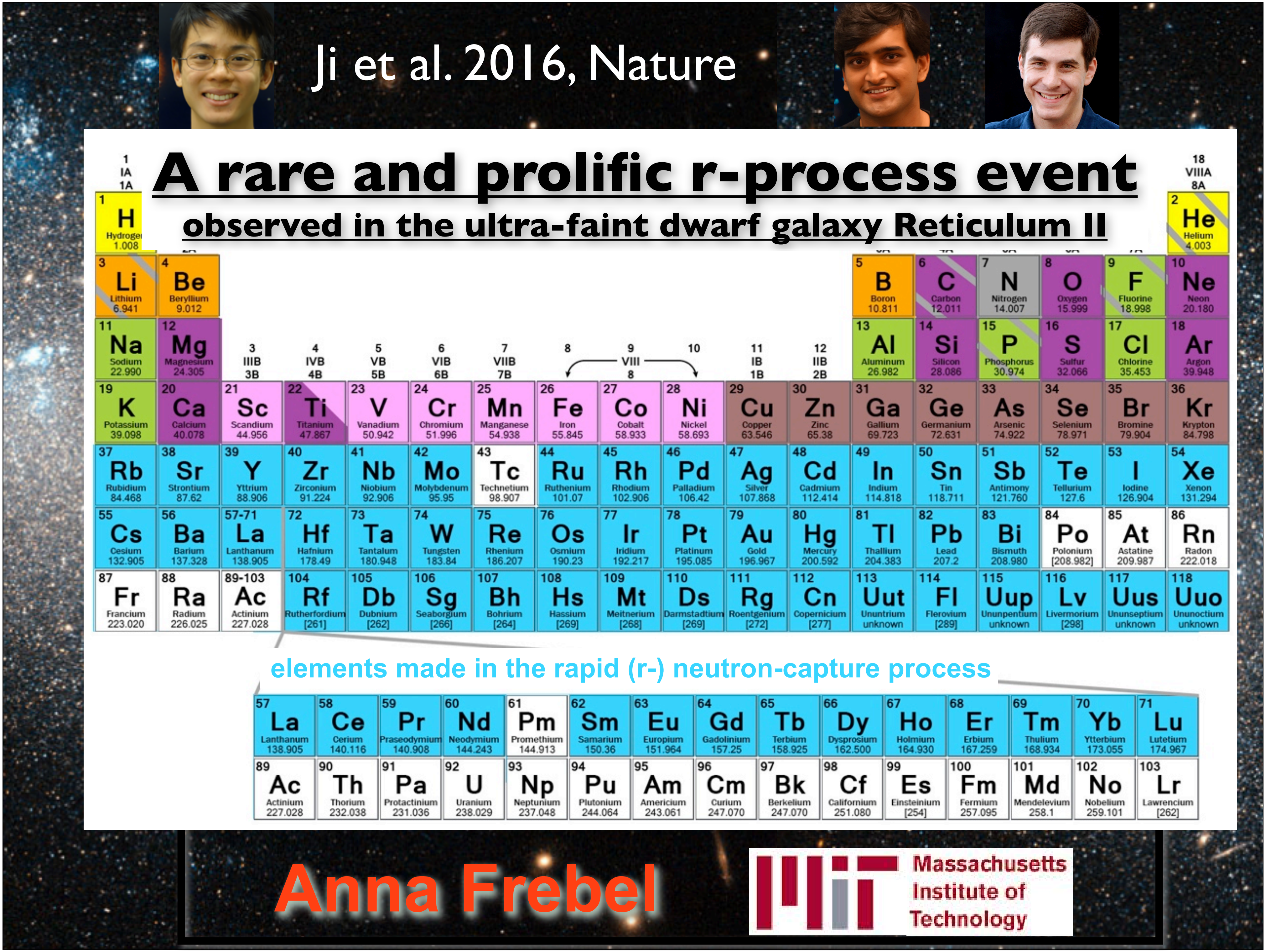
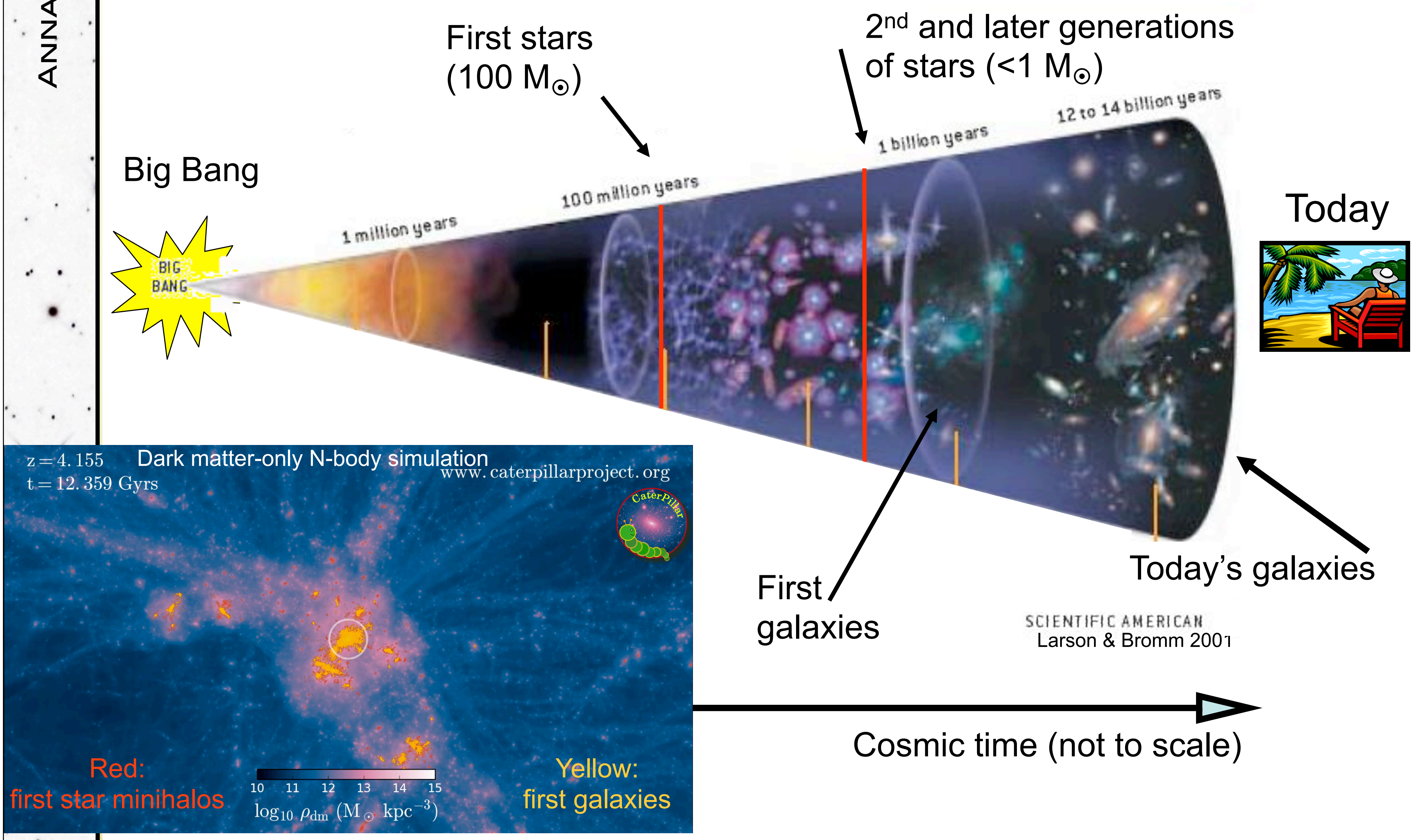
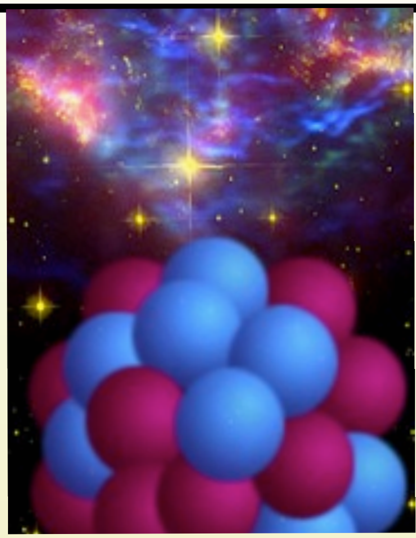

Ji et al. 2016, Nature
A rare and prolific r-process event
observed in the ultra-faint dwarf galaxy Reticulum II
elements made in the rapid (r-) neutron-capture process
Anna Frebel
Massachusetts Institute of Technology

Anna Frebel

A long time ago...



The Story of Reticulum II



[Nuclear Astrophysics]

Cosmic origin of the chemical elements

[Stellar Archaeology]

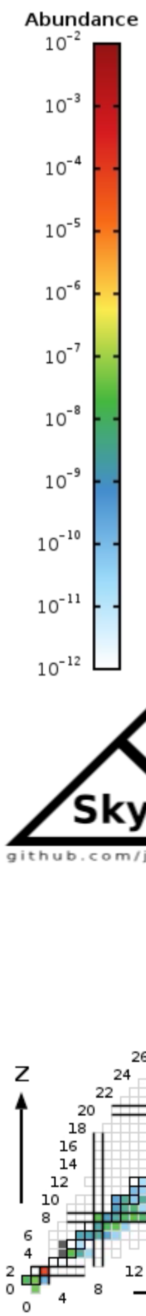
Clues to the astrophysical site of r-process nucleosynthesis

[Dwarf Galaxy Archaeology]

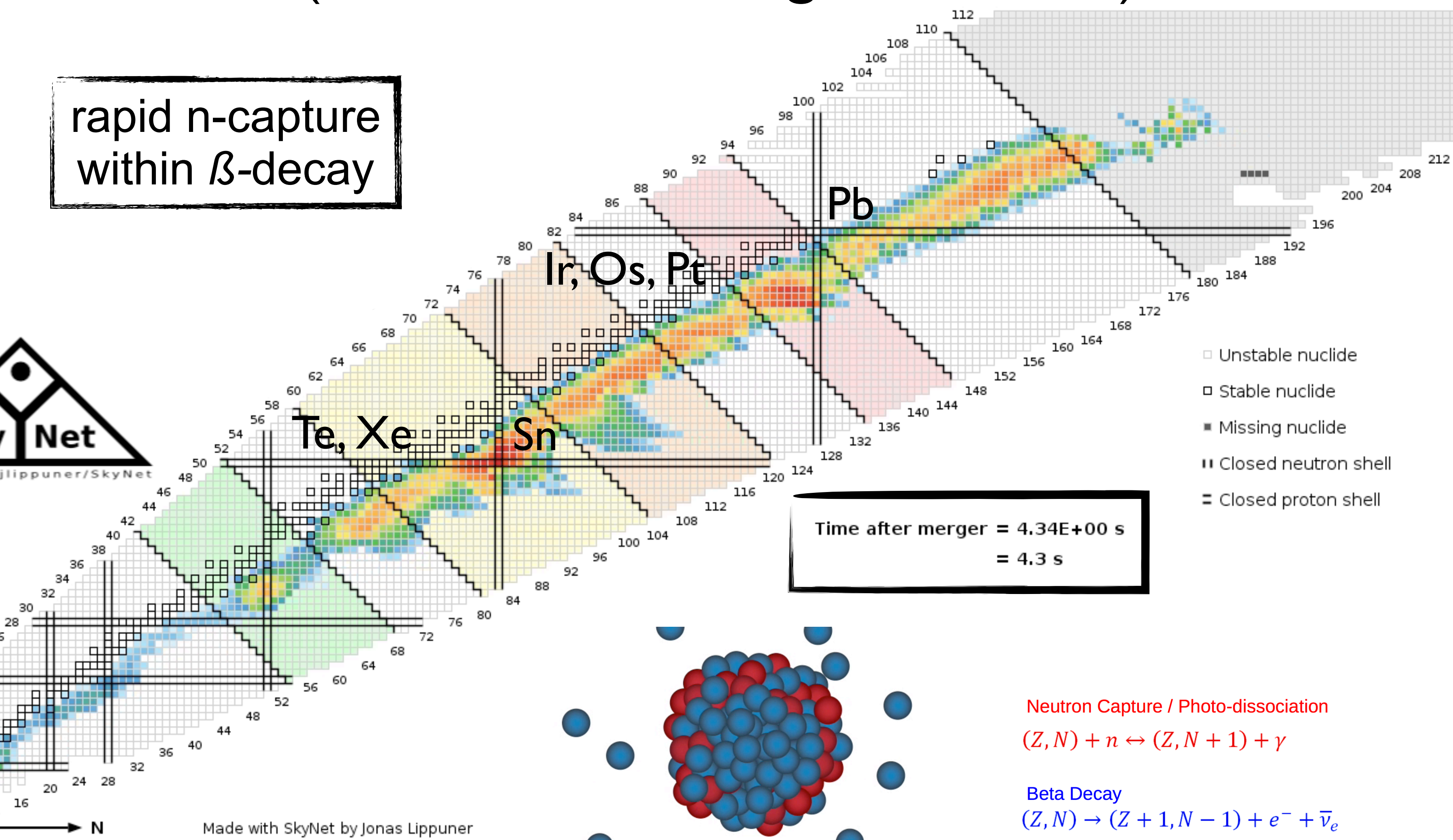
Ancient, clean chemical enrichment signatures

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

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

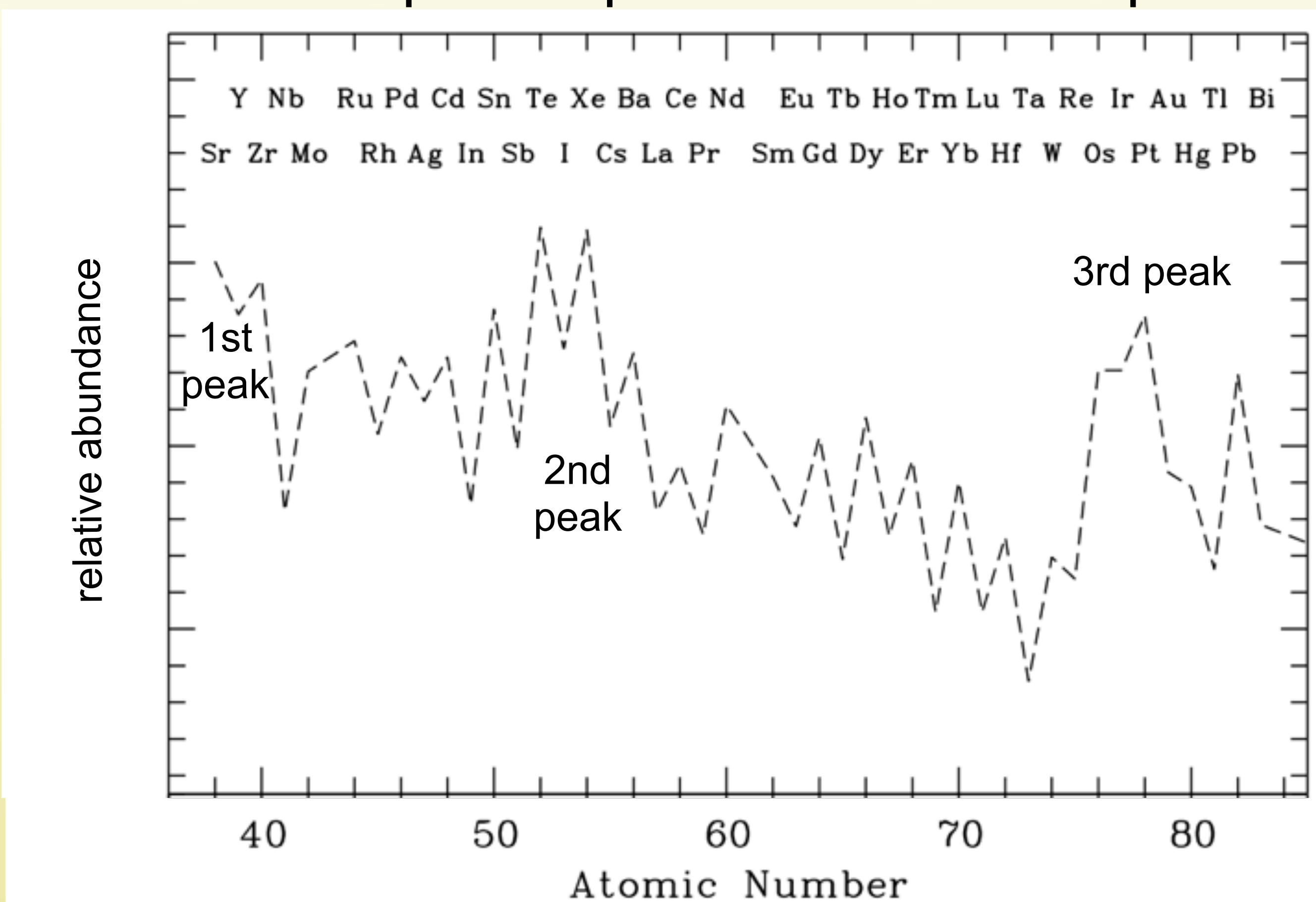
to stability

R-PROCESS PATTERN

Anna Frebel

Nuclear Astrophysics

neutron-capture r-process elemental pattern

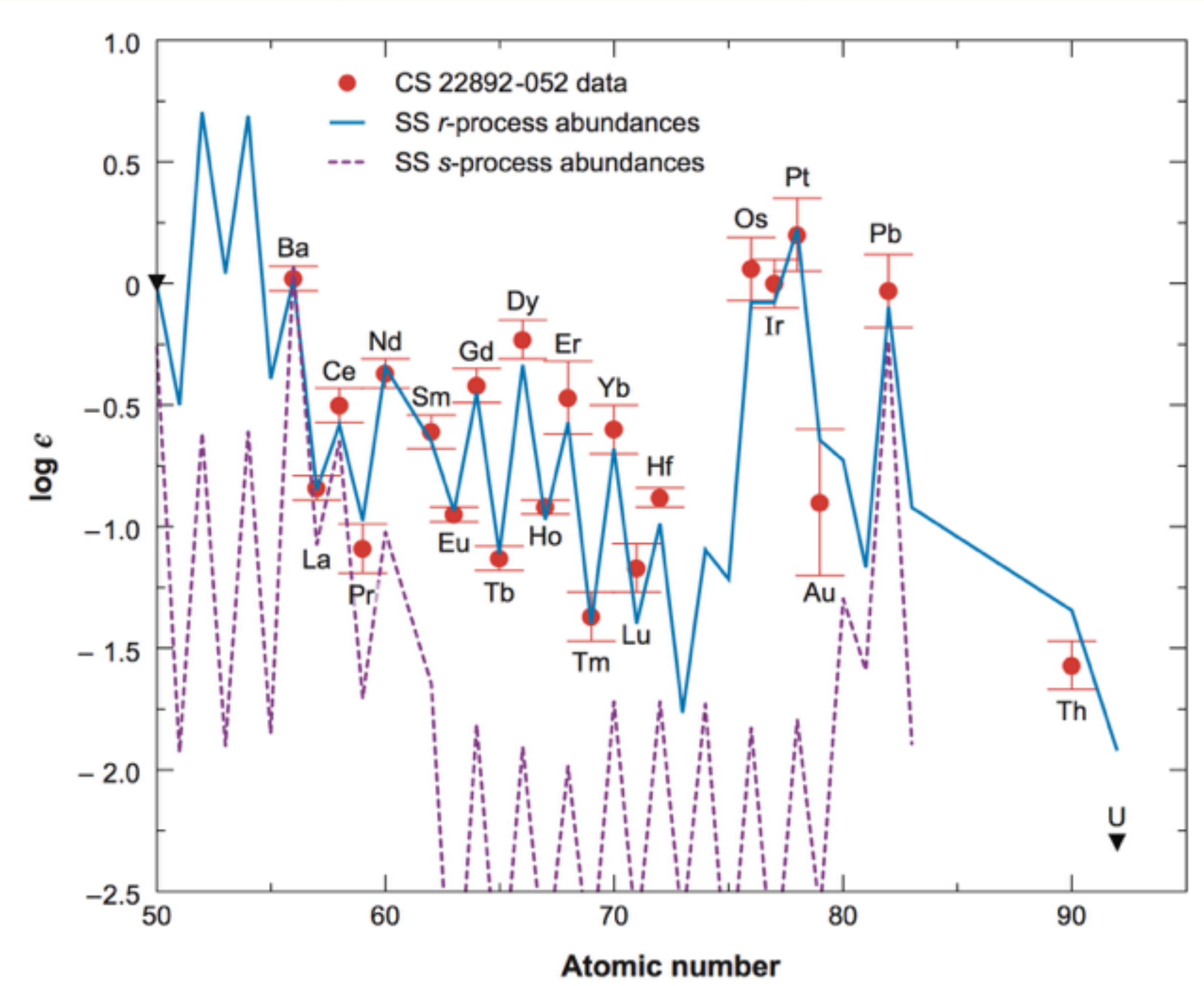


Universal r-process pattern observed in metal-poor stars

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

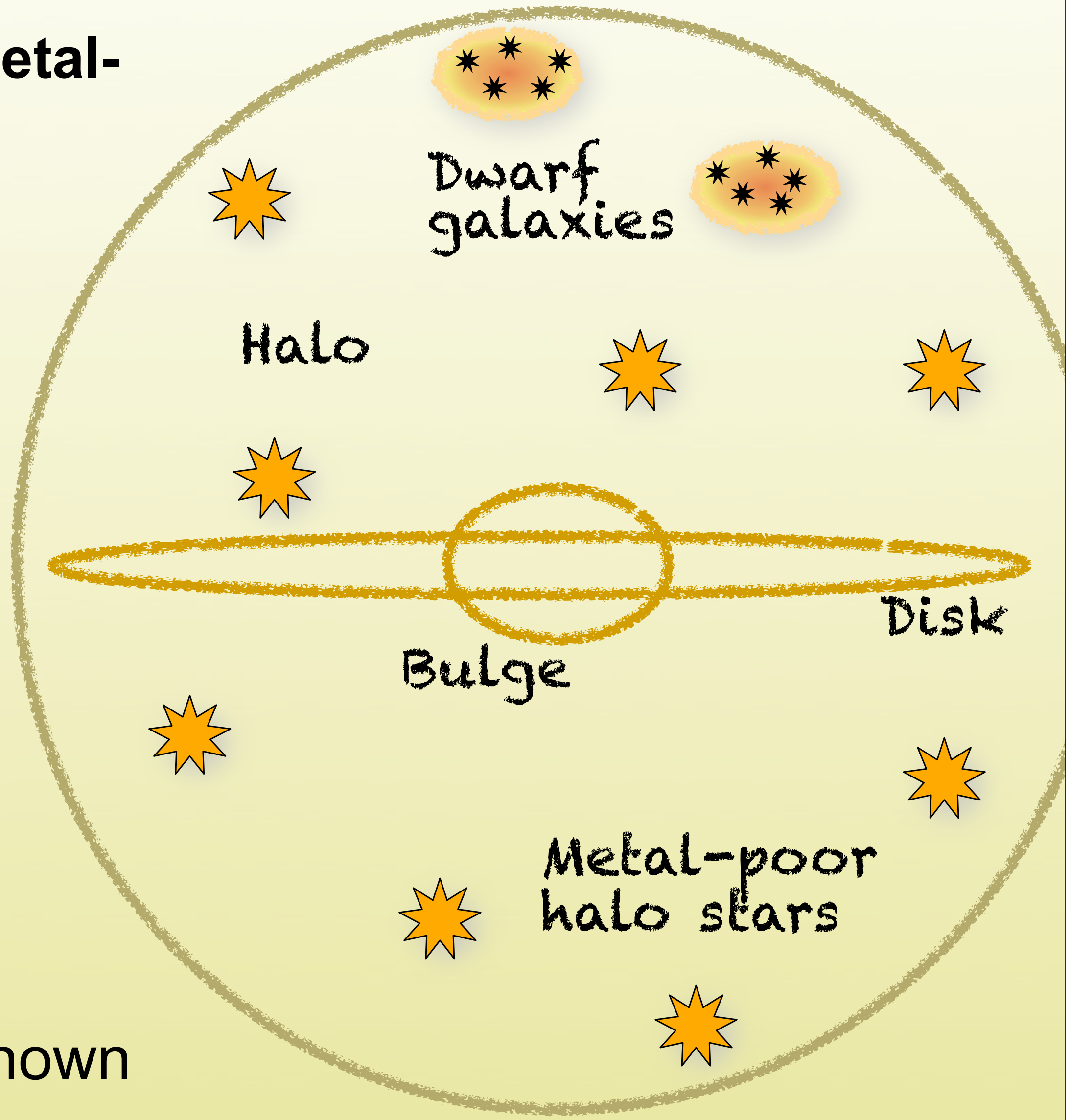
How common are r-process metal-poor stars in the Milky Way?

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**

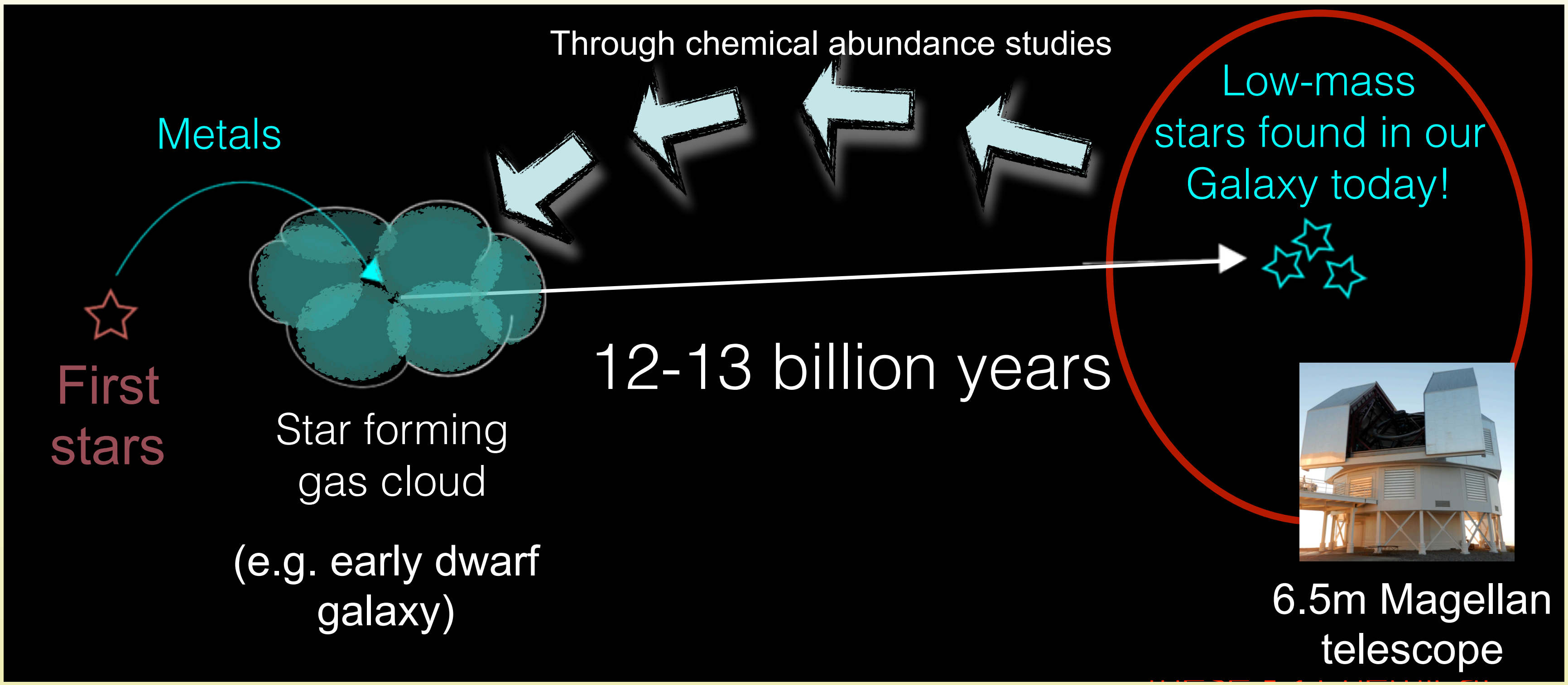
=> Origin of these stars is unknown



STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

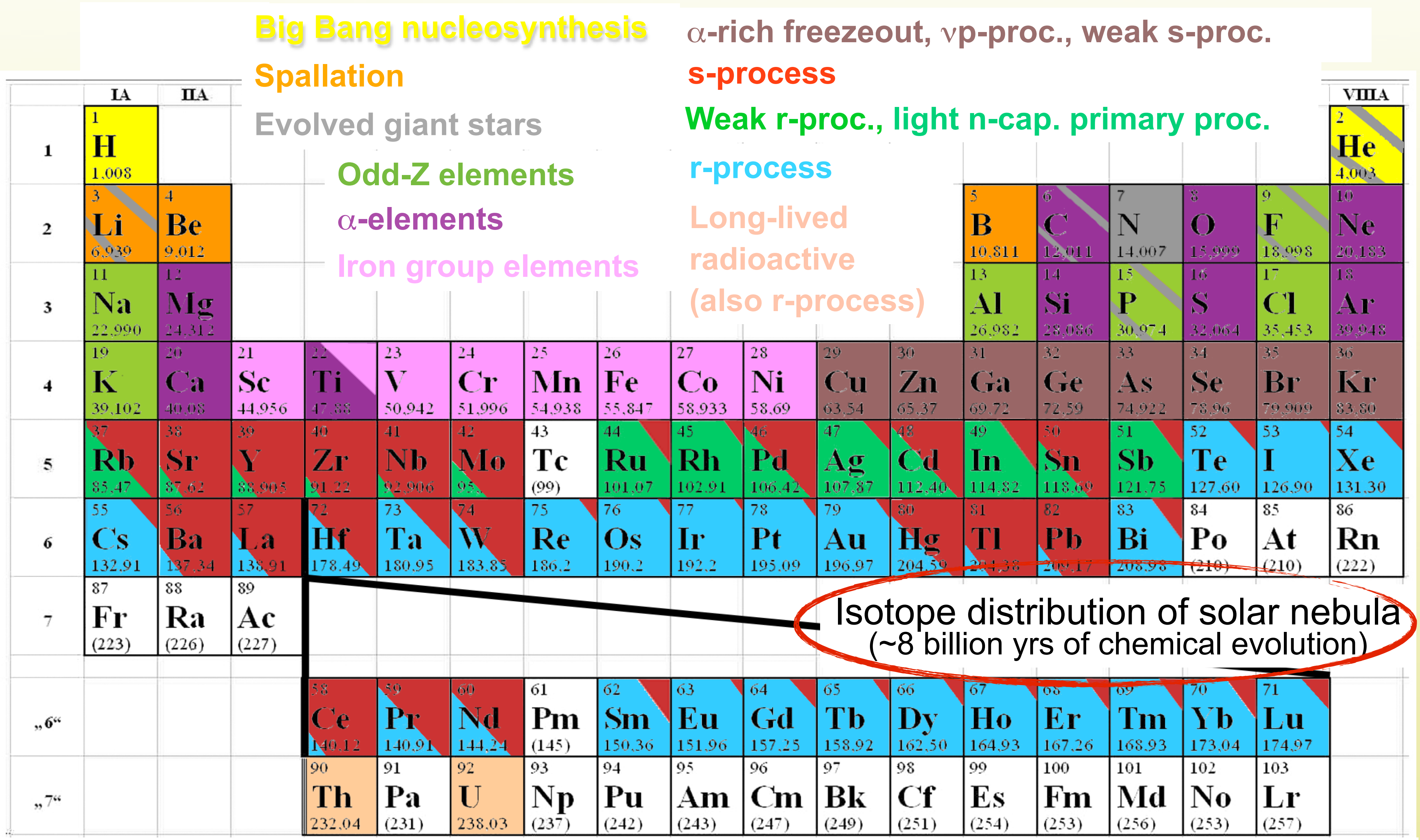
Low-mass stars with $M < 1 M_\odot$: Lifetimes > 10 billion years => they are still around!



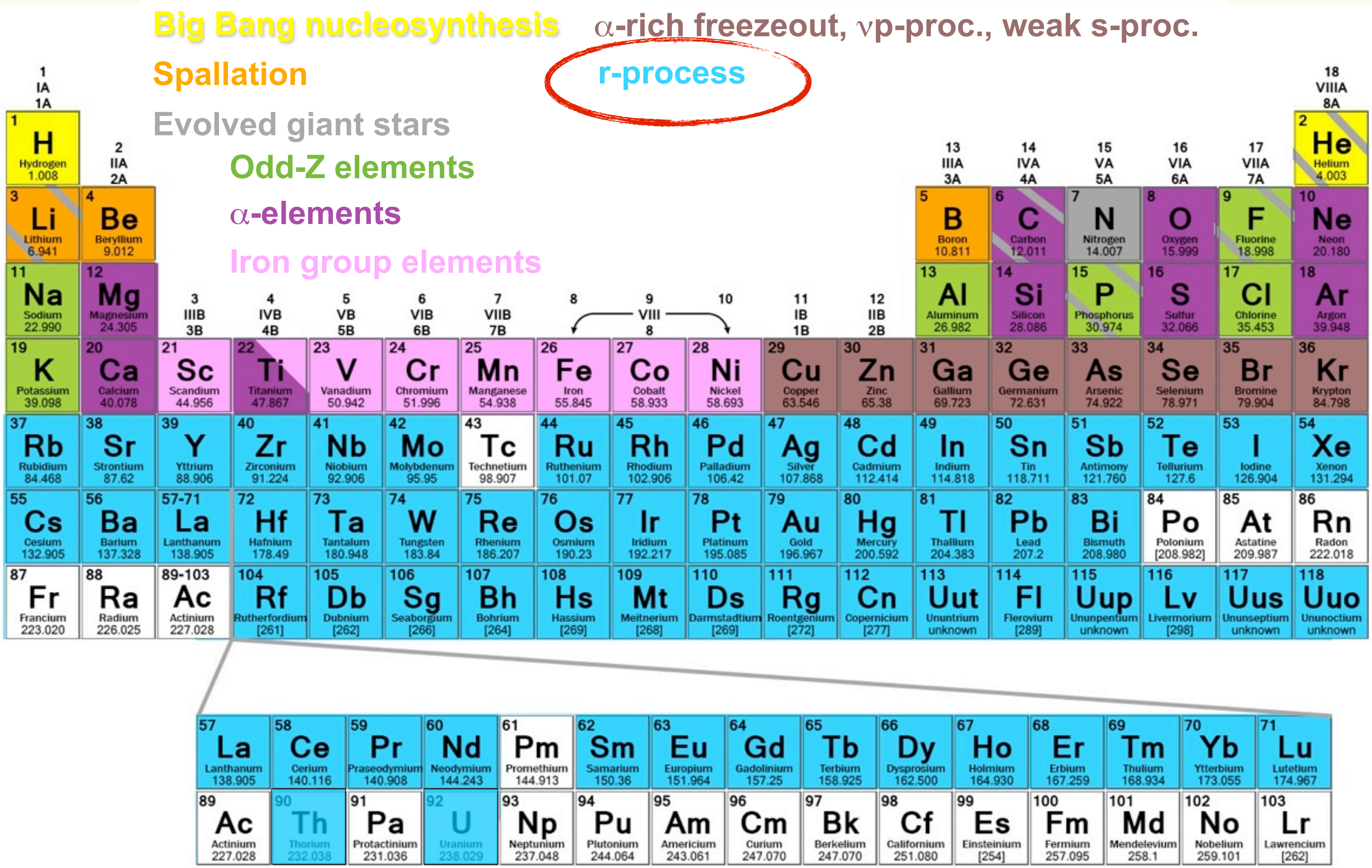
[Fe/H] ≤ –3
(= 1/1000th of solar Fe)

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

The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table

Big Bang nucleosynthesis

Spallation

Evolved giant stars

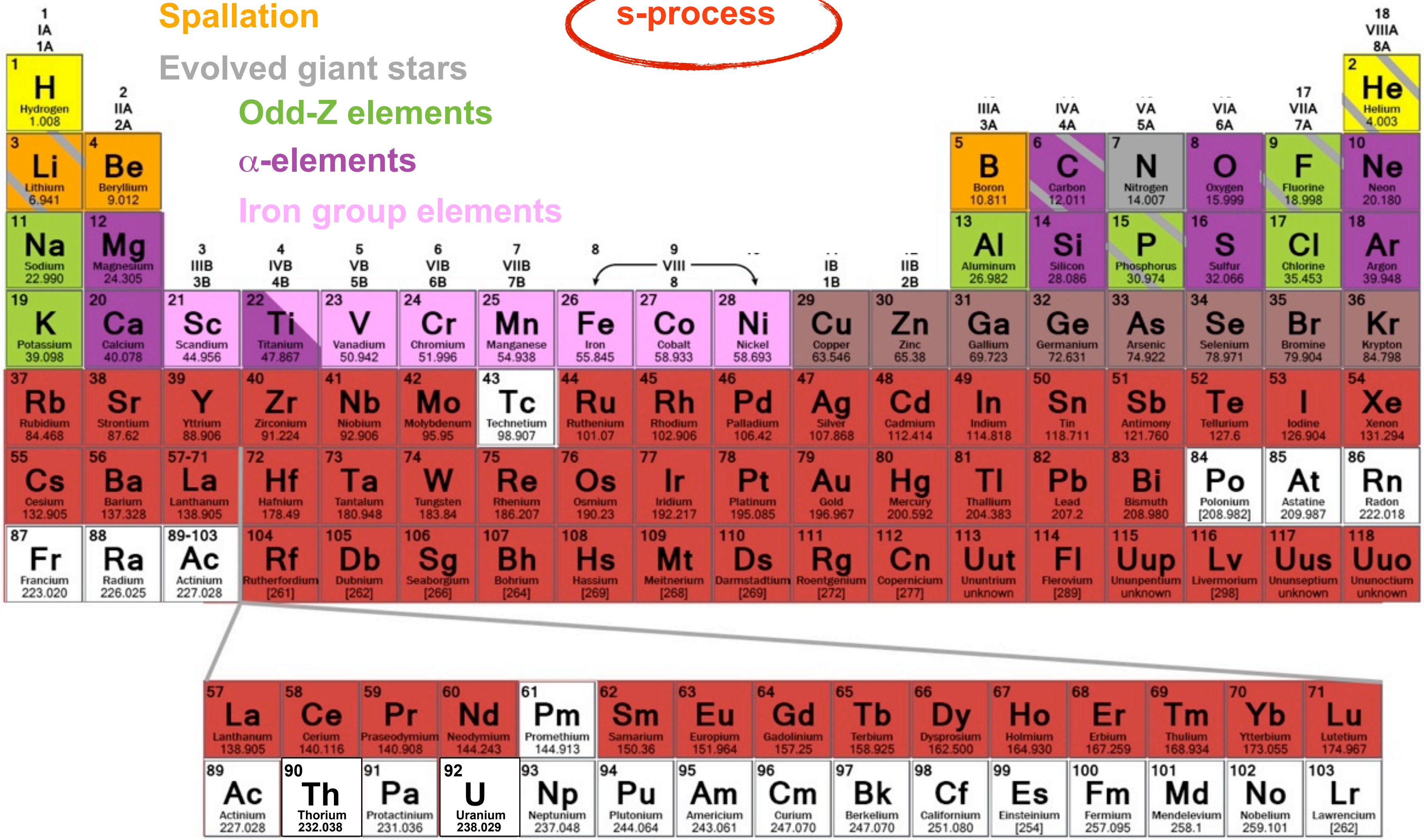
Odd-Z elements

α-elements

Iron group elements

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

s-process



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)

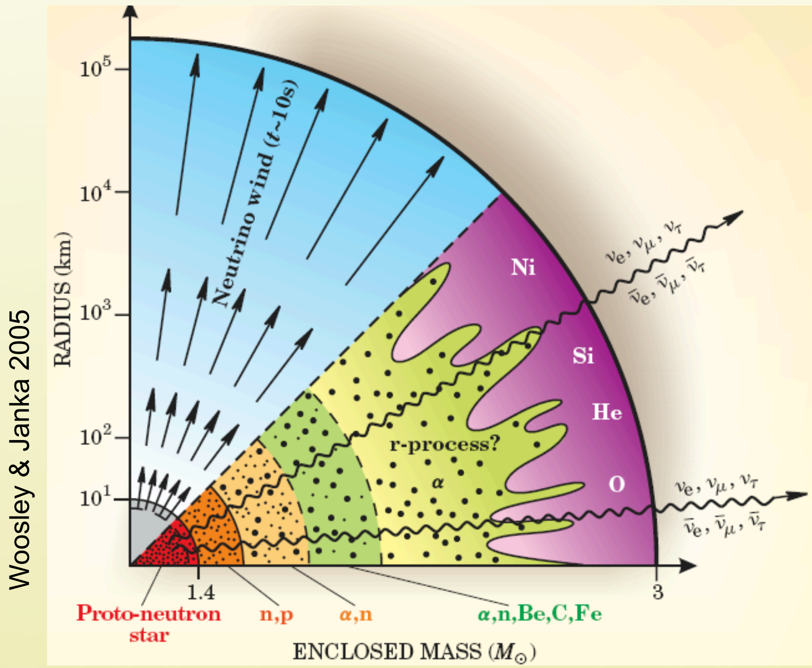
★ **What is the rate and yield of the event?**

★ **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)

Ultra-faint dwarf galaxy properties (UFDs)

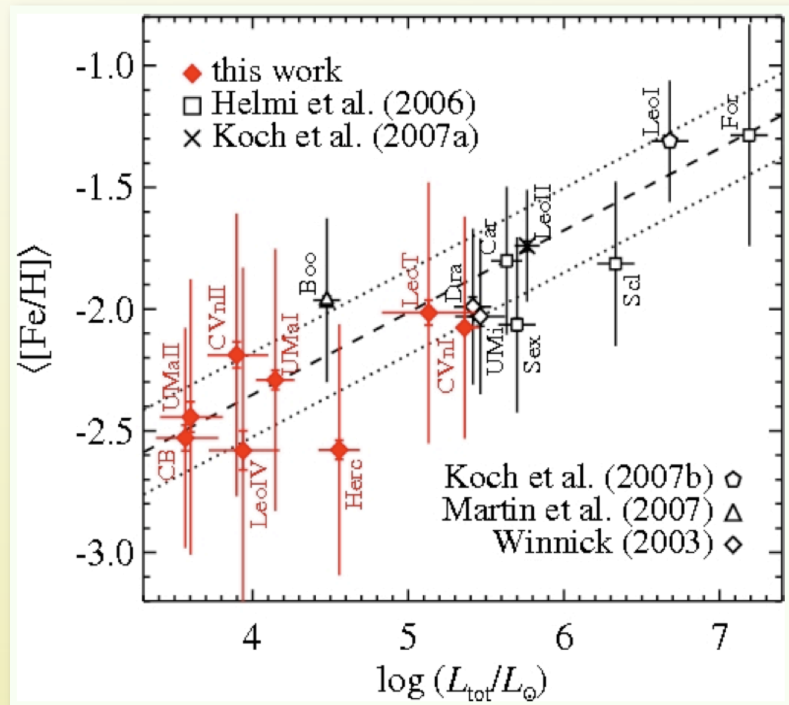
Low luminosity (300 - 3,000 L_{sun})

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

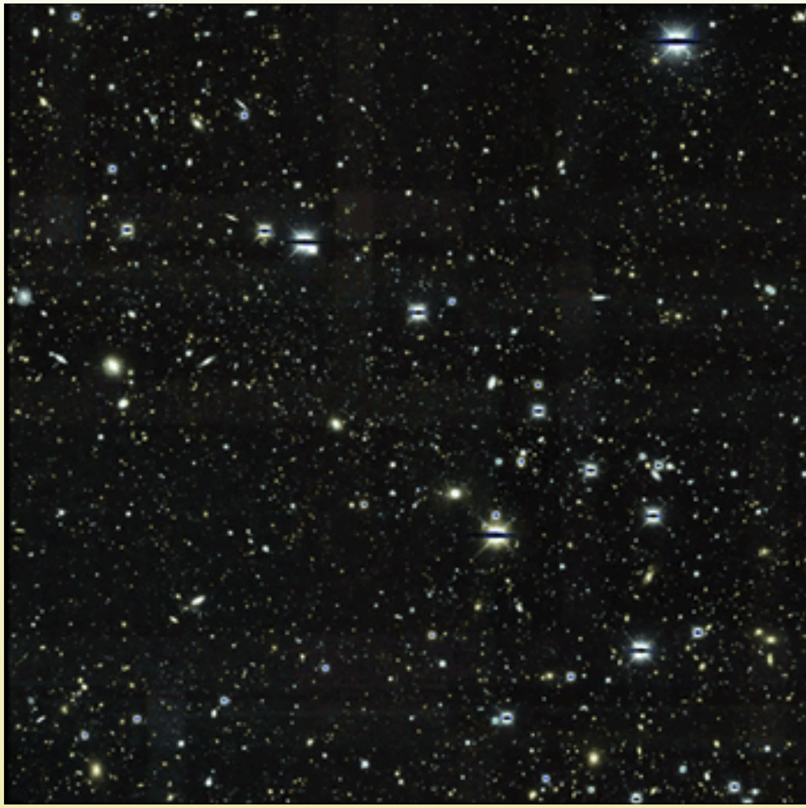
Classical dSphs

Ideal targets for Dwarf Galaxy Archaeology

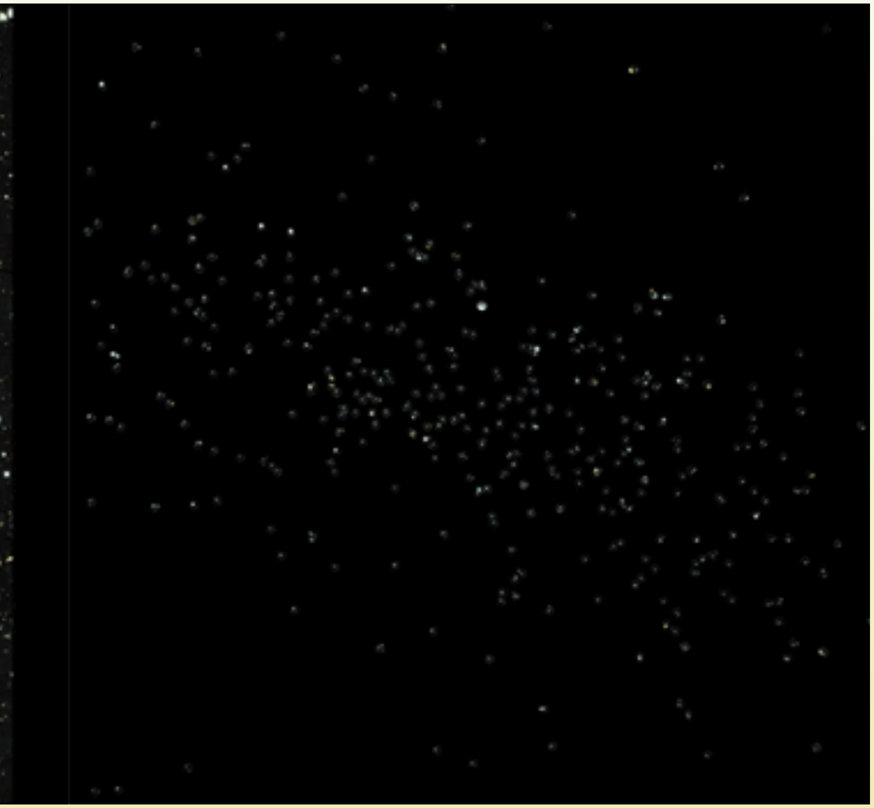
Use entire galaxy as fossil record of the early universe.

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

Meet Reticulum II



All stars



Reticulum II stars

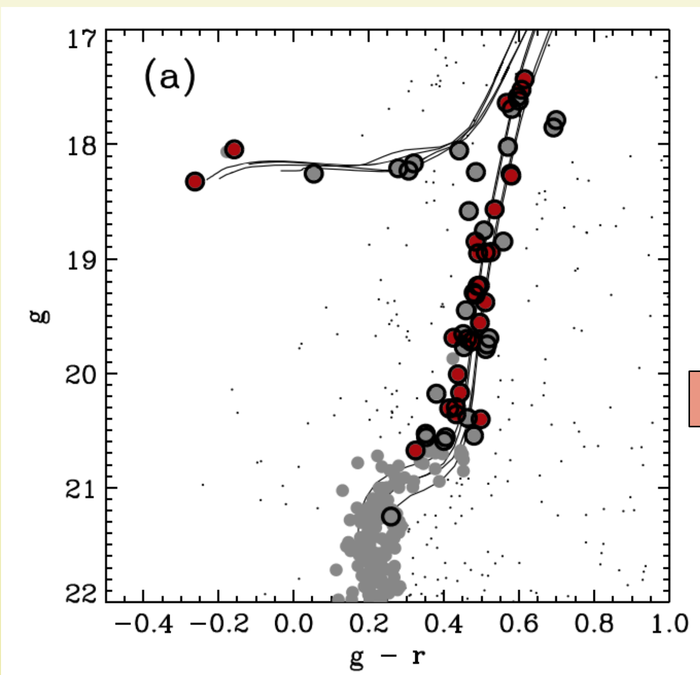
(Dark Energy Survey, 2015)

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)



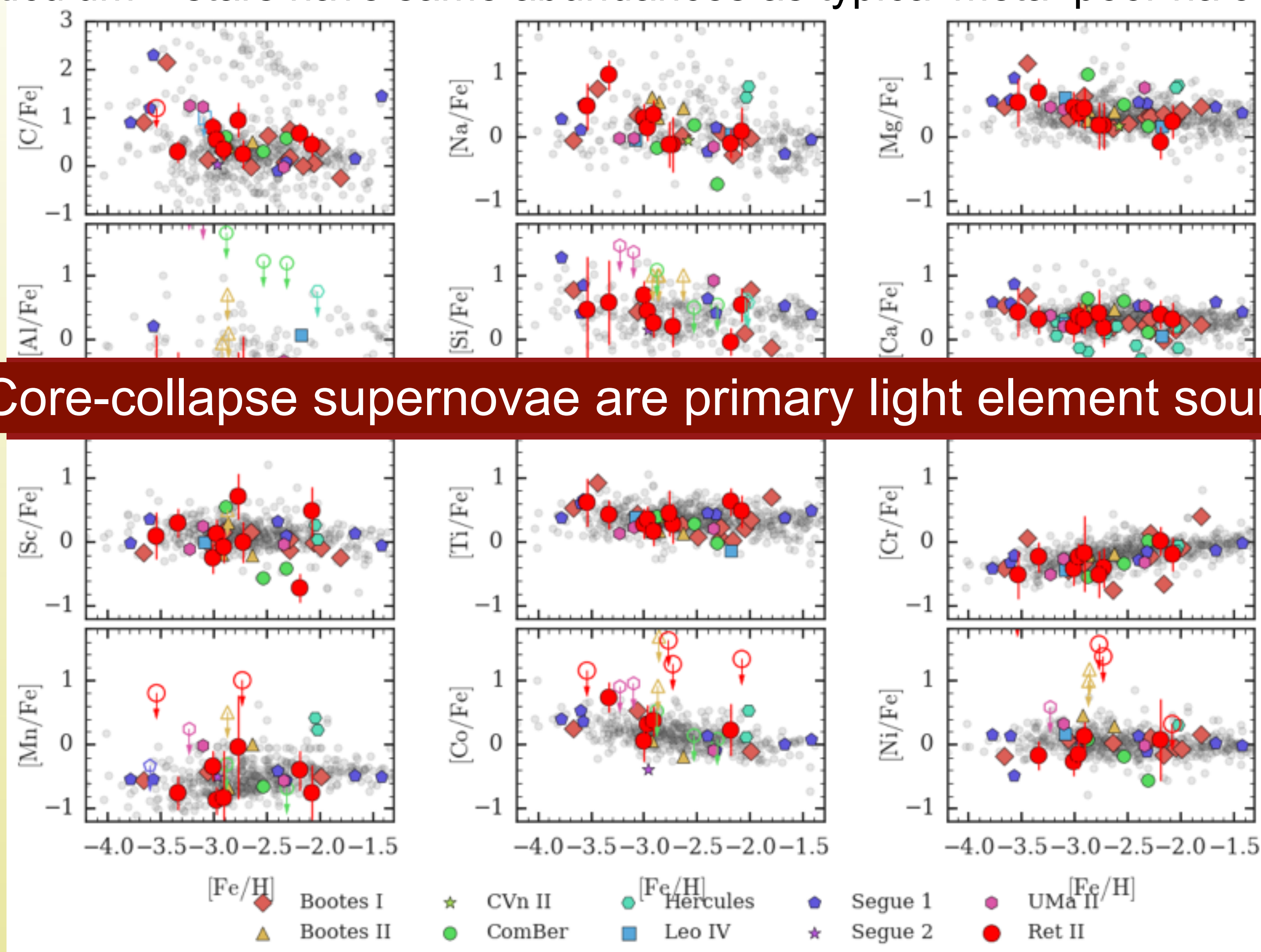
Color-magnitude-diagram of Ret II
(red = confirmed members)

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)

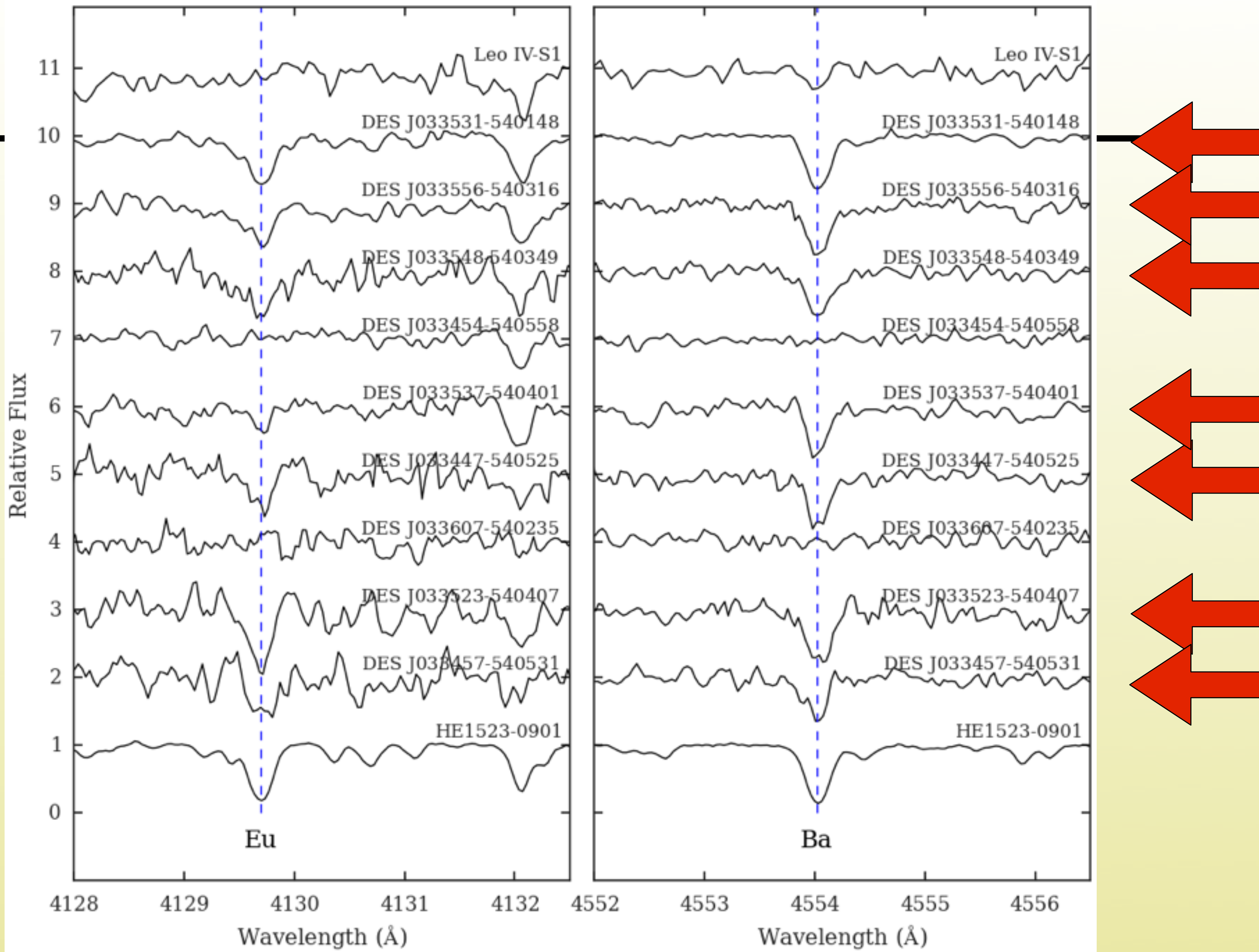
Reticulum II stars have same abundances as typical metal-poor halo stars



Core-collapse supernovae are primary light element source

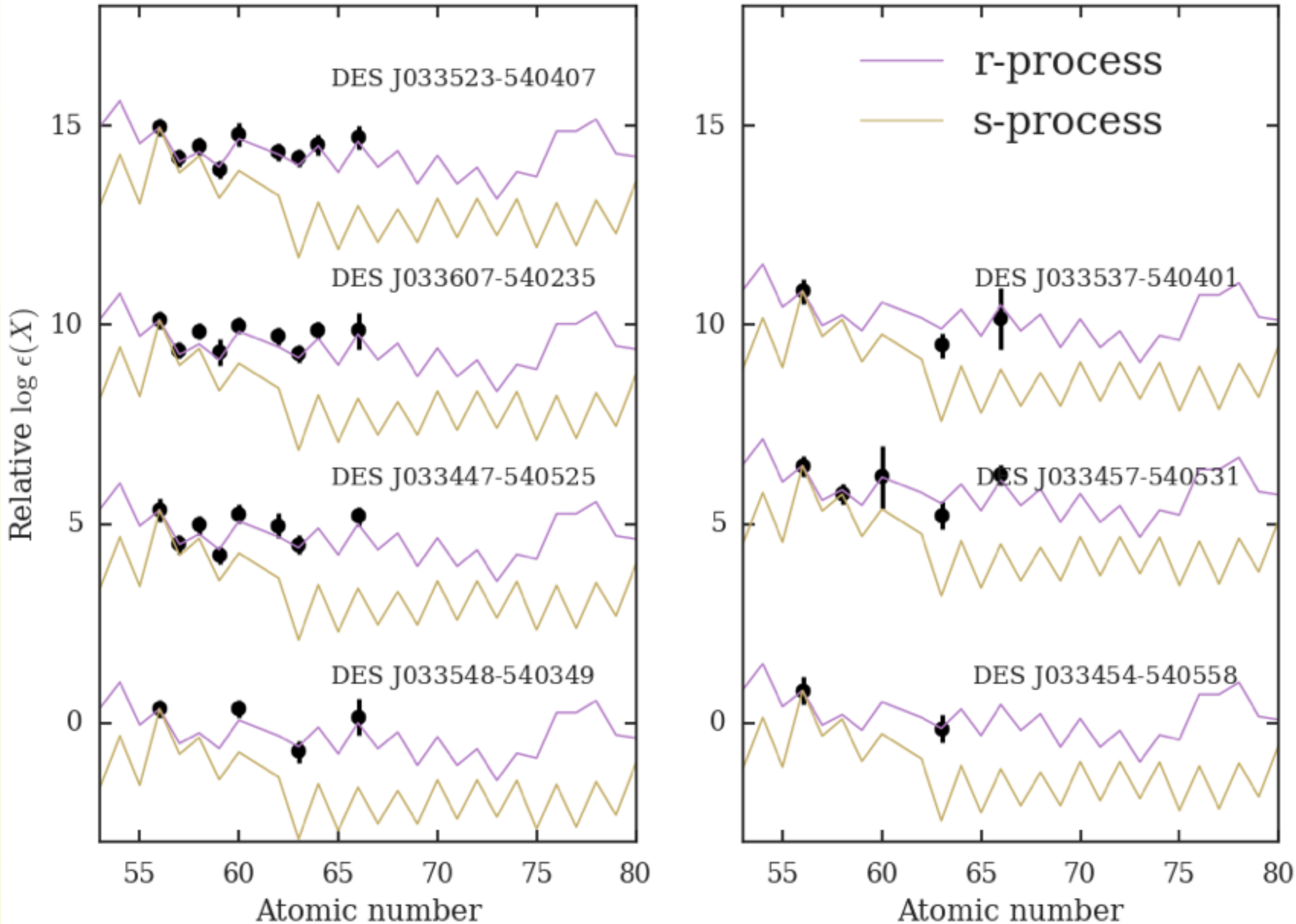
gray dots metal-poor halo stars

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



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)

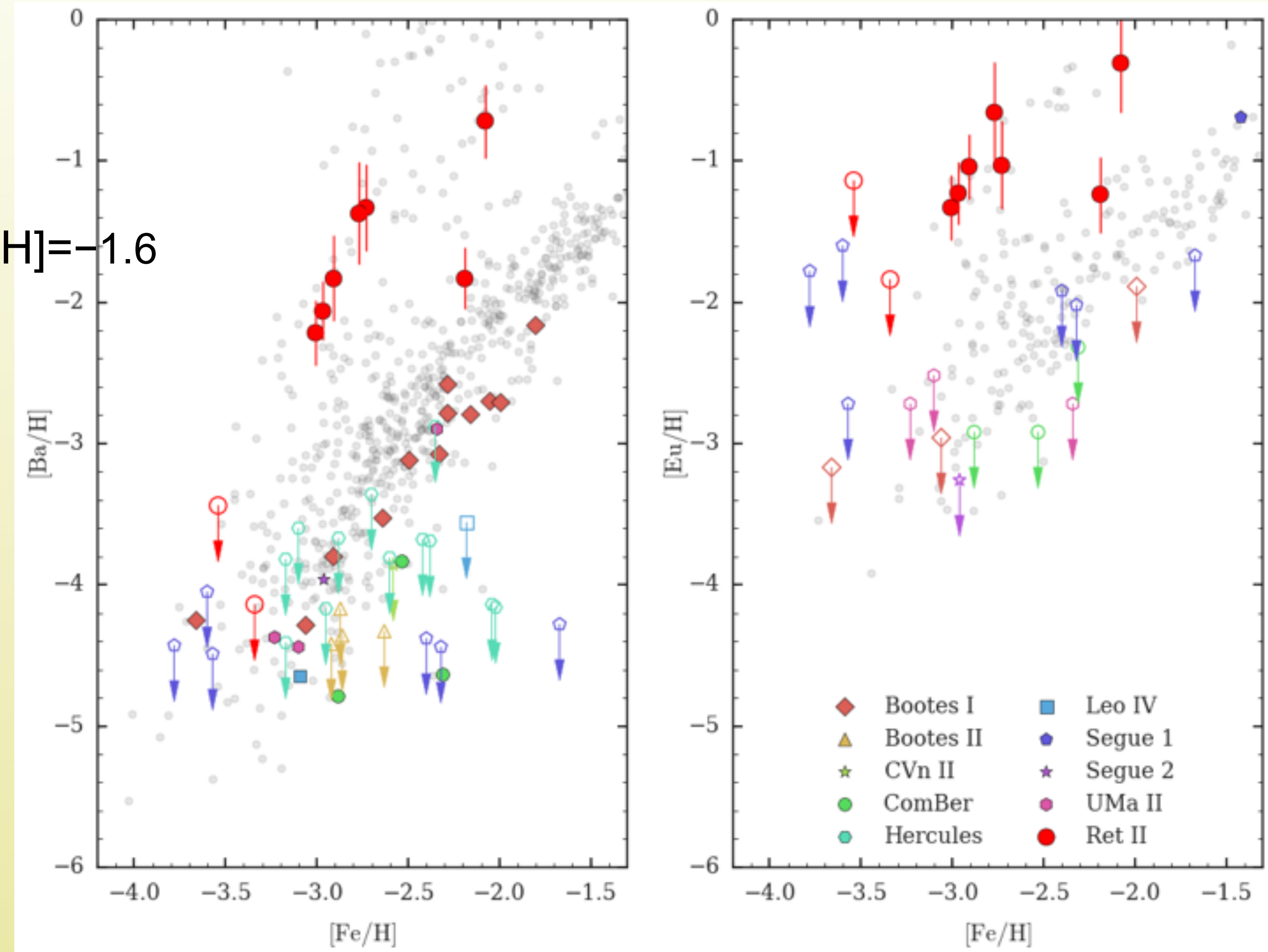
All seven Ret II stars display the r-process pattern



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

Ret II stars: ≥ 100x higher 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}

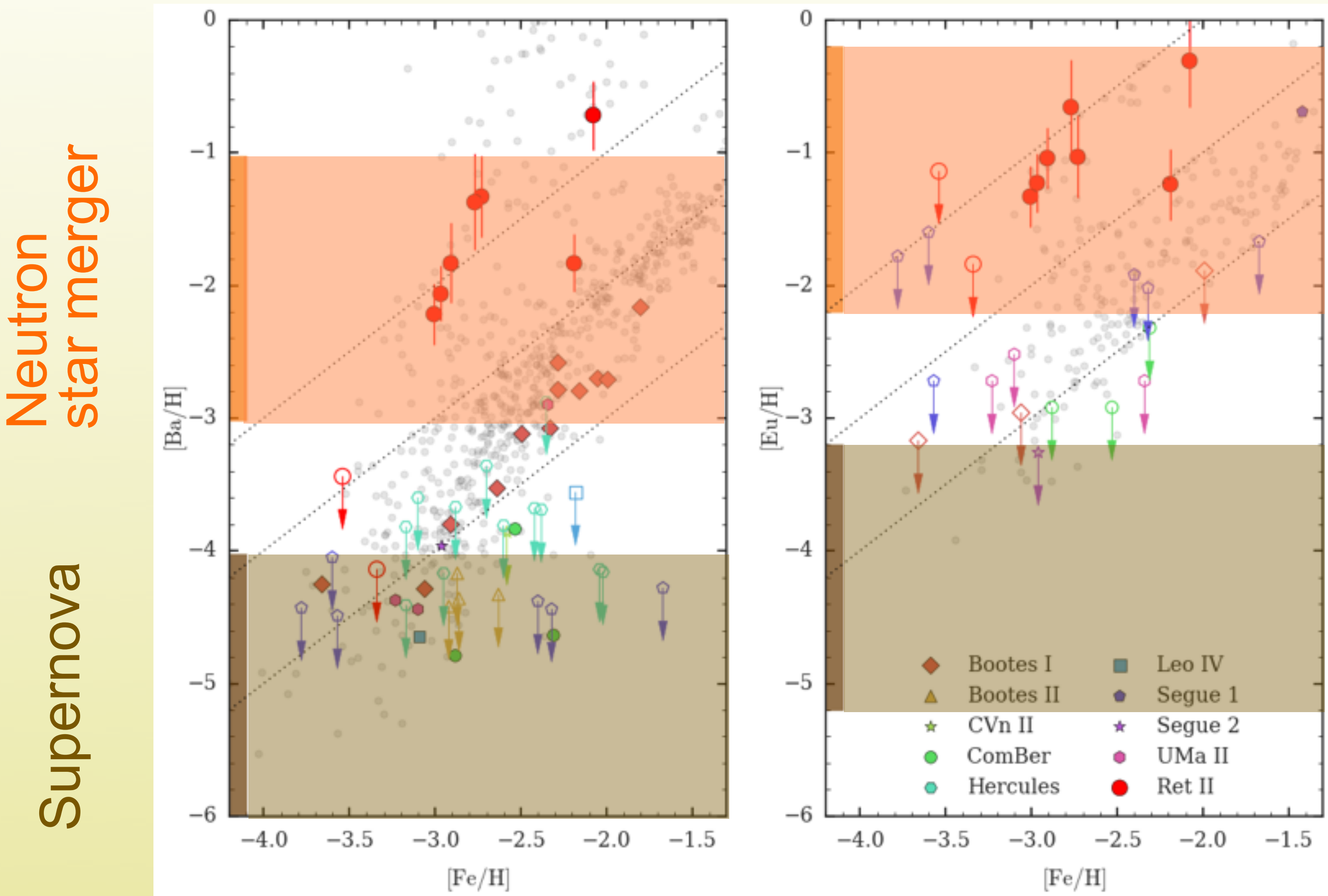
<u>Back-of-the-envelope calculation</u>

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

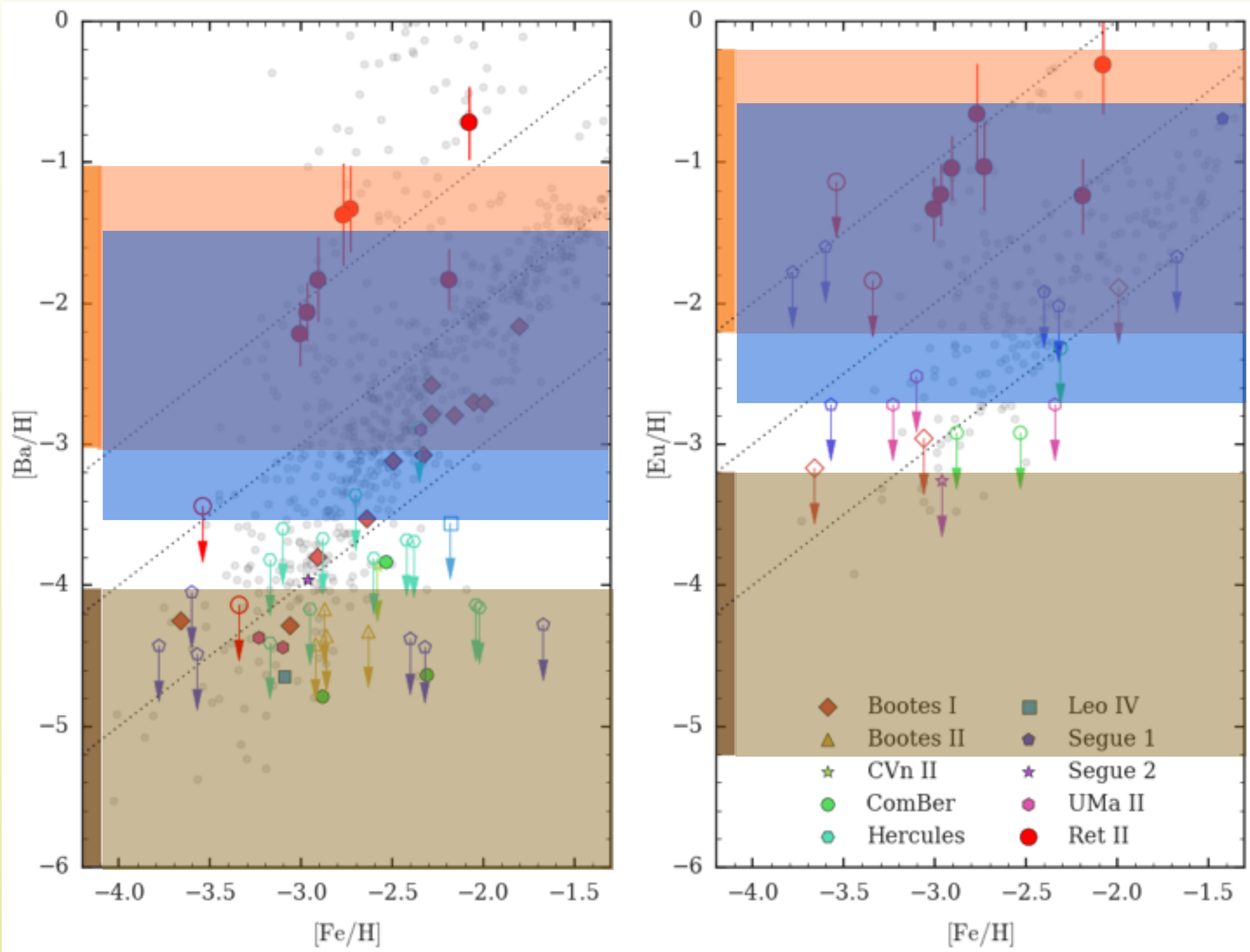


Ji et al 2016, *Nature*, 531, 610

Rare and prolific jet-driven supernova remains possibility

Neutron star merger

Supernova



Jet-driven supernova

(e.g. Winteler et al. 2012)

...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

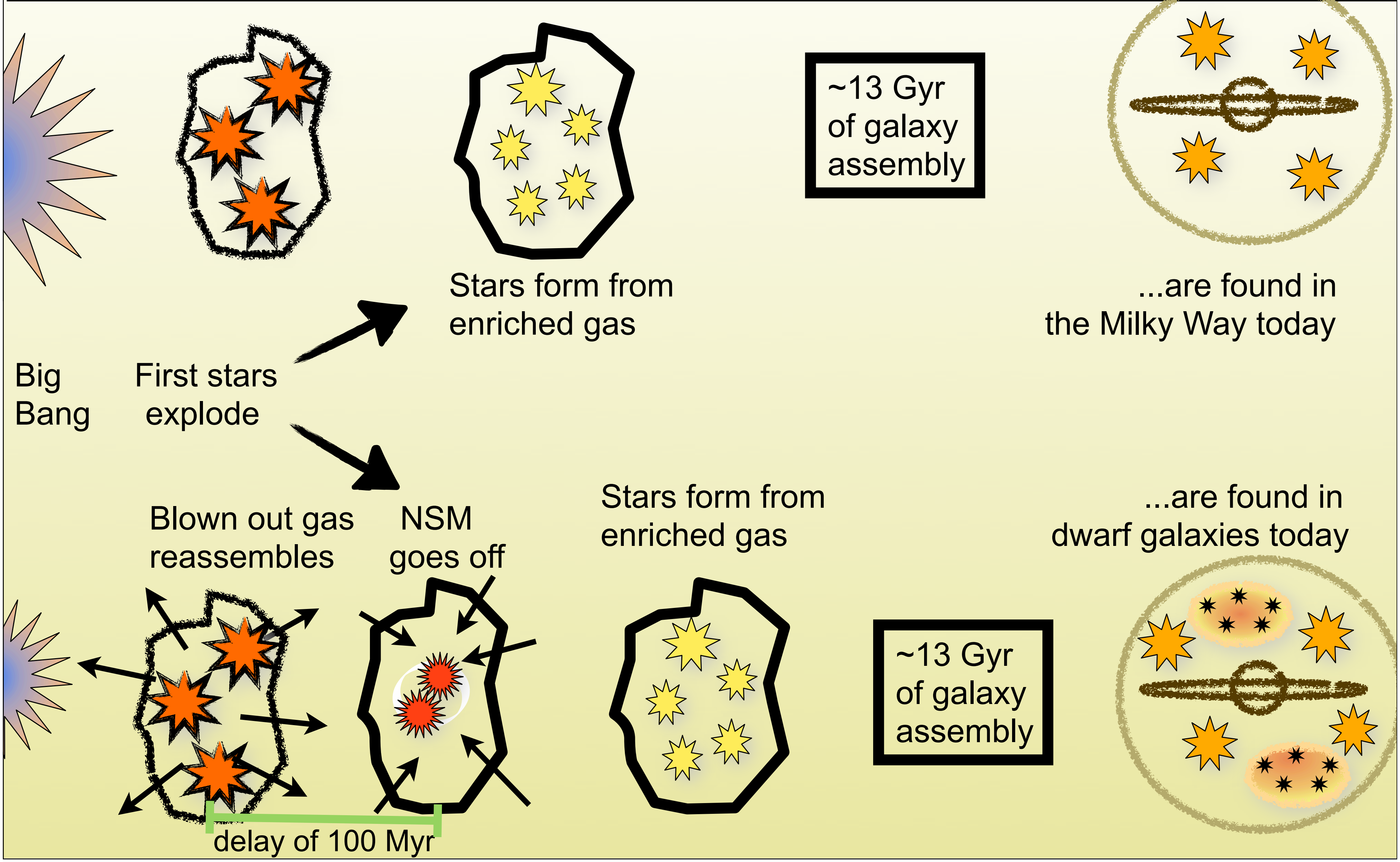
➡ Need to be just one/few massive events

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



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 superı ⇨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!

COMMON NOMENCLATURE
(FOCUSSED ON PHYSICS PROCESS)

Enables astronomers to identify nuclear physics processes among stellar observational data!

Table 2 Nucleosynthesis processes that can contribute to neutron-capture element patterns observed in metal-poor stars

Name	Description	Elements produced	Y_e	Site(s)	References	Star(s)
Terminal QSE	insufficient n-rich α-, n-, p-capture and reverse extension from hot, dense state	Sr → Ag	< 0.5	"standard" proto-NS wind in CCSN shock-heated/disk ejecta	TBD	? light el. of rI/rII stars?
νp-process	p-rich, $\bar{\nu}_e$-rich QSE + $\bar{\nu}_e$-capture	Sr → Ag → Mo	> 0.5	"standard" proto-NS wind in CCSN shock-heated/disk ejecta		? light el. of rI/rII stars?
Limited[a] r-process	n/s $\sim$ 100 QSE + (limited) n-capture no fission cycling	Sr → Ba (limited production towards Ba)	< 0.5	modified proto-NS wind(?) NSM disk (after merger)[b] shock-heated ejecta (during merger)[c]		HD122563 ? light el. of rI/rII stars?
Main r-process	n/s >> 100; QSE + n-capture any fission cycling	Ba→ U	< 0.2	NSM tidal ejecta (during interaction) dynamical ejecta during merger		**rI/II stars**
Robust (main) r-process	n/s >> 100; QSE + n-capture fission cycling limit	Ba → U	< 0.2	NSM tidal ejecta (during interaction) dynamical ejecta during merger		**rI/II stars**

[a] Sometimes referred to as weak r-process of Light Element Primary Process (LEPP); "Weak", however, does not well describe the nature of the actual r-process physics, and "LEPP" does not refer to a specific nuclear physics process.
[b] On "viscous"/wind timescales.
[c] On dynamical timescales.

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.)

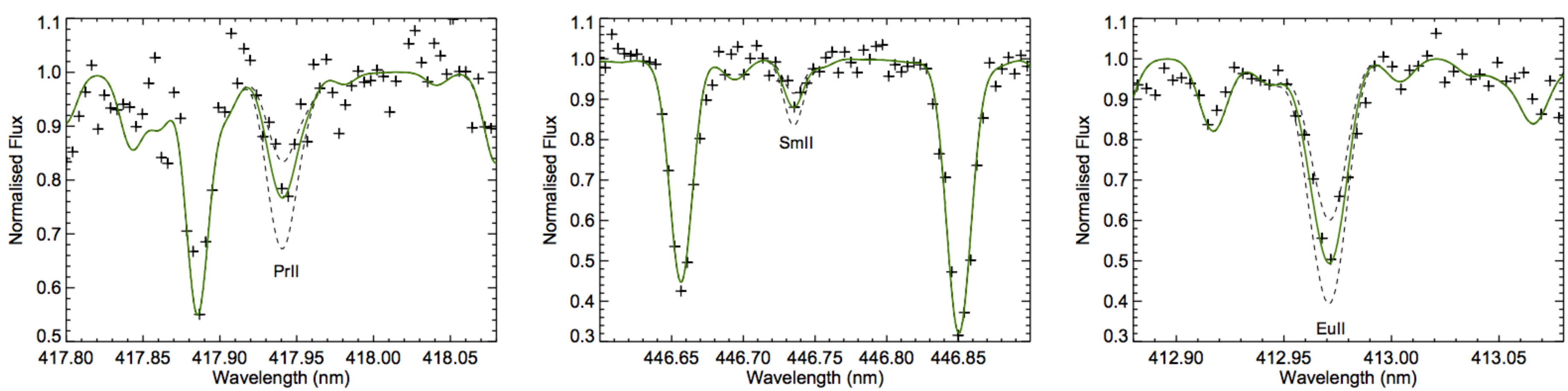
Ideal system to model given all these obs constraints!

Is Reticulum II 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 !

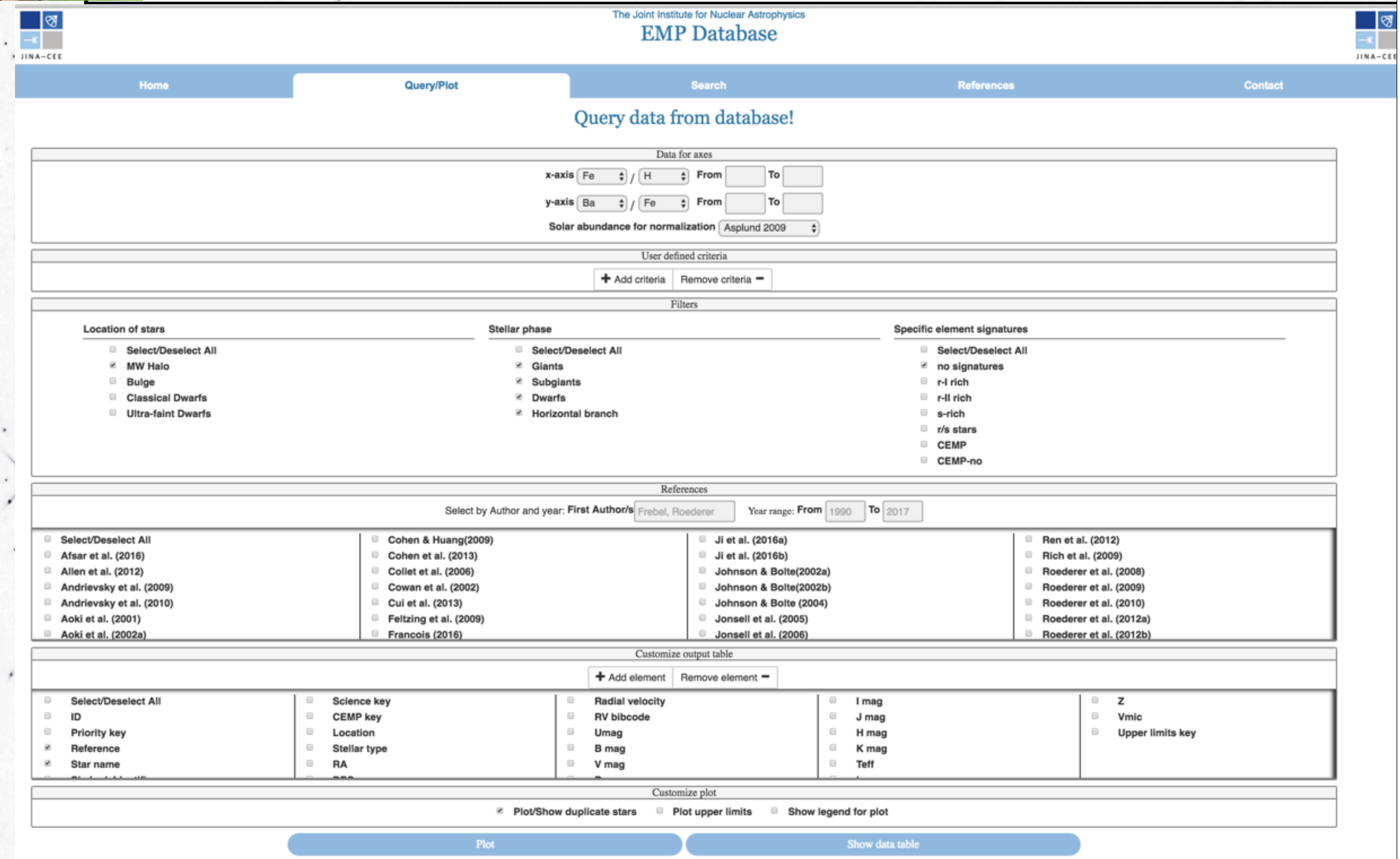
=> 2/12 UFDs show strong r-process enrichment



Abdu Abohalima

JINABASE

A NEW DATABASE OF METAL-POOR STARS



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

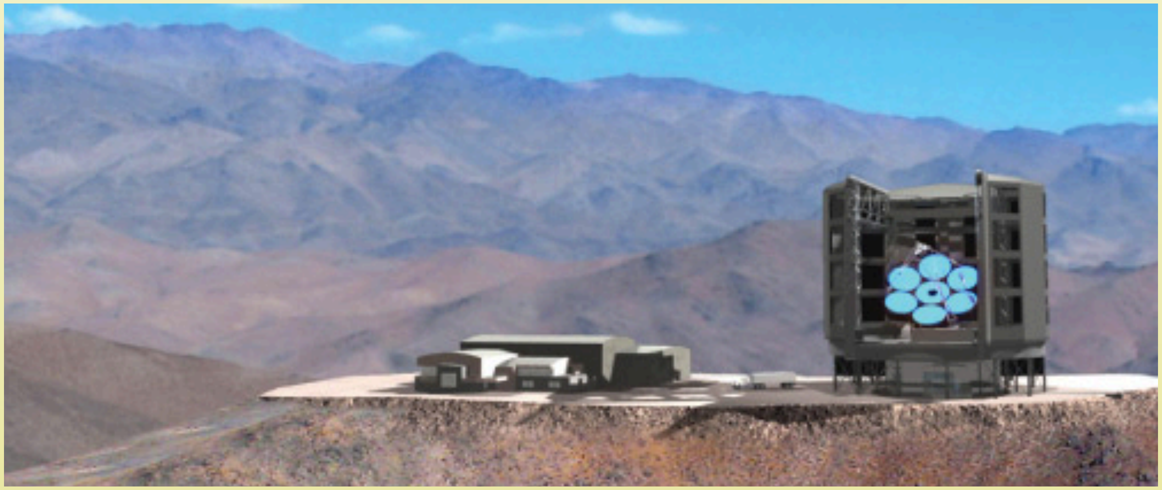
➡ Unprecedented astrophysics constraints for nuclear physics, early chemical evolution, first galaxy formation, metal mixing processes, galaxy assembly, etc.

✓ 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