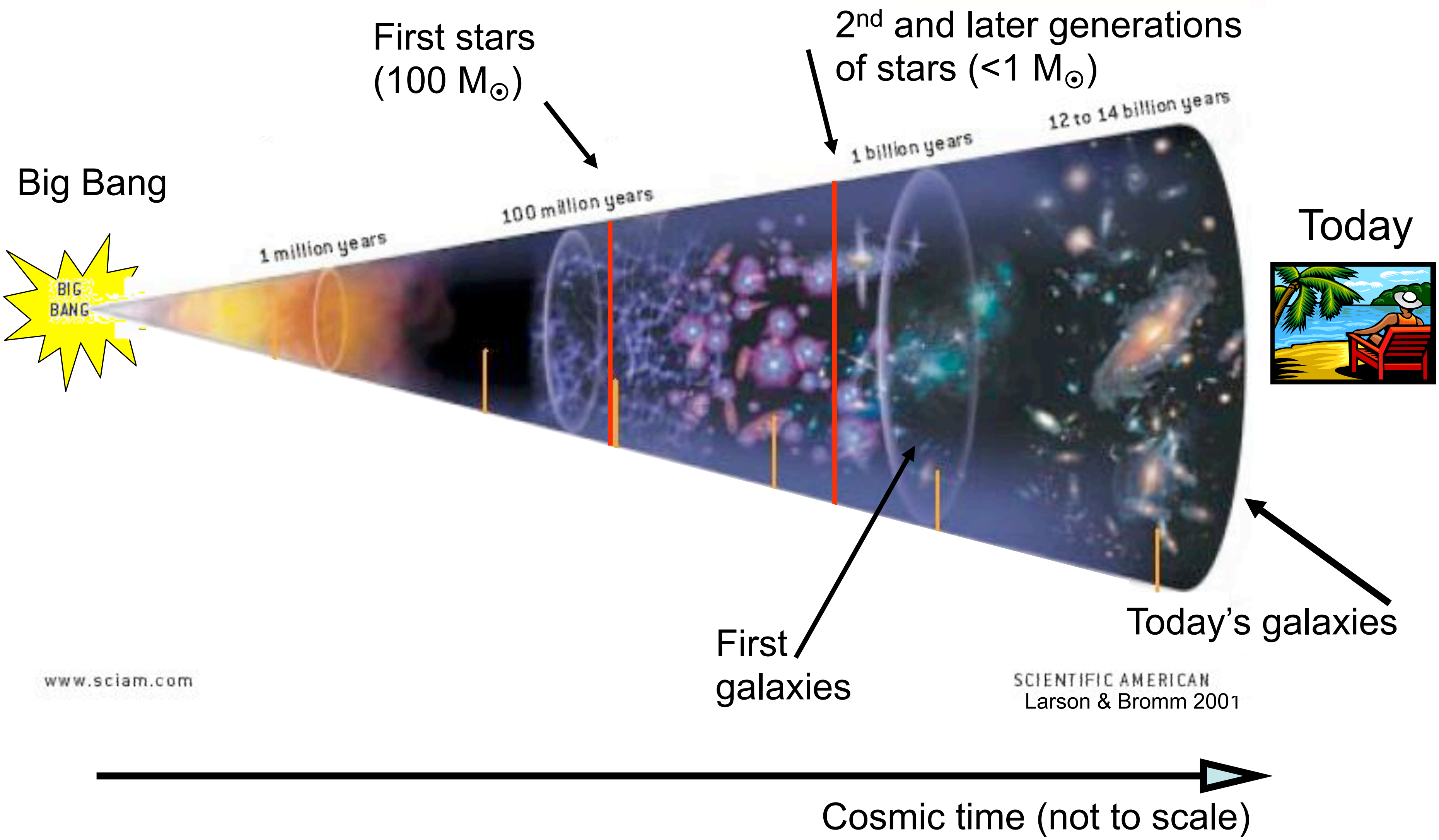
Observing the r-process in the oldest, most metal-poor stars

Part II (of sorts)

Massachusetts Institute of Technology

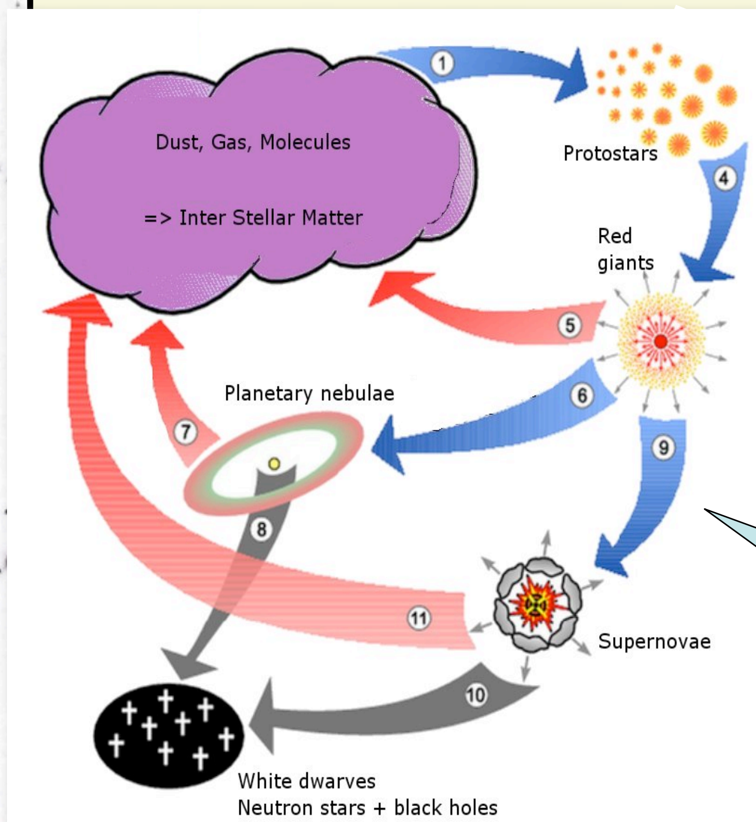
Anna Frebel

A Long Time Ago...



CHEMICAL EVOLUTION

Chemical evolution & cosmic recycling



H: X

Astronomers' Periodic Table

He: Y

3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg													13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

With time, more and more <u>of</u> all elements were made!

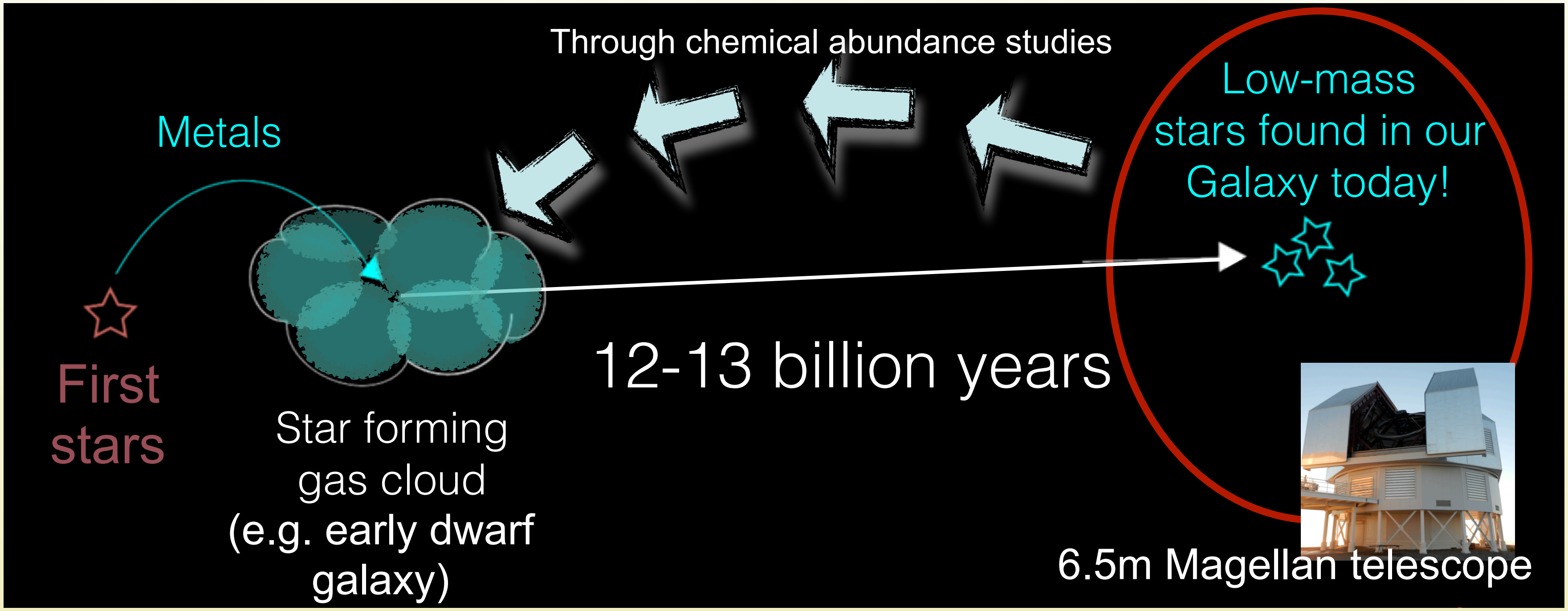
We look for stars with the <u>least amounts</u> of elements heavier than H and He!

Zentrum fuer Astronomie und Astrophysik, TU Berlin

STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

Low-mass stars with M < 1 M⊙: Lifetimes > 10 billion years => they are still around!



Back-of-the-envelope calculation

Estimated H gas mass of typical star forming cloud: ~10^5 M_{sun}

Estimated Fe yield of typical supernova: ~0.1 M_{sun}

Assume homogenous and instantaneous mixing of Fe in gas

=> [Fe/H] = −3.2 is abundance of next-generation star

=> [Fe/H] ≤ −3: only ~1 progenitor star produced that iron

(= 1/1000th of solar Fe)

Anna Frebel

Nuclear Astrophysics

Updated metal-poor star classifications

Table 1 Classes and signatures of metal-poor stars

Description	Definition	Abbreviation
Population III stars	Postulated first stars, formed from metal-free gas	Pop III
Population II stars	Old (halo) stars formed from low-metallicity gas	Pop II
Population I stars	Young (disk) metal-rich stars	Pop I
Super-metal-rich	$[Fe/H] > 0.0$	MR
Solar	$[Fe/H] = 0.0$	None
Metal-poor	$[Fe/H] < -1.0$	MP
Very metal-poor	$[Fe/H] < -2.0$	VMP
Extremely metal-poor	$[Fe/H] < -3.0$	EMP
Ultra-metal-poor	$[Fe/H] < -4.0$	UMP
Hyper-metal-poor	$[Fe/H] < -5.0$	HMP
Mega-metal-poor	$[Fe/H] < -6.0$	MMP
Septa-metal-poor	$[Fe/H] < -7.0$	SMP
Octa-metal-poor	$[Fe/H] < -8.0$	OMP
Giga-metal-poor	$[Fe/H] < -9.0$	GMP
Ridiculously metal-poor	$[Fe/H] < -10.0$	RMP
Signature	Metal-poor stars with neutron-capture element patterns	Abbreviation
Main r-process	$0.3 \leq [Eu/Fe] \leq +1.0$ and $[Ba/Eu] < 0.0$	r-I
	$[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0.0$	r-II
Limited r-process[a]	$[Eu/Fe] < 0.3$, $[Sr/Ba] > 0.5$, and $[Sr/Eu] > 0.0$	$r_{\rm lim}$
s-process	$[Ba/Fe] > +1.0$, $[Ba/Eu] > +0.5$, $[Ba/Pb] > -1.5$	s
r- and s-processes	$0.0 < [Ba/Eu] < +0.5$ and $-1.0 < [Ba/Pb] < -0.5$[b]	$r+s$
i-process	No unambiguous match to neutron-capture element patterns/criteria	i
Signature	Metal-poor stars with other element characteristics	Abbreviation
Neutron-capture normal	$[Ba/Fe] < 0$	No
Carbon enhancement	$[C/Fe] > +0.7$ for $\log(L/L_\odot) \leq 2.3$	CEMP[c]
	$[C/Fe] \geq [+3.0 - \log(L/L_\odot)]$ for $\log(L/L_\odot) > 2.3$[d]	CEMP
α-element enhancement	$[Mg, Si, Ca, Ti/Fe] \sim +0.4$	α-enhanced

[a] Also referred to as the light-element primary process (LEPP) (19) or "weak" r-process.

[b] Based on only one known carbon-enhanced metal-poor (CEMP)-$r+s$ star (20); may require future adjustments.

[c] The CEMP star definitions are from Reference 21. s- and i-process-enhanced stars are always CEMP stars; r-process-enhanced stars may or may not be CEMP stars. There is also a class of CEMP-no stars.

[d] Carbon corrections as a function of luminosity can also be obtained from Reference 22.

Frebel 2018 ARNP

OBSERVATIONAL CONSTRAINTS ON THE R-PROCESS

Constraints provided by r-process star observations

✓ Limited r-process stars

✓ Deviations from scaled solar r-process pattern for first peak elements

a. Some stars have higher relative abundances
b. Some stars have lower relative abundances

✓ Actinide element variations

a. Actinide boost stars (relative to a 13Gyr decay age)
b. Actinide deficient stars (relative to a 13Gyr decay age)

✓ Robust main pattern for elements Ba and above

ZOO OF R-PROCESSES...!

Table 2 Nucleosynthesis processes that can contribute neutron-capture elements

Process	Conditions	Elements produced	Y_e	Astrophysical sites
Terminal QSE[a]	Insufficiently neutron rich; α-, neutron-, proton-capture and reverse; expansion from hot, dense state	Sr $\rightarrow$ Ag	< 0.5	Standard proto–neutron star wind in core-collapse supernovae; shock-heated/disk ejecta
νp-process	Proton rich, $\bar{\nu}_e$ rich; QSE and $\bar{\nu}_e$ capture	Sr $\rightarrow$ Ag	> 0.5	Standard proto–neutron star wind in core-collapse supernovae; shock-heated/disk ejecta
Limited[b] r-process	Neutron-to-seed ratio $<< 100$; QSE and (limited) neutron capture; no fission cycling	Sr $\rightarrow$ Ba (limited production) toward Ba	< 0.5	Modified proto–neutron star wind; neutron star merger: disk (after merger, viscous/wind timescales); shock-heated ejecta (during merger, dynamical timescales)
Main r-process	Neutron-to-seed ratio > 100; QSE and neutron capture; any fission cycling	Ba$\rightarrow$ U	< 0.2	Neutron star merger: tidal ejecta (during interaction); dynamical ejecta (during merger)
Robust (main) r-process	Neutron-to-seed ratio > 100; QSE and neutron capture; fission cycling limit	Ba $\rightarrow$ U	< 0.2	Neutron star merger: tidal ejecta (during interaction); dynamical ejecta (during merger)

[a]Quasi-statistical equilibrium; see Reference 102 for a detailed description and treatment.

[b]Often referred to as the weak r-process or the light-element primary process (LEPP). However, the term "weak" does not well describe the nature of the underlying r-process physics, and "LEPP" does not refer to a specific nuclear physics process.

Frebel 2018, ARNP

Rare r-process stars in the Milky Way

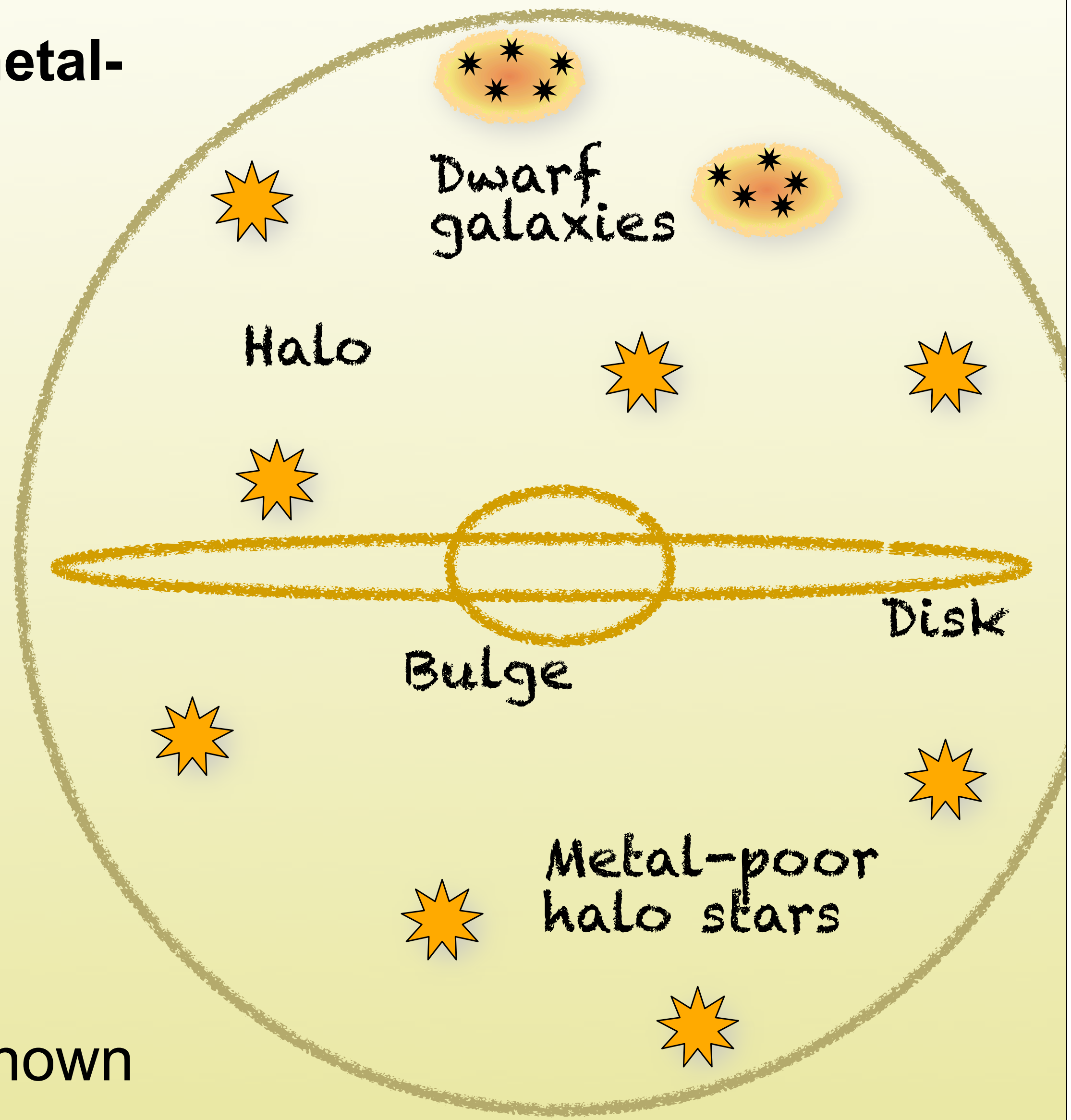
How common are r-process metal-poor stars in the Milky Way?

3 to 5% of metal-poor stars w/ [Fe/H]<−2.5 (Barklem et al. 05)

Only **~40 stars known** so far w/ [Eu/Fe] > 1.0; i.e. clear r-process pattern above Ba

More stars known with lower levels of 0.3 < [Eu/Fe] < 1.0; **unclear what lowest level is**

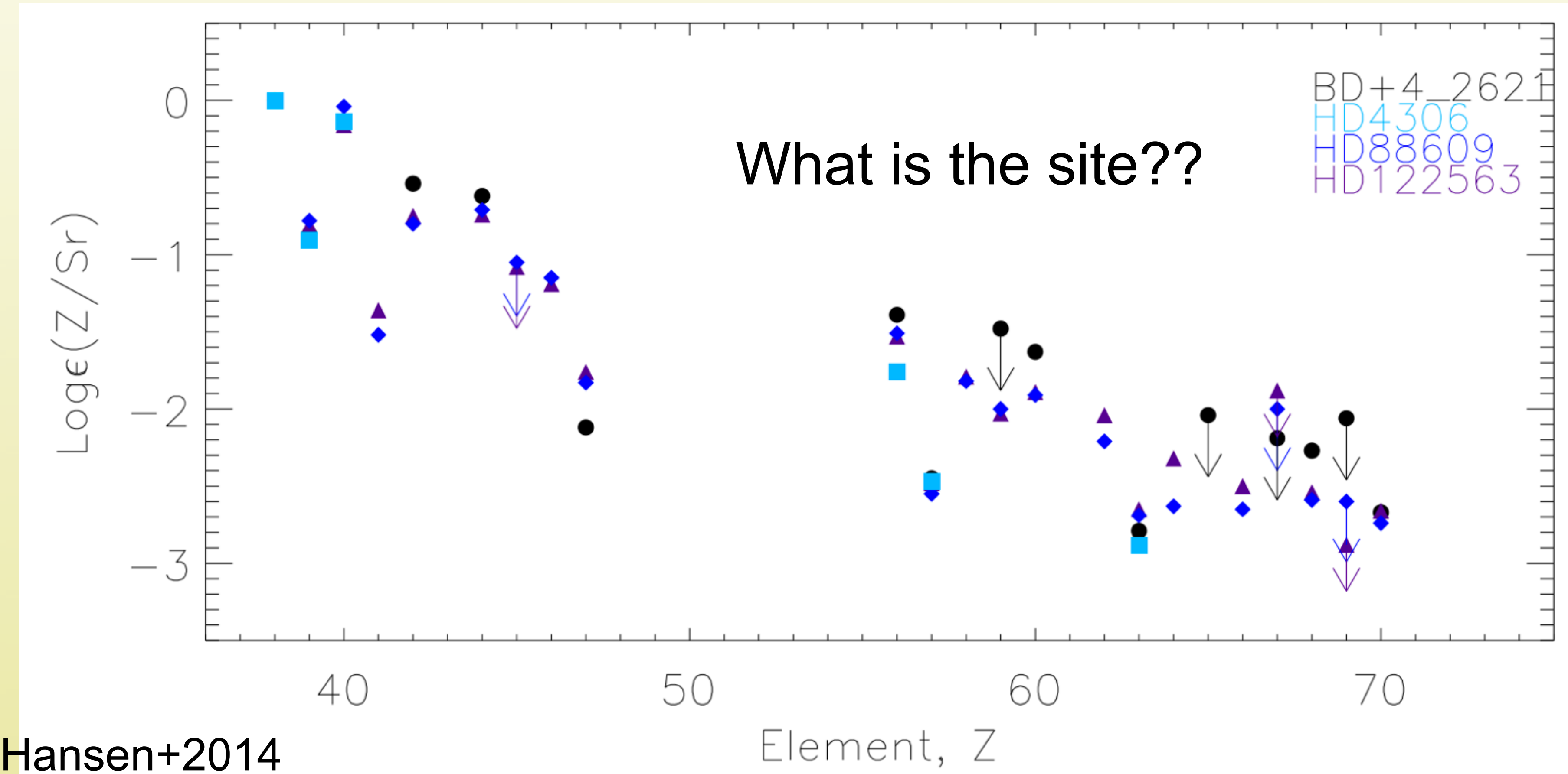
=> Origin of these stars is unknown



Limited r-process stars

Among 1658 metal-poor stars in JINAbase (Abohalima & Frebel 2017), 42 stars have abundances that match the limited-r definition

=> **> ~3%** (strict lower limit due to observ. limitations of Eu detections!)



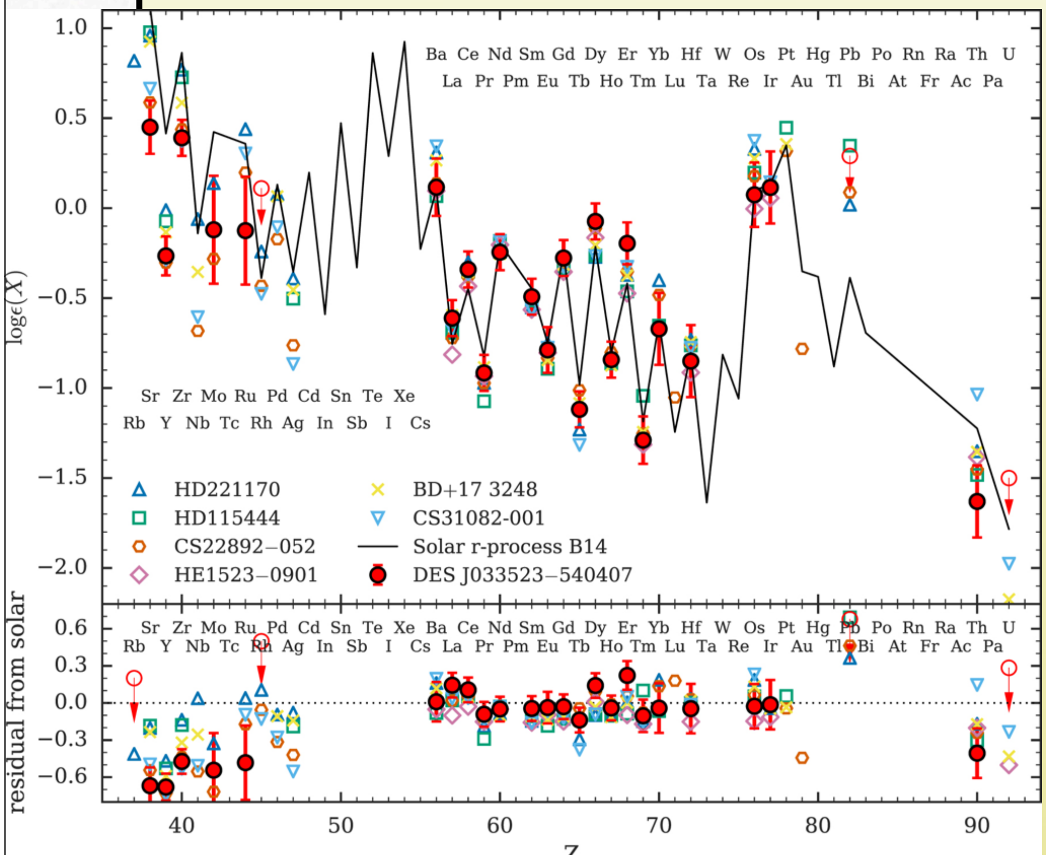
Hansen+2014

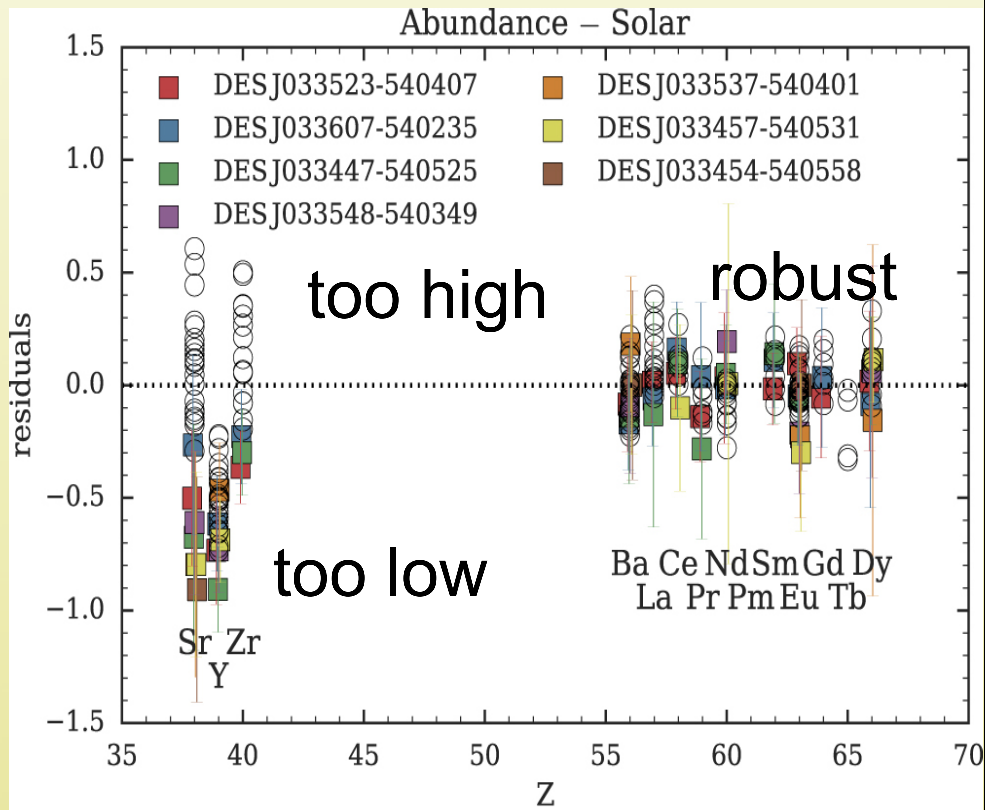
Limited-r stars: [Sr/Ba] > +0.5, [Eu/Fe] < +0.3

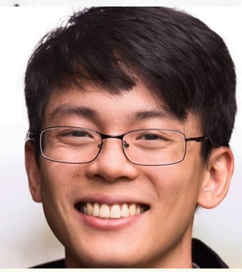
Deviations of first peak elements

R-process dwarf galaxy Ret I has **lowest relative first peak abundances!**

=> purest r-process pattern available to us





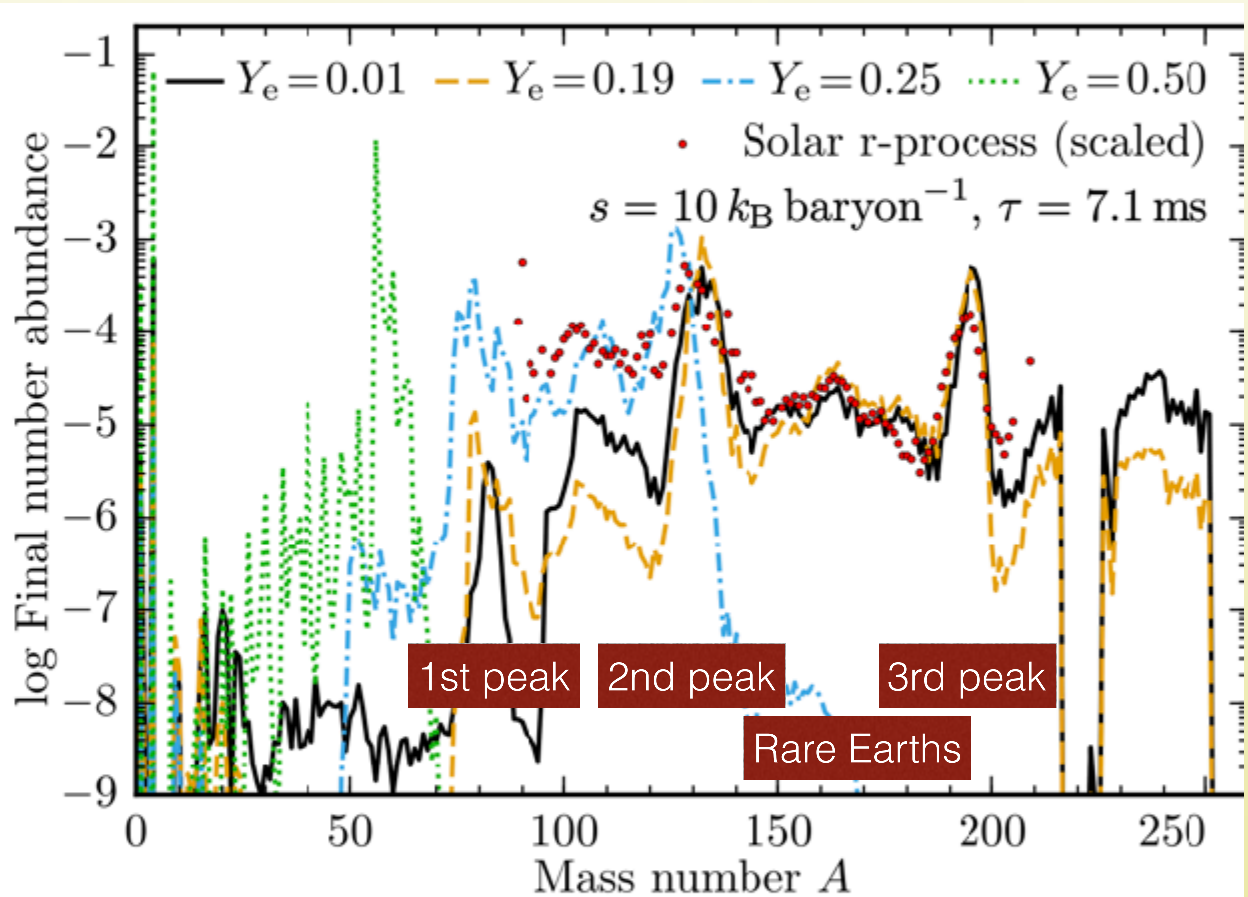


Element production driven by Y_e

High Y_e (neutron-poor) => first peak

Low Y_e (neutron-rich) => second peak

$Y_e = N_e / (N_n + N_p)$

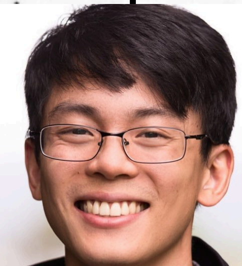


Critical $Y_e \sim 0.20$

(to make it all...?!?)

Can Y_e be observationally constrained?

Lippuner&Roberts 2015

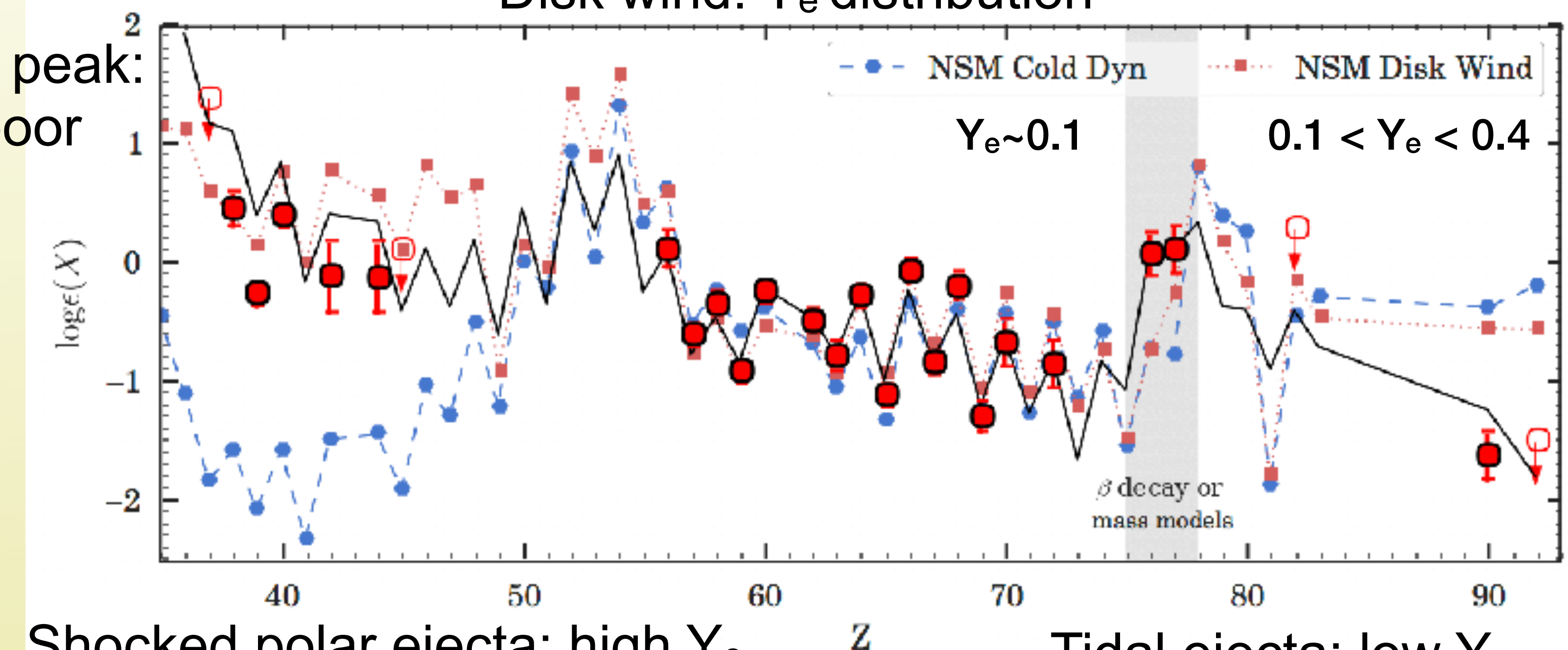


To produce the entire observed pattern...

...NSM must eject material (mass) in multiple ways!

Disk wind: Y_e distribution

1st peak: n-poor



2nd/3rd peak: n-rich

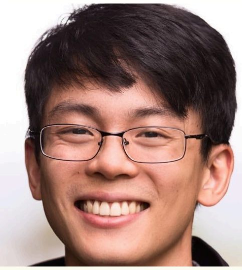
Shocked polar ejecta: high Y_e

Tidal ejecta: low Y_e

Adding up mass of elements in different regions:

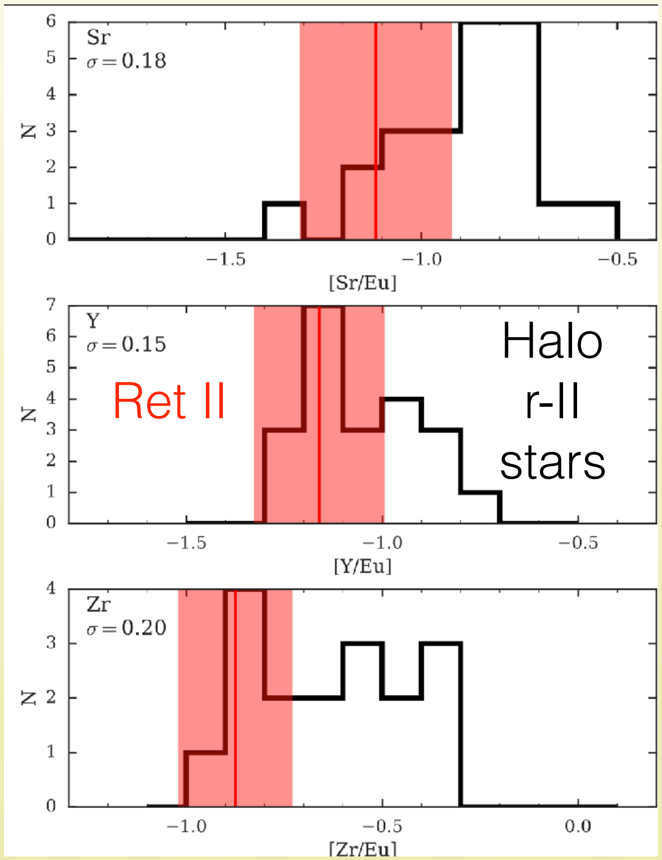
$M_{n\text{-poor}}/M_{n\text{-rich}}$ ~ 0.6 ± 0.1 (from brightest RetII star)

Models: Eichler+2015, Wu+ 2016, Ji & Frebel 2018



What about that mass ratio more generally?

Halo r-process stars show some scatter of 1st peak to 2nd/3rd peak

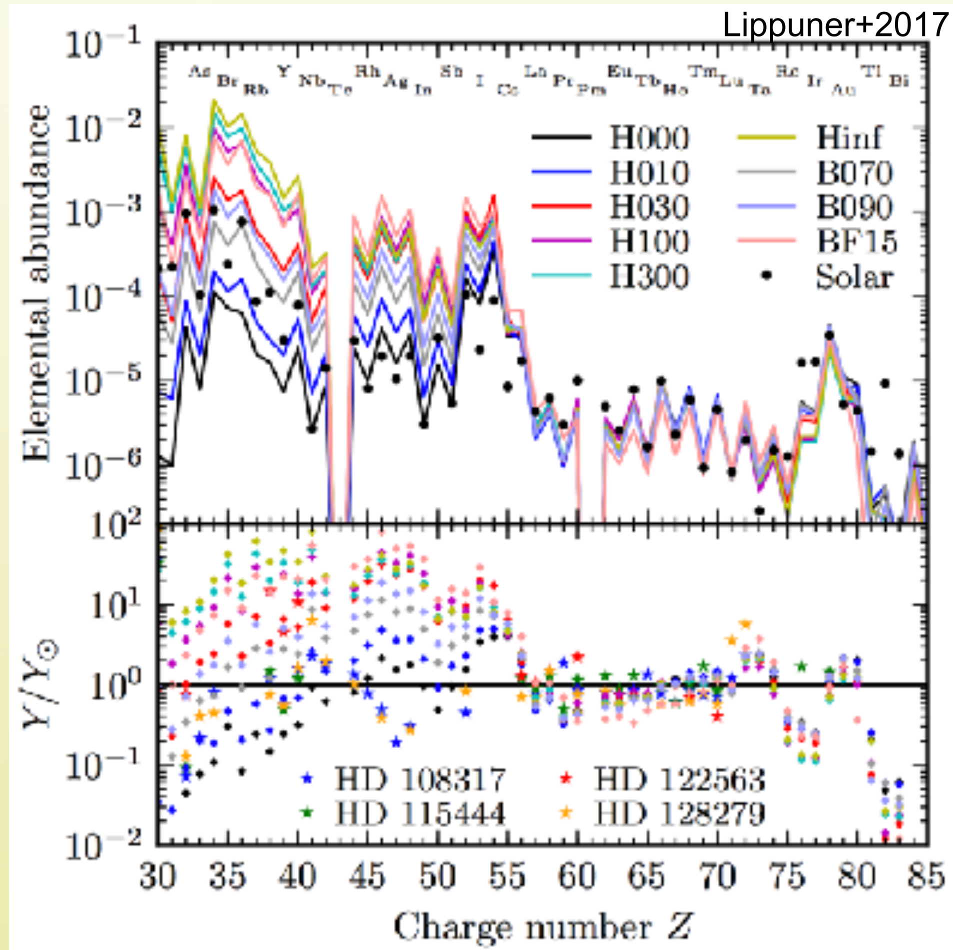


1st peak/Lanthanide

Note: 1st peak could be contaminated by CCSN/limited r-process

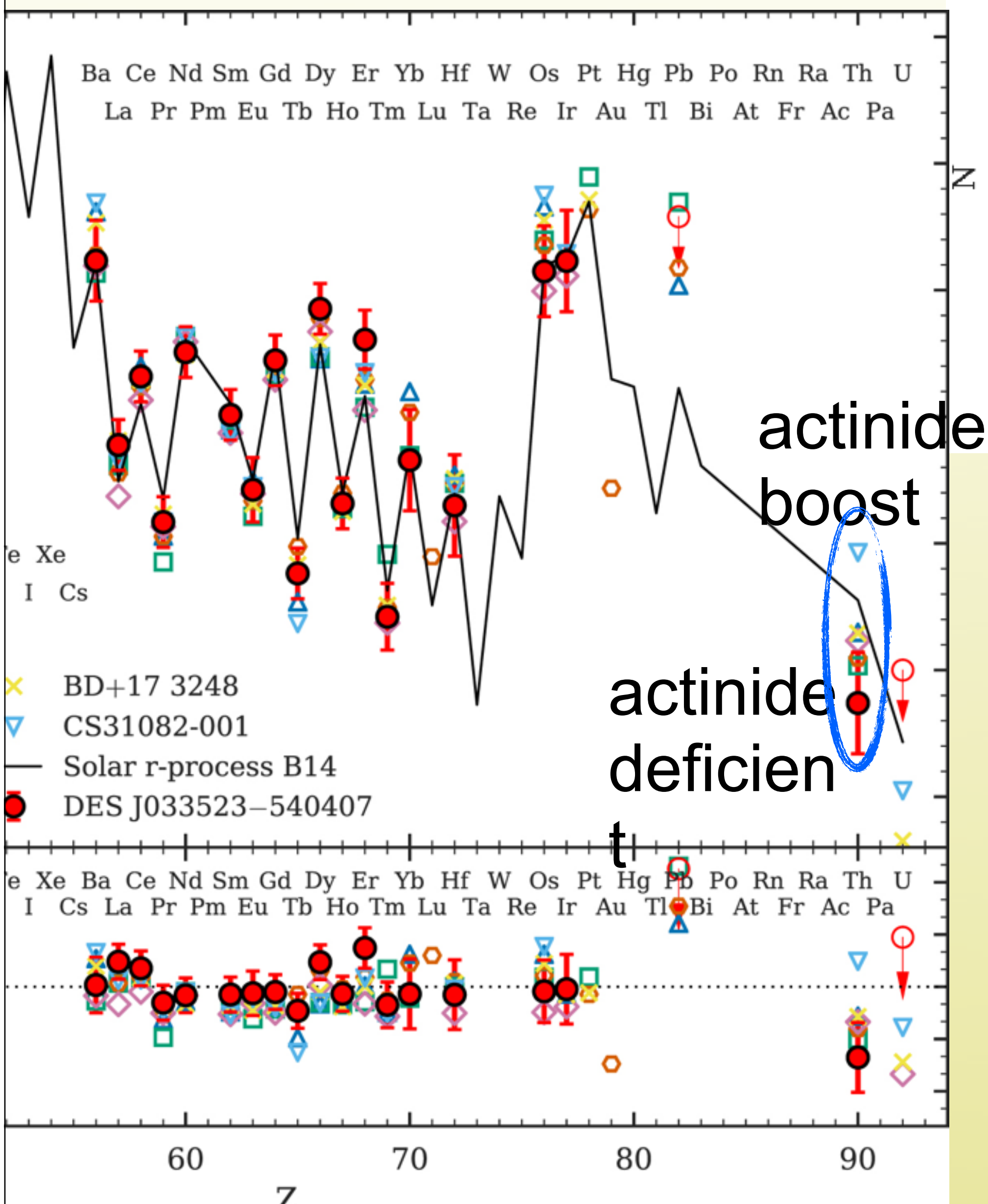
$M_{n\text{-poor}}/M_{n\text{-rich}} \sim 0.5$ to 2

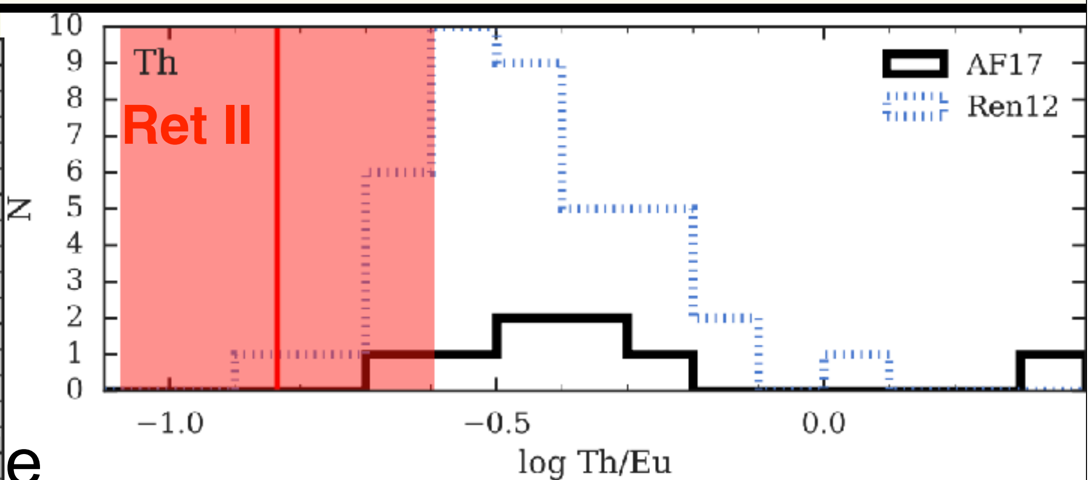
>10x variations in NSM models



Some physical mechanism must link amount of n-rich and n-poor ejecta!

Actinides





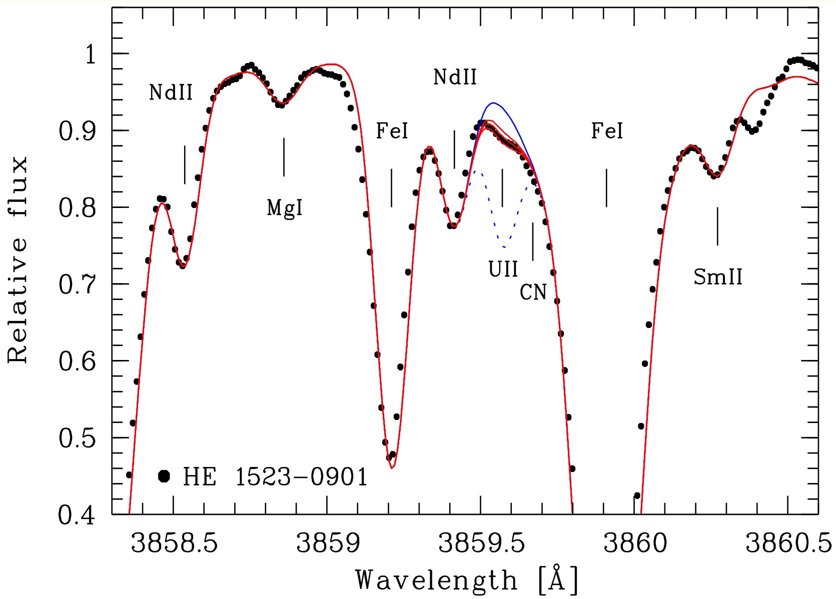
Initial production ratios are not universal!

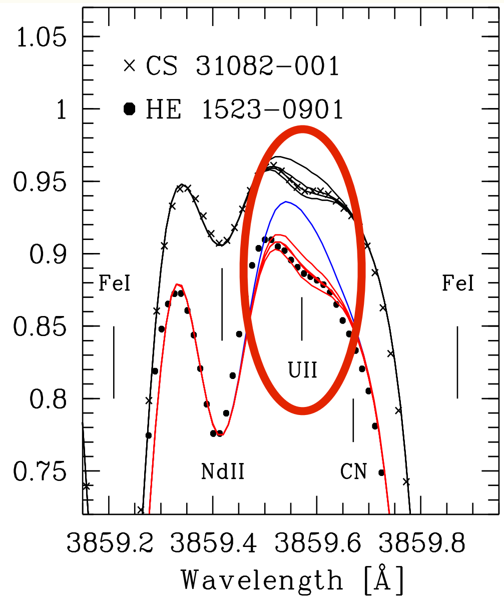
Need to be calculated per event (or class of events)

Need to characterize site and all the details...

Th/U ratio may hold - but hard to measure!

6 U and 4 Pb measurements



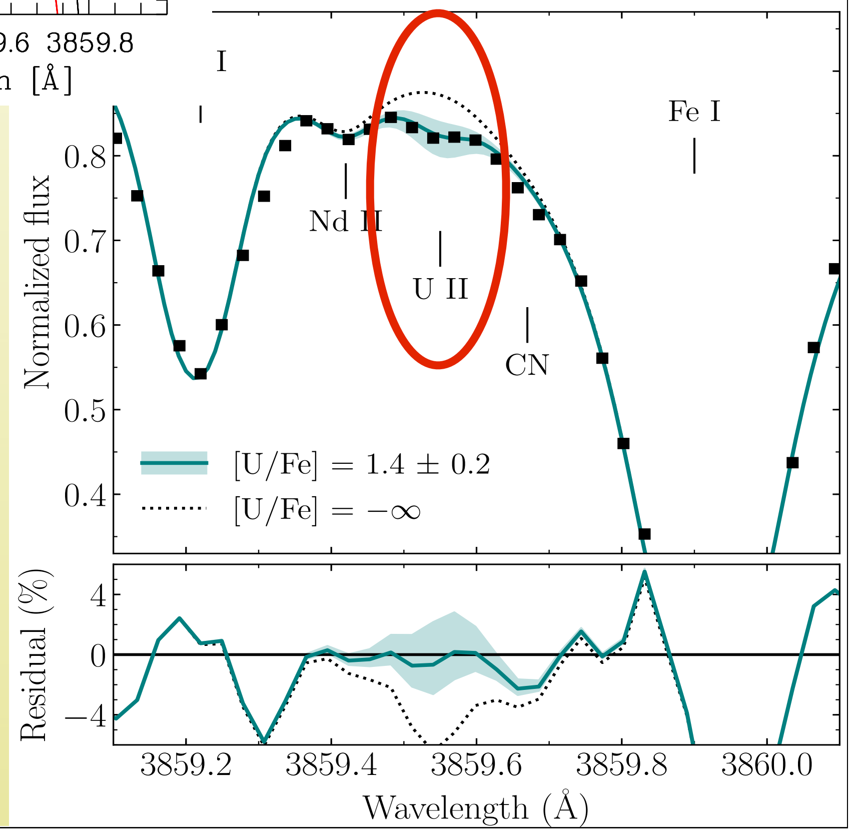


Also:

CS29496-004 (Hill+2017)

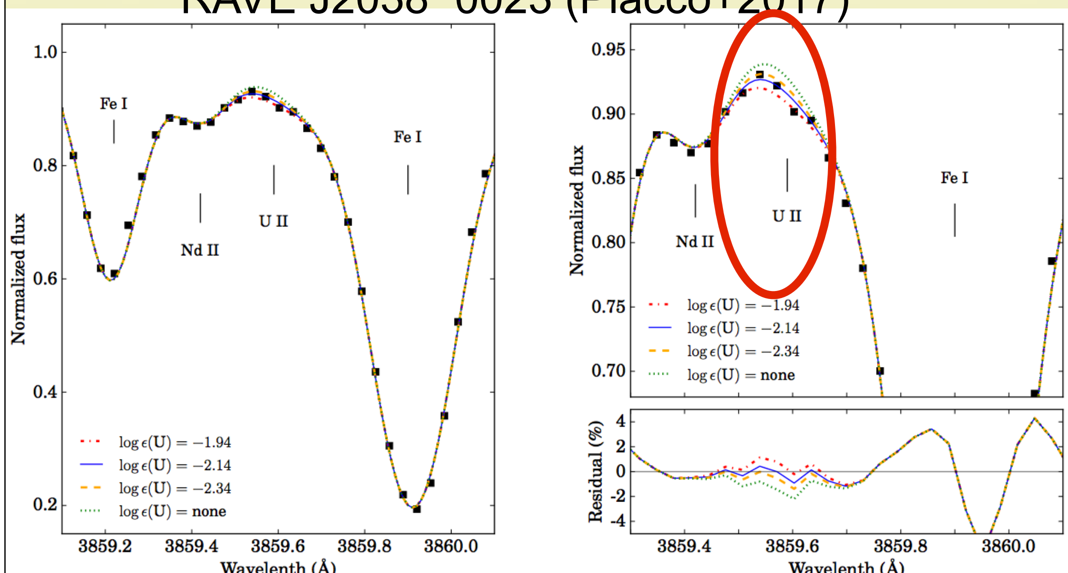
BD+17 3248 (Cowan+2002)

2MASS J0954+5246
(Holmbeck+2018)

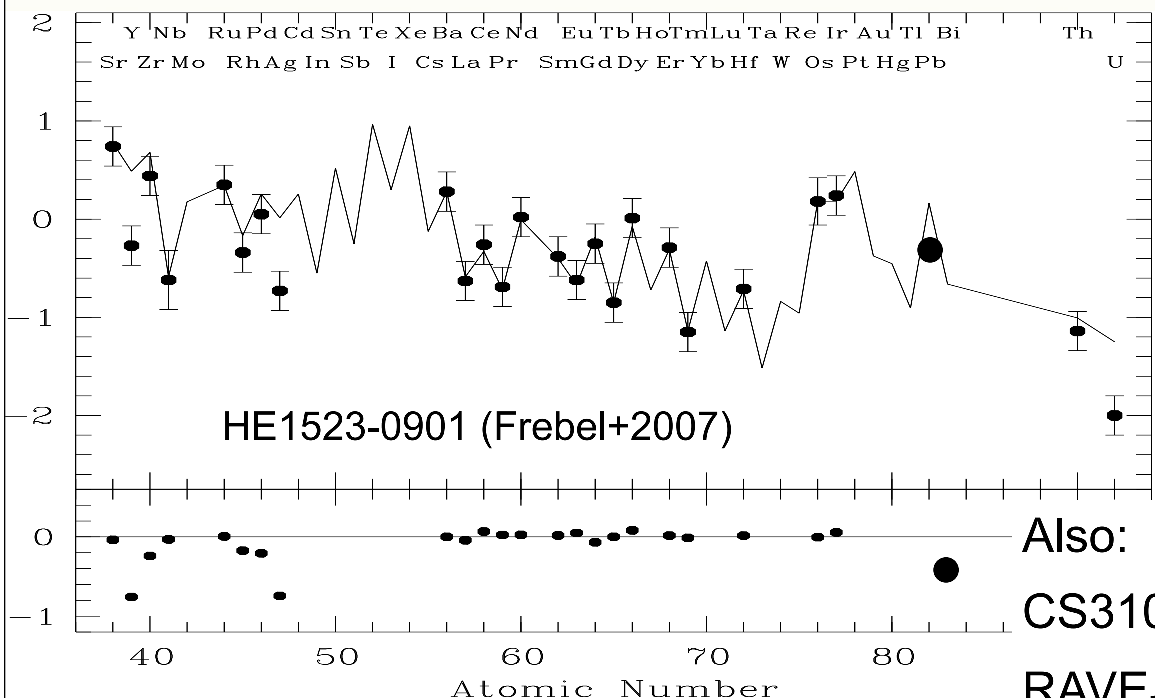


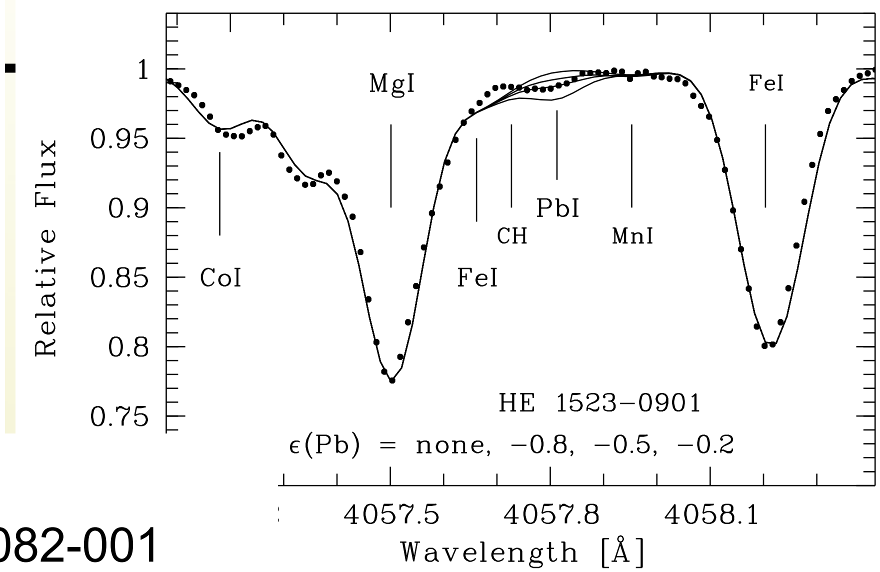
CS31082-001 (Cayrel+2001); HE1523-0901 (Frebel+2007)

RAVE J2038−0023 (Placco+2017)

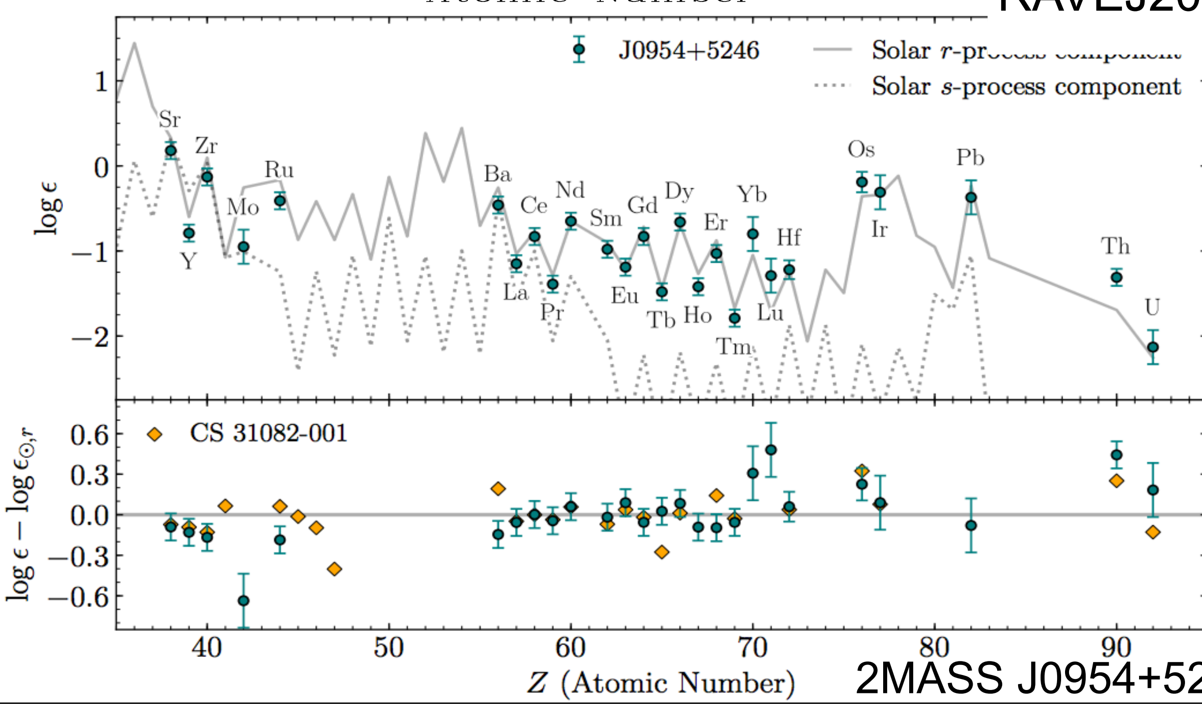


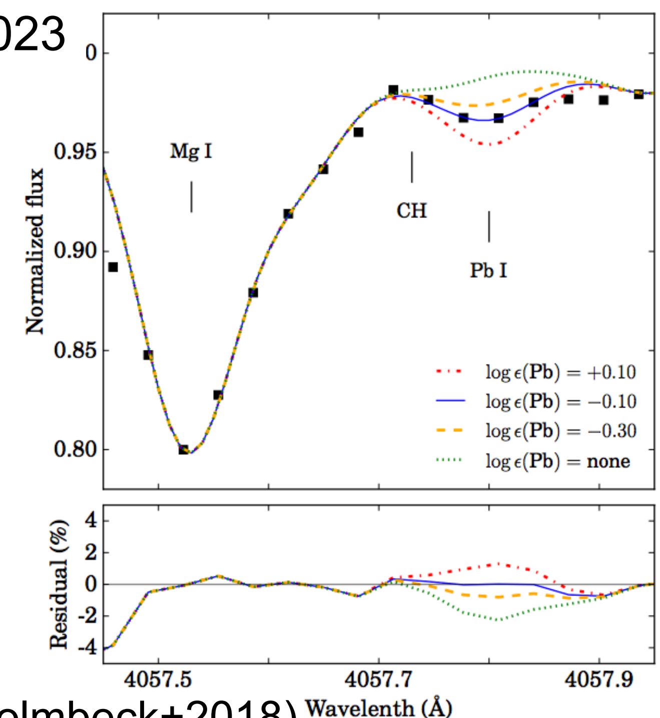
6 U and 4 Pb measurements





Also:
CS31082-001
RAVEJ2038−0023





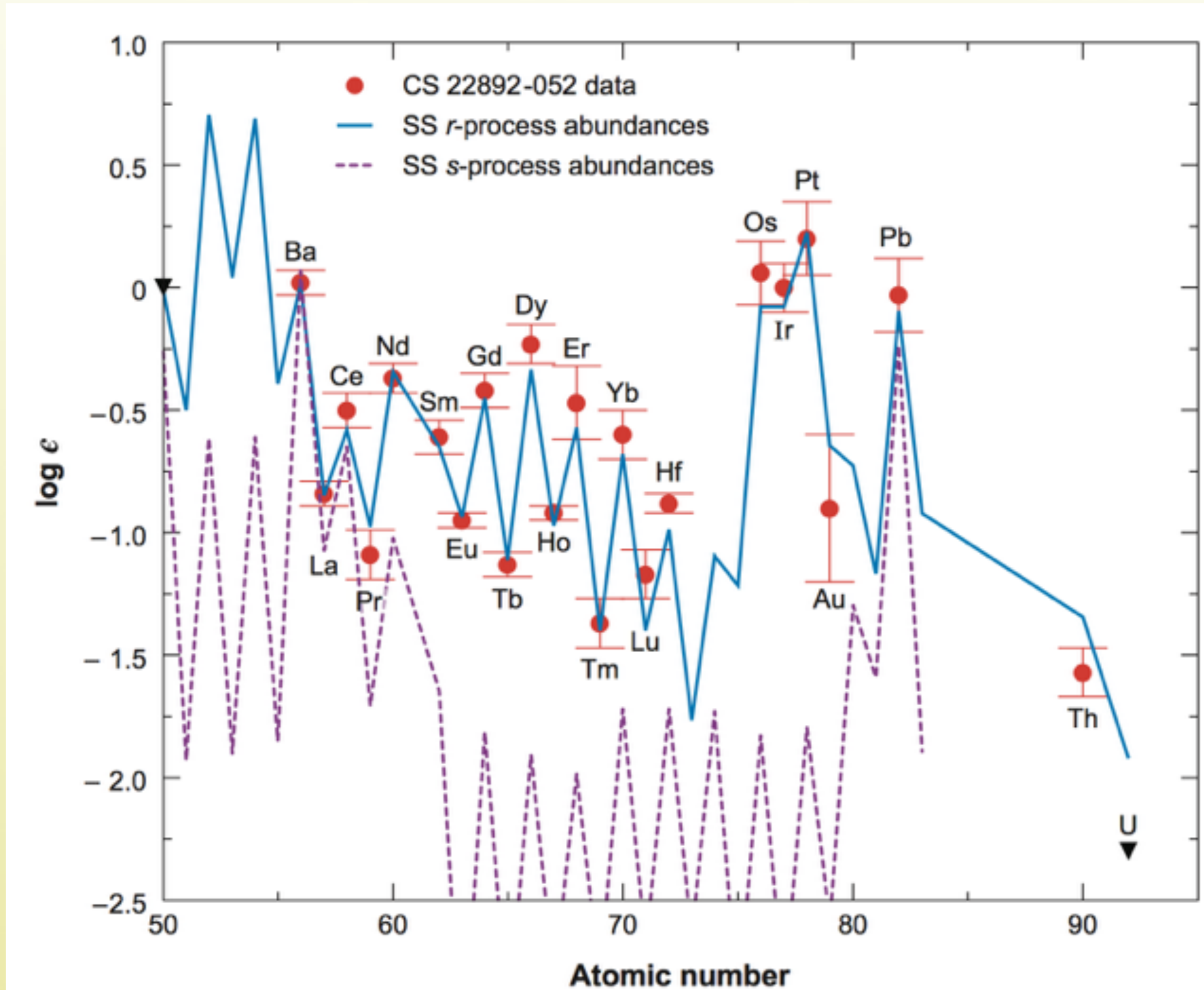
2MASS J0954+5246 (Holmbeck+2018)

ROBUST R-PROCESS IN METAL-POOR HALO STARS

r-process abundance **patterns** are the same in the Sun and old metal-poor stars

r-process stars are all extremely metal-poor: [Fe/H]~−3.0

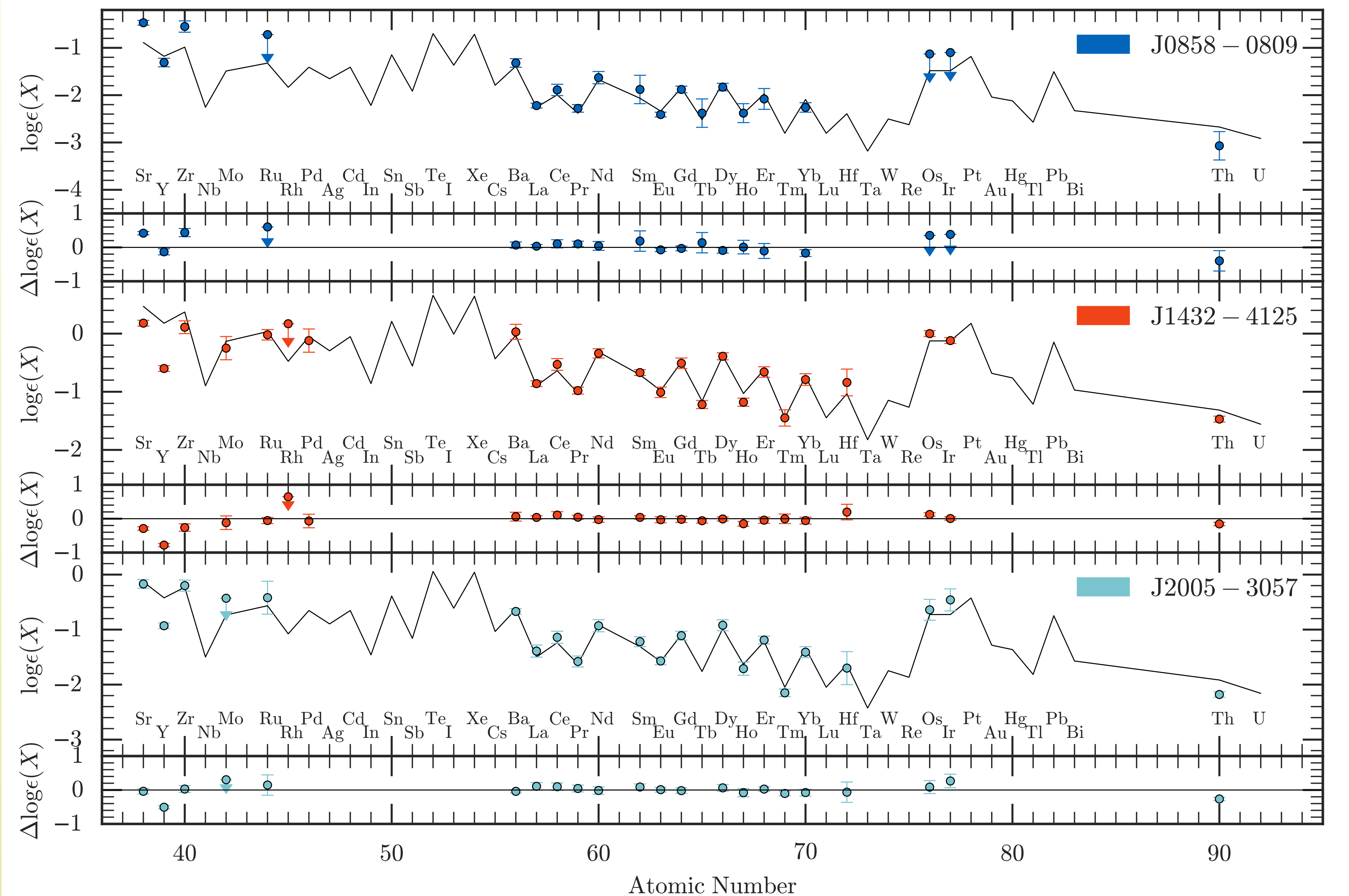
(= 1/1000th of solar Fe value)



Sneden et al. 2008

Definition: $[Fe/H] = \log_{10}(N_{Fe}/N_H)_{star} - \log_{10}(N_{Fe}/N_H)_{Sun}$

Cain et al: New r-process stars



Anna Frebel

Nuclear Astrophysics

R-Process Alliance

Goal: To build up sample of galactic r-process stars to provide the astrophysical data for tackling outstanding questions about the r-process

Connect observational data set with nuclear physic theory and chemical evolution efforts

Core group: Tim Beers, Rana Ezzeddine, Anna Frebel, Terese Hansen, Vini Placco, Ian Roederer, Charli Sakari. With ~20 more associated astronomers

Observational goals

Uncover many (nearly all?) bright

=> **r-process stars** in the Milky Way: rI, rII stars but also r0 (low Eu but shows r-process pattern), some rIII; also CEMP-r stars

=> **Limited r-process stars**, i.e. stars with relative enhancement of Sr, Y, Zr compared to Eu and lanthanides

=> Others, such as **r+s stars;** occasional **s-process/ i-process star**

R-Process Alliance

Observations

Throughout: Leverage JINA connections!

Observing: We came together through JINA

Expertise in nuclear theory, nucleosynthesis

Experiments: Flood of nuclear data coming in and more during FRIB era

Phase I
Medium-resolution spectroscopy

Phase II
Snapshot high-resolution spectroscopy

Phase III
High S/N high-resolution spectroscopy

Theory

Component T1
R-process modeling

Component T2
Chemical evolution modeling

Experimental

Component E1
Current experiments
FRIB

Component E2
Lab astro
Gravitational waves

Early results

Published:

Placco et al. 2017: U star

Sakari et al. 2018: brightest rII star

Hansen et al. 2018: first data release paper

Placco et al. 2018: med-resolution results

Holmbeck et al. 2018: actinide boost U star

Submitted:

Gull et al. 2018: first r+s star

Cain et al. 2018: three new rI/rII stars

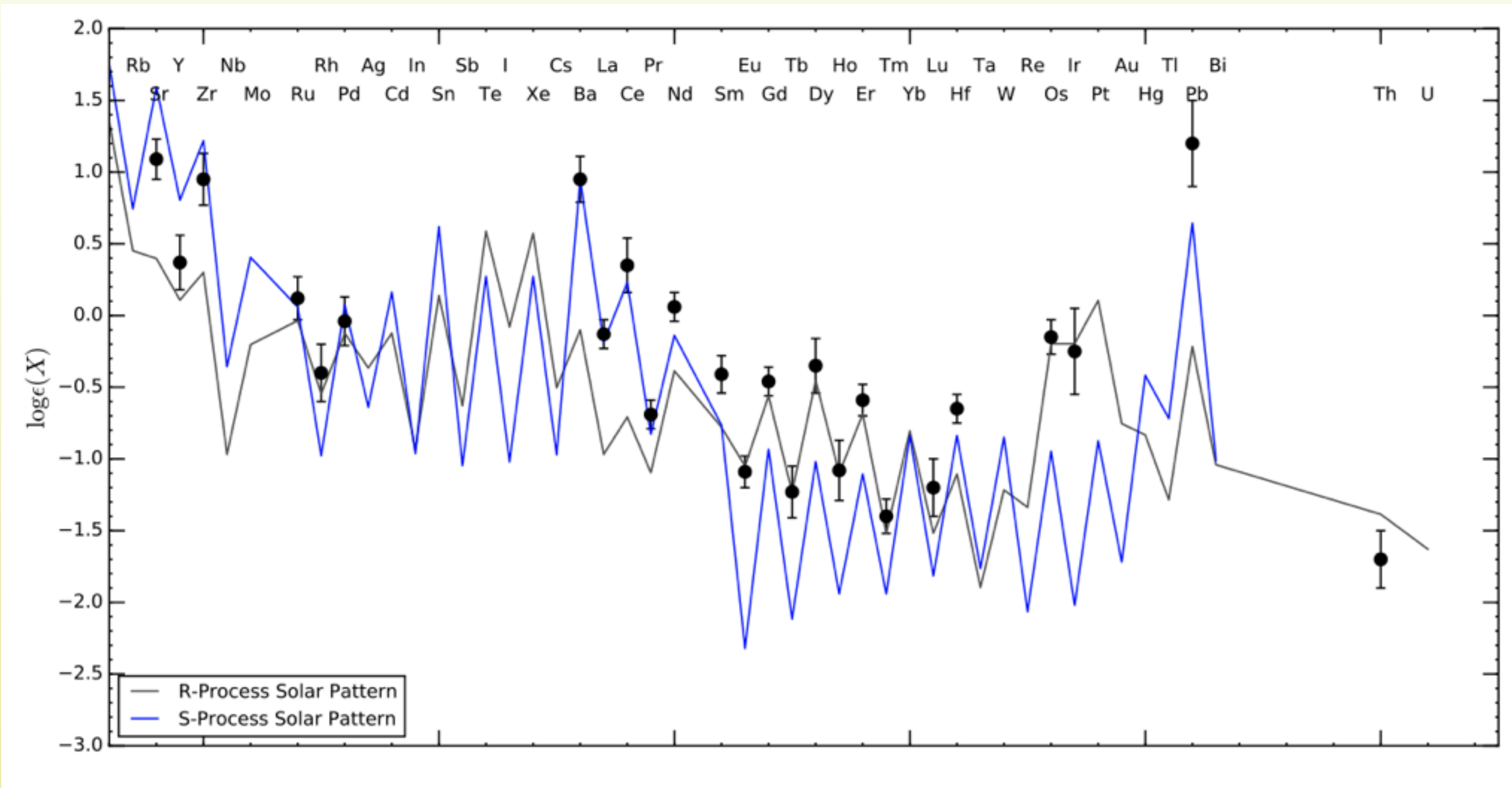
In prep:

Sakari et al. 2018: second data release paper

...and more!

The first true r+s star!

An s-process star with [Fe/H] = -2.3
that formed from r-process enhanced gas!



Gull, Frebel et al. 2018

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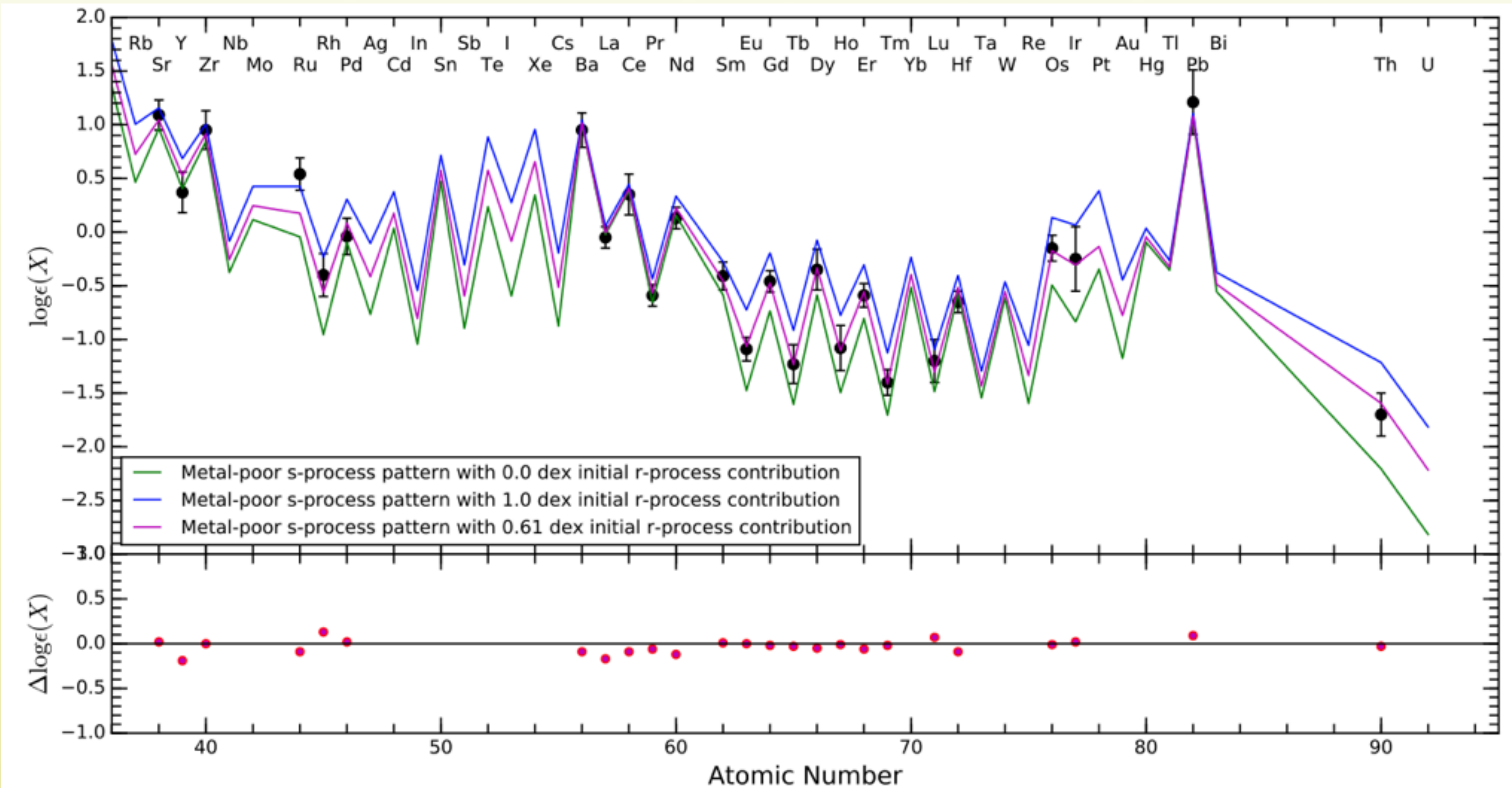


Gull, Frebel et al. 2018

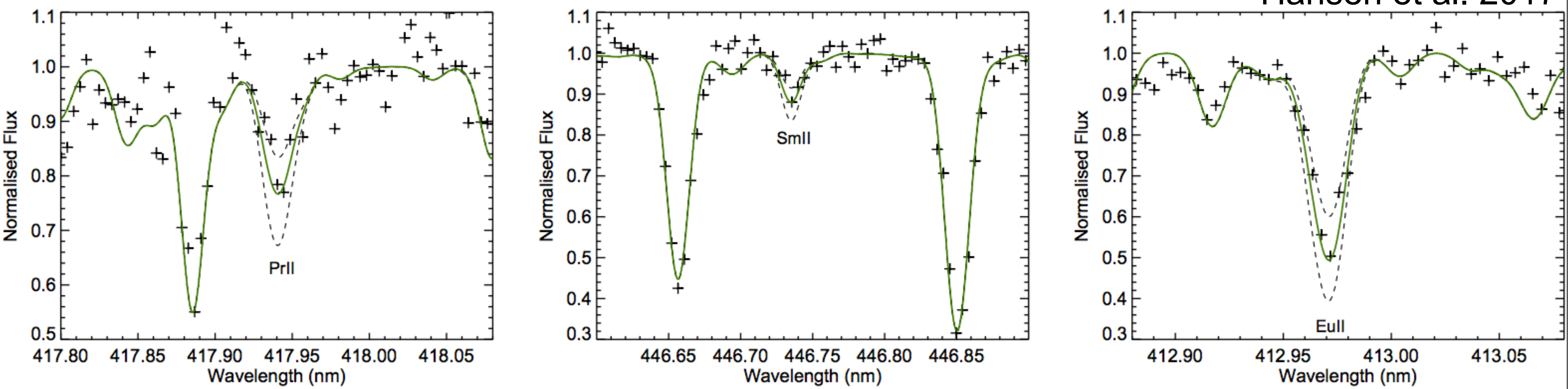
Reticulum II is not the only r-process galaxy!

Nope!

Feb 2017: newly discovered UFD Tucana III hosts at least 1 mildly r-process enriched star with [Fe/H] = -2.25!

=> 2 of 15 ultra-faint dwarfs show r-process enrichment

Hansen et al. 2017



Hunt for more r-process galaxies is in full swing! :)

Their value to astrophysics + nuclear physics has been fully recognized by now

R-PROCESS OPERATES IN DWARF GALAXIES

20 rI stars in

- Tucana III
- Ursa Minor
- Draco
- Sculptor
- Fornax
- Carina

-2.5 < [Fe/H] < -0.8

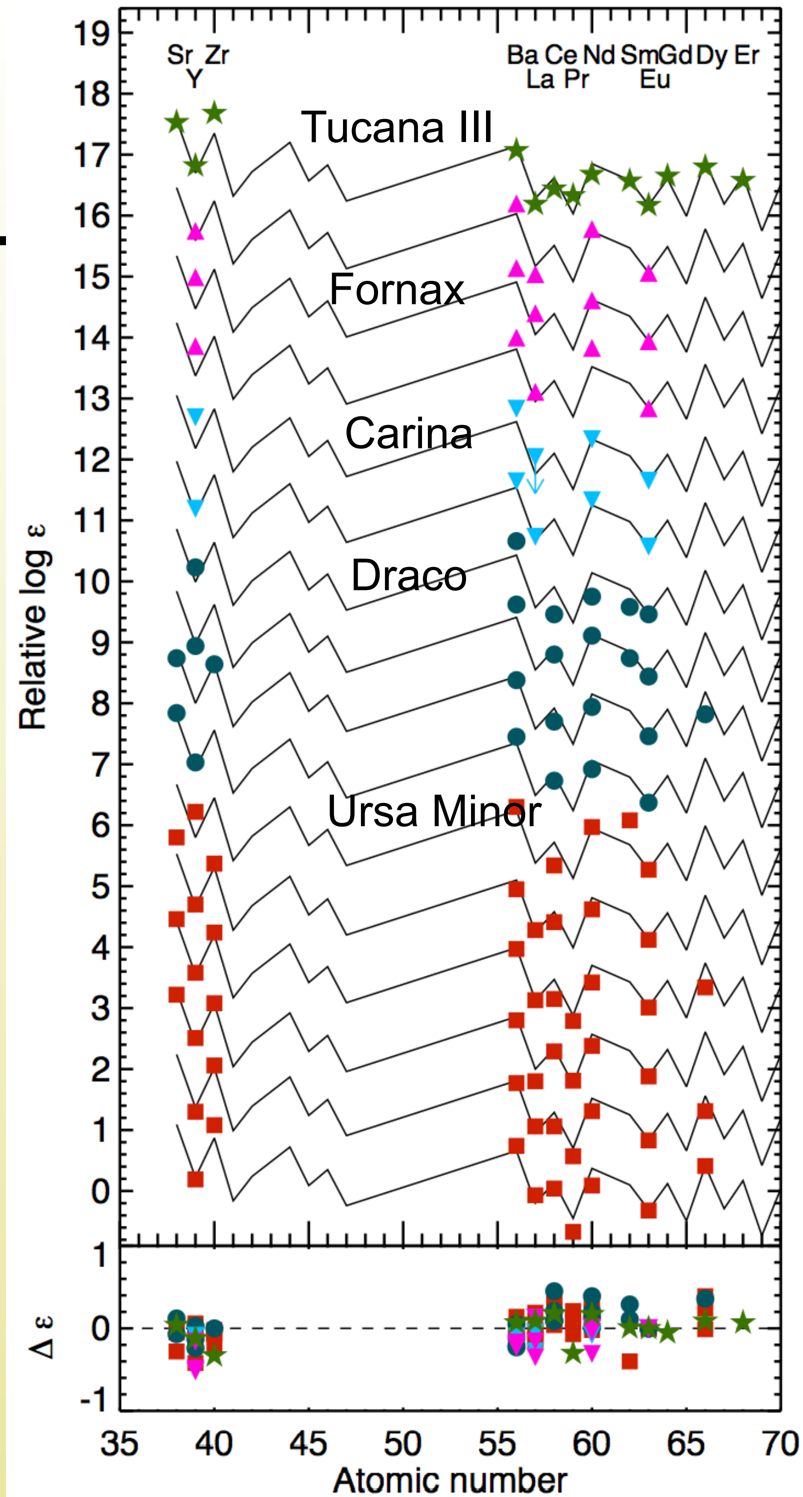
0.3 < [Eu/Fe] < 1.0

13 r II stars in

- Reticulum II -3.0 < [Fe/H] < -2.1
- Ursa Minor 1.0 < [Eu/Fe] < 2.1

- Draco -2.6 < [Fe/H] < -0.8
- Fornax 1.1 < [Eu/Fe] < 1.7

How can a variety of dwarfs have so different r-process levels?
=> Internal or external enrichment?
=> Different dilution masses?
=> Different accretion history
(accreted r-process stars)?



Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

JINA–CEE

JINAbase

- Home
- Query/Plot
- Search
- References
- User Page
- Logout

Flask powered

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Welcome to JINAbase!

The admins need to assign you a role to access the internal pages of JINAbase. If it has been longer than 48 hours since you registered, please contact one of the admins below.

JINAbase: A database for metal-poor stars

This web application enables you to easily access the database. The different tabs in the navigation bar guide you through the website.

To get access to the user interface to upload your data and help maintain the database, please sign up using the form on this page.

If you find JINAbase useful for your work/plots, please do the following:

1. Cite the original papers where the data comes from. (We've made that easy for you, just head to the references tab and you'll find a link to the bibtex entry.)
2. Cite our paper (Abohalima & Frebel 2018, submitted).
   Find it here on arxiv.

Updates:

The web application is still under development, if you face any errors or have any suggestions please contact us.

Query/Plot

This tab has options to query the database for a customized sample of stars, it includes several options to customize your sample. After you select your preferences, the queried sample could then be retrieved as an ascii table (for now) or plotted in an interactive plot.

Search

In this tab you can search for a star in JINAbase. There are two options; 1) diplay user selected information for a star or list of stars, 2) plot the abundances as a function of the atomic number(the option to plot scaled solar values will be added soon).

References

Here you can find all the original papers where the data comes from. You can also find a link to the paper on ADS as well as a direct link to the bibtex entry.

http://jinabase.pythonanywhere.com

Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

http://jinabase.pythonanywhere.com

JINA-CEE

JINAbase

- Home
- Query/Plot
- Search
- References
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Query JINAbase

Choose abundances for your sample and plotting

X-axis Fe / H From To

Y-axis C / Fe From To

Solar abundances Asplund 2009

To plot the log(eps) abundances leave the denominator element empty. (the first option in the list)

Leave upper and lower limit options empty to include all stars with abundances for selected elements.

Plot abundances | Show data table

Need more abundances or stellar parameter criteria?

Use this option to add a selection criteria using elemental abundances other than those selected above.

+ Add criterion | Remove criterion −

Further customize your sample

Use these criteria to select your sample of stars.

Location of stars

Select/deselect all · MW Halo · Bulge · Classical Dwarfs · Ultra-faint Dwarfs

Stellar evolutionary phase

Select/deselect all · Giants · Subgiants · Dwarfs · Horizontal branch

Specific element signatures

Select/deselect all · Ordinary stars · CEMP · CEMP-no · r-I rich · r-II rich · s-rich · i-rich (Not implemented yet!) · r/s stars

Select references

The reference list is updated after a successful query to reflect the references included in the customized sample. If you change any of the optoins above to do a new query, you need to ***reselect the desired references manually***, otherwise the references selected in the previous query would be used. This extra step is to make sure that you manually inspect the references selected for each query.

Select by author and year: **First author/s** e.g. Frebel, Roederer

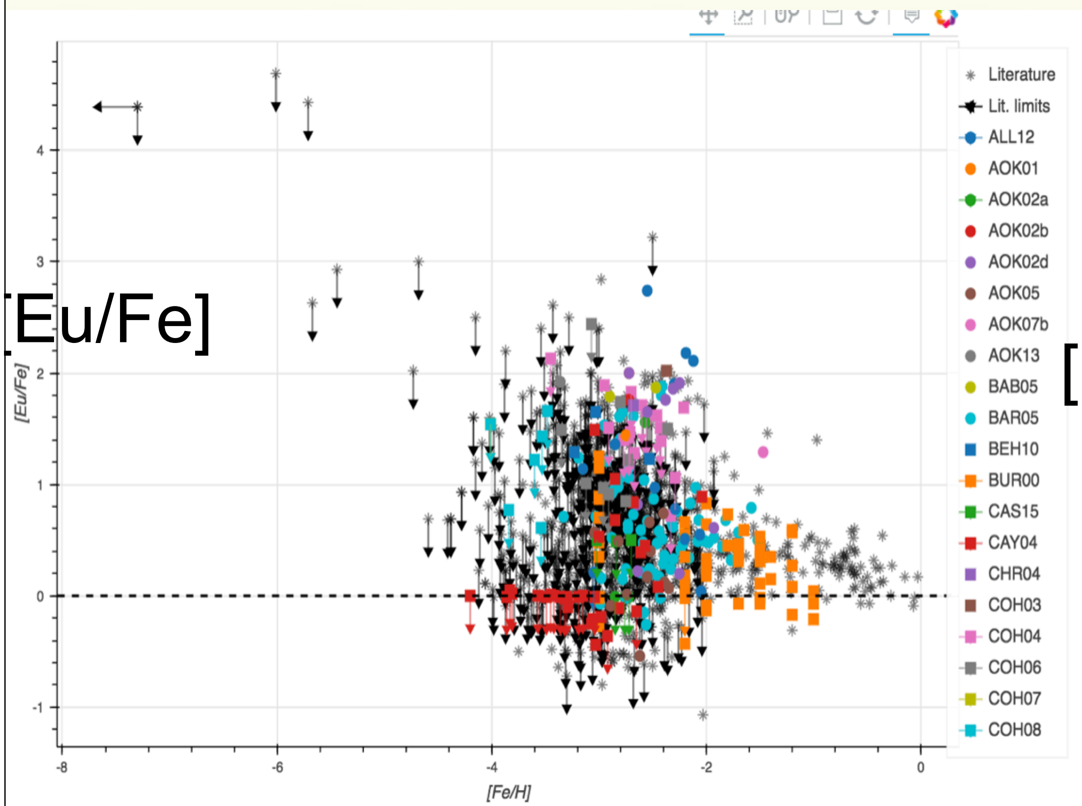
Year range: **From** e.g. 1990 **To** e.g.2017

Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

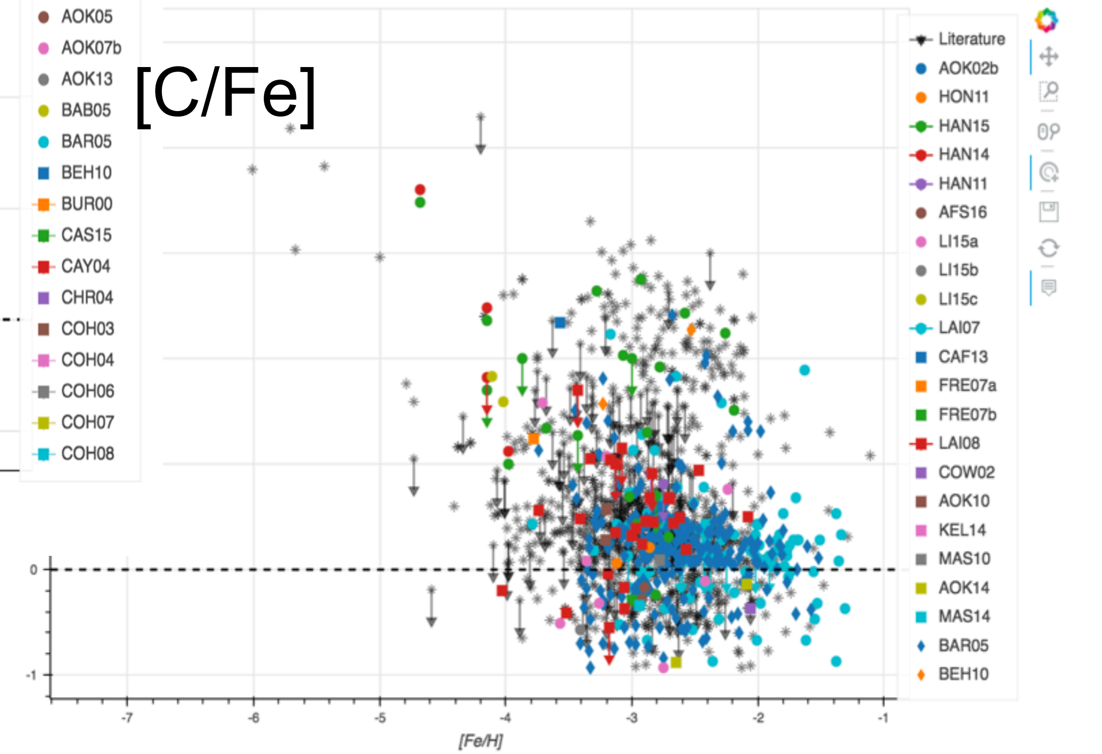


Note: The list of references on the query page will be updated to include only those studies that fulfill your selection criteria

Upper limits are shown as inverted triangles when the option is selected on the query page.

Try hovering over the data points!

Click on entries in the legend to remove them from the plot.



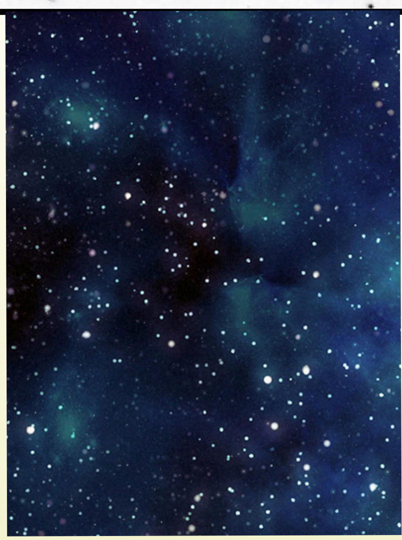
Statistics of plotted data:

Number of stars: 1341,

Number of upper limits: 133

Total number: 1474

The puzzle pieces for exploring the r-process



Stellar Archaeology

Stellar element abundance patterns tell about previous enrichment events

Nuclear Astrophysics

Astrophysical origin(s) of the chemical elements

Dwarf Galaxy Archaeology

Clean nucleosynthesis signatures in known environments