THE AGE OF THE OLDEST STARS AS A CONSTRAINT ON COSMOLOGICAL MODELS

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Outstanding Questions for the Standard Cosmological Model (March 27, 2007)

Abundance Clues and Constraints

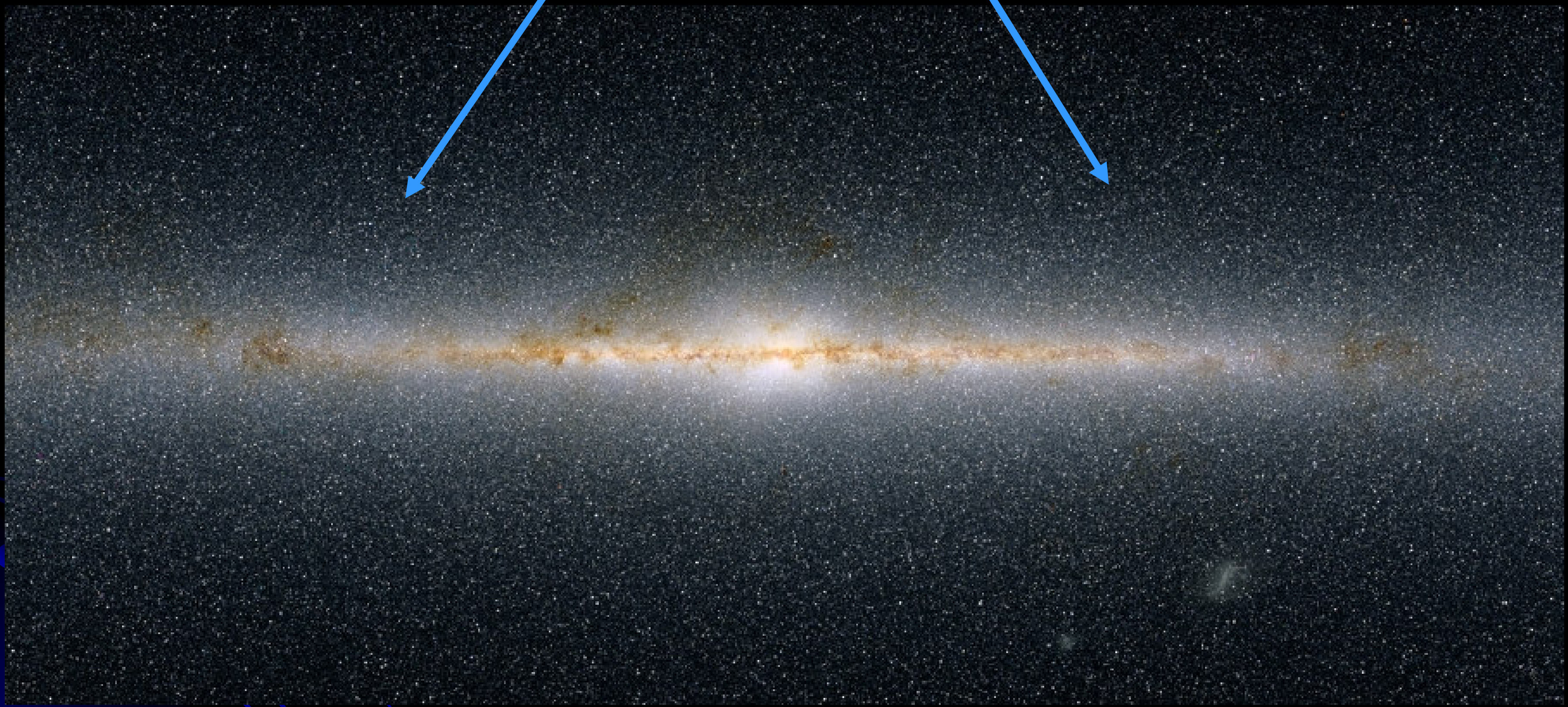
- New observations of n-capture elements in low-metallicity Galactic halo stars providing clues and constraints on:

1. Synthesis mechanisms for heavy elements early in the history of the Galaxy
2. Identities of earliest stellar generations, the progenitors of the halo stars
3. Suggestions on sites, particularly site or sites for the r-process
4. Galactic chemical evolution
5. Ages of the stars and the Galaxy → chronometers

Solar System Abundances

2MASS View of the Milky Way

Galactic Halo Stars



- Metal-poor Halo Stars are ``fossils'' of the Early Universe
- These Stars are Relatives of the First Stars in the Universe

``Near Field Cosmology''

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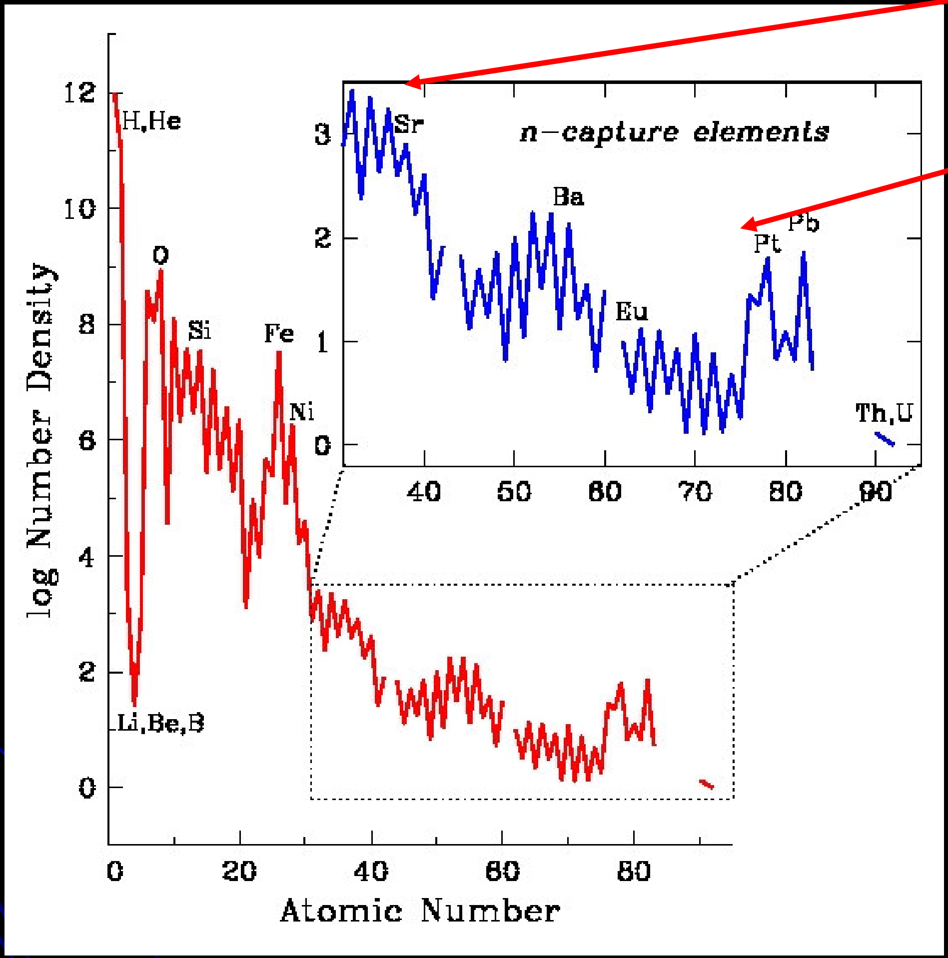
Solar System (``Cosmic") Abundances



Ge, Zr

Os, Pt

Jewelry store items

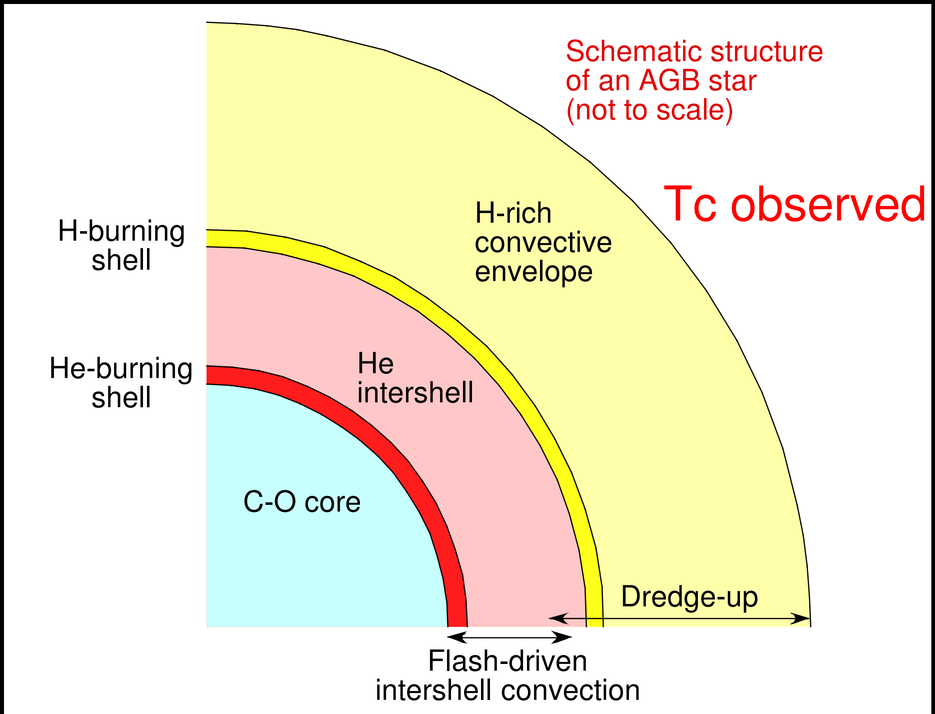
Sneden & JC (2003)

Heavy Element Synthesis

- About ½ of nuclei above iron formed in the slow (s) neutron capture process
- The other half of the nuclei formed in the rapid (r) neutron capture process
- Timescale (slow or fast) with respect to radioactive decay time of unstable nuclei produced by the neutron capture

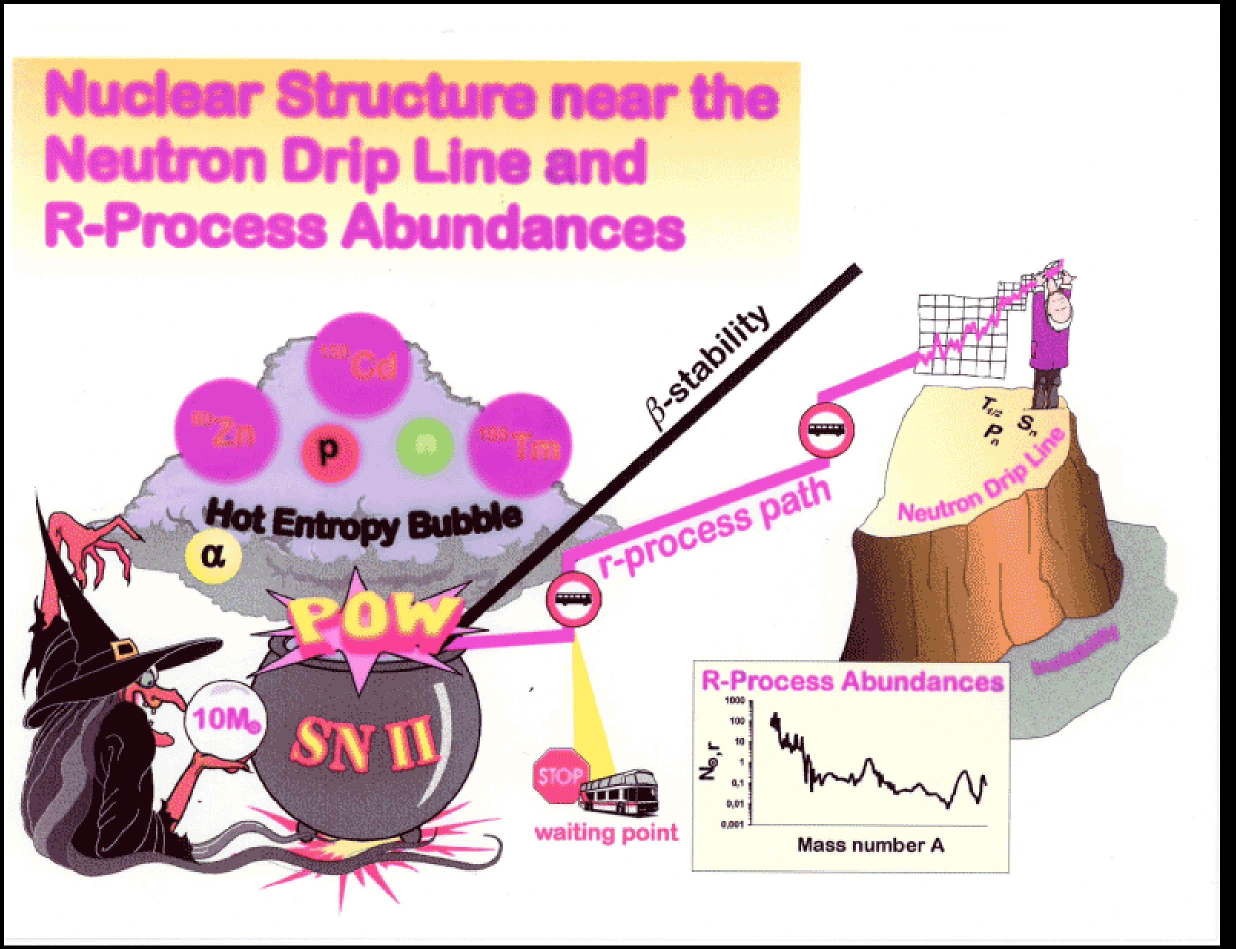
s-Process Nucleosynthesis

- For the s-process:
- τ_{nc} >> τ_{β} decay (typically hundreds to thousands of years)
- Site for the s-process well identified as AGB (red giant) stars

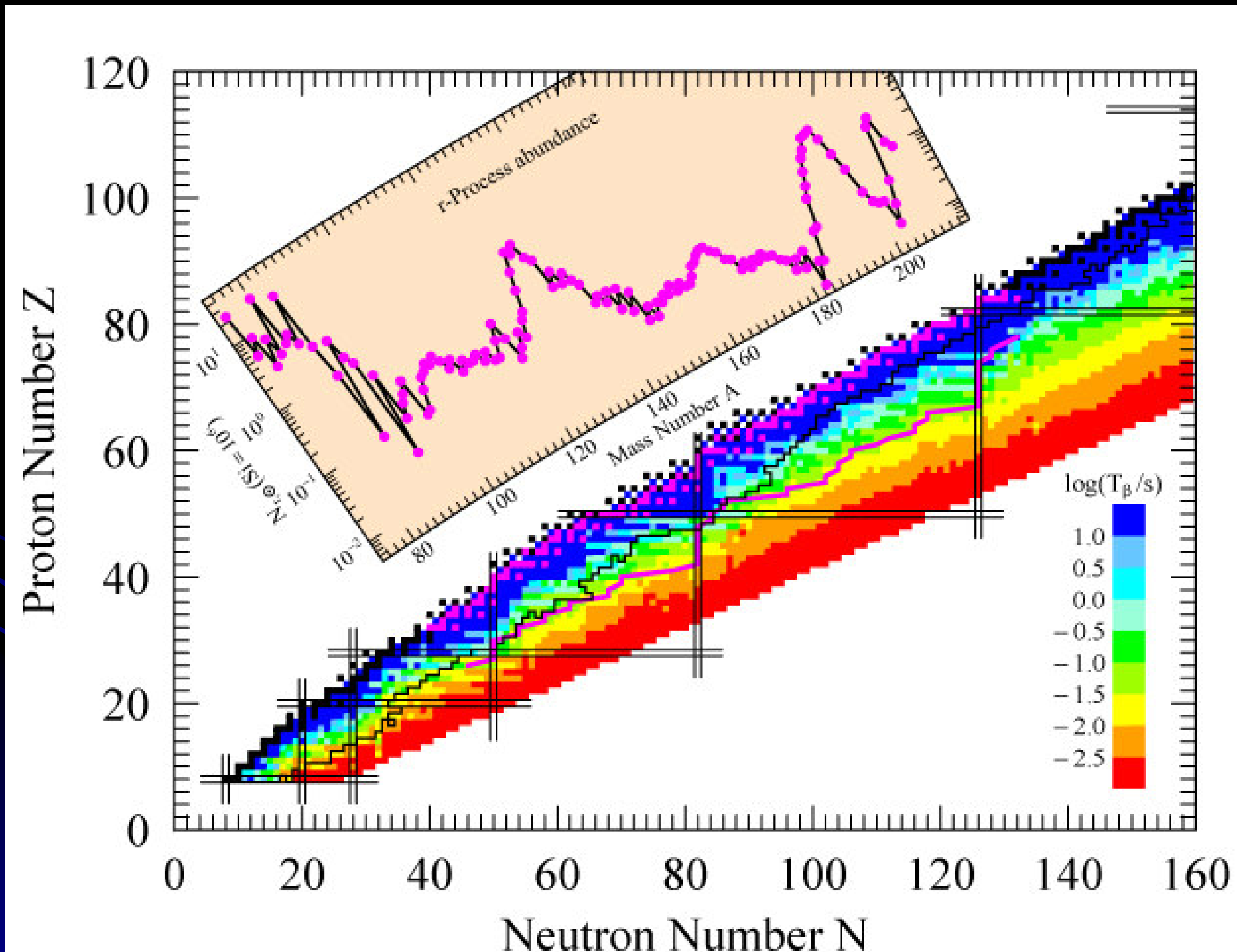


r-Process Nucleosynthesis

- For the r-process:
- $\tau_{nc} << \tau_{\beta}$ decay (typically 0.01–0.1 s)
- Site for the r-process still not still not identified

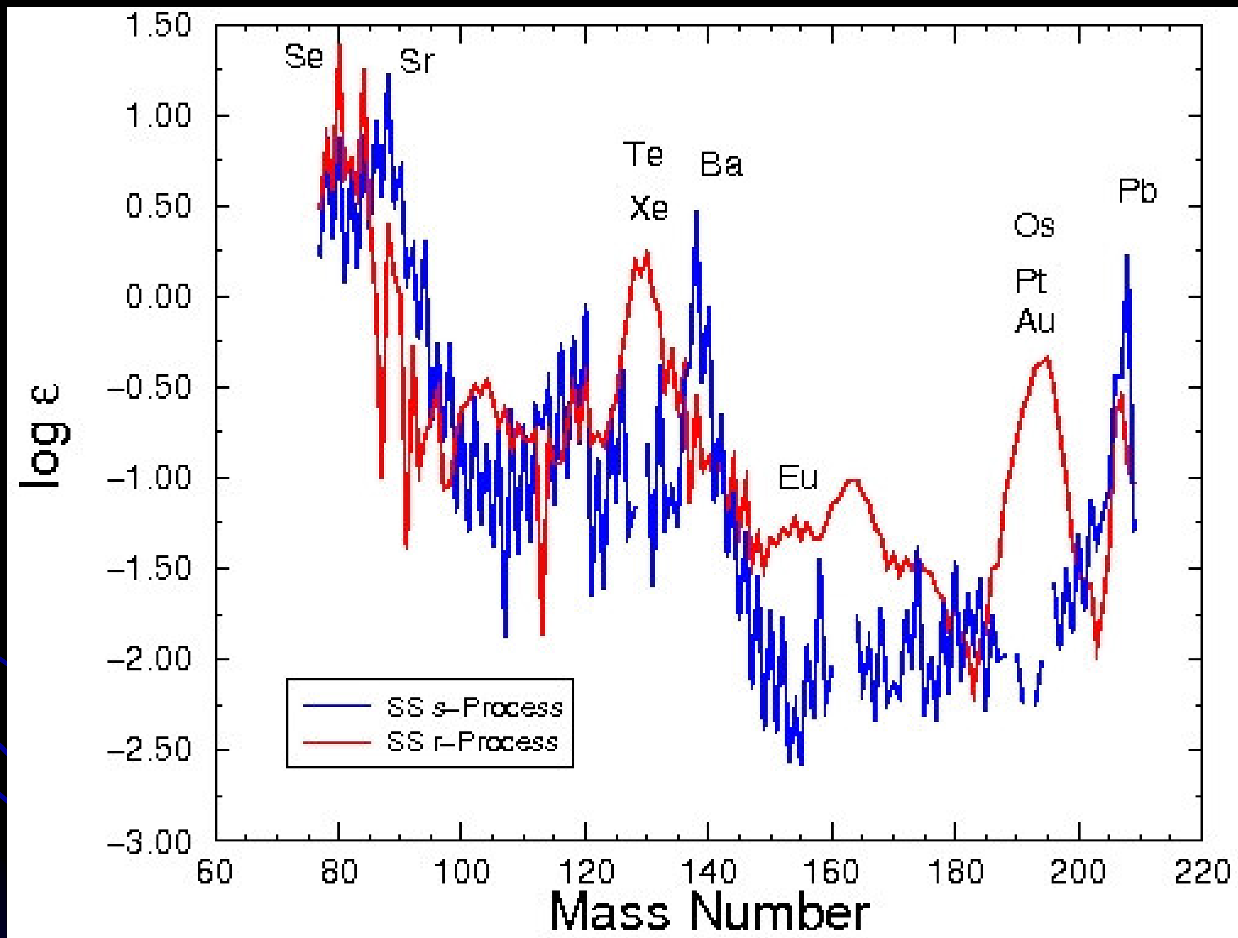


The Nuclear Isotopes in Nature



details

Solar System s- and r-Process Abundance Peaks



SS isotopic deconvolution by s- and r-process

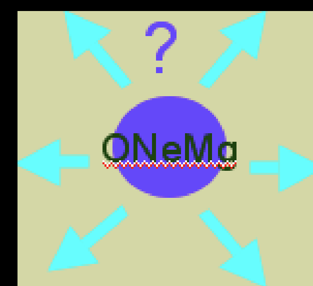
$\log \varepsilon(A) = \log_{10}(N_A/N_H) + 12$

Most Likely Site(s) for the r-Process

- Supernovae: The Prime Suspects

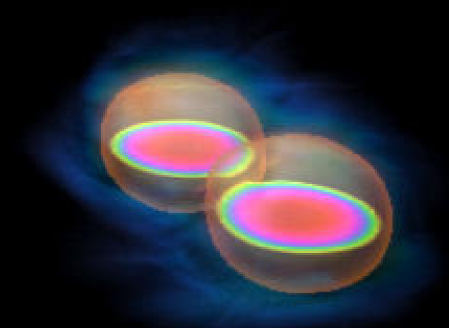
→ Regions just outside neutronized core: 1957 (Woosley et al. 1994; Wanajo et al. 2002) (v-wind)

→ Prompt explosions of low-mass Type II SNe (Wheeler, JC & Hillebrandt 1998)



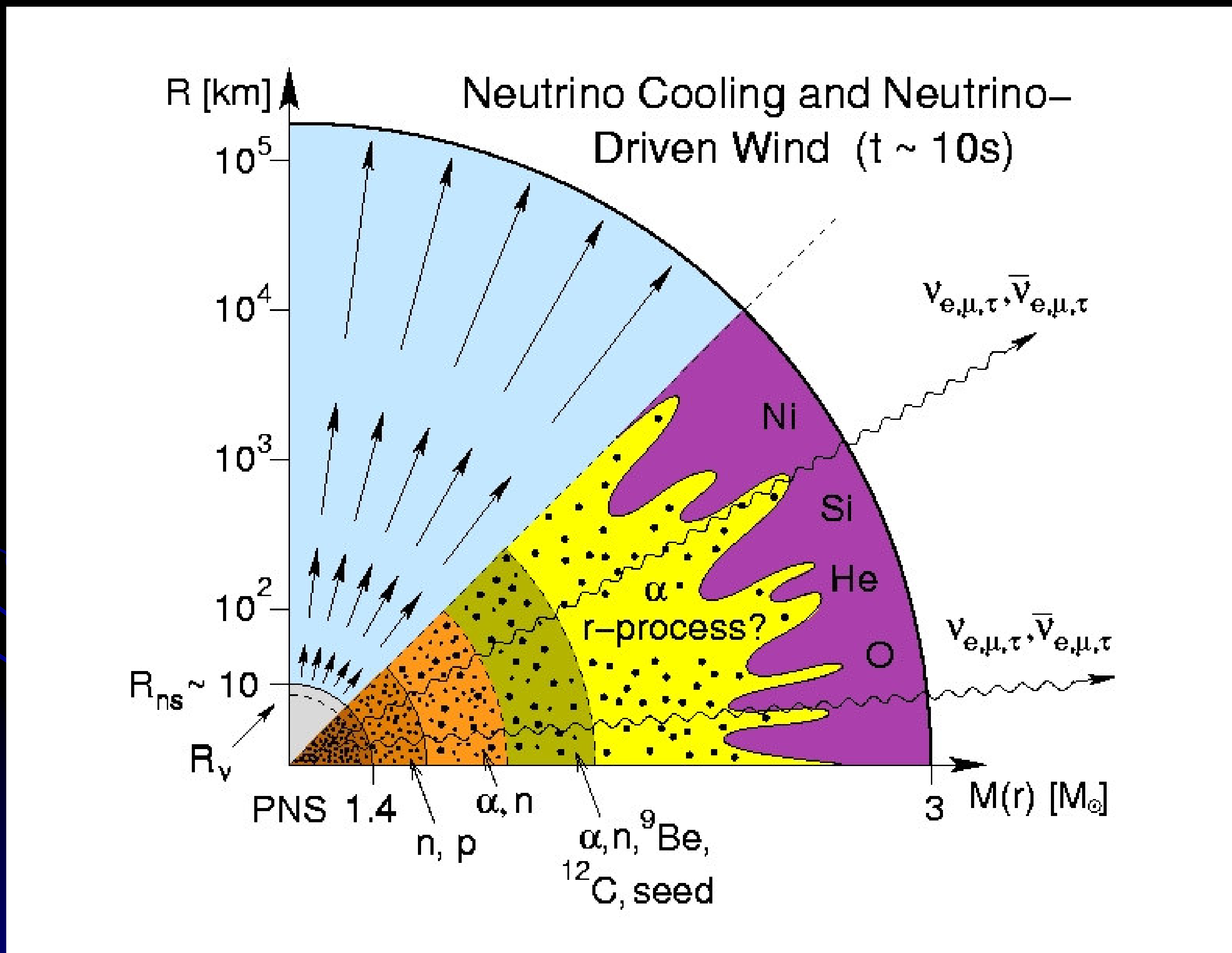
→ Jets and bubbles (Cameron 2001)

- NS & NS-BH mergers (Rosswog et al. 1999; Freiburghaus et al. 1999)



Observations of r-process elements in a cool giant

Rapid Neutron Capture in Type II SNe ?



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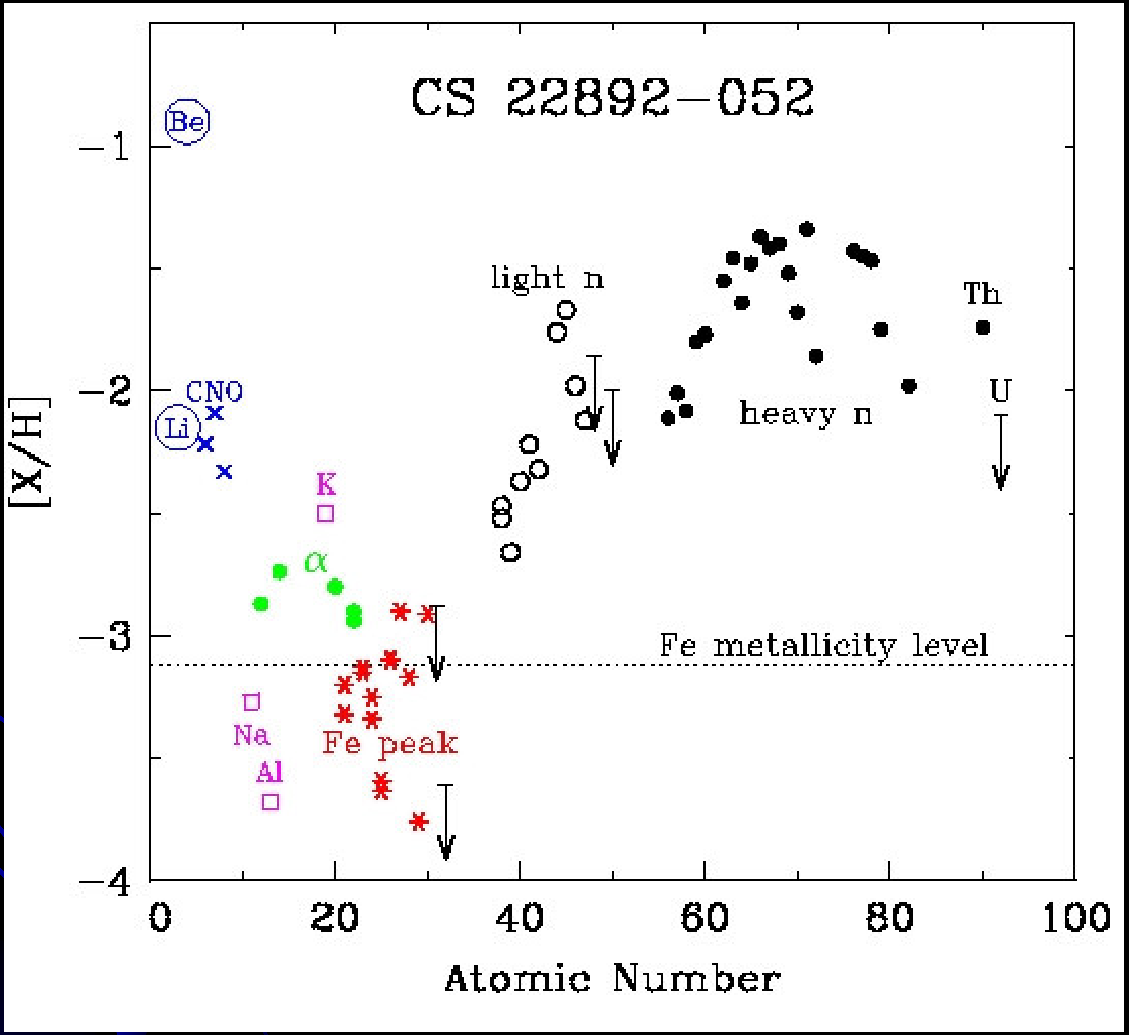
Total Abundances in CS 22892-052: A Metal-Poor Halo Star



Light elements mostly scale with [Fe/H].

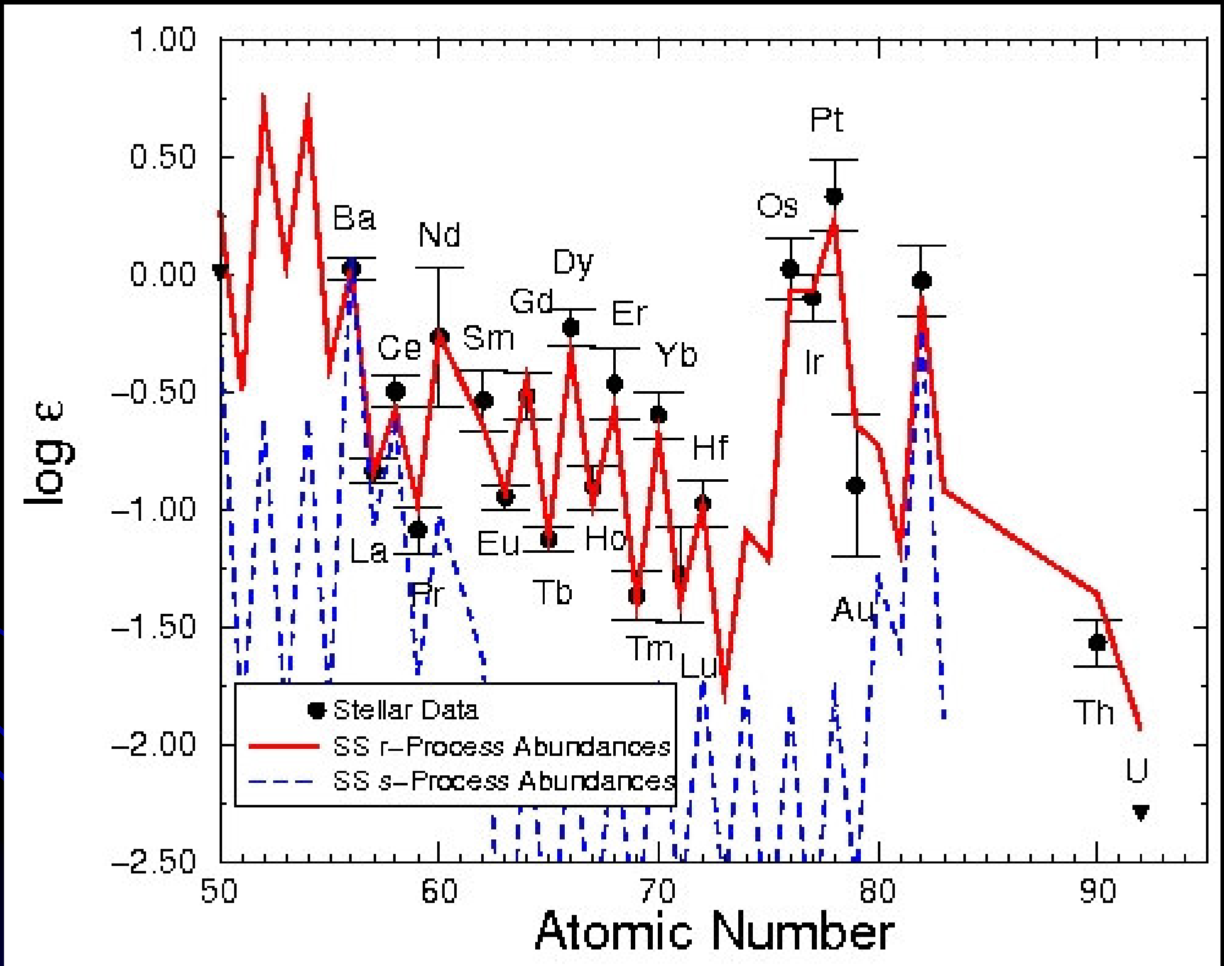
Heavy n-capture elements greatly enhanced (≈ 40-50) over iron abundance.

[Fe/H] = -3.1

$$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$$

n-Capture Abundances in CS 22892-052

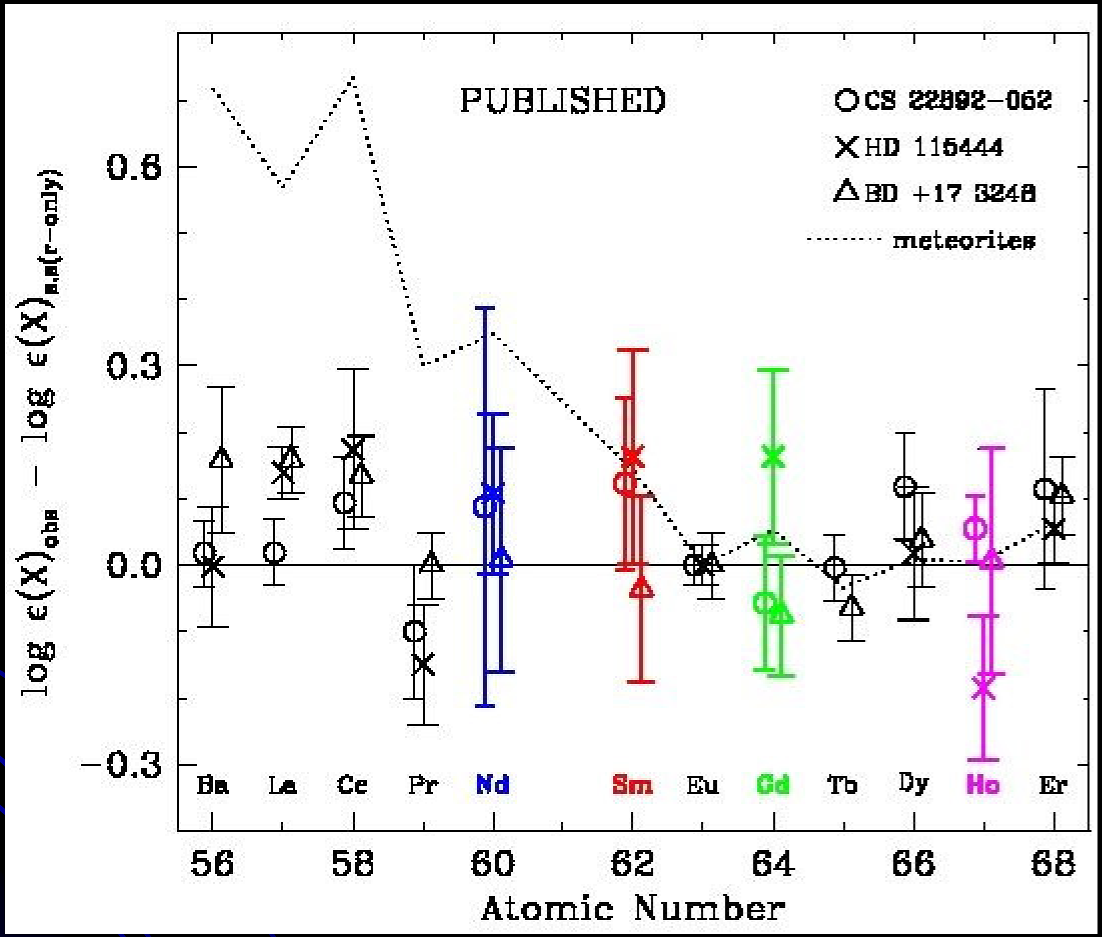
Even s-process elements like Ba made in r-process early in the Galaxy.



Very old star. Robust r-process over the history of the Galaxy.

Stellar elemental abundances consistent with scaled SS r-process only

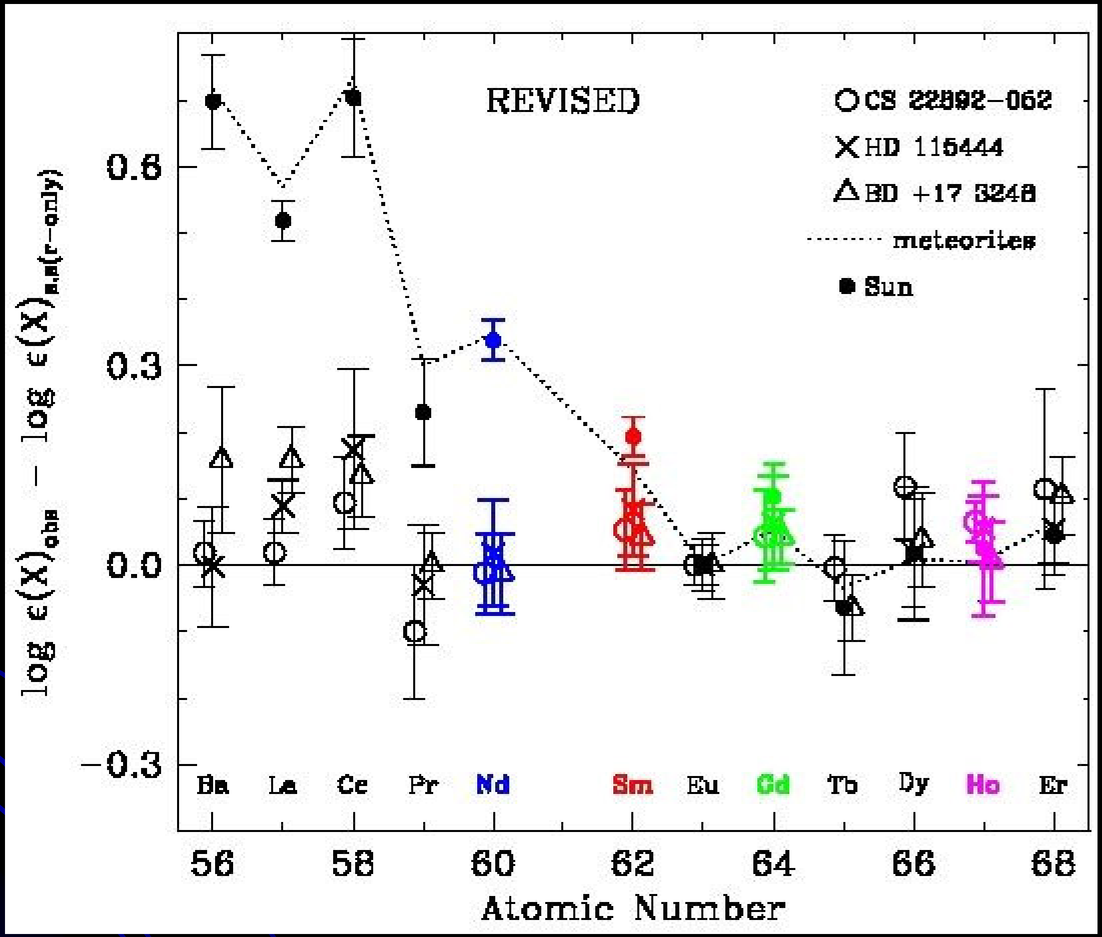
Focus On Individual Elements: Nd, Sm, Gd & Ho



Previous abundance determinations based upon older atomic data.

Reduce abundance uncertainties with new experimental atomic physics data.

Focus On Individual Elements: Nd, Sm, Gd & Ho



New experimental atomic physics data:

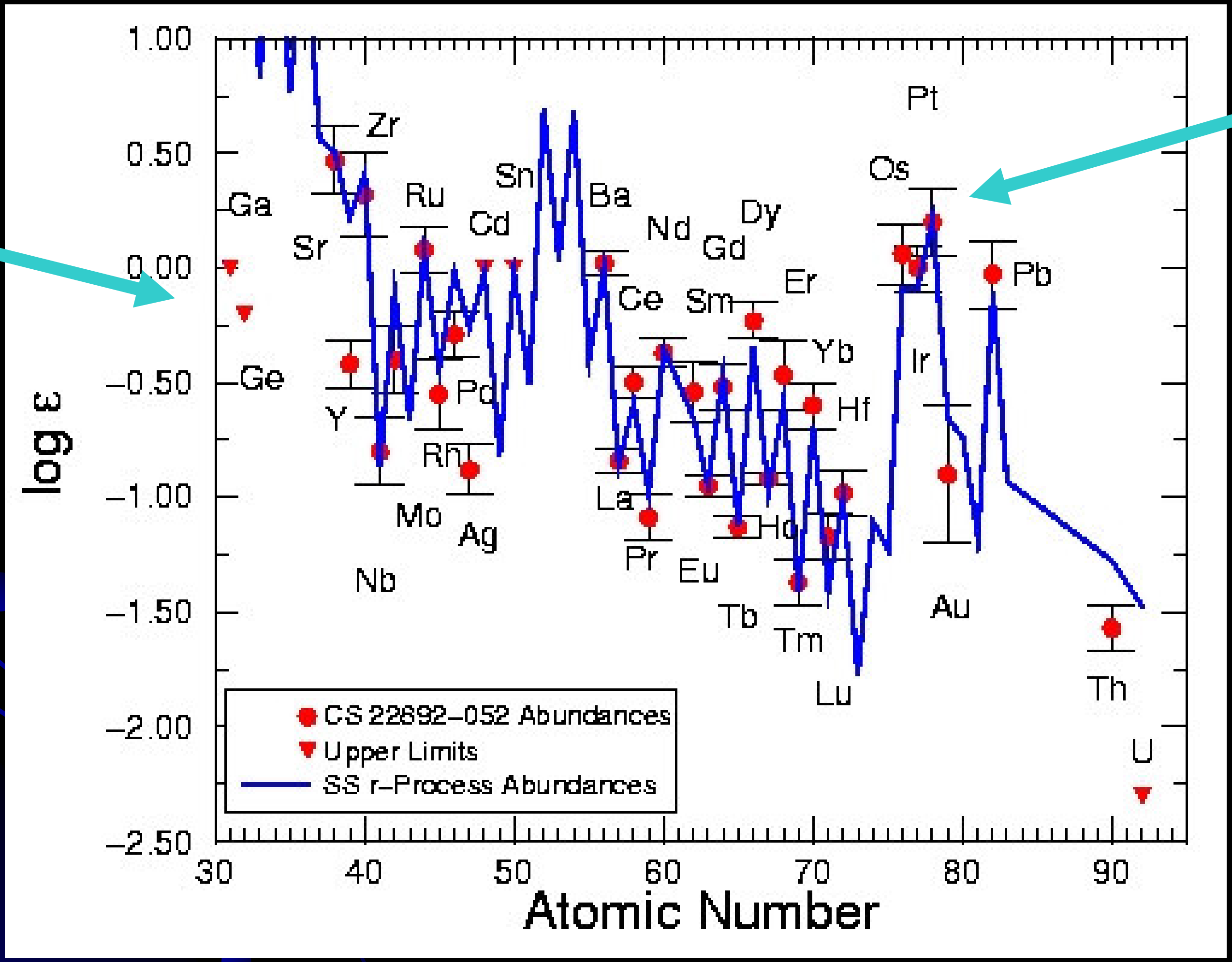
- Nd done (Den Hartog et al. 2003)
- Ho done (Lawler et al. 2004)
- Pt done (Den Hartog et al. 2005)
- Sm done (Lawler et al. 2006)
- Gd done (Den Hartog et al 2006)
- Hf done (Lawler et. al. 2007)

Working our way through the Periodic Table!

CS 22892-052 Abundances

(with new atomic and stellar data, JC et al. 2005)

Germanium



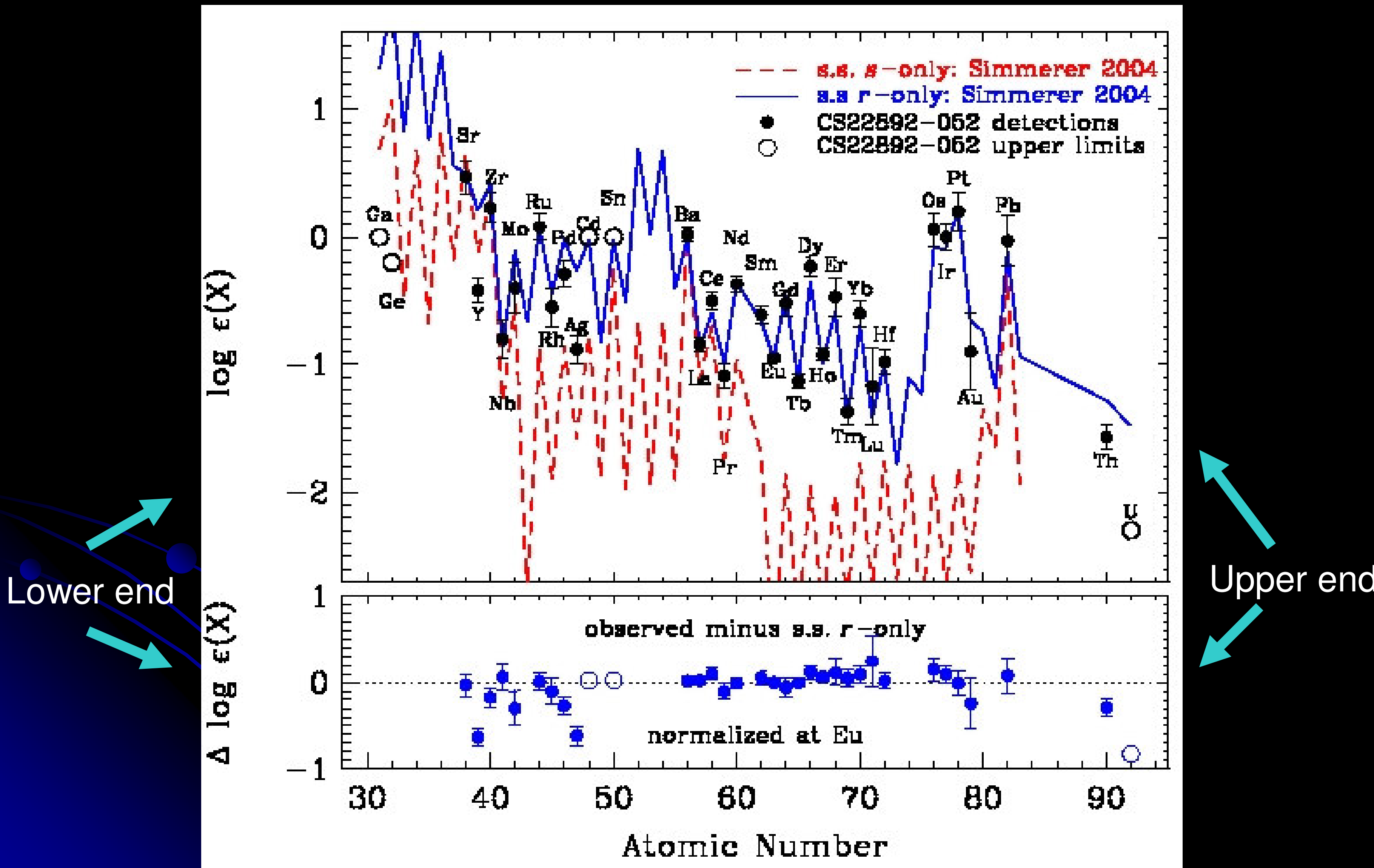
Platinum

(64 HST Orbits)

57 elements observed. More than any star except the Sun.

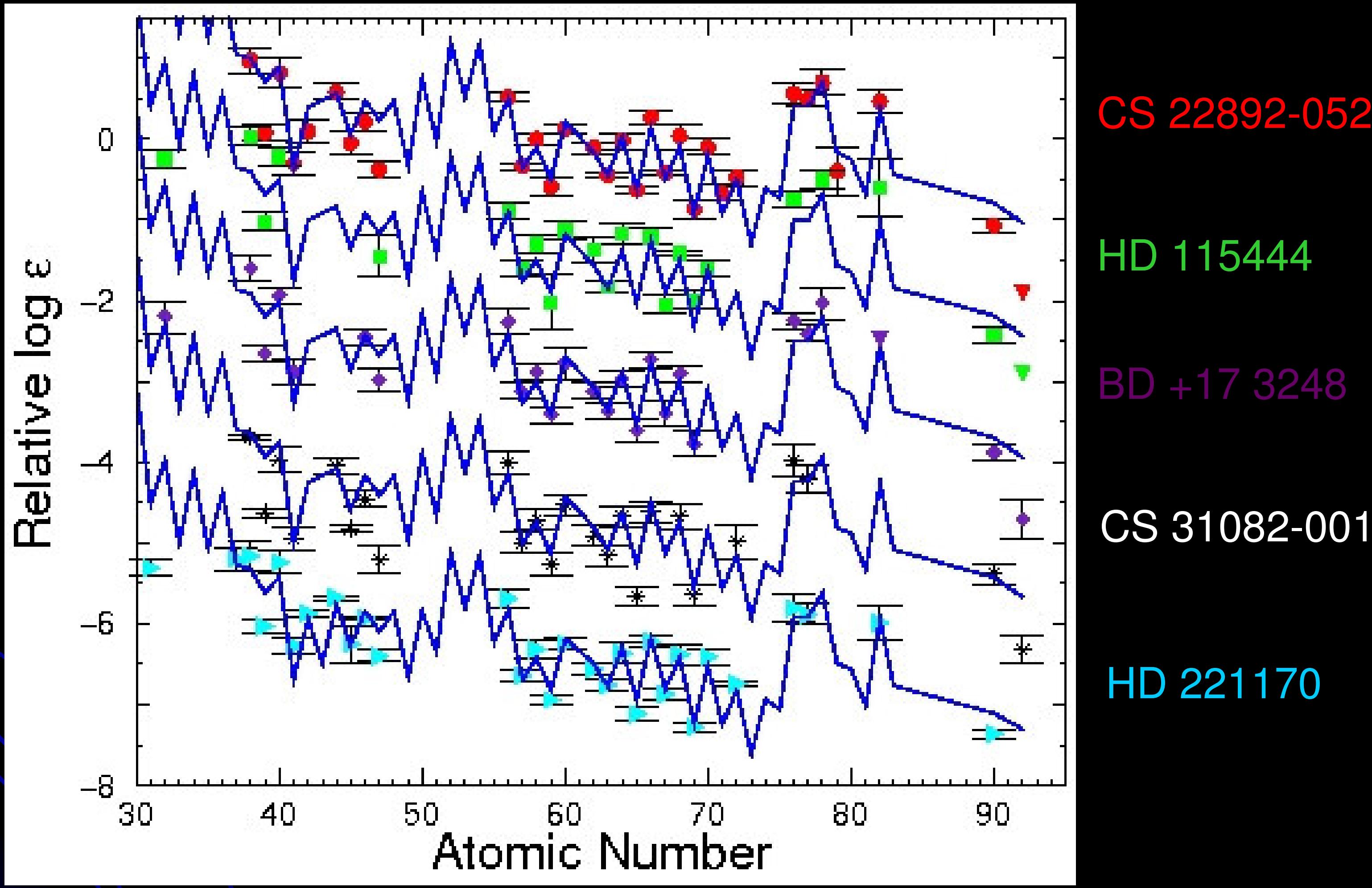
$$\text{Log } \varepsilon(A) = \text{Log}_{10}(N_A/N_H) + 12$$

CS 22892-052 Abundances



(Cowan & Sneden 2006)

Observational Summary of Total Abundances

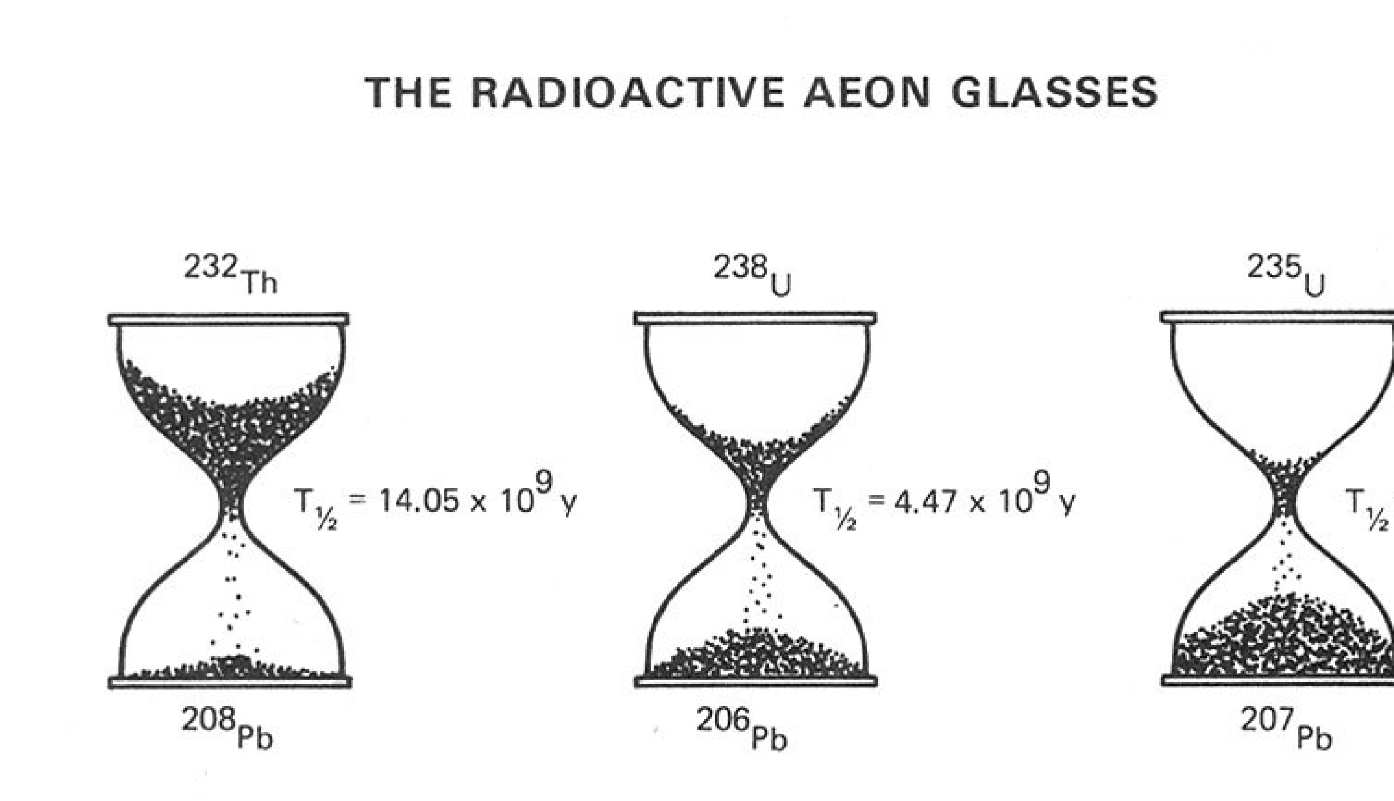


5 r-process rich stars

Same abundance pattern at the upper end and ? at the lower end.

chronometers

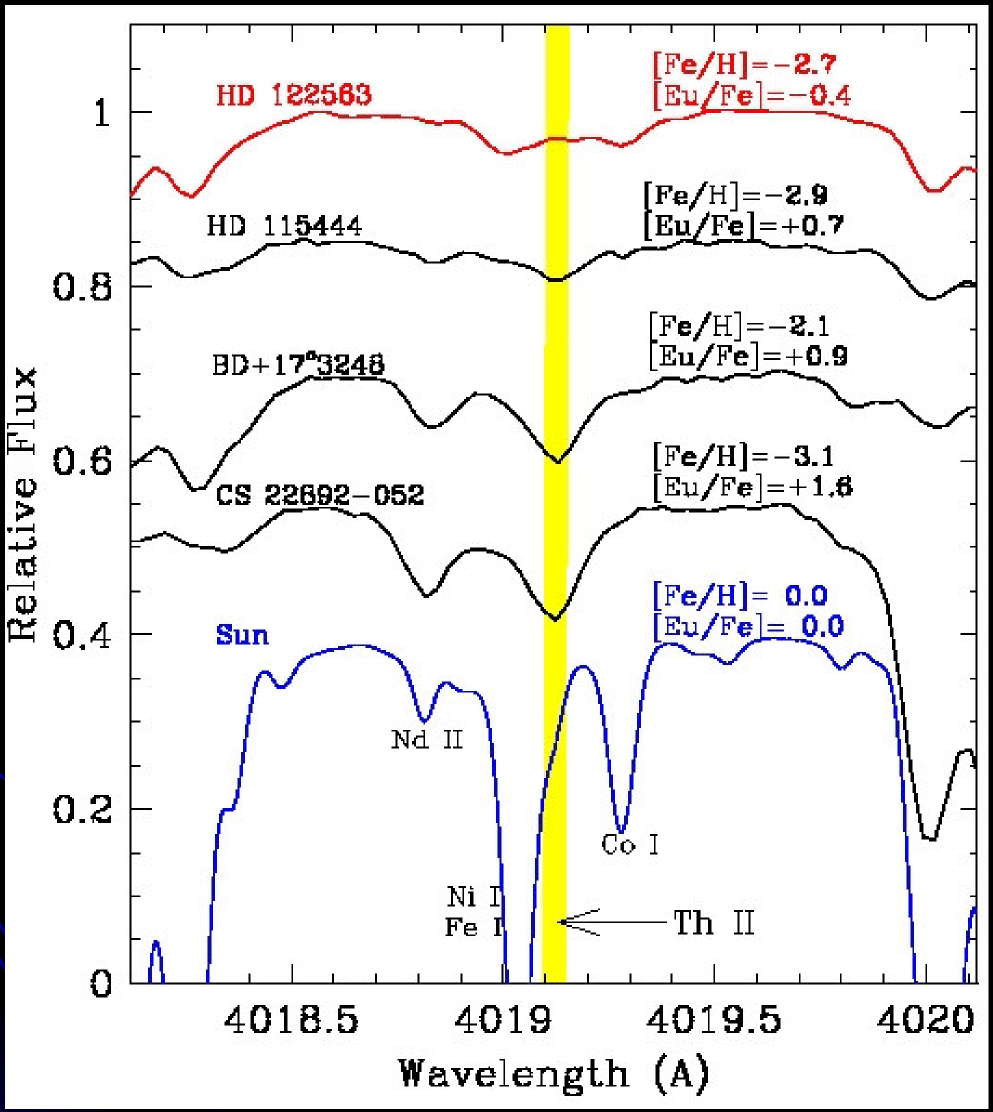
Cosmochronometers



[irrelevant; decays too quickly]

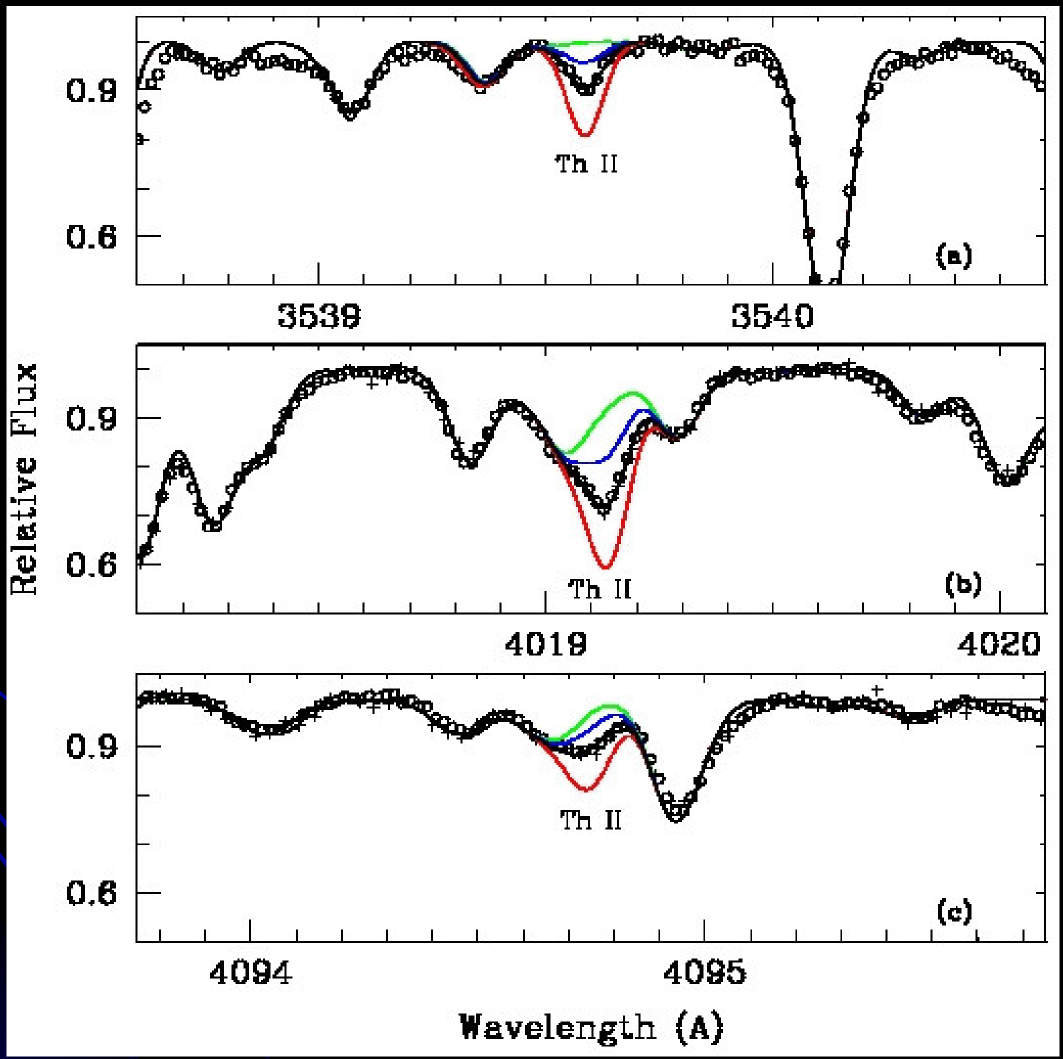
Rolfs & Rodney (1988)

Th Detections in Four Halo Stars and the Sun



Note the strength of the Th lines independent of metallicity

Observed and Synthetic Spectra of Th Lines in HD 221170



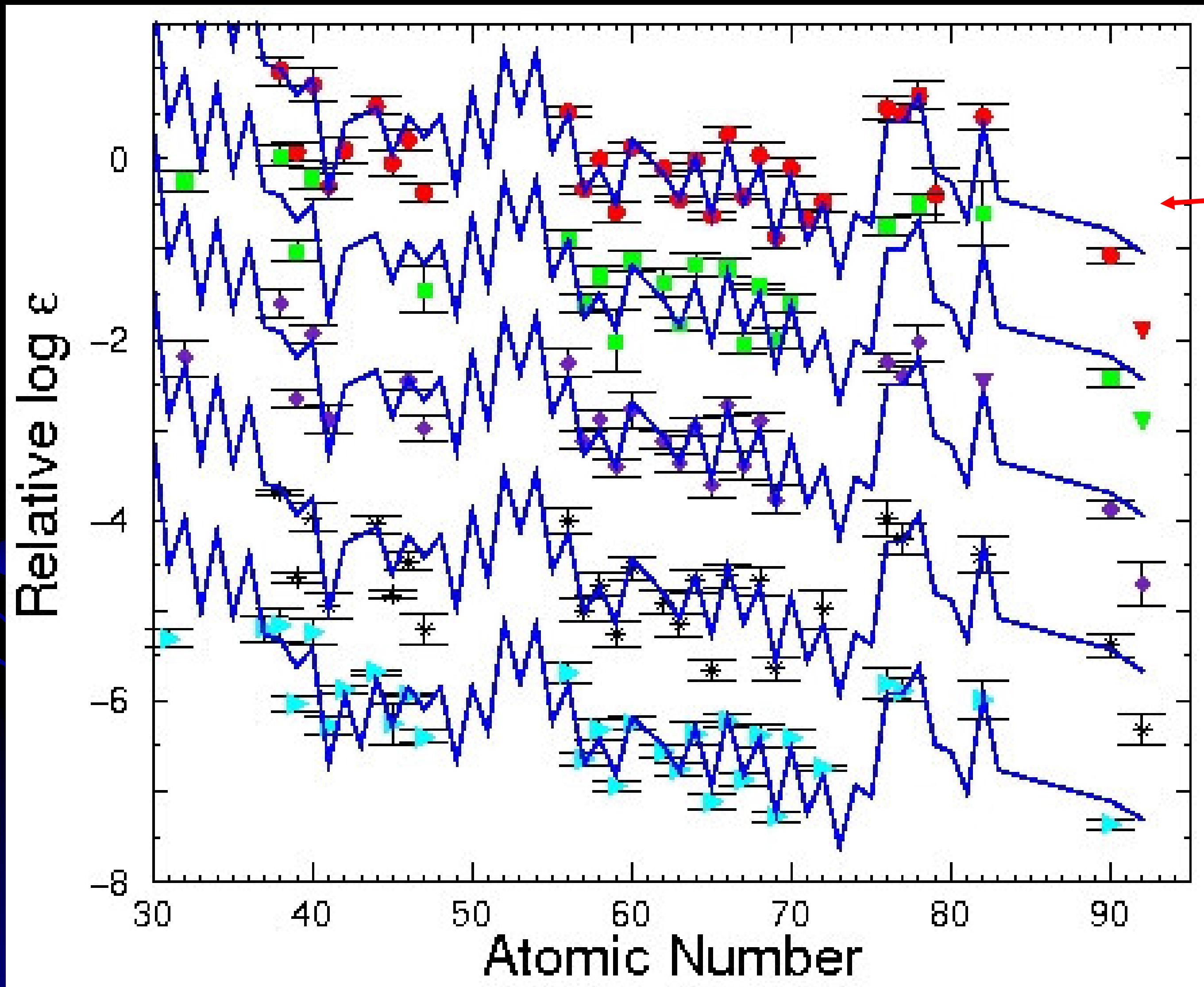
Keck o
McDonald +

Ivans et al. (2006)

Radioactive-Decay Age Estimates

- The measured abundance of Th in stars such as CS 22892-052 allows for age determinations using the long half-life of ^{232}Th (14 Gyr).
- $N_{Th(t)} = N_{Th(t0)} \exp(-t/\tau_{Th})$
- SS Th/Eu (today) = 0.344
- SS Th/Eu (at formation) = 0.463
- Predicted Th/Eu = 0.48 (Cowan et al. 1999), 0.42 (Kratz et al. 2007)
- Measured Th/Eu in CS 22892-052 = 0.24

Halo Star Abundances vs. SS (Time of Formation)

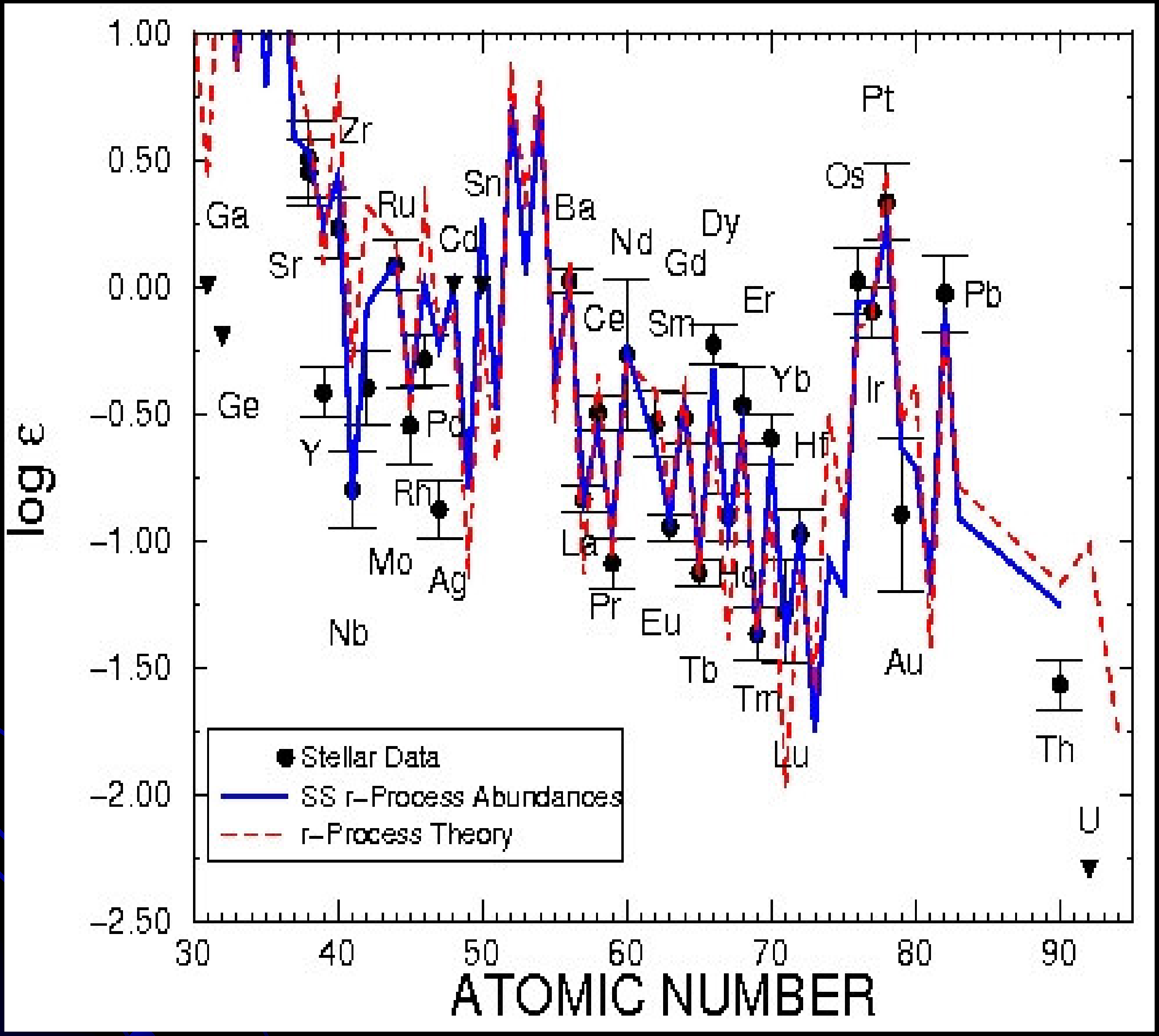


note difference between radioactive Th, U and solid line

R-Process Chronometers

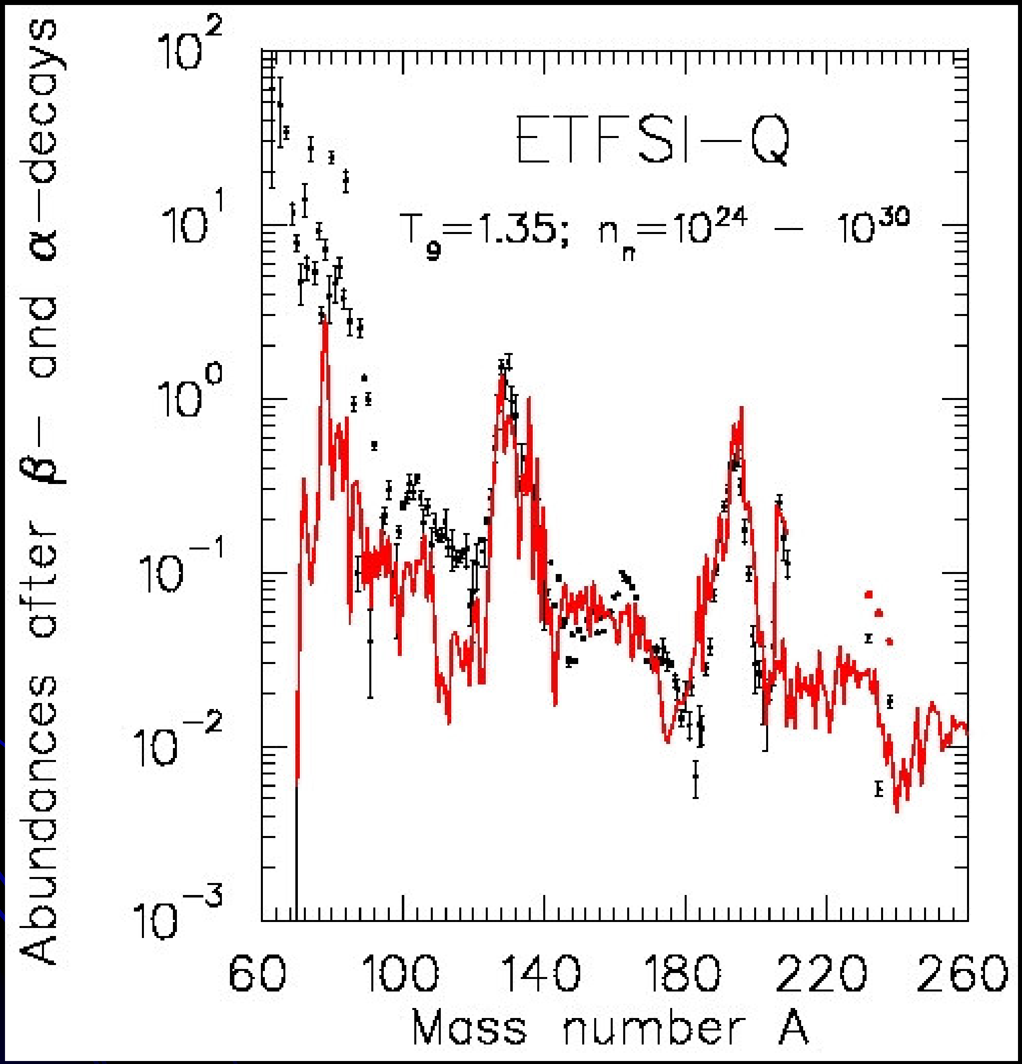
- Use various radioactive abundance ratios: (chronometer pairs both made in the r-process) Th/Eu, Th/U, Th/Pt, etc. to predict initial time-zero values (all made in the r-process)
- Compare with observed ratios
- Is independent of chemical evolution models
- Is independent of cosmological models
- A range of values depending upon uncertainties in nuclear physics predictions (i.e., mass formulae) and abundance uncertainties

Theoretical r-Process Predictions



Calculate radioactive abundance ratios based upon fitting stable elemental & isotopic values.

Theoretical r-Process Predictions



Kratz et al. (2007)

Newer
fit to SS isotopic
stable abundances
allows for
chronometric
ratios

New values of Th/Pt
& Th/U

Chronometric and Other Ages

- For CS 22892-052 (latest values of Th/Eu, Th/Pt) give <14.2> +/- 3 Gyr
- For bd+17 3248 (with the detection of U) Th/U, Th/Eu, Th/Pt, etc. (<13.8> +/- 3 Gyr)
- For CS 31081-001 Th/U = <14.0> +/- <2.8> Gyr
- For HD 221170 Th/Eu = 11.7 +/- 2.8 Gyr
- For HE 1523-0901 Th/U, Th/Eu, Th/Os, etc. = <13.2> +/- 1.1 +/- 2 Gyr
- Compare to globular values (M15 ≈ 14Gyr, from chronometers) & typically 13-15 Gyr
- WMAP of 13.7 Gyr
- SN Ia of 14.2 +/- ≈ 2 Gyr

Typical Errors & Uncertainties

- Observational errors typically +/- 0.05 in log epsilon
- Th/Eu can be done from the ground but widely separated in A
- Th/U desirable but hard to observe

→ +/- ~ 1-2 Gyr

- Theoretical predictions based upon various chronometers: e.g., Th/Eu, Th/U and depending upon nuclear mass models

→ +/- 2-3 Gyr

Errors uncorrelated leading to total uncertainty of ~ 3 Gyr.

Cosmochronometers

Current Status

- Detections of radioactive elements (Th & U) allow age estimates for oldest stars: putting limits on the age of the Galaxy & Universe
- Using chronometer pairs Th/U, Th/Eu, etc. we find an average age of <13-14> +/- ~ 3 Gyr for the oldest stars
- Technique is independent of cosmological models & parameters
- We are seeing dramatic improvements in abundance values due to new experimental atomic data
- Experimental nuclear data along with the improved stellar data are also constraining nuclear predictions for initial radioactive abundances

Cosmochronometers

The Future

- These new experimental data are driving down age uncertainties
- Eventually these improvements will allow for very accurate chronometric age determinations
- These new more precise values could constrain cosmological parameters (Hubble constant, etc.) and cosmological models

With Collaborators at:

- U. of Texas
- MSU
- U. of Chicago
- Caltech
- MIT
- Carnegie Obs.
- U. of Wisconsin
- U. of Mainz
- Obs. de Paris
- U. of Basel
- U. di Torino
- ESO

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