Abundances of Newly Discovered r-Process Enhanced Stars from Optical Spectroscopy

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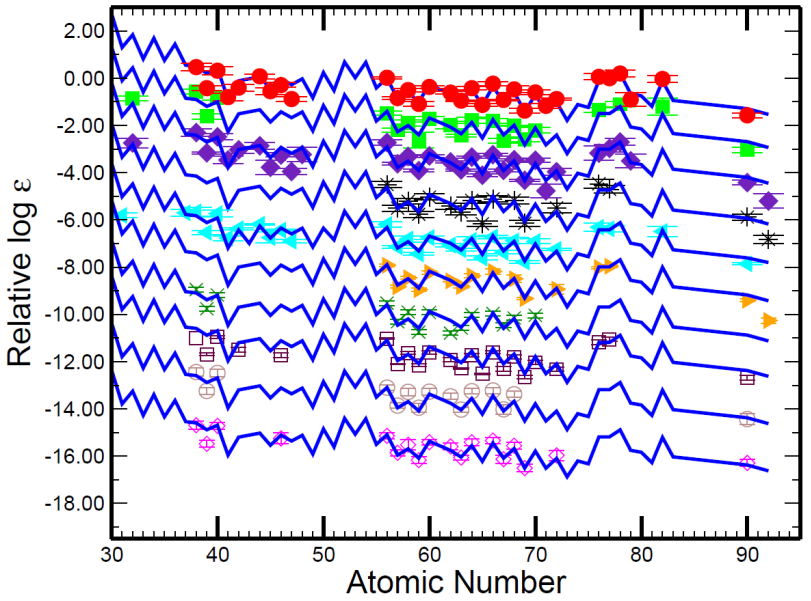
Outline

- r-Process Enhanced Metal-Poor Stars
  - Why they are an ideal site for studying the r-process
  - Previous observations
- Searching for new r-I and r-II stars
- The future

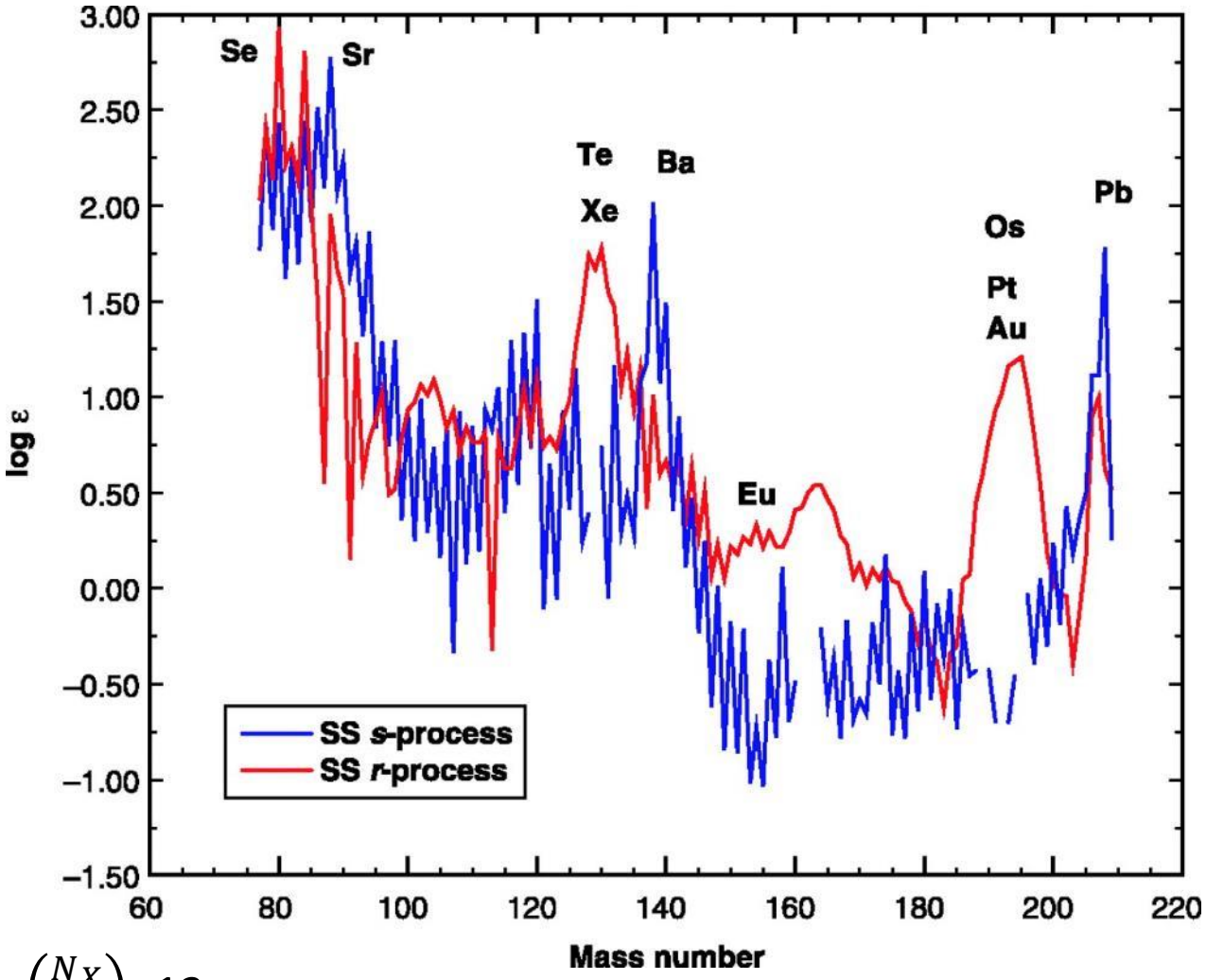


Cowan et al. (2011)

Promising Sites to Study the r-Proc

Solar and Heliospheric Observatory; NASA

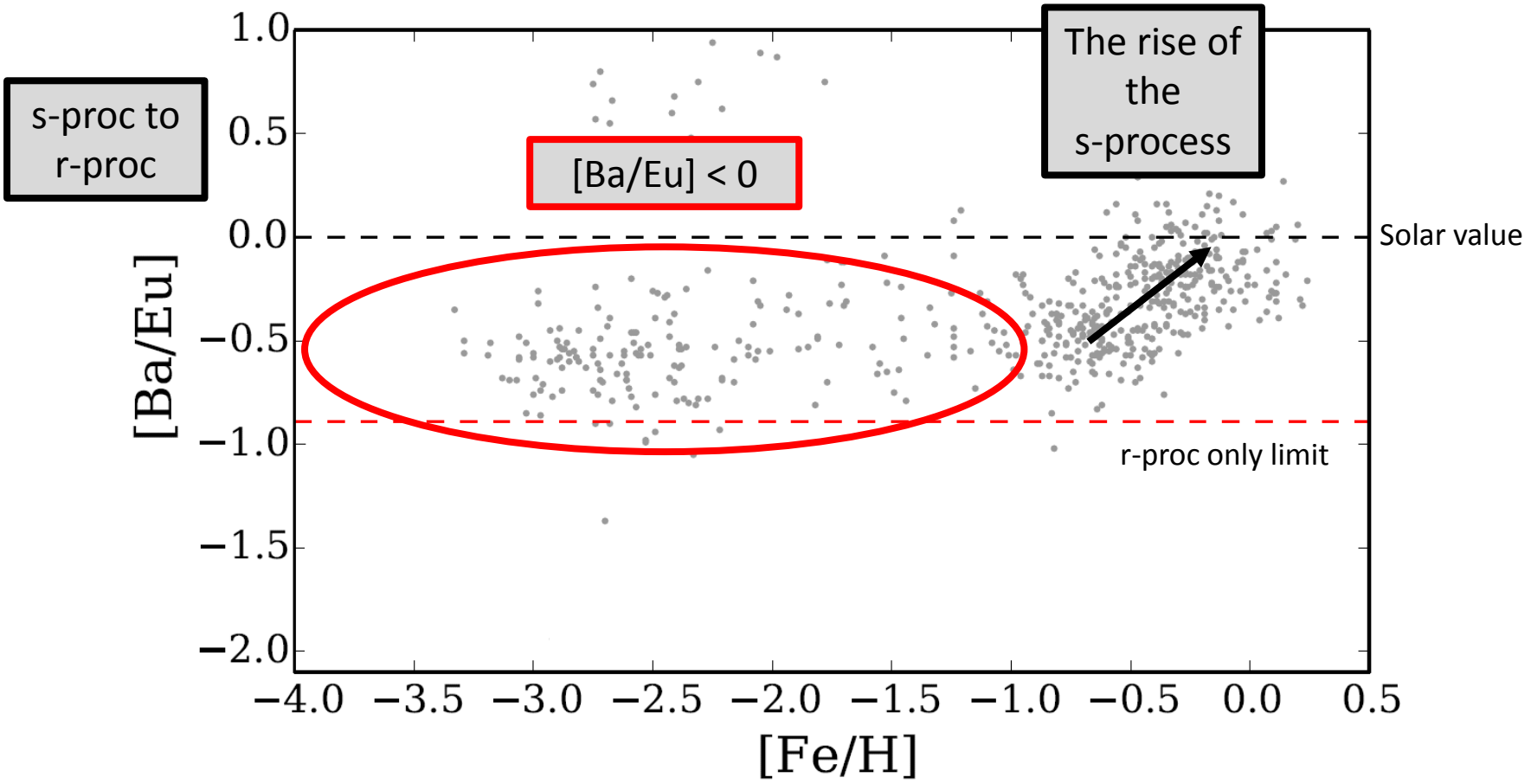
Promising Sites to Study the r-Proc



$$\log \varepsilon_X = \log\left(\frac{N_X}{N_H}\right)+12$$

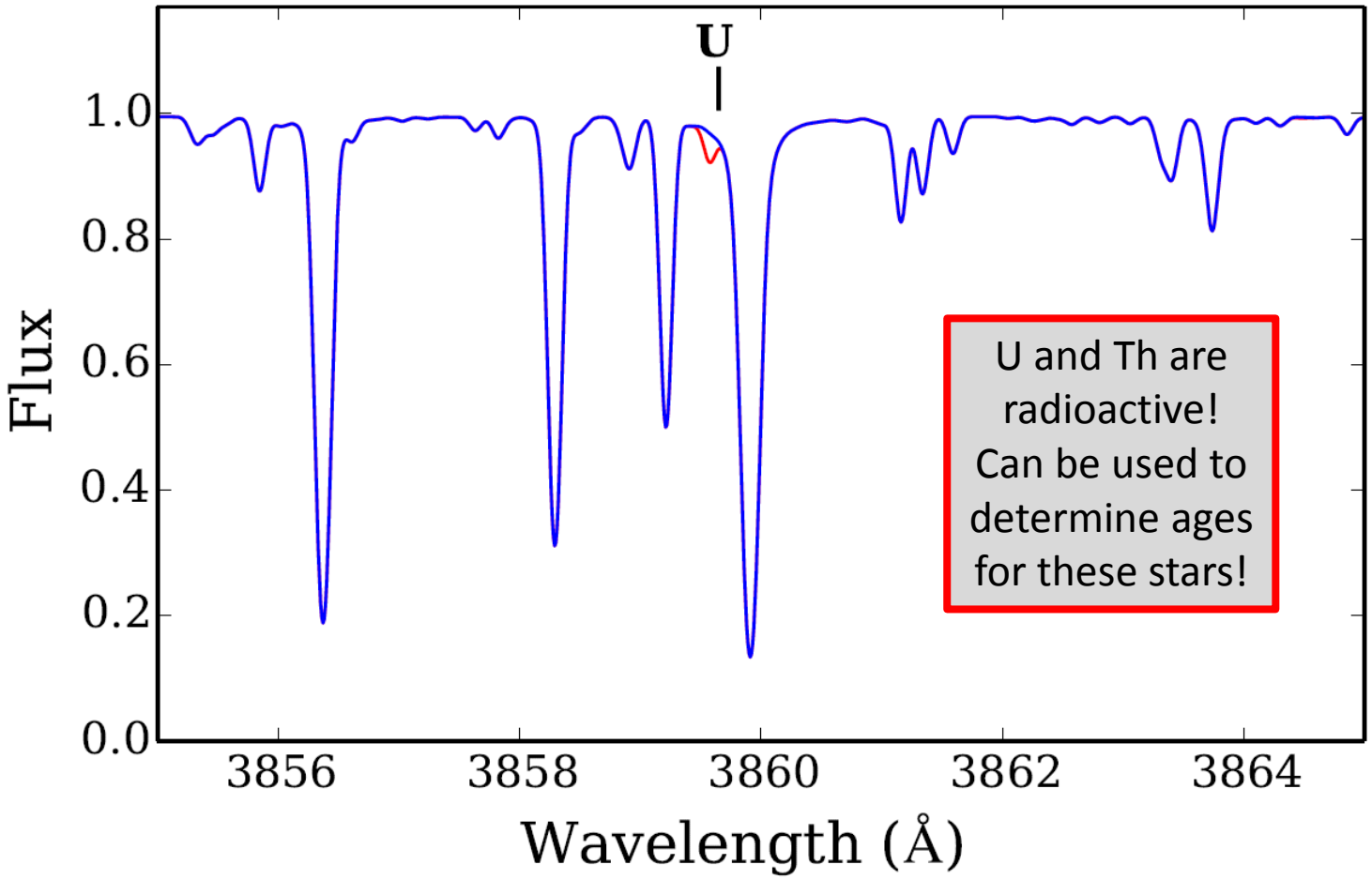
Sneden et al. (2003)

Promising Sites to Study the r-Proc



Simmerer et al. (2004); Venn et al. (2004); Reddy et al. (2006)

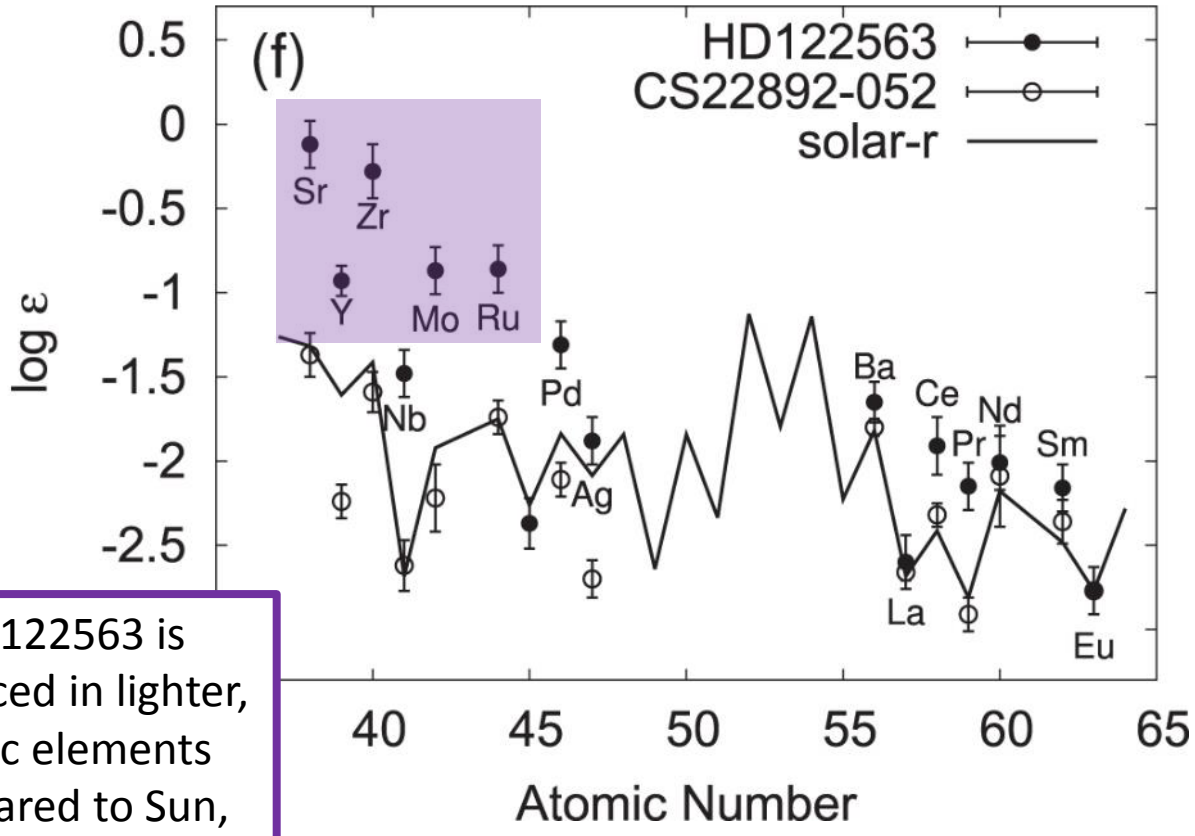
Promising Sites to Study the r-Proc



Promising Sites to Study the r-Proc

- Metal-poor stars ([Fe/H] < -1.5)
- [Ba/Eu] < 0 (little-to-no contribution from s-process)
- Enhanced in r-process elements
  - Take Eu to be the tracer element for the r-process
  - r-I stars: 0.3 < [Eu/Fe] < 1
  - r-II stars: [Eu/Fe] > 1

These Criteria Miss Some Interesting Stars…



HD 122563 is enhanced in lighter, r-proc elements compared to Sun, r-II stars

Aoki et al. (2017)

Known r-I and r-II Stars: CS 22892-052

THE ASTROPHYSICAL JOURNAL, 431:L27–L30, 1994 August 10

ULTRAMETAL-POOR HALO STARS: THE REMARKABLE SPECTRUM OF CS 22892−052

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Received 1994 April 11; accepted 1994 May 27

ABSTRACT

The star CS 22892−052, discovered in the HK Objective-Prism survey of the southern Galactic halo, is extremely weak-lined at low resolution. At higher resolution, features of very heavy neutron-capture elements and CH dominate the spectrum. An abundance analysis reveals that this star is indeed very metal-poor: [Fe-peak/H] ~ -3.1. The α elements Mg, Ca, and Ti are enhanced by factors typical for halo stars, [α/Fe] $\simeq +0.4$. The neutron-capture elements are strongly overabundant: $+0.3 <$ [*n*-capture/Fe] $< +1.8$ in the range $38 \leq Z \leq 68$, with the enhancements generally growing with increasing Z. The ratio [C/Fe] $\sim +1$ also is much larger than in any other known star of this metallicity range. The total *n*-capture element distribution is well represented by an *r*-process nucleosynthesis yield. This star provides the clearest evidence for element enrichment from "local" supernovae nucleosynthesis events in an unmixed early Galactic halo.

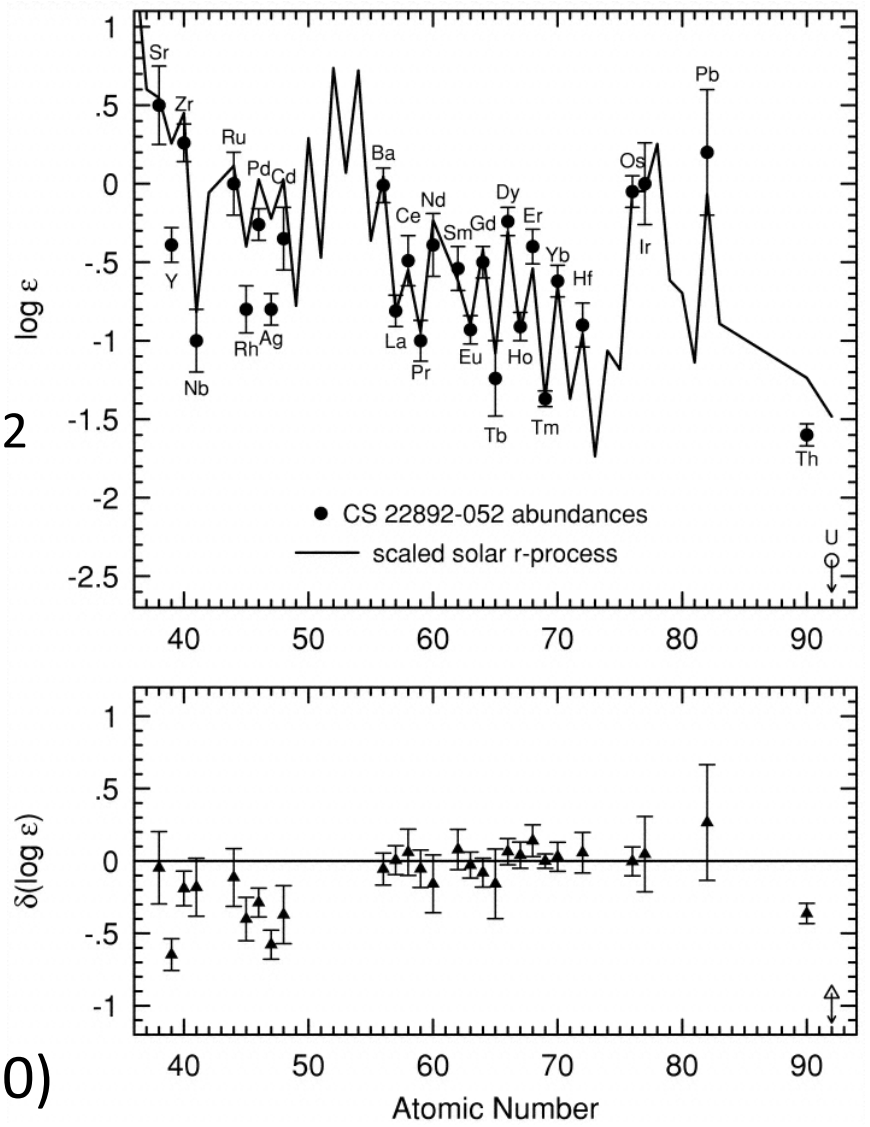
Subject headings: Galaxy: halo — Nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (CS 22892−052) — stars: Population II

Sneden et al. (1994)

Known r-I and r-II Stars: CS 22892-052

Deviations at the light end… Suggestive of multiple r-proc sites?

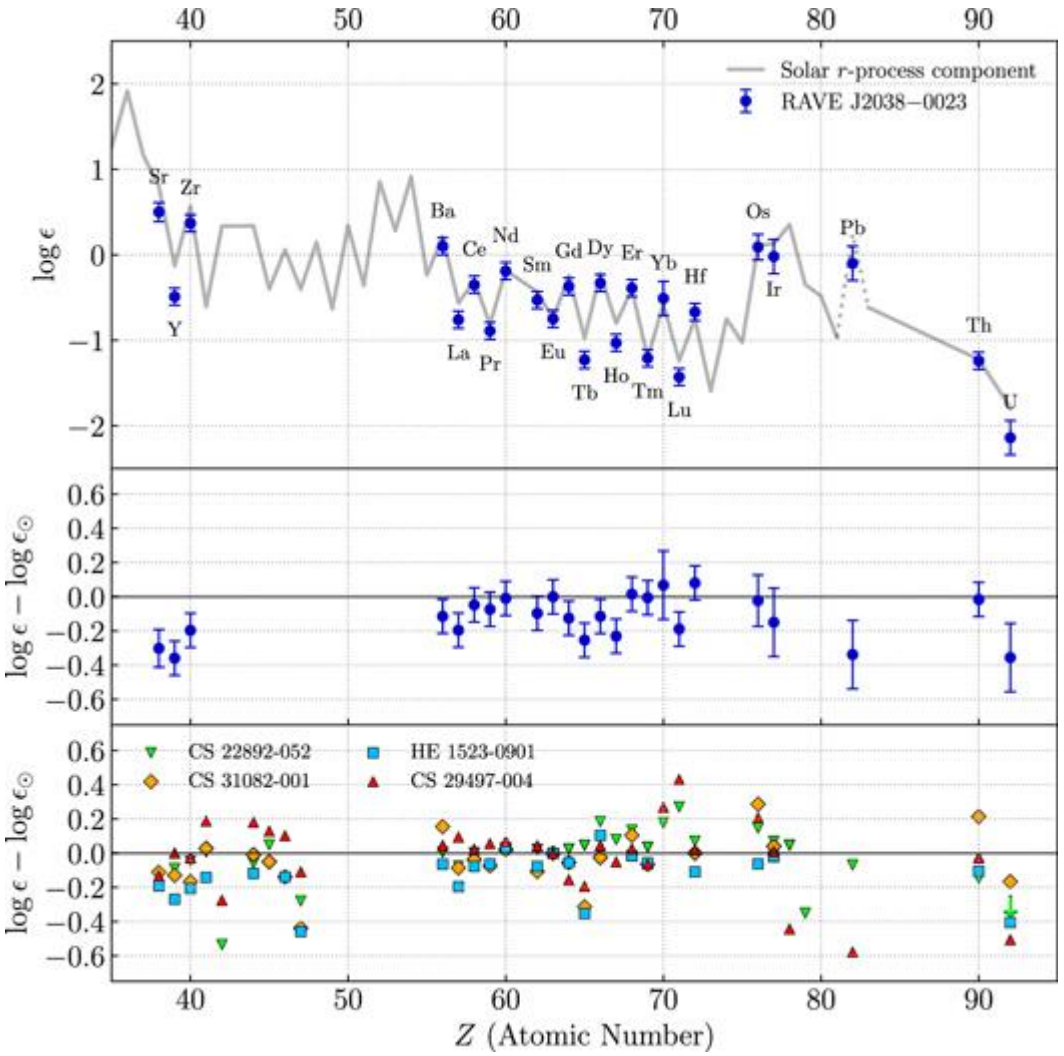
$$\log \varepsilon_X = \log\left(\frac{N_X}{N_H}\right)+12$$



Age of 16 +/- 4 Gyr from U and Th

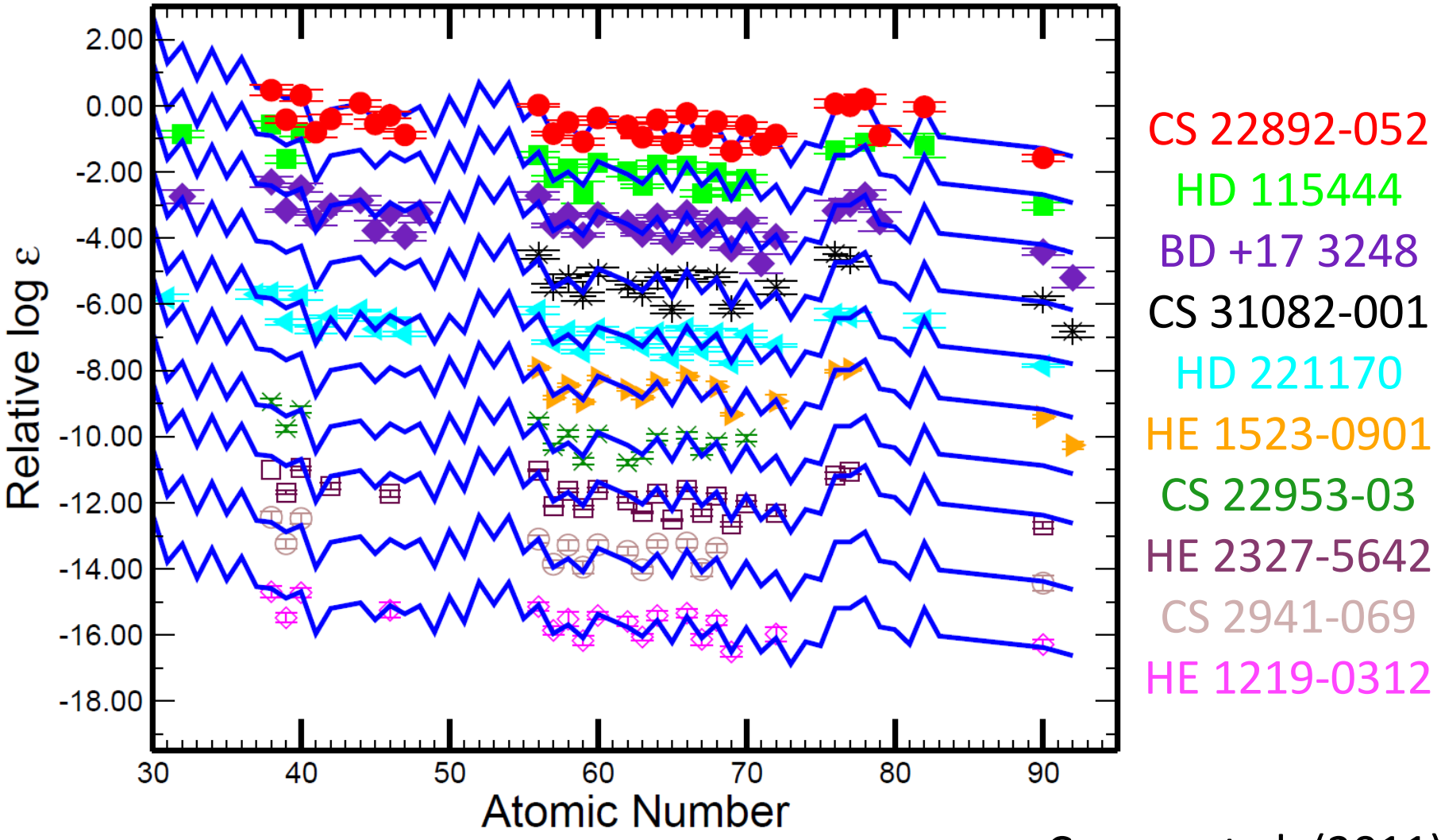
Sneden et al. (2000)

A new r-II star: RAVE J2038−0023



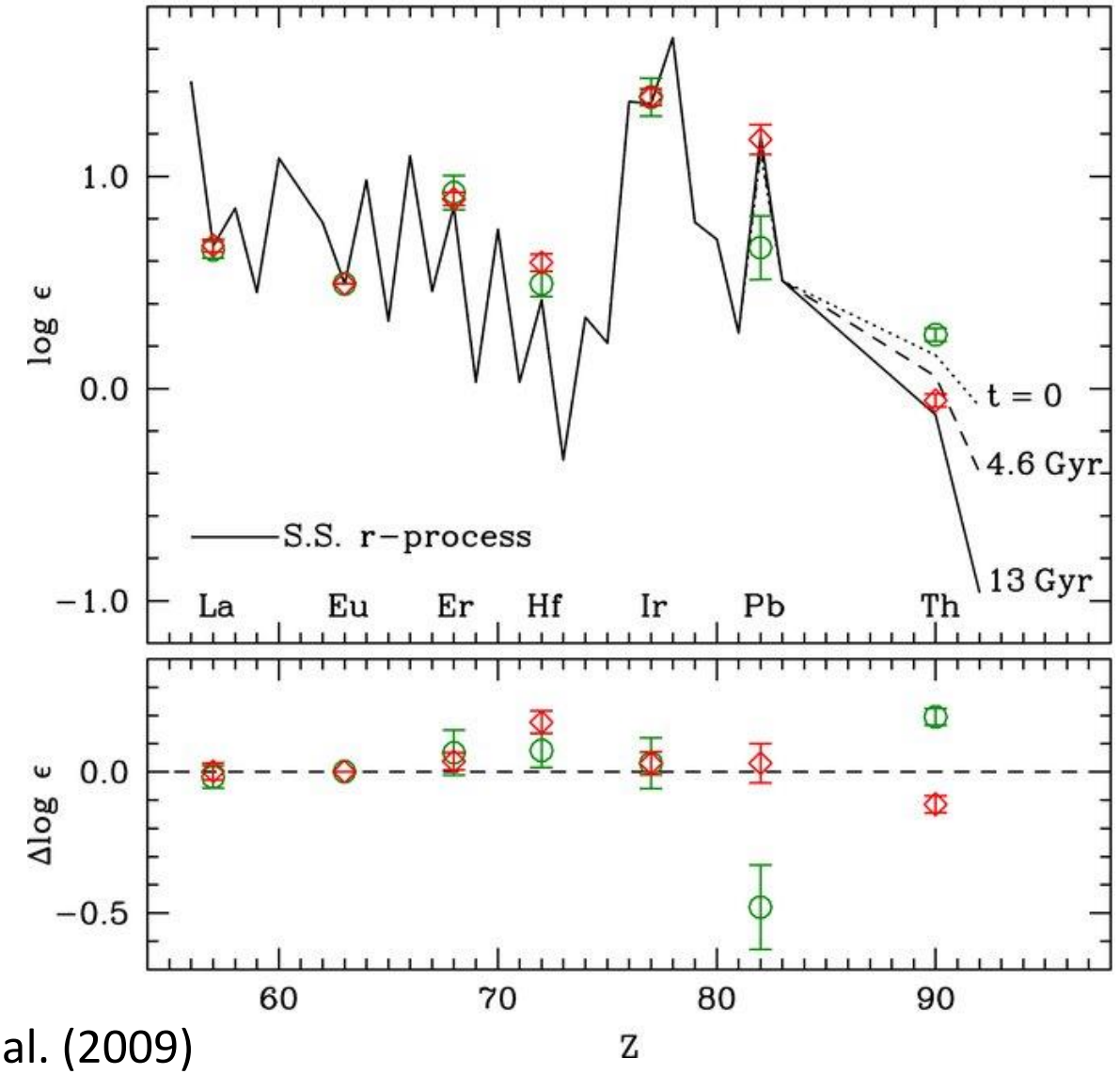
Placco et al. (2017)

The Robustness of the Pattern



Cowan et al. (2011)

But… some have an “actinide boost”

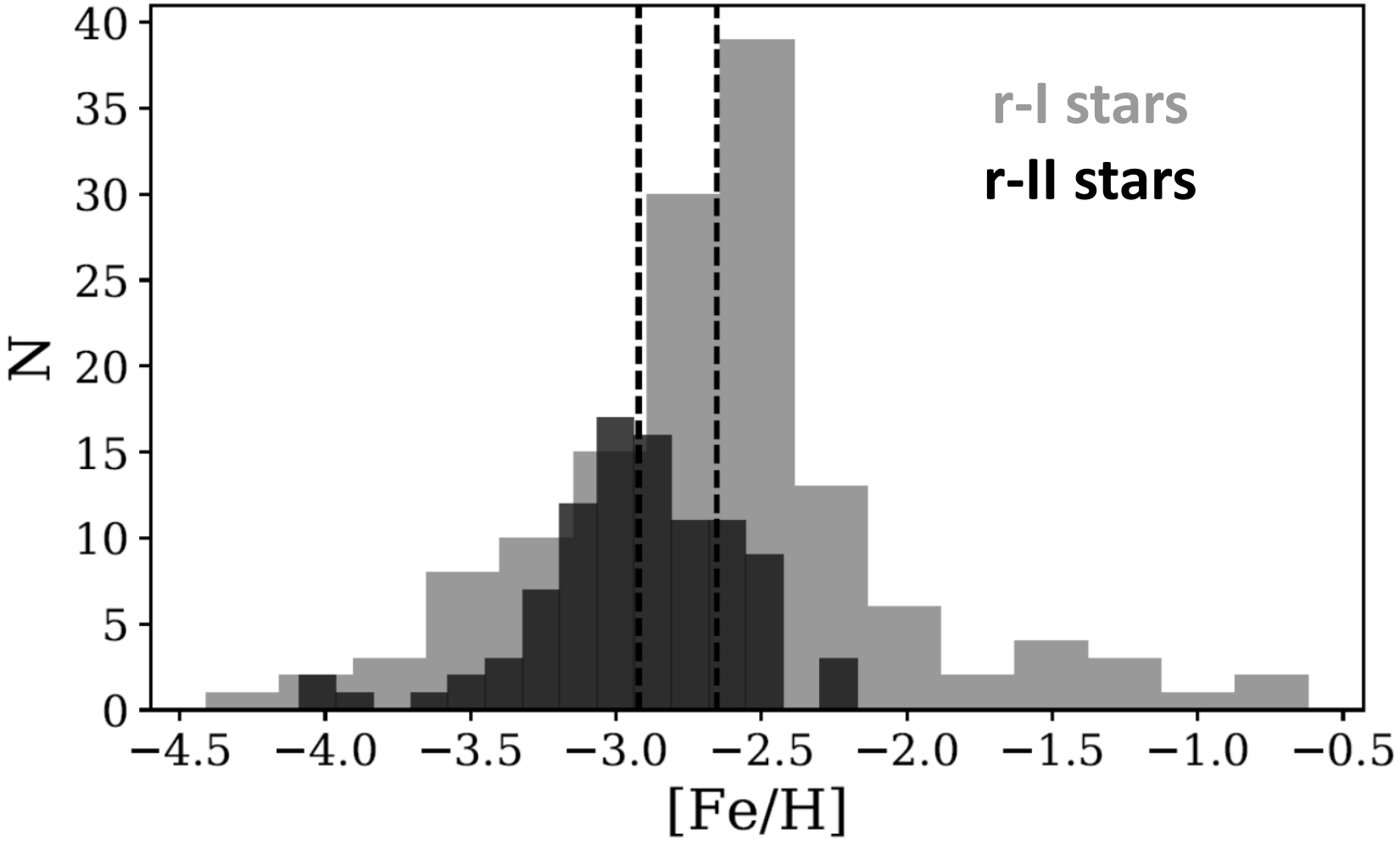


Mean: “Normal” r-proc enhanced stars

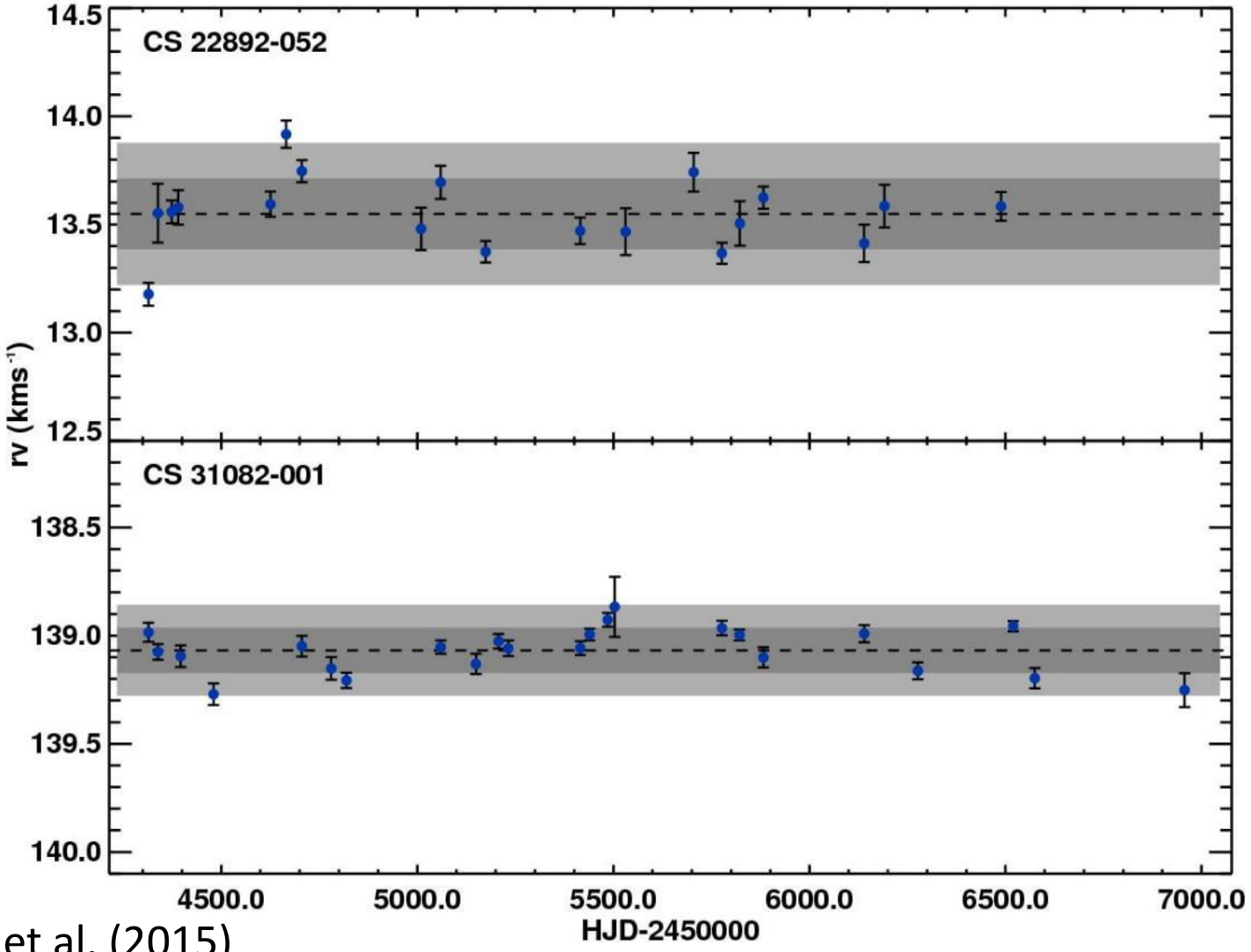
Mean: Actinide boost stars

Roederer et al. (2009)

Metallicity Distributions

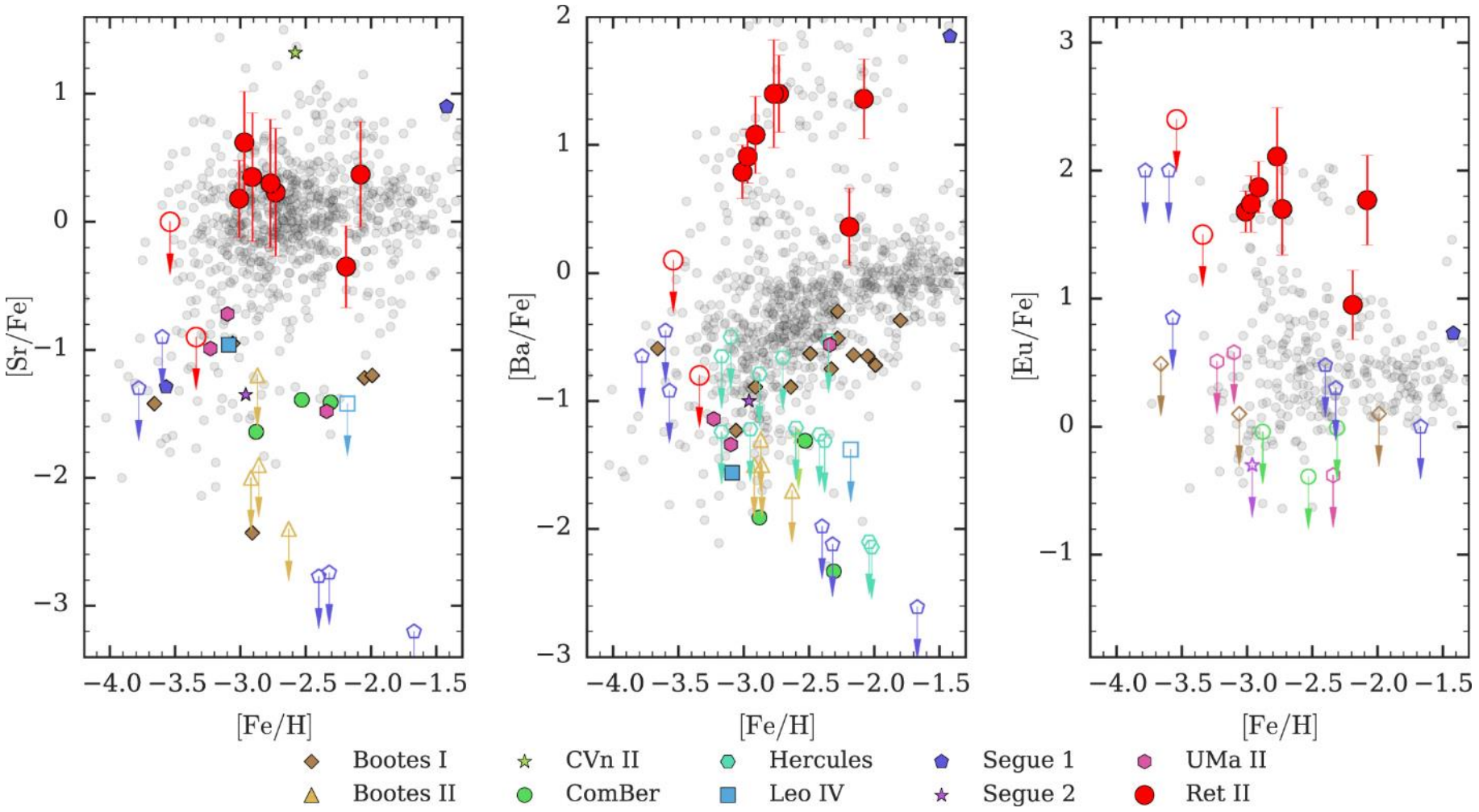


r-II stars: Not necessarily binaries



Hansen et al. (2015)

Reticulum II



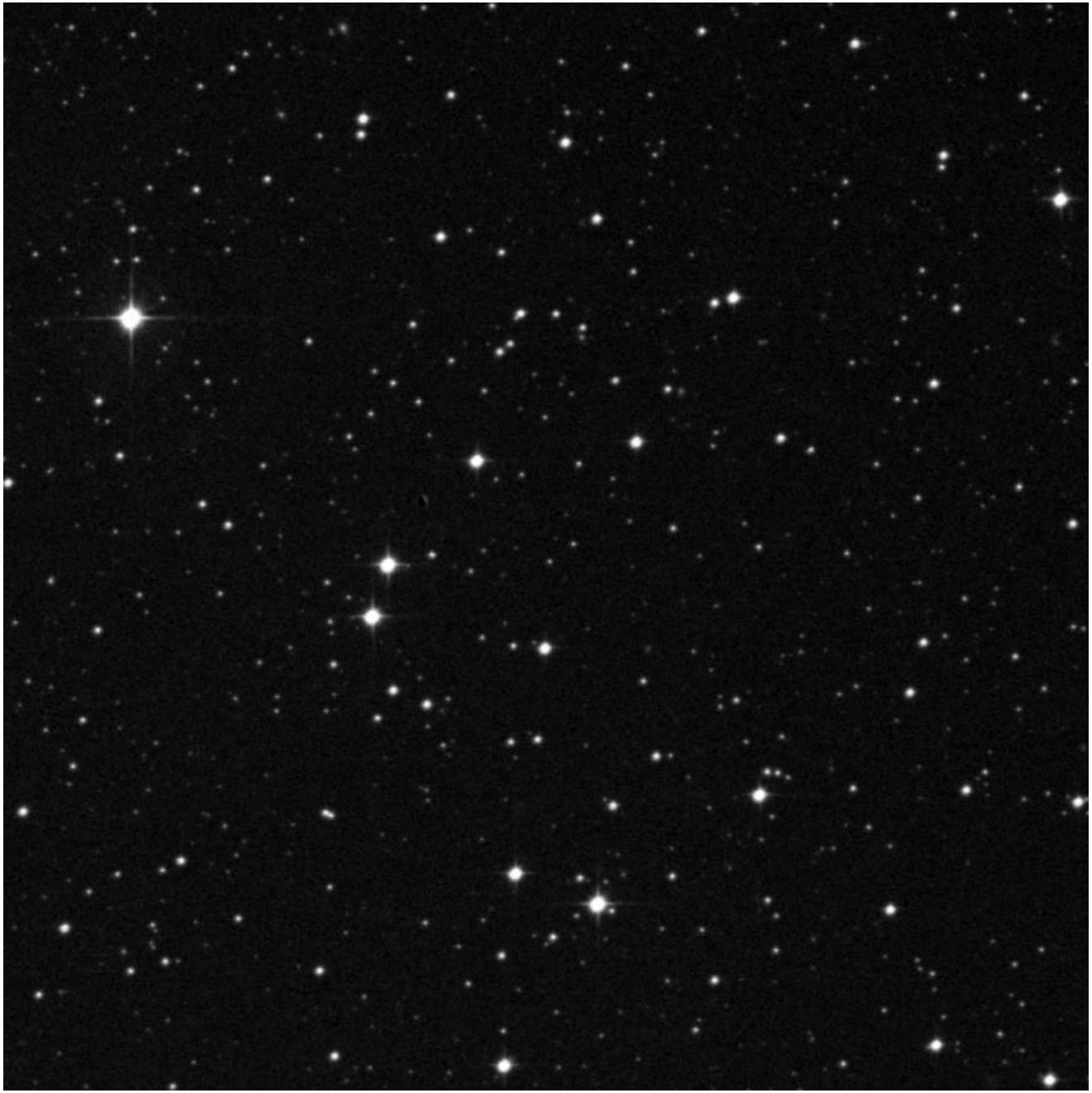
Ji et al. (2016); see Anna's talk this afternoon

What We Know and Remaining Questions

- There a…ced in r-process
  - Wha…ss elem…nts?
  - How…onsistent with …
  - Whe…laxies?
- The pat…s very robust …
  - Does…ss?
  - What about the lighter r-process elements?
  - What about the actinides?

We need more data!

(Specifically, we need to discover more r-I and r-II stars)



Digitized Sky Survey: 15’ x 15’

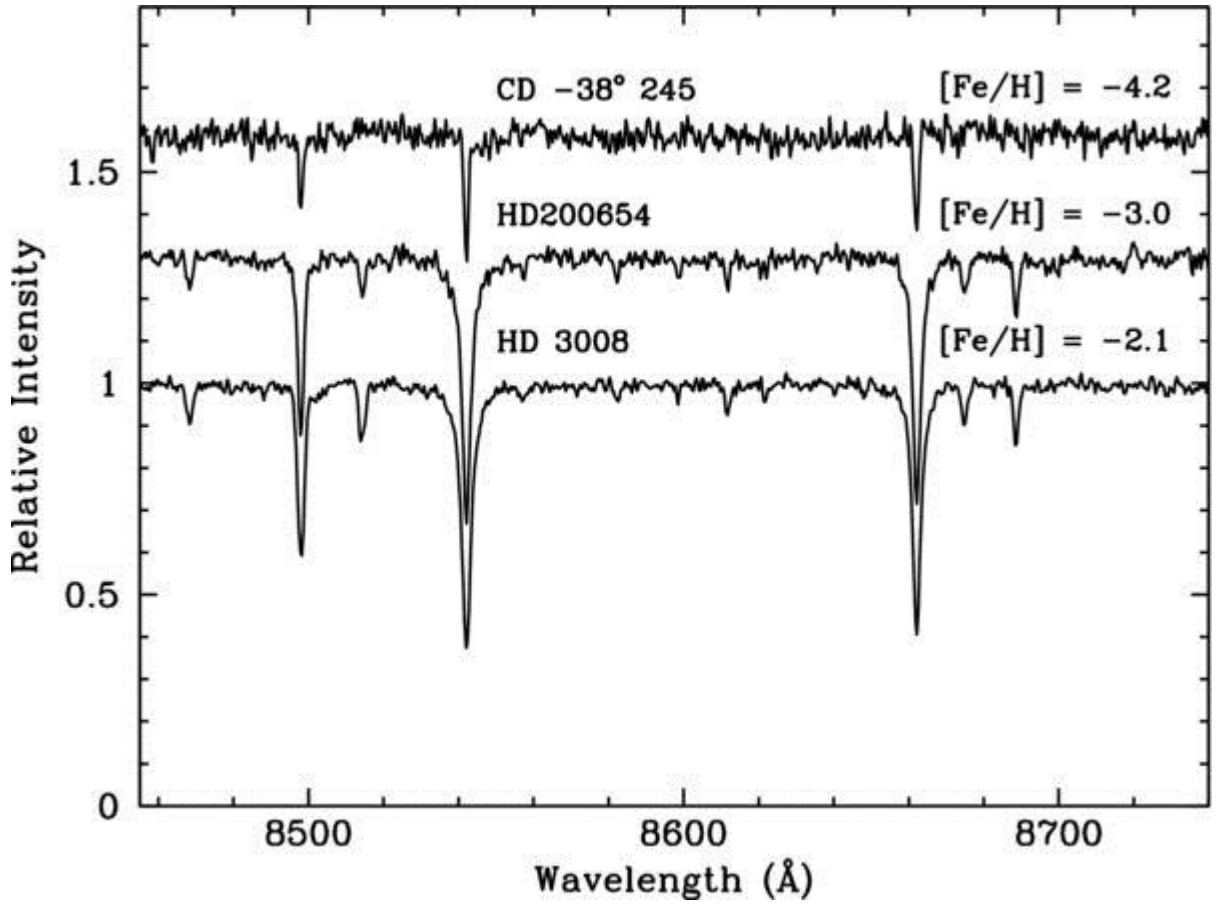
More Data: The Near Future

Limited to MW and nearest neighbors

- Large Surveys will find new metal-poor stars:
  E.g., RAVE, APOGEE, GALAH, GAIA-ESO, Skymapper, Pristine, others…
- Medium resolution spectroscopic follow-up
  Can provide rough abundances of some elements (Fe, C, etc.)
- High resolution follow-up (R~30,000)
  Some neutron capture elements: e.g,. Y, Ba, Eu
- Higher resolution follow-up (R~80,000)
  More elements: e.g., U
- UV observations (requires *HST*)
  Even more r-process elements: Ge, Mo, Cd, Te, Pt, Au, Bi

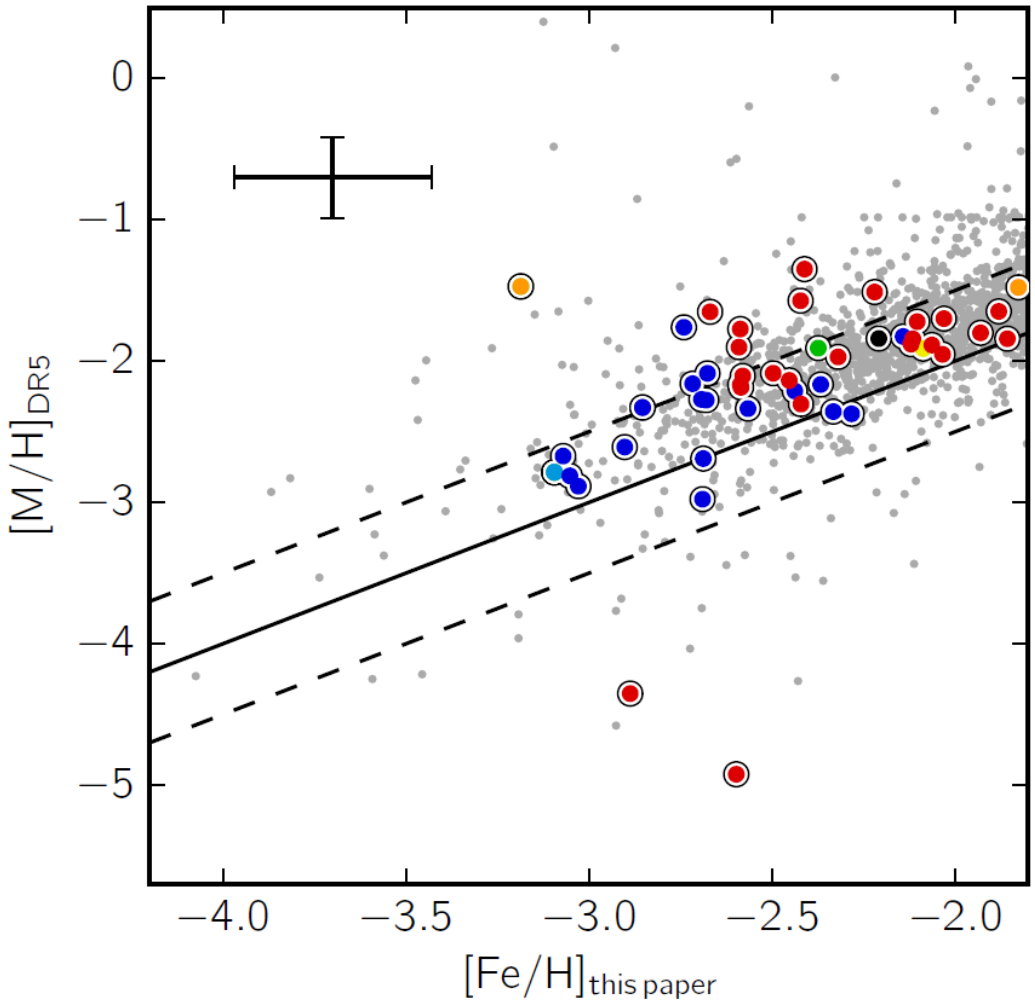
Very limited to the brightest, nearby stars

The RAVE Survey



Fulbright et al. (2010)

Re-calibration of RAVE [Fe/H]



Matijevic et al. (2017)

Medium Resolution Follow-Up

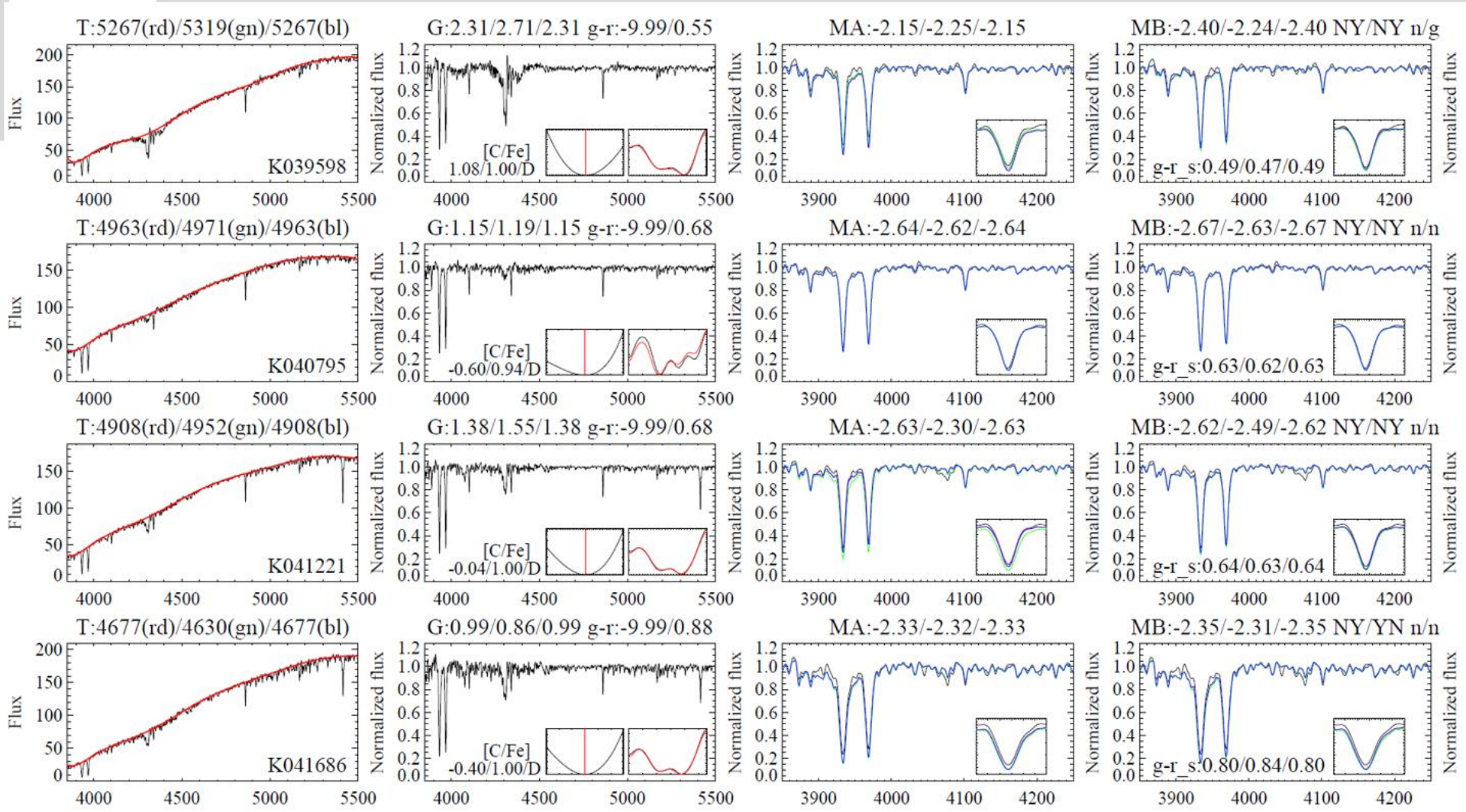
- With Vini Placco and Tim Beers…

The Future is Bright !

- Having recognized many of the "players" involved with developing an understanding of the origin of the elements, based on large-scale spectroscopic survey efforts over the past ~25 years, future progress will be greatly accelerated by identification of the BRIGHTEST – most information rich – examples of various chemically peculiar stars

- Multiple survey efforts underway to accomplish this:
  - Medium-res spectroscopic follow-up of RAVE survey stars claimed to have [Fe/H] < -2.0, with 10 < V < 14 (ESO/NTT + SOAR + LNA + McDonald)
  - Medium-res spectroscopic follow-up of "Best & Brightest" candidates using Gemini 8m bad weather time + ESO/NTT + SOAR, with 10 < V < 13.5
  - Medium-res spectroscopic follow-up of bright SkyMapper (Australia) metal-poor candidates with -3.0 < [Fe/H] < -2.0 – release of `short-survey' has just happened
  - Anticipated follow-up of bright metal-poor candidates from S-PLUS (Brazil)
- Collaborative effort with personnel from Univ. Sao Paulo (Brazil), PUC (Chile), Lick Observatory, Sydney & Canberra (Australia)

SLIDE FROM TIM BEERS

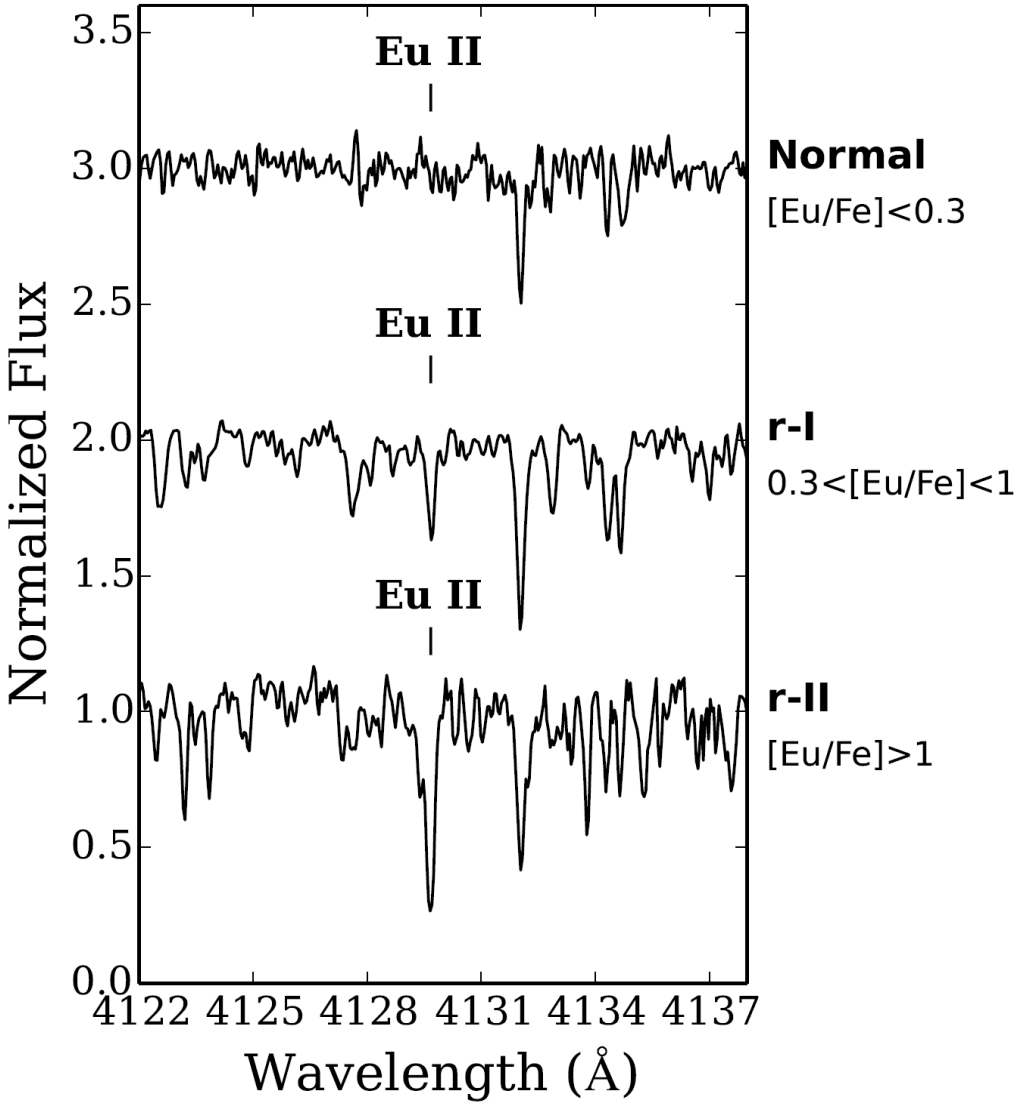


Example R ~ 2000 spectra of RAVE candidates with [Fe/H] < -2.0 – Suitable for identification of r-II, r-I, and CEMP stars for high-resolution follow-up observations

All have 10 < V < 14; ~ 2000 available, about 1700 of which are already observed

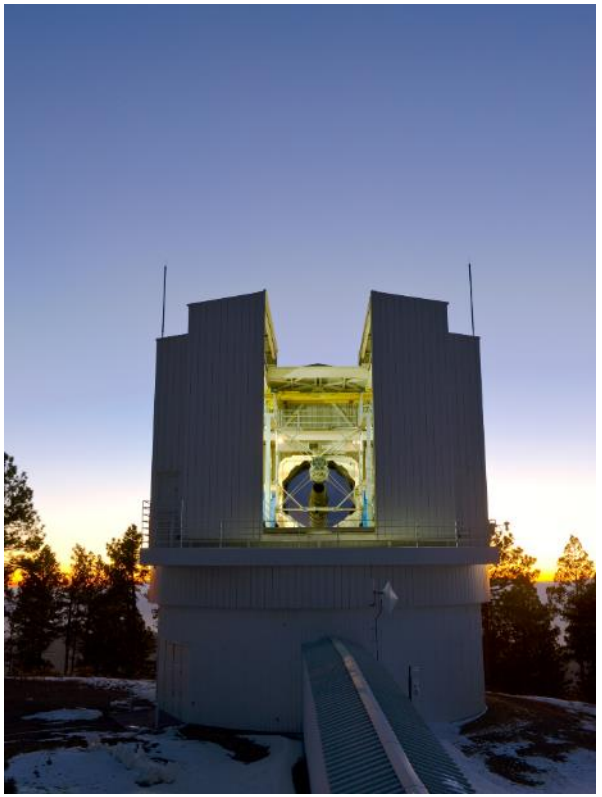
SLIDE FROM TIM BEERS

High resolution Follow Up



High Resolution Follow Up

- With Terese Hansen, Tim Beers, Vini Placco, others
- Southern hemisphere (Chile):
  - Du Pont Telescope (2.5 m)
  - Magellan Telescope (6.5 m)
- Northern hemisphere:
  - ARC Telescope (3.5 m) at the Apache Point Observatory in New Mexico
  - Echelle spectrograph: R = 31,500

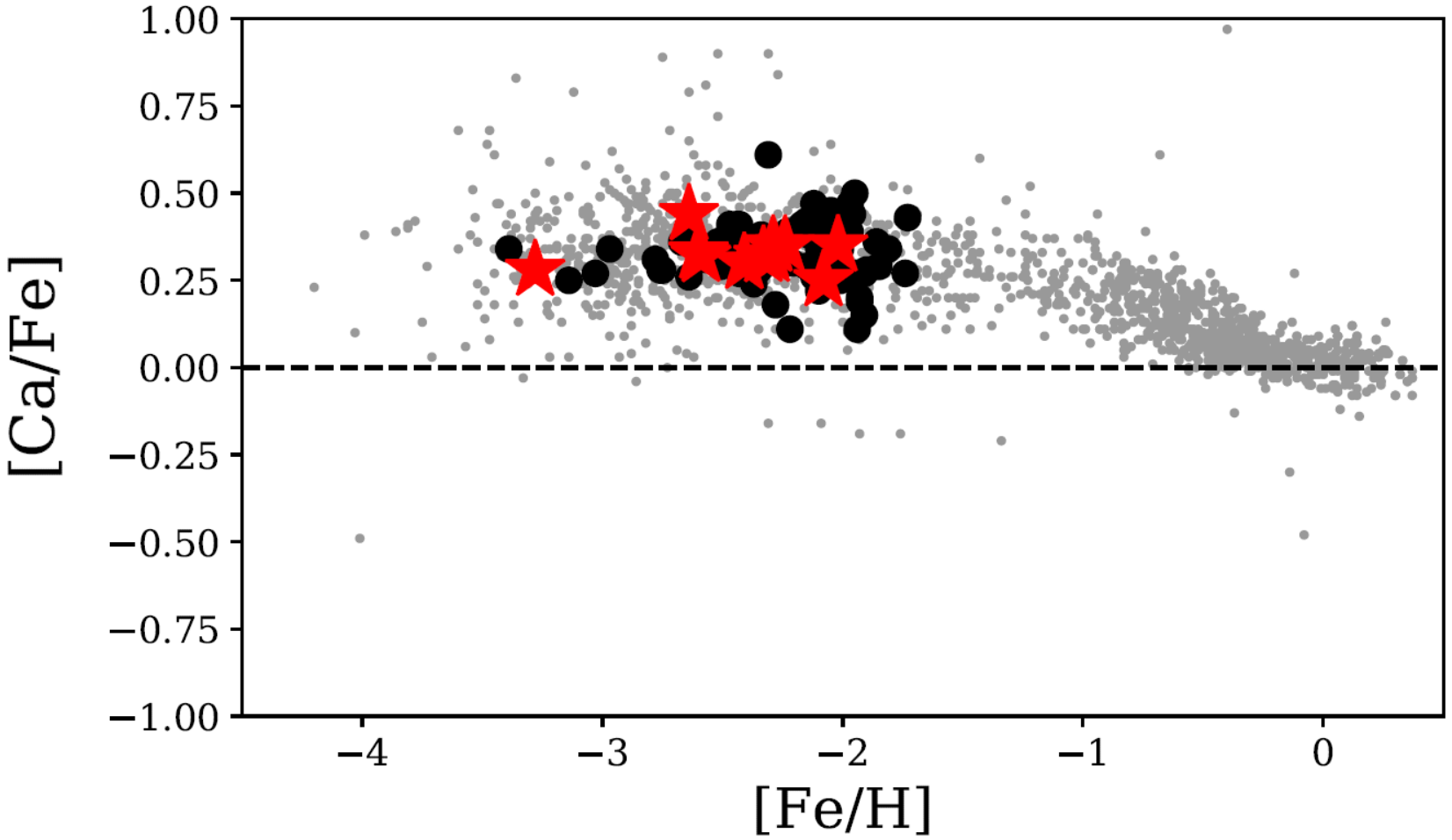


ARC Follow Up

- Spectra of 169 stars
  - 20 standards
  - 79 from the re-calibration of RAVE [Fe/H] (Matijevic et al. 2017)
  - 70 from the optical medium-resolution follow-up (Placco et al. 2017)

- Utilizing the Amarsi et al. (2016) <3D>, NLTE corrections to Fe I lines
  - Atmospheric parameters agree well with independent methods (photometry, parallaxes from GAIA, etc.)
  - Standards are in agreement with other NLTE analyses

[Ca/Fe]



New r-I and –II stars

Of the 149 new stars…

- X are r-I stars
- Y are r-II stars

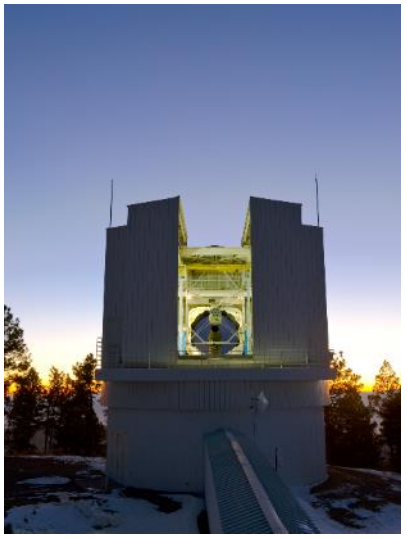
INFORMATION REDACTED

In the full sample of 1500-2000 stars, over the next two years, we might expect

- Many more r-I stars
- Many more r-II stars

- Results slides have been removed…

Summary



- This survey at APO has discovered X new r-I stars and Y new r-II stars (Comparable #s in the south)

INFORMATION REDACTED

- So far, the detailed abundances show that they are similar to the other known r-I and r-II stars, but at a higher [Fe/H]

- Future follow up will determine more abundances