

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

WHY STUDY THE STARS?



by: Apprentice to
Galileo Galilei, 1636

THE PUZZLE PIECES FOR EXPLORING THE EARLY UNIVERSE



Stellar Archaeology

Stellar element
abundance patterns
tell about previous
enrichment events



Nuclear Astrophysics

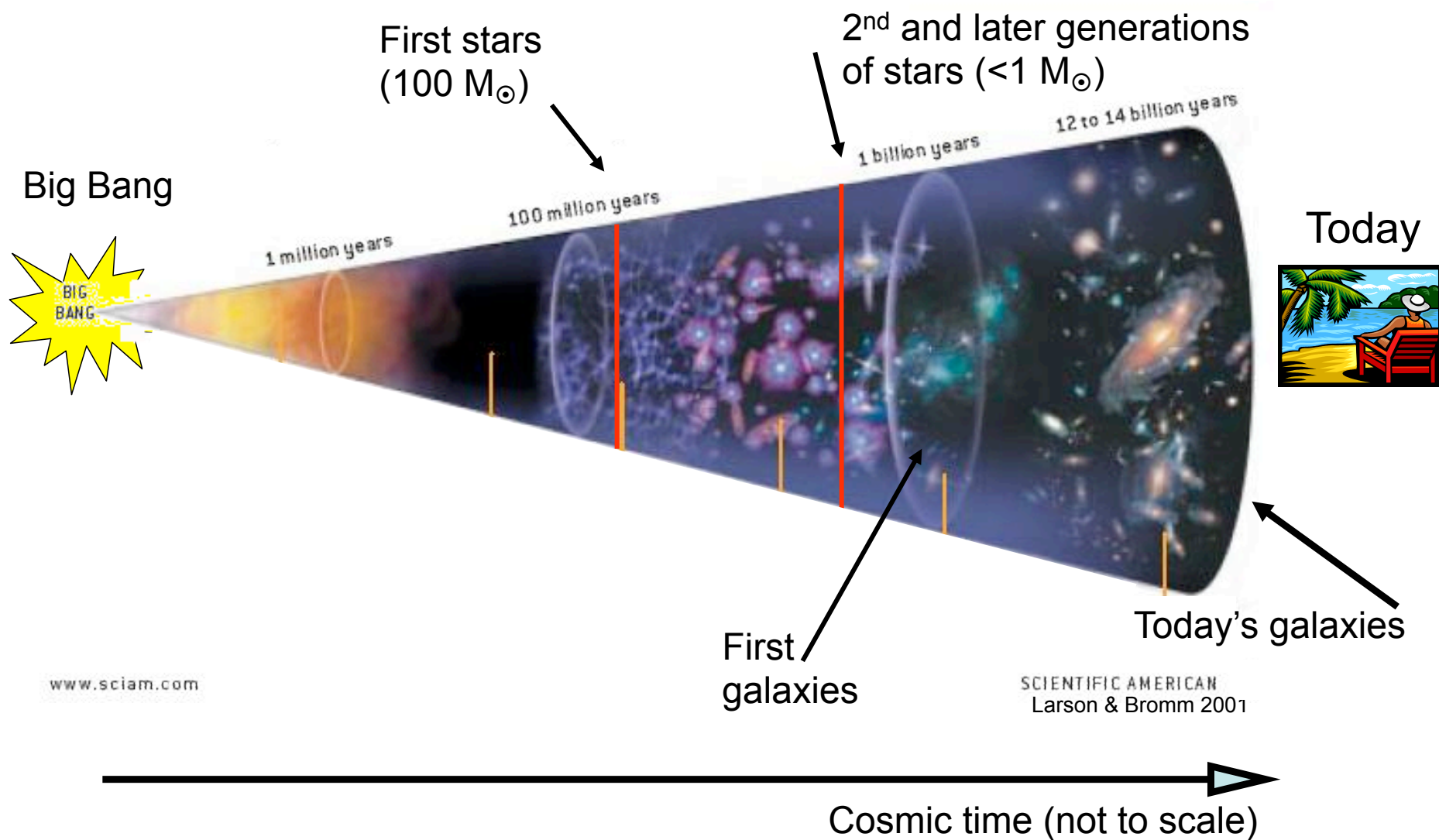
Astrophysical
origin(s) of the
chemical
elements



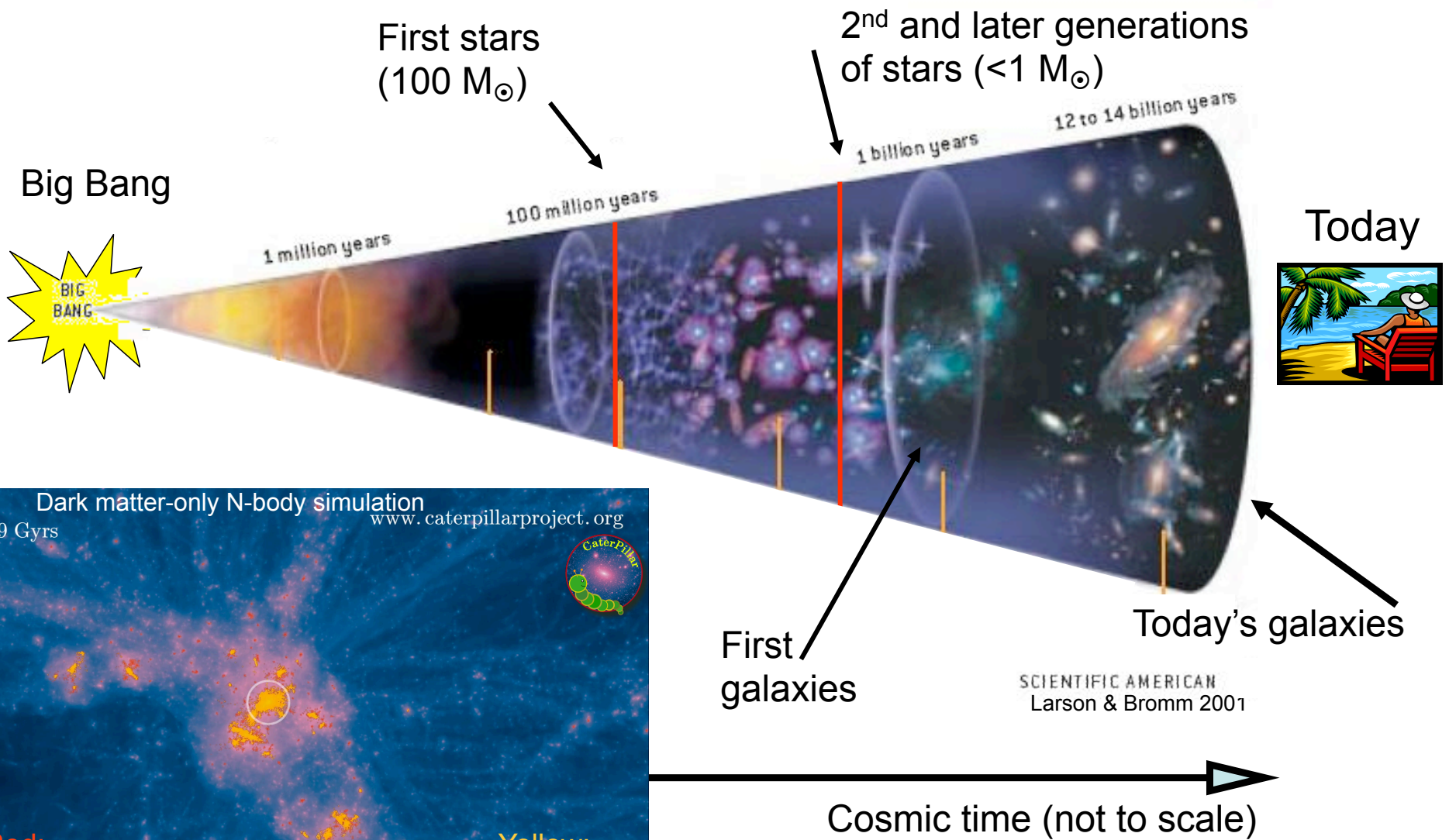
Dwarf Galaxy Archaeology

Clean
nucleosynthesis
signatures in
known
environments

A LONG TIME AGO...



A LONG TIME AGO...



$z = 4.155$ Dark matter-only N-body simulation
 $t = 12.359$ Gyrs
www.caterpillarproject.org



Red:
first star minihalos

$\log_{10} \rho_{\text{dm}} (M_{\odot} \text{ kpc}^{-3})$

Yellow:
first galaxies

CHEMICAL EVOLUTION

Chemical evolution & cosmic recycling

Astronomers'
Periodic Table

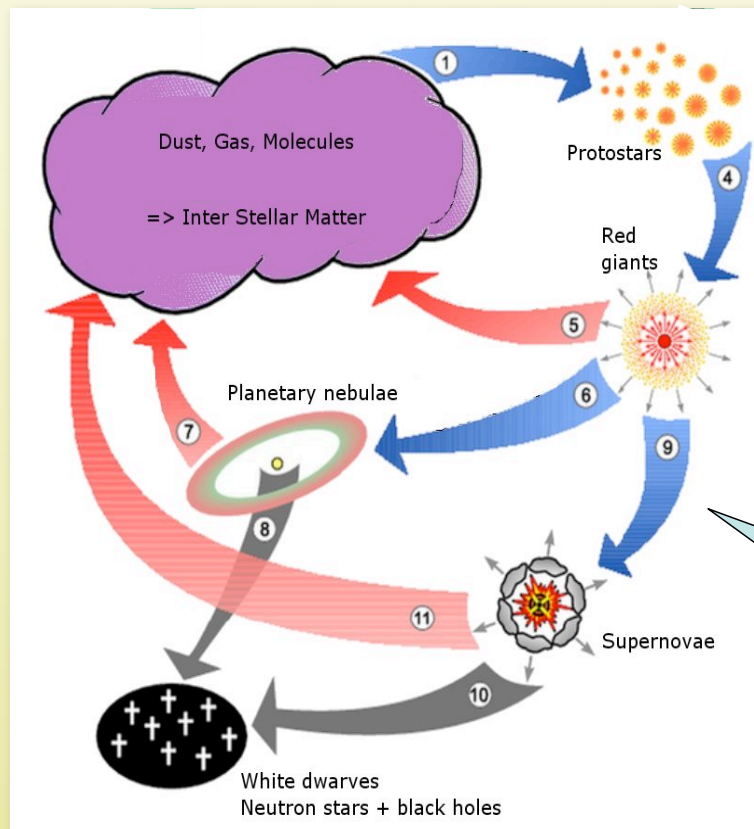
H: X

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 of
all elements were made!

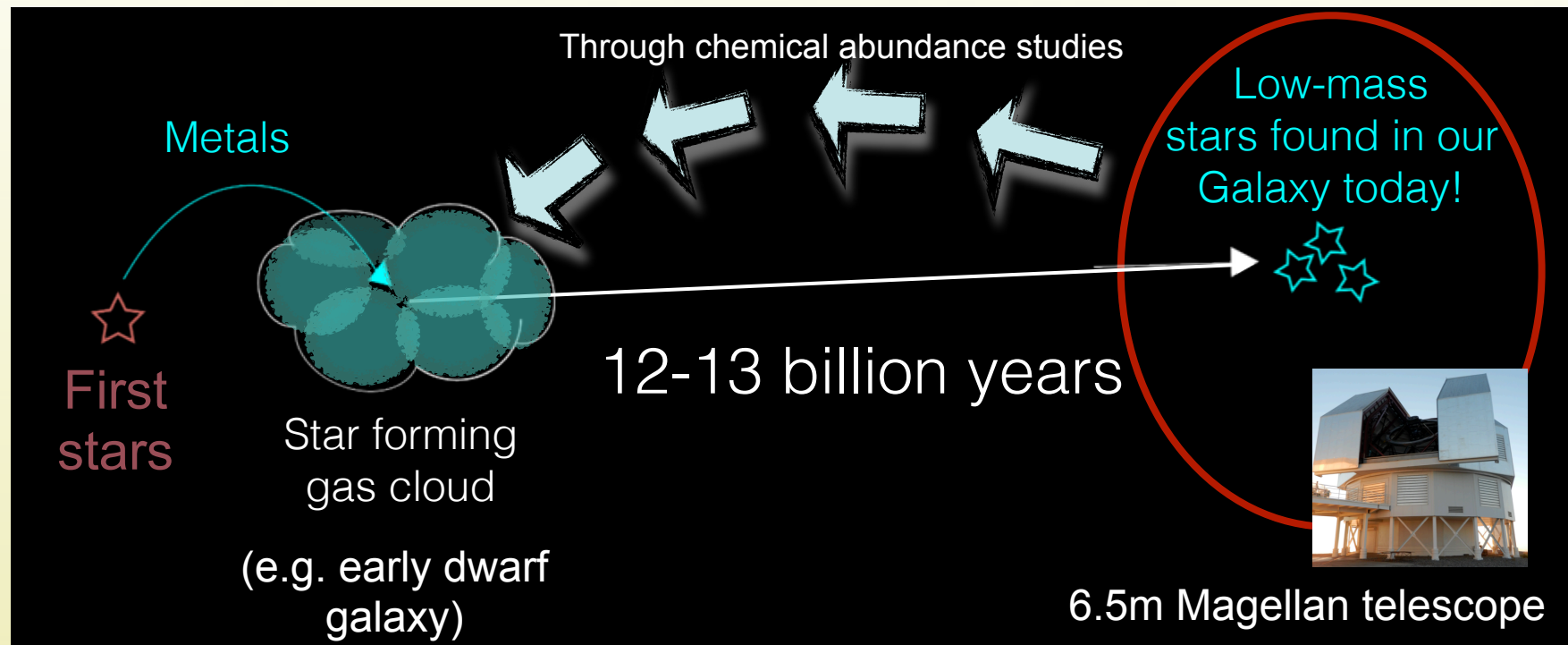
We look for stars
with the least amounts
of elements heavier
than H and He!



STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

Low-mass stars with $M < 1 M_{\odot}$: Lifetimes > 10 billion years \Rightarrow they are still around!



Back-of-the-envelope calculation

Estimated H gas mass of typical star forming cloud: $\sim 10^5 M_{\text{sun}}$

Estimated Fe yield of typical supernova: $\sim 0.1 M_{\text{sun}}$

Assume homogenous and instantaneous mixing of Fe in gas

$\Rightarrow [\text{Fe}/\text{H}] = -3.2$ is abundance of next-generation star

$\Rightarrow [\text{Fe}/\text{H}] \leq -3$: 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	$[\text{Fe}/\text{H}] > 0.0$	MR
Solar	$[\text{Fe}/\text{H}] = 0.0$	None
Metal-poor	$[\text{Fe}/\text{H}] < -1.0$	MP
Very metal-poor	$[\text{Fe}/\text{H}] < -2.0$	VMP
Extremely metal-poor	$[\text{Fe}/\text{H}] < -3.0$	EMP
Ultra-metal-poor	$[\text{Fe}/\text{H}] < -4.0$	UMP
Hyper-metal-poor	$[\text{Fe}/\text{H}] < -5.0$	HMP
Mega-metal-poor	$[\text{Fe}/\text{H}] < -6.0$	MMP
Septa-metal-poor	$[\text{Fe}/\text{H}] < -7.0$	SMP
Octa-metal-poor	$[\text{Fe}/\text{H}] < -8.0$	OMP
Giga-metal-poor	$[\text{Fe}/\text{H}] < -9.0$	GMP
Ridiculously metal-poor	$[\text{Fe}/\text{H}] < -10.0$	RMP
Signature	Metal-poor stars with neutron-capture element patterns	Abbreviation
Main <i>r</i> -process	$0.3 \leq [\text{Eu}/\text{Fe}] \leq +1.0$ and $[\text{Ba}/\text{Eu}] < 0.0$	<i>r</i> -I
	$[\text{Eu}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Eu}] < 0.0$	<i>r</i> -II
Limited <i>r</i> -process ^a	$[\text{Eu}/\text{Fe}] < 0.3$, $[\text{Sr}/\text{Ba}] > 0.5$, and $[\text{Sr}/\text{Eu}] > 0.0$	<i>r</i> _{lim}
<i>s</i> -process	$[\text{Ba}/\text{Fe}] > +1.0$, $[\text{Ba}/\text{Eu}] > +0.5$, $[\text{Ba}/\text{Pb}] > -1.5$	<i>s</i>
<i>r</i> - and <i>s</i> -processes	$0.0 < [\text{Ba}/\text{Eu}] < +0.5$ and $-1.0 < [\text{Ba}/\text{Pb}] < -0.5^b$	<i>r</i> + <i>s</i>
<i>i</i> -process	No unambiguous match to neutron-capture element patterns/criteria	<i>i</i>
Signature	Metal-poor stars with other element characteristics	Abbreviation
Neutron-capture normal	$[\text{Ba}/\text{Fe}] < 0$	No
Carbon enhancement	$[\text{C}/\text{Fe}] > +0.7$ for $\log(L/L_\odot) \leq 2.3$ $[\text{C}/\text{Fe}] \geq [+3.0 - \log(L/L_\odot)]$ for $\log(L/L_\odot) > 2.3^d$	CEMP ^c CEMP
α -element enhancement	$[\text{Mg}, \text{Si}, \text{Ca}, \text{Ti}/\text{Fe}] \sim +0.4$	α -enhanced

^aAlso referred to as the light-element primary process (LEPP) (19) or "weak" *r*-process.

^bBased on only one known carbon-enhanced metal-poor (CEMP)-*r* + *s* star (20); may require future adjustments.

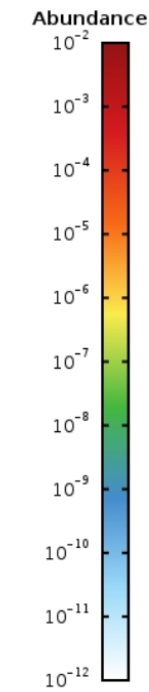
^cThe CEMP star definitions are from Reference 21. *s*- and *i*-process-enhanced stars are always CEMP stars; *r*-process-enhanced stars may or may not be CEMP stars. There is also a class of CEMP-no stars.

^dCarbon corrections as a function of luminosity can also be obtained from Reference 22.

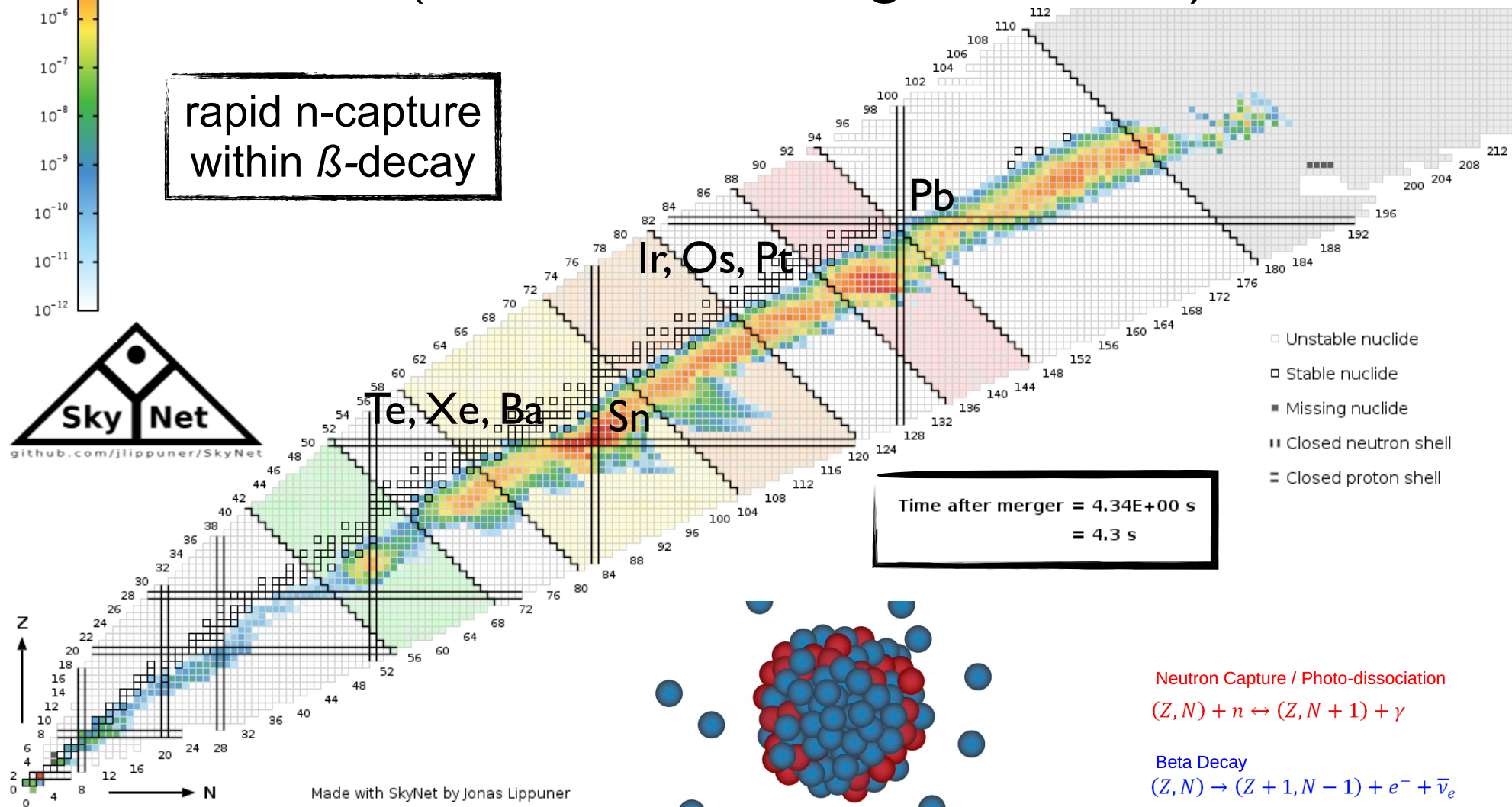
Frebel
2018
ARNP

RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

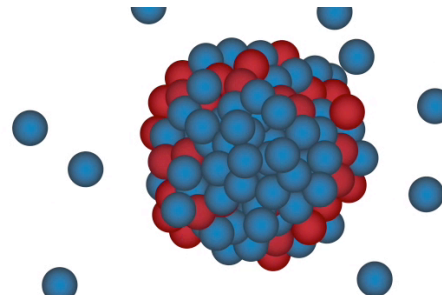
(neutron star merger scenario)



rapid n-capture
within β -decay



Made with SkyNet by Jonas Lippuner



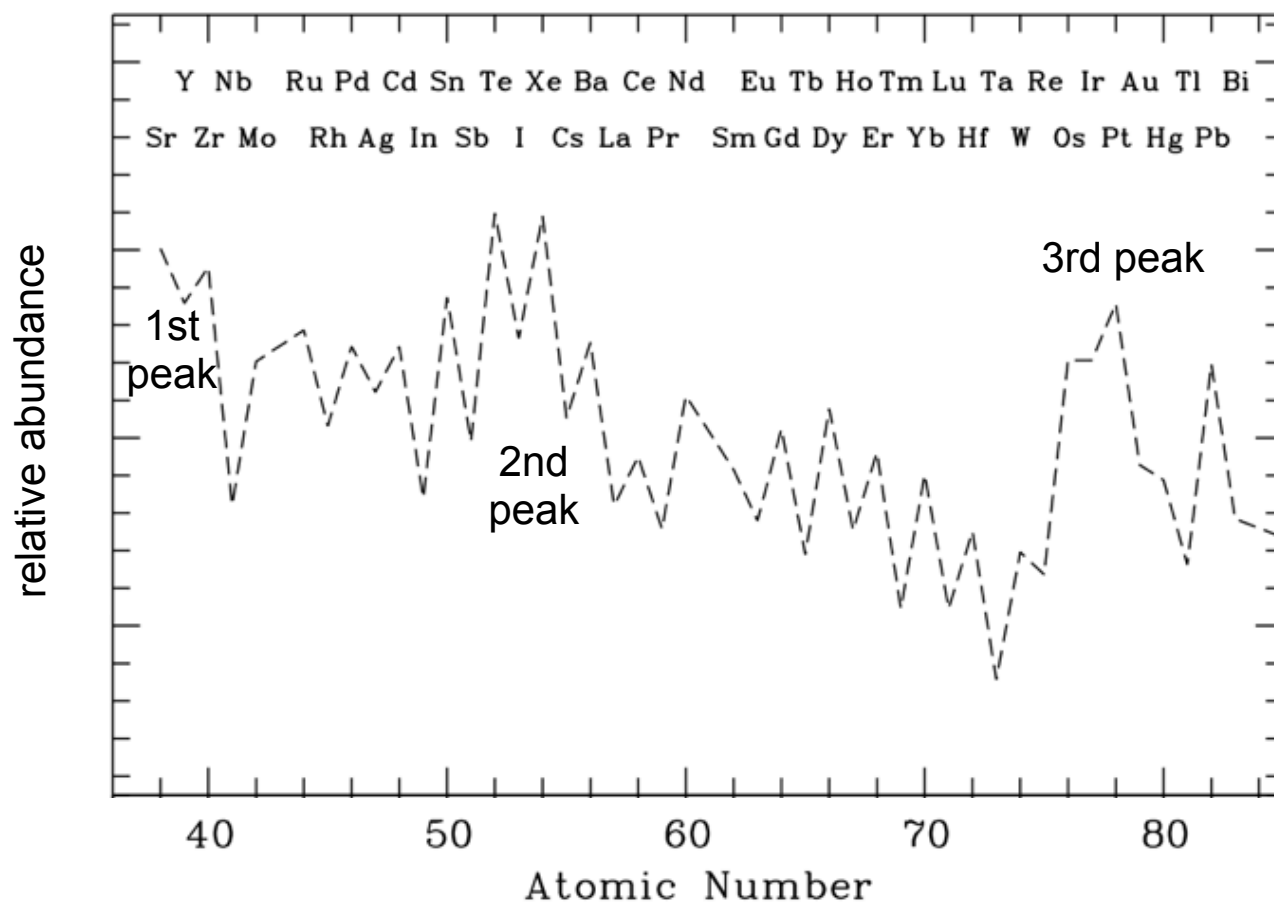
Neutron Capture / Photo-dissociation
 $(Z, N) + n \leftrightarrow (Z, N + 1) + \gamma$

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

decay path to stability

R-PROCESS PATTERN

neutron-capture r-process elemental pattern



THE (DETAILED) ASTRONOMER'S PERIODIC TABLE

Big Bang nucleosynthesis

α -rich freezeout, ν p-proc., weak s-proc.

Spallation

r-process

Evolved giant stars

Odd-Z elements

α -elements

Iron group elements

1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 La Lanthanum 138.905	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Ac Actinium 227.028	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

THE (DETAILED) ASTRONOMER'S PERIODIC TABLE

Big Bang nucleosynthesis

Spallation

Evolved giant stars

Odd-Z elements

α -elements

Iron group elements

α -rich freezeout, ν p-proc., weak s-proc.

s-process

Weak r-proc., light n-cap. primary proc.

r-process

Long-lived

radioactive

(also r-process)

	IA	IIA																	VIIIA					
1	1 H 1.008		Evolved giant stars										Weak r-proc., light n-cap. primary proc.						2 He 4.003					
2	3 Li 6.939	4 Be 9.012	Odd-Z elements										r-process						5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
3	11 Na 22.990	12 Mg 24.312	α -elements										Long-lived radioactive (also r-process)						13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
4	19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80						
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30						
6	55 Cs 132.91	56 Ba 137.34	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 204.59	81 Tl 204.38	82 Pb 208.17	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)						
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	Isotope distribution of solar nebula (~8 billion yrs of chemical evolution)																				
„6“				58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97							
„7“				90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (249)	98 Cf (251)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (253)	103 Lr (257)							

Isotope distribution of solar nebula
(~8 billion yrs of chemical evolution)

RARE R-PROCESS STARS IN THE MILKY WAY

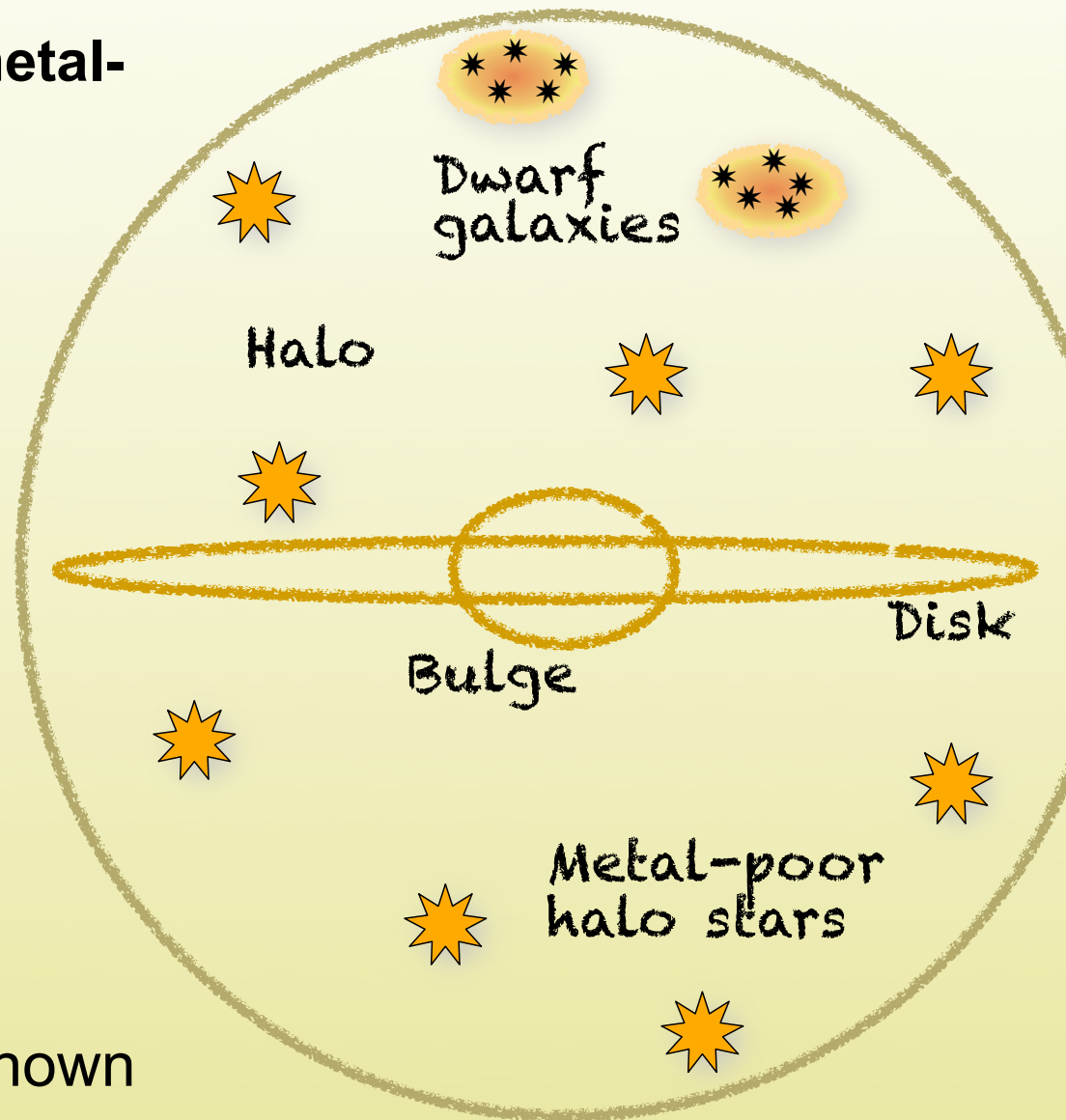
How common are r-process metal-poor stars in the Milky Way?

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

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

More stars known with lower levels of $0.3 < [\text{Eu}/\text{Fe}] < 1.0$; unclear what lowest level is

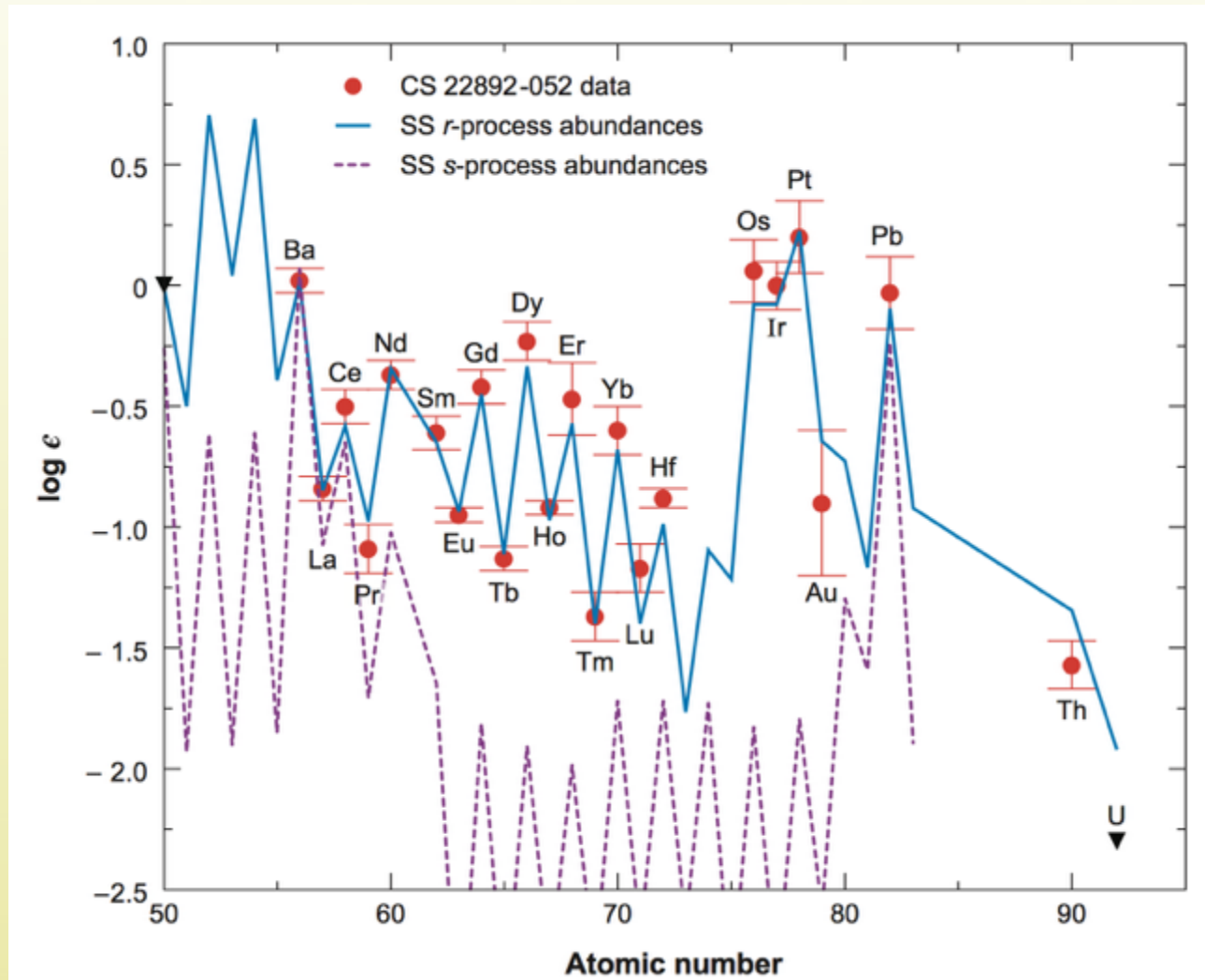
=> Origin of these stars is unknown



UNIVERSAL R-PROCESS PATTERN OBSERVED IN METAL-POOR STARS

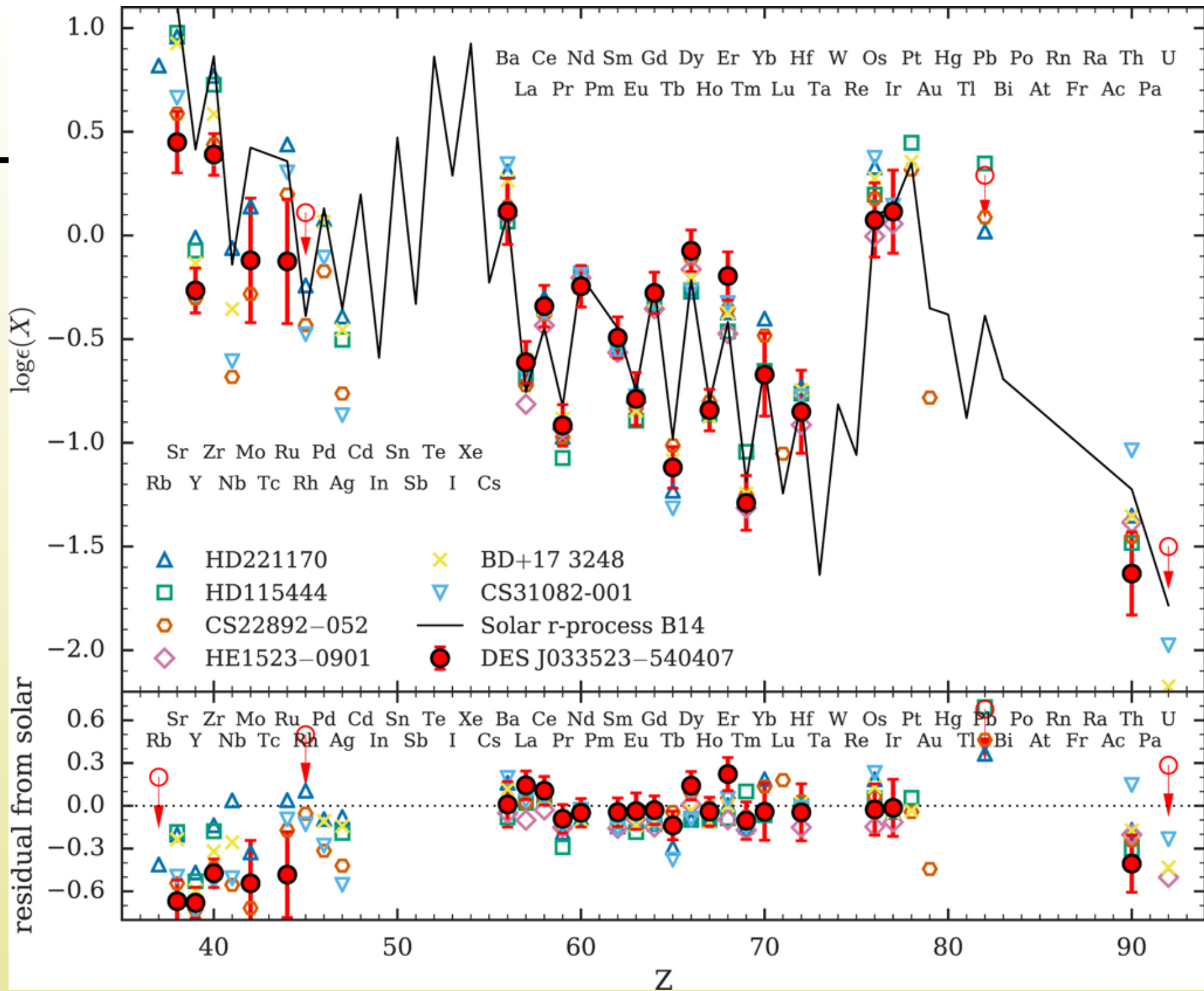
r-process
abundance
patterns are the
same in the Sun
and old metal-
poor stars

r-process stars
are all extremely
metal-poor:
 $[\text{Fe}/\text{H}] \sim -3.0$
(= 1/1000th of solar
Fe value)



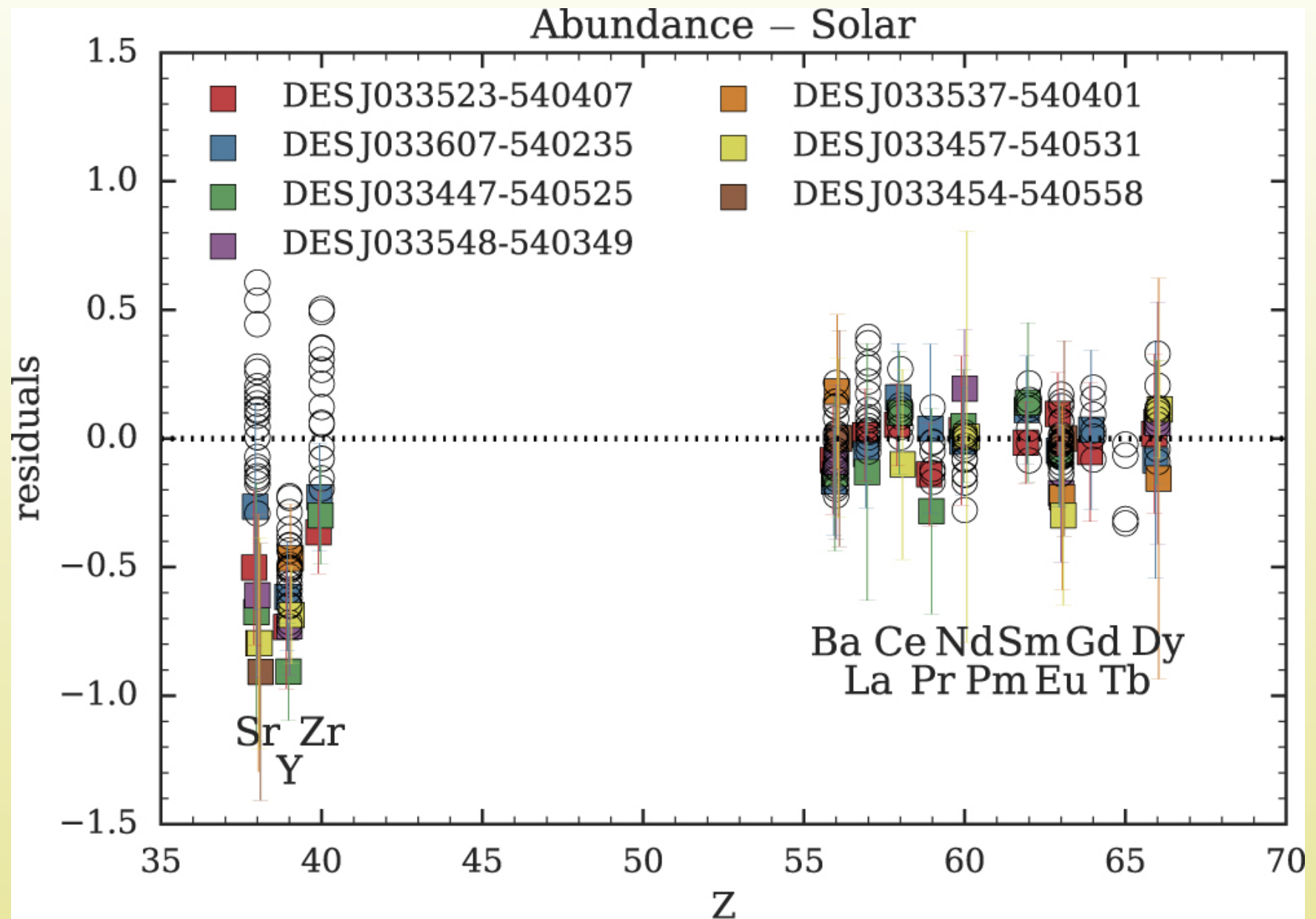
Sneden et al. 2008

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



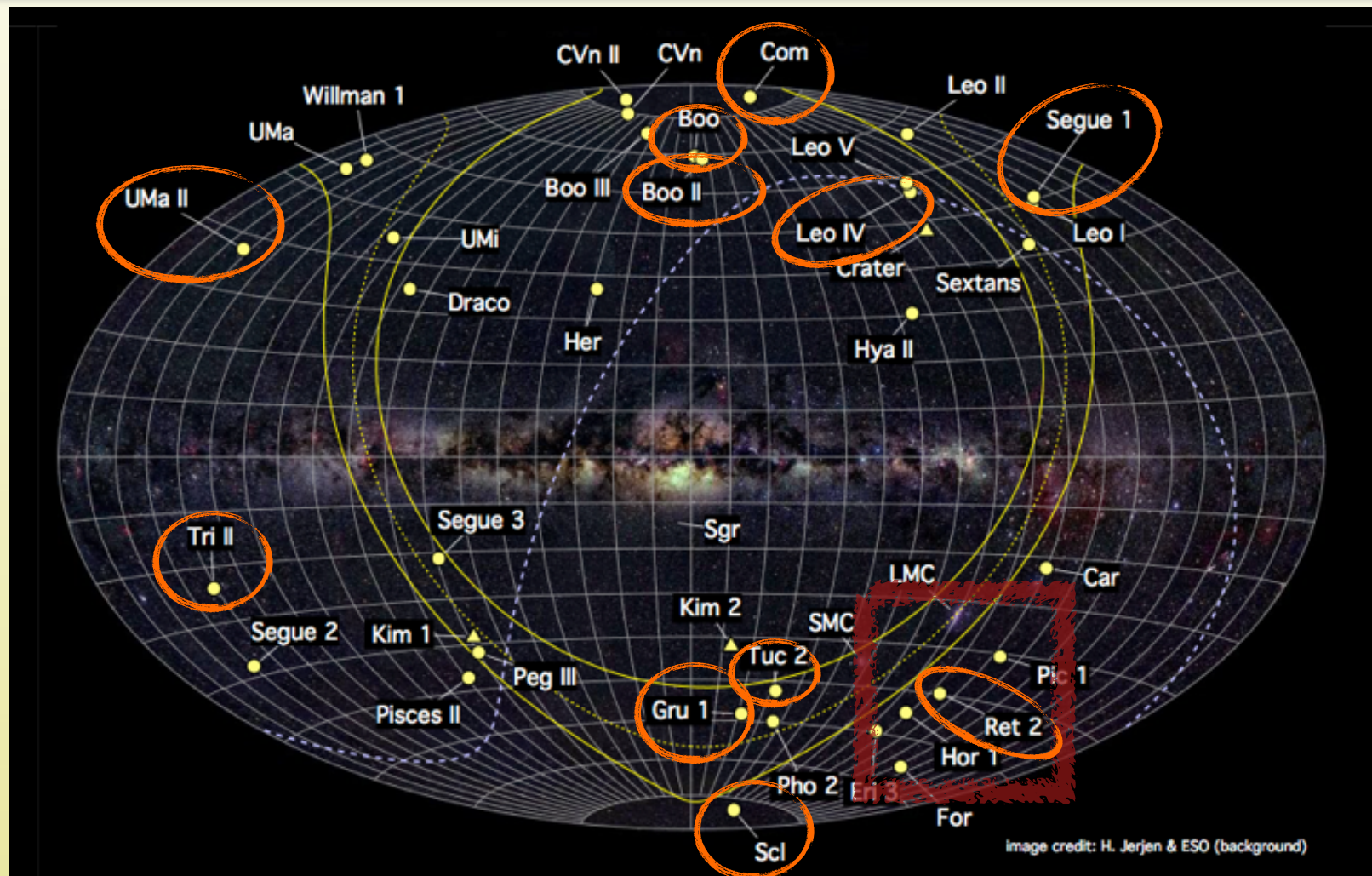
1ST PEAK: HUGE DEVIATIONS

2ND/3RD PEAK: ALL GOOD!

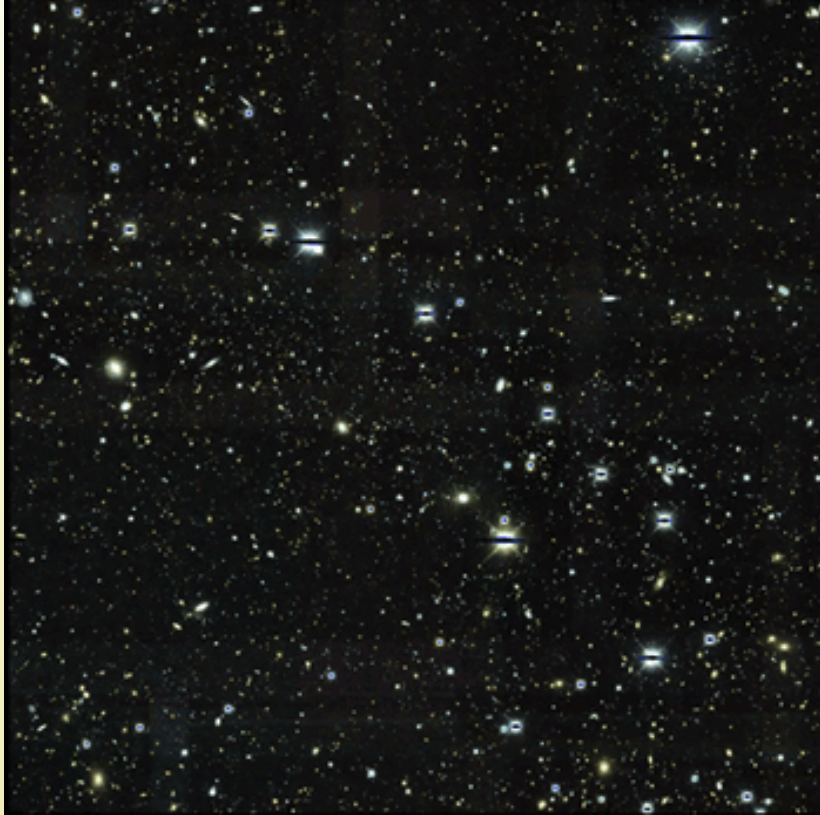


MILKY WAY SATELLITE GALAXIES

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

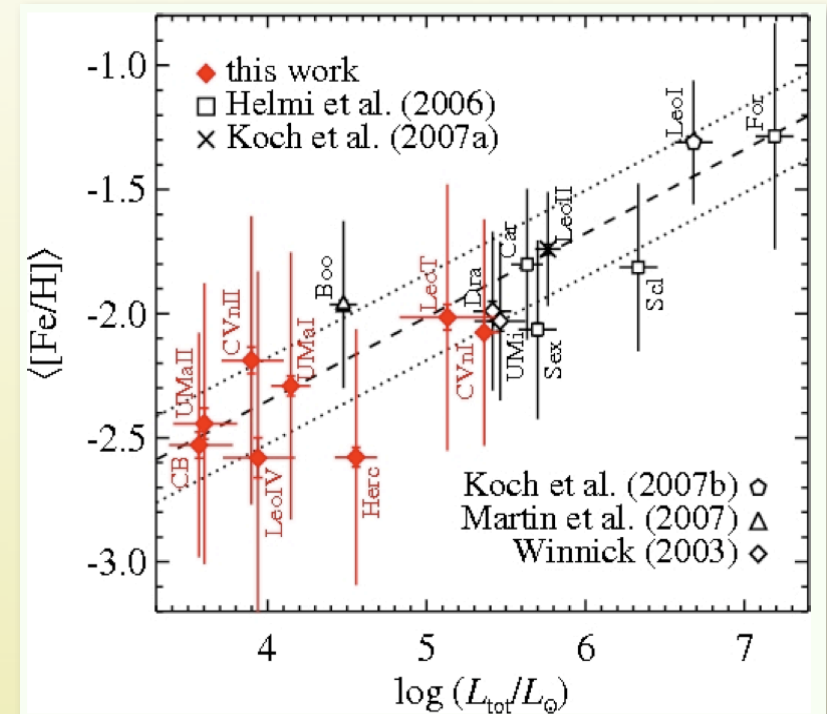


Reticulum II stars

(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 $[Fe/H] \sim -2$)
- Stars are old (mean age 13.3 ± 1 Gyr)
- Few bursts of star formation



Ultra-faint dwarfs

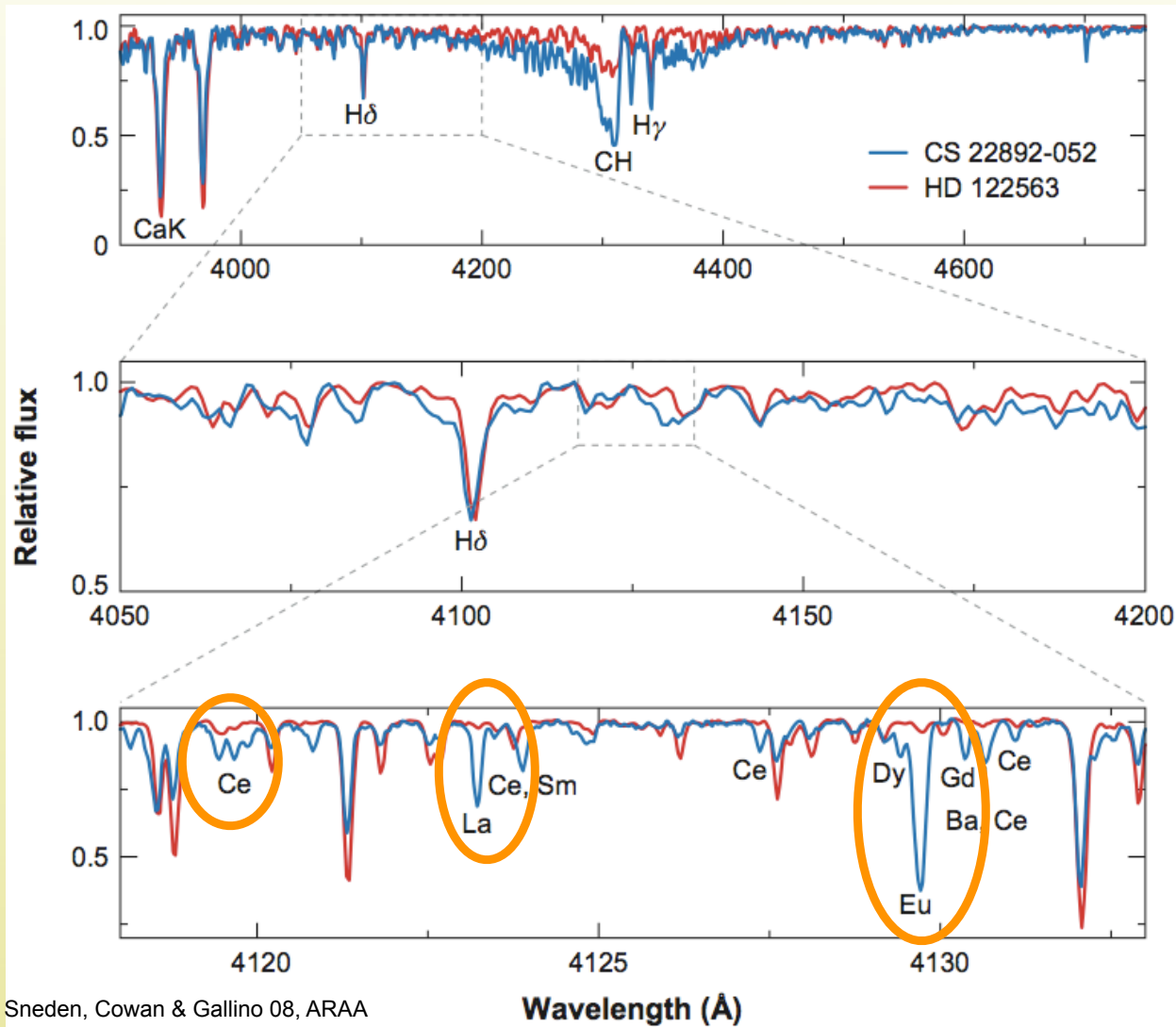
Classical dSphs

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



Snedden, Cowan & Gallino 08, ARAA

HD 122563:
r-process deficient
star

CS 22892-052:
r-process strong star

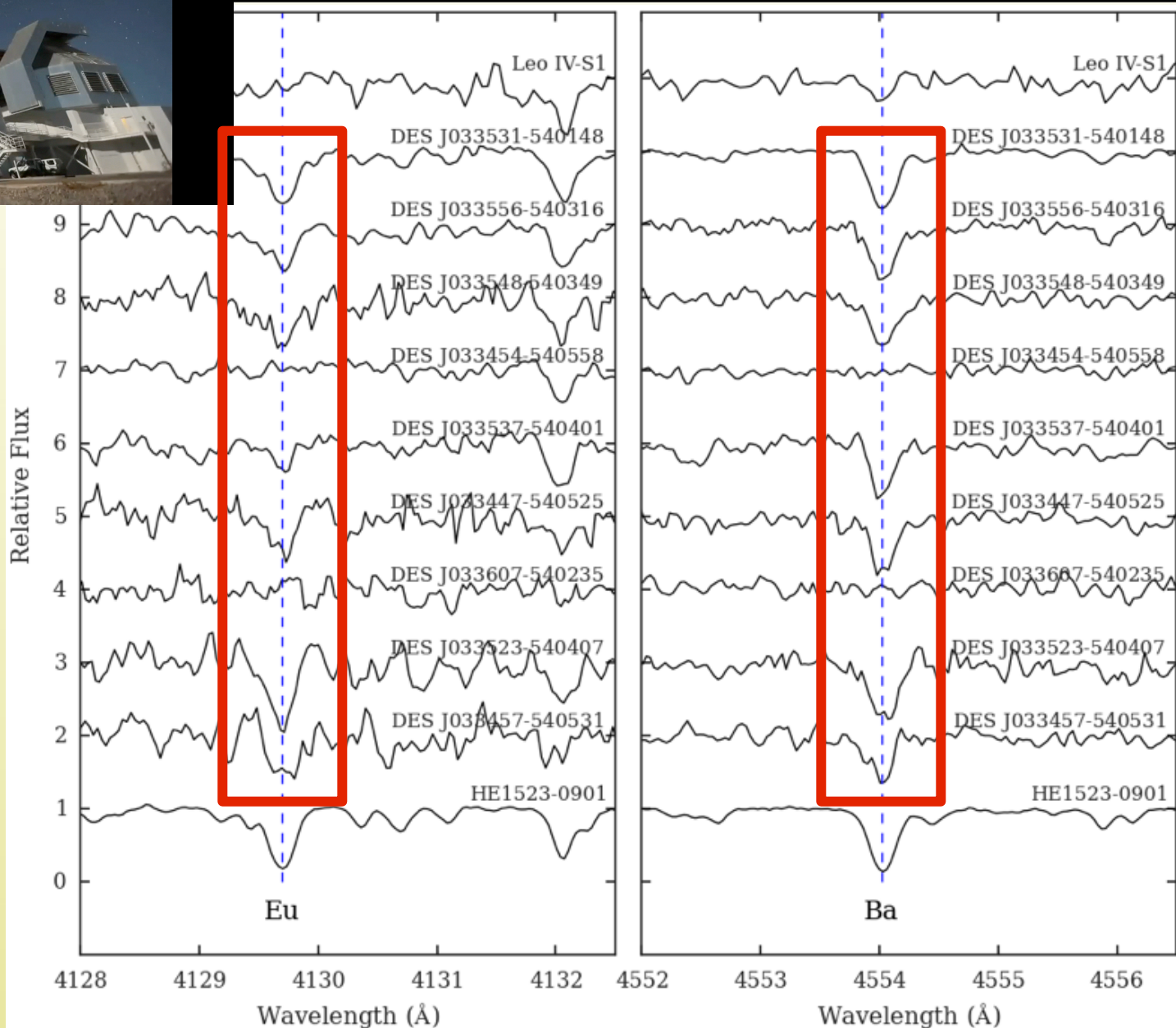
MAGELLAN OBSERVATIONS OF RETICULUM II STARS



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

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

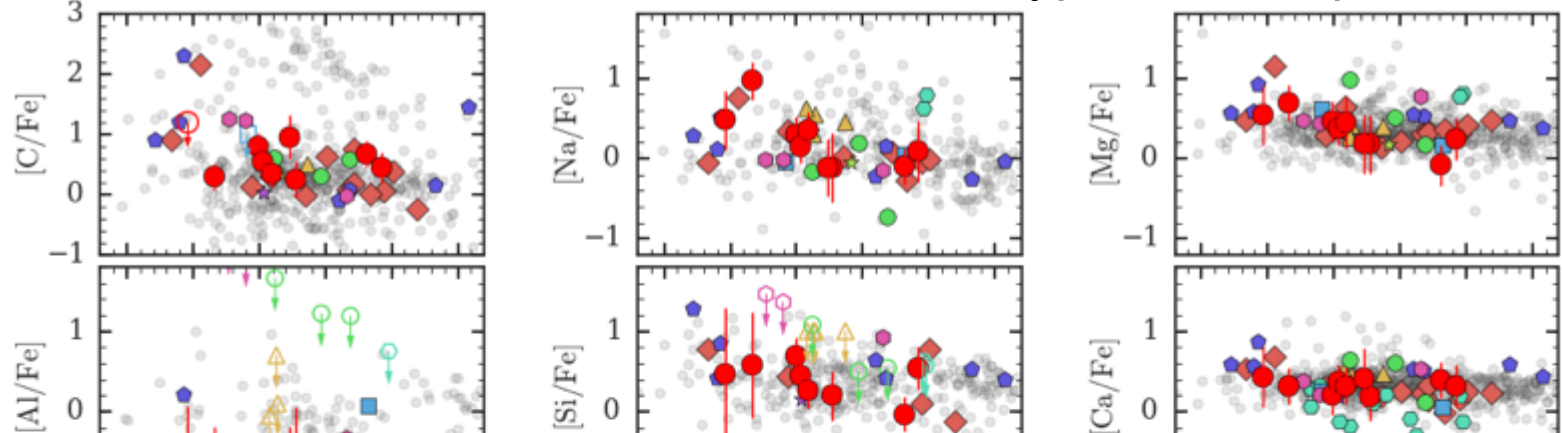
=> Ji et al. (2016)
spent 2-3 hours on
each of the 9 brightest
targets (~23h)



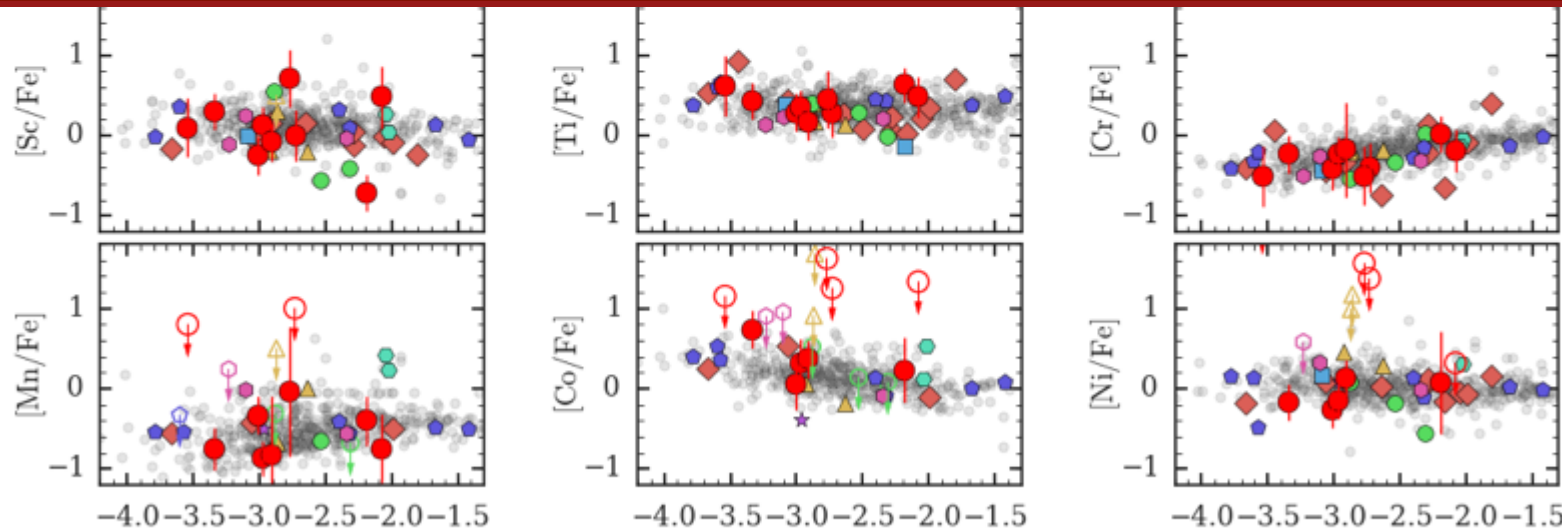
LIGHT ELEMENT ABUNDANCES

(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



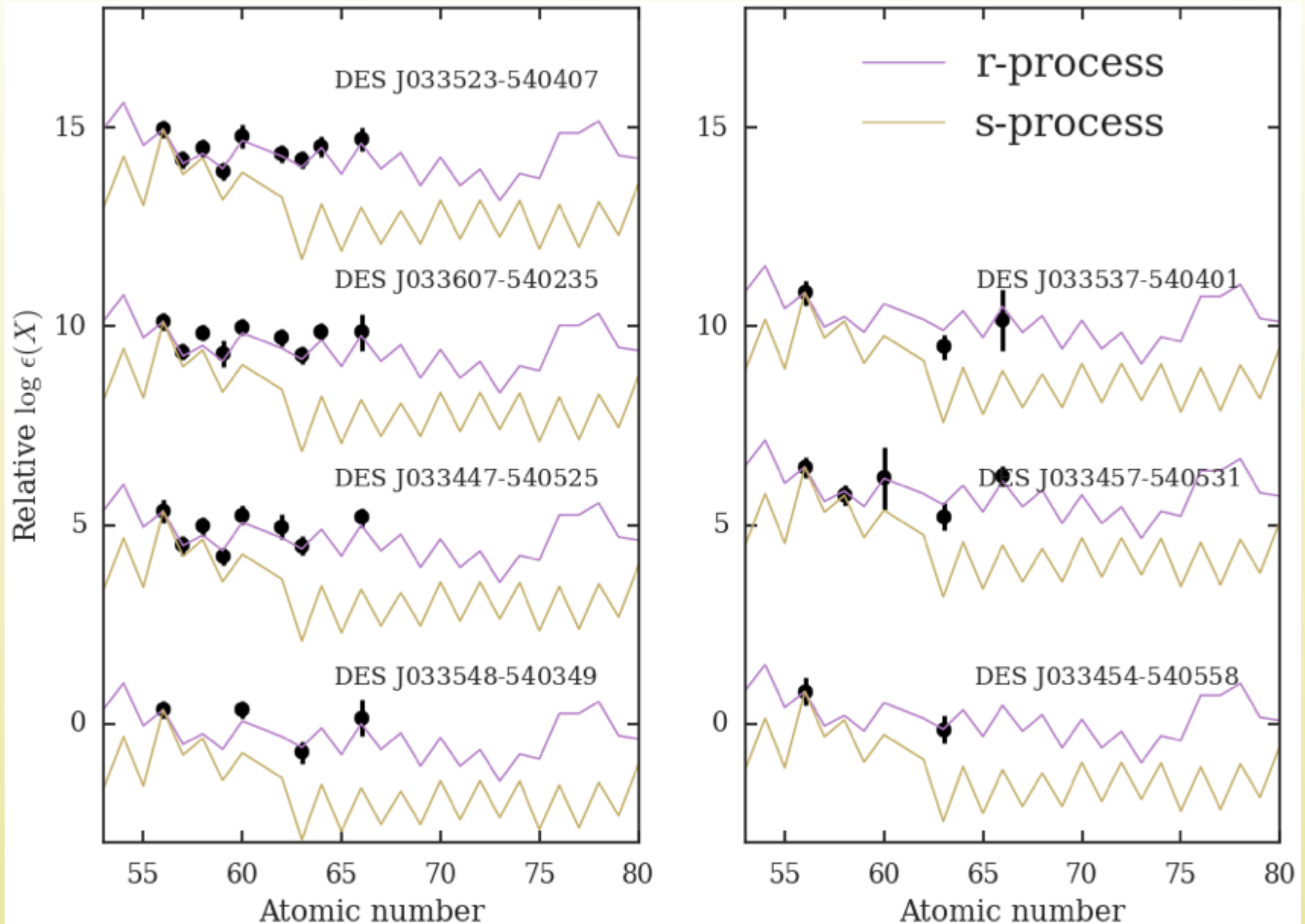
[Fe/H] Bootes I ★ CVn II ● Hercules ● Segue 1 ● UMa II
 ▲ Bootes II ● ComBer ■ Leo IV ★ Segue 2 ● Ret II

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-PROCESSES...!

Table 2 Nucleosynthesis processes that can contribute neutron-capture elements

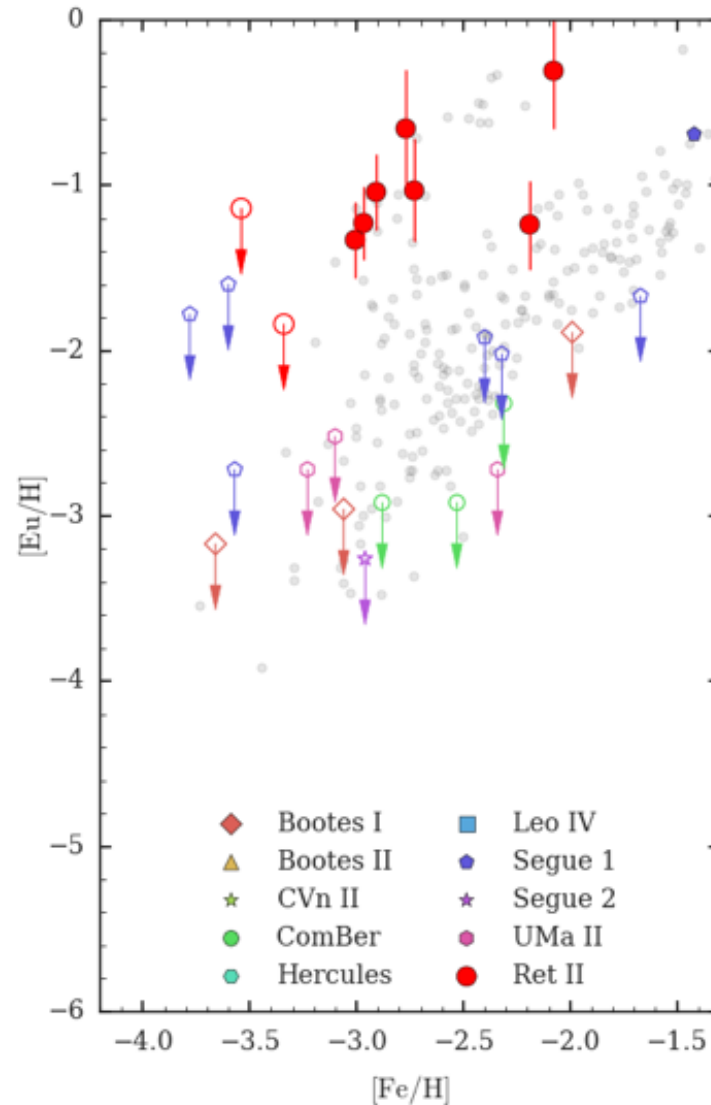
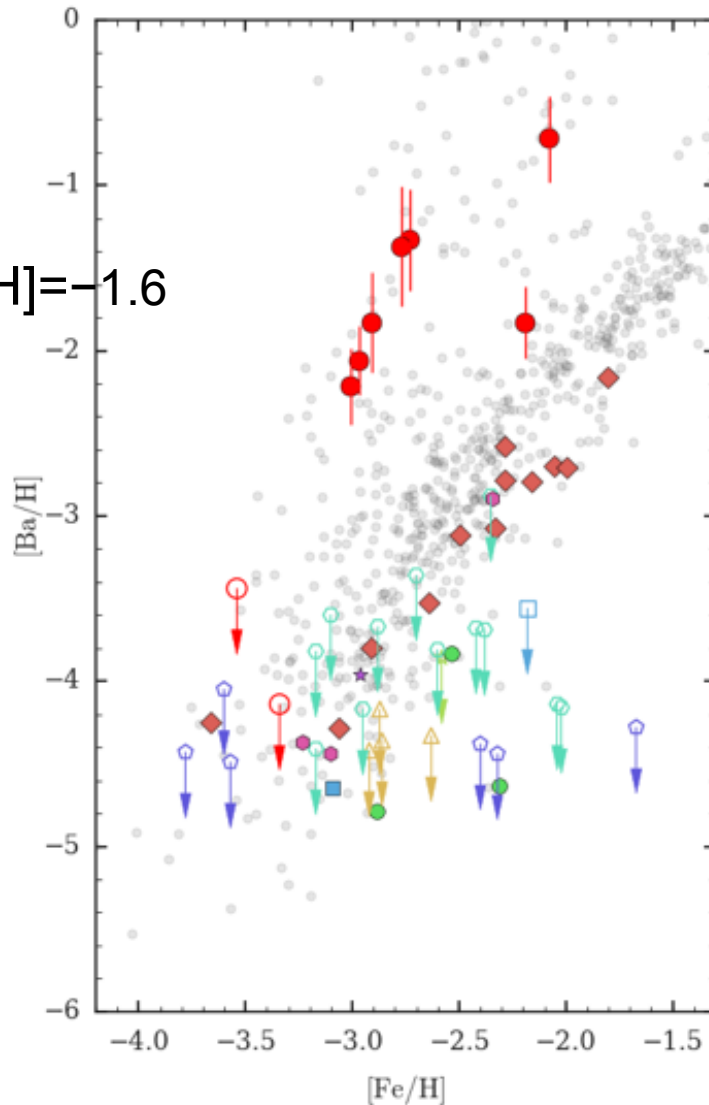
Process	Conditions	Elements produced	Y_e	Astrophysical sites
Terminal QSE ^a	Insufficiently neutron rich; α -, neutron-, proton-capture and reverse; expansion from hot, dense state	Sr \rightarrow Ag	< 0.5	Standard proto-neutron star wind in core-collapse supernovae; shock-heated/disk ejecta
νp -process	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 $\ll 100$; 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)

^aQuasi-statistical equilibrium; see Reference 102 for a detailed description and treatment.

^bOften 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.

RET II STARS: > 100X HIGHER N-CAPTURE ELEMENT ABUNDANCES THAN OTHER UFDs

[Ba/H]=-1.6

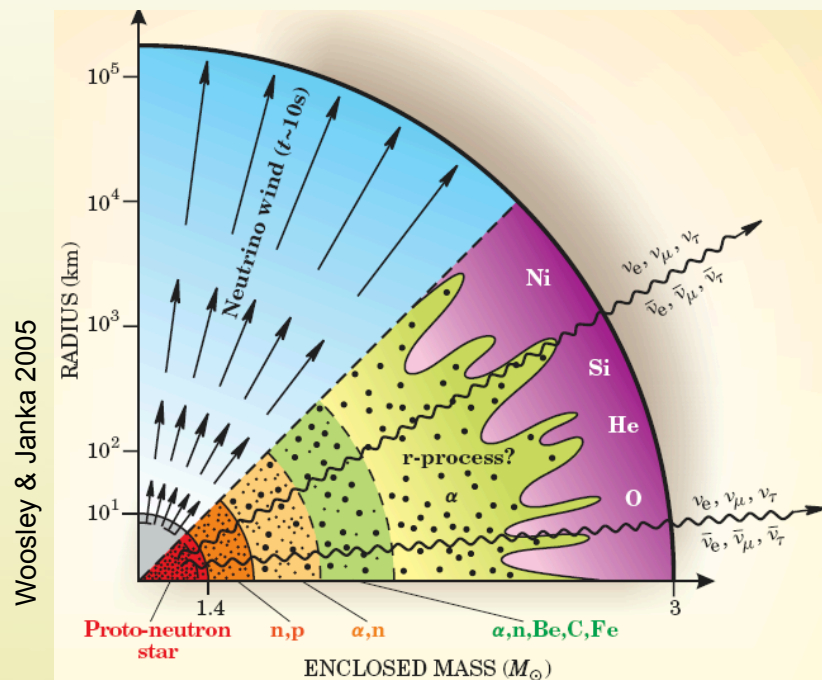


[Eu/H]=-1

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



Theoretical element yield:

$\sim 10^{-6} M_{\text{sun}}$ of total r-process material

$\Rightarrow \sim 10^{-7.5} M_{\text{sun}}$ 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 Rare One binary per ~ 1000 - 2000 supernovae
Long(er) enrichment timescale \Rightarrow Inspiral time > 100 Myr



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

$\Rightarrow \sim 10^{-4.5} M_{\text{sun}}$ 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: **$\sim 10^7 M_{\text{sun}}$**

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

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

Back-of-the-envelope calculation

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

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

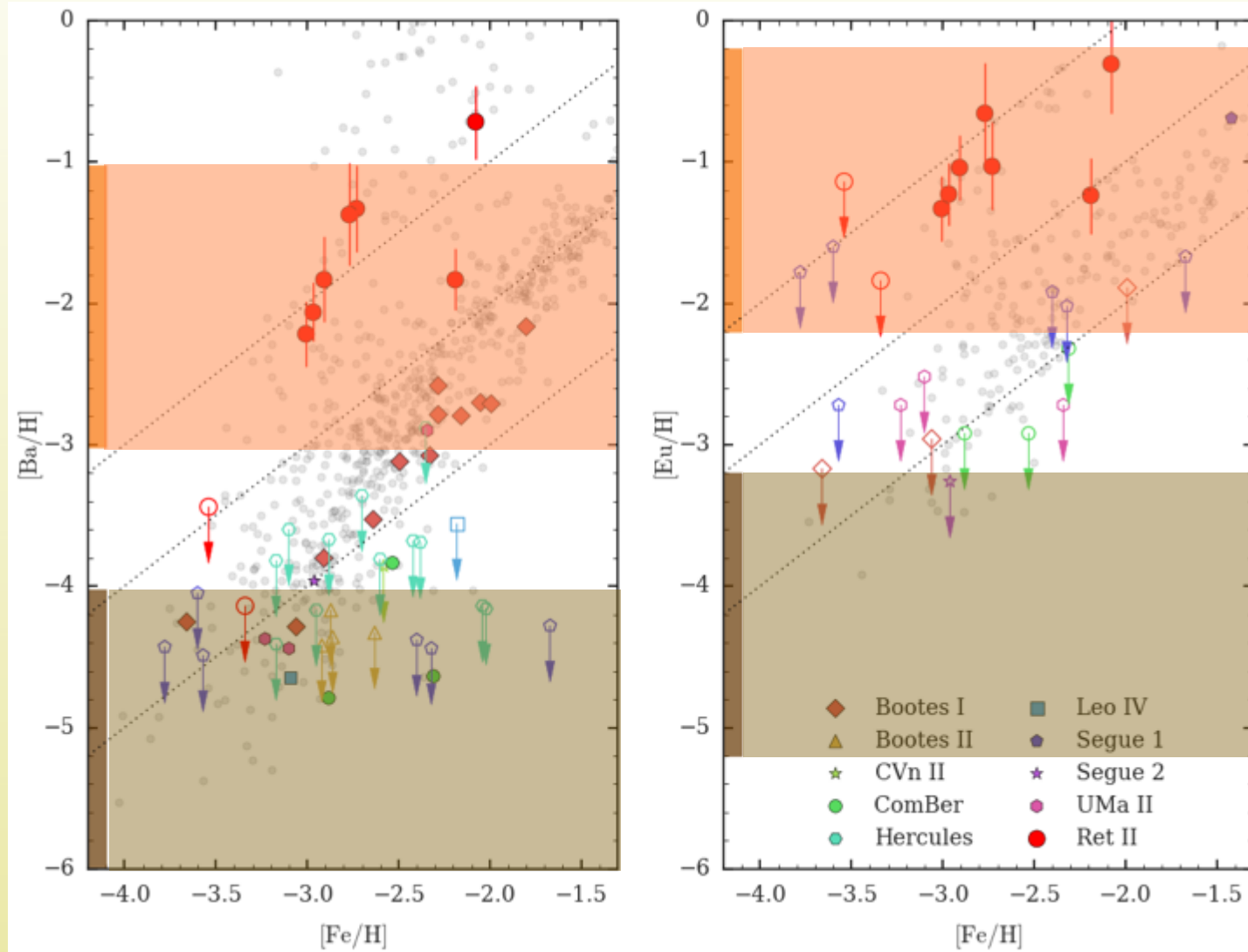
=> Agrees with Ret II abundance results!



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!

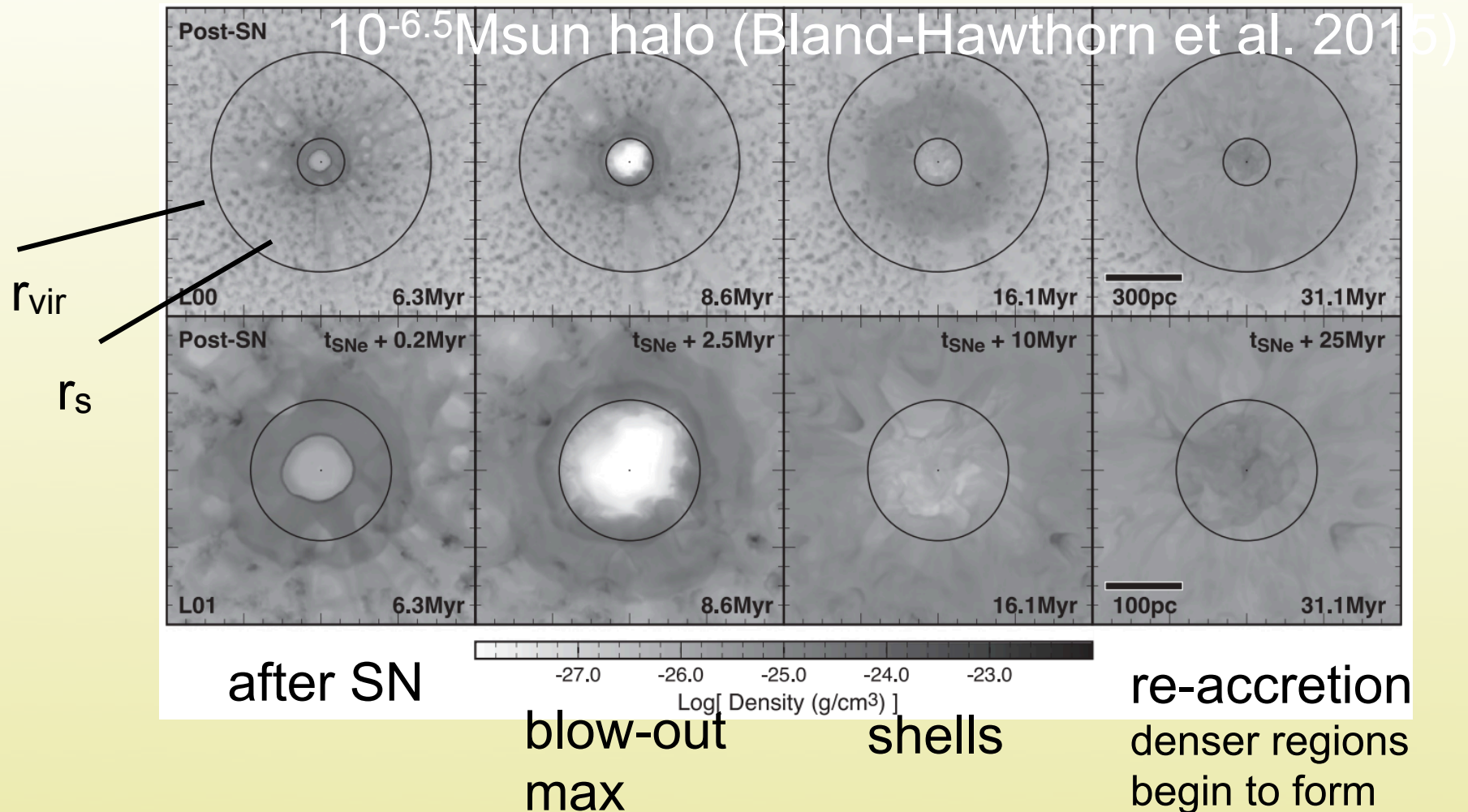
Can't you increase the # of supernovae to get higher yield?

- ➡ 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?

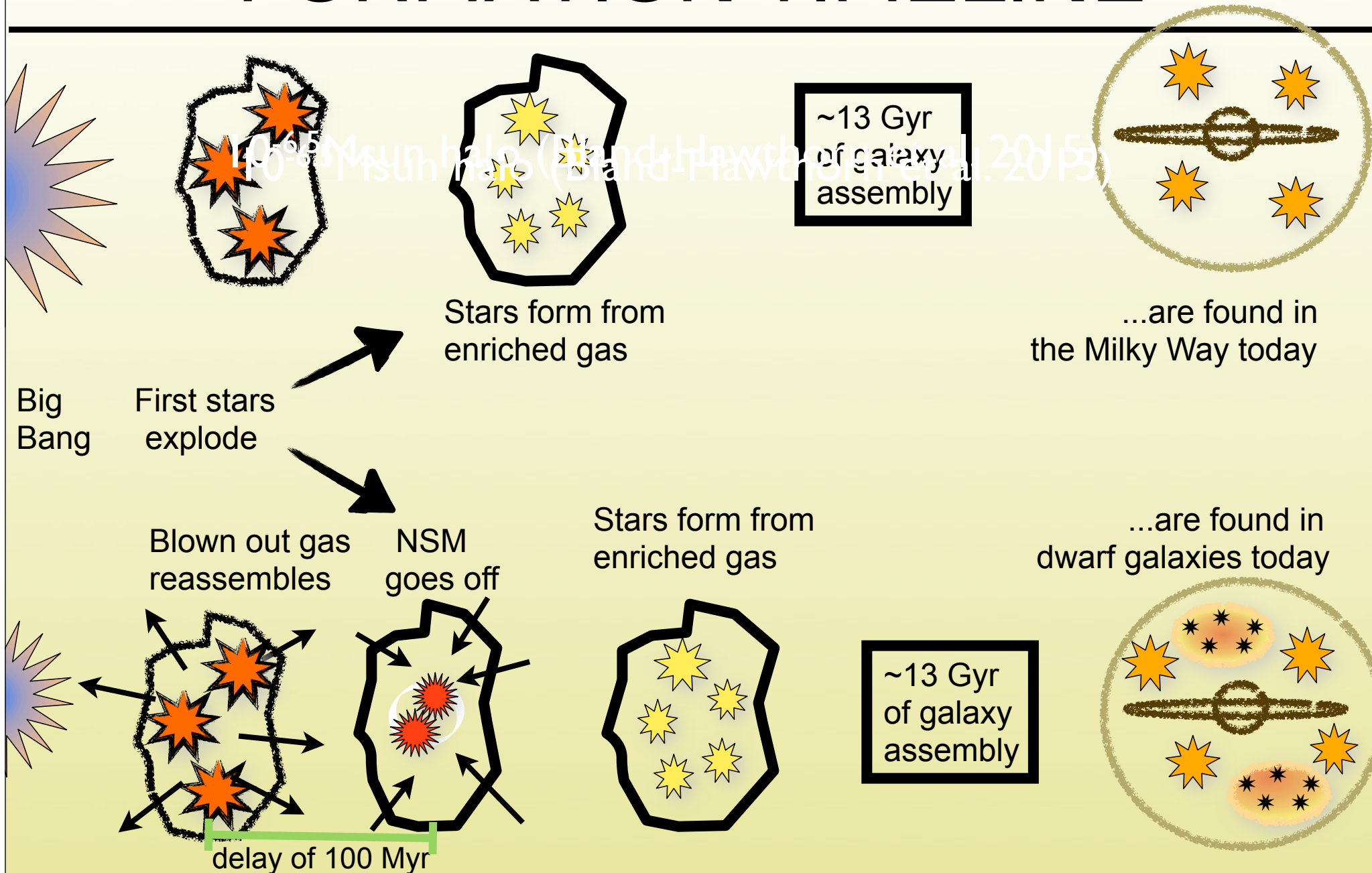
- ➡ After the few (initial) supernovae, it takes time for the system to reassemble again (~100 Myr)
- ➡ Minimum time scales for coalescence is ~100 Myr

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:

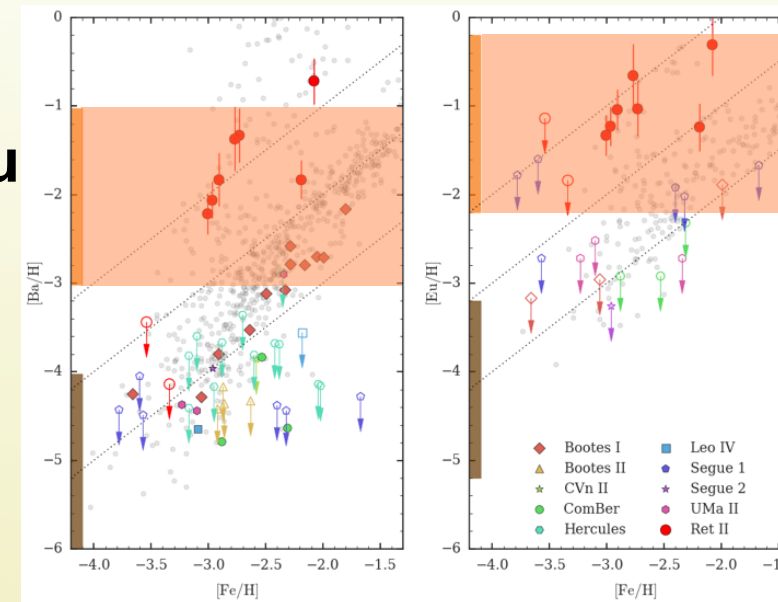
measure $[\text{Eu}/\text{H}] \sim -1.2 \rightarrow 10^{-4.5 \pm 1} M_{\text{sun}} \text{ Eu}$

using gas mass of $10^6 M_{\text{sun}}$

(estimate gas dilution mass 10^5 - $10^7 M_{\text{sun}}$)

NSM simulations: $\sim 10^{-4.3 \pm 1} M_{\text{sun}} \text{ Eu}$

GW170817: $\sim 10^{-4.7 \pm 0.5} M_{\text{sun}} \text{ Eu}$ (Côté+18)



In principle: Gas mass gives \pm factor 10 wiggle room
Focus on main data 'clump': \pm 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

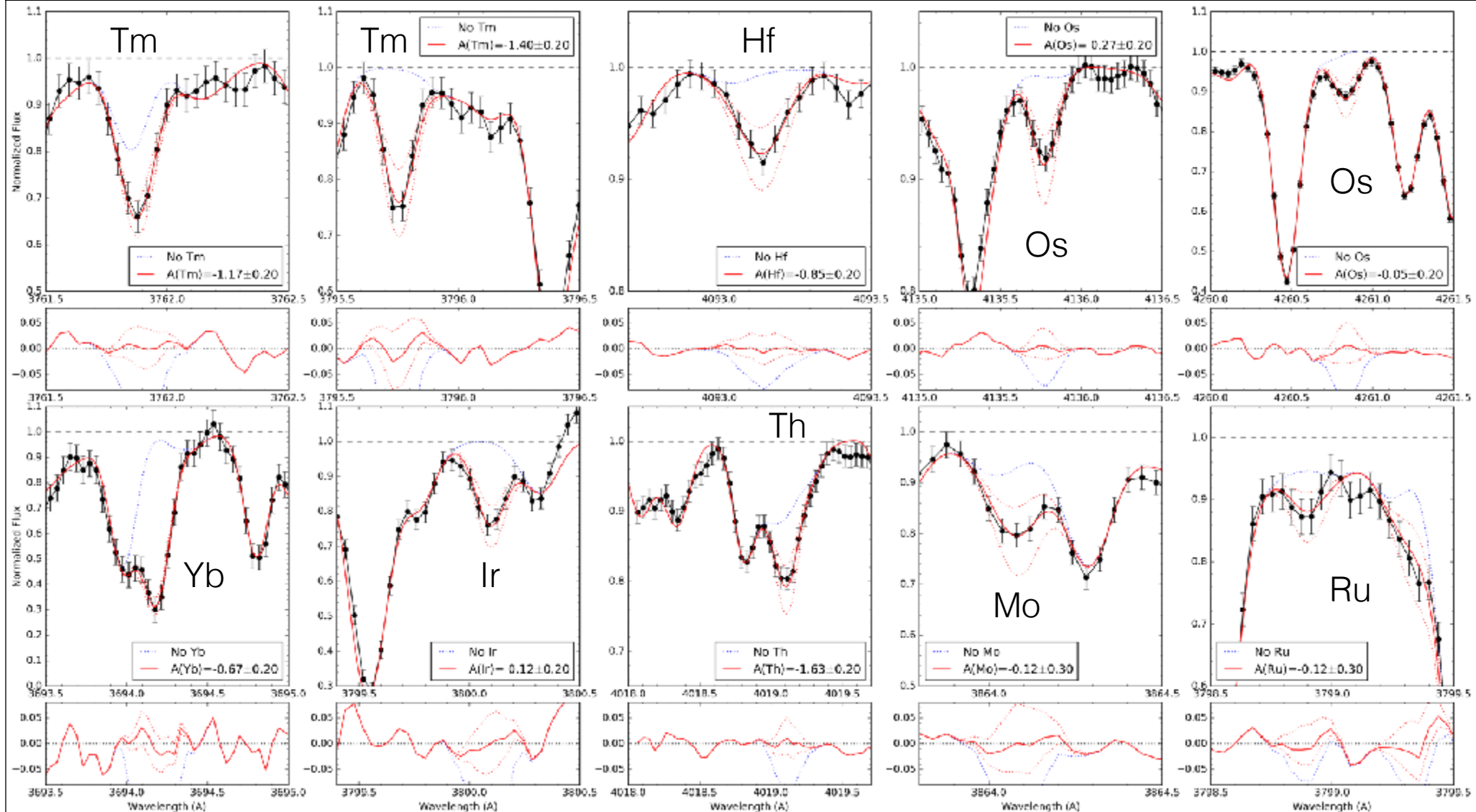
★ What is the rate and yield of the event?

→ ~1 event per 2000 SN; $\sim 10^{-2.5} M_{\text{sun}}$ of r-process

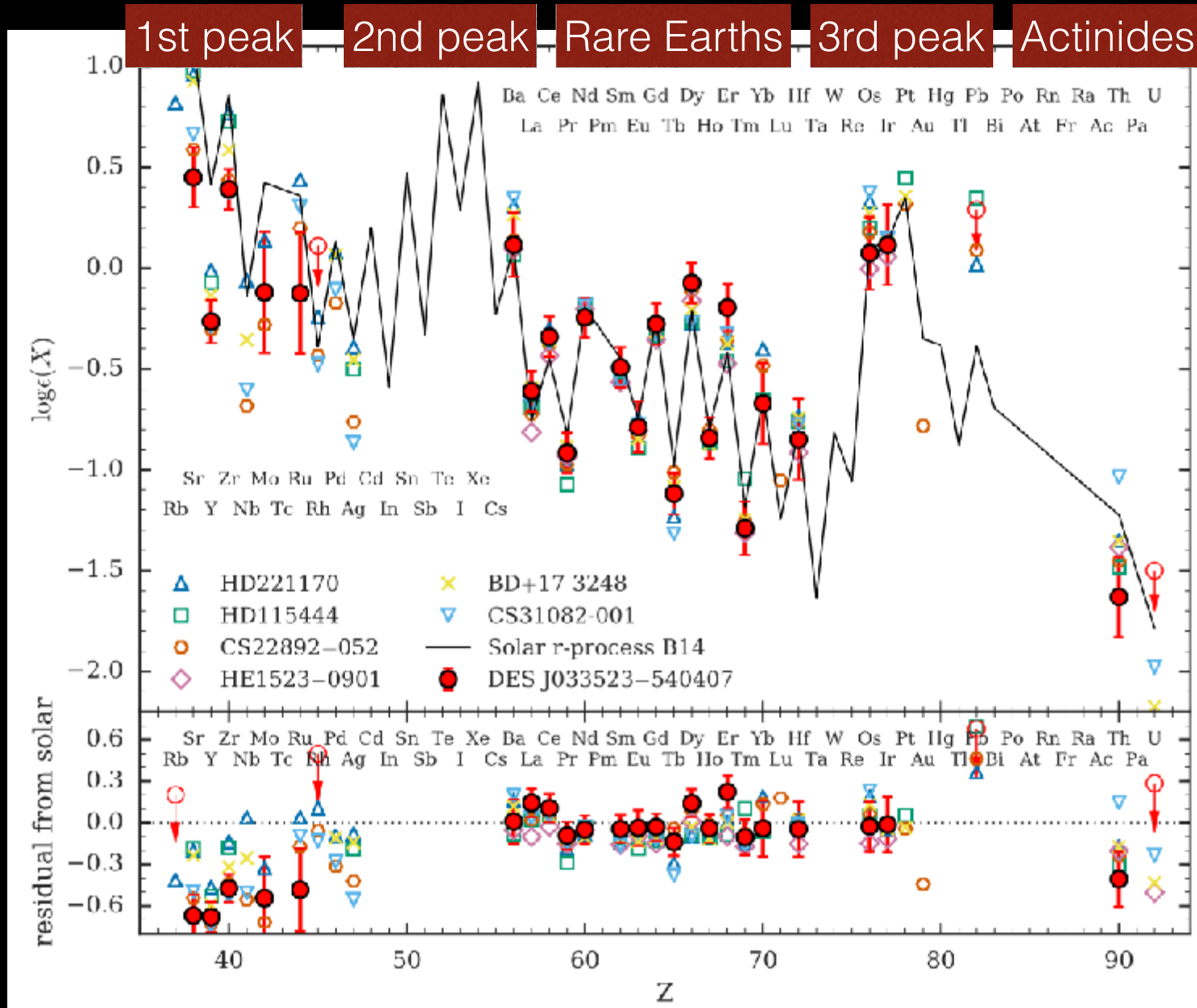
★ Is the dominant site changing over cosmic time?

→ Probably not!

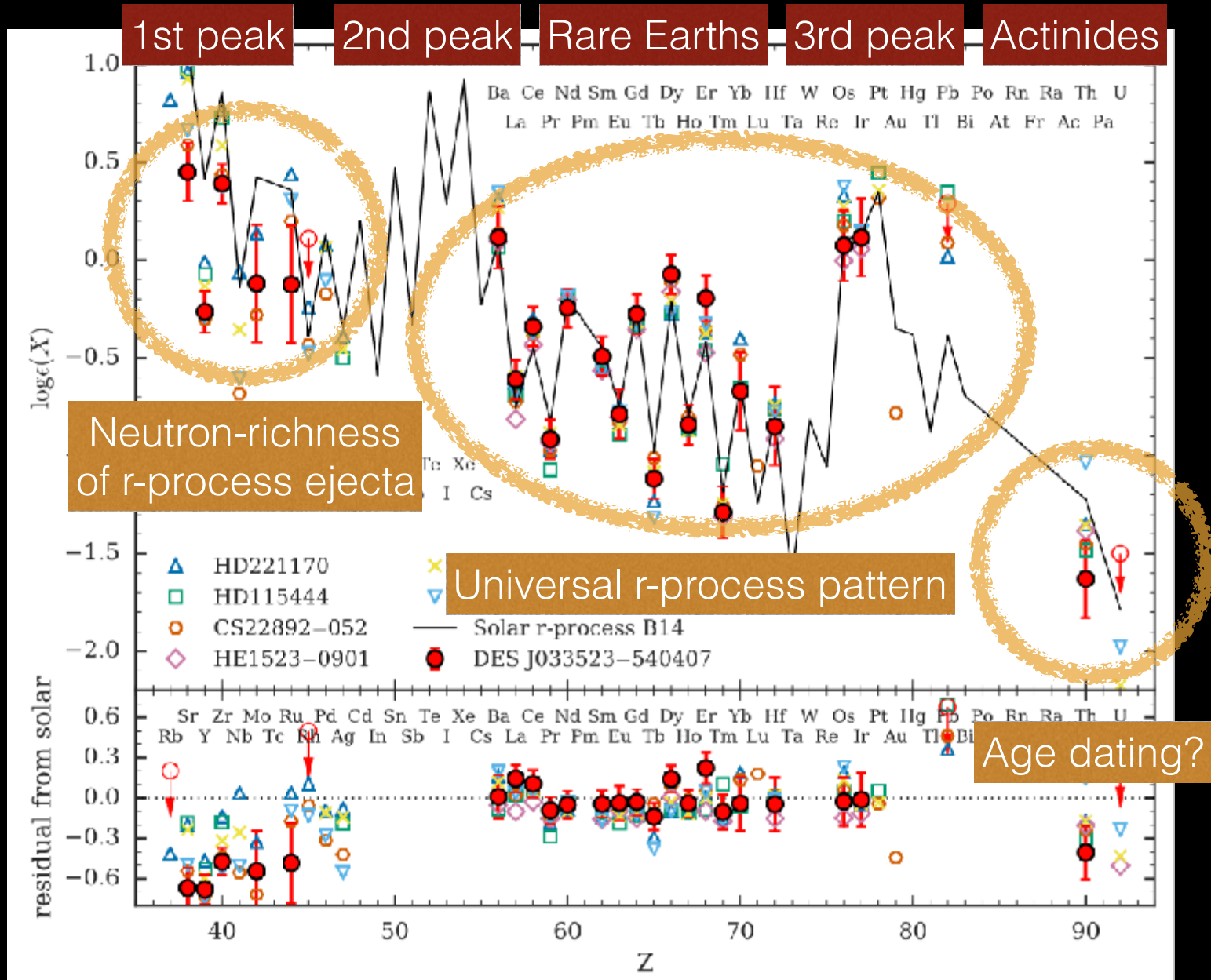
New spectrum of brightest Ret II star provides abundances of 41 elements



The Pure *r*-process Pattern in Ret II

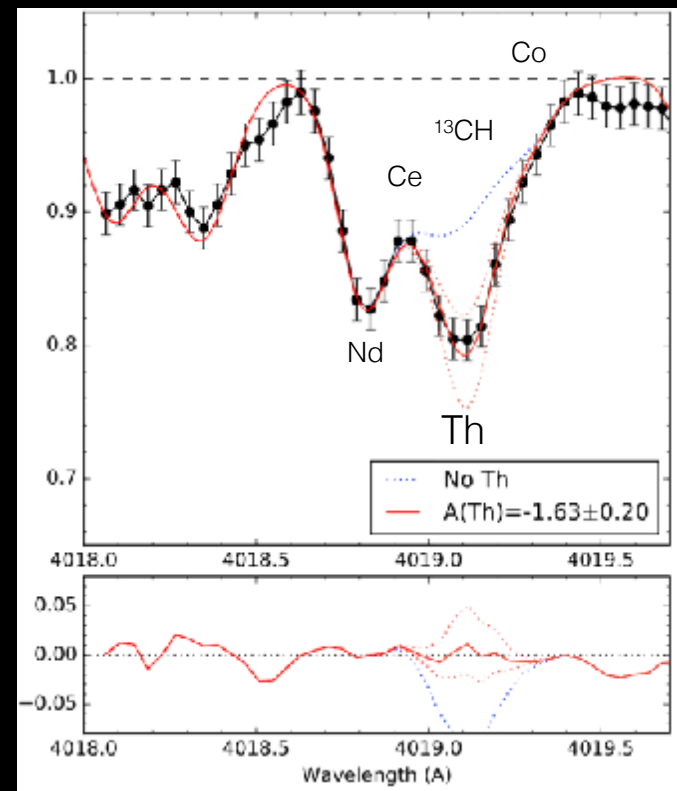


The Pure *r*-process Pattern in Ret II

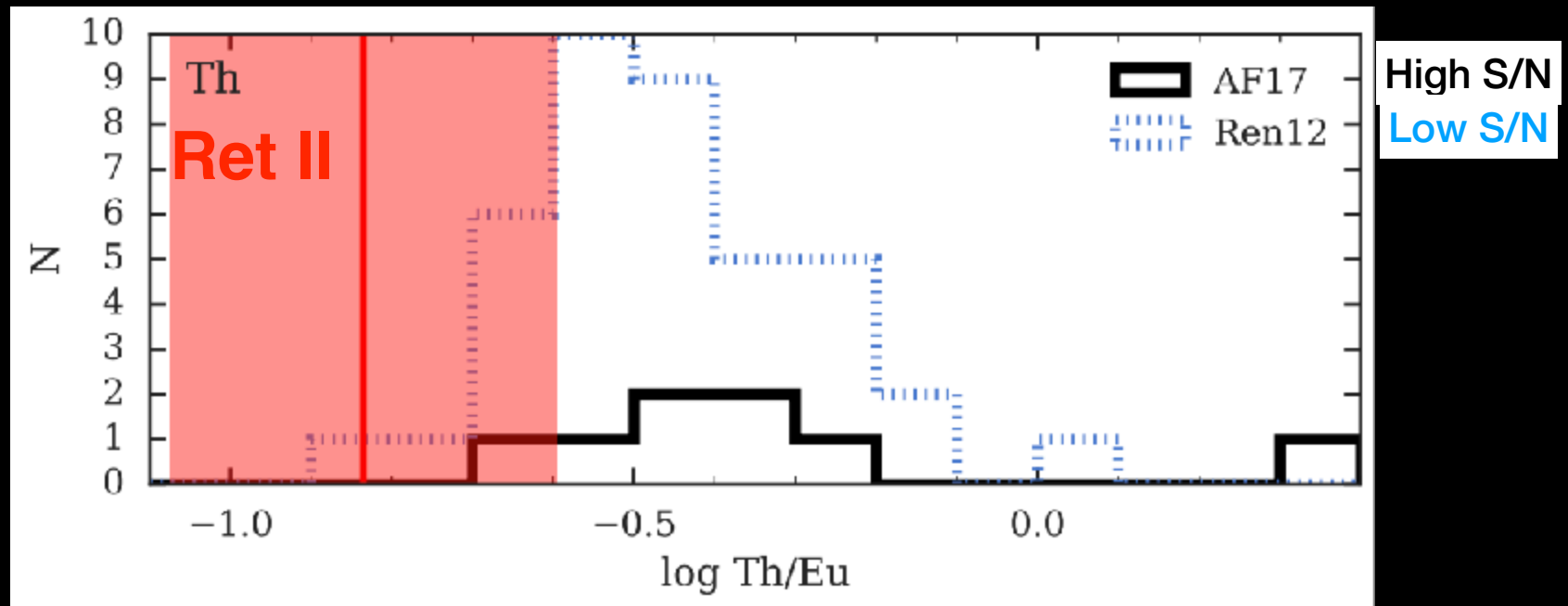


Age Dating with Radioactive *r*-process elements

- ^{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 $[\log(\text{Th}/\text{Eu})_{\text{init}} - \log(\text{Th}/\text{Eu})_{\text{now}}]$
- Th is hard to measure
- Initial production ratios predicted from theory



Ret II has unusually low Th



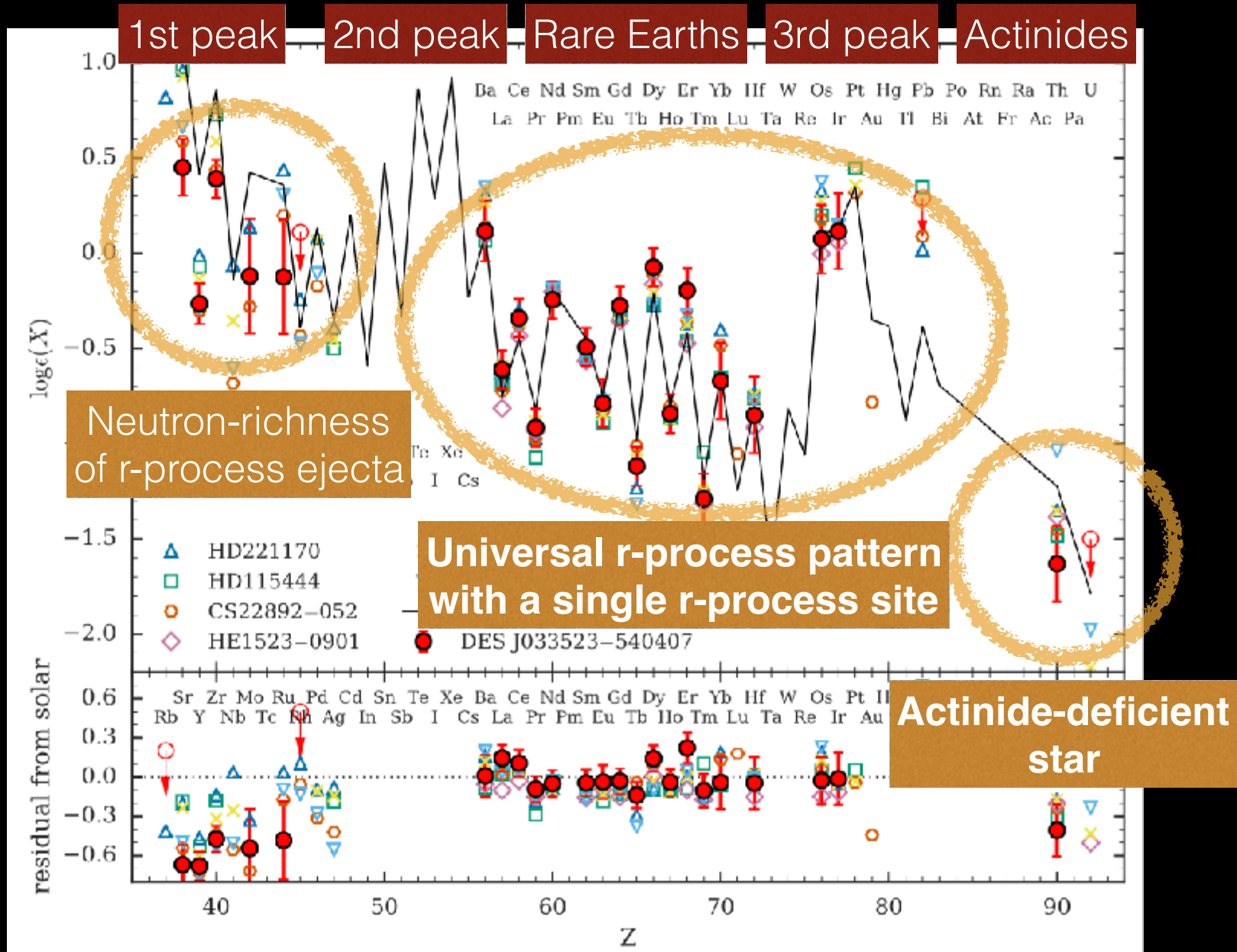
Naive application of literature production ratios:

$$\text{Age} = 24.9 \pm 2.8 \pm 10.3 \pm 3.2 \text{ Gyr}$$

(stat) (sys, obs) (sys, PR)

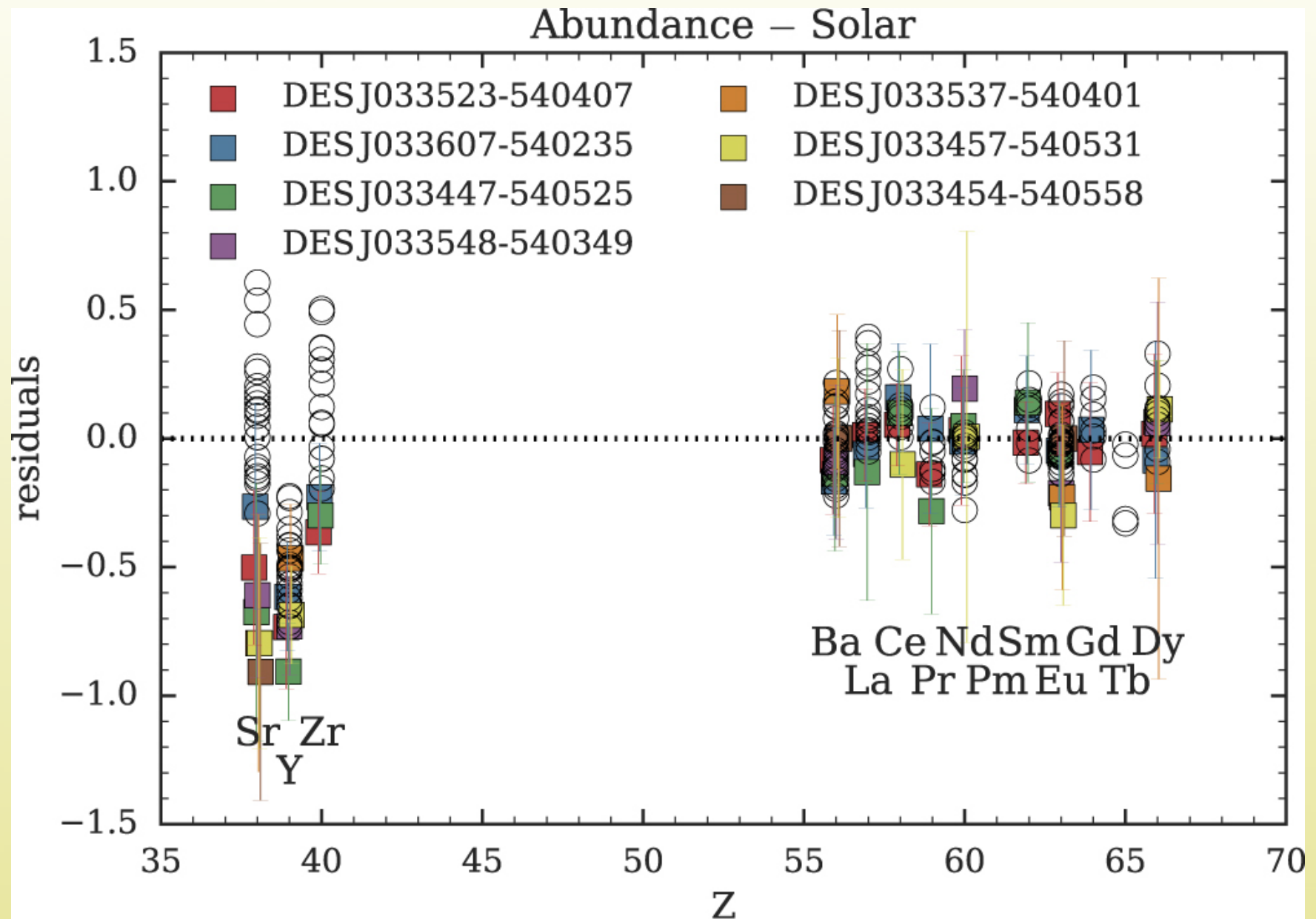
More likely explanation: variable initial production ratios

The Pure *r*-process Pattern in Ret II



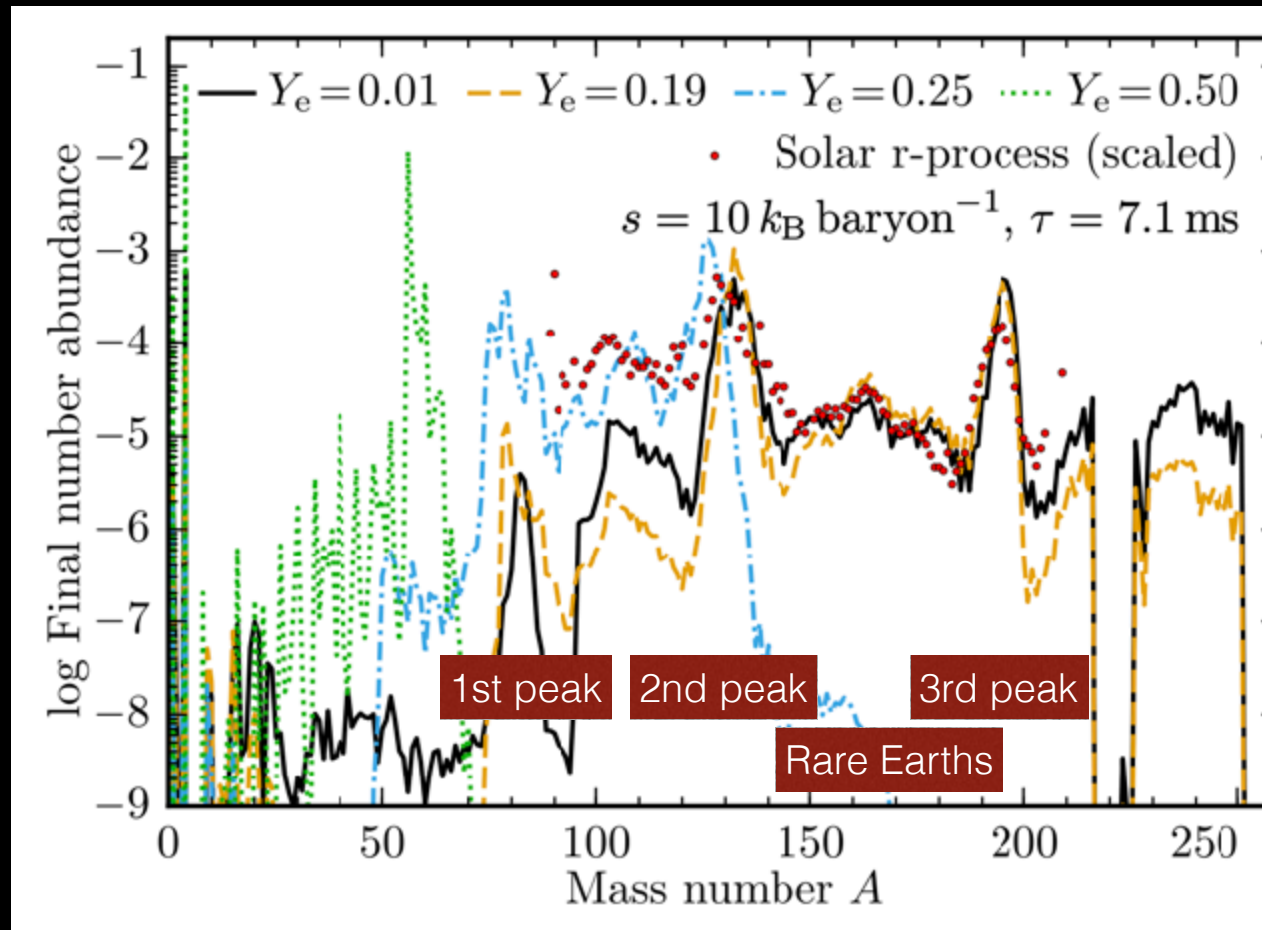
1ST PEAK: HUGE DEVIATIONS

2ND/3RD PEAK: ALL GOOD!



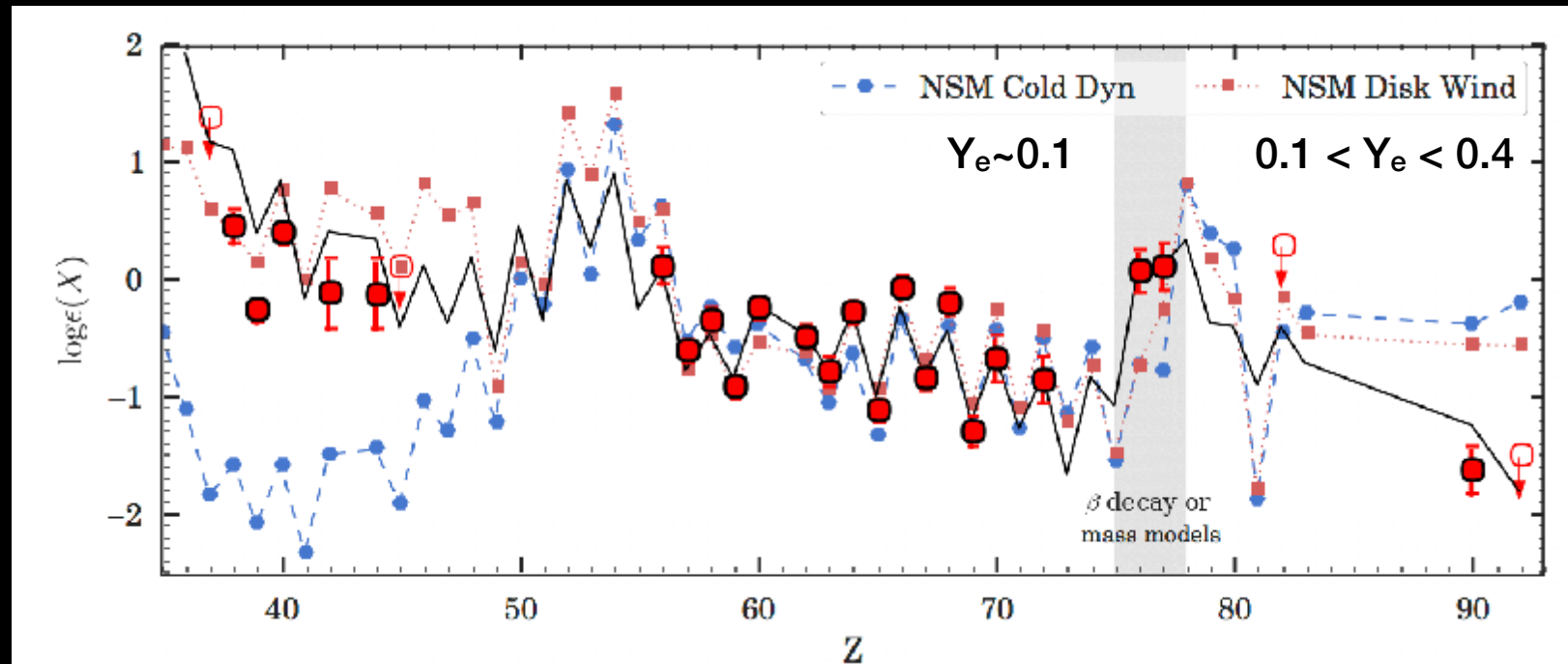
Ejecta Y_e affects element production

$$Y_e = N_e / (N_n + N_p)$$



High Y_e (neutron-poor) \rightarrow 1st peak
Low Y_e (neutron-rich) \rightarrow 2nd + 3rd peak
Critical $Y_e \sim 0.25$

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



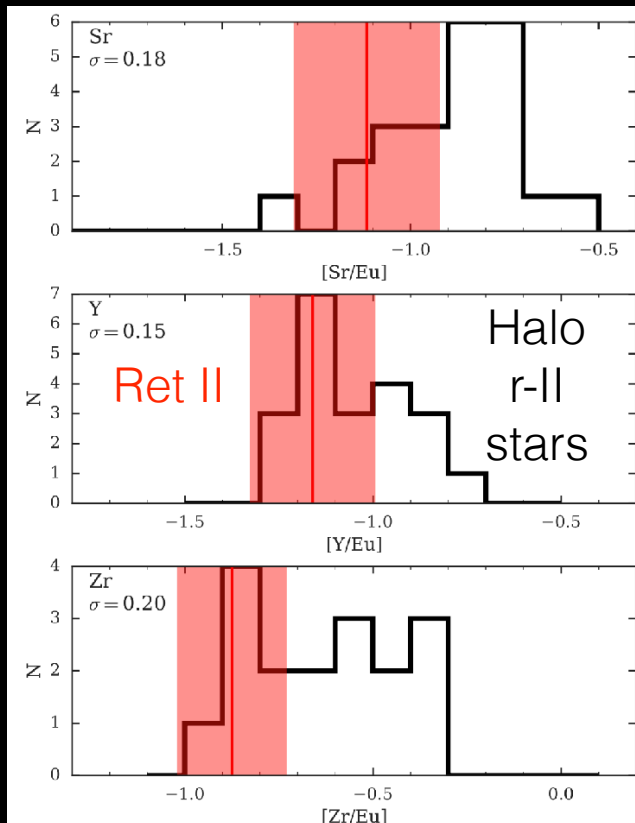
Adding up mass: $M_{\text{n-poor}}/M_{\text{n-rich}} \sim 0.6 \pm 0.1$

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

r-process halo stars show little scatter in Y_e distribution

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

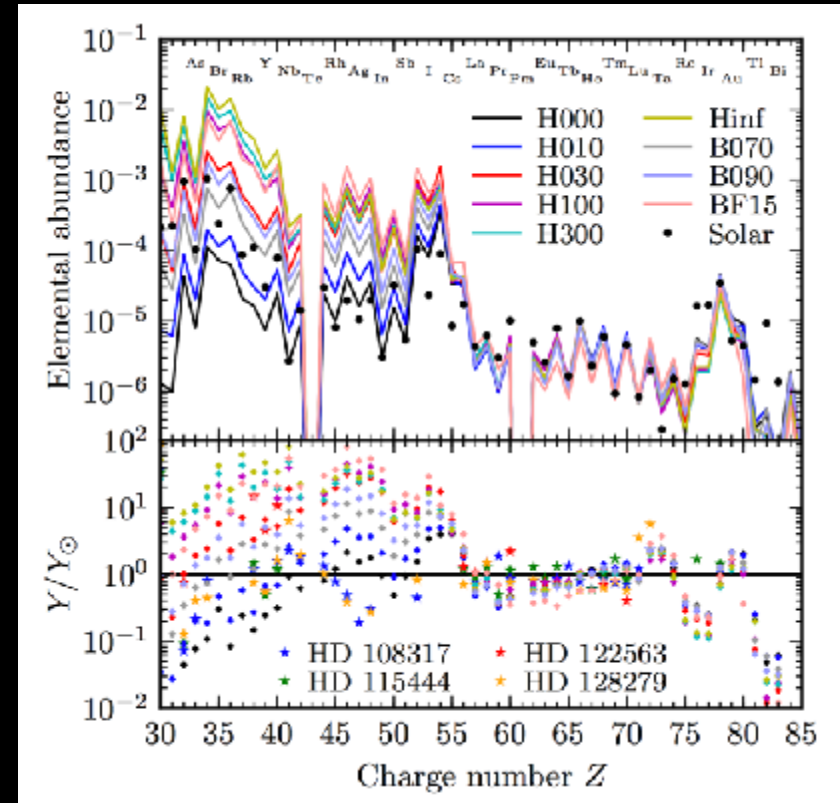
$>10\times$ variation in NSMs



1st peak / Lanthanide

Note: 1st peak in halo stars can be contaminated by CCSNe

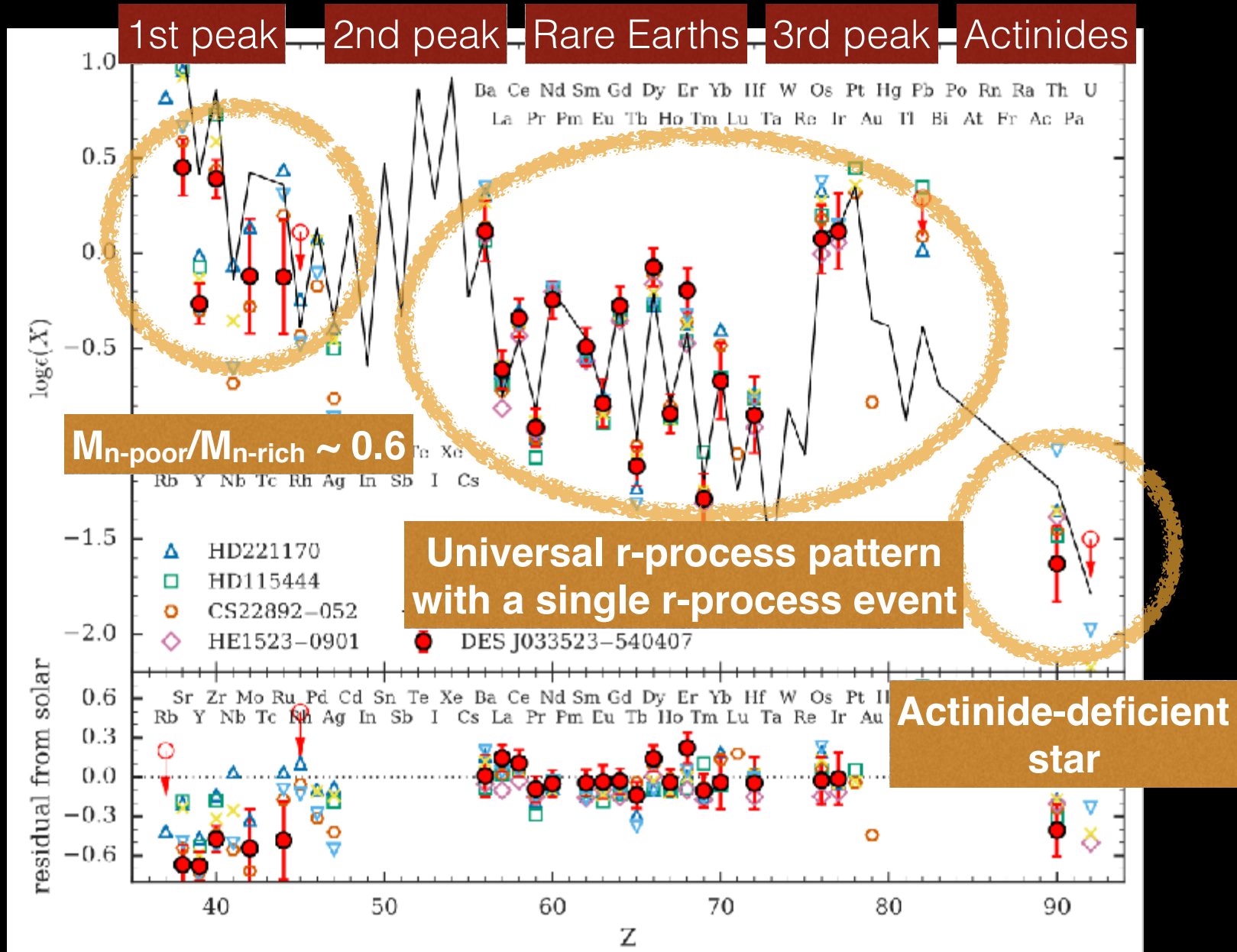
(weak/limited r-process)



Lippuner et al. 2017

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

The Pure *r*-process Pattern in Ret II



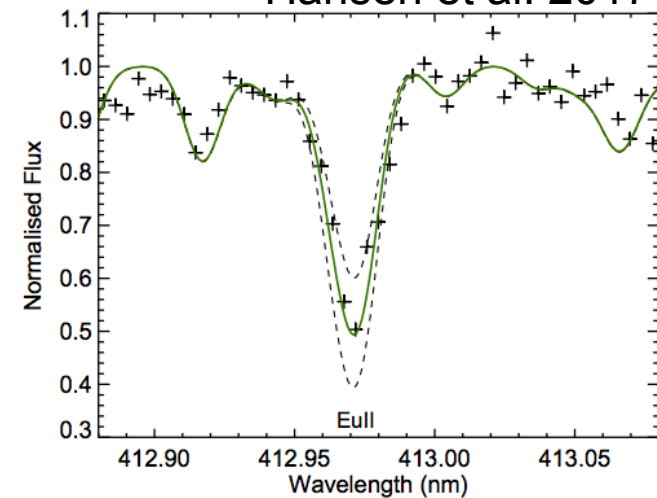
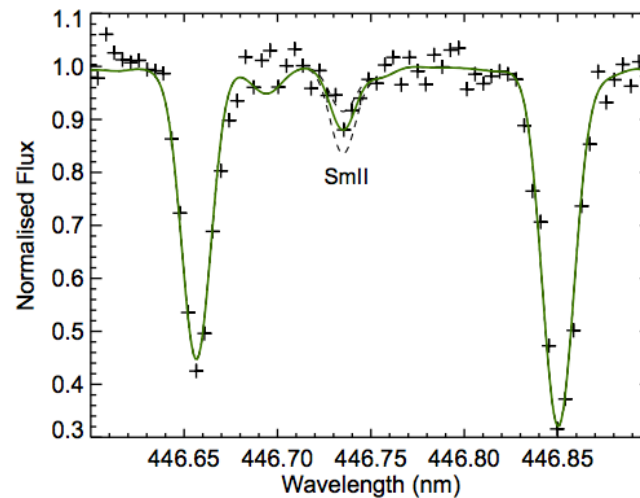
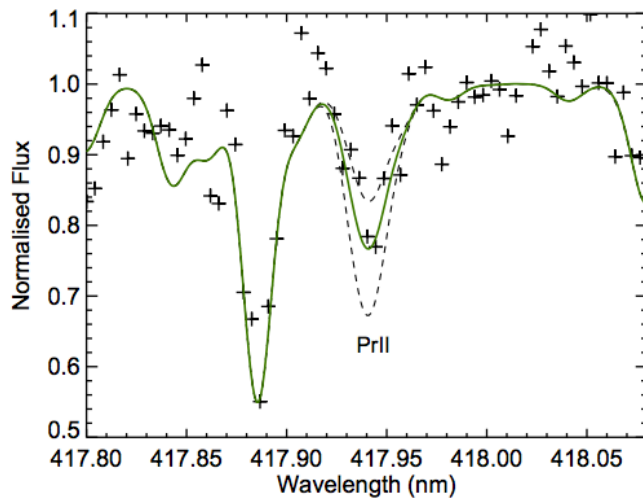
RETICULUM II IS NOT THE ONLY R-PROCESS GALAXY!

Nope!

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

=> 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

$$-2.5 < [\text{Fe}/\text{H}] < -0.8$$

$$0.3 < [\text{Eu}/\text{Fe}] < 1.0$$

13 rII stars in

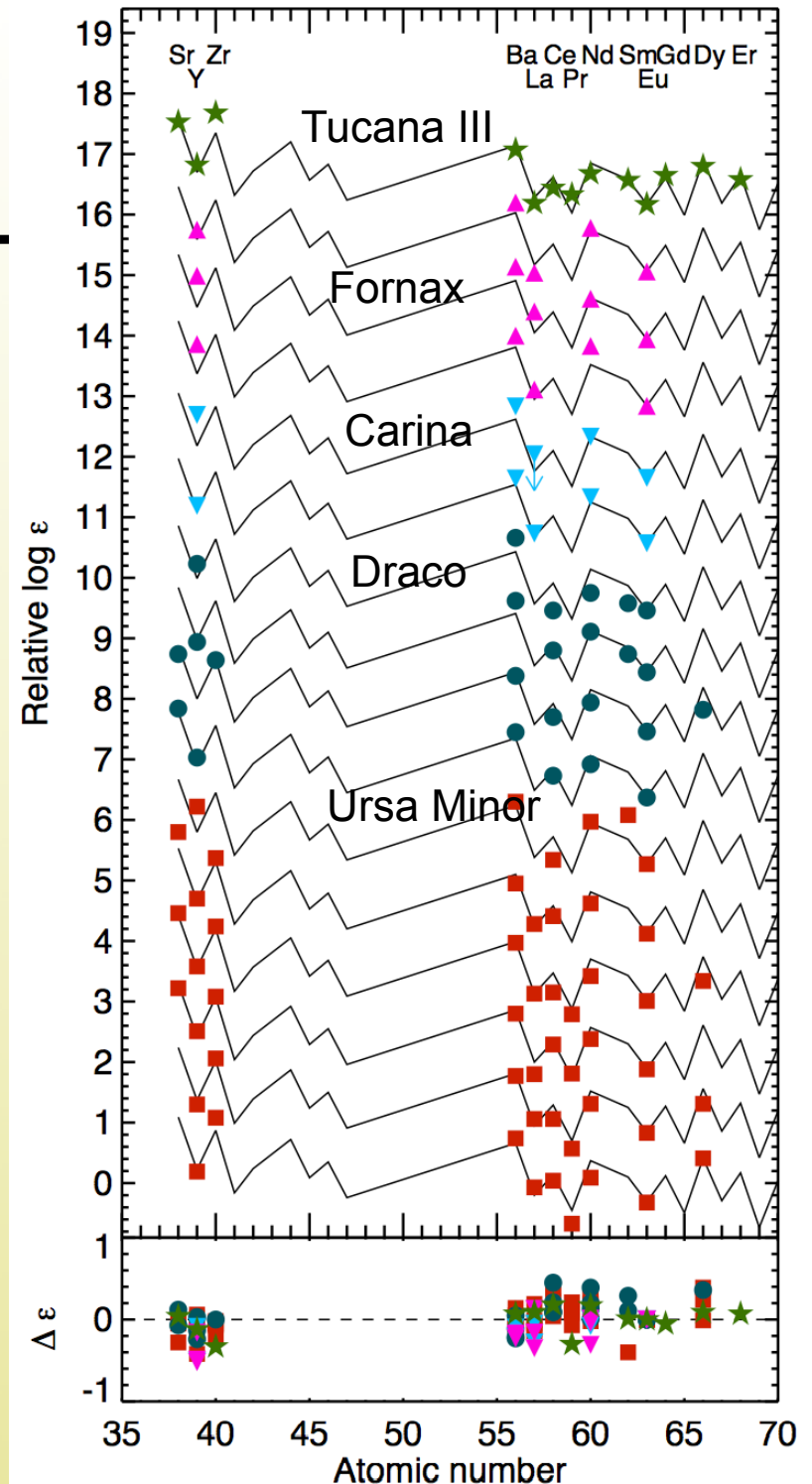
- Reticulum II $-3.0 < [\text{Fe}/\text{H}] < -2.1$
- Ursa Minor $1.0 < [\text{Eu}/\text{Fe}] < 2.1$
- Draco $-2.6 < [\text{Fe}/\text{H}] < -0.8$
- Fornax $1.1 < [\text{Eu}/\text{Fe}] < 1.7$

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 rl/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

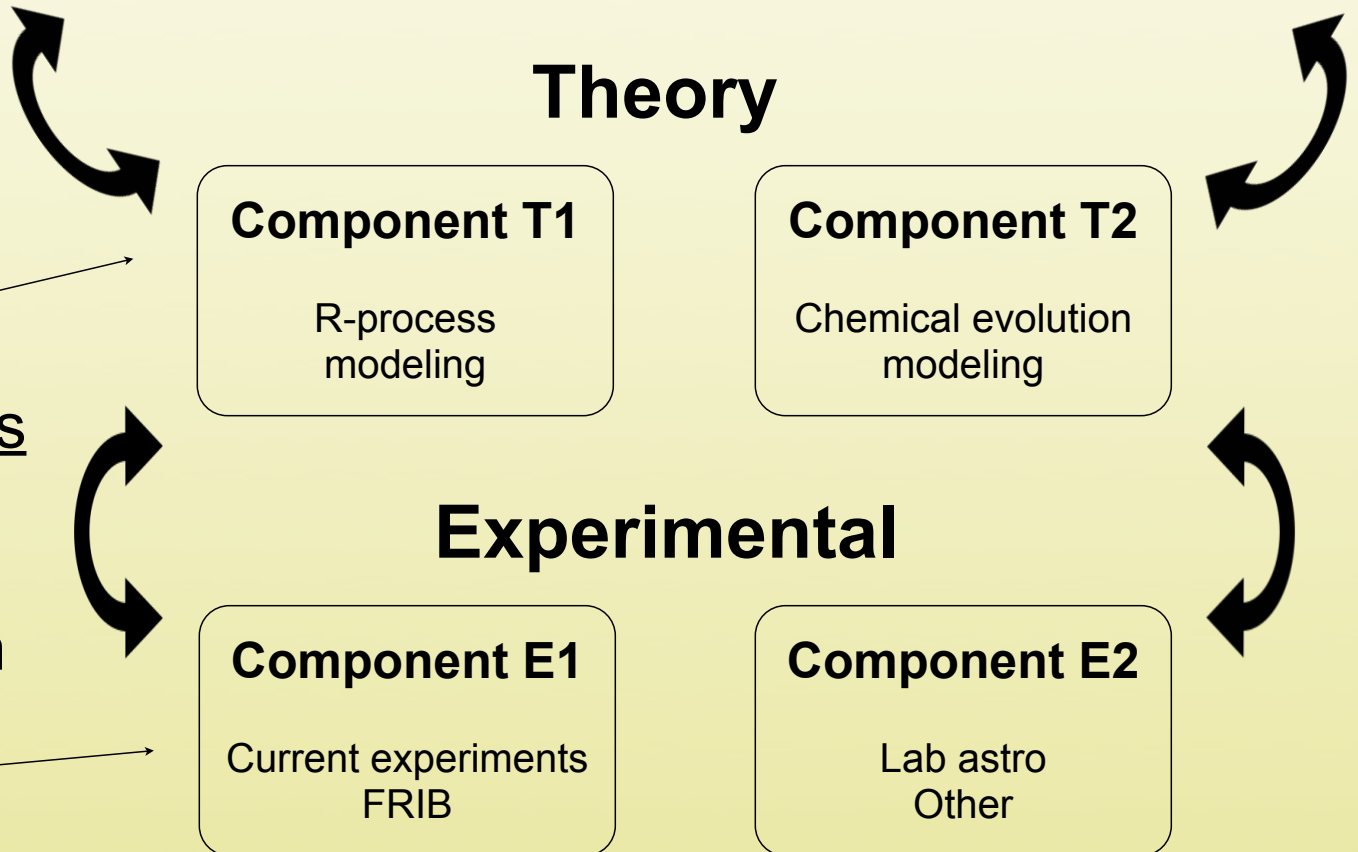
Component T1
R-process modeling

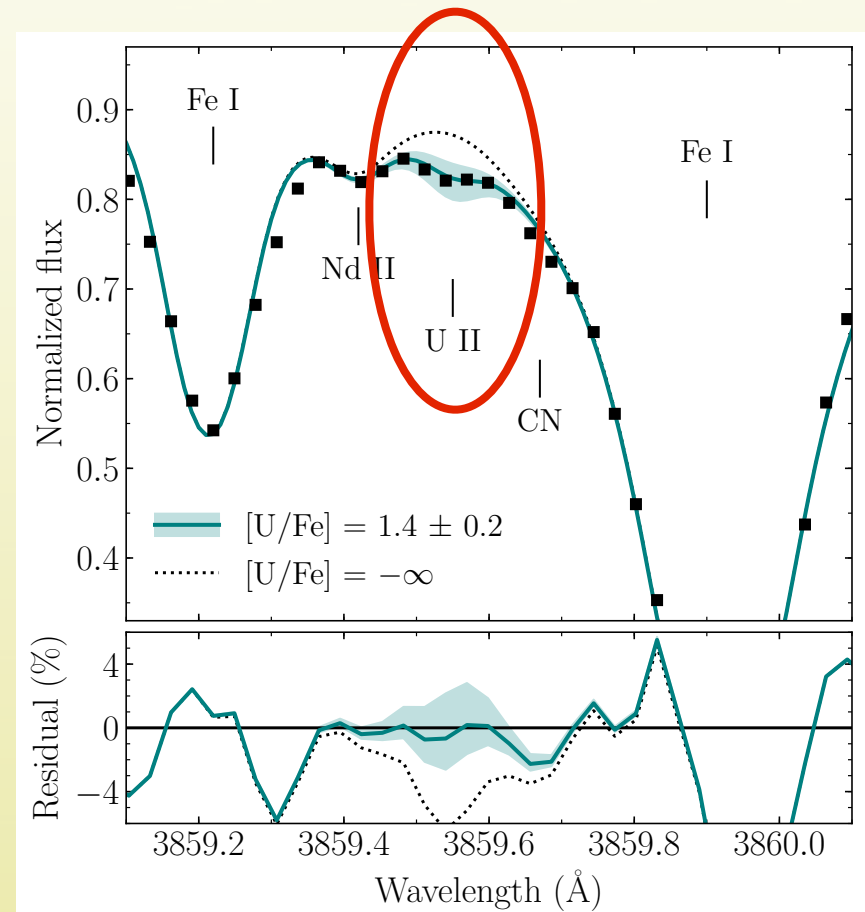
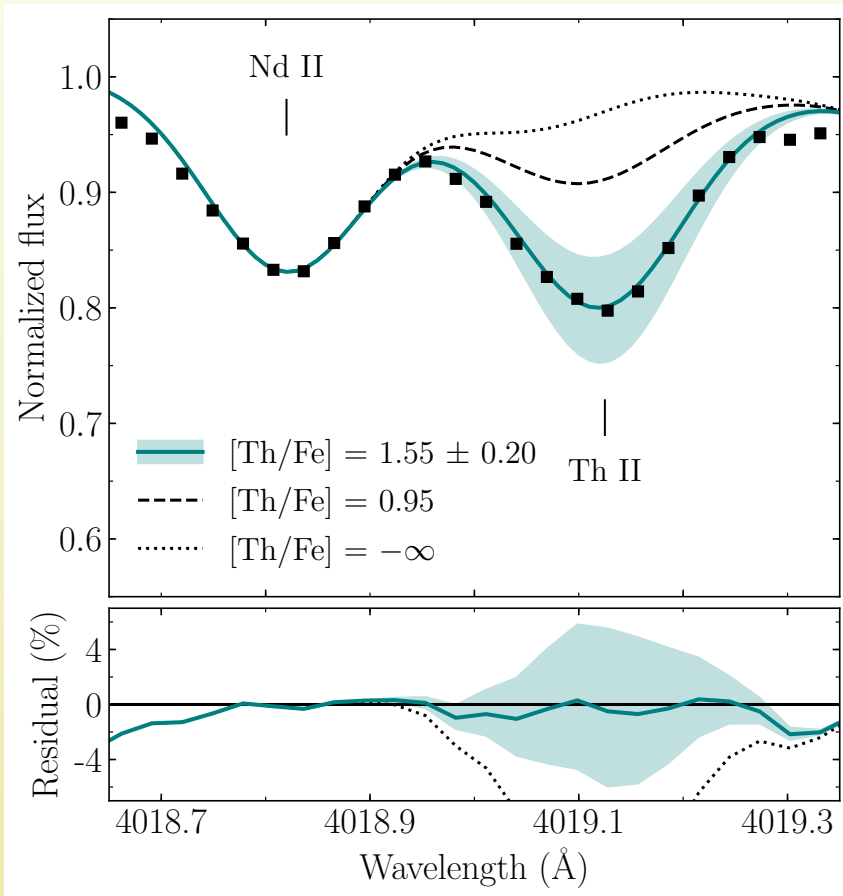
Component T2
Chemical evolution modeling

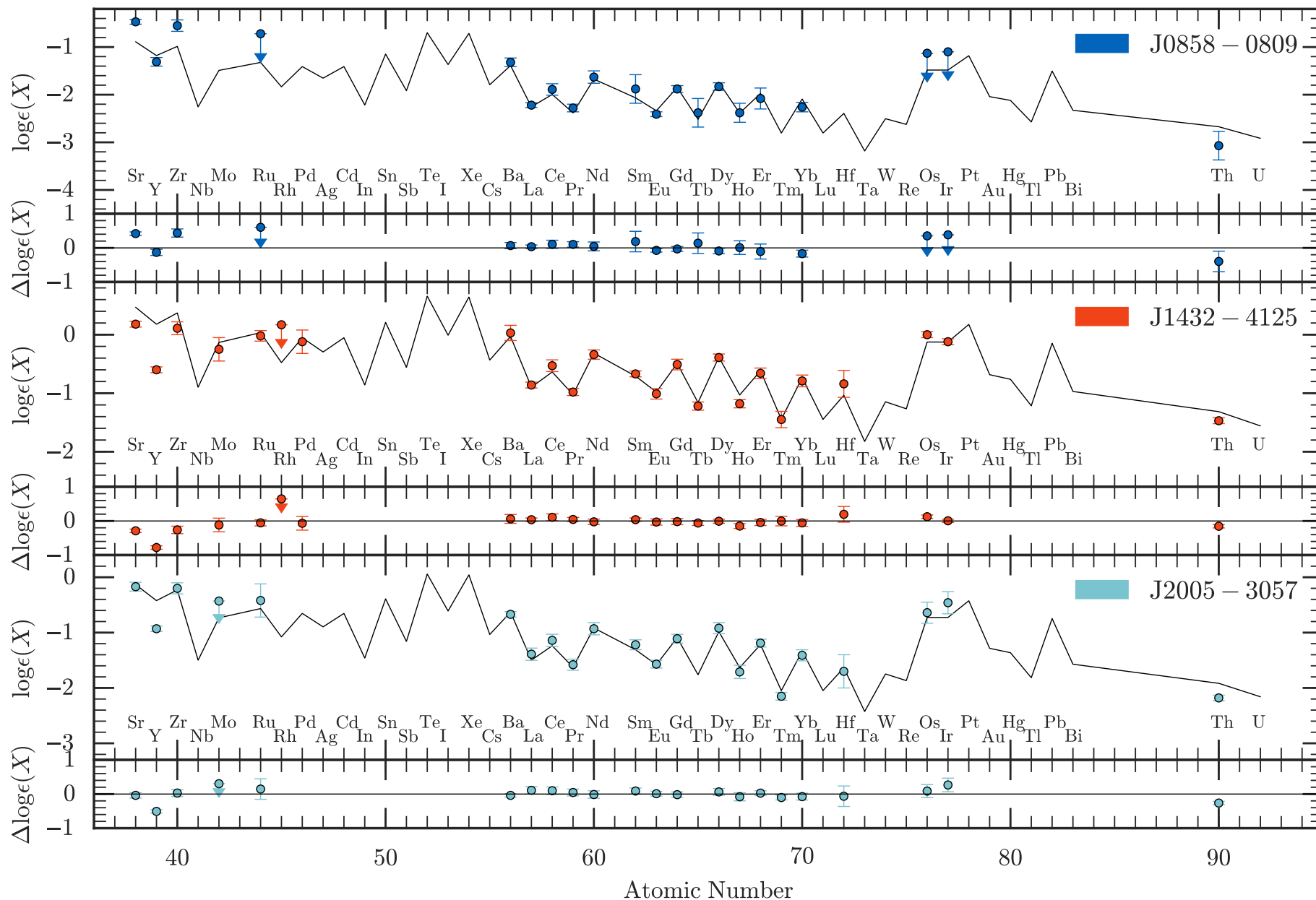
Experimental

Component E1
Current experiments
FRIB

Component E2
Lab astro
Other

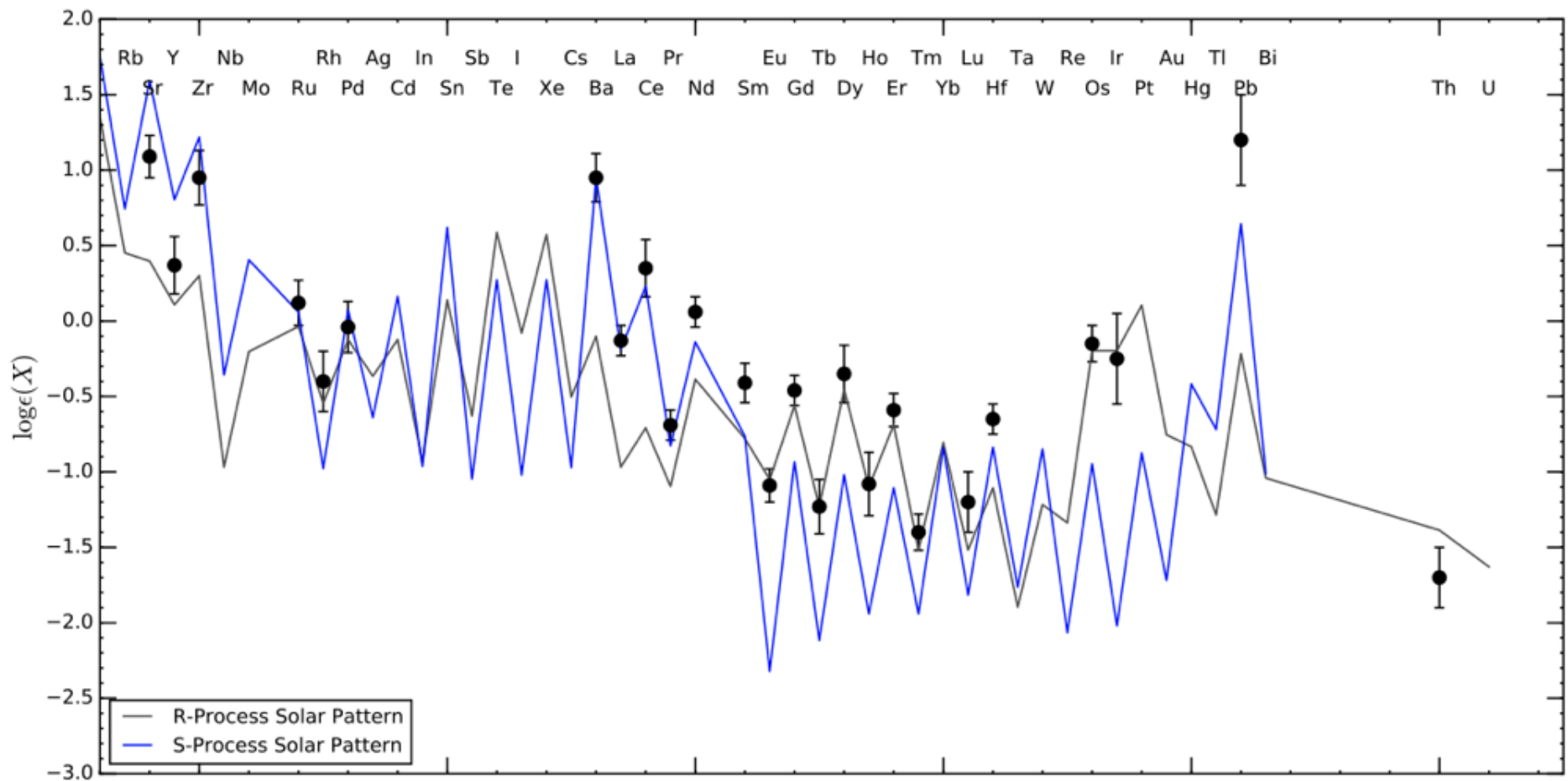


HOLMBECK ET AL:
BRIGHT U STAR

CAIN ET AL:
NEW R-PROCESS STARS

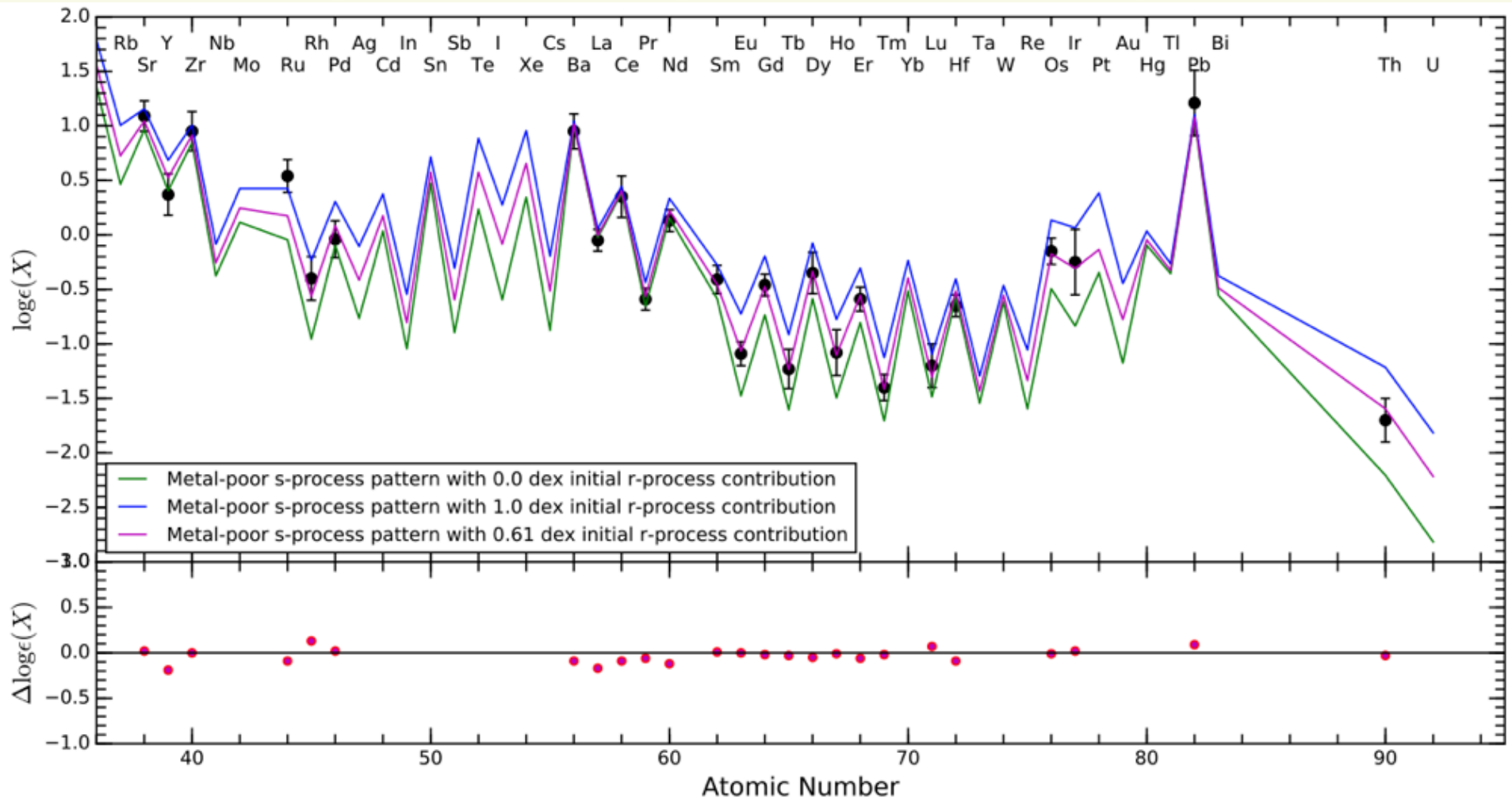
The first true r+s star!

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



The first true r+s star!

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





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



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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) display 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



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<http://jinabase.pythonanywhere.com>

Query JINABase

Choose abundances for your sample and plotting

X-axis / From To
Y-axis / From To
Solar abundances

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

2 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?

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

+ Add criterion

Remove criterion -

Further customize your sample

1 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
☒ t-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 options 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

Year range: From To



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Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

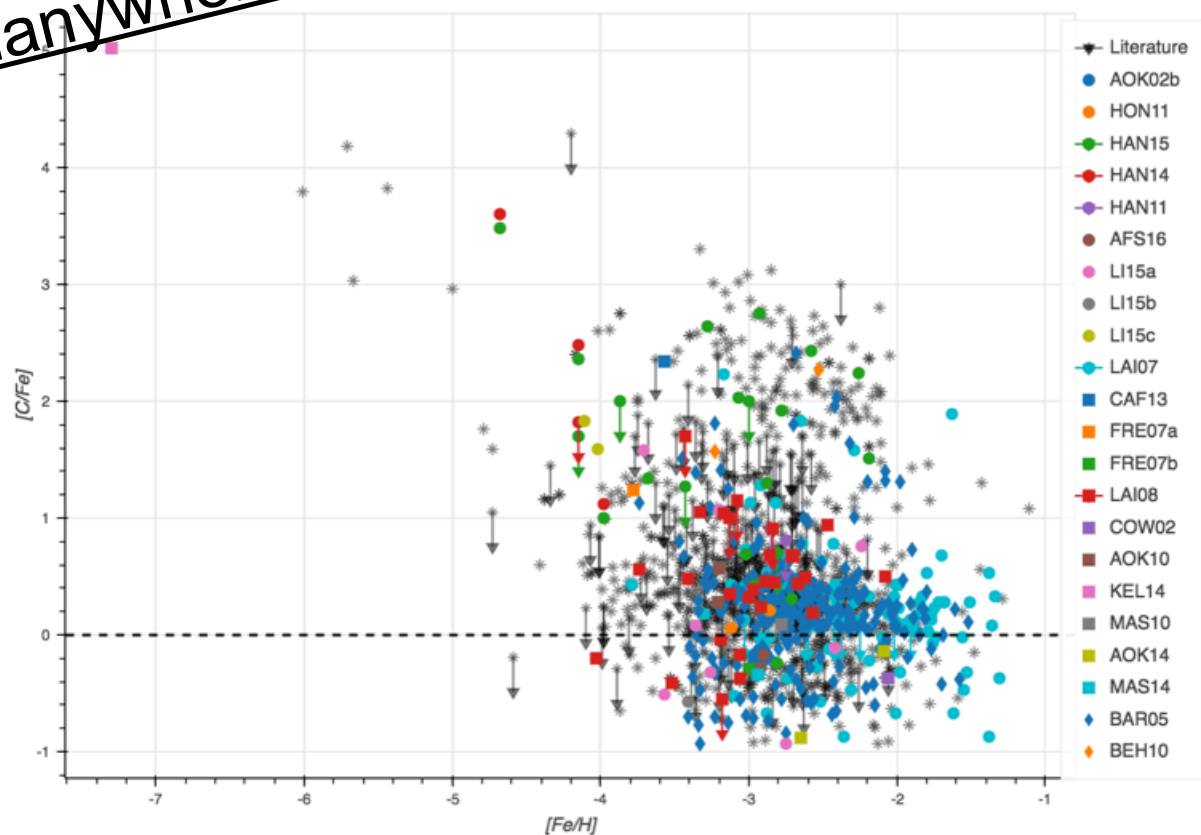
Note: The list of references on the query page will be updated to include only those studies that fulfill your selection criteria.

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.

<http://jinabase.pythonanywhere.com>



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