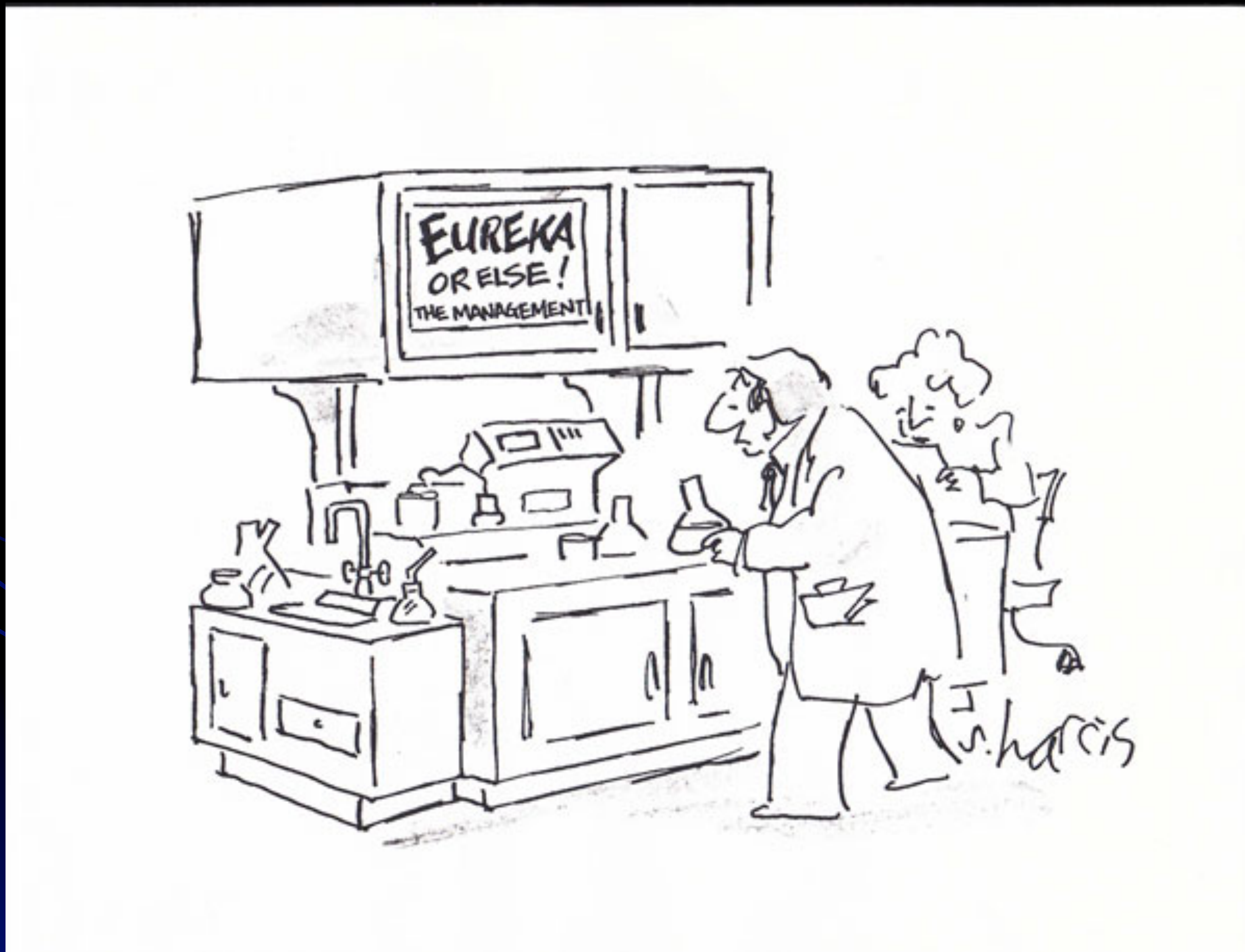
OBSERVATIONAL ASTROPHYSICS II

JOHN COWAN
University of Oklahoma

National Nuclear Physics Summer School: July 23, 2013

Today's Theme

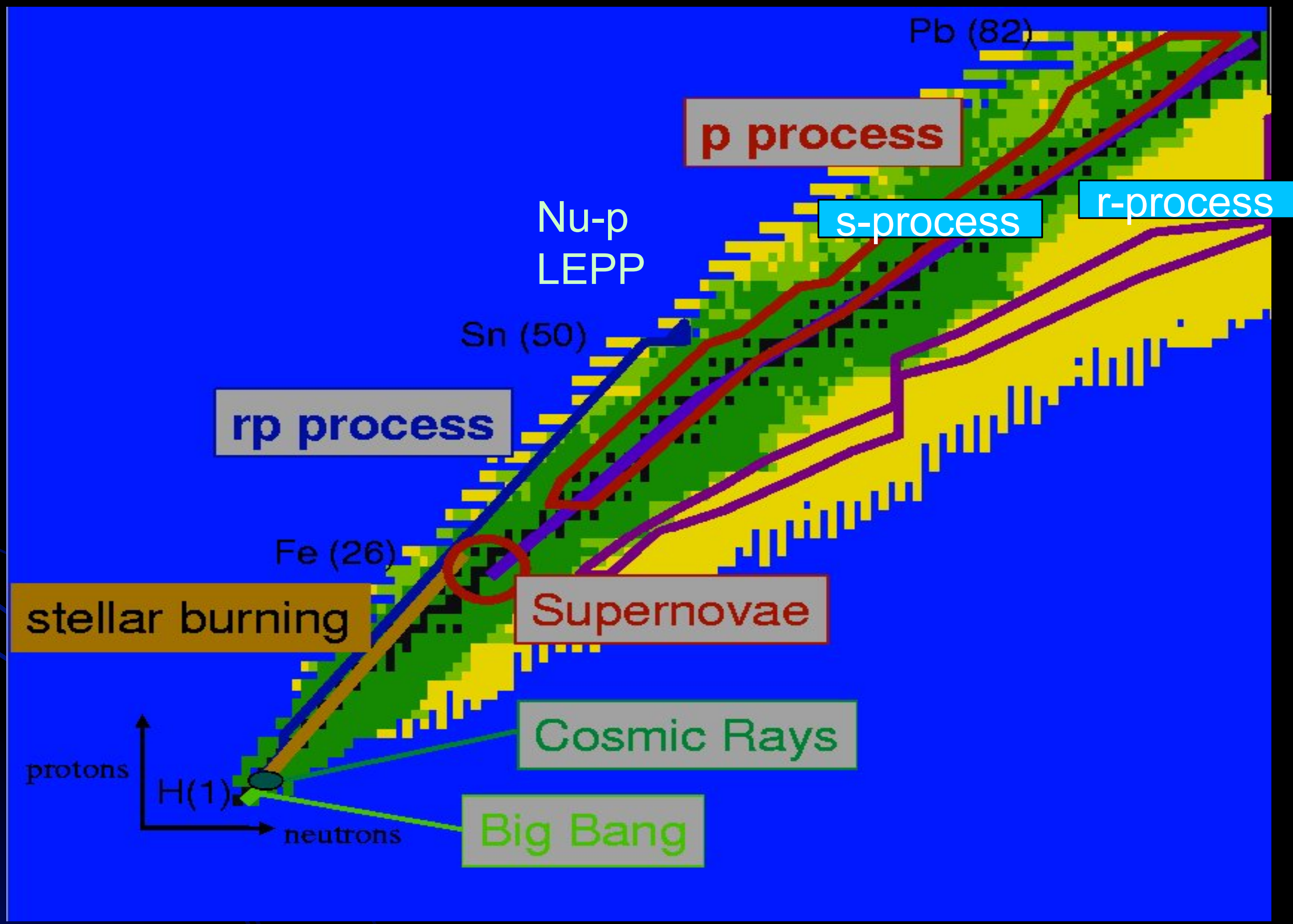


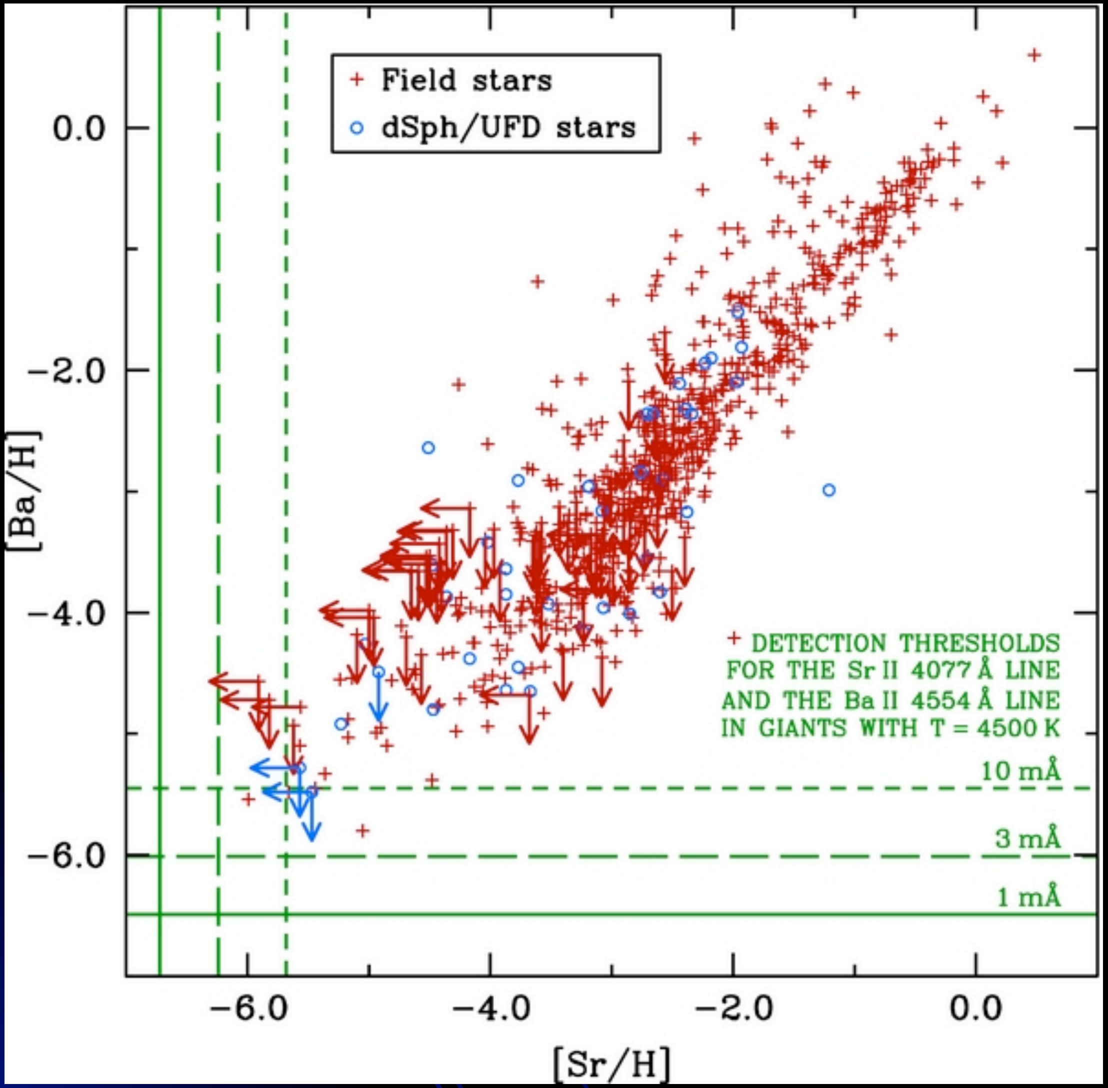
Abundance Clues and Constraints: Outline of the Lectures

- 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

Summary of Nucleosynthetic Processes





Roederer (2013)

This paper suggests that ALL low metallicity stars have neutron-capture elements

upper limits in this figure are maybe just due to spectroscopic detection problems?

But It Is Like Money

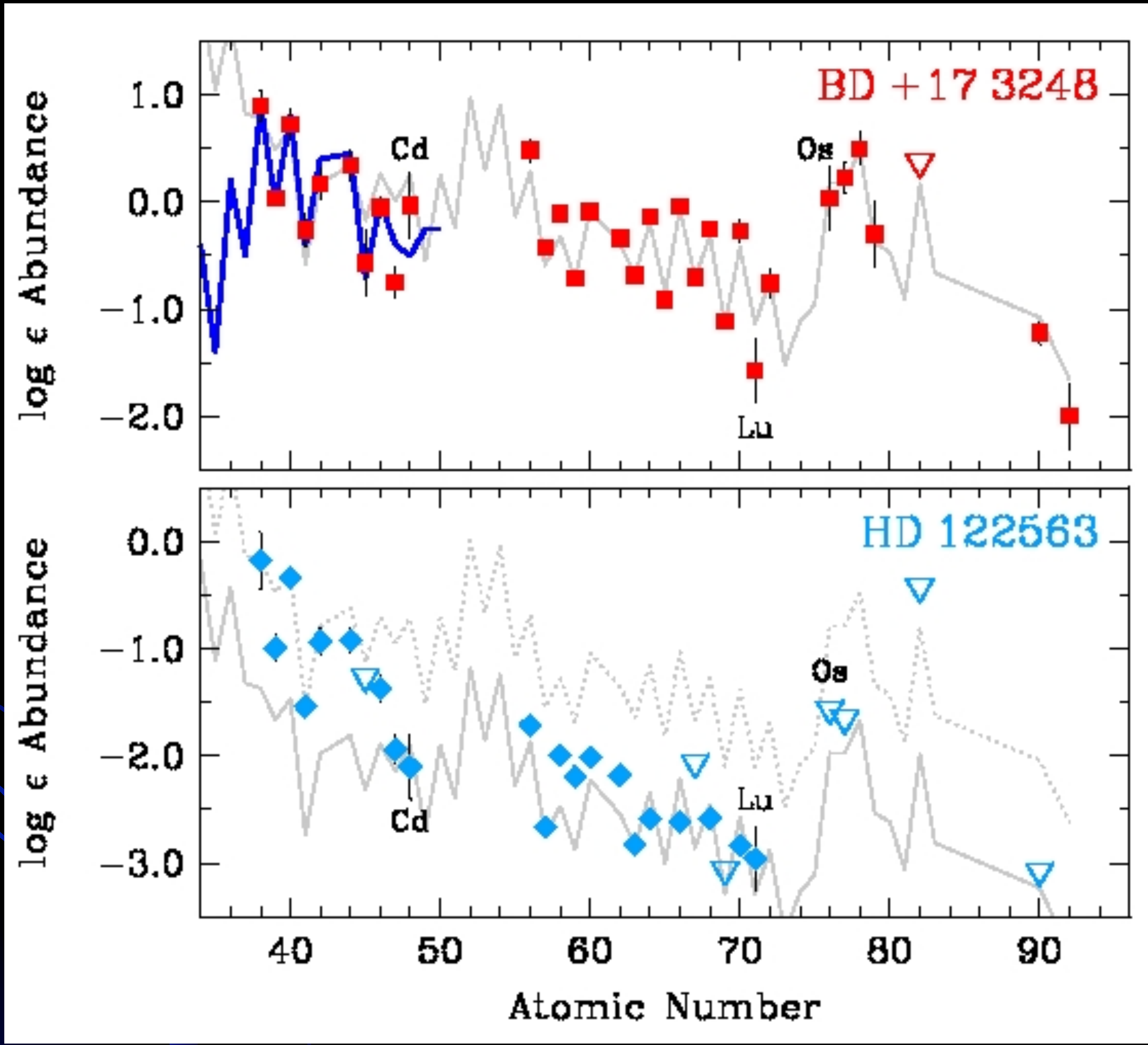
- Everybody's got some : BUT
- there is rich and
- there is poor

Abundance Comparisons: rich vs. poor

HEW

SS r-process

(Sr,Eu)



r-process rich

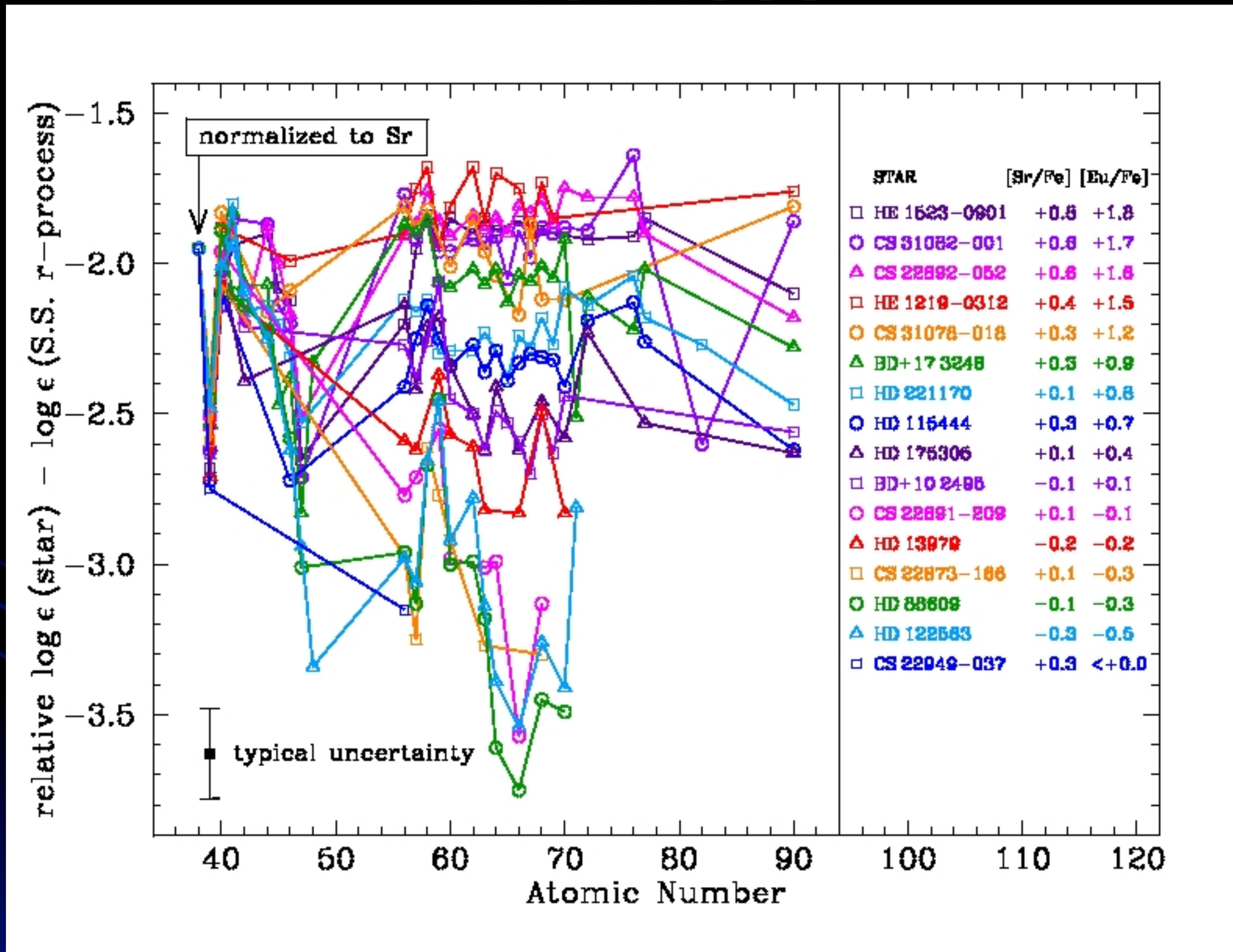
SS r-process

r-process poor

Note general fall off: weak r-process or LEPP (Montes et al. 2007)

Roederer et al. (2010a)

Looking at a Range of r-Process Richness

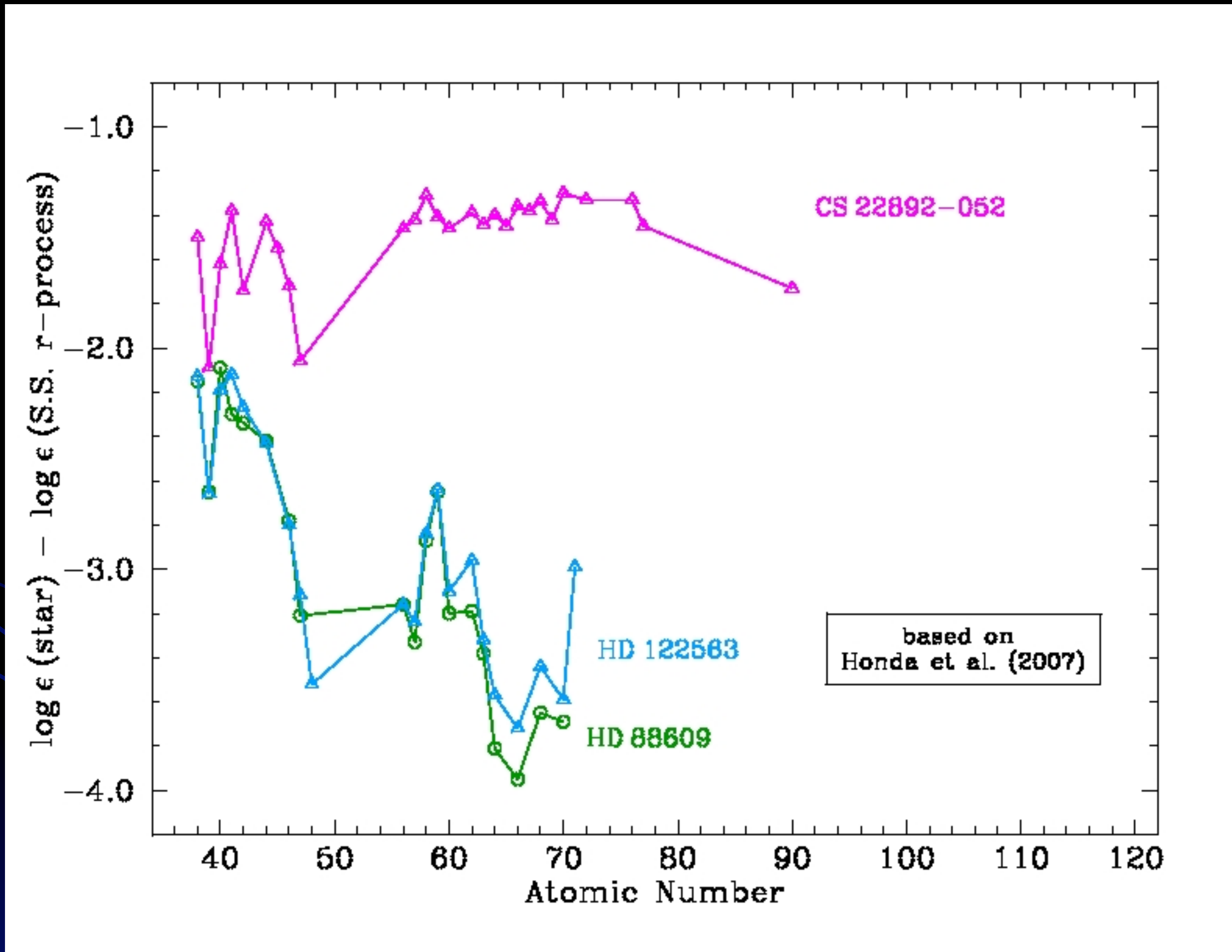


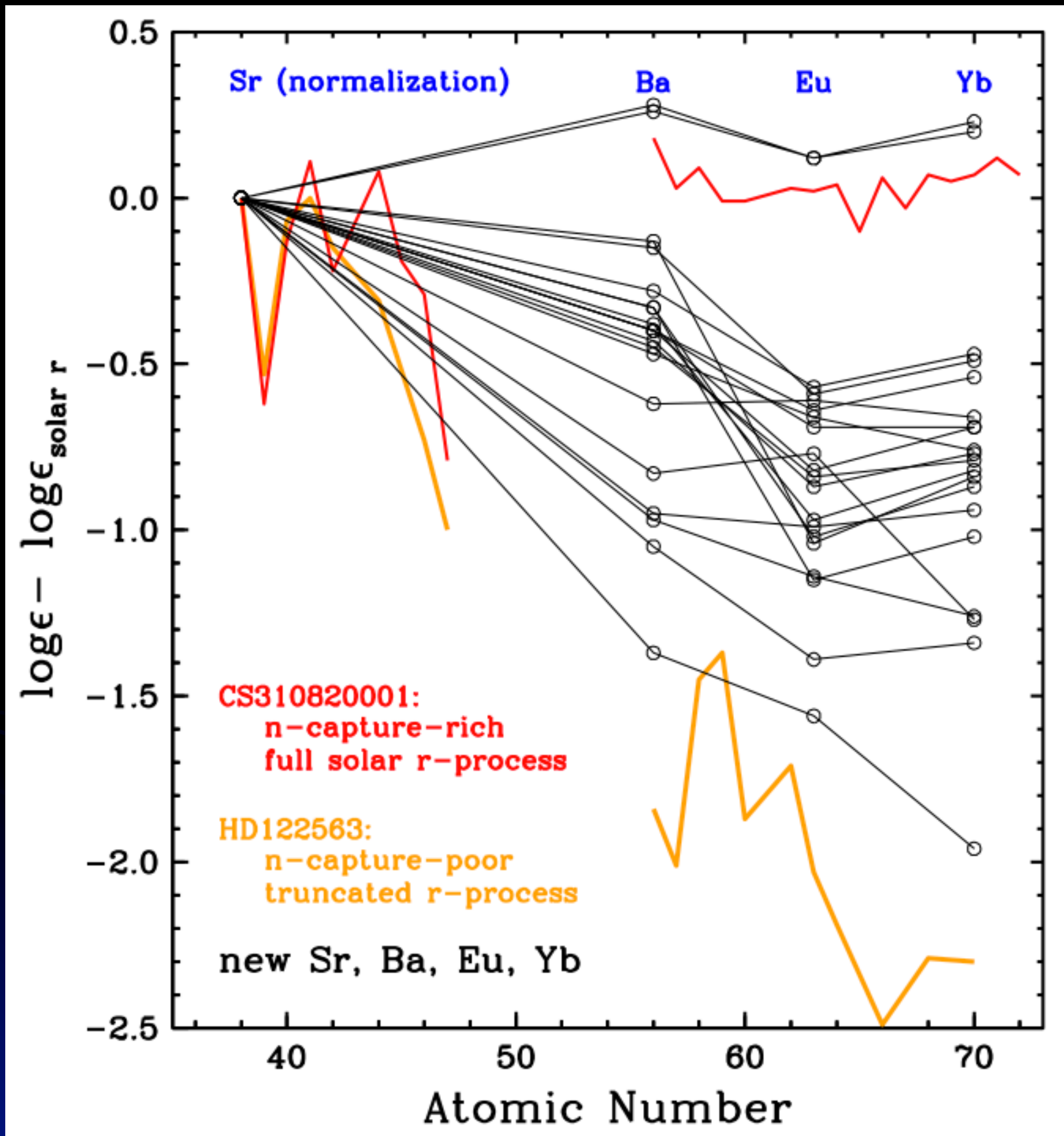
Eu/Fe

(r-process richness)

The ubiqiuity of the r-process (Roederer et al. 2010b)

r-Process Rich vs. r-Process Poor





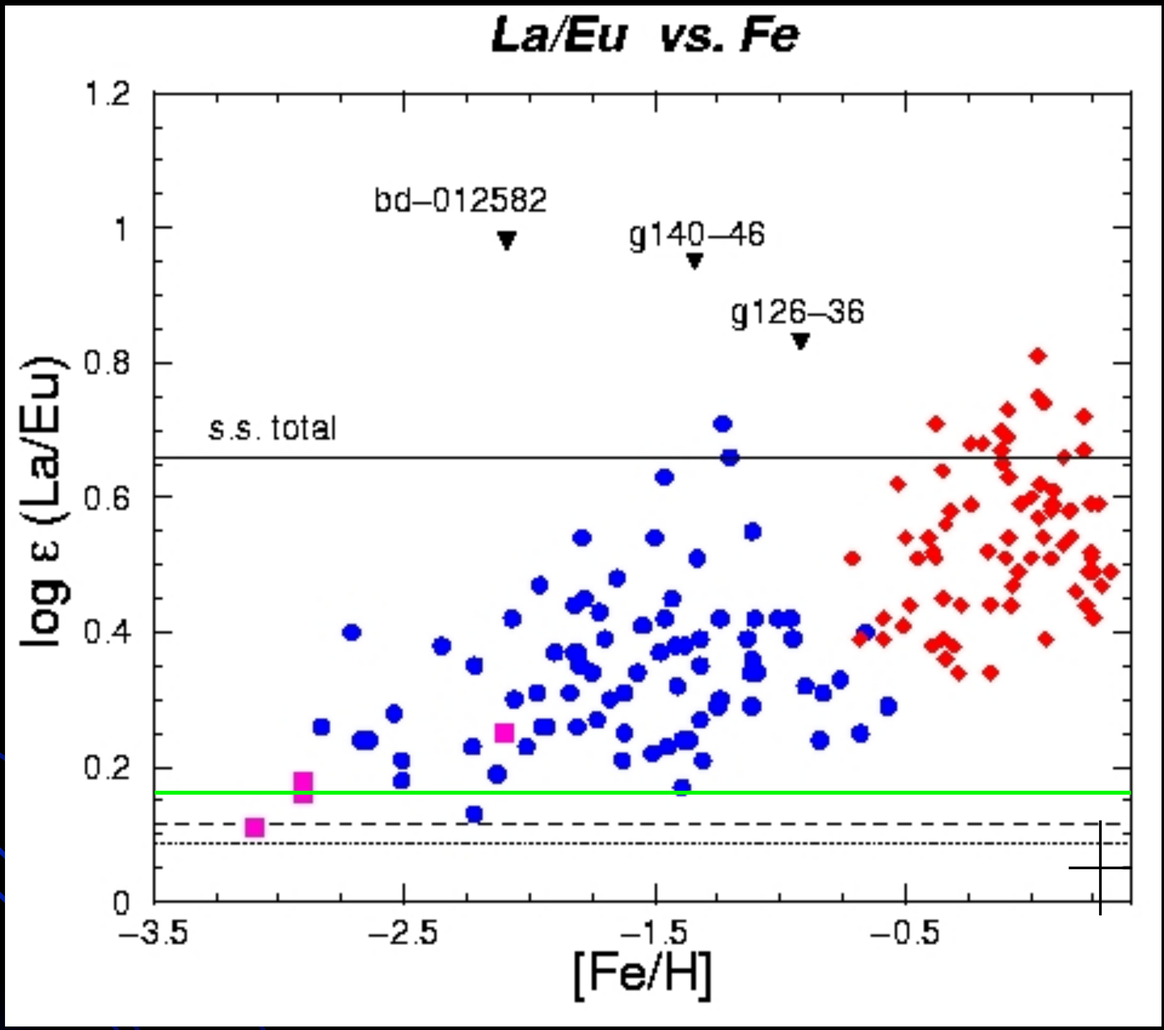
perhaps an easier way: just compare Sr, Ba, Eu & Yb

Have similar atomic structure: can be seen even when n-capture elements have low abundances in low-metallicity stars

being done with Chris Sneden, Jesse Palmerio, Dick Boyd, Ian Roederer

The Onset of the S-Process

Where does it start?



Simmerer et al. (2004)

Trend is upward due to increasing s-process contribution to La

O'Brien et al. (2003)

Burris et al. (2000)

Arlandini et al.

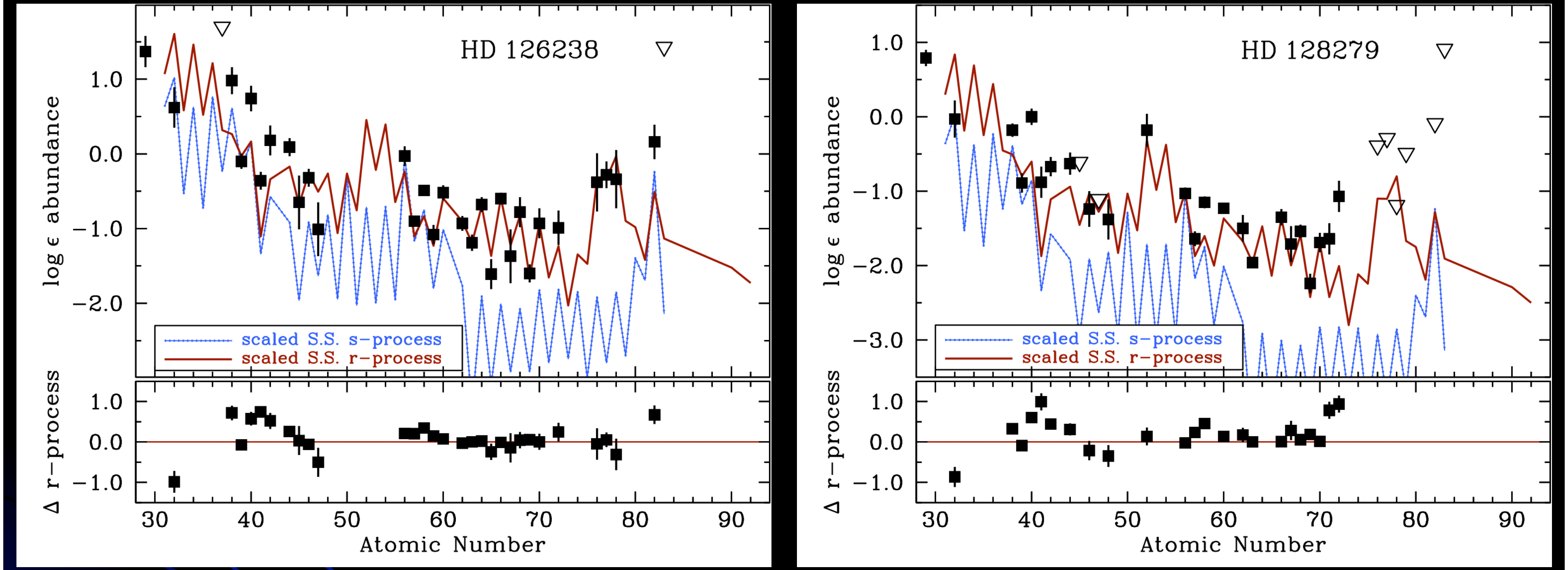
r-process only

R = SS-S
Measure s-n-Cross Section of 139La

Metallicity like time

■ r-process enhanced, • halo stars, ♦ disk stars

Very New Detections in Halo Stars

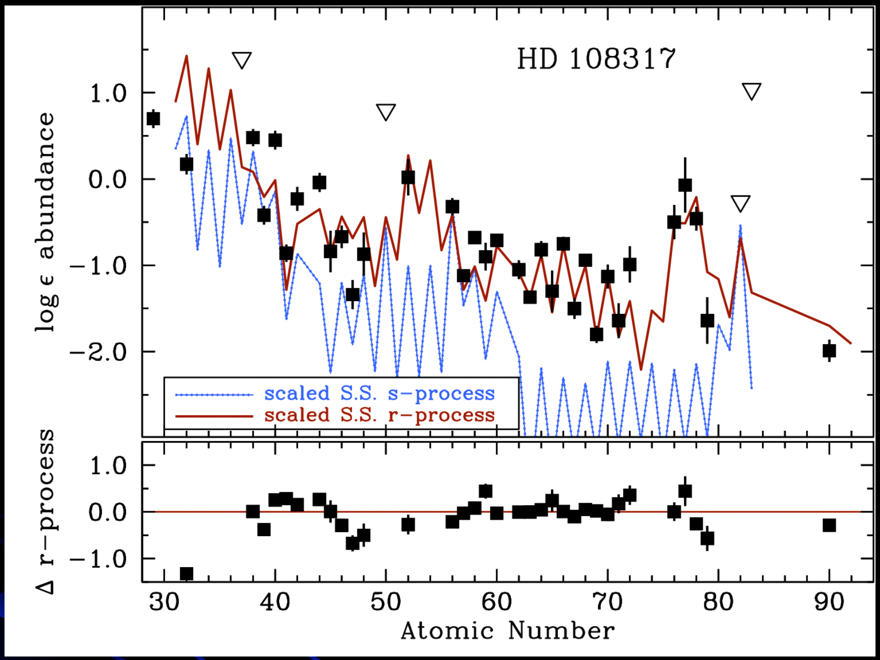


Some s-process?
([Fe/H] = -2)

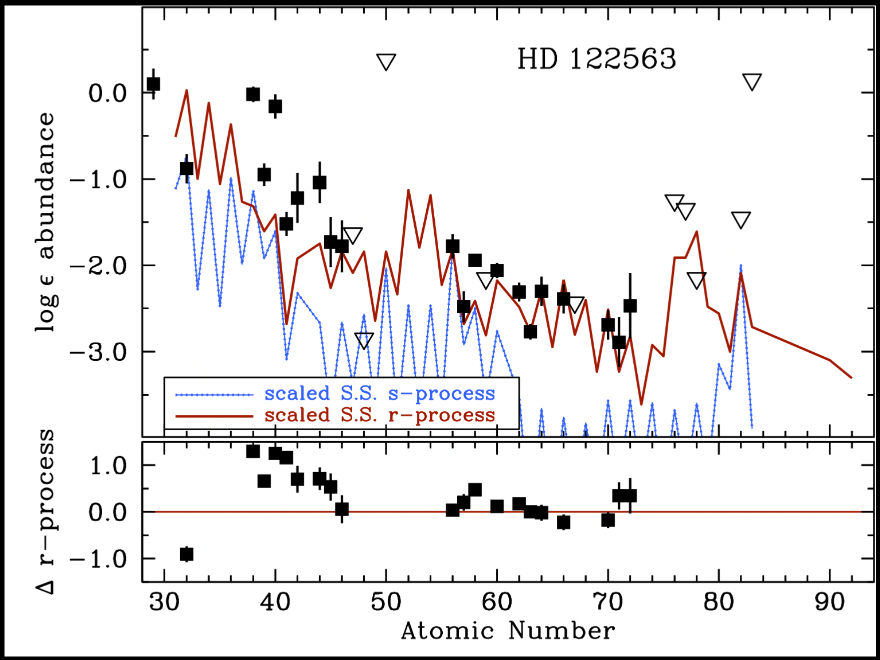
Some s-process?
([Fe/H] = -2.5)

Roederer et al. (2012b)

Very New Detections in Halo Stars



[Fe/H] = -2.5



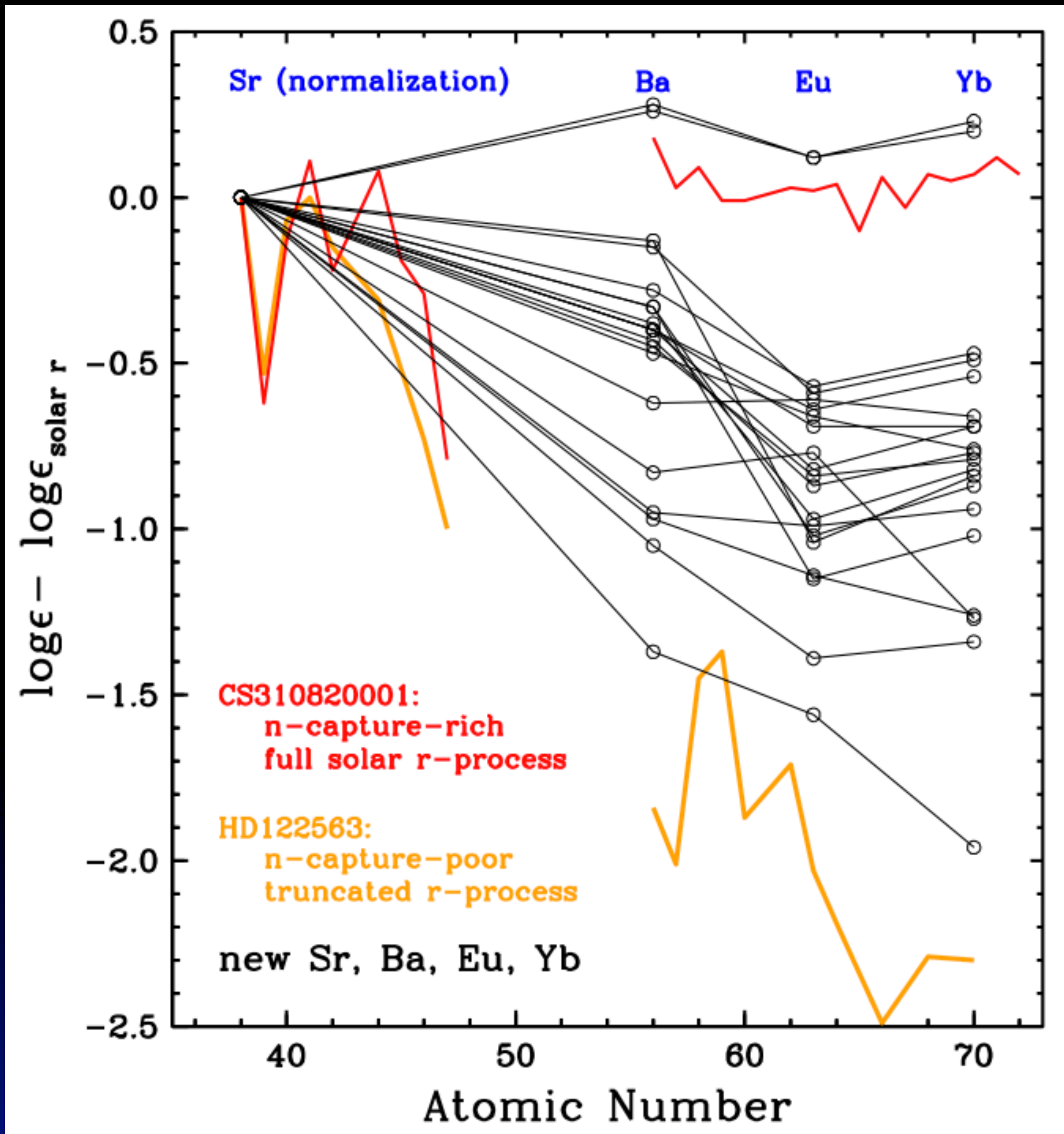
[Fe/H] = -2.7

Note Zn, Ge

Some elements(Sr, Zr, Ce & Pb) would fit better with some s-process

r-star but decrease in abundance with Z, no 3rd peak: incomplete r-process?

Roederer et al. (2012b)



Observational Approach

Sr/Ba: assessment of LEPP

Ba/Eu: assessment of r- or s- dominance

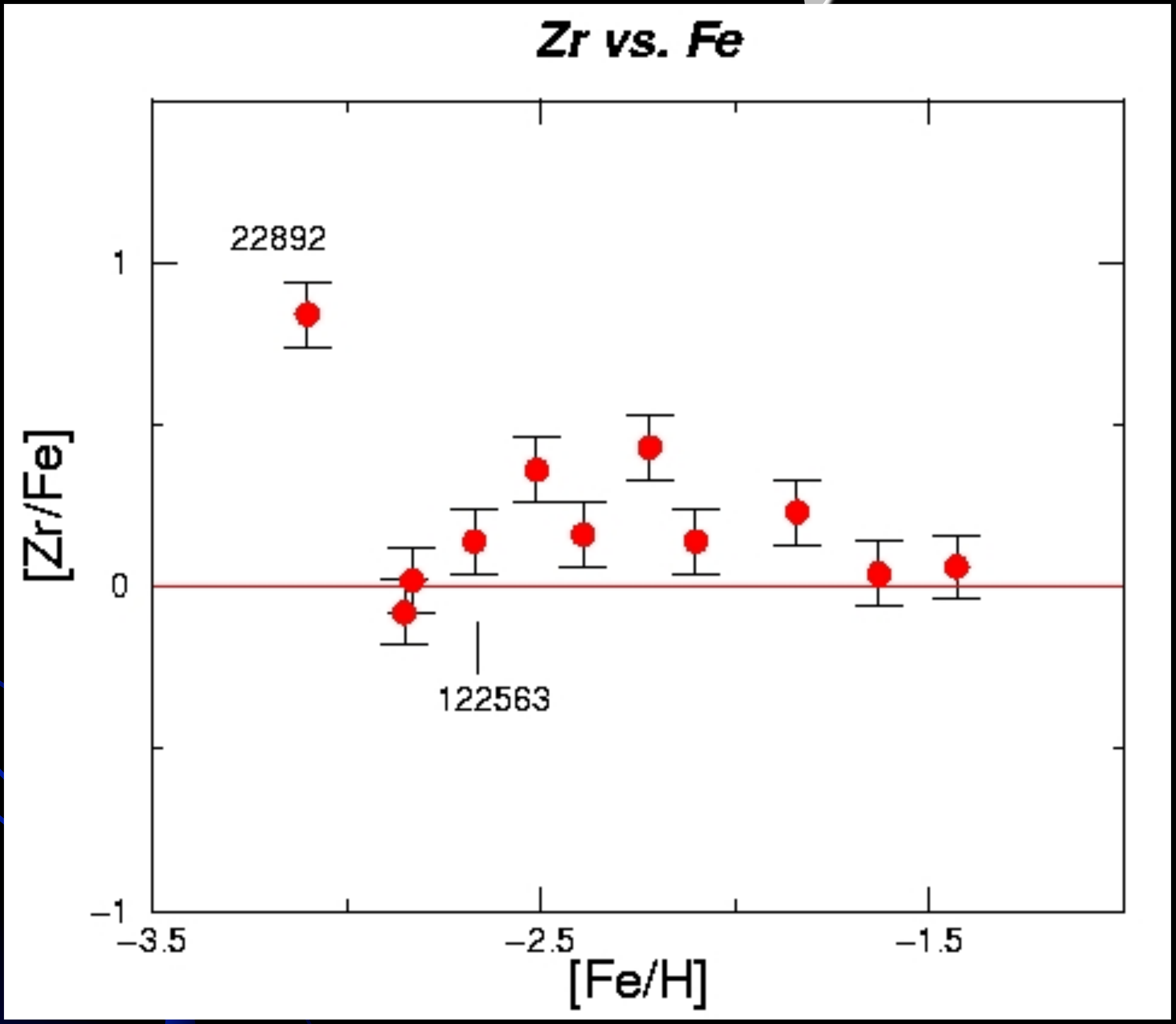
Ba/Yb: assessment of r-process truncation

being done with Chris Sneden, Jesse Palmerio, Dick Boyd, Ian Roederer

Galactic Chemical Evolution: Abundance Changes with Metallicity ([Fe/H]) or Time ➔ Provides Insights Into

- the nature of star formation over the history of the Galaxy
- the earliest generations of stars (``The First Stars'') in the Galaxy
- the earliest synthesis mechanisms in the Galaxy
- the changing nature of synthesis mechanisms in the Galaxy

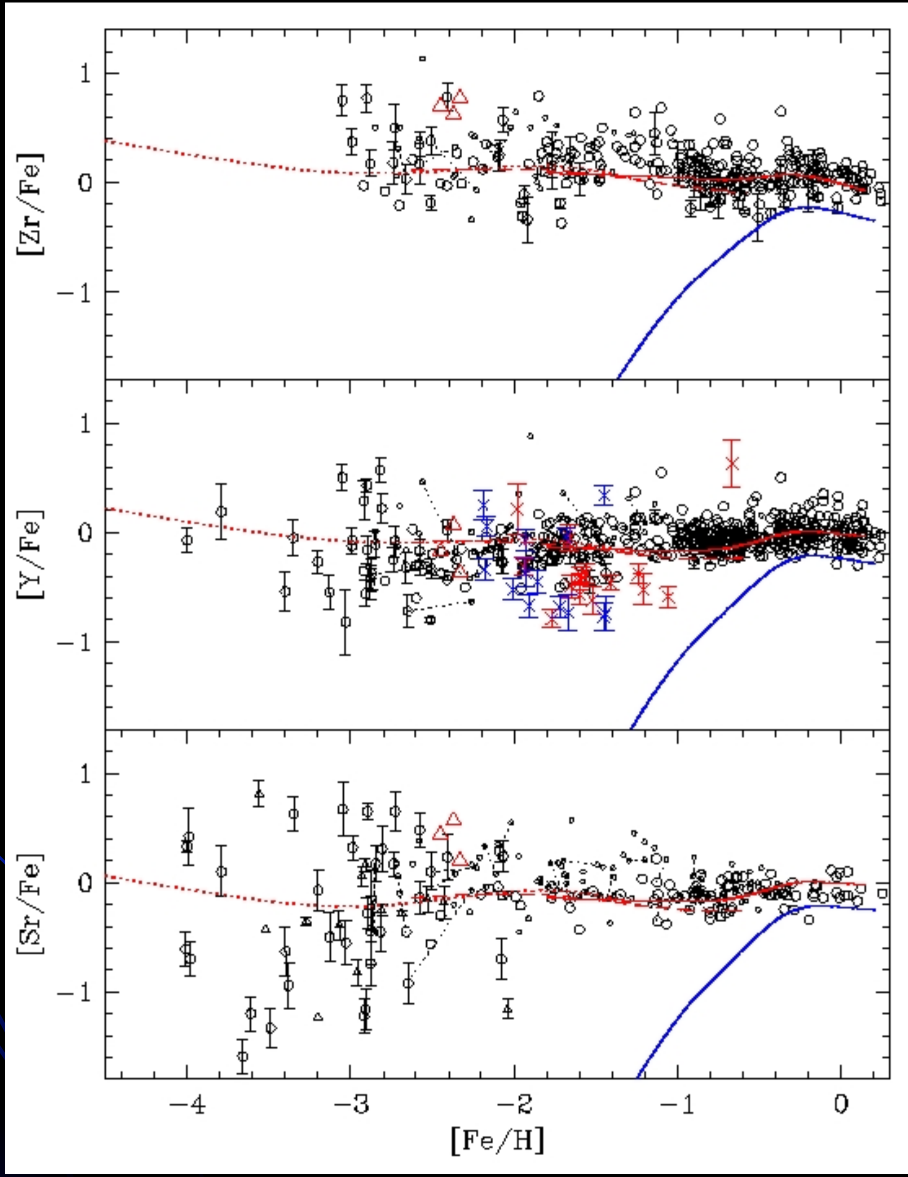
Zr (HST) as a Function of Metallicity



JC et al. (2005)

Zr independent of [Fe/H], as shown already by Travaglio et al. (2004).

Metallicity Effects on Sr-Zr



Travaglio et al. (2004)

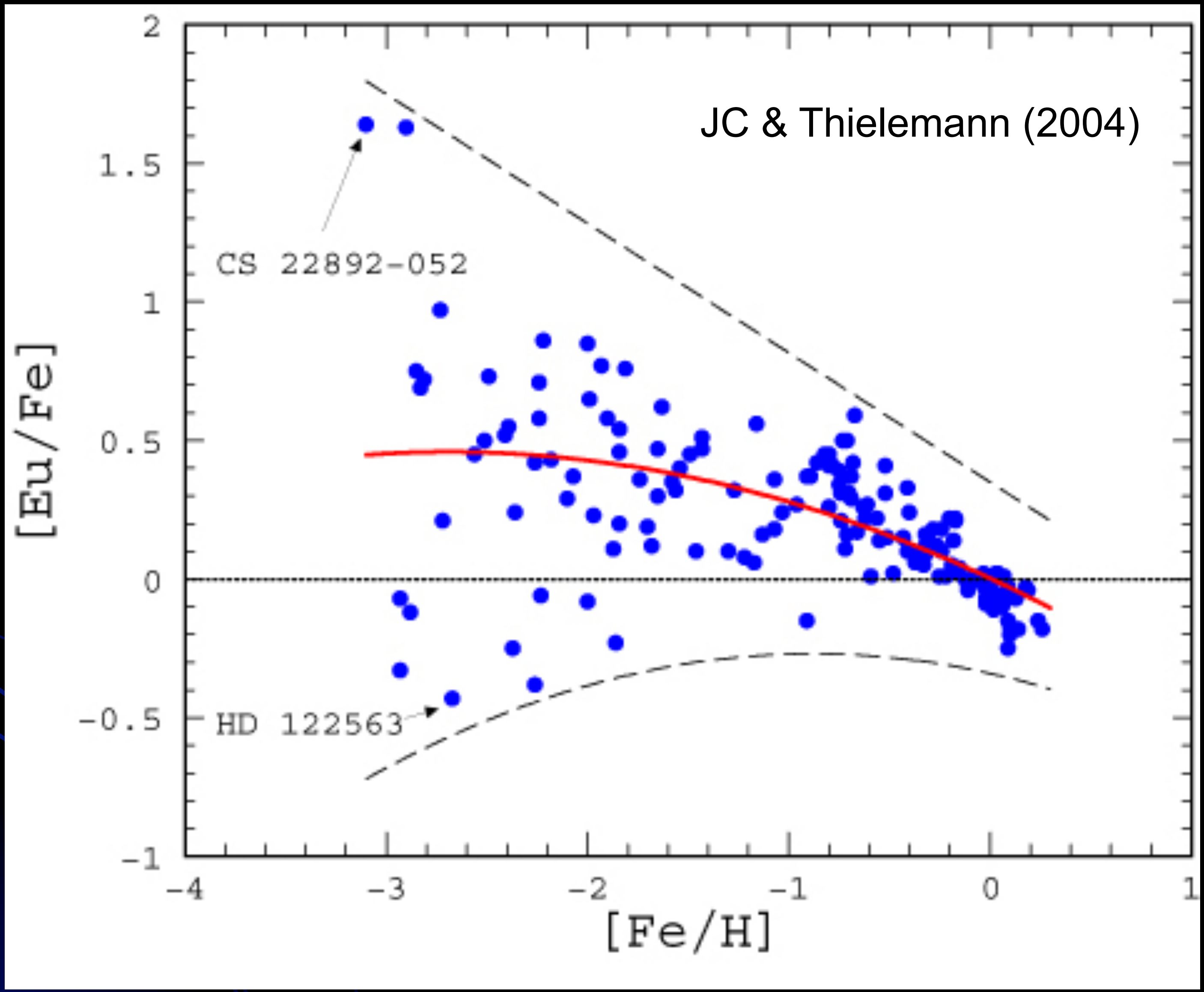
Much more extensive data sets.

Evidence for the LEPP (Lighter Element Primary Process) ?

Models are very complicated!

Eu Abundance Scatter in the Galaxy

GCE



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

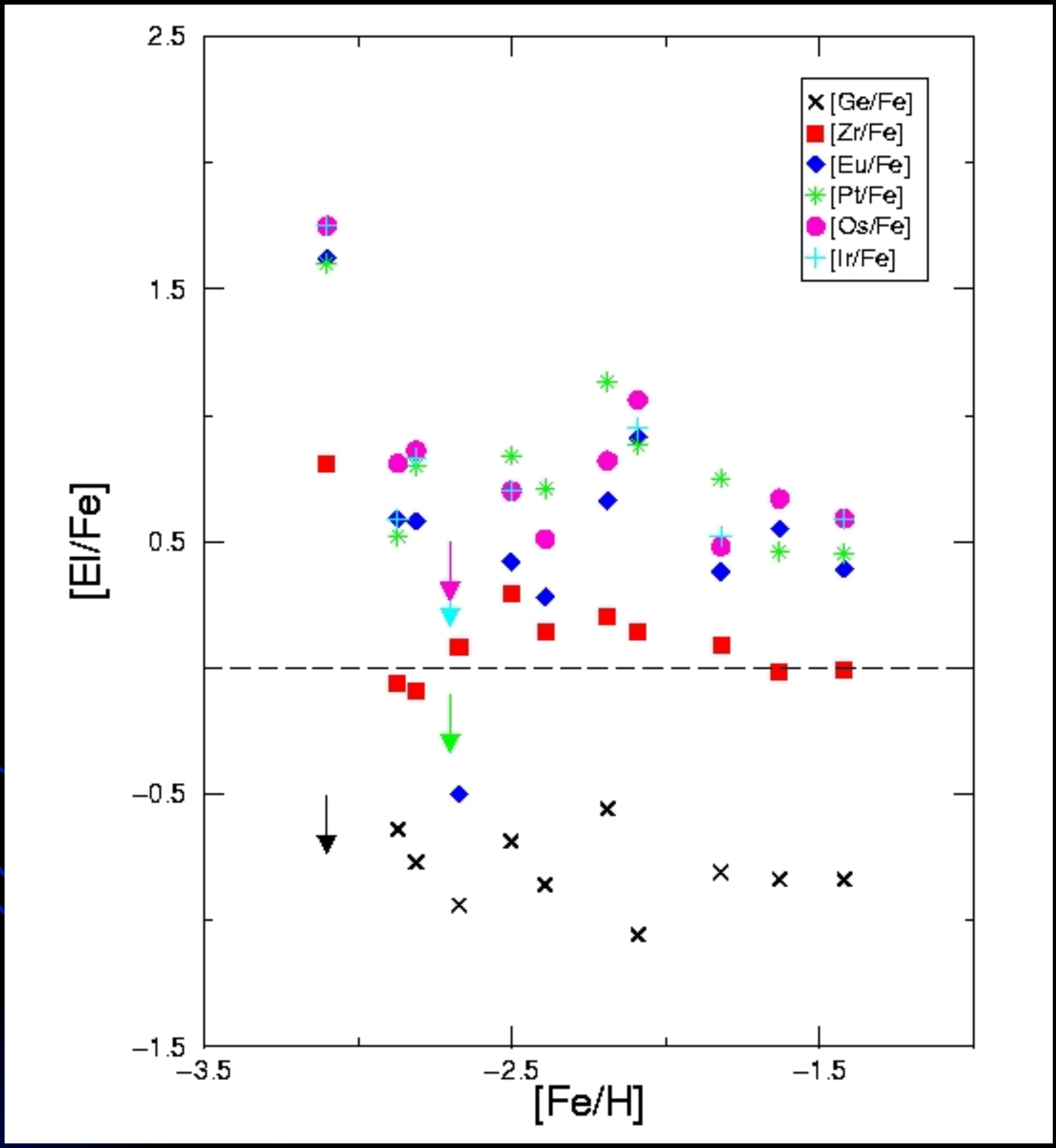
scatter and slope with increasing metallicity

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

n-Capture Element Abundance Trends

Os-Pt & Eu correlated and show similar scatter with [Fe/H]

RARE

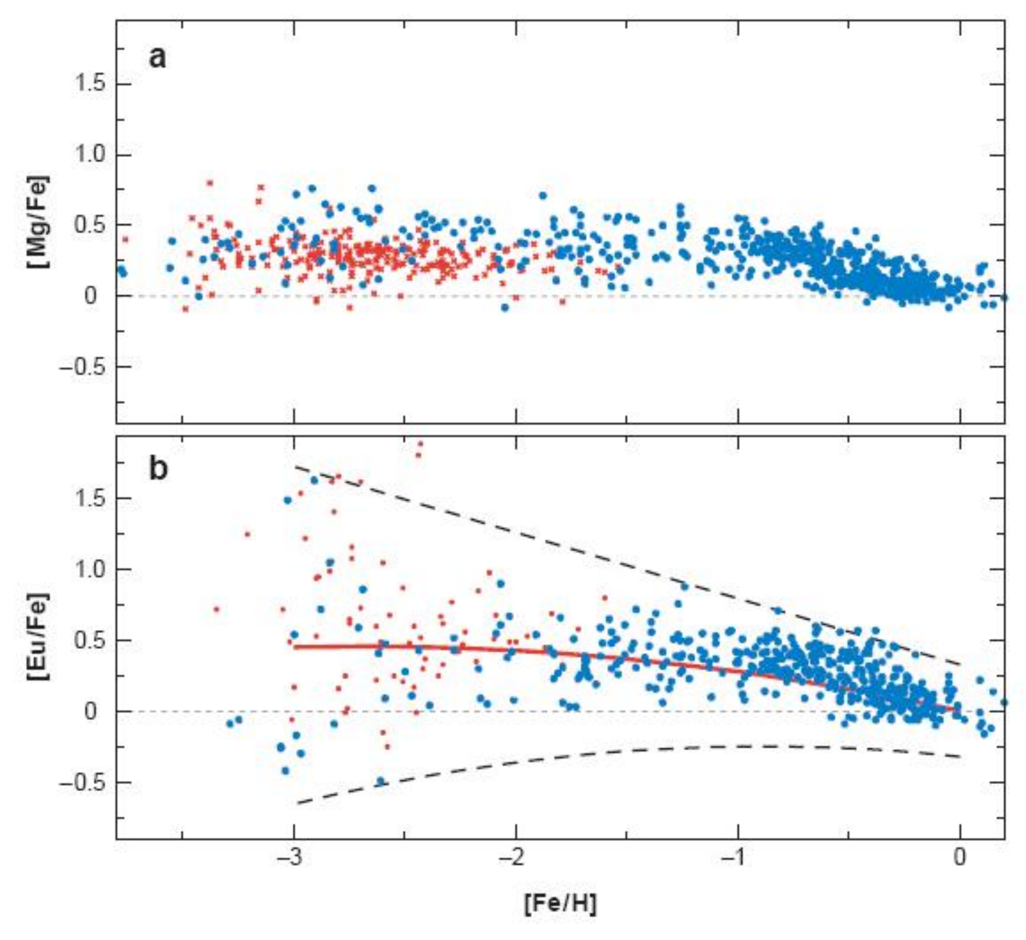


Ge & Zr Show little Scatter.

COMMON

Abundance Scatter and the Sites for the Formation of the Elements

Galactic Chemical Evolution



• = disk stars
• = halo stars

0 = solar values

Sneden, JC & Gallino (2008)

Mg produced in different stars (more massive) than for r-process (Eu) elements.

Abundance Trends of n-Capture Elements in the Galaxy

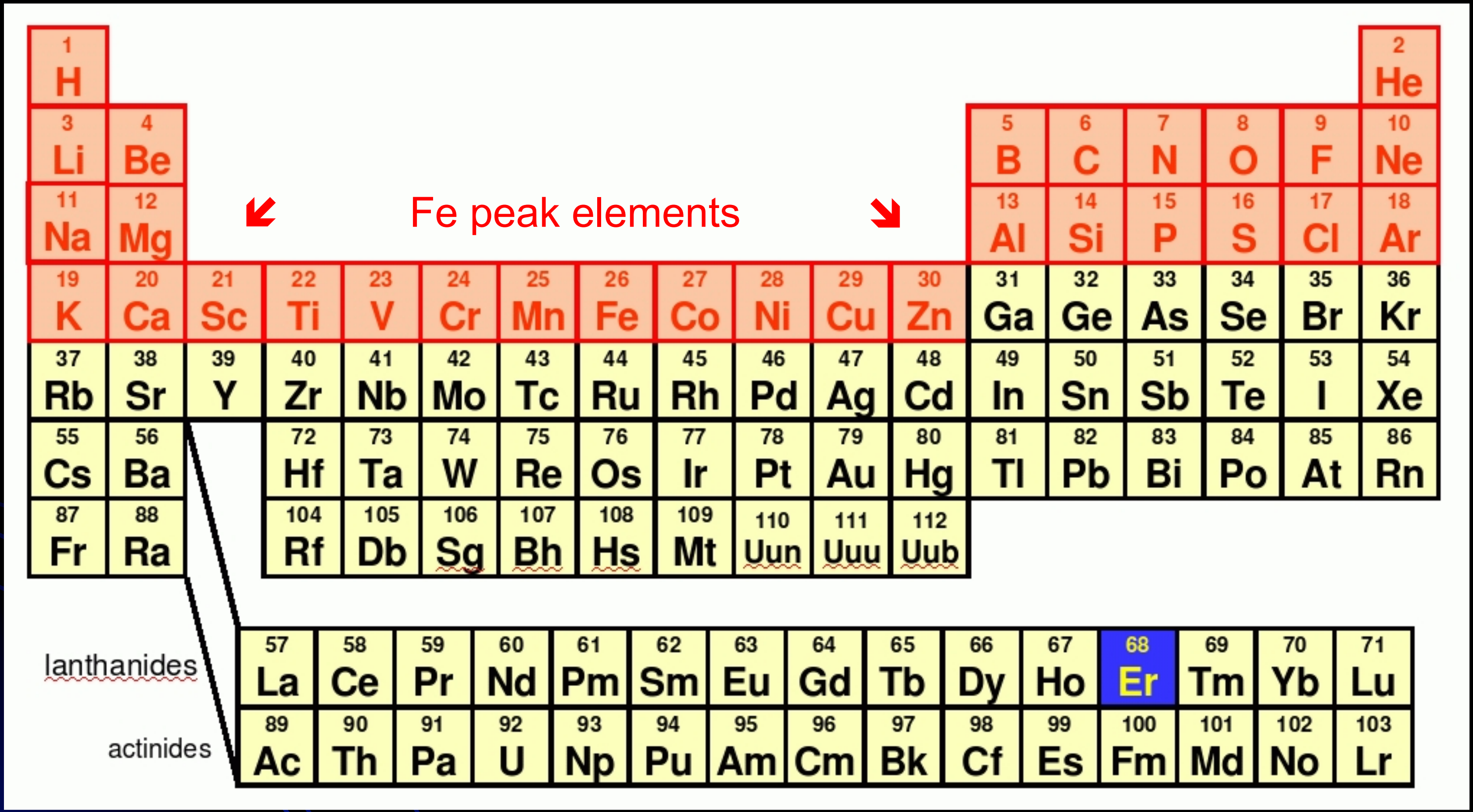
- Os-Pt abundance values show same scatter as [Eu/Fe] at low metallicity
- New La/Eu ratios more reliable than Ba/Eu:

1. N-capture elements show scatter
2. Only most metal-poor stars show r-process only ratio
3. Stresses importance of nuclear measurements
4. Some "dusting" of s-process even at [Fe/H] < -2 ?

What About Iron-Peak Elements?

- Rare earth abundances (experimental data already obtained) in good shape
- Iron-peak elements (new experimental data):
  - → Critical for Supernovae Nucleosynthesis
  - → Iron already done
  - → Ti I and II done (Lawler et al. 2013; Wood et al. 2013): observed [Ti/Fe] > predicted values, problems with SN models
  - → Mn, Cu, Ni & V in progress
  - next on the hit list Co?

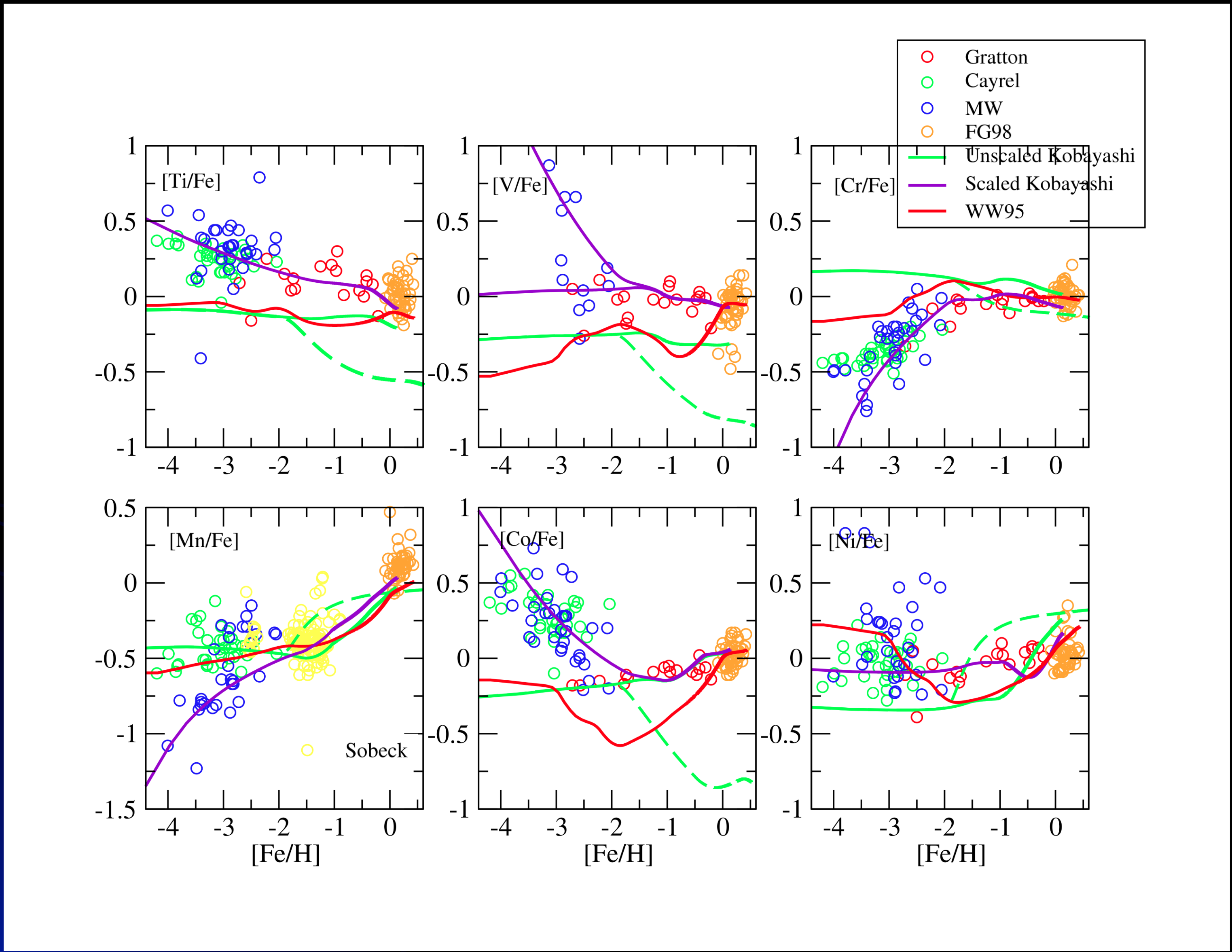
New Atomic Data to Improve Elemental Abundance Values



New focus on the Iron-Peak Elements

transition probabilities from Lawler’s Wisconsin group

Iron-Peak Element Trends

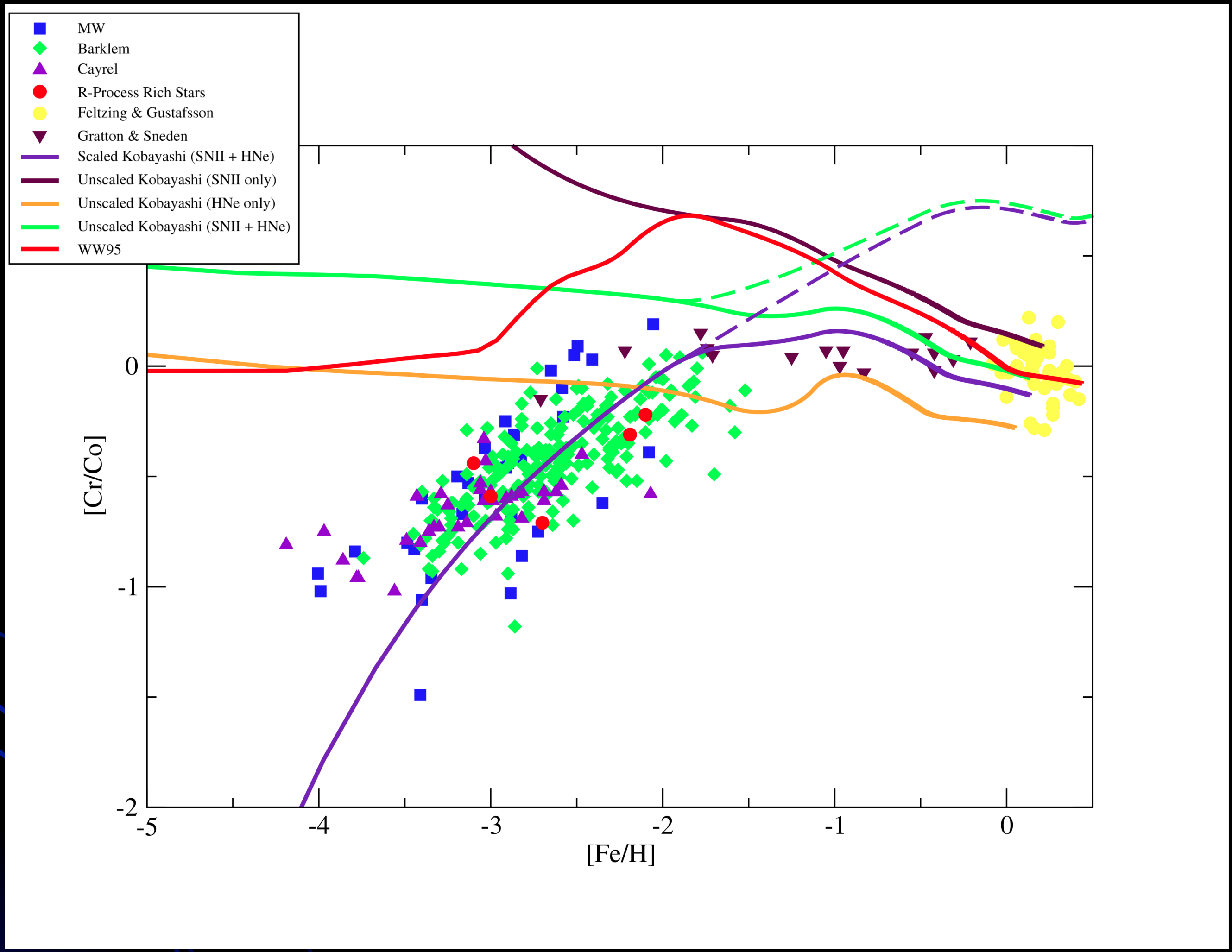


Note Cr and Co

Henry, JC & Sobeck (2010)

But uncertainty in abundance data due to poor atomic physics data

[Cr/Co] vs. Metallicity

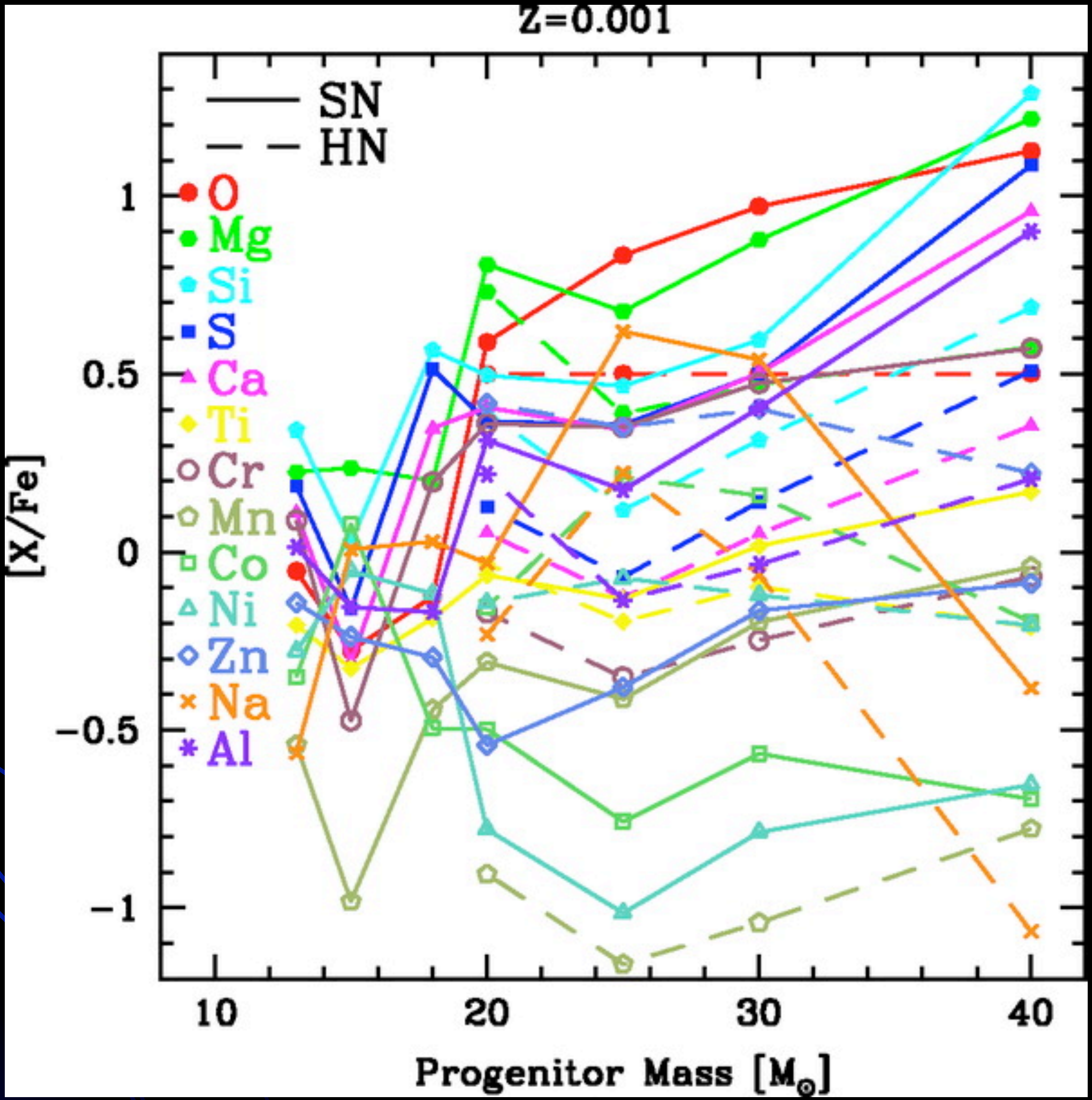


Henry et al. (2010)

Co and Fe (from complete) and Cr (from incomplete) Si burning in SNe models: Coming from alpha capture not Si-Si

theoretical models can generate these elements

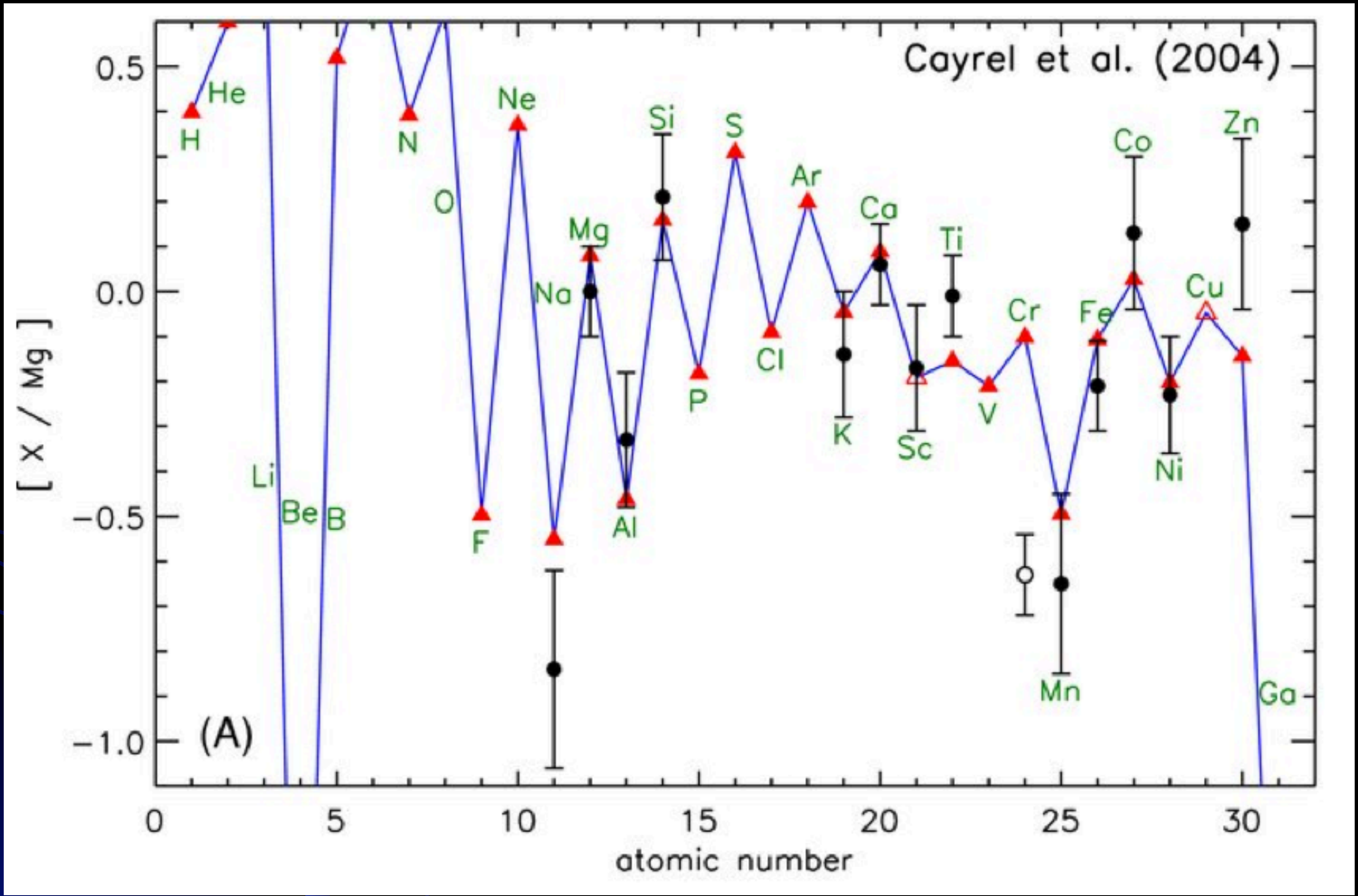
Hypernovae = More energetic SN



Theory ahead of observations

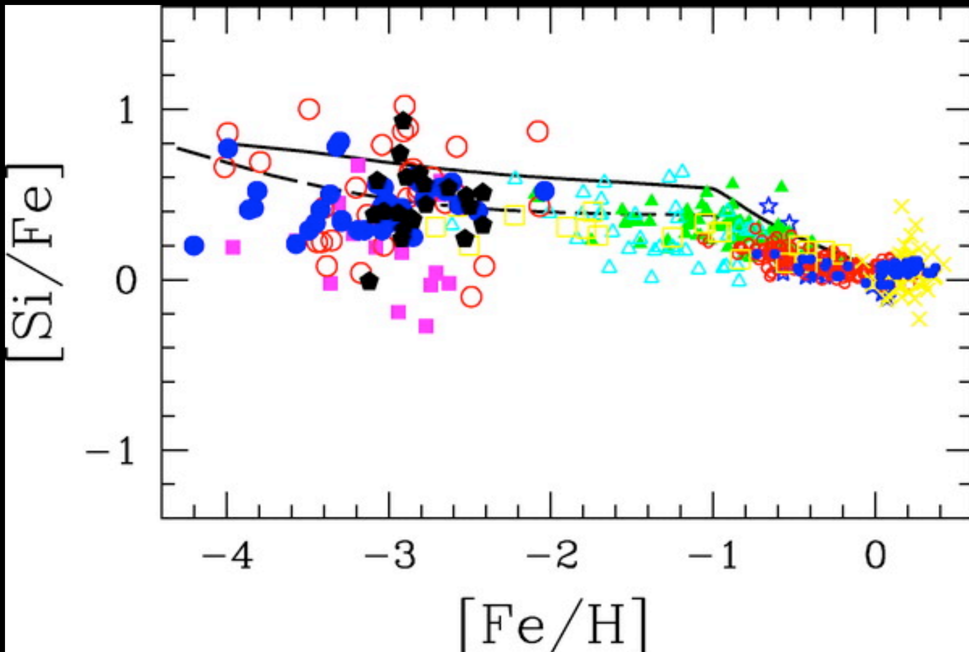
Kobayashi et al. 2006

there are good predictions for "zero-Z" models

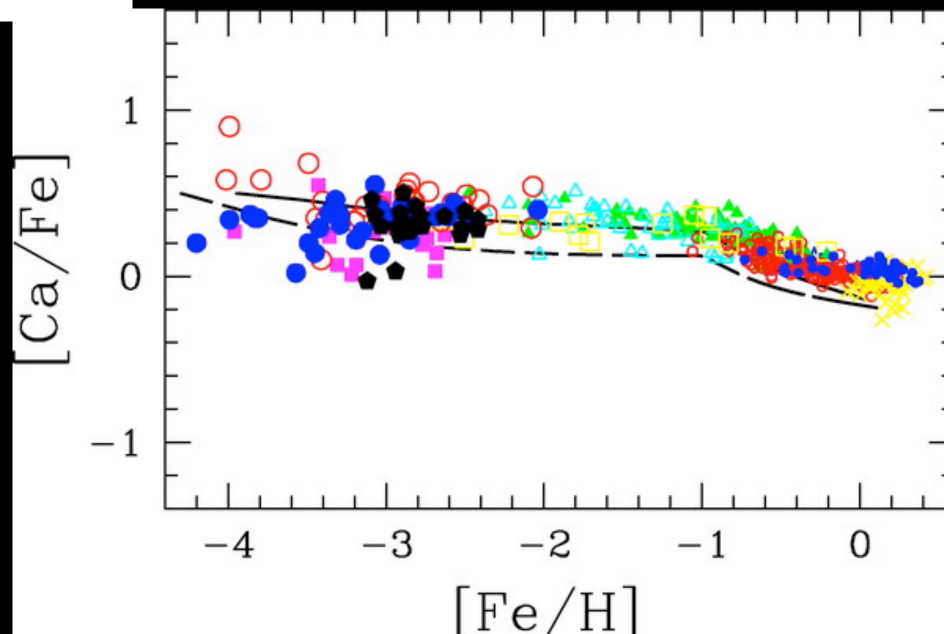


How are these stars different?

Heger & Woosley 2010

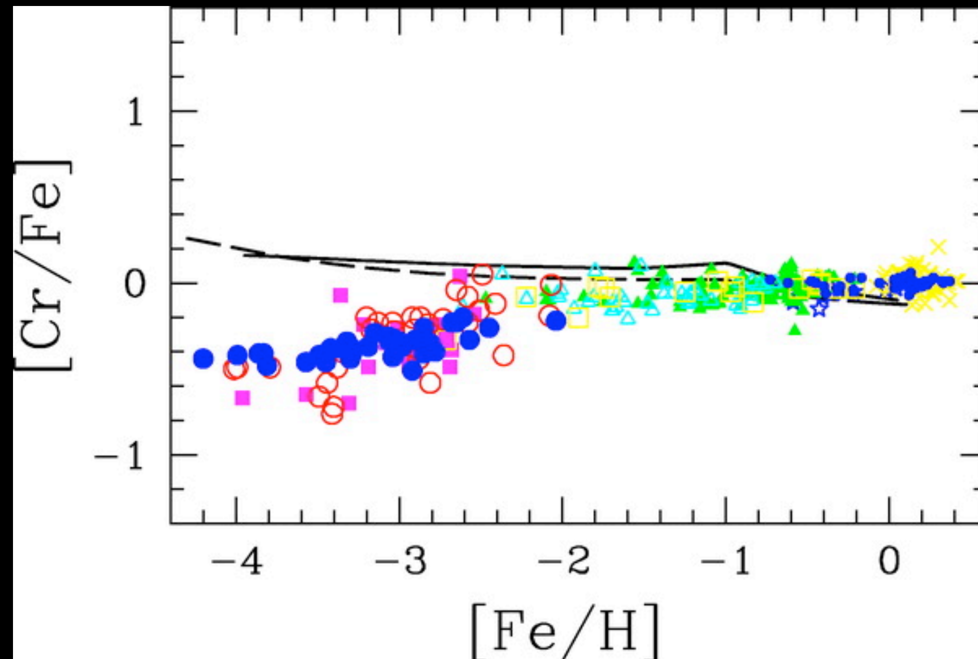


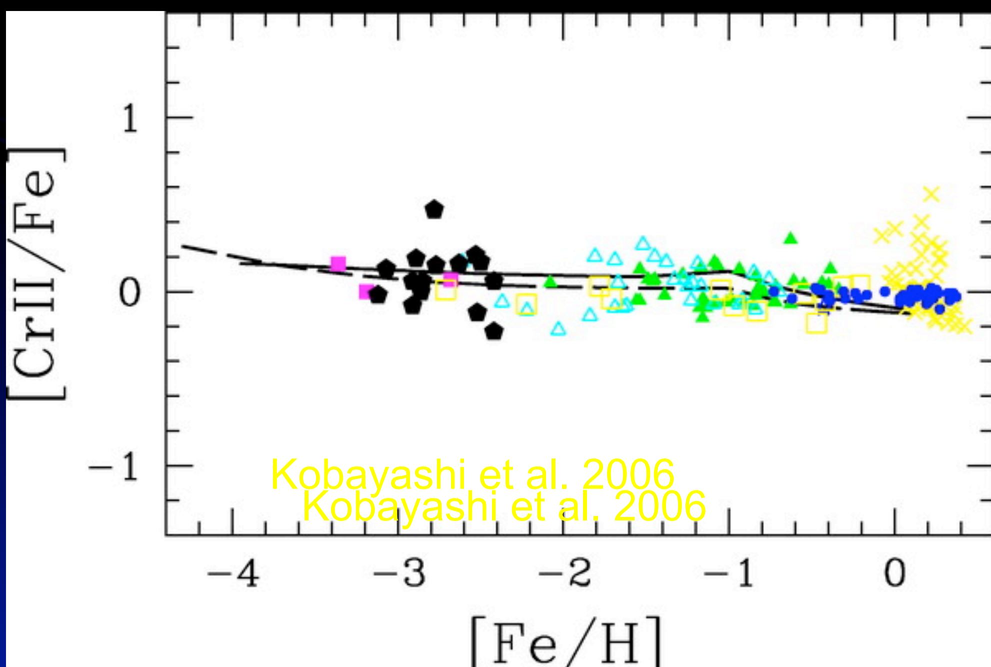
for some elements the theory/ observation match seems happy



Kobayashi et al. 2006

but for others, watch out!

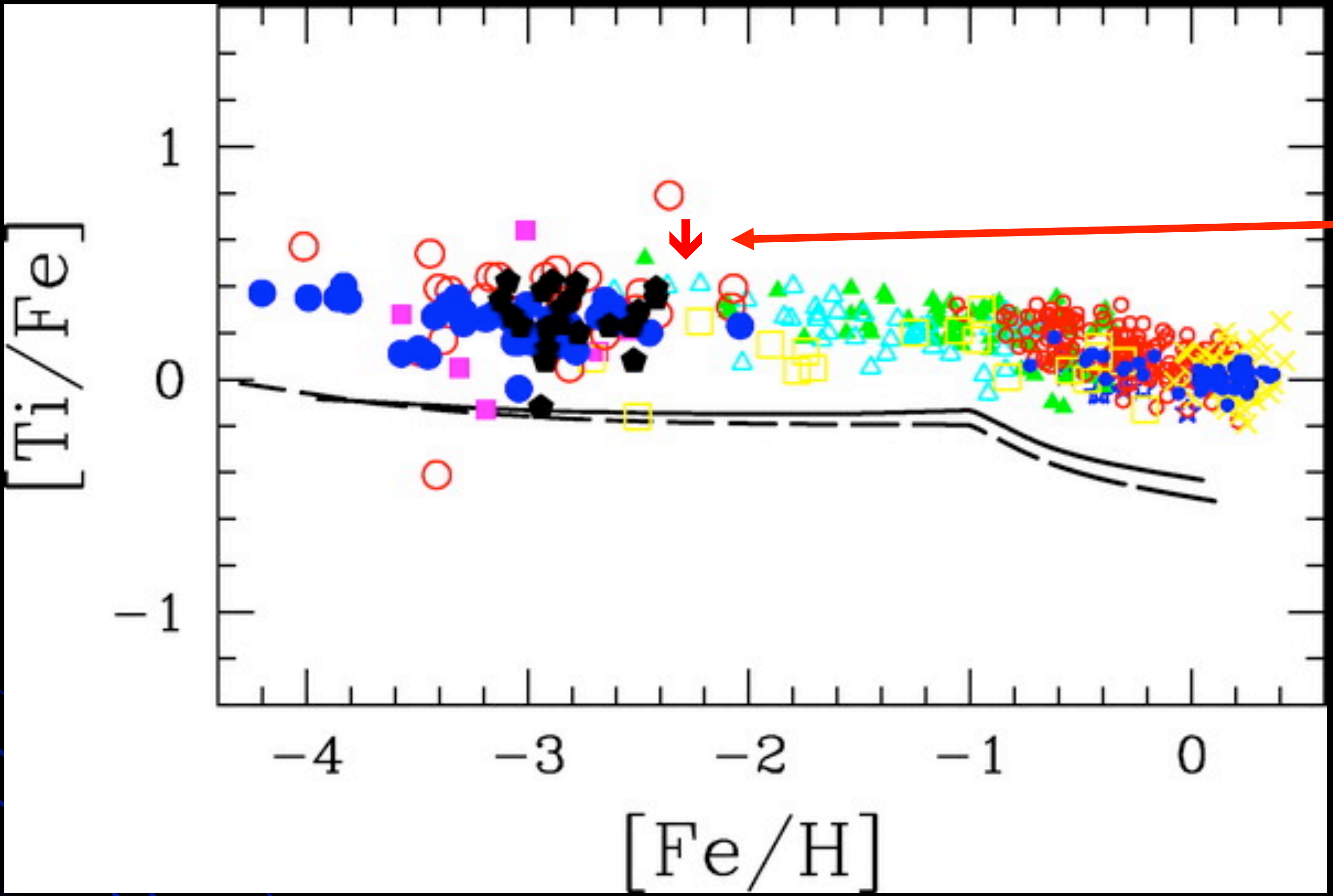




same theory, different observed species of the same element

Kobayashi et al. 2006

A new initiative on Fe-group abundances



Observed in HD 84937 Lawler et al. (2013)

Problems with SN models

Kobyashi et al. (2006)

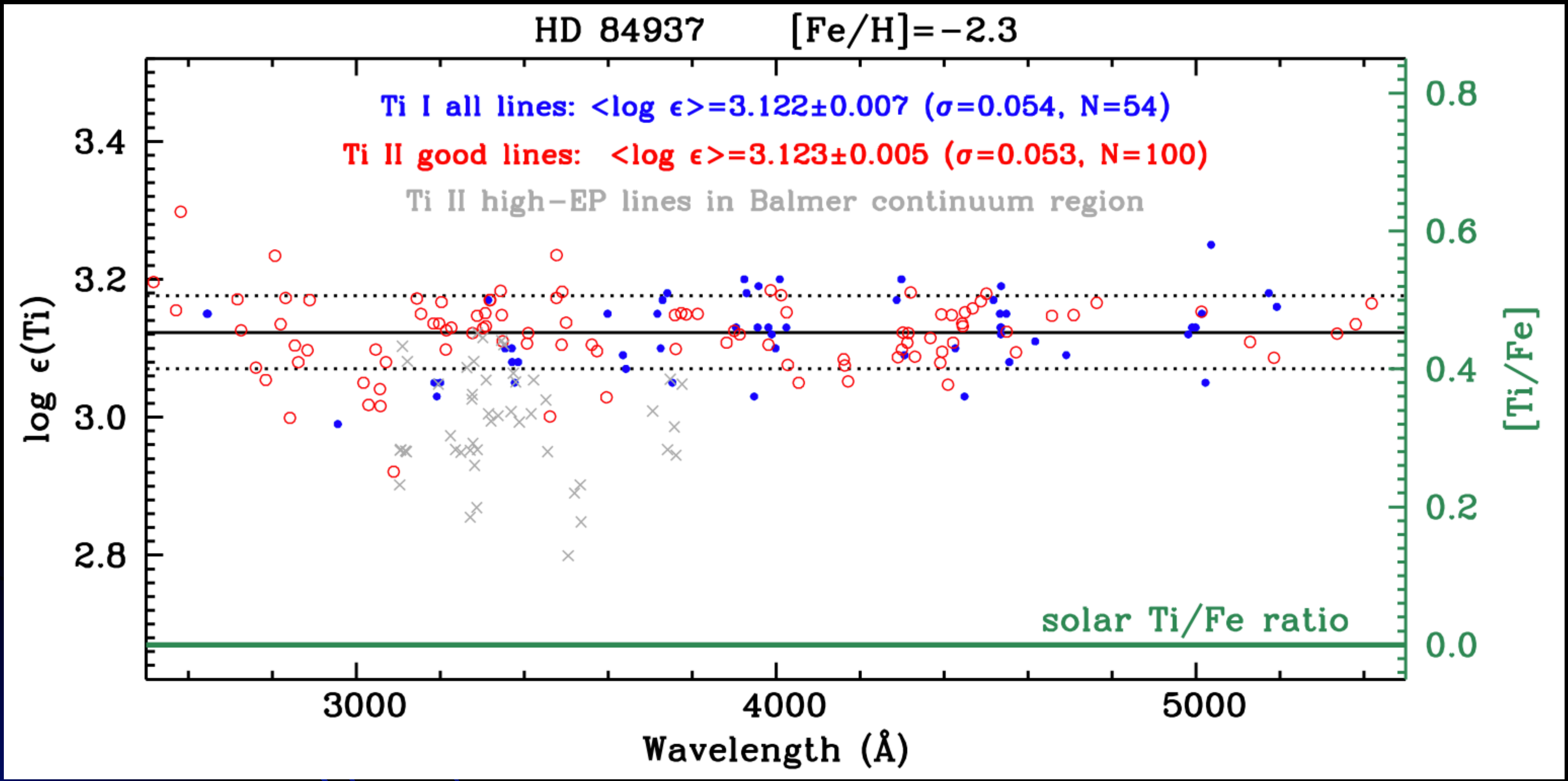
this work concentrates on increasing accuracy of Fe-group elements

the big point: must have better transition probabilities

groups at Wisconsin, London, Belgium lead the way

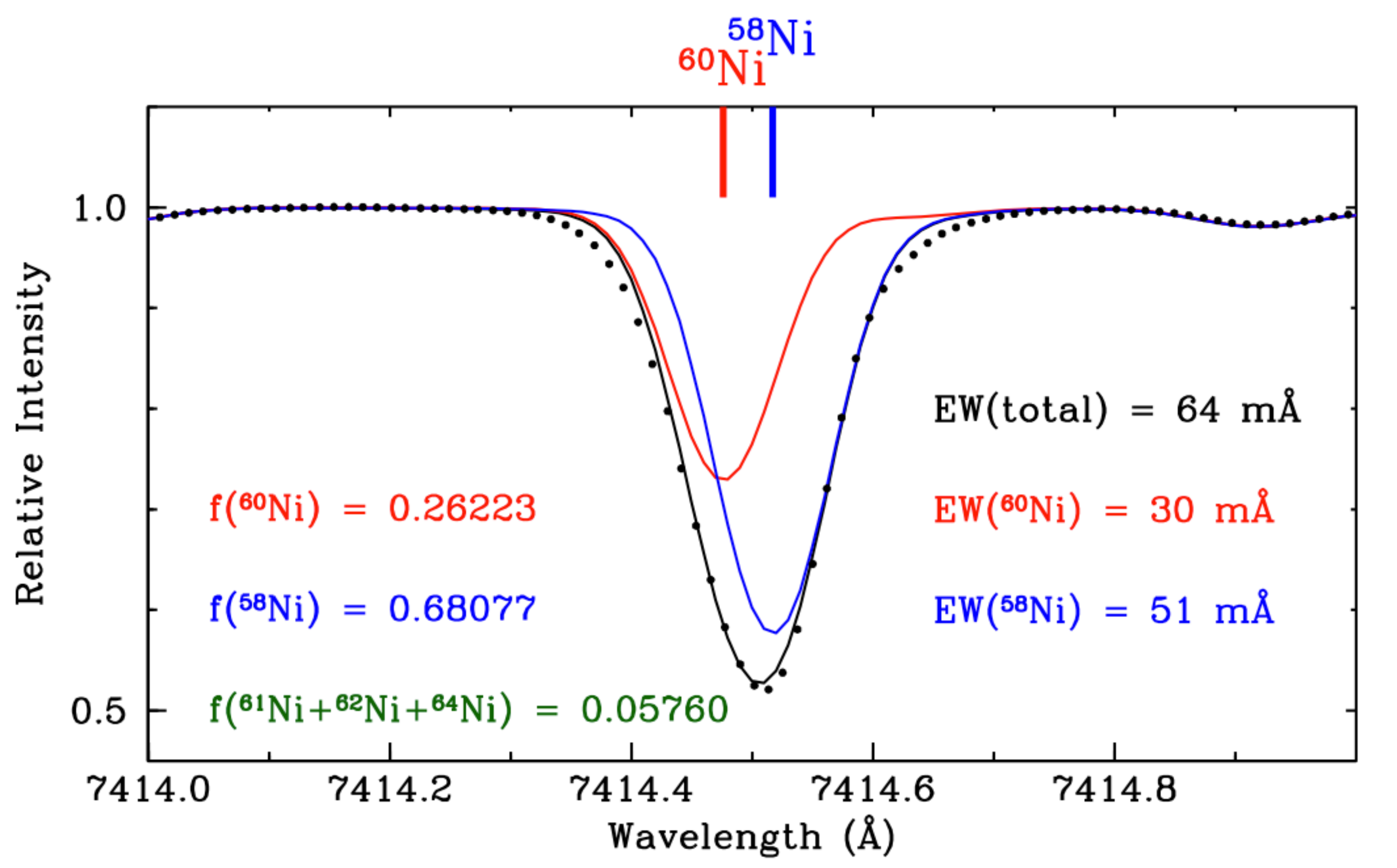
HST data at low metallicity end explores more species

Observed Titanium

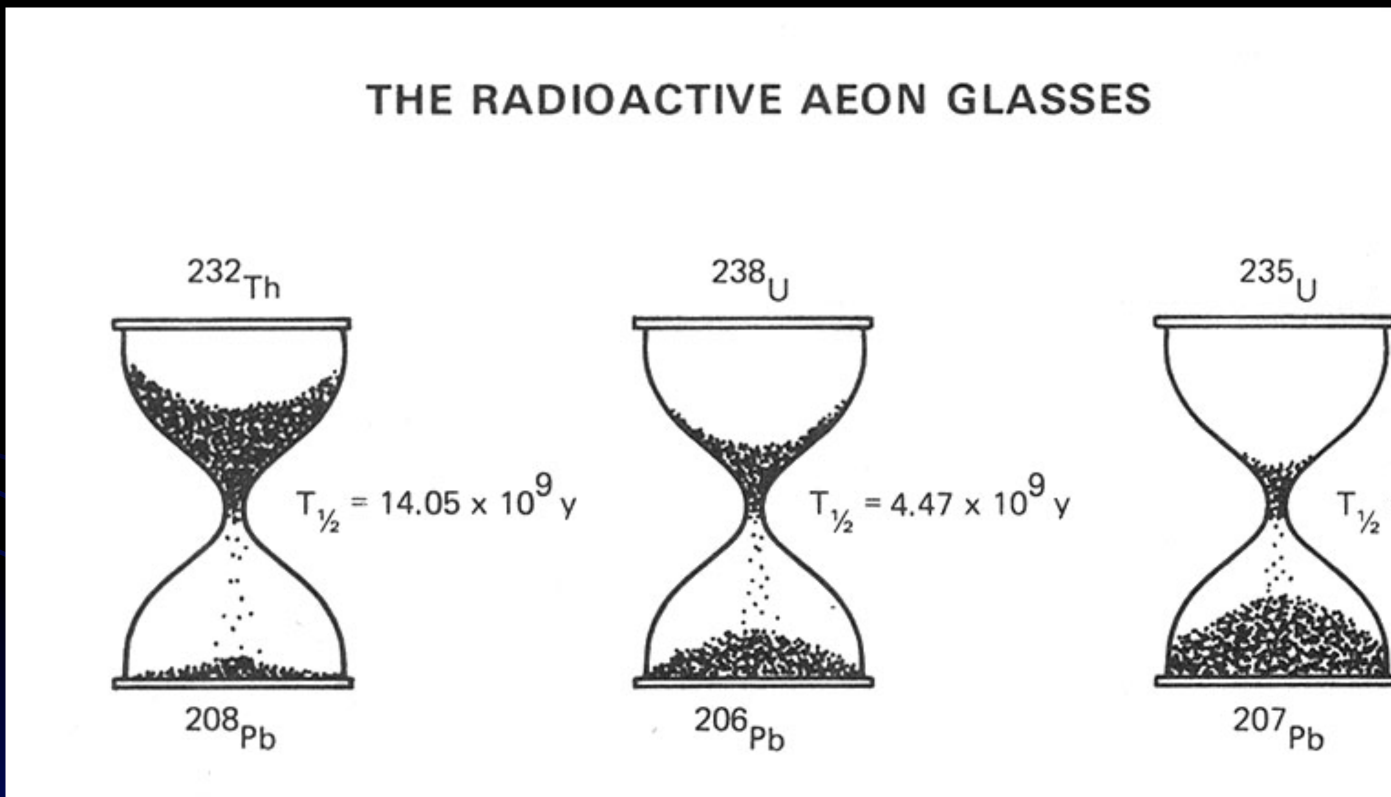


the big point: Ti I & Ti II give same answer; scatter is very low; Ti is really overabundant compared to SN models (Wood, Lawler, Guzman, Sneden, Cowan 2013)

First Attempt at Isotopes for Fe-peak Elements



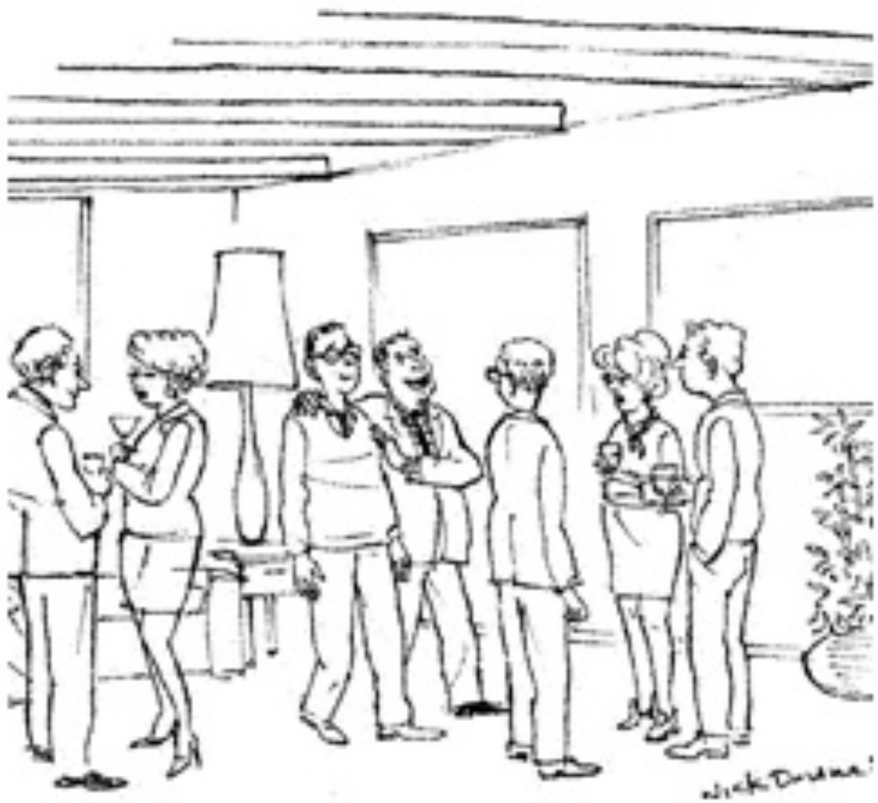
Radioactive Cosmochronometers



[irrelevant; decays too quickly]

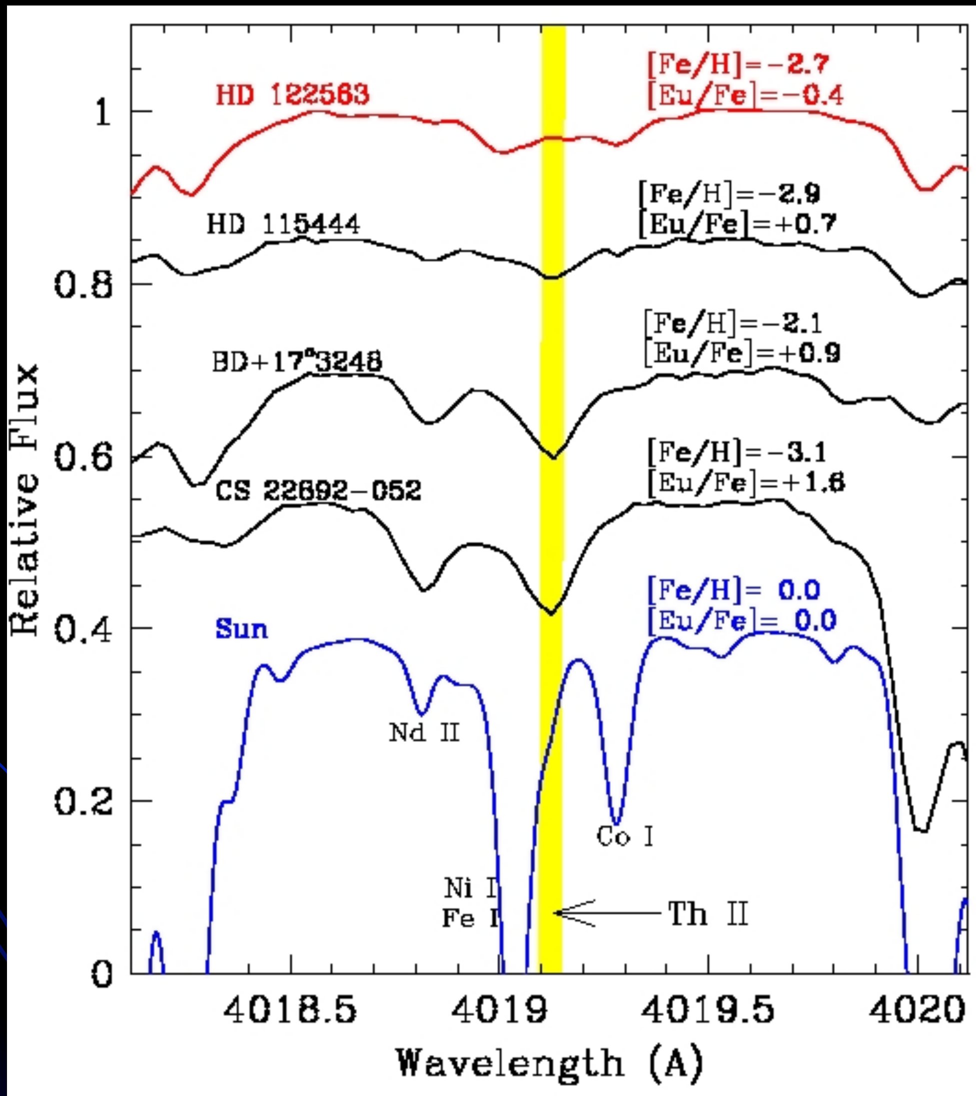
Rolfs & Rodney (1988)

THE WALL STREET JOURNAL.



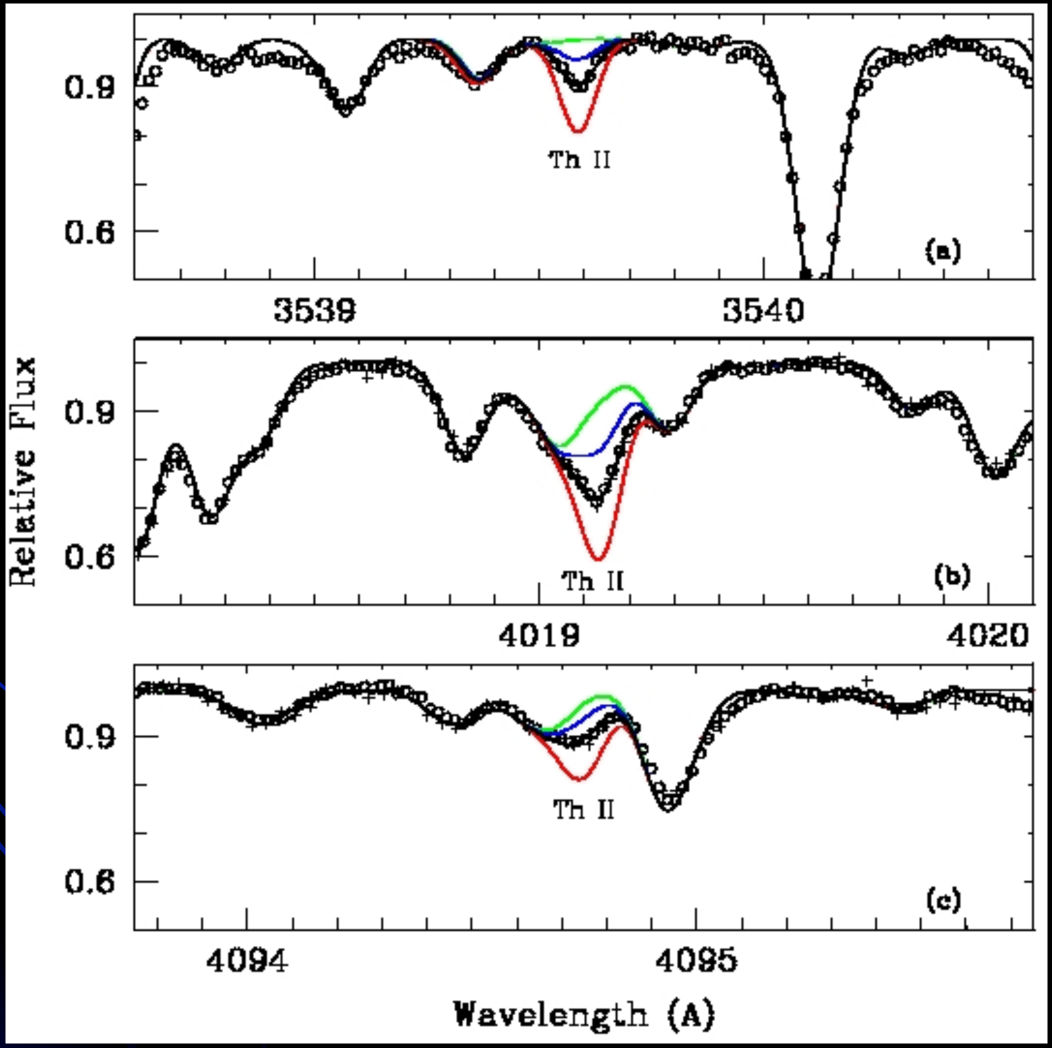
"If there's anything you need to know about radioactive cosmochronometry, ~~Howard~~'s your man."
John's

Th Detections in Four Halo Stars and the Sun



Note the strength of the Th lines independent of metallicity

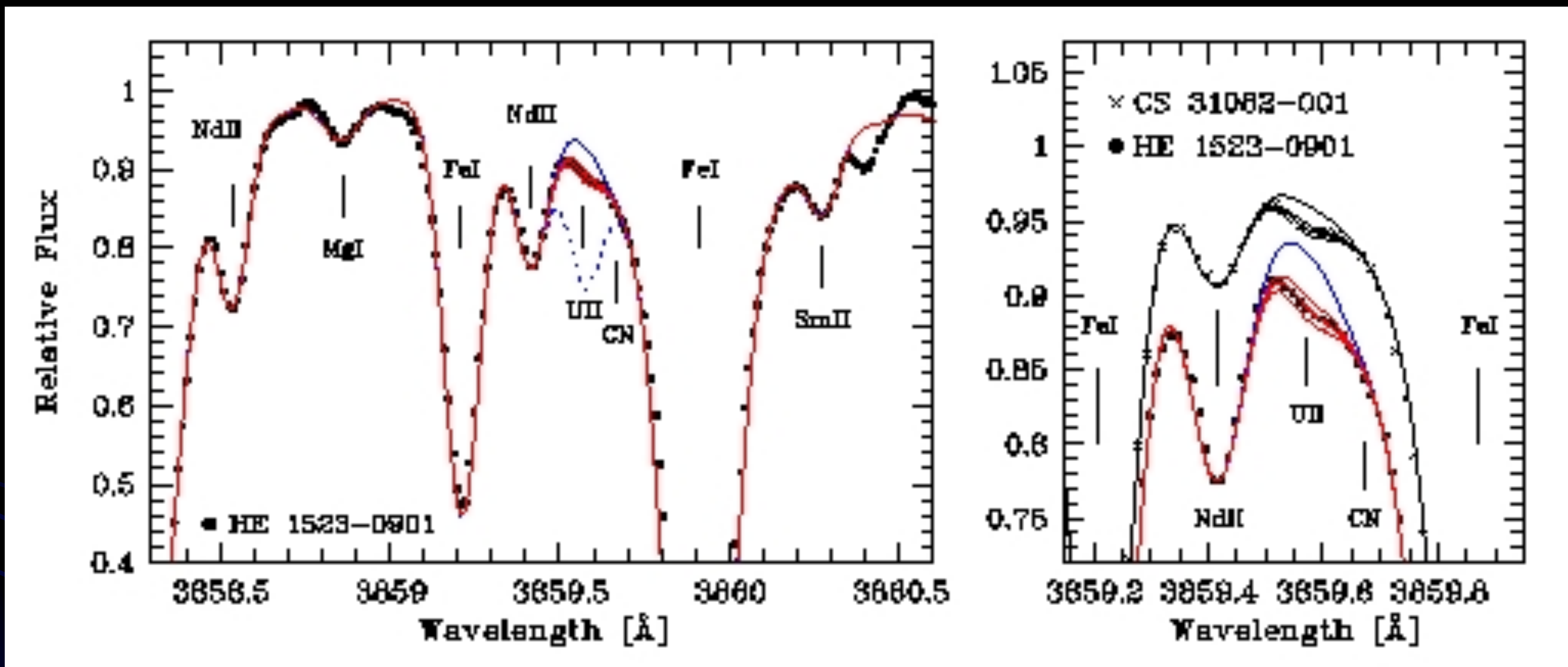
Observed and Synthetic Spectra of Th Lines in HD 221170



Keck o
McDonald +

Ivans et al. (2006)

Observations of Uranium Lines in Stars



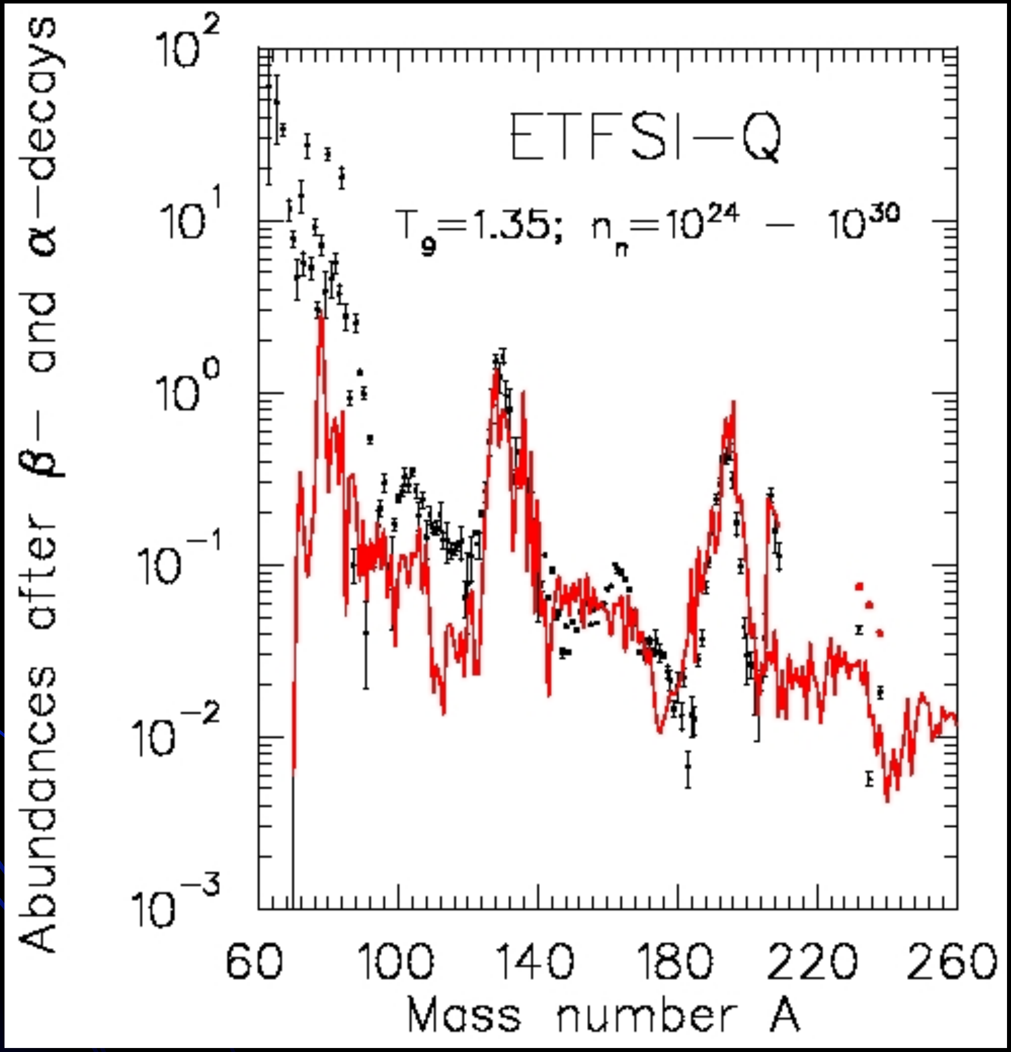
Frebel et al. (2007)

Much Harder! Weak lines.

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: Isotopes

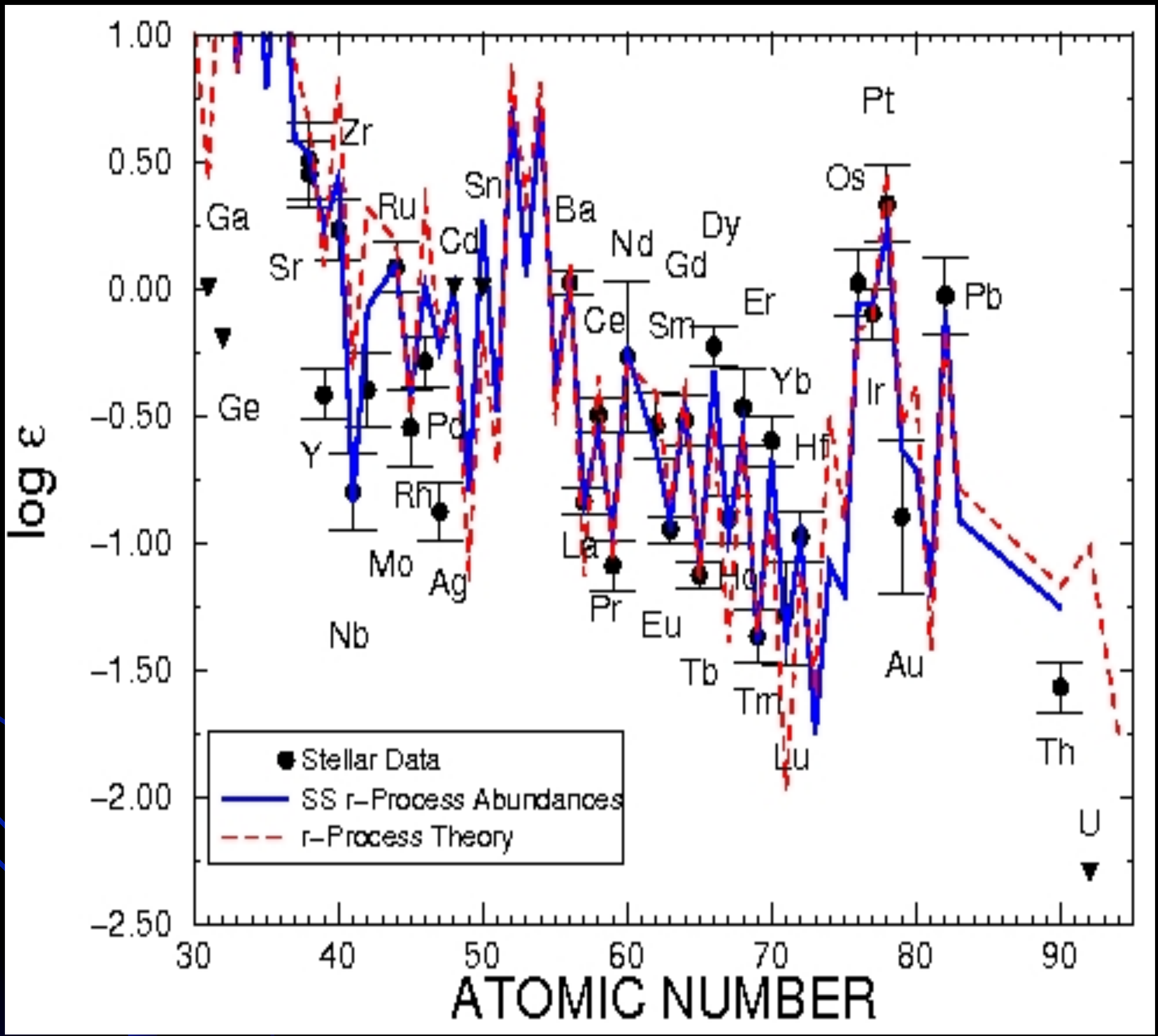


Kratz et al. (2007)

Newer fit to SS isotopic stable abundances allows for chronometric ratios

New values of Th/Pt & Th/U

Theoretical r-Process Predictions: Elements

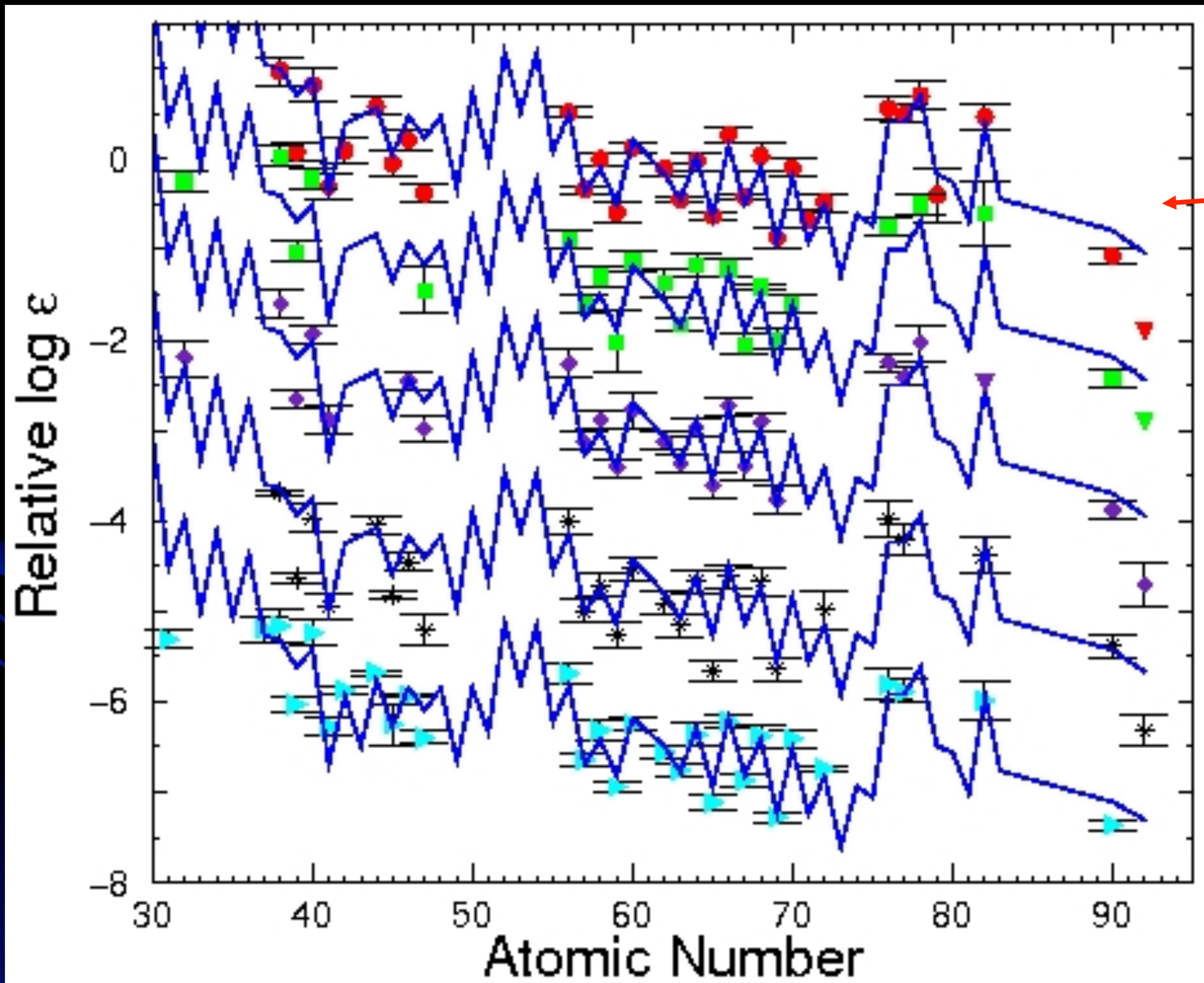


Calculate radioactive abundance ratios based upon fitting stable elemental & isotopic values (Kratz et al. 2007).

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

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

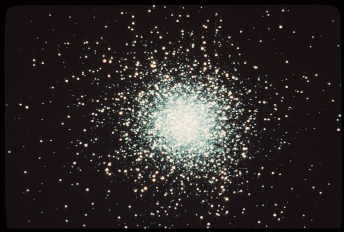
- Theoretical predictions based upon various chronometers: e.g., Th/Eu, Th/U and depending upon nuclear mass models

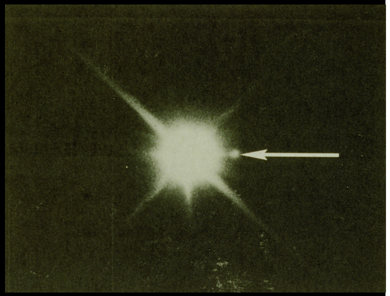
→ +/- 2-3 Gyr

Errors uncorrelated leading to total uncertainty of ~ 3 Gyr.

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

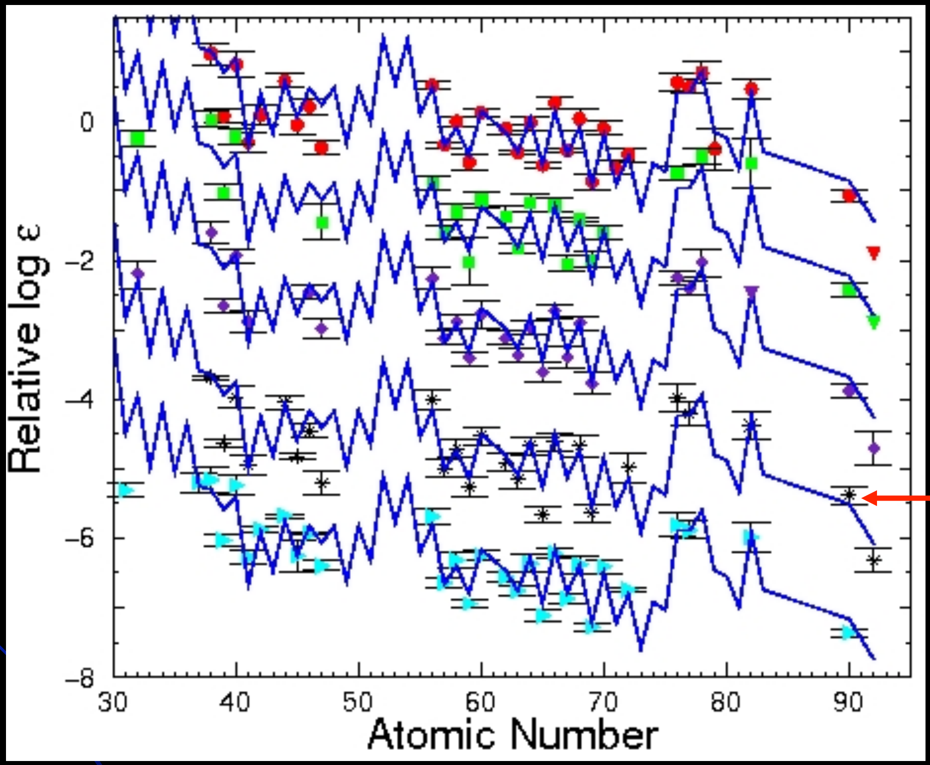




Compared to the Age of the Universe

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

A Few Stars Have Problems



younger than SS!

note Pb in
CS 31082-001

back

Problems and Uncertainties

- What about CS 31082-001? Th/Eu give unrealistic age (younger than the Sun!) – Th/U give 14.1 – 15.5 +/- ≈ 3 Gyr (from different groups) Abundance distribution

→ Th & U very high: actinide boost? fission recycling? What about low Pb?

Are there others with high Th/Eu? Need Pb abundances to confirm, hard without UV

back

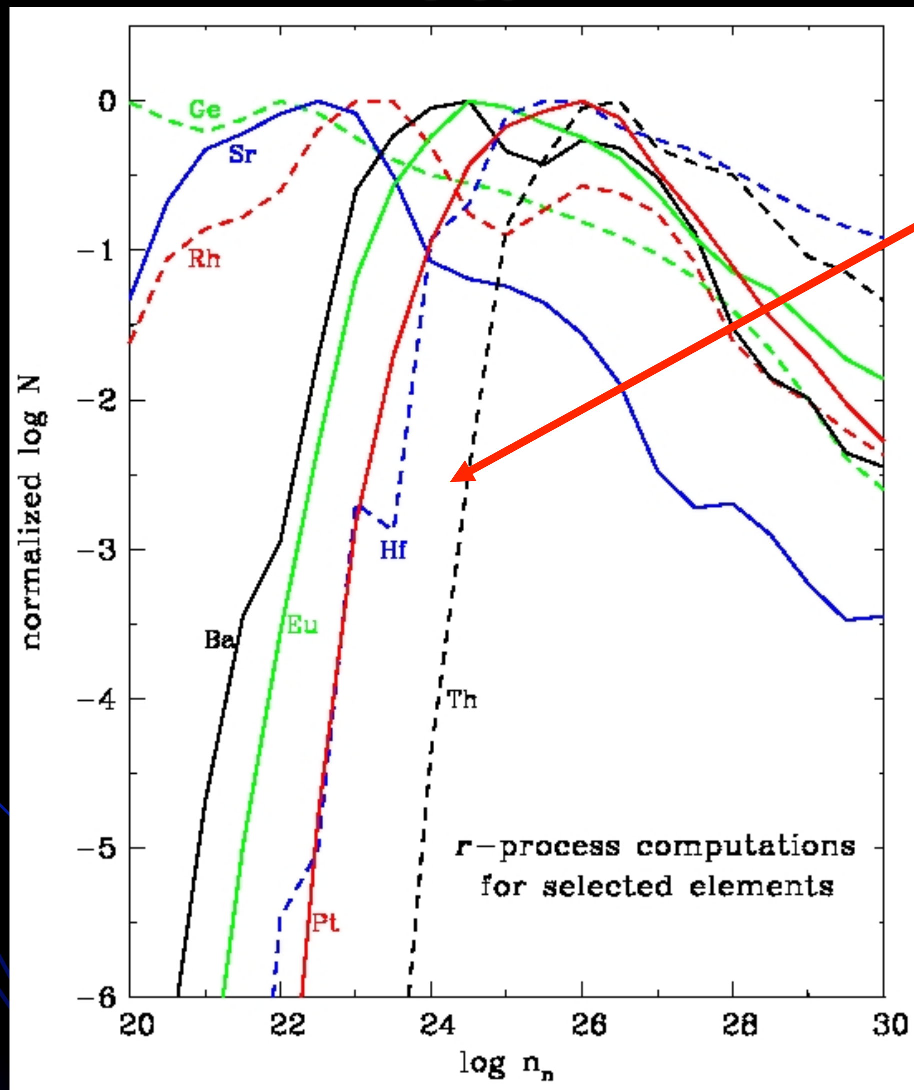
Cosmochronometers: The Future

- We are seeing dramatic improvements in abundance values due to new experimental atomic and nuclear data
- New data are driving down age uncertainties
- Eventually improvements will allow for very accurate chronometric age determinations
- More precise values could constrain cosmological parameters and models

A Possible New Chronometer: Th/Hf

Hf can be observed from the ground.
Do not need UV required for Pt

Death of STIS?
Other UV spectrographs?



Note how Hf tracks the 3rd process peak elements, e.g., Pt.

Th/Hf might be preferable to Th/Eu but only 2 stars so far.

Kratz et al. (2007)

Some Concluding Thoughts

- 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?
- r-process is ubiquitous in the early Galaxy – not necessarily same pattern as r-rich stars
- Detections of radioactive elements (Th & U) allow age estimates for oldest stars: putting limits on the age of the Galaxy & Universe

What is needed now?

- More observations of n-capture elements in the very metal-poor stars (particularly [Fe/H] < -4)

→ more abundance determinations in r-process poor stars (more like HD 122563)

- More observations of lighter n-capture elements, including Ag, Ge, etc. in metal-poor halo stars
- More theoretical models for light n-capture synthesis

→ better (experimental & theoretical) nuclear data, better SN and NS merger models

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

With generous support from:
the National Science Foundation
& the Space Telescope Science Institute.