.42			+ .36	+ .45	+ .28
NGC 6752	1	-1.26			+ .36	+ .25	
NGC 6752	4	-1.53			+ .48	+ .36	+ .17
NGC 4833	1	-1.34				+ .30	+ .36
NGC 4833	4	-1.74			+ .28	+ .48	+ .41
M19	4	-1.46			+ .17	+ .22	+ .35
M13	3	-1.55			+ .35	+ .40	
M13	8	-1.88	+ .30	+ .14	+ .32	+ .24	+ .30
M22	4	-1.56			+ .44	+ .36	+ .40
M22	3	-1.60					+ .10
M22	5	-1.70				+ .40	
NGC 5887	4	-1.85			+ .38	+ .08	- .04
NGC 6397	4	-1.88			+ .44	+ .27	+ .07
M68	4	-1.93			+ .44	+ .42	+ .02
M15	9	-2.40	+ .35	+ .35	+ .60	+ .24	+ .46
M92	6	-2.52		+ .61		+ .31	+ .22

References: (1) Pilachowski, Soden, and Wallerstein 1993; (2) Lepp, Oke, and Wallerstein 1987; (3) Wallerstein, Lepp, and Oke 1987; (4) Gratton and Soden 1990; (5) Lehnert, Bell, and Cohen 1990; (6) Peterson, Korman, and Carney 1990; (7) Soden, Kraft, Prosser, and Langer 1992; (8) Kraft, Soden, Smith, Shetrone, Langer, and Pilachowski 1997; (9) Soden, Kraft, Shetrone, Smith, Langer, and Prosser 1997; (10) Ivans, Soden, Kraft, Suntzeff, Smith, Langer, and Fulbright 1999; (11) Francois and Houllé 1991.

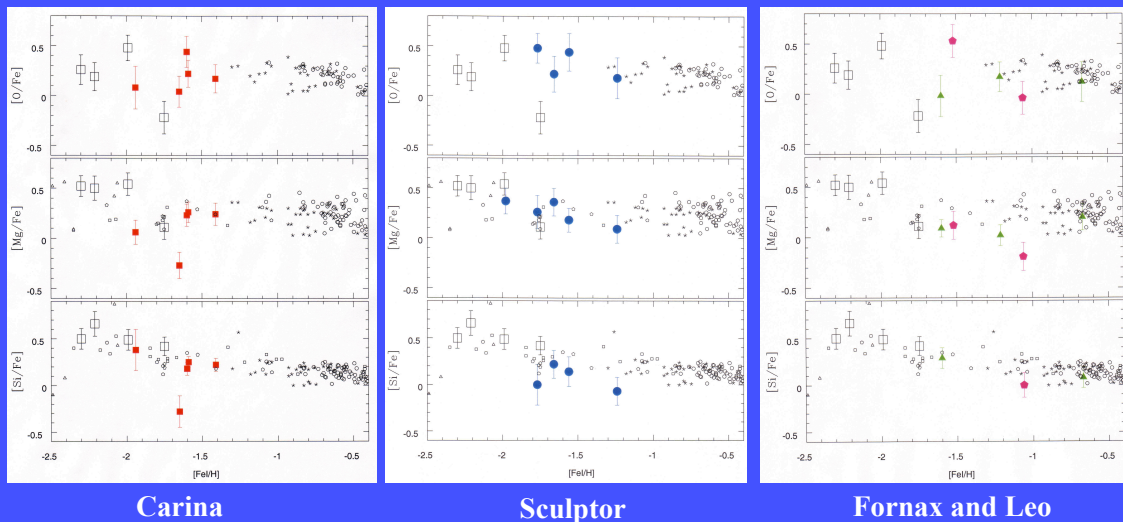
Alpha Elements

N-Capture Abundances in Globular Cluster M15



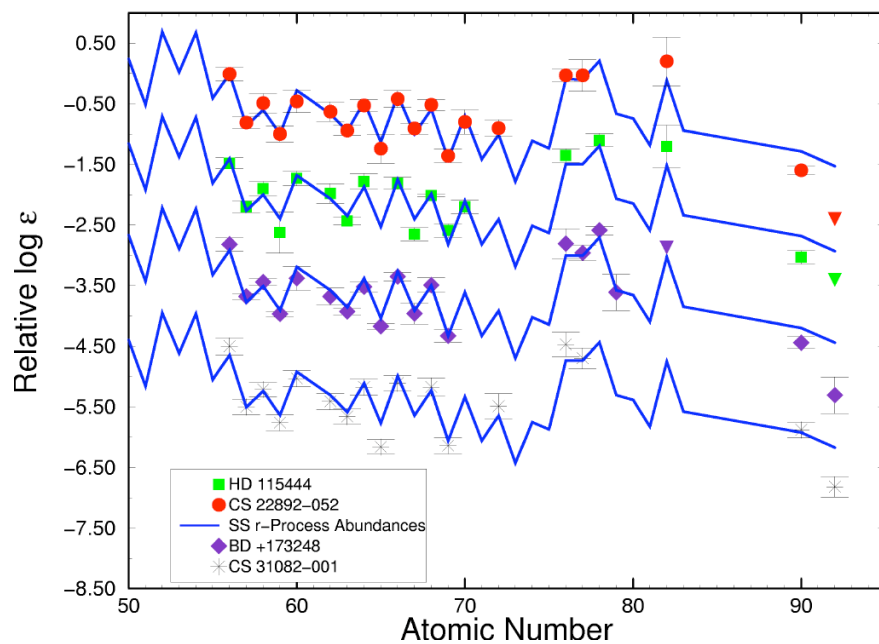
r-Process Elements

Abundances in Dwarf Spheroidal Galaxies

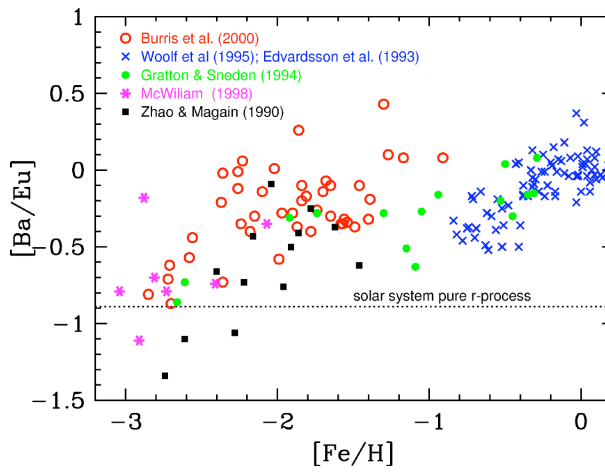


(Shetrone et al. 2003)

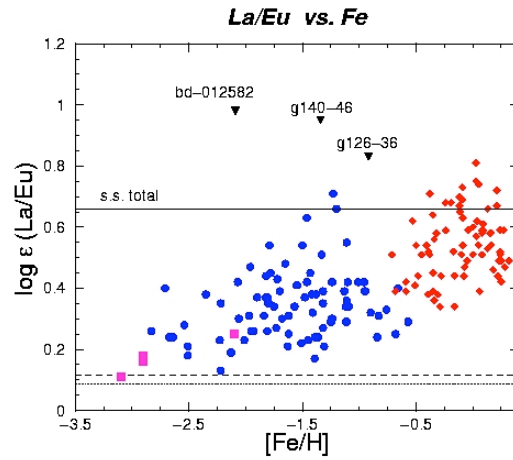
r-Process Abundances in Halo Stars



s-/r-Process Chemical Evolution

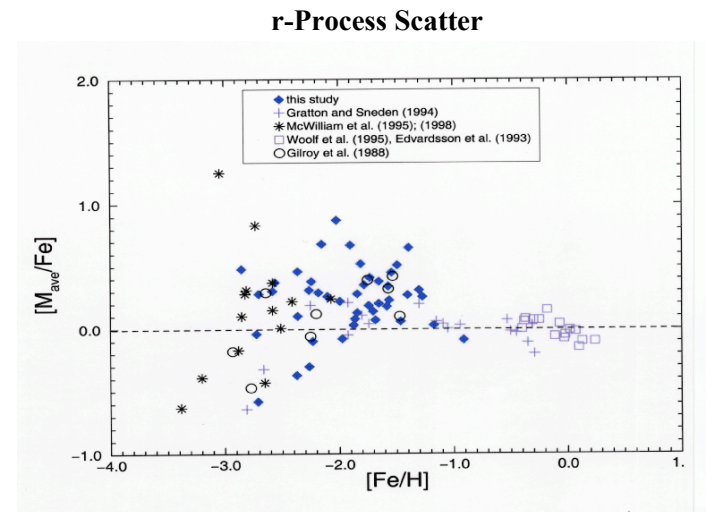
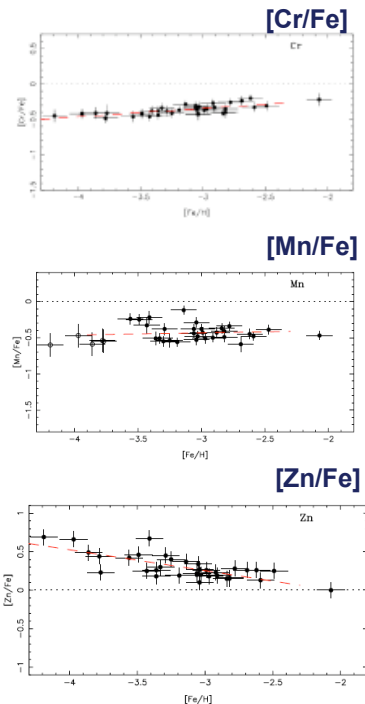


Burris et al. (2000)



Simmerer et al. (2005)

Trends in Early Abundance Scatter



Truran et al. (2002)

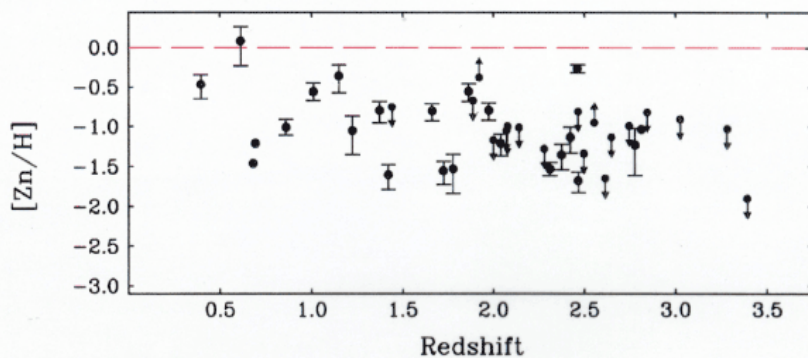
Cayrel et al. (2005)

Abundance Probes of High- z Universe

- ❑ Abundance determinations for the high redshift Universe are now available from studies of Quasar absorption line systems (Lauroesch et al. 1996; Lu et al. 1996).
- ❑ QSO absorption line systems reveal levels of metallicity approaching $\sim 10^{-2}$ to $10^{-1} Z_{\odot}$ at redshifts $z > 2-3$, with abundance patterns consistent with nucleosynthesis in massive stars and SNe II.
- ❑ The Si/Fe ratios for QSO absorbers are generally consistent with the expected α -element ``trends'' with metallicity.

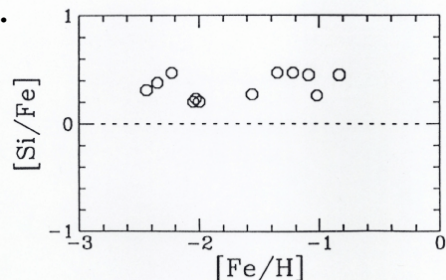
DLAs: Abundance Evolution with Red Shift

(Pettini 2003)



Lower bound on metallicities due to masses of typical clouds in which first stars formed.

(Lu et al. 1996)



Timescale Constraints

☐ Globular Clusters:

- ☐ MS turnoff (Chaboyer) - 13.2 ± 1.5 Gyr

☐ Halo Stars (U/Th chronometer):

- ☐ CS 31082-001 (Hill et al) - 14.0 ± 2.4 Gyr
- ☐ Bd+17° 3248 (Snedden et al) - 13.8 ± 4.0 Gyr

☐ Disk Stars

- ☐ (Edvardsson et al) sample - ≈ 12 Gyr
- ☐ White Dwarfs (Hansen) - 7.3 ± 1.5 Gyr

Lookback Times

- ☐ Cosmology gives the following parameters:
 $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$; $\Omega_{\text{baryons}} = 0.022 \text{ h}^{-2}$; $\Omega_{\text{M}} = 0.3$; $\Omega_{\Lambda} = 0.7$. The implied age of the Universe is 14.5 Gyr (Turner 2002).
- ☐ This gives the following look-back times as a function of redshift:

Look-back Times versus Redshift

Red Shift	Age of the Universe	Look-back Time
∞	0 Gyr	14.5 Gyr
10 (First Stars -	0.5	14.0
6 - SNe II)	1.0	13.5
5	1.2	13.3
4 (AGB Stars)↓	1.6	12.9
3	2.3	12.2
2 (SNe Ia)↓	3.5	11.0
1	6.2	8.3
0.5	9.1	5.4
~0.4 Birth of Sun	9.9	4.6
0	14.5	0

Concluding Remarks

- ❑ Based upon existing observations of abundances in our Galaxy, other galaxies, and QSO absorption line systems, we can conclude:
Only normal stars in a Salpeter-like initial mass function are required to produce the elements seen in the oldest stars.
- ❑ While contributions from massive stars clearly dominate at early epochs, this is most likely a consequence of their shorter production timescales rather than of an altered IMF.
- ❑ Very massive stars ($100 < M_{\odot} < 300 M_{\odot}$) fail to explain the trends in iron peak elements identified at the lowest metallicities, and seem not to have made a significant contribution to galactic nucleosynthesis.
- ❑ Our present knowledge of the *abundance* history of the Universe provides no unambiguous evidence for an earlier Population (III?).
- ❑ The collective trends in halo stars, disk stars, globular clusters, dwarf spheroidal galaxies, and DLAs are generally compatible with our understanding of stellar evolution and supernova nucleosynthesis.