Abundance Constraints on the Two r-Processes

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- **We call attention to problems associated with the character of the two distinct r-process that may participate in the synthesis of nuclei below and above mass A~130-140.**

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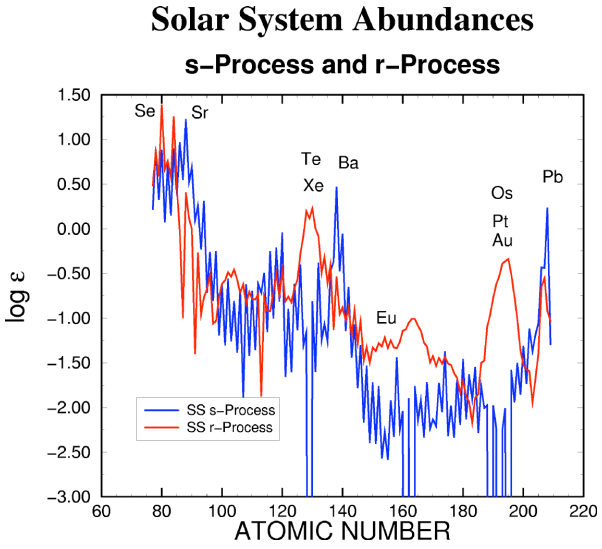
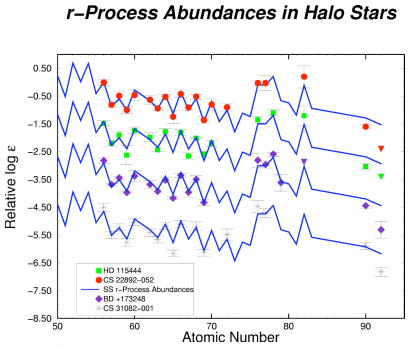
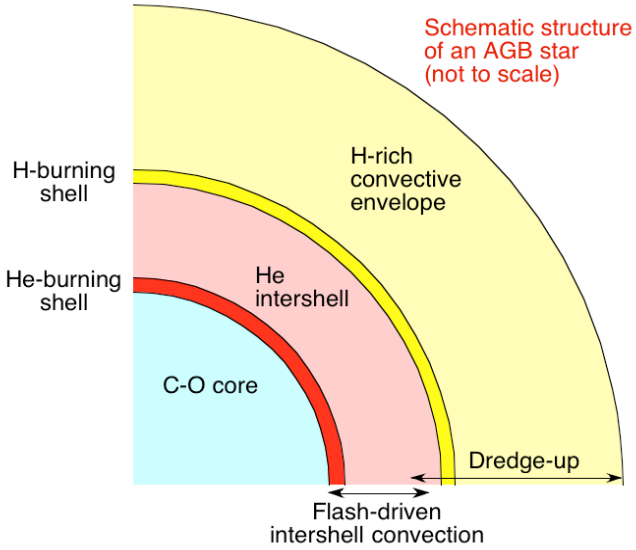
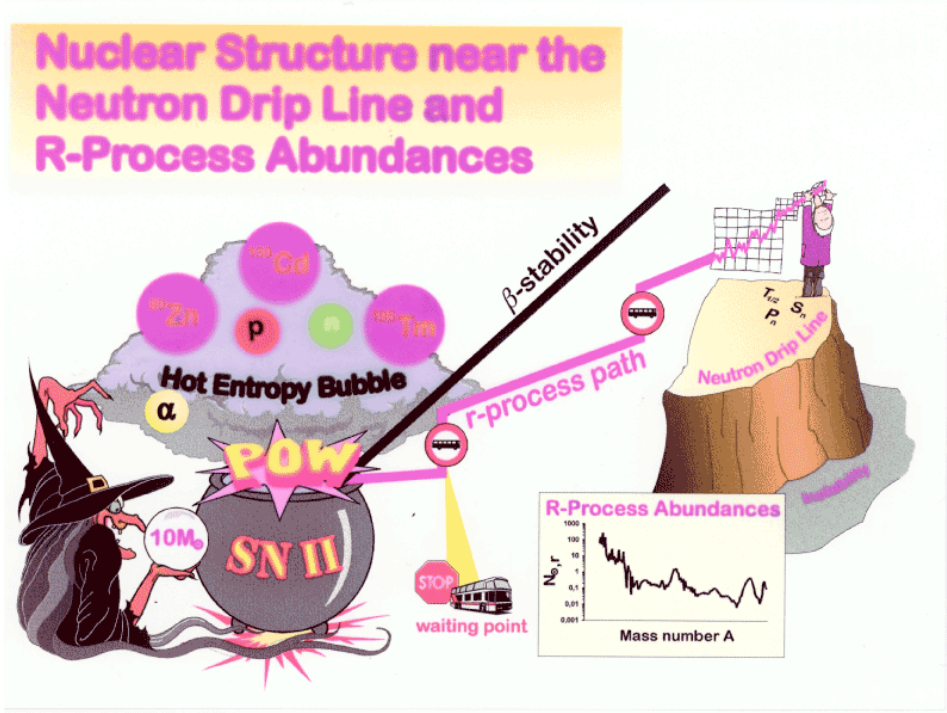
Synthesis of Nuclei Beyond Iron





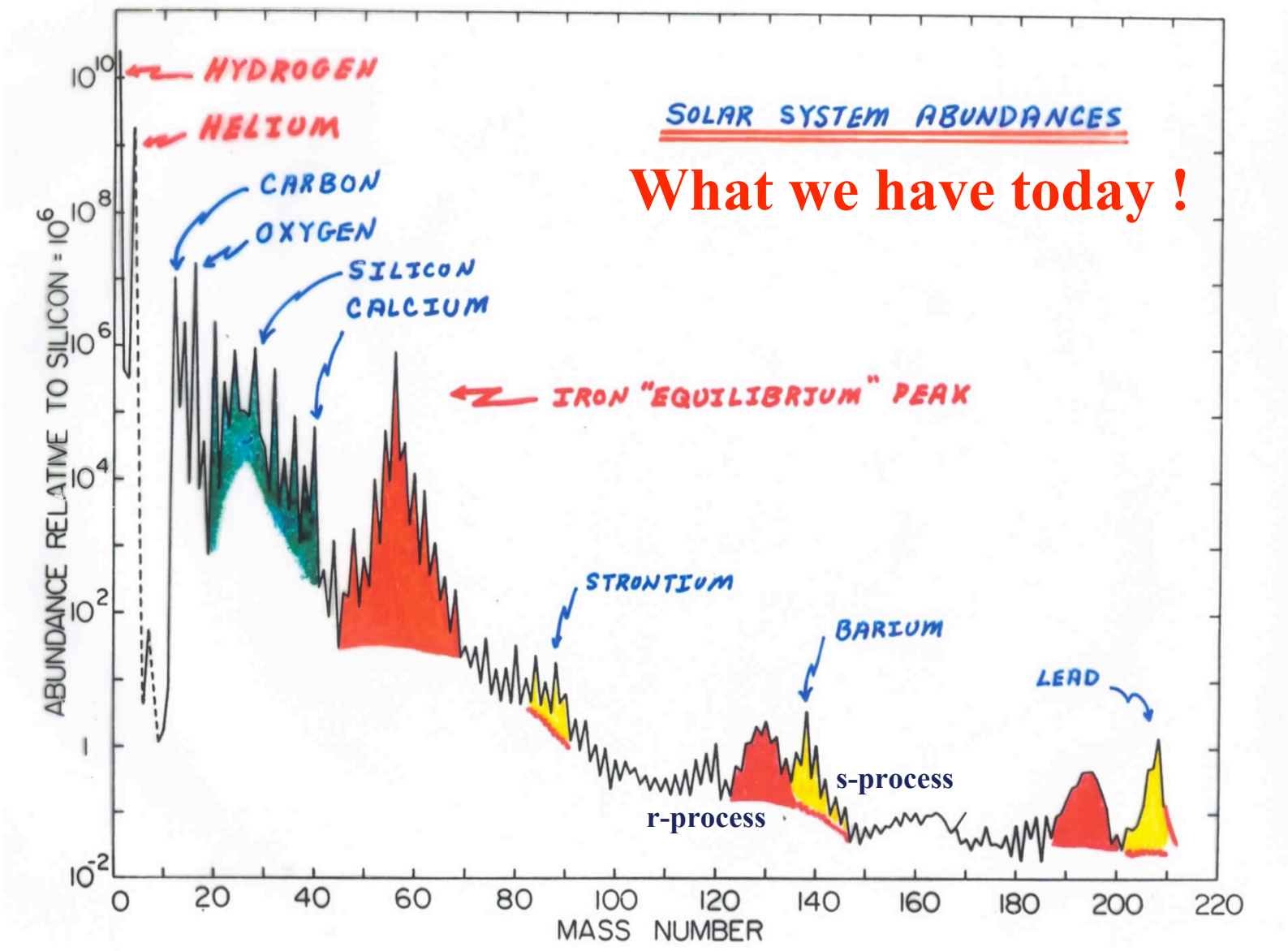


s-process in red giants



r-process in supernovae

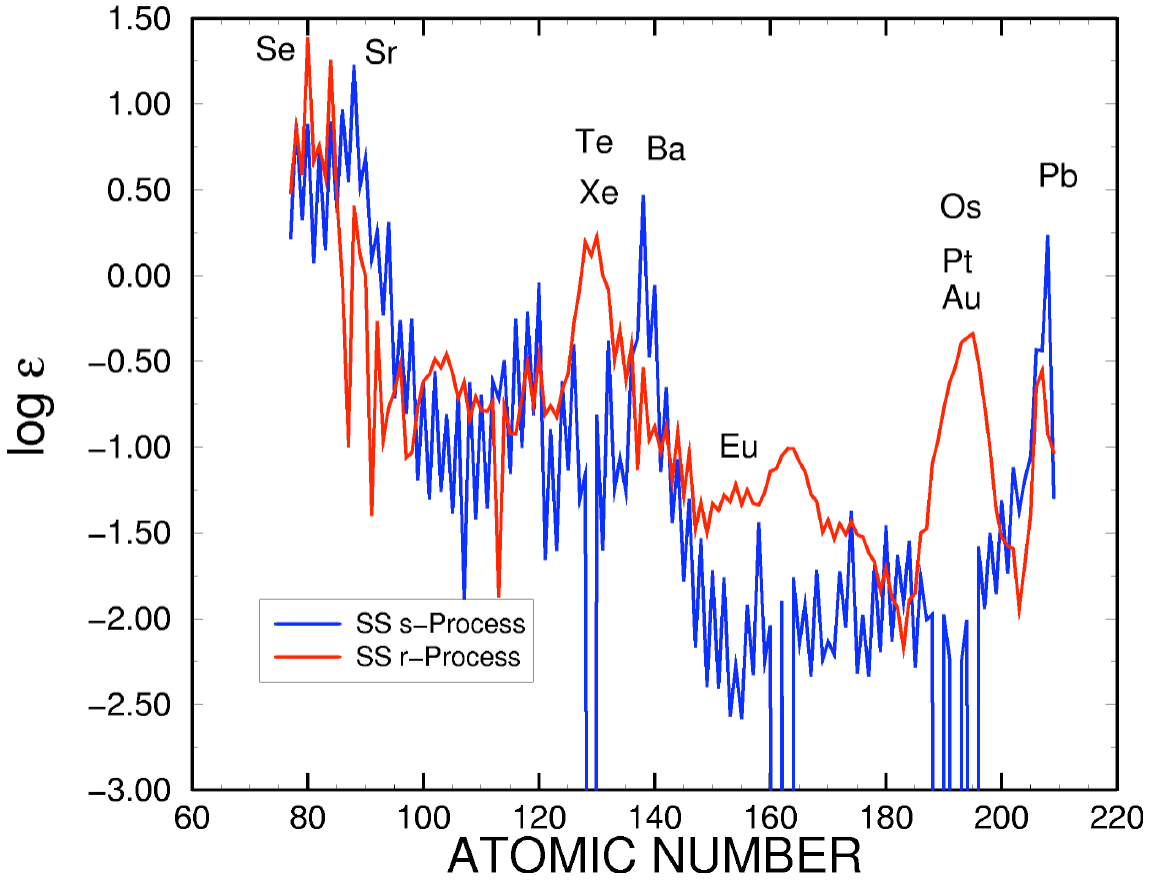
Cosmic Abundances



Distinctive Neutron Capture Products

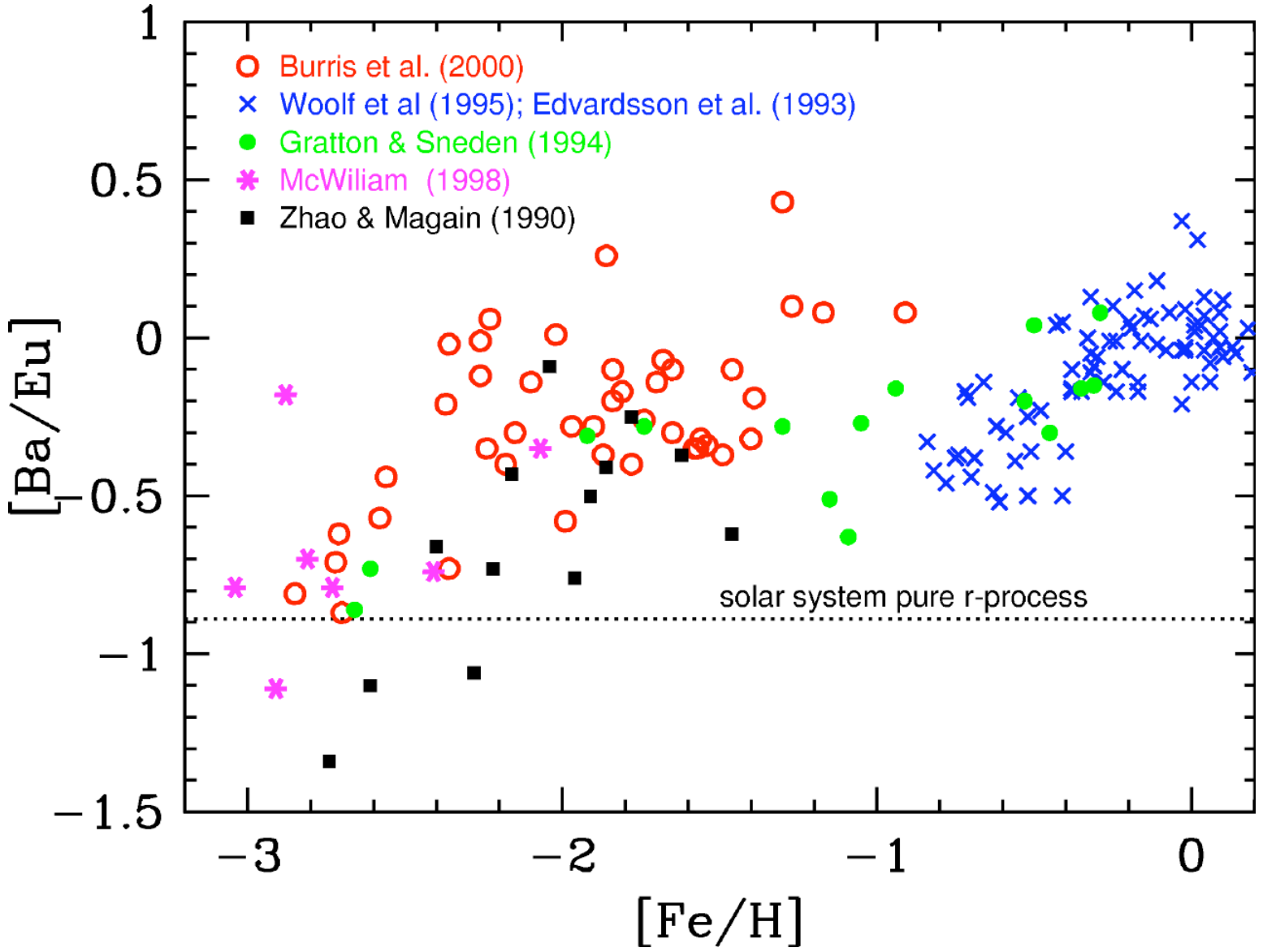
Solar System Abundances

s–Process and r–Process



(A success story of experimental nuclear physics.)

s-Process/r-Process Chemical Evolution



(Truran et al. 2002)

r-Process Sites and Timescales

- **The observation that r-process nuclei in solar abundance patterns characterize the oldest stars in our Galaxy virtually demands that the main astrophysical site is that associated with massive stars (SNe II) and/or their remnants.**
  - **Neutrino-driven winds from SNe II**
  - **Neutron star mergers**
  - **Shock processing of helium/carbon shells**
- **Two sites with different timescales (??): this has both attractive and problematic features**

Interesting Nuclear Chronometers

Long-Lived Galactic Chronometers ($\tau_{1/2} \gtrsim 10^9$ yr)

Nucleus	$\tau_{1/2}$ (Years)	Daughter	Decay Mode	Nucleosynthesis Process
^{40}K	1.3×10^{9}	^{40}Ca	β^-	s$^-$/ ?
^{40}K	1.3×10^{9}	^{40}Ar	β^+	s$^-$/ ?
^{87}Rb	4.9×10^{10}	^{87}Sr	β^-	r-/ s-process
^{138}La	1.1×10^{11}	^{138}Ba	EC	p-process
^{138}La	1.1×10^{11}	^{138}Ce	β^-	p-process
^{147}Sm	1.1×10^{11}	^{143}Nd	α	s-/ r-process
^{176}Lu	3.7×10^{10}	^{176}Hf	β^-	s-process
^{187}Re	4.5×10^{10}	^{187}Os	β^-	r-process
^{232}Th	1.4×10^{10}	^{208}Pb	Decay Chain	r-process
^{235}U	7.0×10^{8}	^{207}Pb	Decay Chain	r-process
^{238}U	4.5×10^{9}	^{206}Pb	Decay Chain	r-process
^{107}Pd	6.5×10^{6}	^{107}Ag	β^-	s-/ r-process
^{129}I	1.6×10^{7}	^{129}Xe	β^-	r-process
^{182}Hf	9.0×10^{6}	^{182}W	β^-	r-process
^{244}Pu	8.2×10^{7}	^{232}Th	Decay Chain / SF	r-process

Evidence for Two r-Processes

- **Uniform Nucleosynthesis of ^{129}I and ^{182}Hf:**
  Wasserburg et al (1996) argue from the inconsistency of the behaviors of ^{129}I and ^{182}Hf for the possible existence of a second r-process that would produce most of the r-isotopes in the mass range A ≤ 130-140.
- **The observed abundances in this range in metal-poor stars (e.g. CS 22892-052) appear to be consistent with such a view.**

Deviations from Uniform Nucleosynthesis

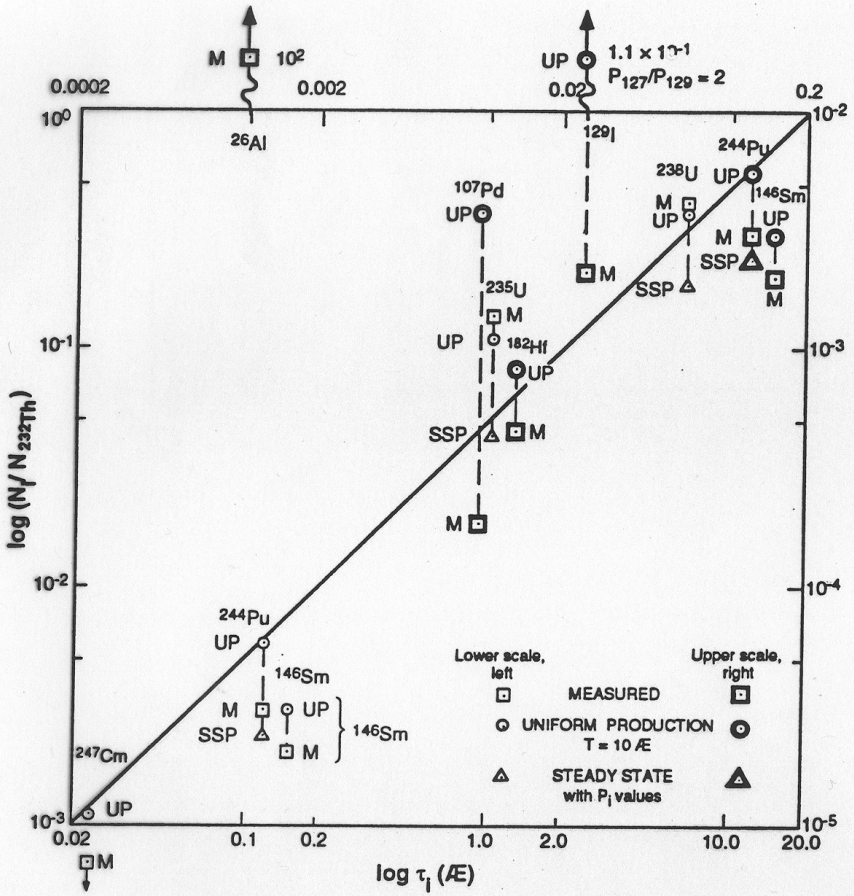


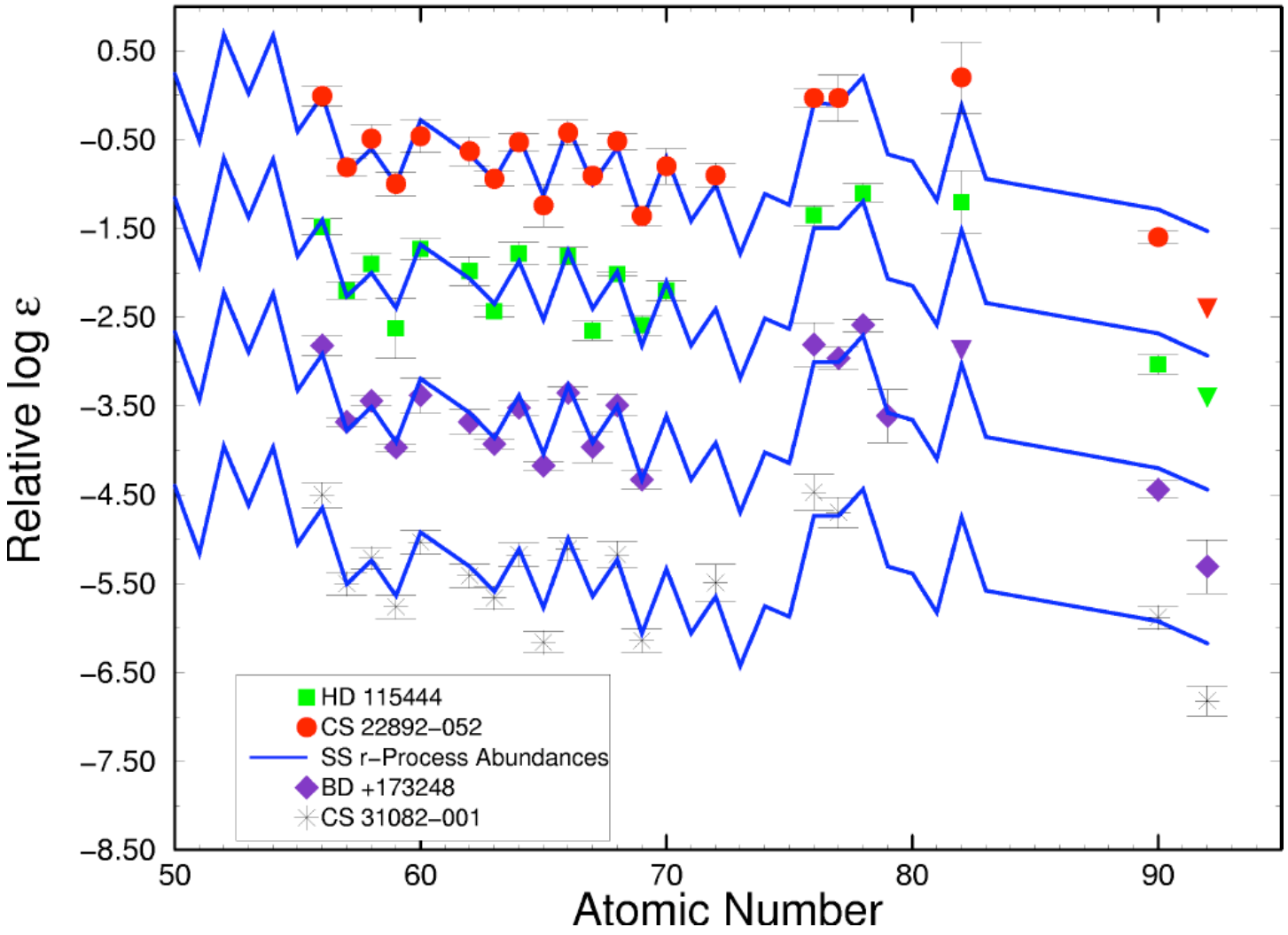
Fig. 1. Graph of $\log(N_i/N_{^{232}Th})$ versus $\log\bar{\tau}_i$. Full line corresponds to steady state with P_i^{AC} = const.; ⧋ for standard production ratios; ⊙ for uniform production over 10 Æ; and ⊡ the observed values.

(Wasserburg, Busso, & Gallino 1996)

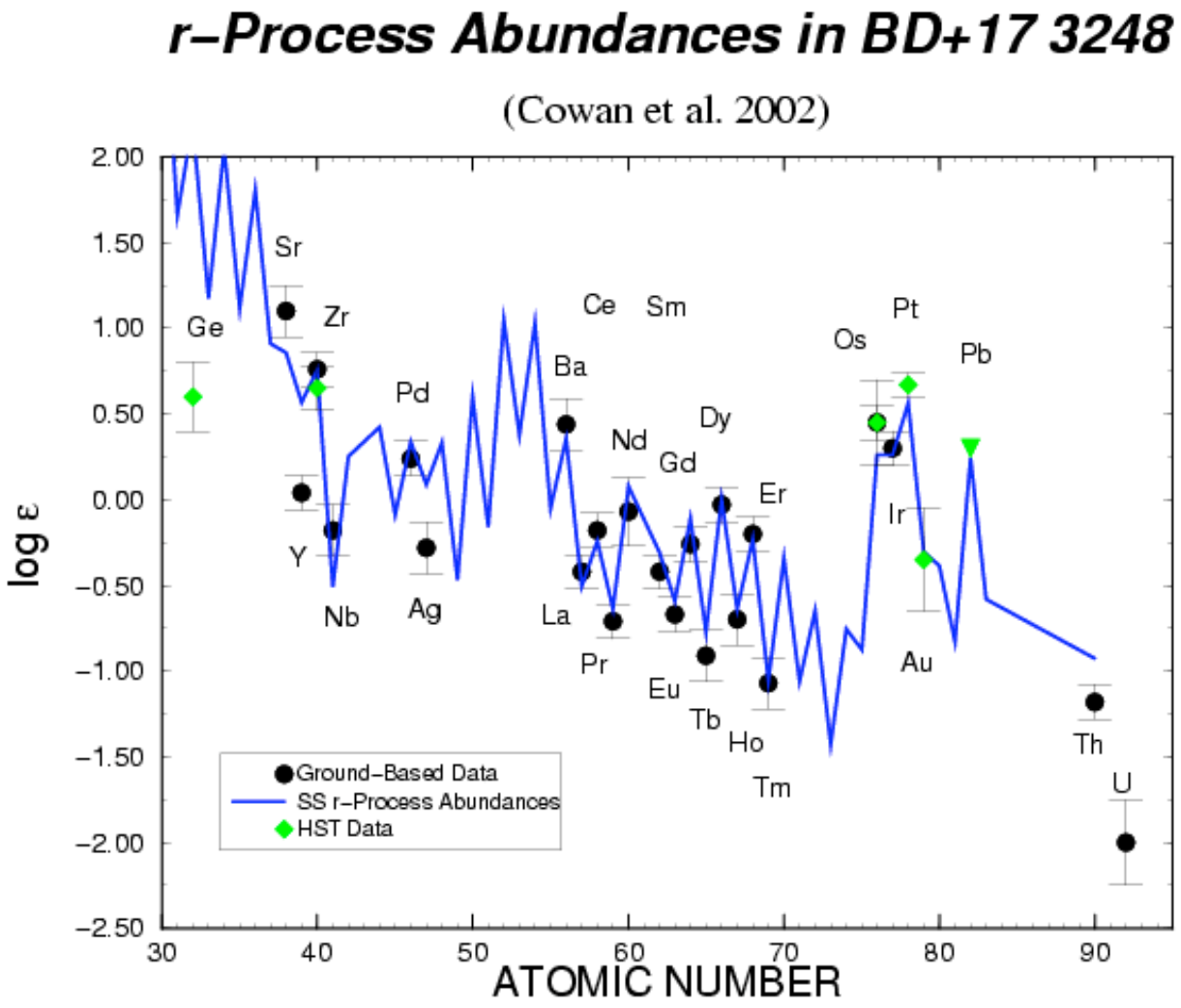
Evidence for Two r-Processes

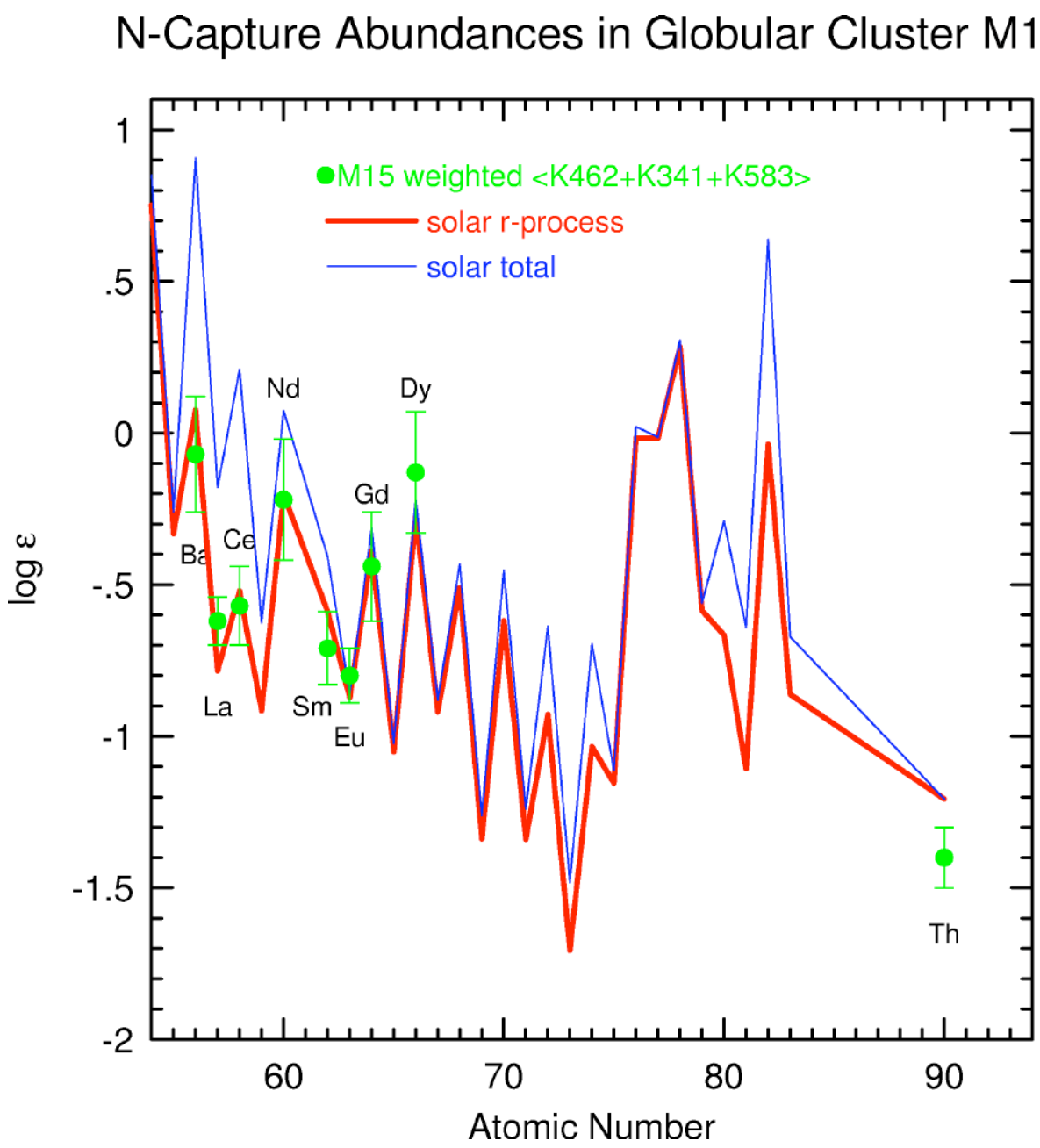
- **r-Process Enrichments in Halo Stars: Observations of extremely metal deficient halo stars confirm that the heavy r-process elements including the important actinide chronometers have a nucleosynthesis history that spans virtually the entirety of Galactic history.**
- **The robustness of the agreement over the mass range 130-140 ≤ A ≤ 210 is particularly significant. (The actinide region is less secure.)**

r–Process Abundances in Halo Stars

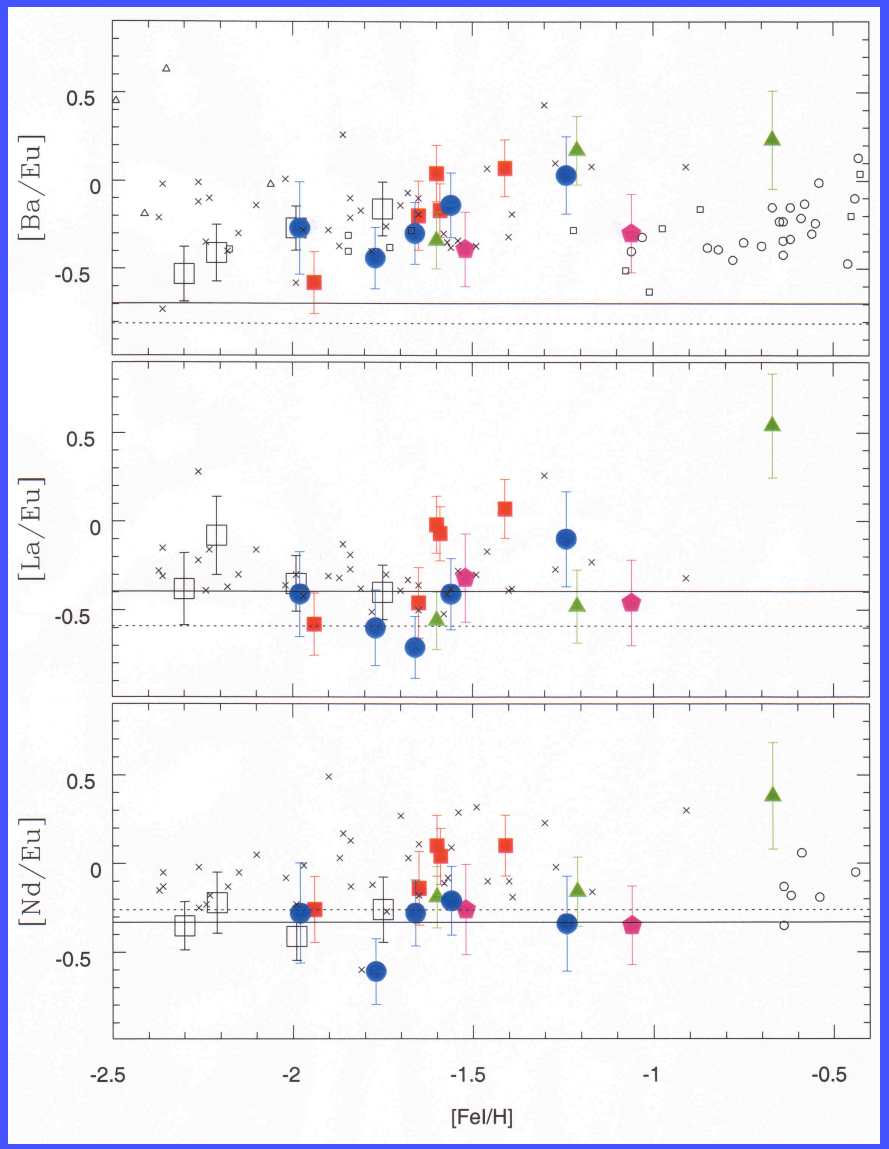


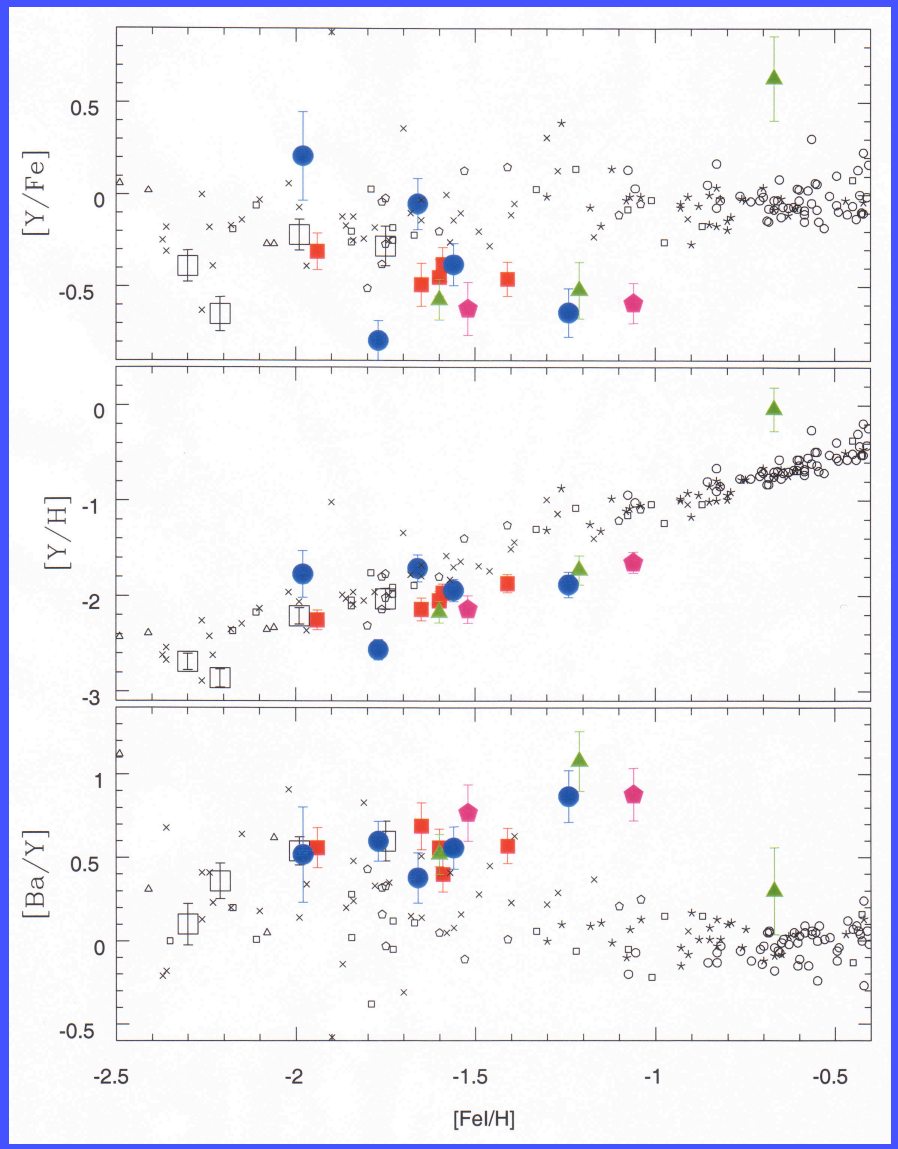
r-Process Abundances in BD+17 3248




N-Capture Abundances in Globular Cluster M15
M15 weighted <K462+K341+K583>
solar r-process
solar total
log ε
Atomic Number
1
.5
0
-.5
-1
-1.5
-2
60
70
80
90
Ba
Ce
Nd
Dy
Gd
La
Sm
Eu
Th

Abundances in Dwarf Spheroidal Galaxies



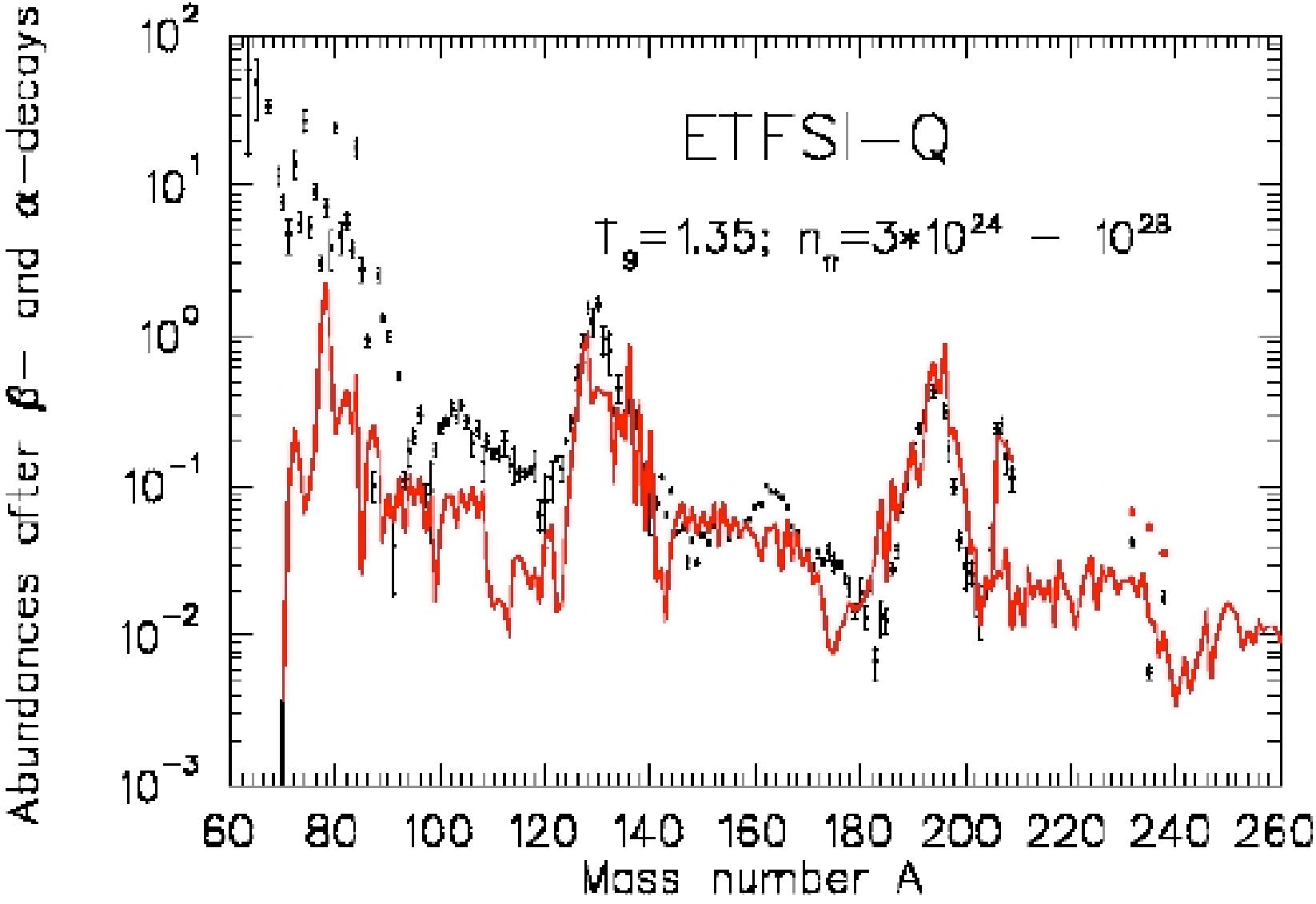


(Shetrone et al. 2003)

R-Process Calculations

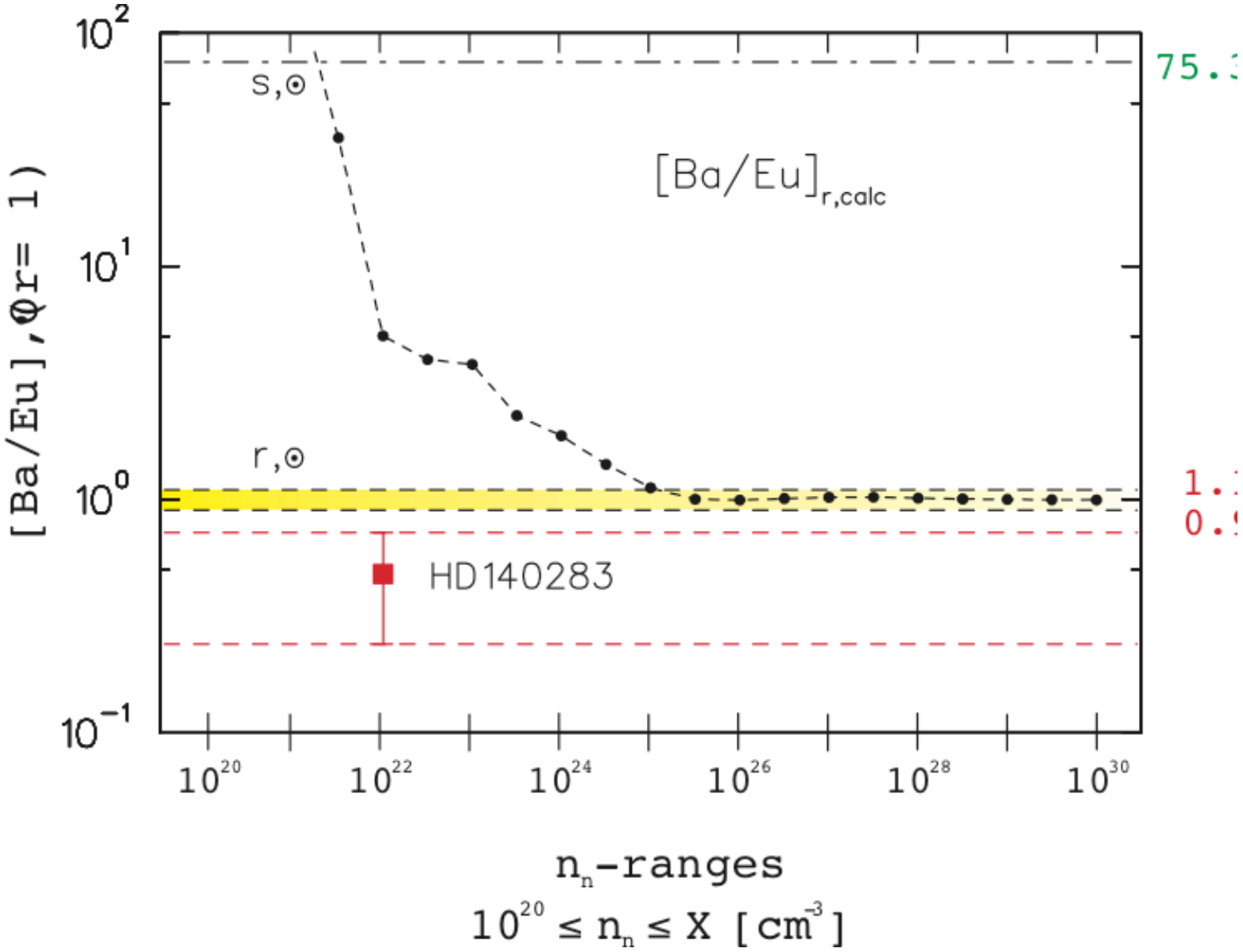
- **We have calculated the r-process patterns for conditions of the waiting-point approximation, in the context of a model reflecting a distribution of neutron exposures, guided by our understanding of the nature of the yet unidentified astrophysical site. This yields:**
  - **a good fit to the solar system r-process pattern Ba to Pb;**
  - **a measure of the conditions for which the mass region A>140 is formed in solar proportions; and**
  - **a measure of the abundance ratio I/Ba as a function of the neutron exposure.**
  - **Our calculations indicate that, for conditions compatible with the "main" r-process producion of the Ba-to-Pb nuclei, the level of production of ^{129}I relative to barium is approximately 90-95 percent of its solar system value.**

Calculated Fit to Solar r-Process Pattern

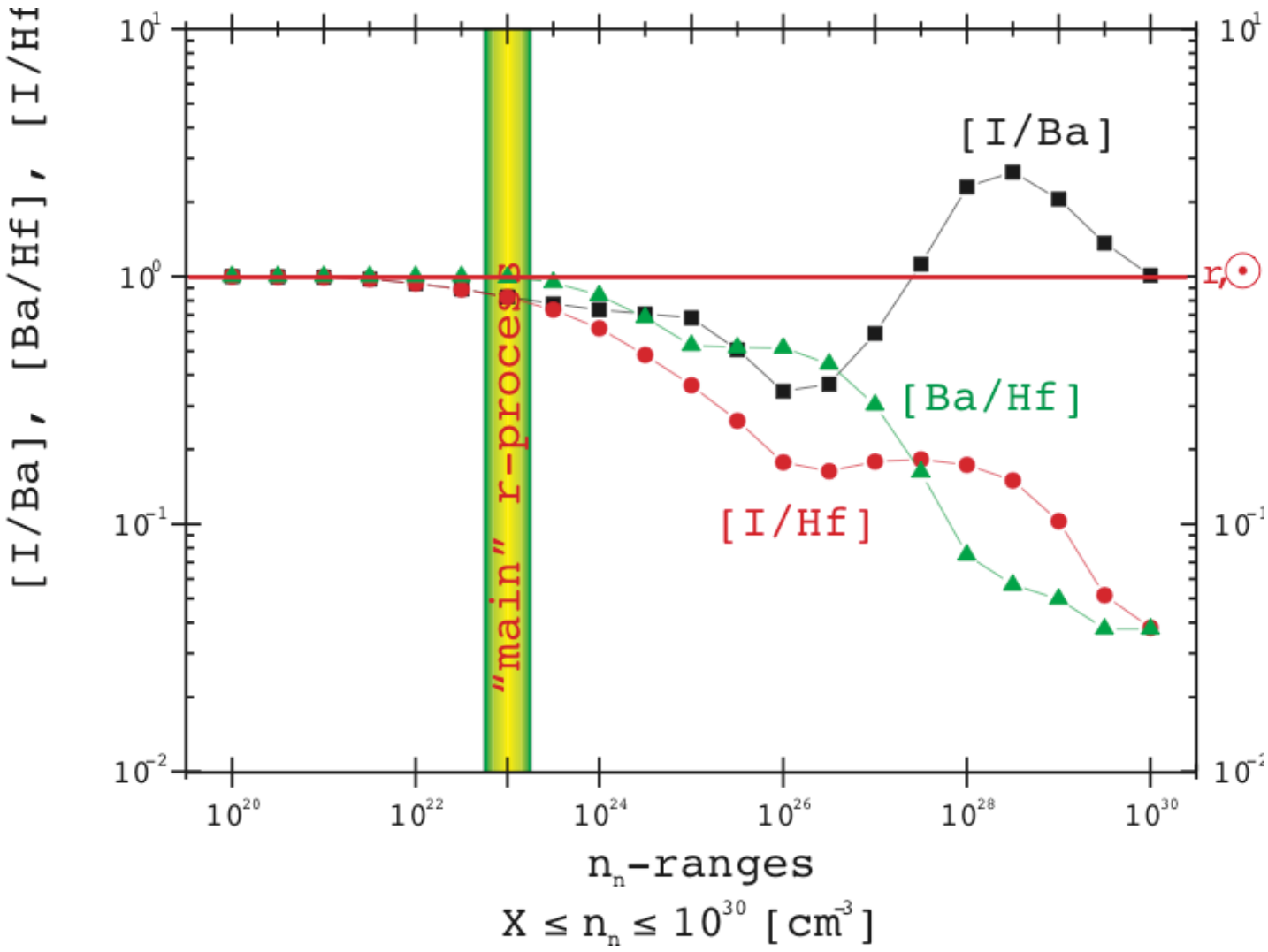


Kratz et al. (2004)

Cosmic Abundances



Cosmic Abundances



A Challenge to the Current Paradigm

- **The combined elemental and isotopic data on low metallicity r-process-rich stars confirms a robust r-process extending over the range $130 \leq A \leq 238$.**
- **The case for a second r-process for the mass region is supported by halo star observations, which indicate that the light r-nuclei in this regime are under produced over a broad range of conditions and [r-process/Fe].**
- **For the studied r-process-rich stars, the observed ratio N(A<130)/N(A>130) is both approximately constant and systematically low with respect to solar r-process abundances. (Debris of the main r-process?)**

A Challenge to the Current Paradigm

- **On the basis of an isotopic analysis of the metal poor ([Fe/H]=-2.4) halo star HD140283, Lambert and Prieto (2002) argue for an r-process origin for the barium in this star.**
- **The r-process model calculations we have performed in the context of the waiting point classical r-process approximation indicate that the associated level of production of ^{129}I is at a level ~ 90 percent its solar r-process value, relative to the Ba-Pb region.**
- **This behavior is in conflict with the Wasserburg *et al.* (1996) model that argues that there must be different sources for ^{129}I and ^{182}Hf.**

A Challenge to the Current Paradigm

- **On the basis of an analysis of the $^{244}Pu/^{238}U$ ratio, in the context of an infall model for galactic chemical evolution, Dauphas (2005) has argued alternatively that ^{129}I and ^{244}Pu in the early solar system must be inherited from chemical evolution, while ^{107}Pd and ^{182}Hf are rather injected into the early solar nebula by the explosion of a nearby supernova.**

- **There thus would appear to remain significant open questions concerning the use of these radioactivities to constrain models of r-process nucleosynthesis.**