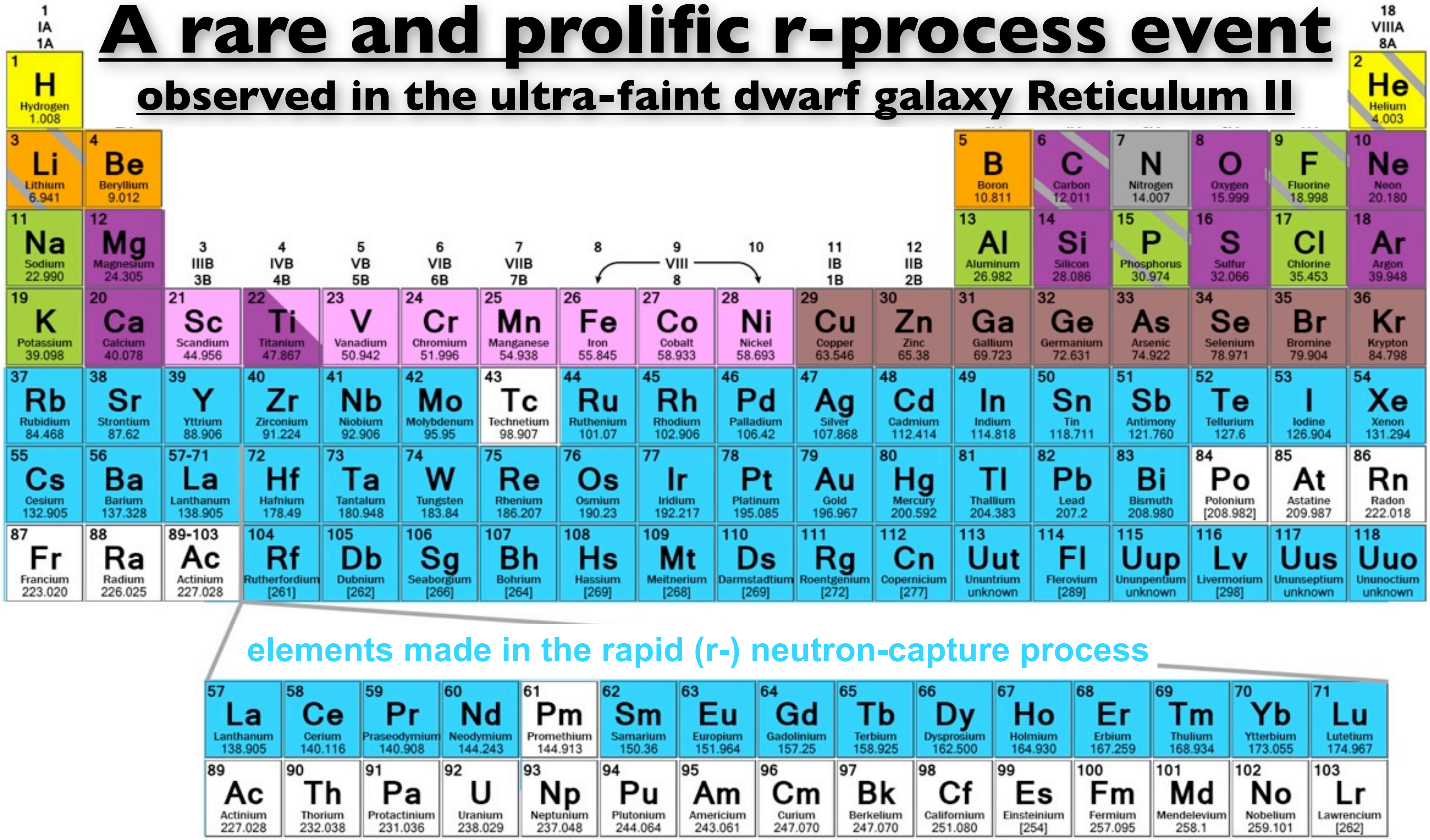
A rare and prolific r-process event

observed in the ultra-faint dwarf galaxy Reticulum II

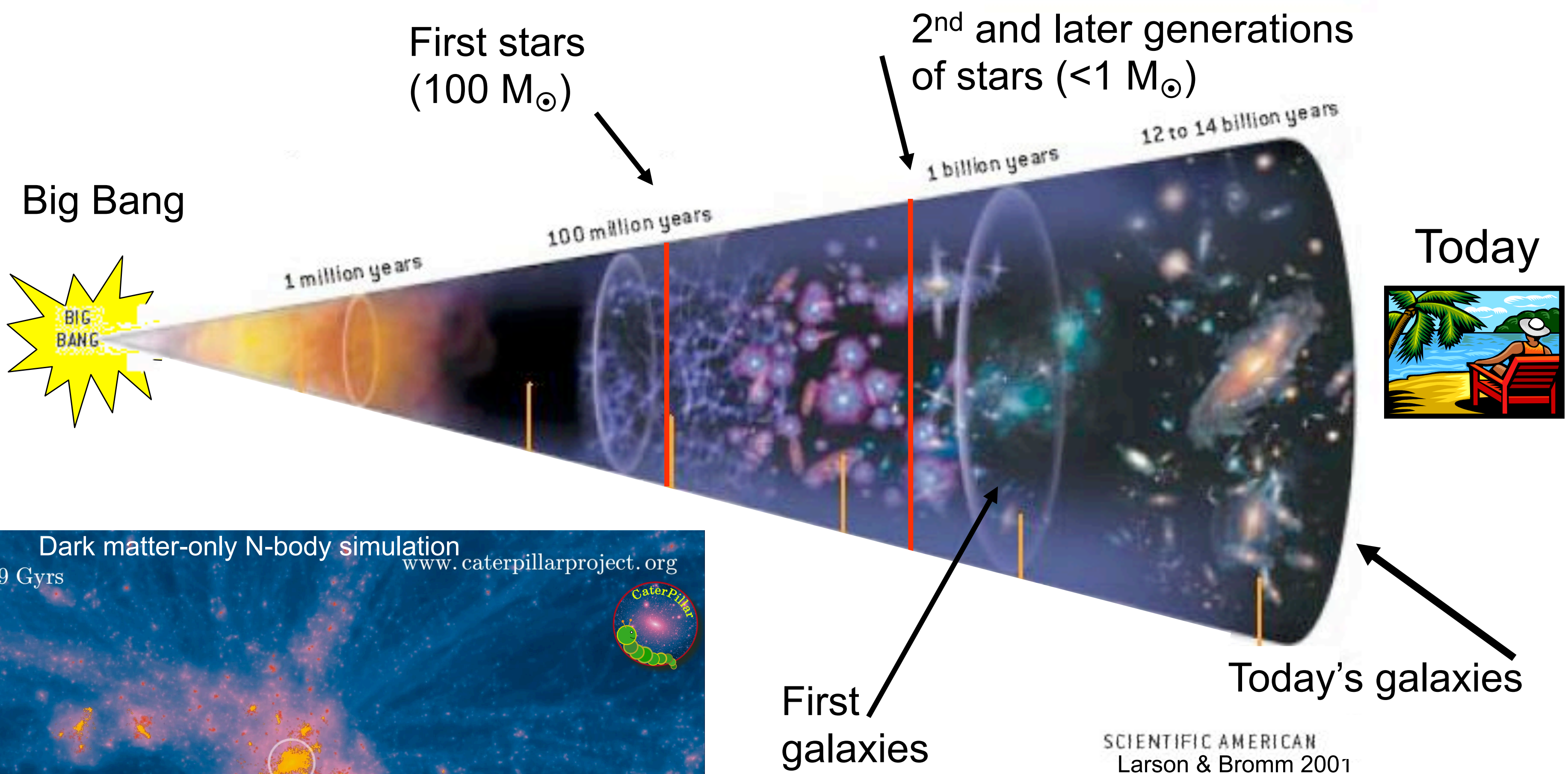


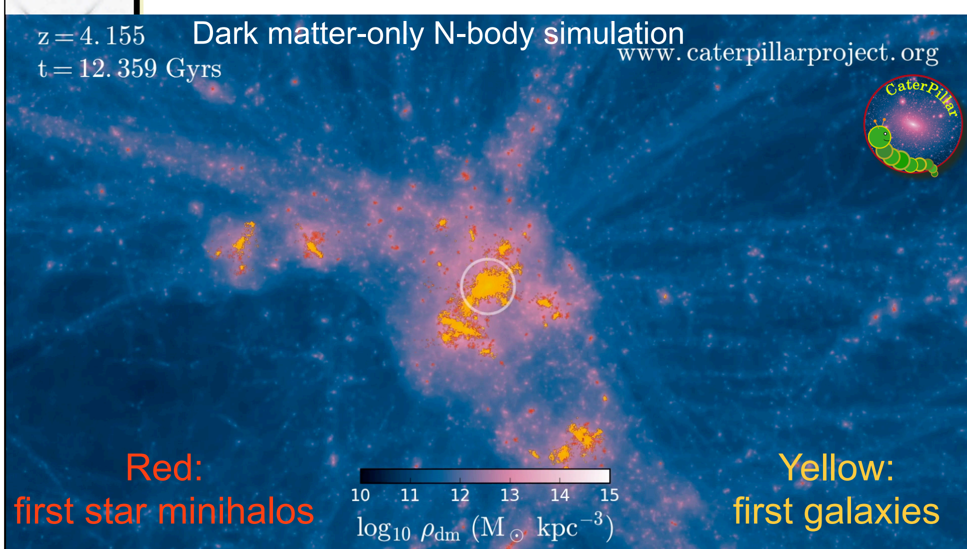
Anna Frebel

Massachusetts Institute of Technology

Anna Frebel

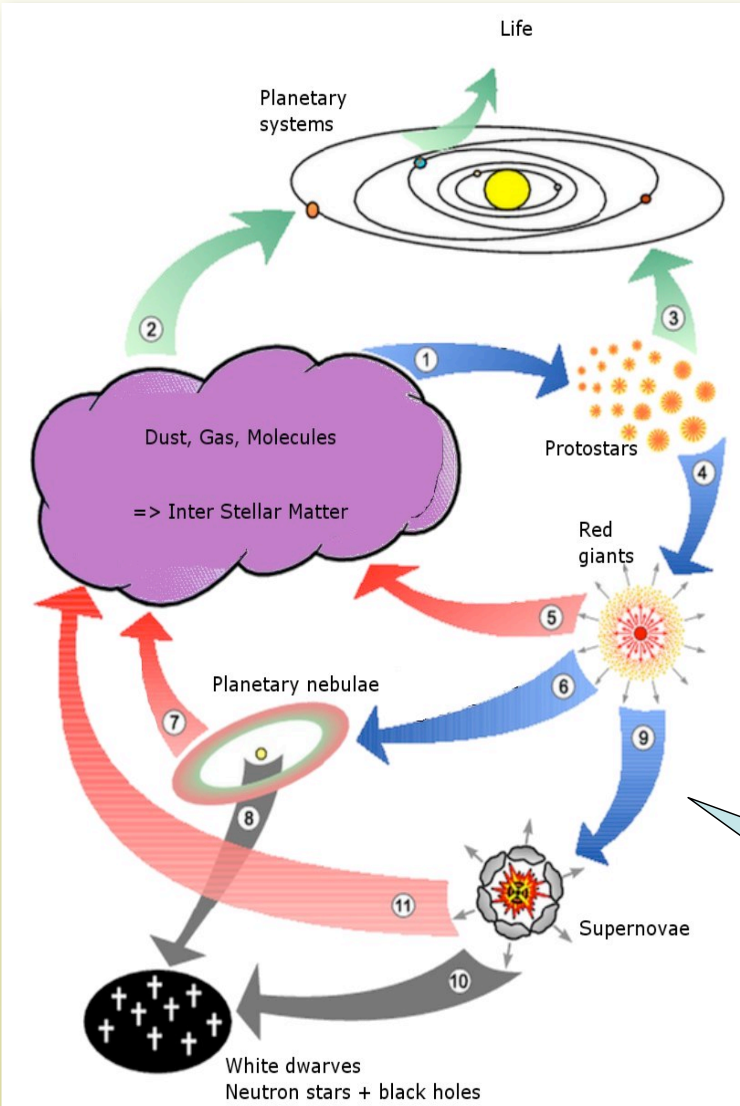
A long time ago...





Cosmic time (not to scale)

CHEMICAL EVOLUTION



Zentrum fuer Astronomie und Astrophysik, TU Berlin

Stars are made from ~75% H and ~25% He, but:

⇒ Early stars contain little of all elements

⇒ Younger stars contain larger amounts

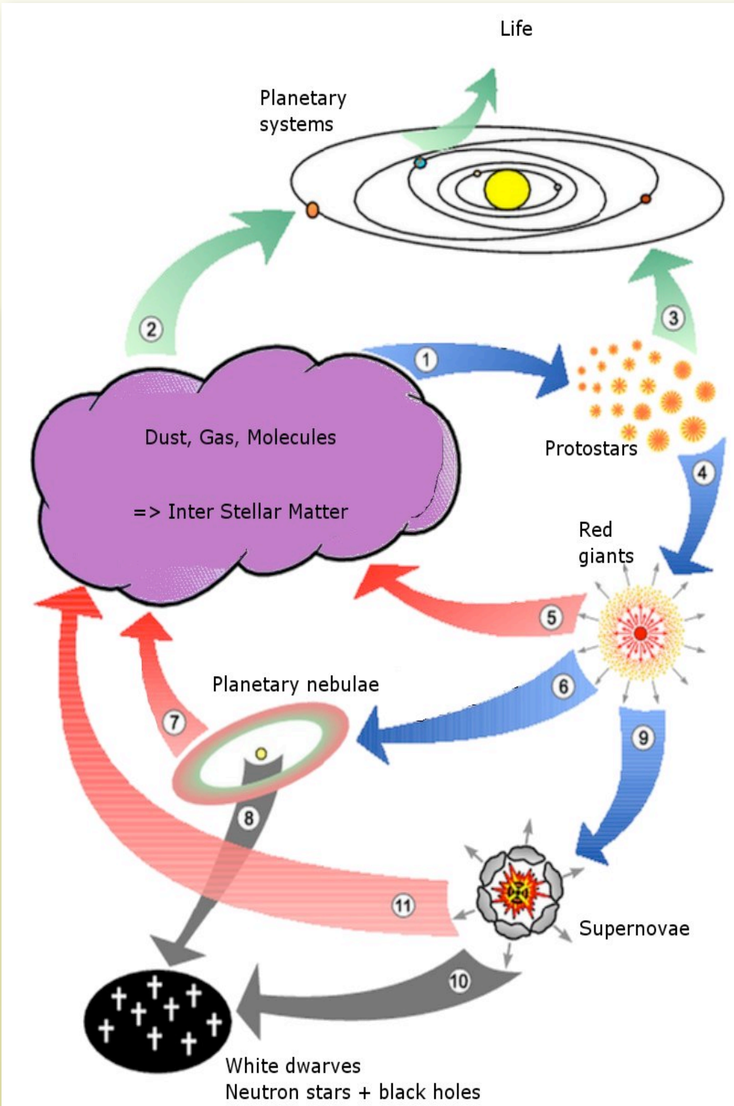
Examples

Sun: contains 1.4 % heavy elements (by mass)

Oldest stars: 10^{-4} to 10^{-7} % heavy elements

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

CHEMICAL EVOLUTION

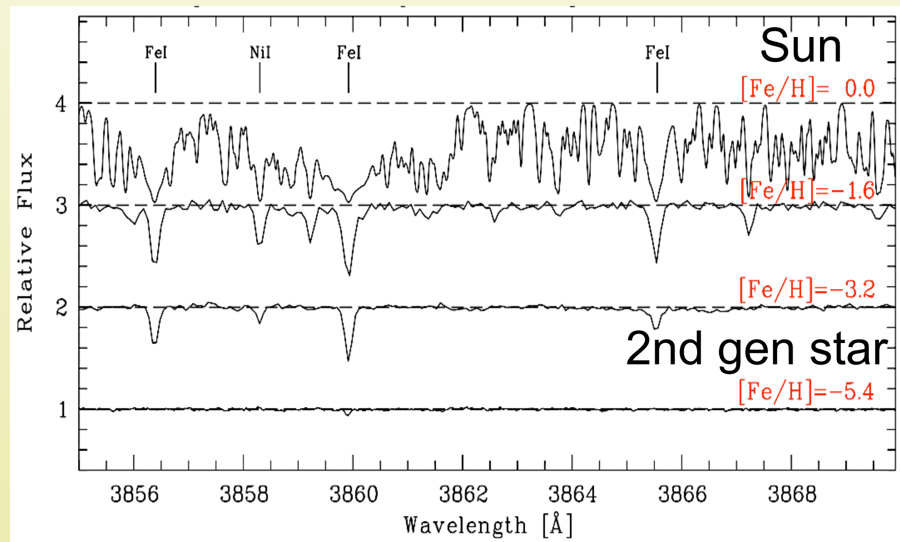


Stars are made from ~75% H and ~25% He, but:

⇒ Early stars contain little of all elements

⇒ Younger stars contain larger amounts

“Look-back time”



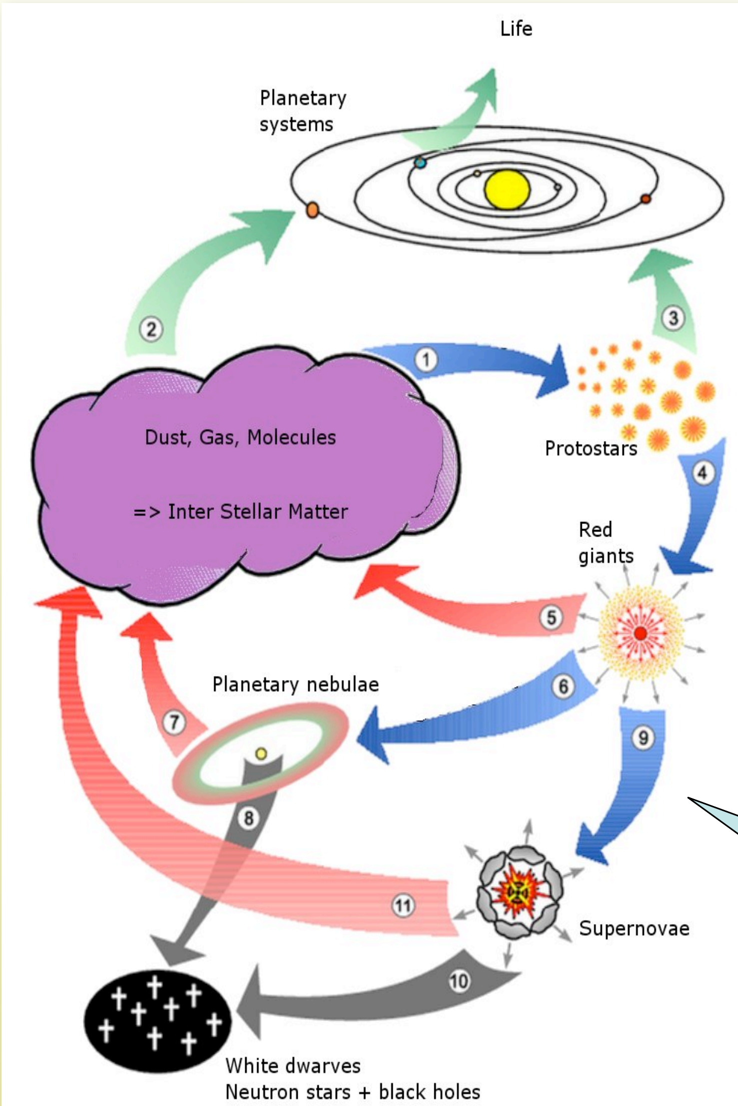
Galactic chemical evolution

Abundances are derived from integrated absorption line strengths

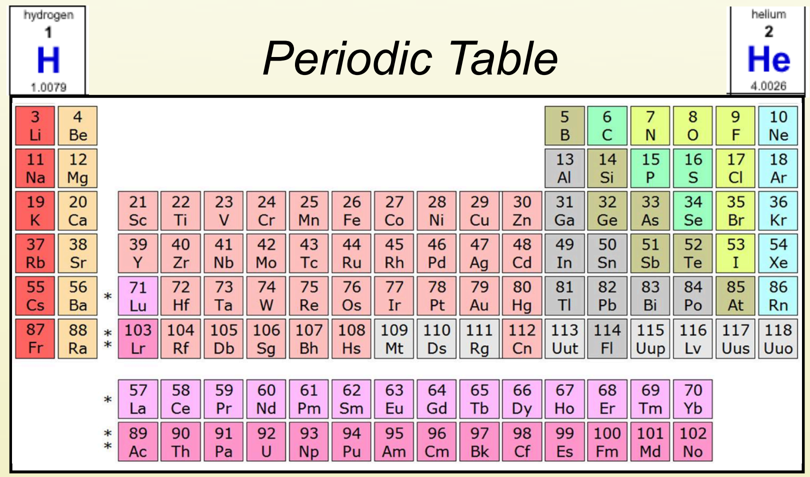
$$[Fe/H] = \log(N_{Fe}/N_H)_* - \log(N_{Fe}/N_H)_\odot$$

Zentrum fuer Astronomie und Astrophysik, TU Berlin

CHEMICAL EVOLUTION



Zentrum fuer Astronomie und Astrophysik, TU Berlin

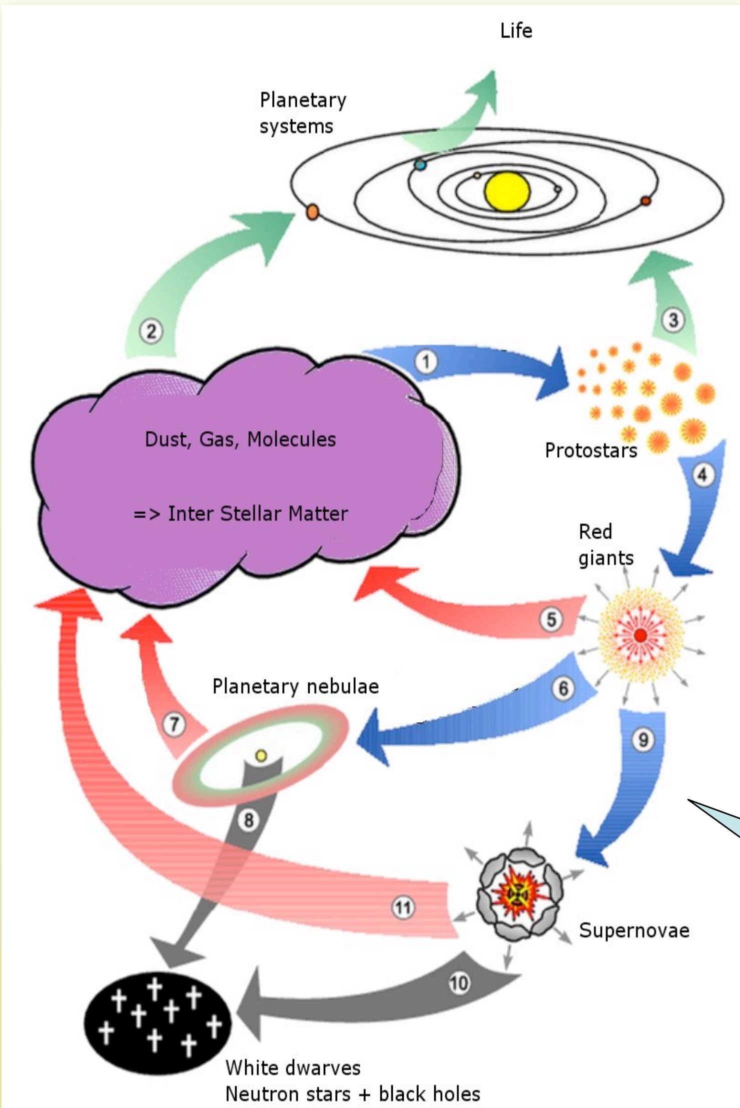


With time, more and more of all elements were made!

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

CHEMICAL EVOLUTION

Zentrum fuer Astronomie und Astrophysik, TU Berlin



H: X

Astronomers' Periodic Table

He: Y

Metals Z

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

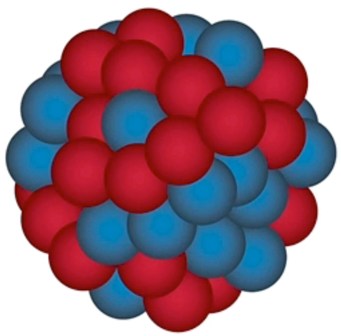
We look for stars **that are <u>metal-poor</u> compared to the Sun's composition!**

The Story of Reticulum II

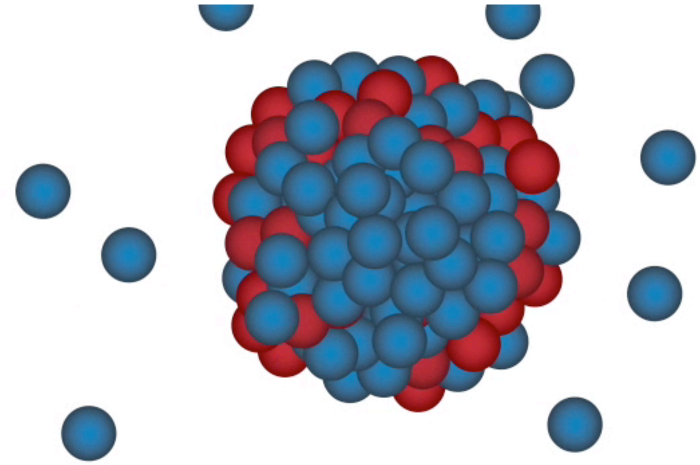
Nuclear Astrophysics	Stellar Archaeology	Dwarf Galaxy Archaeology
Cosmic origin of the chemical elements	Clues to the astrophysical site of r-process nucleosynthesis	Ancient, clean chemical enrichment signatures

NUCLEOSYNTHESIS IN STARS

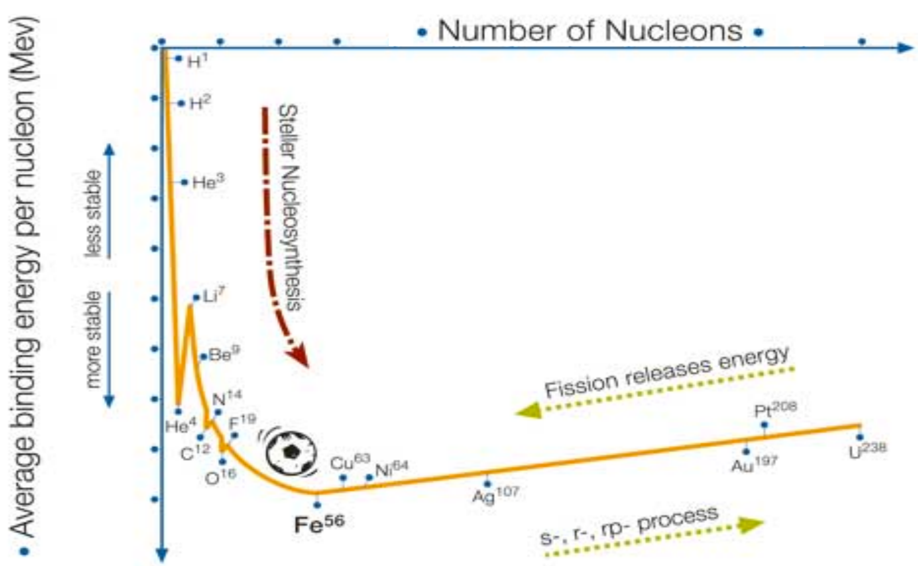
(Depends on stellar mass, stellar evolutionary status, others...)



^{56}Fe Iron

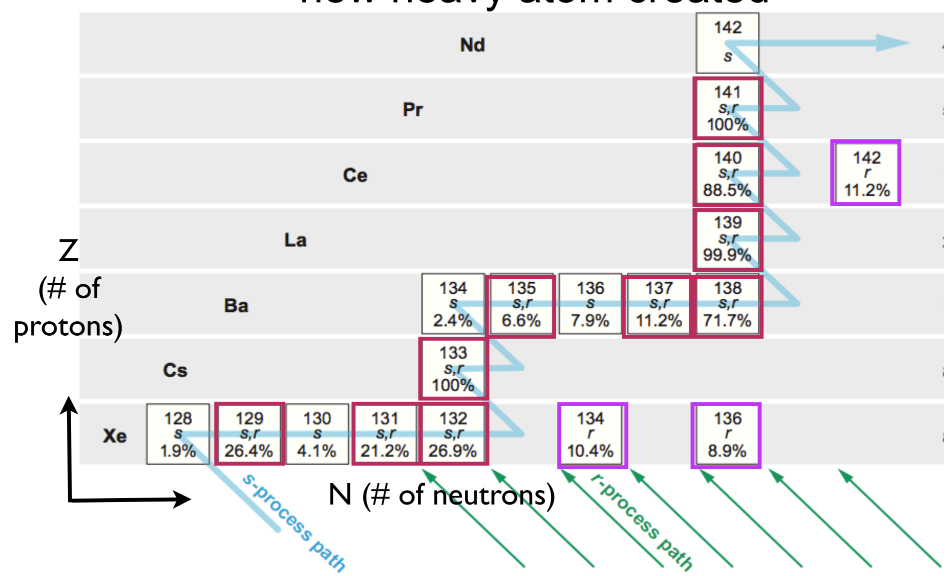


new heavy atom created



Fusion: H to iron

during stellar evolution



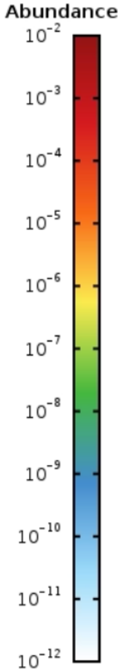
Neutron-capture processes

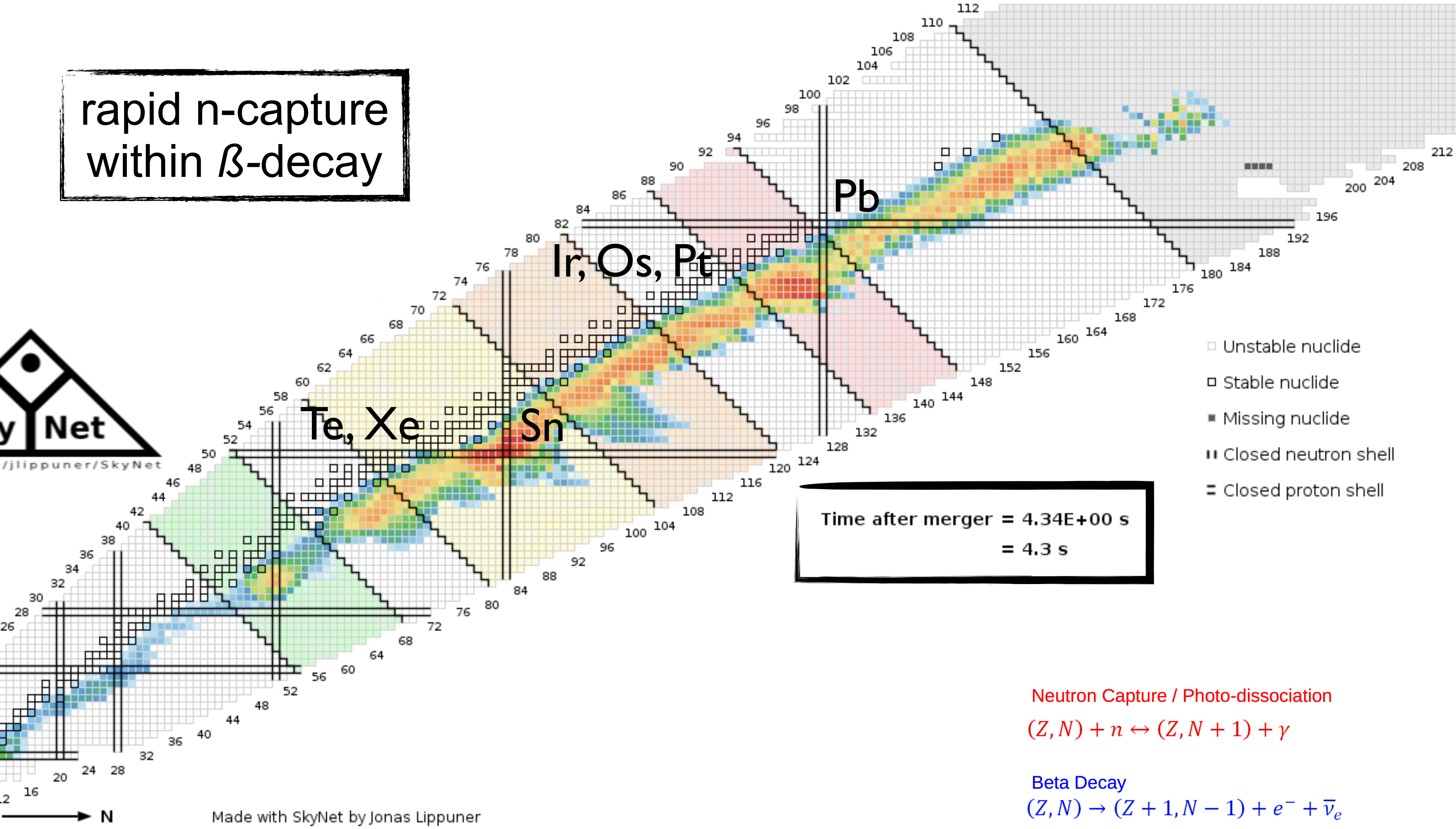
slow n-capture: advanced stellar evolution

rapid n-capture: site undetermined(!)

RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

(neutron star merger scenario)





Neutron Capture / Photo-dissociation

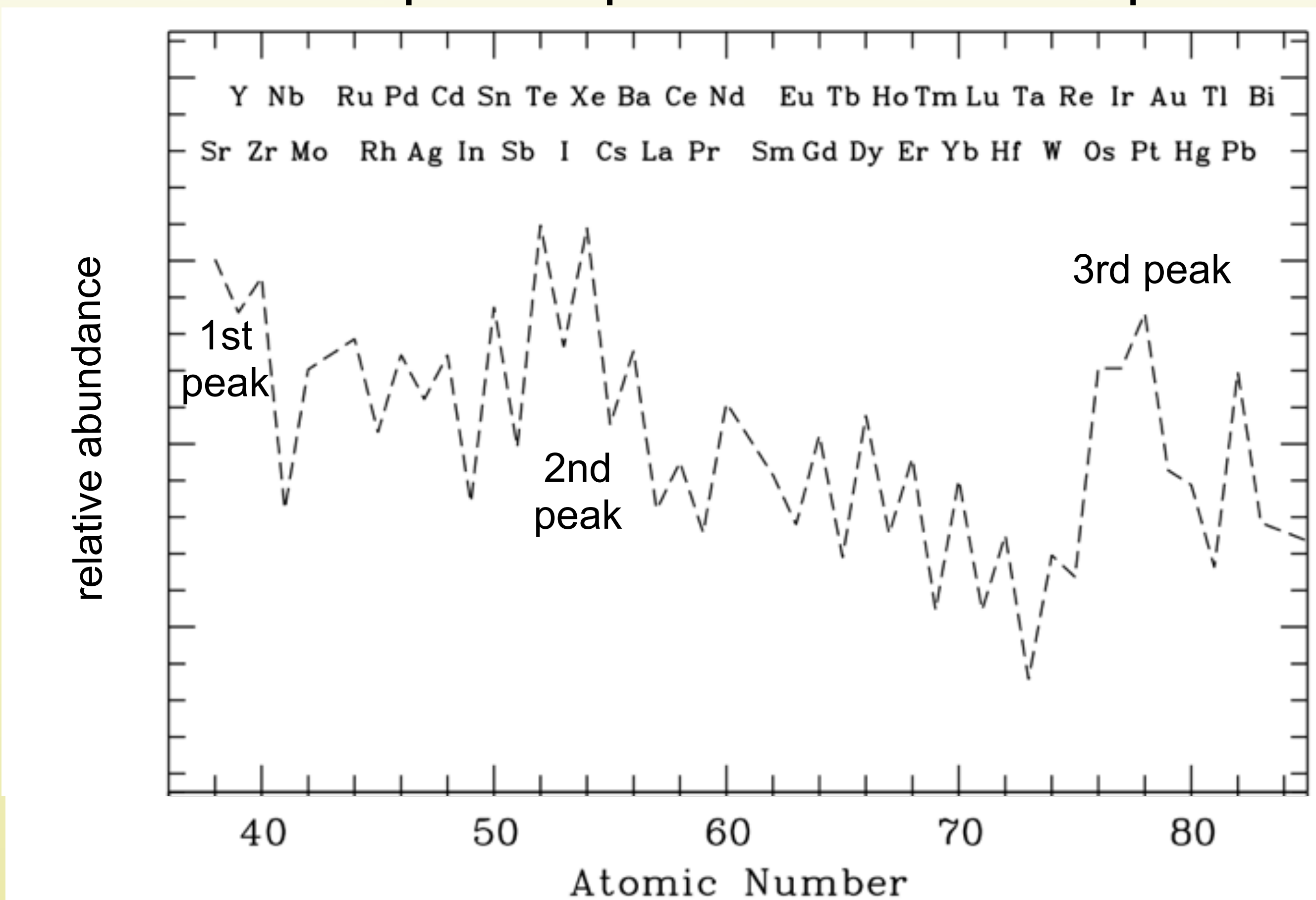
$$(Z, N) + n \leftrightarrow (Z, N+1) + \gamma$$

Beta Decay

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

R-PROCESS PATTERN

neutron-capture r-process elemental pattern

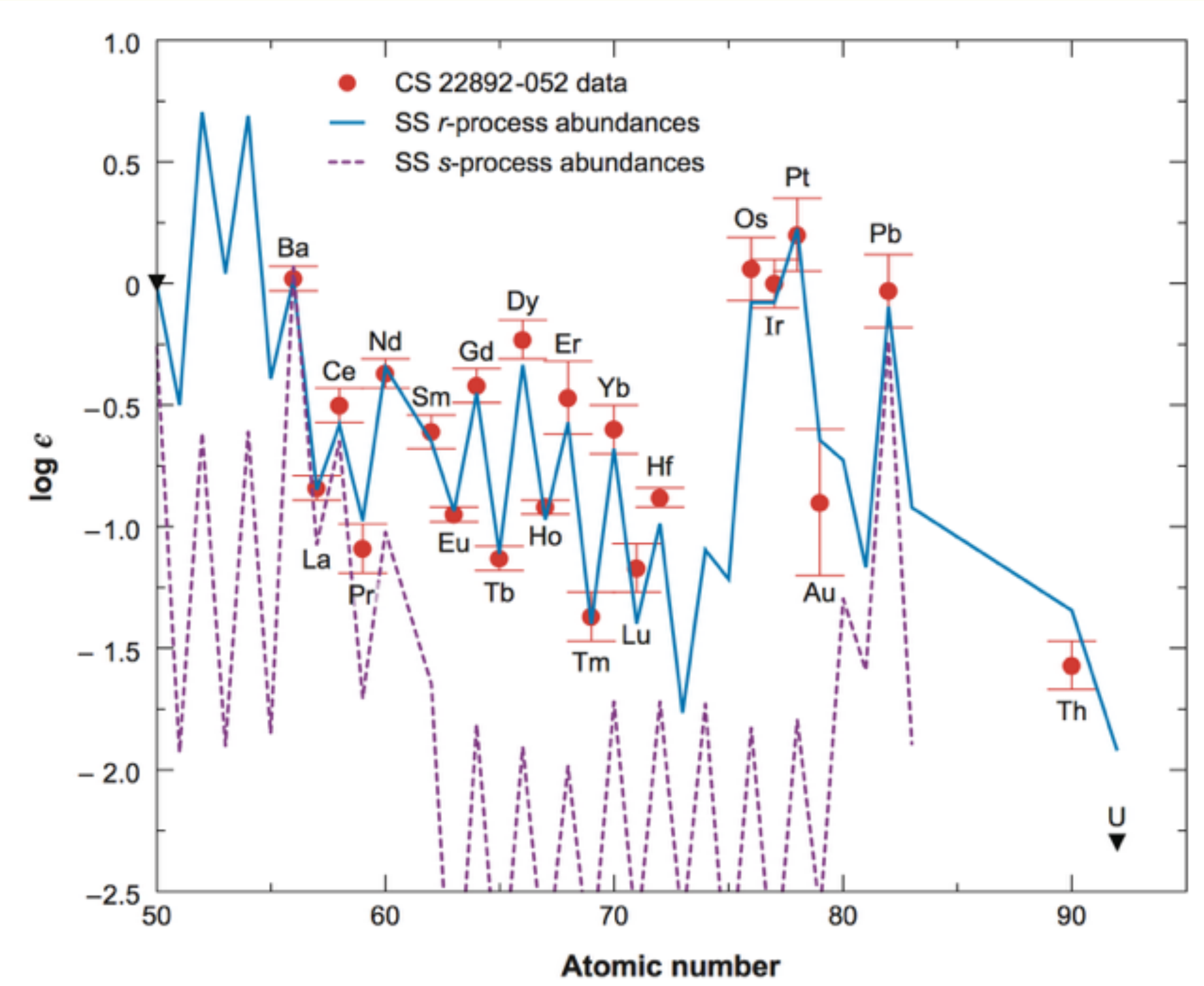


Universal r-process pattern observed in metal-poor stars

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

(= 1/1000th of solar Fe value)



Sneden et al. 2008

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

Rare r-process stars in the Milky Way

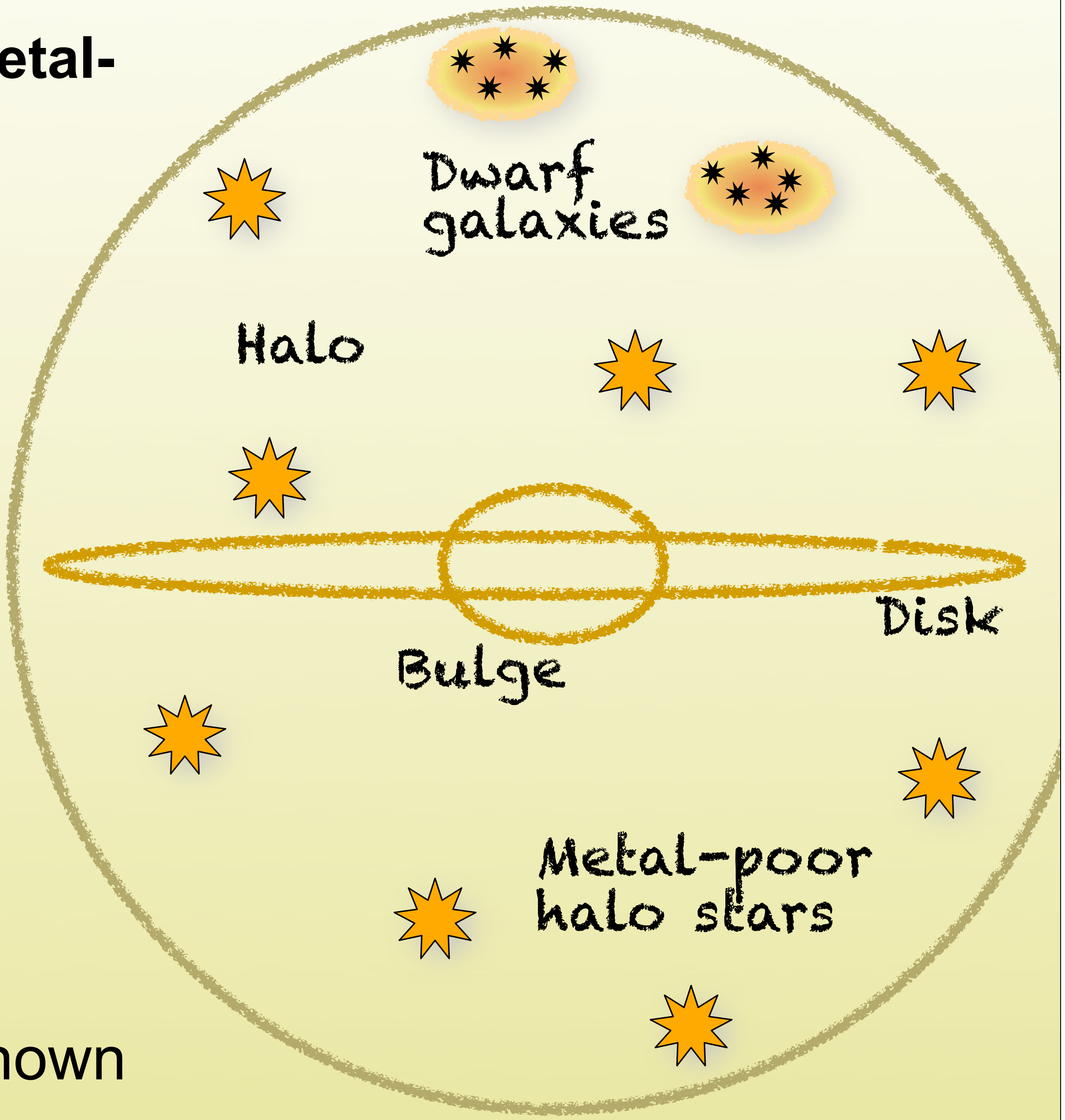
How common are r-process metal-poor stars in the Milky Way?

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

Only **~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**

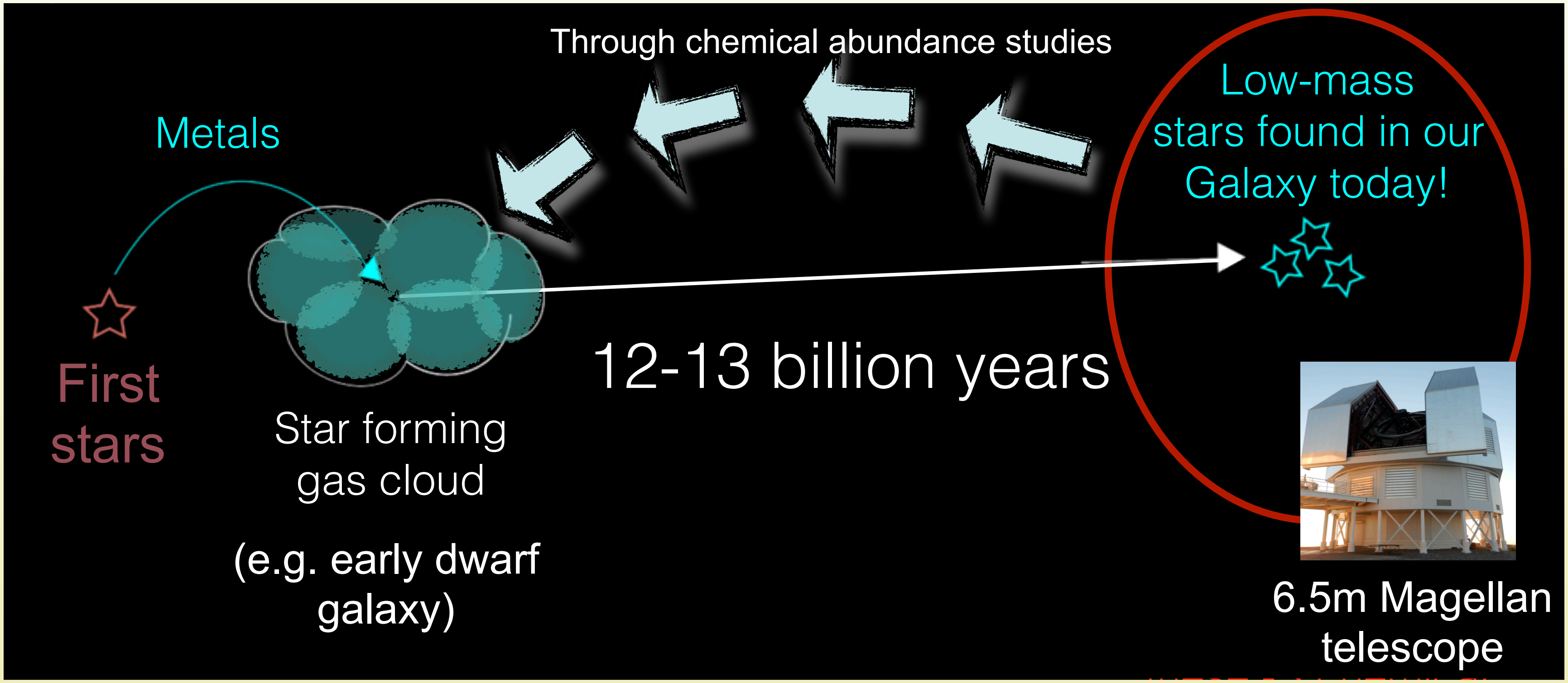
=> Origin of these stars is unknown



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!

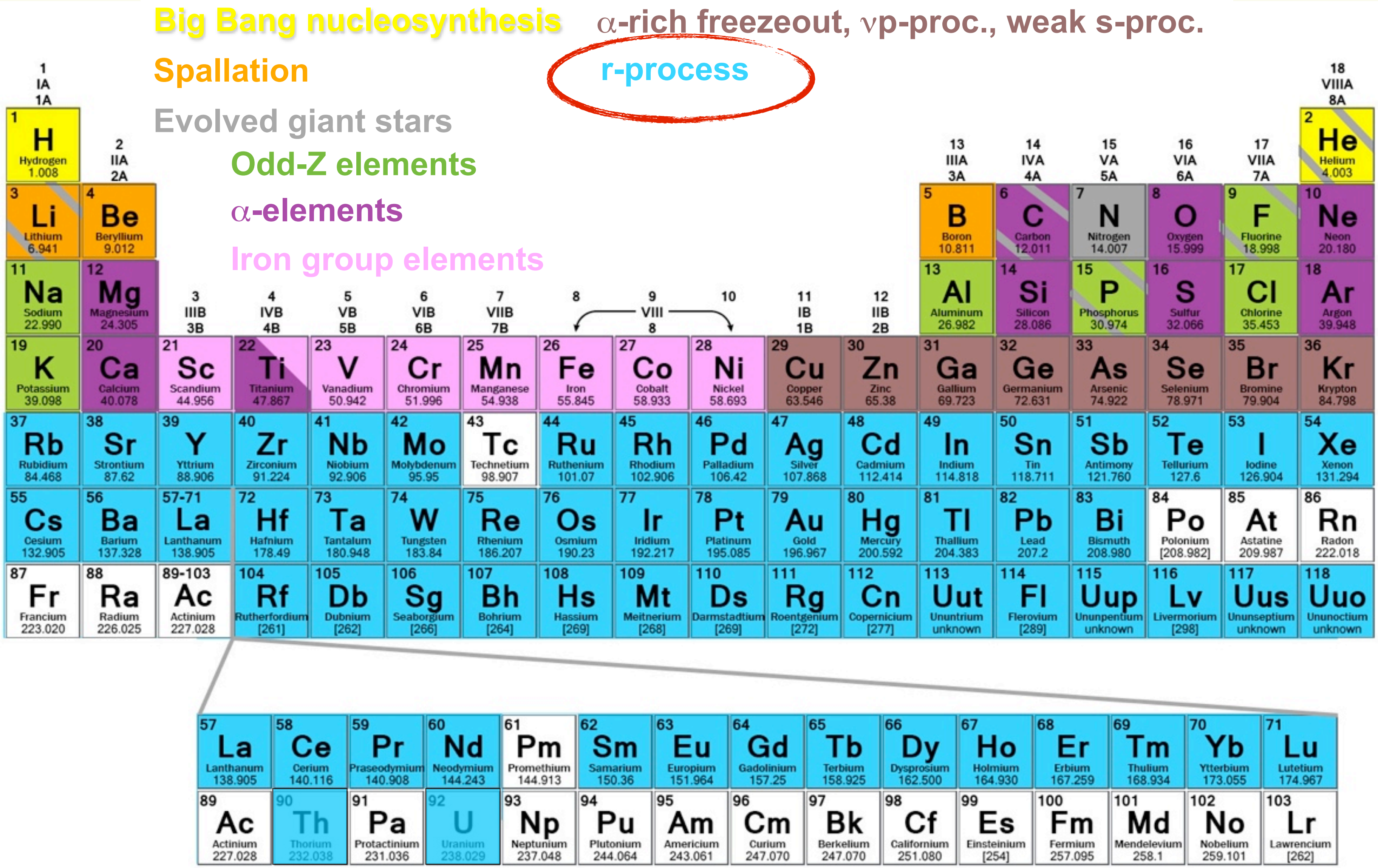


$[Fe/H] \leq -3$
(= 1/1000th of solar Fe)

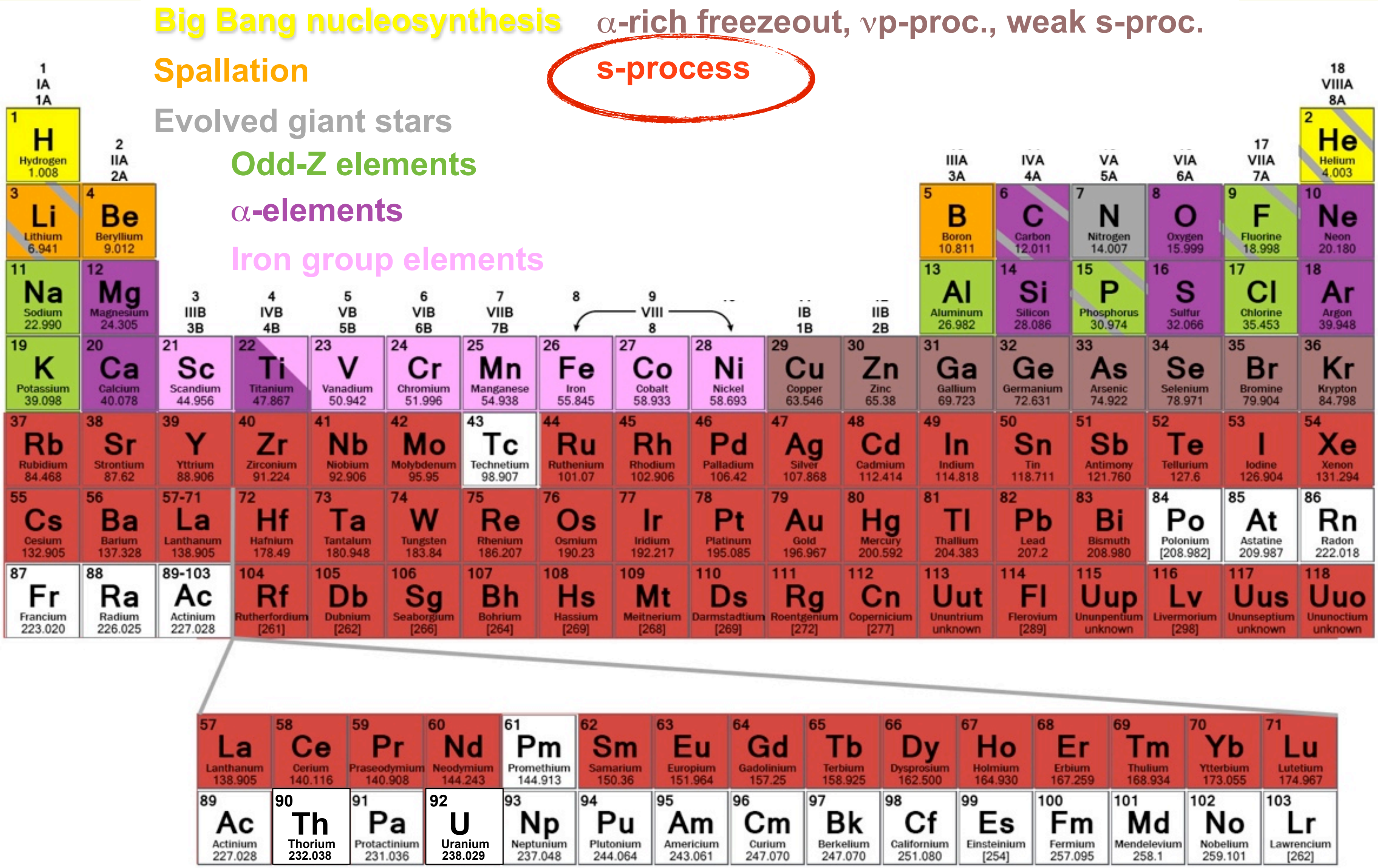
=> only ~1 progenitor star produced that iron
=> only ~1 nucleosynthesis event made heavier elements

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

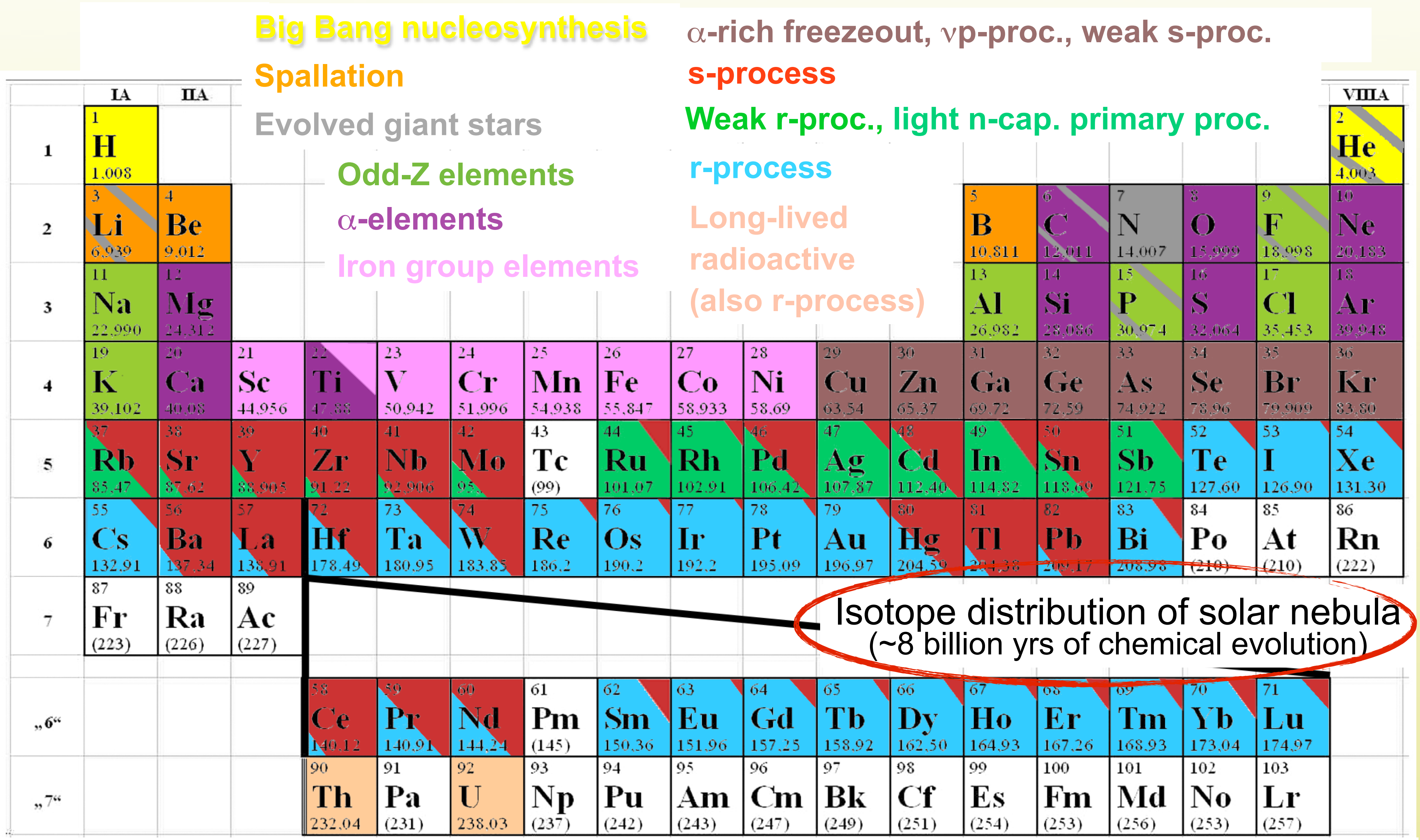
The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table



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)

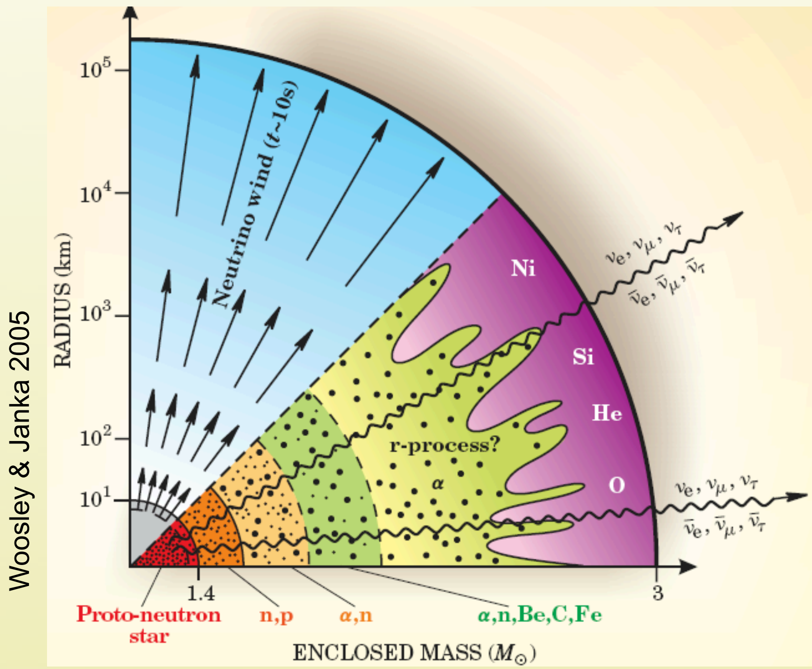
★ **What is the rate and yield of the event?**

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

Core-collapse supernova

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

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



Theoretical element yield:

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

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

Pros

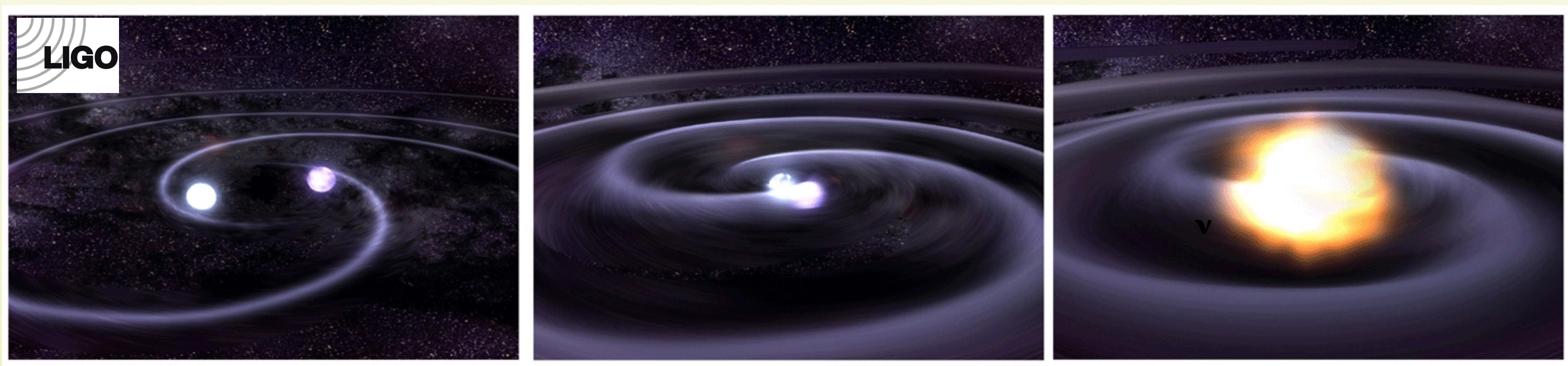
✓Metal-poor stars only have one/few progenitors
✓Provides the fast enrichment needed; small & steady r-process yields

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 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)

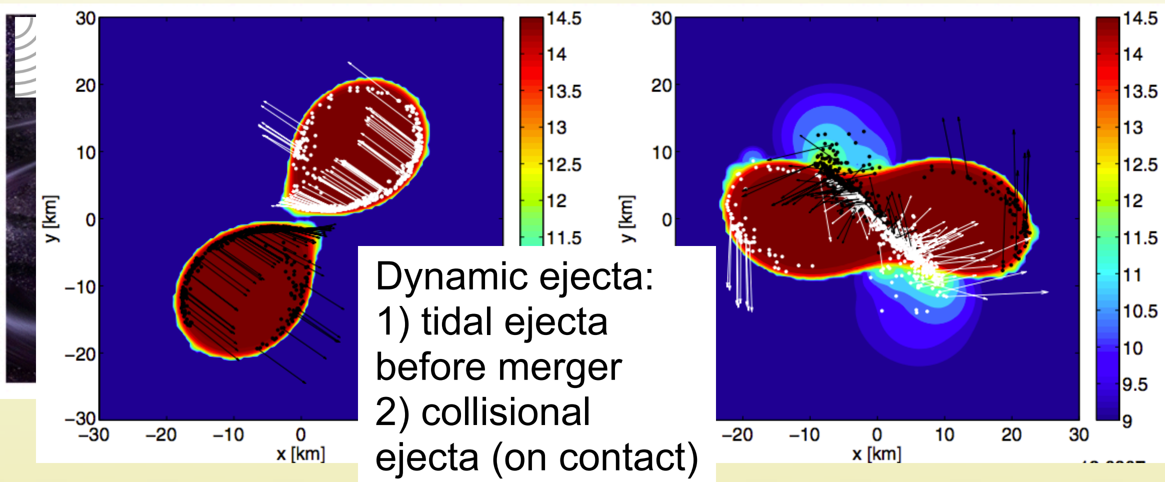
Additional (indirect) evidence for local r-process nucleosynthesis

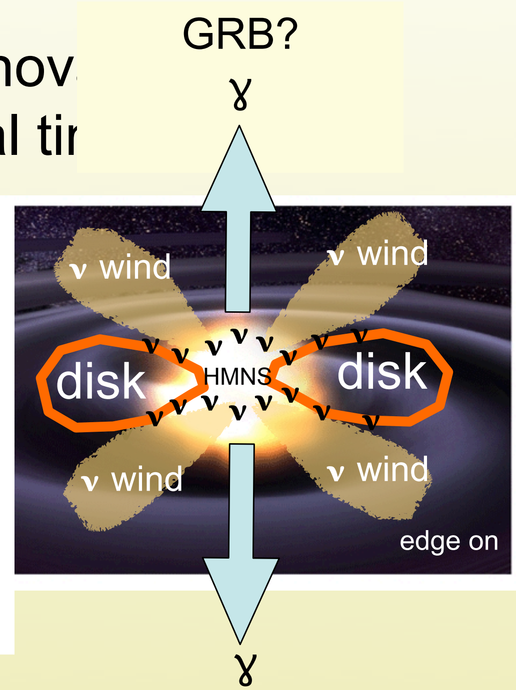
1) Short gamma-ray bursts: Afterglow from decay of radioactive r-process elements detected (Tanvir et al. 13)
2) Radioactive deep sea measurements suggest local neutron star mergers (Wallner et al. 15, Hotokezaka et al.15)

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)

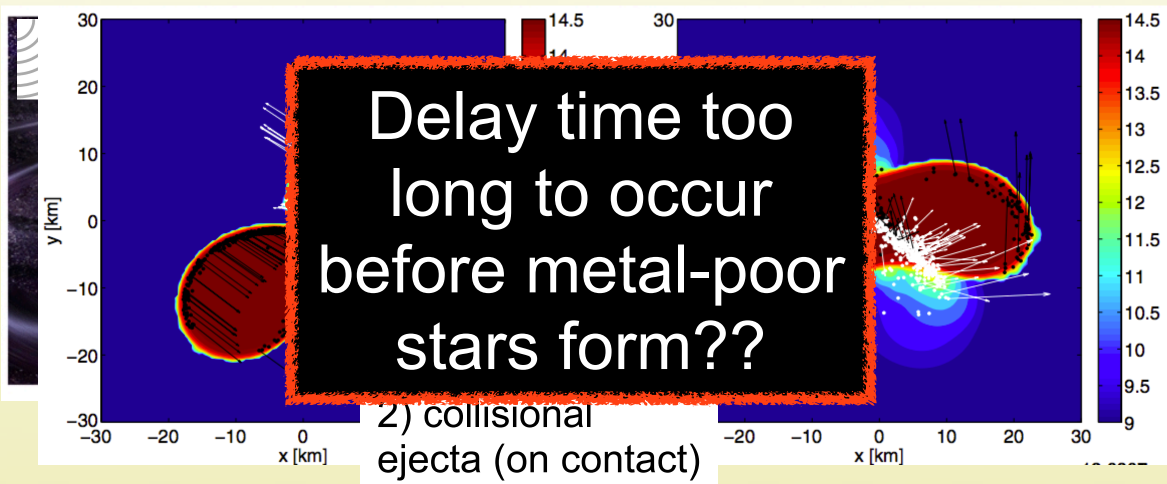
Additional (indirect) evidence for local r-process nucleosynthesis

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)

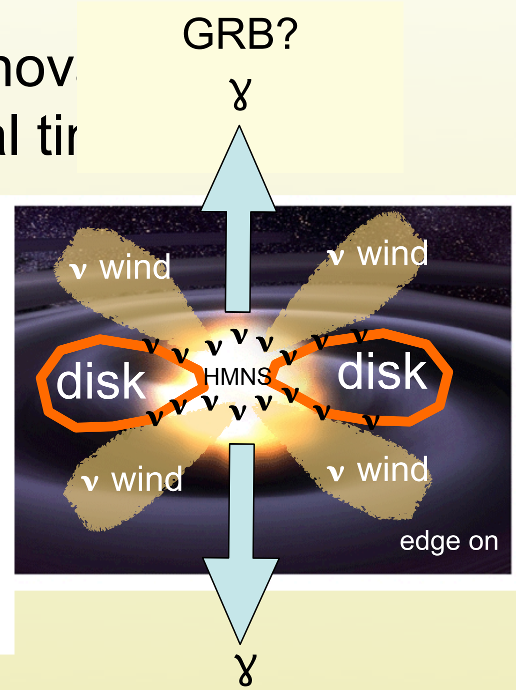
Neutron star binary merger
(two compact supernova remnants)

Pros Easily produces elements heavier than Ba

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



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



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

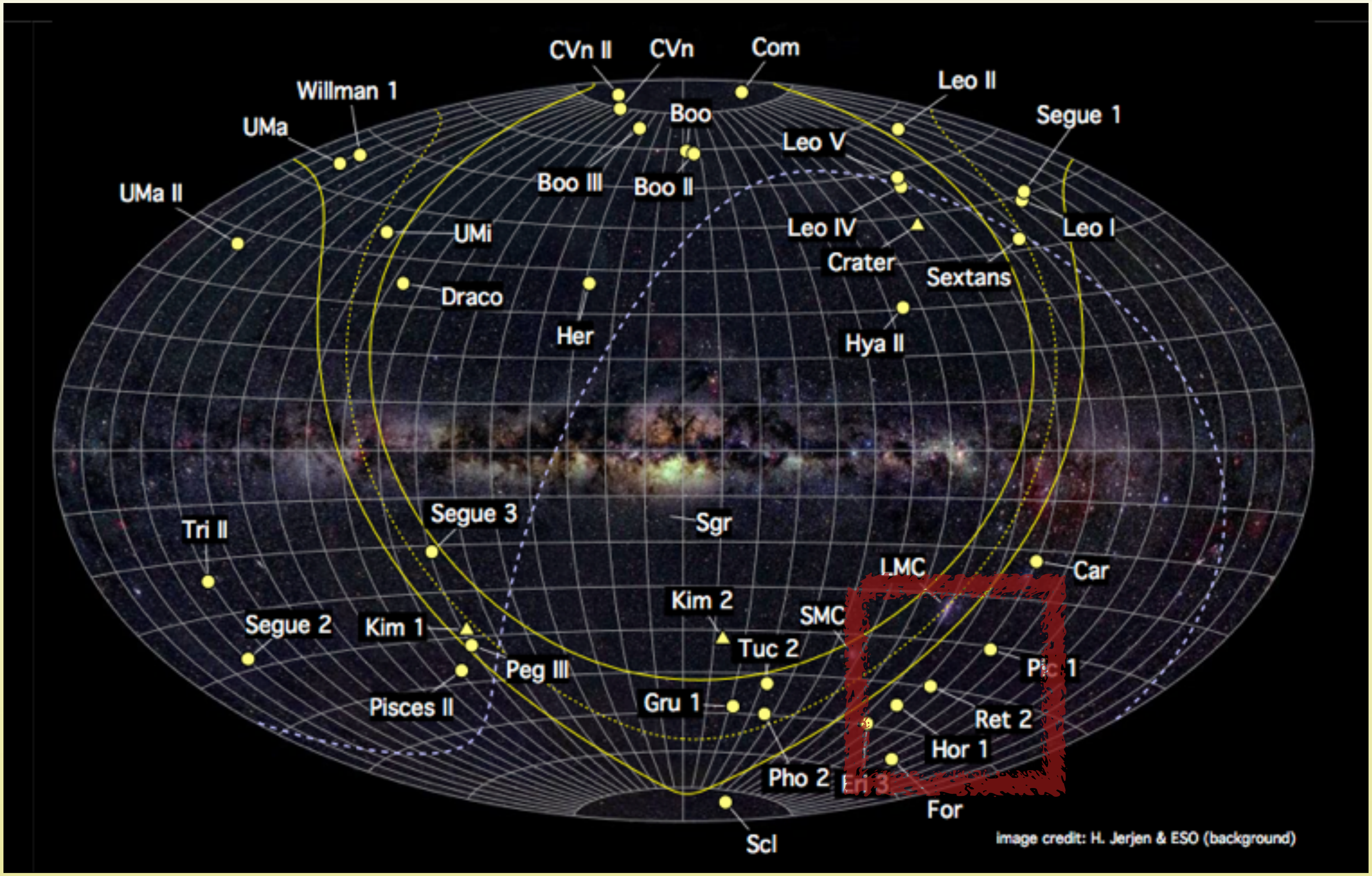
=> ~$10^{-4.5}$ M_{sun} of Eu (per event)

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)

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



Ultra-faint dwarf galaxy properties (UFDs)

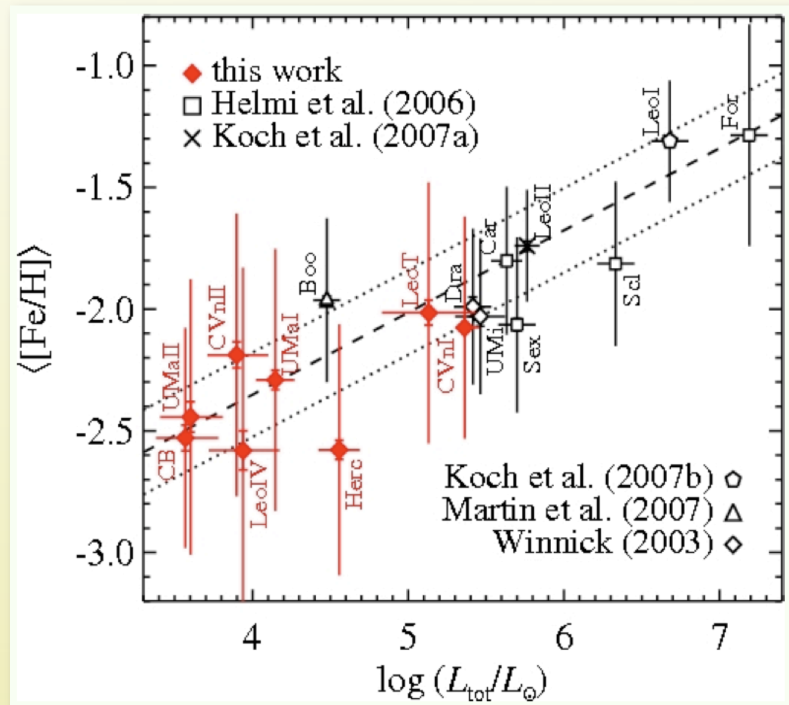
Low luminosity (300 - 3,000 L_{sun})

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



Ultra-faint dwarfs

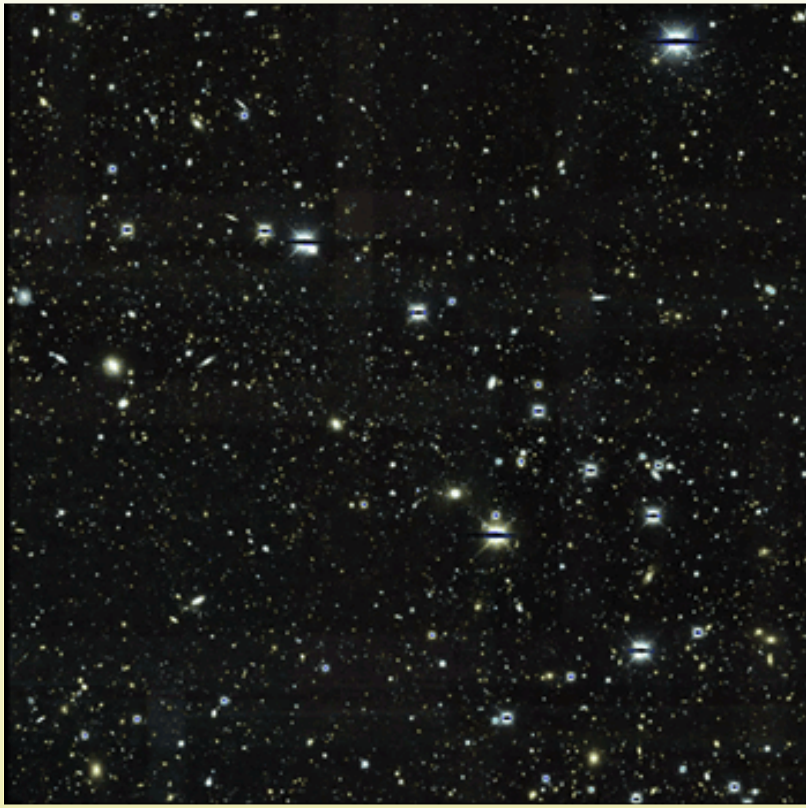
Classical dSphs

Ideal targets for Dwarf Galaxy Archaeology

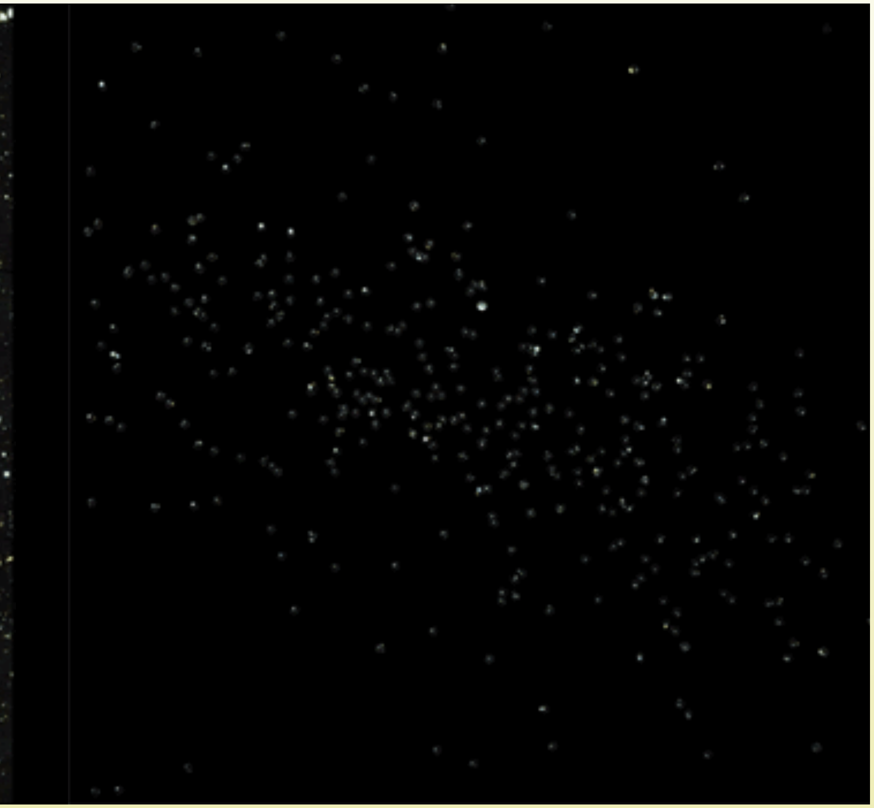
Use entire galaxy as fossil record of the early universe.

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

Meet Reticulum II



All stars



Reticulum II stars

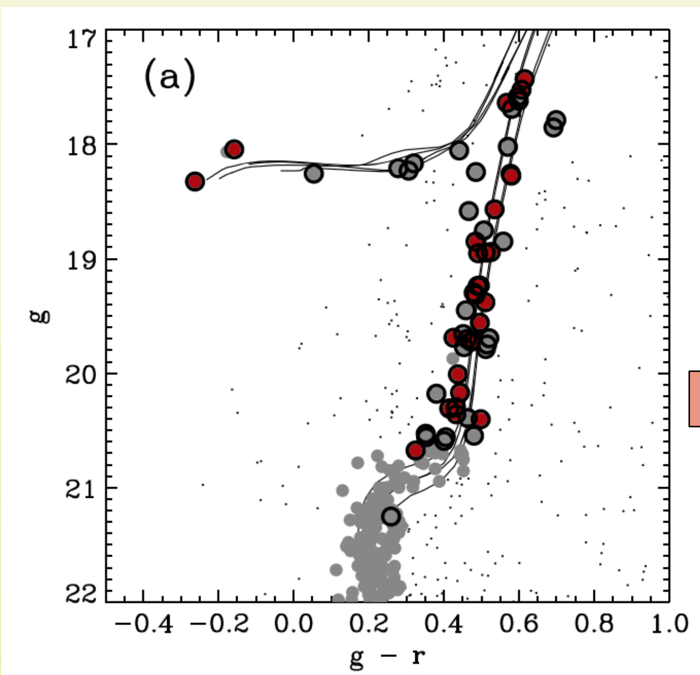
(Dark Energy Survey, 2015)

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)



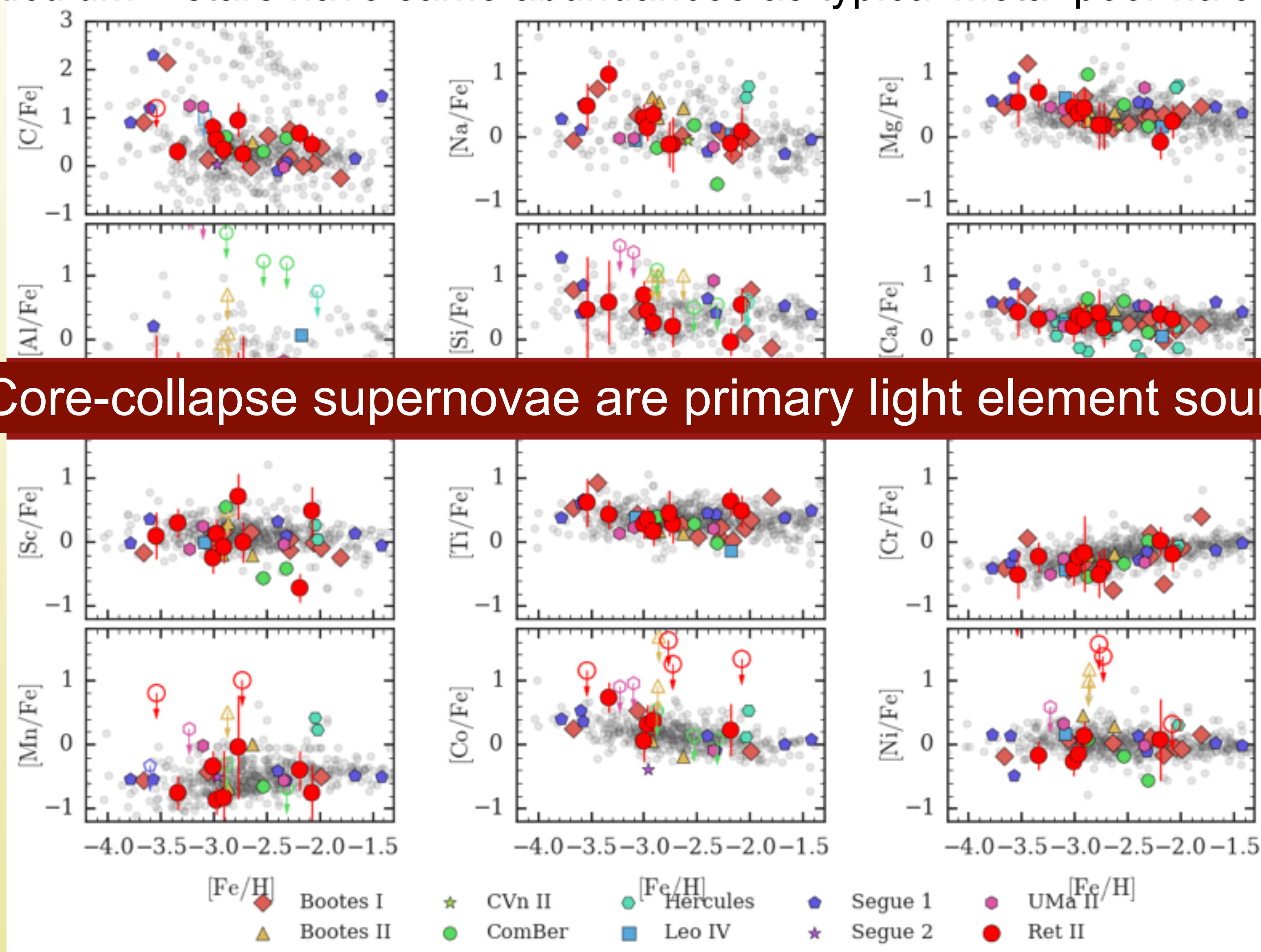
Color-magnitude-diagram of Ret II
(red = confirmed members)

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)

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



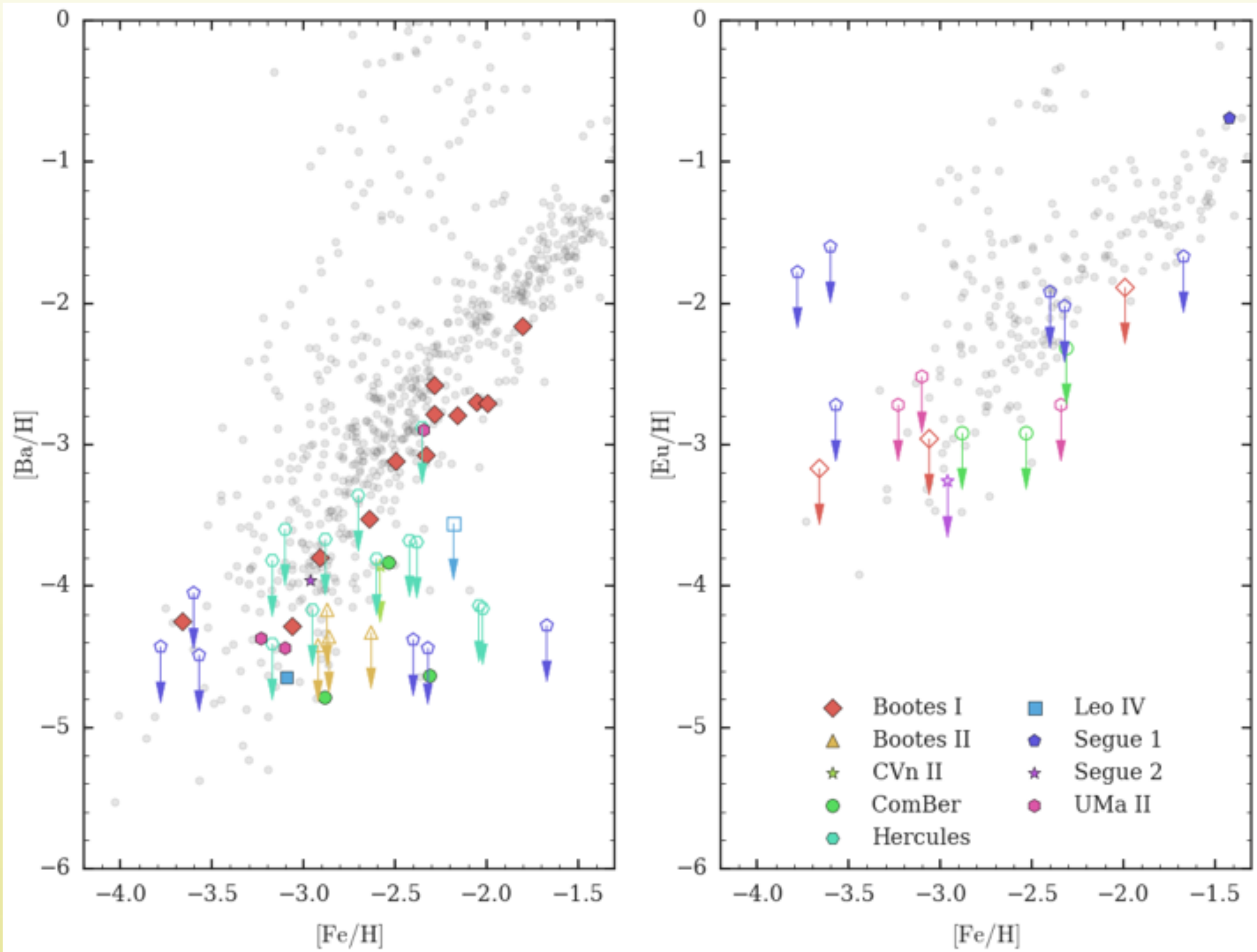
Core-collapse supernovae are primary light element source

gray dots metal-poor halo stars

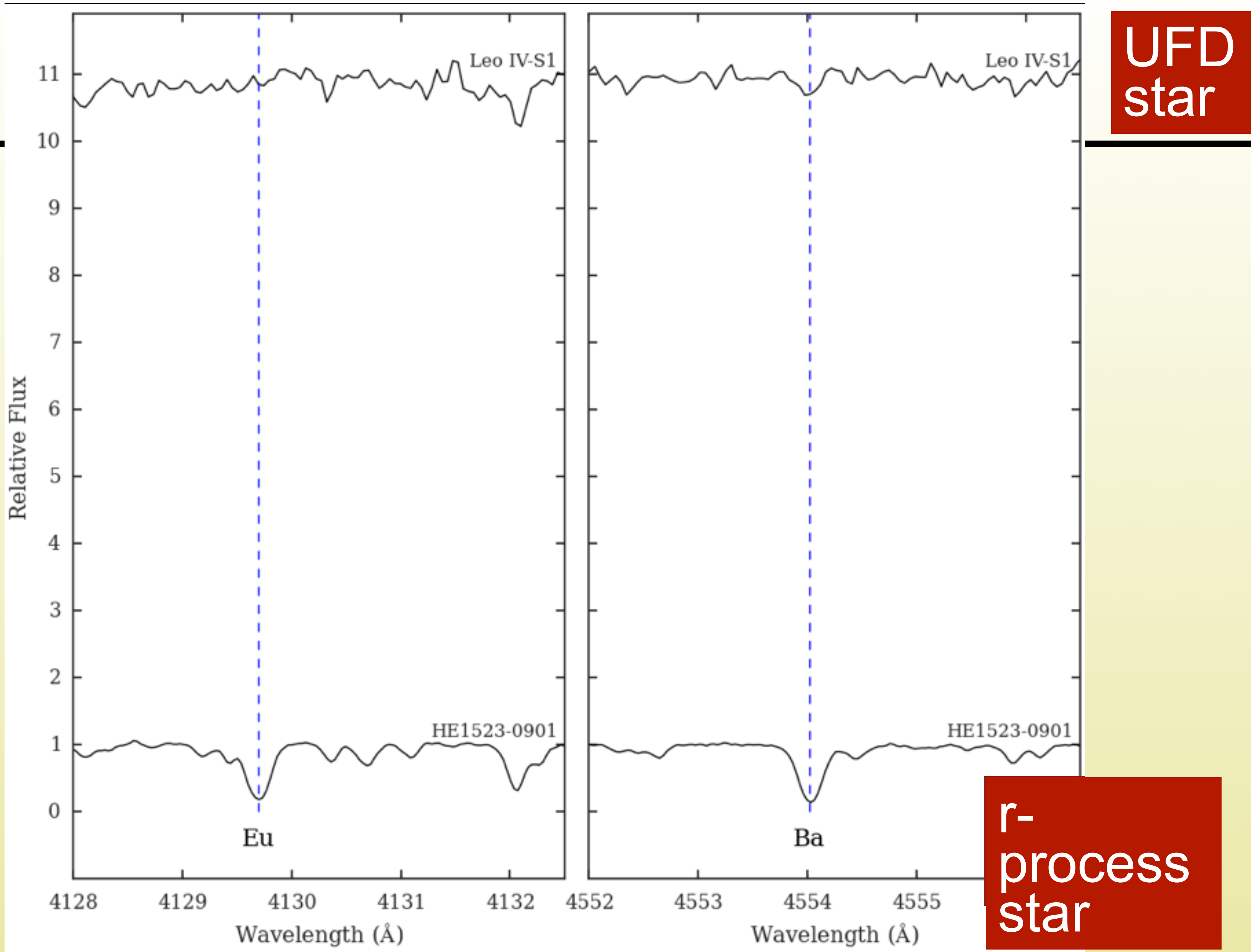
Ji et al 2016, *Nature*, 531, 610

Neutron-capture element abundances (Ba and Eu)

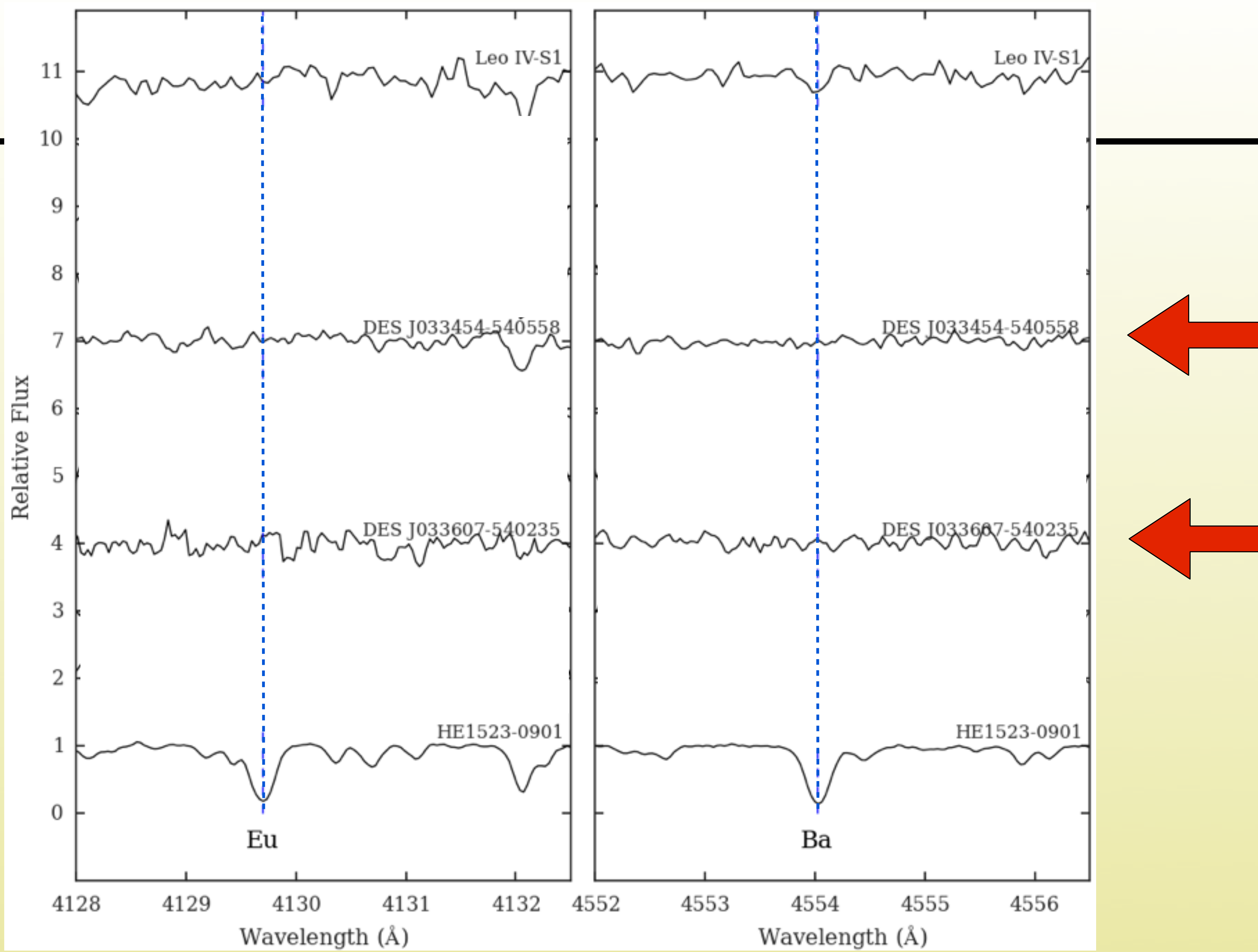
The other ten UFDs have
uniquely low neutron-capture element abundances!



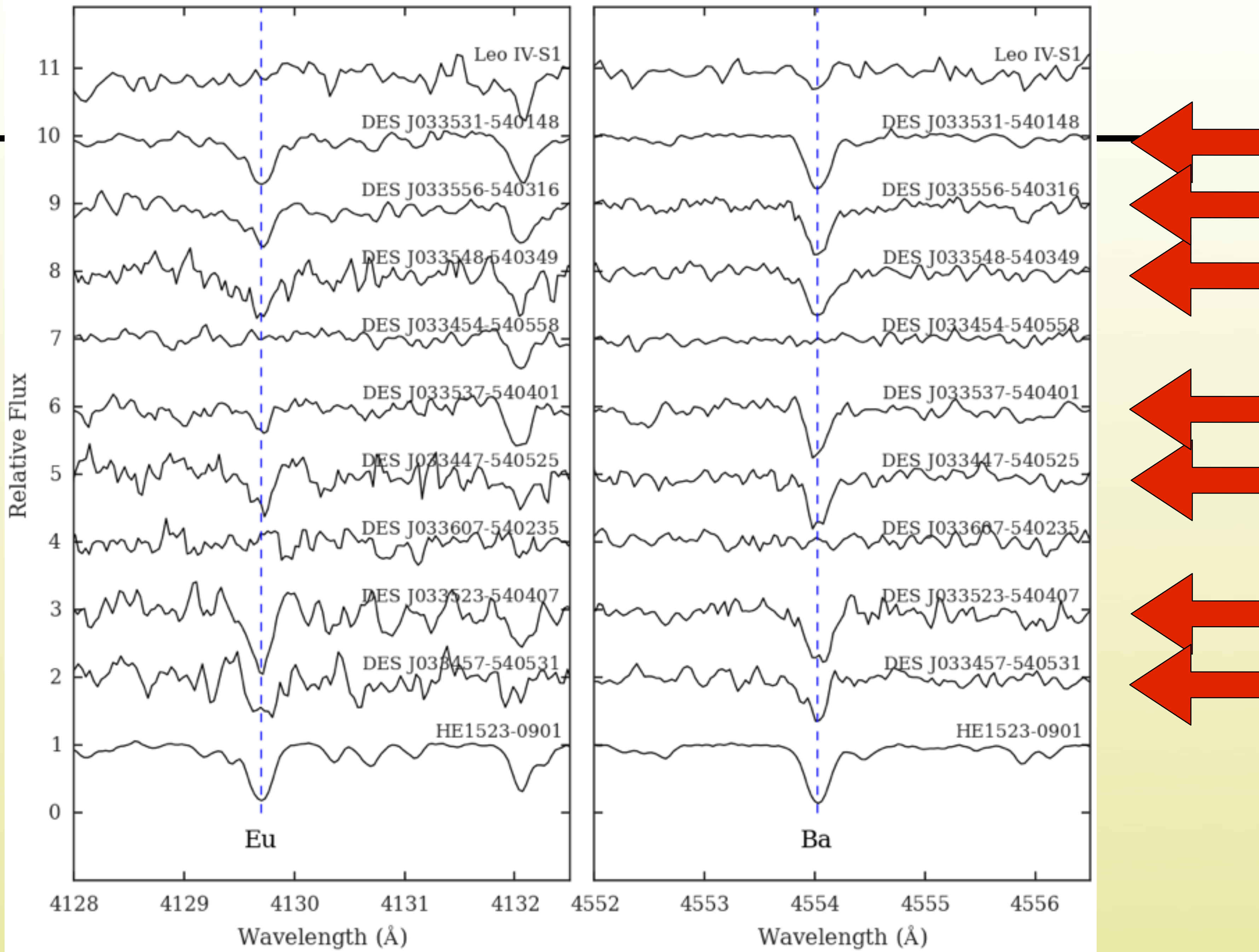
gray dots: metal-poor halo stars



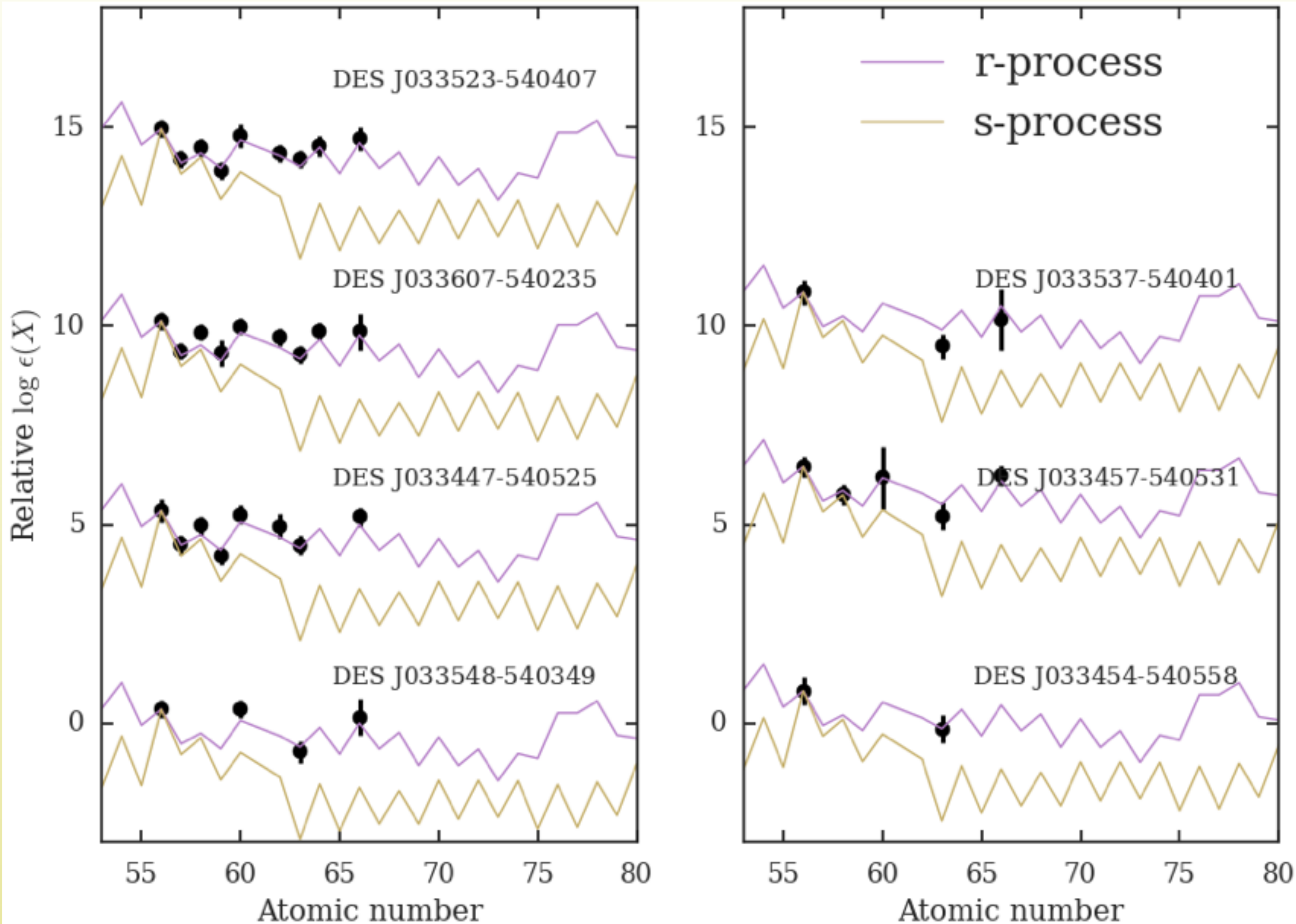
UFD star
r-process star
Leo IV-S1
HE1523-0901
Eu
Ba
Relative Flux
Wavelength (Å)
4128
4129
4130
4131
4132
4552
4553
4554
4555
0
1
2
3
4
5
6
7
8
9
10
11



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

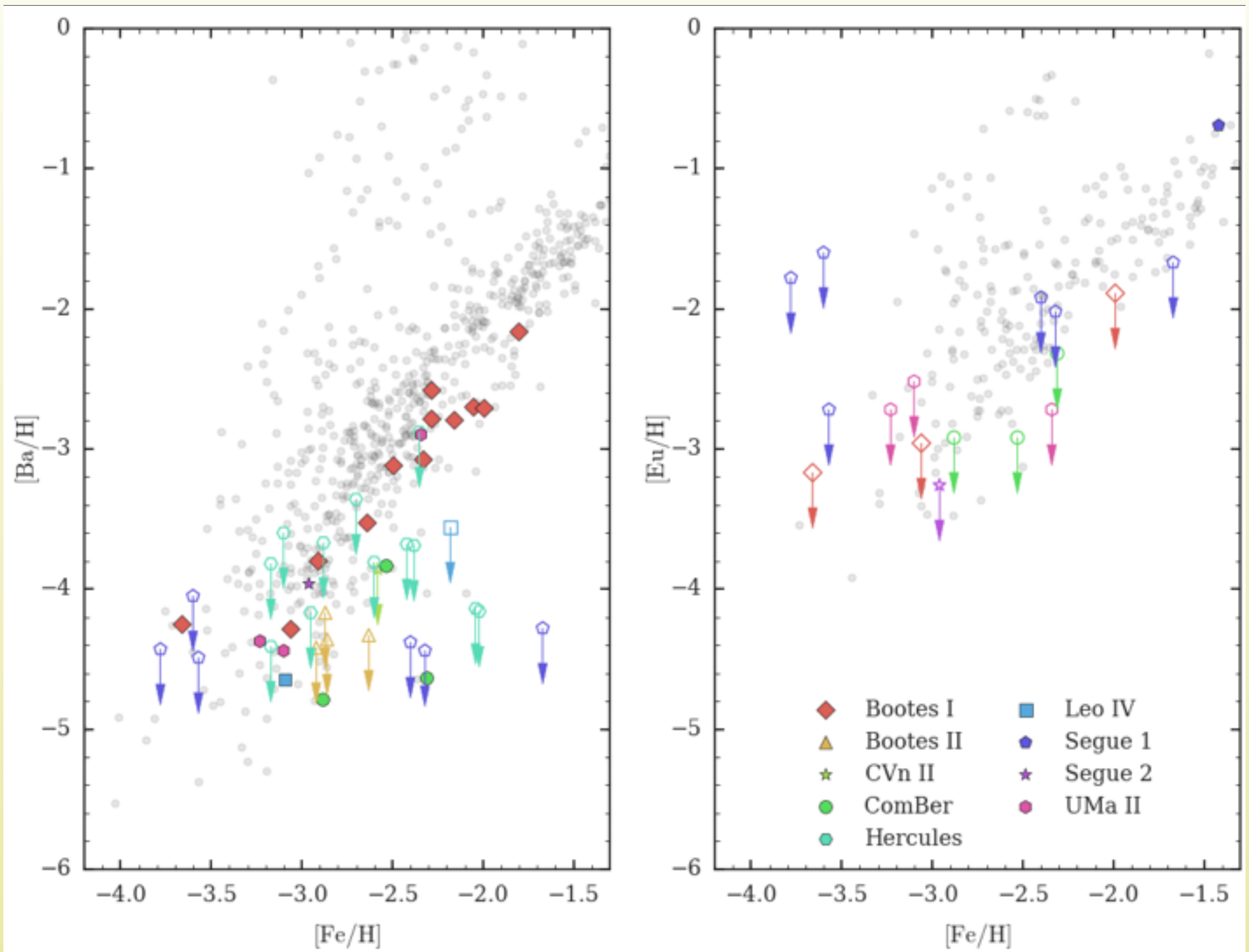

Leo IV-S1
DES J033531-540148
DES J033556-540316
DES J033548-540349
DES J033454-540558
DES J033537-540401
DES J033447-540525
DES J033607-540235
DES J033523-540407
DES J033457-540531
HE1523-0901
Eu
Ba
Relative Flux
Wavelength (Å)
4128
4129
4130
4131
4132
4552
4553
4554
4555
4556
0
1
2
3
4
5
6
7
8
9
10
11

All seven Ret II stars display the r-process pattern



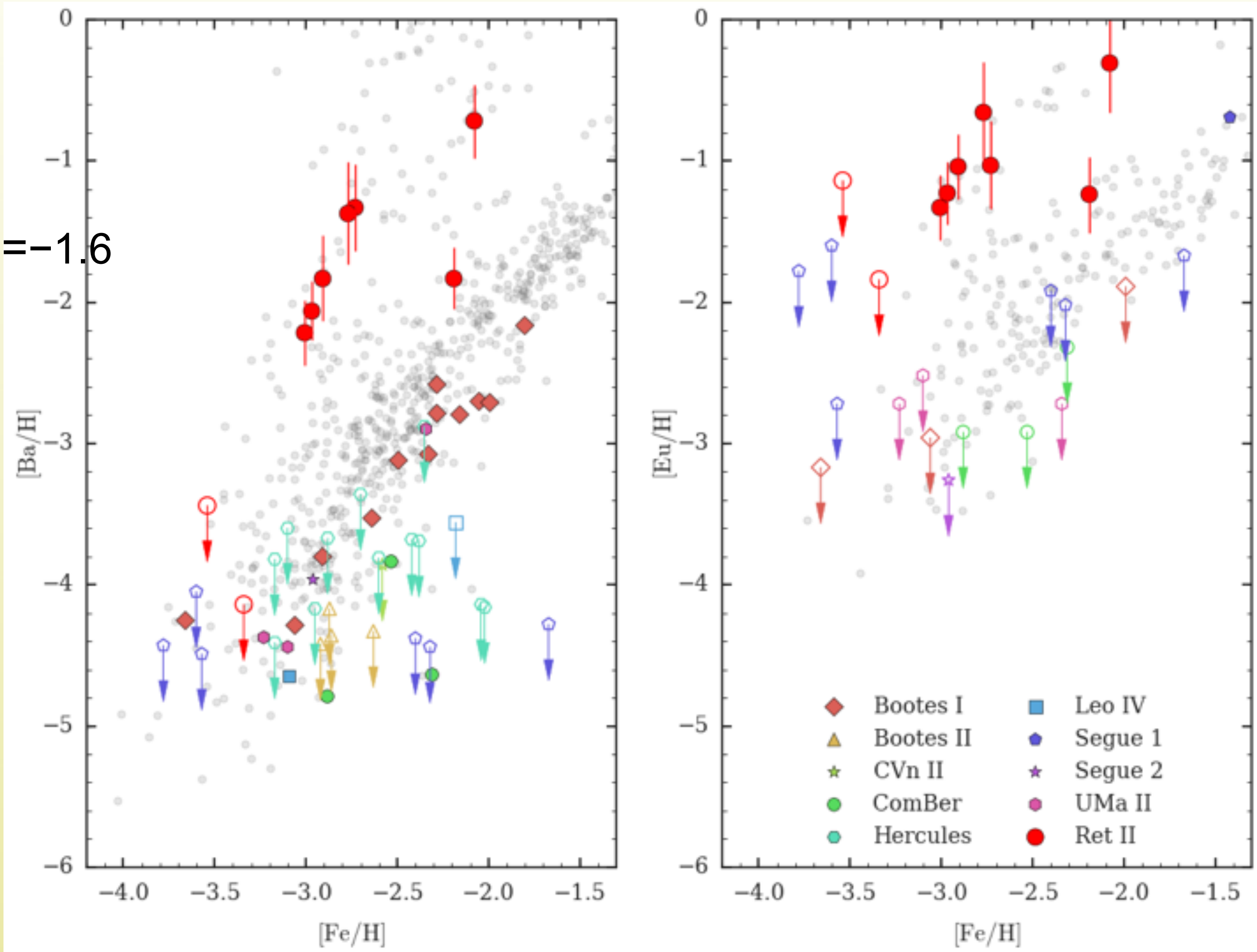
Ji et al 2016, *Nature*, 531, 610

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



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

[Ba/H]=−1.6



[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: ~10^7 M_{sun}

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

➡Min. dilution mass: ~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!)

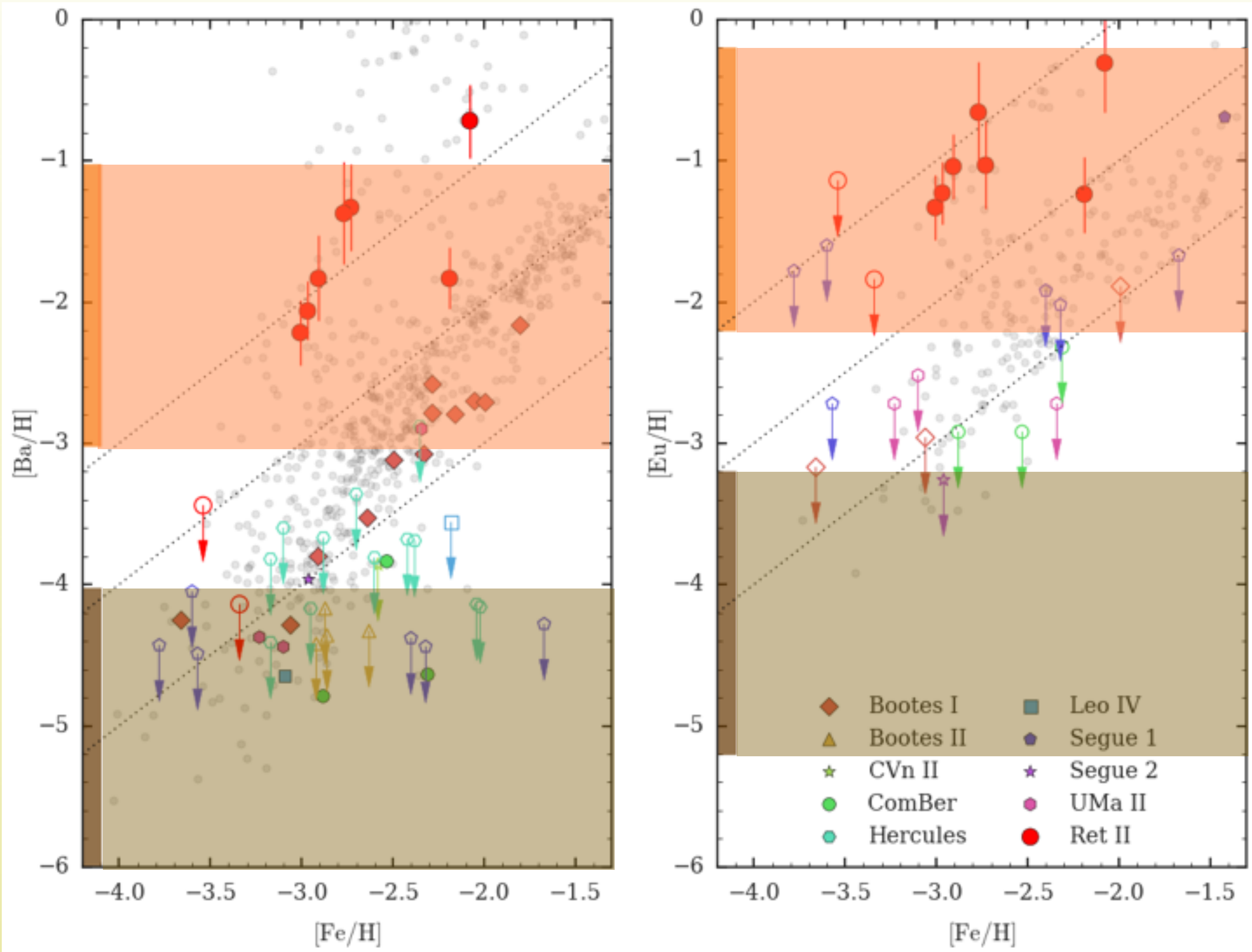
=> [Eu/H] = −1.2 is abundance of next-generation star

=> Agrees with Ret II abundance results!

Ret II abundances consistent w/ neutron-star merger yield

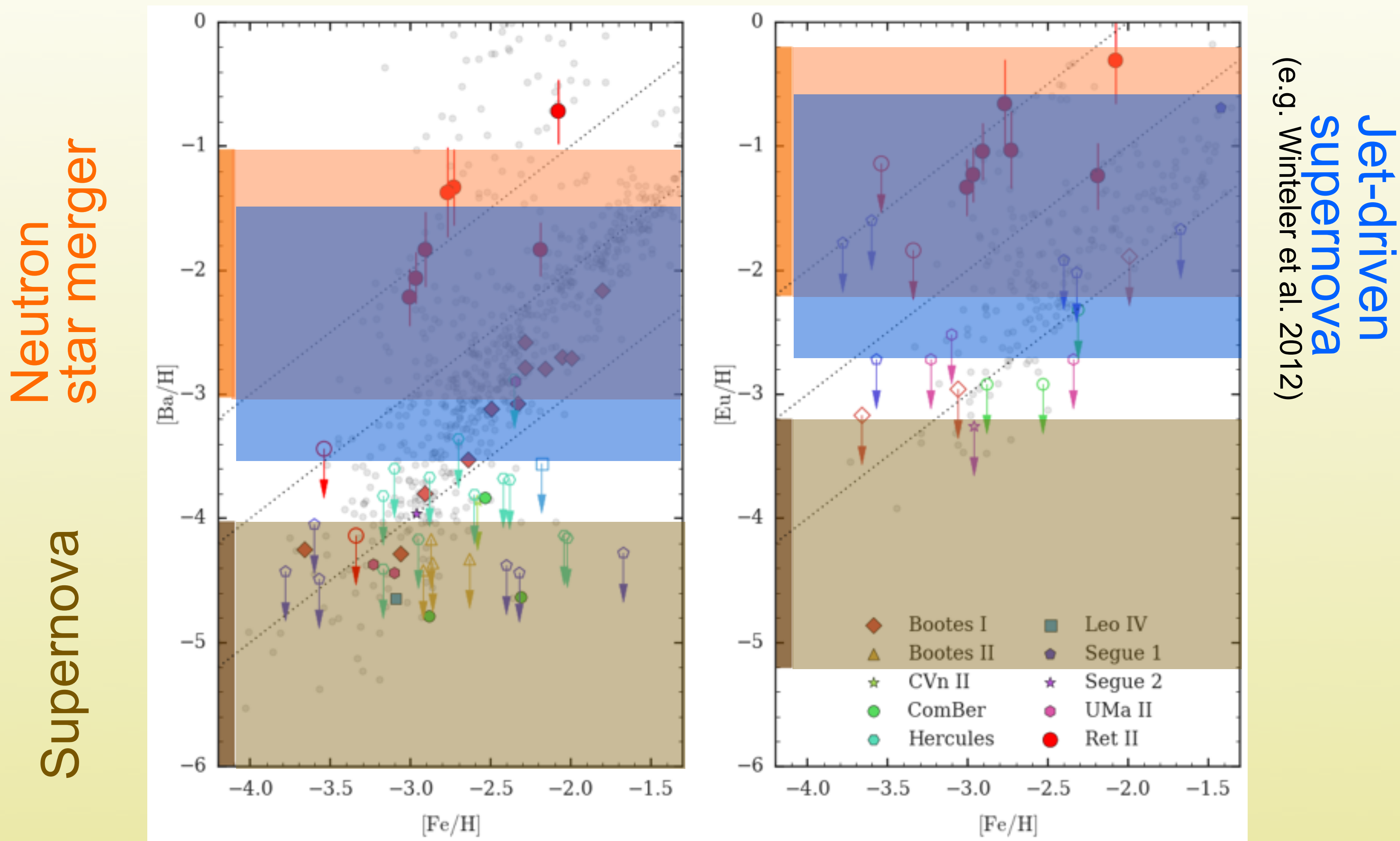
Neutron star merger

Supernova



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 <u>rare</u>, <u>prolific</u> and <u>delayed</u> r-process event

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

<u>Can't you increase the # of supernovae to get higher yield?</u>

➡ No, 1000+ supernovae would disrupt the system

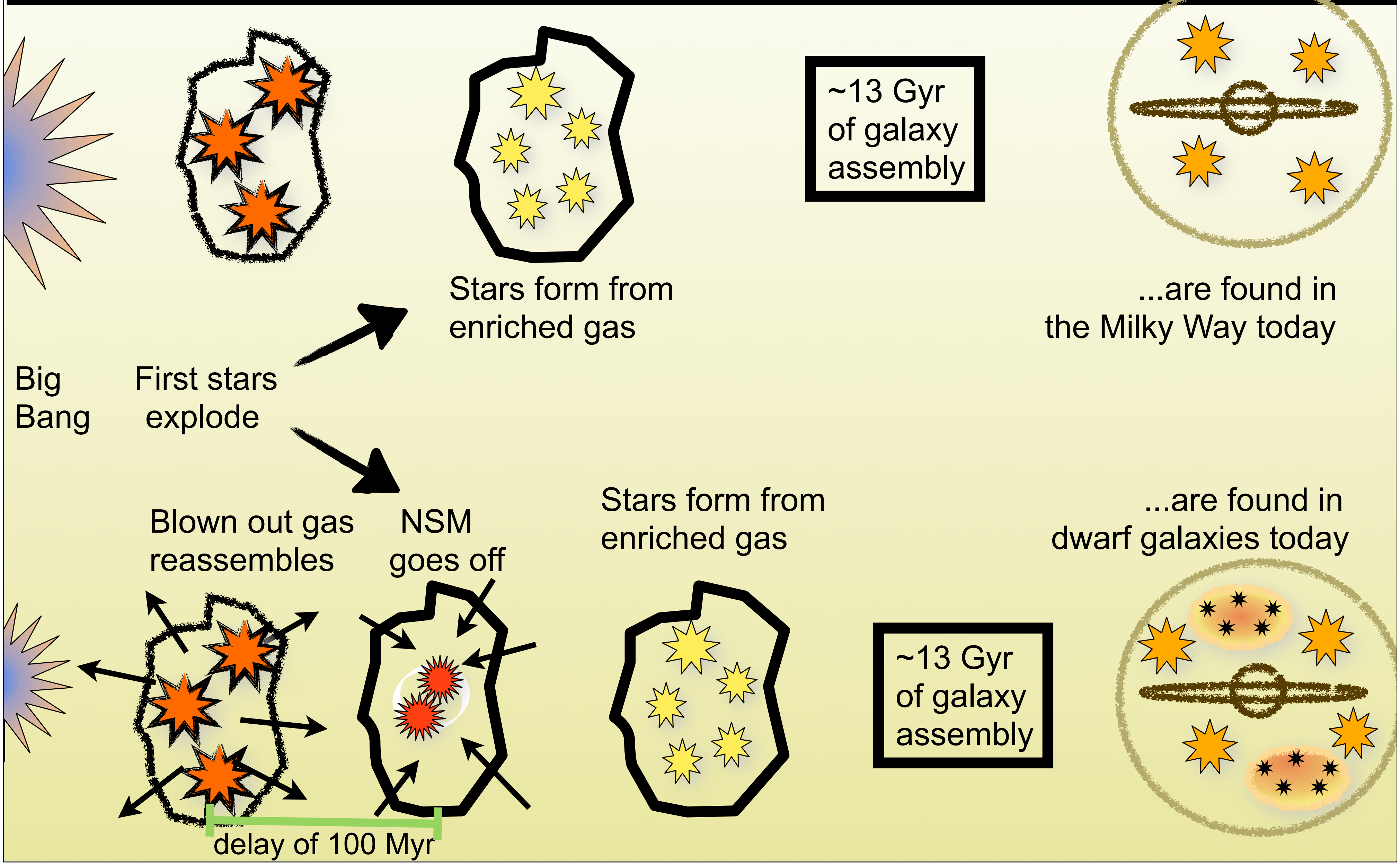
➡ Need to be just one/few massive events

<u>Aren't NSM taking too long to enrich the galaxy?</u>

➡ 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



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!