Rapid Neutron-Capture Process -Clues From Metal-Poor Stars

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Carnegie Observatories

GW170817: The First Double Neutron Star Merger

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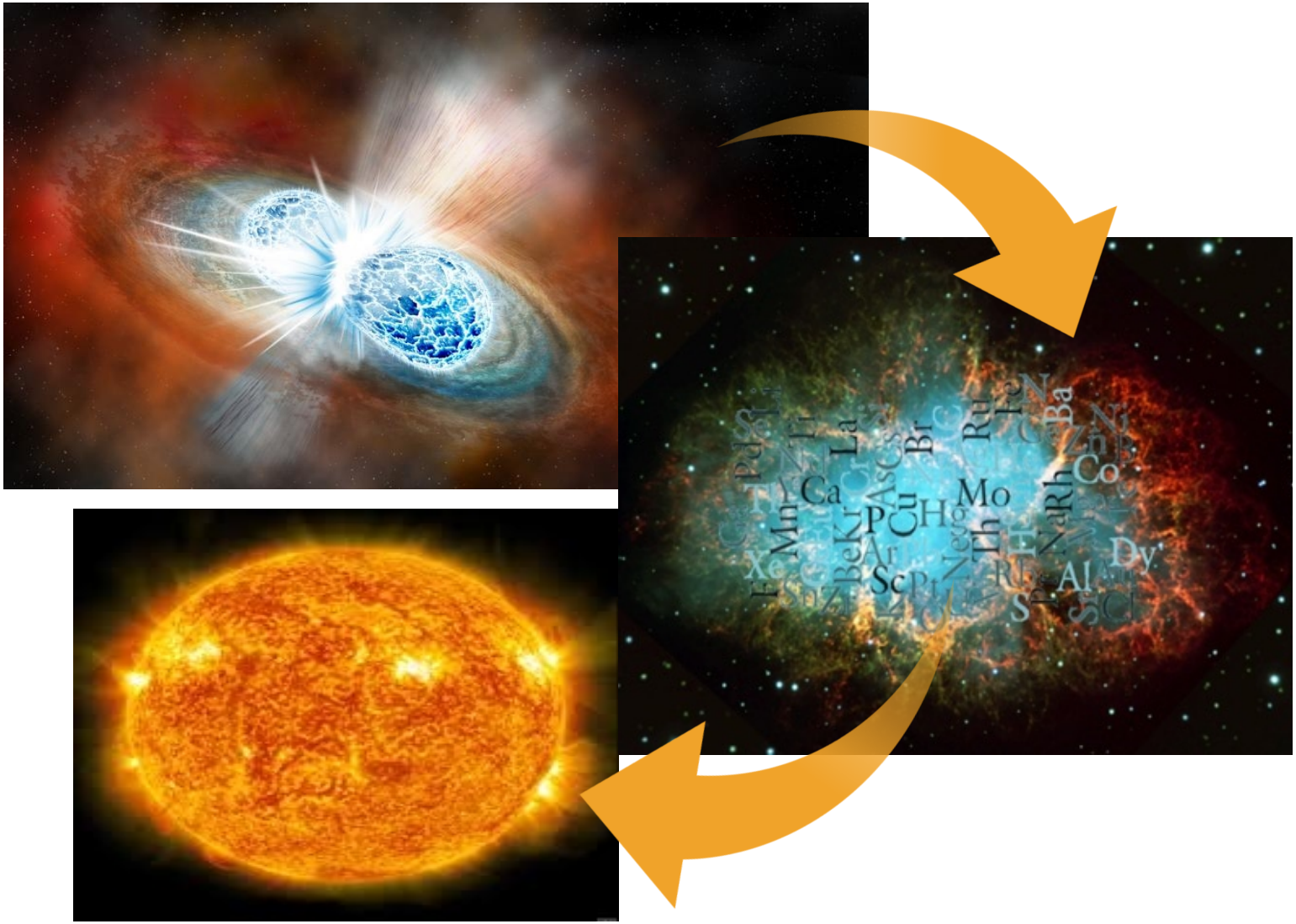
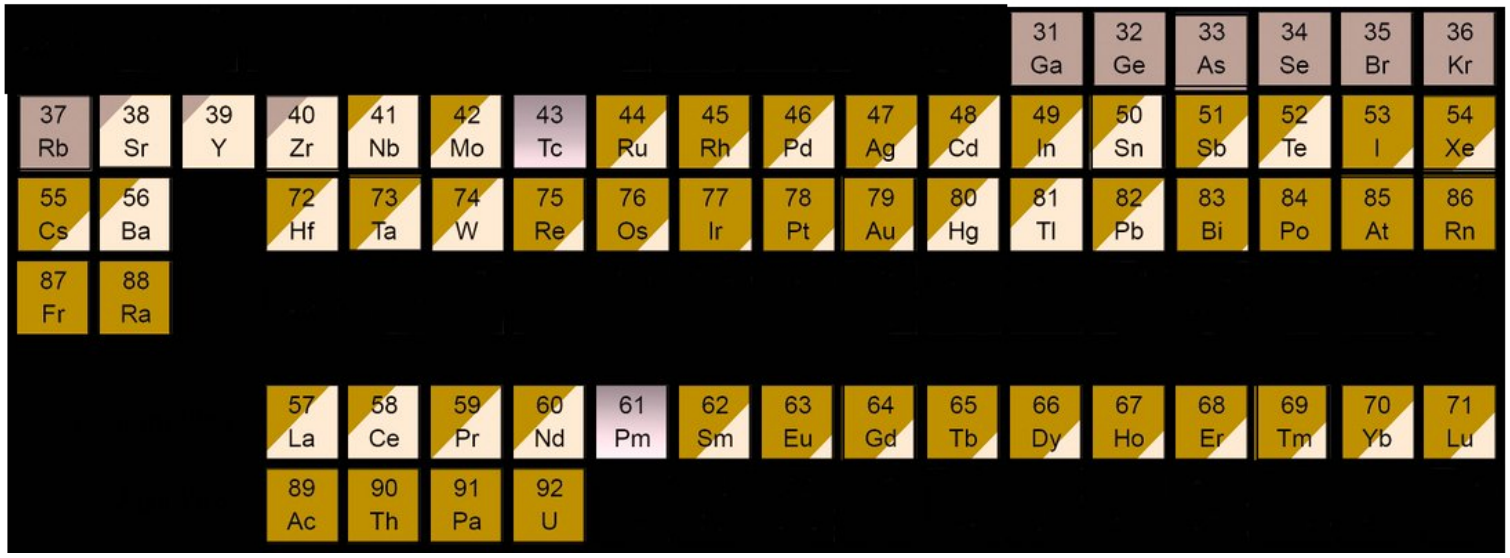
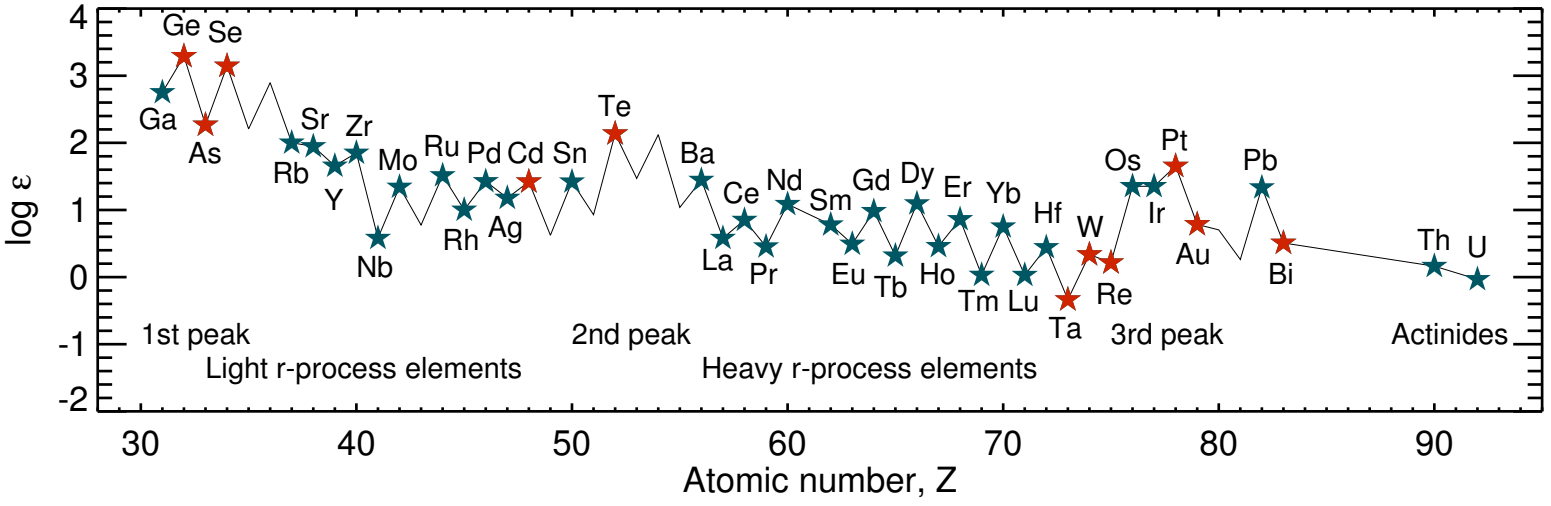
Elements produced in neutron star mergers



Rapid neutron capture

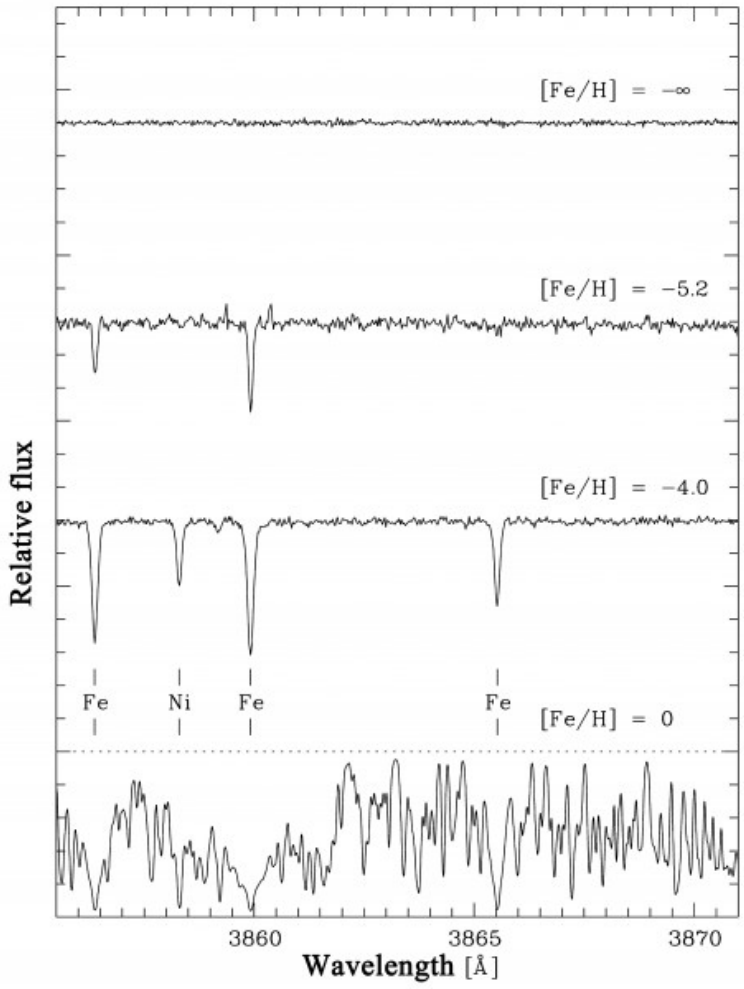


Obtainable from stellar spectra



Ground, Space

Metal-poor stars



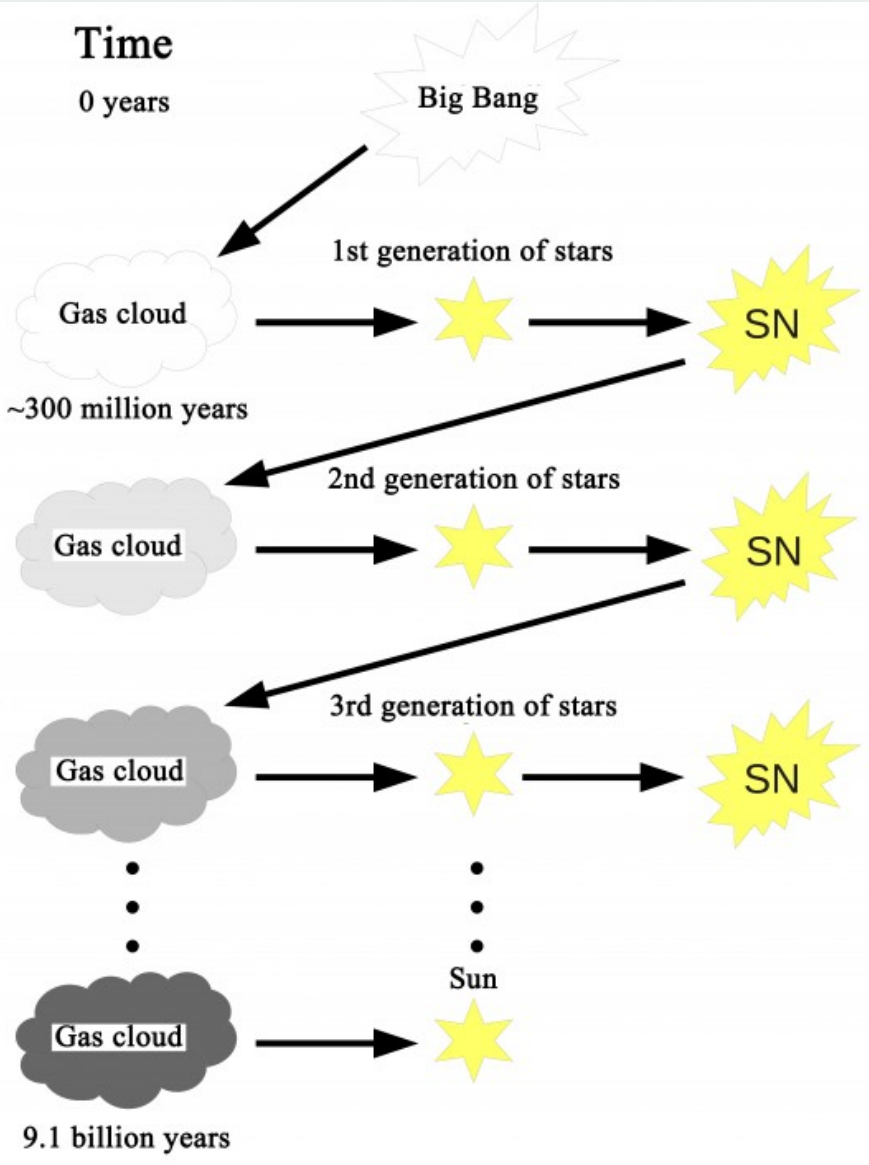
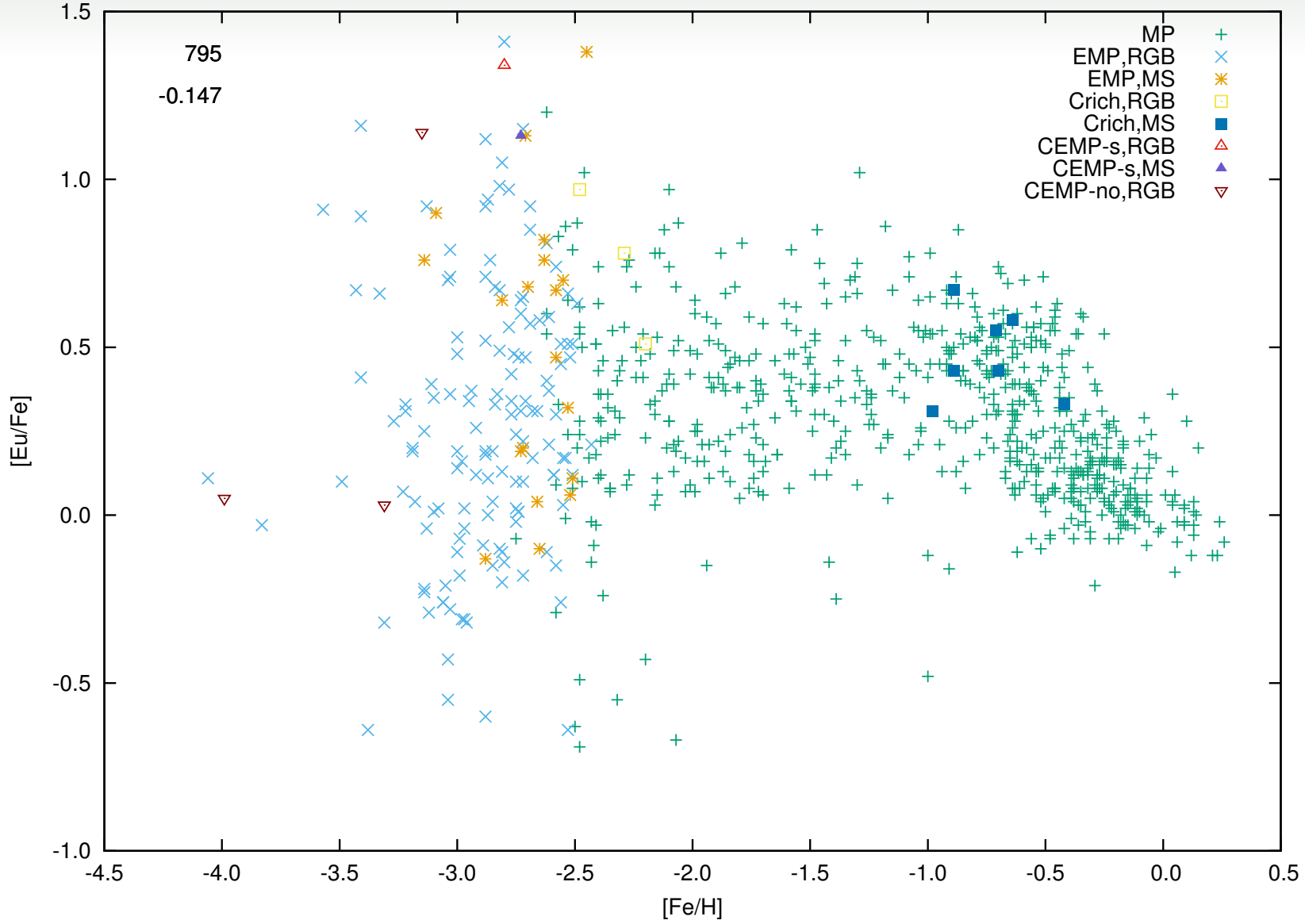


Image credit: Norbert Christlieb

Eu - tracer of r-process in stellar spectra



Data from SAGA database, $[\mathrm{X/Y}] = \log\left(\frac{N_X}{N_Y}\right)_* - \log\left(\frac{N_X}{N_Y}\right)_\odot$

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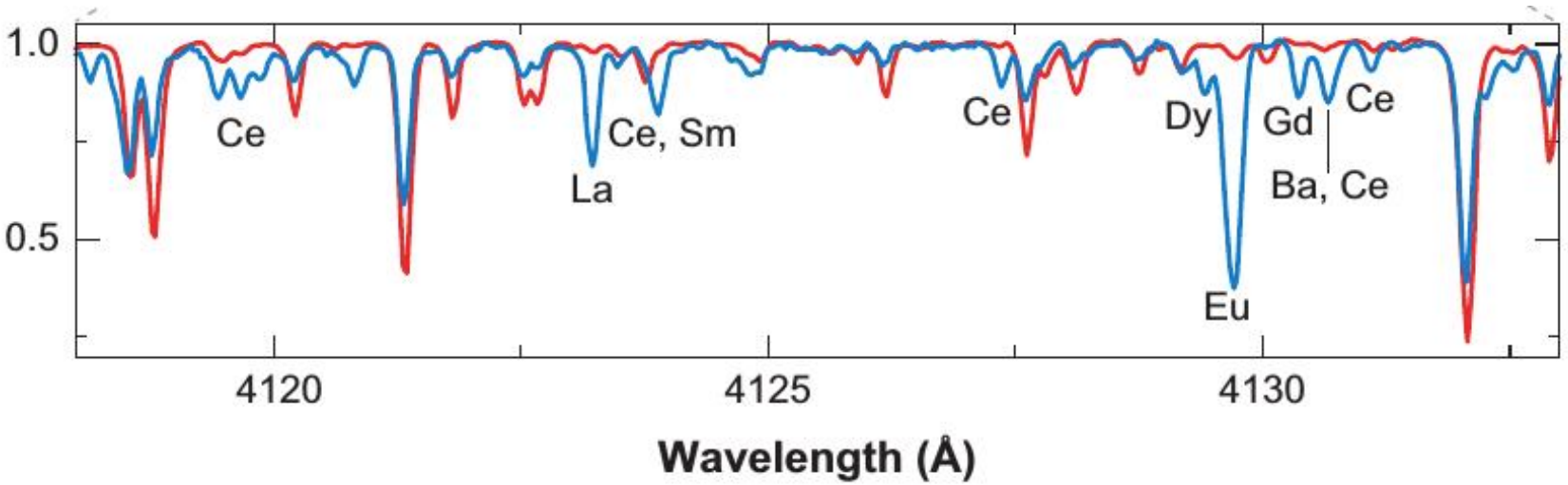
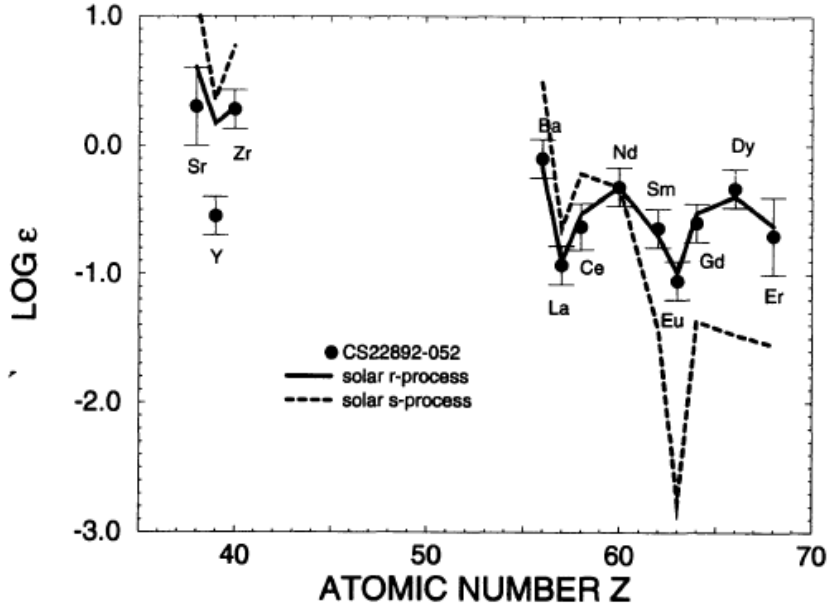
R-process enhanced stars



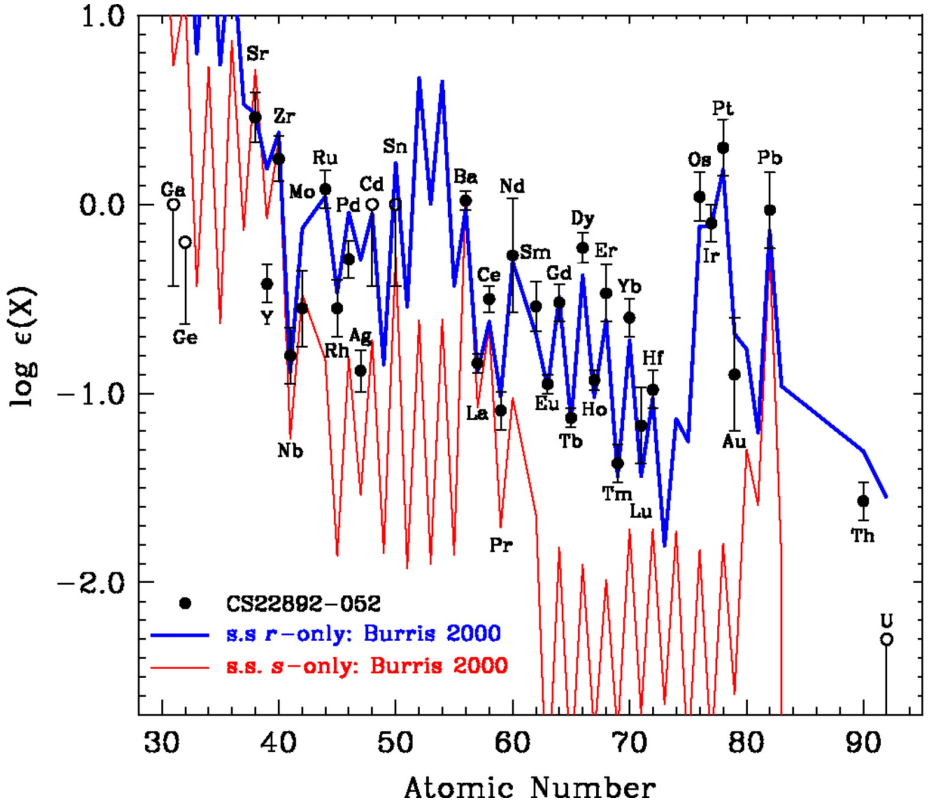
CS 22892−052 (blue) and HD 122563 (red), Sneden+ 2008

- r-I $0.3 < [\mathrm{Eu/Fe}] < 1.0$, $[\mathrm{Ba/Eu}] < 0$
- r-II $[\mathrm{Eu/Fe}] > 1.0$, $[\mathrm{Ba/Eu}] < 0$

The first r-process enhanced star - CS 22892-052



Cowan+ 1995



Sneden+ 2003

$$\log \epsilon(X) = \log\left(\frac{N(X)}{N(H)}\right) + 12$$

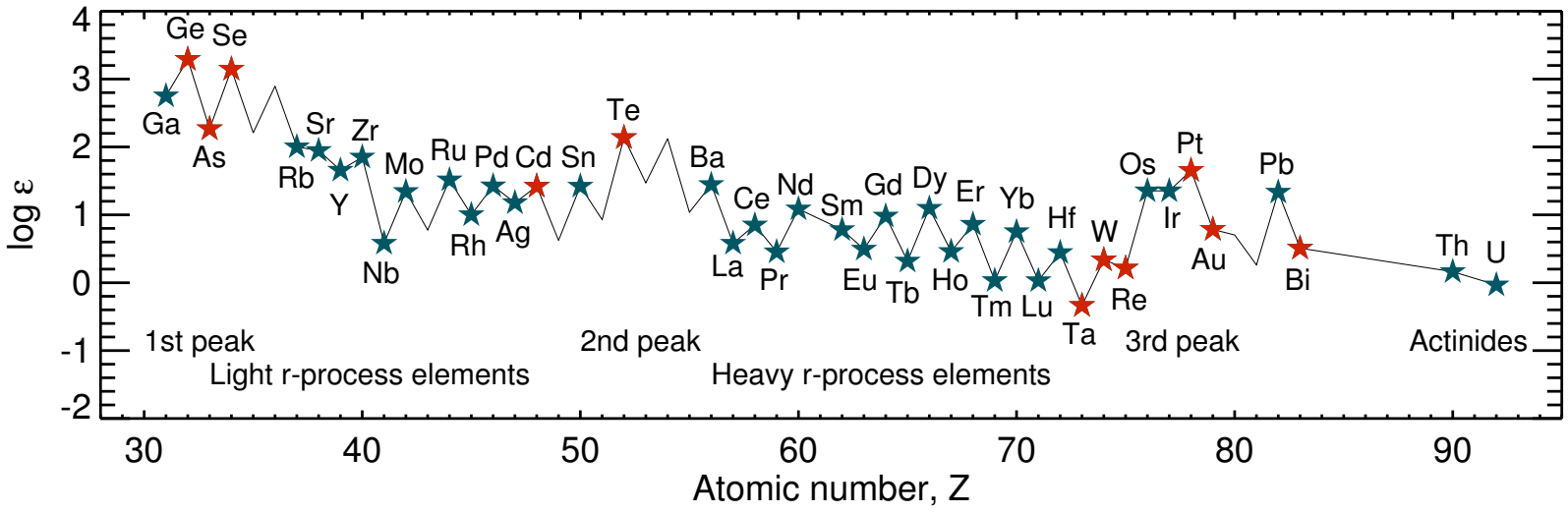
Dedicated search for r-process enhanced stars in the halo

- Barklem+ 2005 took snapshot of 253 stars and discovered 8 r-II and 35 r-I stars $\rightarrow$ r-II stars are very rare!

Today:

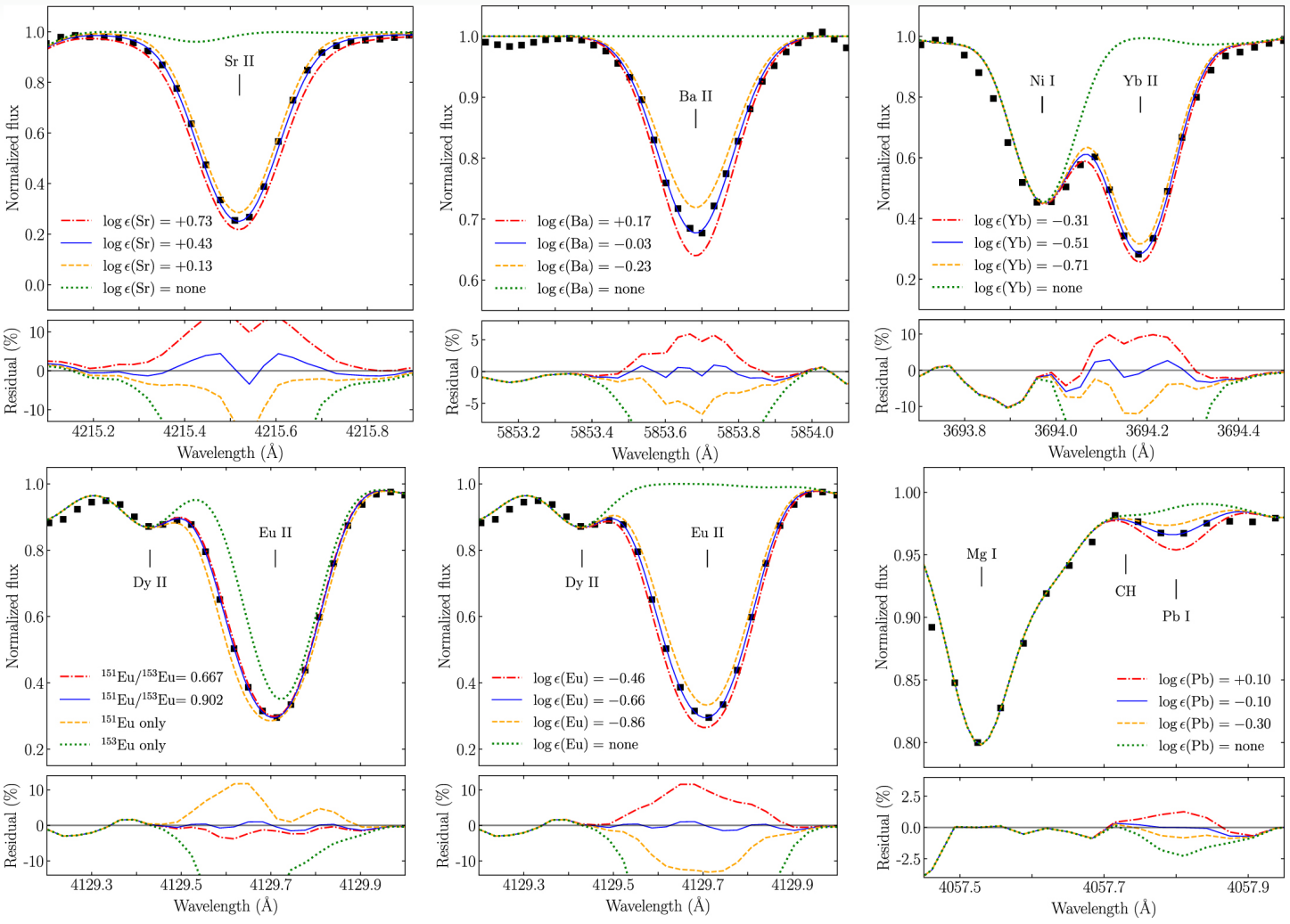
- 30 r-II
  $[\mathrm{Eu/Fe}] > 1.0$, $[\mathrm{Ba/Eu}] < 0$
- $\sim$125 r-I stars
  $0.3 < [\mathrm{Eu/Fe}] < 1.0$, $[\mathrm{Ba/Eu}] < 0$

Elements from r-process enhanced stars



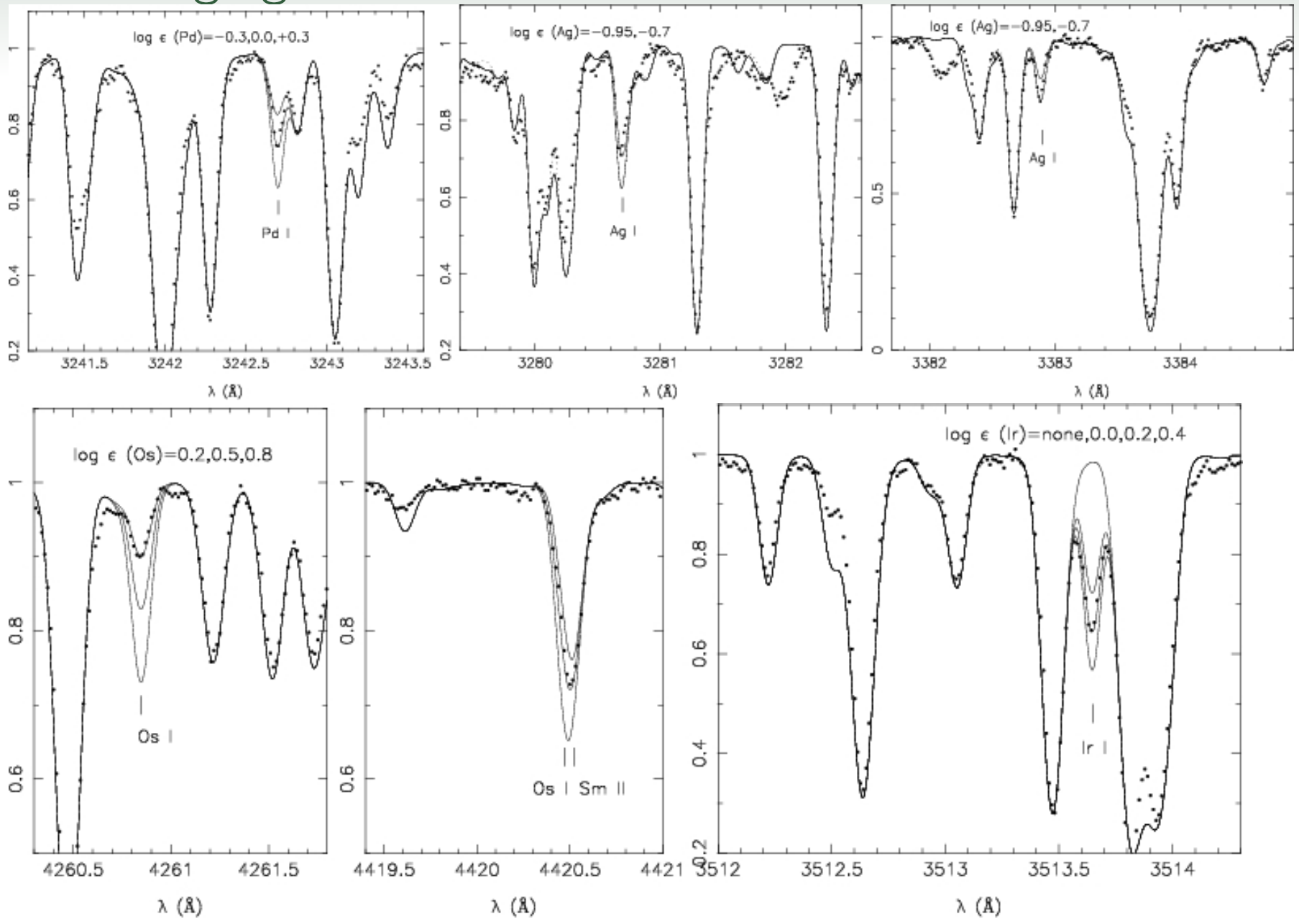
Ground, Space

The easy ones



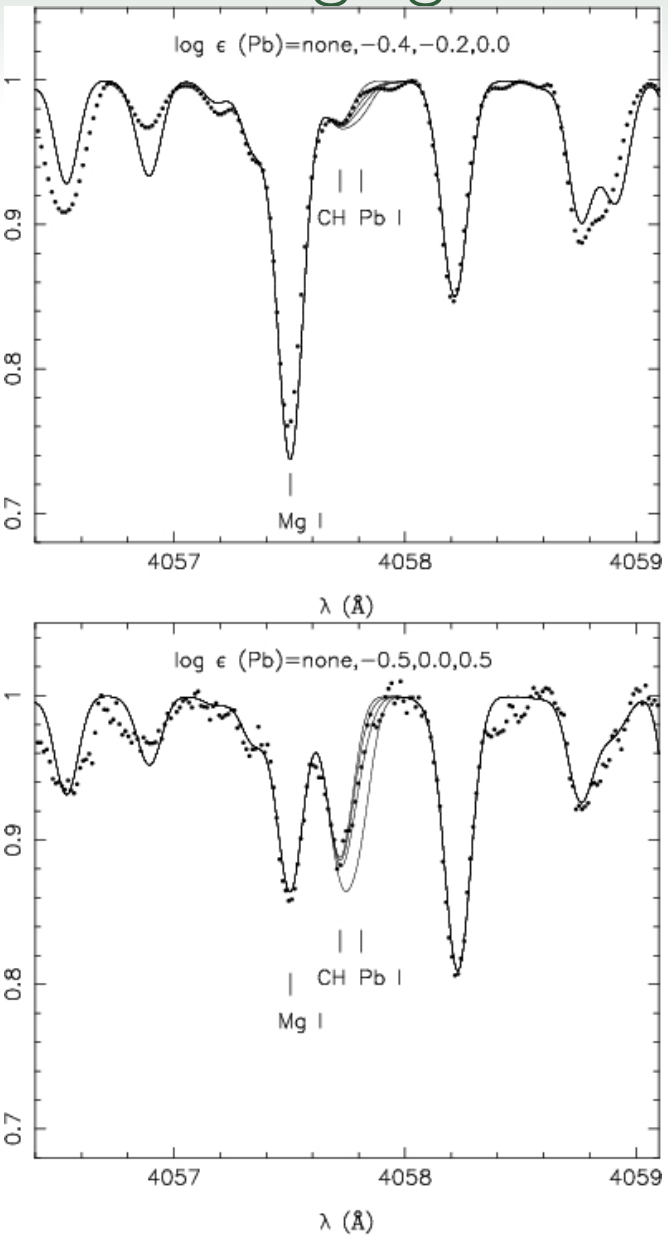
Placco+ 2017

The challenging ones

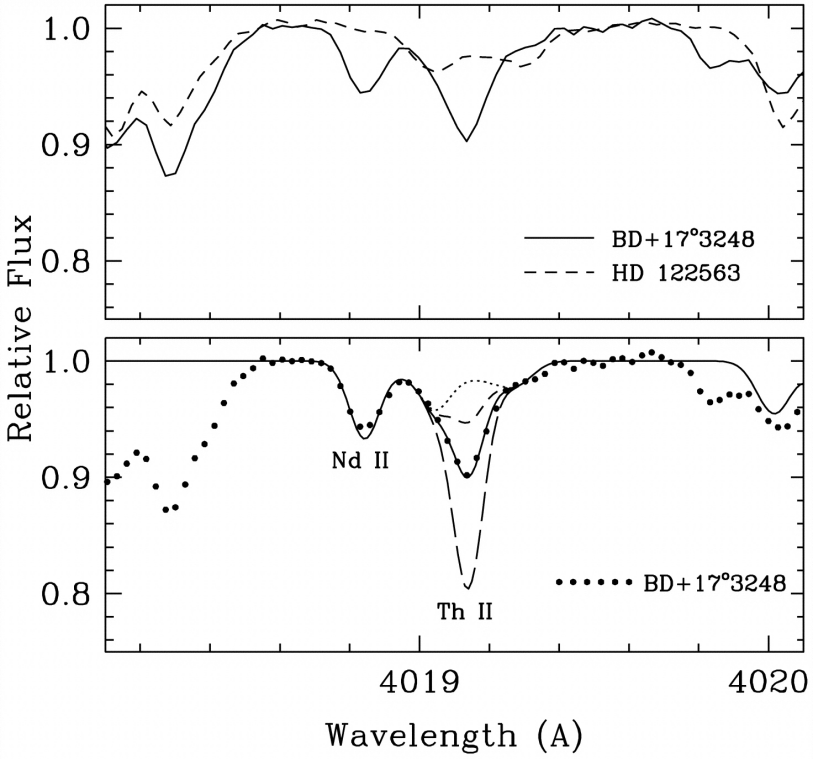


Hill+ 2002

The challenging ones



Hill+ 2002



Cowan+ 2002

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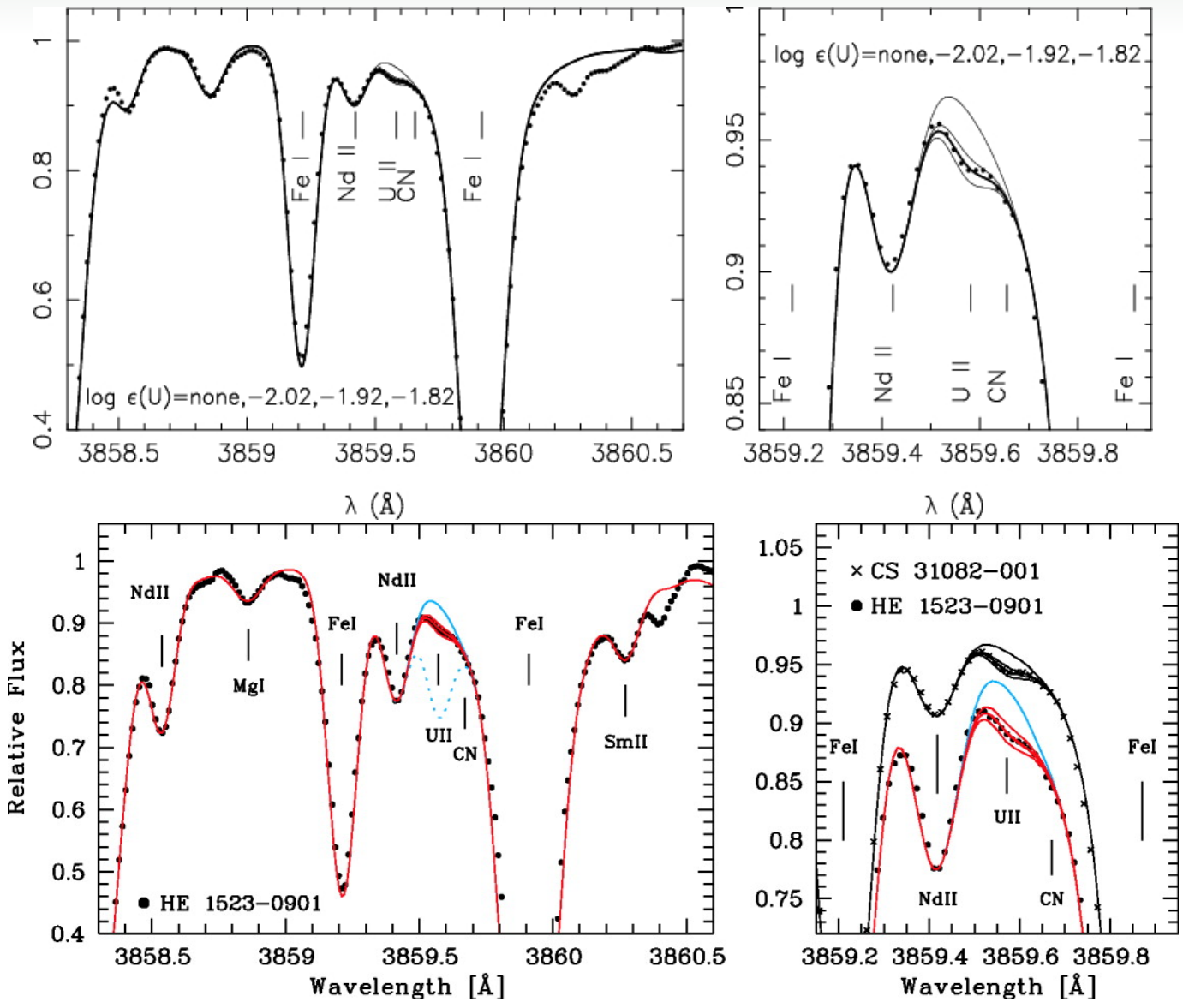
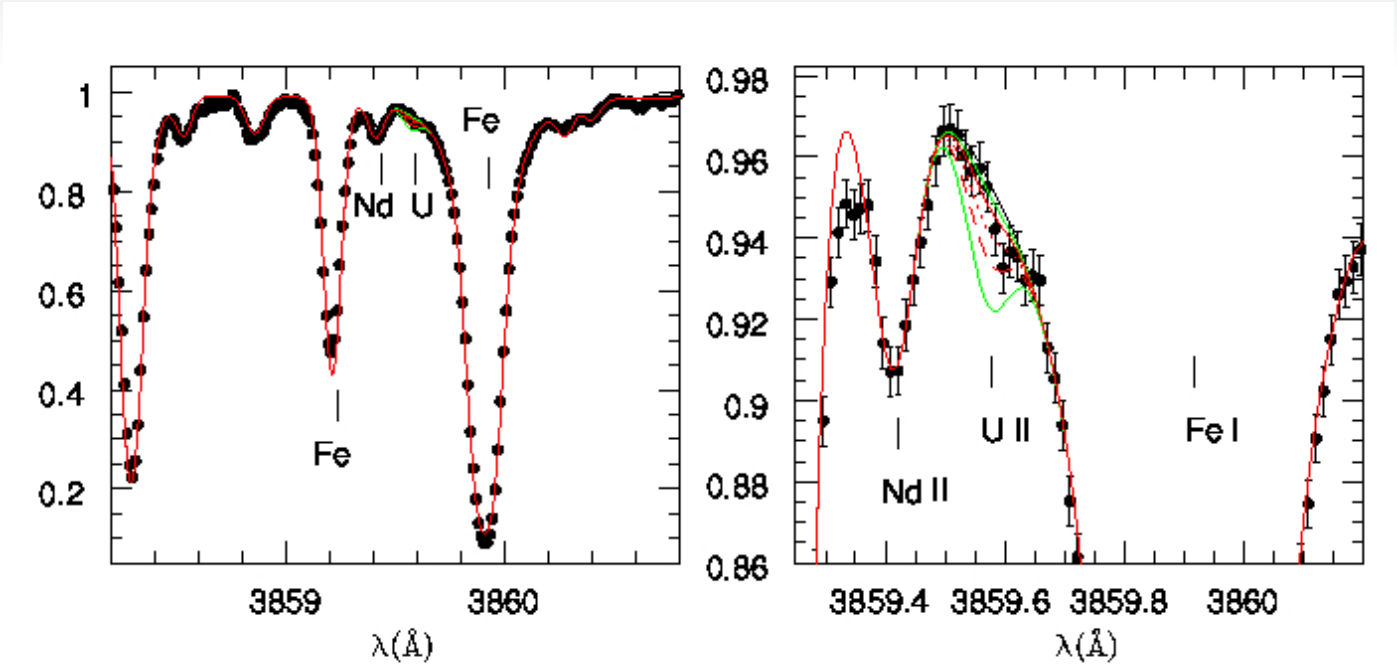
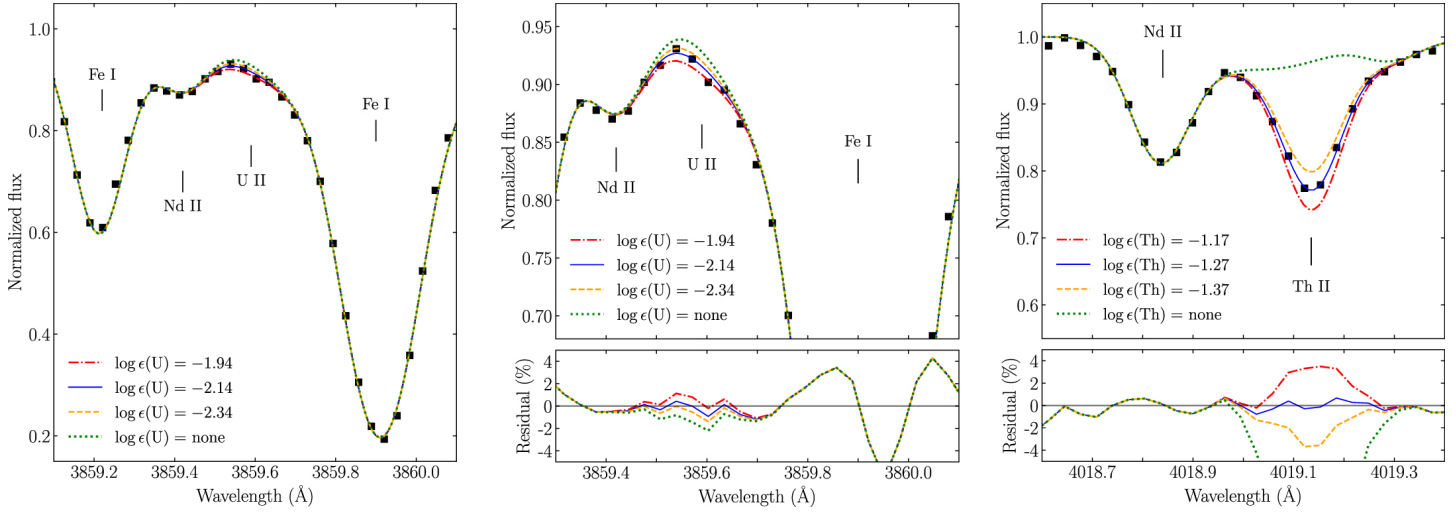
The difficult ones



Hill+ 2002, Frebel+ 2007

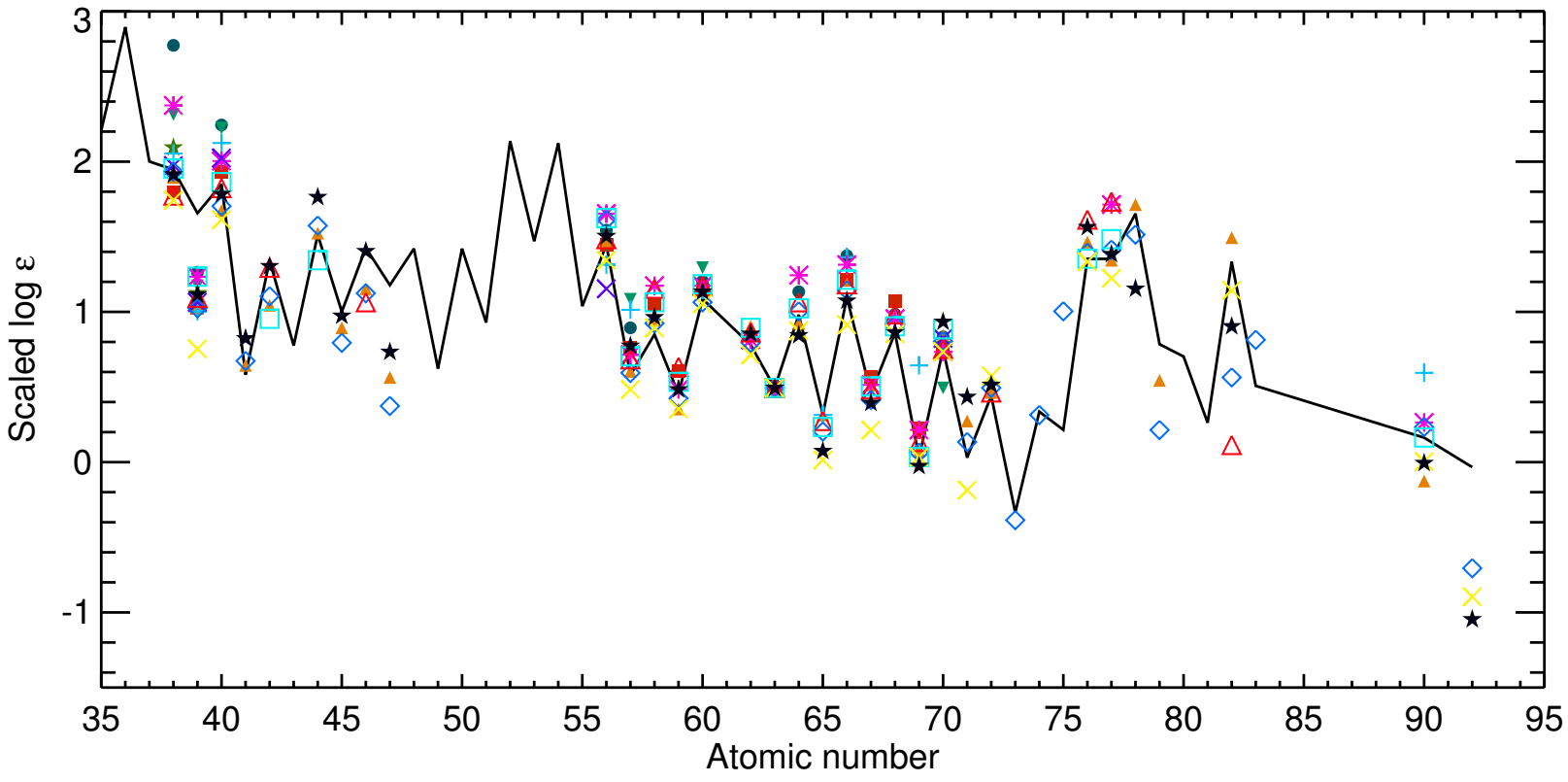
The difficult ones



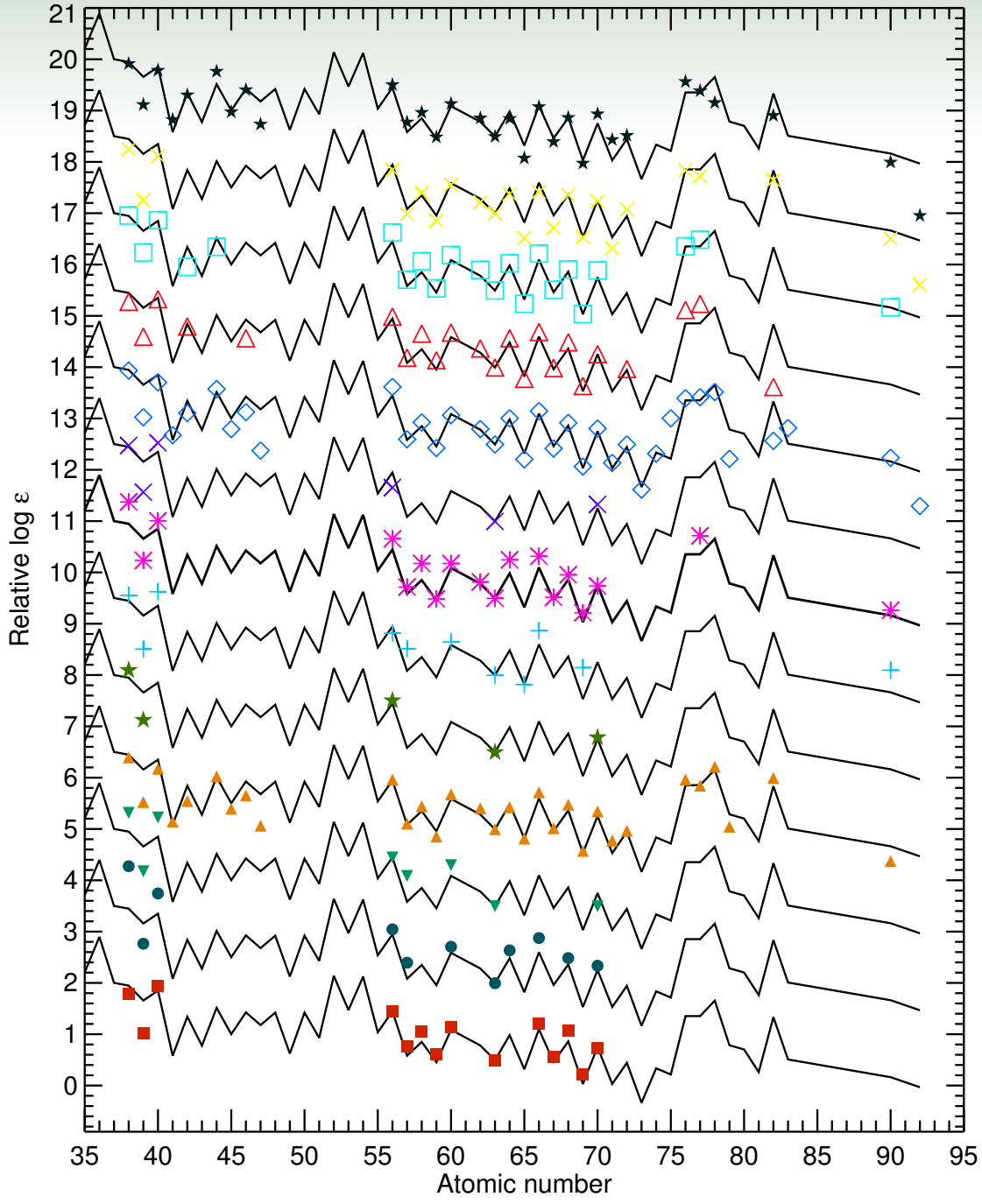


Hill+ 2017, Placco+ 2017

Abundance pattern of heavy r-process enhanced stars - r-II stars

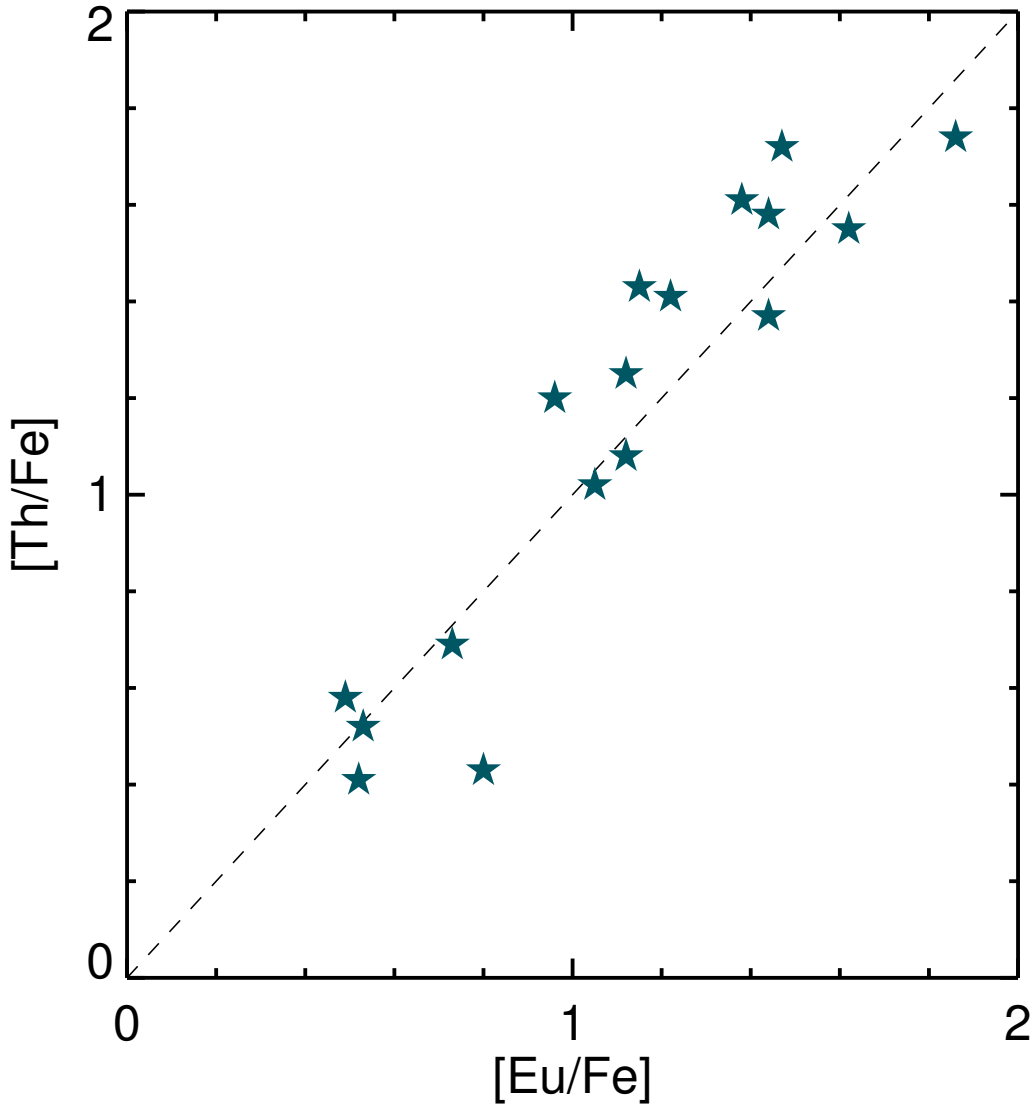


Roederer+ 2014, Mashonkina+ 2010, Placco+ 2017, Hill+ 2017



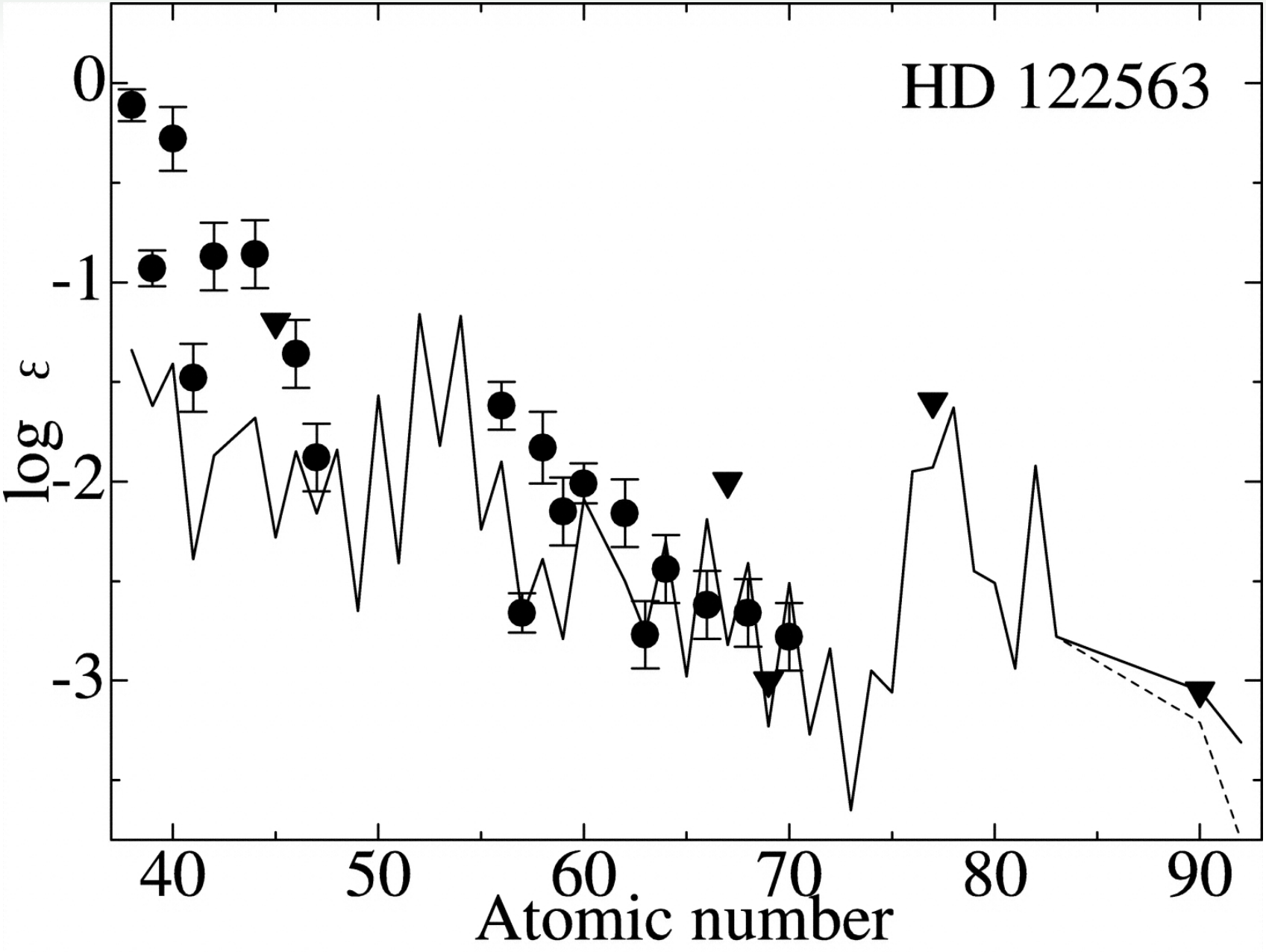
Roederer+ 2014, Mashonkina+ 2010, Placco+ 2017, Hill+ 2017

Actinide boost stars



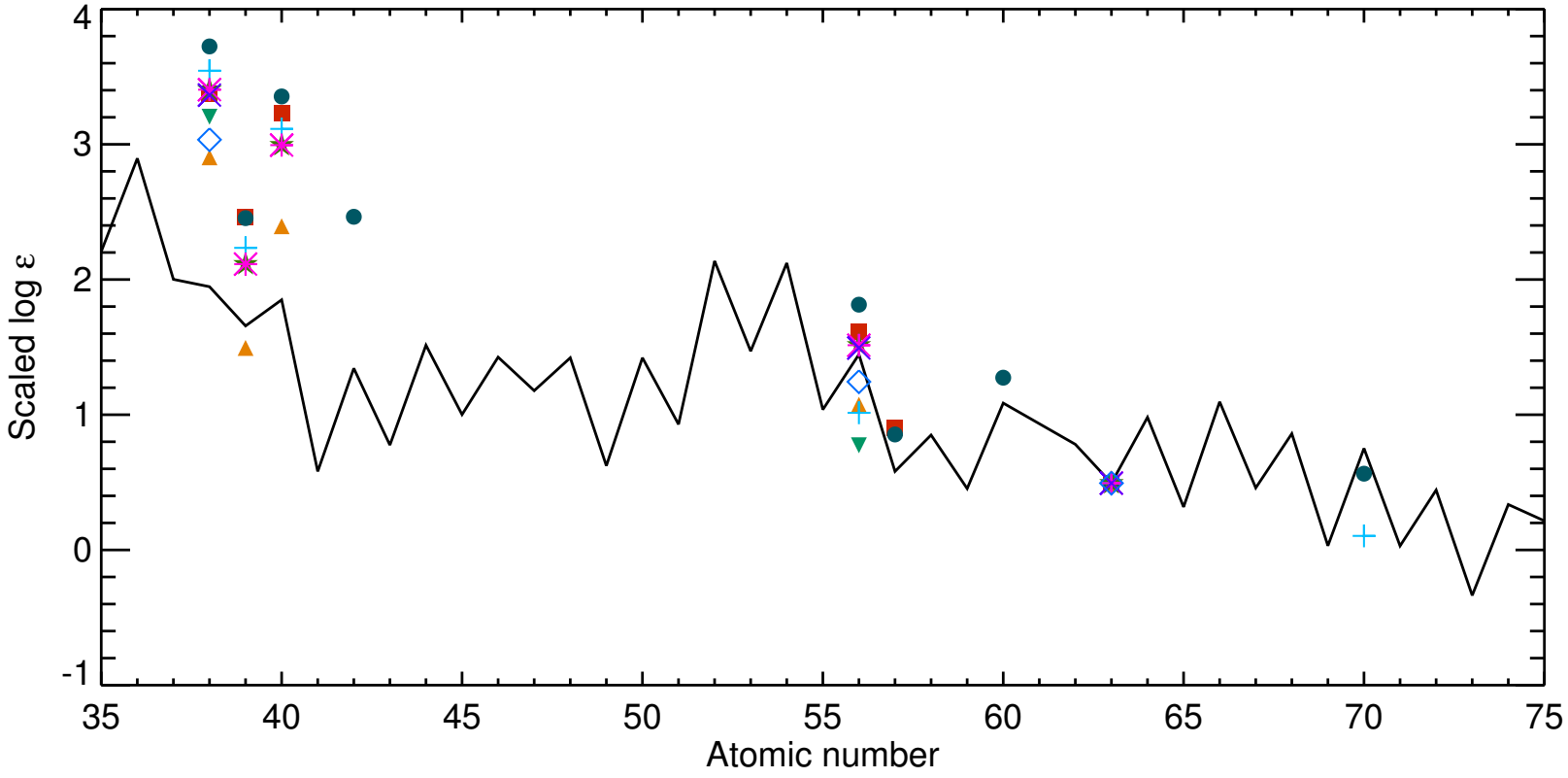
Roederer+ 2009,2014, Ren+ 2012, Hayek+ 2009, Lai+ 2008, Frebel+ 2007, Mashonkina 2014

Stars enhanced in light r-process elements



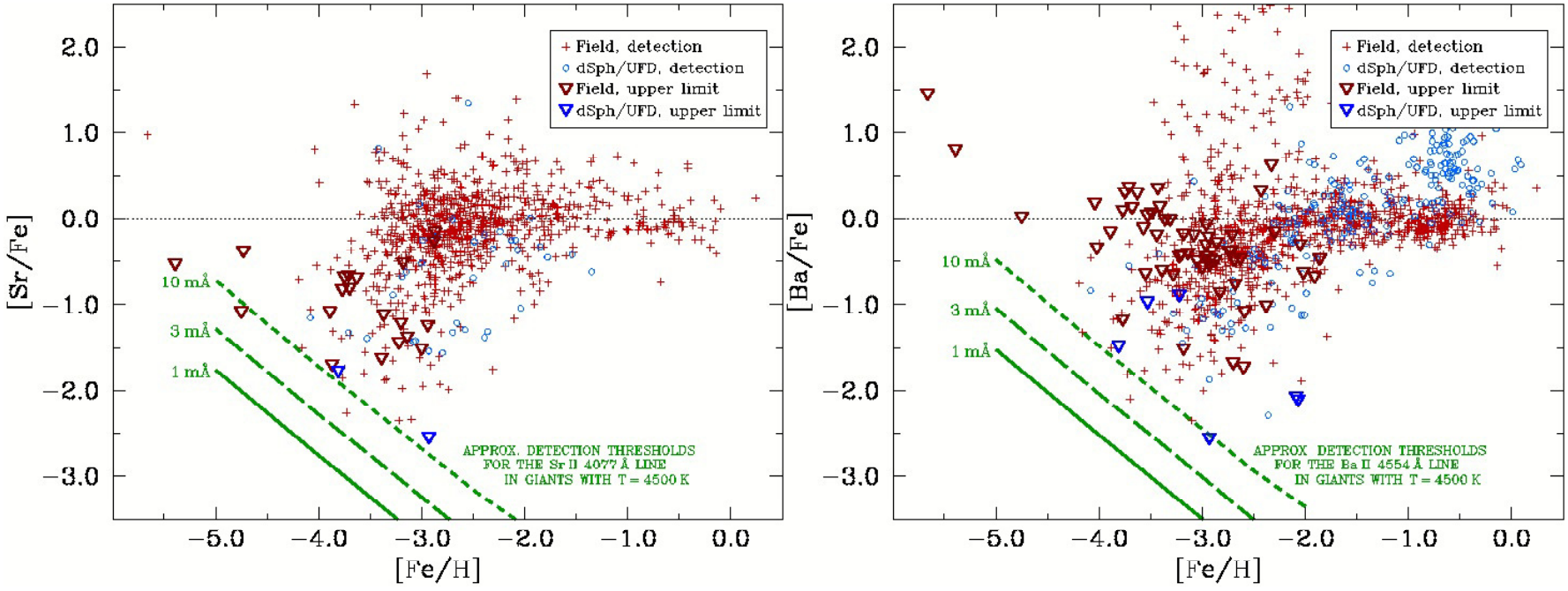
Honda+ 2004

Stars enhanced in light r-process elements



Roederer+ 2014, Honda+ 2004, Jacobson+ 2015, Hansen+ 2015

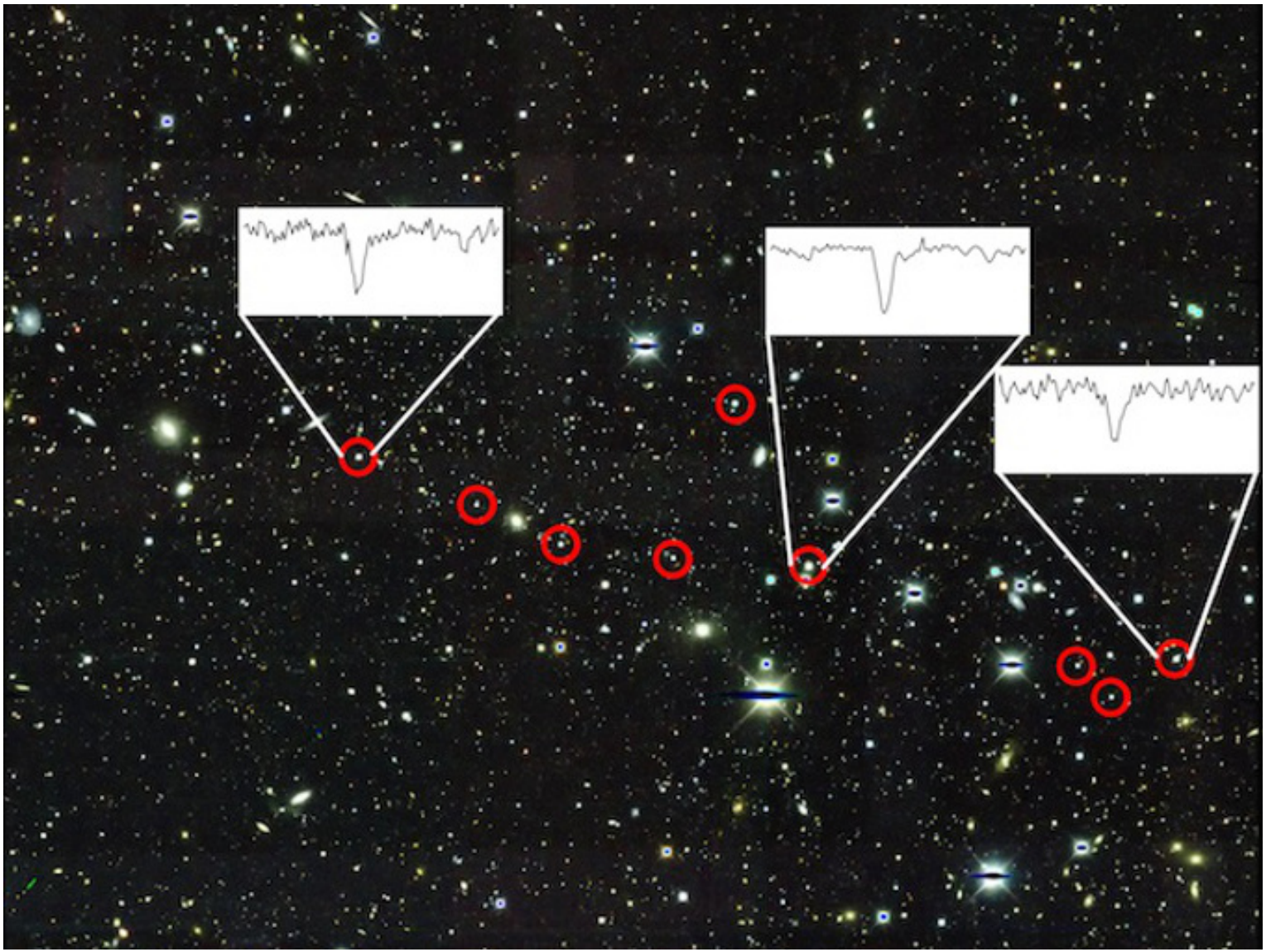
r-process elements at all times



Roederer 2010

r-process enhanced stars in dwarf galaxies

Reticulum II - 7 of 9 stars analysed strongly enhanced in r-process elements



Ji+ 2016

r-process enhanced stars in other dwarf galaxies

Dwarf galaxy	r-I	r-II
Ursa Minor	6	1
Draco	4	1
Sculptor	1	0
Fornax	6	4
Carina	2	0
Reticulum II	0	7
Tucana III	1	0
Total:	20	13

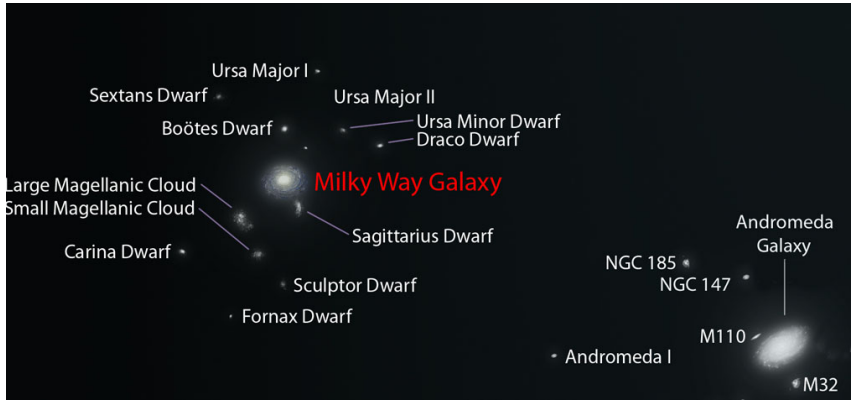
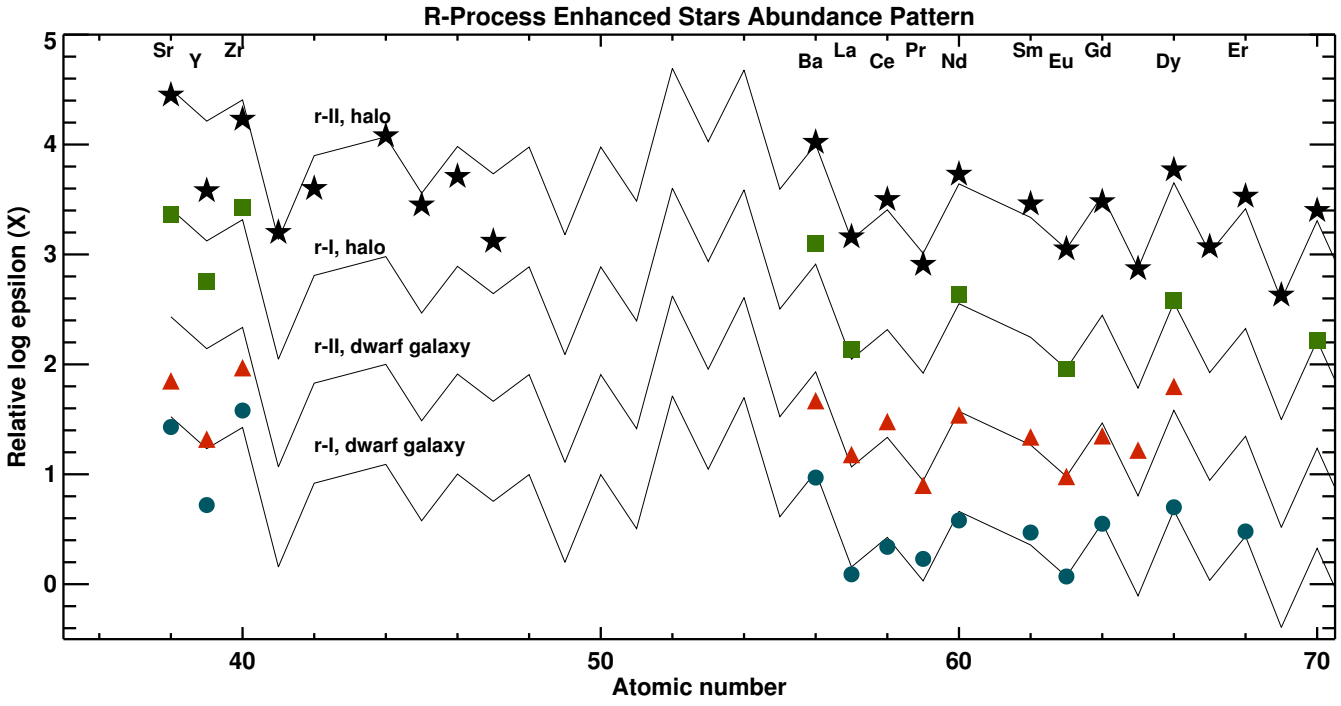


Image credit: Andrew Colvin

Abundances of r-process enhanced stars in dwarf galaxies



Sneden+ 2008, Siqueira-Mello+ 2014, Roederer+ 2016, Hansen+ 2017

Open questions

- Is there variation in the lanthanide abundances?
- What creates the spread in the light and heavy r-process abundances?
- What is the source for the neutron-capture elements seen in the light r-process enhanced stars?
- Other sources of r-process elements?
- How many NSM do we need to reproduce abundance patterns seen in halo?

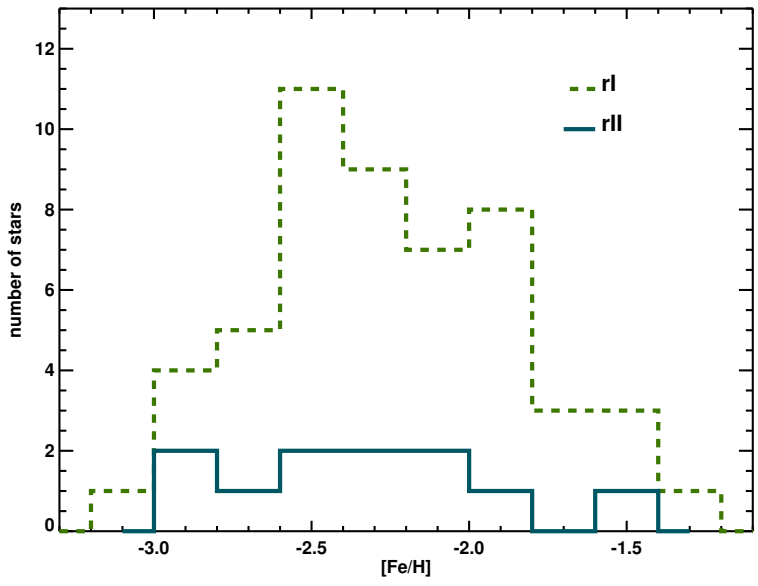
Answers: New survey for r-process enhanced stars

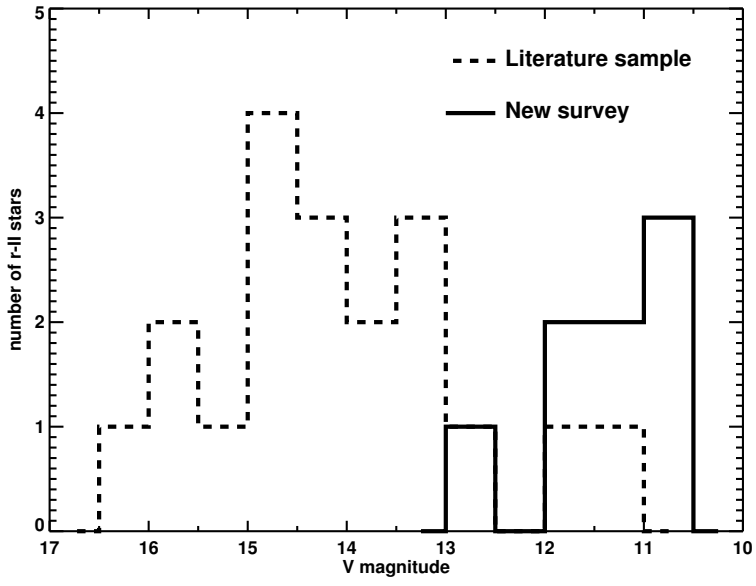
Obtain high resolution spectra for $\sim$2000 stars to find $\sim$75 new r-II stars, more light r-process enhanced stars plus a large number of r-I stars.

Selection:

- Bright $V < 13.5 \rightarrow$ can observe many stars in short time
- Cool $4000 < \mathrm{T_{eff}} < 5500 \rightarrow$ Get Eu abundance or good upper limits
- Metal poor $[\mathrm{Fe/H}] < -2 \rightarrow$ Only few nucleosynthesis events

New r-I and r-II stars detected in pilot sample





Hansen+ in prep

More data to come

- Large sample with full abundance pattern -especially for light and heavy r-process elements
- More stars with Th and U detections, possible actinide boost
- Better statistics for r-process enhanced stars

Summary

- Abundance pattern from Ba to Hf same for r-I and r-II stars in halo and dwarf galaxies $\rightarrow$ possible NSM
- Scatter in abundances of the light and heavy r-process elements $\rightarrow$ additional source of r-process elements, varying output from NSM
- New survey to find more r-process enhanced stars $\rightarrow$ large number of r-process enhanced stars