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

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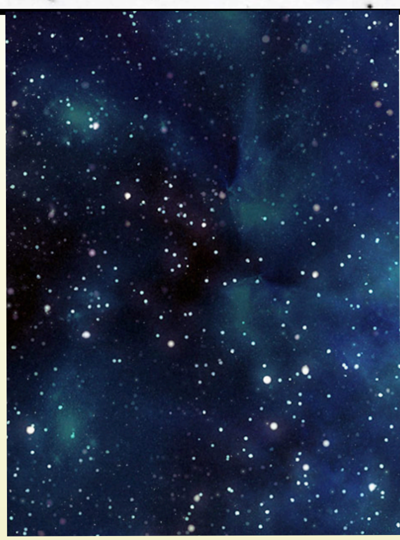
Why study the stars?

by: Apprentice to
Galileo Galilei, 1636

The puzzle pieces for exploring the early universe



<u>Stellar Archaeology</u>

Stellar element abundance patterns tell about previous enrichment events

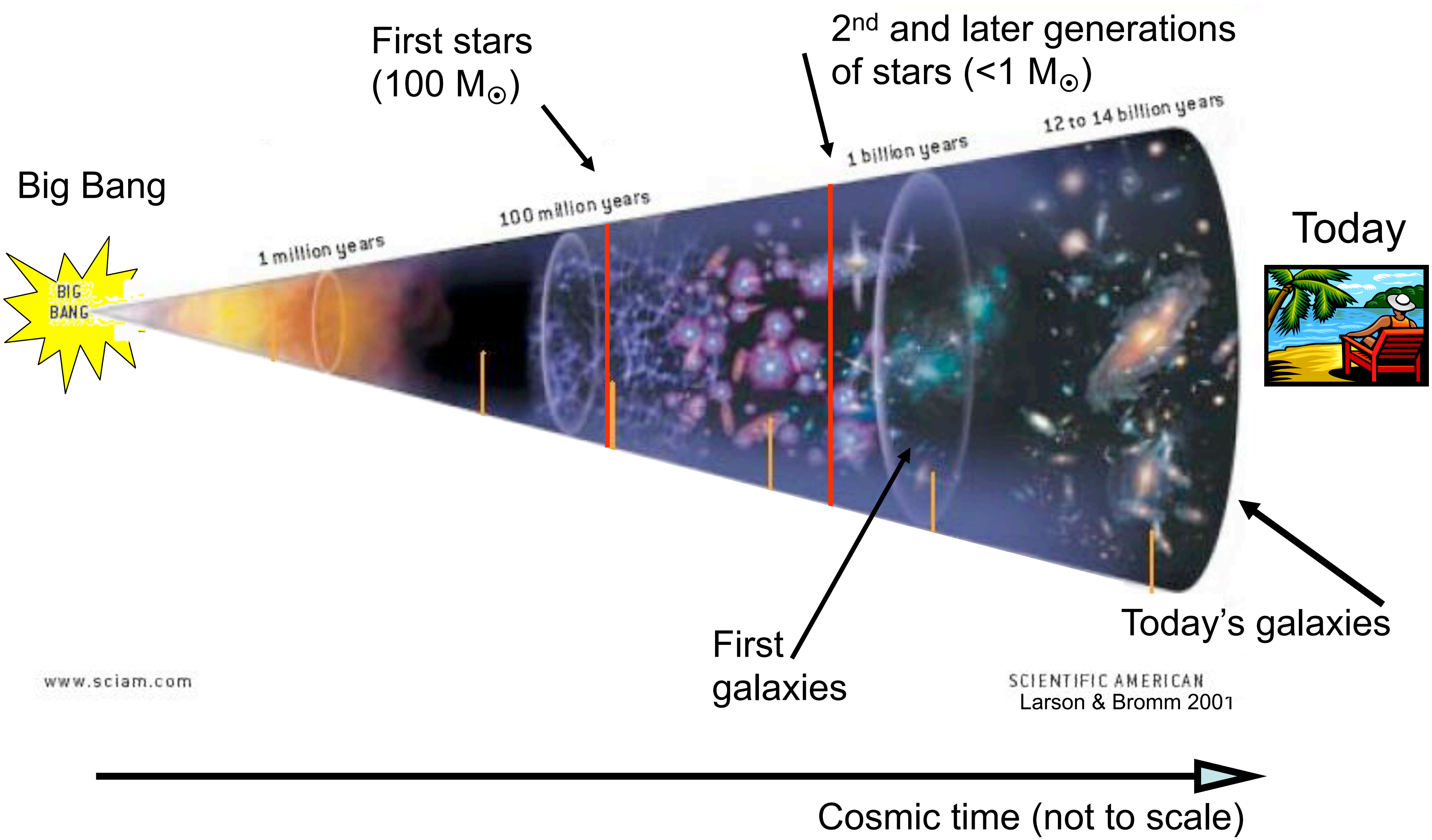
<u>Nuclear Astrophysics</u>

Astrophysical origin(s) of the chemical elements

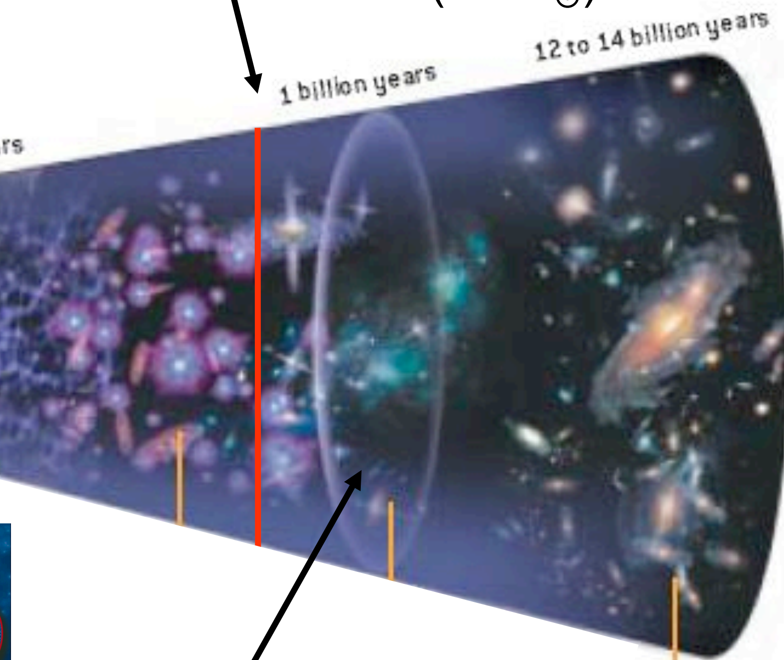
<u>Dwarf Galaxy Archaeology</u>

Clean nucleosynthesis signatures in known environments

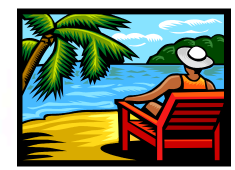
A long time ago...

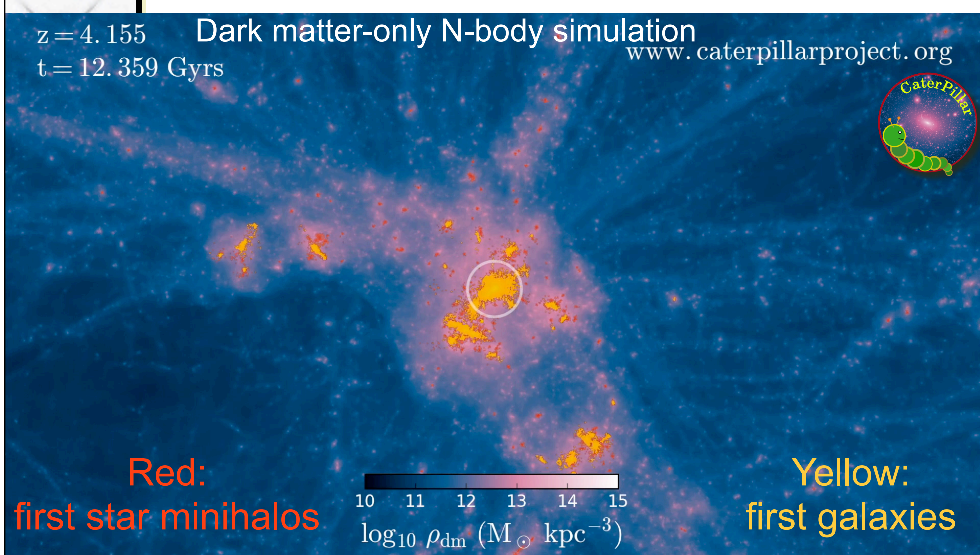


A LONG TIME AGO...



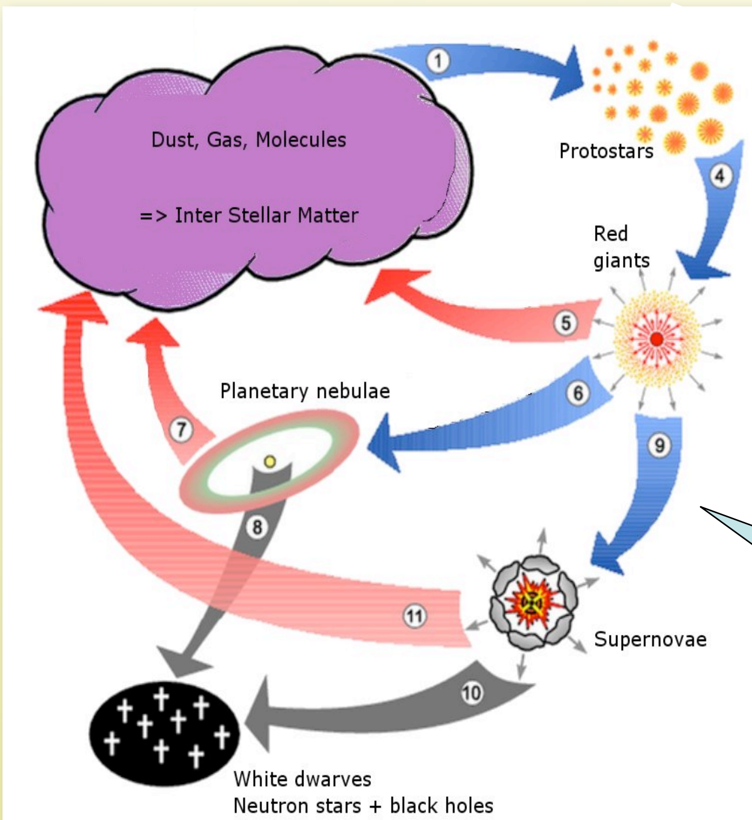
Today





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!

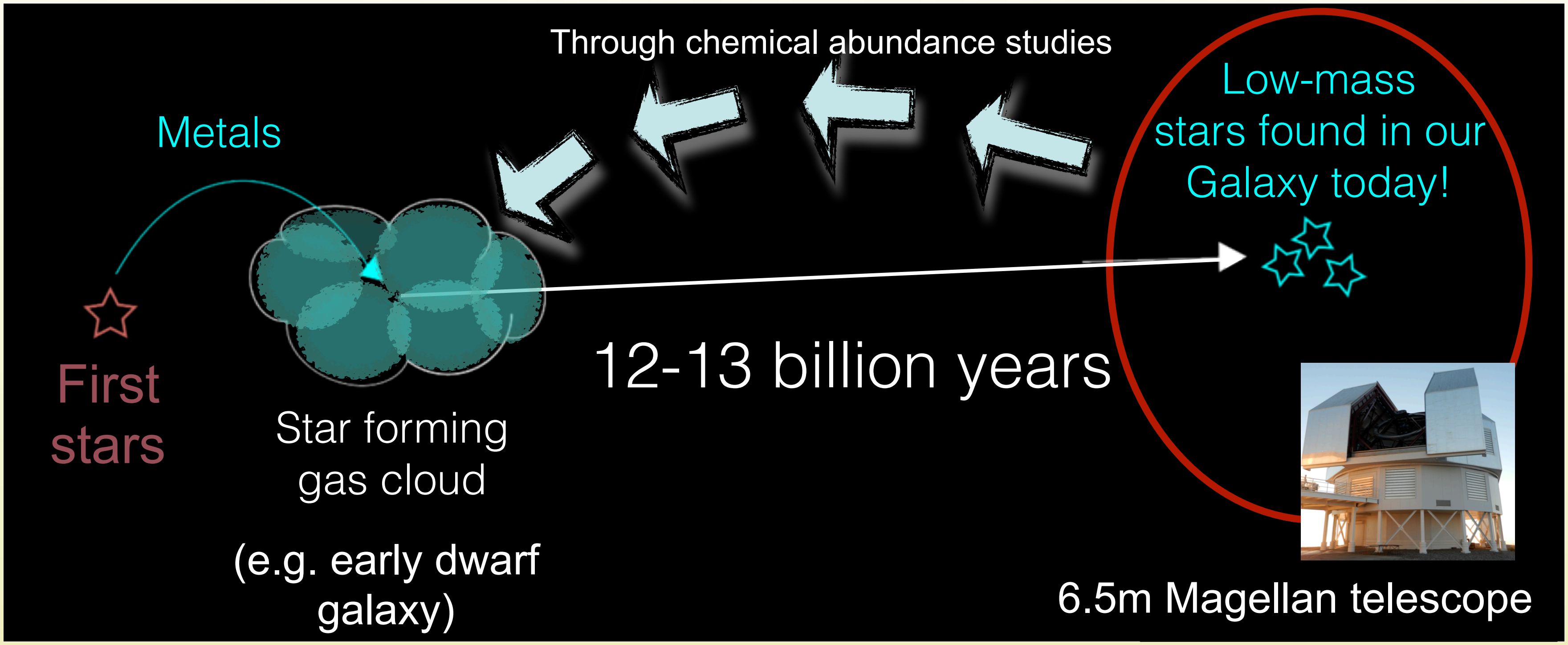
We look for stars with the <u>least amounts</u> of elements heavier than H and He!

Zentrum fuer Astronomie und Astrophysik, TU Berlin

STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

Low-mass stars with M < 1 $M_\odot$: 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)

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_{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.

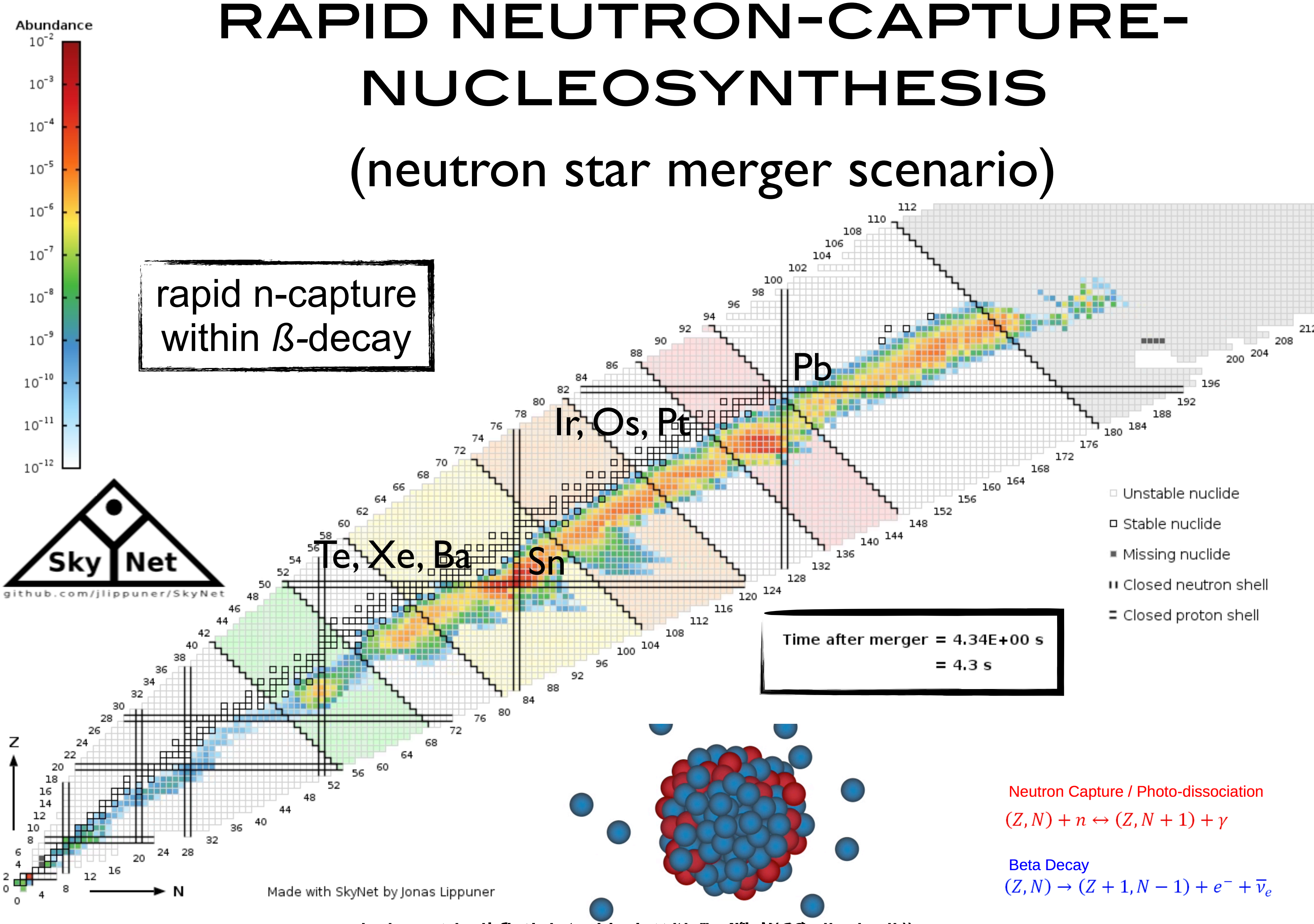
[c] The CEMP star definitions are from Reference 21. s- and i-process-enhanced stars are always CEMP stars; r-process-enhanced stars may or may not be CEMP stars. There is also a class of CEMP-no stars.

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

Frebel 2018 ARNP

RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

(neutron star merger scenario)



rapid n-capture within ß-decay

Neutron Capture / Photo-dissociation

$(Z, N) + n \leftrightarrow (Z, N+1) + \gamma$

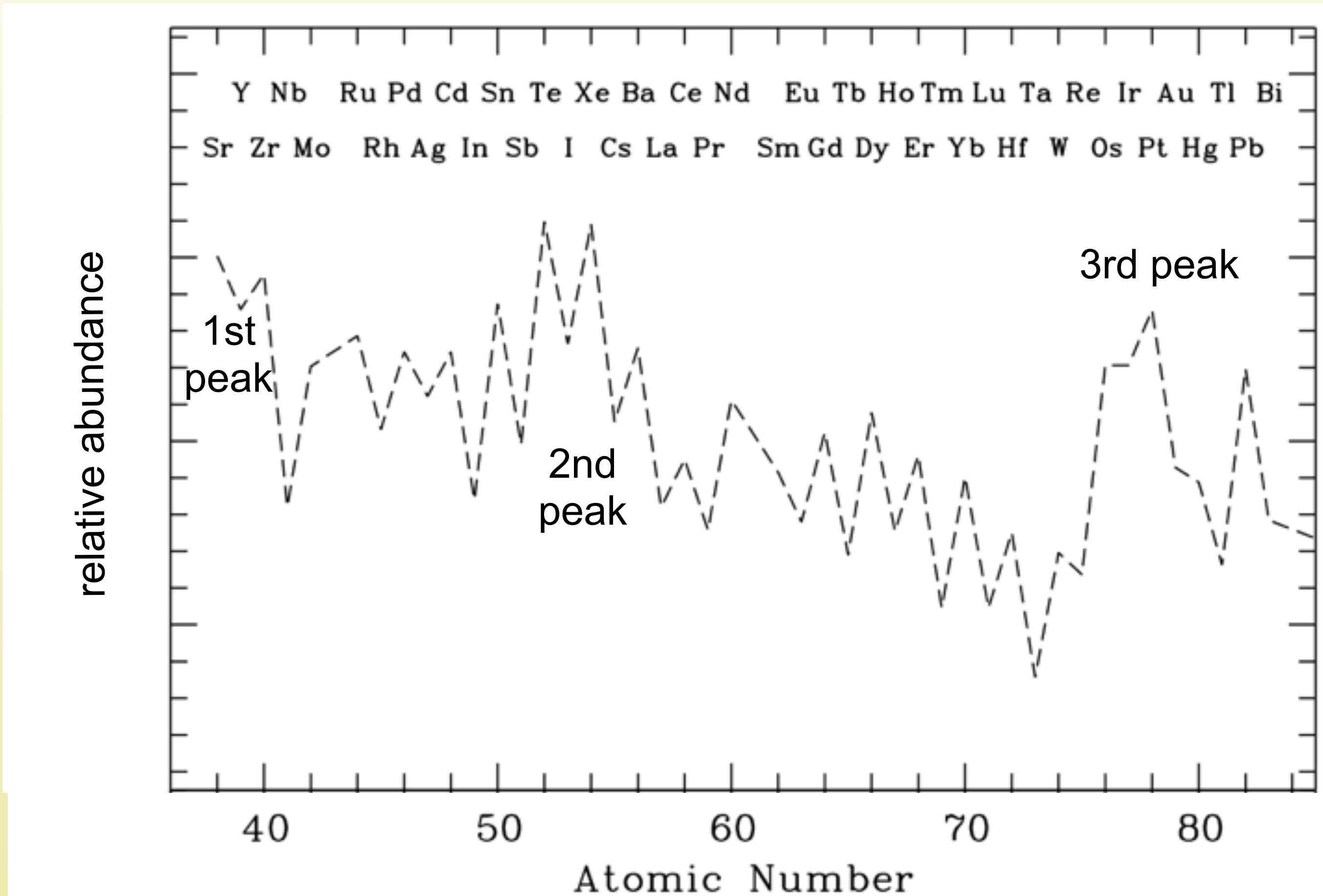
Beta Decay

$(Z, N) \rightarrow (Z+1, N-1) + e^- + \bar{\nu}_e$

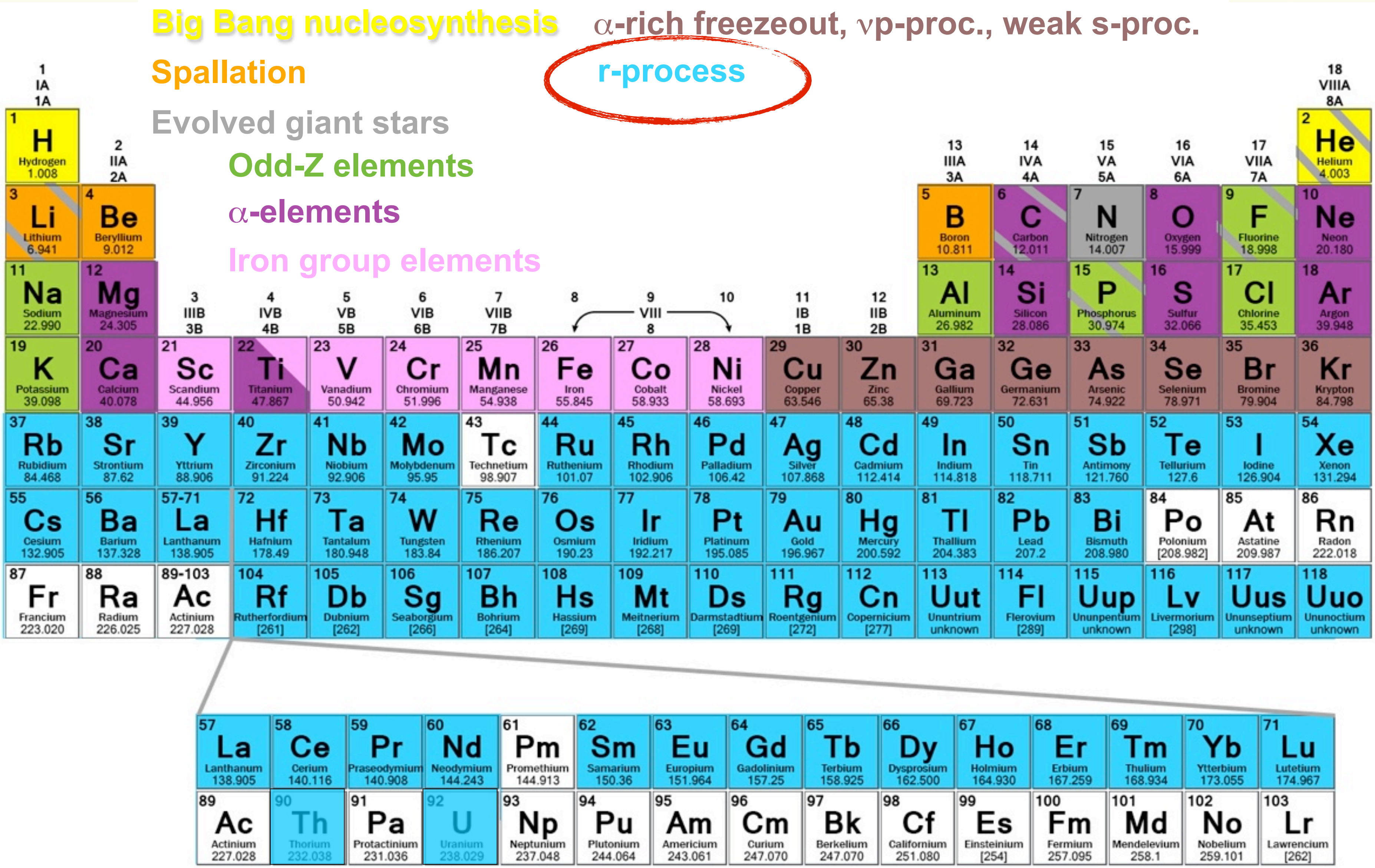
to stability

R-PROCESS PATTERN

neutron-capture r-process elemental pattern



The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table

Big Bang nucleosynthesis

Spallation

Evolved giant stars

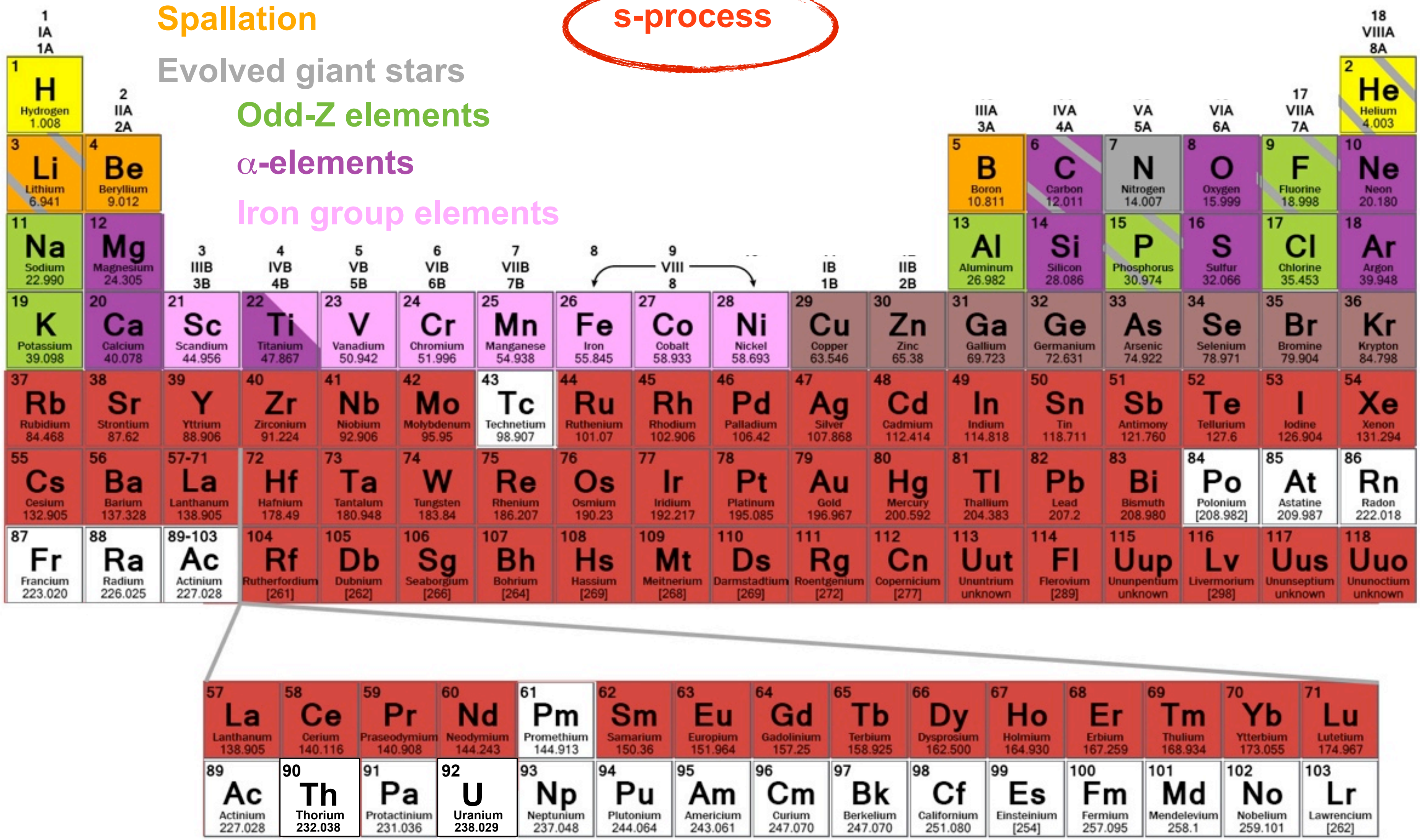
Odd-Z elements

α-elements

Iron group elements

α-rich freezeout, νp-proc., weak s-proc.

s-process



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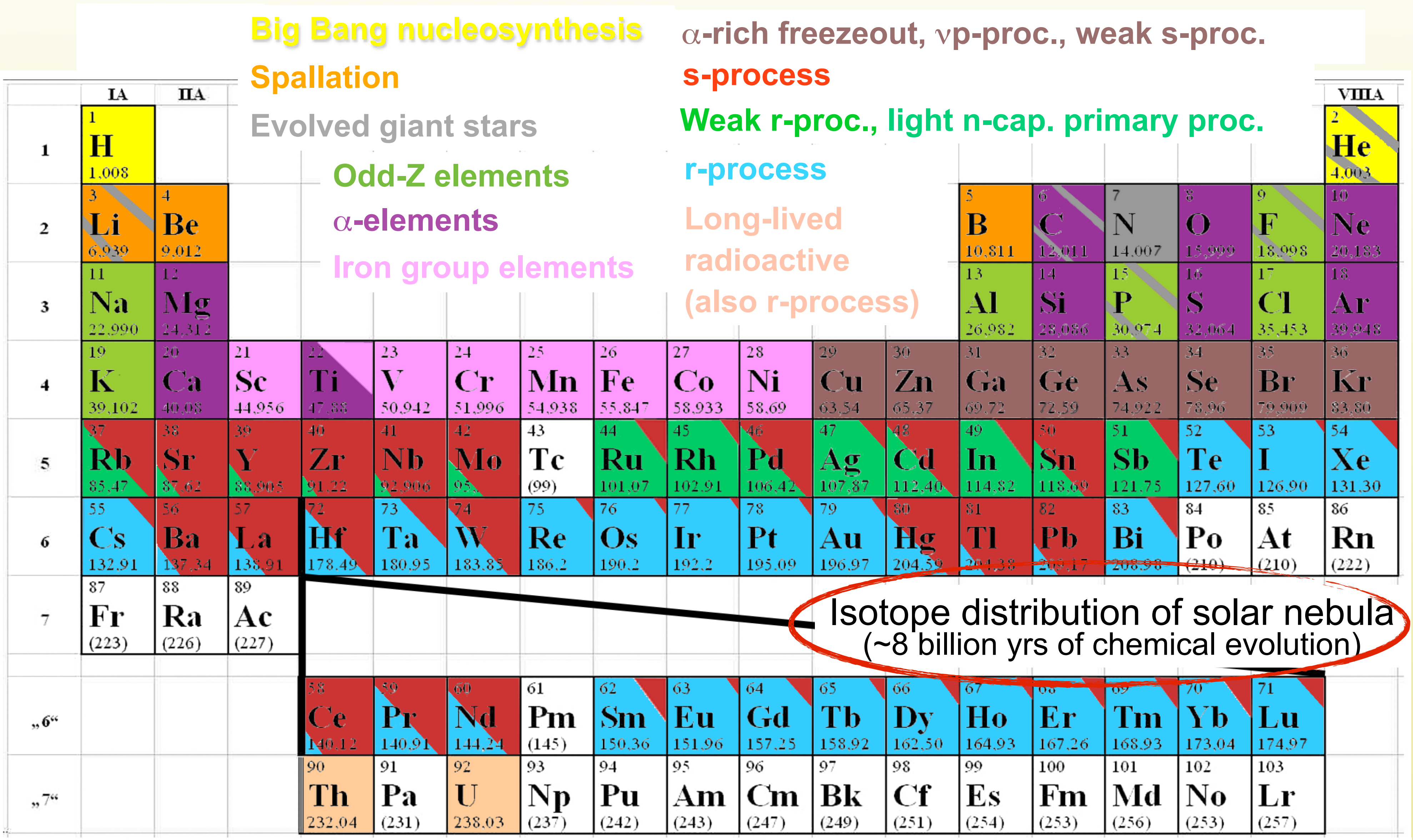


Rare r-process stars in the Milky Way

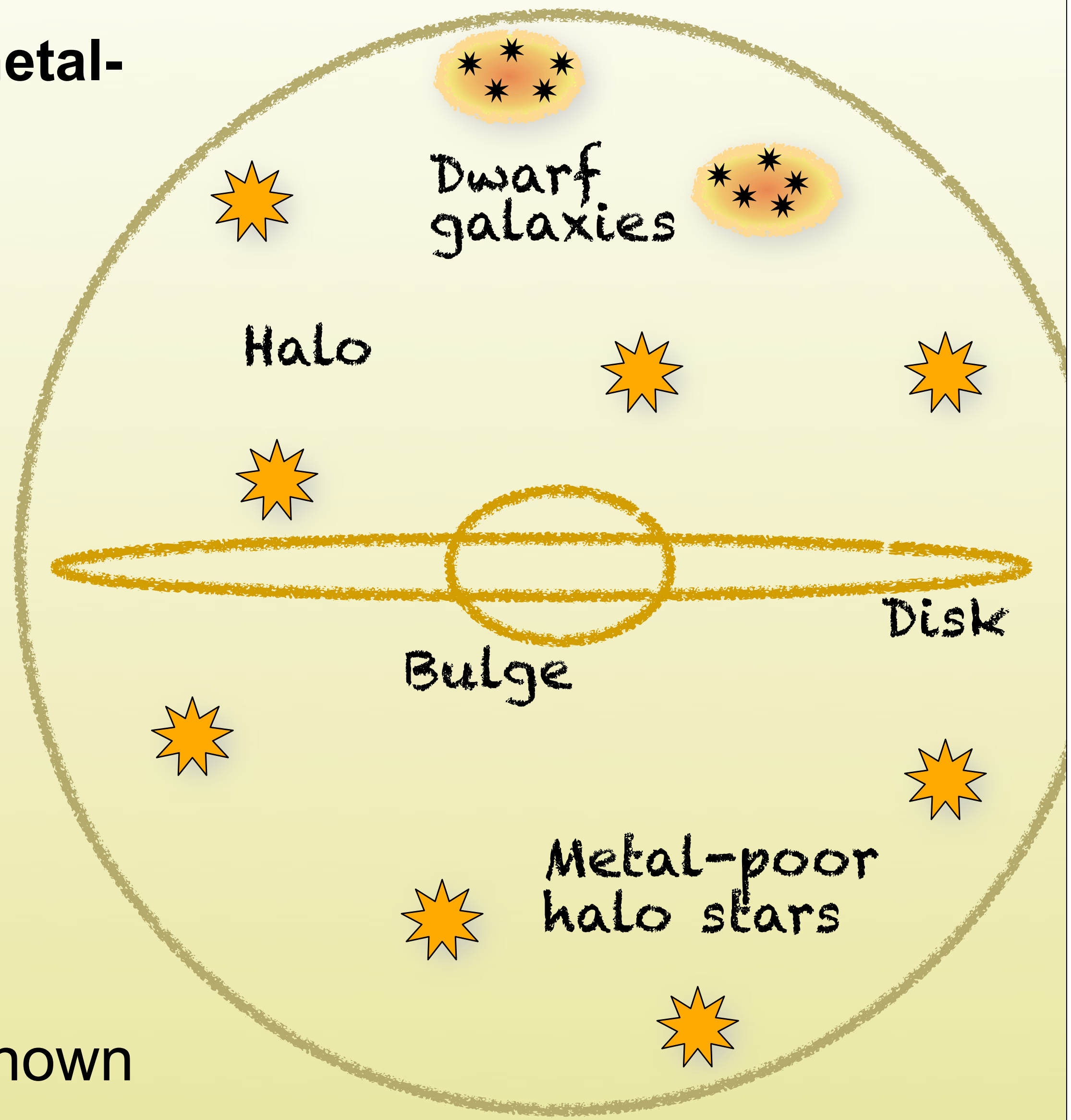
How common are r-process metal-poor stars in the Milky Way?

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

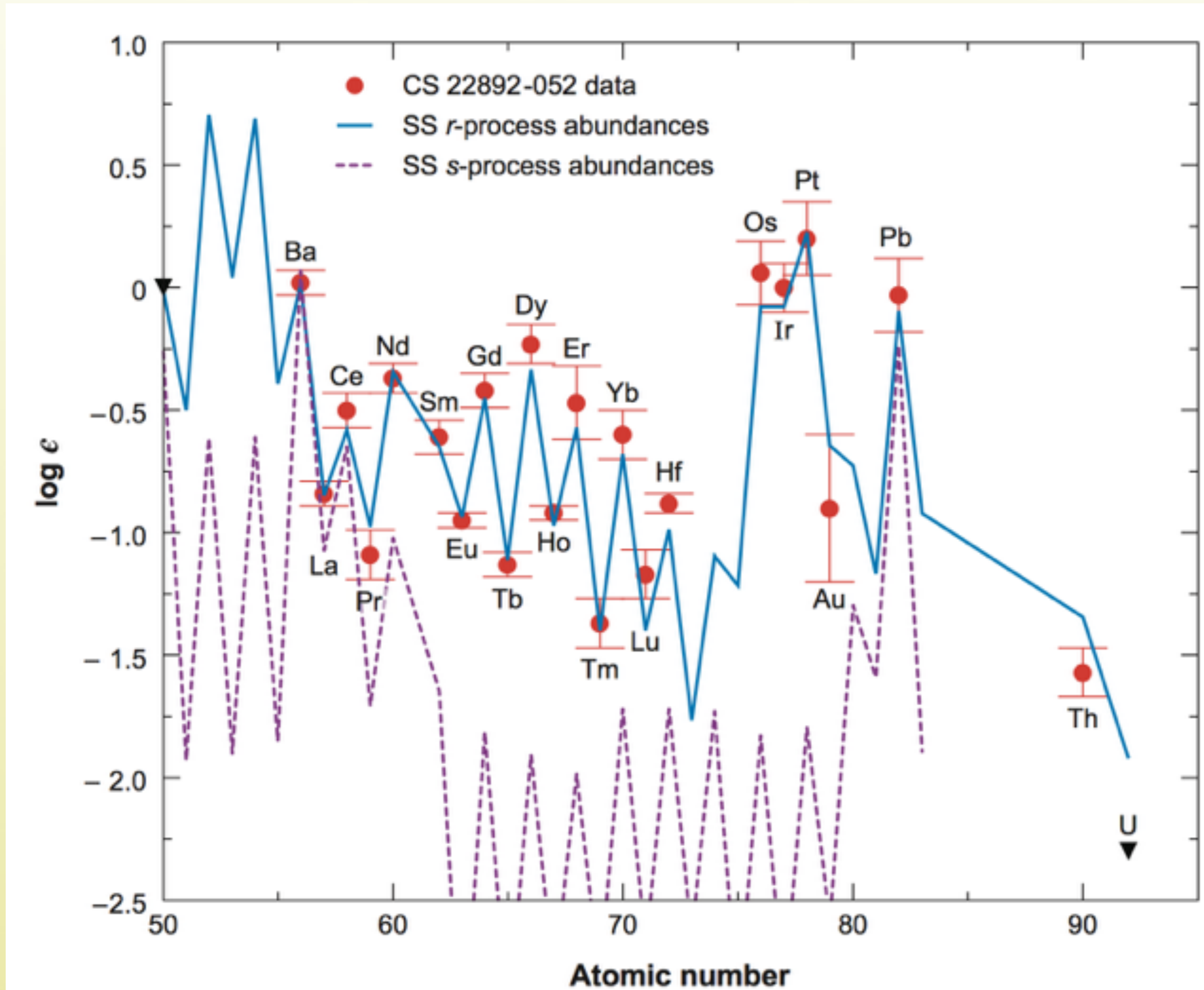


Universal r-process pattern observed in metal-poor stars

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

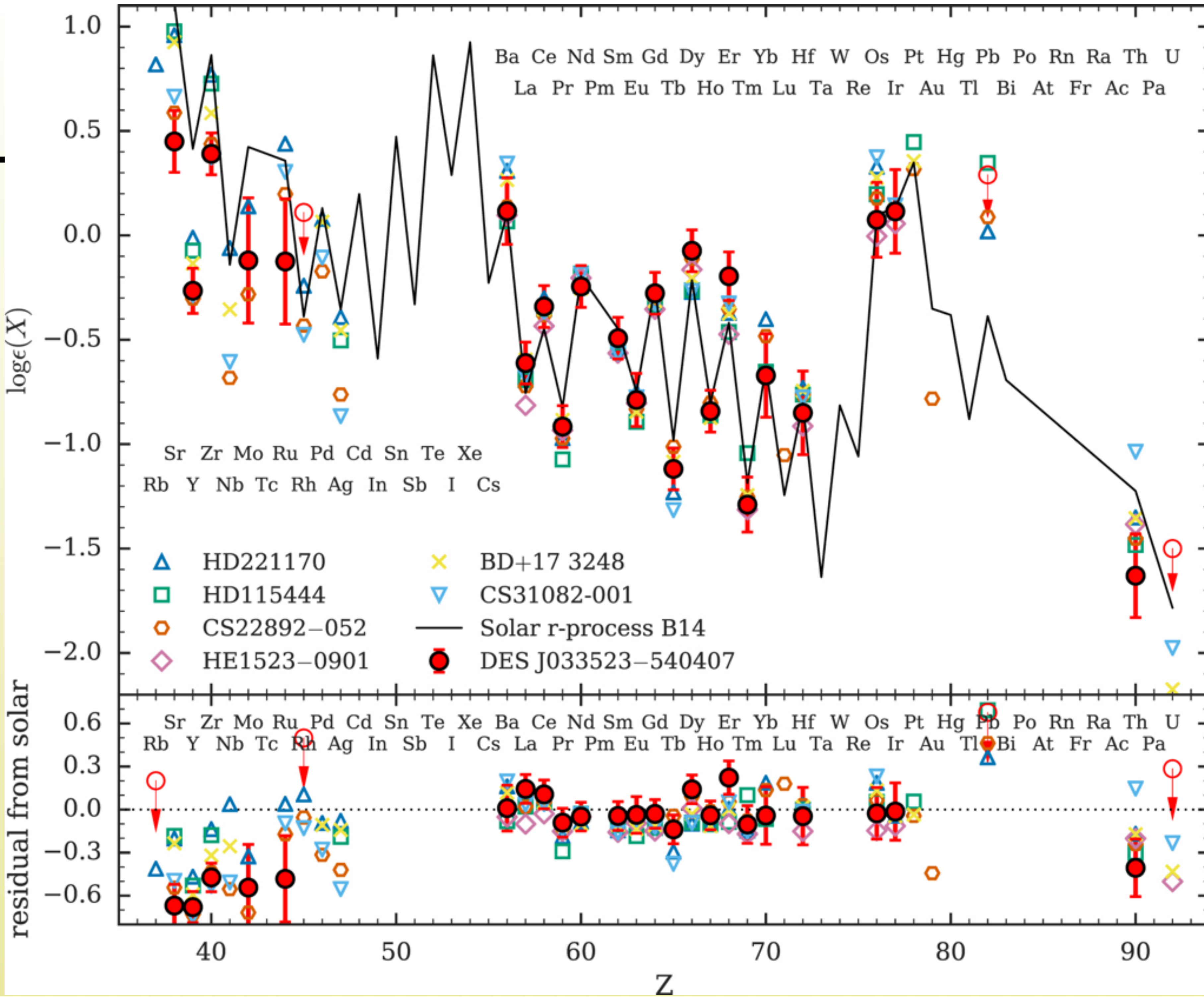
r-process stars are all extremely metal-poor: [Fe/H]~−3.0

(= 1/1000th of solar Fe value)



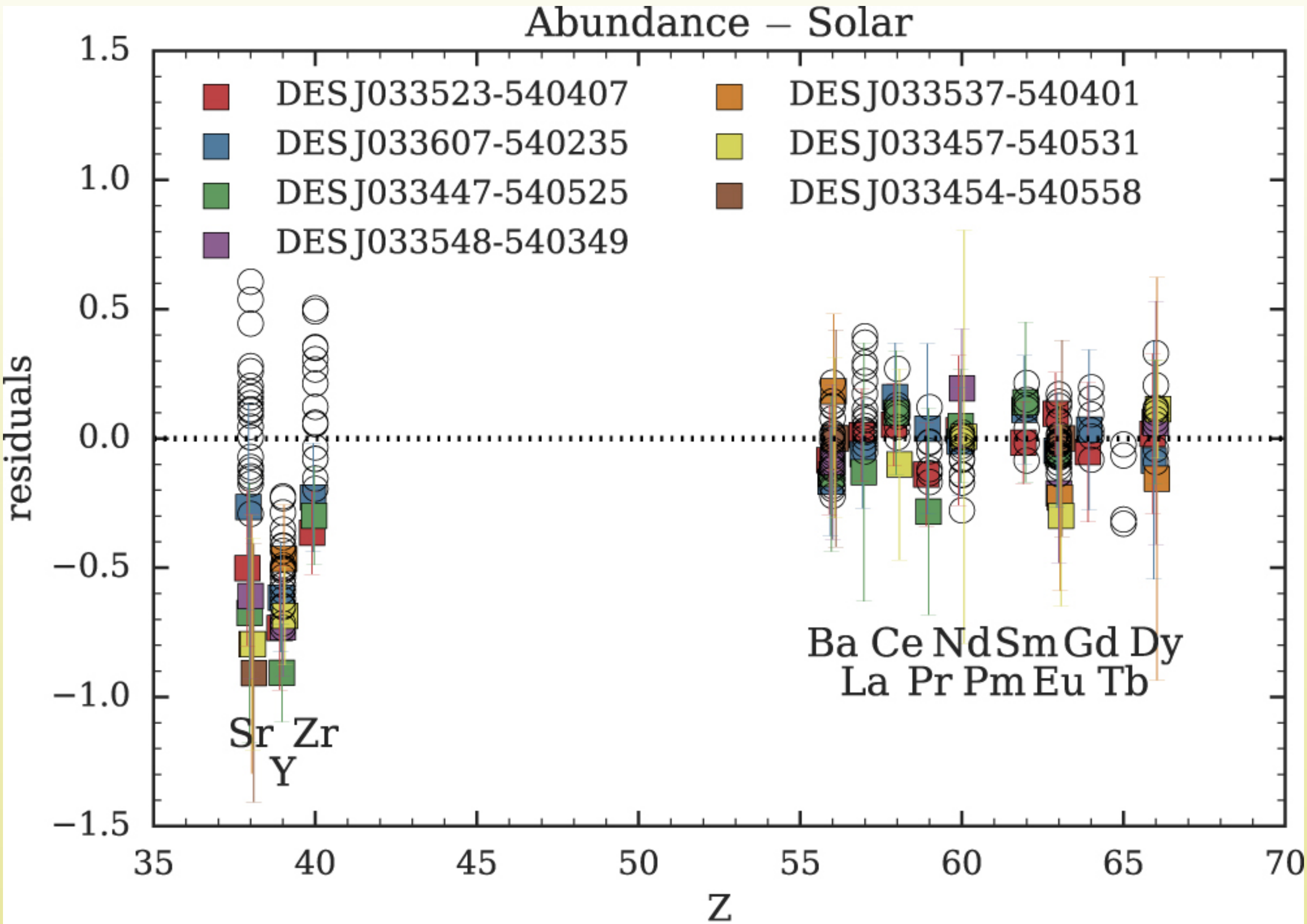
Sneden et al. 2008

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



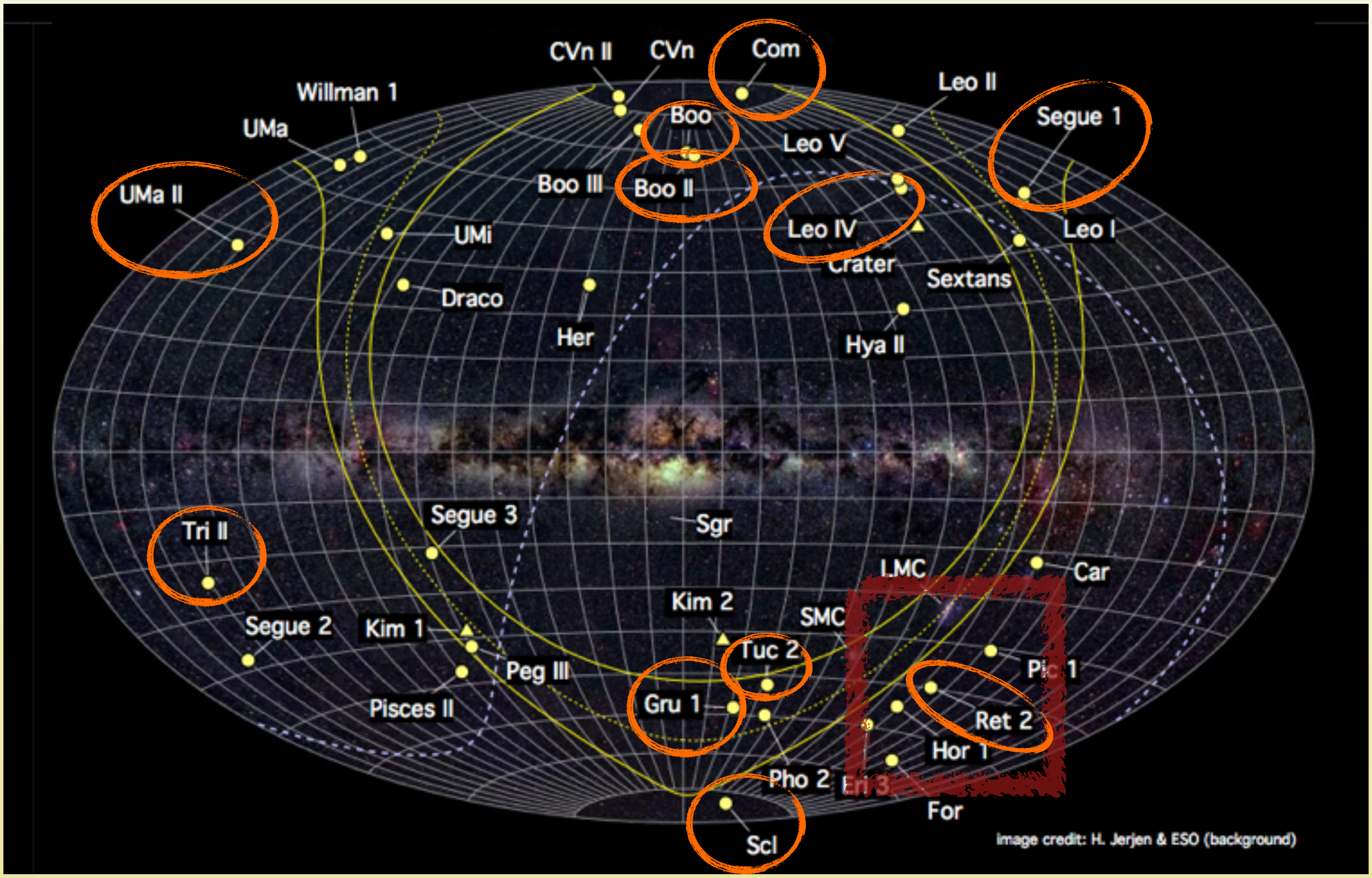
log ε(X)
residual from solar
Z
Sr Zr Mo Ru Pd Cd Sn Te Xe
Rb Y Nb Tc Rh Ag In Sb I Cs
Ba Ce Nd Sm Gd Dy Er Yb Hf W Os Pt Hg Pb Po Rn Ra Th U
La Pr Pm Eu Tb Ho Tm Lu Ta Re Ir Au Tl Bi At Fr Ac Pa
HD221170
HD115444
CS22892−052
HE1523−0901
BD+17 3248
CS31082-001
Solar r-process B14
DES J033523−540407

1st peak: huge deviations
2nd/3rd peak: all good!

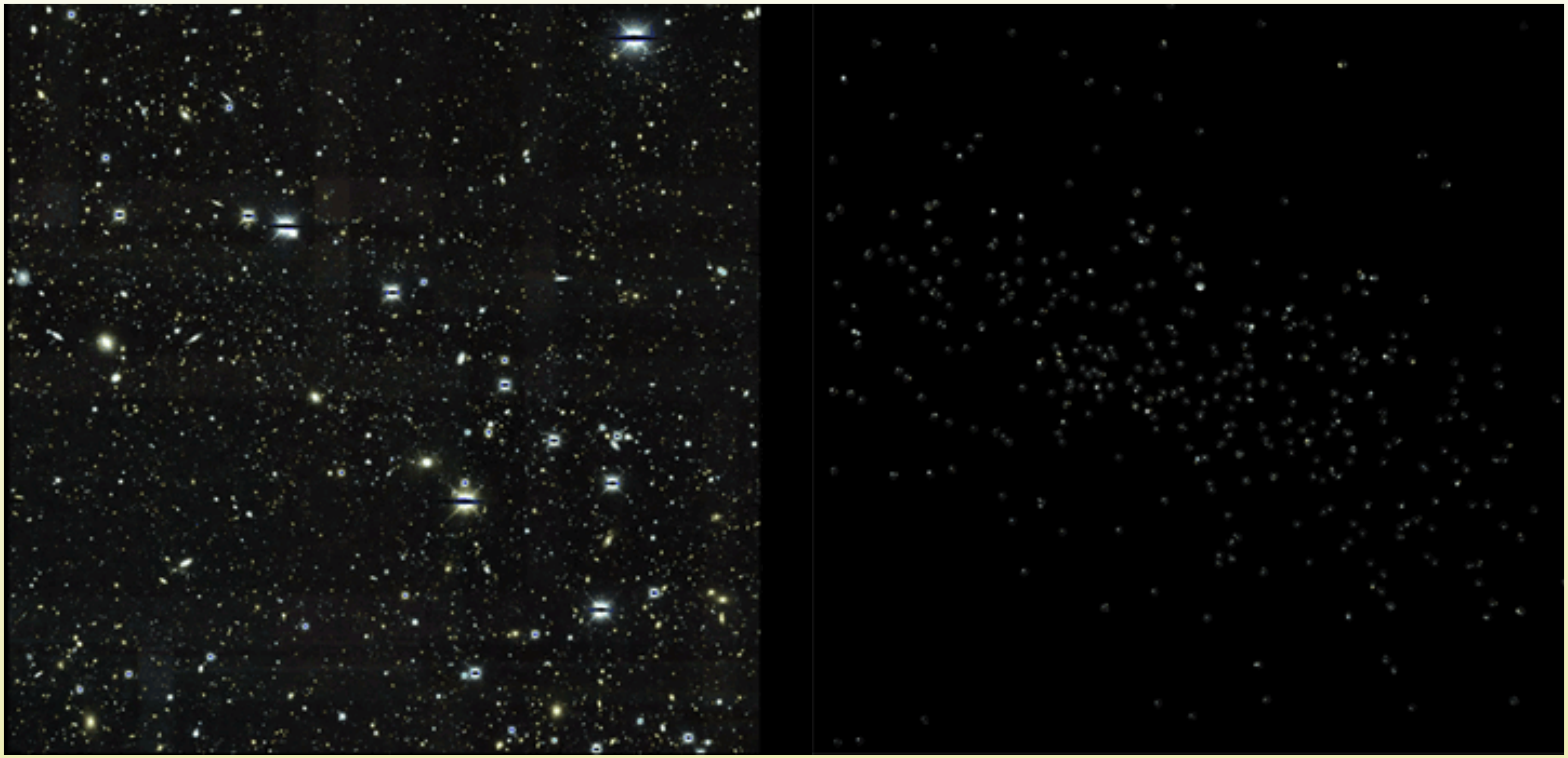


Milky Way Satellite galaxies

Dwarf galaxies are useful tools to study star formation and chemical evolution, early galaxy formation and the build-up of the Milky Way



MEET RETICULUM II



All stars

Reticulum II stars

(Dark Energy Survey, 2015)

Ultra-faint dwarf galaxy properties (UFDs)

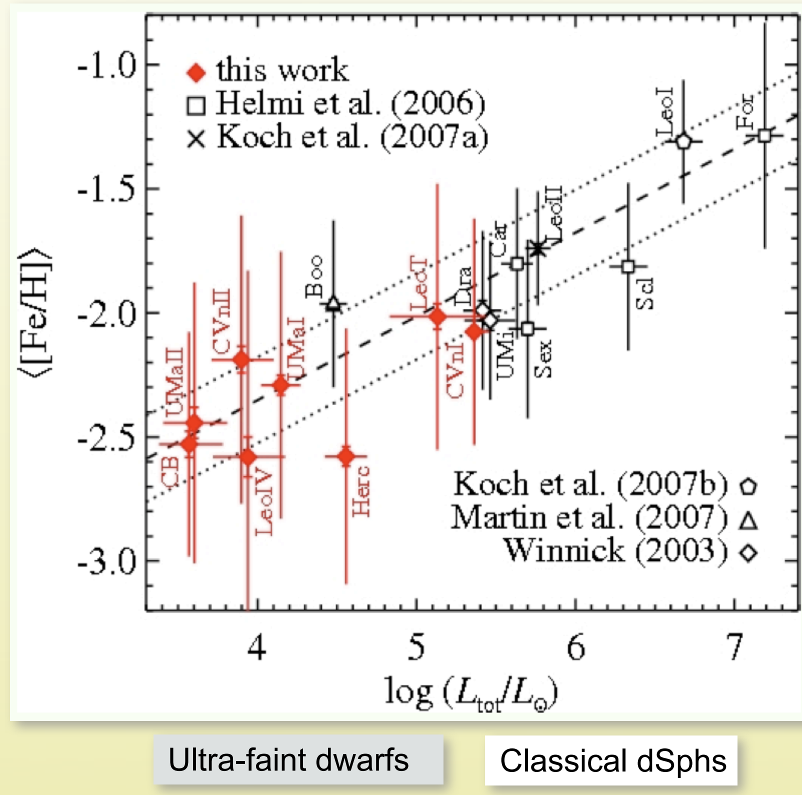
Low luminosity (300 - 3,000 L_{sun})

Dark matter-dominated (M/L > 100)

Metal-poor (mean [Fe/H] ~ −2)

Stars are old (mean age 13.3 +/− 1 Gyr)

Few bursts of star formation

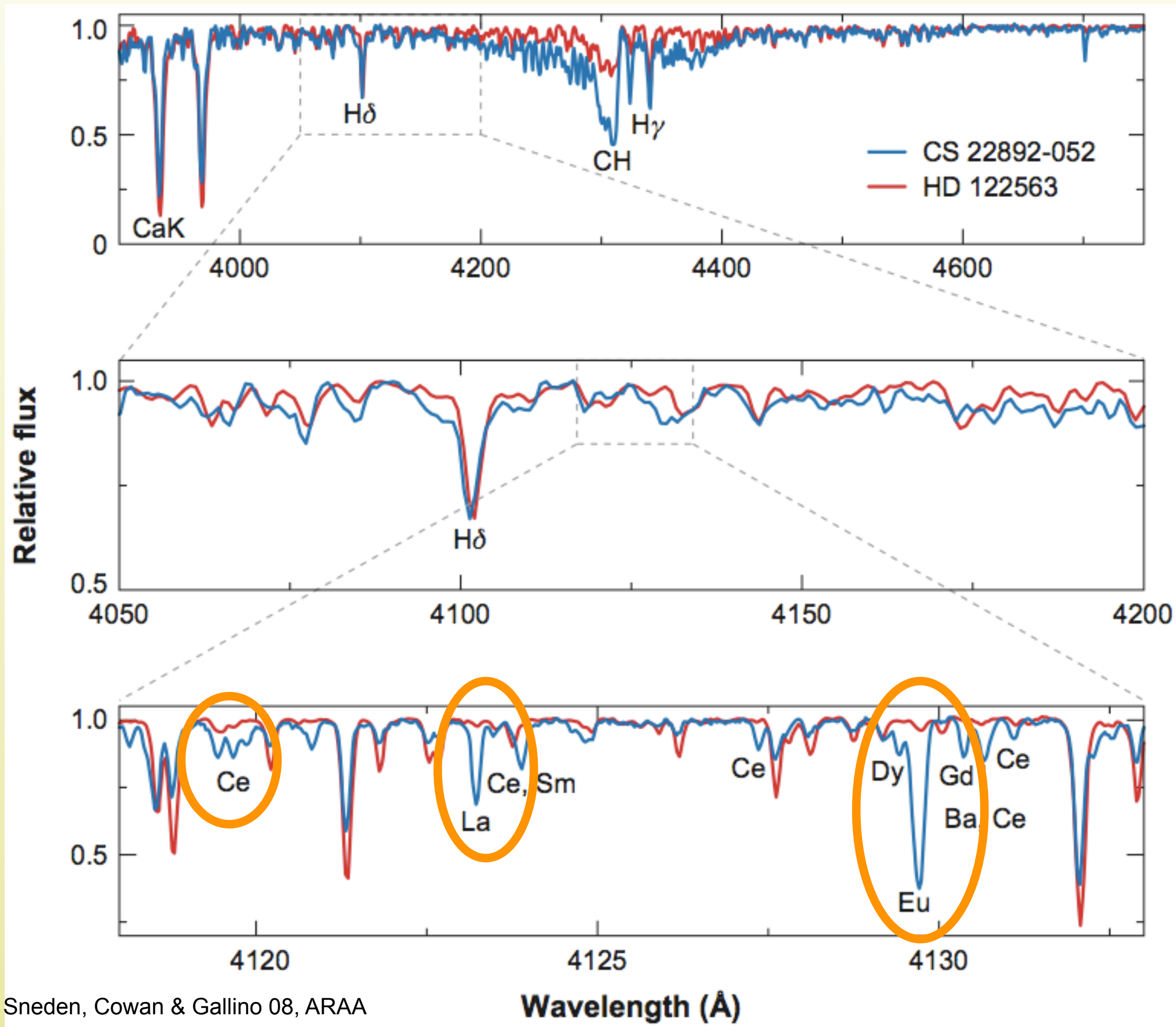


Ideal targets for Dwarf Galaxy Archaeology

Use entire galaxy as fossil record of the early universe.

Bonus: get environmental information because we know where stars were born

Observing neutron-capture elements



Sneden, Cowan & Gallino 08, ARAA

HD 122563: r-process deficient star

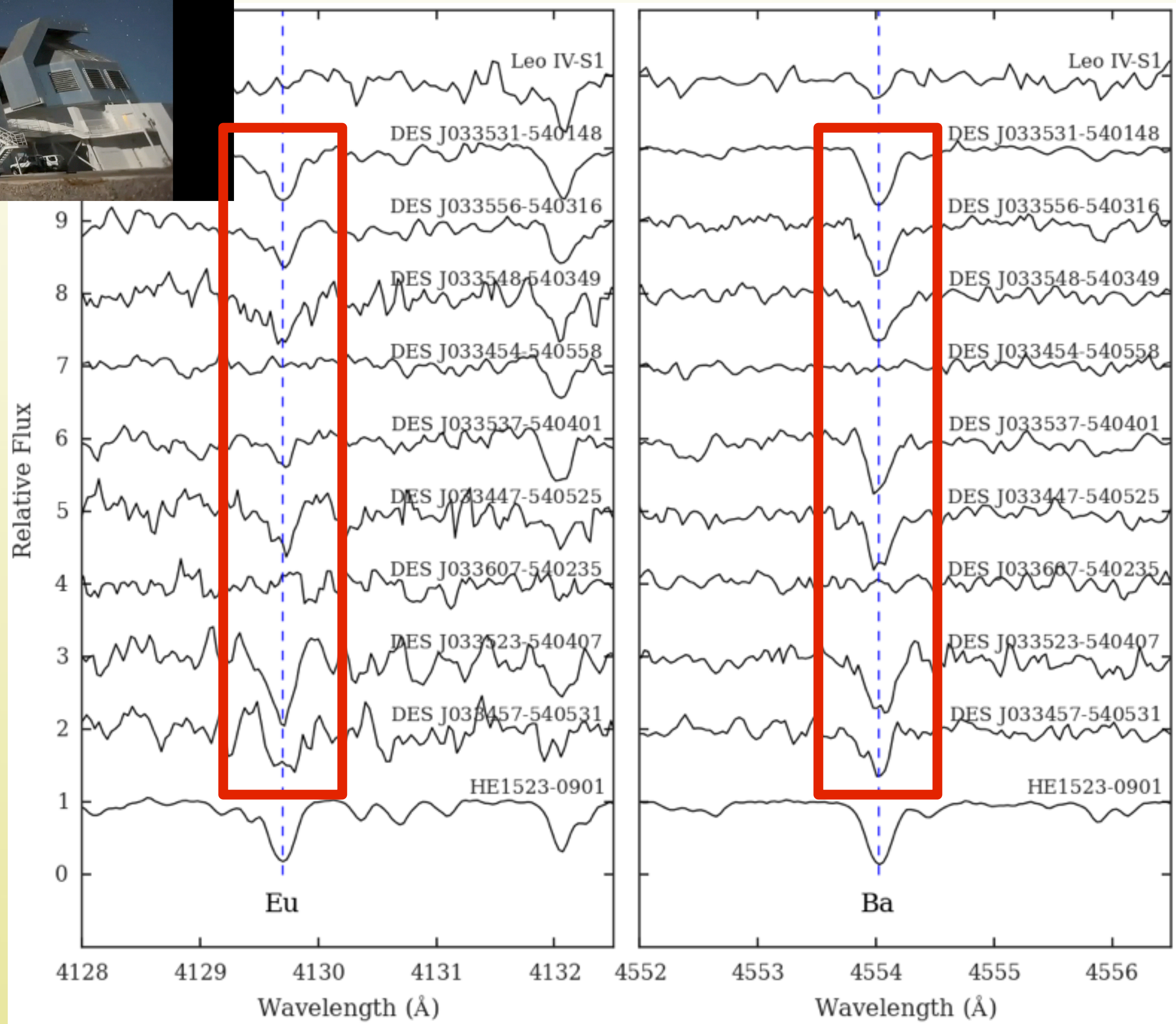
CS 22892-052: r-process strong star

Magellan observations of Reticulum II stars

Clay 6.5m Magellan telescope (on left) at Las Campanas Observatory, Chile

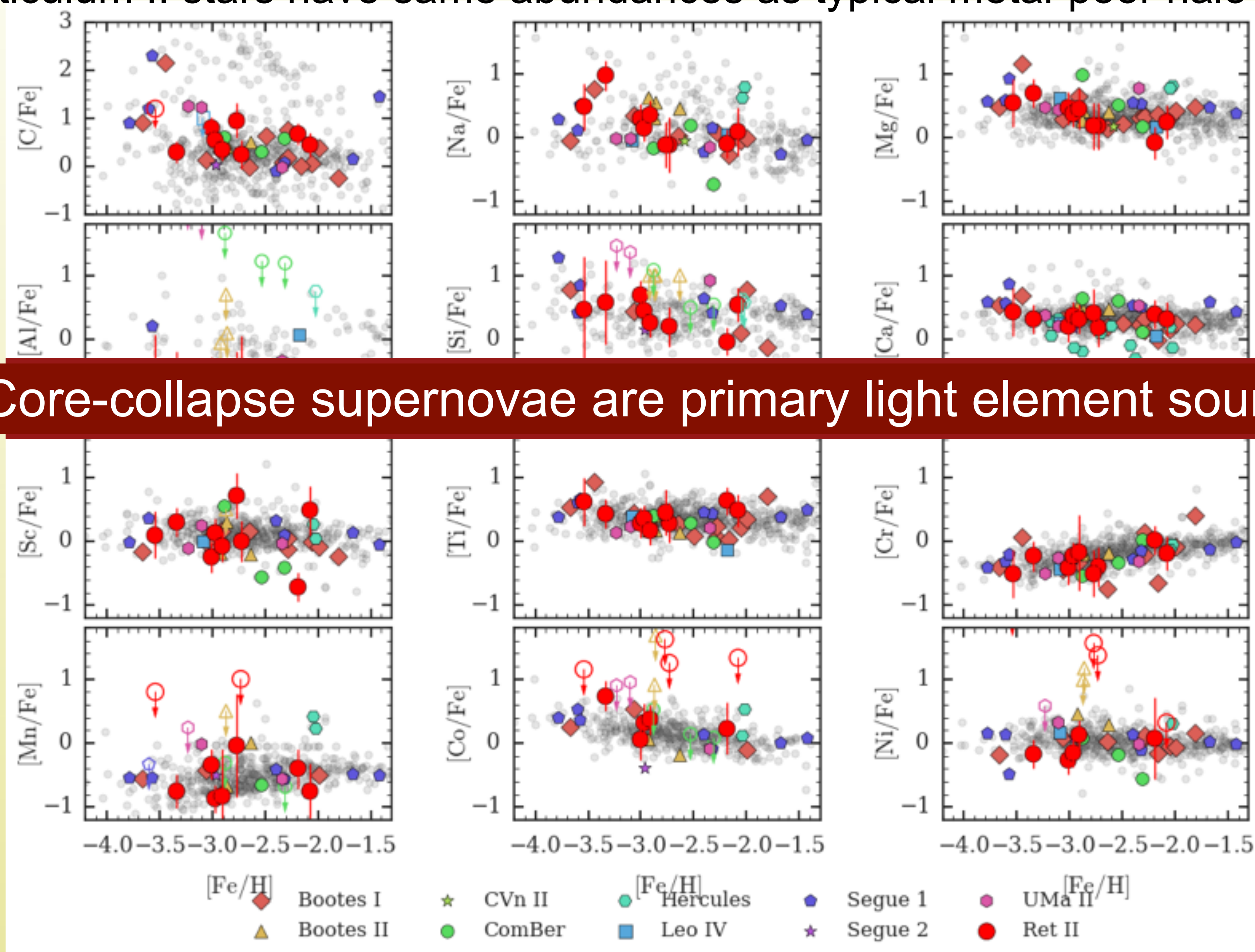
Brightest members (V=17-19) observable w/ high-resolution spectroscopy

=> Ji et al. (2016) spent 2-3 hours on each of the 9 brightest targets (~23h)



Light element abundances
(C, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Co, Ni)

Reticulum II stars have same abundances as typical metal-poor halo stars

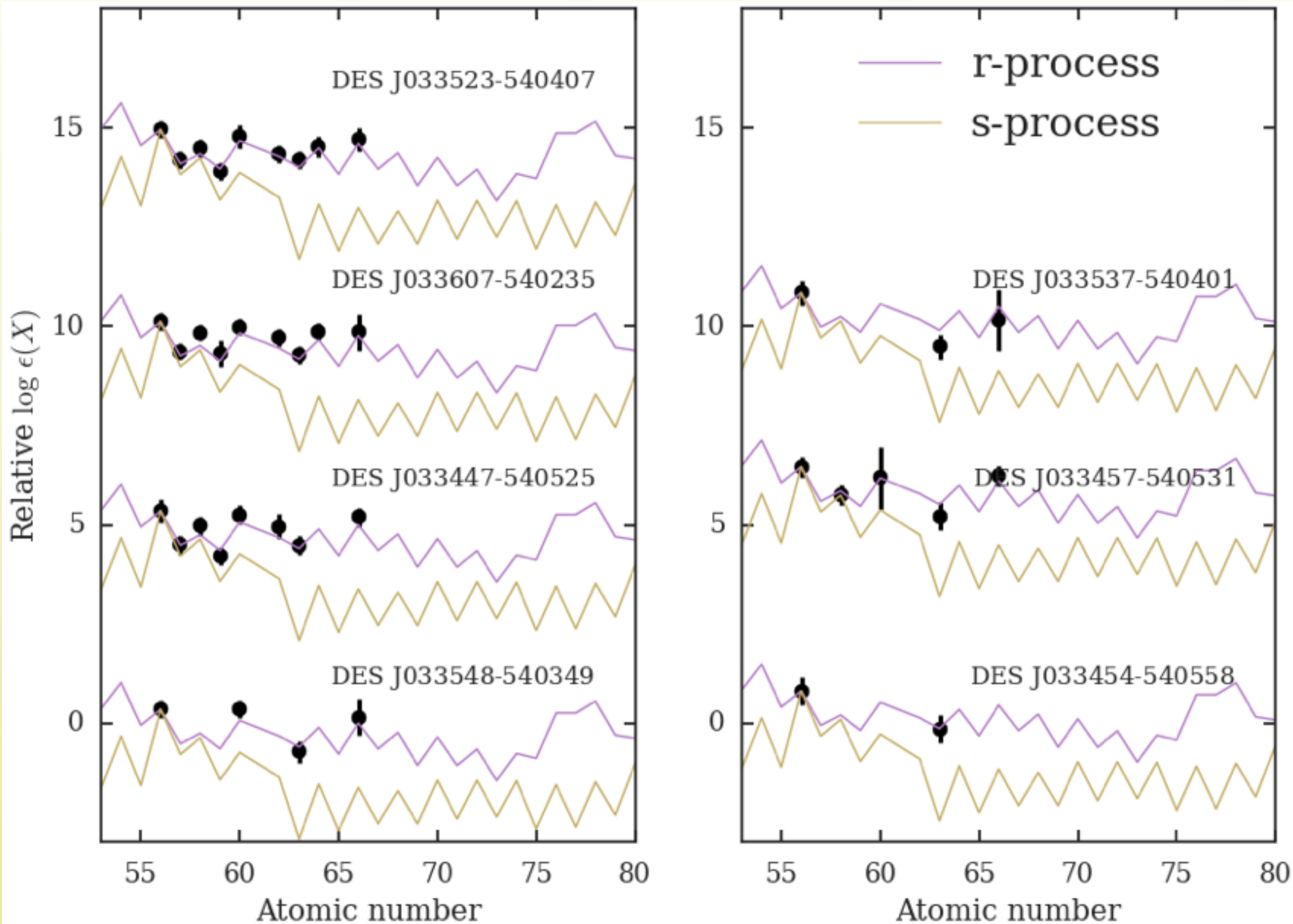


Core-collapse supernovae are primary light element source

gray dots metal-poor halo stars

Ji et al 2016, *Nature*, 531, 610

All seven Ret II stars display the (main) r-process pattern



Ji et al 2016, *Nature*, 531, 610

Zoo of r-process<u>es</u>...!

Table 2 Nucleosynthesis processes that can contribute neutron-capture elements

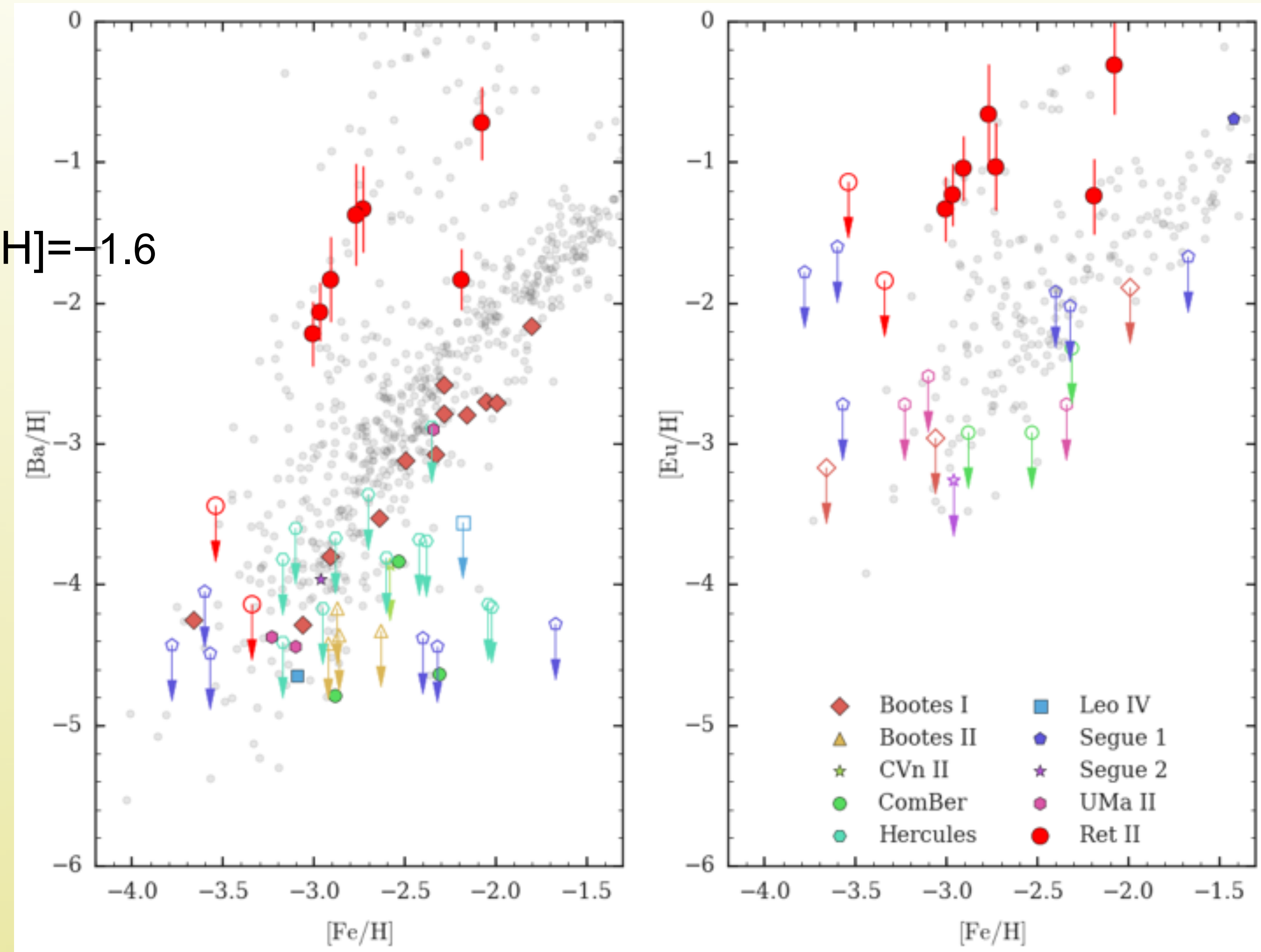
Process	Conditions	Elements produced	Y_e	Astrophysical sites
Terminal QSE[a]	Insufficiently neutron rich; α-, neutron-, proton-capture and reverse; expansion from hot, dense state	Sr $\rightarrow$ Ag	< 0.5	Standard proto–neutron star wind in core-collapse supernovae; shock-heated/disk ejecta
νp-process	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

Ret II stars: ≥100x higher n-capture element abundances than other UFDs



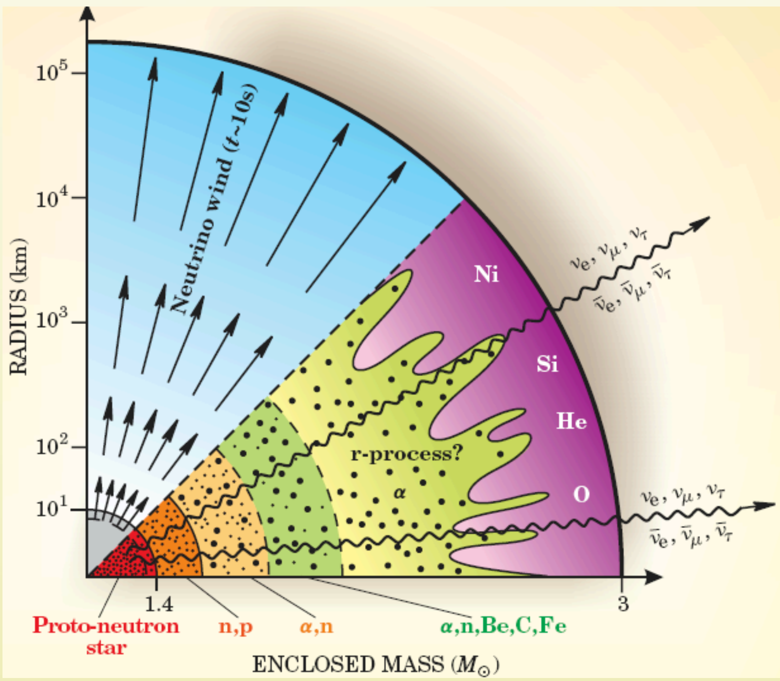
[Ba/H]=−1.6

[Eu/H]=−1

Core-collapse supernova

(death of a massive star with M > 8 $M_\odot$)

Supernovae are common; produce light elements w/ Z<30 in their cores
Responsible for these light elements when observed in metal-poor stars



Woosley & Janka 2005

Theoretical element yield:

~10^{-6} M_{sun} of total r-process material

=> ~$10^{-7.5}$ M_{sun} of Eu (per event)

Pros

✓Metal-poor stars only have one/few progenitors
✓Provides the fast enrichment needed; small & steady r-process yields

Con Theoretical difficulties for r-process nucleosynthesis to produce elements heavier than Ba (e.g. Arcones et al.)

Neutron star binary merger
(two compact supernova remnants)

Pros Easily produces elements heavier than Ba

Cons <u>Rare</u> One binary per ~1000- 2000 supernovae
Long(er) enrichment timescale => Inspiral time >100 Myr

Yield: ~10^{-3} -10^{-2} M_{sun} of r-process material (across all n-cap elements)

=> ~$10^{-4.5}$ M_{sun} of Eu (per event)

Additional (indirect) evidence for local r-process nucleosynthesis

1) Short gamma-ray bursts: Afterglow from decay of radioactive r-process elements detected (Tanvir et al. 13)
2) Radioactive deep sea measurements suggest local neutron star mergers (Wallner et al. 15, Hotokezaka et al.15)

Dwarf galaxy archaeology

(= using an entire dwarf galaxy to study the early universe)

How Rare?

Population of 10 UFDs:

➡1 of 10 r-process events

➡Est. stellar mass of ***all*** UFDs: ~2000 SNe expected

➡Consistent w/ expected NSM rate of 1 per 1000-2000 SNe

(LIGO will deliver answer in 2+ yrs)

How Prolific?

Estimate gas mass of UFD:

Total gas in UFD galaxy

➡Max. dilution mass: $\sim 10^7\ M_{sun}$

Gas swept up by a 10^{51}erg energy injection into typical ISM

➡Min. dilution mass: $\sim 10^5\ M_{sun}$

Back-of-the-envelope calculation

Mix NSM yield mass of $10^{-4.5}\ M_{sun}$ into $10^6\ M_{sun}$ of H gas (can NOW be estimated!)

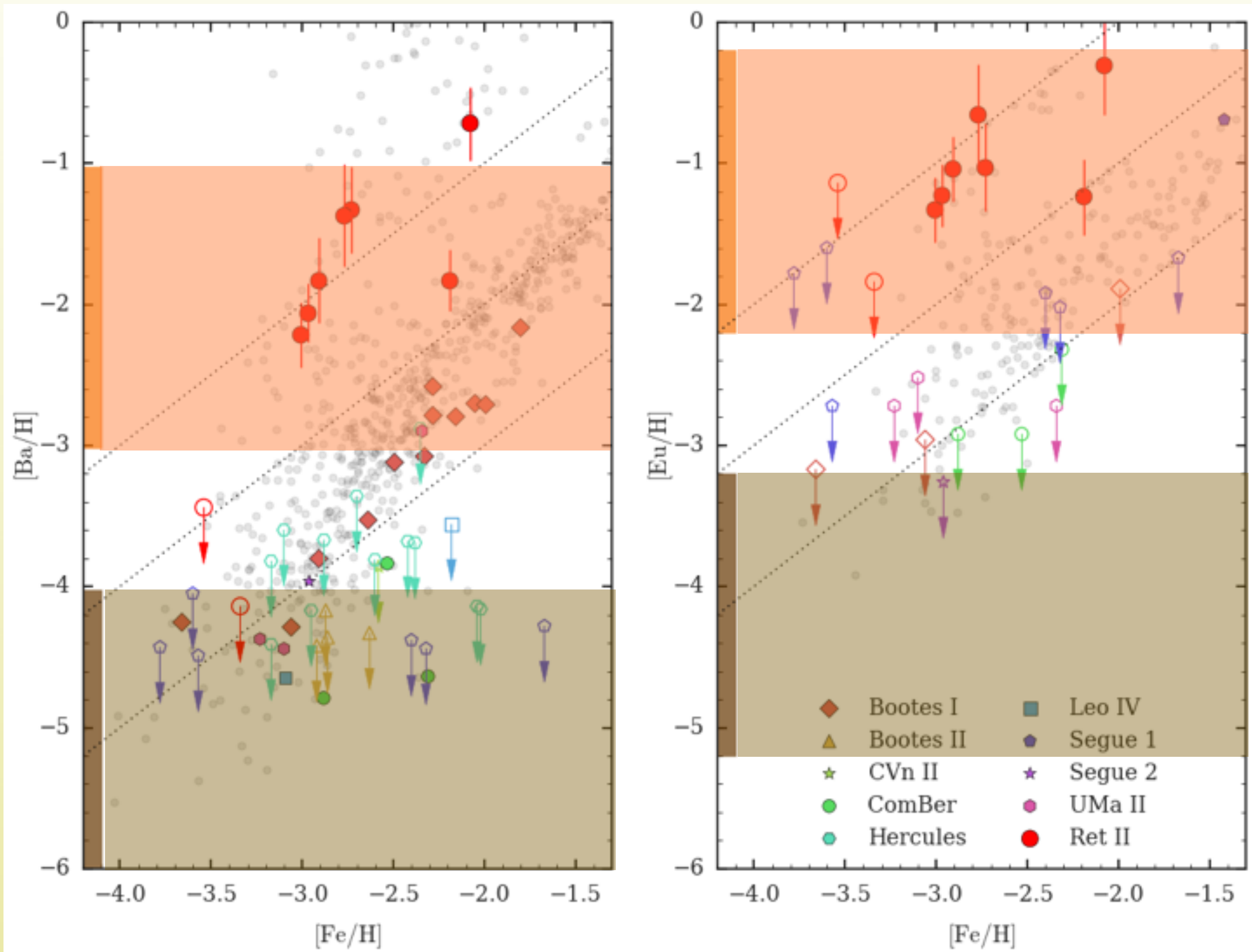
=> [Eu/H] = −1.2 is abundance of next-generation star

=> Agrees with Ret II abundance results!

Ret II abundances consistent w/ neutron star merger yield

Neutron star merger

Supernova



Ji et al 2016, *Nature*, 531, 610

RETICULUM II WAS ENRICHED BY A RARE, PROLIFIC AND DELAYED R-PROCESS EVENT

A typical core-collapse supernova could not be responsible for the Ret II r-process signature!

Can't you increase the # of supernovae to get higher yield?

➡ No, 1000+ supernovae would disrupt the system

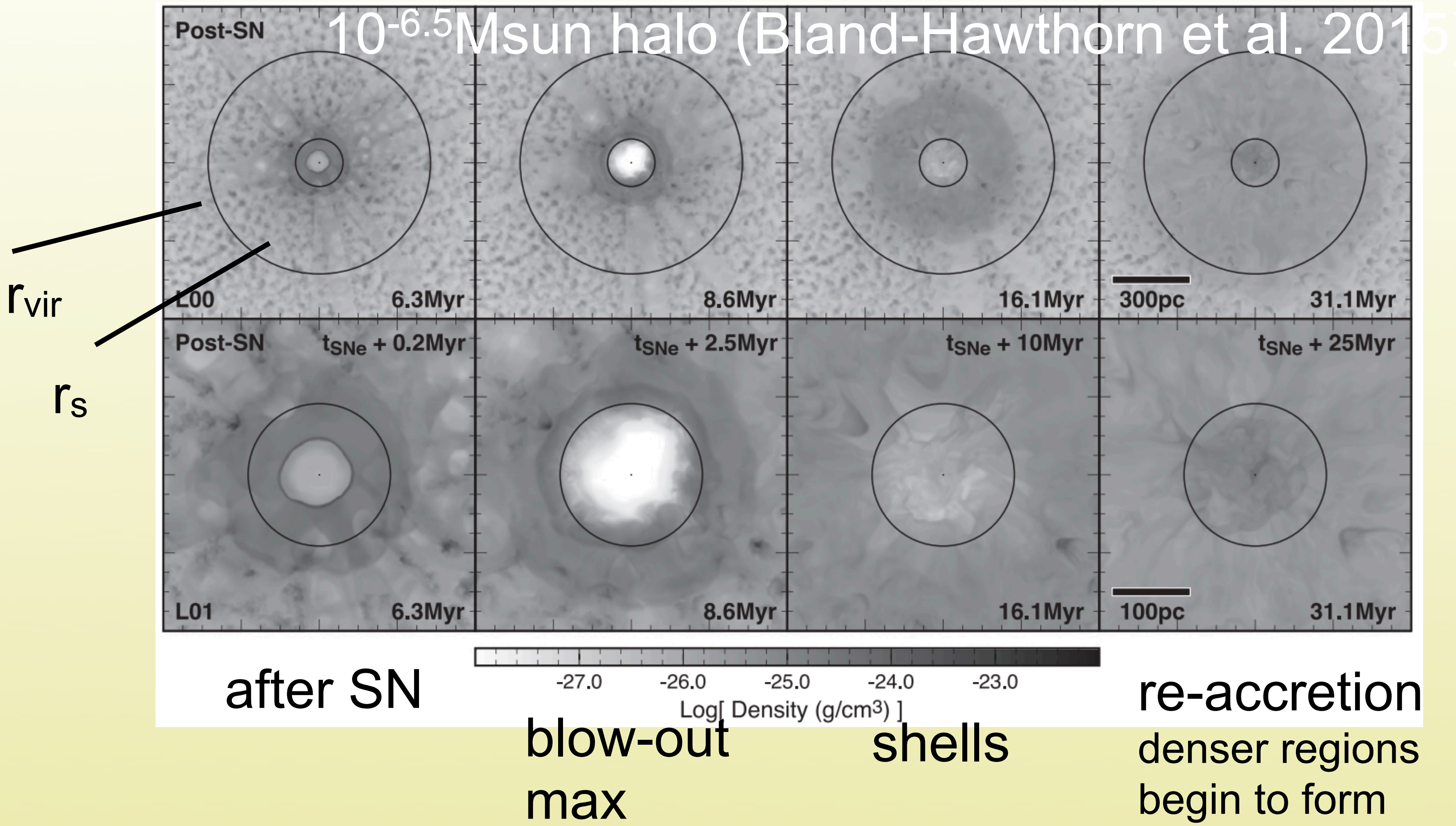
➡ Need to be just one/few massive events

Aren't NSM taking too long to enrich the galaxy?

➡ After the few (initial) supernovae, it takes time for the system to reassemble again (~100 Myr)

➡ Minimum time scales for coalesence is ~100 Myr

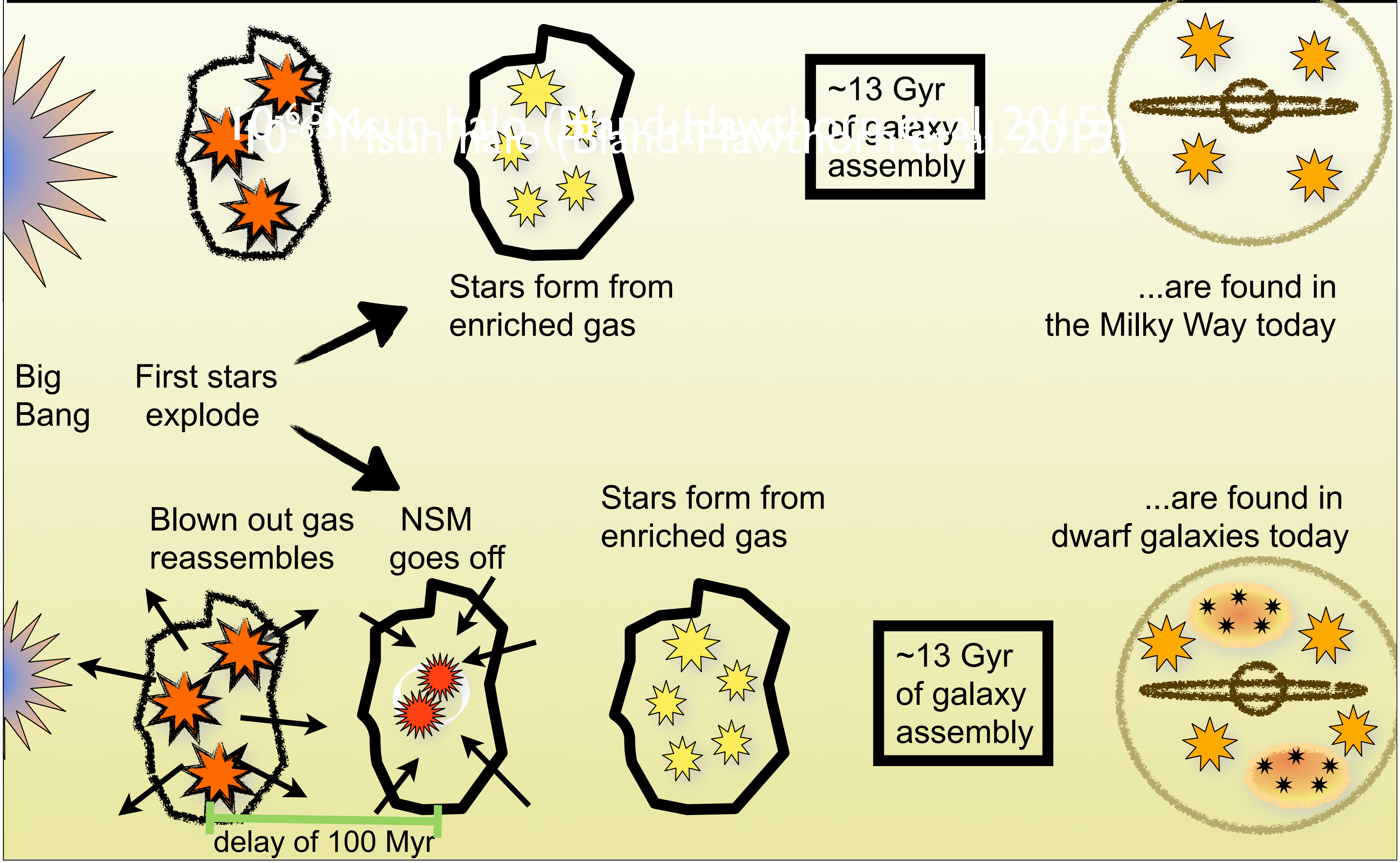
Supernova feedback delays star formation in early galaxies



Single supernova can delay star formation for 25 Myr

Very inefficient star formation

Enrichment and star formation timeline



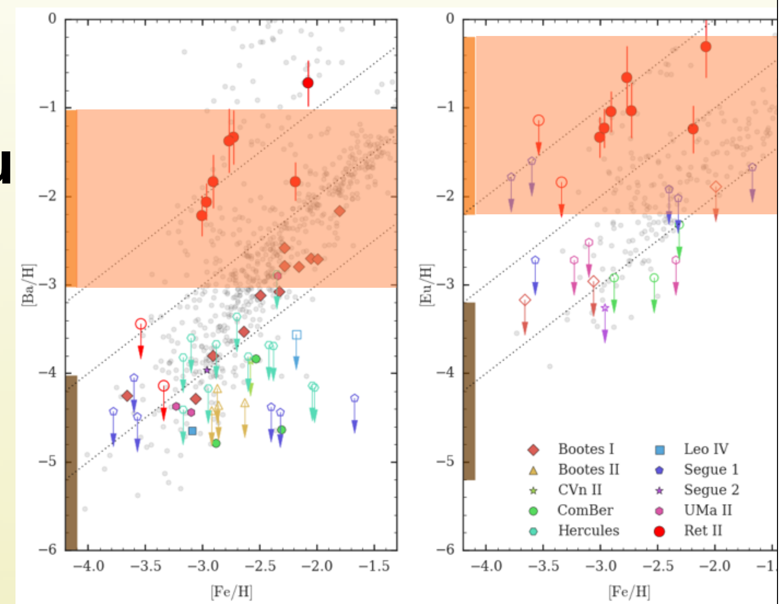
What yields are compatible with RetII observations?

Yield:

measure [Eu/H] ~ -1.2 → $\mathbf{10^{-4.5\pm1}}$ **Msun Eu**

using gas mass of $\mathbf{10^{6}}$ **Msun**

(estimate gas dilution mass 10^{5}-10^{7} Msun)



NSM simulations: ~$\mathbf{10^{-4.3\pm1}}$ **Msun Eu**

GW170817: ~$\mathbf{10^{-4.7\pm0.5}}$ **Msun Eu** (Côté+18)

In principle: Gas mass gives +- factor 10 wiggle room
Focus on main data 'clump': +- factor of 3

=> Agreeable with range of sims and GW170817 (for now)

Answers to the Big Question

★ **What is the (dominant) astrophysical site of the r-process?**

➡No, but a rare and prolific site

- ➡ Core-collapse supernovae
- ➡ Neutron star mergers ➡Consistent w/ Ret II abunds.
- ➡ Others (e.g., jet-driven supernovae)

➡Remain possible

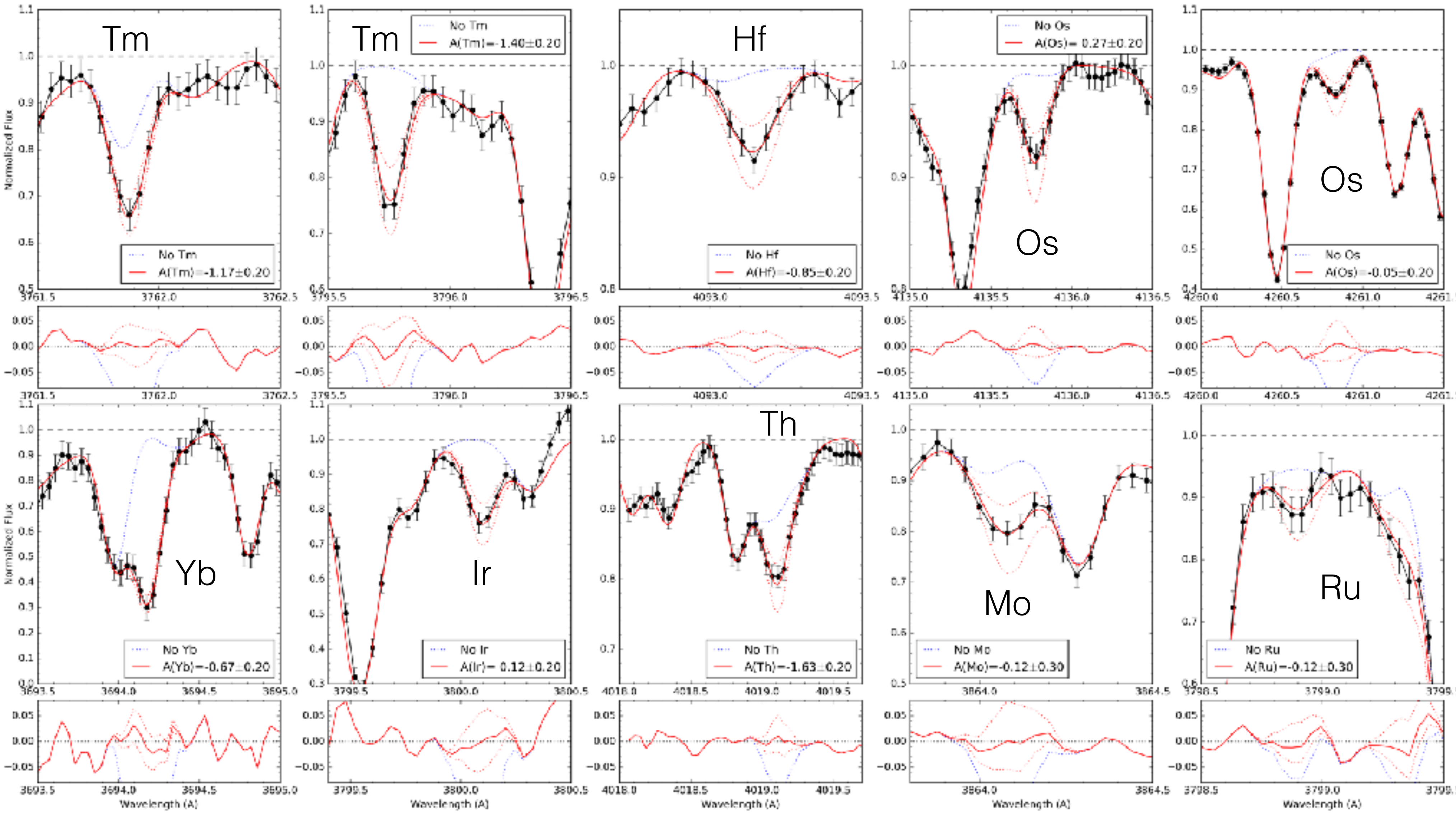
★ **What is the rate and yield of the event?**

➡ ~1 event per 2000 SN; ~$10^{-2.5}$ M_{sun} of r-process

★ **Is the dominant site changing over cosmic time?**

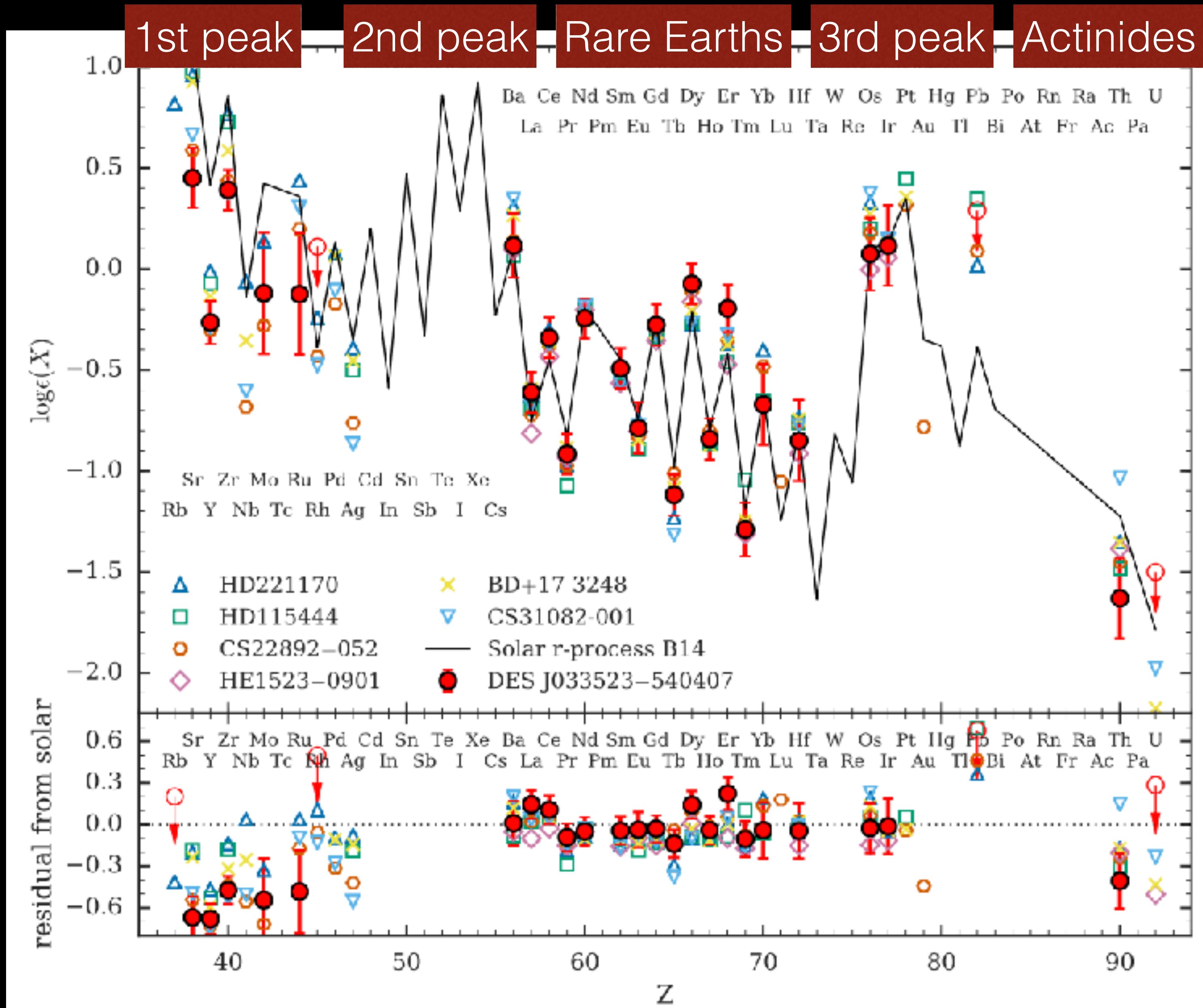
➡Probably not!

New spectrum of brightest Ret II star provides abundances of 41 elements



Alex Ji S/N ~ 70-240 Ji + Frebel 2018

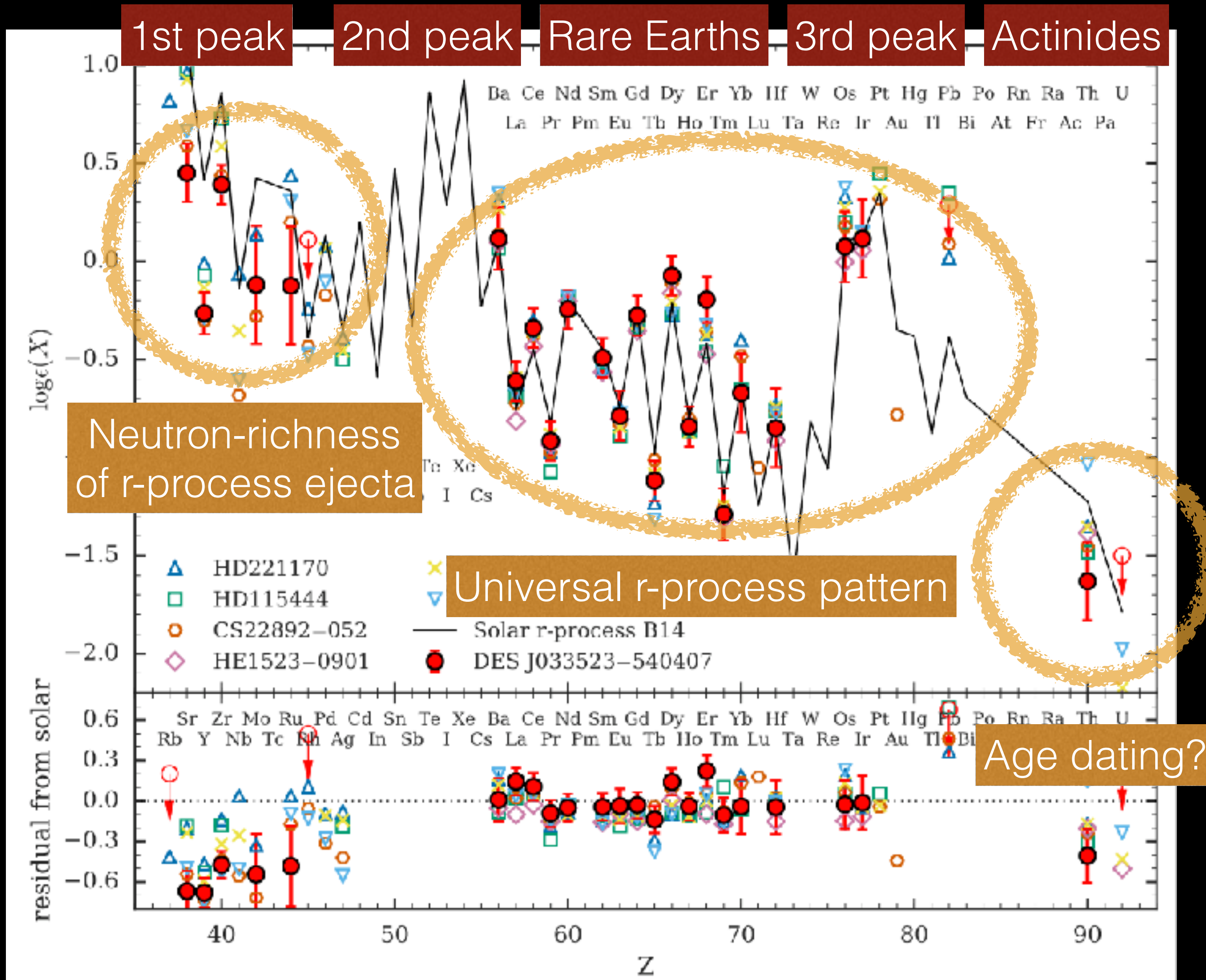
The Pure *r*-process Pattern in Ret II



Alex Ji

Ji + Frebel 2018

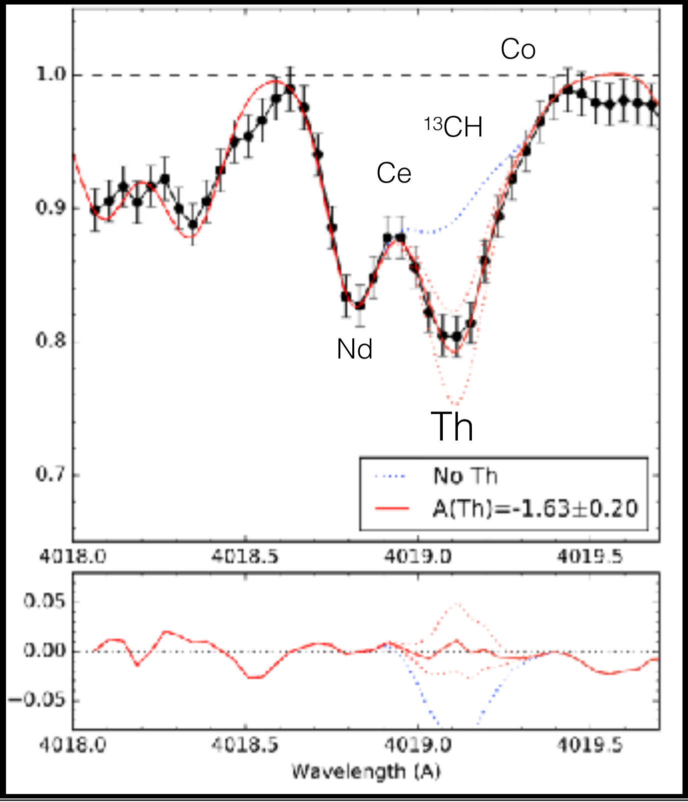
The Pure *r*-process Pattern in Ret II



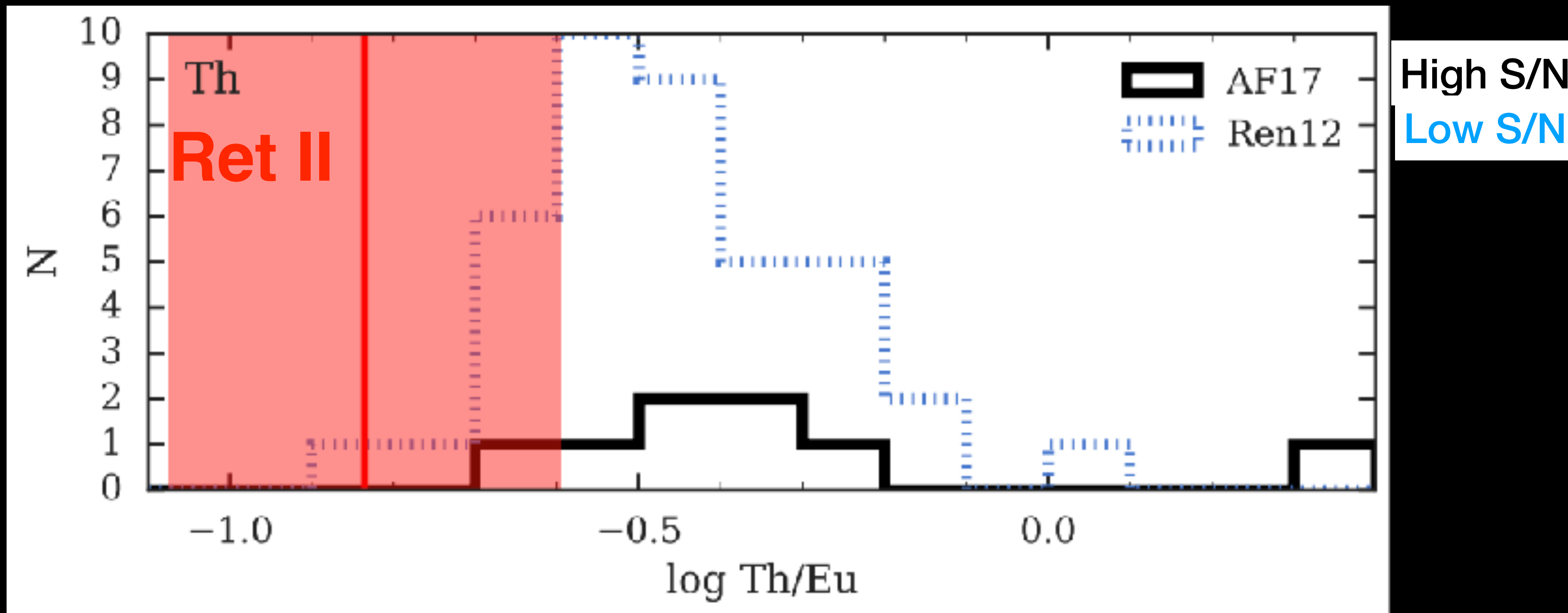
Ji + Frebel 2018

Age Dating with Radioactive *r*-process elements

- ^{232}Th, ^{238}U have long half lives (14.0, 4.5 Gyr)
  (U measured in only ~6 metal-poor stars)
- Age = 46.67 Gyr [log(Th/Eu)$_{init}$ - log(Th/Eu)$_{now}$]
- Th is hard to measure
- Initial production ratios predicted from theory



Ret II has unusually low Th



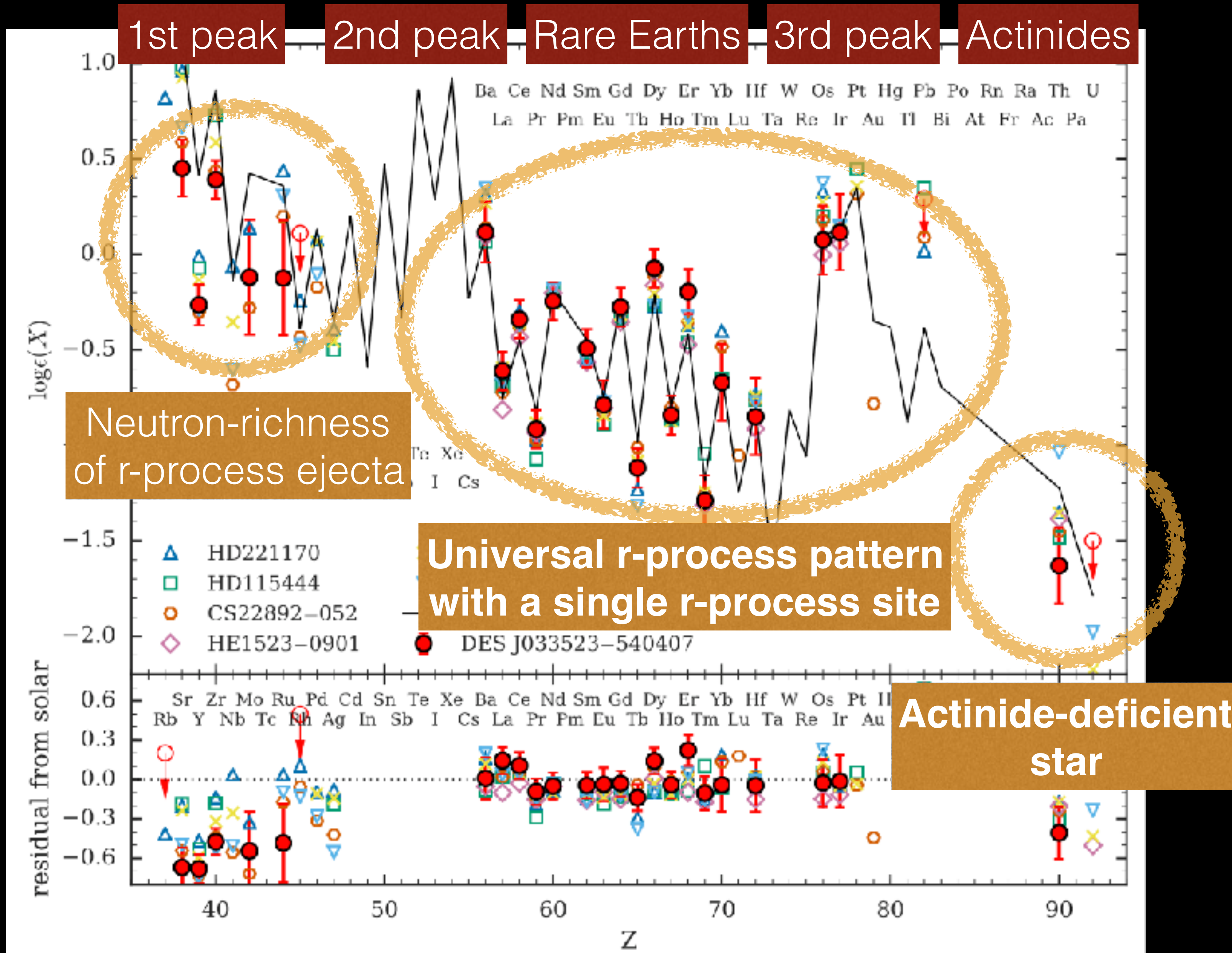
Naive application of literature production ratios:

Age = 24.9 ± 2.8 ± 10.3 ± 3.2 Gyr
(stat) (sys, obs) (sys, PR)

More likely explanation: variable initial production ratios

Ji + Frebel 2018

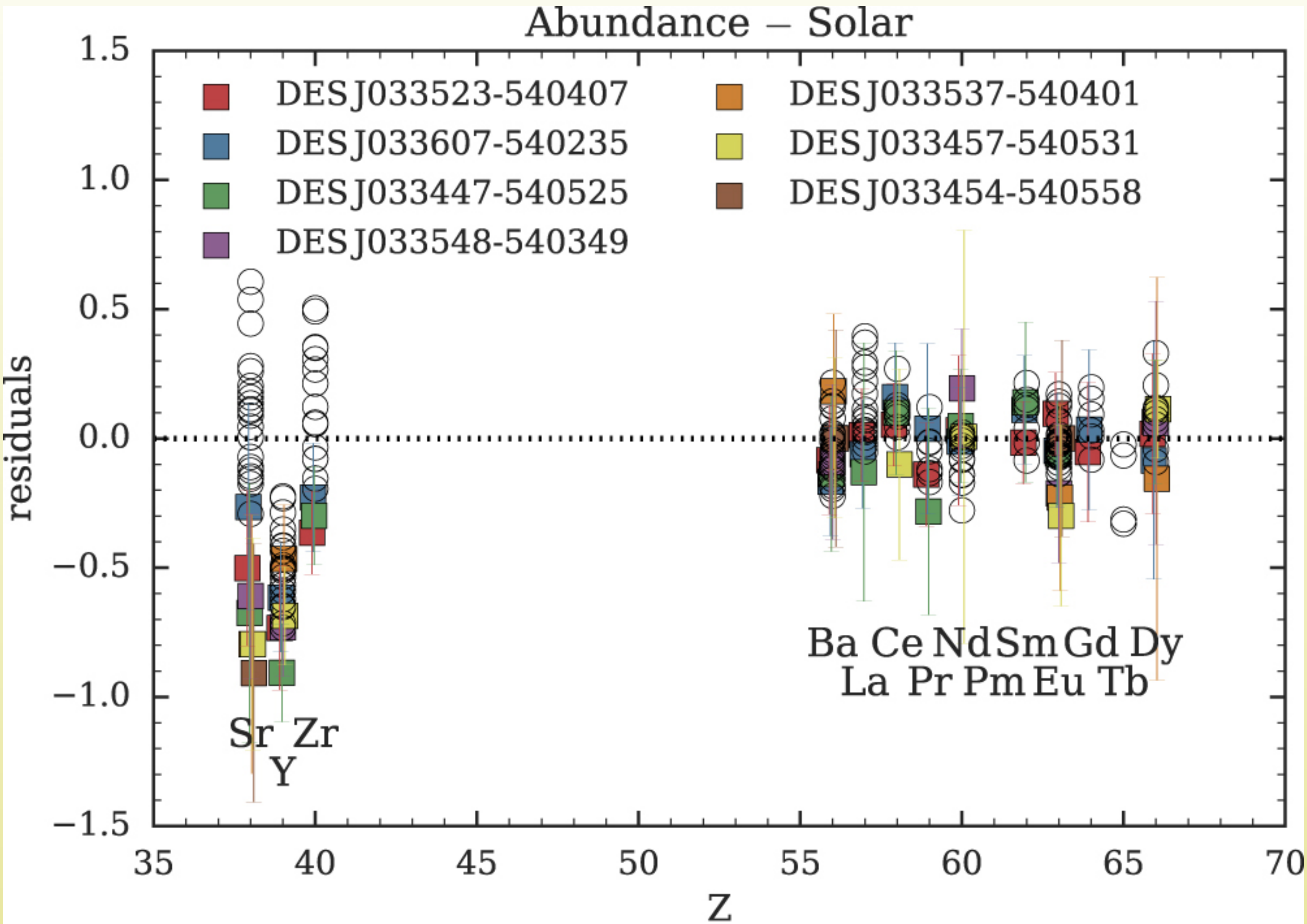
The Pure *r*-process Pattern in Ret II



Alex Ji

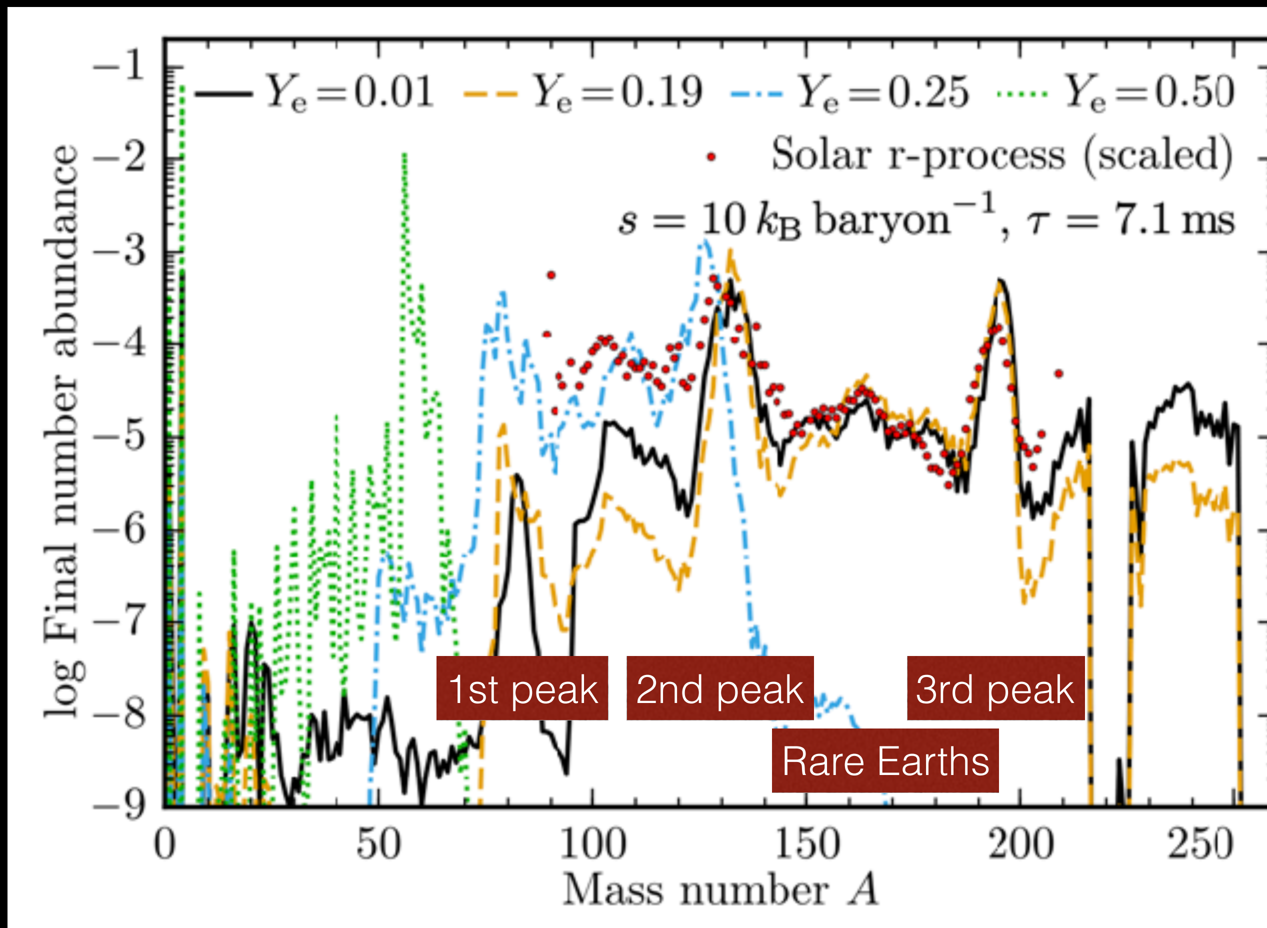
Ji + Frebel 2018

1st peak: huge deviations 2nd/3rd peak: all good!



Ejecta Y_e affects element production

$Y_e = N_e/(N_n + N_p)$



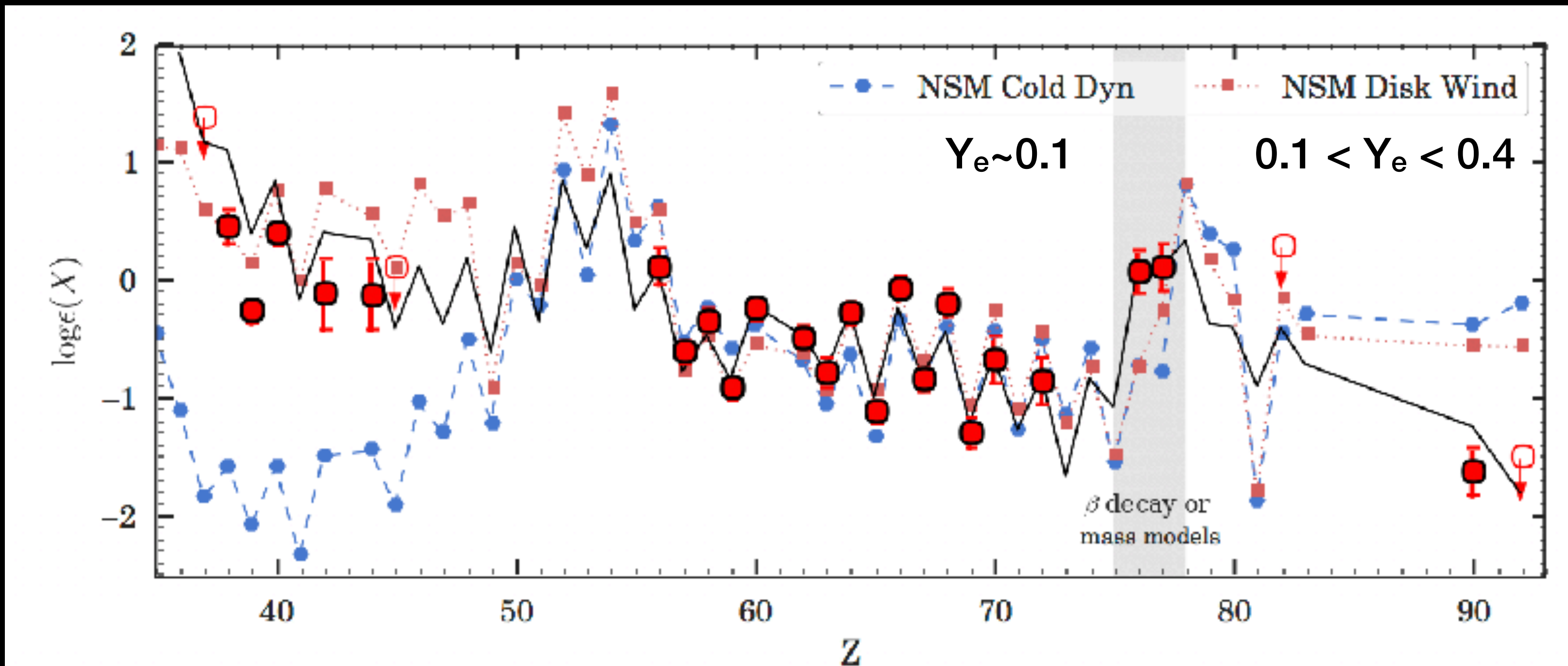
High Y_e (neutron-poor) —> 1st peak

Low Y_e (neutron-rich) —> 2nd + 3rd peak

Critical Y_e ~ 0.25

Lippuner + Roberts 2015

NSMs need to eject mass in multiple ways to reproduce the full pattern



Adding up mass: $M_{n\text{-poor}}/M_{n\text{-rich}}$ ~ 0.6± 0.1

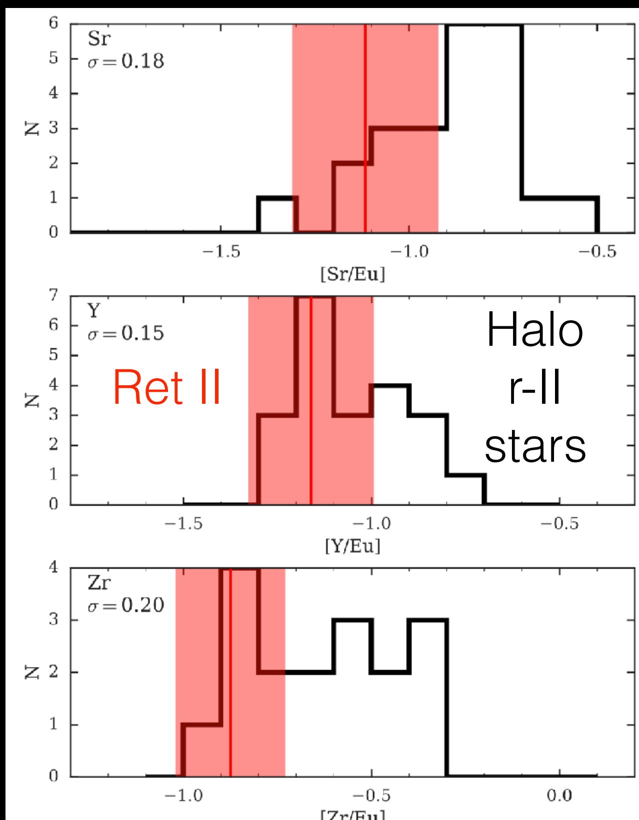
Tidal ejecta: low Y_e
Shocked polar ejecta: high Y_e
Disk winds: Y_e distribution

Alex Ji

Models: Eichler et al. 2015, Wu et al. 2016; Ji + Frebel 2018

r-process halo stars show little scatter in Y_e distribution

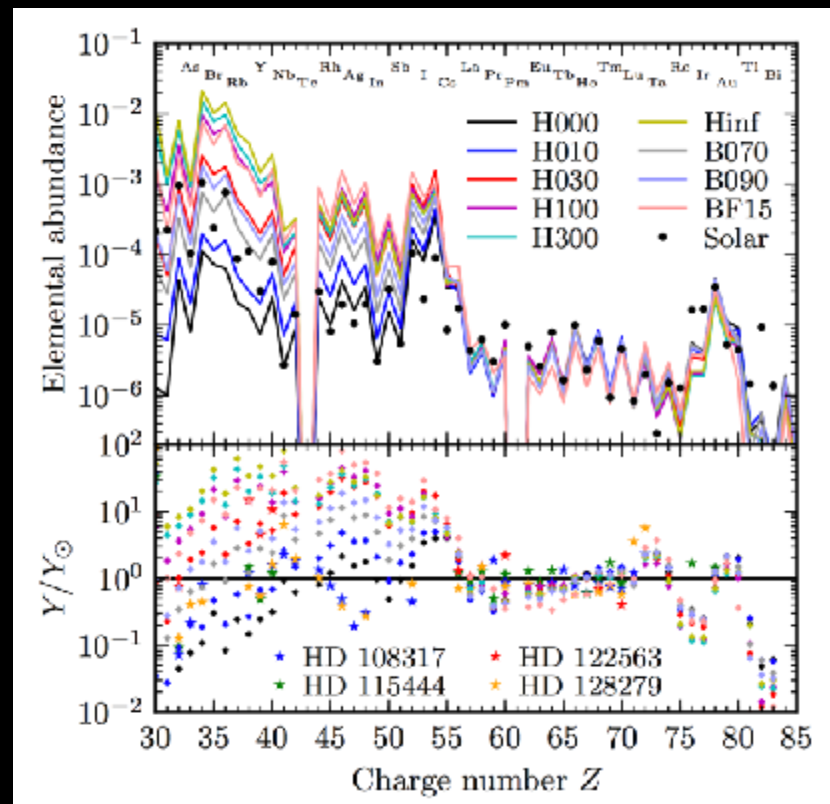
$M_{n\text{-poor}}/M_{n\text{-rich}}$ ~0.5 to 2



1st peak / Lanthanide

Note: 1st peak in halo stars can be contaminated by CCSNe (weak/limited r-process)

>10x variation in NSMs



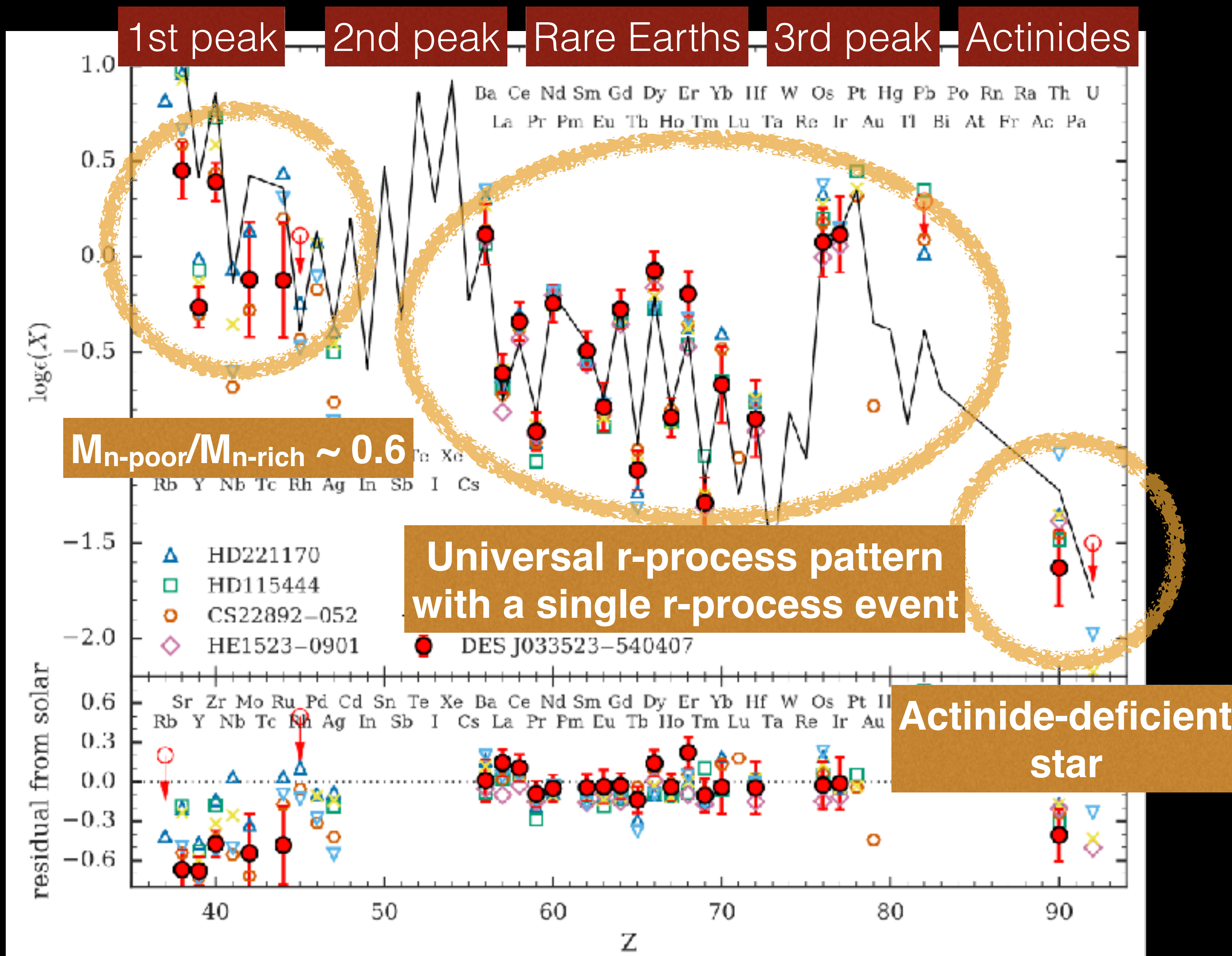
Lippuner et al. 2017

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

Alex Ji

Ji + Frebel 2018

The Pure *r*-process Pattern in Ret II



Ji + Frebel 2018

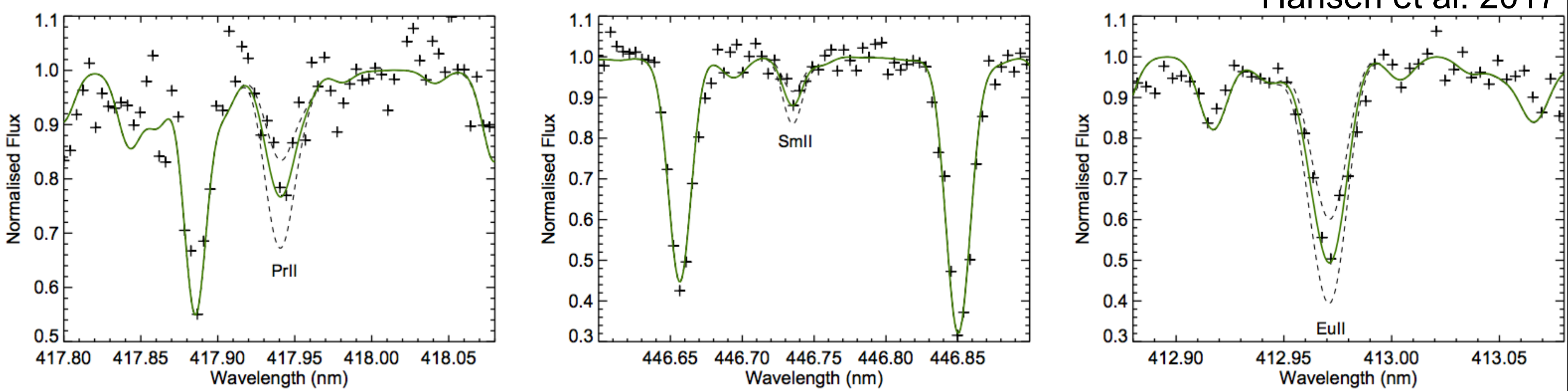
Reticulum II is not the only r-process galaxy!

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

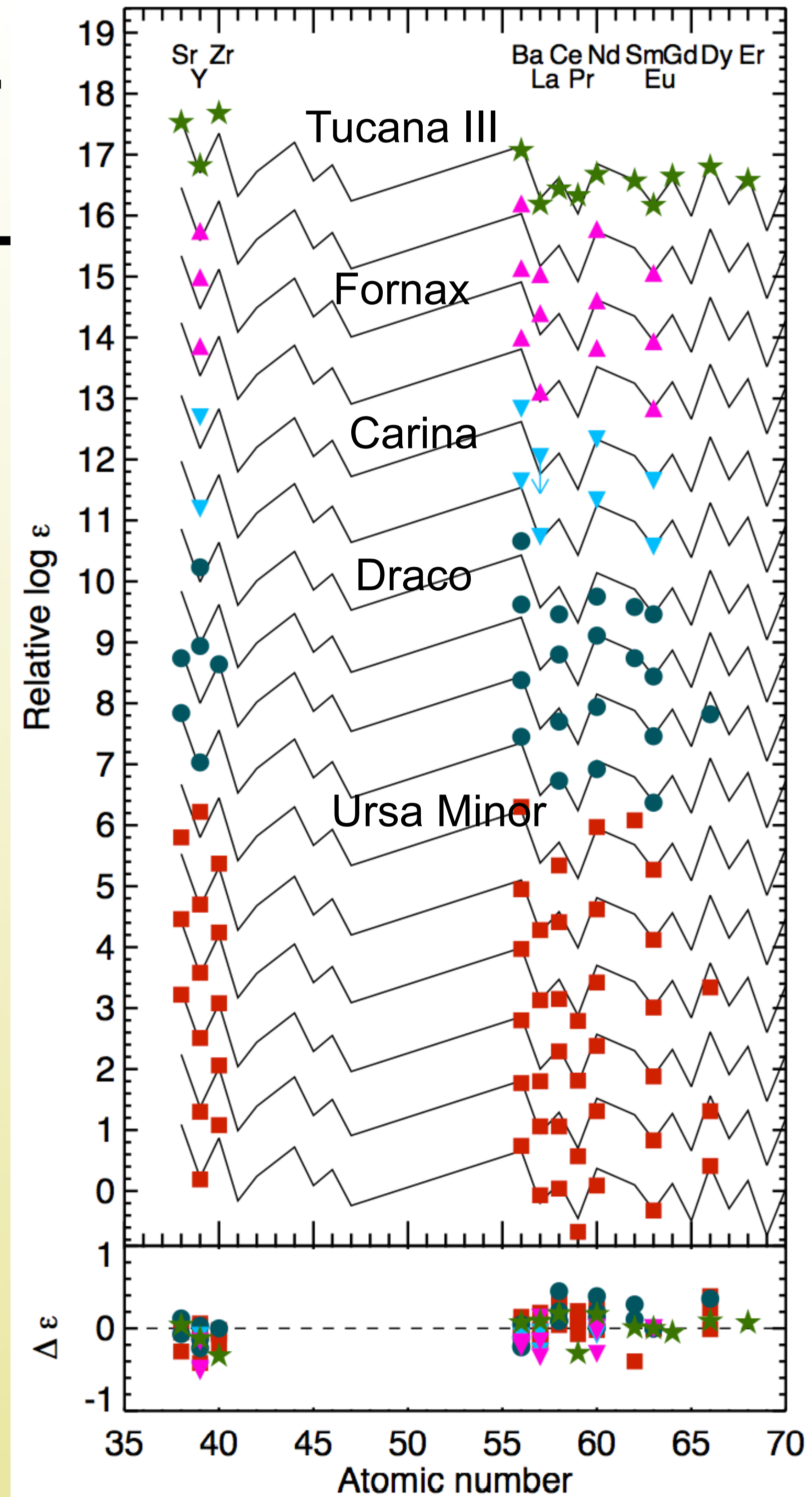
- Draco -2.6 < [Fe/H] < -0.8
- Fornax 1.1 < [Eu/Fe] < 1.7

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)?



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**

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!

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

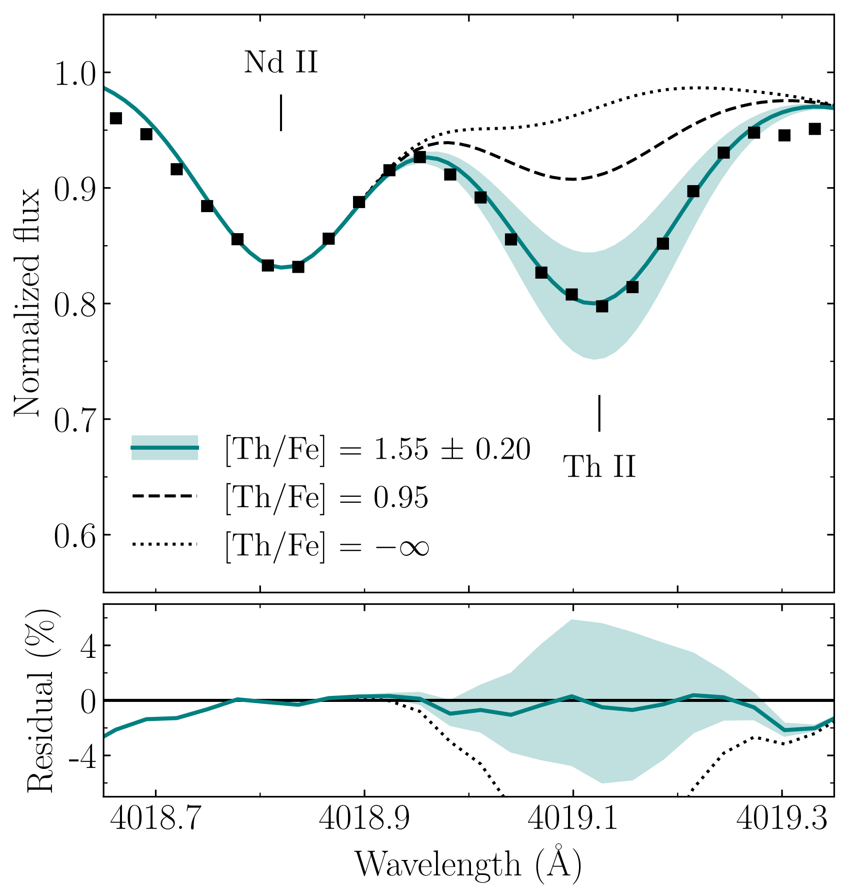
Component T2
Chemical evolution modeling

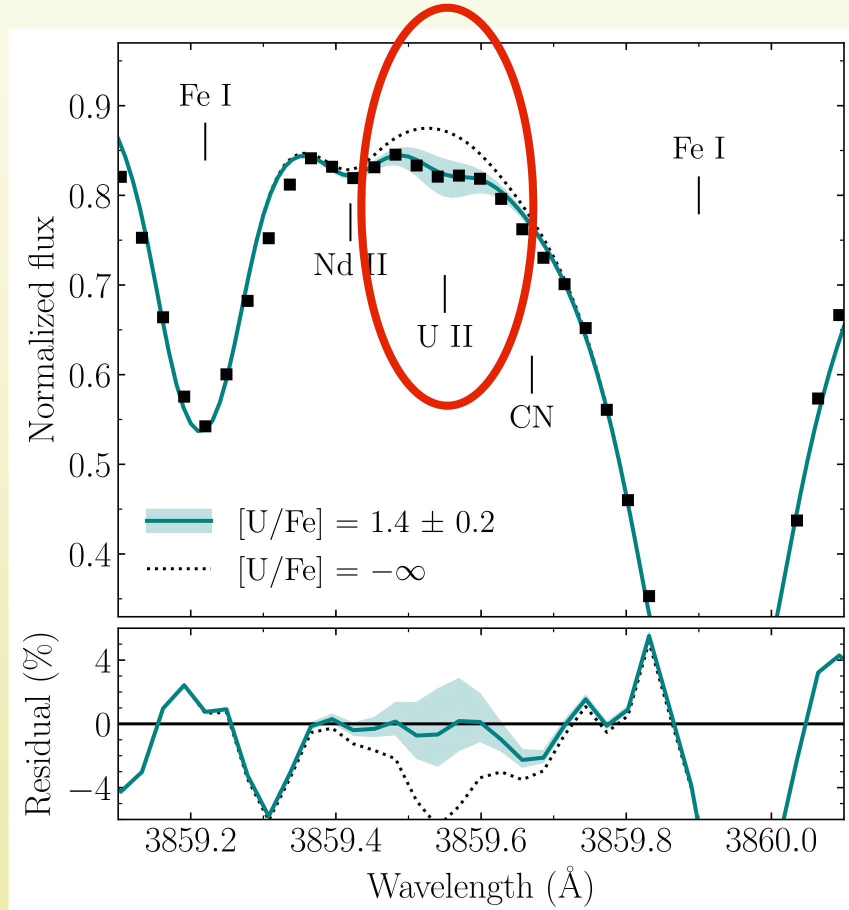
Experimental

Component E1
Current experiments
FRIB

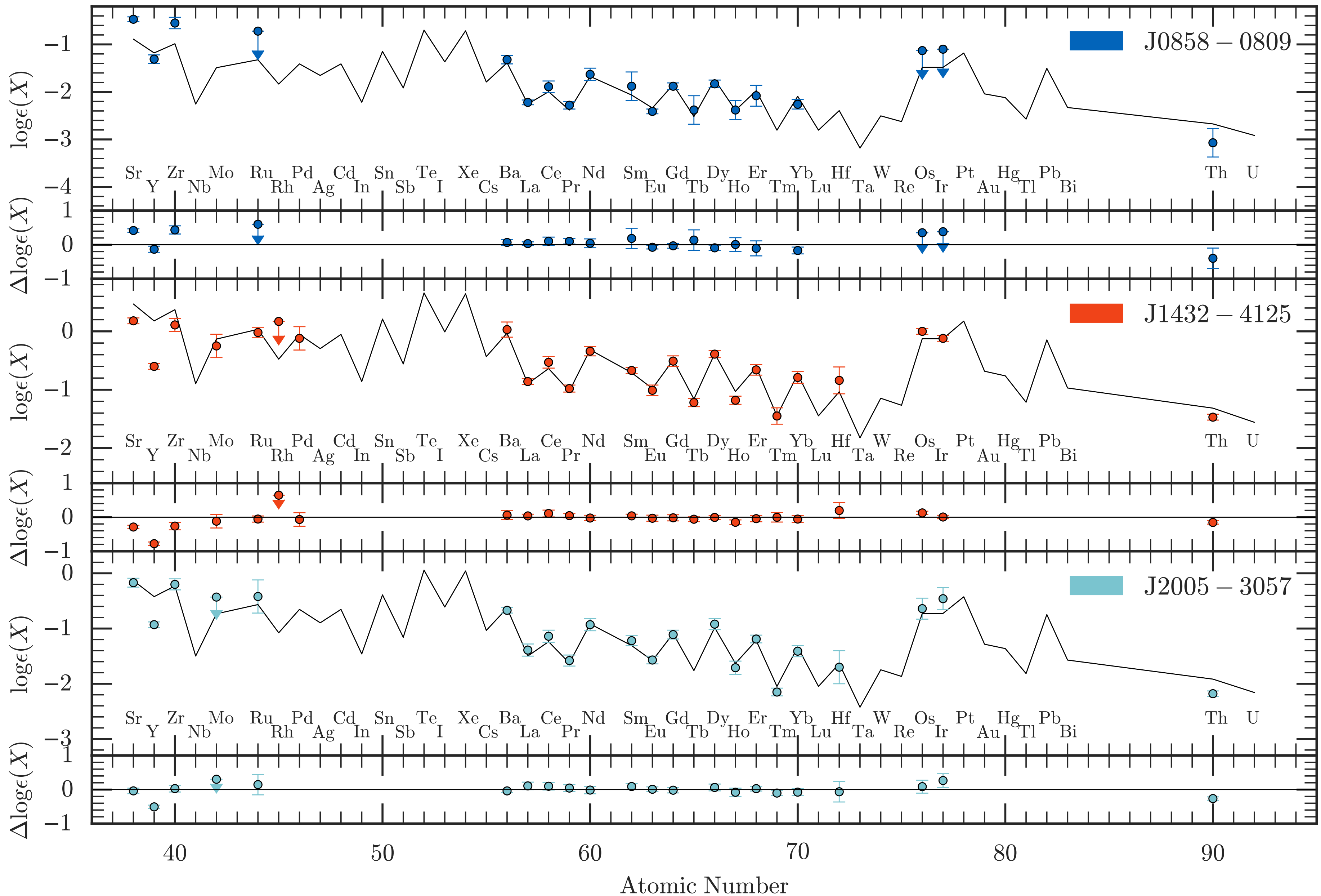
Component E2
Lab astro
Other

Holmbeck et al: bright U star





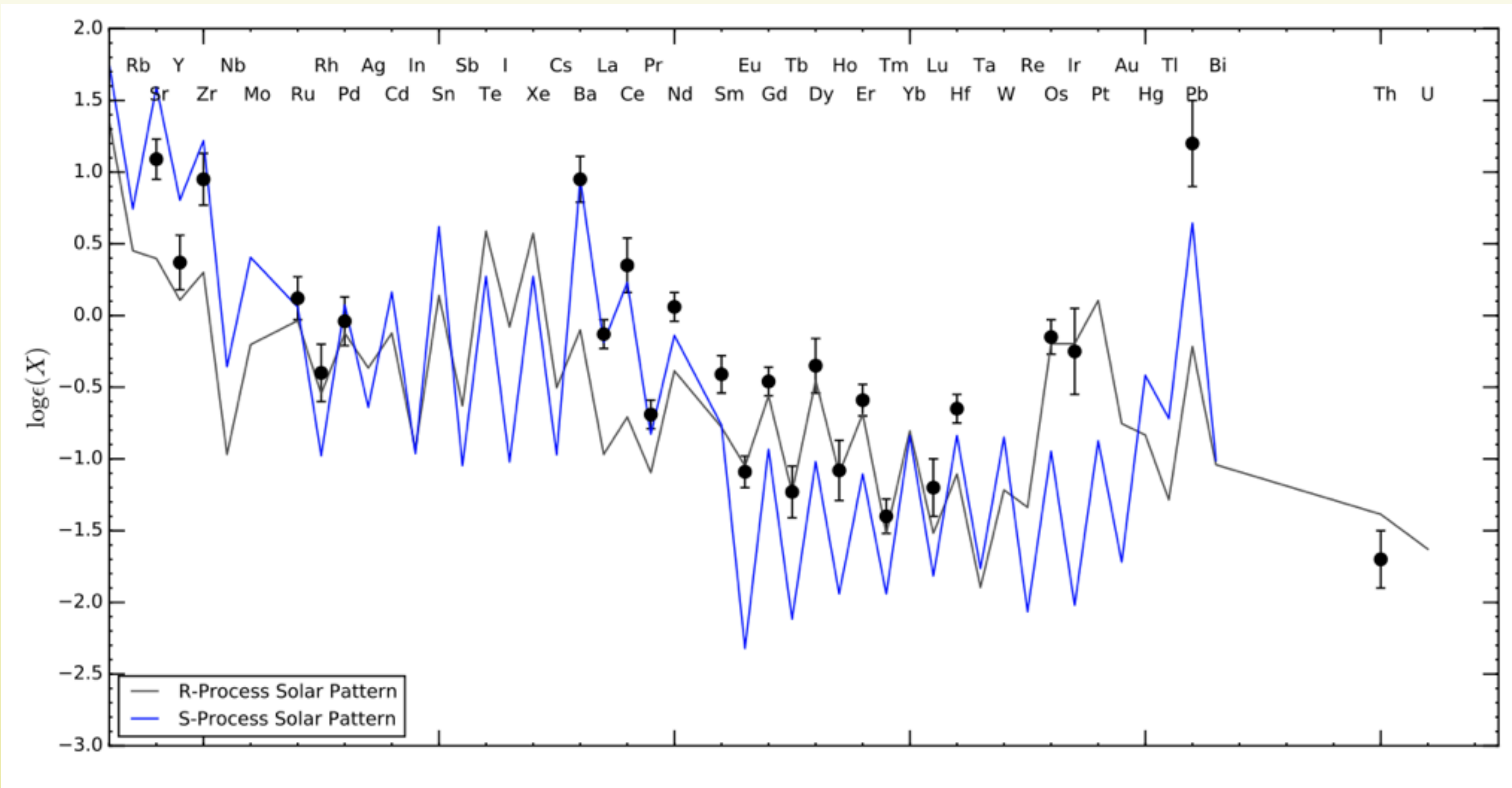
Cain et al: New r-process stars



Anna Frebel — r-process Galaxy Reticulum II

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

The first true r+s star!

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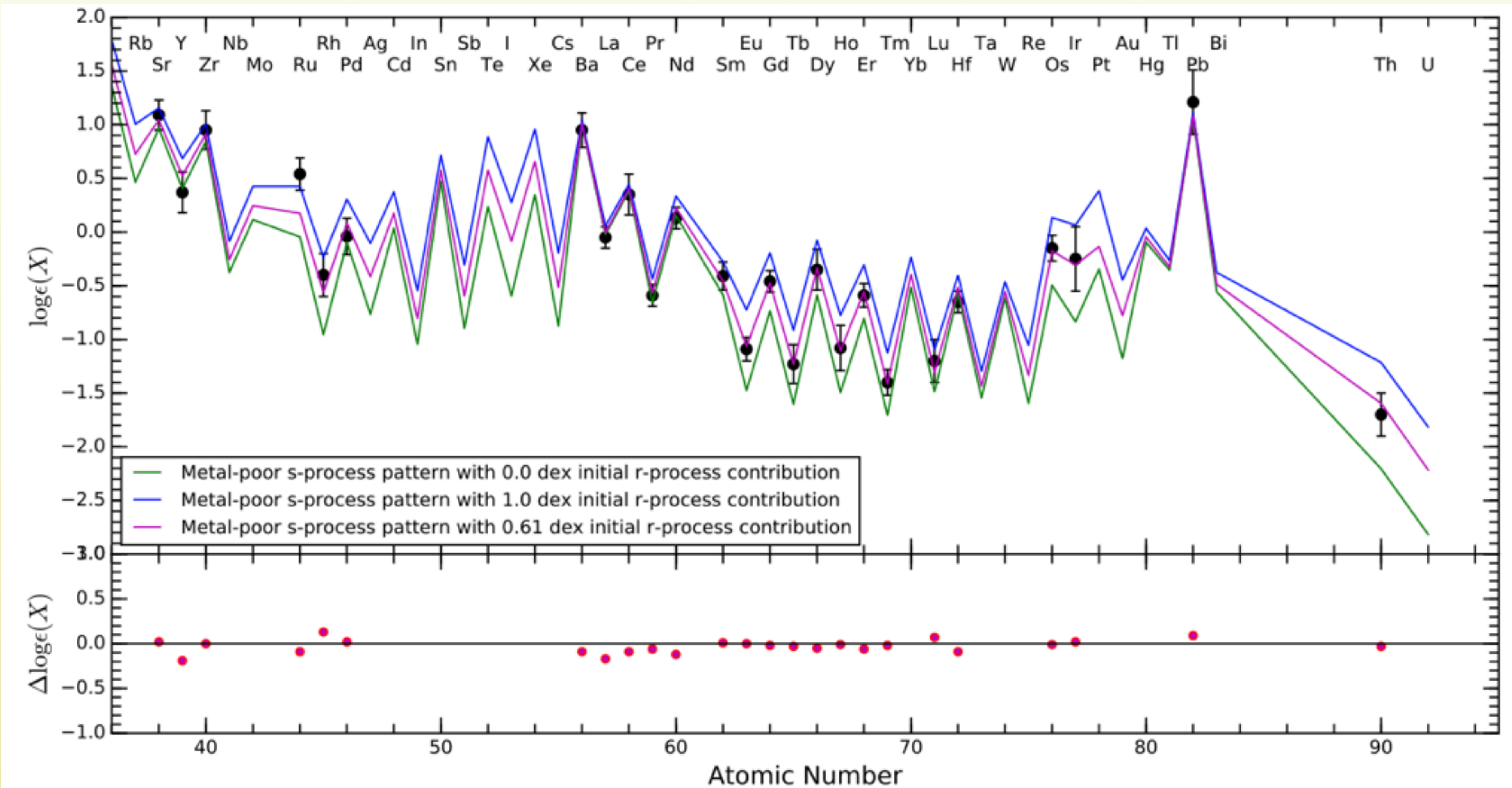


Gull, Frebel et al. 2018

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

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

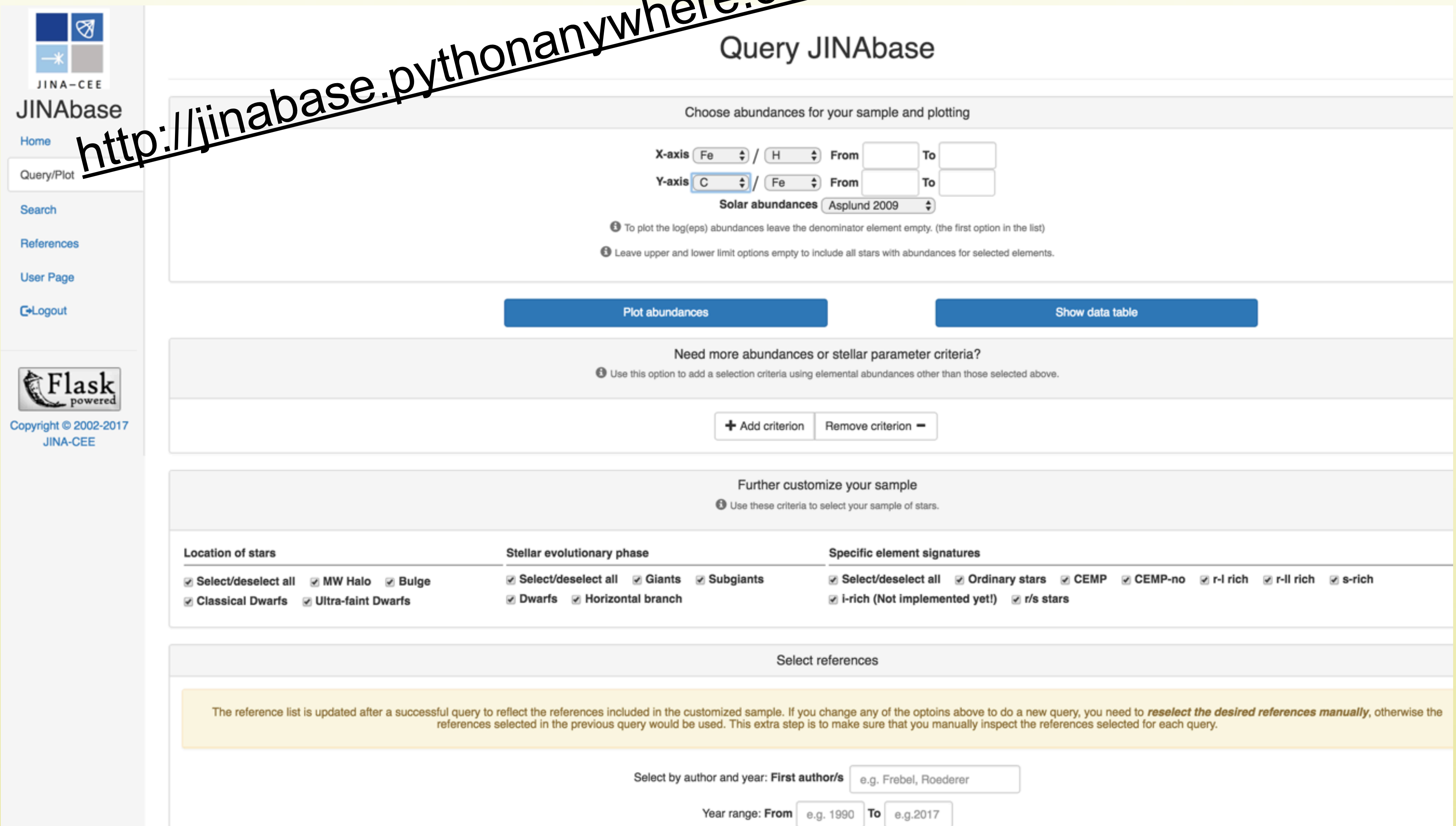
Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

http://jinabase.pythonanywhere.com



Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

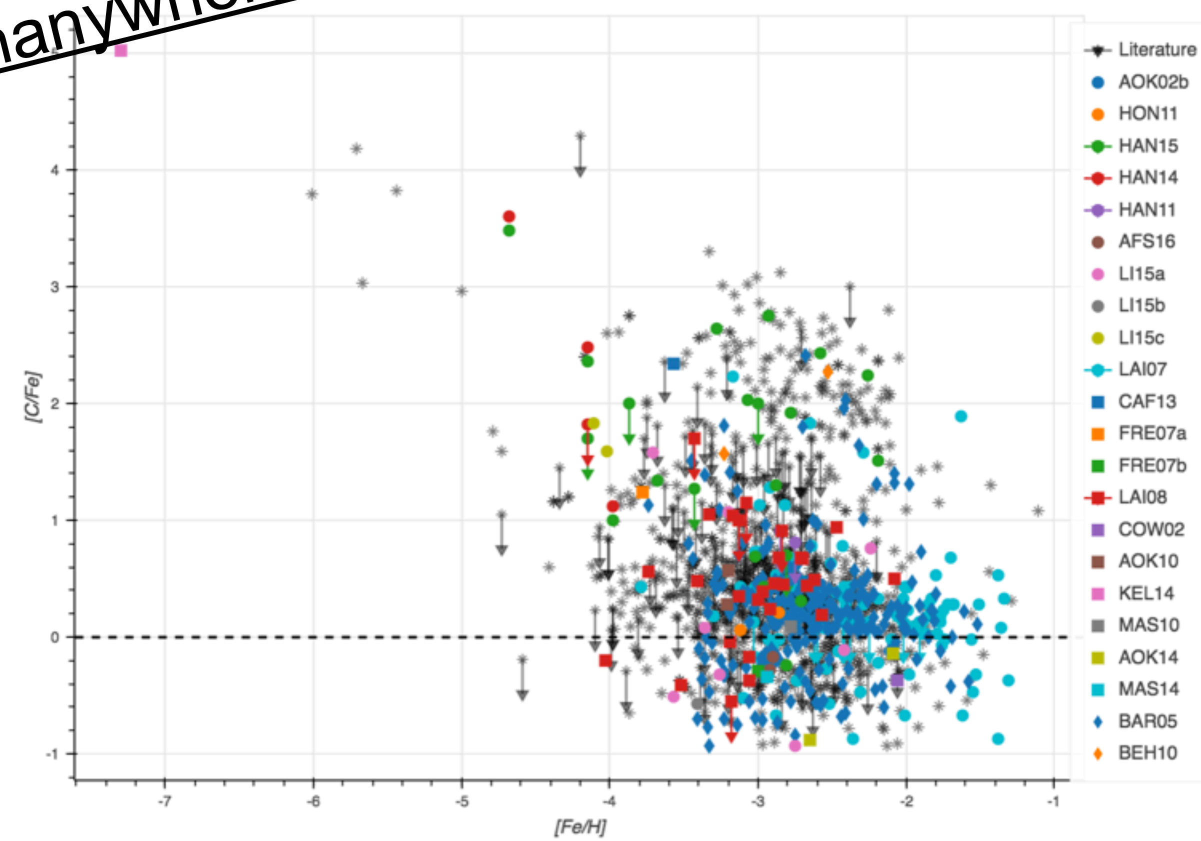
http://jinabase.pythonanywhere.com

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

Open Issues

Only *all* of these different approaches will ultimately provide the inputs to fully constrain the r-process

Observations:

Need more dwarf galaxies to find more r-process galaxies

Need more halo star observations to detailed pattern analysis

=> Dwarf galaxies are being searched for (DES, DEcam)

=> R-Process Alliance: Aims to provide data needed to tackle the r-process from the astrophysics/metal-poor star end

GW/multi-messenger astronomy:

Merger rate, environments

Yields(!), how many components, explosion/merger details => Next run(s)

Theory:

Formation of 1st/2nd peak in different NSM components => Lots of people

Experiments:

Improved nuclear physics input to reduce modeling uncertainties => FRIB