OBSERVATIONAL ASTROPHYSICS I

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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).

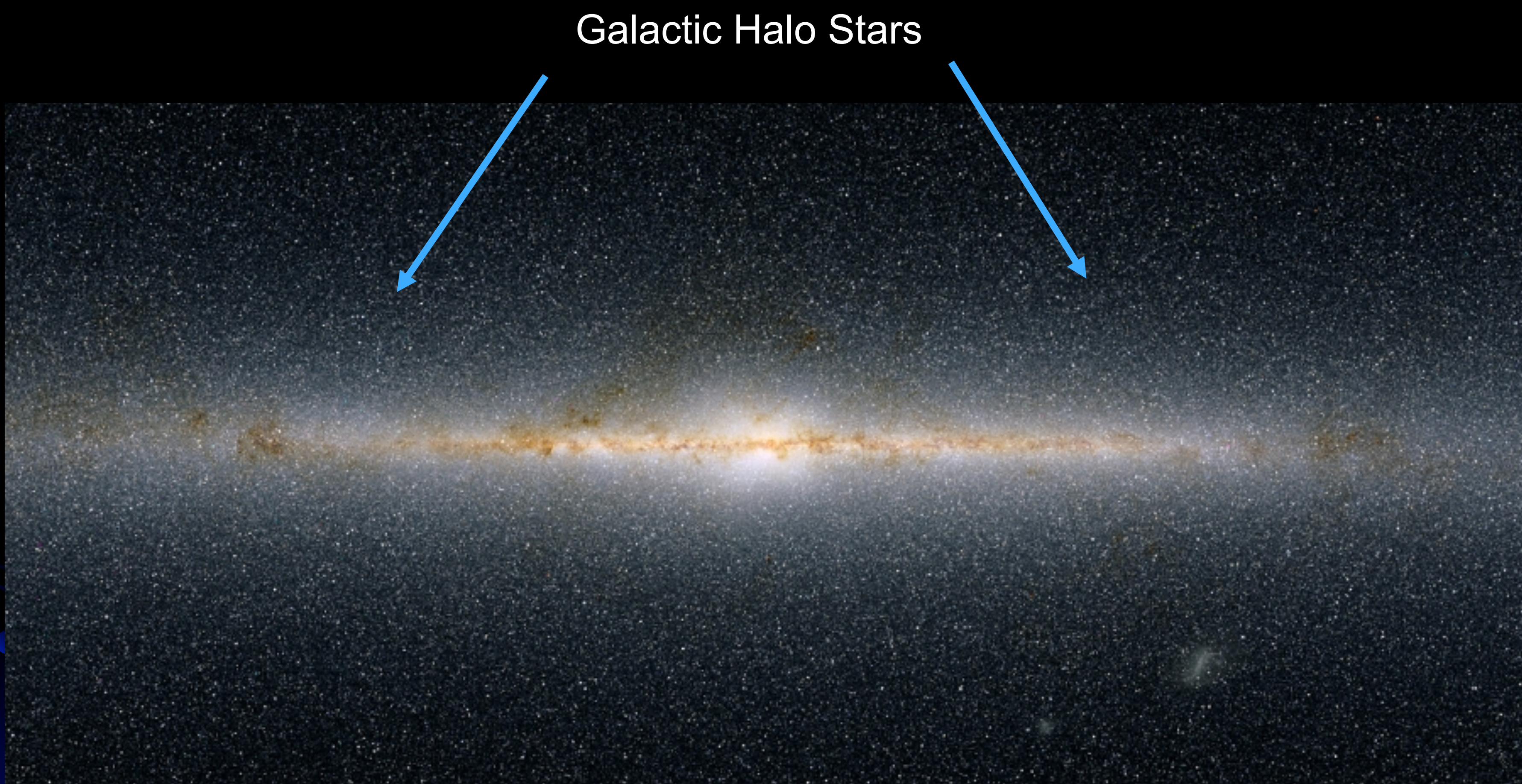
Abundance Clues and Constraints: Outline of the Lectures

- 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

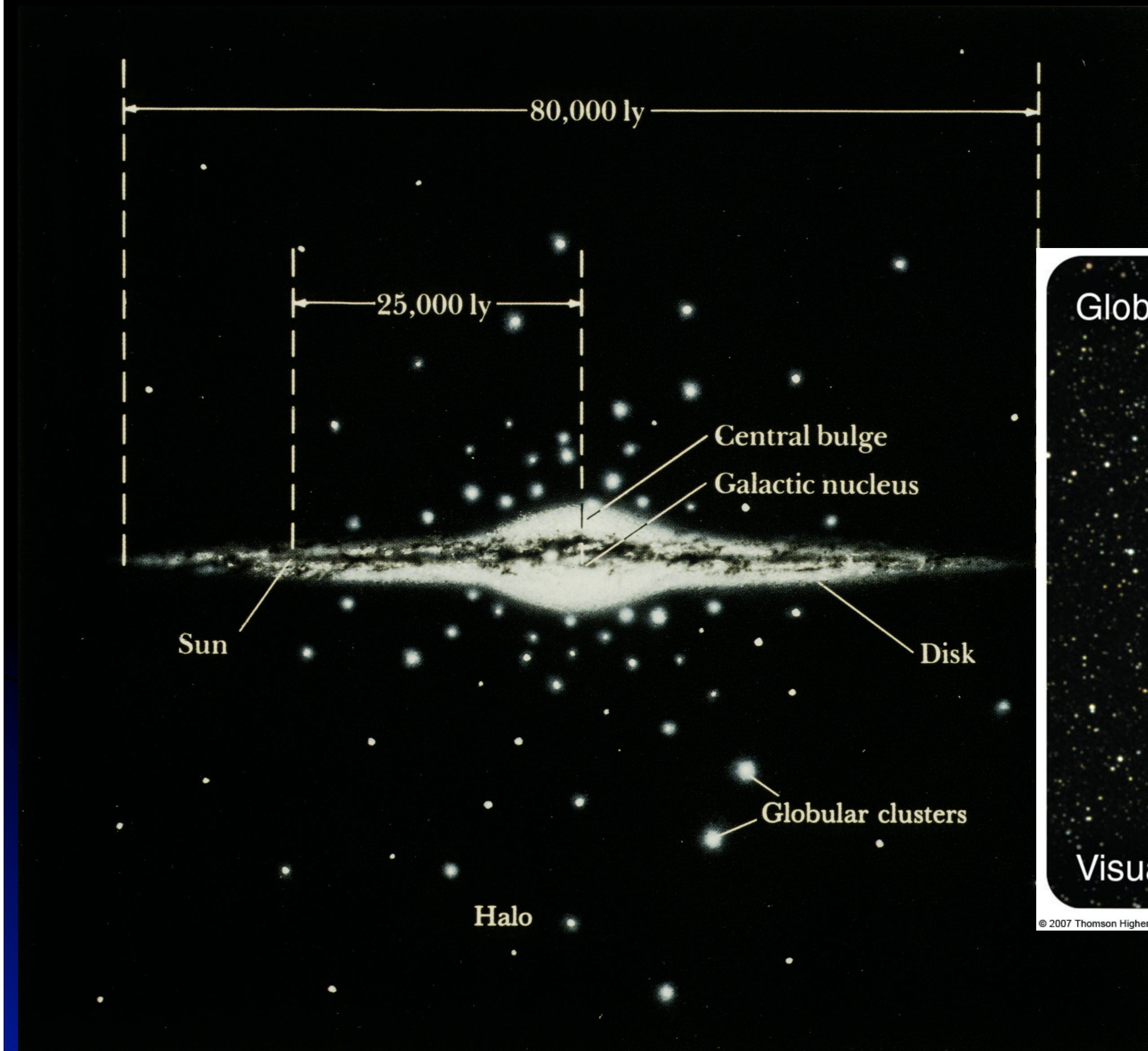
2MASS View of the Milky Way

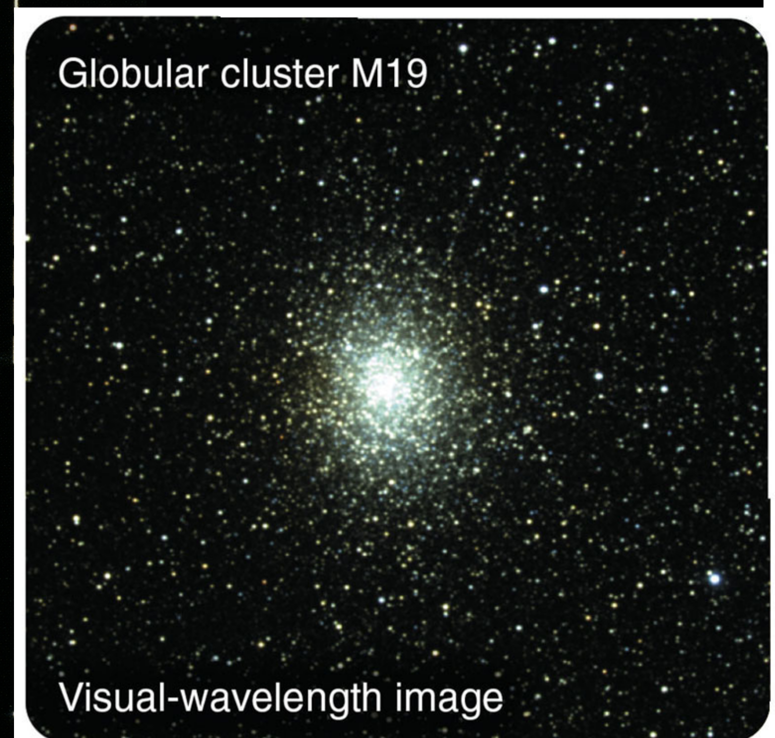


- Metal-poor Halo Stars are ``fossils'' of the Early Universe
- These Stars are Relatives of the First Stars in the Universe

``Near Field Cosmology''

Artistic View of the Milky Way





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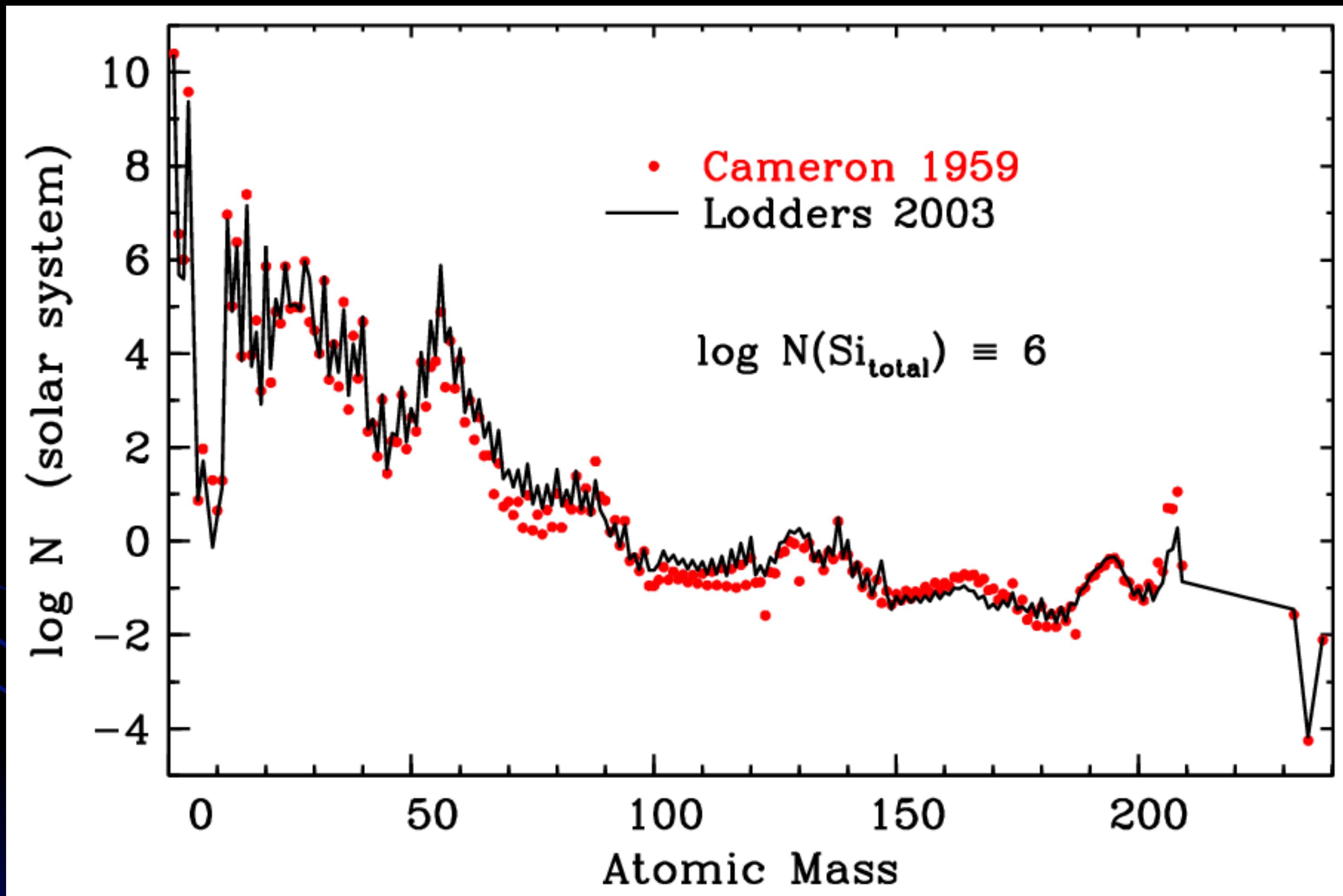
Solar System Abundances

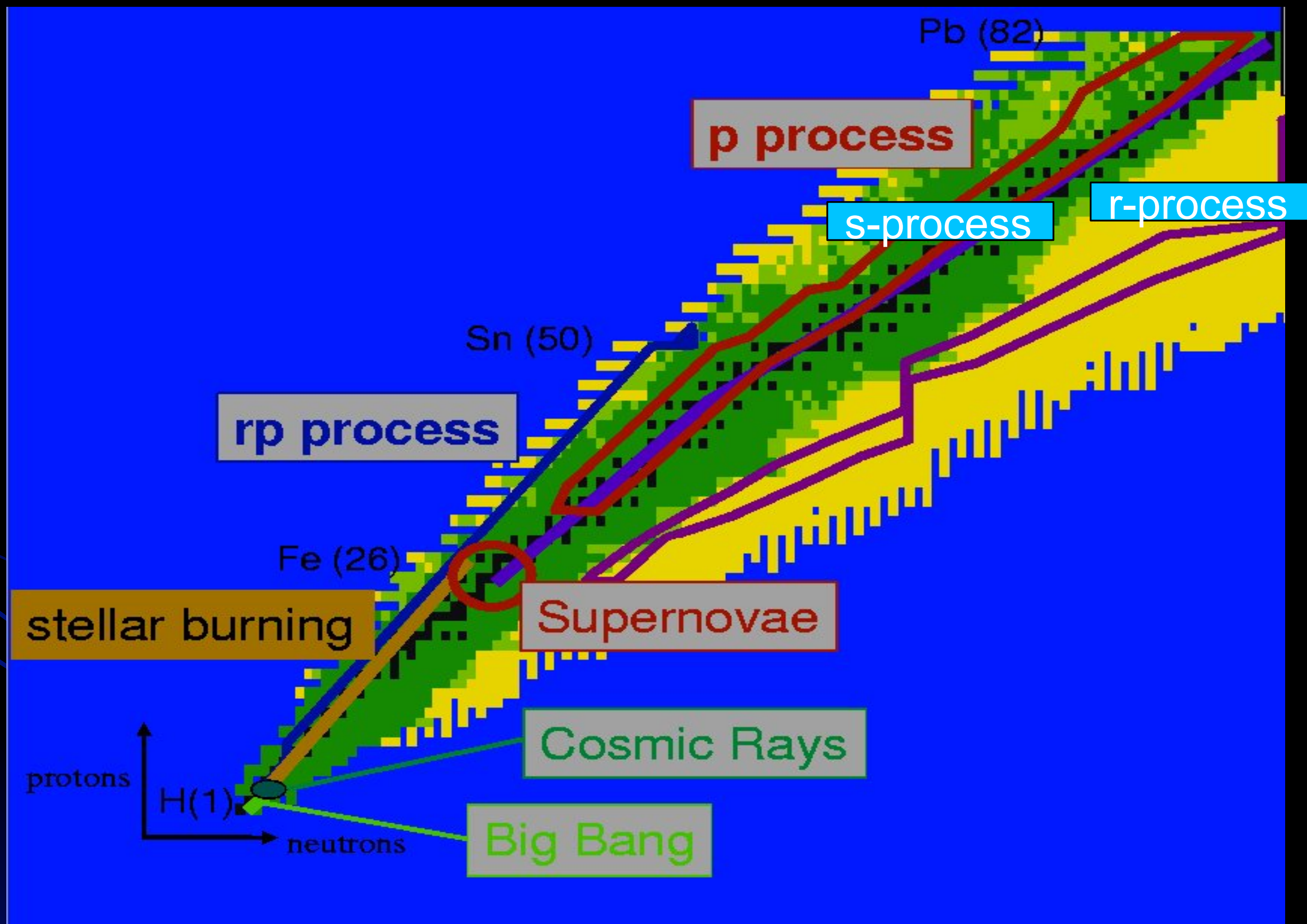


Note odd-even effect

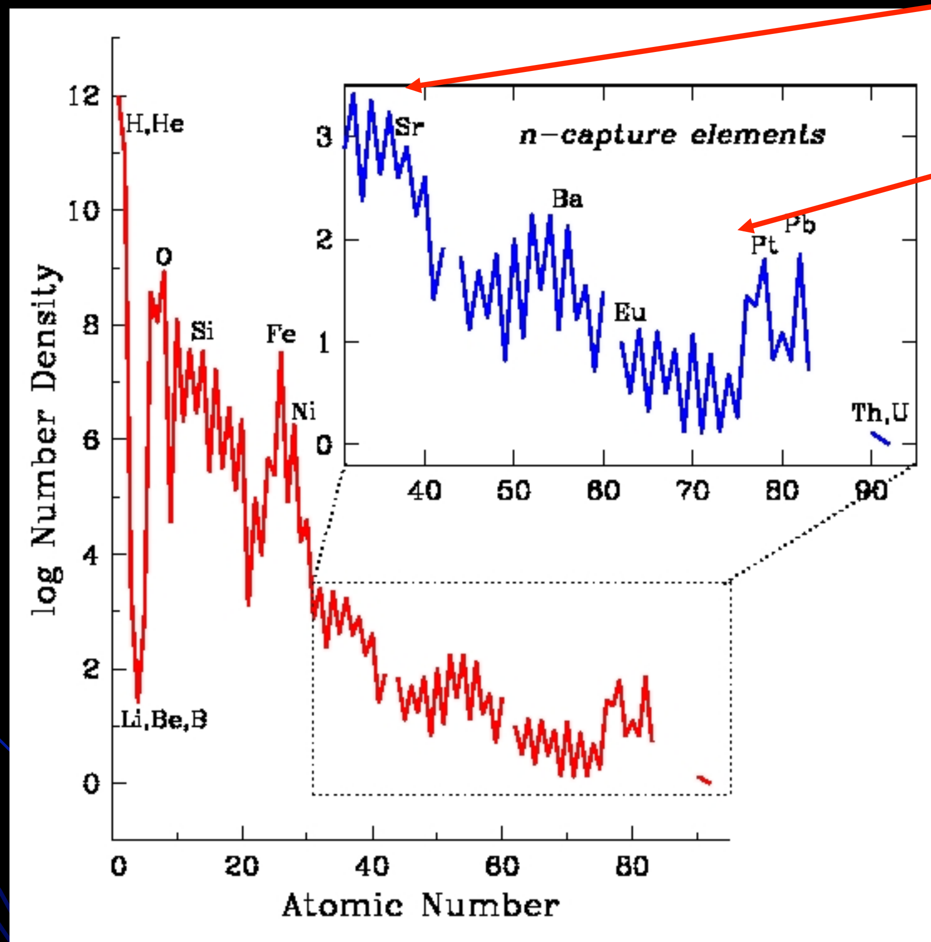
Meteoritic scale

Sneden, Cowan & Gallino (2008)

Summary of Nucleosynthetic Processes that Make Elements



Solar System (``Cosmic”) Abundances



Ge, Zr

Os, Pt

Jewelry store items

radioactive

Sneden & JC (2003)

Spectroscopic Scale: log N(H) = 12

Evolution of Stars

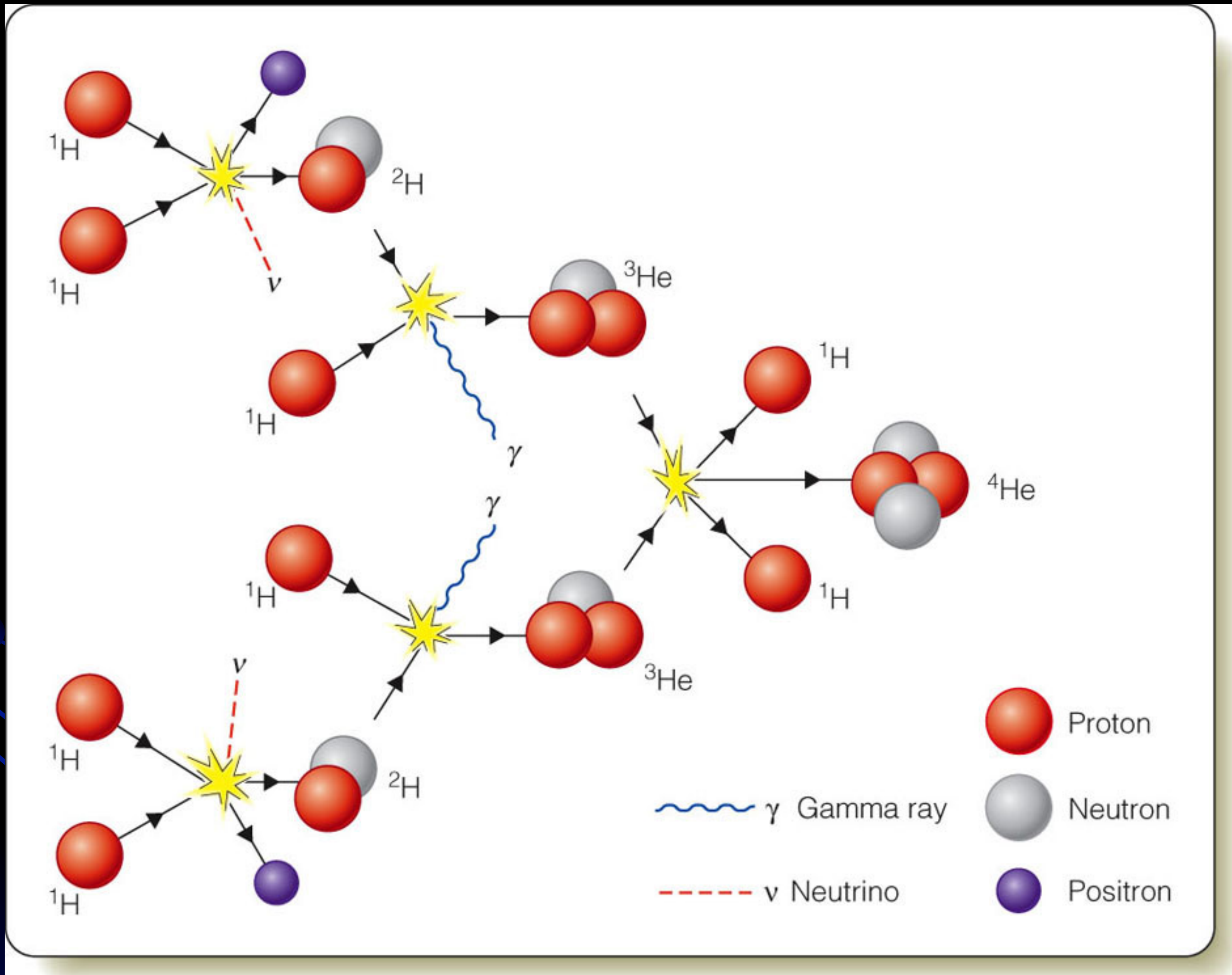
How do stars live and die?

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

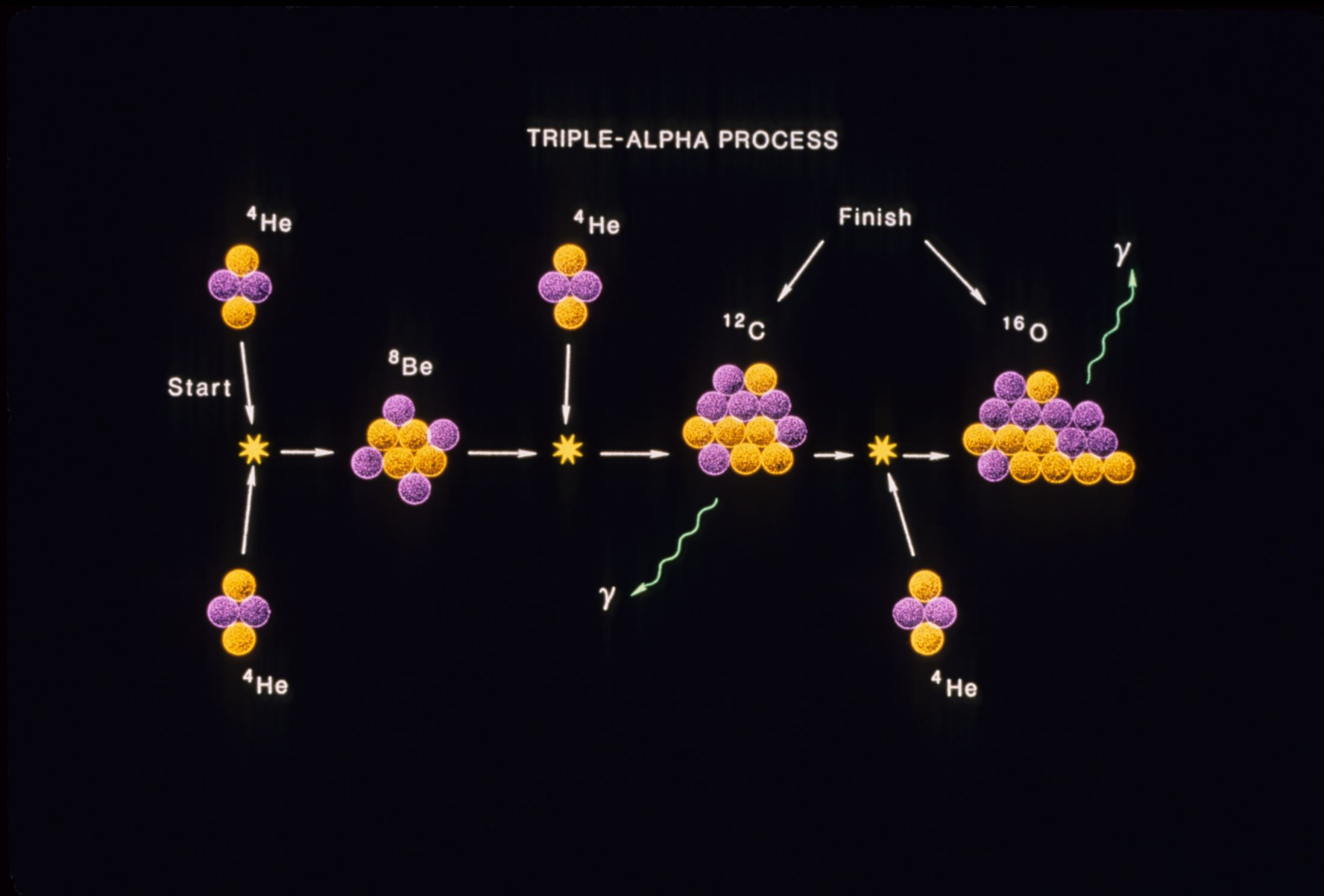
How do stars eject those heavy elements into space and into gas that will make new stars and planets?

- Evolution of Stars;/z005a.swf

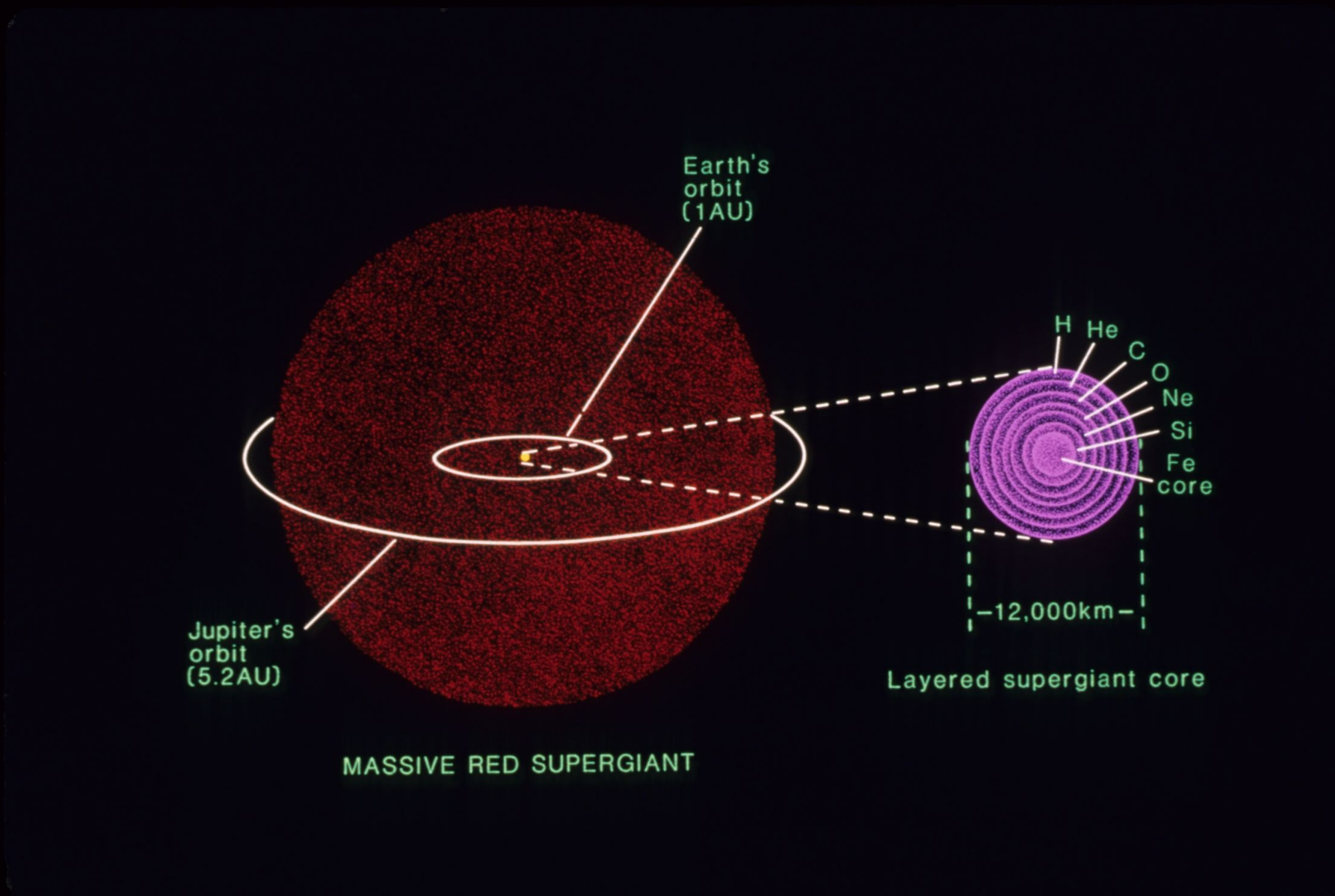
Stellar Burning: Hydrogen Fusion



Stellar Burning: Helium Fusion



Red Giant Prior to SN II Explosion

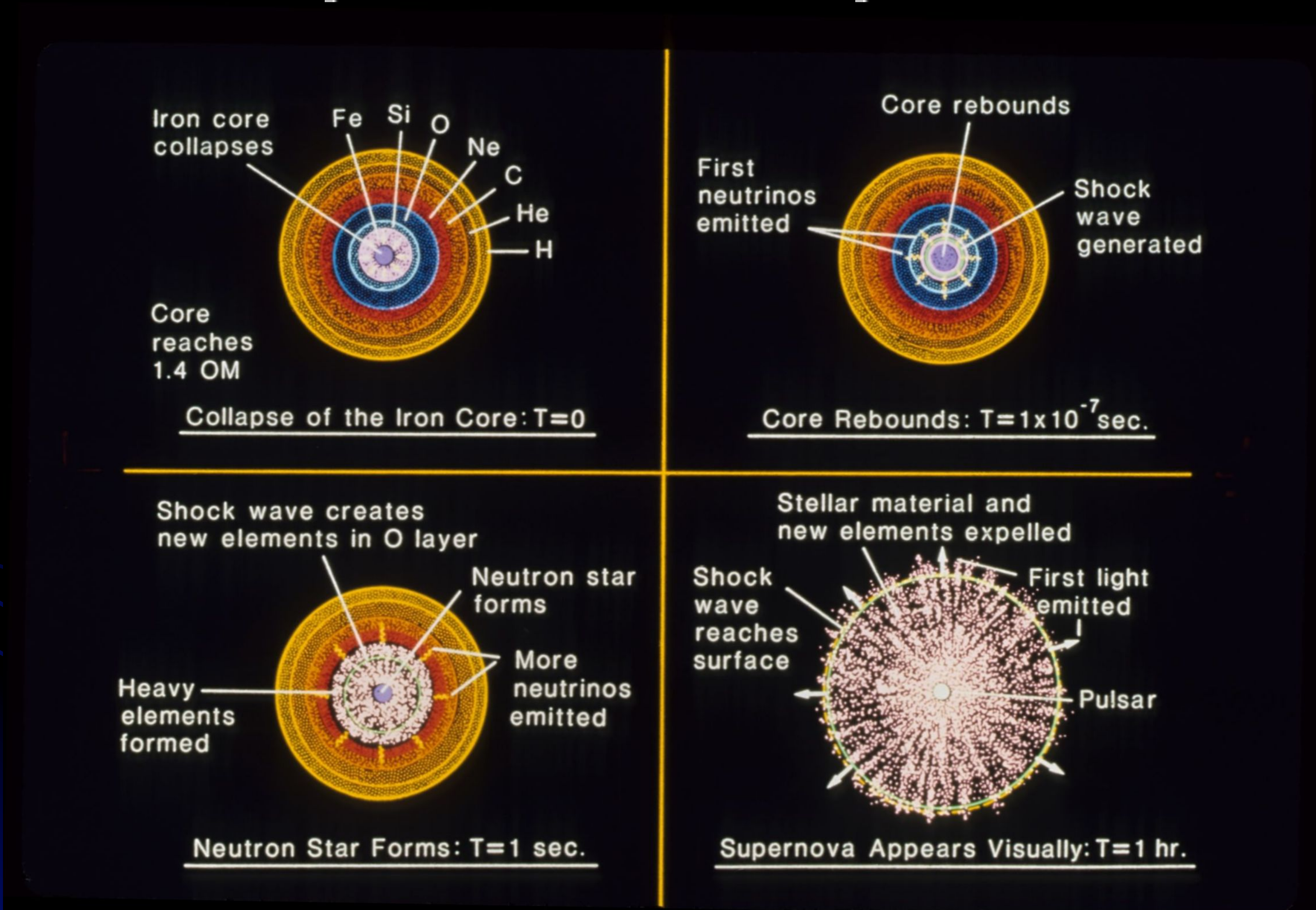


Massive Star Stages Prior to SN II Explosion

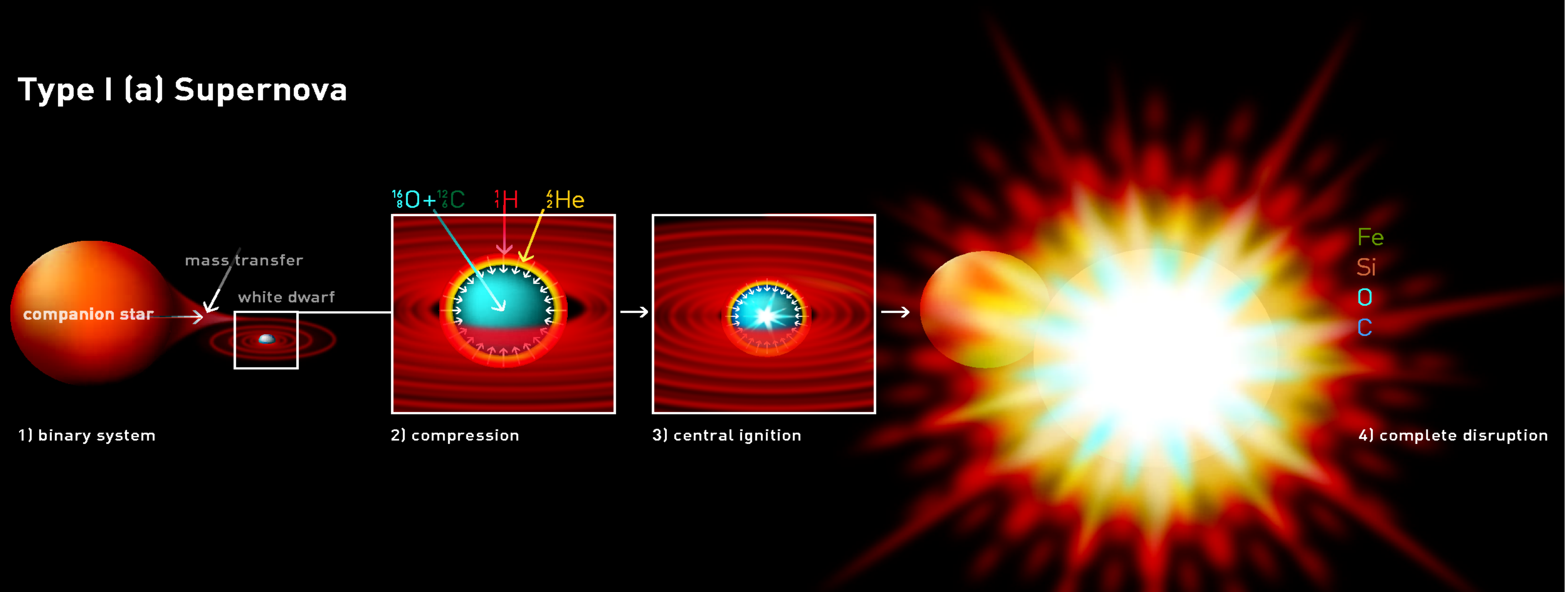
EVOLUTIONARY STAGES IN A 25 SOLAR MASS STAR

STAGE	TEMPERATURE (K)	DENSITY (g/cm_3)	DURATION
HYDROGEN BURNING	4×10^7	5	7×10^6 YEARS
HELIUM BURNING	2×10^8	700	5×10^5 YEARS
CARBON BURNING	6×10^8	2×10^5	600 YEARS
NEON BURNING	1.2×10^9	4×10^6	1 YEAR
OXYGEN BURNING	1.5×10^9	10^7	6 MONTHS
SILICON BURNING	2.7×10^9	3×10^7	1 DAY
CORE COLLAPSE	5.4×10^9	3×10^9	1/4 SECOND
CORE REBOUND	2.3×10^{10}	4×10^{14}	MILLISECONDS
SUPERNOVA	$\sim10^9$	VARIABLE	10 SECONDS

Supernova II Explosion



Explosions caused by accretion in binary stellar systems



binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

- white dwarfs (novae, type Ia supernovae)
- neutron stars (type I X-ray bursts, superbursts?)

Thielemann (2012)

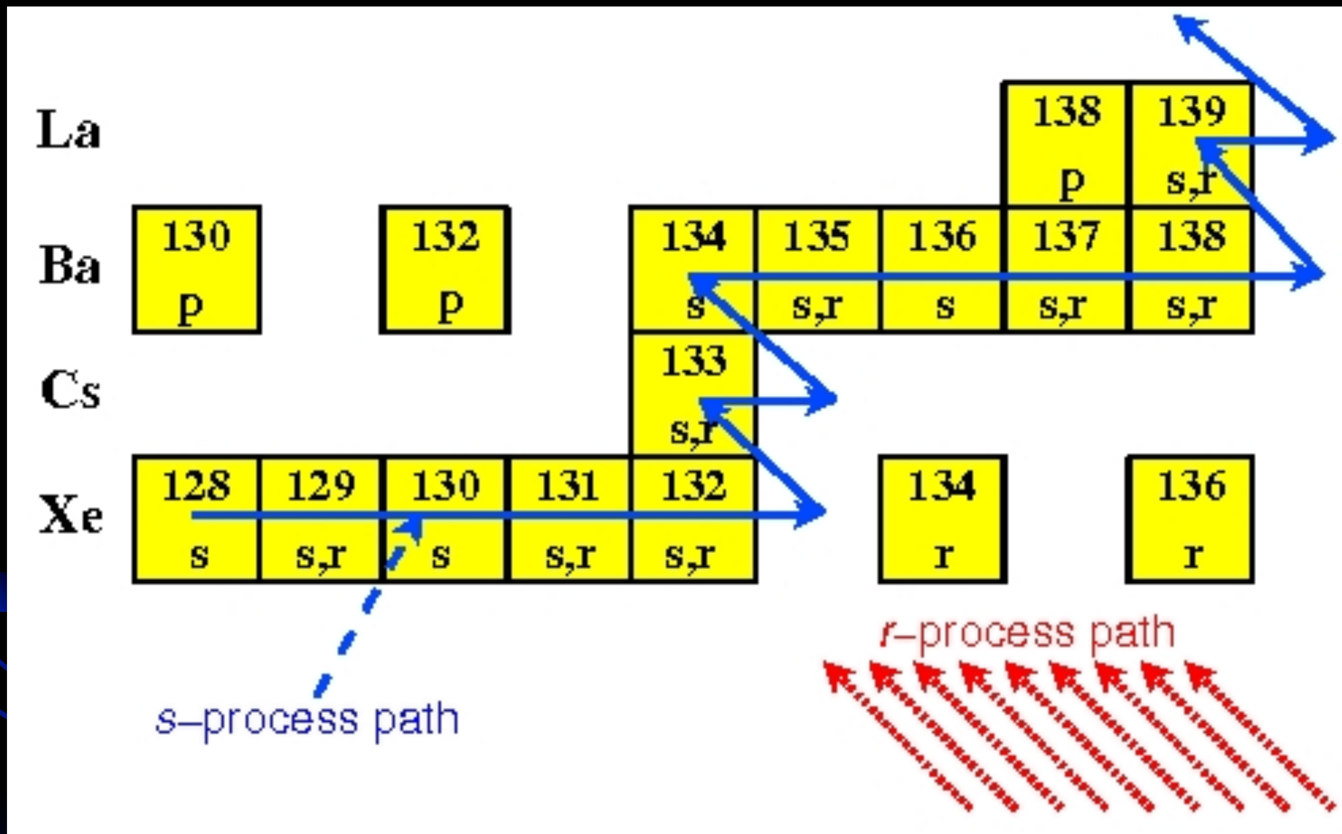
Other options:
White Dwarf Mergers (super-Chandrasekhar)
He-accretion on WD (sub-Chandra)

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

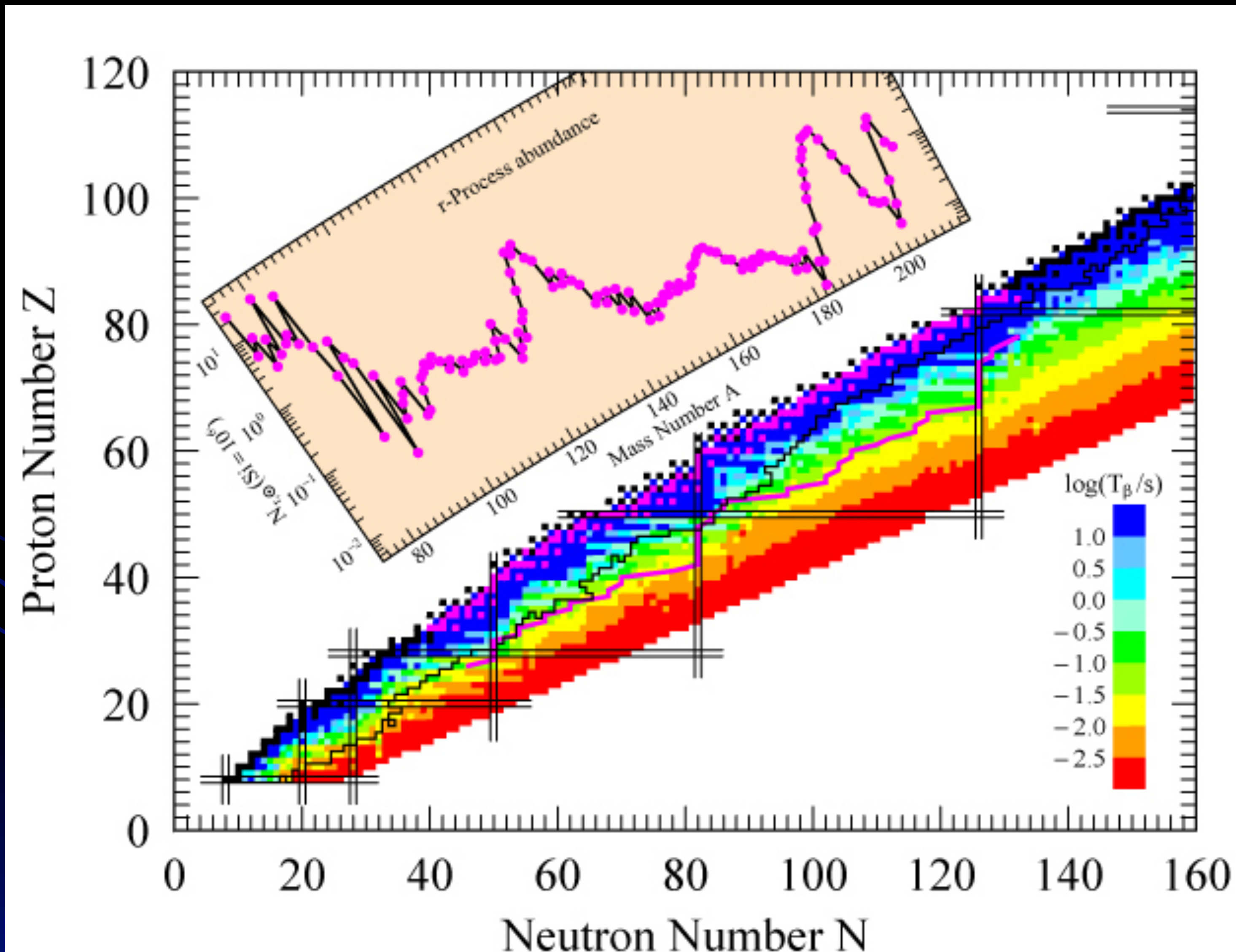
R- and S-Process Paths

	% S-	% R-
La	75	25
Ba (S-process element)	85	15
Cs	15	85
Xe (R-process element)	20	80



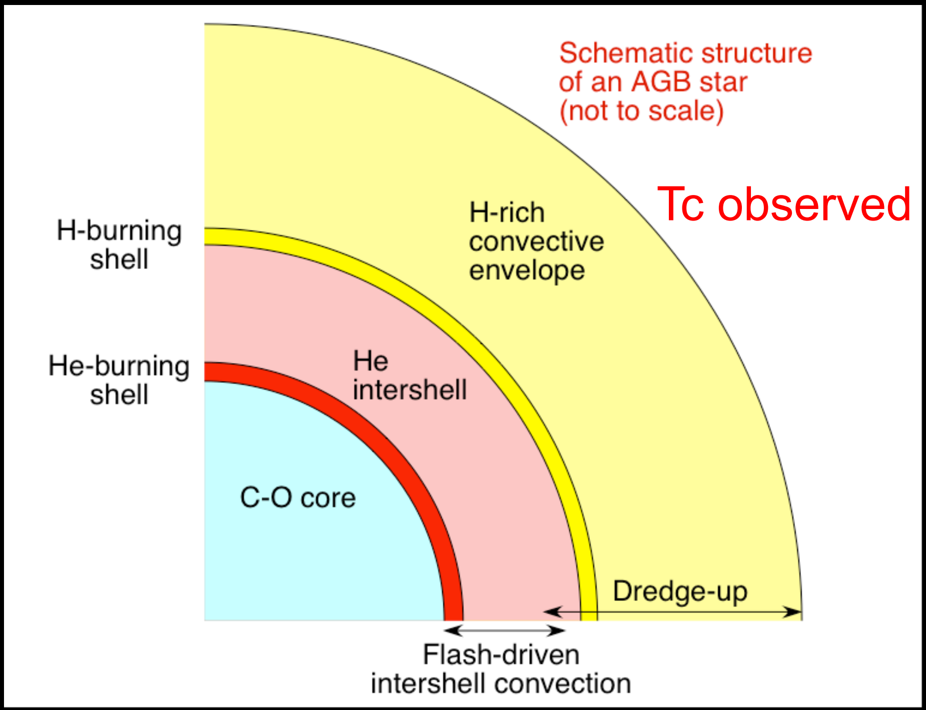
Sneden and JC (2003); Sneden, JC & Gallino (2008)

The Nuclear Isotopes in Nature



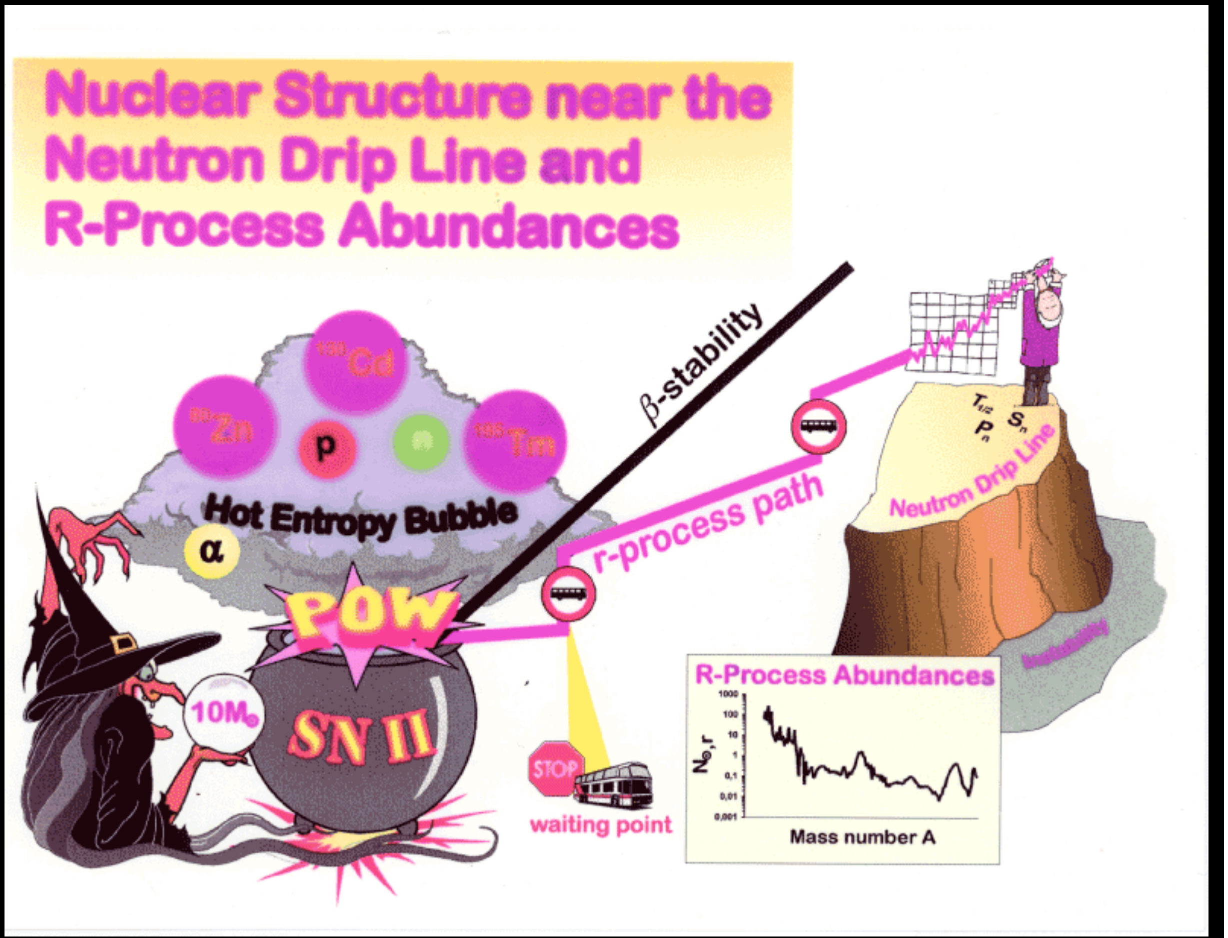
s-Process Nucleosynthesis

- 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



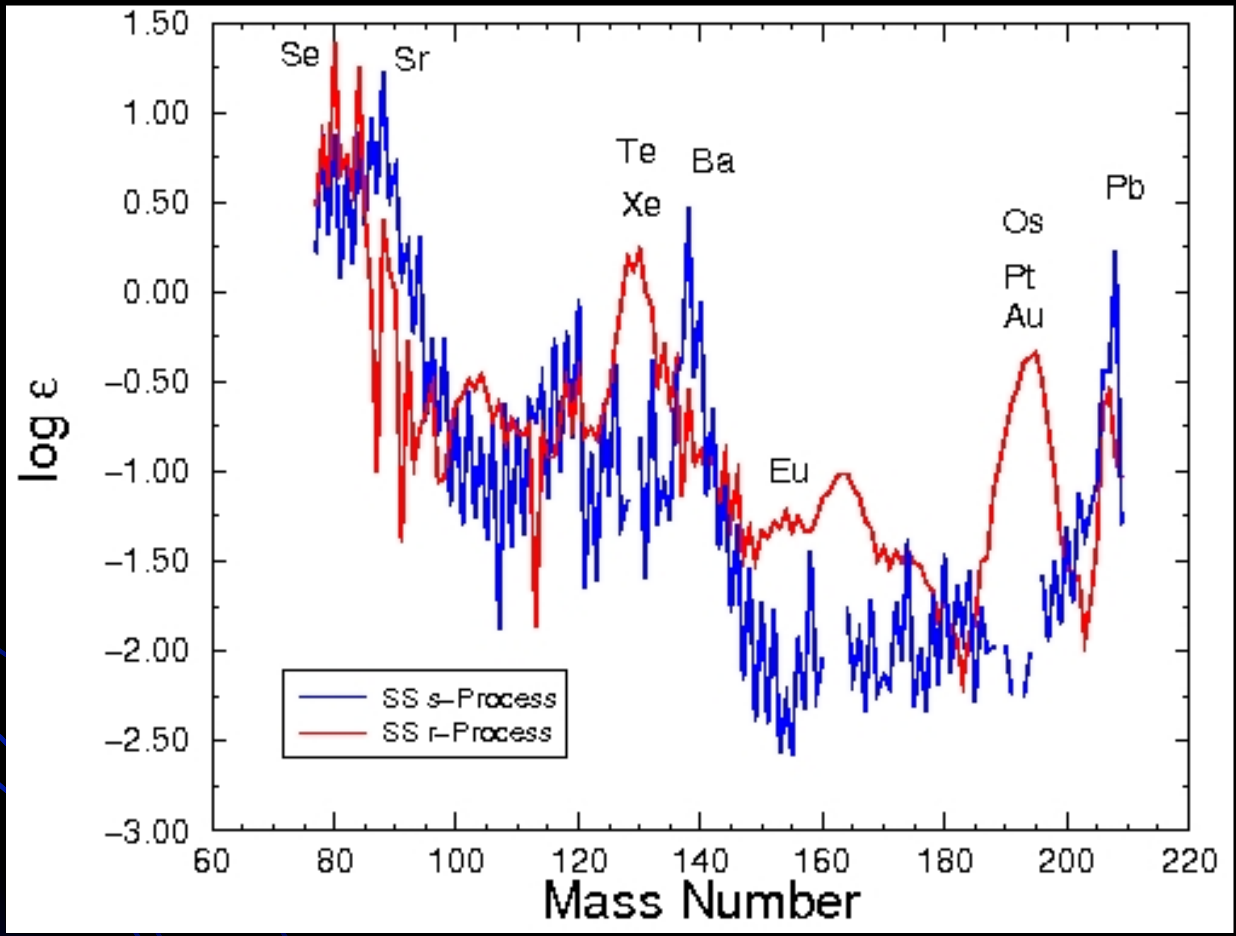
r-Process Nucleosynthesis

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



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

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



SS isotopic deconvolution by s- and r-process

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

Most Likely Site(s) for the r-Process

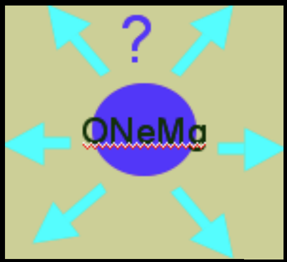
Crab Nebula First Seen in 1054

Supernova Explosion in the Milky Way

- Supernovae: The Prime Suspects

→ Regions just outside neutronized core: 1957 (B2FH; Cameron) (Woosley et al. 1994; Wanajo et al. 2002) (ν-wind)

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

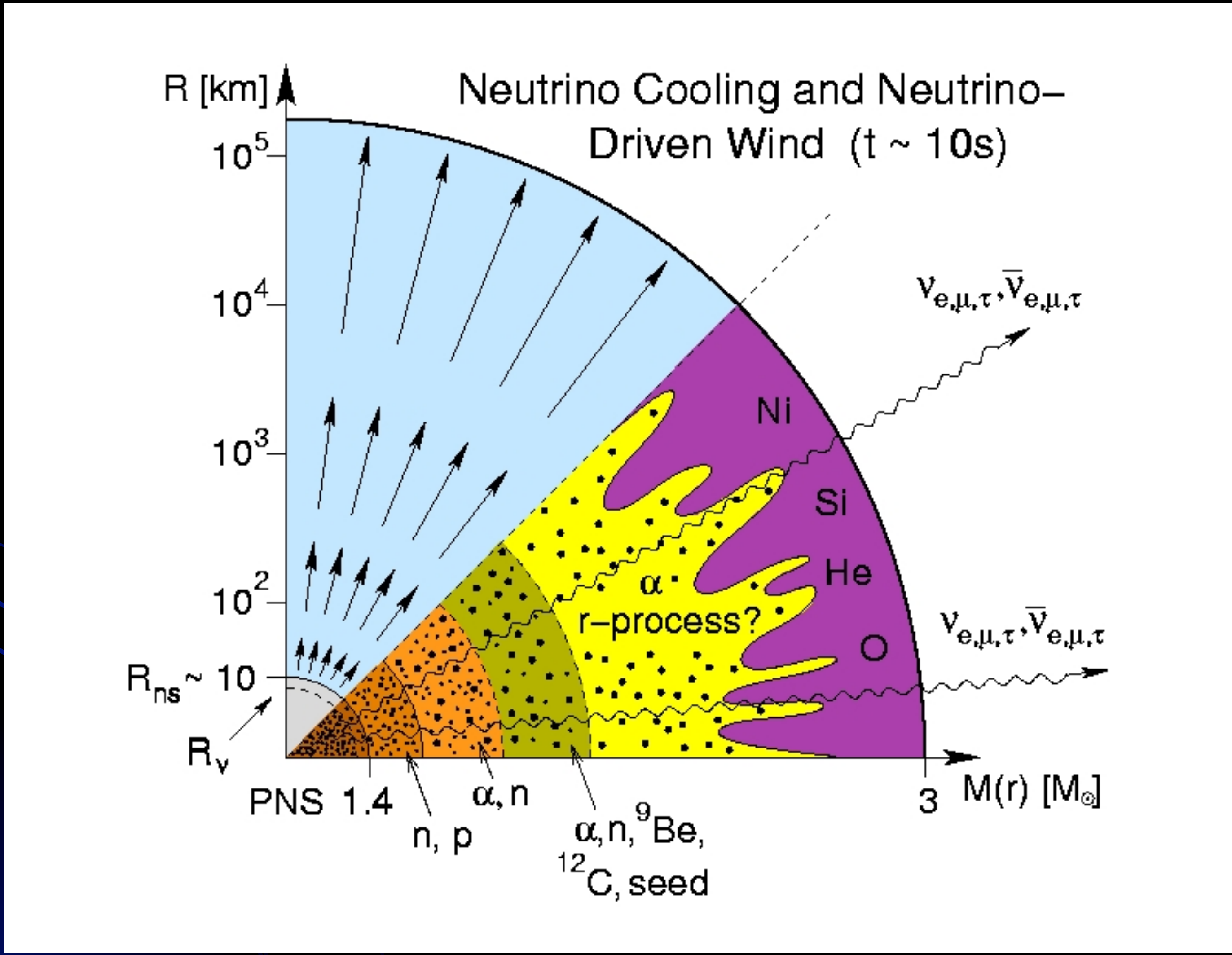


→ Jets and bubbles (Cameron 2001)

- NS & NS-BH mergers (Lattimer & Schramm 70s); Rosswog et al. 1999; Freiburghaus et al. 1999; Korobkin et al. 2012)

Stellar Spectroscopy

Rapid Neutron Capture in Type II SNe ?



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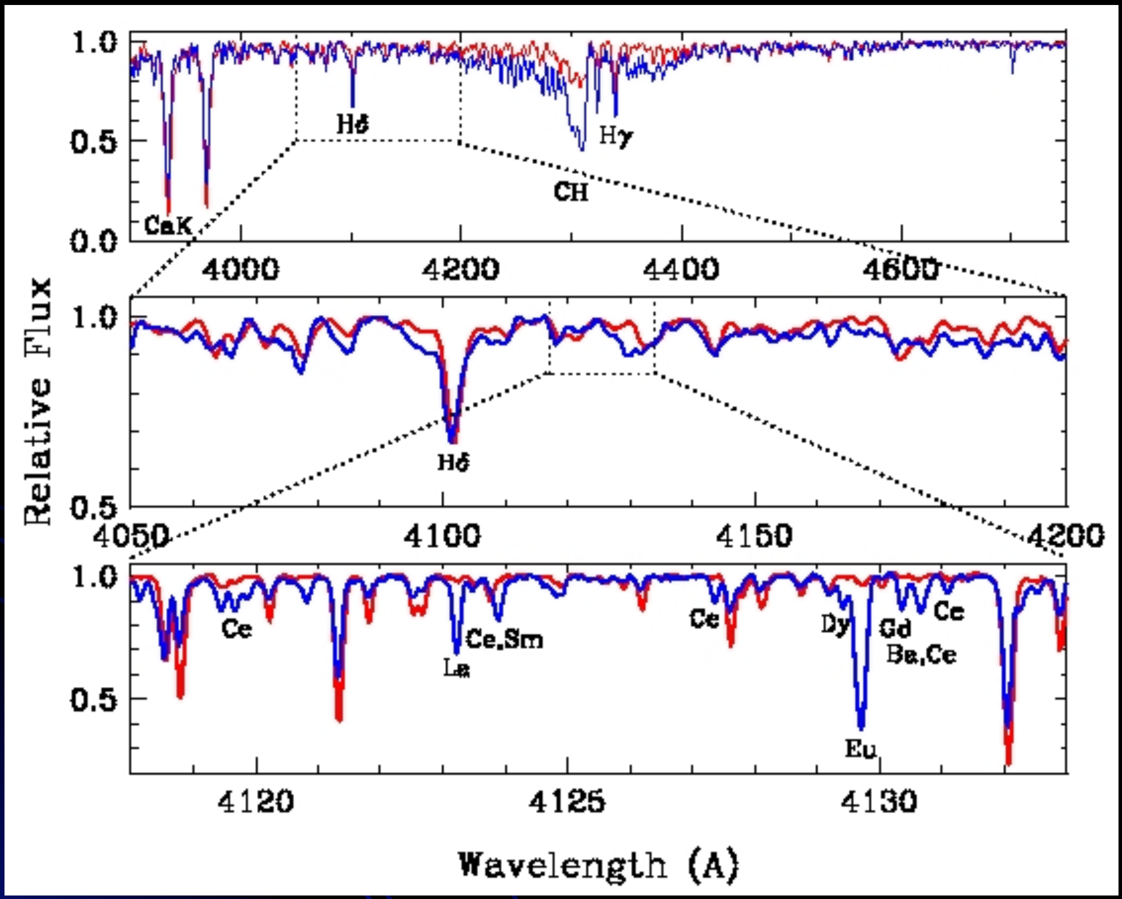
Stellar Spectroscopy: Absorption Lines



Low resolution

Expanded view

← n-capture heavy elements: rare earths

High resolution

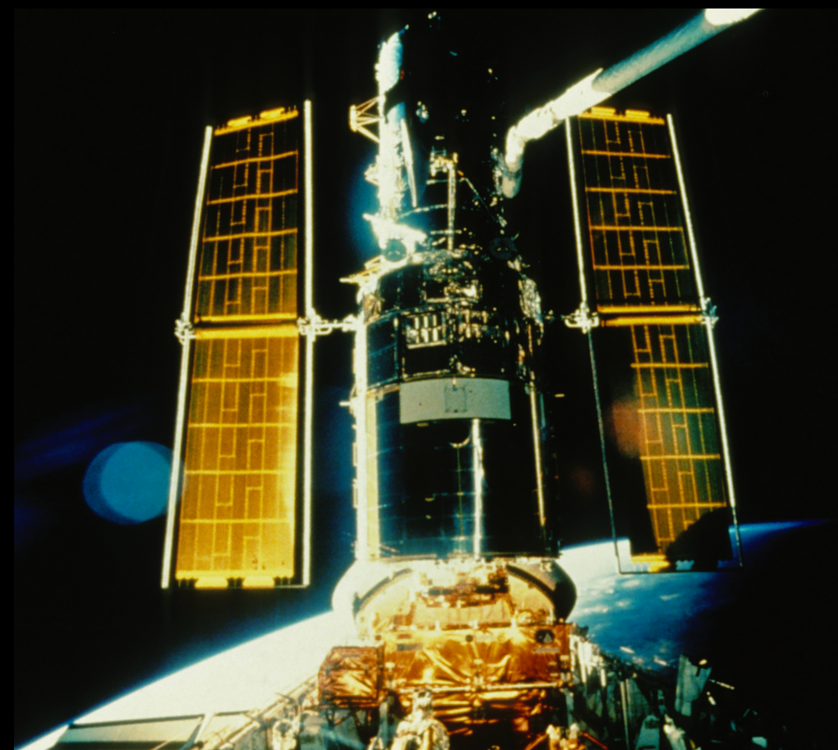
CS 22892-052 (blue line)

HD 122563 (red line)

Some of the Telescopes We Use

Keck Observatory in Hawaii

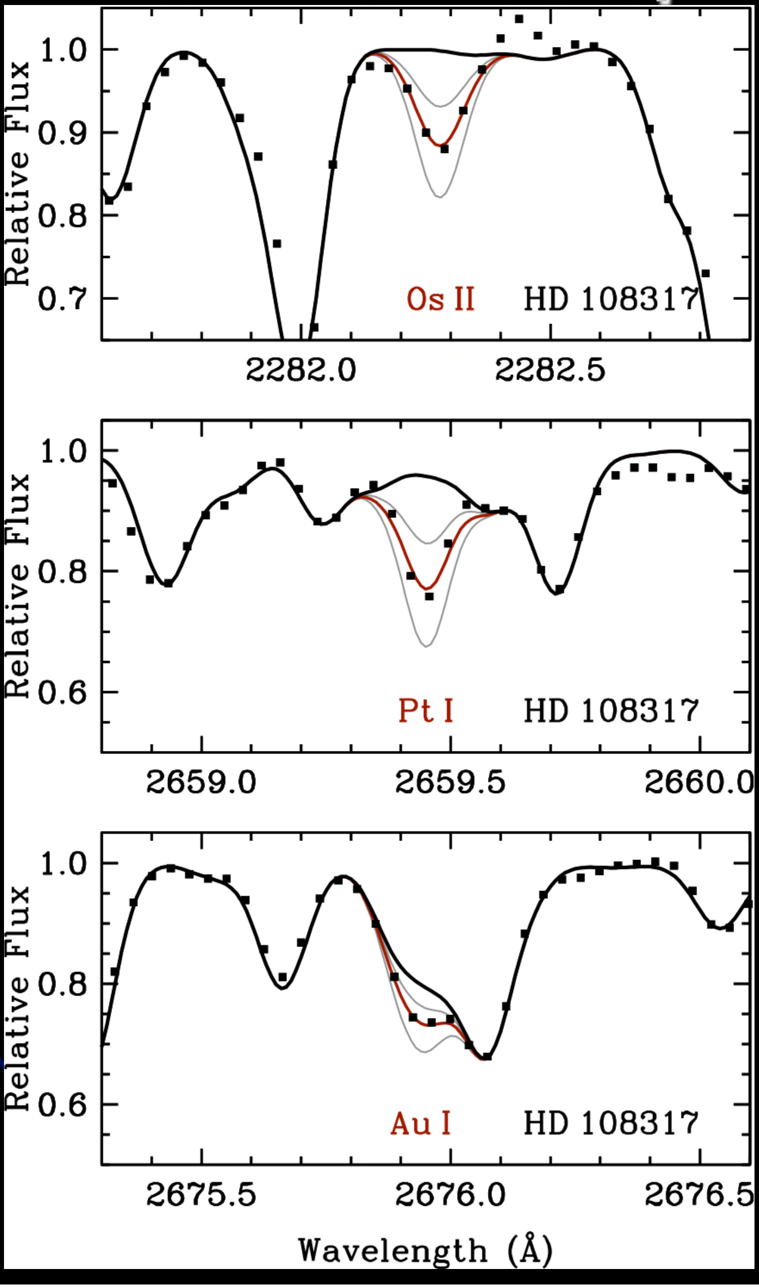
Hubble Space Telescope



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

Space Telescope Integrated Spectrograph

NUV HST STIS Spectra



How do we determine elemental abundances?

Synthetic spectra:
red line best fit,
black line, nothing,
gray lines = +/- 30%

HD 108317
([Fe/H] = -2.5)

Roderer et al.
(2012b)

Rare Earths are Everywhere!

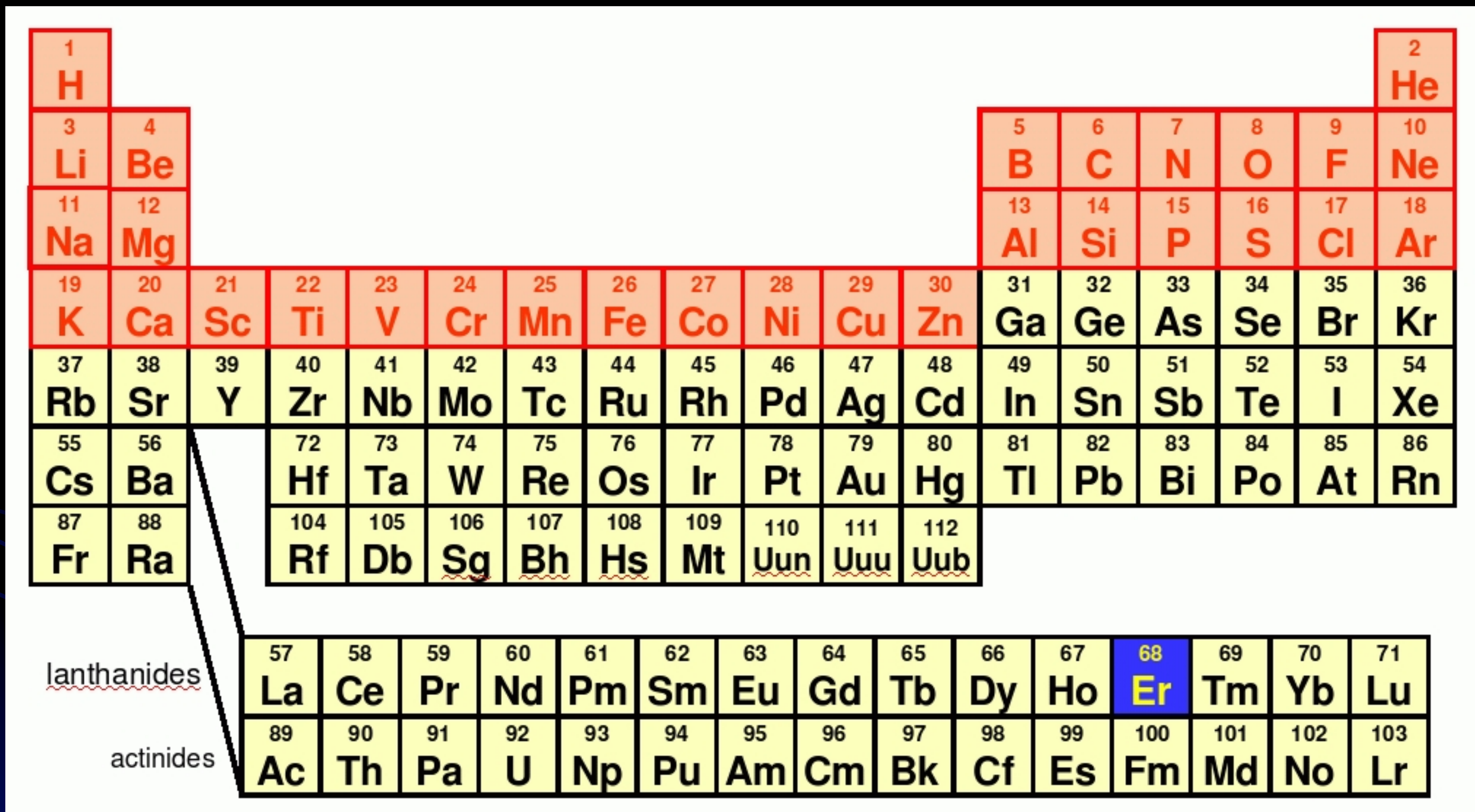

THE SECRET
(Chinese)
INGREDIENTS OF
(almost)
EVERYTHING

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

New Atomic Data to Improve Elemental Abundance Values



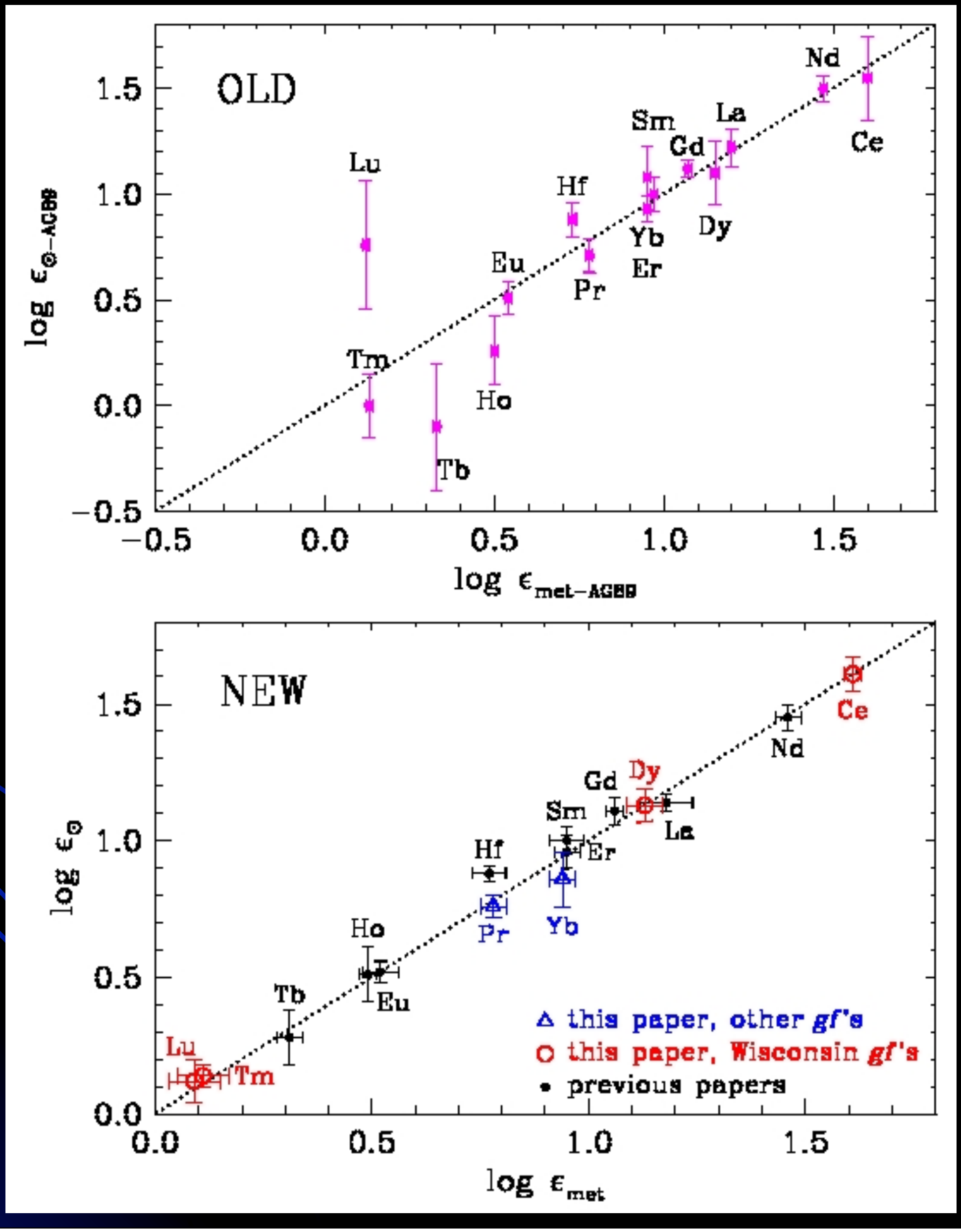
Concentrating on the Rare-Earth Elements

transition probabilities from Lawler’s Wisconsin group

Focus On Rare Earth Elements

Comparisons of SS meteoritic & photospheric values of the REE

Working our way through the periodic Table!

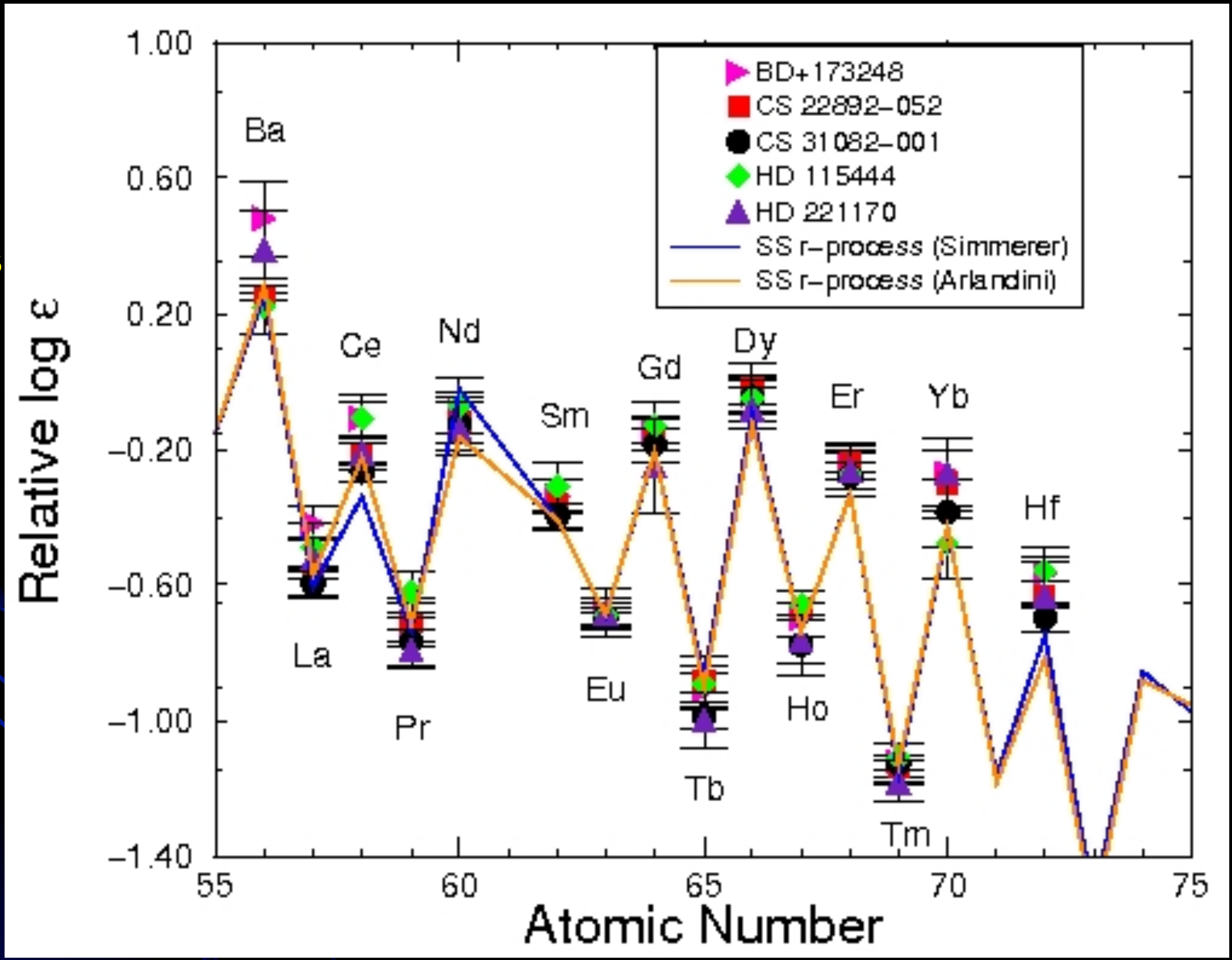


New experimental atomic physics data:

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



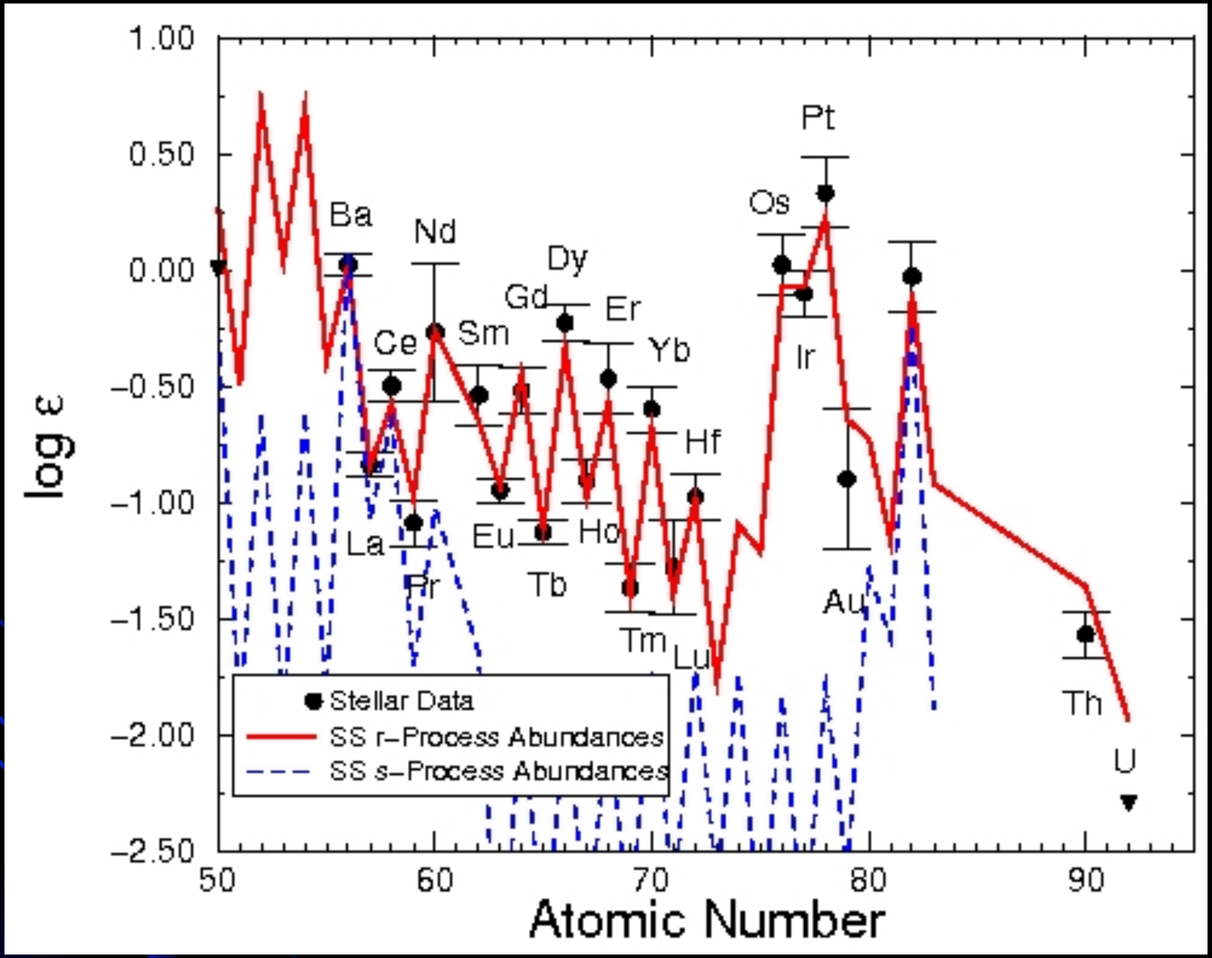
Very little scatter

All normalized to Eu

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

n-Capture Abundances in CS 22892-052: Metal-Poor Halo Star

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



Historical (~ 1996)

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

Stellar elemental abundances consistent with scaled SS r-process only

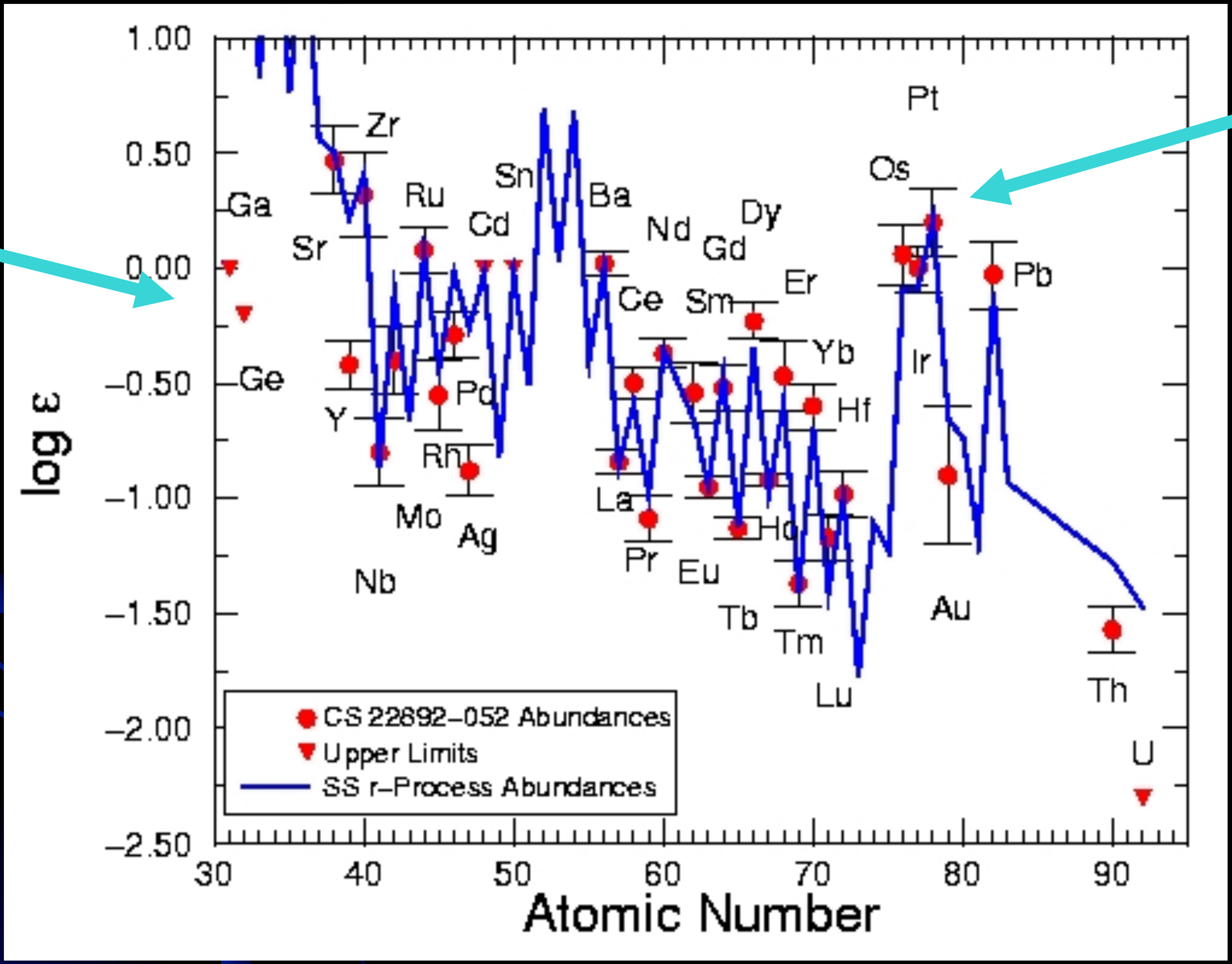
CS 22892-052 Abundances

(with new atomic and stellar data)

31 N-Capture Elements Detected ➡ The Old King

Germanium

Note lighter n-elements do not fall on SS r-process curve



Platinum

(64 HST Orbits)

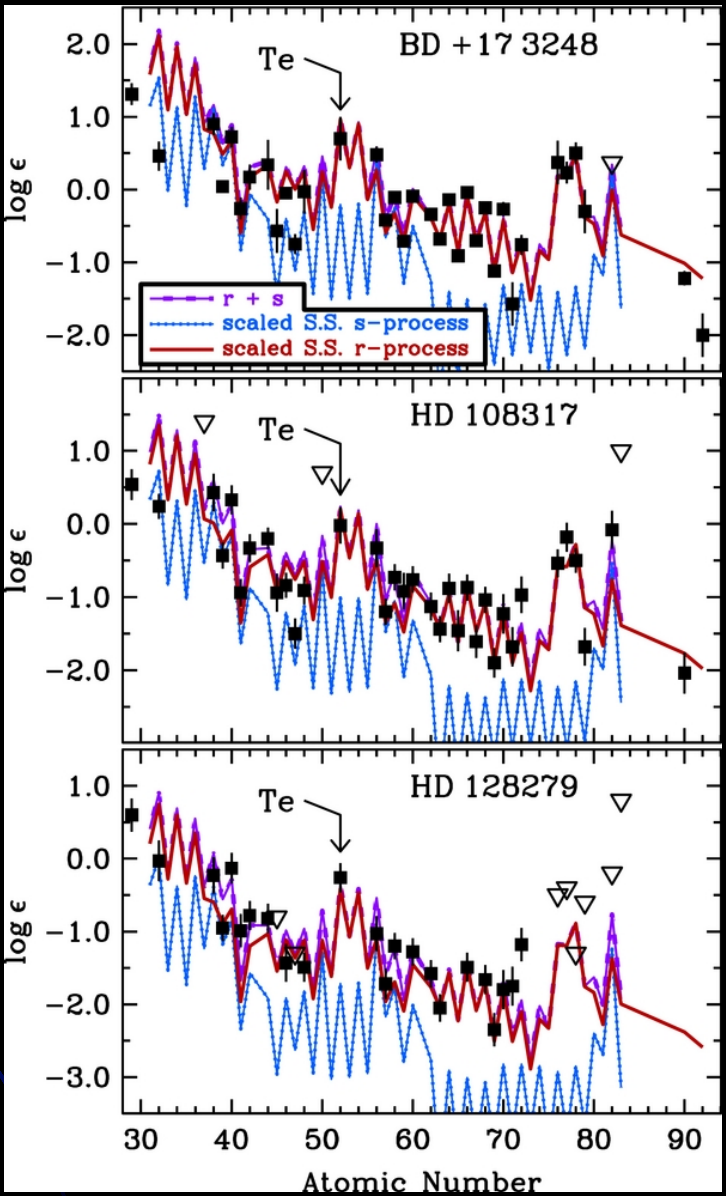
57 elements observed. More than any star except the Sun.

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

First Detections of Te in Halo Stars

➔

Te in second peak produced along with REE and main r-process

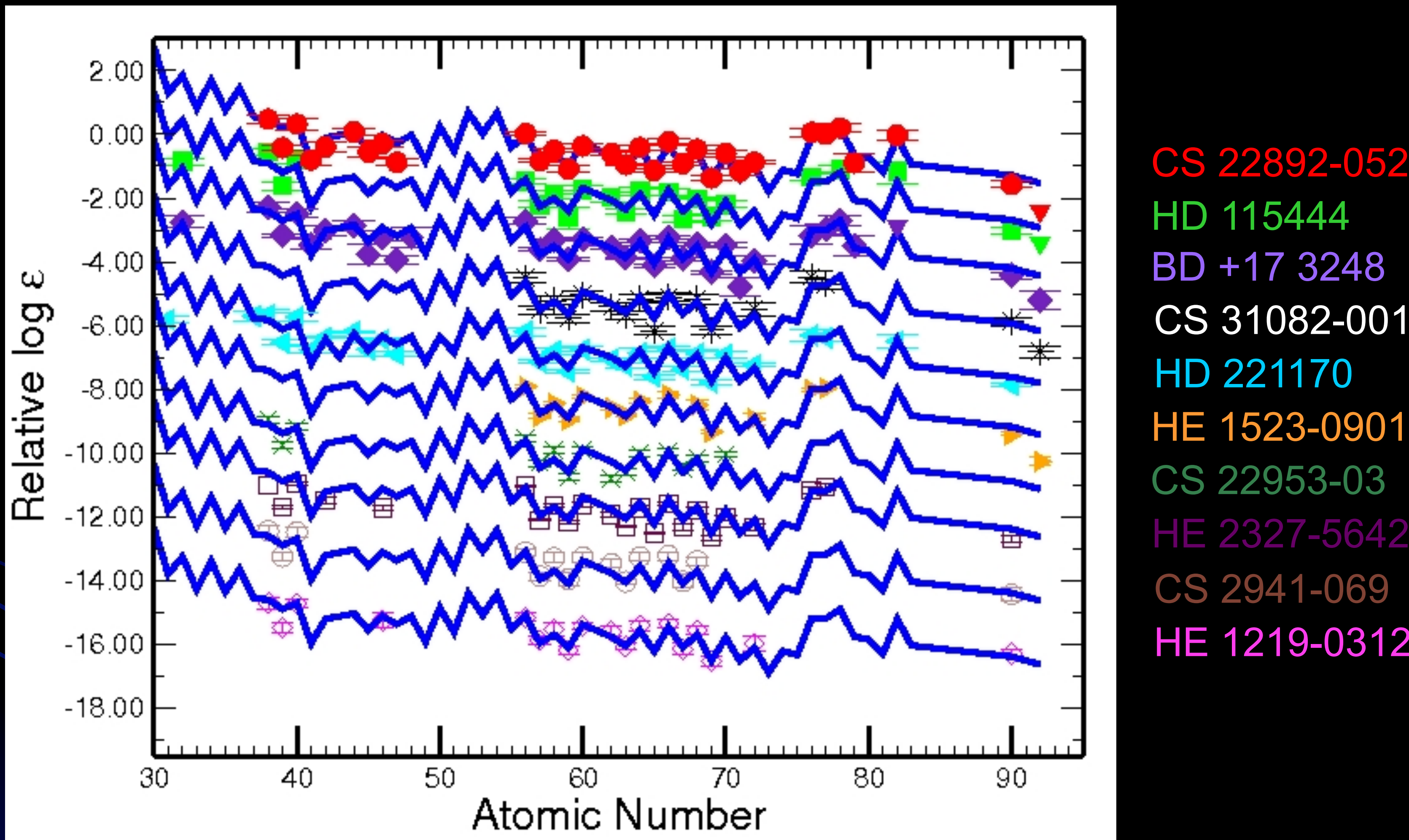


34 n-capture elements detected in BD +17 3248 & HD 108317.

➡ Most in any metal-poor halo stars to date!

Roederer et al. (2012a)

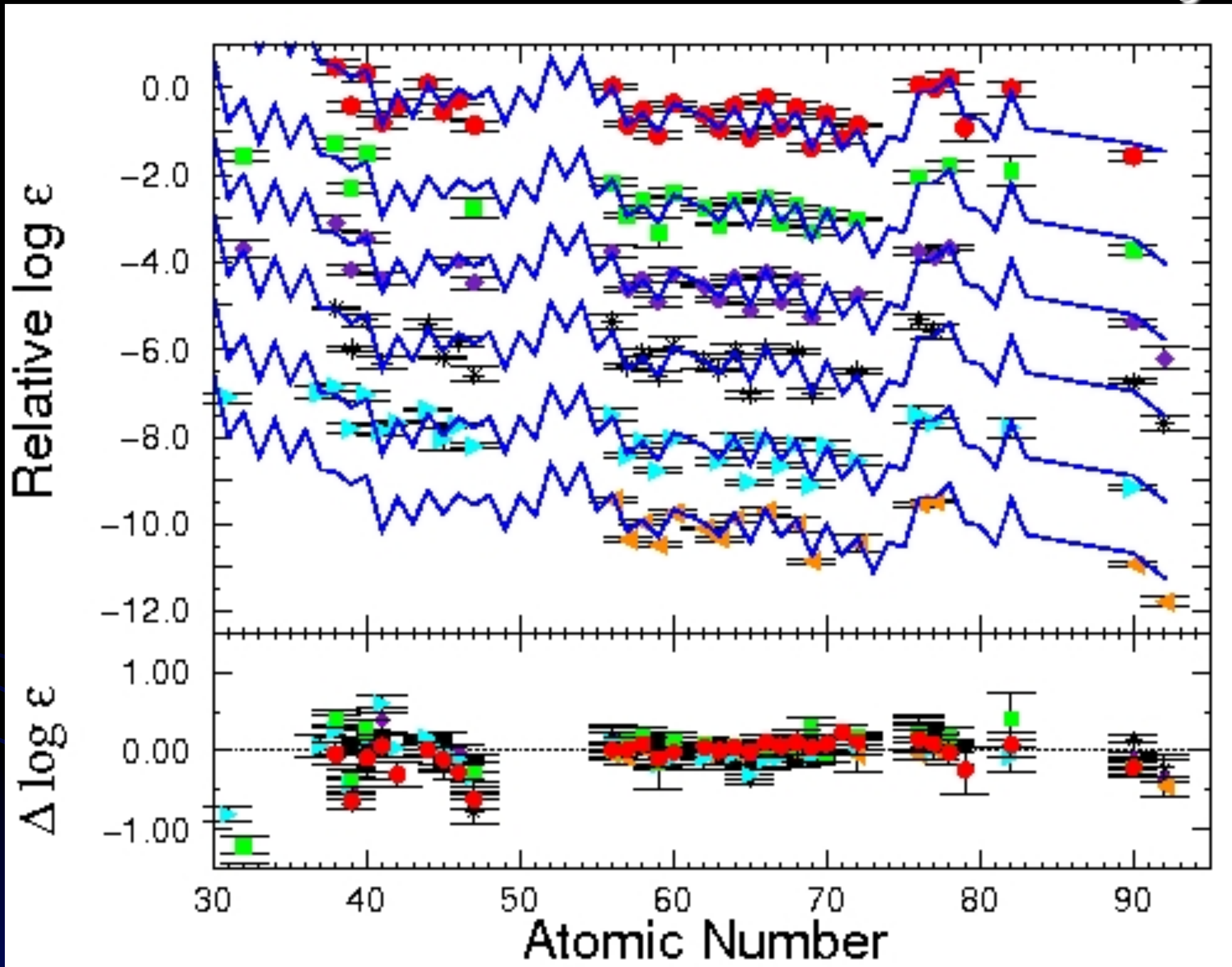
Consistency for r-Rich Stars



10 r-process rich stars

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

Observational Summary



CS 22892-052

HD 115444

BD +17 3248

CS 31082-001

HD 221170

HE 1523-0901

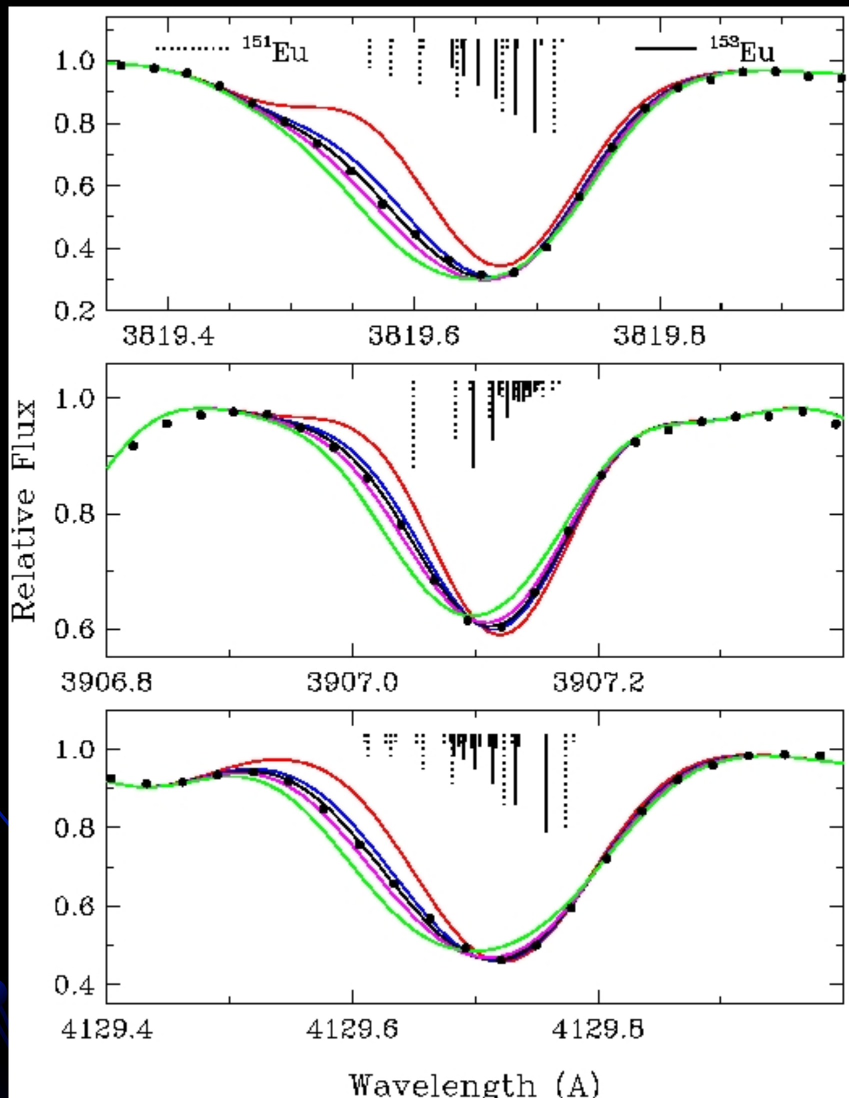
Sneden, JC & Gallino (2008)

6 r-process rich stars

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

Eu Isotopic Abundances in BD +17 3248: 3 Lines

Same isotopic ratio seen in all 3 lines!



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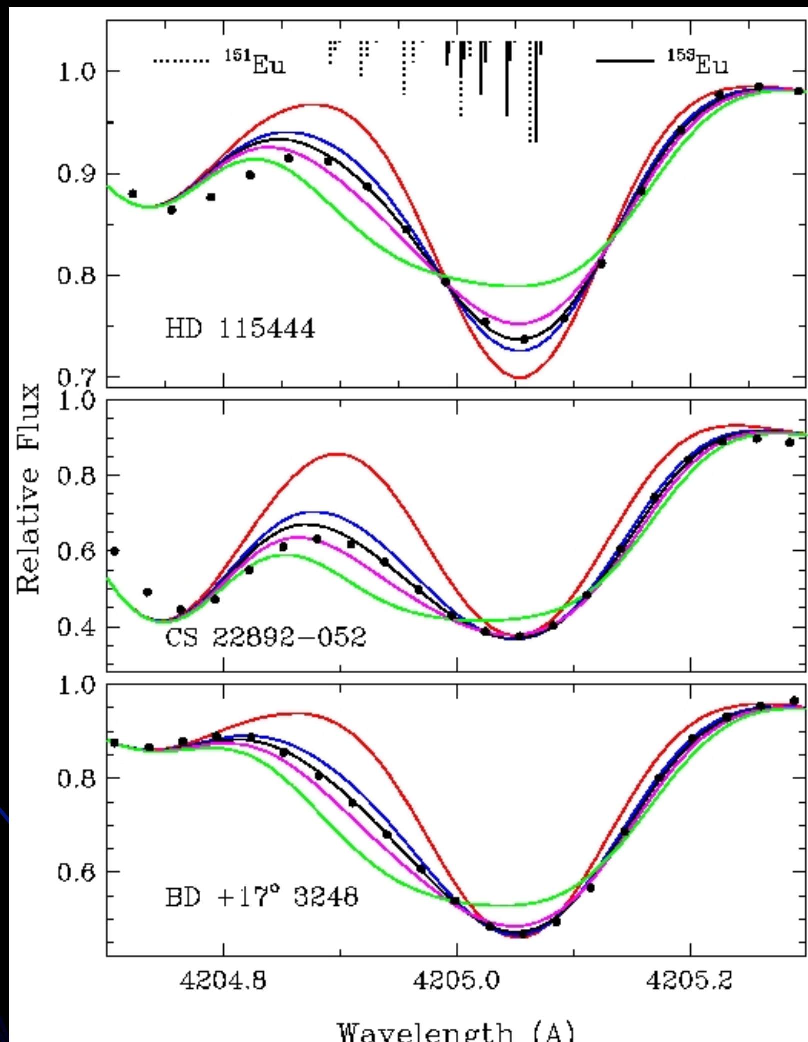
Eu Isotopic Abundances in Three Metal-Poor Halo Stars

^{151}Eu:
- → 100%
- → 65%
- → 48%
- → 35%
- → 0%



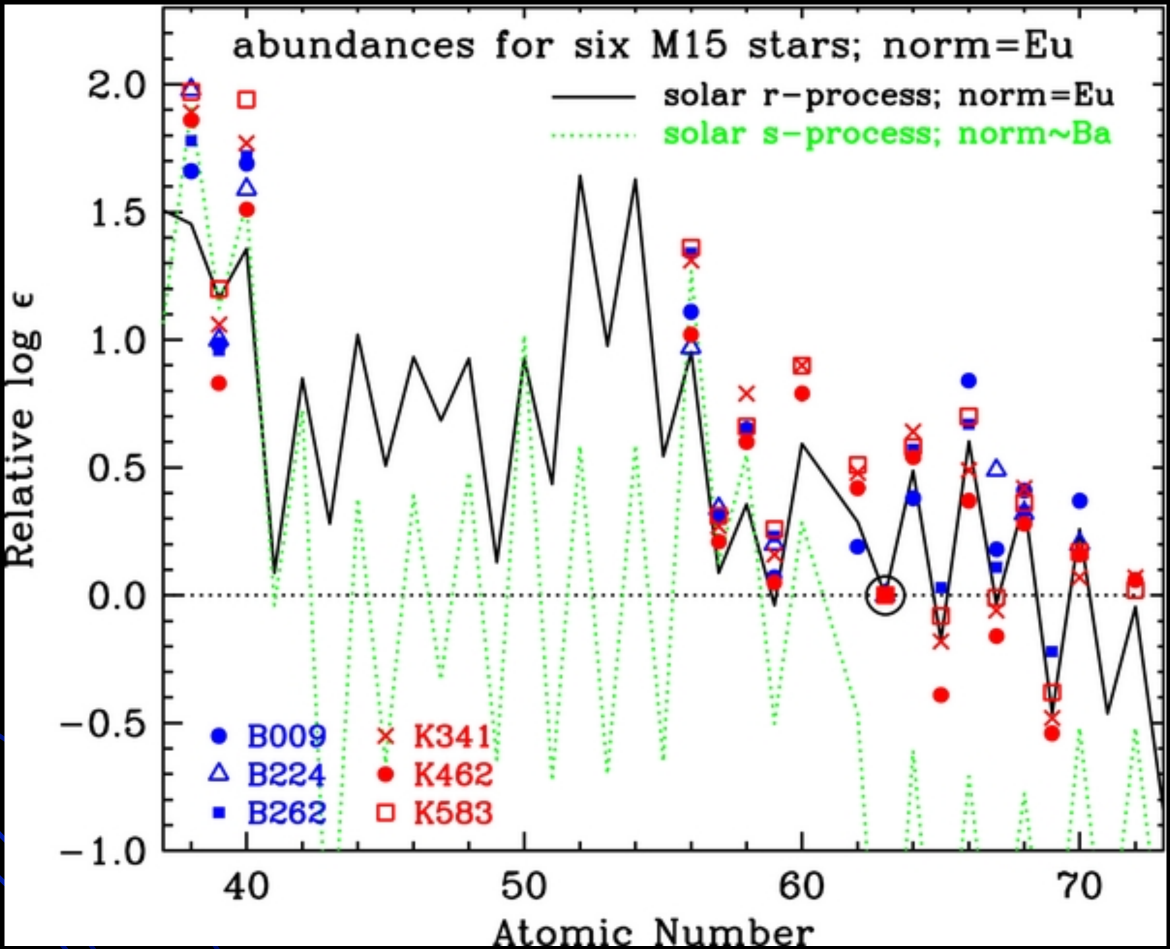
Many more examples of Eu isotopes in other stars. Same ratio found.

Ba now seen as well in one star: isotopes appears to be consistent with SS ratios.

More lines in the same star

Sneden et al. (2002)

Abundances in a Globular Cluster



Abundance pattern same as in single field halo stars

Sobeck et al. (2011)

RGB and RHB stars

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

Summary So Far

- 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: → like solar abundances
- Robust for heaviest elements but not lighter n-capture elements: → multiple element synthesis processes?

Focus on Observations of Ranges of Lighter N-Capture Elements

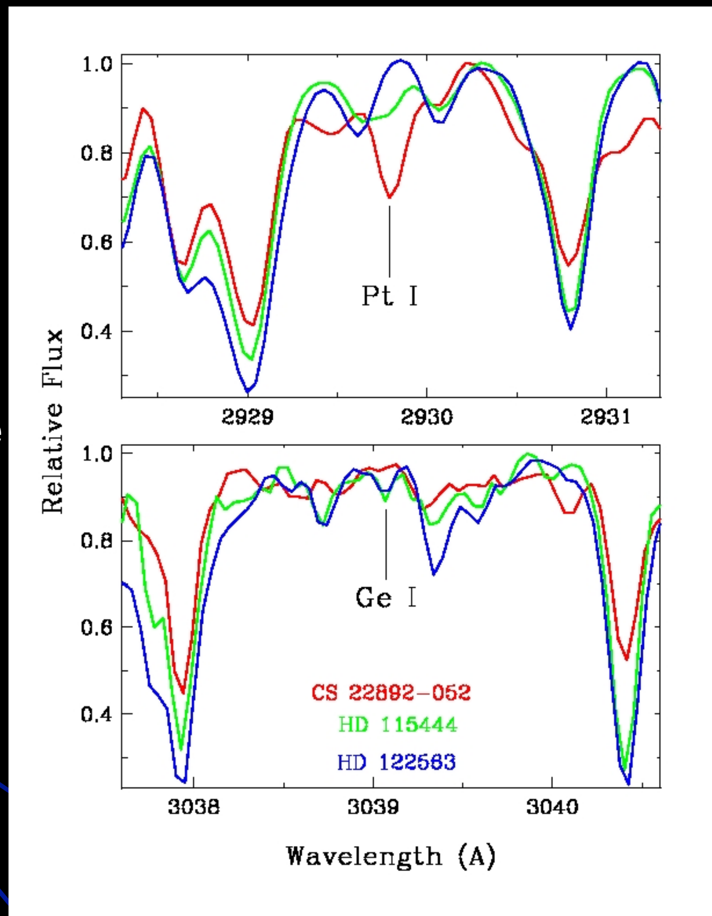
- Elements just past the iron peak: Ge
- Sr, Y and Zr
- Z=40-50 including Ag and Cd
- New abundance determinations for selected elements from Sr to Yb

NUV HST STIS Spectra

Heavy n-capture elements do not scale with iron (i.e., metallicity).

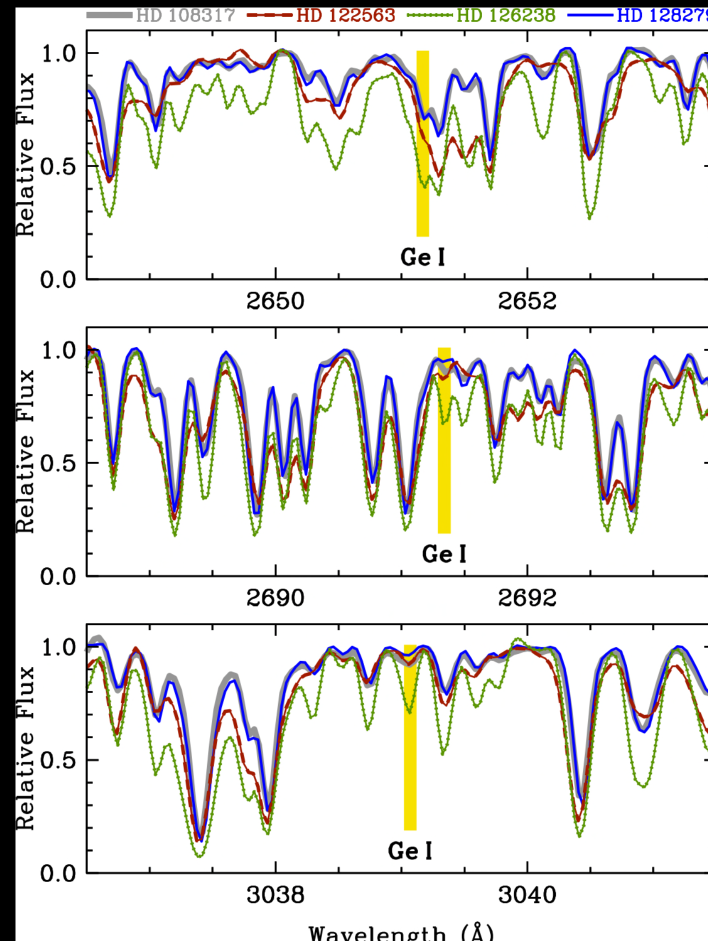
Ge scales with Fe

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



JC et al. (2005)

Roderer et al. (2012b)

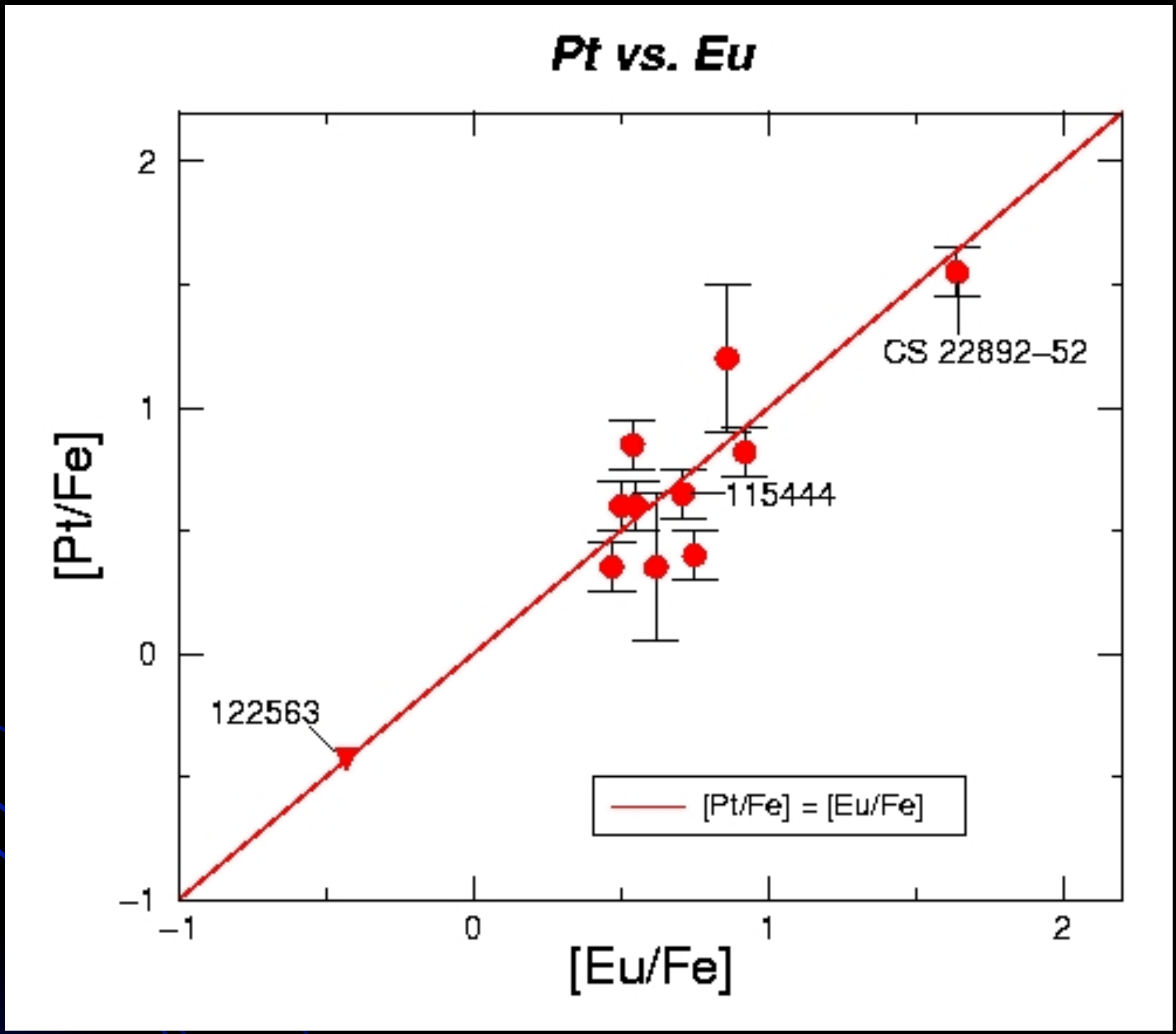


HD 108317 ([Fe/H] = -2.5), HD 122563 ([Fe/H] = -2.6), HD 126238 , ([Fe/H] = -2), HD 128279, ([Fe/H] = -2.5)

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

Note the resolution.

n-Capture Element Correlations



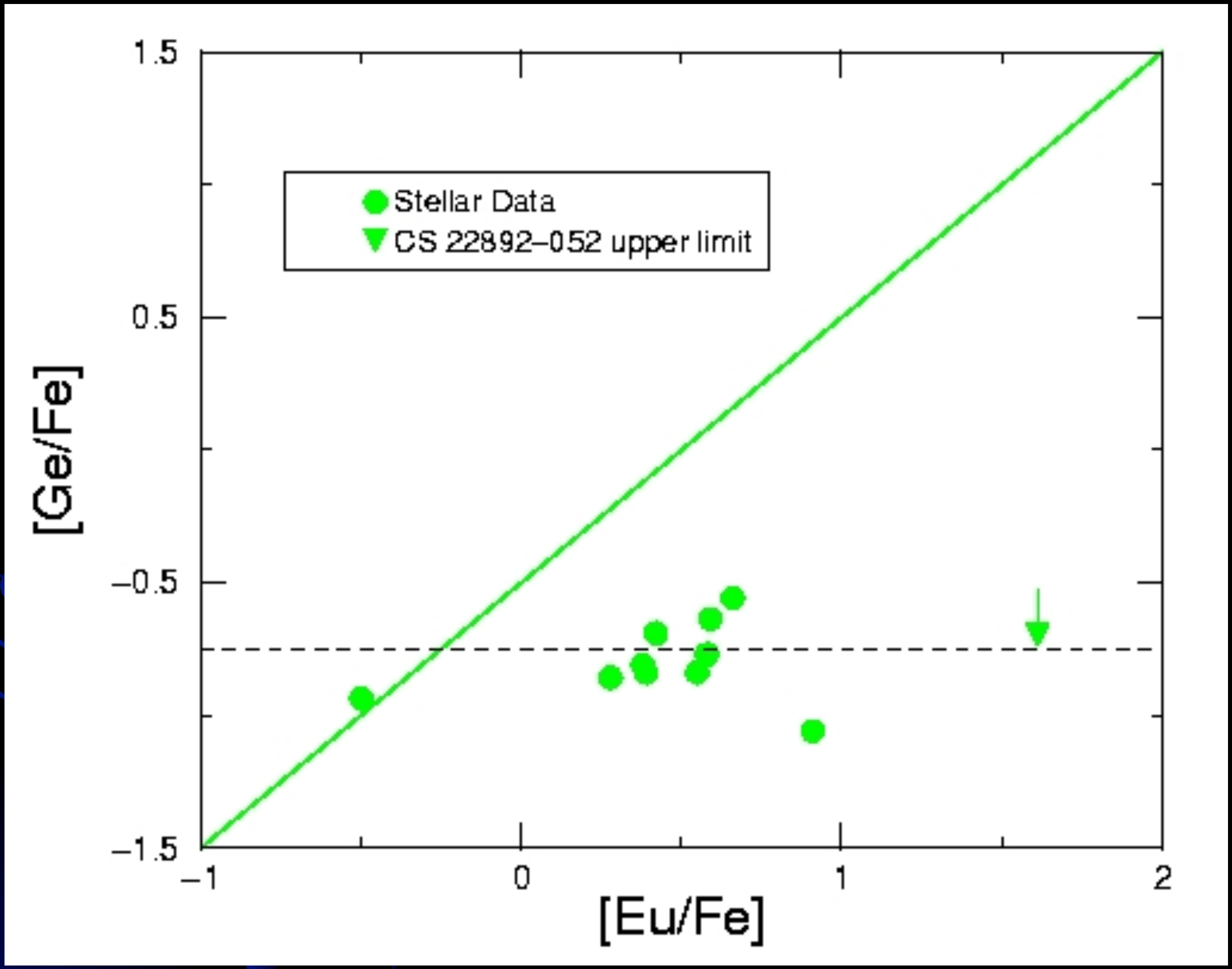
Pt ∝ Eu

Os shows same correlation

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

Ge vs. Eu in Halo Stars

If Ge and Eu are both n-capture elements and both synthesized in same process they should be correlated?

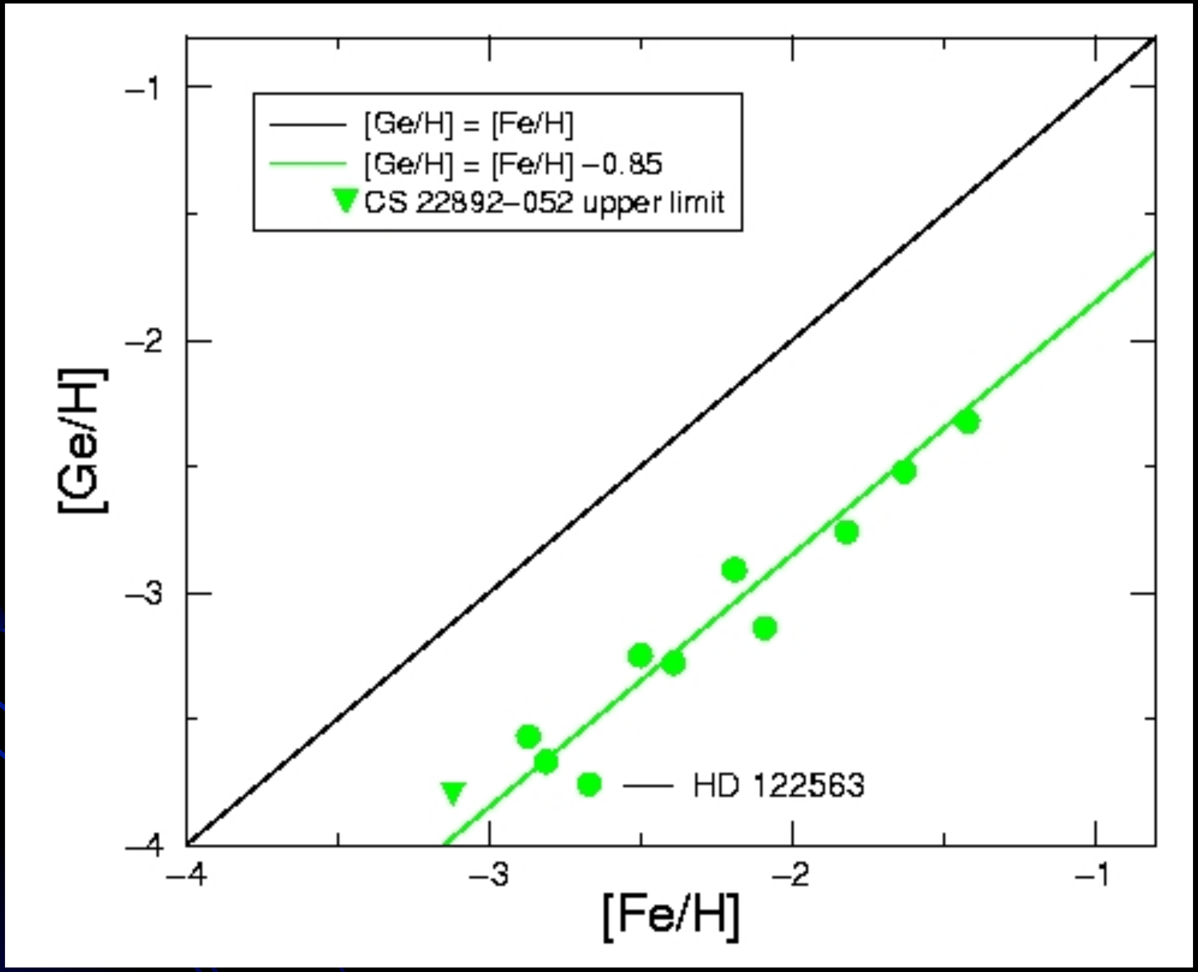


Ge $\not\propto$ Eu

JC et al. (2005)

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

Ge Abundances in Halo Stars



Ge ∝ Fe

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

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

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

JC et al. (2005)

νp-process

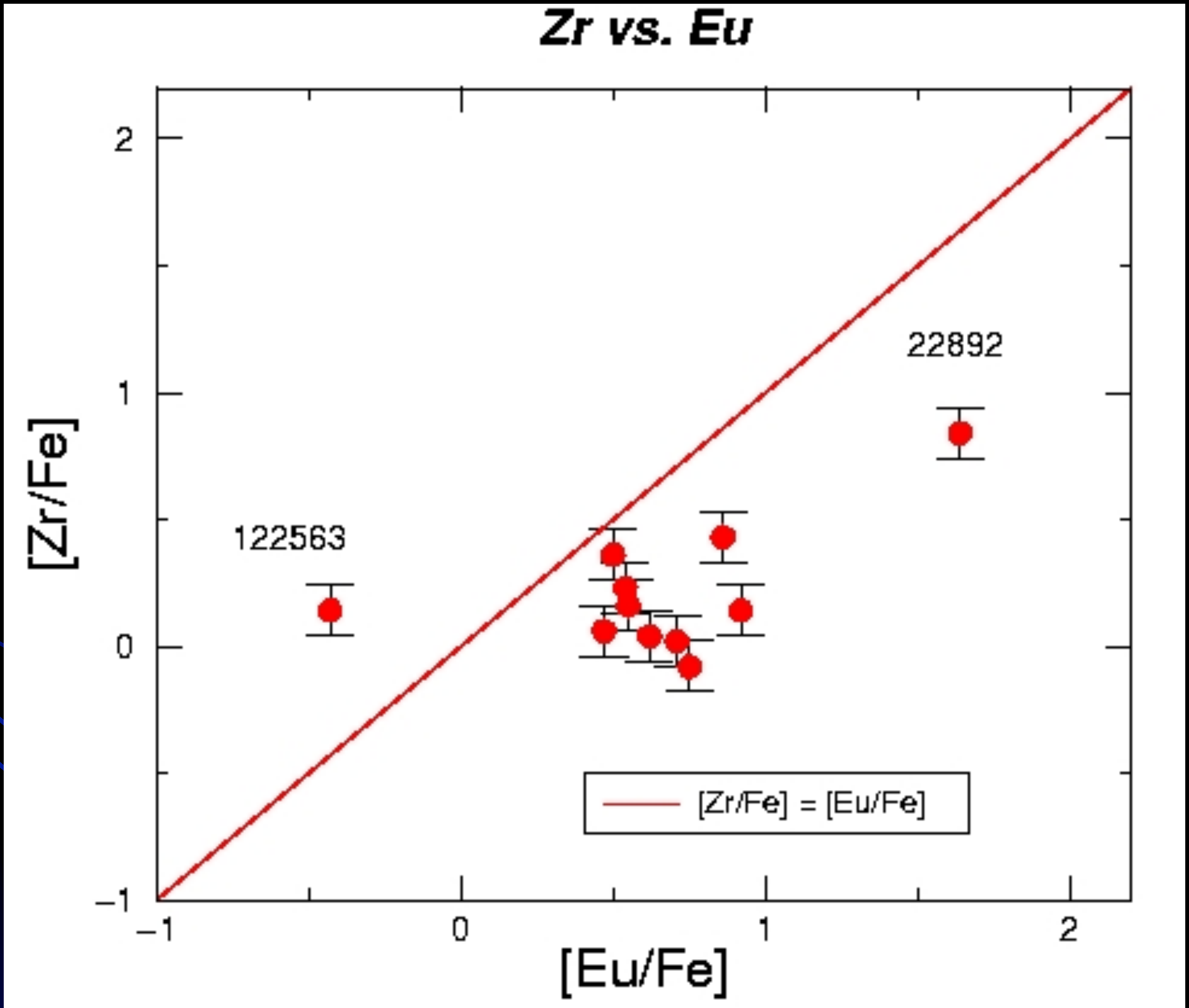
In exploding models matter in innermost ejected zones becomes proton-rich (Y_e>0.5)

if the neutrino flux is sufficient (scales with $1/r^2$)! :

$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p; \quad {}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge}; \ldots$$

Fröhlich et al. (2006)

Zr (HST) and Eu Abundances in Halo Stars



Zr $\not\propto$ Eu

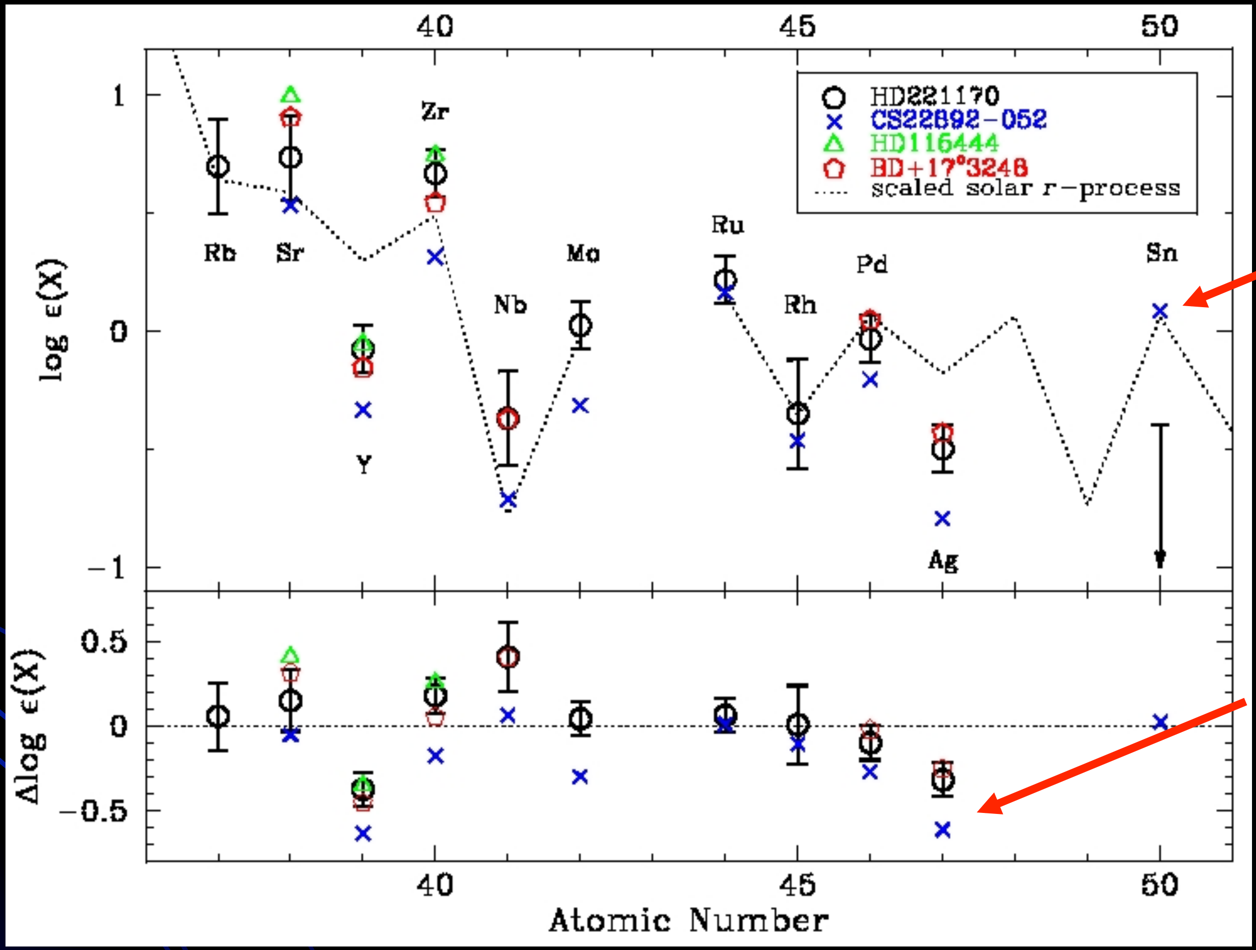
Both n-cap elements but not from same source?

LEPP?
SN models?

JC et al. (2005)

Trend first noticed by Travaglio et al. (2004)

Zooming in on the Lighter n-Capture Elements in Halo Stars

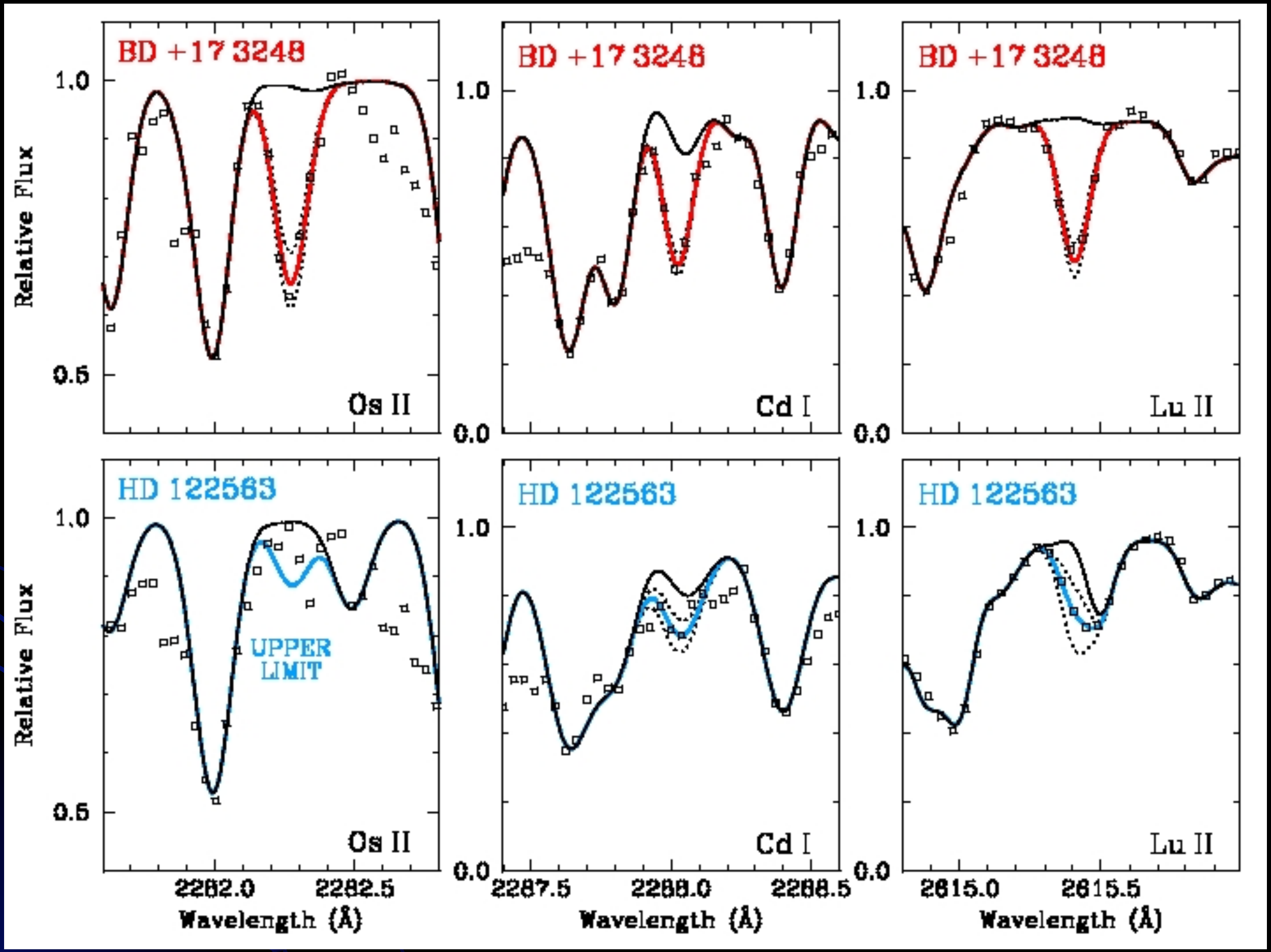


only upper limits on Sn

Ag (Z=47) is low in all cases!

Ivans et al. (2006)

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



Roederer et al. (2010a)

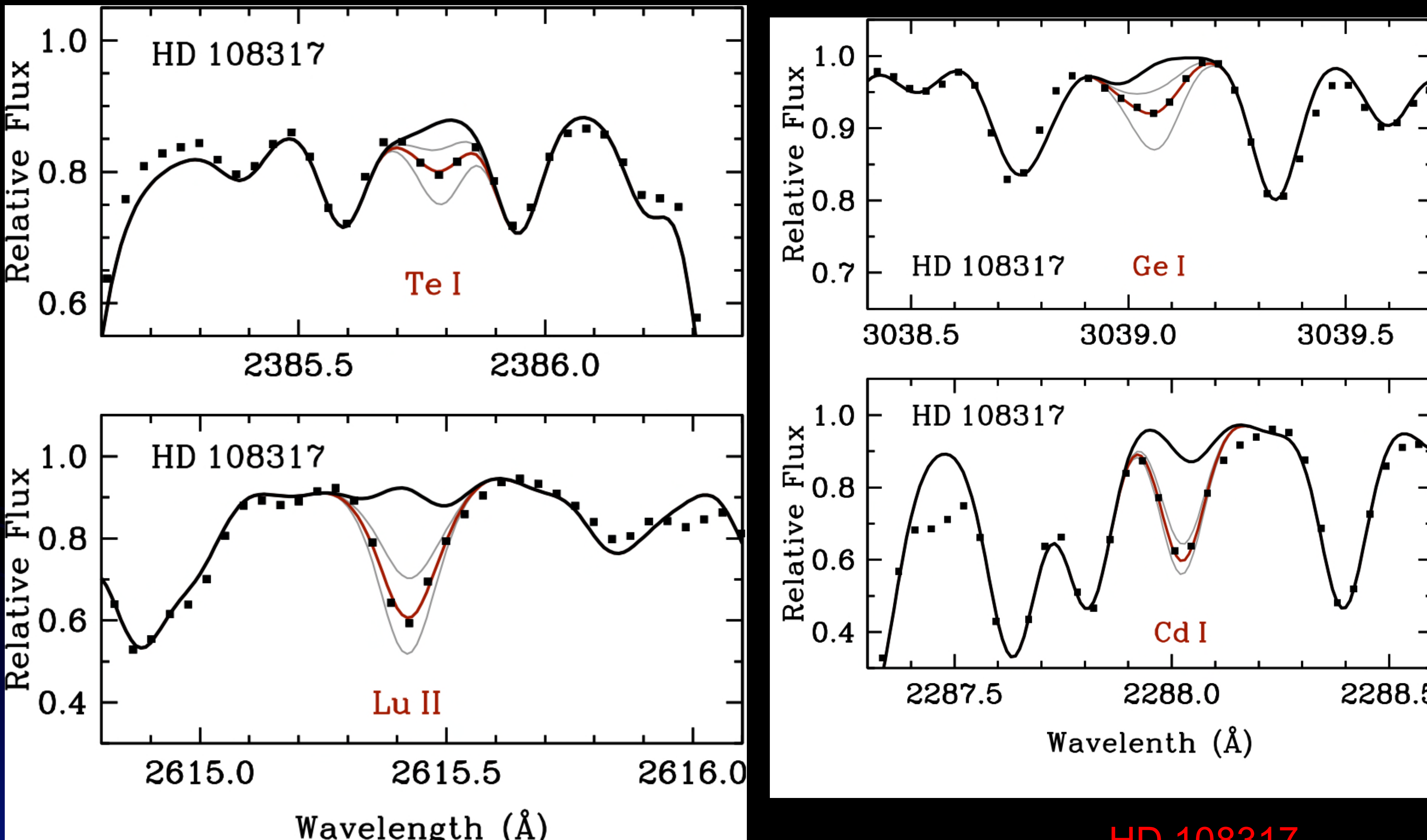
First detections of these n-cap species in metal-poor stars

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

NUV HST STIS Spectra



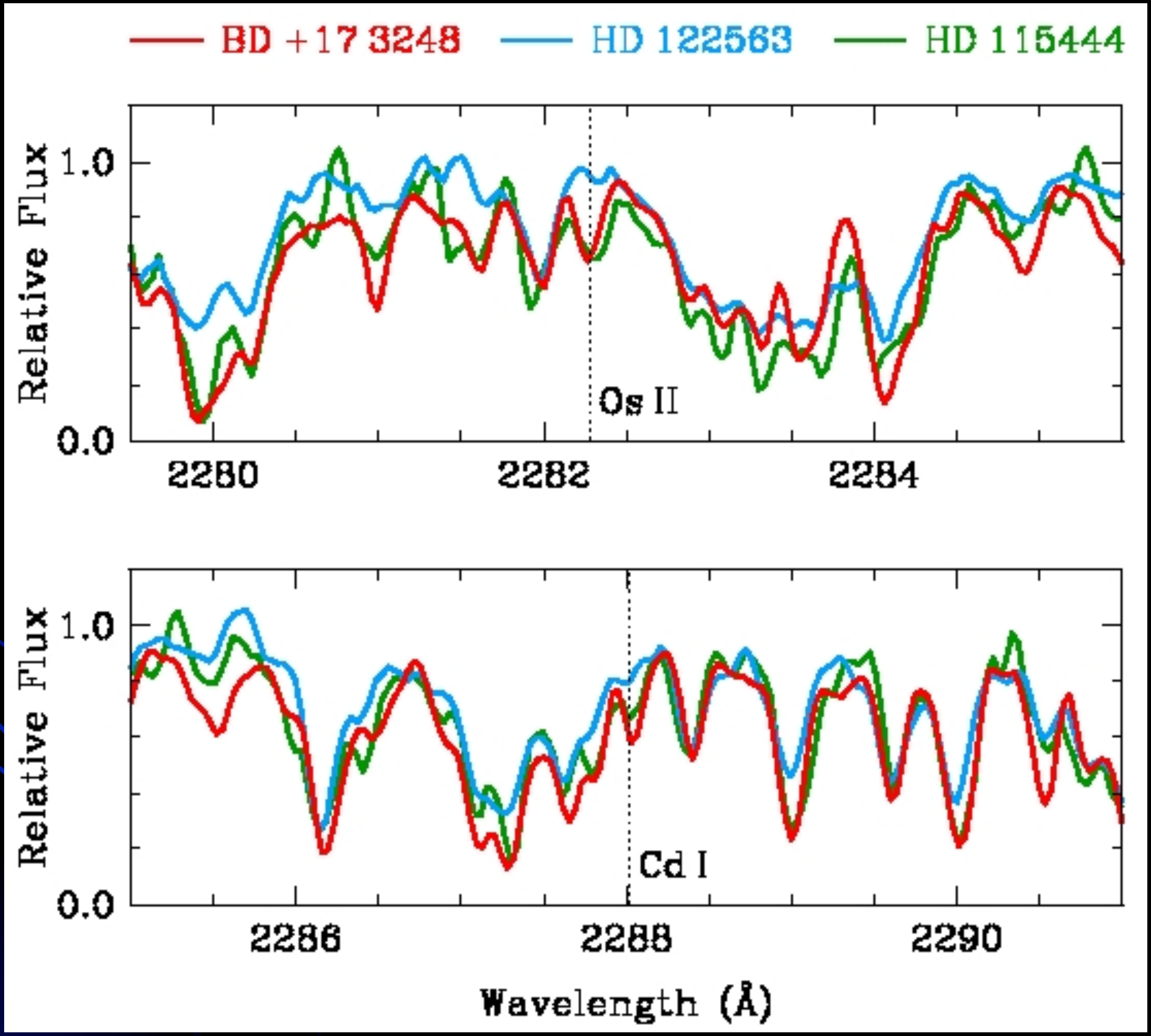
Roderer et al. (2012b)

Note the resolution.

HD 108317 ([Fe/H] = -2.5)

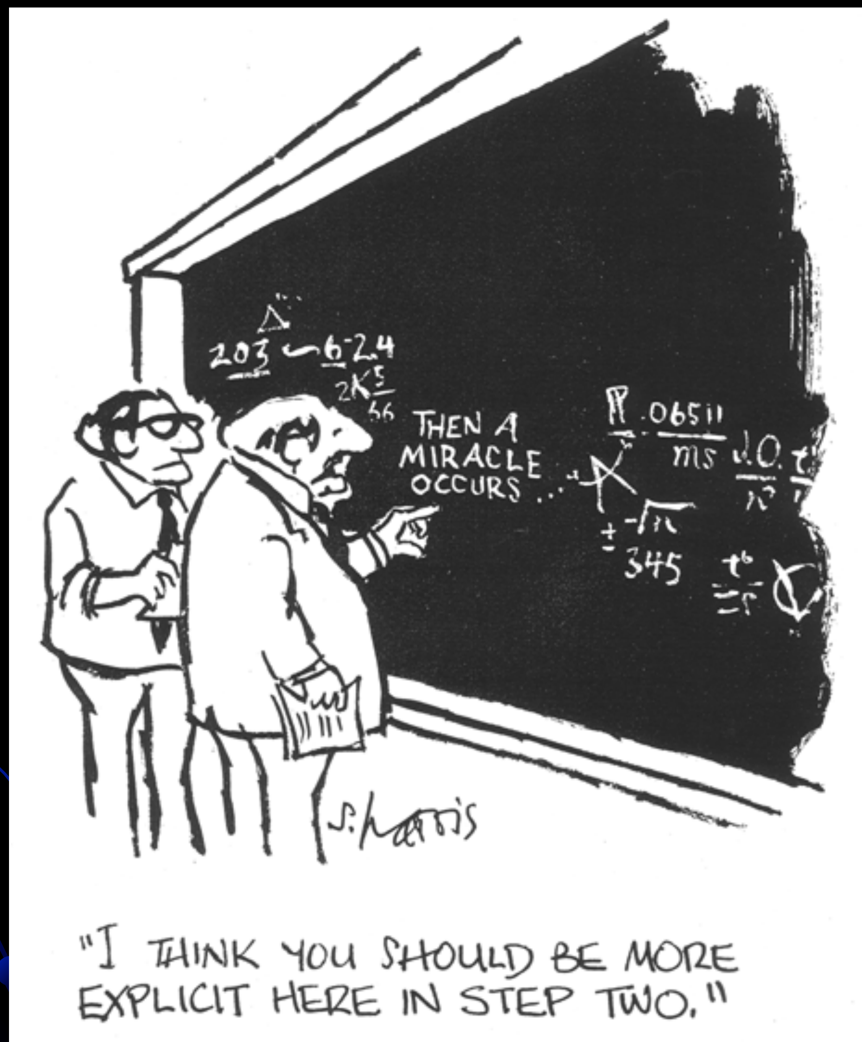
New Abundance Detections in BD +17 3248

UV: HST STIS



Roederer et al. (2010a)

Theoretical Calculations to Explain the Observations:



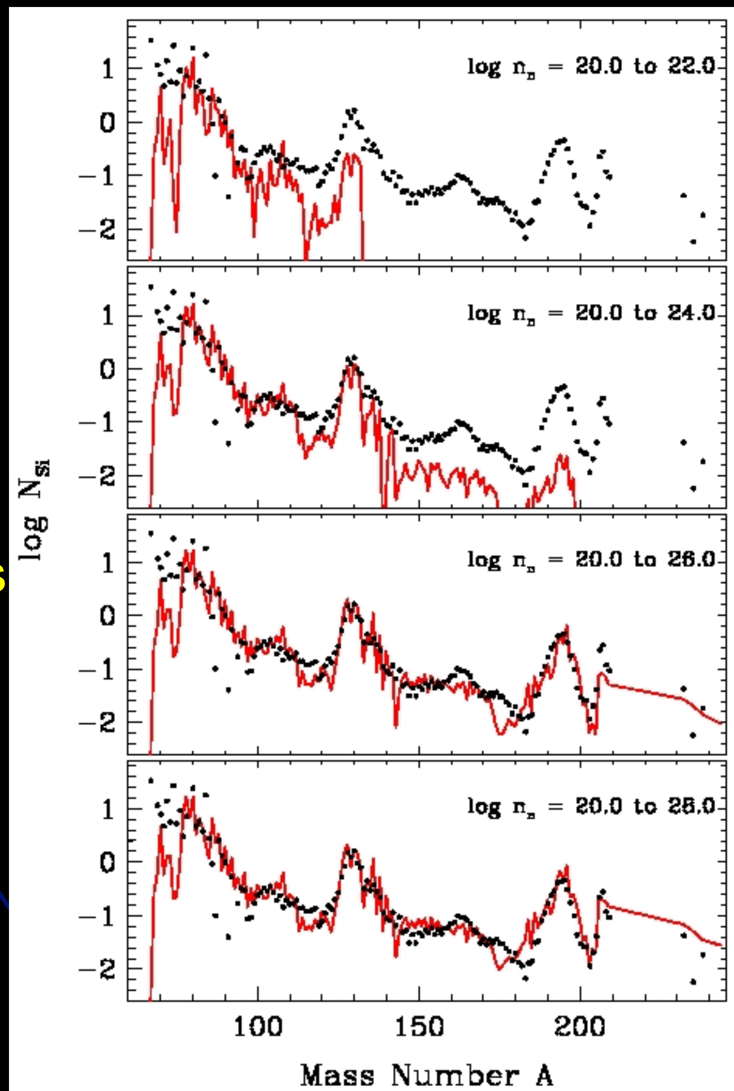
Solar System Isotopic Abundances Versus Neutron Number Densities

Adding more components with higher neutron number densities

Solar System meteoritic abundances

Theoretical fit after α and β decays

Kratz et al. (2007)

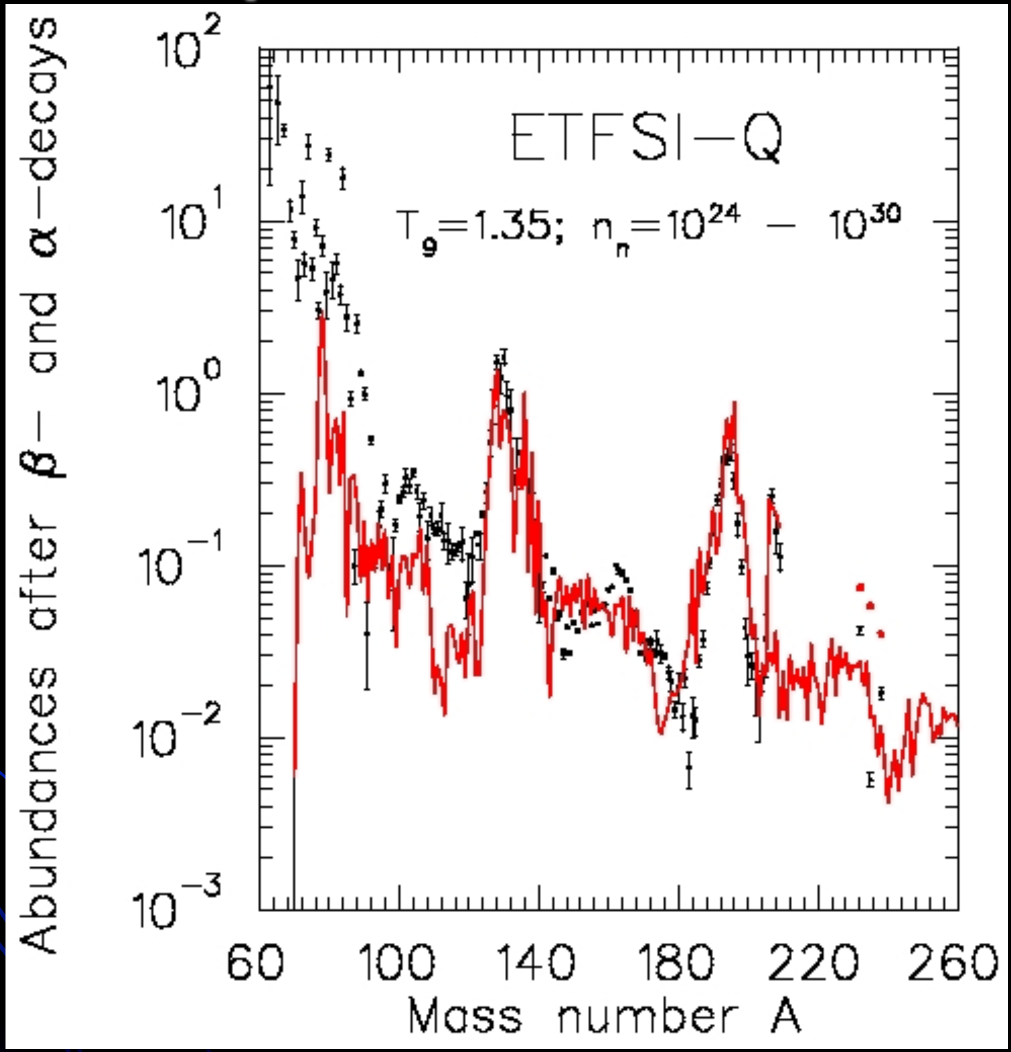


$N_n = 10^{20}$

$N_n = 10^{28}$

Theoretical Fit to the Solar System Isotopic Abundances

Waiting point approximation calculations



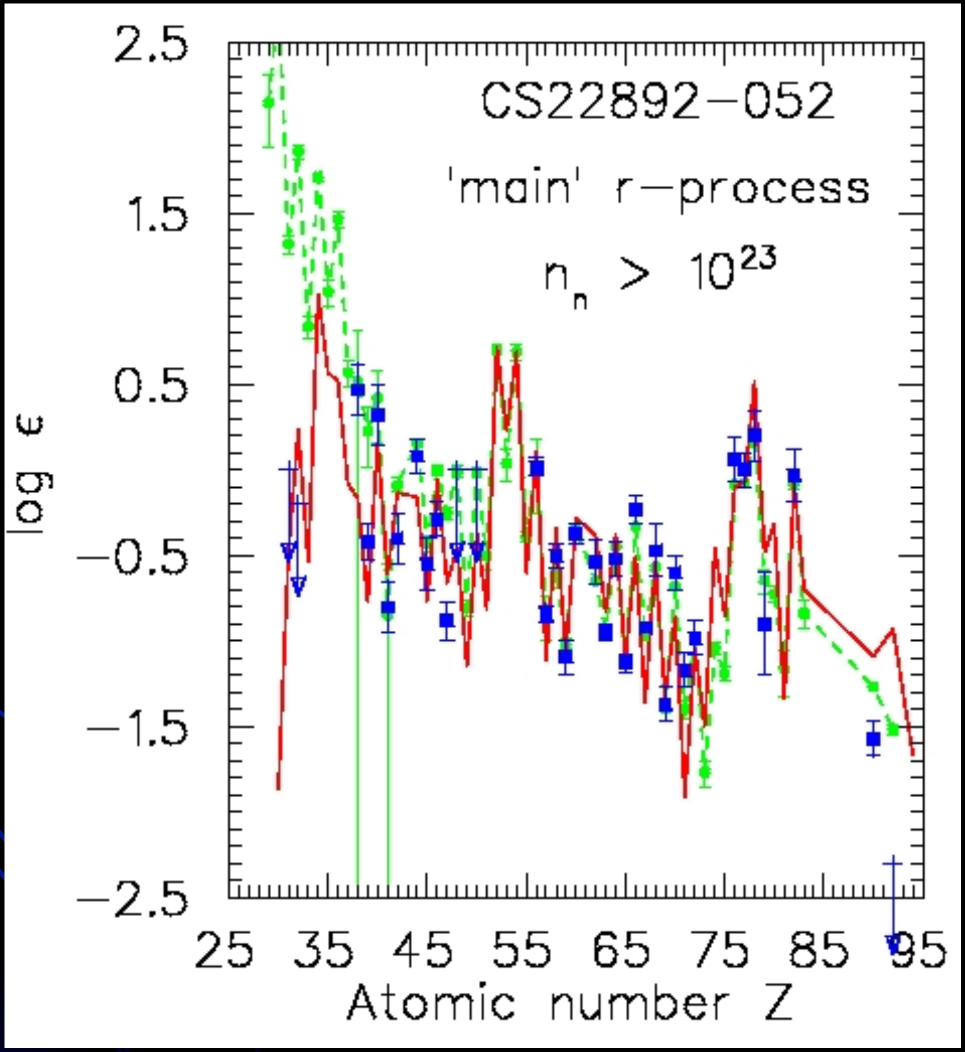
Kratz et al. (2007)

Superposition of components with different neutron number densities

Theoretical Fit to the Elemental Abundance Data of CS 22892-052

Simmerer et al. (2004) - - - -

Sneden et al. (2003) ■



Heavier n-capture elements formed at higher n-number densities

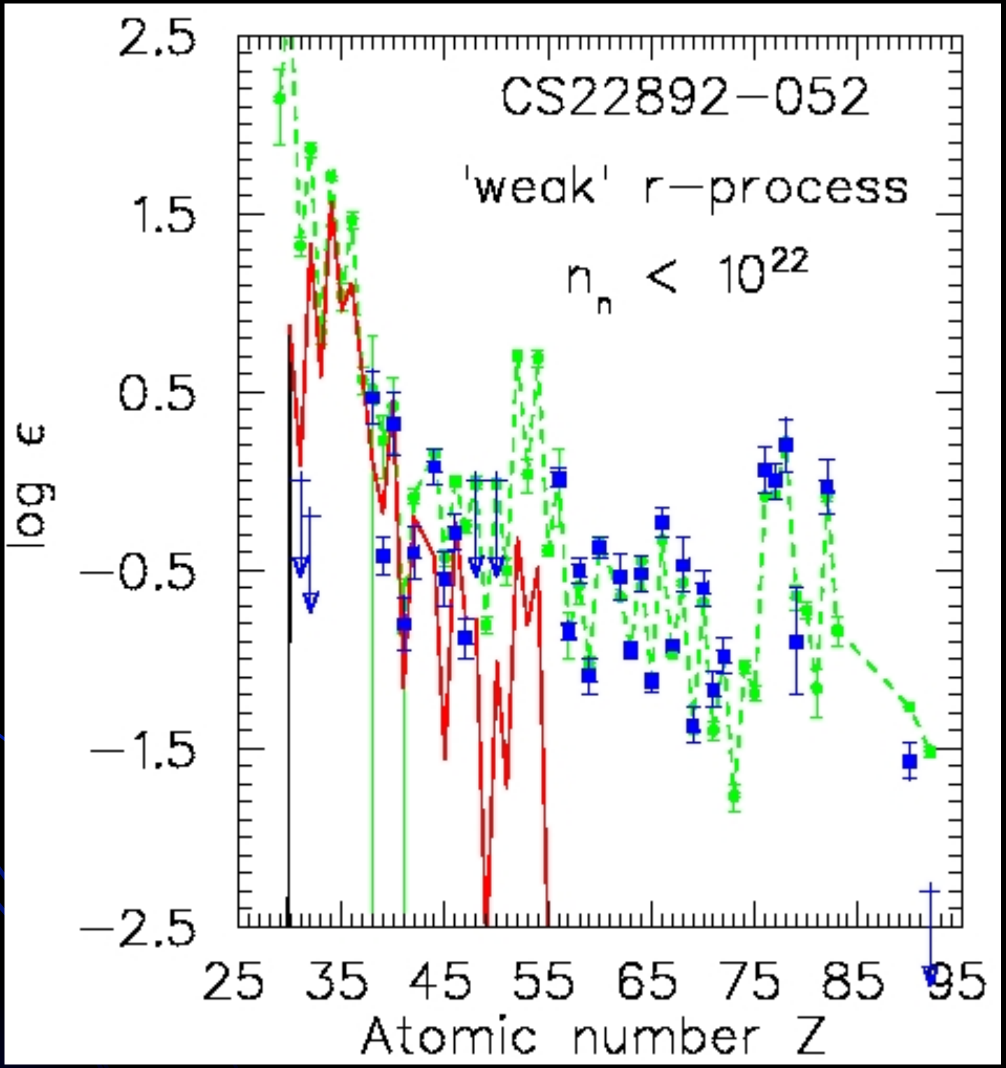
main r-process

Kratz et al. (2007)

What Is Left Over at the Lower Neutron Number Densities?

Only lighter
n-capture
elements
formed at
lower n-number
densities
no Ba

weak
r-process

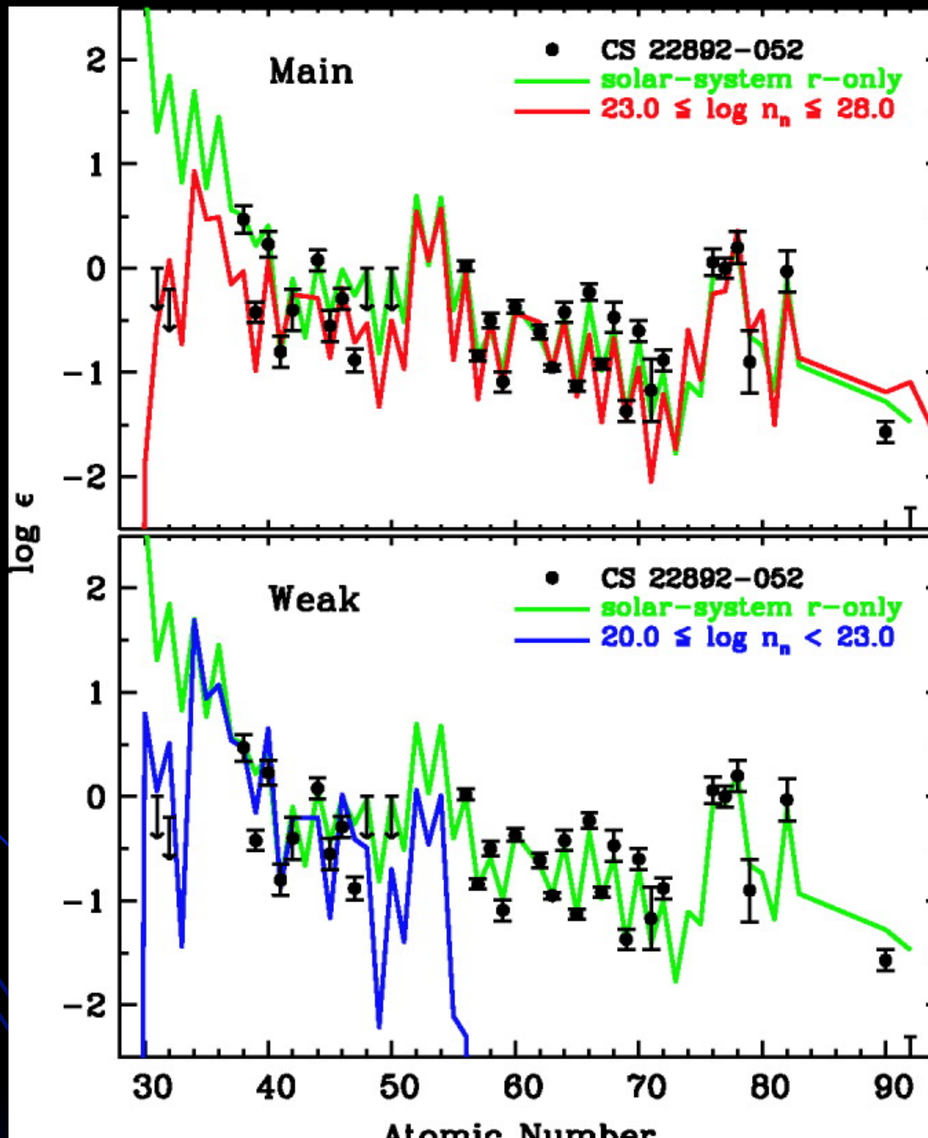


Simmerer et al. (2004) - - - -

Sneden et al. (2003) ■

Kratz et al. (2007)

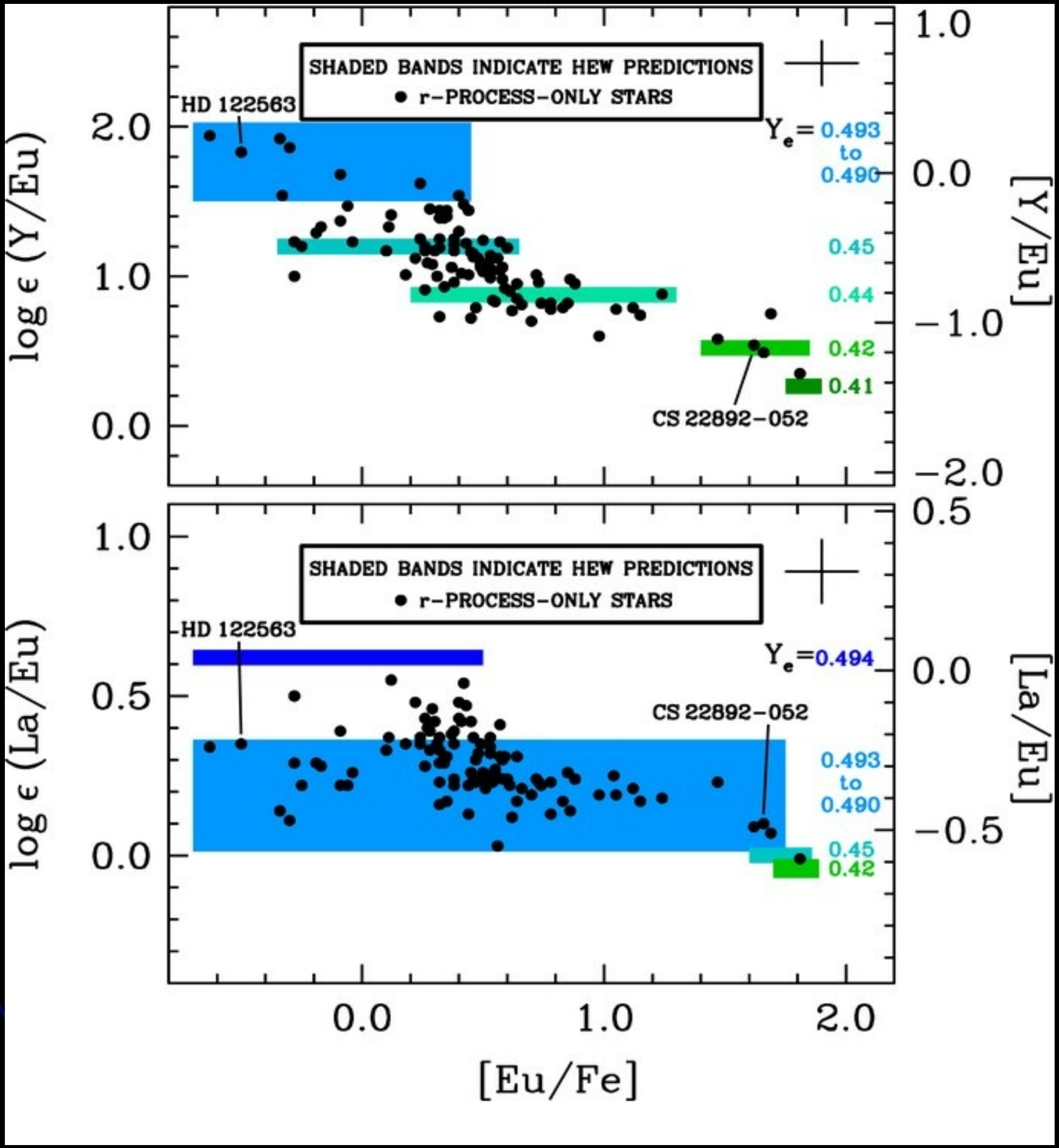
W-P Models for CS 22892-052



Kratz et al. (2007)

HEW Models

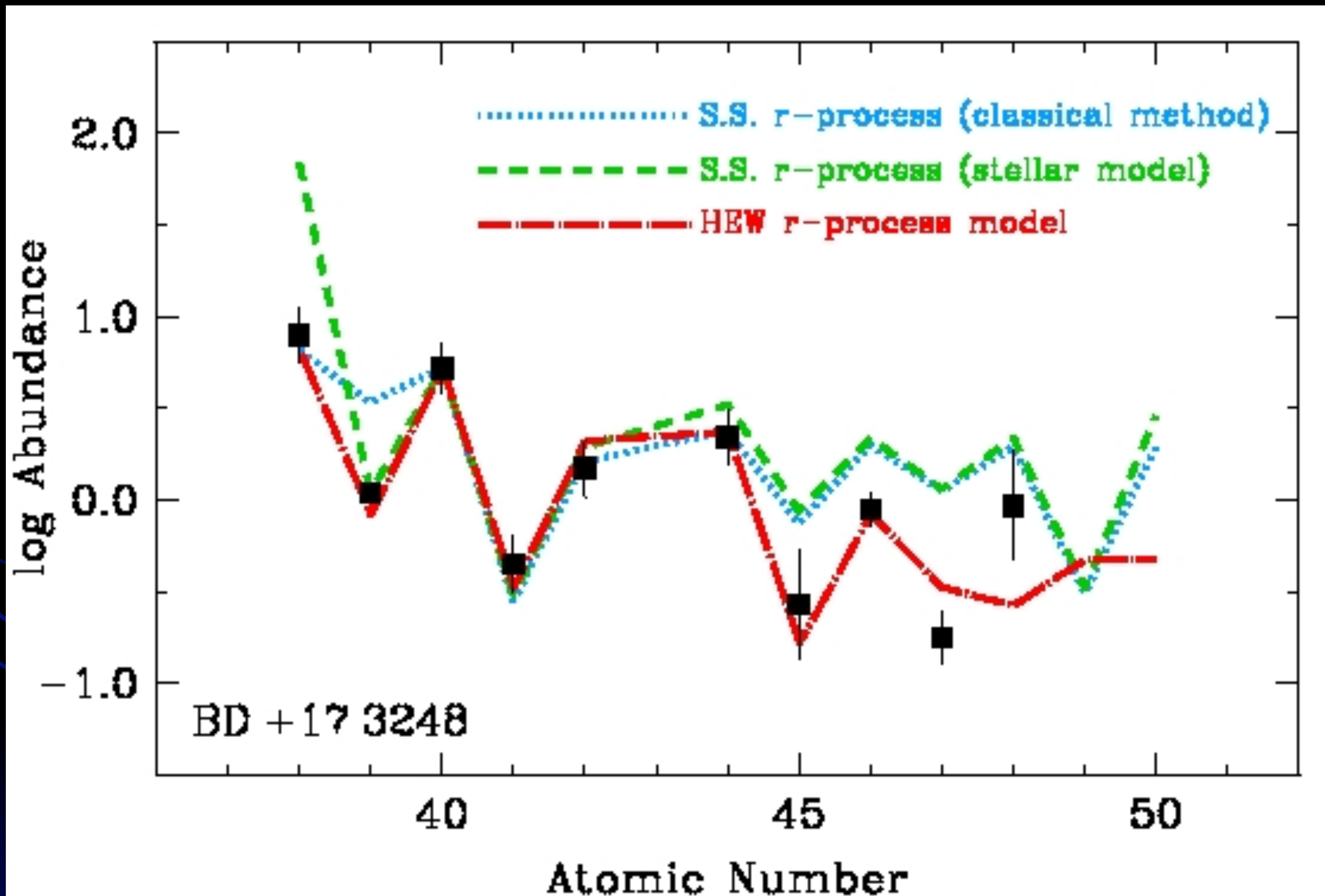
CP or a-rich freezeout
+ beta-delayed ns
⟶ low entropy components
for Sr-Zr ⟶ LEPP?



Complicated models: shows there are some successes and some failures still

Roederer et al. (2010b)

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



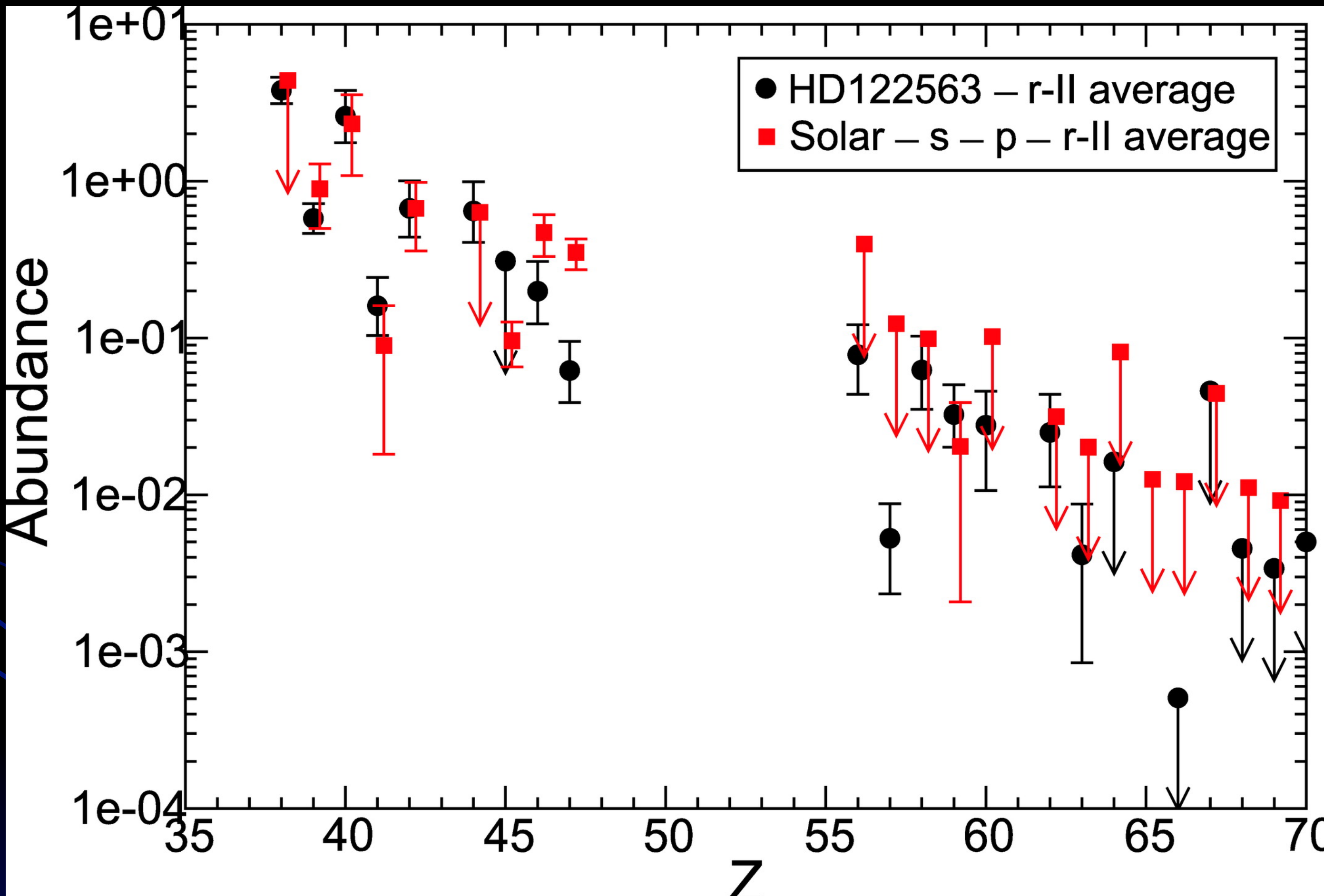
Note Ag, Cd

JC et al. (2011)

The Famous LEPP Invention

- Making use of the very *r*-process rich and very metal-poor stars like CS 22892-052 and CS 31082-001, we find hints and discuss the possibility of a *primary process* in low-metallicity massive stars, different from the "classical *s*-process" and from the "classical *r*-process" that we tentatively define LEPP (lighter element primary process). (Travaglio et al. 2004)

Abundance Pattern Created by the LEPP from Montes et al.



Solar LEPP and stellar LEPP

Lighter n-Cap Element Origin?

- Incomplete (``weak'') r-process, classical wp approximation, lower n-number densities
- More sophisticated: alpha-rich (charged particle with beta-delayed neutron recapture) freeze-out/ HEW (Kratz and Farouqi et al.) makes many of the elements from Sr-Pd but not Ag and Cd
- What about LEPP (Travaglio et al. and Montes et al.)? Weak s-process at low [Fe/H] for Sr-Zr?
- For some elements like Ge (and others?) nu-p process (Frohlich et al.)
- Maybe multiple processes?

At This Point?