STELLAR ABUNDANCES, HEAVY ELEMENT FORMATION AND THE AGE OF THE GALAXY

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University of Basel - October 14, 2011

Top 11 Greatest Unanswered Questions of Physics

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the Universe begin?

National Research Council Report, Discover Magazine (2002).

Abundance Clues and Constraints

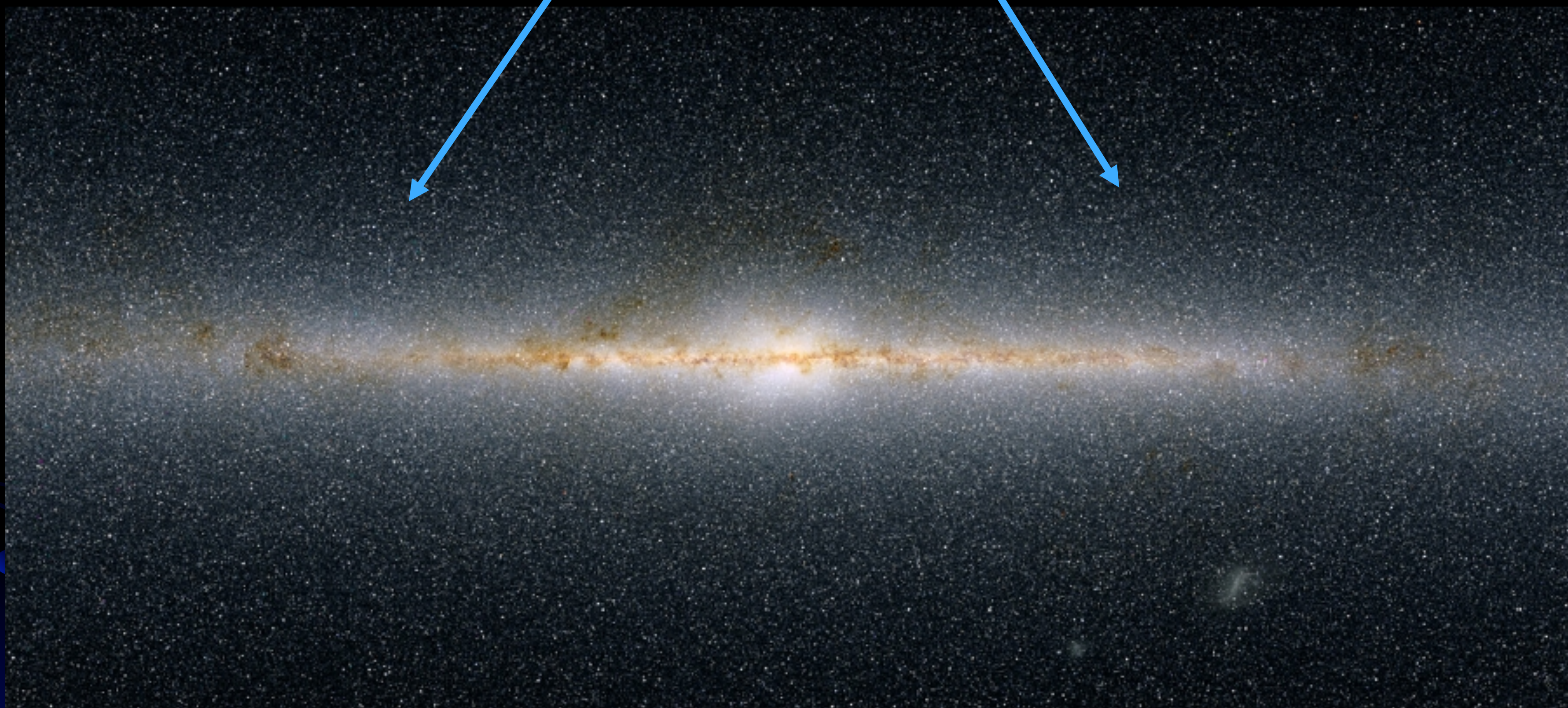
- New observations of n-capture elements in low-metallicity Galactic halo stars providing clues and constraints on:

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

Heavy Element Syntheis

2MASS View of the Milky Way

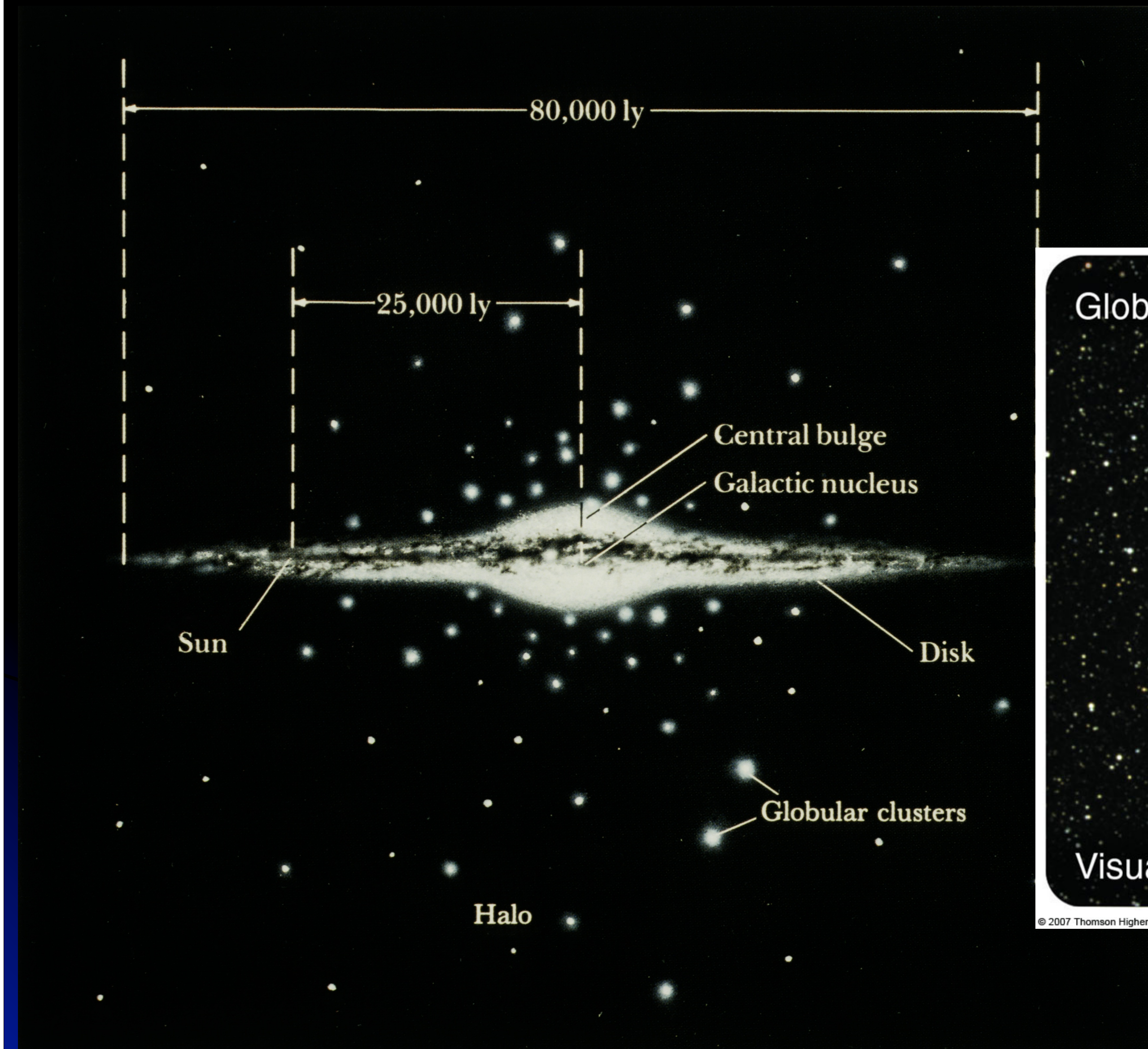
Galactic Halo Stars

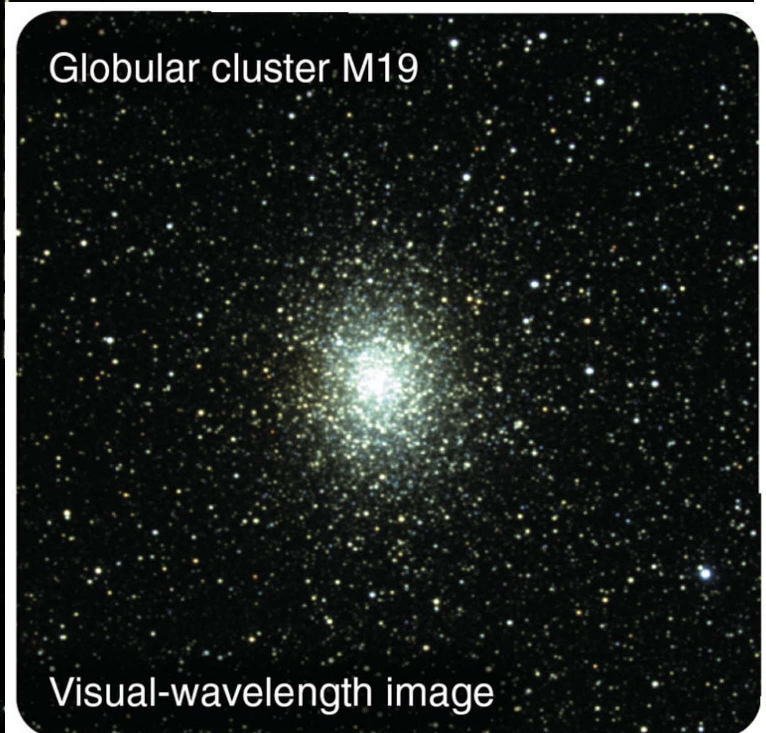


- Metal-poor Halo Stars are ``fossils'' of the Early Universe
- These Stars are Relatives of the First Stars in the Universe

``Near Field Cosmology''

Artistic View of the Milky Way





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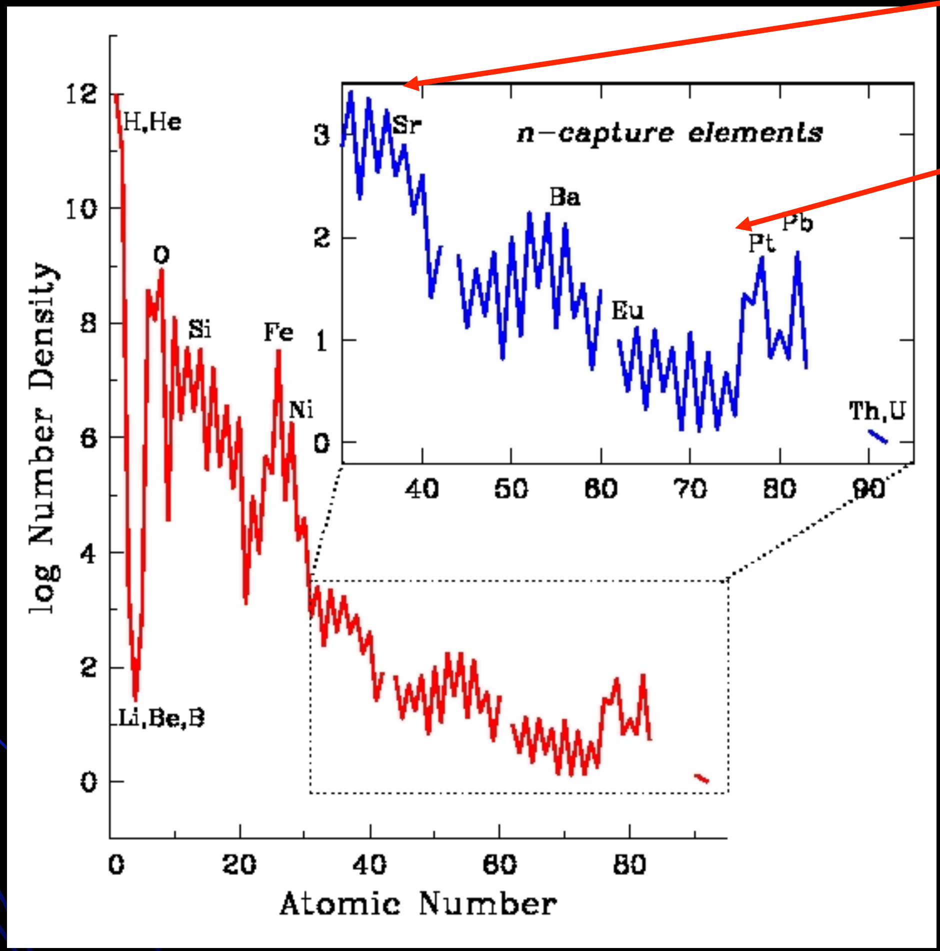
Heavy Element Synthesis

- 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

Solar System (``Cosmic") Abundances



Ge, Zr

Os, Pt

Jewelry store items

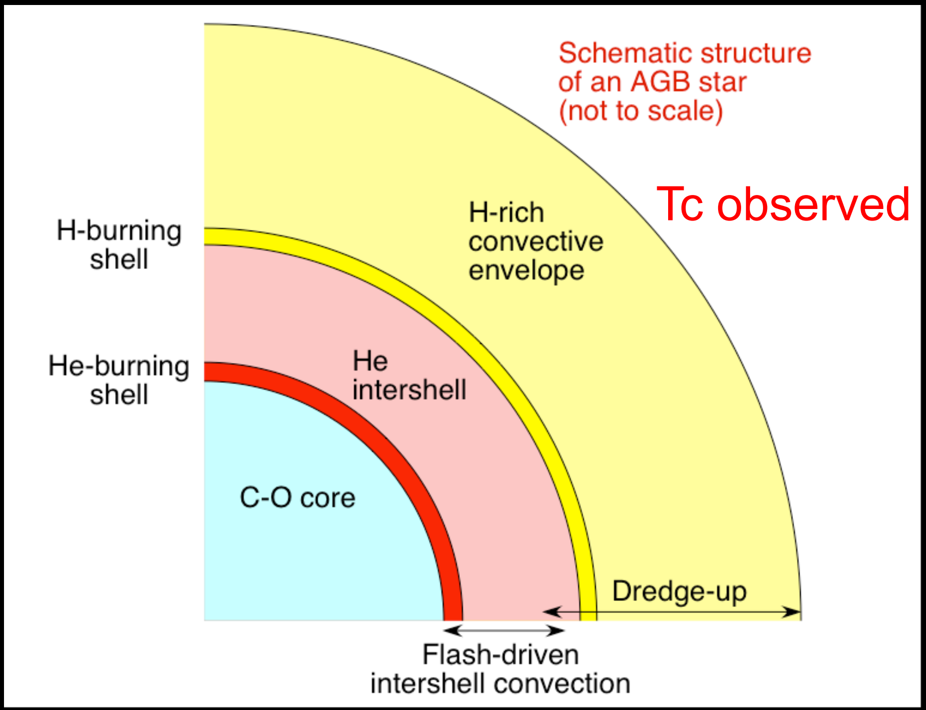
radioactive

Sneden & JC (2003)

Mostly based upon meteorites

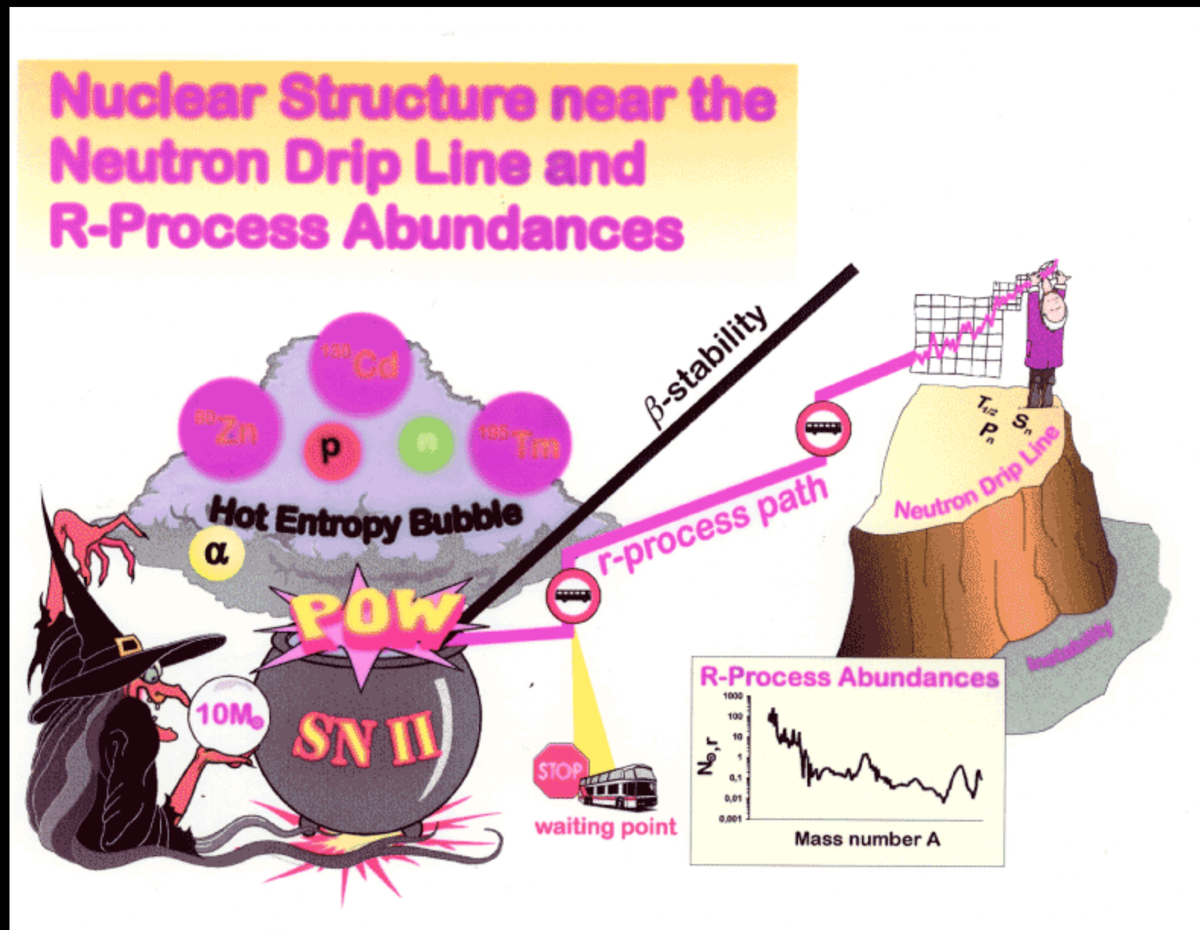
s-Process Nucleosynthesis

- 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

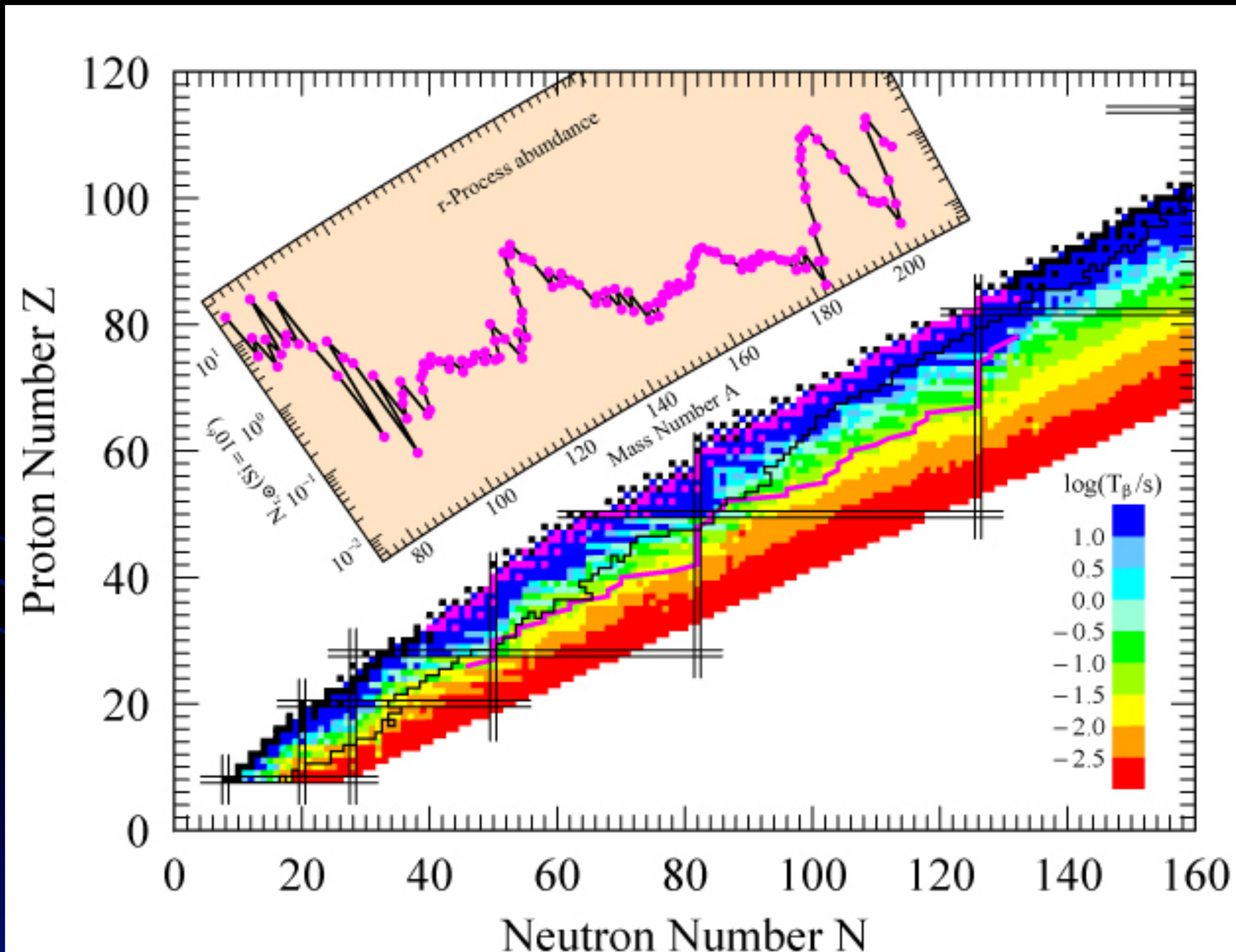


r-Process Nucleosynthesis

- 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



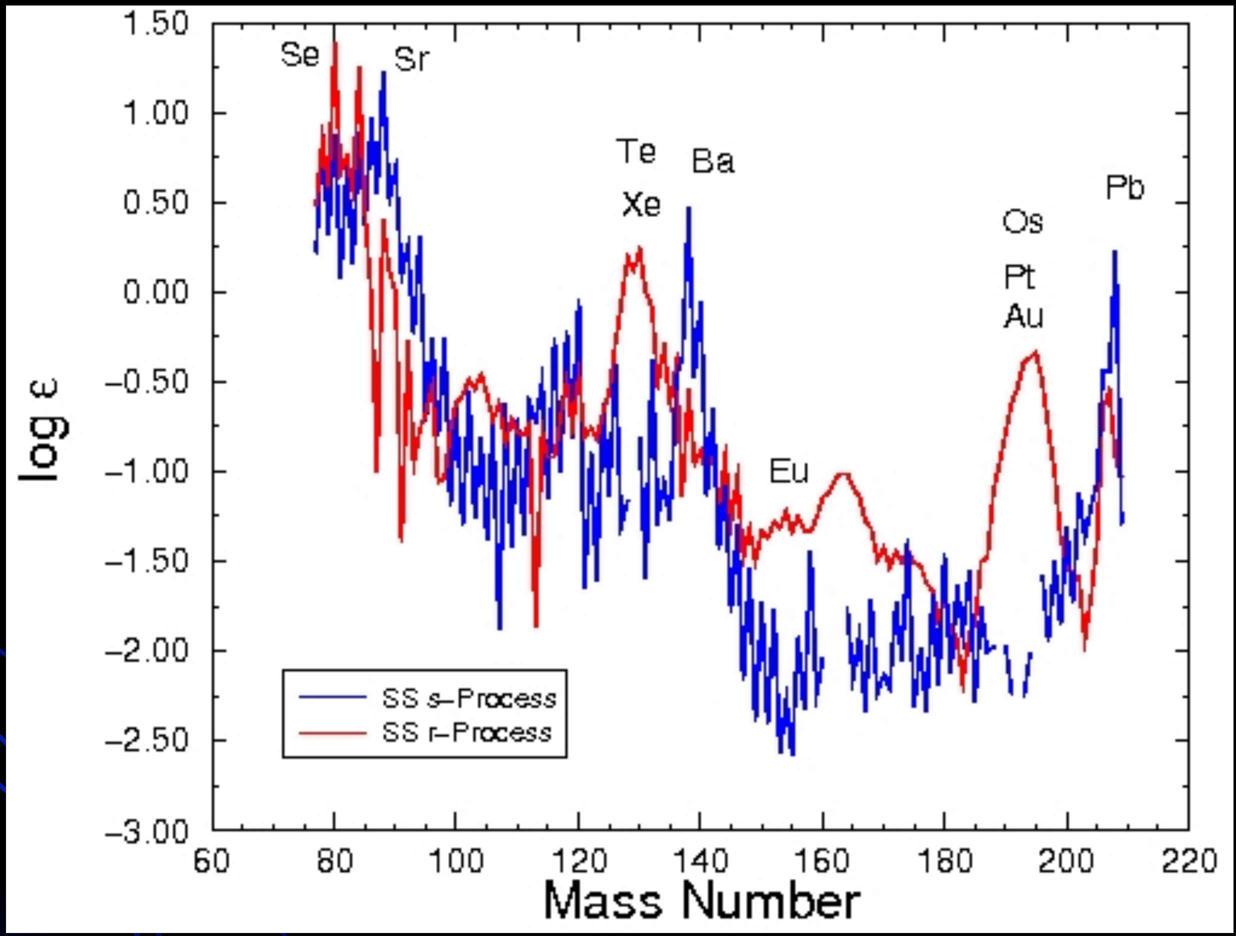
The Nuclear Isotopes in Nature



details

Solar System s- and r-Process Abundance ``Peaks"

Most elements made in combination, but certain elements made in only one process



SS isotopic deconvolution by s- and r-process

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

Evolution of Stars

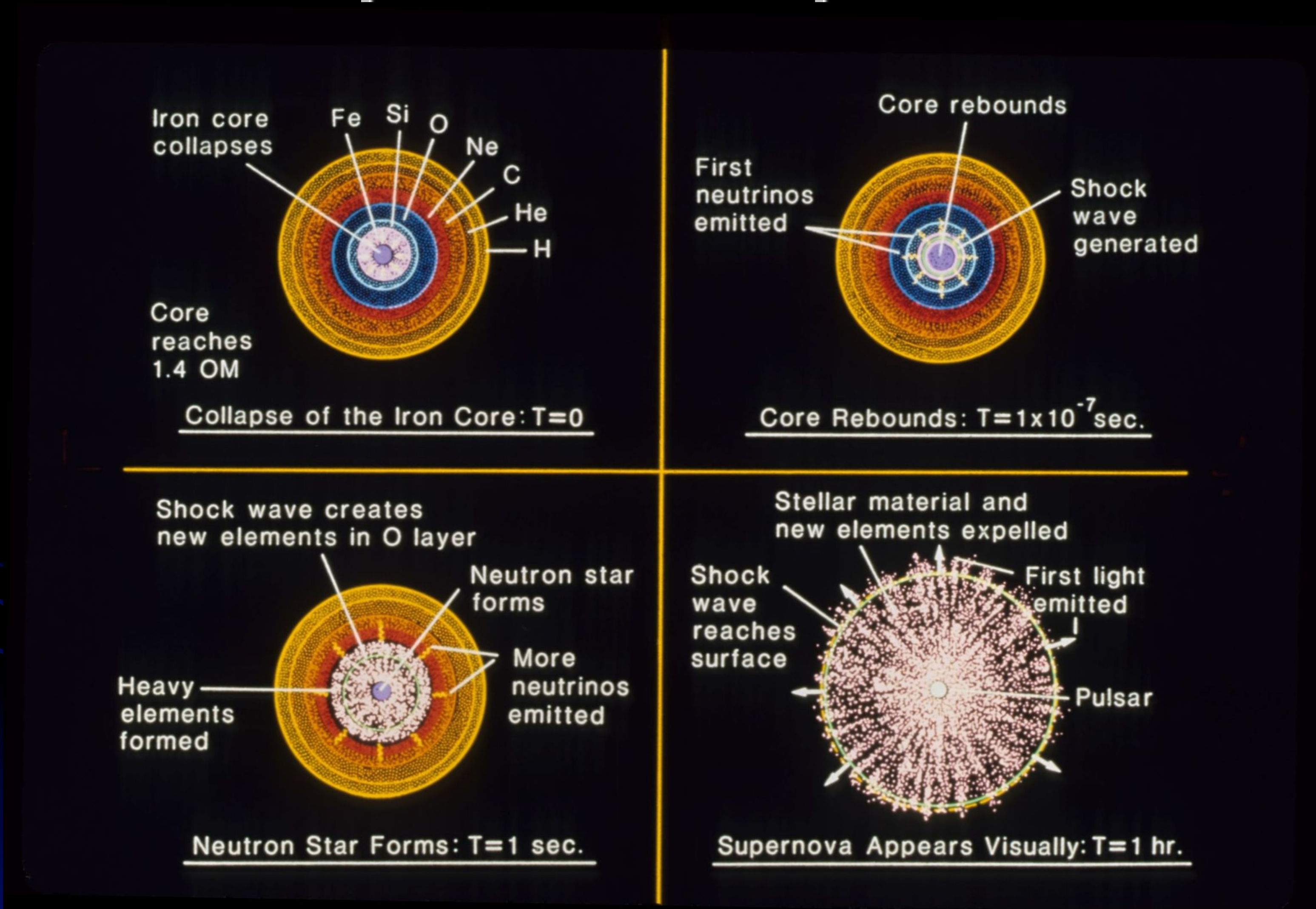
How do stars live and die?

Where do stars make the heavy elements:
where is the platinum?

How do stars eject those heavy elements into space and into gas that will make new stars and planets?

- Evolution of Stars;/z005a.swf

Supernova Explosion



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) (ν-wind)

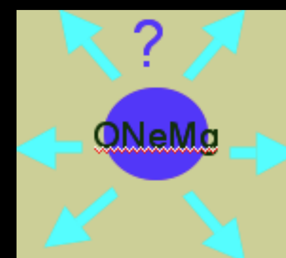
→ Prompt explosions of low-mass Type II SNe (Wheeler, JC & Hillebrandt 1998)

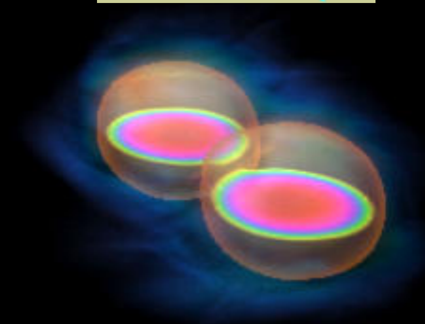
→ Jets and bubbles (Cameron 2001)

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

Supernova Explosion in the Milky Way

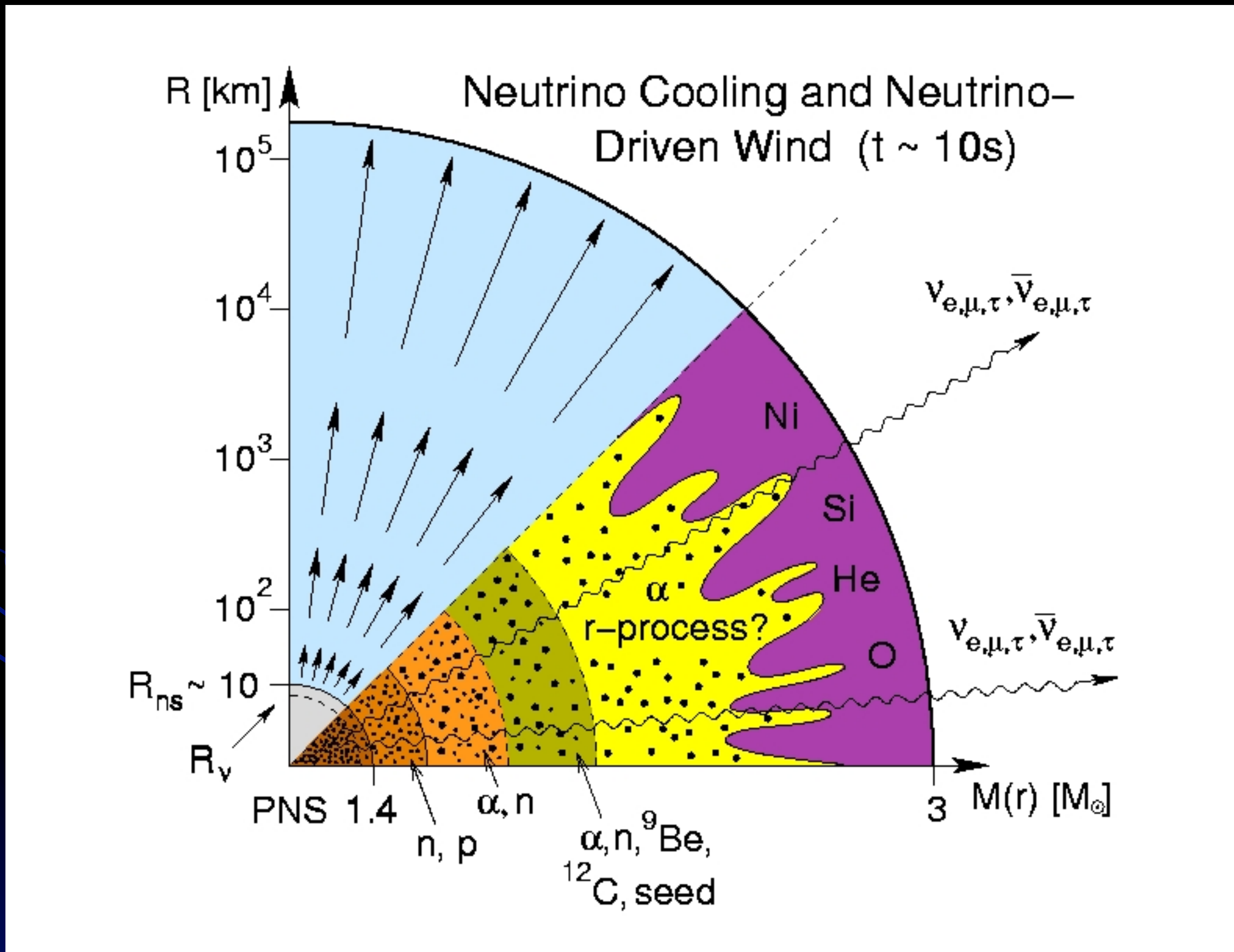
Crab Nebula First Seen in 1054





Stellar Spectroscopy

Rapid Neutron Capture in Type II SNe ?



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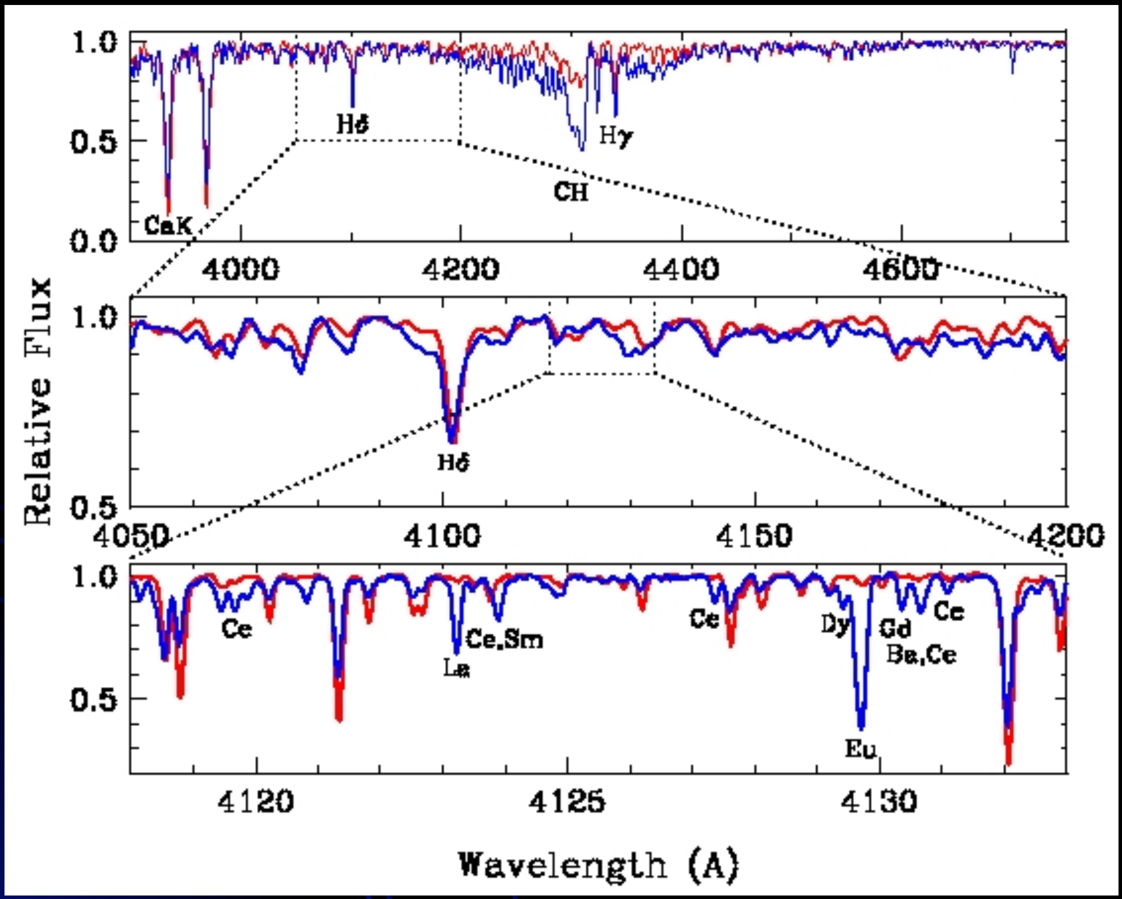
Stellar Spectroscopy: Absorption Lines



Low resolution

Expanded view

n-capture heavy elements

High resolution

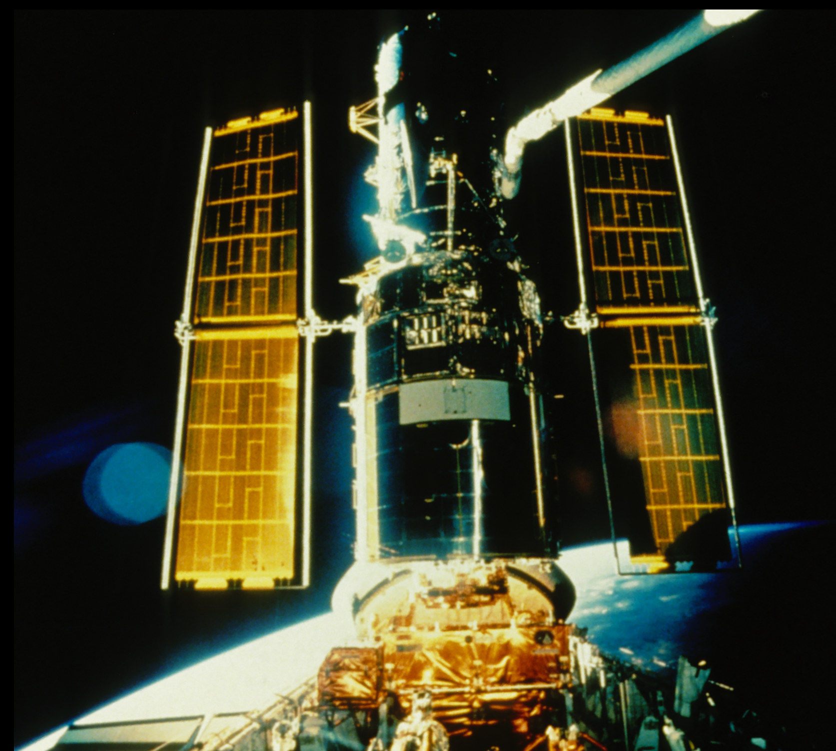
CS 22892-052

HD 122563

Some of the Telescopes We Use

Keck Observatory in Hawaii

Hubble Space Telescope



For abundances of some important heavy elements we need to get UV spectra

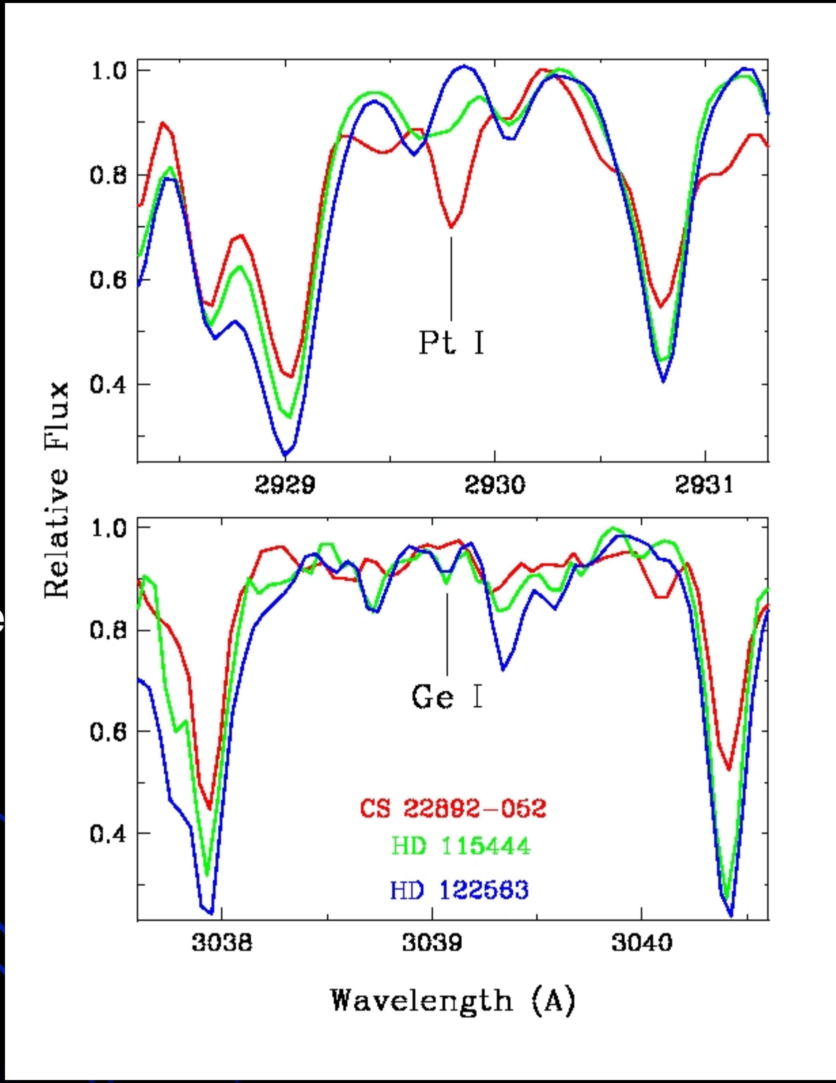
Space Telescope Integrated Spectrograph

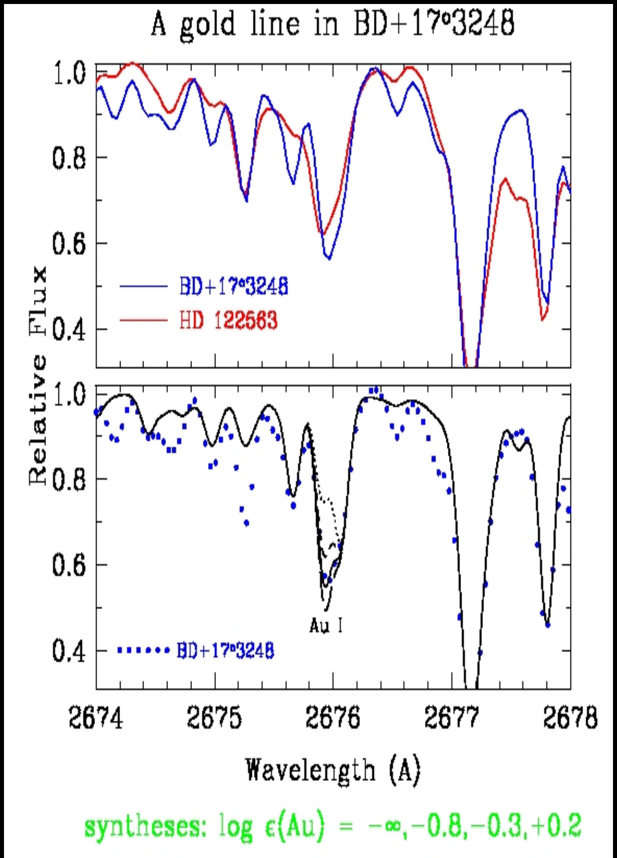
NUV HST STIS Spectra

Heavy n-capture elements do not scale with iron.

Ge scales with Fe

CS 22892-052 ([Fe/H] = -3.1)
HD 115444 ([Fe/H] = -2.7)
HD 122563 ([Fe/H] = -2.6)

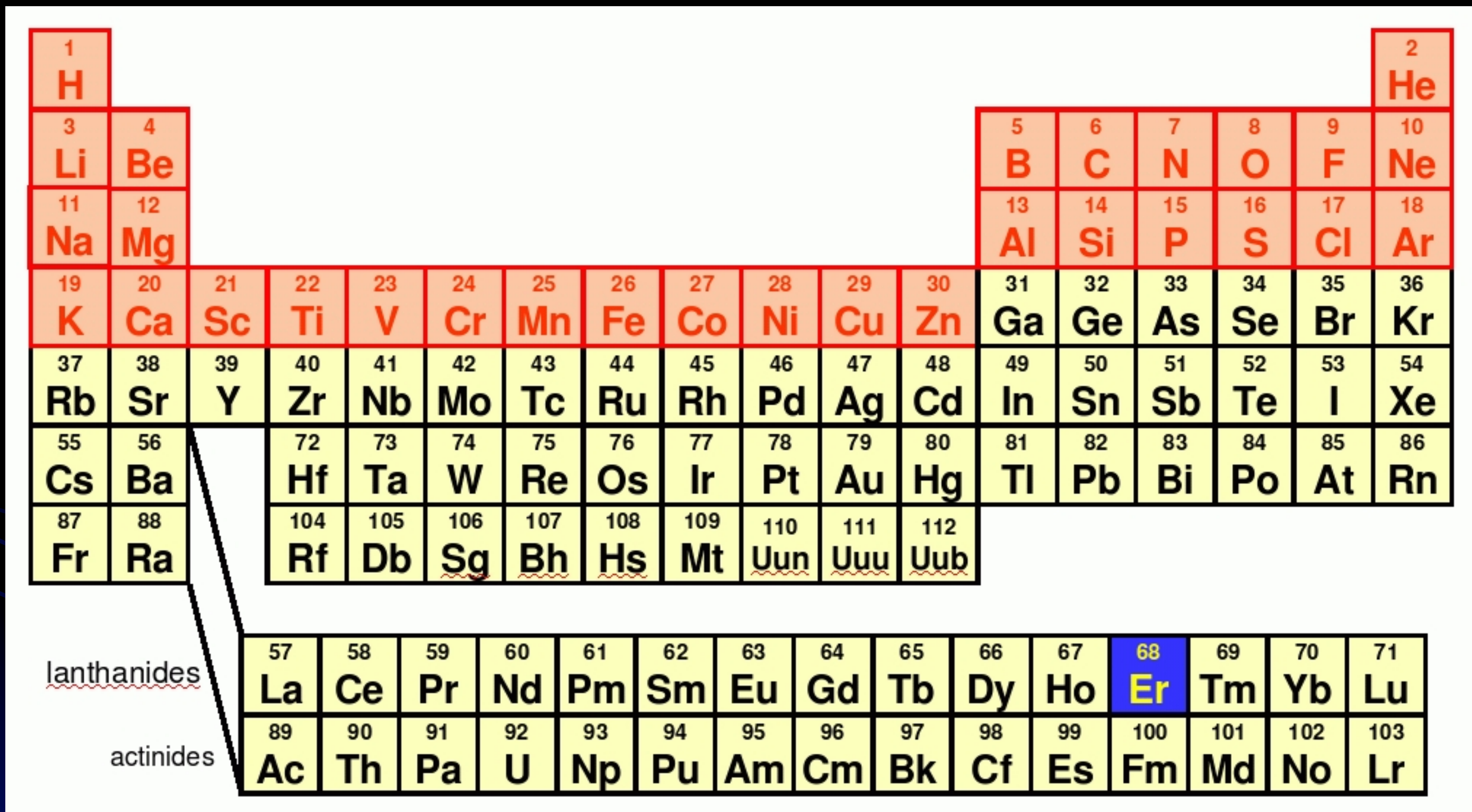




Note the resolution.

More spectra

New Atomic Data to Improve Elemental Abundance Values



Concentrating on the Rare-Earth Elements

transition probabilities from Lawler’s Wisconsin group

Rare Earths are Everywhere!

THE SECRET

(Chinese)

INGREDIENTS OF

(almost)

EVERYTHING

From smart phones to hybrid vehicles to cordless power drills, devices we all desire are made with a pinch of rare earths—exotic elements that right now come mostly from China.

Samarium, one of the 17 rare (but widely useful) earths, helps convert sound into electricity in the magnetic pickups of electric guitars. It is also in the control rods of some nuclear reactors.

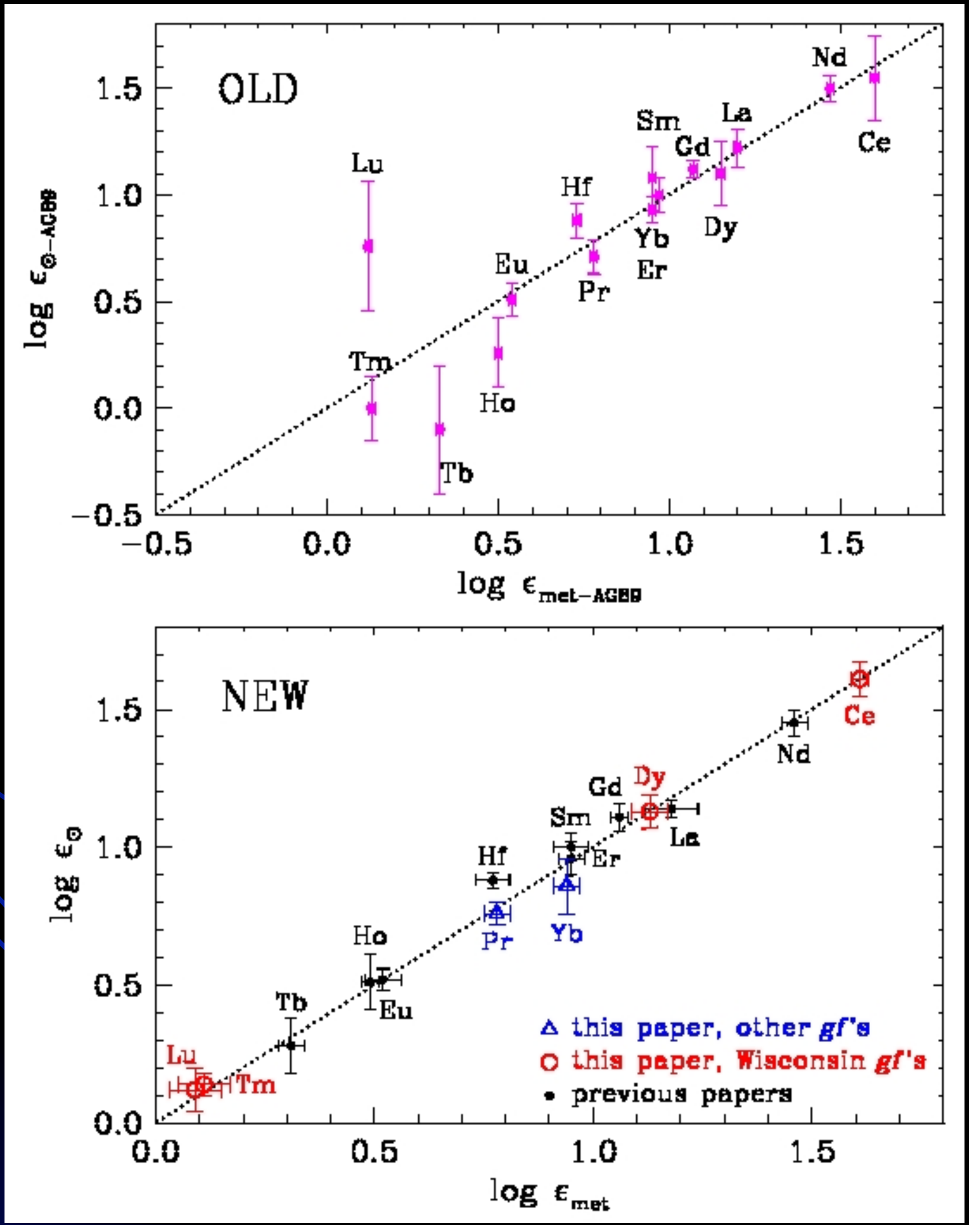
Actual size

136 NATIONAL GEOGRAPHIC • JUNE 2011

Focus On Rare Earth Elements

Comparisons of SS meteoritic & photospheric values of the REE

Working our way through the periodic Table!

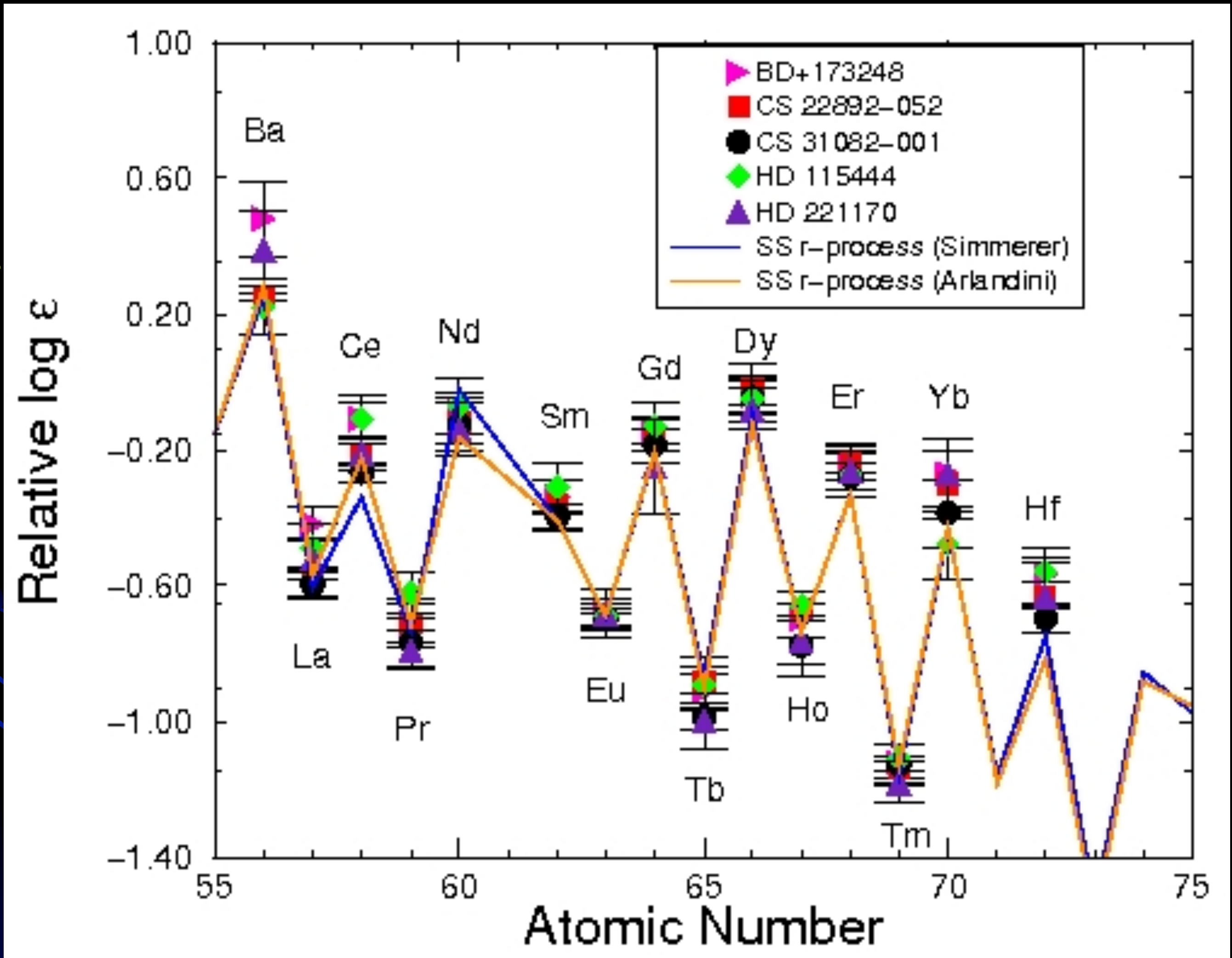


New experimental atomic physics data:

- 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)
- Er done (Lawler et al. 2008)
- Ce, Pr done (Lawler et al. 2009, Sneden et al. 2009)

Rare Earth Abundances in Five r-Rich Stars

Comparisons of new REE abundances with SS r-only predictions



Very little scatter

All normalized to Eu

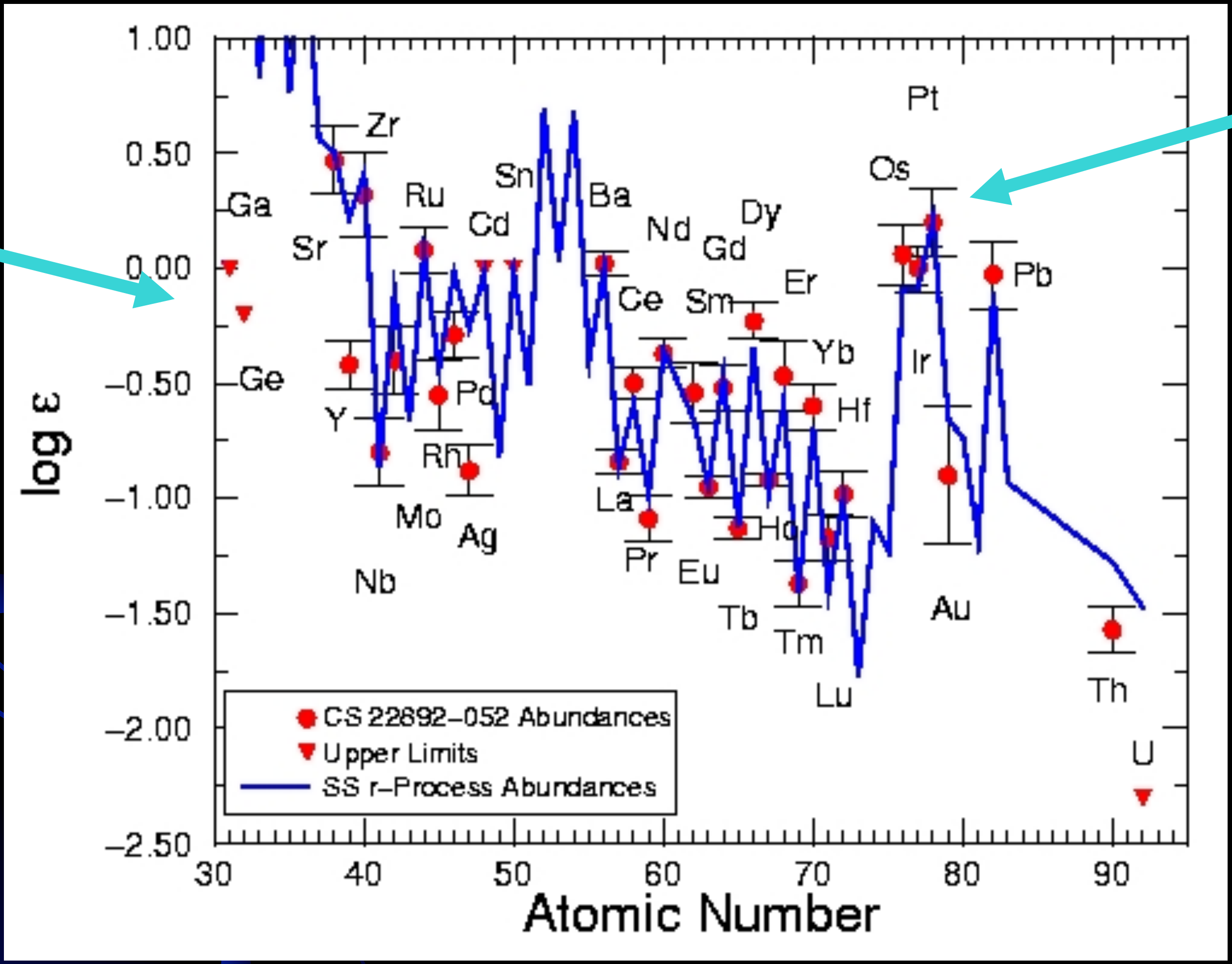
Sneden et al. (2009): culmination of years of effort

CS 22892-052 Abundances

(with new atomic and stellar data)

31 N-Capture Elements Detected ➡ The Old King

Germanium



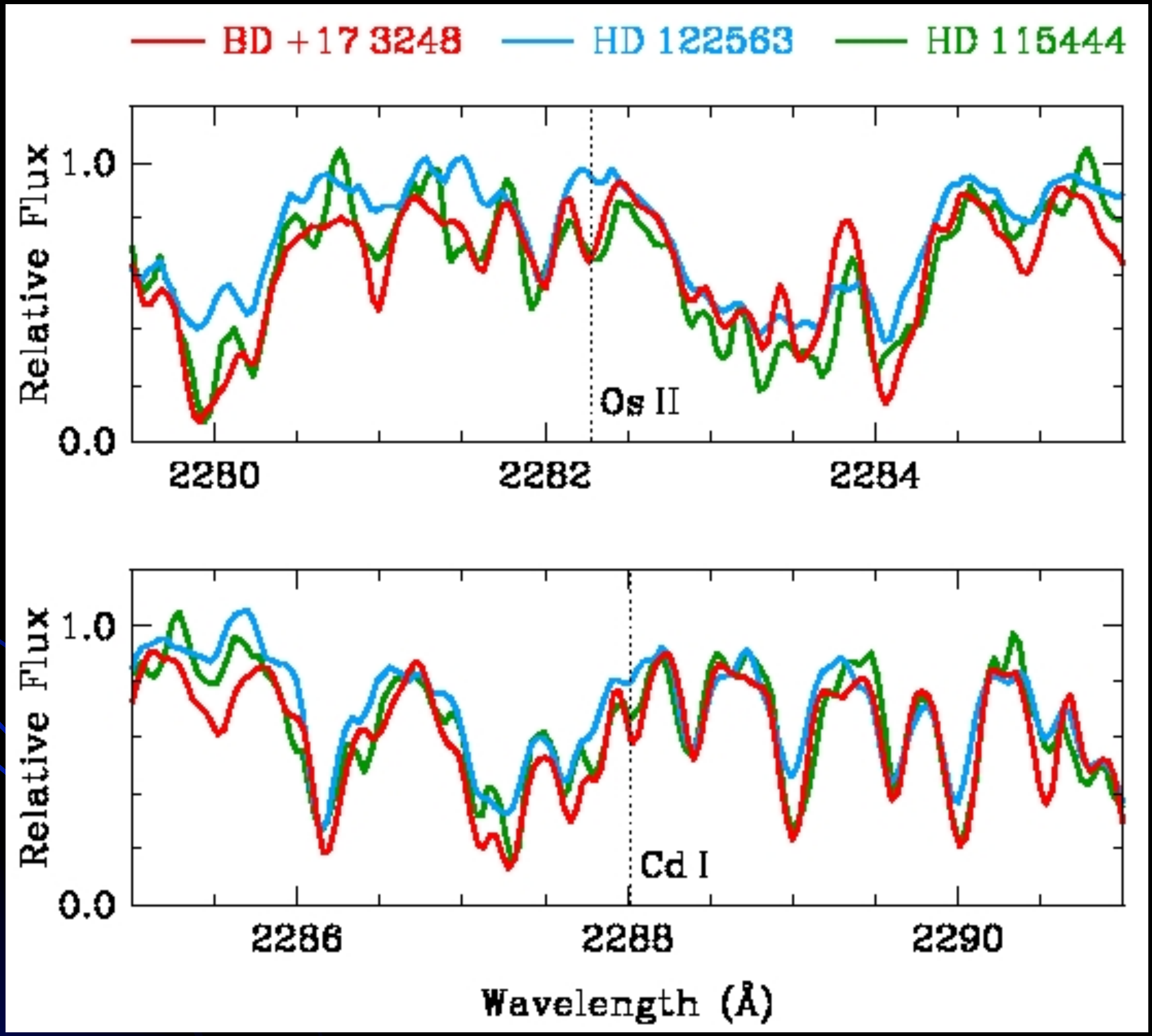
Platinum

(64 HST Orbits)

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

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

New Abundance Detections in BD +17 3248



UV: HST STIS

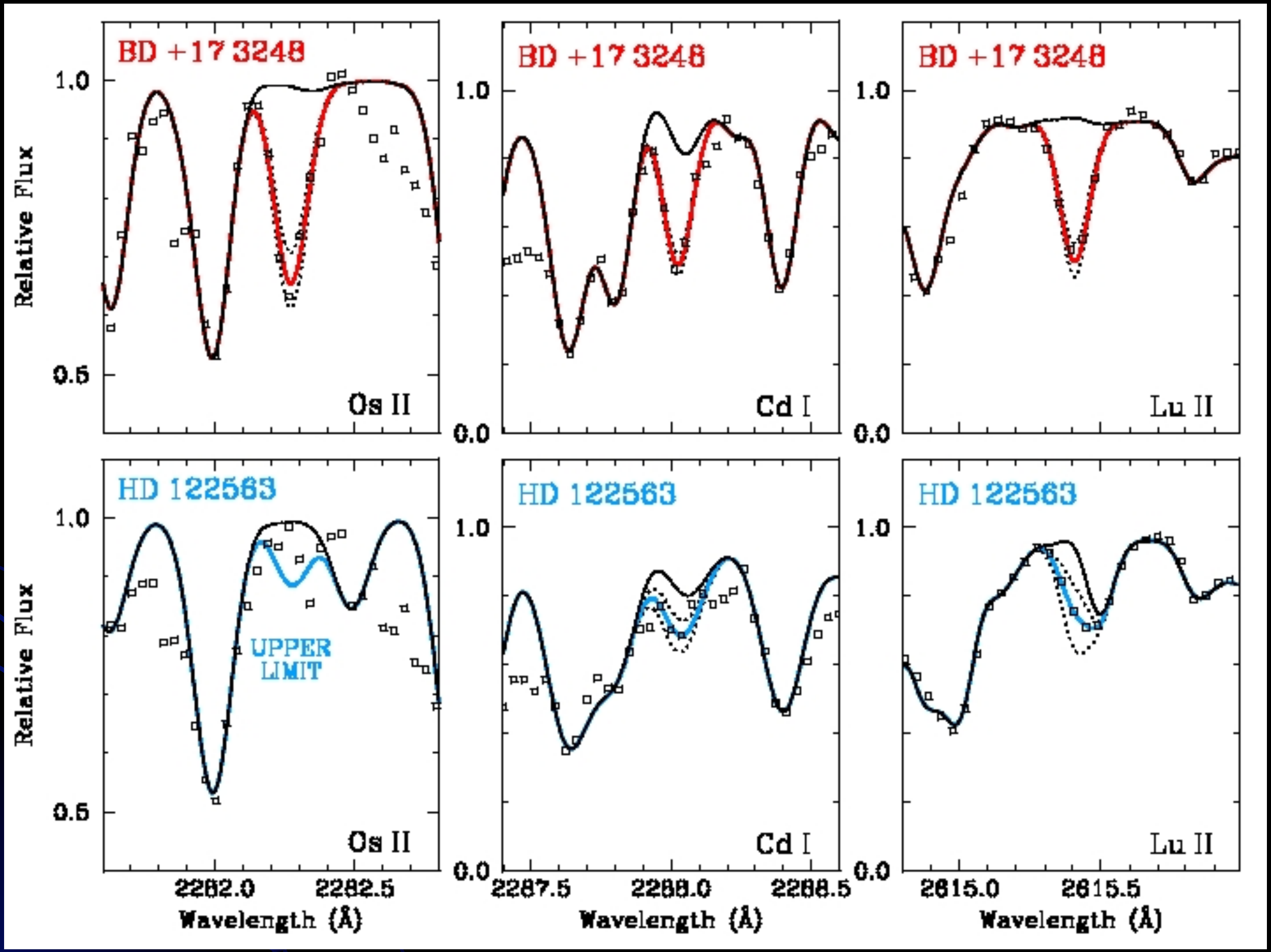
Roederer et al. (2010a)

Cadmium: Good in Stars, Bad in People!

- Heavy Metal: It is not as pervasive as lead. But a study is underway to establish safe levels of cadmium.
- McDonald's recently recalled 12 million Shrek-themed glasses because of concern about the level of cadmium contained in the enamel.

Time Magazine – July 12, 2010

New Abundance Detections of Cd I, Lu II and Os II in BD +17 3248



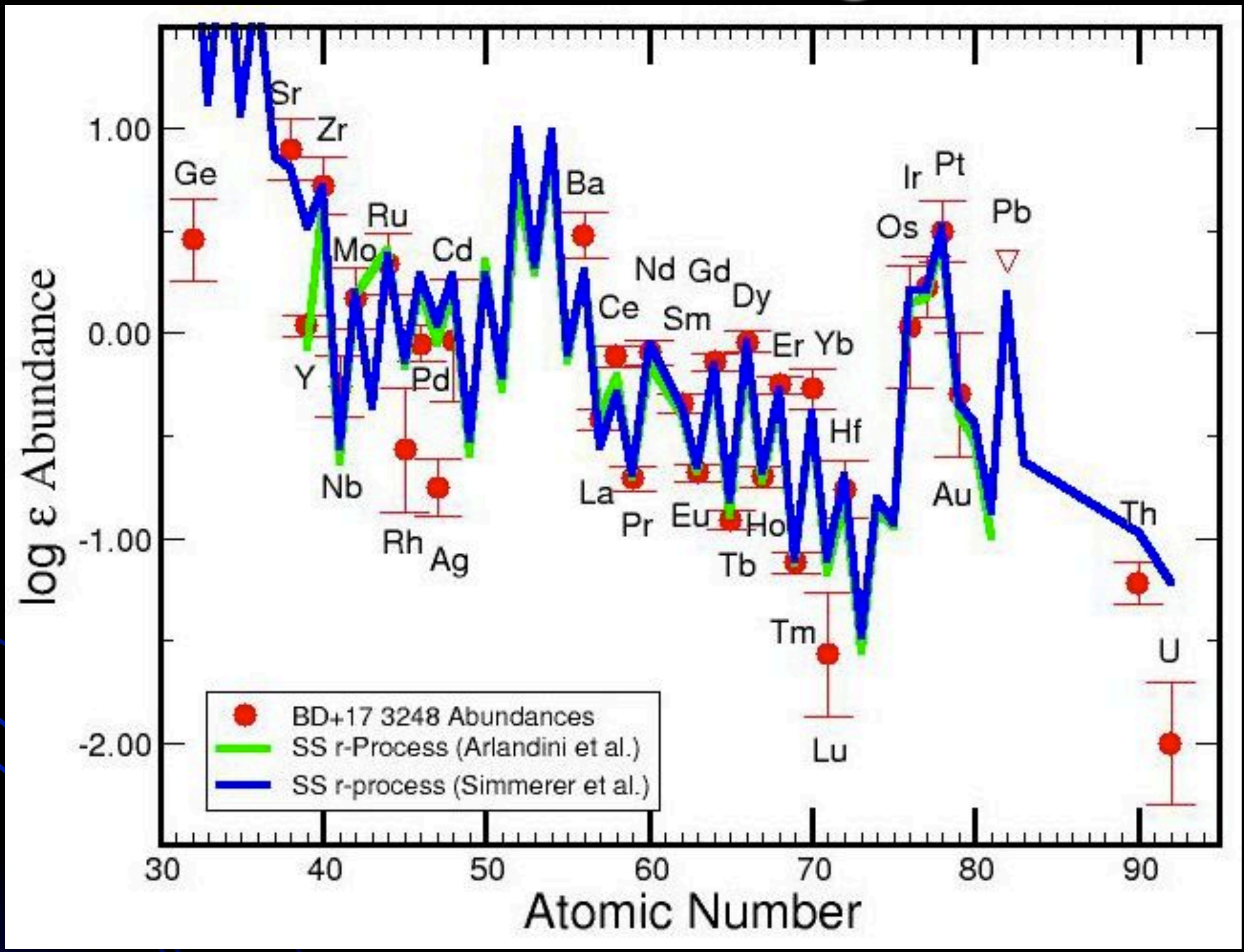
Roederer et al. (2010a)

First detections of these n-cap species in metal-poor stars

Abundances in BD+17 3248: Meet the New King!

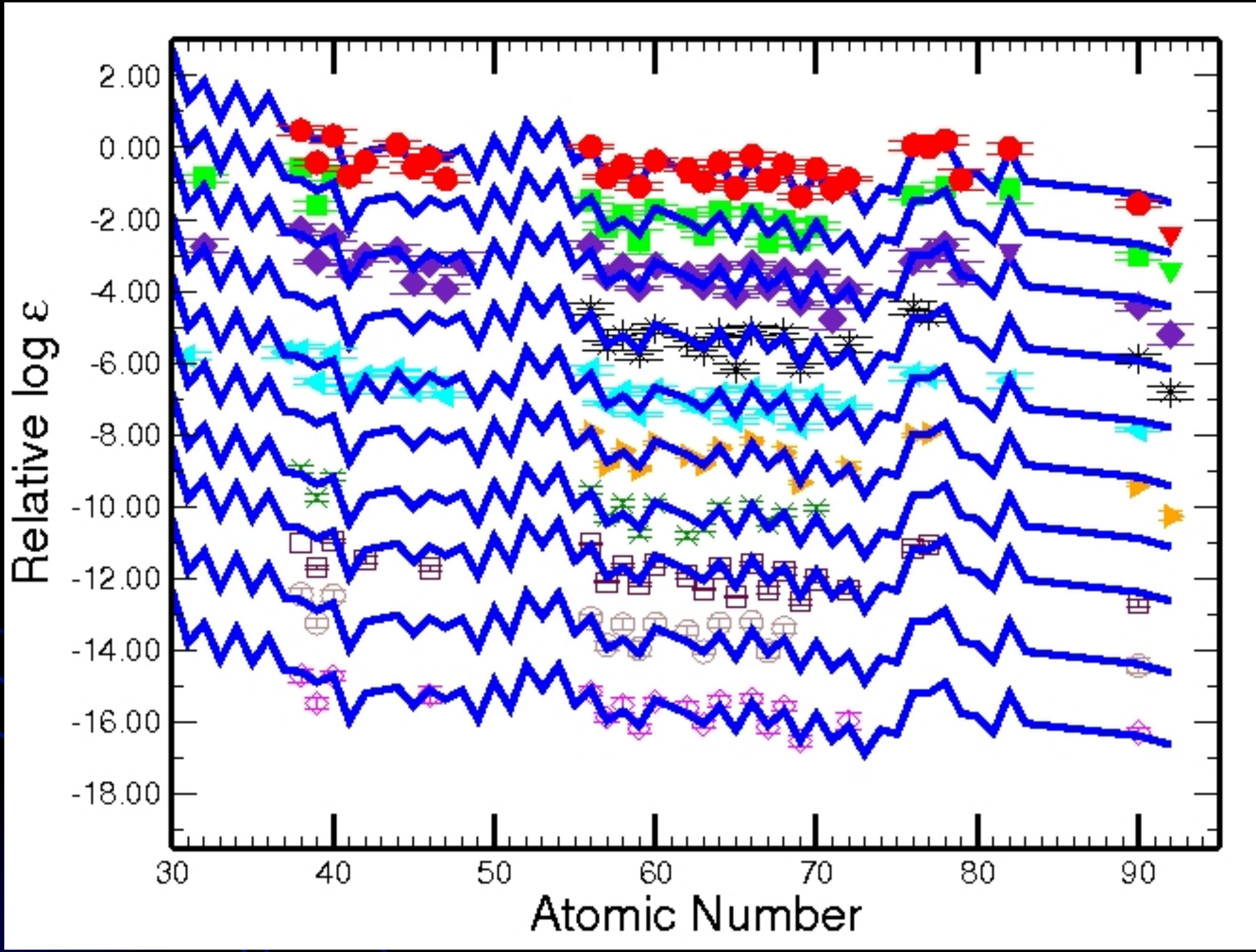
➔

note Ge: for halo stars not from n-cap



32 n-capture elements detected in BD +17 3248 ➔ Most in any metal-poor halo star to date!

Consistency for r-Rich Stars

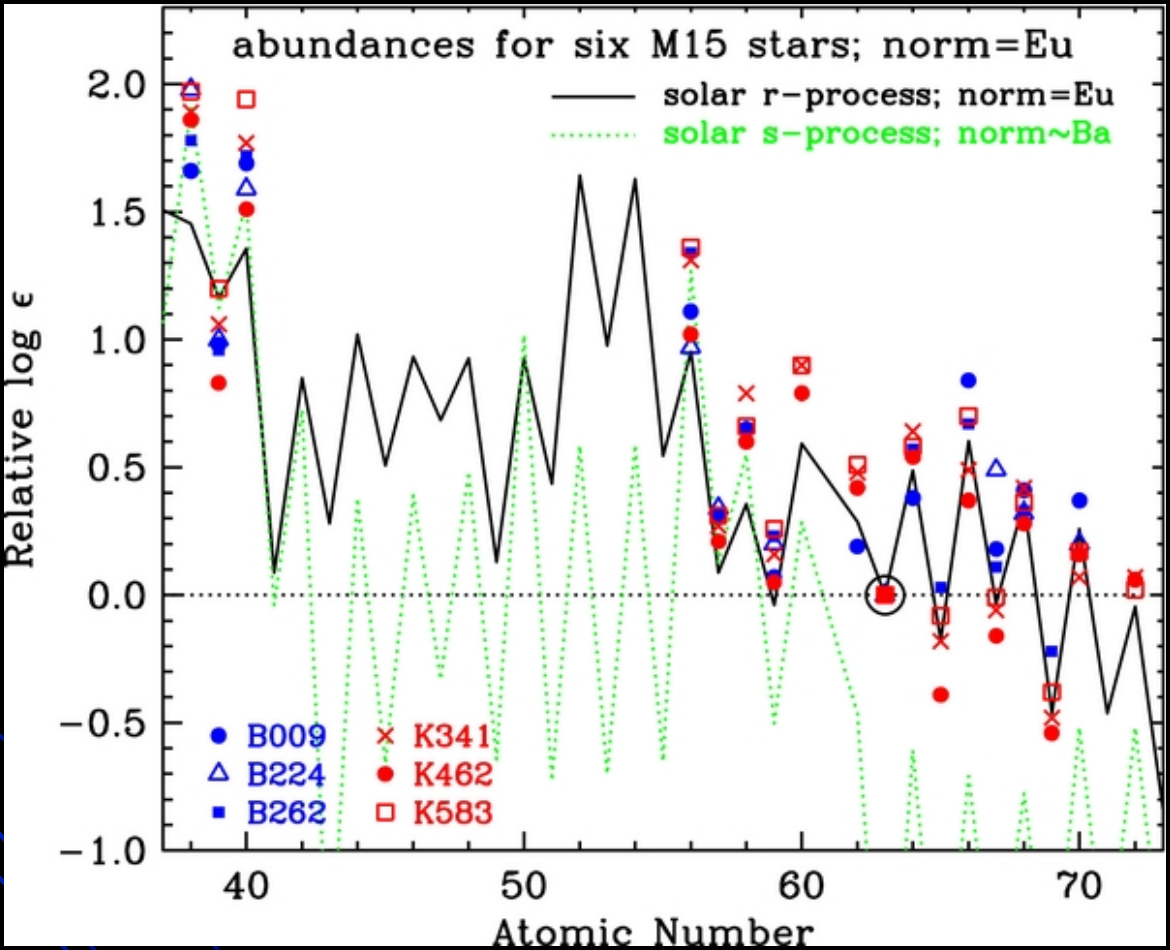


CS 22892-052
HD 115444
BD +17 3248
CS 31082-001
HD 221170
HE 1523-0901
CS 22953-03
HE 2327-5642
CS 2941-069
HE 1219-0312

10 r-process rich stars

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

Abundances in a Globular Cluster



Sobeck et al. (2011)

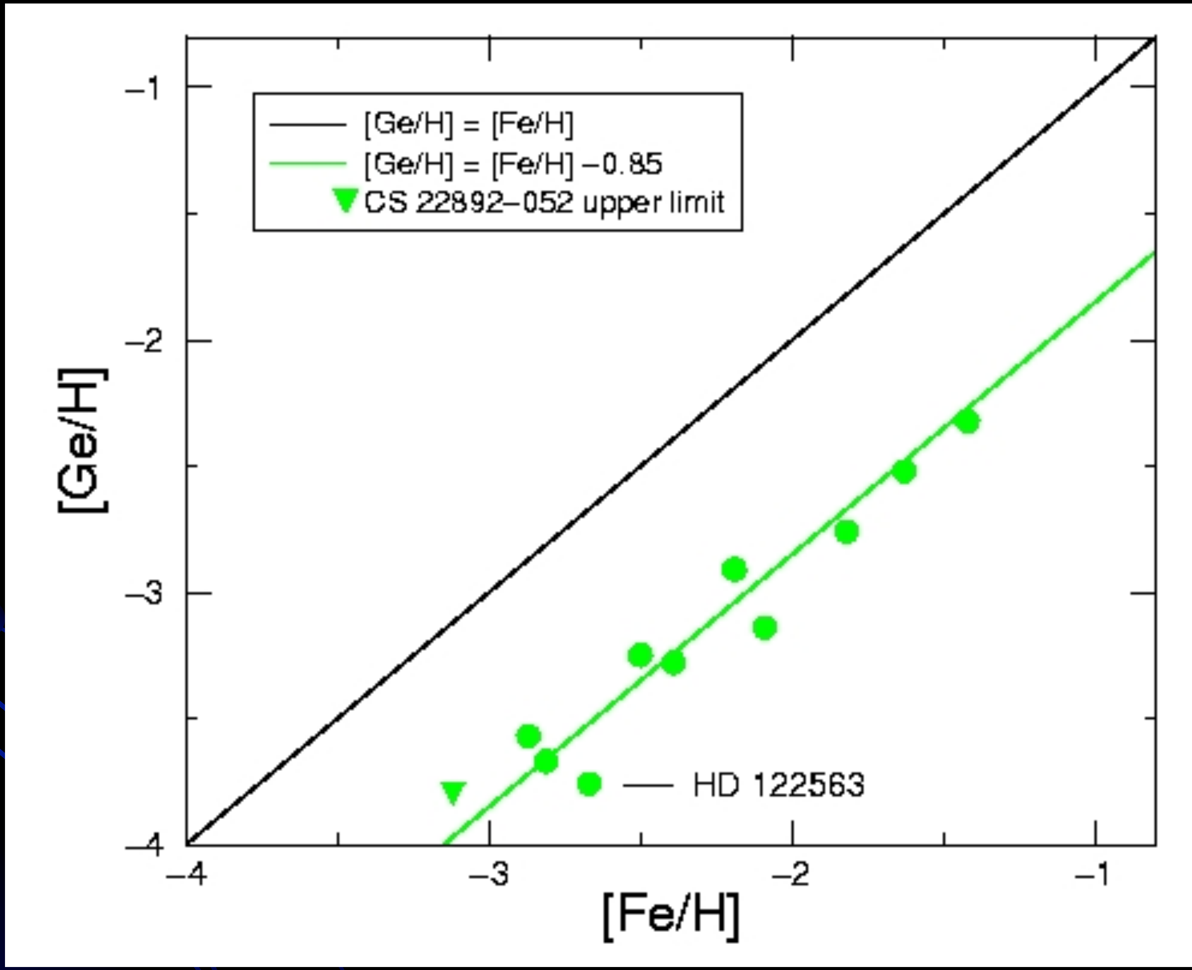
RGB and RHB stars

Upper end SS r-process. Sr-Zr not fit.

Focus on Observations of Ranges of Lighter N-Capture Elements

- Elements just past the iron peak: Ge
- Sr, Y and Zr
- Z=40-50 including Ag and Cd
- New abundance determinations for selected elements from Sr to Yb

Ge Abundances in Halo Stars



Ge $\propto$ Fe

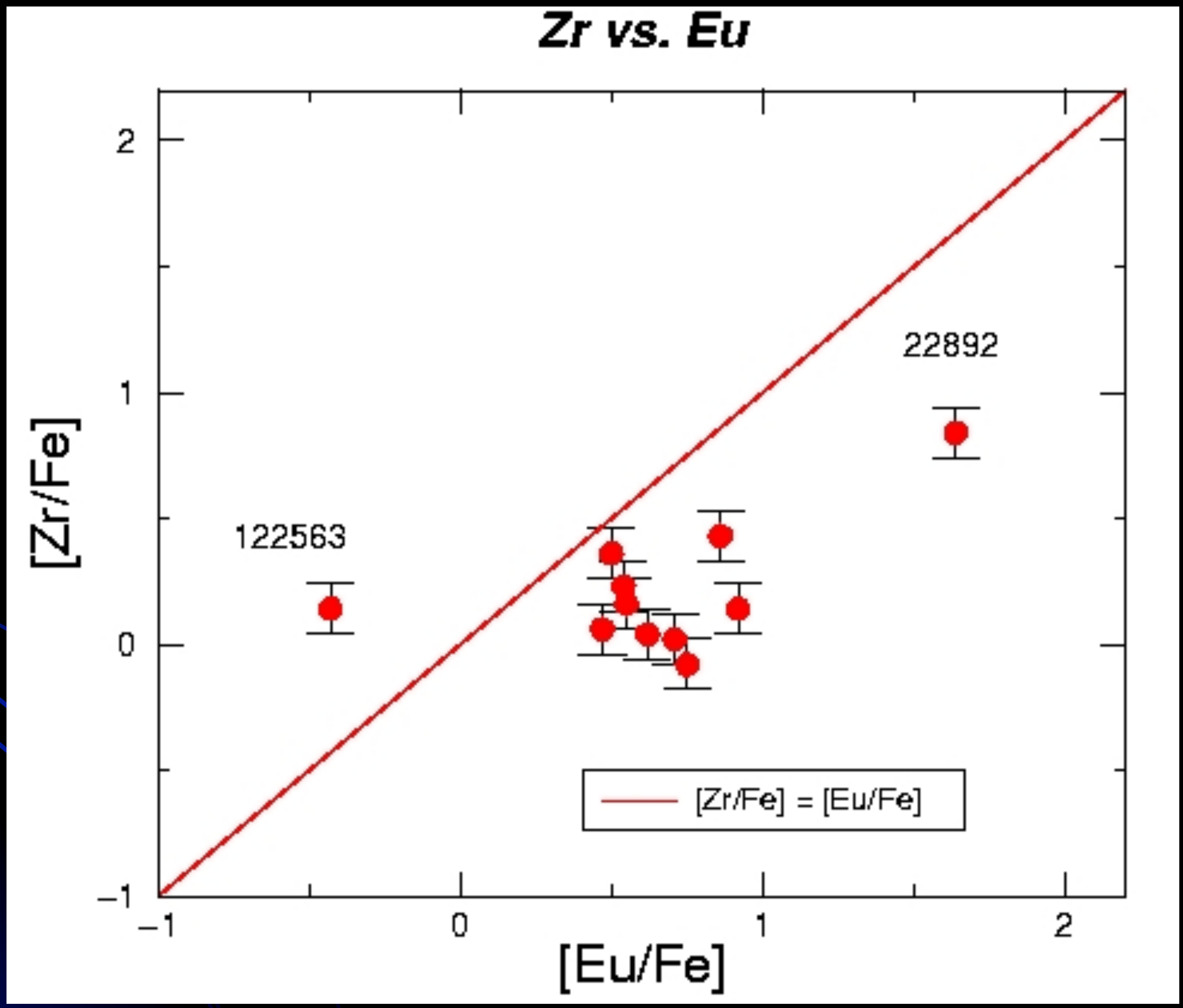
Challenge to theorists.
νp-process (Frolich et al.)

What happens at higher [Fe/H] with the s-process?

JC et al. (2005)

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

Zr and Eu Abundances in Halo Stars

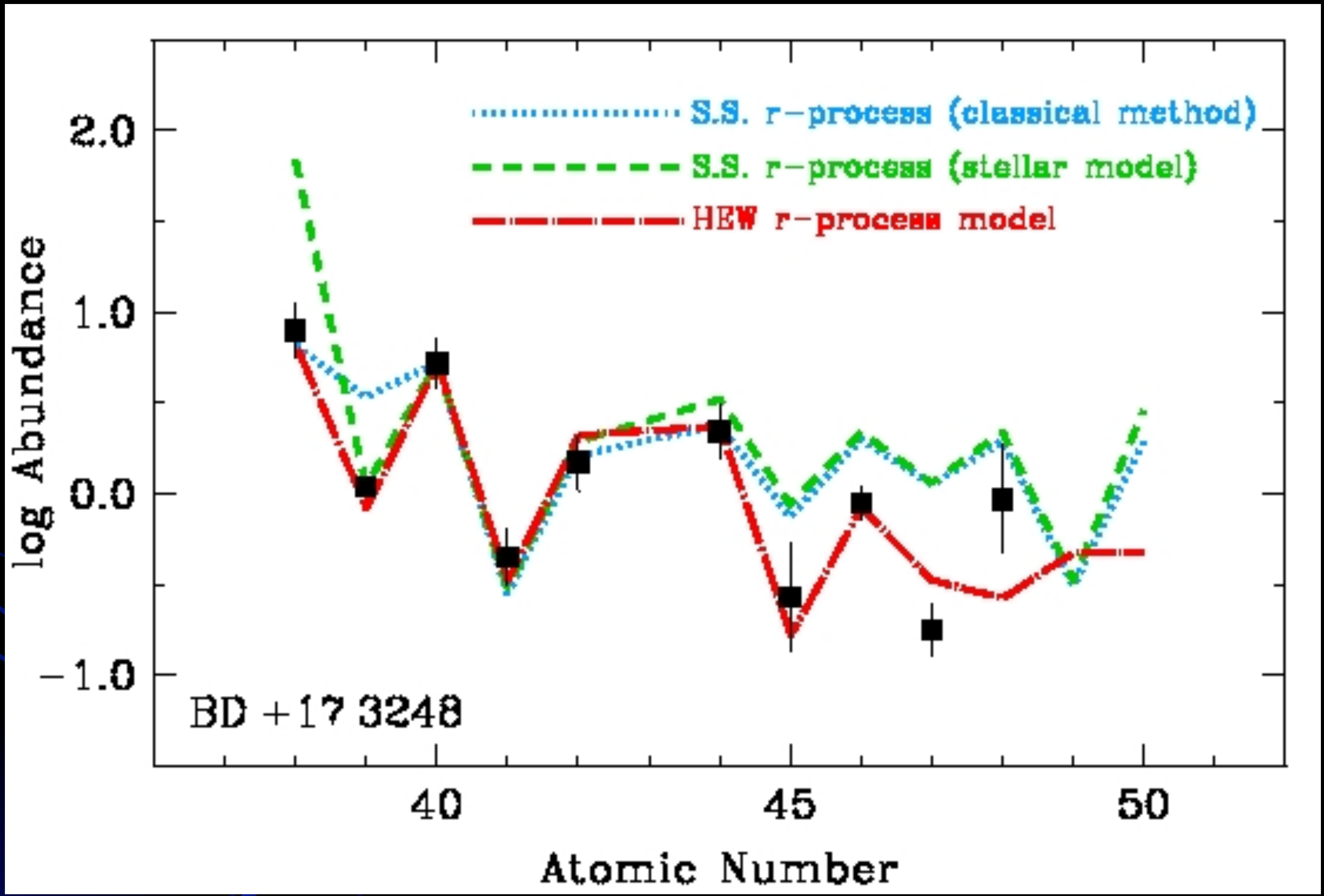


Zr $\not\propto$ Eu

Both n-cap elements but not from same source?

LEPP?
SN models?

Origin of the Lighter n-Capture Elements: Work in Progress

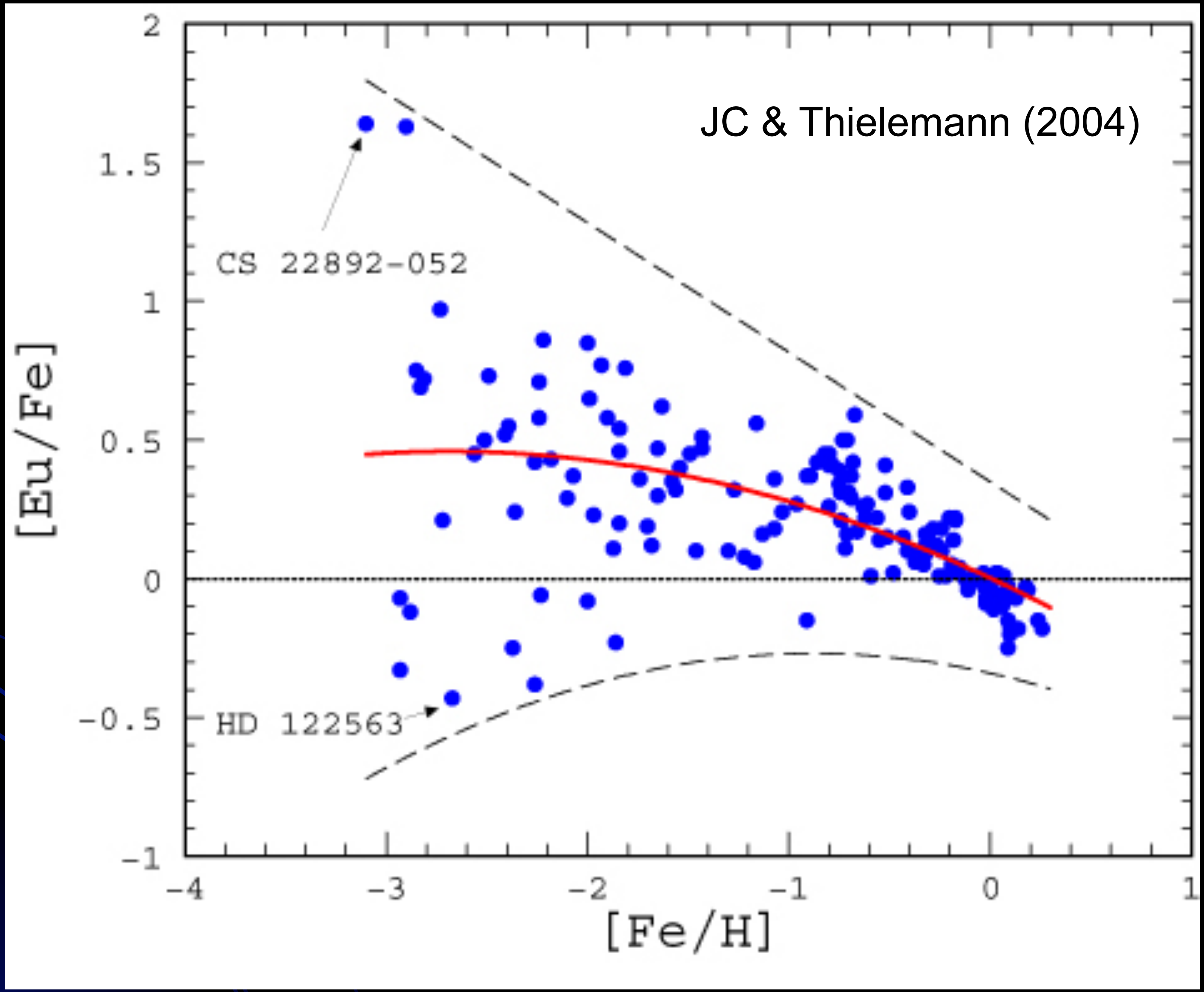


Note Ag, Cd

JC et al. (2011)

Eu Abundance Scatter in the Galaxy

GCE

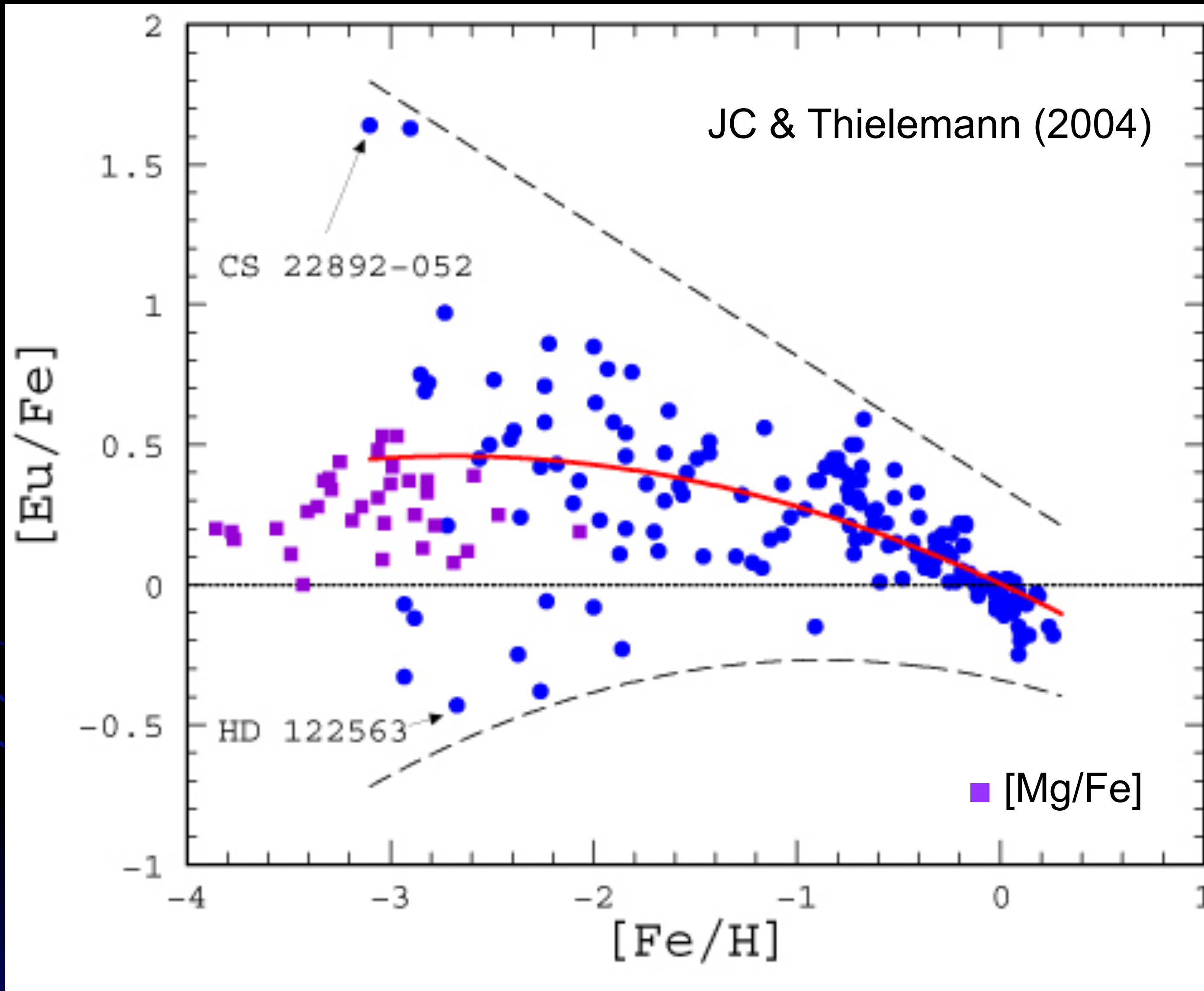


First seen by Gilroy et al. (88) Single SNe at early times?

Early Galaxy chemically inhomogeneous and unmixed for r-process elements.

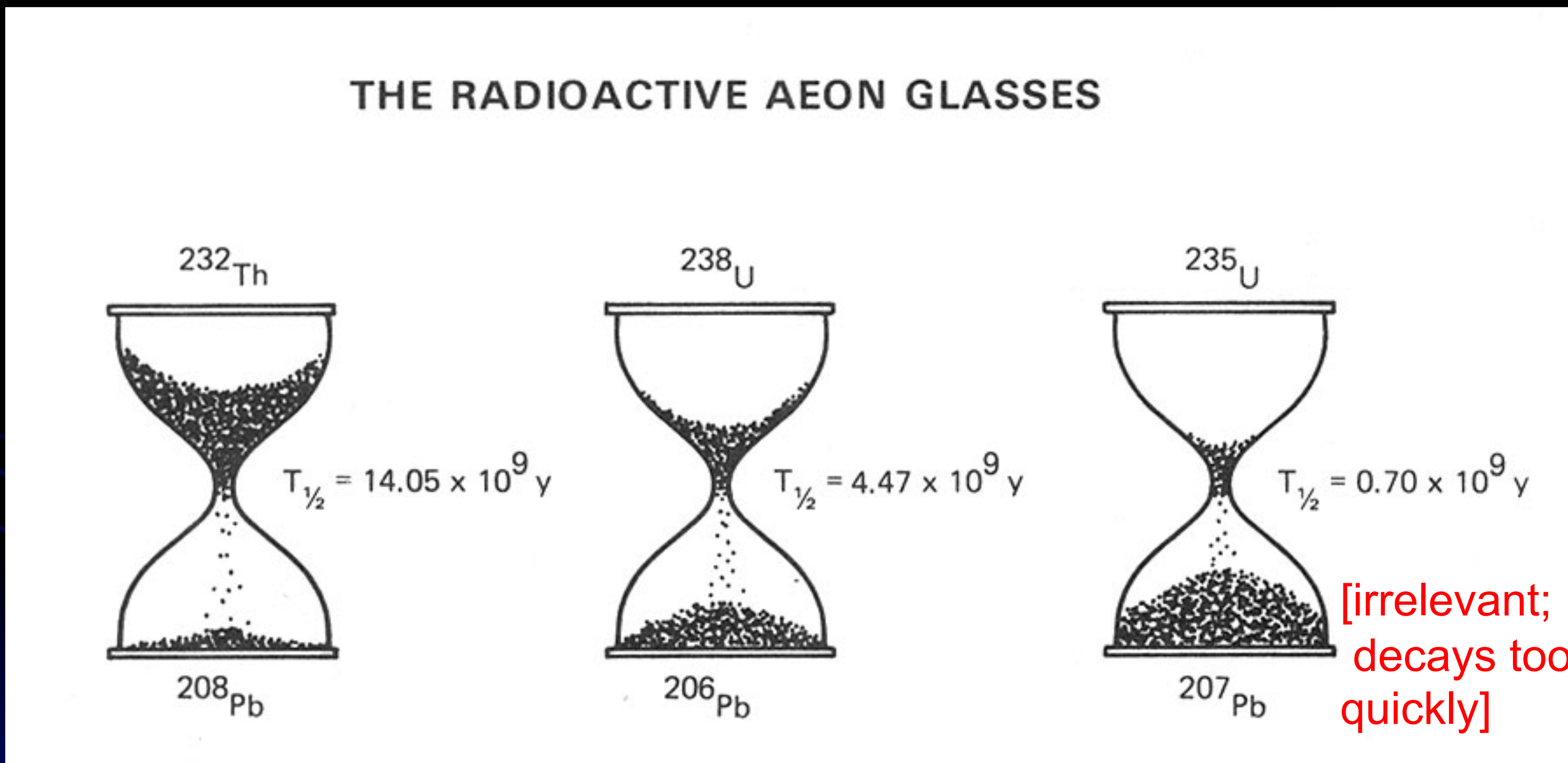
Eu Abundance Scatter in the Galaxy

GCE



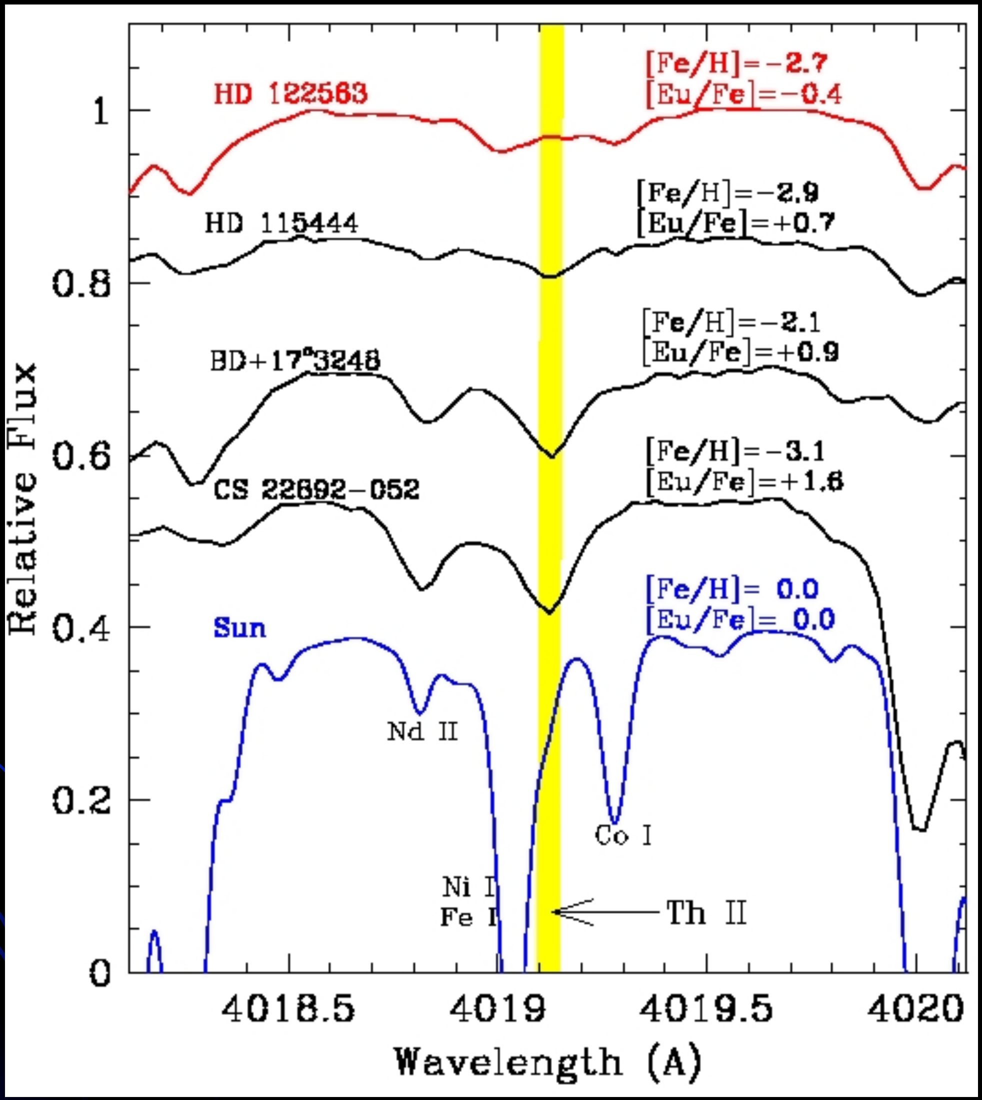
Early Galaxy chemically inhomogeneous and unmixed for r-process elements.

Cosmochronometers



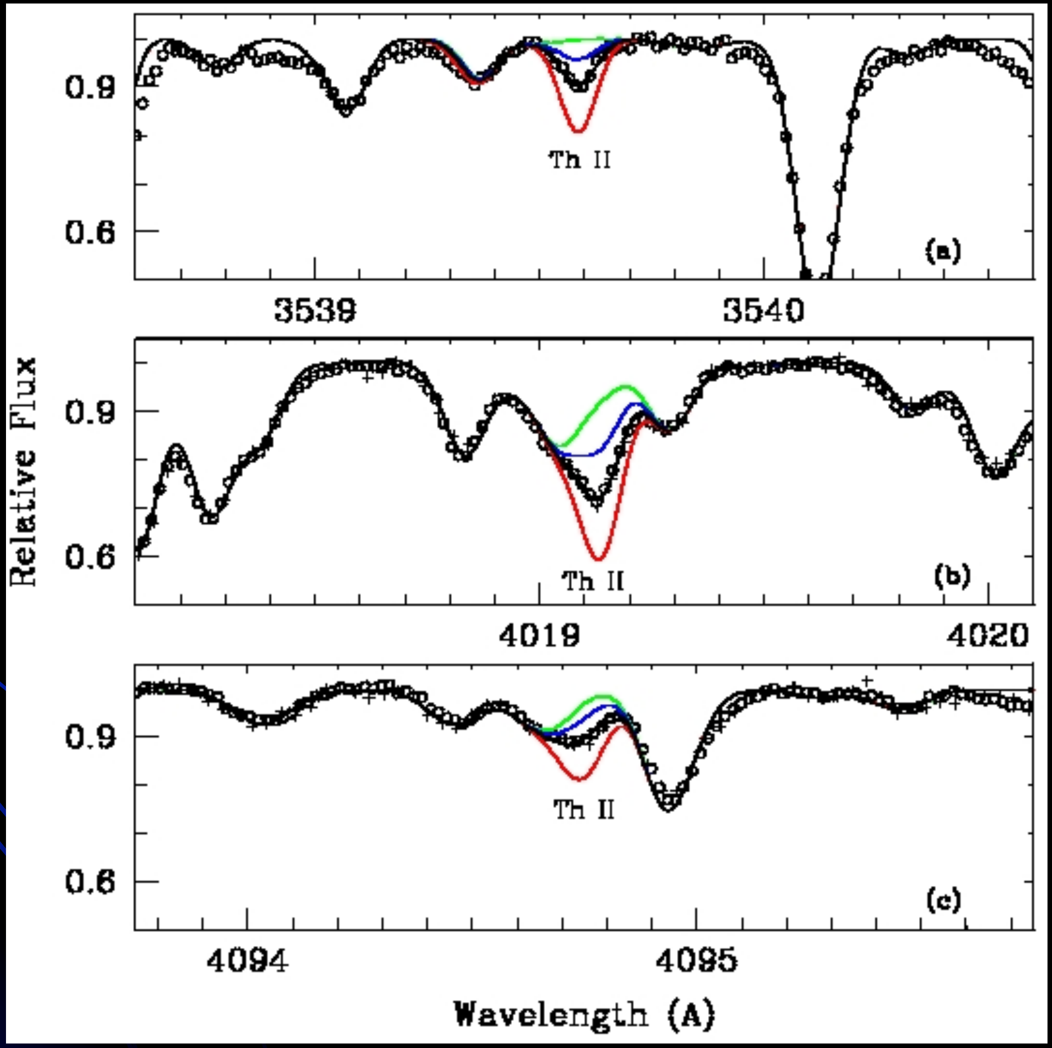
Rolfs & Rodney (1988)

Th Detections in Four Halo Stars and the Sun



Note the strength of the Th lines independent of metallicity

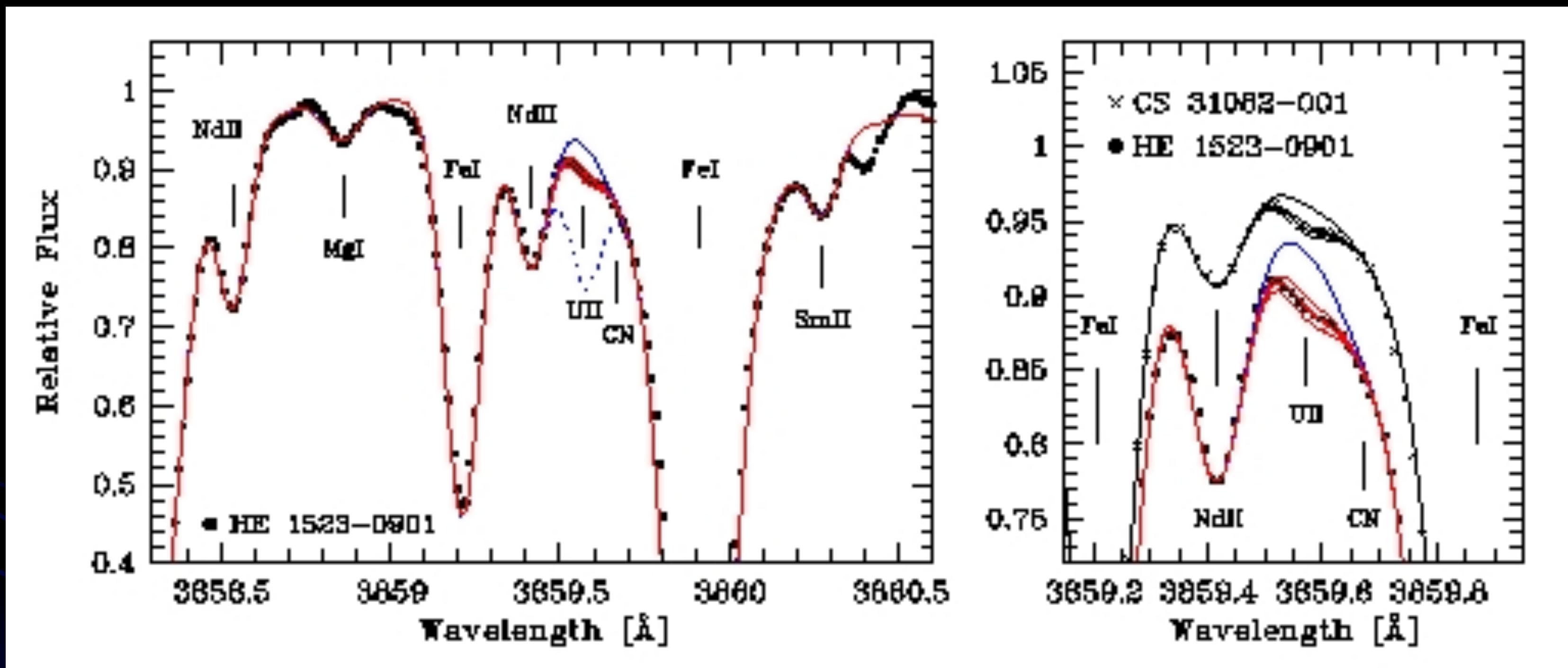
Observed and Synthetic Spectra of Th Lines in HD 221170



Keck o
McDonald +

Ivans et al. (2006)

Observations of Uranium Lines in Stars

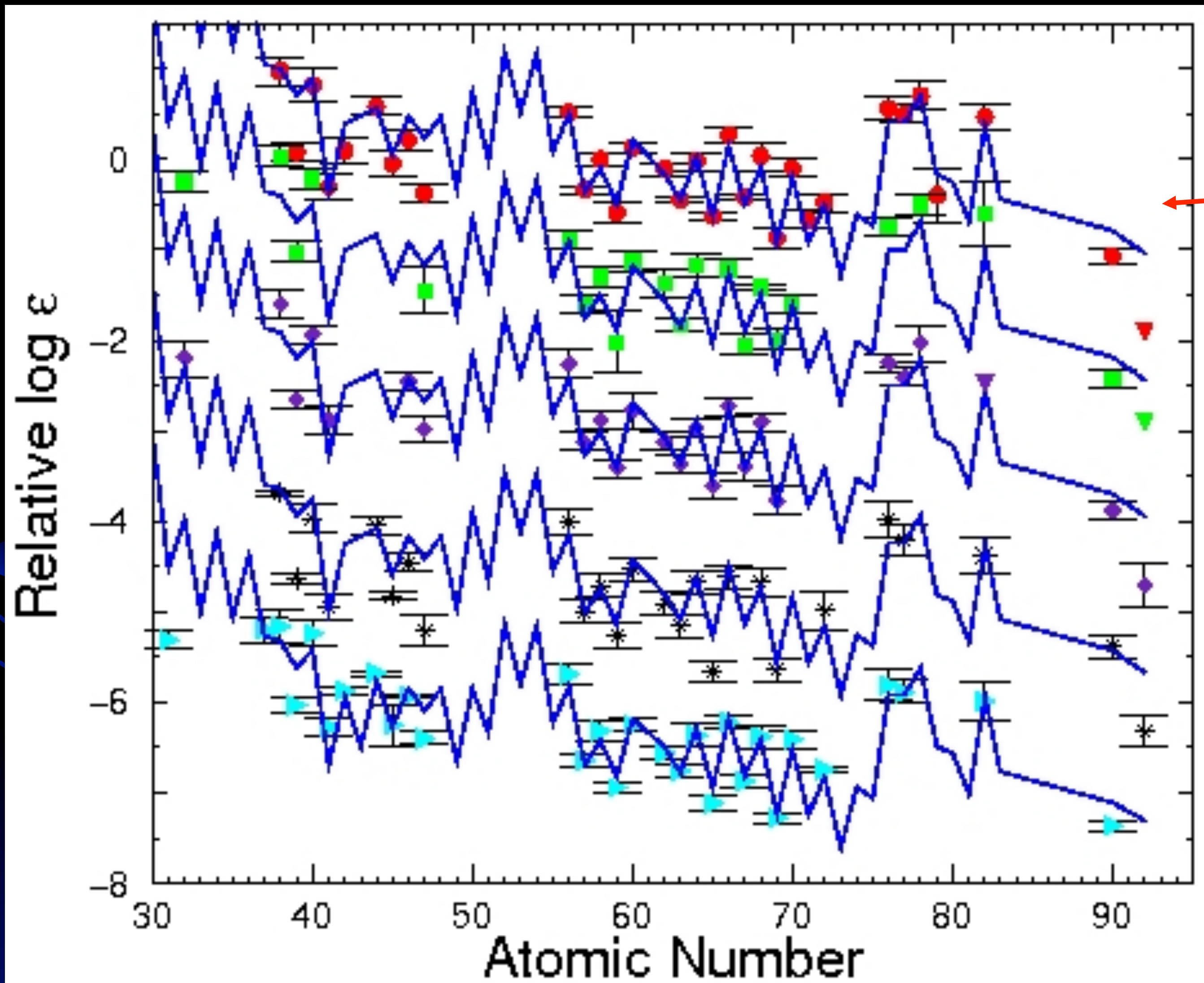


Frebel et al. (2007)

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)

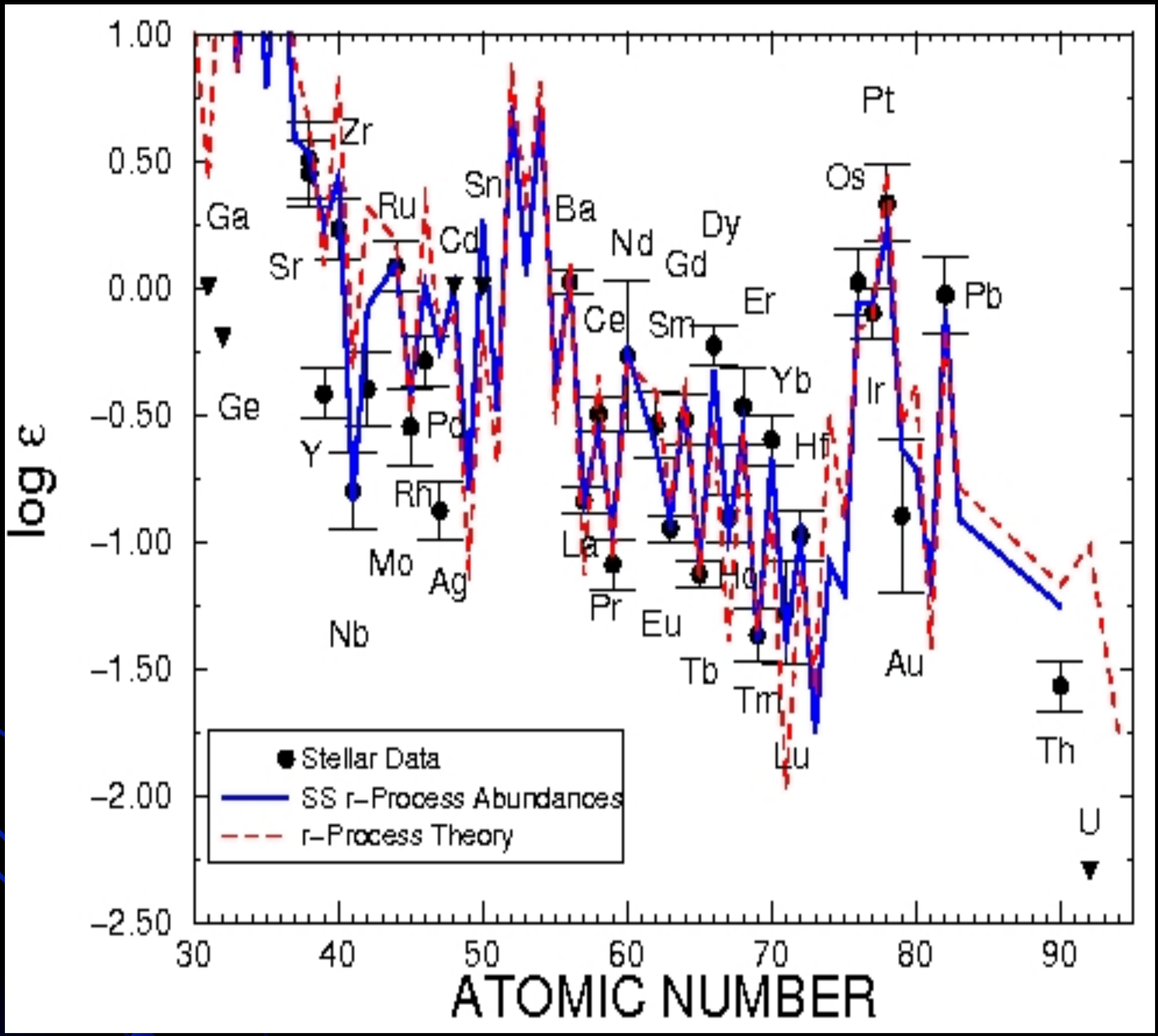


note difference between radioactive Th, U and solid line

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

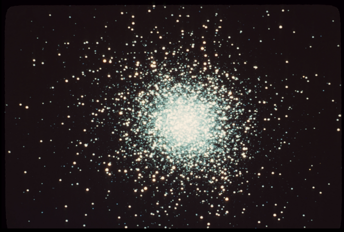


Calculate radioactive abundance ratios based upon fitting stable elemental & isotopic values.

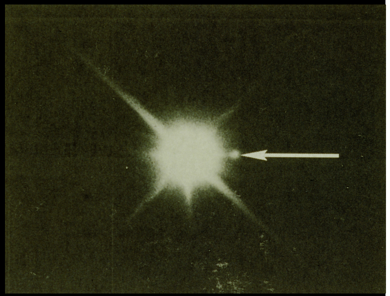
The Age of the Milky Way

- From Radioactive Elements in Stars (cosmochronometers) get a range of 11.7 – 14.2 +/- 3 Gyr

- From Globular Cluster Stars get a range of 13-15 Gyr



- Can also use White Dwarf Stars (cooling times) to get age of the disk of 10-11 Gyr



Compared to the Age of the Universe

- Cosmological big bang radiation (WMAP) = 13.7 +/- 1 Gyr
- Supernovae: expansion of the Universe (dark energy discovery) = 14.2 +/- 2 Gyr

Some Concluding Thoughts on: Nucleosynthesis Early in the Galaxy

- r-process elements observed in very metal-poor (old) halo stars
- Implies that r-process sites, earliest stellar generations

→ rapidly evolving: live and die, eject r-process material into ISM prior to formation of halo stars

- Elements (even s-process ones like Ba) produced in r-process early in Galaxy
- Robust for heavy end:

→ places constraints on sites for the r-process

More Deep Thoughts on: Element Synthesis

- Ge and Zr complicated element formation: challenge to theorists
- Evidence for additional synthesis processes?
- Os, Ir & Pt correlated (and scatter) with Eu
- s-process onset at low [Fe/H]: how?
- Detections of radioactive elements (Th & U) allow age estimates for oldest stars: putting limits on the age of the Galaxy & Universe

With Collaborators at:

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

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