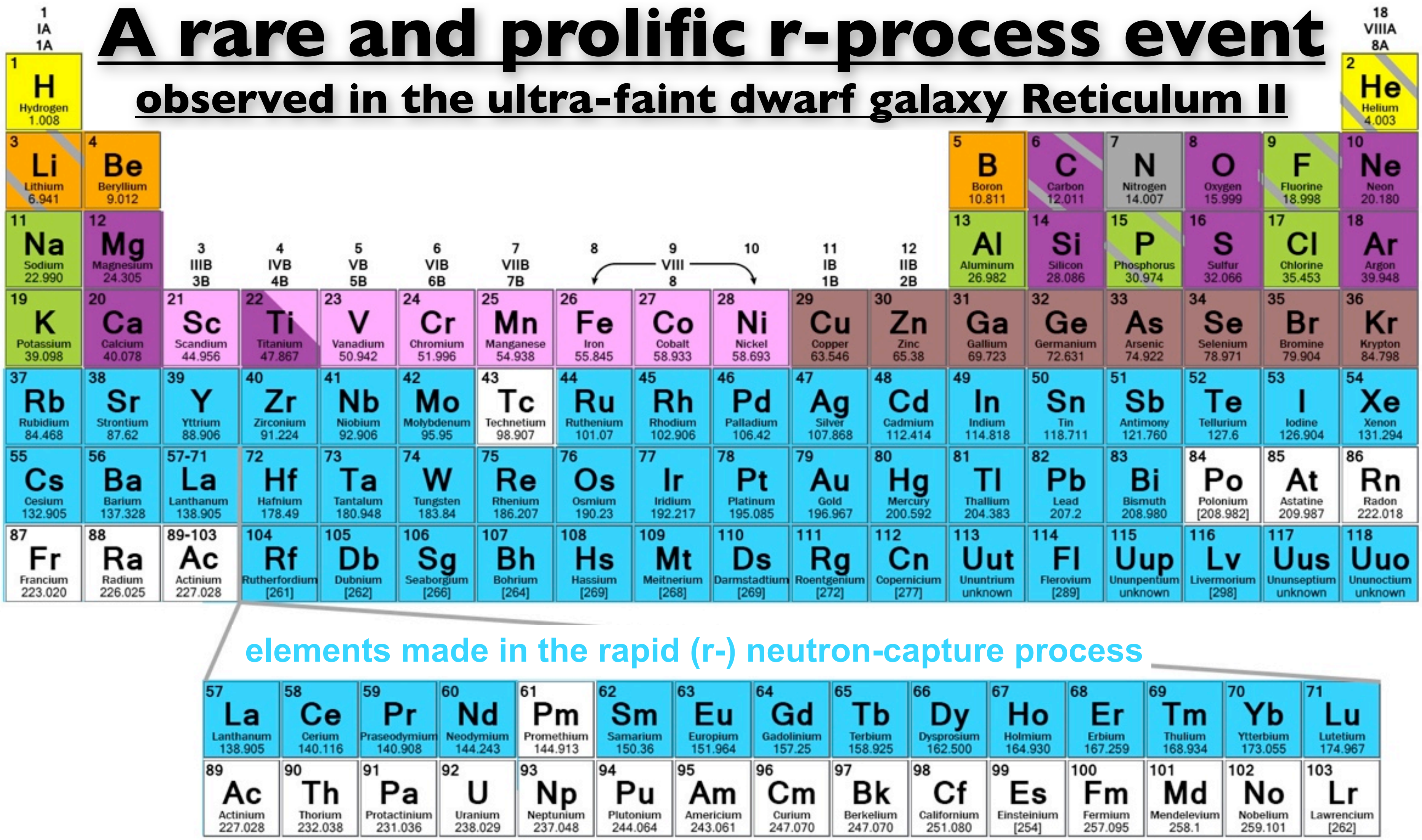
A rare and prolific r-process event

observed in the ultra-faint dwarf galaxy Reticulum II



Anna Frebel

Massachusetts Institute of Technology

The Story of Reticulum II

Nuclear Astrophysics

Cosmic origin of the chemical elements

Stellar Archaeology

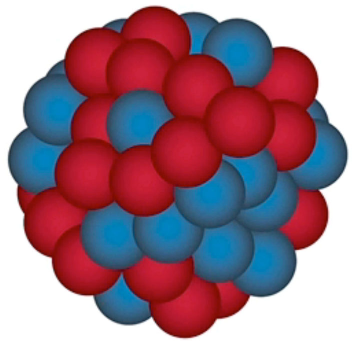
Clues to the astrophysical site of r-process nucleosynthesis

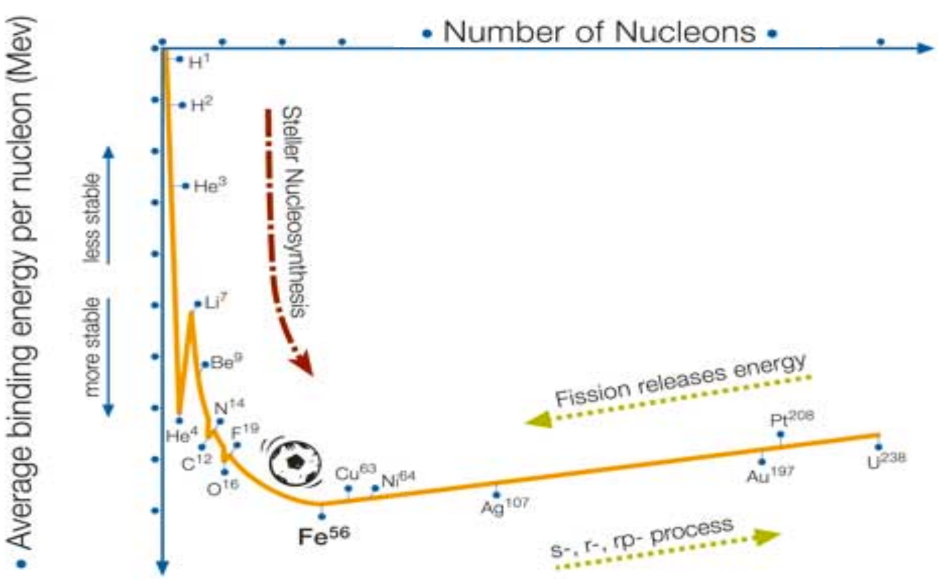
Dwarf Galaxy Archaeology

Ancient, clean chemical enrichment signatures

NUCLEOSYNTHESIS IN STARS

(Depends on stellar mass, stellar evolutionary status, others...)



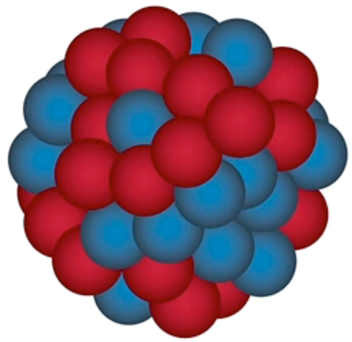


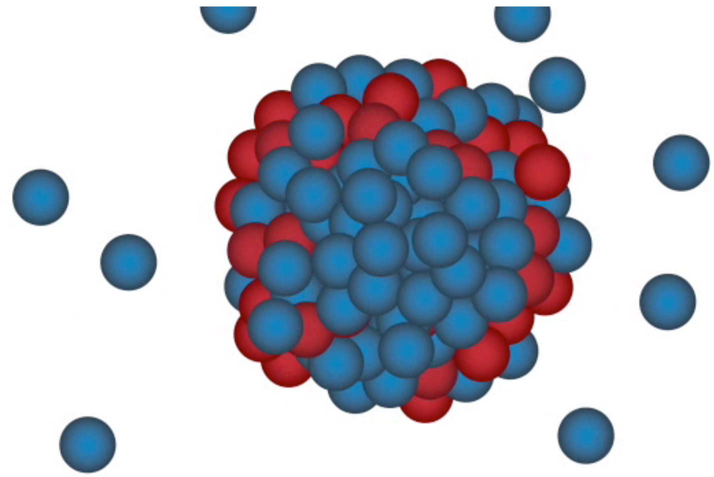
Fusion: H to iron

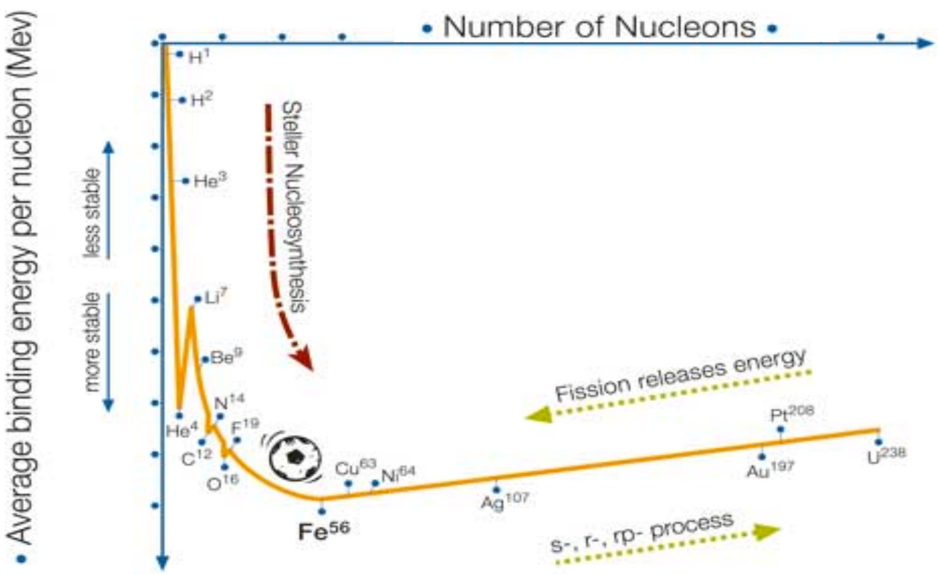
during stellar evolution

NUCLEOSYNTHESIS IN STARS

(Depends on stellar mass, stellar evolutionary status, others...)







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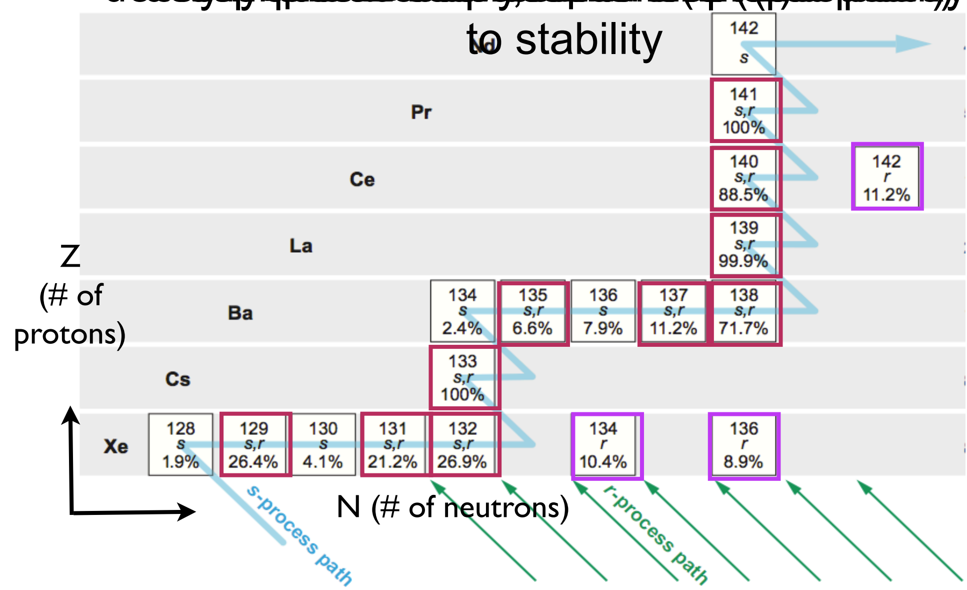


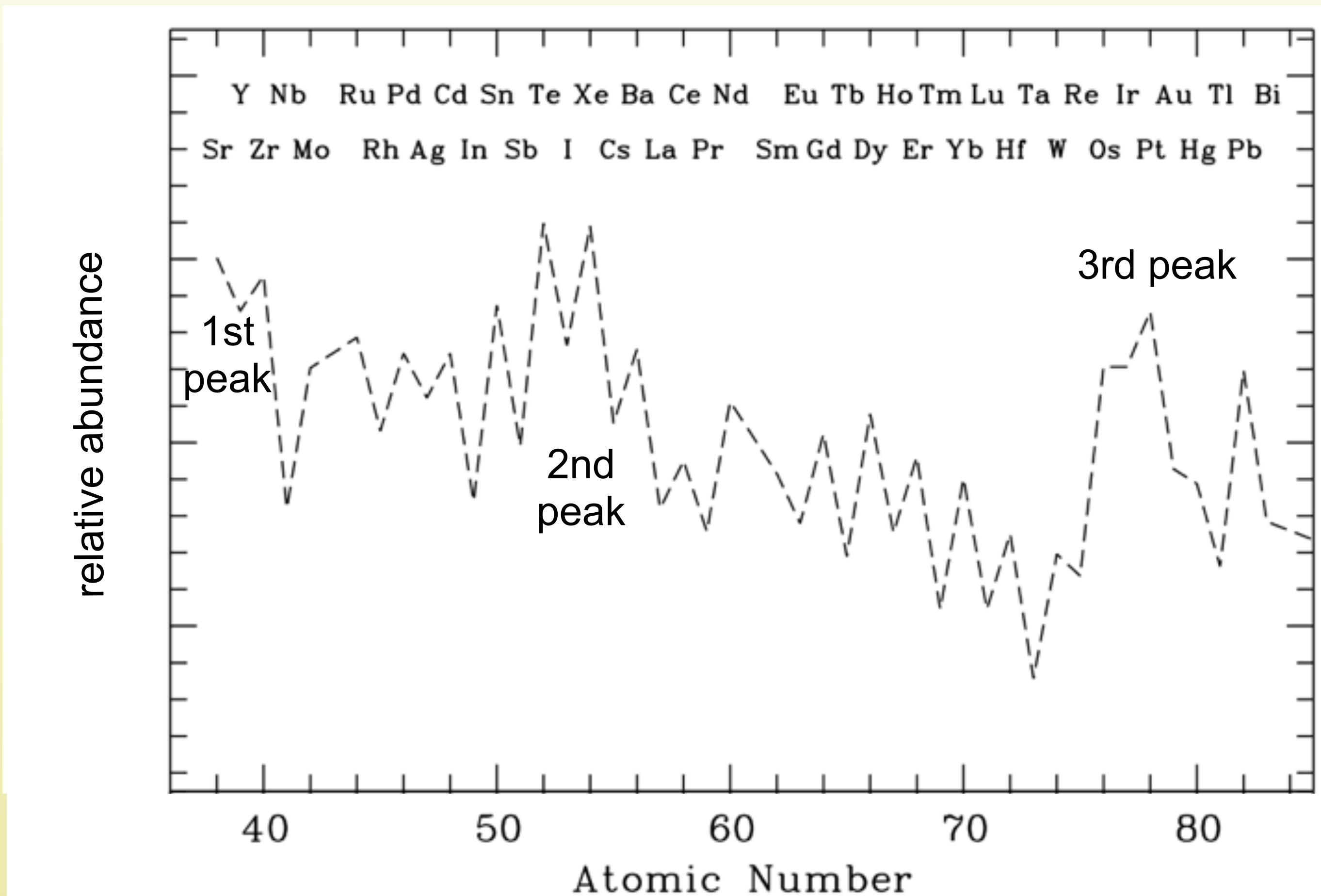
Neutron-capture processes

slow n-capture: advanced stellar evolution

rapid n-capture: site undetermined(!)

R-PROCESS PATTERN

neutron-capture r-process elemental pattern

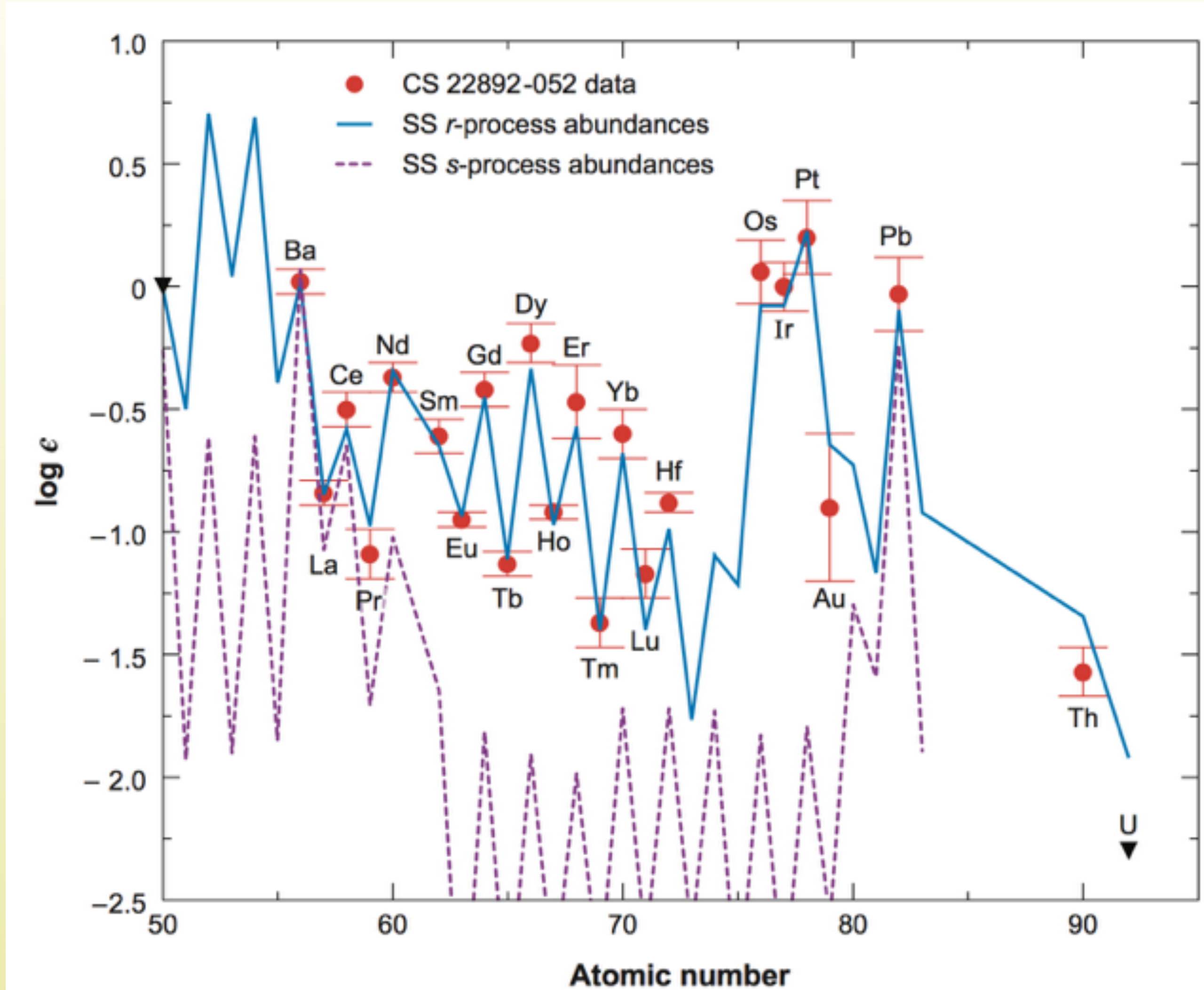


Universal r-process pattern observed in metal-poor stars

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

and rare: Only **~30 stars known** so far w/ [Eu/Fe] > 1.0; i.e. clear r-process pattern above Ba



=> Origin of these stars is unknown!

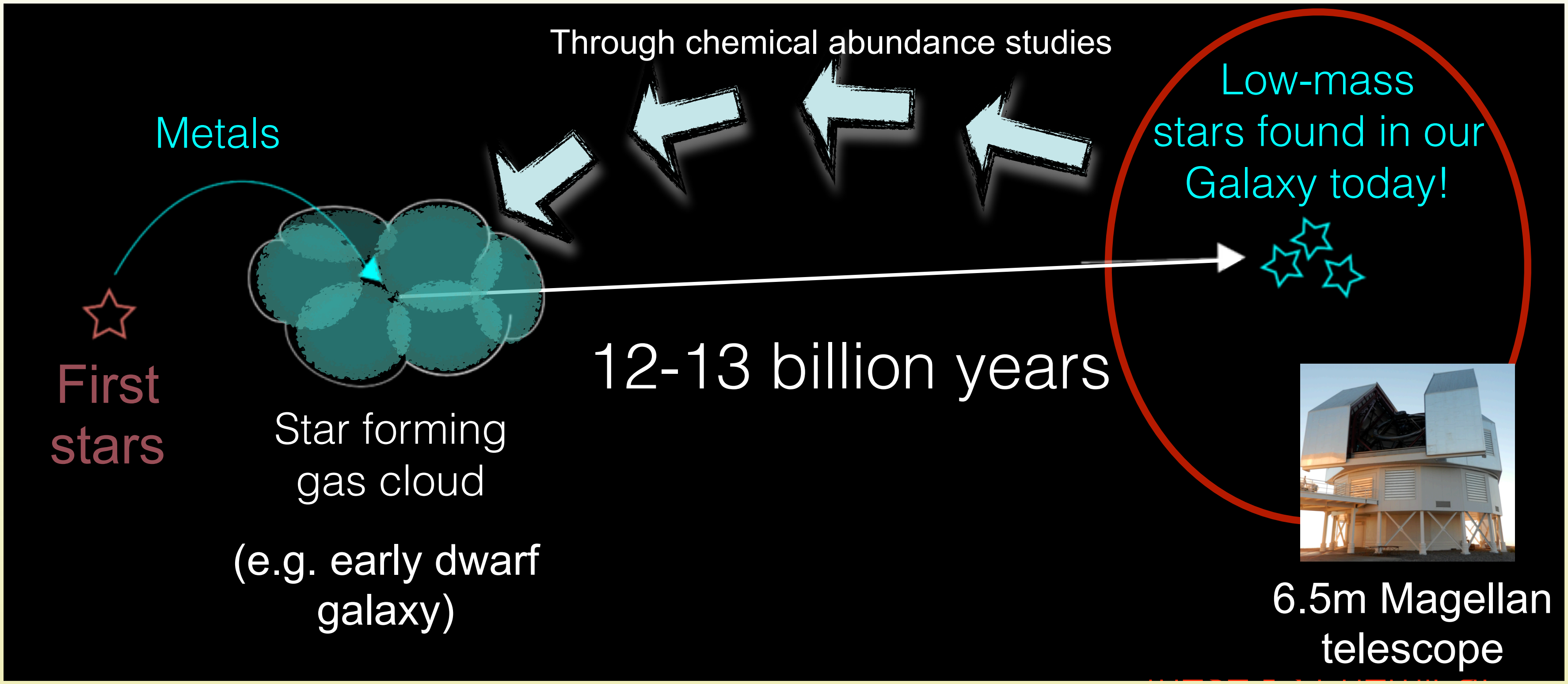
Sneden et al. 2008

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

STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

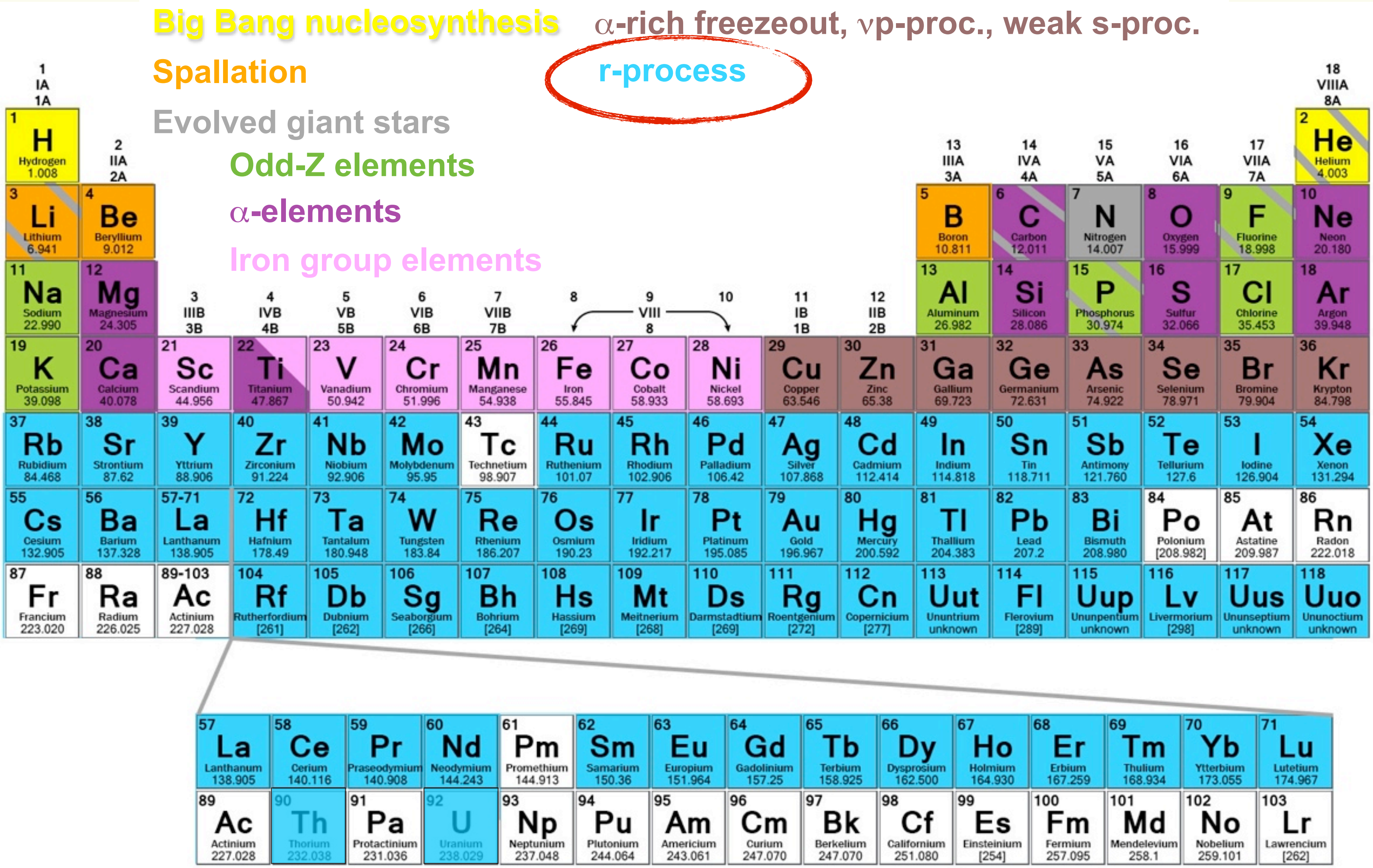
Low-mass stars with M < 1 $M_\odot$: Lifetimes > 10 billion years => they are still around!



[Fe/H] ≤ –3 (= 1/1000th of solar Fe) => only ~1 progenitor star produced that iron
=> only ~1 nucleosynthesis event made heavier elements

Galactic metal-poor stars are a great tool for near-field cosmology because they are the local equivalent of the high-redshift Universe!

The (detailed) astronomer's periodic table



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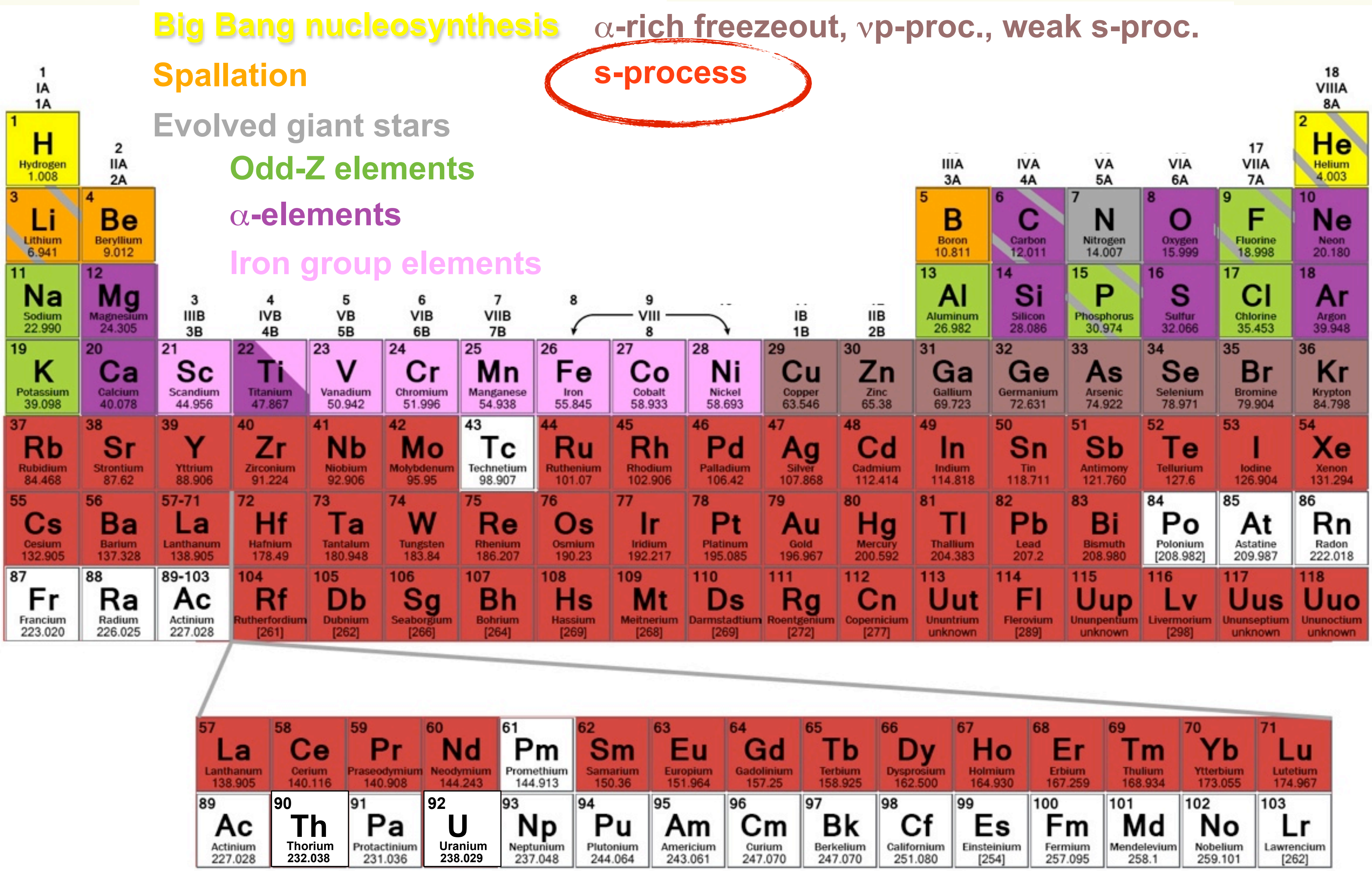
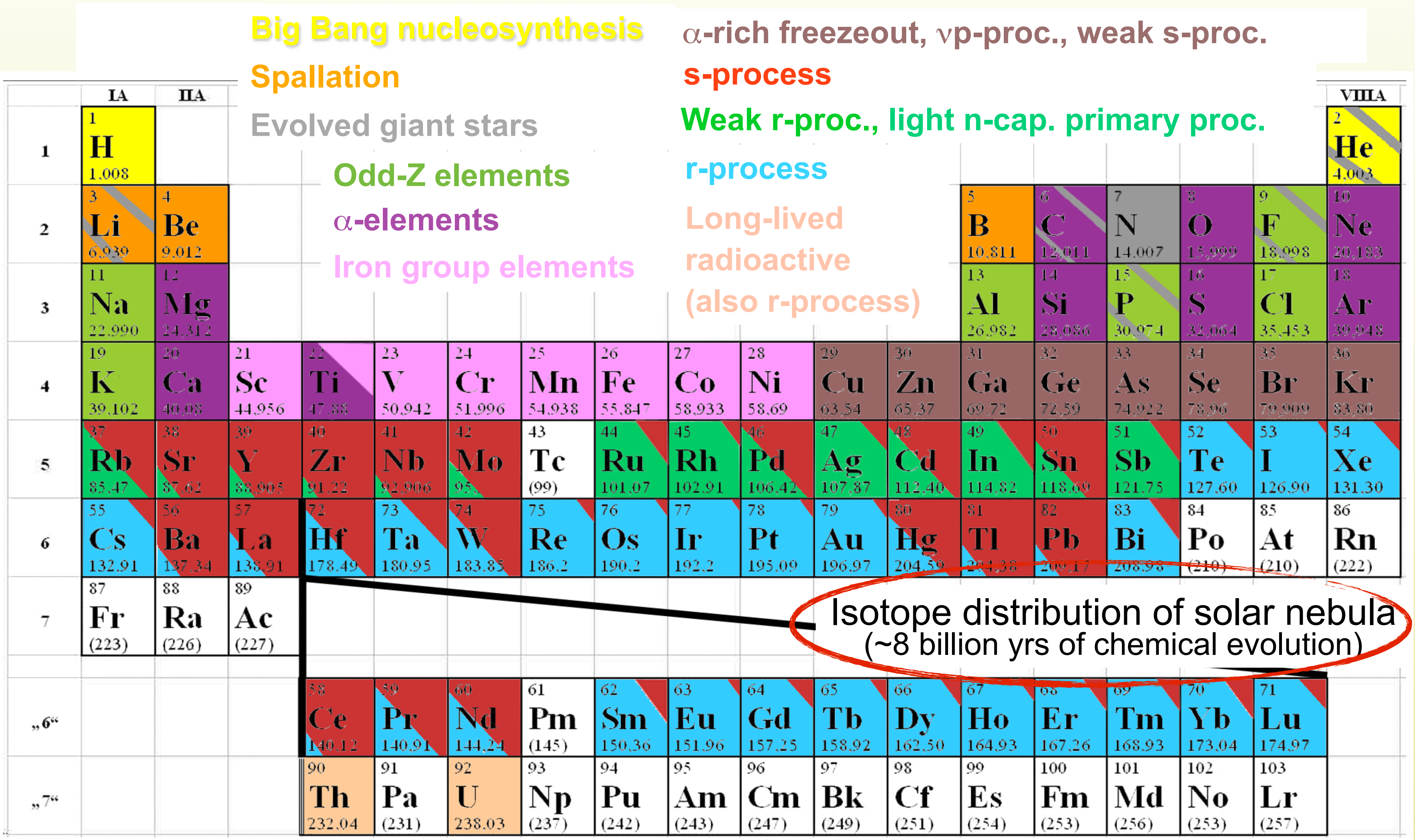


The (detailed) astronomer's periodic table



The Big Question

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

- ➡ Core-collapse supernovae
- ➡ Neutron star mergers
- ➡ Others (e.g., jet-driven supernovae)

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

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

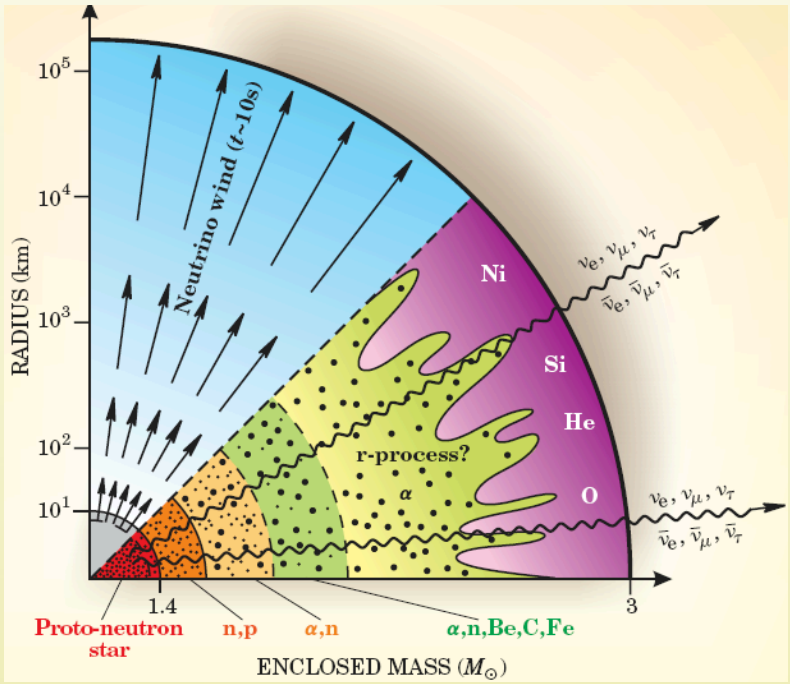
Core-collapse supernova

(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

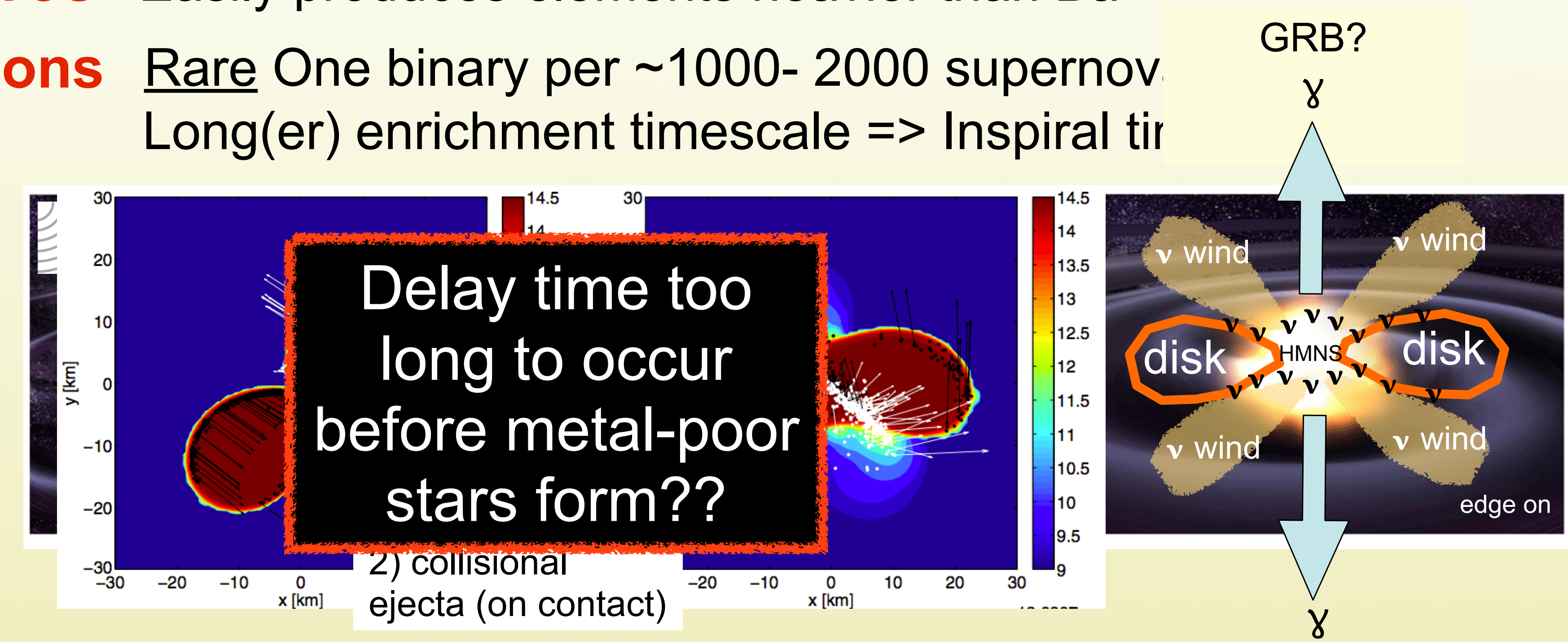
✓Provides the fast enrichment needed; small & steady r-process yields

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 Rare One binary per ~1000- 2000 supernov
Long(er) enrichment timescale => Inspiral tir



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

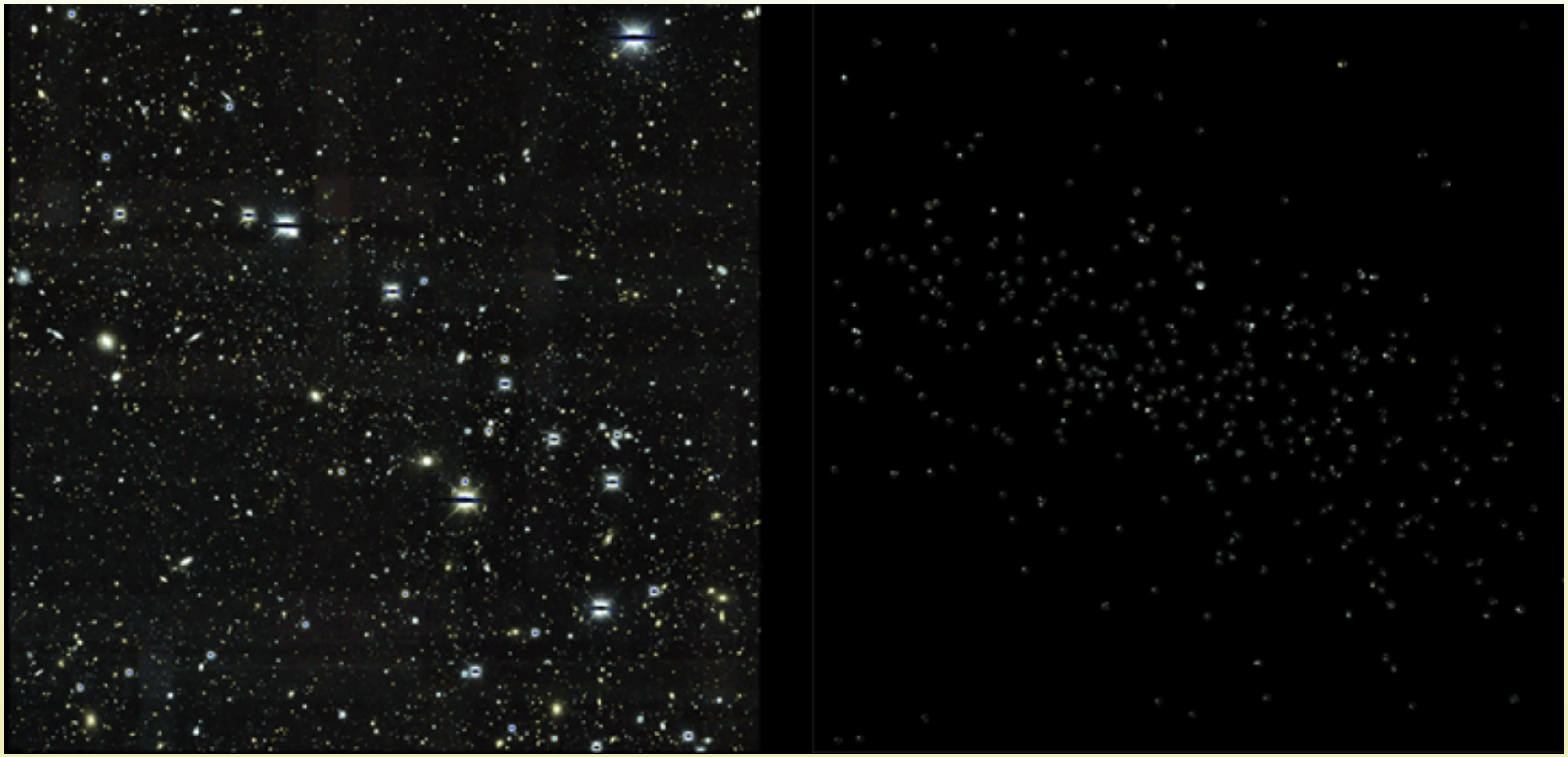
1) Short gamma-ray bursts: Afterglow from decay of radioactive r-process elements detected (Tanvir et al. 13)

2) Radioactive deep sea measurements suggest local neutron star mergers (Wallner et al. 15, Hotokezaka et al.15)

Meet Reticulum II

All stars

Meet Reticulum II



All stars

Reticulum II stars

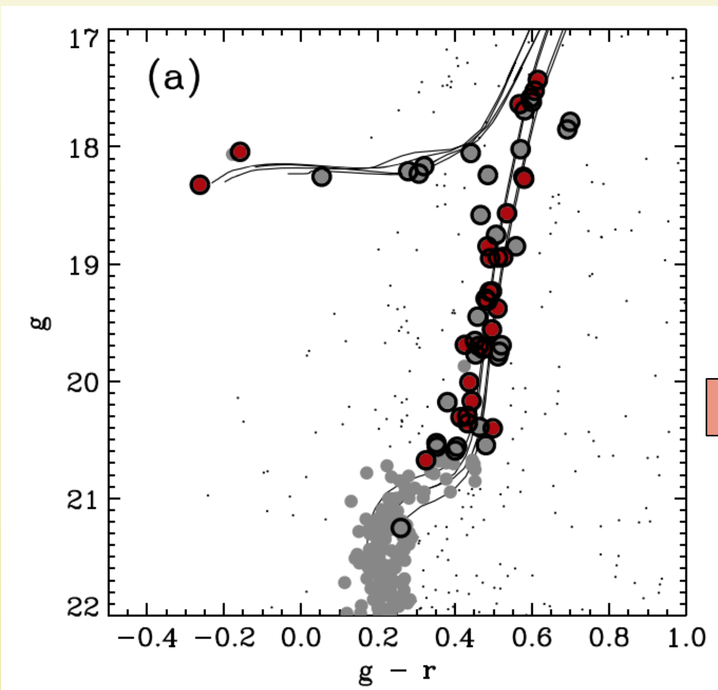
(Dark Energy Survey, 2015)

Magellan observations

Simon et al. 2015: radial velocity members confirm Ret II to be a galaxy

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

=> Ji et al. (2015) spent 2-3 hours on each of 9 brightest targets (~23h)



Color-magnitude-diagram of Ret II
(red = confirmed members)

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

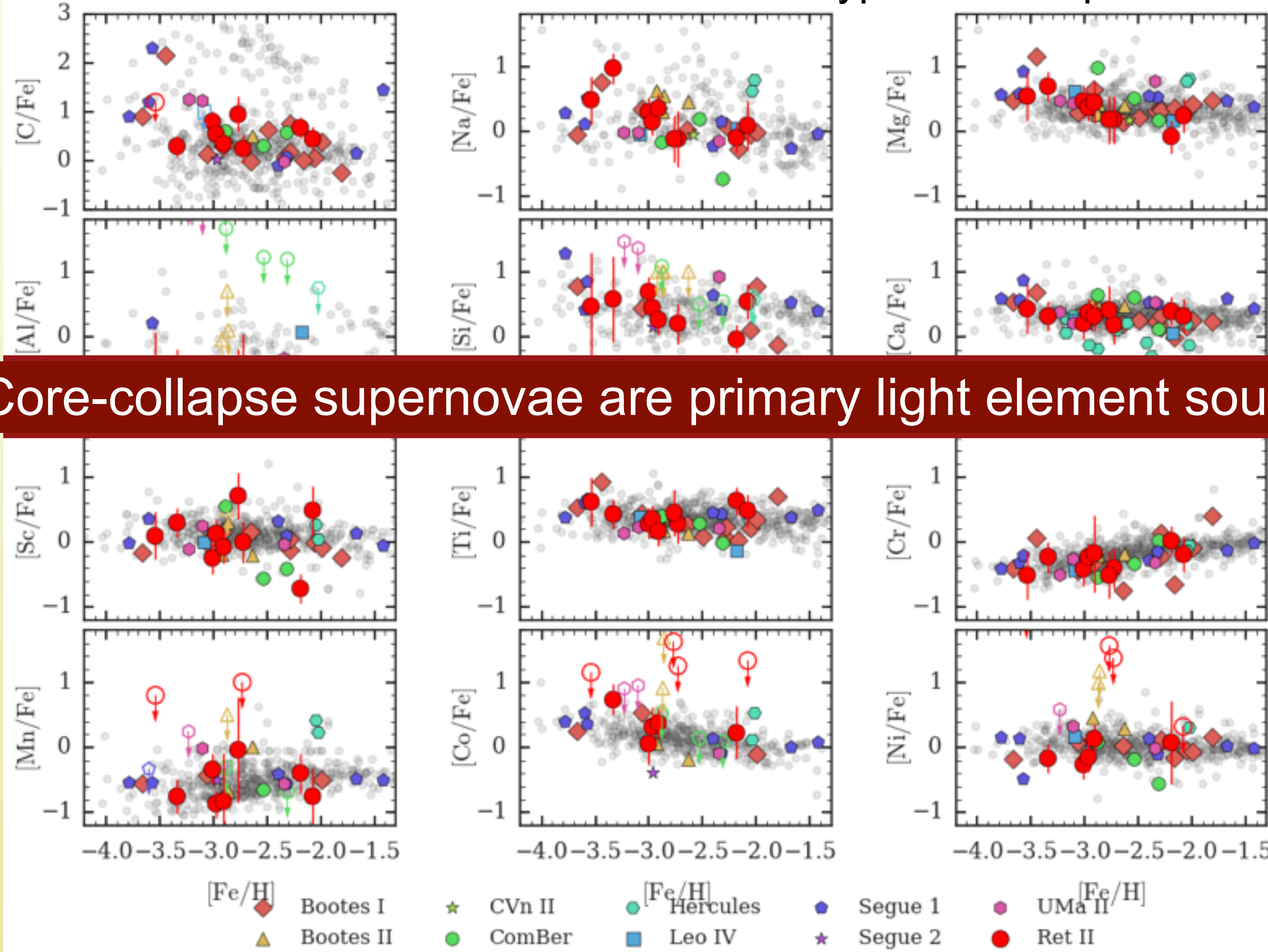
Light element abundances

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

Anna Frebel

R-process galaxy Reticulum II

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



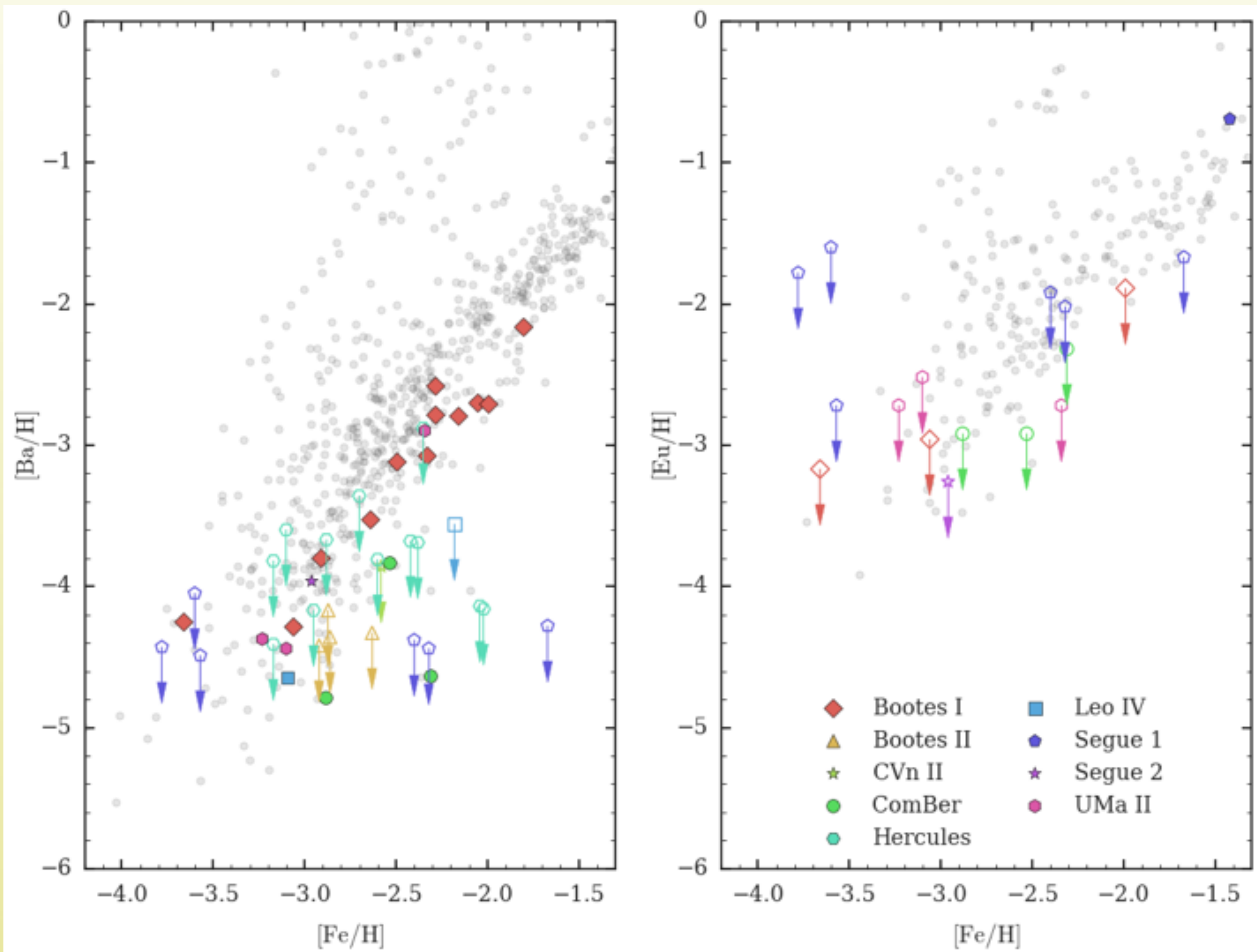
Core-collapse supernovae are primary light element source

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

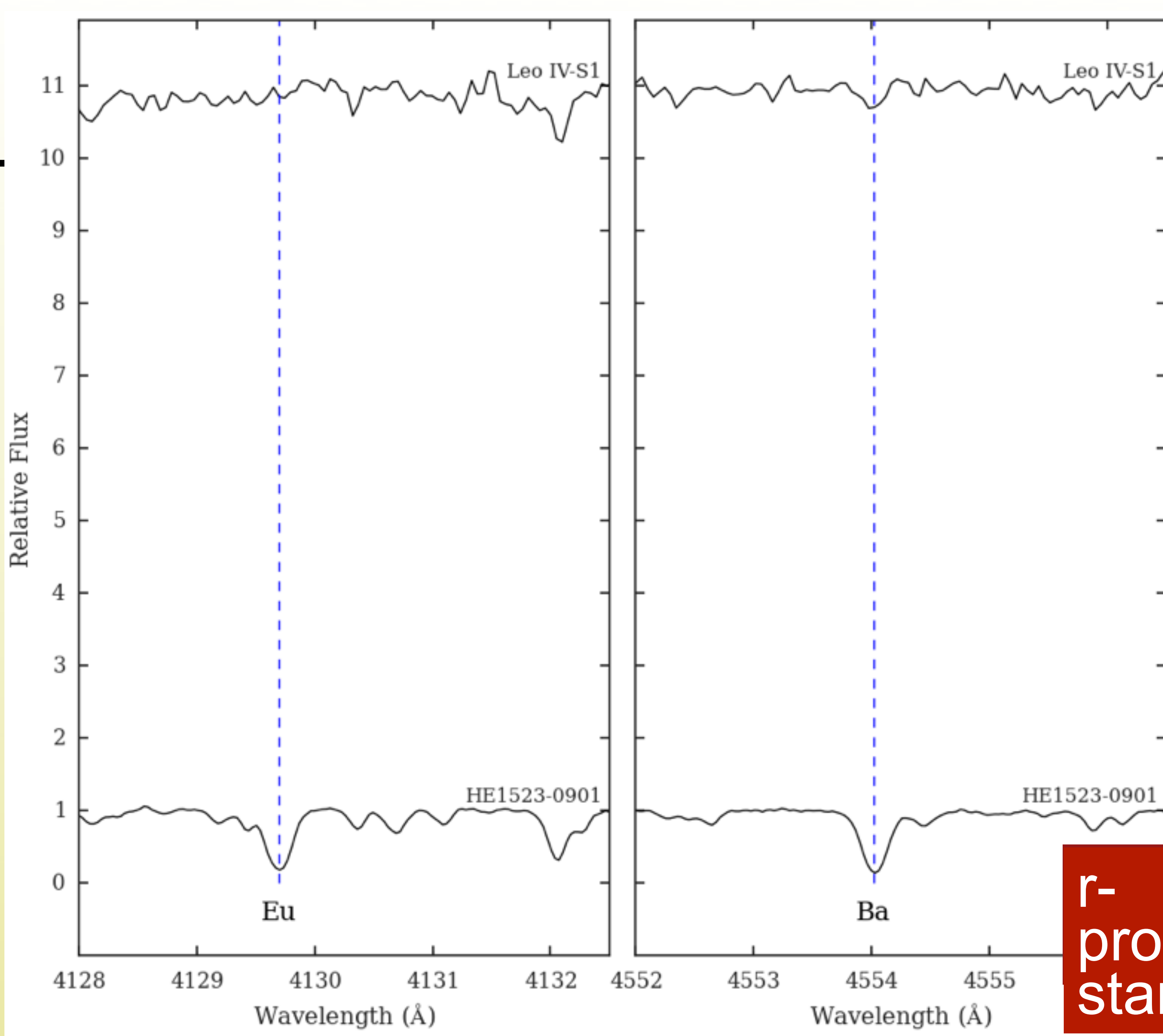
gray dots metal-poor halo stars

NEUTRON-CAPTURE ELEMENT ABUNDANCES (BA AND EU)

The other ten UFDs have
uniquely low neutron-capture element abundances!

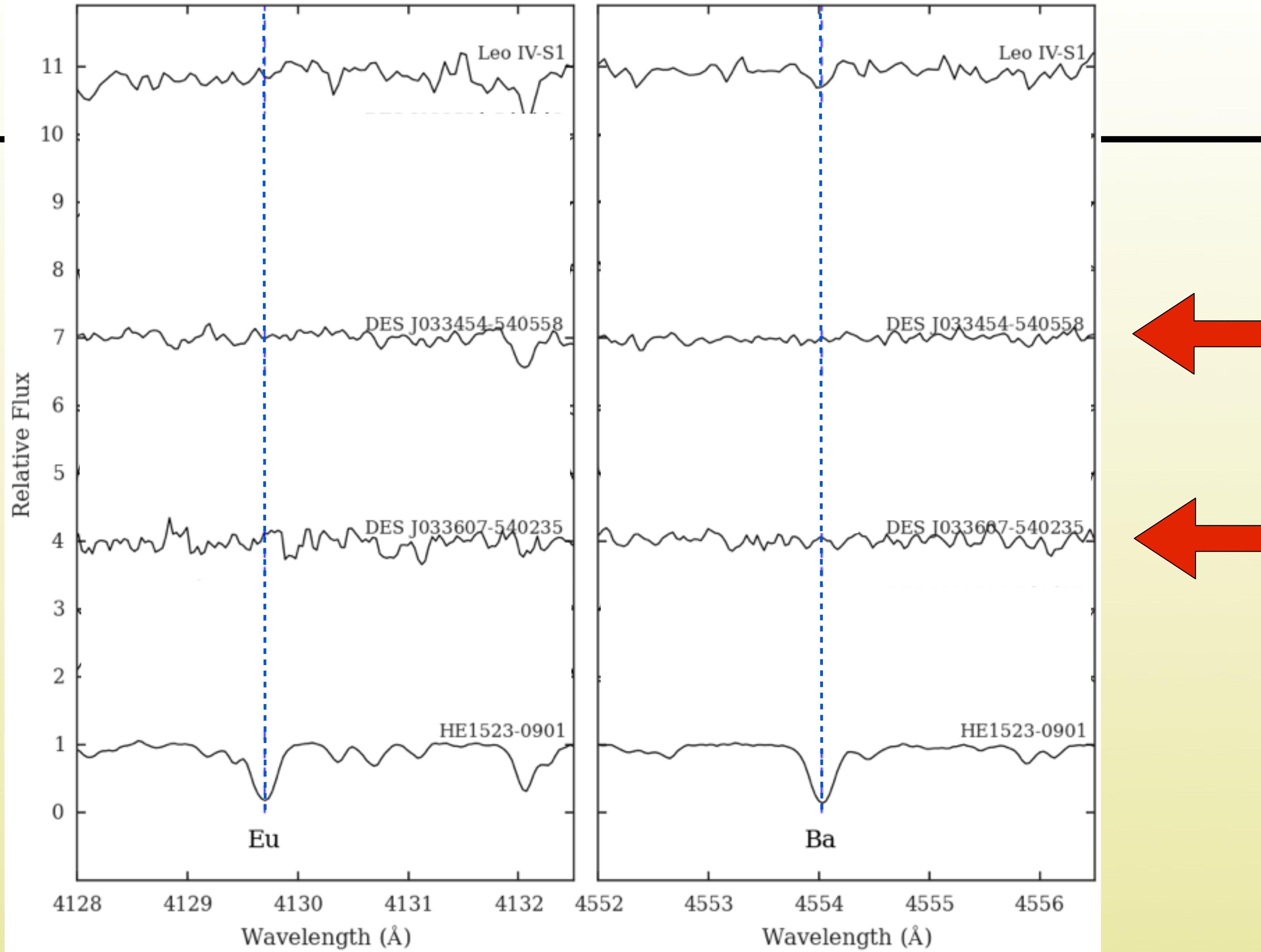


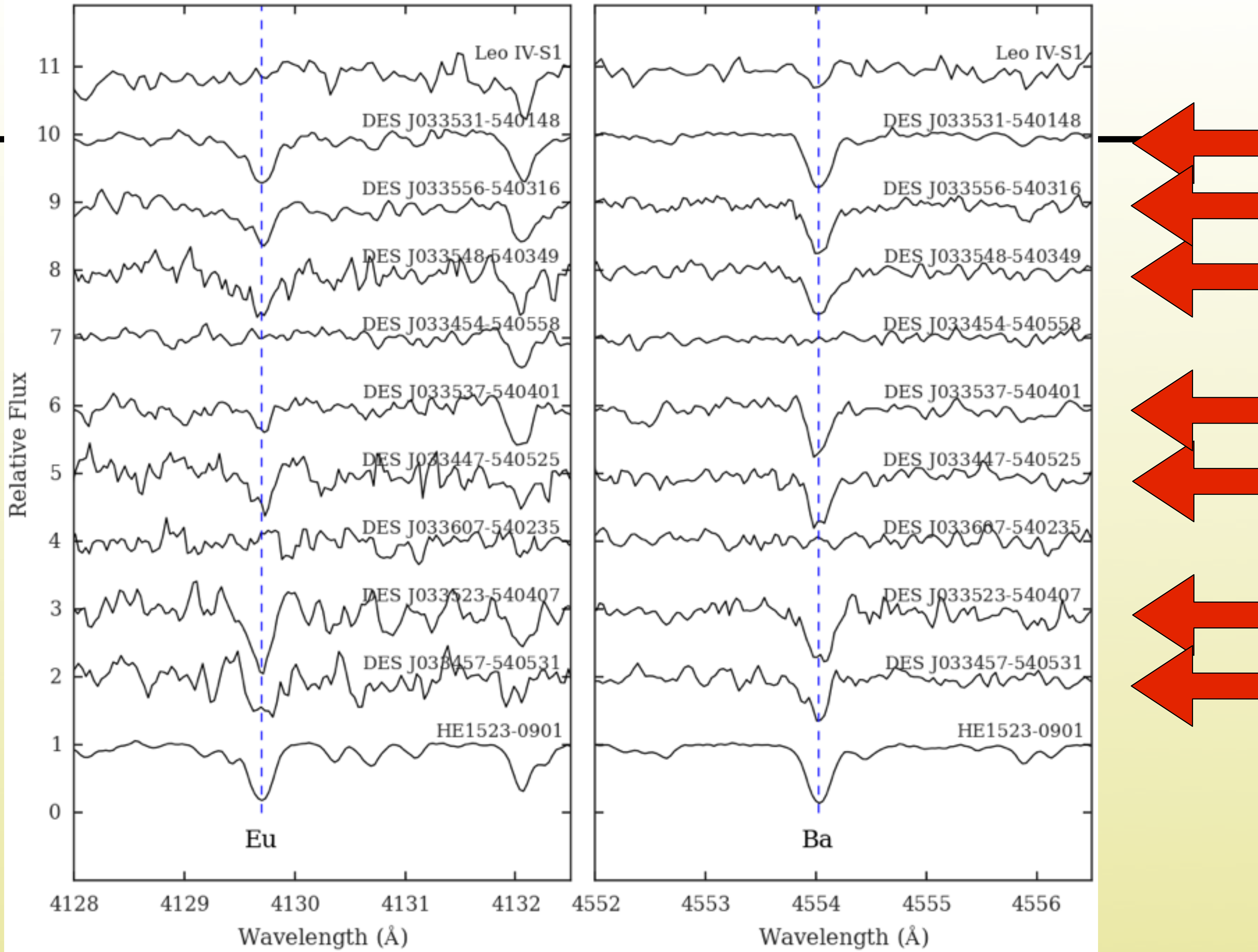
gray dots: metal-poor halo stars



UFD star

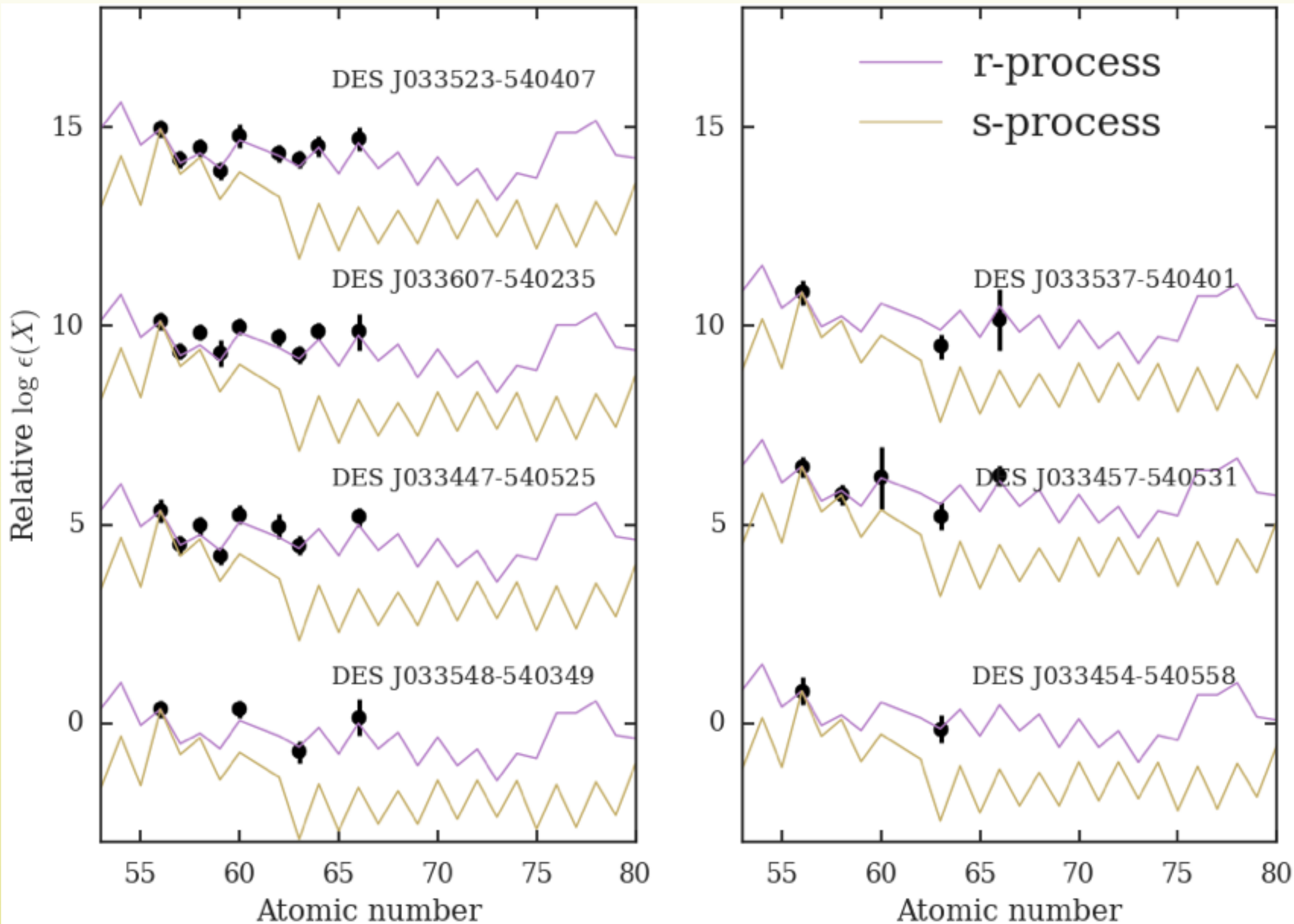
r-process star


Leo IV-S1
DES J033454-540558
DES J033607-540235
HE1523-0901
Eu
Ba
Relative Flux
Wavelength (Å)
Wavelength (Å)
0
1
2
3
4
5
6
7
8
9
10
11
4128
4129
4130
4131
4132
4552
4553
4554
4555
4556



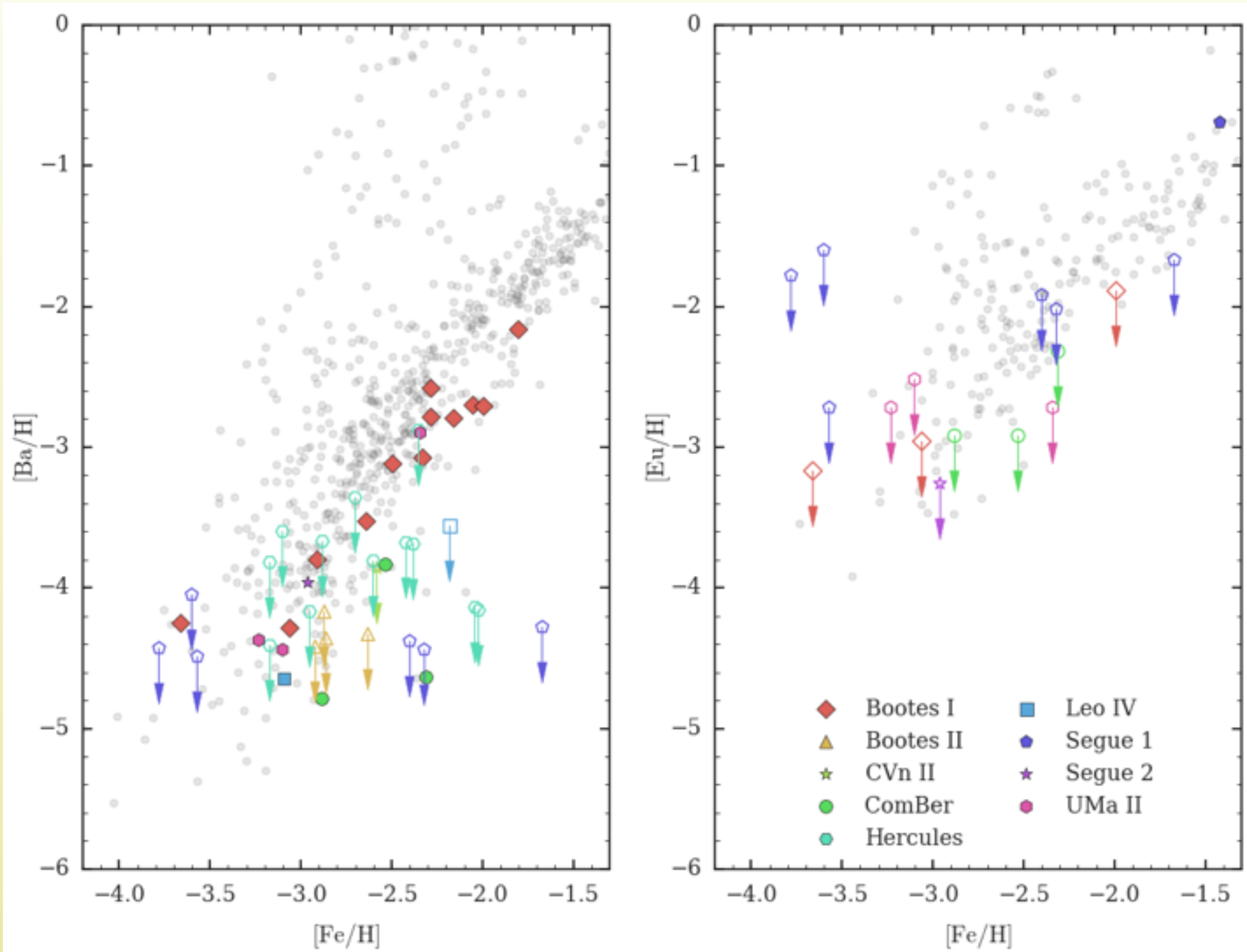
Leo IV-S1
DES J033531-540148
DES J033556-540316
DES J033548-540349
DES J033454-540558
DES J033537-540401
DES J033447-540525
DES J033607-540235
DES J033523-540407
DES J033457-540531
HE1523-0901
Relative Flux
Eu
Ba
Wavelength (Å)
Wavelength (Å)

All seven Ret II stars display the r-process pattern



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

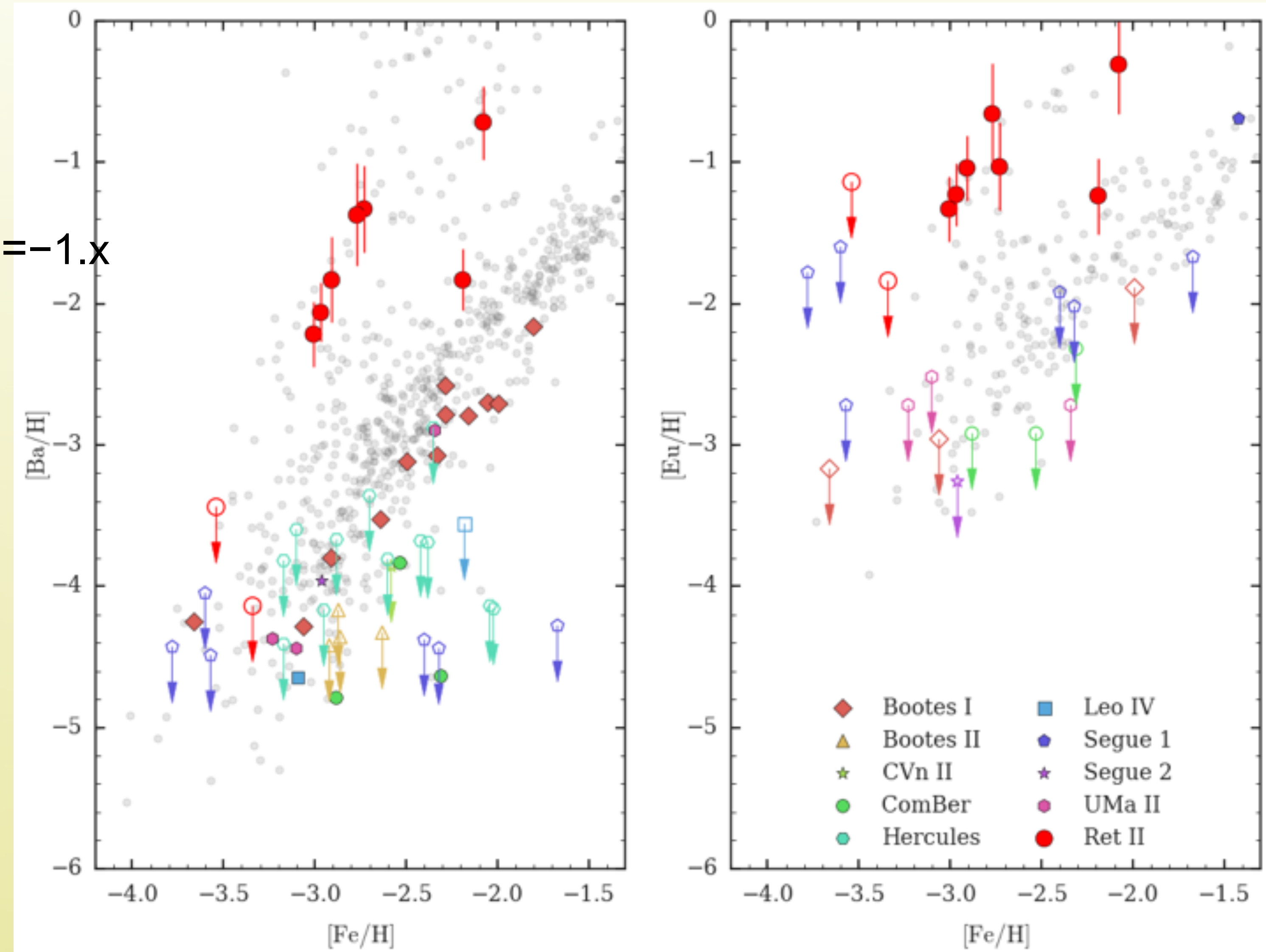
Neutron-cap. elements in UFD stars (before adding Ret II)



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

R-process galaxy Reticulum II   Anna Frebel

[Ba/H]=−1.x



[Eu/H]=−1

Dwarf galaxy archaeology

(= USING AN ENTIRE DWARF GALAXY TO STUDY THE EARLY UNIVERSE)

How Rare?

<u>Population of 10 UFDs:</u>

➡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?

<u>Estimate gas mass of UFD:</u>

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: $\sim 10^5\ M_{sun}$

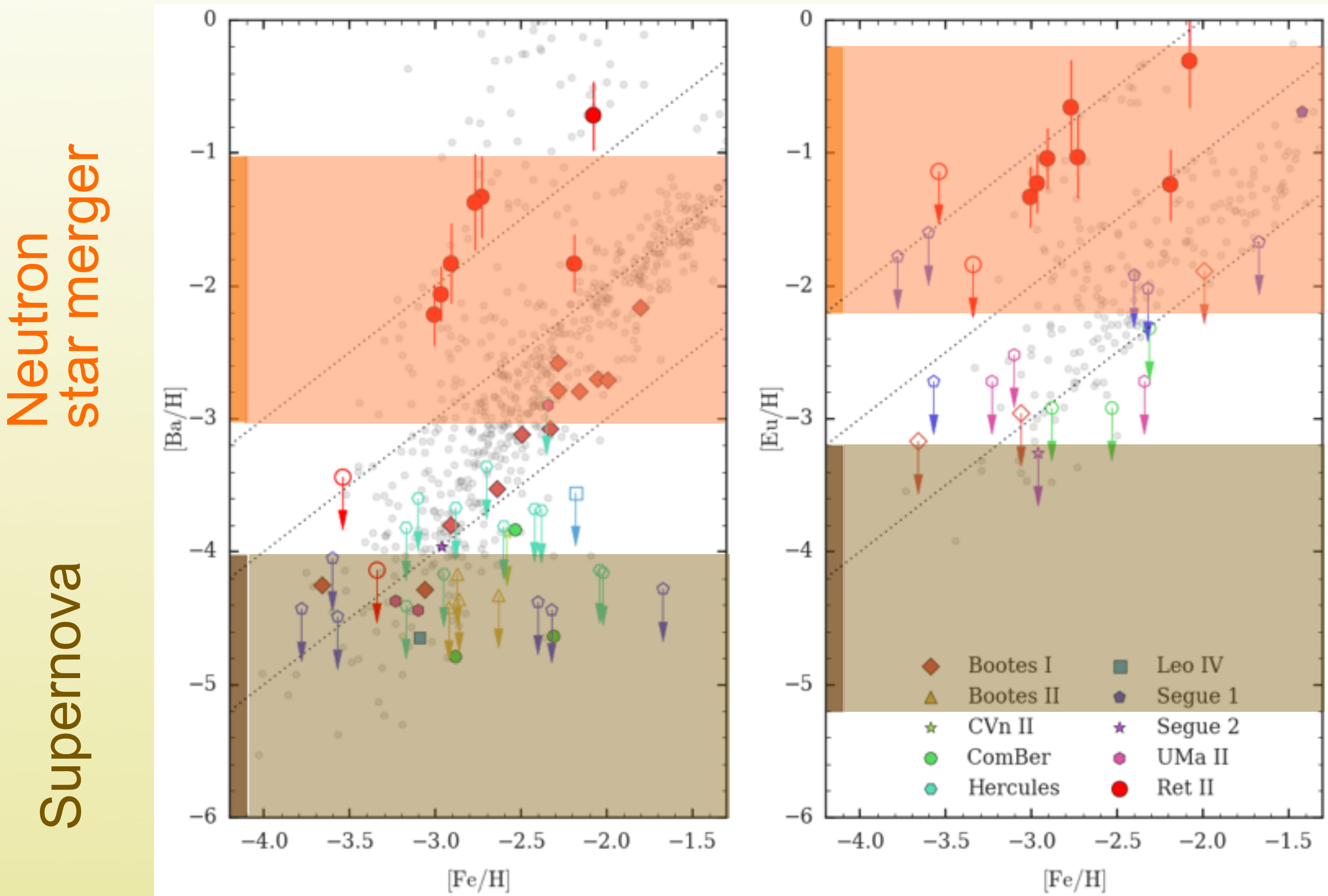
<u>Back-of-the-envelope calculation</u>

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

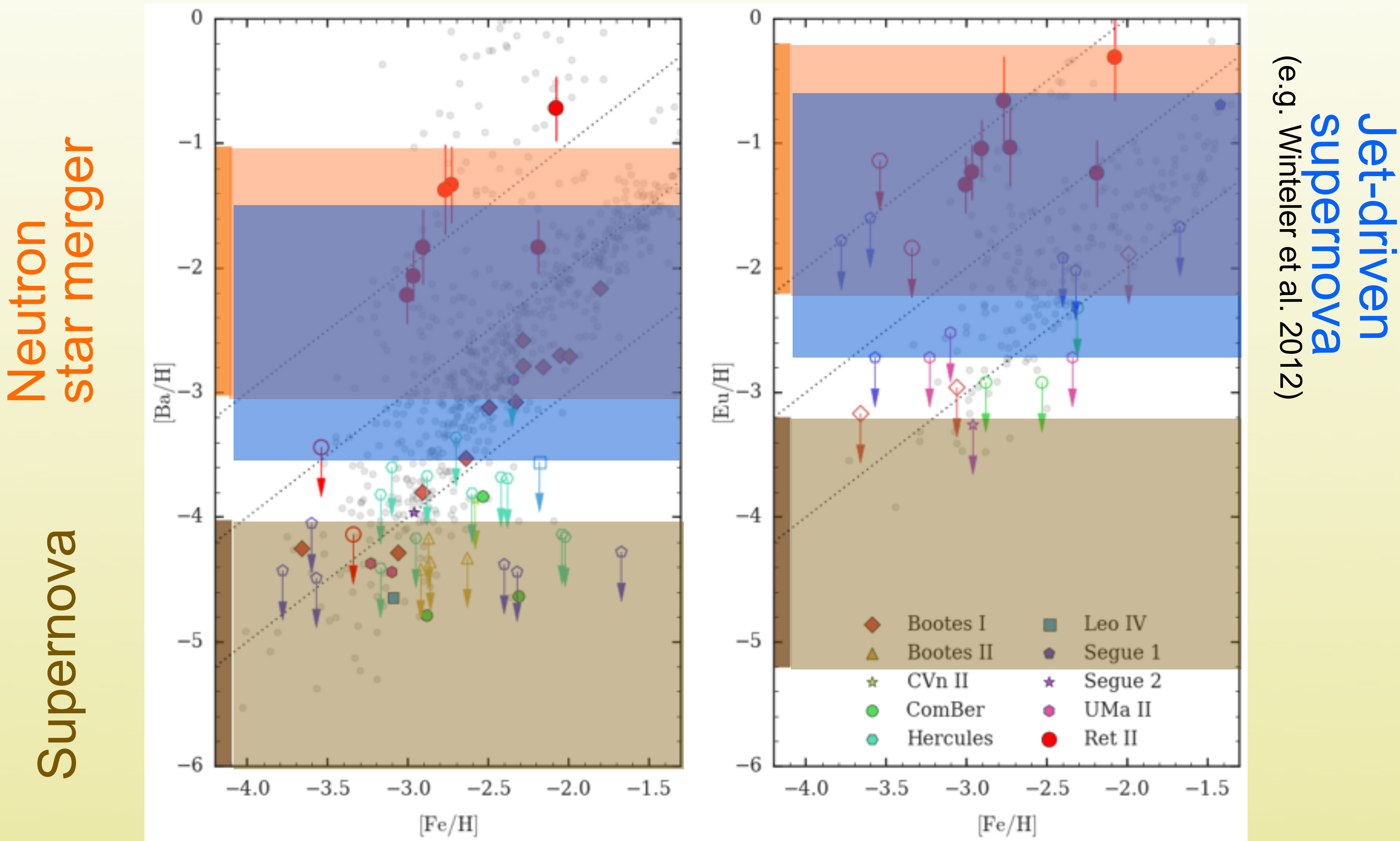
=> Agrees with Ret II abundance results!

Ret II abundances consistent w/ neutron-star merger yield



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

Rare and prolific jet-driven supernova remains possibility



...but ordinary supernovae remain ruled out!

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

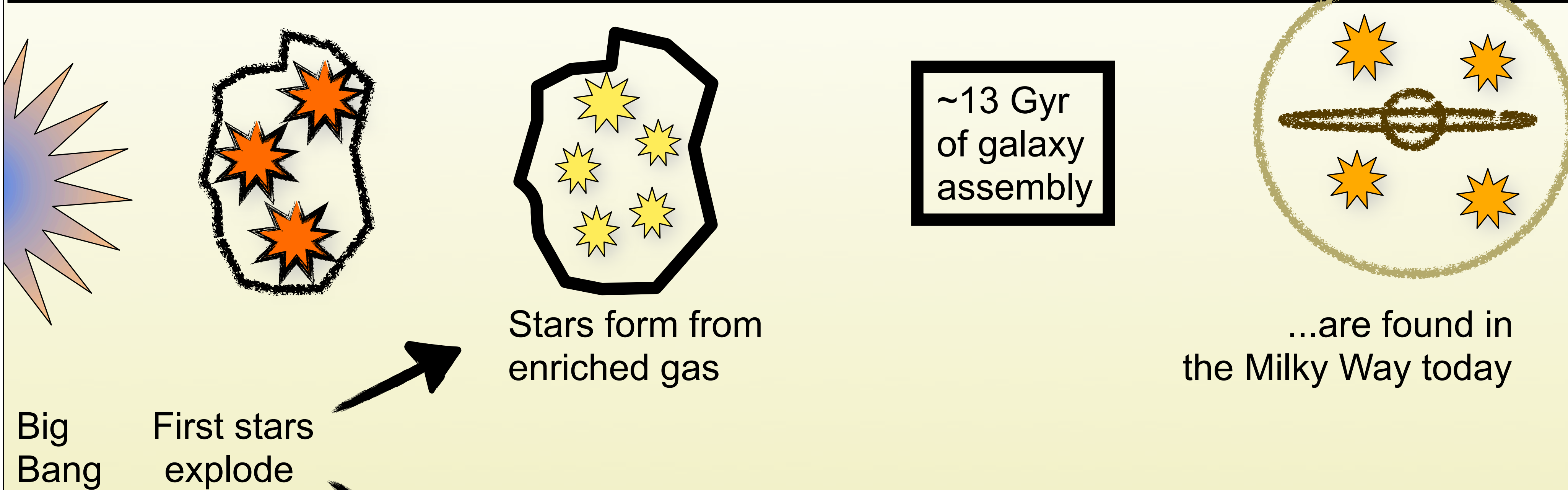
➡ Need to be just one/few massive events

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

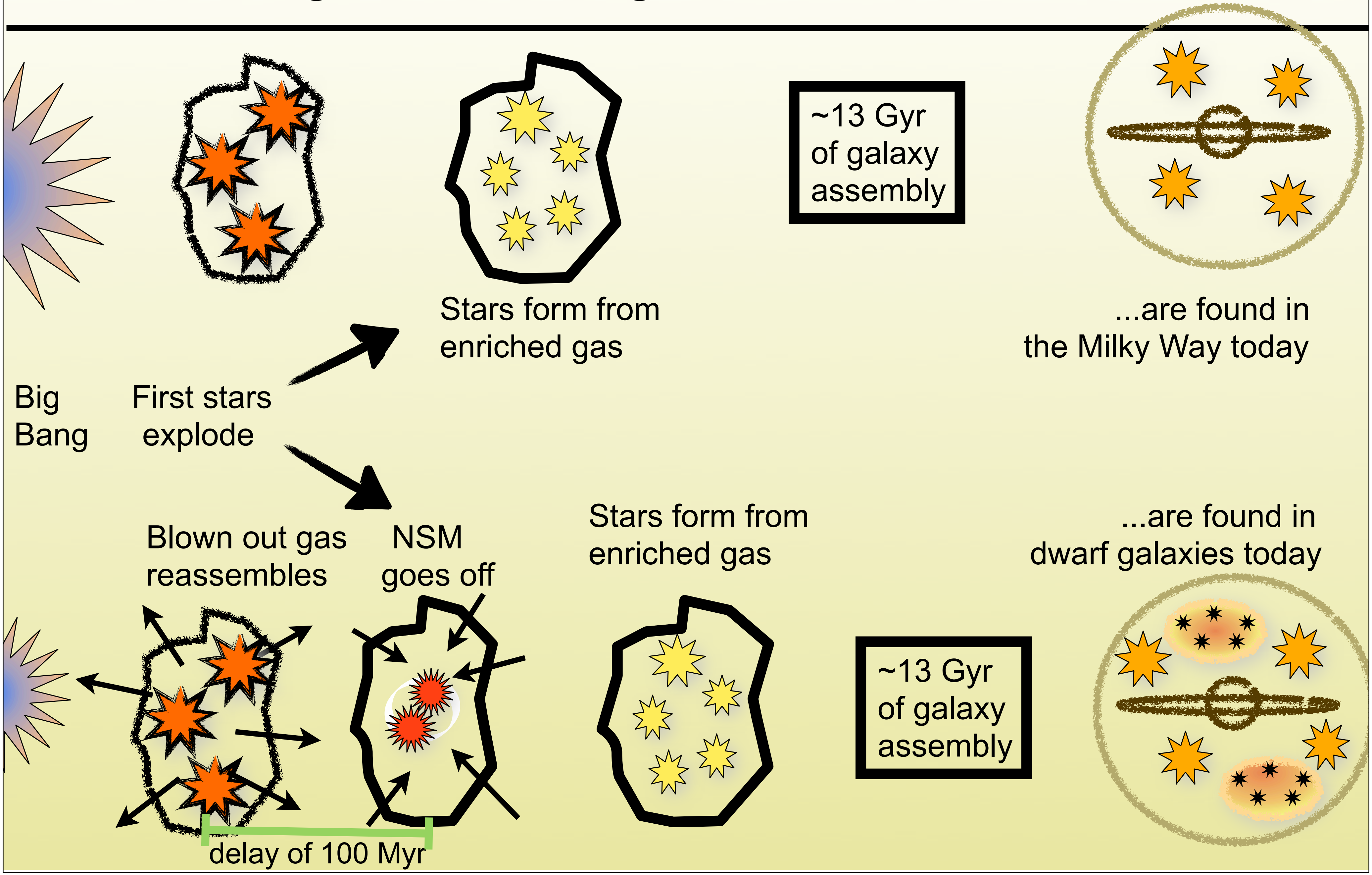
➡ After the few (initial) supernovae, it takes time for the system to reassemble again (~100 Myr)

➡ Minimum time scales for coalesence is ~100 Myr

Enrichment and star formation timeline



Enrichment and Star Formation Timeline



ANSWERS TO THE BIG QUESTION

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

- ➡ Core-collapse supe ➡No, but a rare and prolific site
- ➡ Neutron star me ➡Consistent w/ Ret II abundances
- ➡ Others (e.g., jet-driven super ➡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!

Anything else to learn?

A puzzle: Chemical Enrichment in Ret II

Need to explain: 7+1 r-process-rich, 2 n-capture poor stars

➡ Sequential bursts of star formation?
n-cap poor stars have lower [Fe/H]

➡ Inhomogeneous metal mixing?
Seems unlikely given homogeneity of light elements

➡ Accretion of other, smaller galaxy?
No more than 1 accreted galaxy possible
(Griffen et al. 2016, subm.)

The future is here

The first glimpse of the incredible potential of UFDs for early universe studies

From nuclear astrophysics to near-field cosmology

✓ Clean nucleosynthesis event(s) w/ actual information on the site and environment

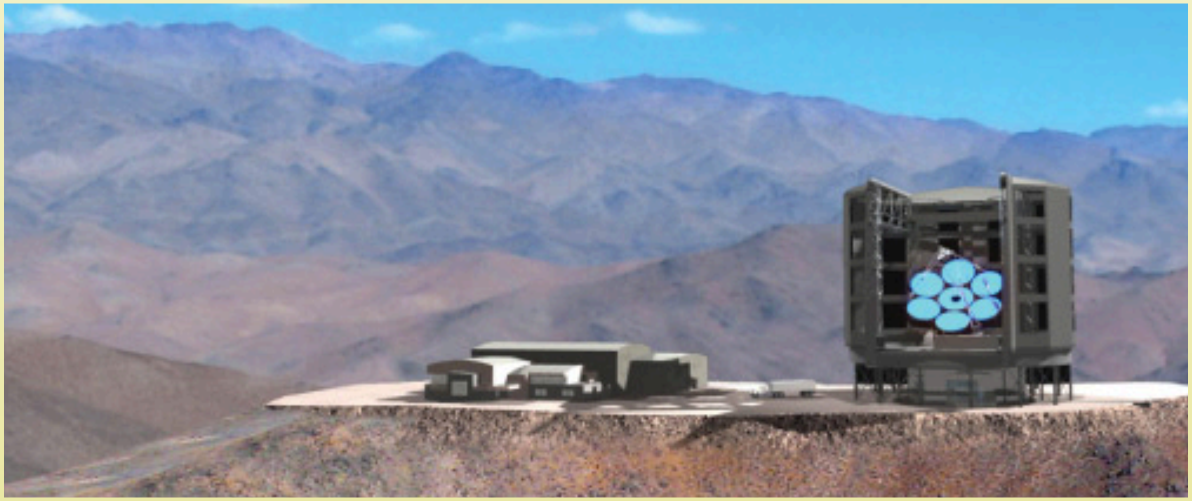
➡ Unprecedented astrophysics constraints for nuclear physics, early chemical evolution, first galaxy formation, metal mixing processes, galaxy assembly, etc.

✓ New dwarf galaxies are still being discovered (e.g. in Dark Energy Survey)

➡ New observable target stars; firm up fraction of r-process ultra-faint dwarf galaxies

✓Only stars w/ V≤19mag can be observed w/ current telescopes (= only few stars per galaxy!)

➡ New telescopes are needed with high-resolution spectrographs, i.e. GCLEF on GMT



25m Giant Magellan Telescope (GMT), from 2020