The Origin of the Astrophysical r-Process

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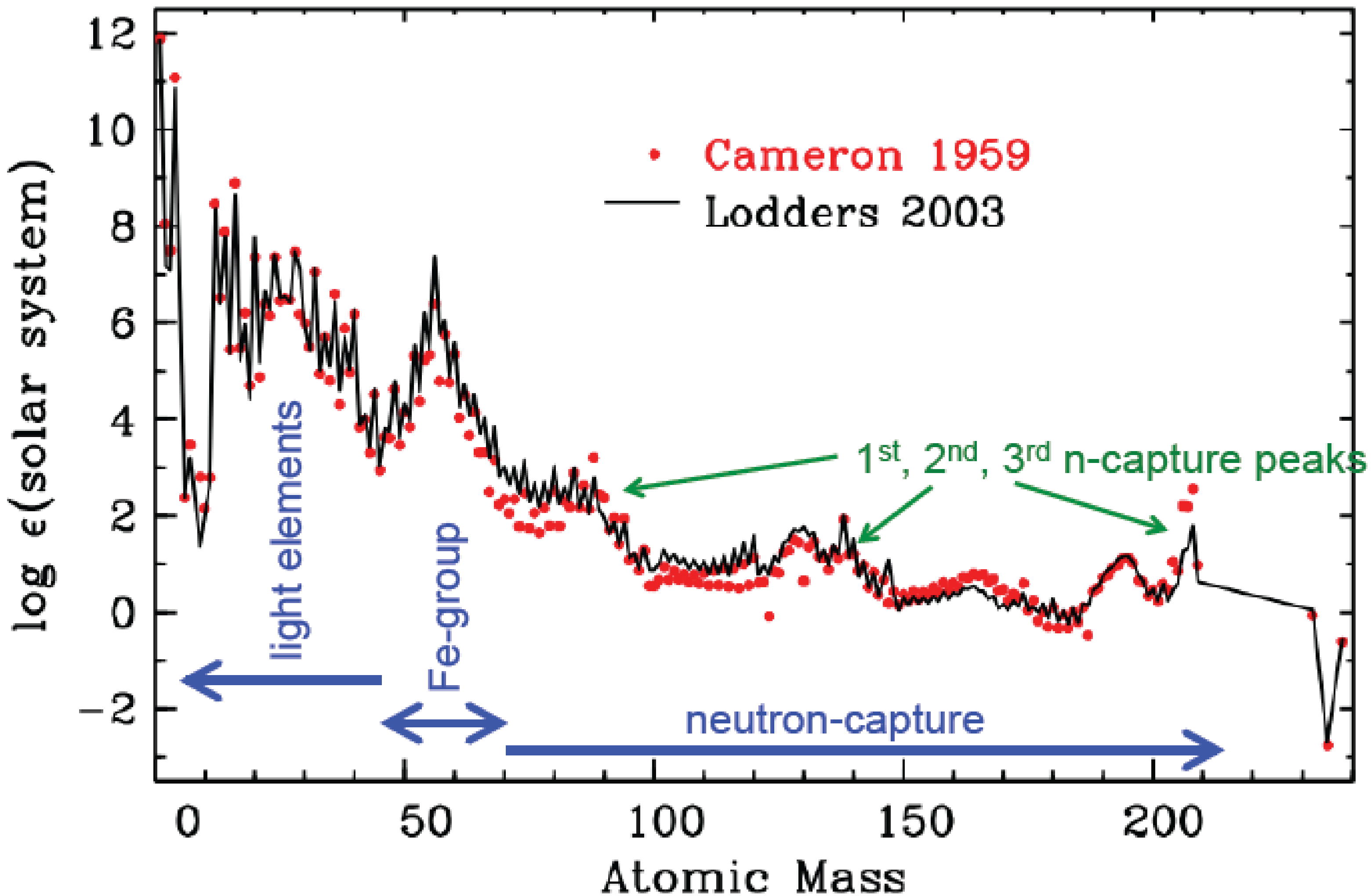
SDSS

Ultimate Goal – Understanding the Solar and Cosmic Abundance Distribution



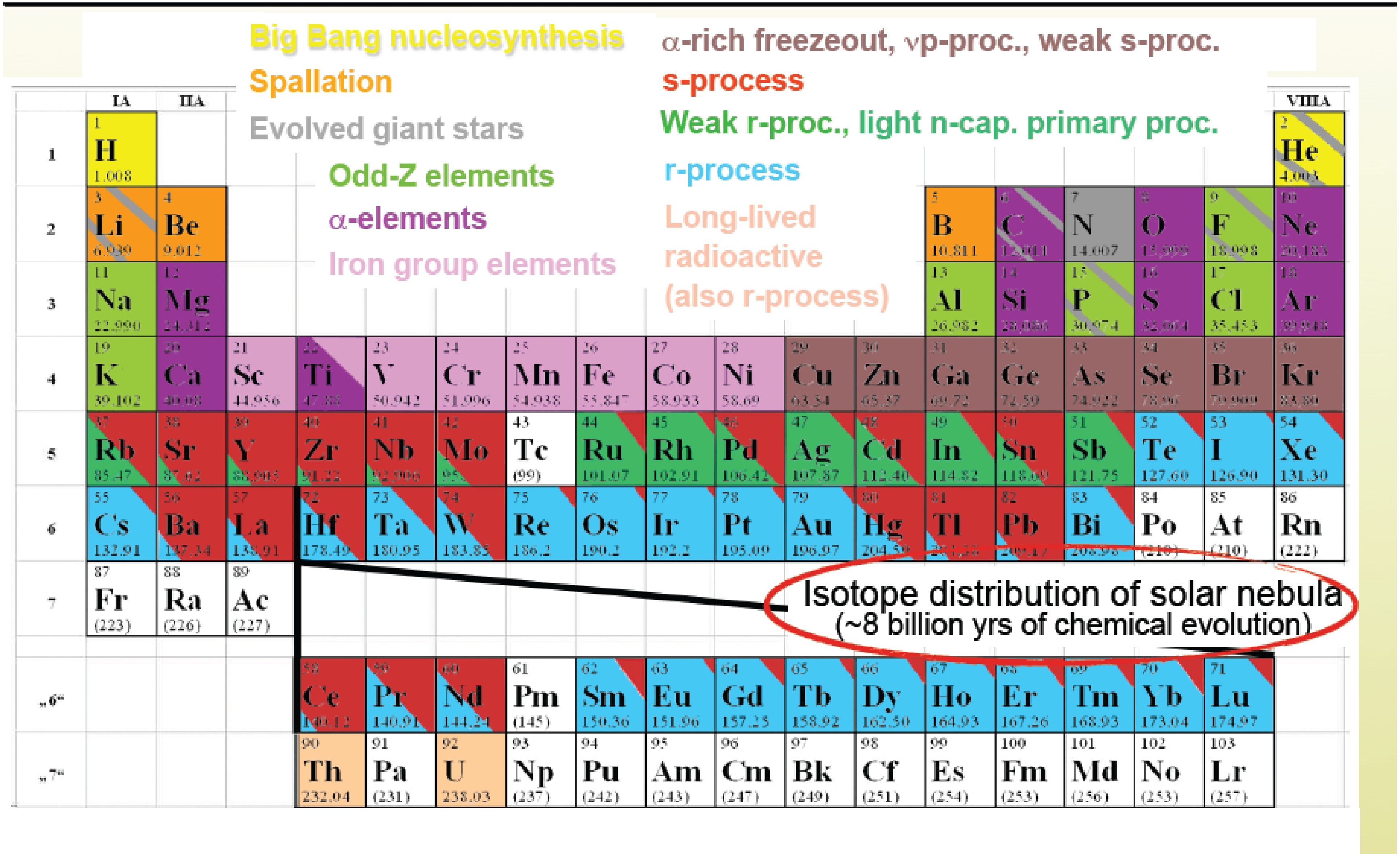
Neutron-Capture Processes

- Neutron-capture reactions proposed by Burbidge et al. (1957) and Cameron (1957) to explain origin of elements beyond Fe.

- Two flavors:
  - Slow (s) process – beta decay before next neutron capture
  - Rapid (r) process – neutron capture before next beta decay

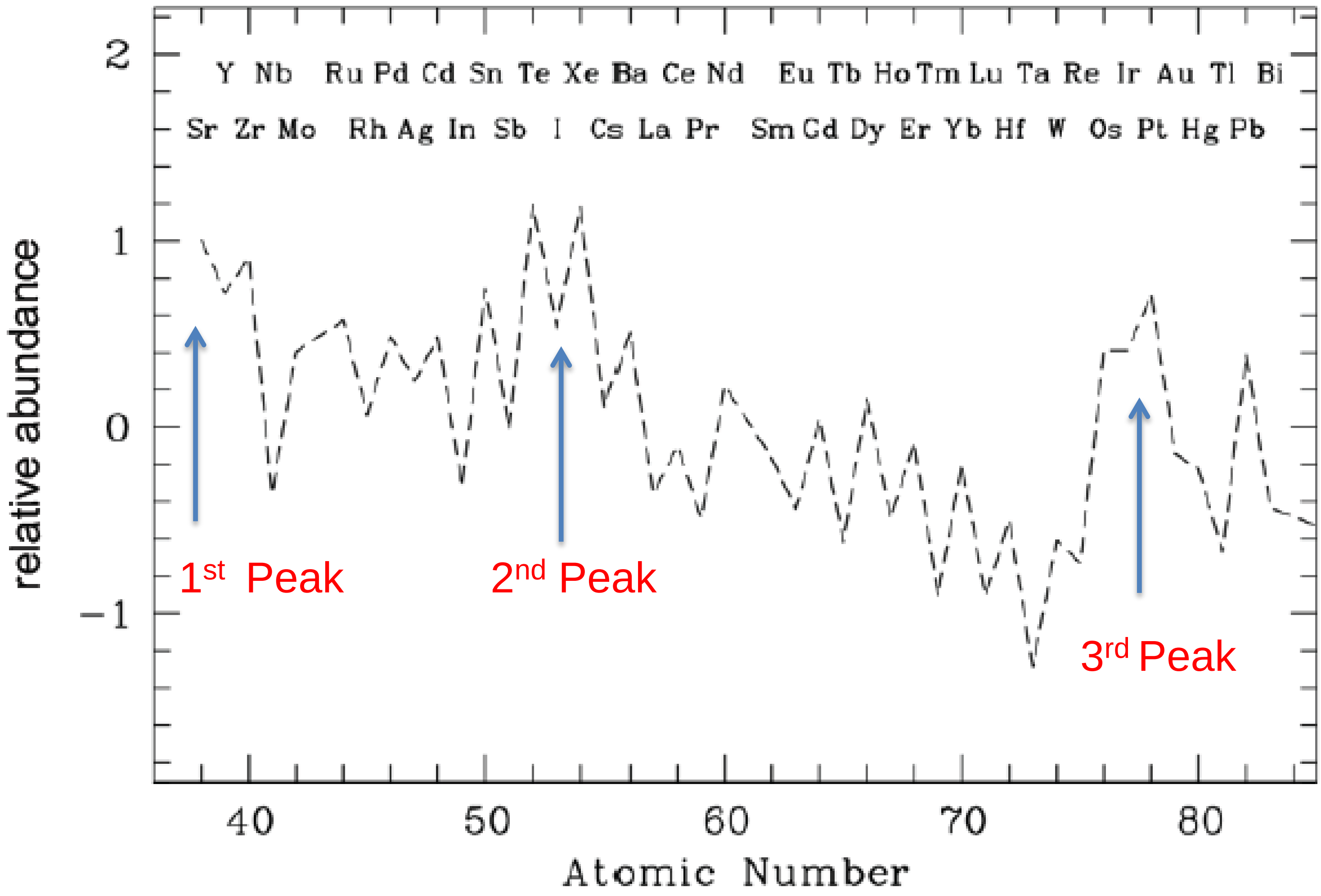
- Astrophysical sites:
  - s-process – Asymptotic Giant Branch (AGB) stars (1-3 Mo) and massive stellar evolution (> 30 Mo)
  - r-process – Unknown. Long thought to be moderate mass (8-10 Mo) supernovae, but there are complications

The Detailed Astronomer's Periodic Table

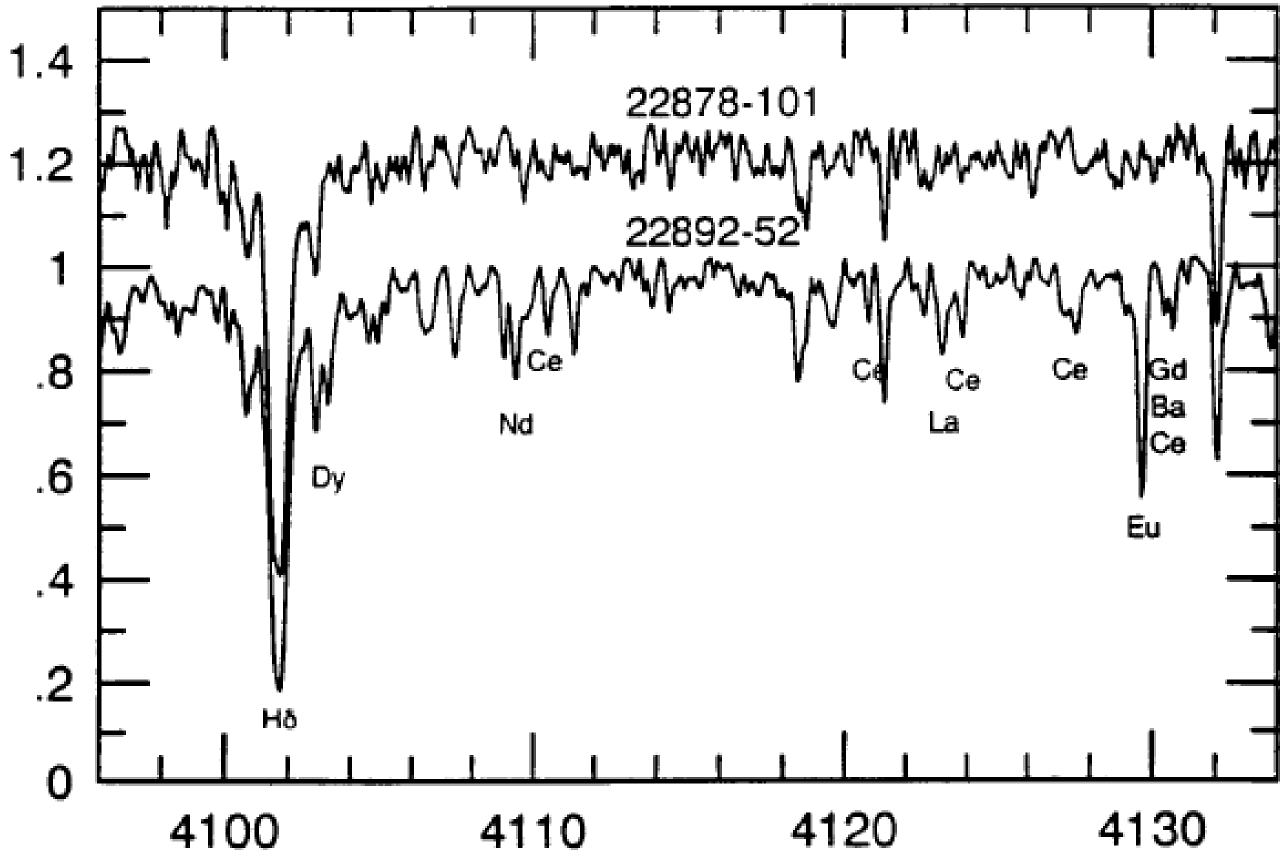


Courtesy A. Frebel

The r-Process Pattern



The First r-Process Enhanced Star in the Halo of the Galaxy – CS 22892-052

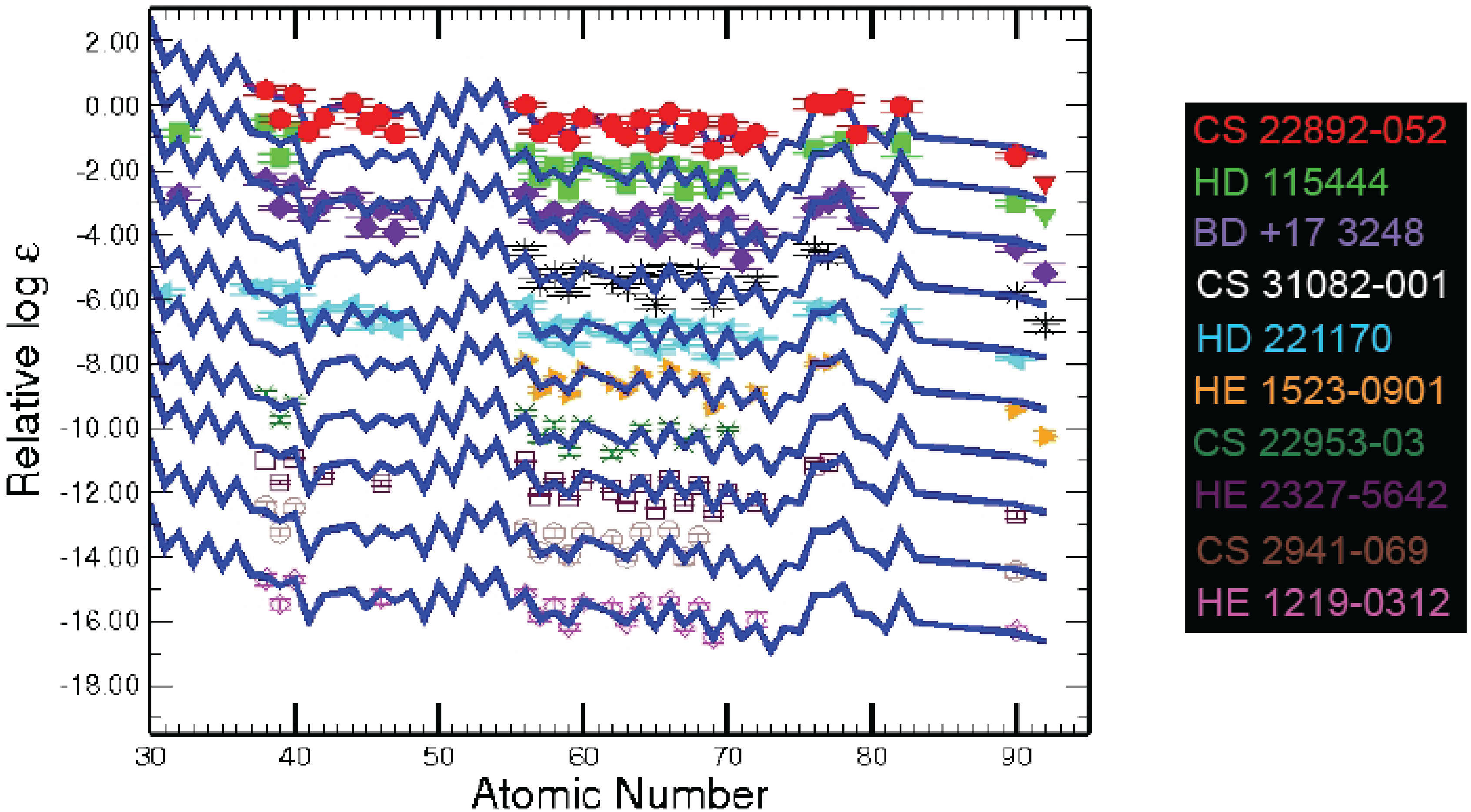


Distribution of heavy n-capture elements consistent with scaled SS results

[Fe/H] ~ -3.0

Sneden / McWilliam ~1995

The Universality of the r-Process – A Robust Production Site ?



Very little star-to-star variation in the pattern of r-process elements

Basic Facts and Realities of the Problem

- The halo population in the Galaxy contains small fractions of stars at very low metallicity, yet moderate to large enhancements of r-process elements relative to iron, compared to the Solar ratio (Beers & Christlieb 2005):
  - r-II: [Eu/Fe] > +1.0 (factor of 10-100 enhancement)
  - r-I: +0.3 < [Eu/Fe] < +1.0 (factor of 2-10 enhancement)
  - CEMP-r-II: As above but also [C/Fe] > +0.7
  - CEMP-r-I: As above but also [C/Fe] > +0.7
- Recent detection of r-II stars in the Ultra Faint Dwarf (UFD) galaxy Reticulum II (Ji et al. 2016, Roederer et al. 2016) have refocused attention on the possible nucleosynthetic origin of such stars, and the astrophysical site of the r-process
- One important consideration concerning the nature of the halo r-II stars has not received adequate attention …

Basic Facts and Realities of the Problem

THAT THEY EXIST AT ALL

- Q. How do you create a simultaneously HIGH r-process-element abundance while maintaining a LOW iron abundance ?

- A. You must limit the mixing process with large amounts of material lacking this abundance signature, and capable of diluting/erasing evidence for its presence

THIS HAS IMPLICATIONS

The BIG Question(s)

- What is the dominant astrophysical site of the r-process ?
  - Core-collapse supernovae
  - Neutron star mergers
  - Others (e.g., Magneto-Rotational Instability SNe? aka Jet-SNe)

- What is the rate and yield of the event(s) ?

- Does the dominant site change over time and is it dependent on environment ?

The Path Forward – Lets Solve this Problem !

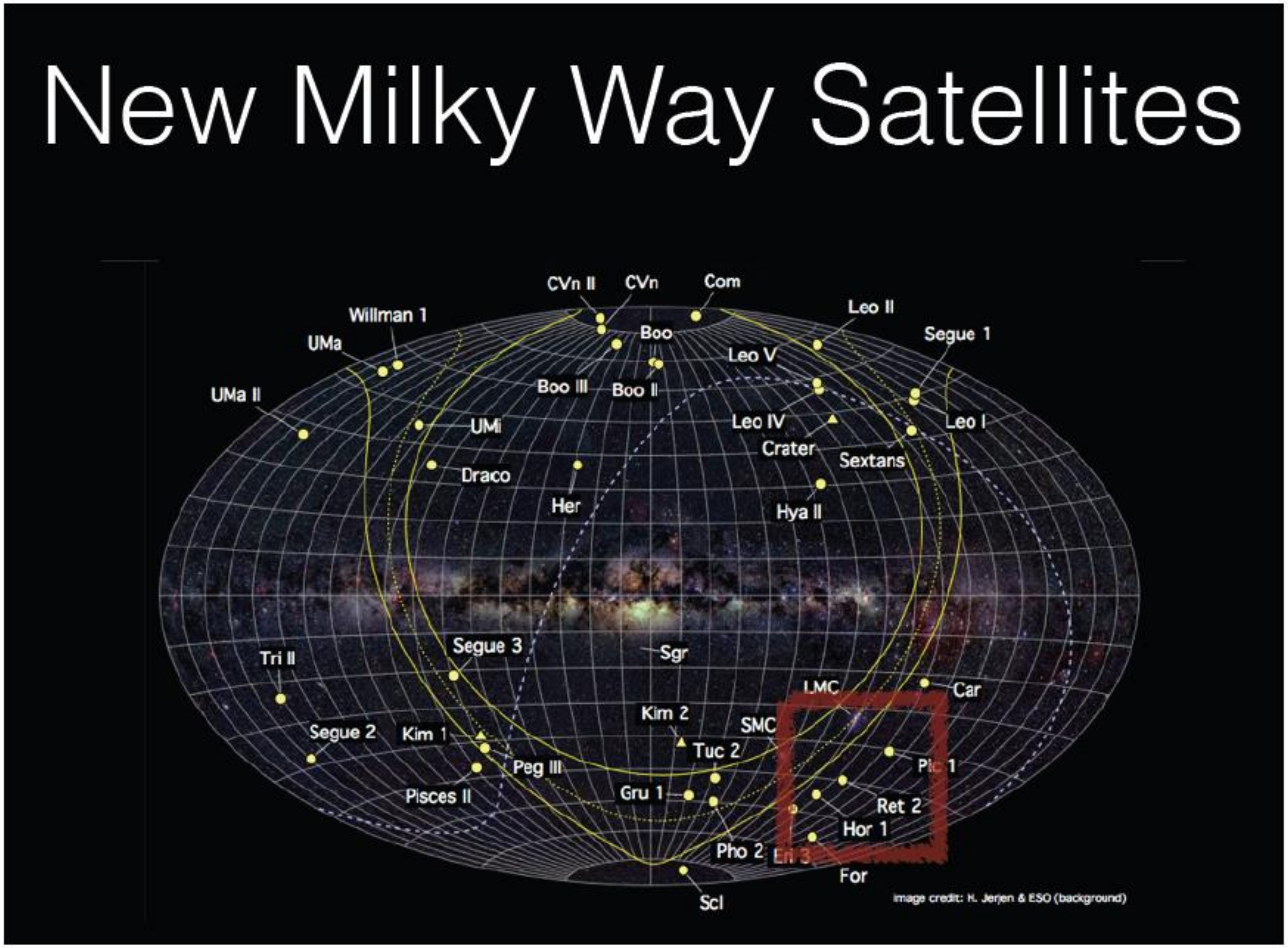
- There now exist a number of observational constraints on the nature of the r-process, based on halo r-II and r-I stars [including some not presented here] -- no extant progenitor model satisfies all of even the current constraints

- These must be kept in mind as various progenitors for the r-process are developed and evaluated. It is possible to produce too many (!) as well as too few r-II stars

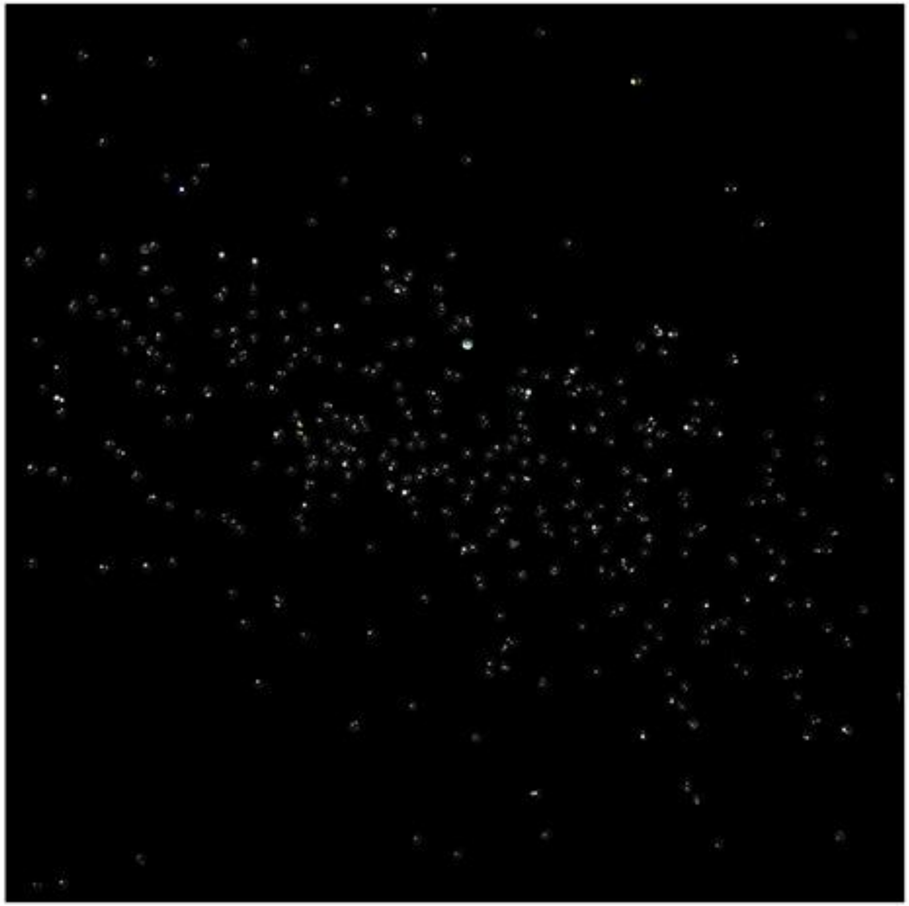
- Ideally, progenitor models would predict testable abundance signatures that are uniquely associated with those sites, even if presently difficult to measure

- Real progress demands a significant increase in the numbers of known r-II (and r-I) stars in the halo, enabling statistical studies of the frequencies of various abundance signatures that constrain models for their progenitors

New Probes of the Origin of the r-Process



New Probes of the Origin of the r-Process

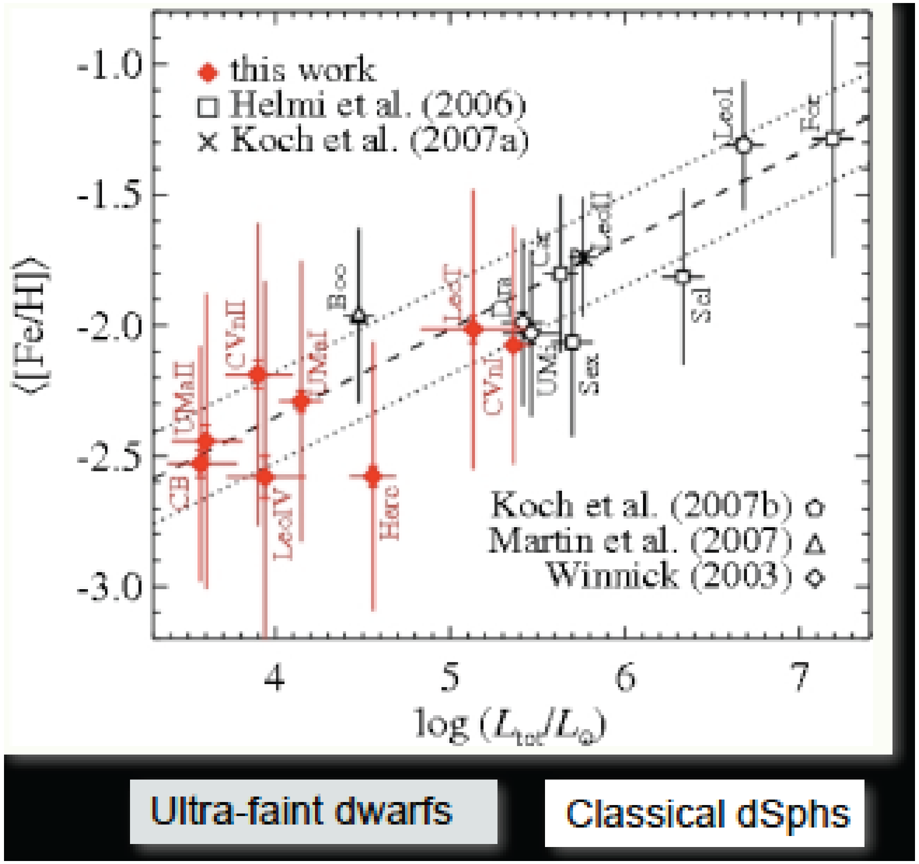


Making the Invisible → Visible

DES Collaboration

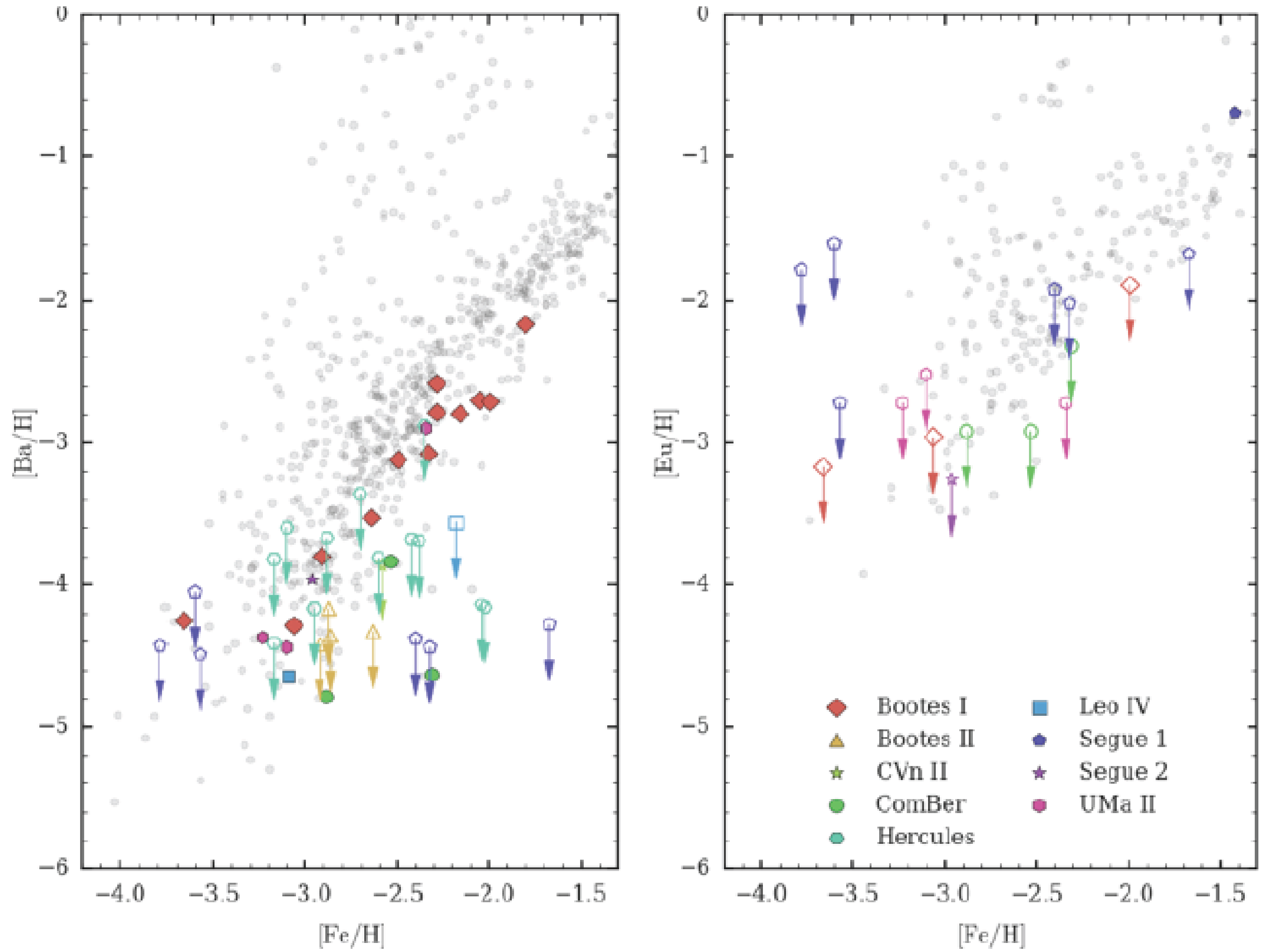
Ultra Faint Dwarf (UFD) Properties

- Low luminosity
  (300 – 3000 L_{sun})
- Dark matter dominated
  (M/L > 100)
- Very metal-poor
  (mean [Fe/H] < -2.0)
- Stars are old
  (mean age ~13.3 Gyr)
- Relatively inefficient star formation



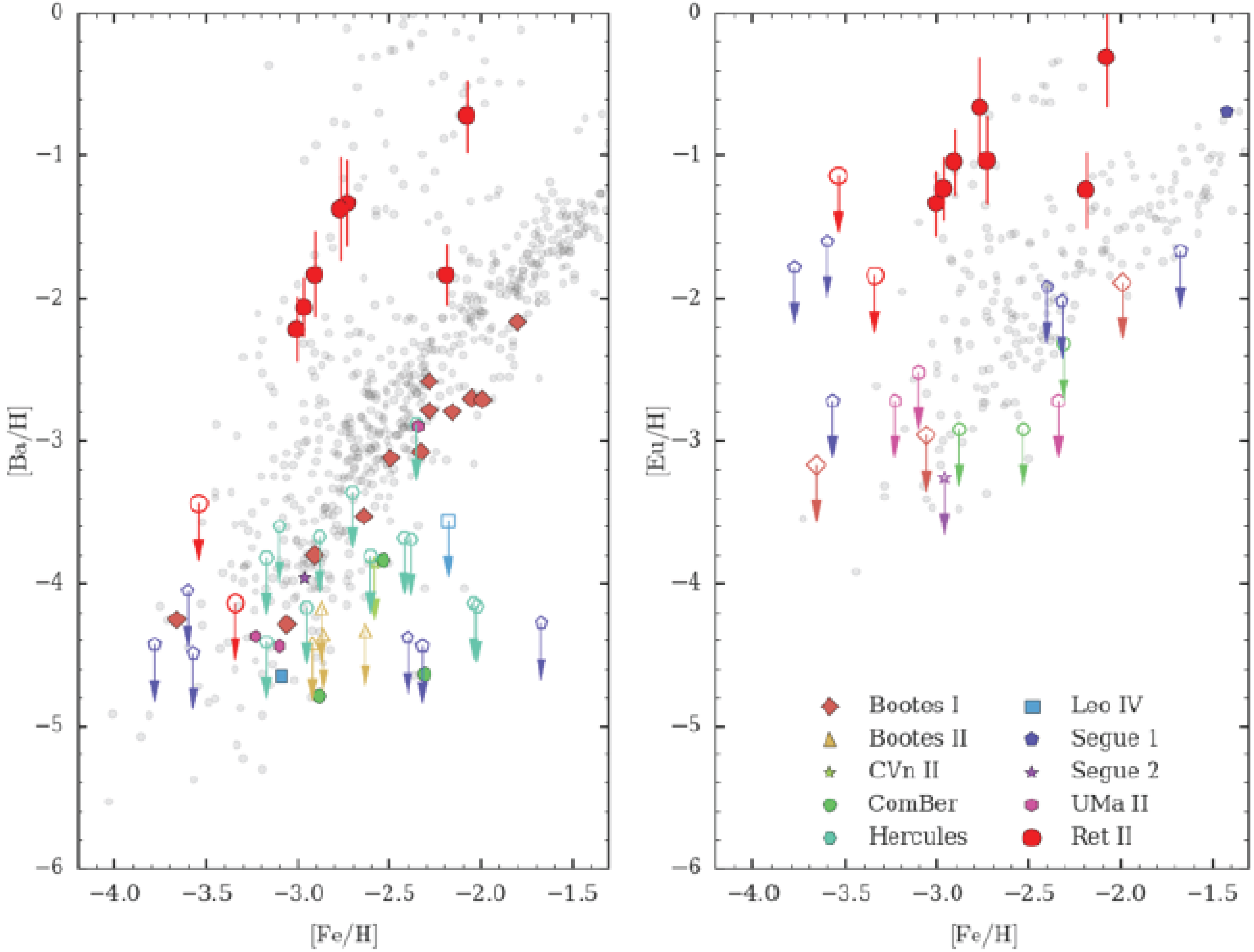
Frebel and collaborators

Stars in the First Nine UFDs with High-Resolution Spectroscopy had LOW n-capture Elements



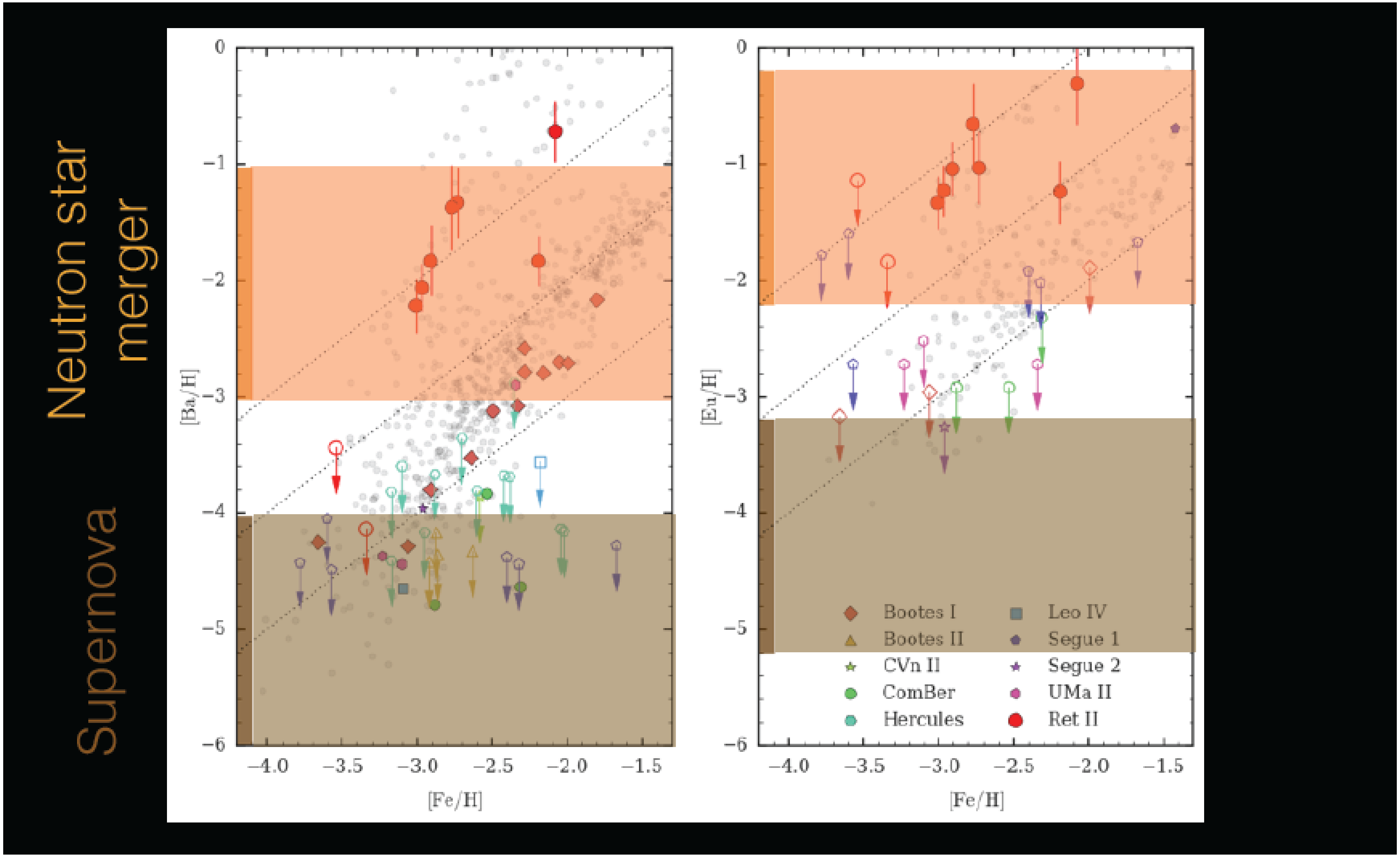
Frebel and collaborators

Along Comes Reticulum II -> 100 Times Higher n-capture Elements than Other UFDs



Frebel and collaborators

Reticulum II Abundances Consistent with Neutron Star Merger Origin



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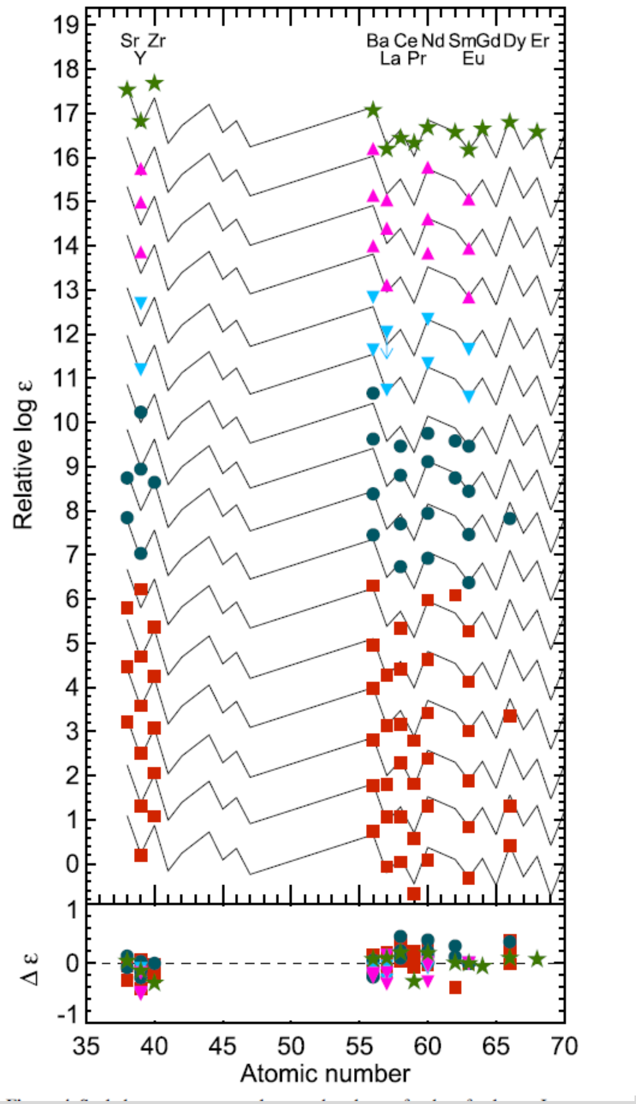
Winteler et al. (2012)

What About r-I Stars ?

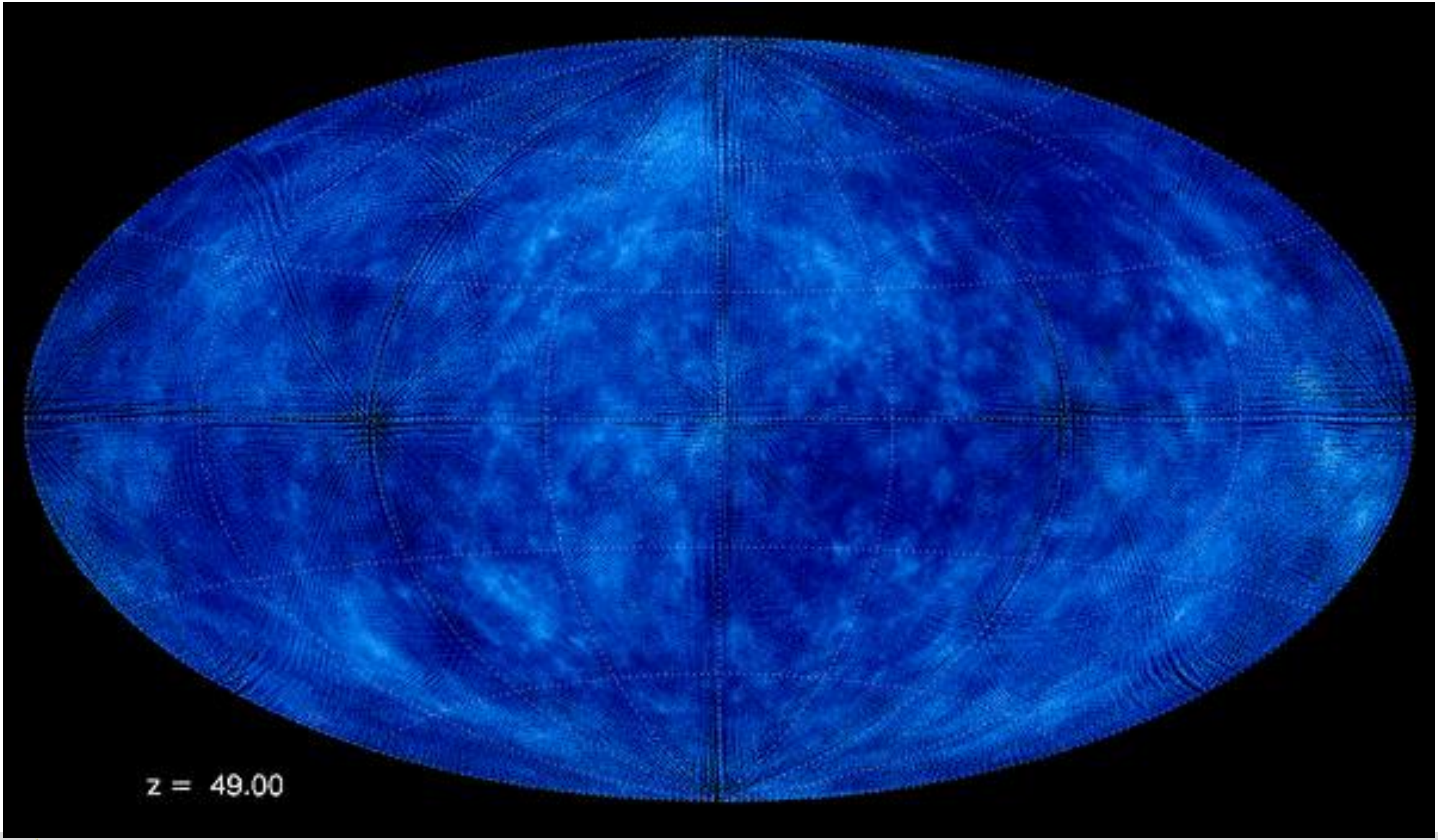
There are r-I stars found in other dwarf galaxies, most recently the UFD Tuc III, but also in the "canonical dwarfs" including Carina, Draco, and Sculptor, of higher baryonic mass.

Note comparison to pattern of r-II star CS 22892-052



T. Hansen et al. (2017)

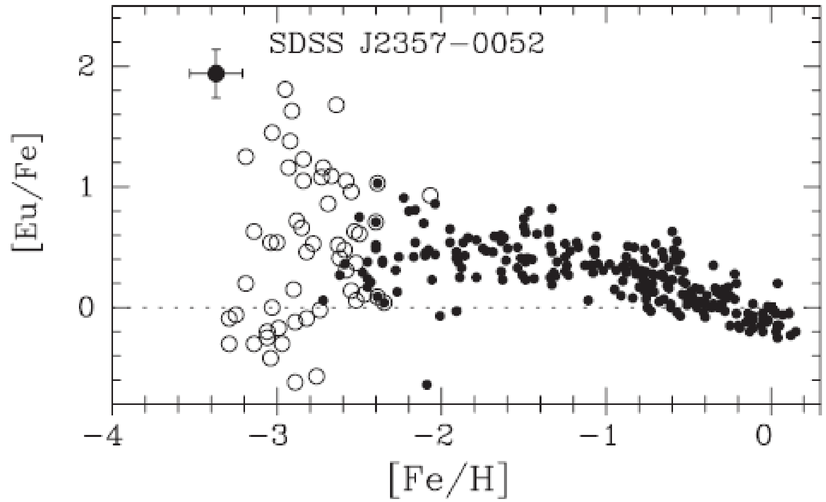
Assembly History of the Milky Way



Courtesy J. Tumlinson

They are Found in ALL Stages of Stellar Evolution

- Until recently, all of the r-II stars known were red giants, allowing for the possibility that some peculiar atmospheric effect was the cause for the apparent excess of r-process elements. This is now precluded by observation
  - Aoki et al. (2010) – Discovery of r-II nature for a cool, main-sequence dwarf, SDSS J2357-0052 (Teff = 5000 K, [Fe/H] = -3.4, [Eu/Fe] = +1.9)
  - Roederer et al. (2014) – Discovery of r-I and r-II stars in the subgiant and red horizontal-branch evolutionary stage

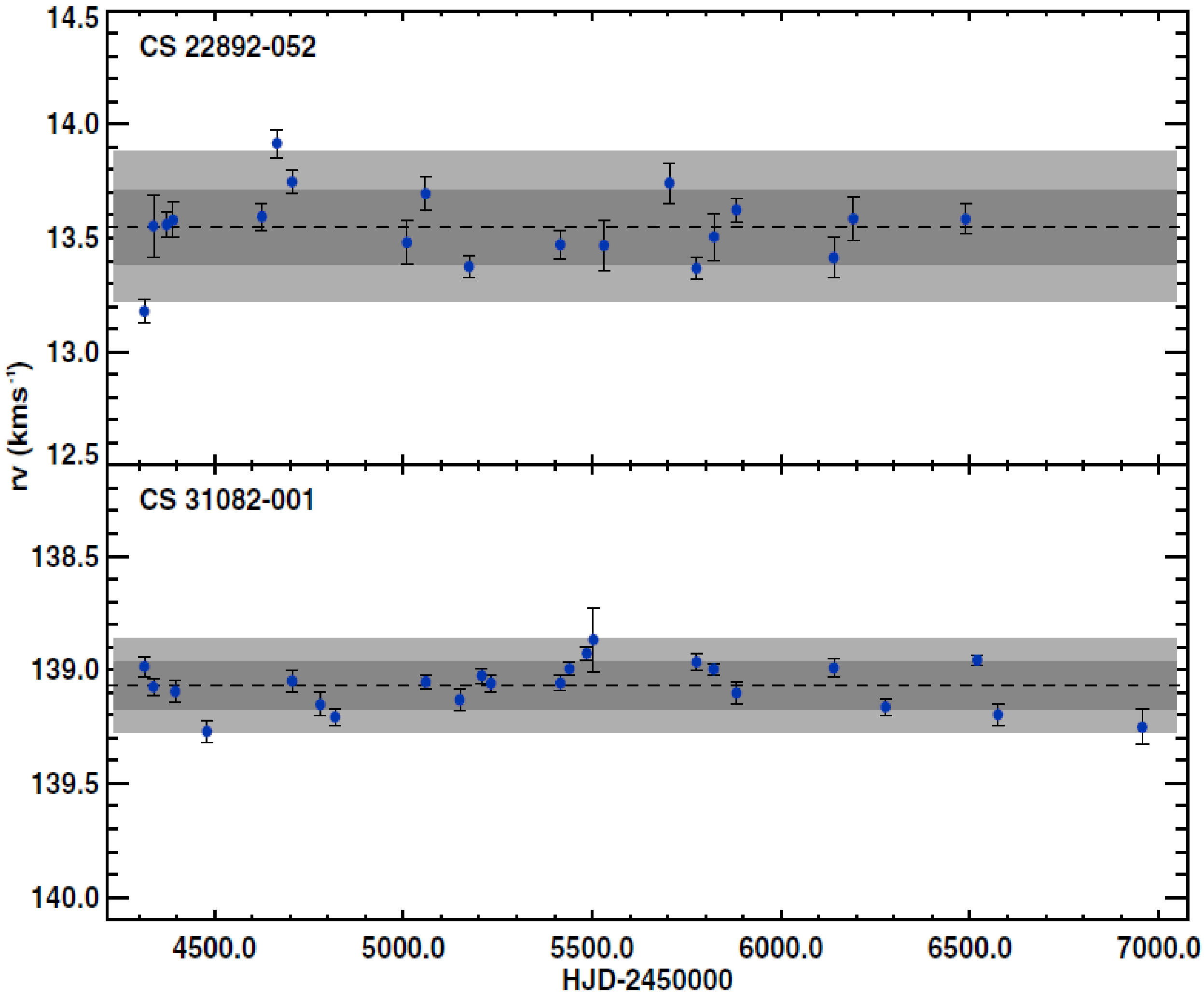


Aoki et al. (2010)

They are not (Required to be) Binaries

- Although a number of authors (Wanajo and collaborators, Qian & Wasserberg, others) have considered the possibility of mass-transfer of r-process-enhanced material from a binary companion, this is now rejected based on long-term radial velocity monitoring of r-II (and r-I) stars
- Hansen et al. (2015) – The binary fraction of such stars is only 18%, consistent with the observed binary fraction of other metal-poor halo stars, including two canonical examples, CS 22892-052 and CS 31082-001
- Observations conducted over temporal window of 8-10 years, using the NOT 2.5m telescope and FIES spectrograph, with precision (and accuracy) on the order of 50-100 m/s

They are not (Required to be) Binaries



Hansen, T.T. et al. (2015)

They are Exquisitely Rare but Display Surprisingly Uniform Heavy-Element Patterns

- The r-II stars are the rarest of the rare among metal-poor stars in the halo of the Milky Way
  - About 25-30 r-II stars have been found in the field over the past 25 years since their recognition
  - Only 3% (at most 5%) of very metal-poor stars (VMP, [Fe/H] < -2) are r-II stars
  - About 15% are r-I (5 times greater frequency)
- This argues for their creation by relatively rare progenitors, compared to the progenitors of "normal" VMP stars
- The "universality" of the r-process-element abundance pattern (identical to the Solar pattern) among 2^{nd} and 3^{rd} peak elements suggests a single progenitor population, rather than a collection of different progenitors mixed together

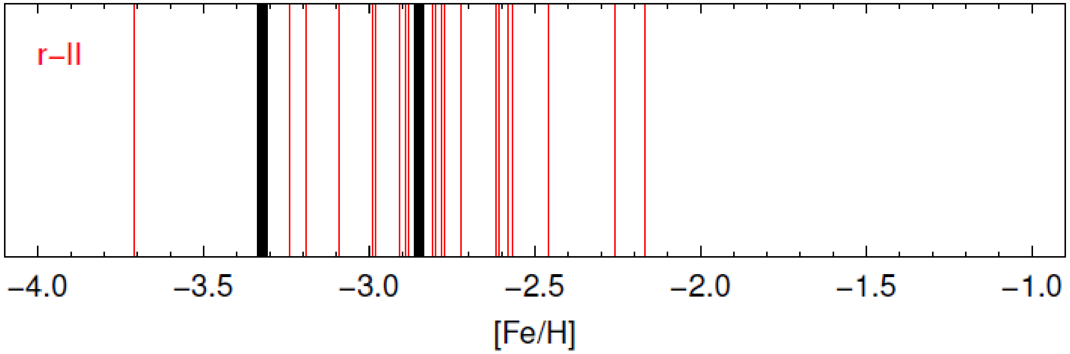
Interpretation of the r-II MDF and Enhancement Range

- The r-II stars preferentially occupy the metallicity range -3.5 < [Fe/H] < -2.0, the same range covered by the VMP and EMP stars found in the UFDs
- The range of r-process-element enhancement among the halo stars matches that of the r-II stars found in the Ret-II UFD

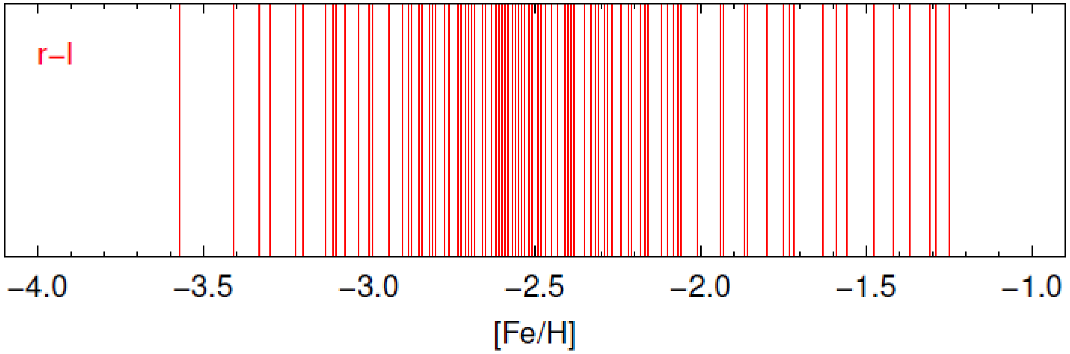
This evidence strongly suggests that the UFD environment is their likely formation site, followed by accretion into the halo

The r-II Stars and r-I Stars Exhibit Different Metallicity Distribution Functions (MDFs)

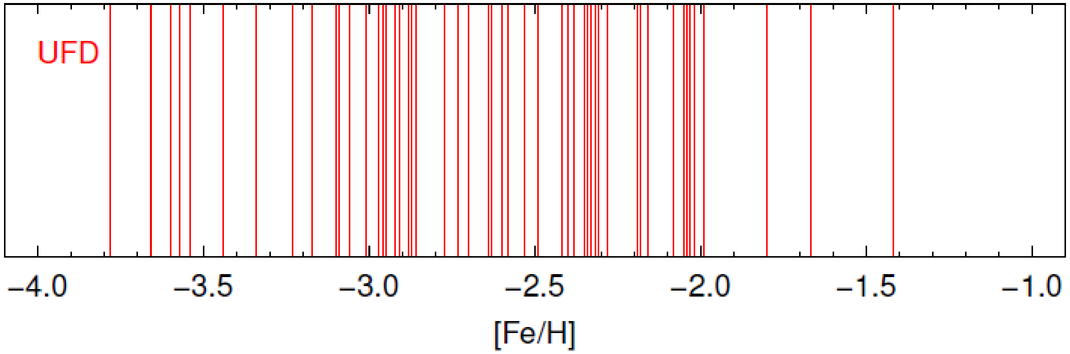
N = 24



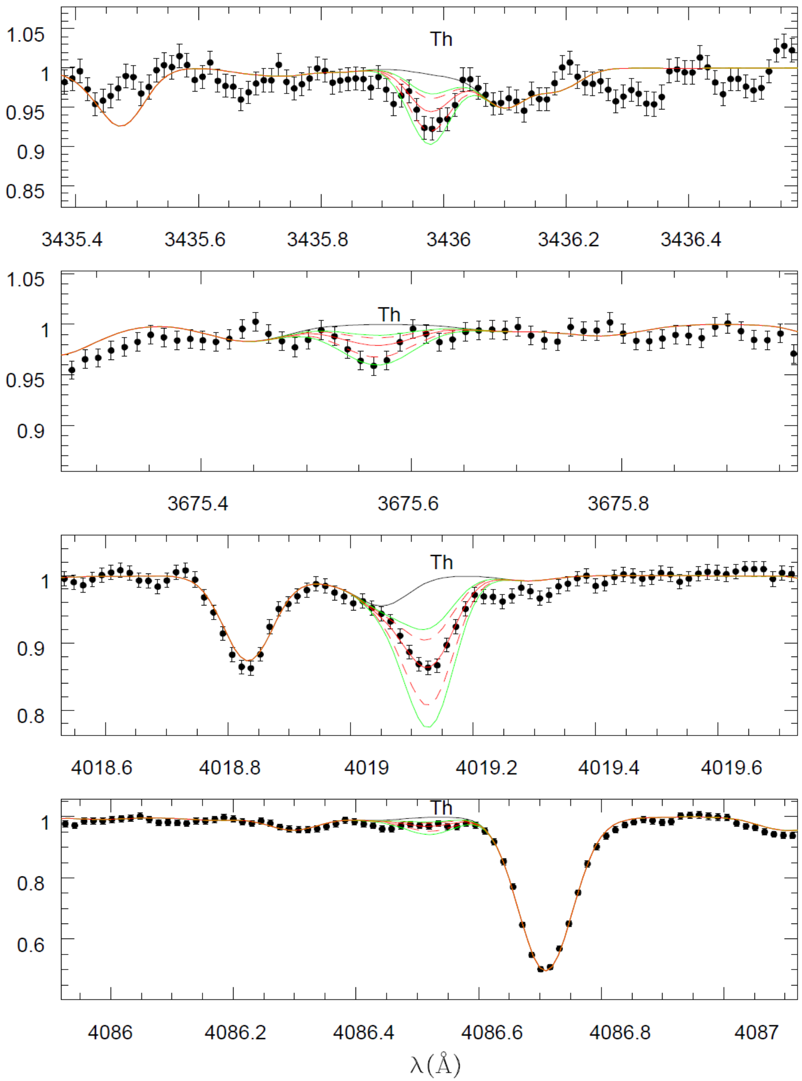
N = 133

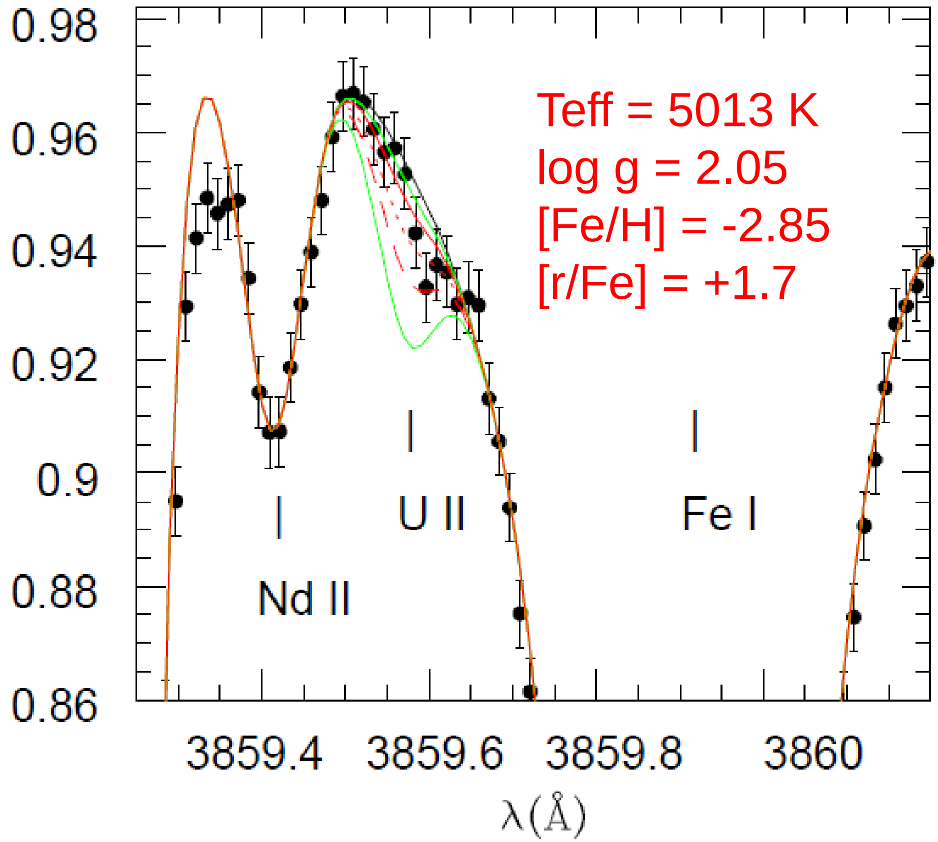


N = 55



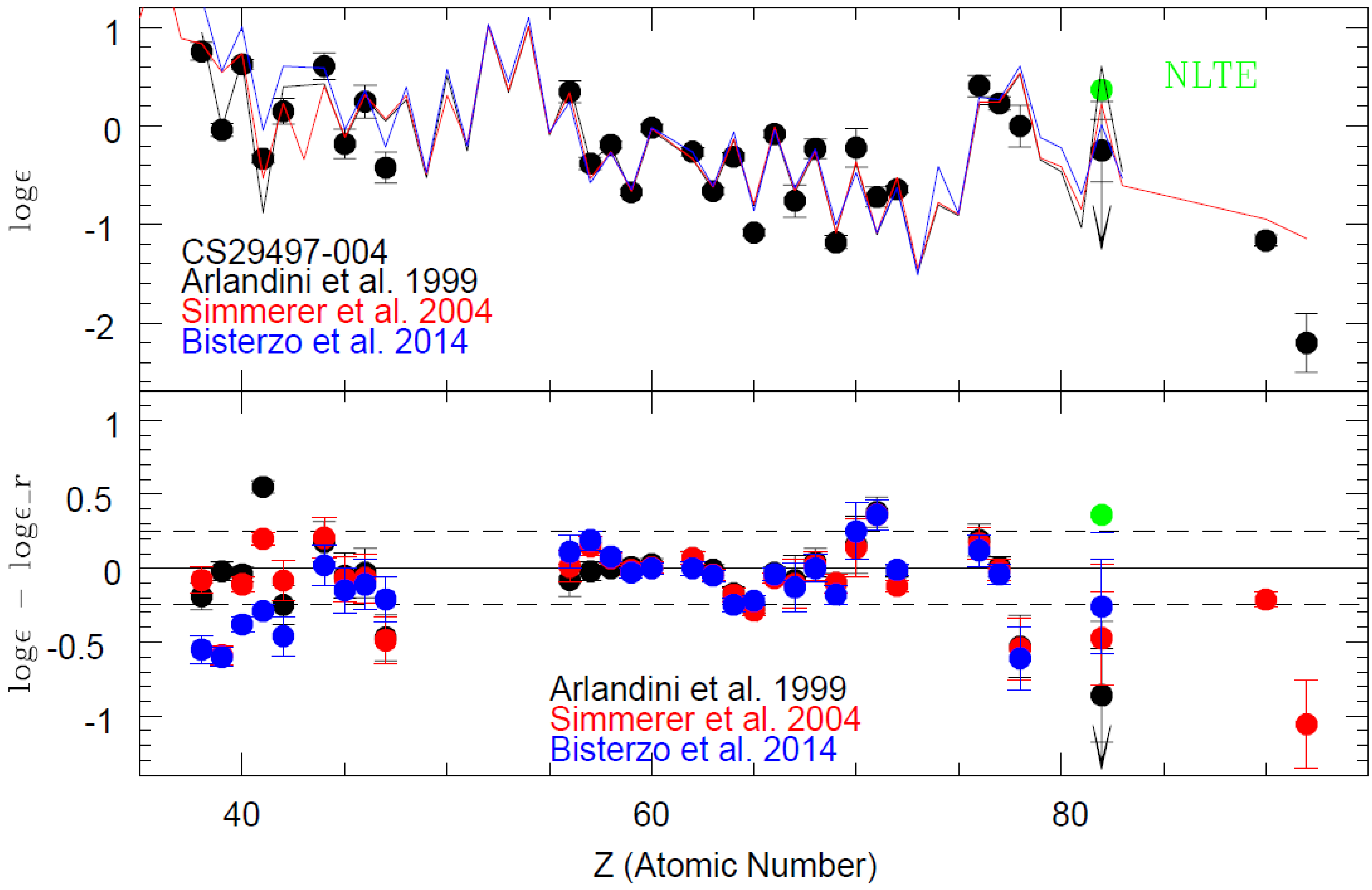
VLT Observations of a new r-II Star with Th and U – CS 29497-004





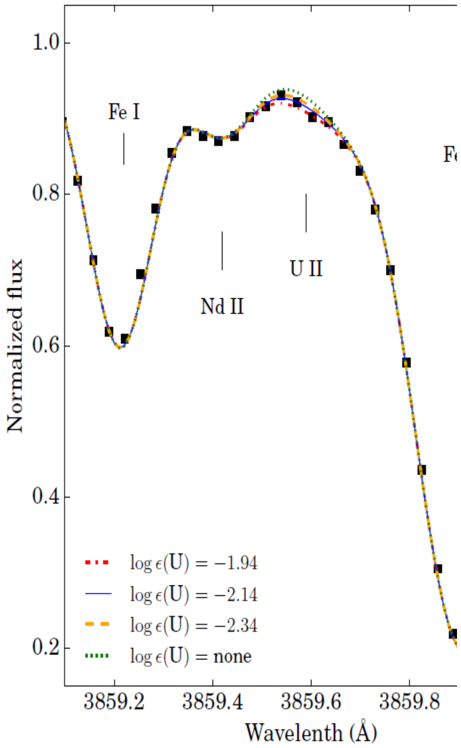
Hill et al. (2017)

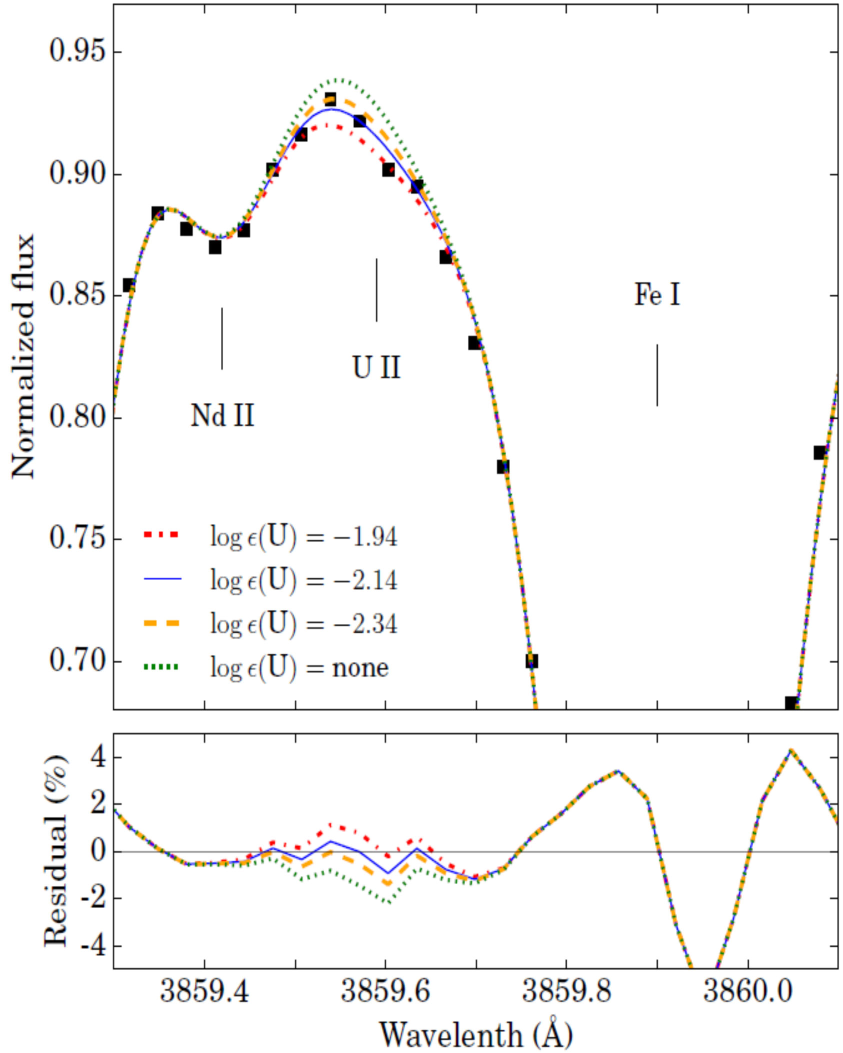
VLT Observations of a new r-II Star with Th and U – CS 29497-004

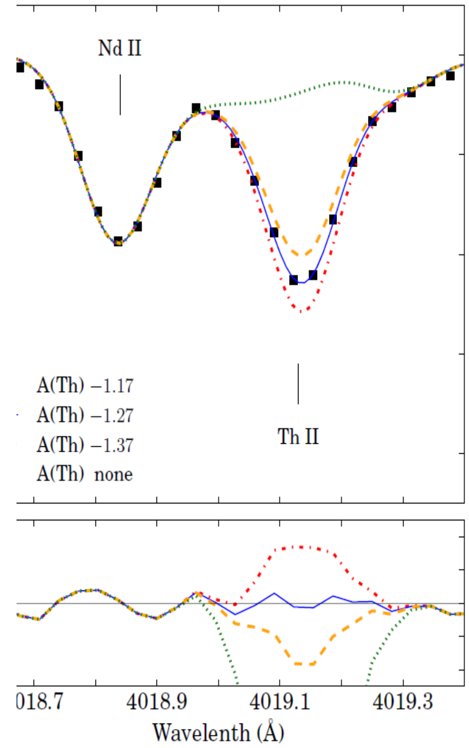


Hill et al. (2017)

Magellan Observations of a new r-II Star with Th and U – RAVE 2038-0023







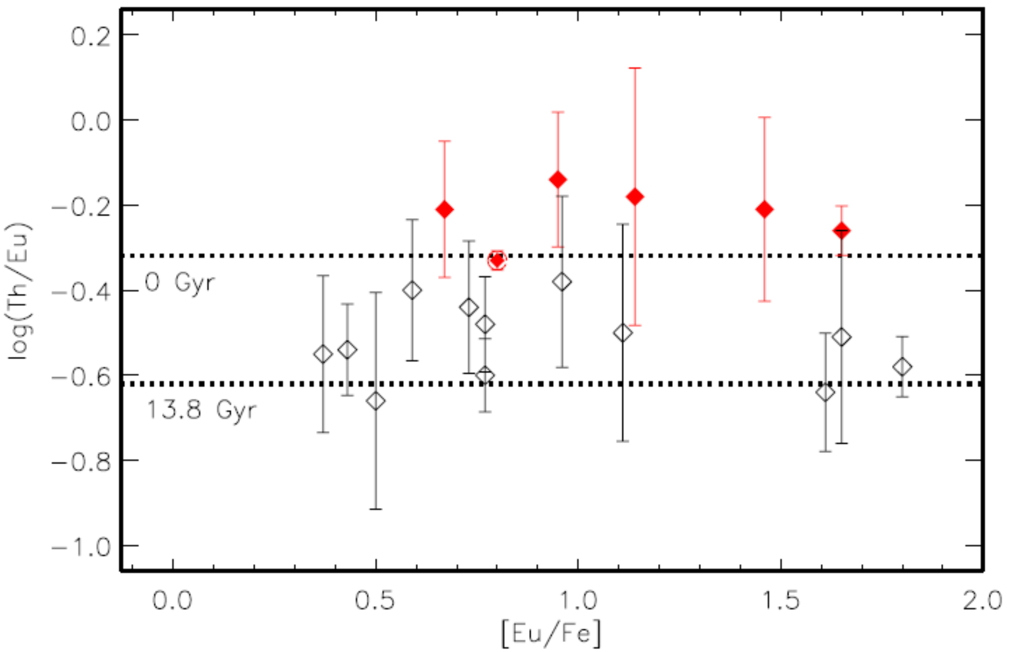
Teff = 47

[r/Fe] = +1.6

Placco et al. (2017)

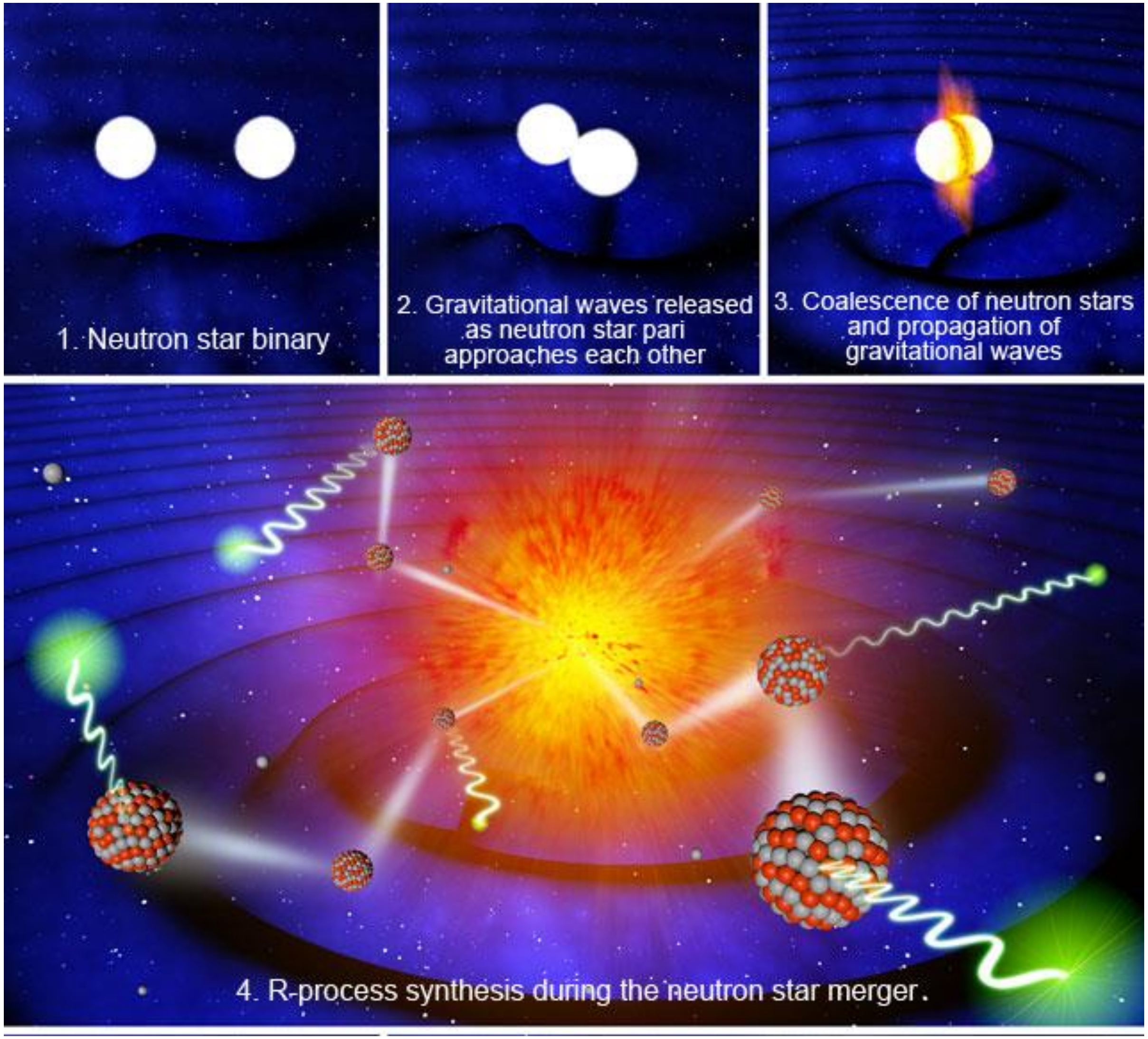
Presence of the Actinide Boost Among r-II Stars – What does it mean ?

- Observed differences in the abundance patterns of actinides (Th, U) in r-II stars
  - About 1/3rd of r-II stars exhibit an actinide boost
  - Provides a hint that, if there is a single class of progenitors, there must be variations within that class



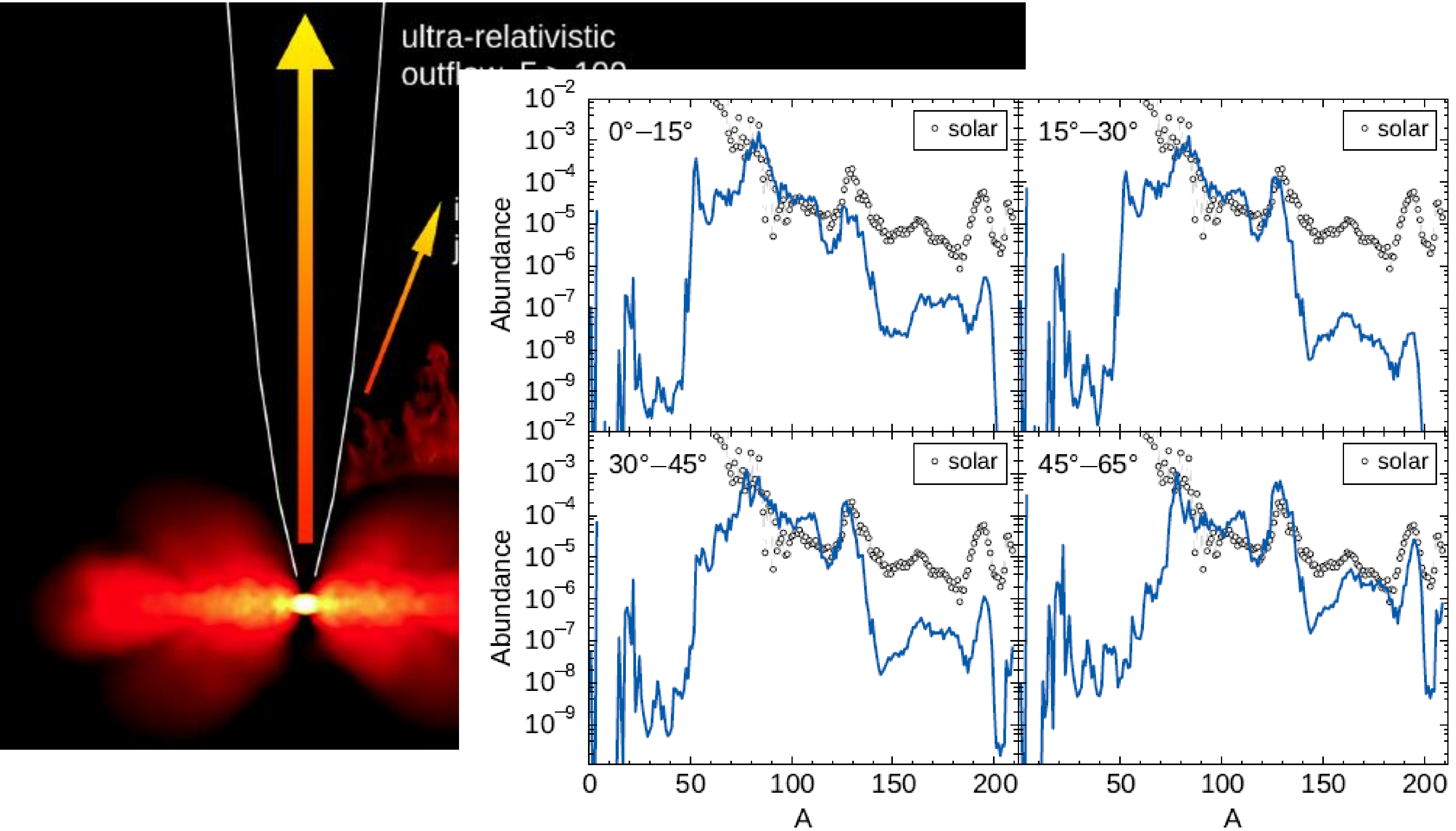
Mashonkina et al. (2014)

Presence of the Actinide Boost Among r-II Stars – Variations in a Single Source



NAOJ (2014)

Presence of the Actinide Boost Among r-II Stars – Variations in a Single Source



Martin et al. (2015)

One More Thing …

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http://vis.sciencemag.org/breakthrough2017/

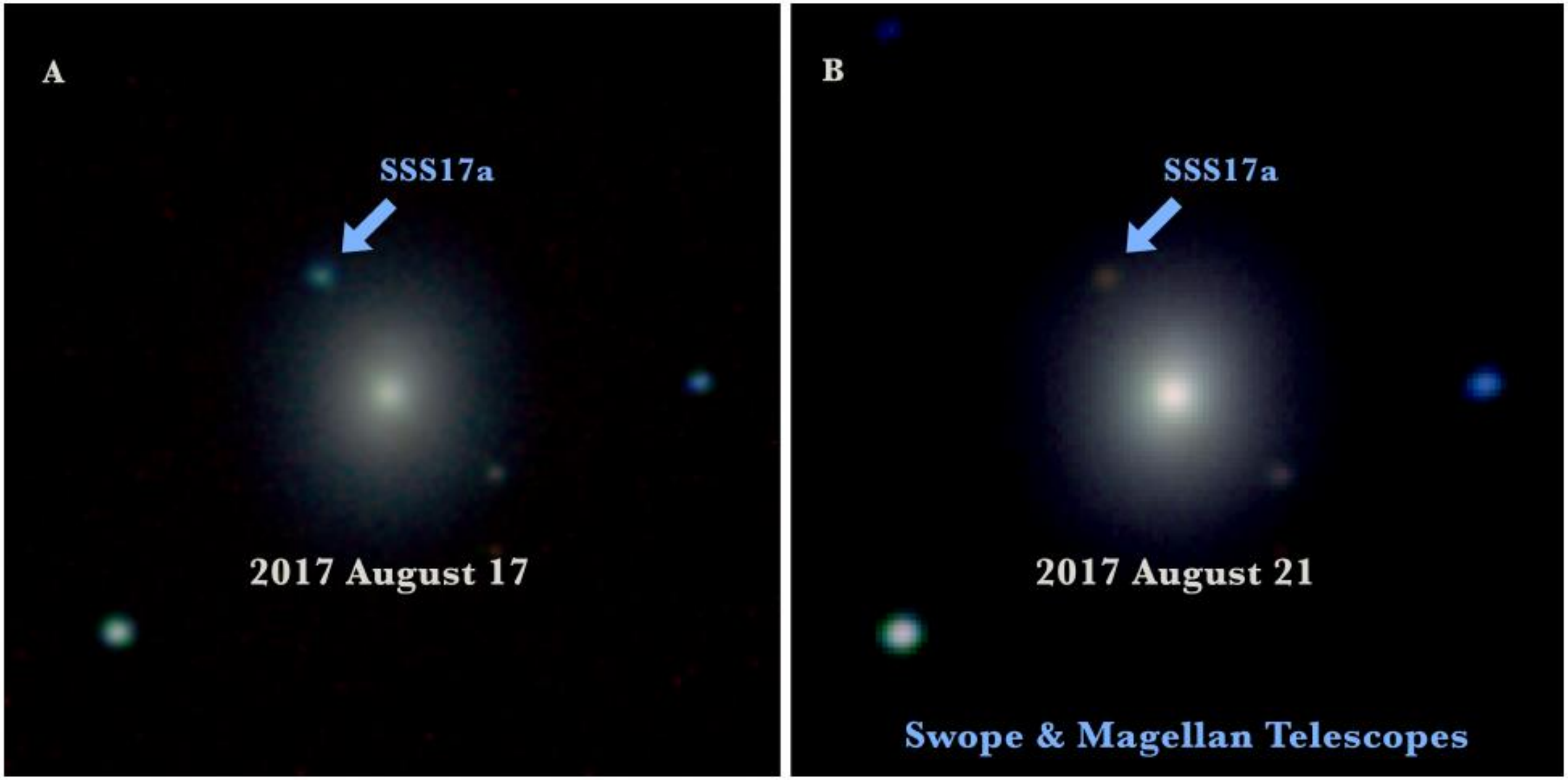
https://youtu.be/e_uIOKfv710

One More Thing …

Light Curves of the Neutron Star Merger GW170817/SSS17a: Implications for R-Process Nucleosynthesis

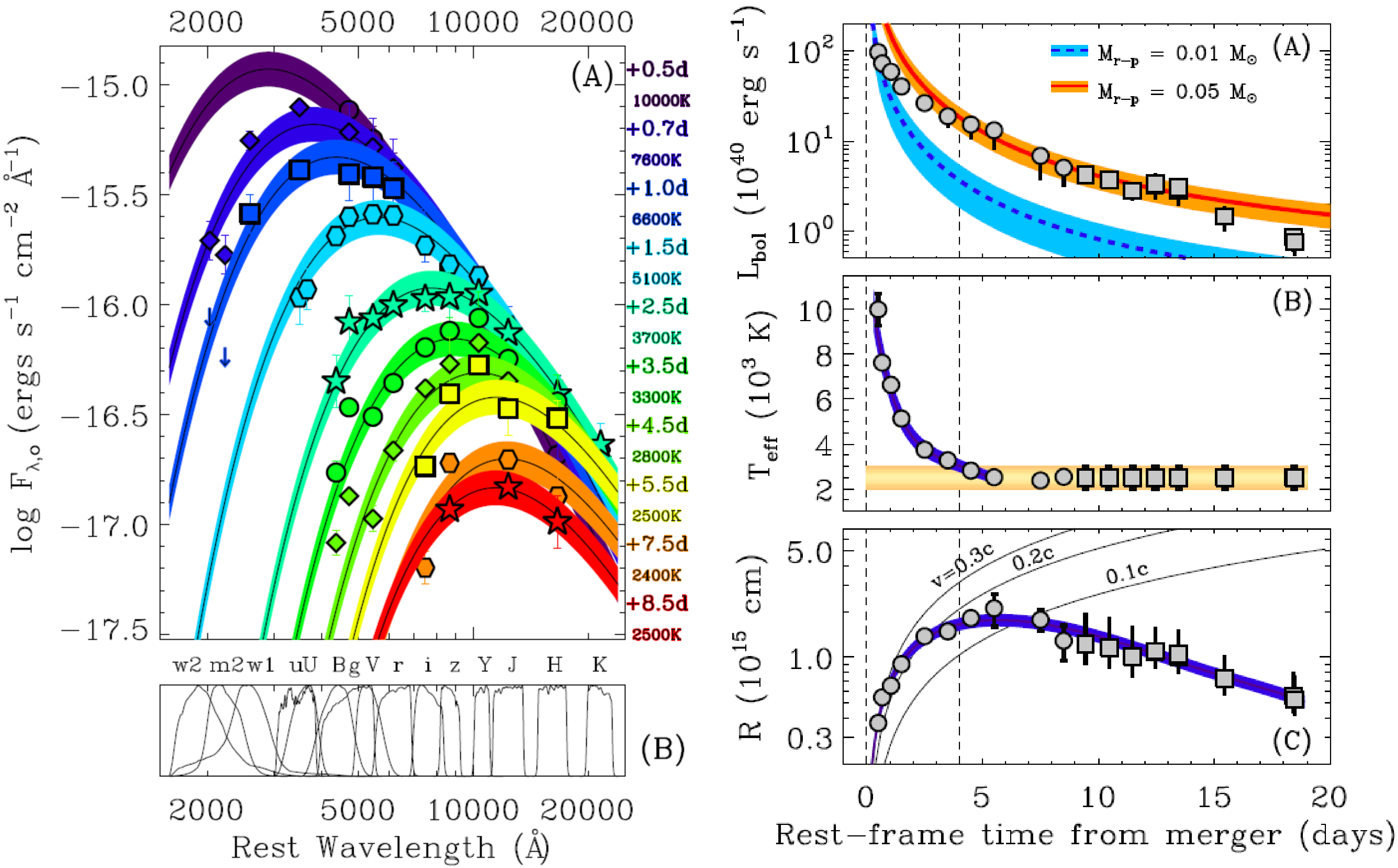
M. R. Drout,[1*] A. L. Piro,[1] B. J. Shappee,[1,2] C. D. Kilpatrick,[3] J. D. Simon,[1] C. Contreras,[4] D. A. Coulter,[3] R. J. Foley,[3] M. R. Siebert,[3] N. Morrell,[4] K. Boutsia,[4] F. Di Mille,[4] T. W.-S. Holoien,[1] D. Kasen,[5,6] J. A. Kollmeier,[1] B. F. Madore,[1] A. J. Monson,[1,7] A. Murguia-Berthier,[3] Y.-C. Pan,[3] J. X. Prochaska,[3] E. Ramirez-Ruiz,[3,8] A. Rest,[9,10] C. Adams,[11] K. Alatalo,[1,9] E. Bañados,[1] J. Baughman,[12,13] T. C. Beers,[14,15] R. A. Bernstein,[1] T. Bitsakis,[16] A. Campillay,[17] T. T. Hansen,[1] C. R. Higgs,[18,19] A. P. Ji,[1] G. Maravelias,[20] J. L. Marshall,[21] C. Moni Bidin,[22] J. L. Prieto,[13,23] K. C. Rasmussen,[14,15] C. Rojas-Bravo,[3] A. L. Strom,[1] N. Ulloa,[17] J. Vargas-González,[4] Z. Wan,[24] D. D. Whitten[14,15]

One More Thing …



Images taken on the night of 2017 August 17, 0.5 days after the merger. **(B)** Images taken on the night of 2017 August 21, 4.5 days after the merger. Over four days SSS17a both faded and became redder.

One More Thing …



Identification of the Astrophysical Site(s) of the r-Process

- All of the above issues (and others) require a significant increase in the numbers of known r-II (and r-I) stars in the halo, enabling statistical studies of the frequencies of various abundance signatures that constrain models for their progenitors
  - Goal is to quadruple the number of known r-II stars, ~25 → ~100-125
  - Numbers of known r-I stars will increase as well, ~125 → ~375-500
- This effort has now begun, using a first-pass high-resolution spectroscopic survey of bright very metal-poor (VMP; [Fe/H] < -2) and extremely metal-poor (EMP; [Fe/H] < -3) stars identified by the medium-resolution survey efforts
- Recall: r-II stars represent only about 3-5% of all VMP/EMP stars

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

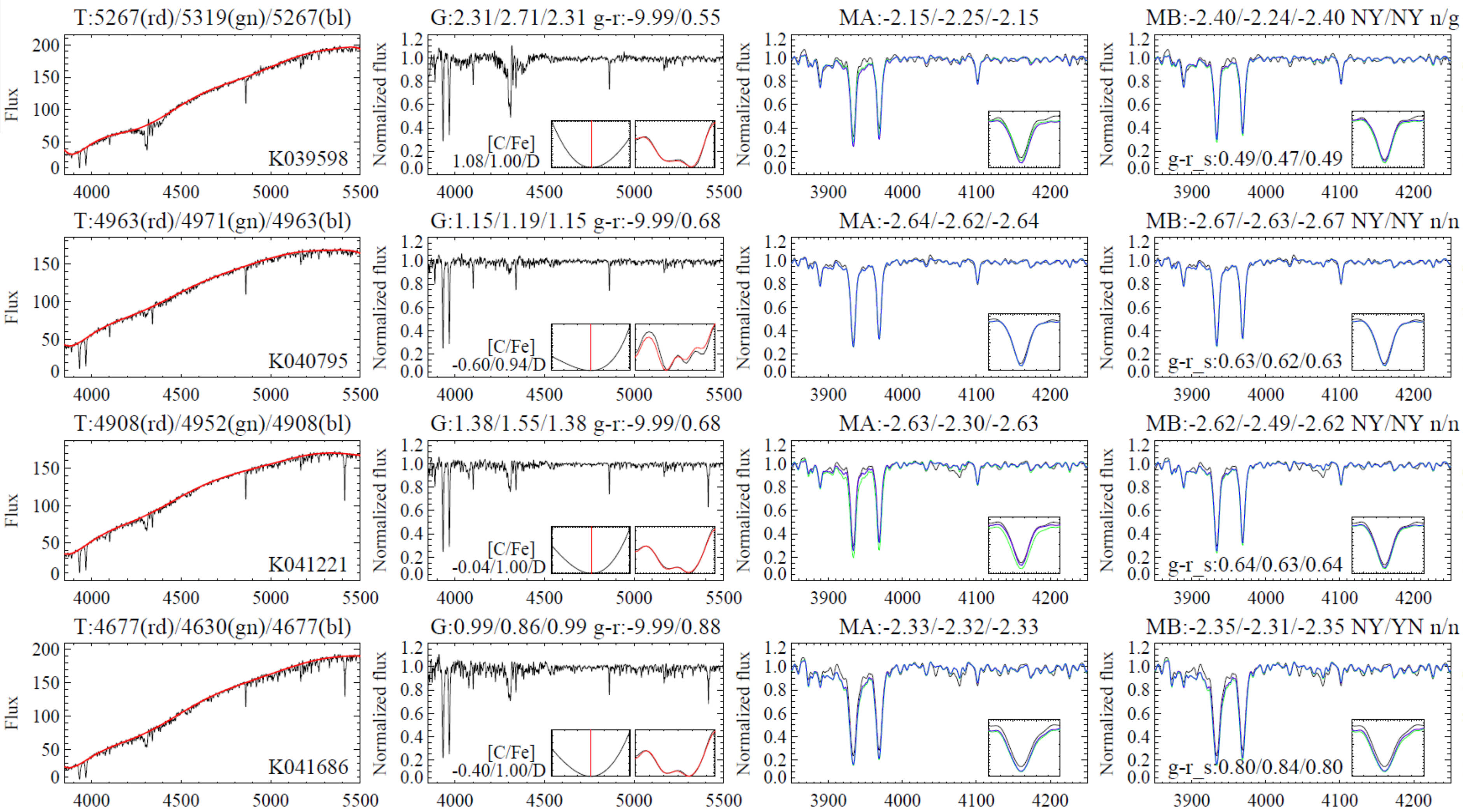
- Multiple survey efforts underway to accomplish this:
  - Medium-res spectroscopic follow-up of RAVE survey stars claimed to have [Fe/H] < -2.0, with 10 < V < 14 (ESO/NTT + SOAR + LNA + McDonald)
  - Medium-res spectroscopic follow-up of "Best & Brightest" candidates using Gemini 8m bad weather time + 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), Pontificia Universidad Chile (PUC), Univ. of Concepcion, CTIO, etc.

When the Weather Turns Bad ☺

Gemini-S 8m Telescope (Chile)

Gemini-N 8m Telescope (Hawaii)



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

Placco et al. (in press)

Identification of the Astrophysical Site(s) of the r-Process

Baseline plan is for "snapshot" high-resolution observations with the du Pont 2.5m telescope on Las Campanas (Chile), operated by the Carnegie Observatory (in collaboration with Hansen)

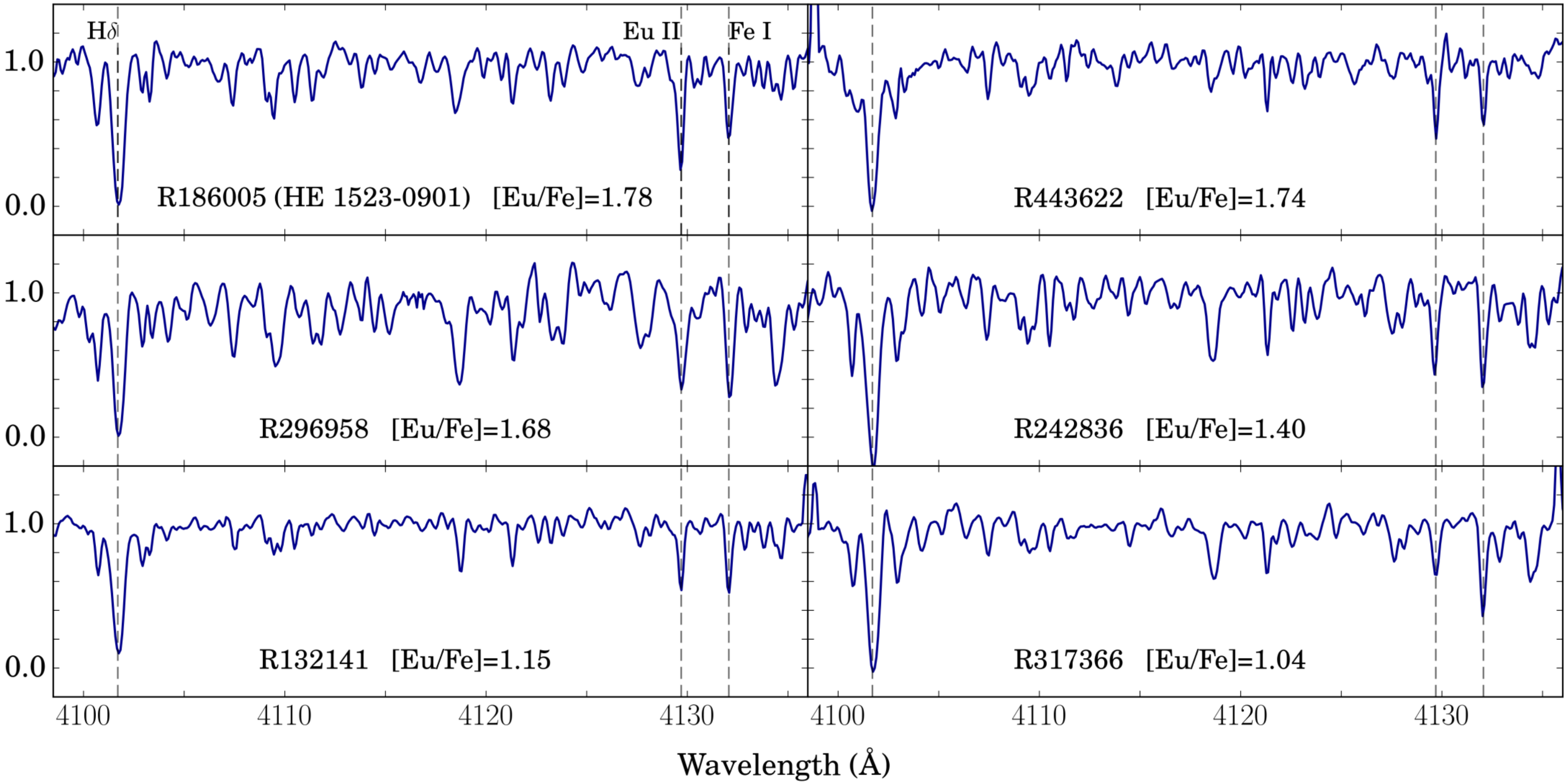
- Echelle spectrograph upgraded using Carnegie Observatory funds
- Pilot survey of ~100 candidates successful (Sep. 2016) – total now ~ 750 stars
- Full survey of ~1500-2000 candidates over next two years

Additional snapshot spectroscopy

- APO 3.5m (New Mexico, in collaboration with Charli Sakari)
- Magellan 6.5m (Chile, in collaboration with Frebel, Roederer, Hansen)
- McDonald 2.7m (in collaboration with Sneden, Marshall -- HET soon)
- SOAR 4.1m telescope (Chile) ← STELES under commissioning soon!

Additional higher resolution, higher S/N observations (portrait spectroscopy) to be taken of best r-II (and r-I) stars to be obtained with Magellan, Gemini/GHOST, VLT, etc., for measurement of precise Th and U abundances, among many others. HST a possibility if sufficiently bright

New r-II Stars from the Pilot Survey of Snapshot High-Resolution Spectroscopy



10 new r-II stars (40% increase) / ~50 new r-I stars (30% increase)

New r-II Stars from the Pilot Survey of Snapshot High-Resolution Spectroscopy

THE R-PROCESS ALLIANCE: FIRST RELEASE FROM THE SOUTHERN SEARCH FOR *R*-PROCESS-ENHANCED STARS IN THE GALACTIC HALO*

Terese T. Hansen,[1] Erika M. Holmbeck,[2,3] Timothy C. Beers,[2,3] Vinicius M. Placco,[2,3] Ian U. Roederer,[4,3] Anna Frebel,[5,3] Charli M. Sakari,[6] Joshua D. Simon,[1] and Ian B. Thompson[1]

The recent detection of a binary neutron star merger and the clear evidence for the decay of radioactive material observed in this event have, after 60 years of effort, provided an astrophysical site for the rapid neutron-capture (r-) process, which is responsible for the production of the heaviest elements in our universe. However, observations of metal-poor stars with highly-enhanced r-process elements have revealed abundance patterns suggesting that multiple sites may be involved. To address this issue, and advance our understanding of the r-process, we have initiated an extensive search for bright ($V < 13.5$) metal-poor stars in the Milky Way halo exhibiting strongly-enhanced r-process signatures. This paper presents the first sample collected in the Southern Hemisphere. We have observed and analyzed 108 stars, and find 12 stars that are strongly enhanced in heavy r-process elements, 42 stars with moderate enhancements of heavy r-process material, and 19 stars that exhibit low abundances of the heavy r-process elements and higher abundances of the light r-process elements relative to the heavy ones. This search is more successful at finding r-process-enhanced stars compared to previous searches, primarily due to a refined target-selection procedure.

Hansen et al. (2018)

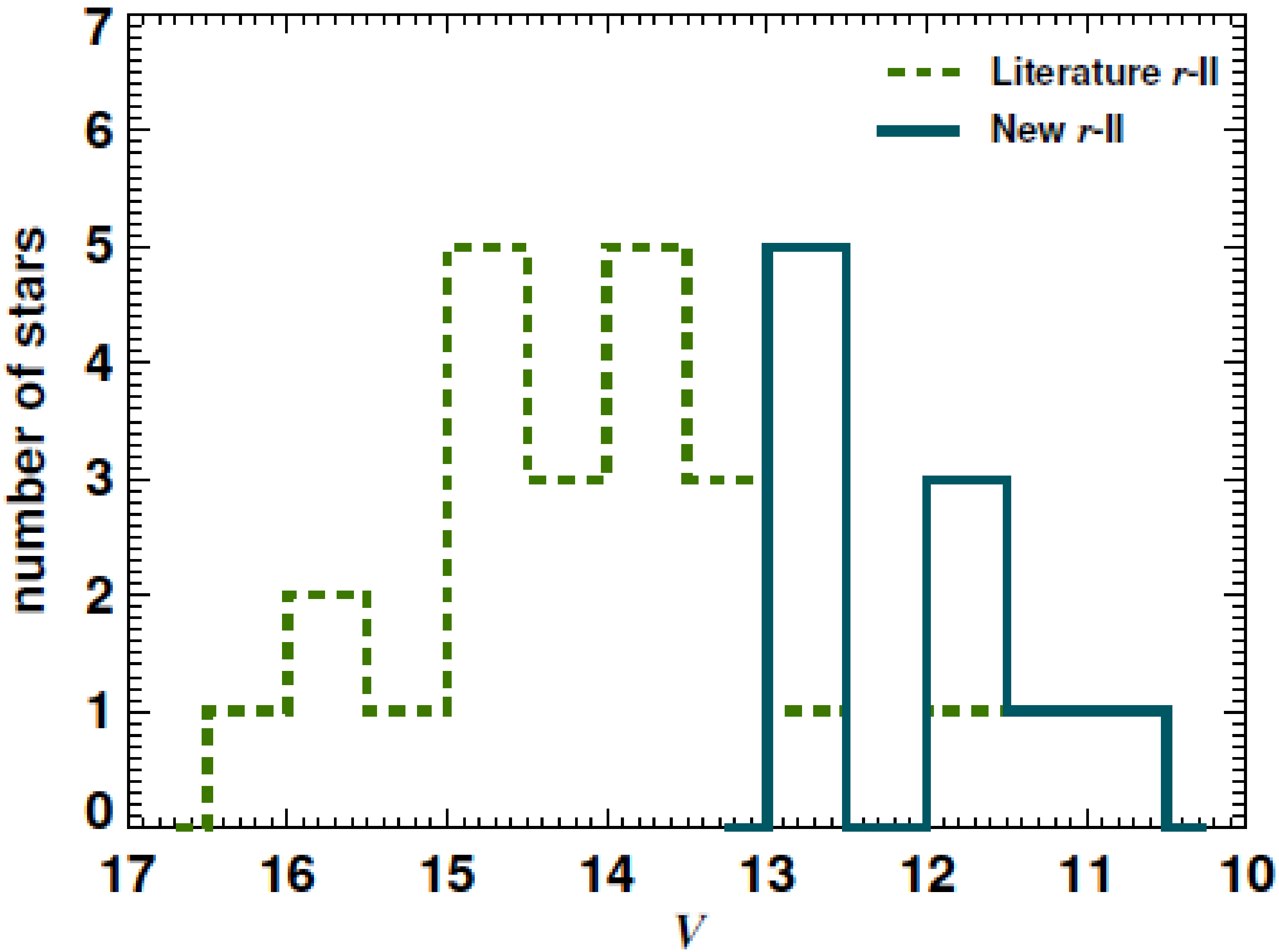
New r-II Stars from the Pilot Survey of Snapshot High-Resolution Spectroscopy

Table 4. Abundances

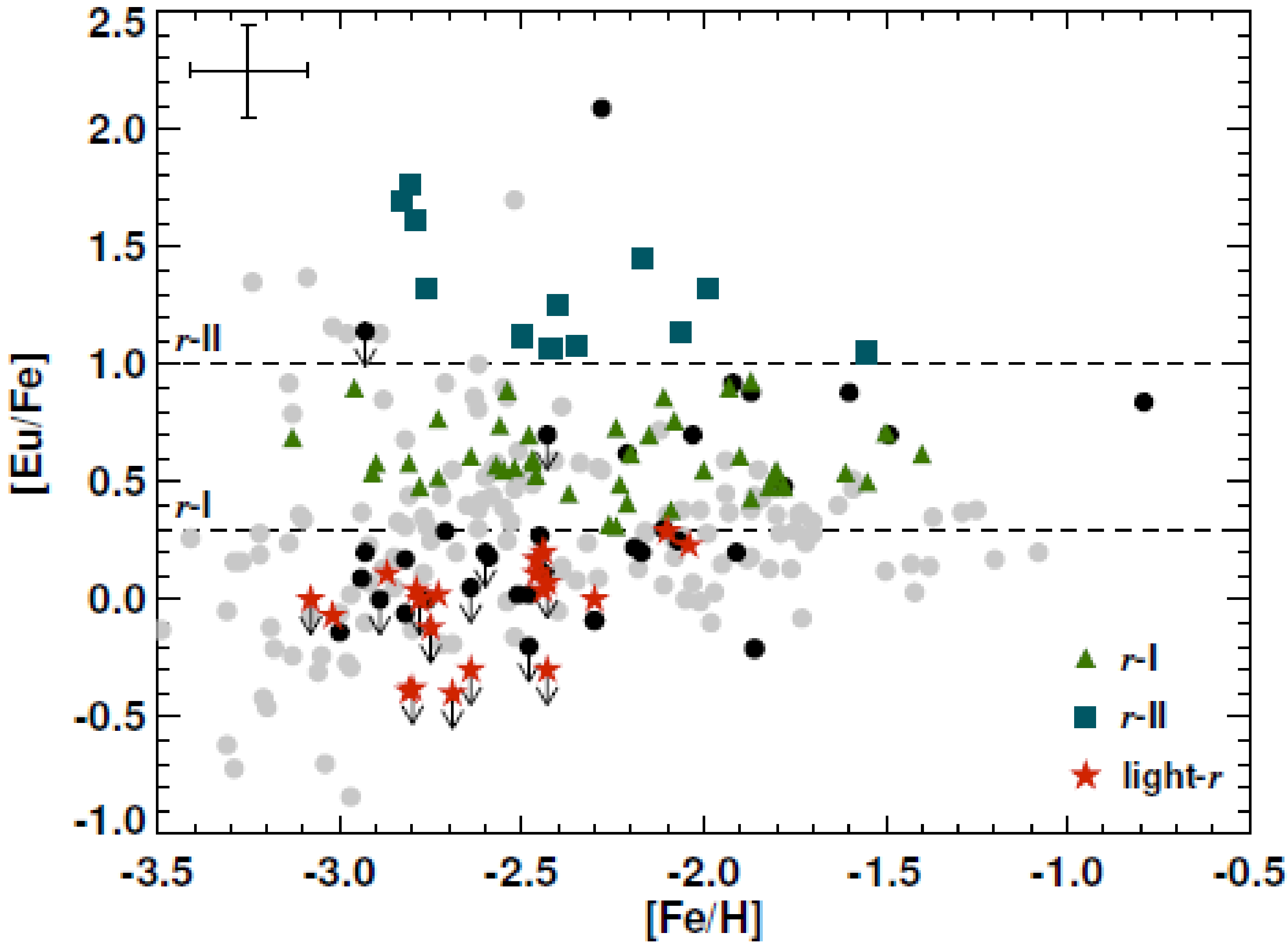
2MASS ID	[Fe/H]	[C/Fe]	[Sr/Fe]	[Ba/Fe]	[Eu/Fe]	[Ba/Eu]	[Sr/Ba]	Sub-class
J00002259−1302275	−2.90	−0.65	−1.20	−0.38	+0.58	−0.96	−0.82	*r*-I
J00021222−2241388	−2.19	−0.19	−0.13	−0.41	+0.22	−0.63	+0.28	
J00021668−2453494	−1.81	−0.88	+0.59	+0.10	+0.52	−0.42	+0.49	*r*-I
J00133067−1259594	−2.82	−0.58	−0.25	−0.55	−0.06	−0.49	+0.30	
J00233067−1631428	−2.45	+0.37	−0.75	−0.55	$<$ +0.27	$>$ −0.82	−0.20	Unknown
J00400685−4325183	−2.55	−0.85	−1.52	−1.56	+0.55	−2.11	+0.04	*r*-I
J00405260−5122491	−2.11	−0.04	+0.09	−0.04	+0.86	−0.90	+0.13	*r*-I
J00453930−7457294	−2.00	+0.93	+0.83	+0.37	+0.55	−0.18	+0.46	*r*-I
J01202234−5425582	−2.11	−0.09	+0.50	+0.16	+0.30	−0.14	+0.34	*r*-I
J01293113−1600454	−2.81	+0.35	+0.88	+0.95	+1.76	−0.81	−0.07	*r*-II
J01334657−2727374	−1.60	+1.64	+1.40	+1.61	+0.88	+0.73	−0.21	CEMP-*s*
J01425422−5032488	−2.09	+0.07	+0.13	−0.13	+0.38	−0.51	+0.26	*r*-I
J01430726−6445174	−3.00	−0.14	−1.00	−0.51	−0.14	−0.37	−0.49	
J01451951−2800583	−2.80	−0.69	+0.30	−0.98	$<$ −0.38	$>$ −0.60	+1.28	light-*r*

+ ~ 95 more

New r-II Stars from the Pilot Survey of Snapshot High-Resolution Spectroscopy



New r-II Stars from the Pilot Survey of Snapshot High-Resolution Spectroscopy



New r-II Stars with Portrait High-Resolution Spectroscopy

- J1538-1804 – V = 10.9, [Fe/H] = –2.1 (Portrait by Magellan 6.5m)

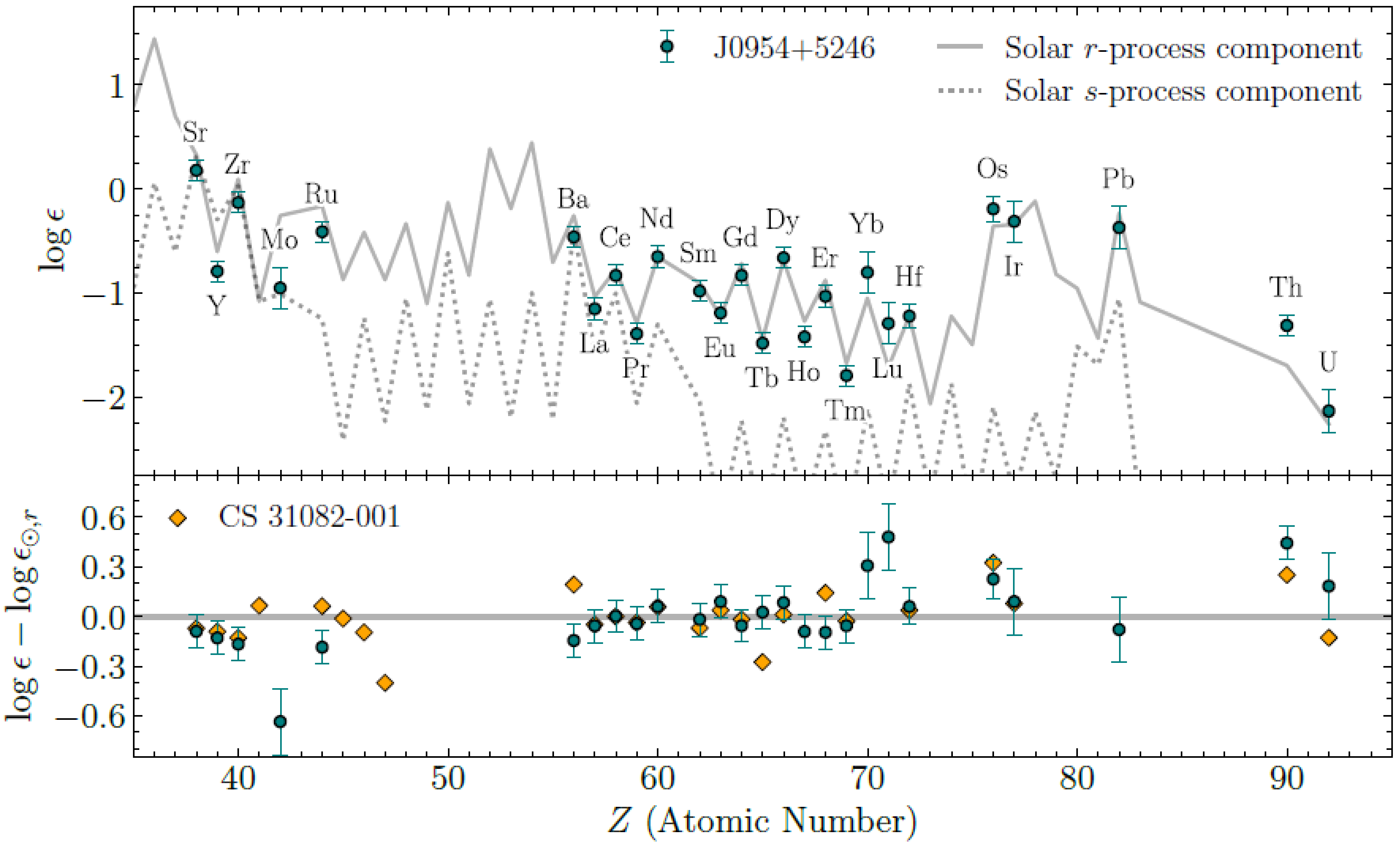
  - One of the brightest r-II star known
  - One of most metal-rich r-II stars yet found
  - No actinide boost
  - Sakari et al. (2018)

- J0954+5246 – V = 10.1, [Fe/H] = –3.1, (Portrait by McDonald 2.7m)

  - THE brightest r-II star known
  - One of the highest [Th/Eu] stars yet found
  - Highest actinide boost yet found
  - Holmbeck et al. (in press)

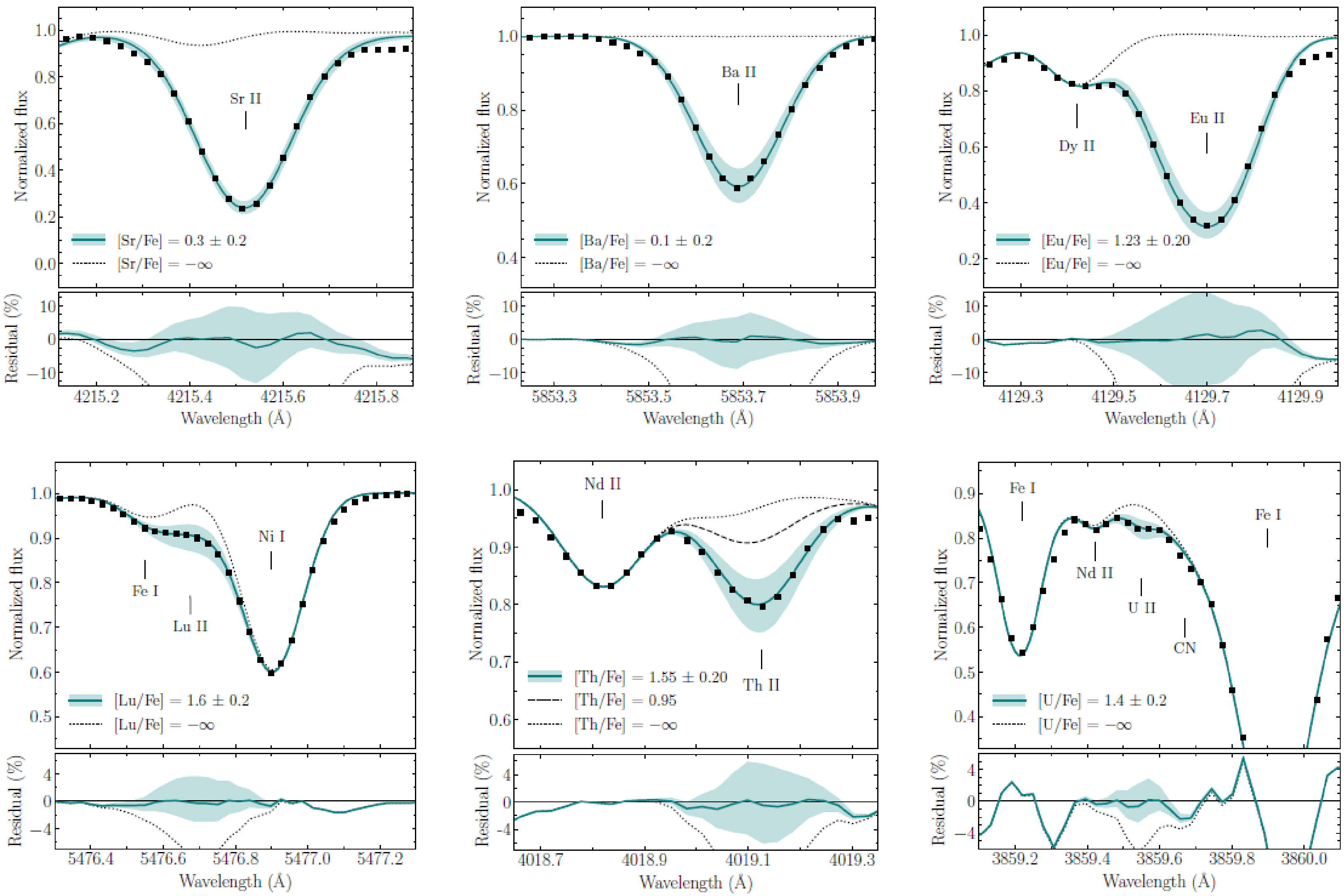
- A total of 25-30 portrait r-II spectra taken to date and more coming soon !

New r-II Stars with Portrait High-Resolution Spectroscopy



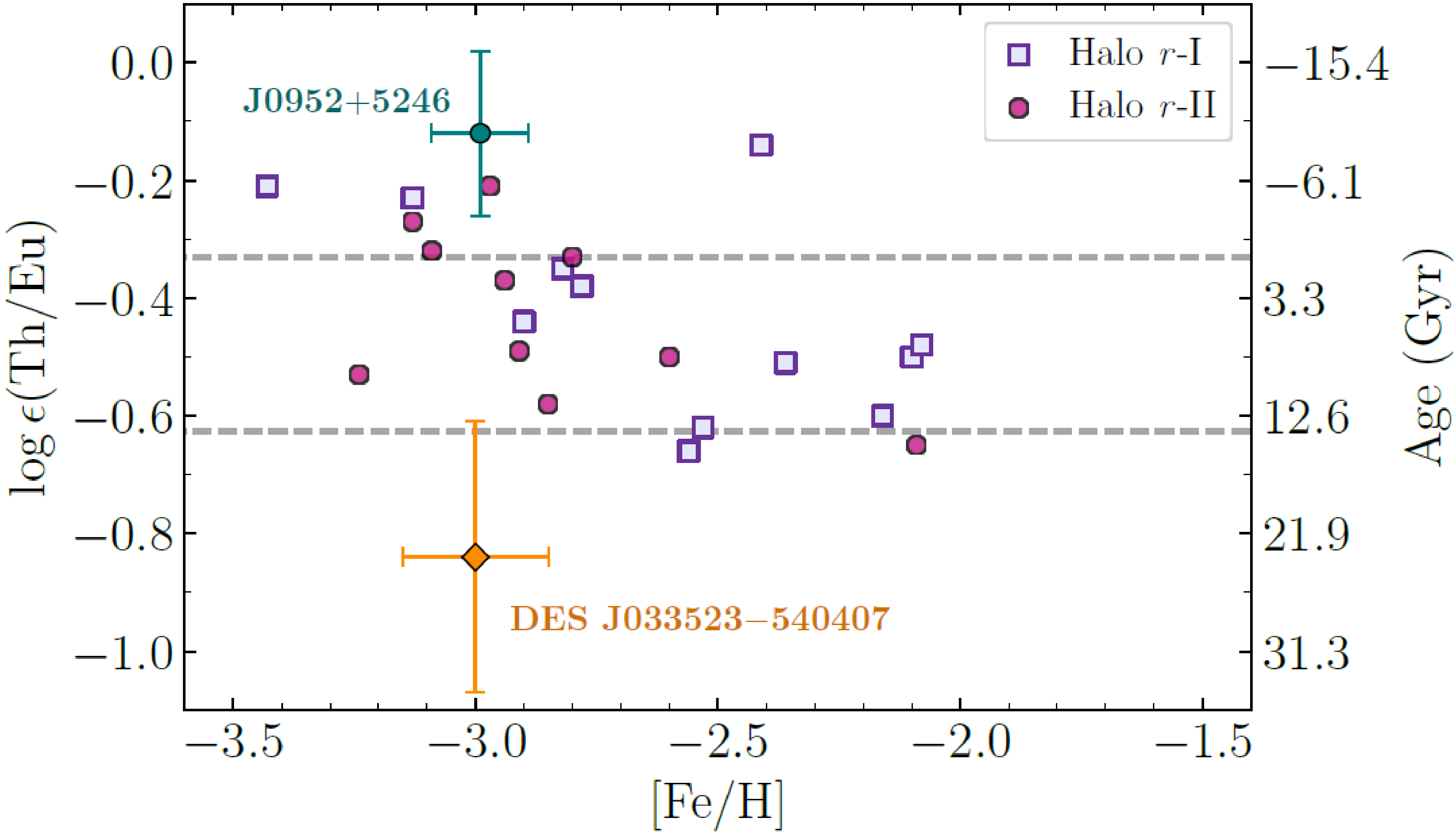
Holmbeck et al. (in press)

New r-II Stars with Portrait High-Resolution Spectroscopy



Holmbeck et al. (in press)

New r-II Stars with Portrait High-Resolution Spectroscopy



Holmbeck et al. (in press)

Astronomical Magic – What Can We do with a Statistical Sample of r-II and r-I stars ?

- Assuming n = 100 r-II and n = 500 r-I, 20-30 with both Th and U
  - Definitive measurement of fraction of stars that exhibit the actinide boost, providing a strong constraint on site and nature of the r-process
  - Are there r-I stars that show the actinide boost (yes) ? How do their fractions compare to r-II stars ? Same ? Different ?
  - Comparison of kinematic properties of r-II and r-I stars, to test if associated with mini-halos (dwarfs) of different masses (dilution)
  - From U/Th radioactive chronometer, test for uniformly early origin or distributed formation over history of Galaxy
  - If demonstrated uniformly early, turn problem around, assume age of 13.0-13.5 Gyr, and derive the production ratio, of U/Th, as well as Th/Eu and other ratios, which will never be measured in nuclear accelerators
- Understanding the origin of the r-process is a 60 YEAR OLD problem. It is now a 5 (4) YEAR problem that will yield its secrets soon.