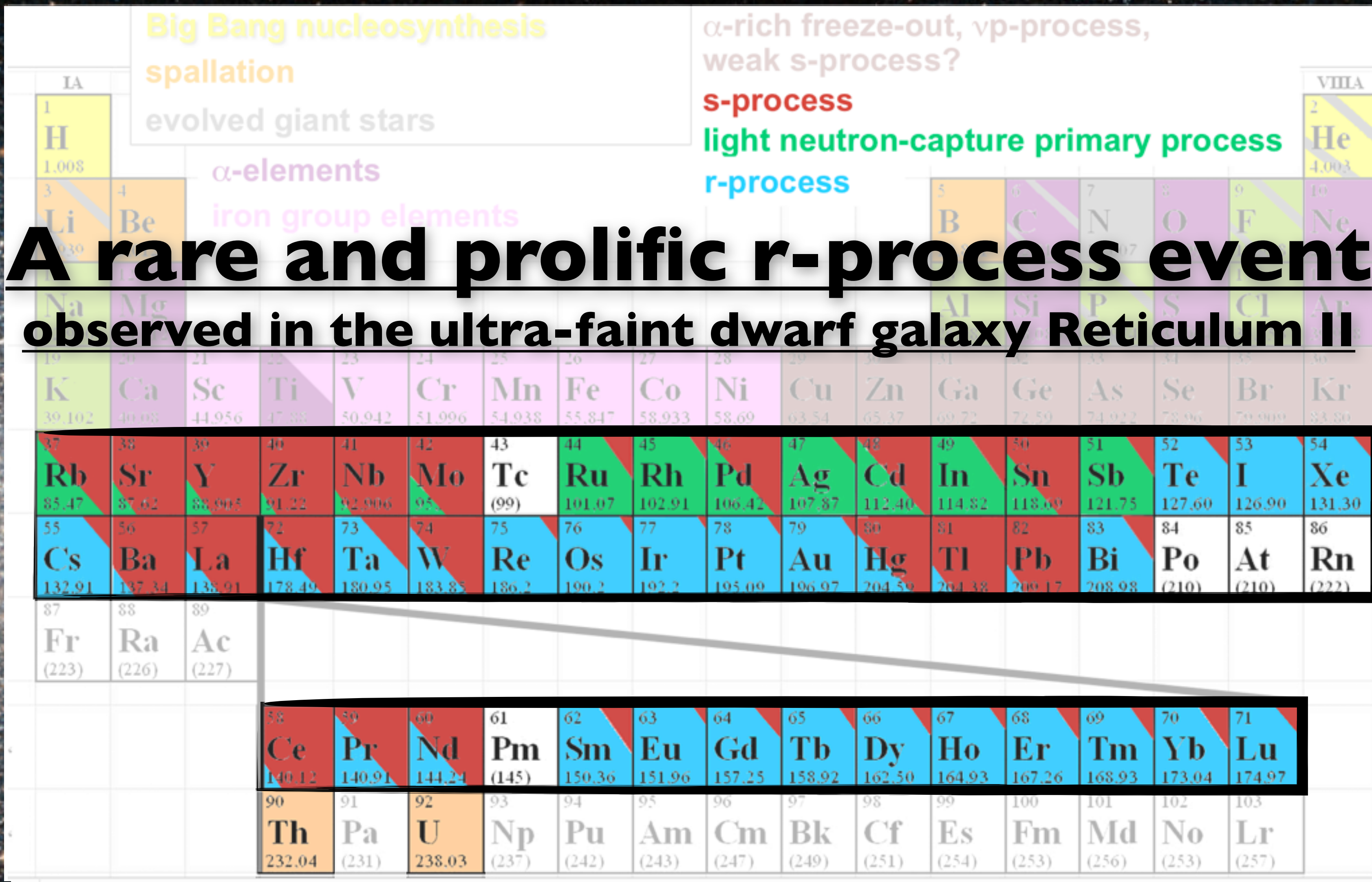


A rare and prolific r-process event

observed in the ultra-faint dwarf galaxy Reticulum II

by Alex Ji, Anna Frebel, Ani Chiti & Josh Simon (*Nature*, 2016, 531, 610)

Anna Frebel

Massachusetts Institute of Technology

Outline

Nuclear Astrophysics: Origin of the heavy elements

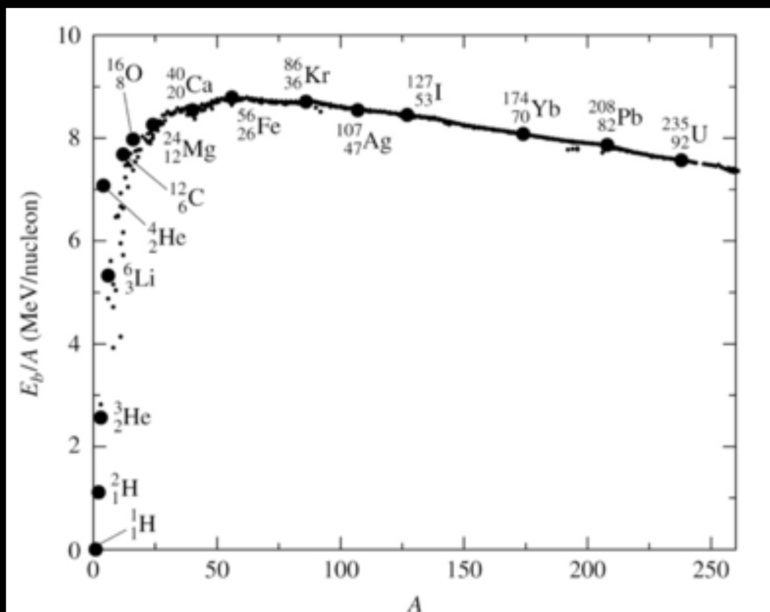
Stellar Archaeology: Clues to the astrophysical site of r-process nucleosynthesis

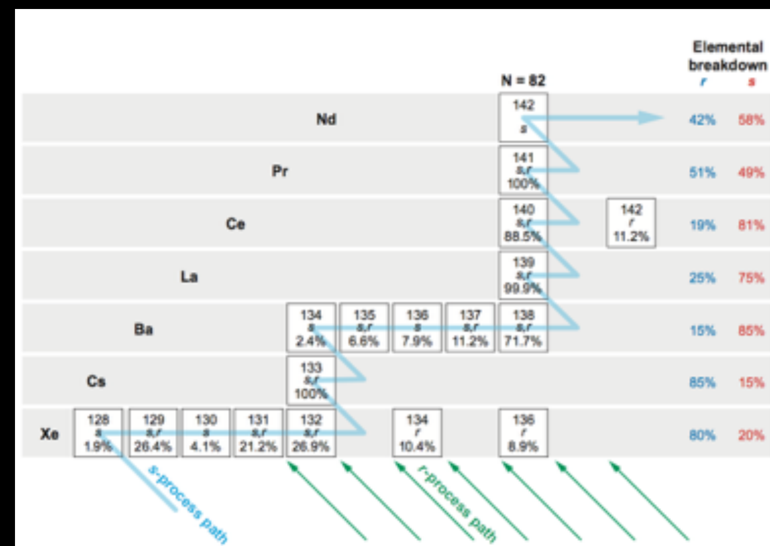
Dwarf Galaxy Archaeology: Ancient, clean chemical enrichment signatures

Results: Evidence for a rare and prolific r-process event in the early universe

Element nucleosynthesis in stars

(Depends on stellar mass and stellar evolutionary state)





Fusion up to iron

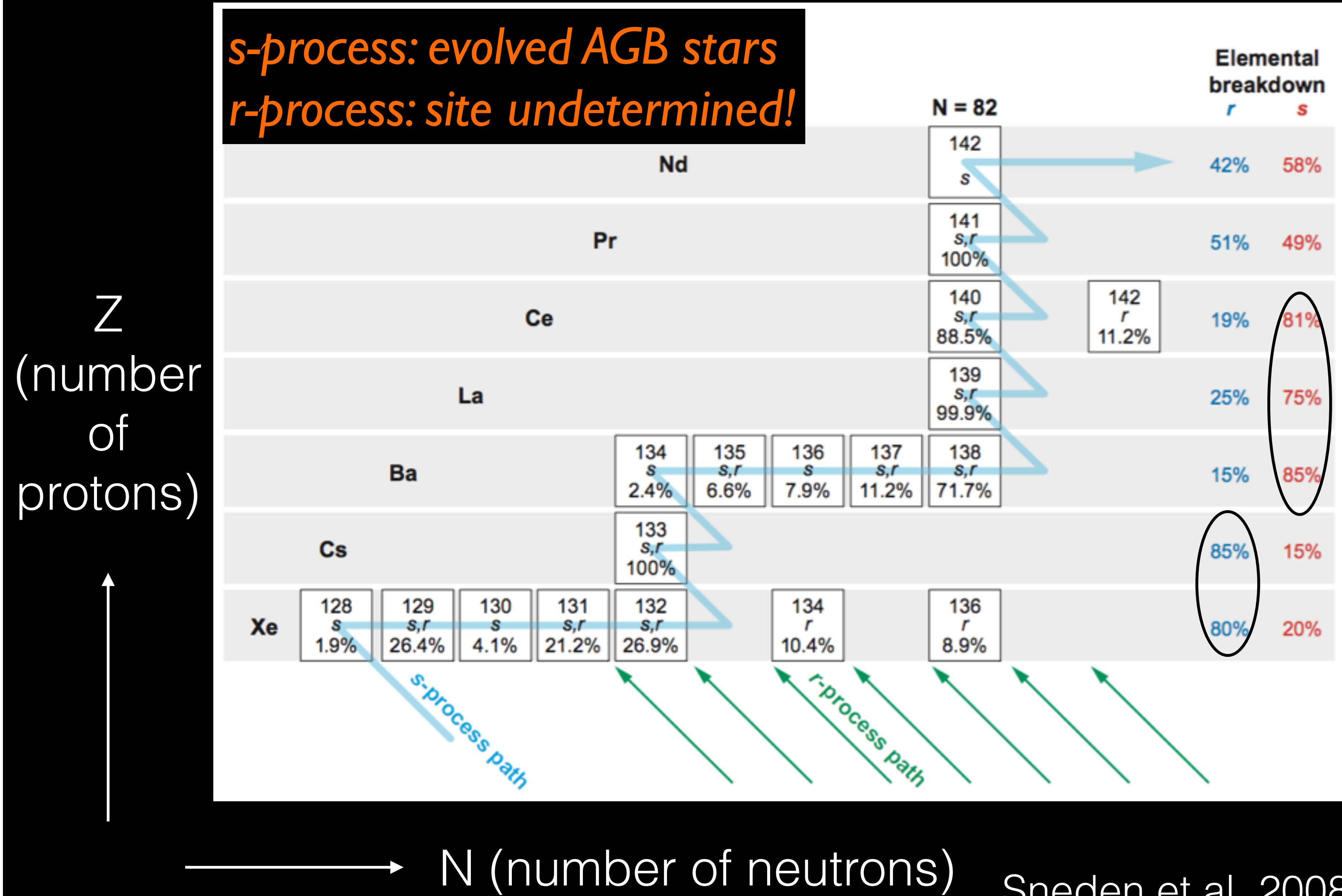
during stellar evolution

Neutron-capture processes above iron

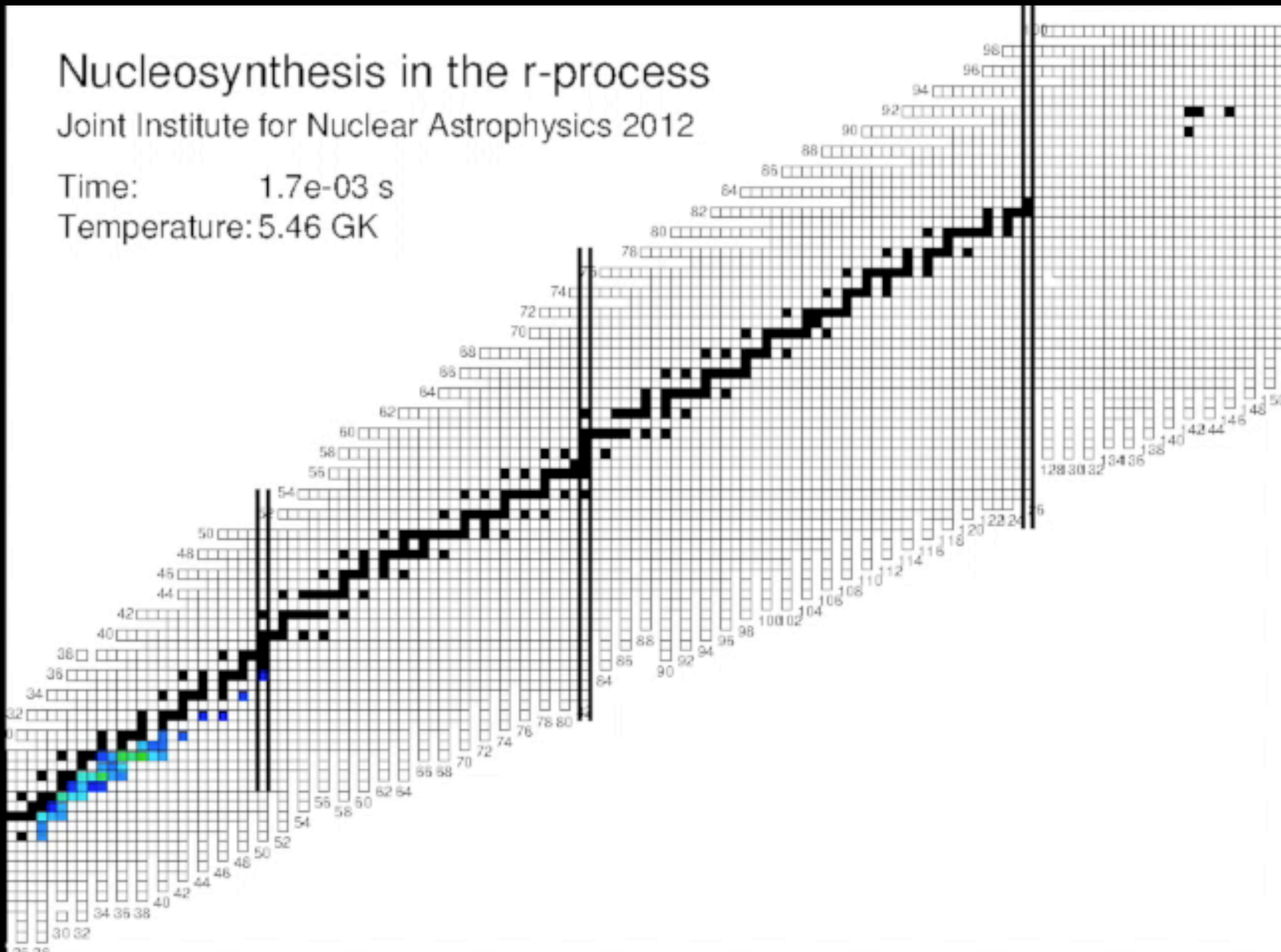
during advanced stellar evolution and elsewhere(!)

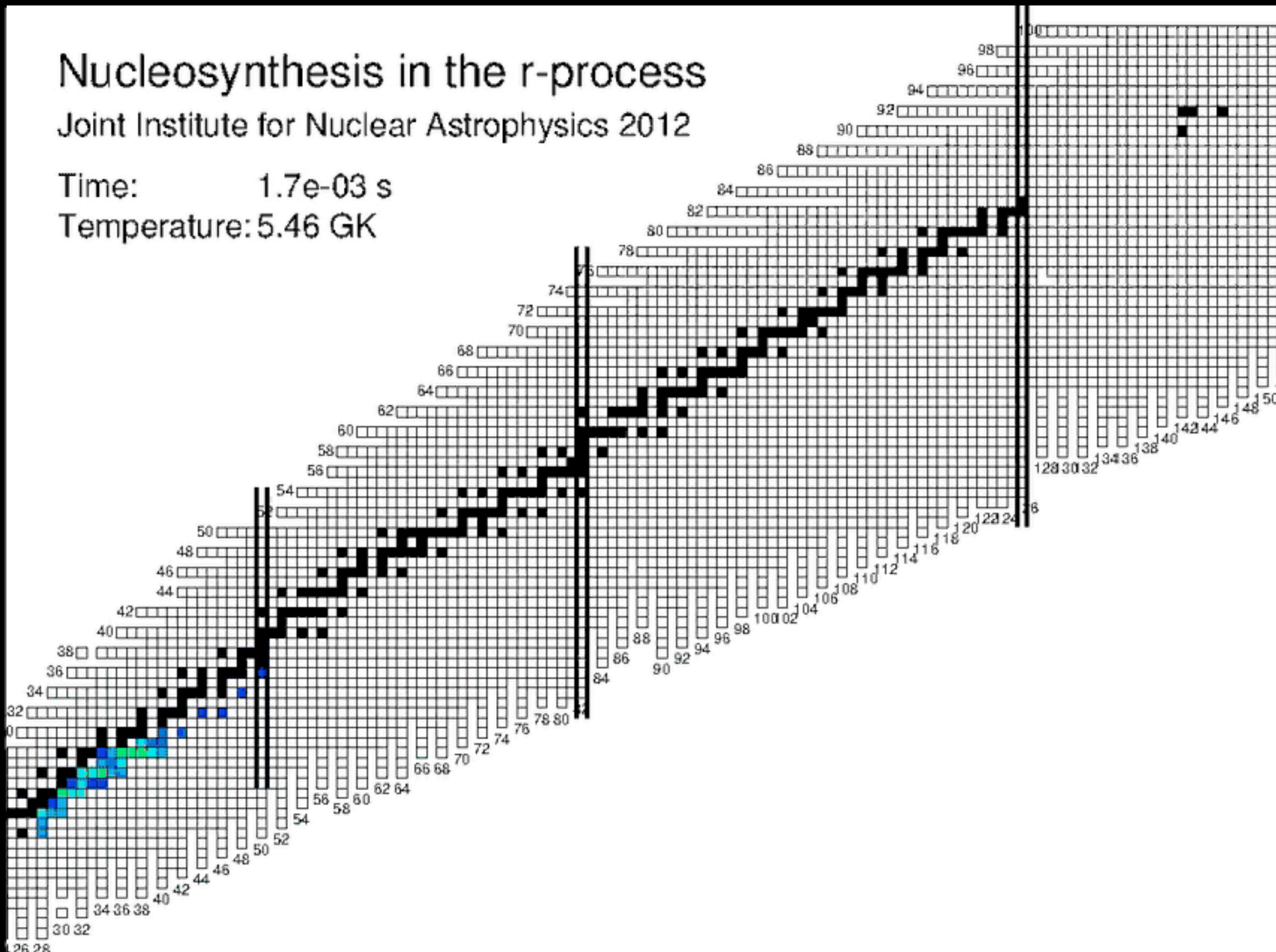
Neutron-capture nucleosynthesis

s-process: evolved AGB stars
r-process: site undetermined!



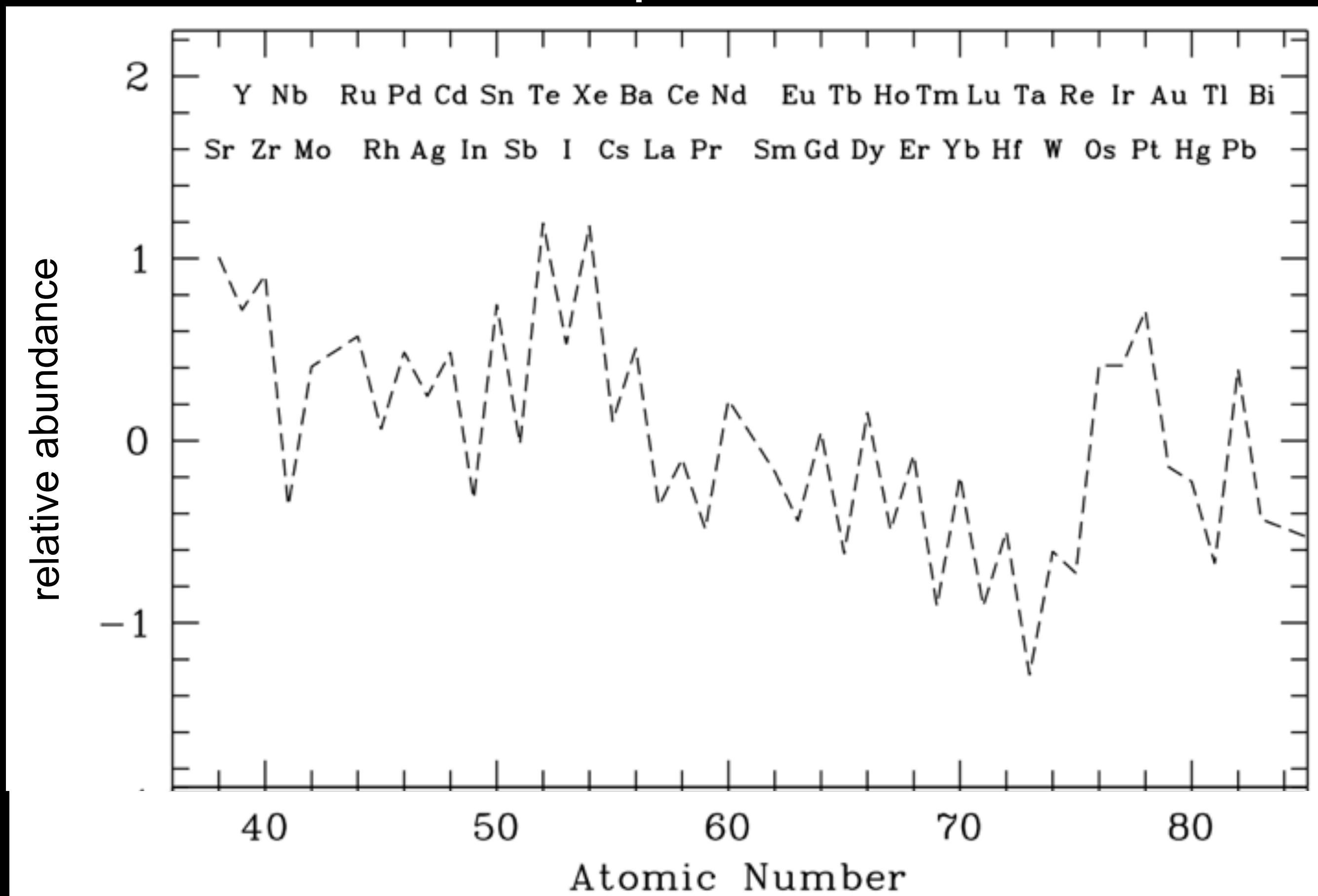
Sneden et al. 2008


Nucleosynthesis in the r-process
Joint Institute for Nuclear Astrophysics 2012
Time: 1.7e-03 s
Temperature: 5.46 GK

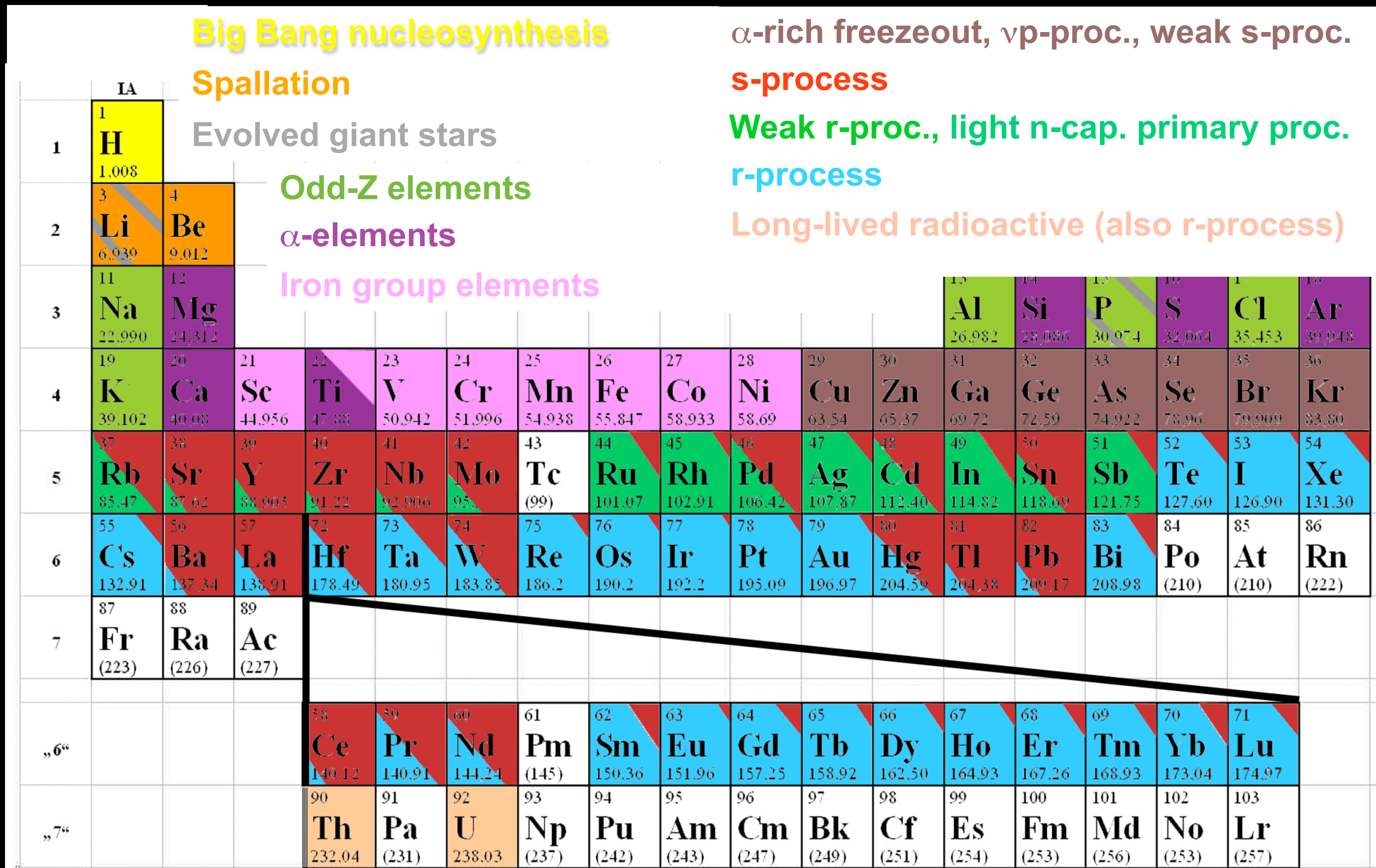

Nucleosynthesis in the r-process
Joint Institute for Nuclear Astrophysics 2012
Time: 1.7e-03 s
Temperature: 5.46 GK

R-PROCESS PATTERN

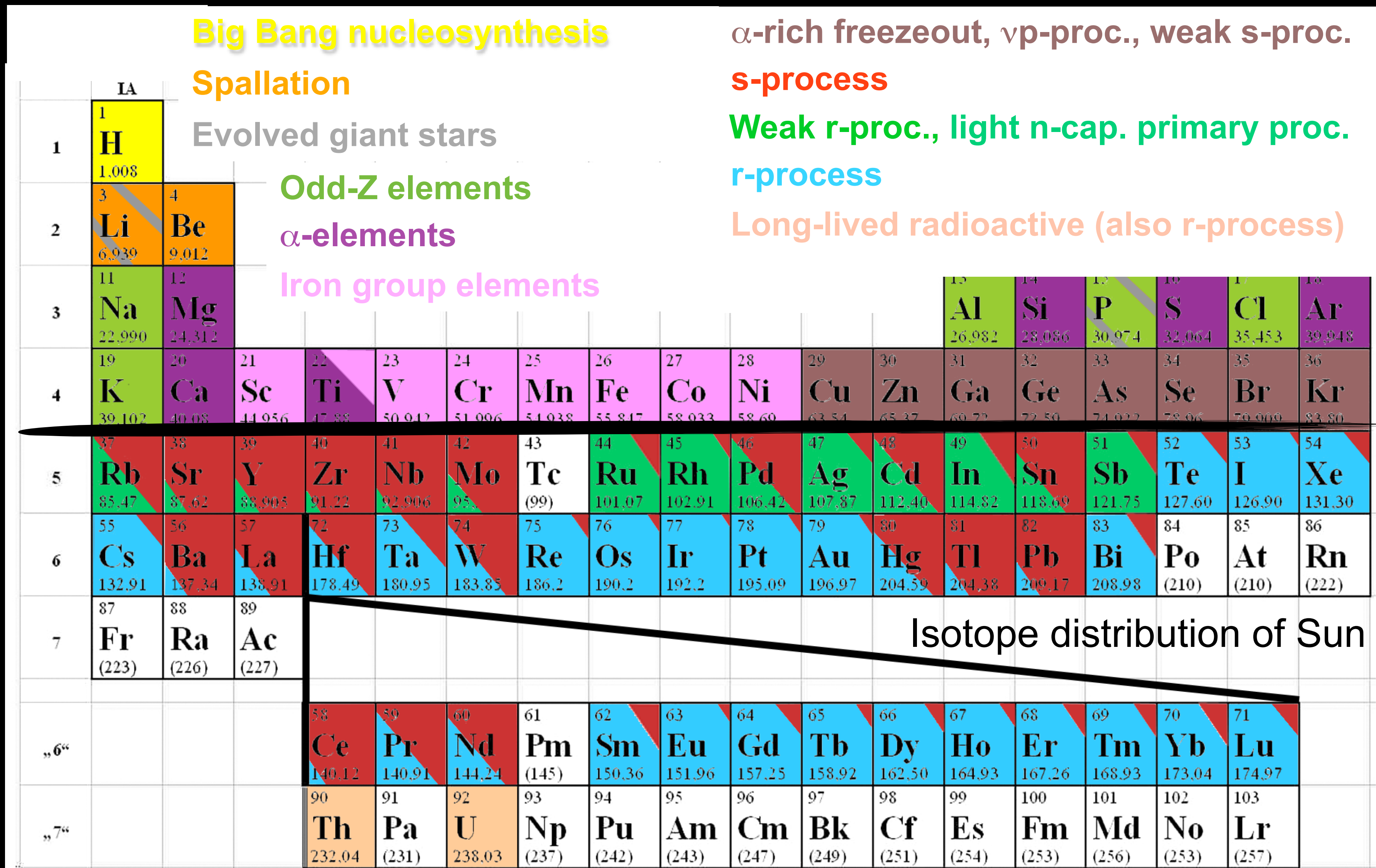
Neutron-capture elements



The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table



REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

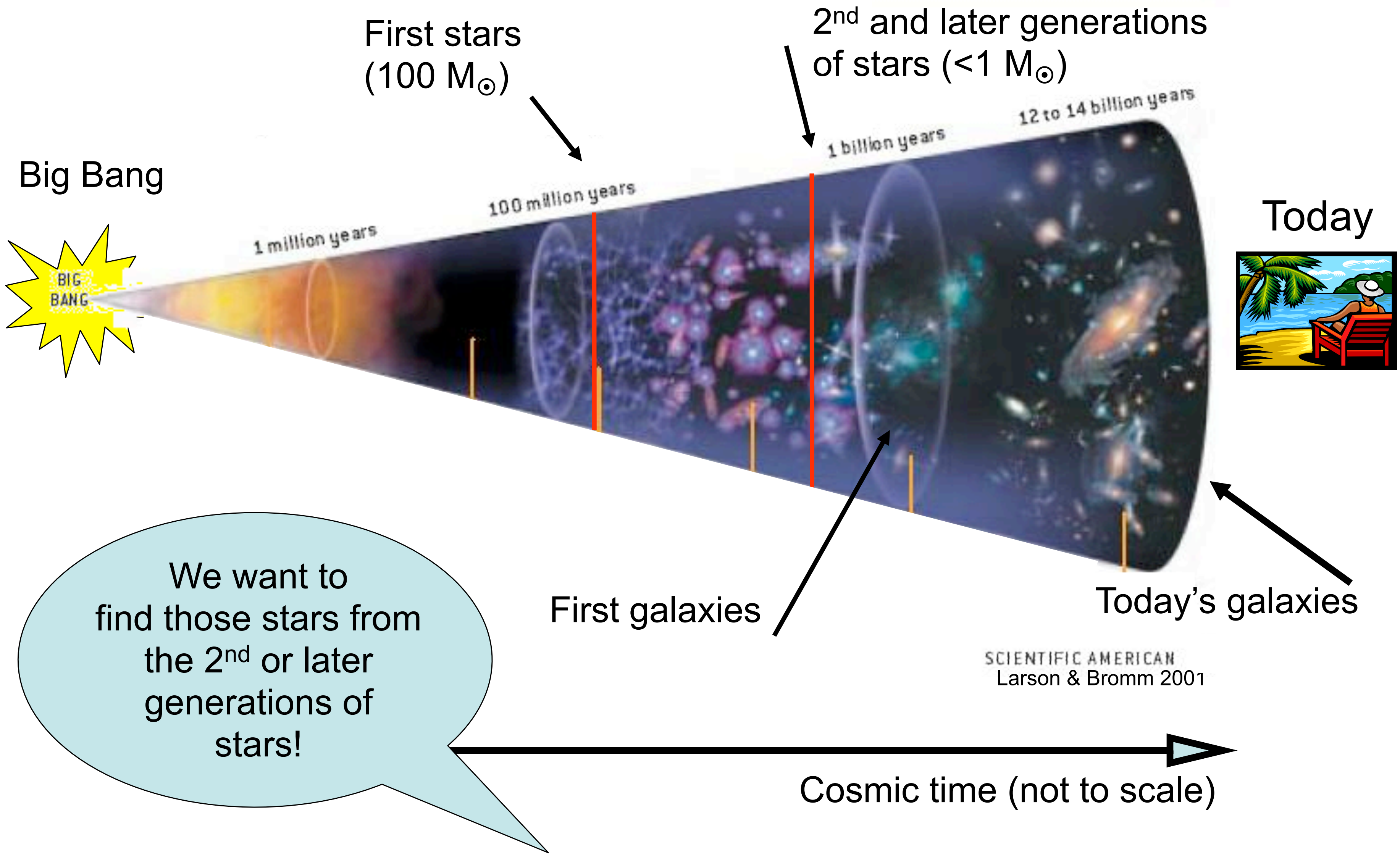
XI. Variations in Chemical Composition among Stars, and Their Bearing on the Various Synthesizing Processes 620
A. Hydrogen Burning and Helium Burning 621
B. α Process 626
C. Synthesis of Elements in the Iron Peak of the Abundance Curve, and the Aging Effect as It Is Related to This and Other Types of Element Synthesis 626
D. s Process 627
E. r Process 629
F. p Process 629
.... 629
d Element Synthesis in Surfaces of Stars 629

E. r Process

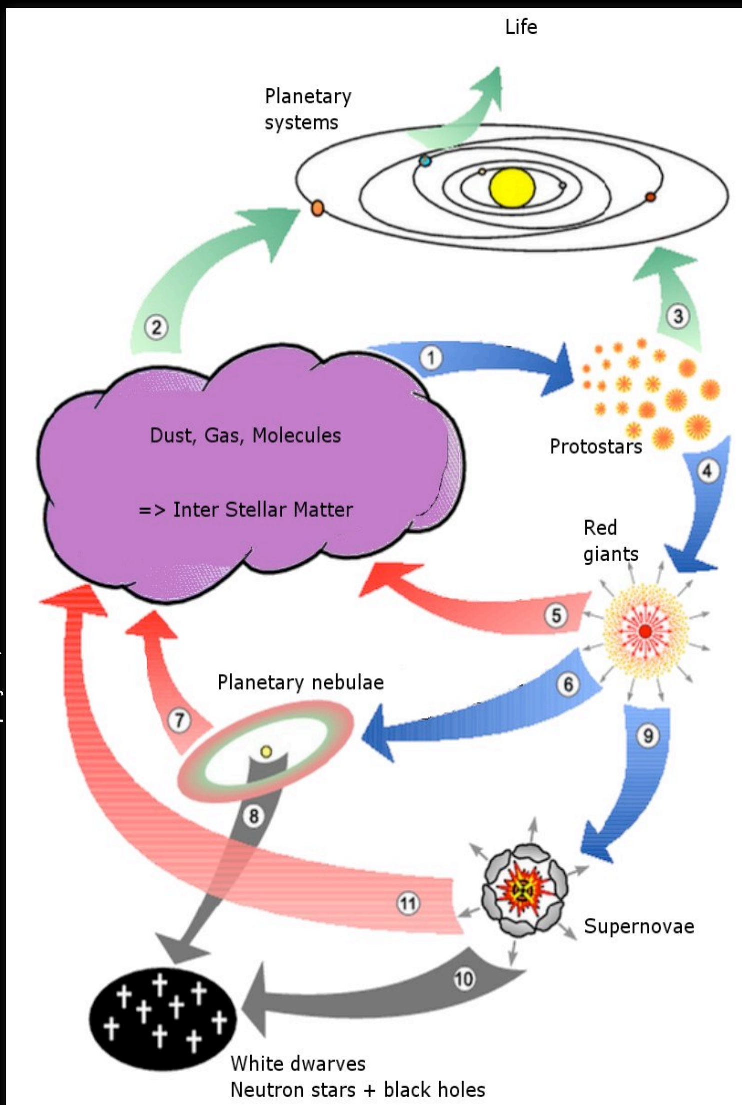
The outstanding piece of observational evidence that this takes place is given by the explanation of the light curves of supernovae of Type I as being due to the decay of Cf^{254} (Bu56, Ba56), together with some other isotopes produced in the r process. Further evidence can be obtained only by interpreting the spectra of Type I supernovae, a problem which has so far remained unsolved.

We have since discovered old stars with r-process enhancement!

A LONG TIME AGO...



CHEMICAL EVOLUTION



Zentrum fuer Astronomie und Astrophysik, TU Berlin

We are made of stardust!

Old stars contain fewer elements (e.g. iron) than younger stars

hydrogen 1 **H** 1.0079

Astronomer's Periodic Table

helium 2 **He** 4.0026

Metals Z

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

Extremely Metal-poor Stars

Facts and Definitions

- Fe traces the overall stellar metal content
- Fe is easy to measure
- $[Fe/H] = \log_{10}(N_{Fe}/N_H) - \log_{10}(N_{Fe}/N_H)_{sun}$
- Lower [Fe/H] —> Older Star
- [Fe/H] <= -3 —> ~1 progenitor supernova produced that iron

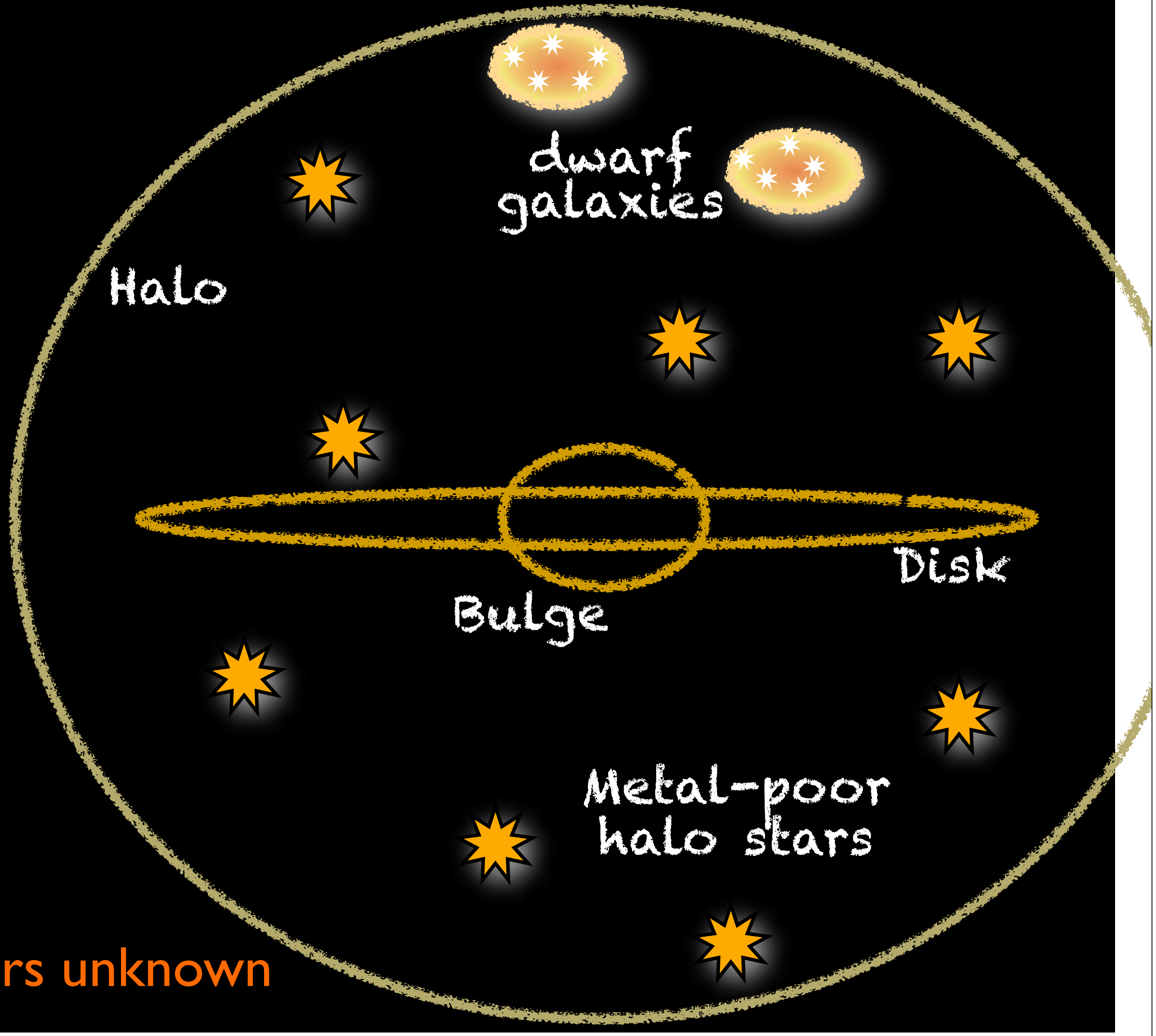
The Milky Way

How common are r-process metal-poor stars?

~3-5% of metal-poor stars w/ [Fe/H]<− 2.5 (Barklem et al. 2005)

=> Only ~30 stars known so far w/ [Eu/Fe] > 1.0, i.e. clear r-process pattern above Ba

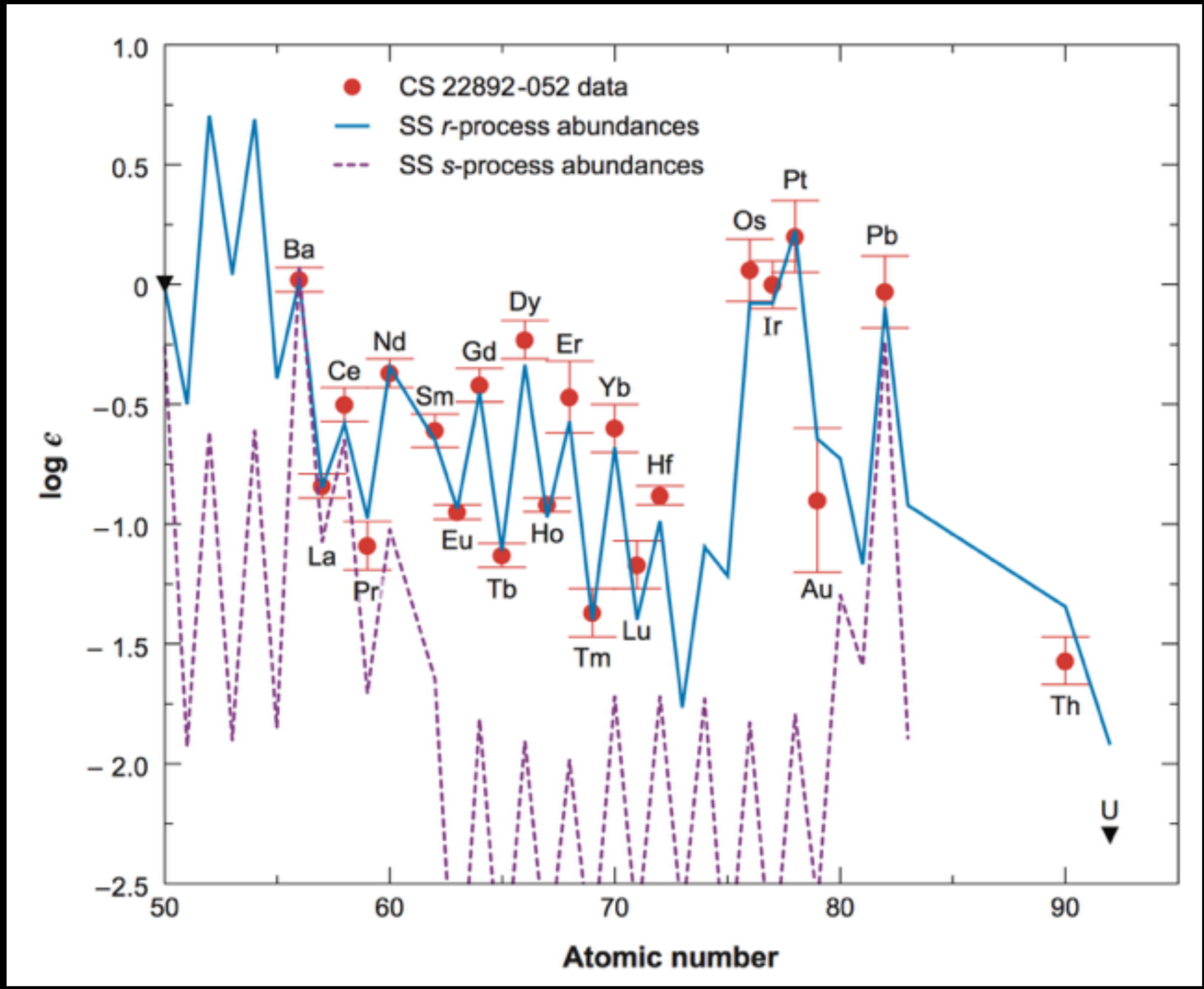
=> More stars known with lower levels of 0.3< [Eu/Fe] < 1.0; unclear what lowest level is



=> Origin of these stars unknown

Universal r-process pattern

- r-process abundance *pattern* the same in the Sun and metal-poor stars
- r-process stars all extremely metal poor ([Fe/H] ~ -3)



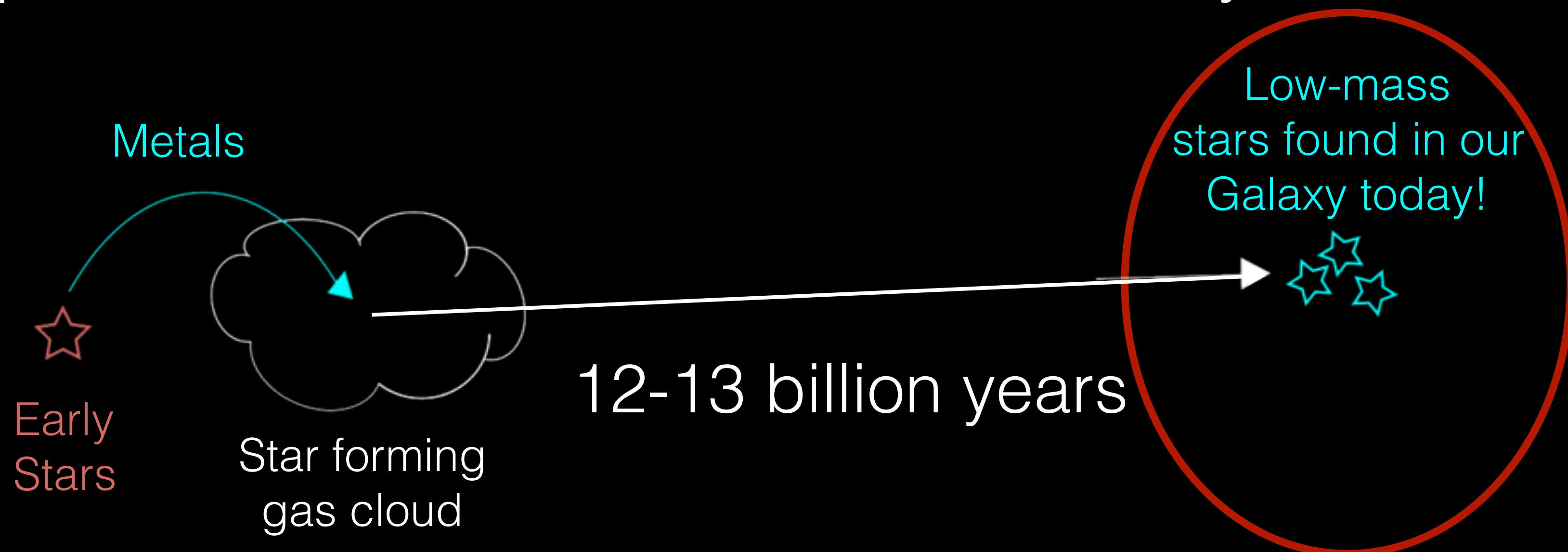
Sneden et al. 2008

The Big Question

- ★ **What is the (dominant) astrophysical site of the r-process?**
  - ➡ Core-collapse supernovae
  - ➡ Neutron star mergers
  - ➡ Others (e.g., magnetars)
- ★ **What is the rate and yield of the event?**
- ★ **Does the dominant site change?**

Clues to the r-process site

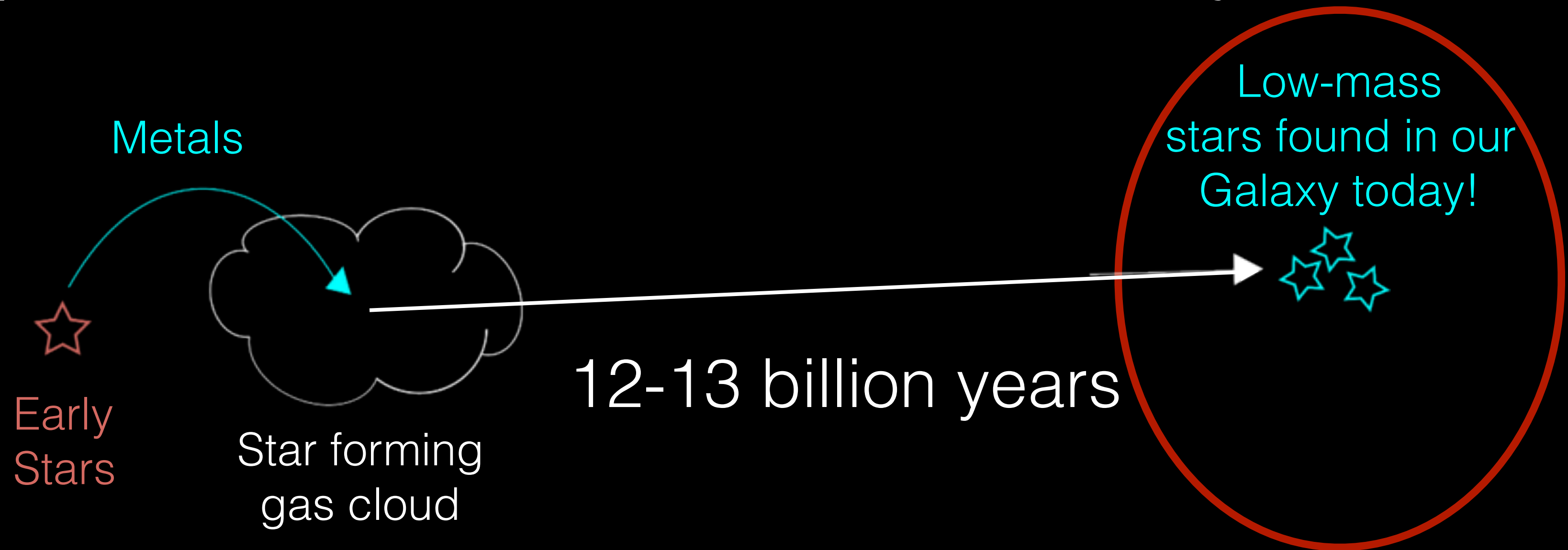
- *Stellar Archaeology:* using metal-poor stars to probe the chemical content of the early universe



Observe chemical abundances of these -> chemical content of old gas clouds!

Clues to the r-process site

- *Stellar Archaeology:* using metal-poor stars to probe the chemical content of the early universe

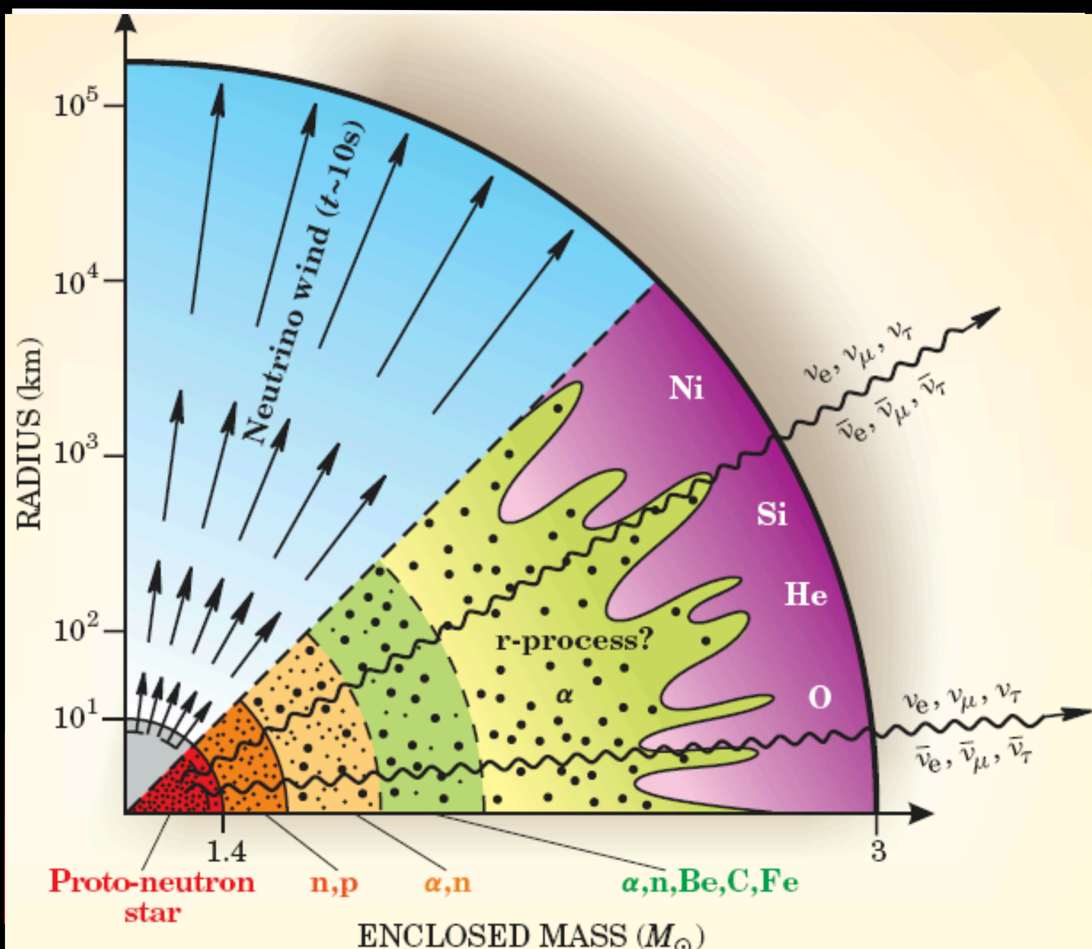


[Fe/H] <= -3 => Only ~1 progenitor supernova produced that iron

Observe chemical abundances of these -> chemical content of old gas clouds!

Core-collapse supernova

SN are common; produce light elements with Z<30;
Responsible for those elements when observed in metal-poor stars



Yield:

10^{-5} M_{sun} of wind material

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

$10^{-7.5}$ M_{sun} of Eu

Woosley and Janka 2005

Supernova enrichment

Big Bang

First/early stars explode

Metal-poor stars form from enriched gas...

...are found in the Milky Way today

How it works:

✓Fast enrichment; small & steady r-process yields

✓Metal-poor stars only need one/few progenitors

BUT... Theoretical difficulties for r-process nucleosynthesis (e.g. Arcones et al.)

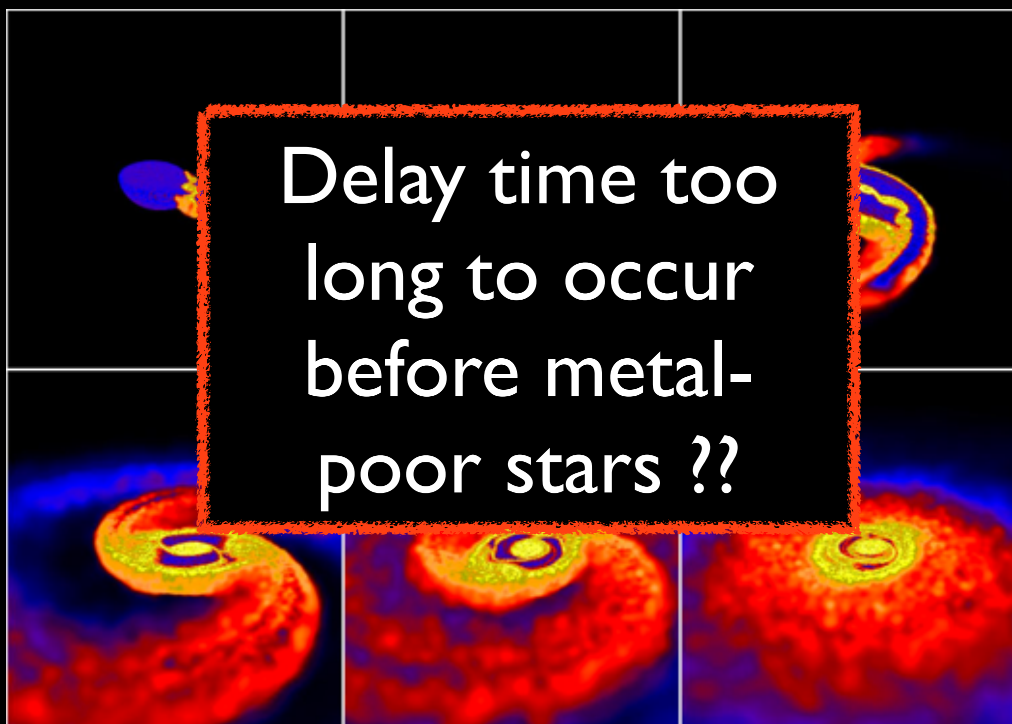
Neutron star binary merger

Rare

One binary per ~1000- 2000 supernovae

Long(er) enrichment timescale

Inspiral time of NSM takes time; >100 Myr



Delay time too long to occur before metal-poor stars ??

Yield:

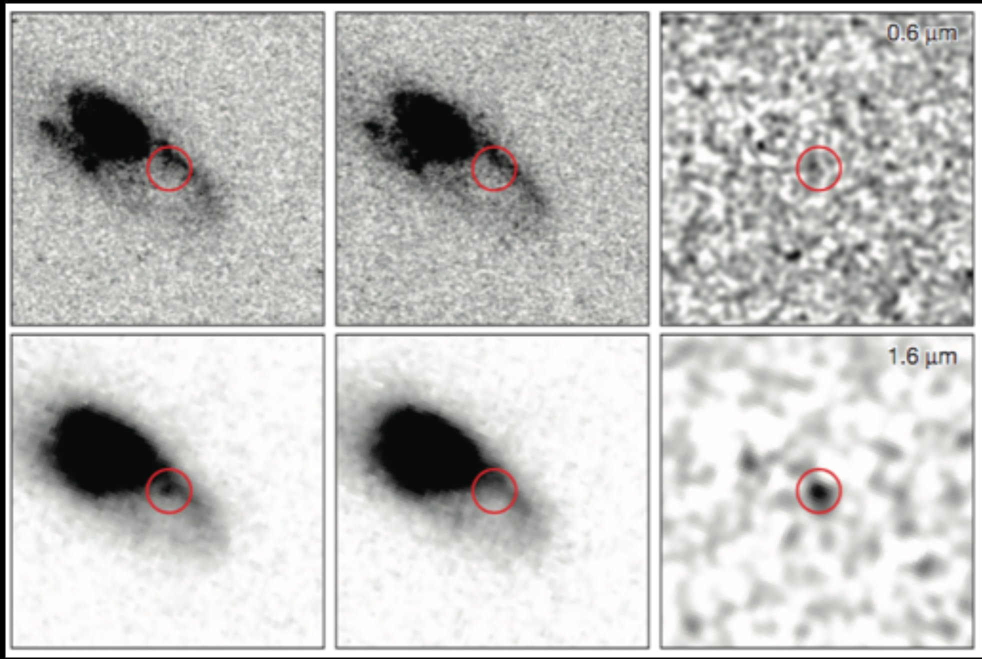
10^{-3} -10^{-2} M_{sun} of r-process material

=> $10^{-4.5}$ M_{sun} of Eu

Image Credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

Indirect observations of local r-process nucleosynthesis

- Short gamma ray burst <-> Neutron star merger
- Afterglow from decay of radioactive r-process elements detected in 2013

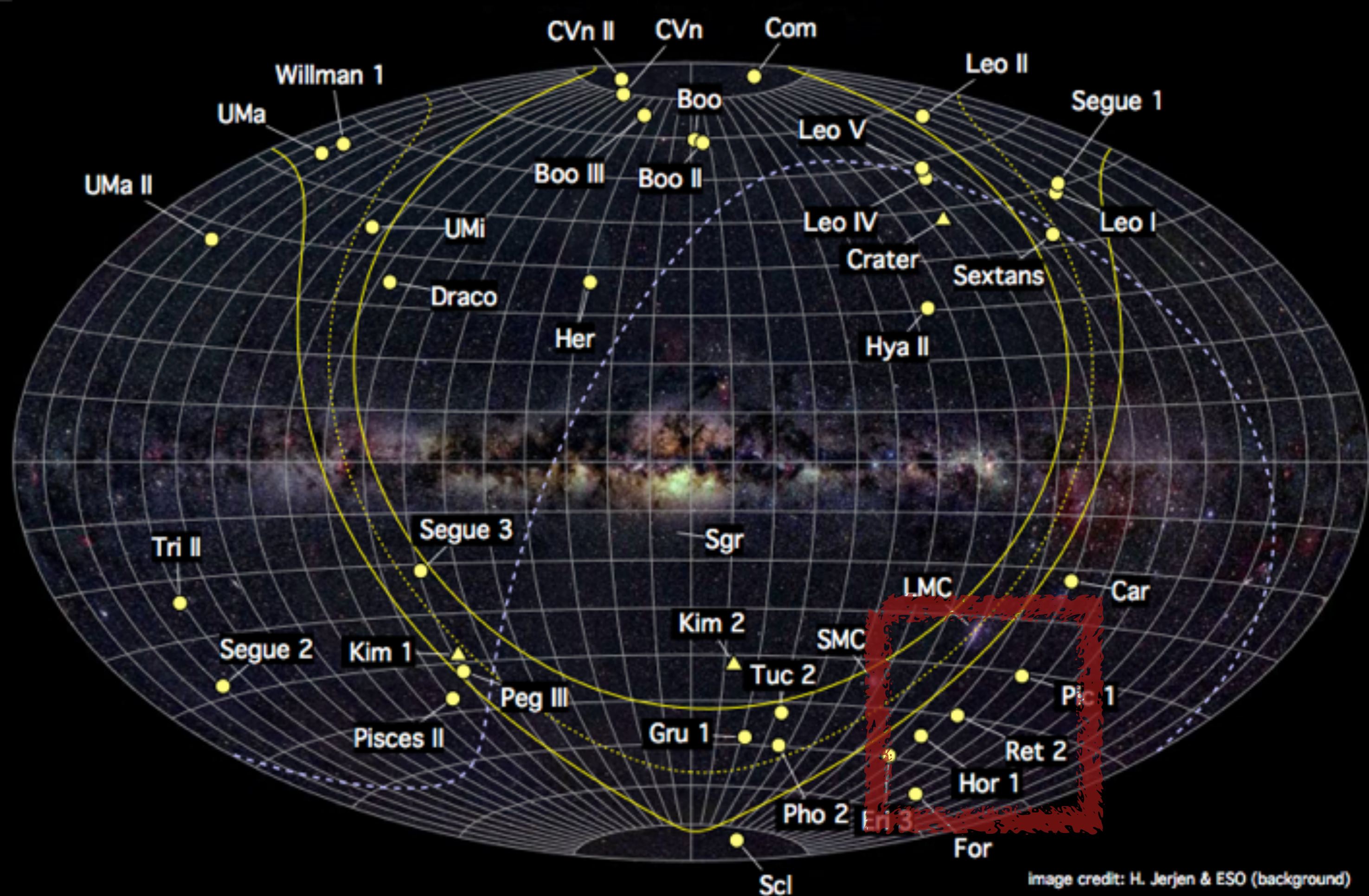


- Also see radioactive deep sea measurements
Wallner et al. 2015
Hotokezaka et al. 2015

Tanvir et al. 2013

Let’s consider something new...!

New Milky Way Satellites

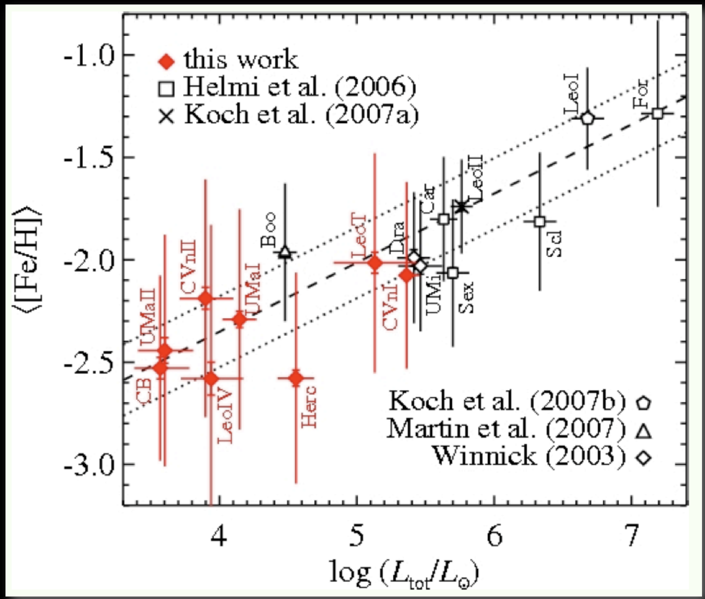


Reticulum II

Dark Energy Survey

Ultra-faint dwarf galaxies 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 generations of star formation

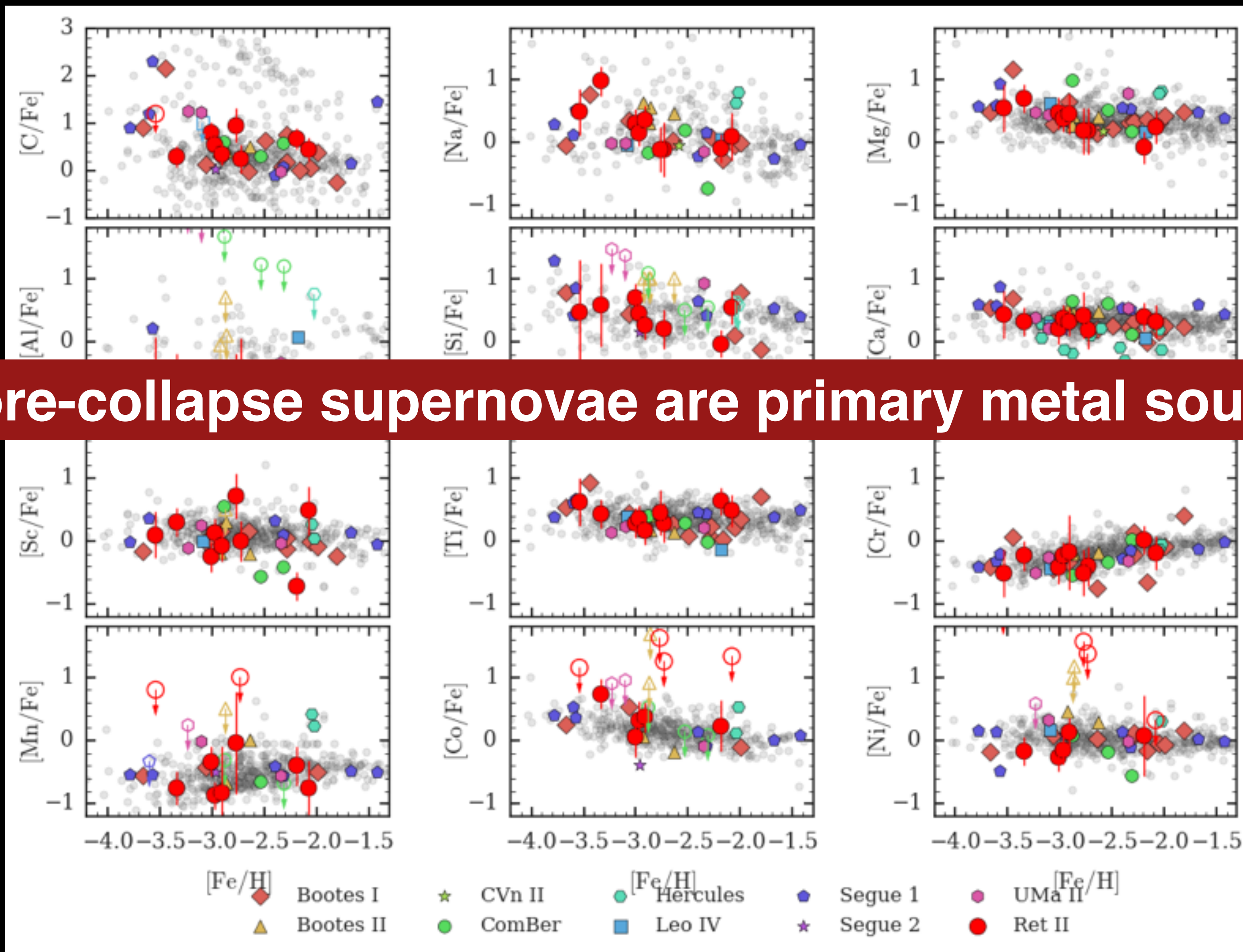


Ultra-faint dwarfs

Classical dSphs

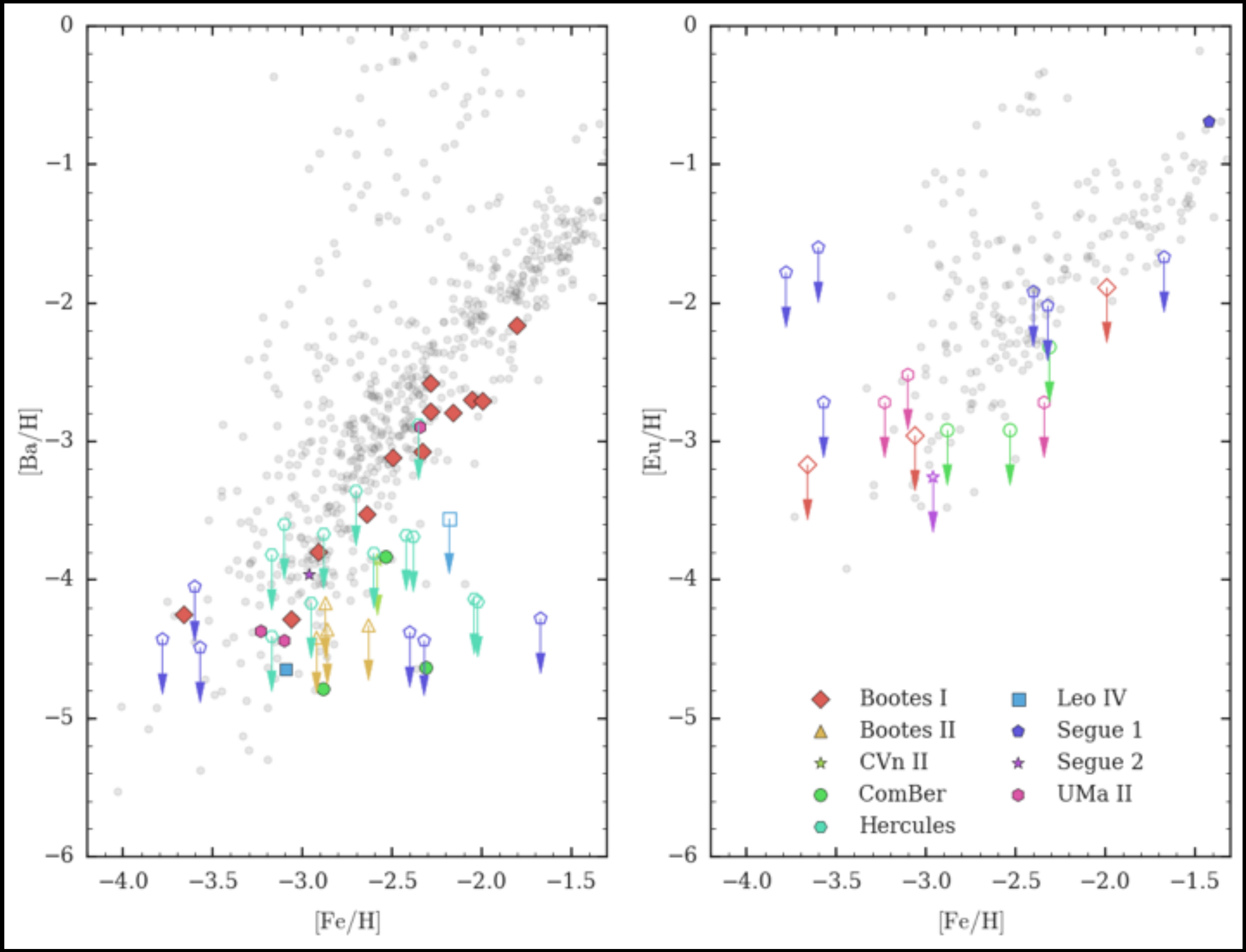
Light elements

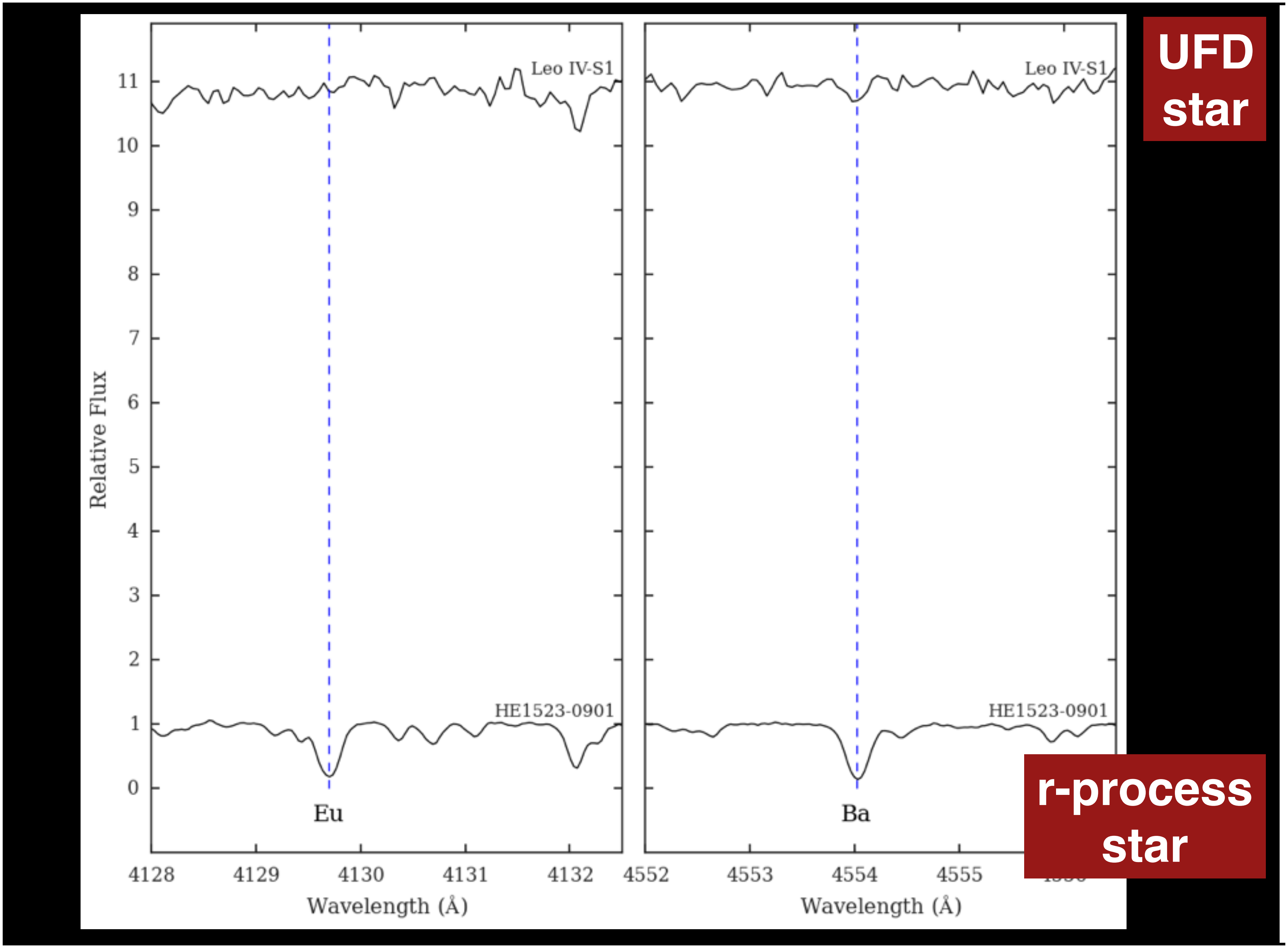
Ret II stars have similar abundances to UFD and halo stars



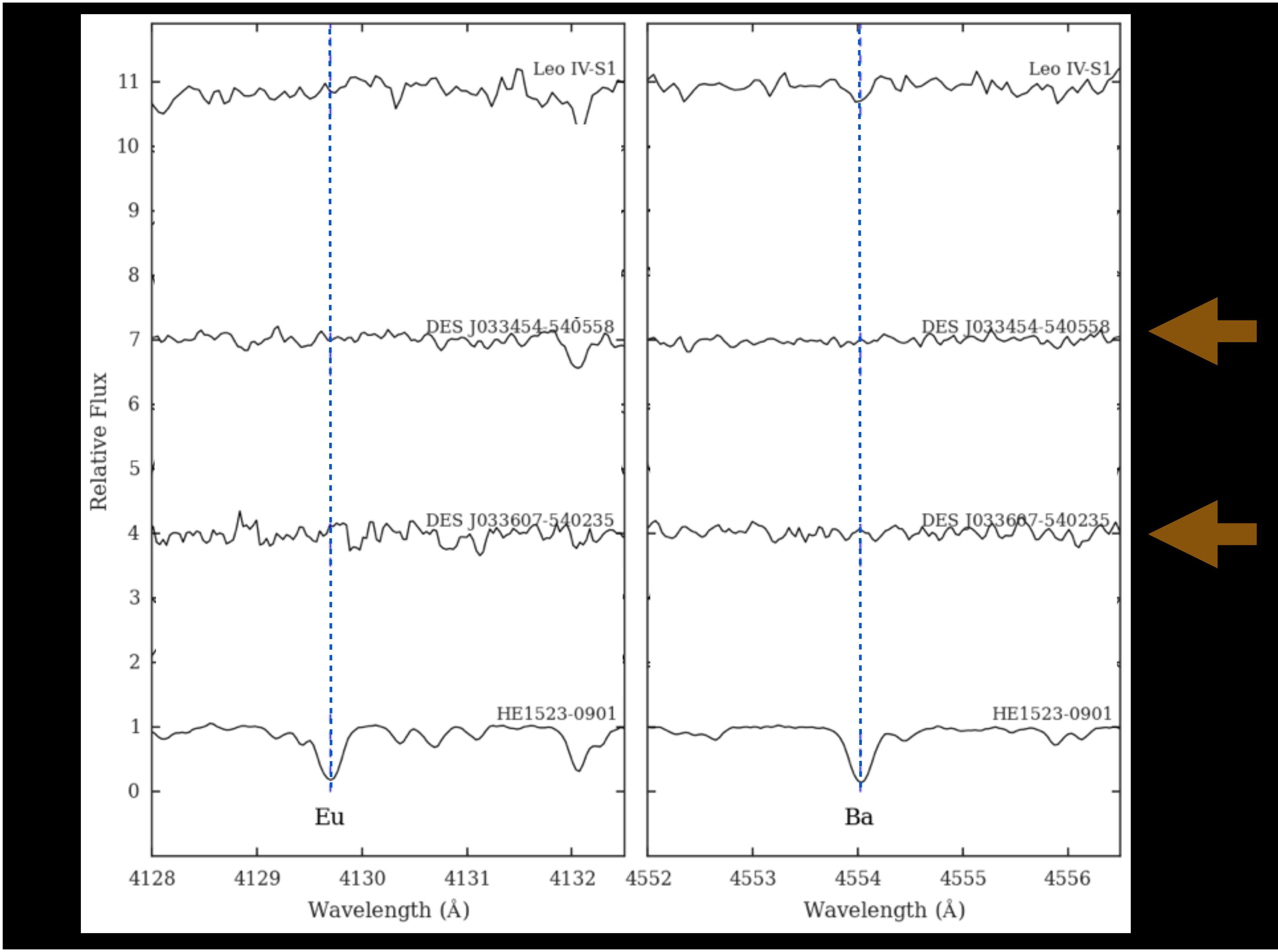
Core-collapse supernovae are primary metal source

Stars in *first nine* UFDs have low neutron-capture element abundances

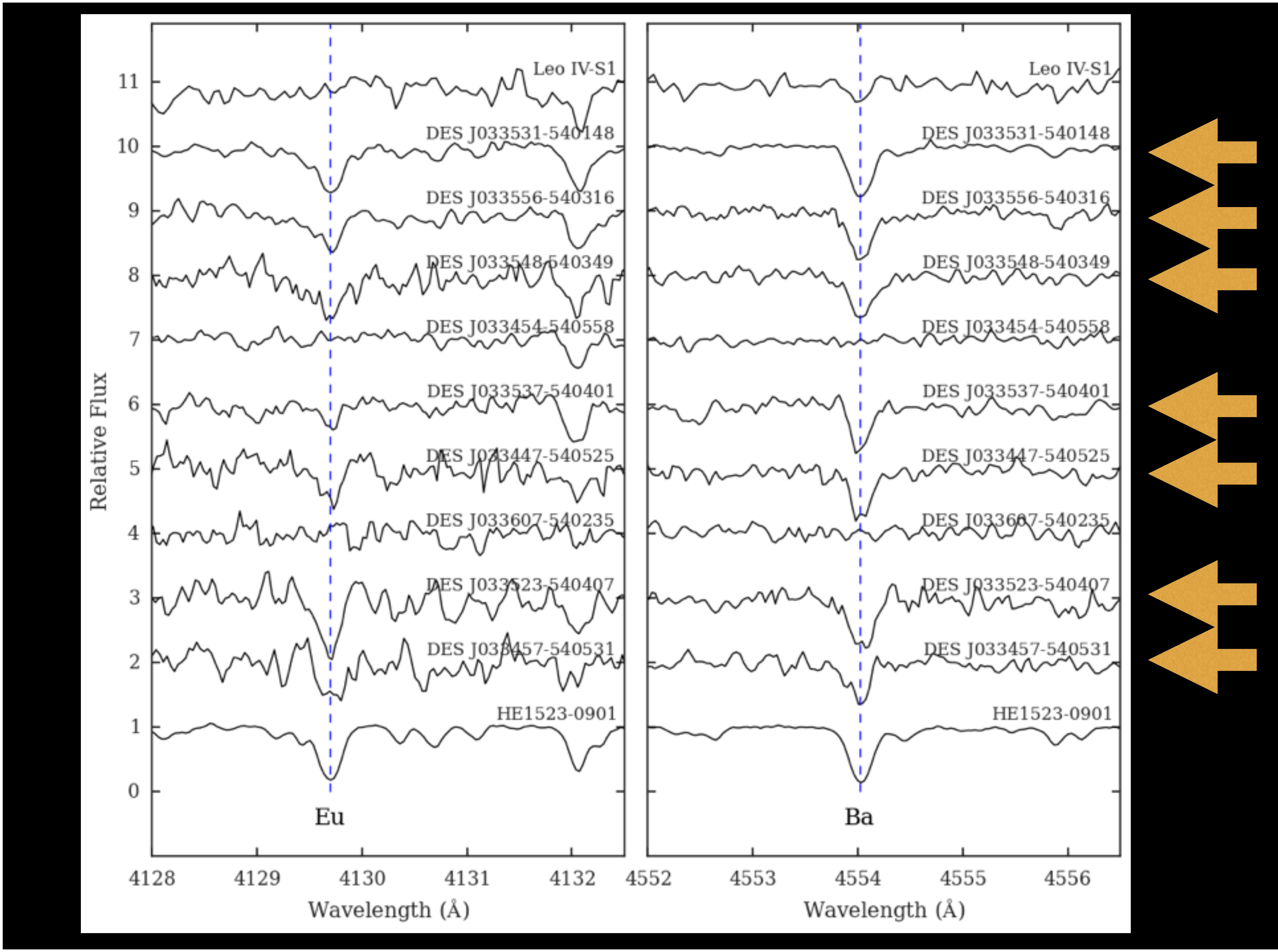




Relative Flux
Leo IV-S1
HE1523-0901
Eu
Ba
Wavelength (Å)
Wavelength (Å)
UFD star
r-process star

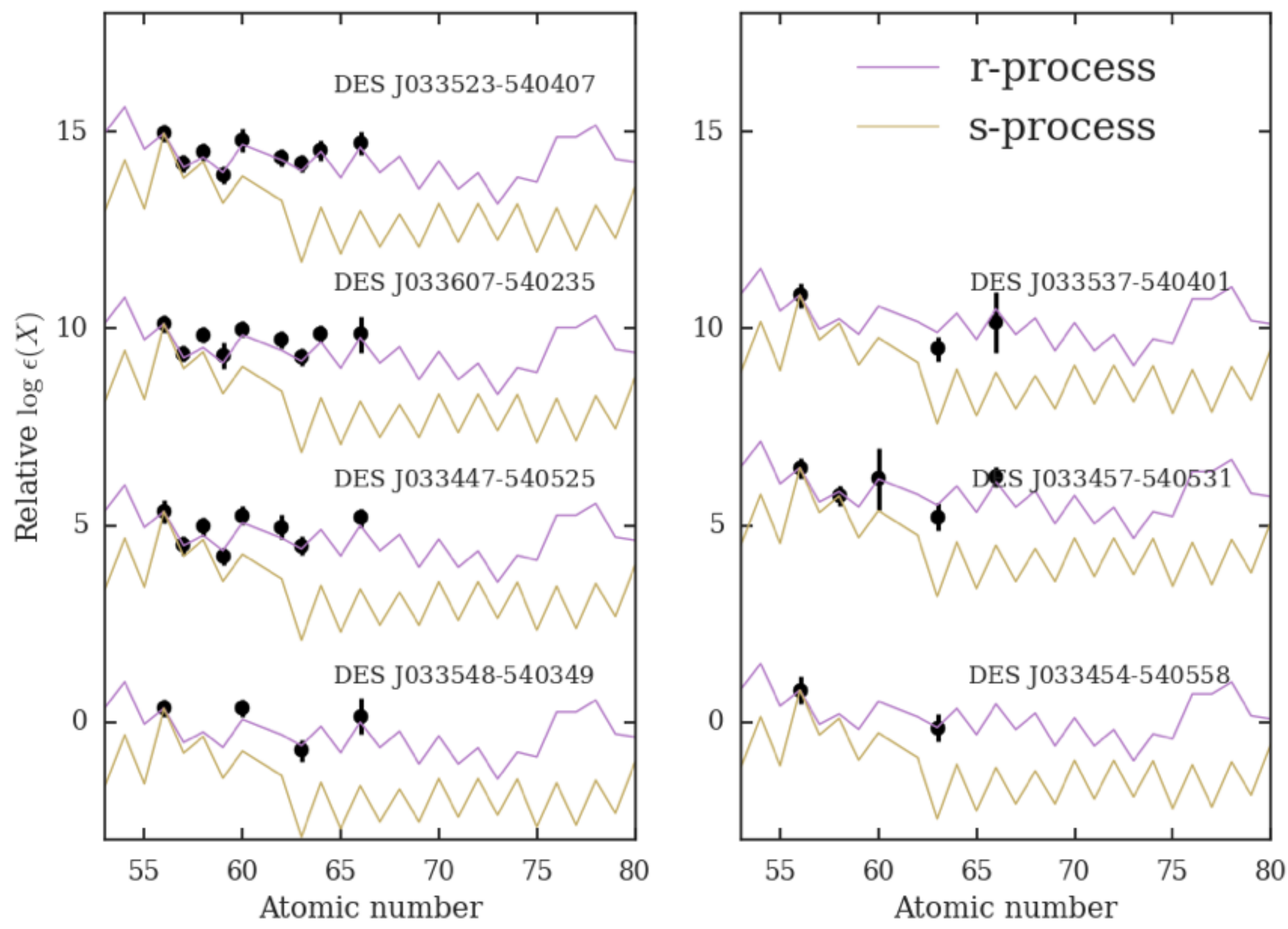


Relative Flux
Leo IV-S1
DES J033454-540558
DES J033607-540235
HE1523-0901
Eu
Ba
Wavelength (Å)
Wavelength (Å)

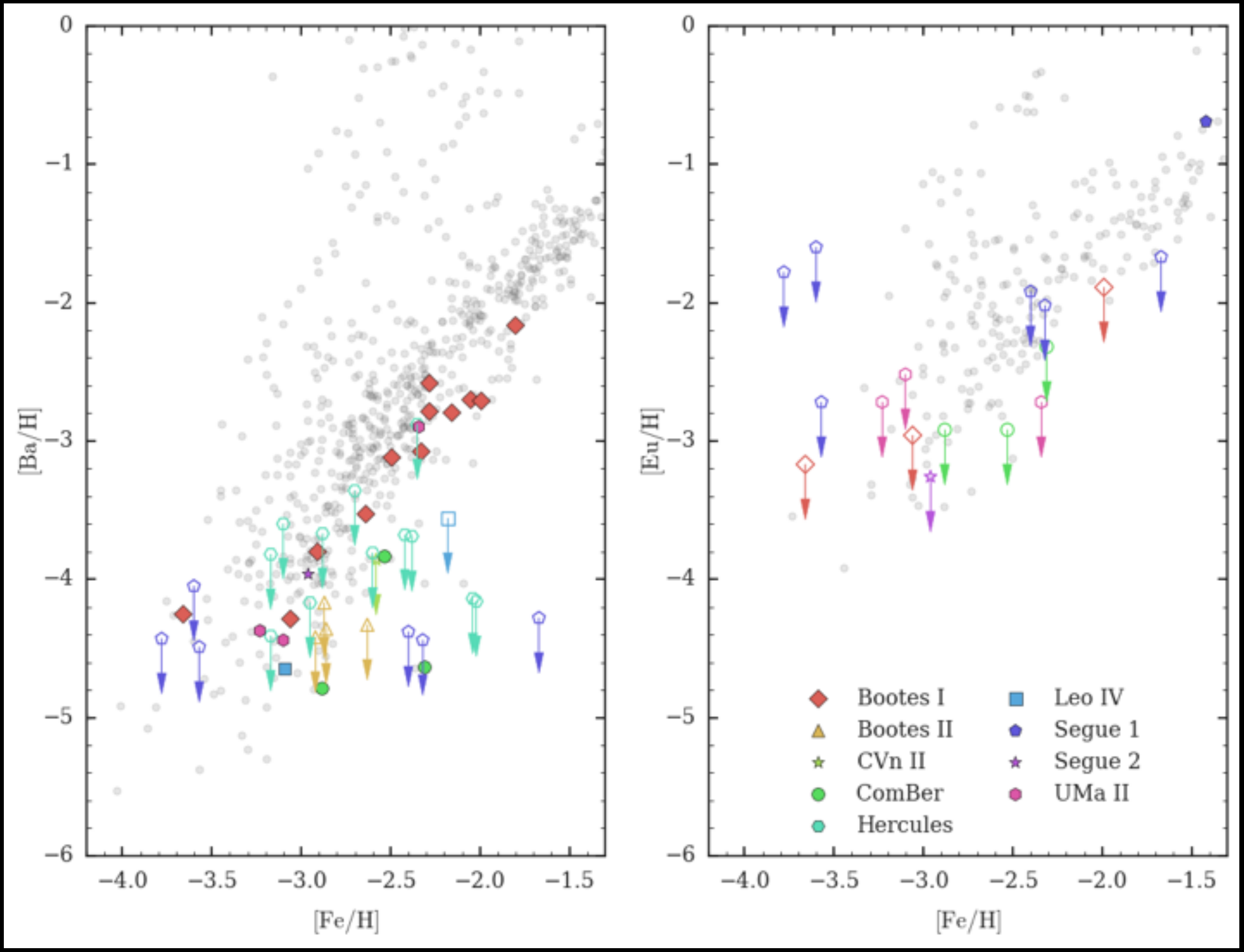


Leo IV-S1
DES J033531-540148
DES J033556-540316
DES J033548-540349
DES J033454-540558
DES J033537-540401
DES J033447-540525
DES J033607-540235
DES J033523-540407
DES J033457-540531
HE1523-0901
Eu
Ba
Relative Flux
Wavelength (Å)
Wavelength (Å)

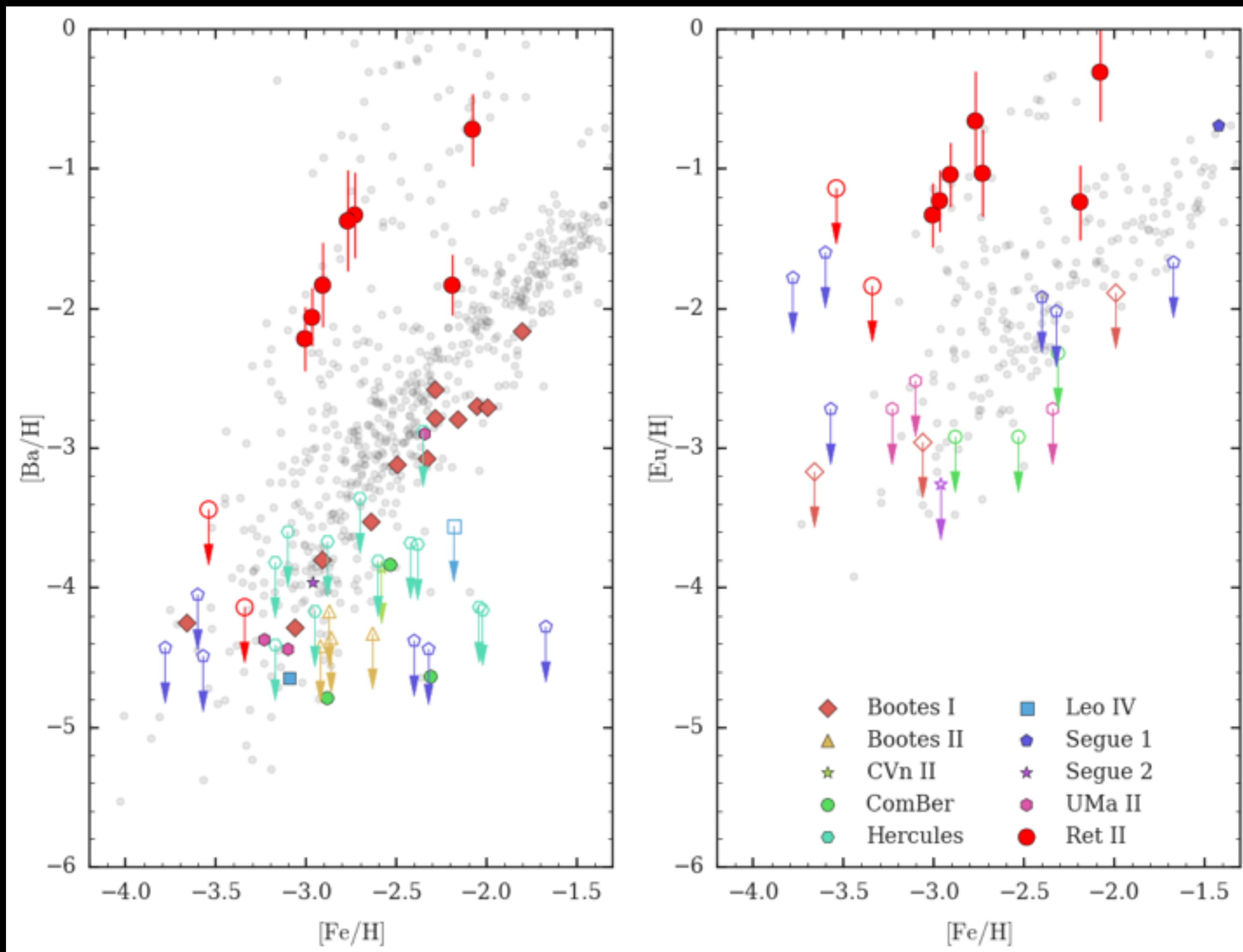
All Ret II stars match r-process pattern



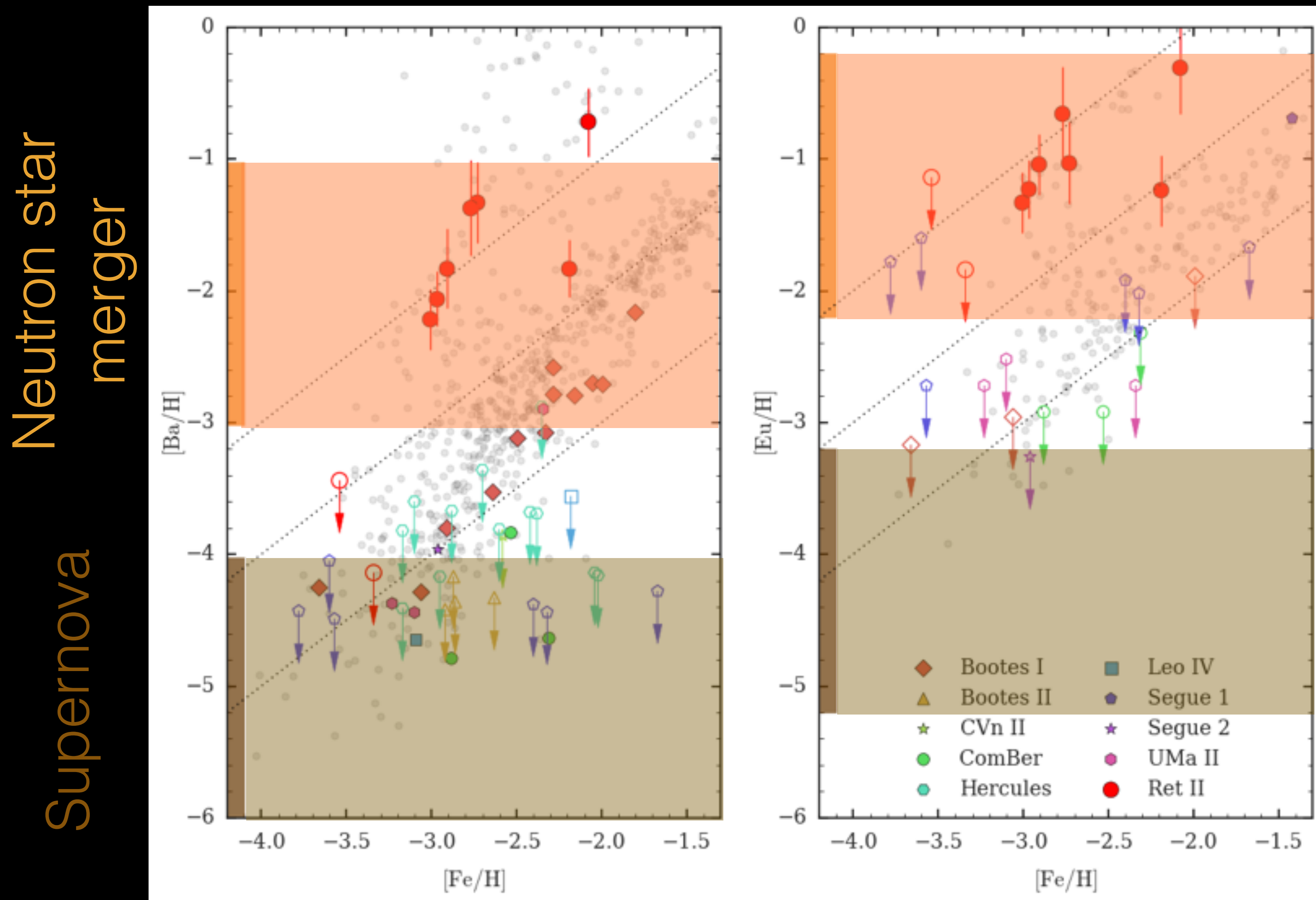
UFD neutron-capture abundances *before* Reticulum II



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

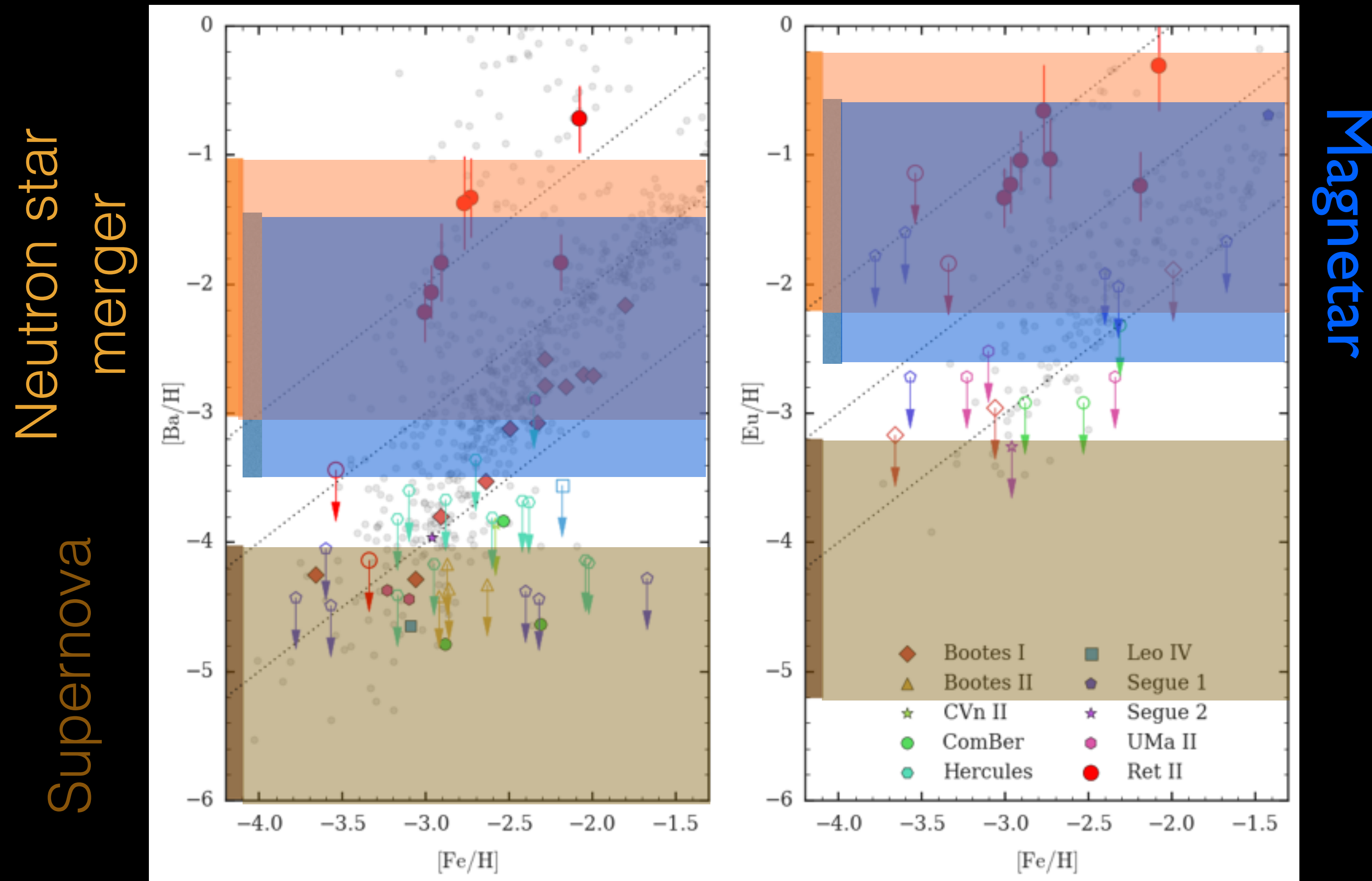


Ret II abundance consistent with neutron star merger



Rare and prolific supernovae also allowed

Jet supernovae from magnetorotational instability



e.g., Winteler et al. 2012

Reticulum II was enriched by a rare, prolific and possibly 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 SNe?

➡ No, 1000+ SNe would disrupt the system

➡ Need to be one/few massive events

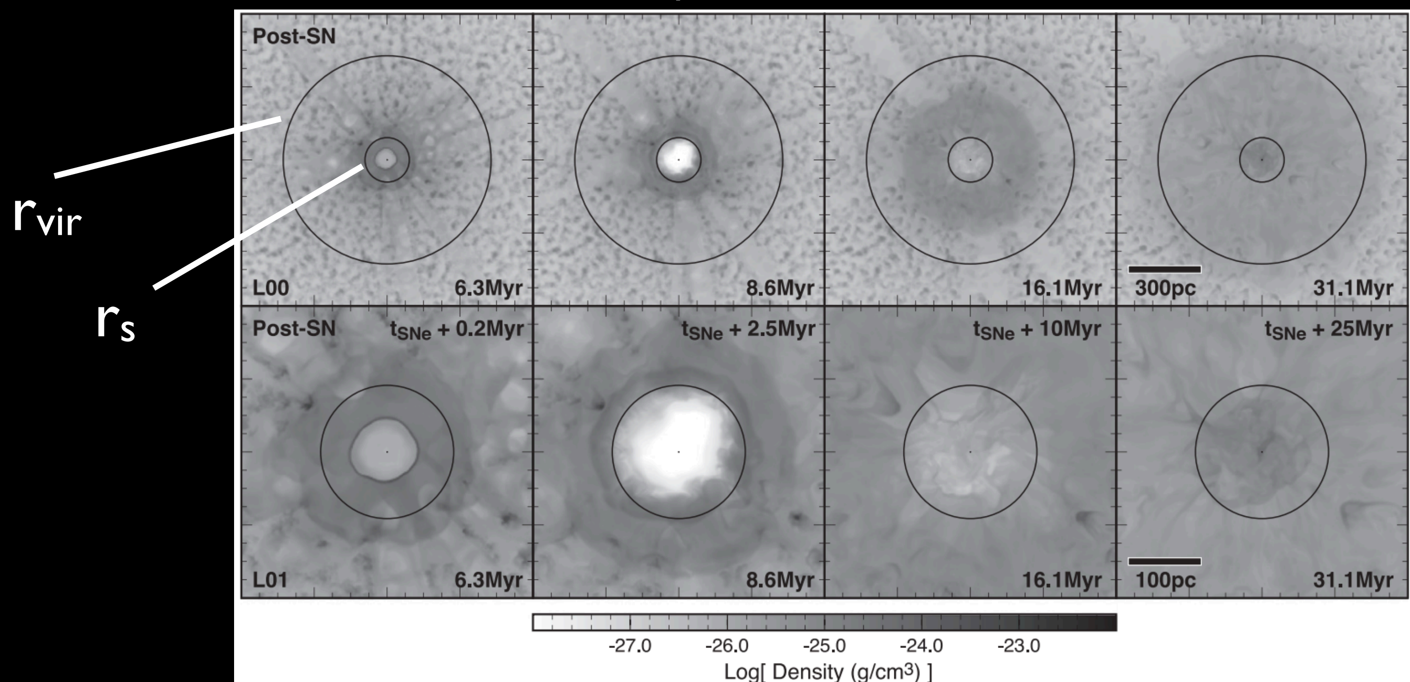
Aren't NSM taking too long to enrich the galaxy?

➡ After the few (initial) SNe 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

$10^{-6.5}$Msun halo (Bland-Hawthorn et al. 2015)



after SN

blow-out max

shells

re-accretion
denser regions begin to form

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

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

How Prolific?

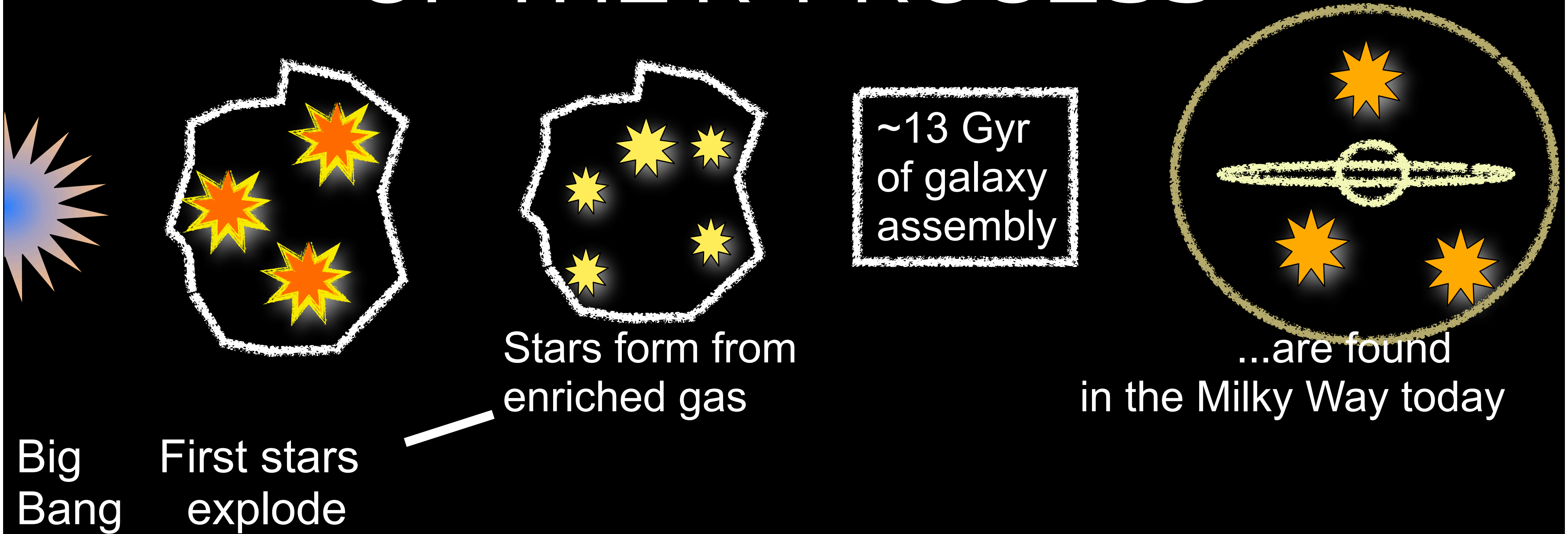
Estimate gas mass of UFD:

Total gas in UFD galaxy
➡Max. dilution mass: $\sim 10^7\ M_{sun}$

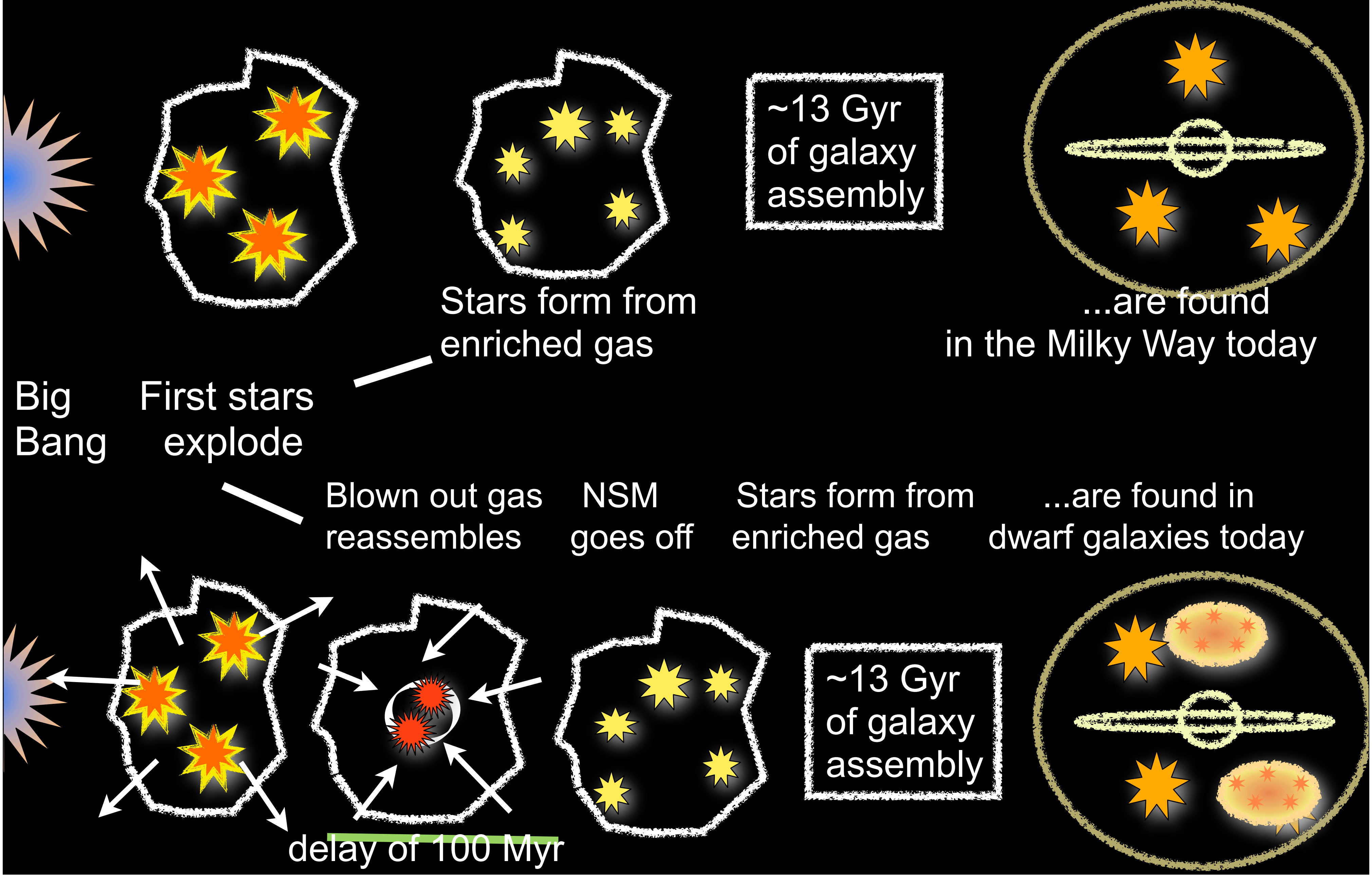
Gas swept up by a 10^{51}erg energy injection into typical ISM
➡Min. dilution mass: $\sim 10^5\ M_{sun}$

➡Use with yields to compare to observations

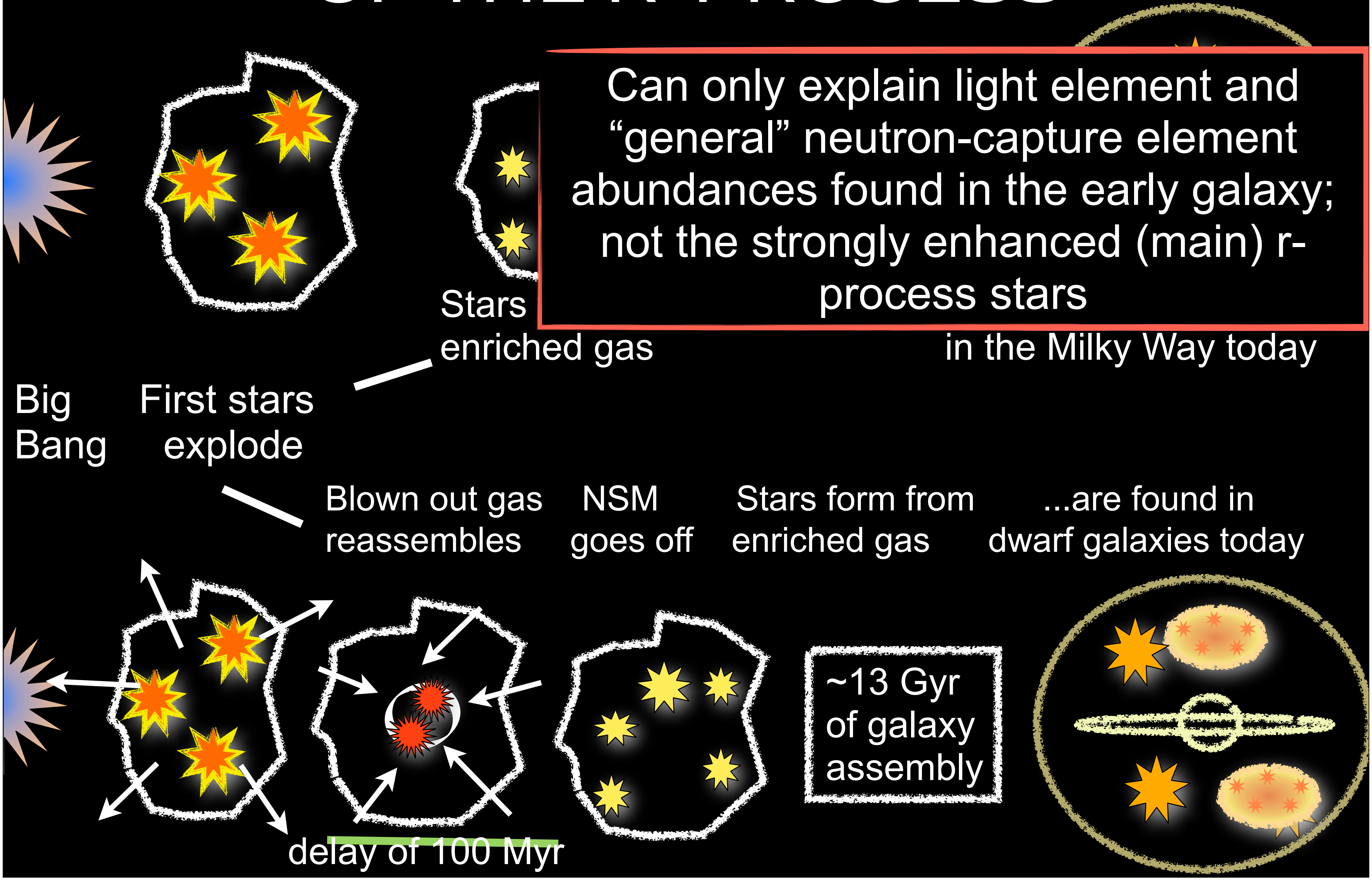
Astrophysical environment of the r-process



Astrophysical Environment of the R-Process



Astrophysical environment of the r-process



Answers to the Big Question

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

- ➡ Core-collapse supernovae ➡Rare and prolific site
- ➡ Neutron star mer ➡Consistent w/ Ret II abundances
- ➡ Others (e.g., magnetars) ➡Remain possible

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

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

★ **Does the dominant site change?** ➡Probably not!

Another puzzle:
Chemical Enrichment in Ret II

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

➡ Sequential bursts of star formation?

➡ Inhomogeneous metal mixing?

➡ Accretion of other, smaller galaxy?

The future is here

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

Near-field cosmology meets nuclear astrophysics

✓ 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, etc.

Characterize the formation history of Ret II

➡ Need better abundances of (more) stars in Ret II

➡ Narrow down the identity of the rare and prolific r-process event (**w/ better data and better predictions**)

Looking ahead

"See the forest for the trees"

Re-interpreting population of r-process halo stars in the context of a dwarf galaxy environment

➡ *Where did these halo stars originate?*

➡ *Do they uniquely trace a 1/10 UFD population?*

➡ *Can we use them to trace the early assembly of the Milky Way/the low-metallicity tail of the MW MDF?*