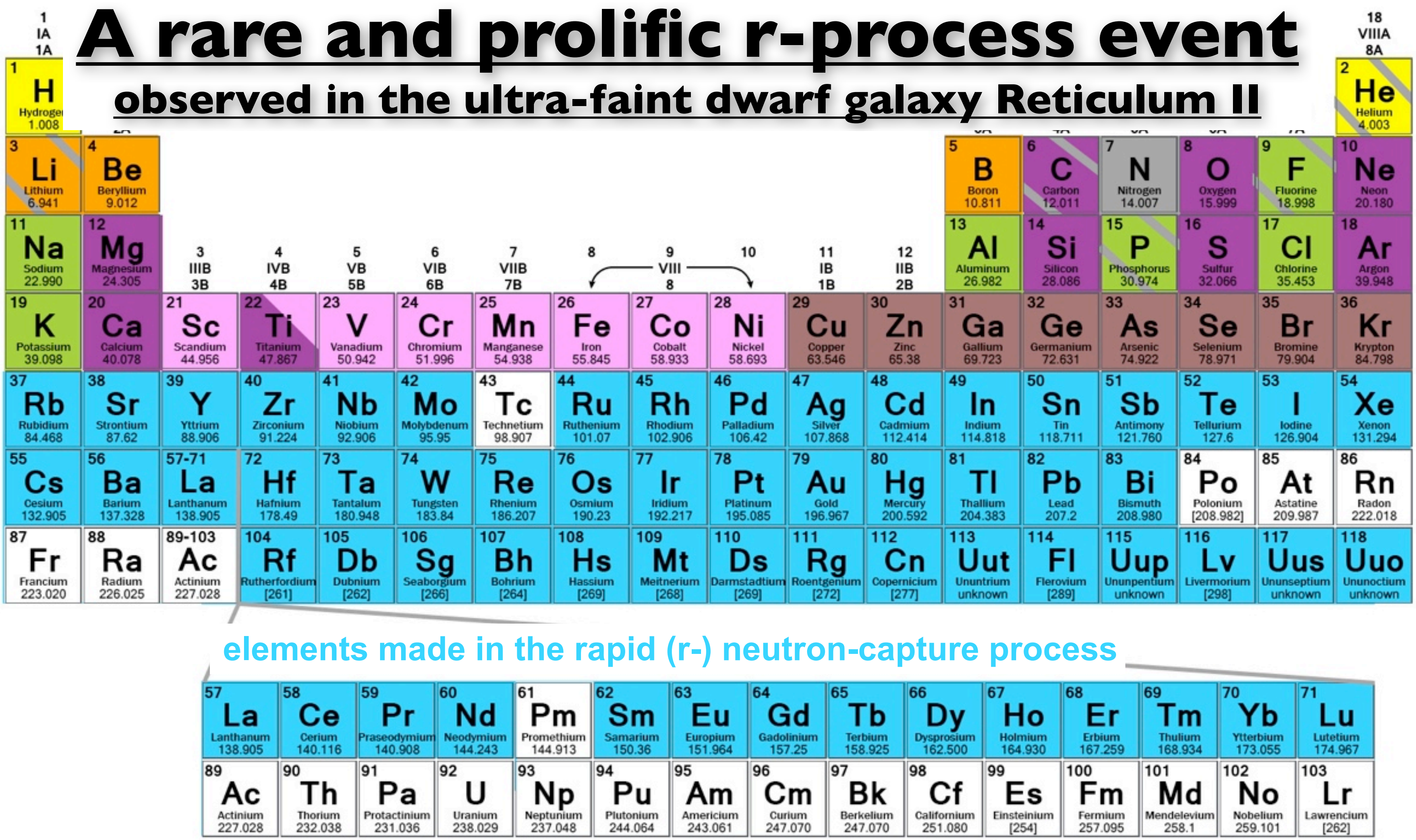
Ji et al. 2016, Nature

A rare and prolific r-process event

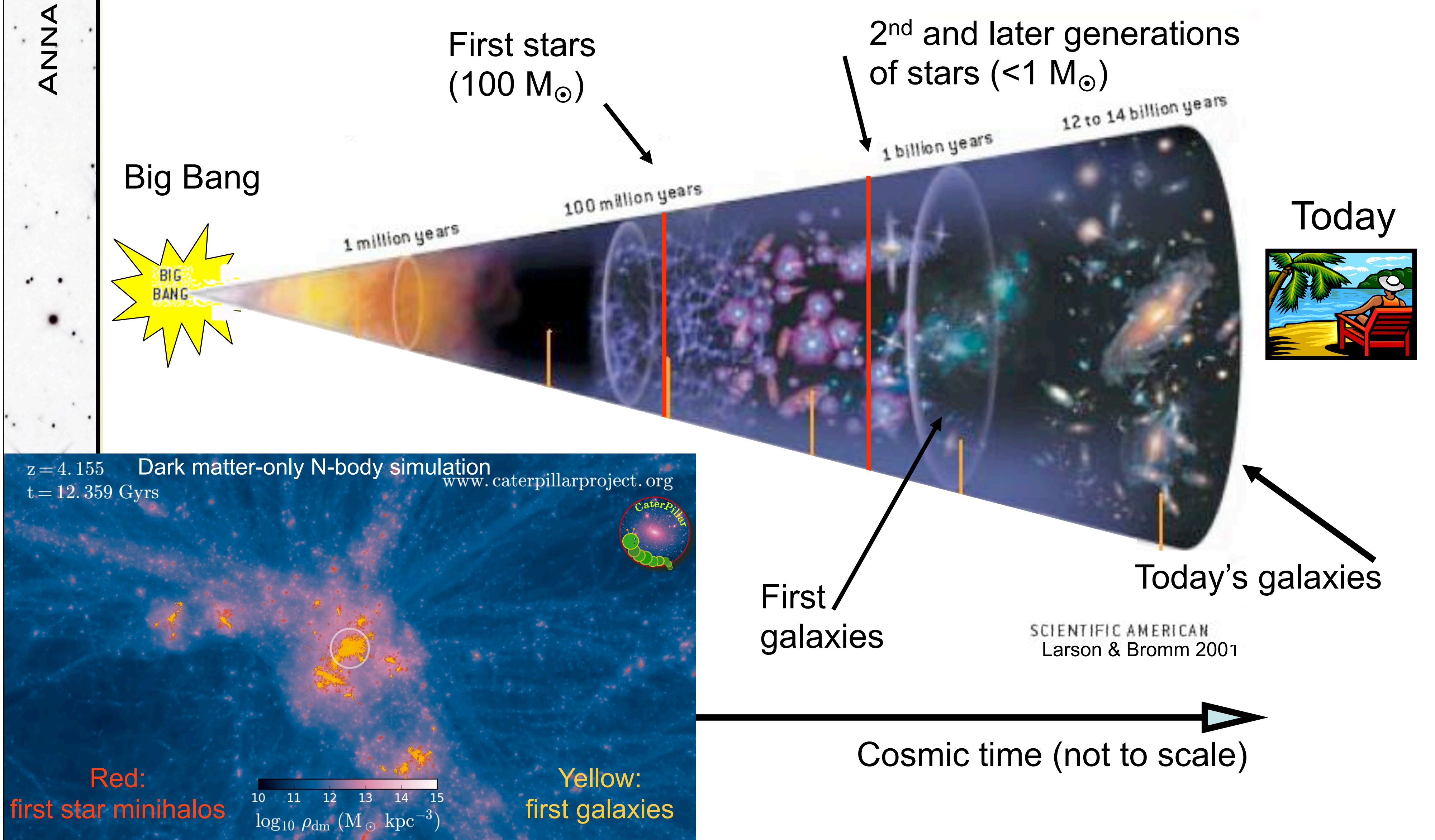
observed in the ultra-faint dwarf galaxy Reticulum II



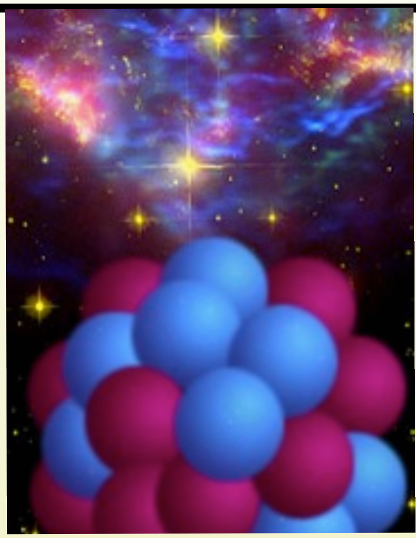
Anna Frebel

Massachusetts Institute of Technology

A long time ago...



The Story of Reticulum II



Nuclear Astrophysics

Cosmic origin of the chemical elements

Stellar Archaeology

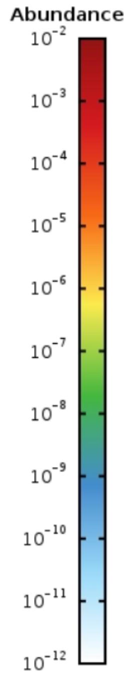
Clues to the astrophysical site of r-process nucleosynthesis

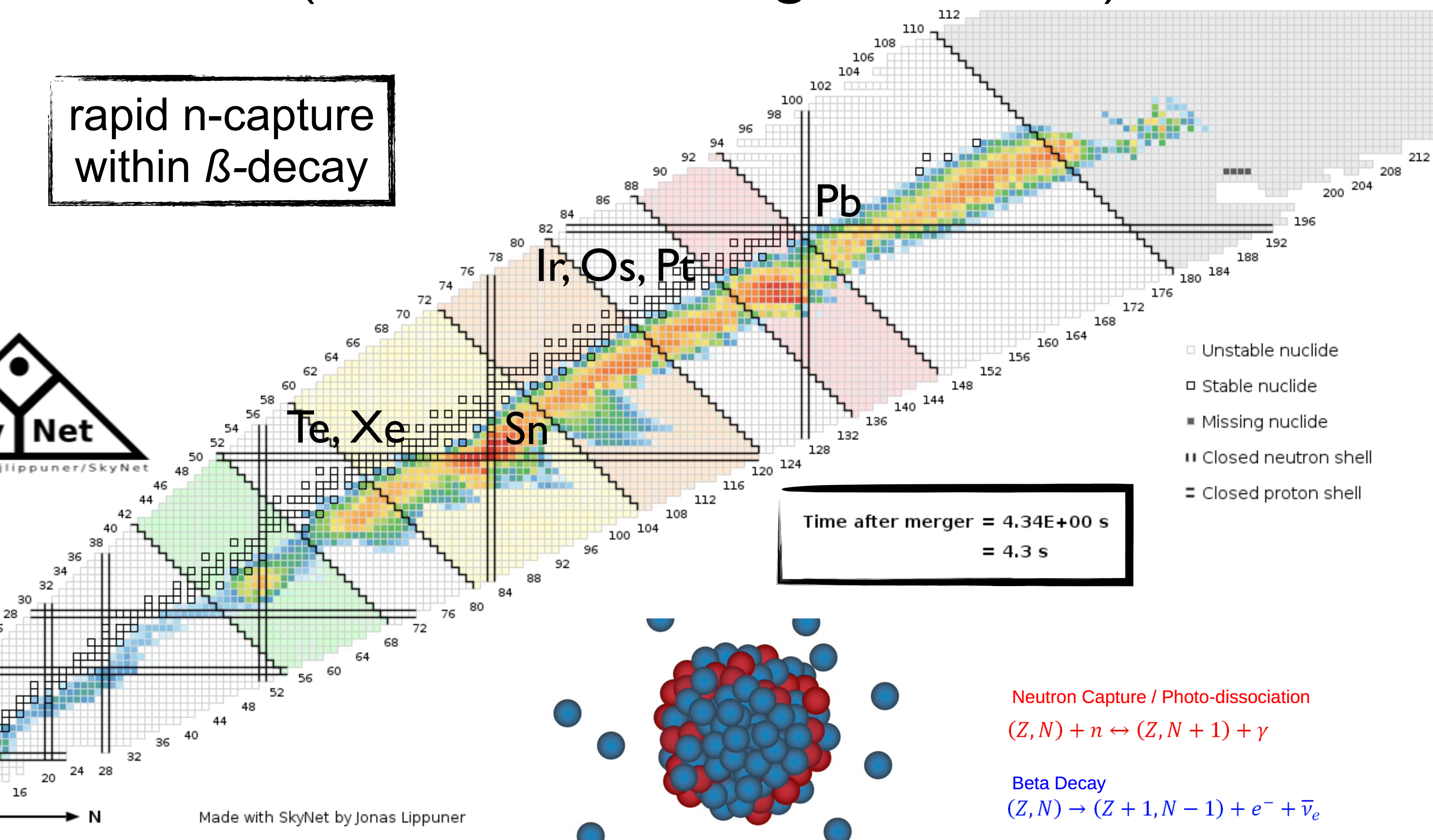
Dwarf Galaxy Archaeology

Ancient, clean chemical enrichment signatures

RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

(neutron star merger scenario)





Neutron Capture / Photo-dissociation

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

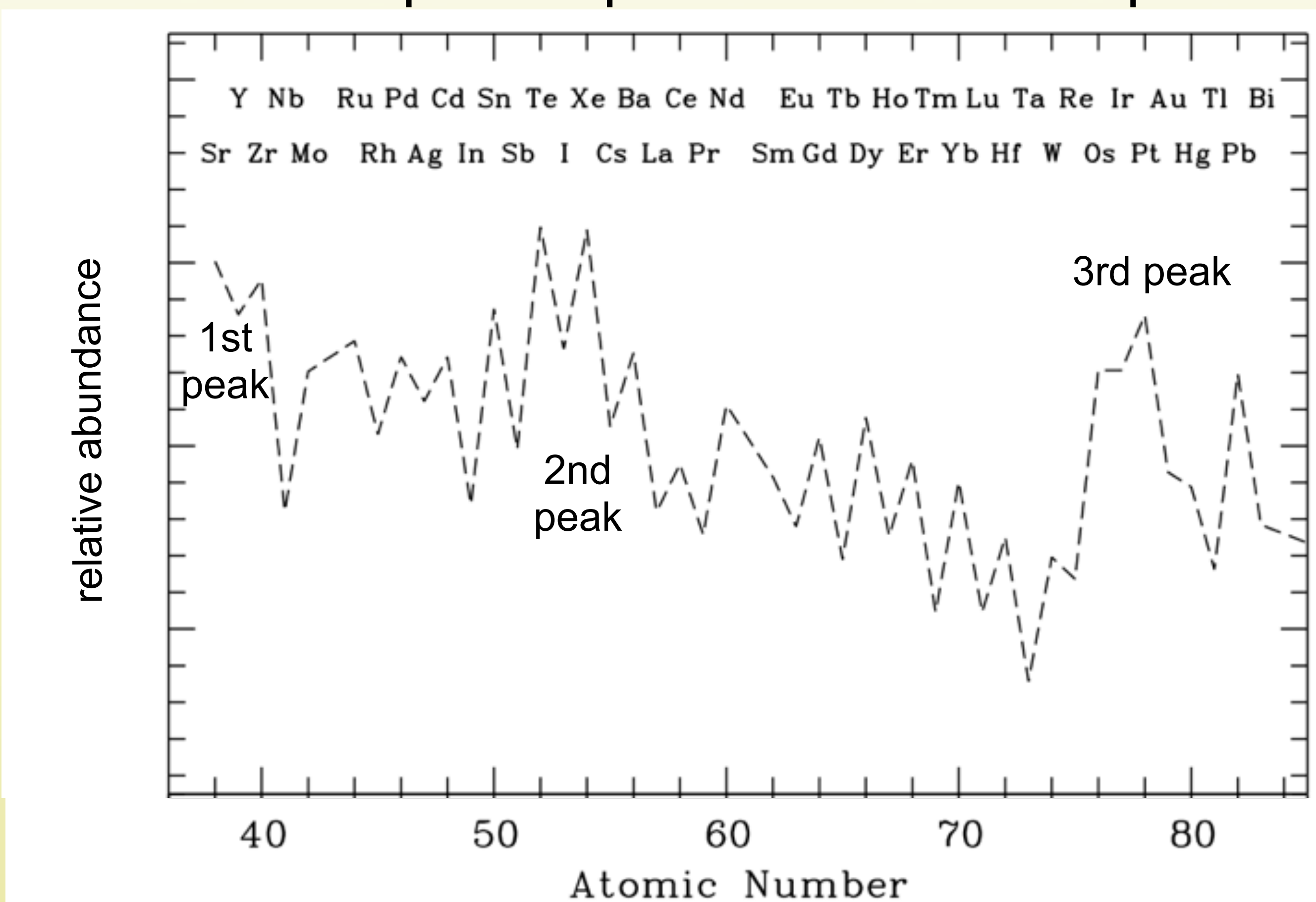
Beta Decay

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

to stability

R-PROCESS PATTERN

neutron-capture r-process elemental pattern

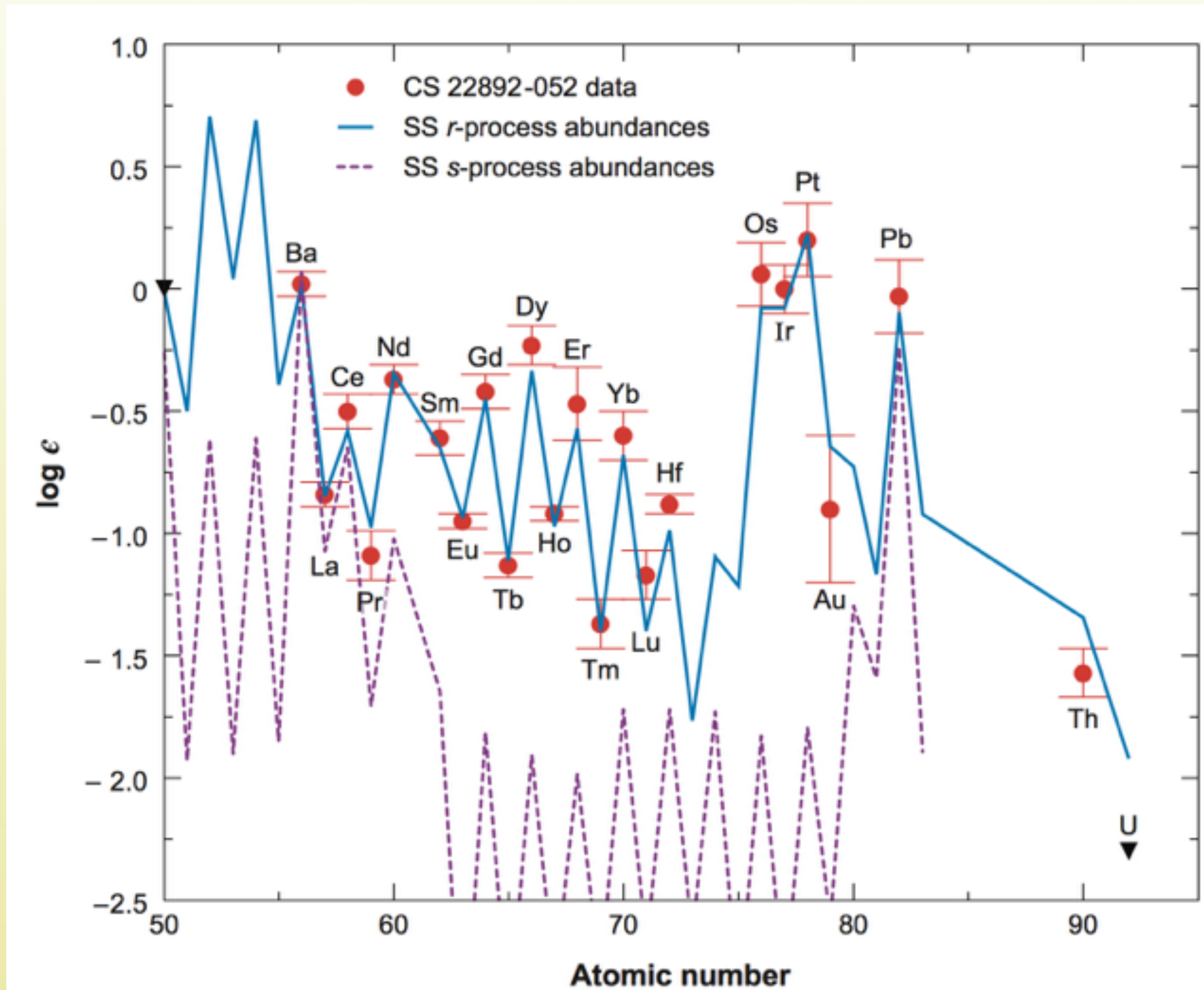


Universal r-process pattern observed in metal-poor stars

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

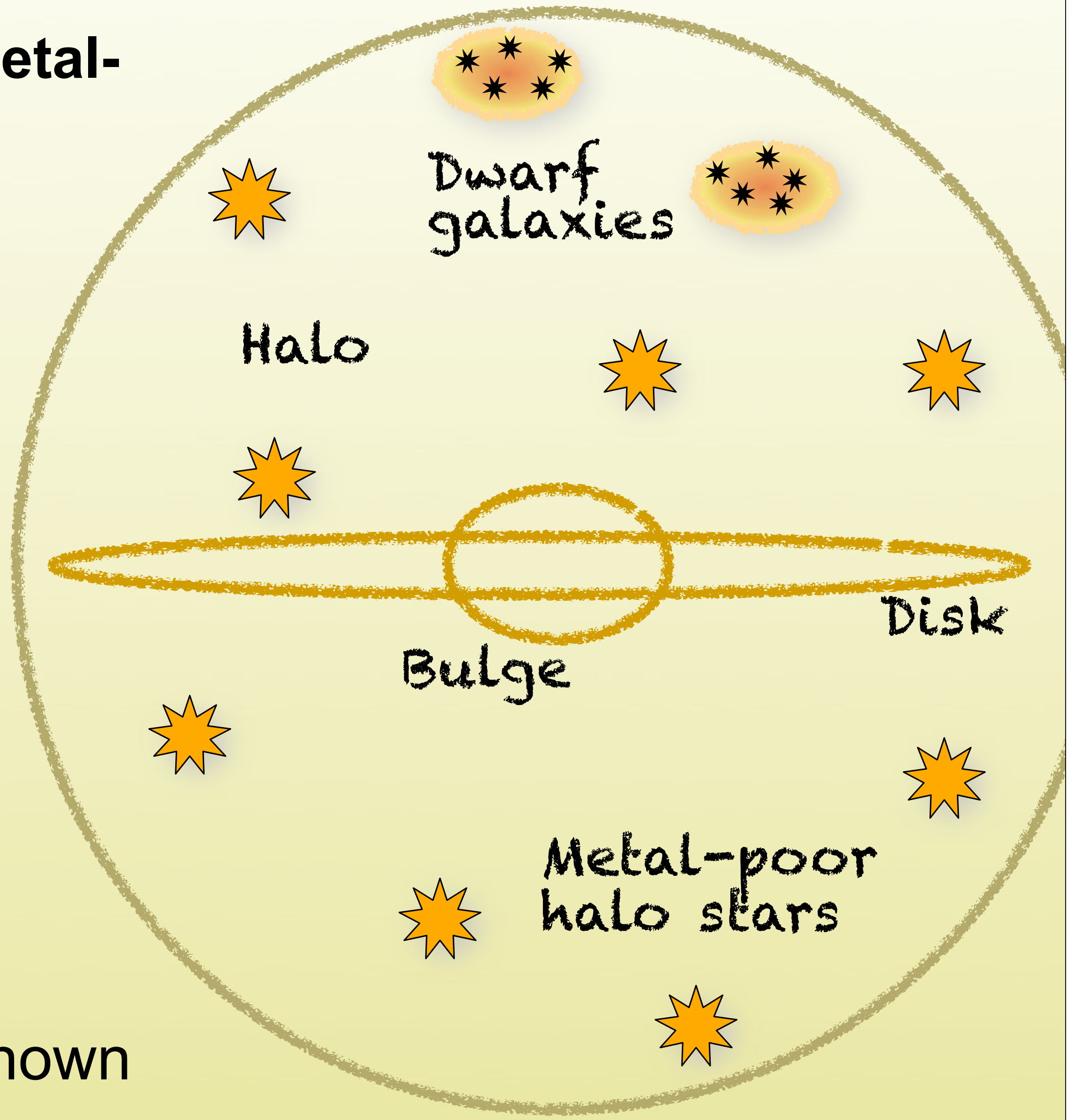
How common are r-process metal-poor stars in the Milky Way?

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**

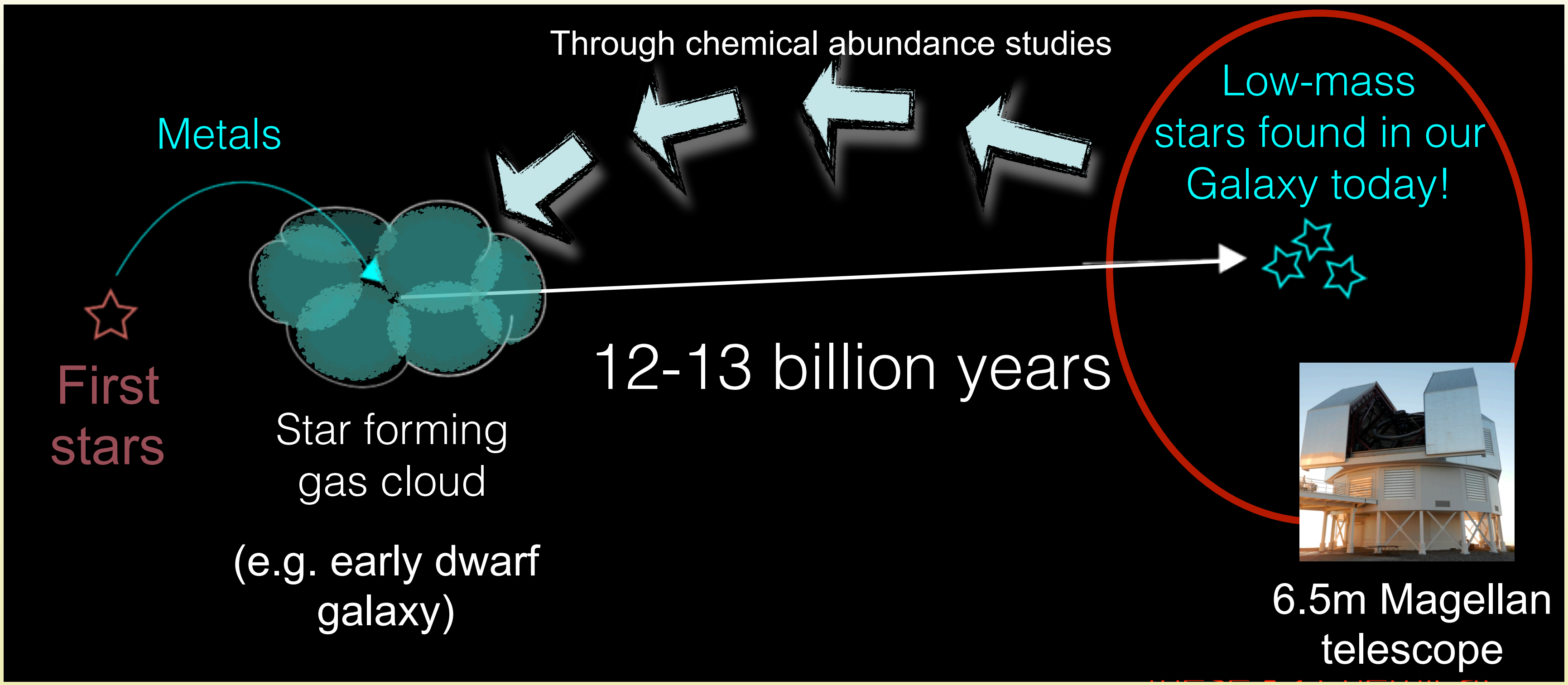
=> Origin of these stars is unknown



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!

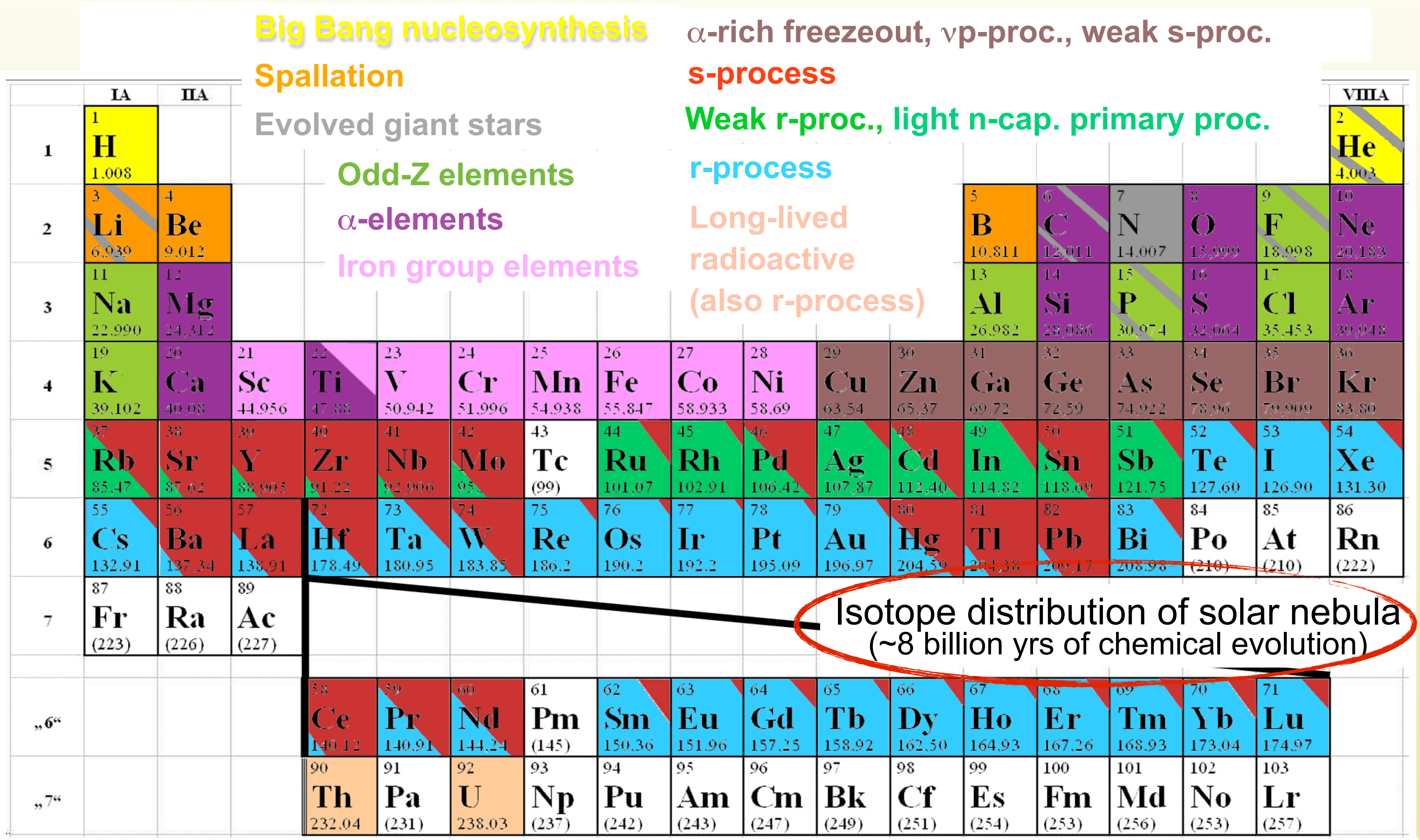


[Fe/H] ≤ –3
(= 1/1000th of solar Fe)

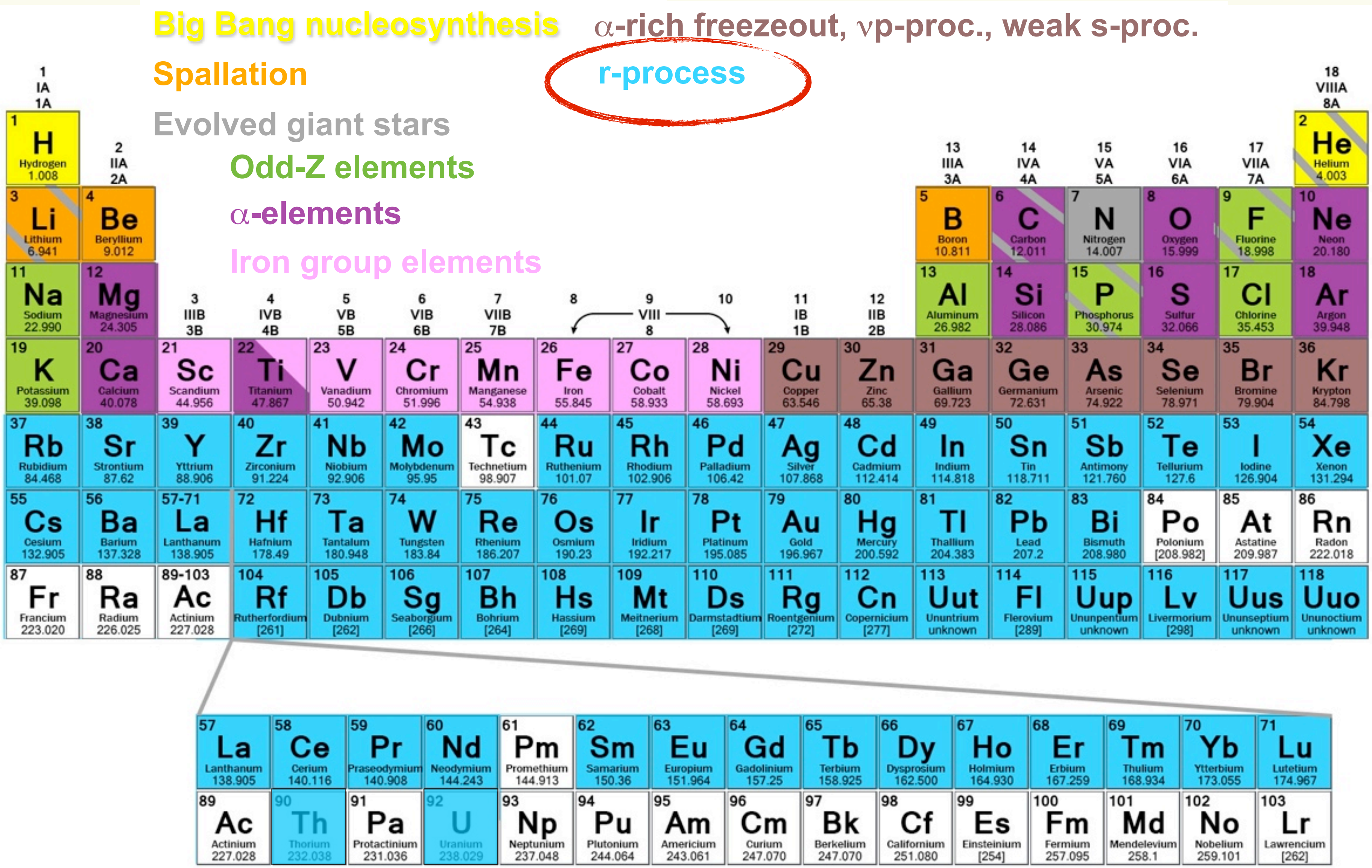
=> only ~1 progenitor star produced that iron

=> only ~1 nucleosynthesis event made heavier elements

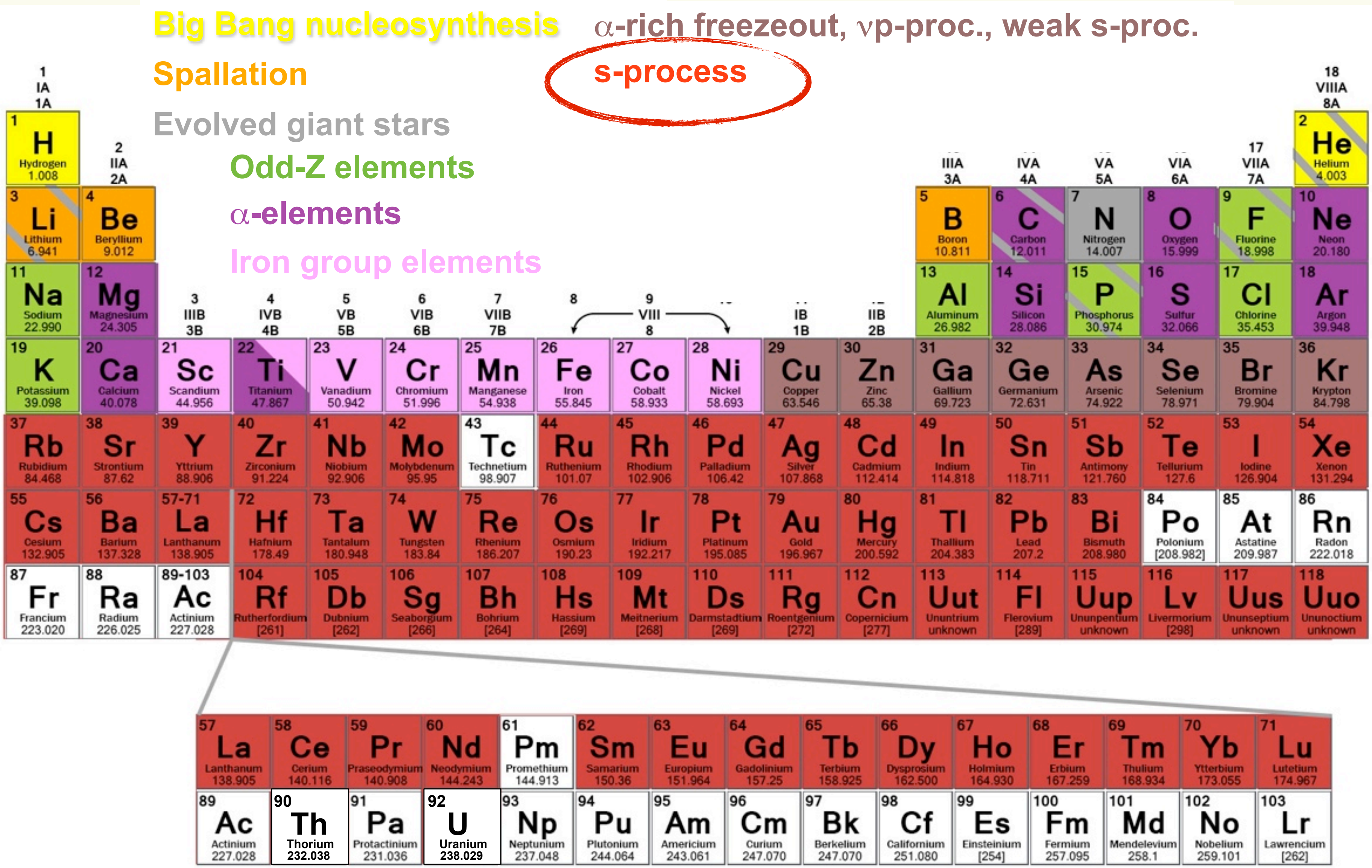
The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table



The (detailed) astronomer's periodic table



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)

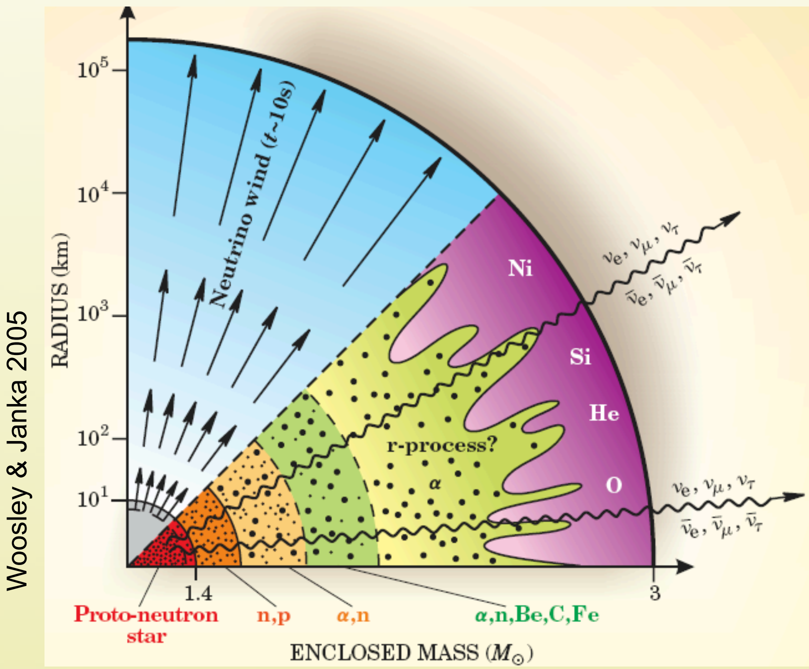
★ **What is the rate and yield of the event?**

★ **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 <u>Rare</u> 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)

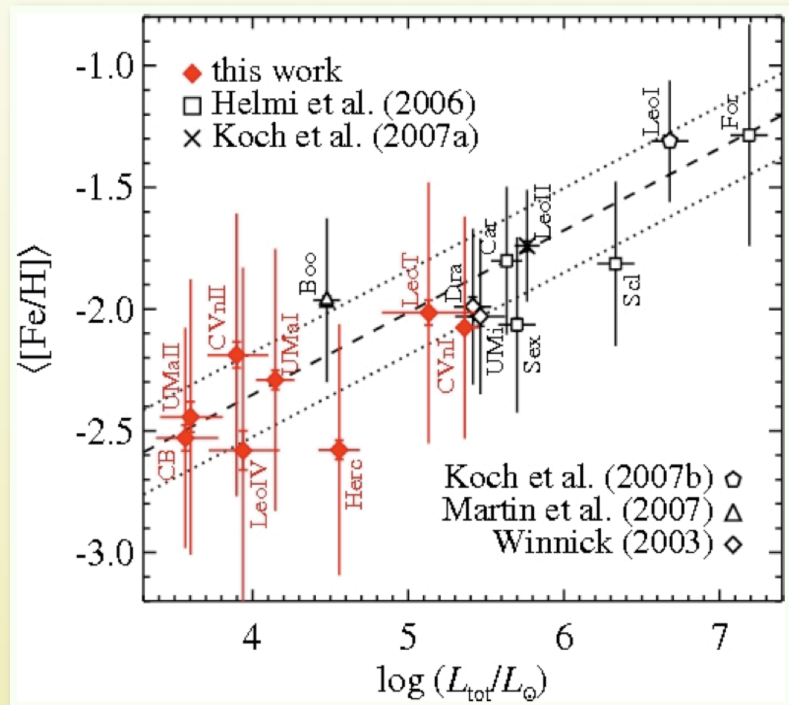
Low luminosity (300 - 3,000 L_{sun})

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

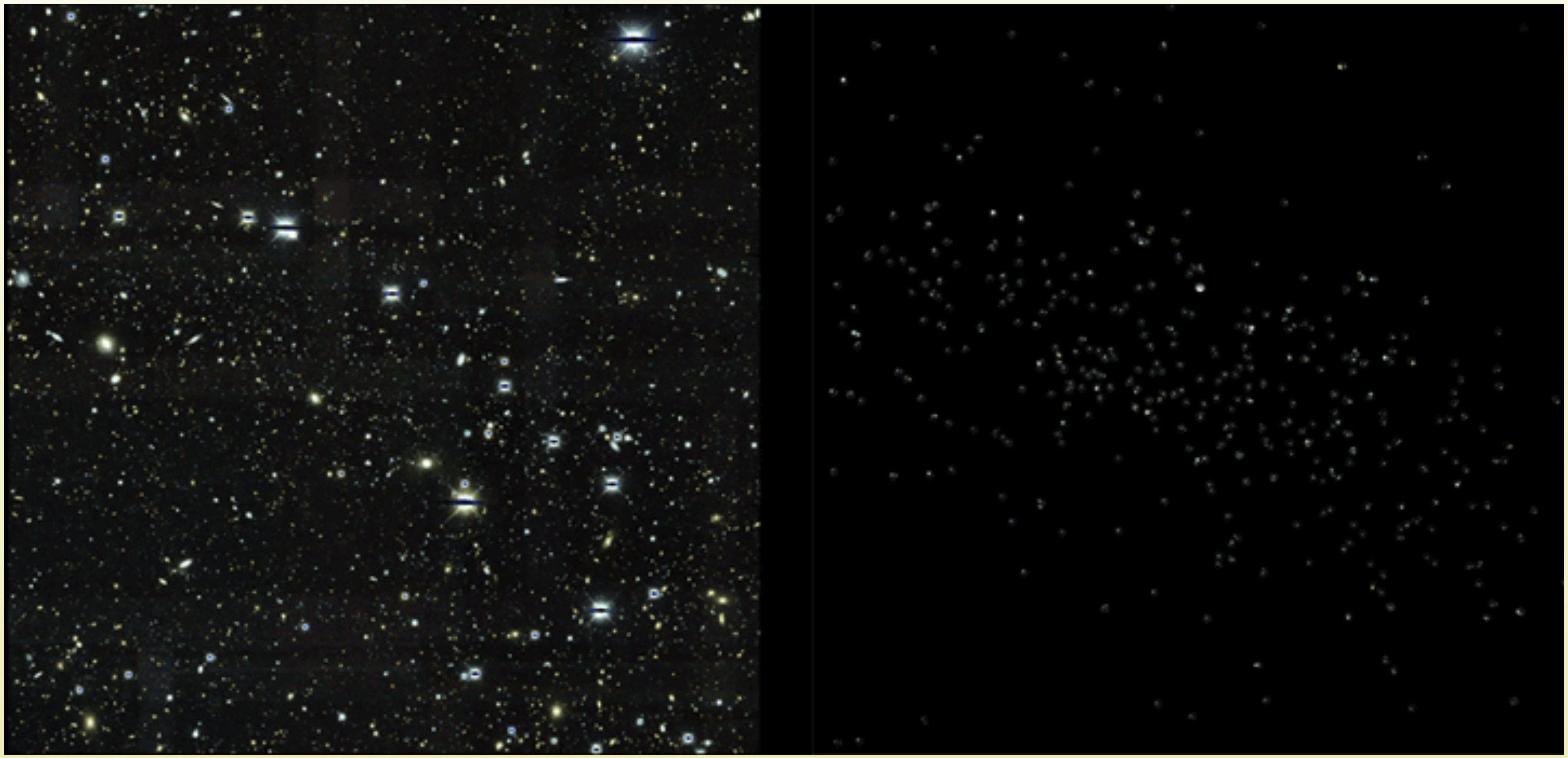
Classical dSphs

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

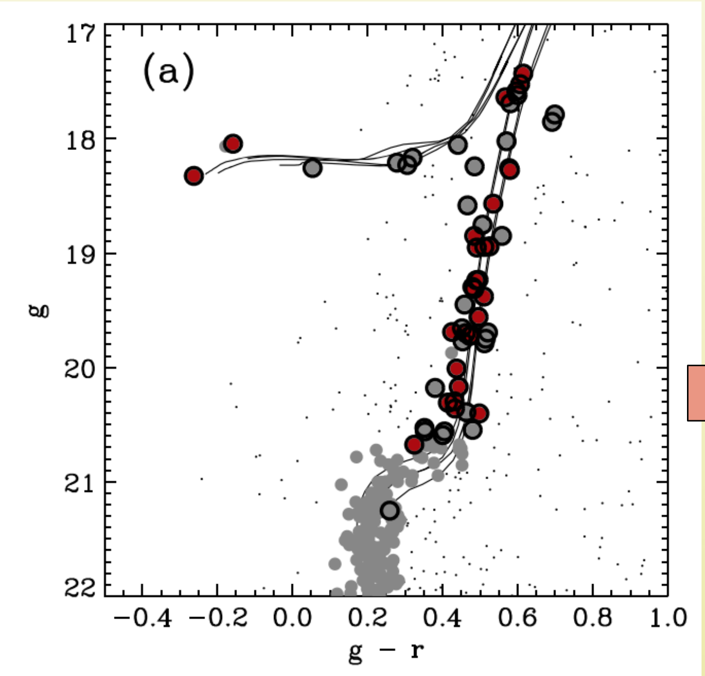
(Dark Energy Survey, 2015)

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)

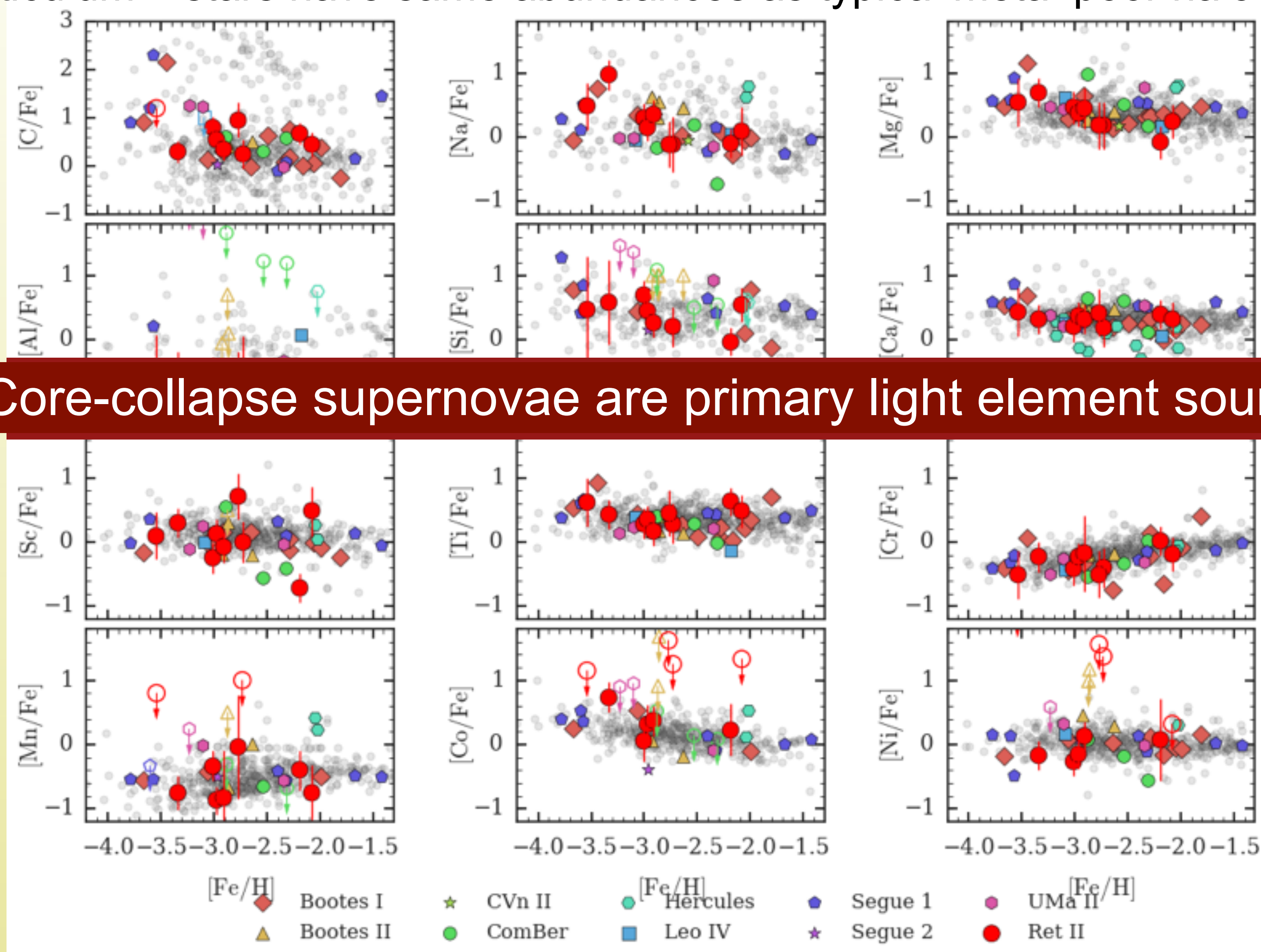


Color-magnitude-diagram of Ret II
(red = confirmed members)

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)

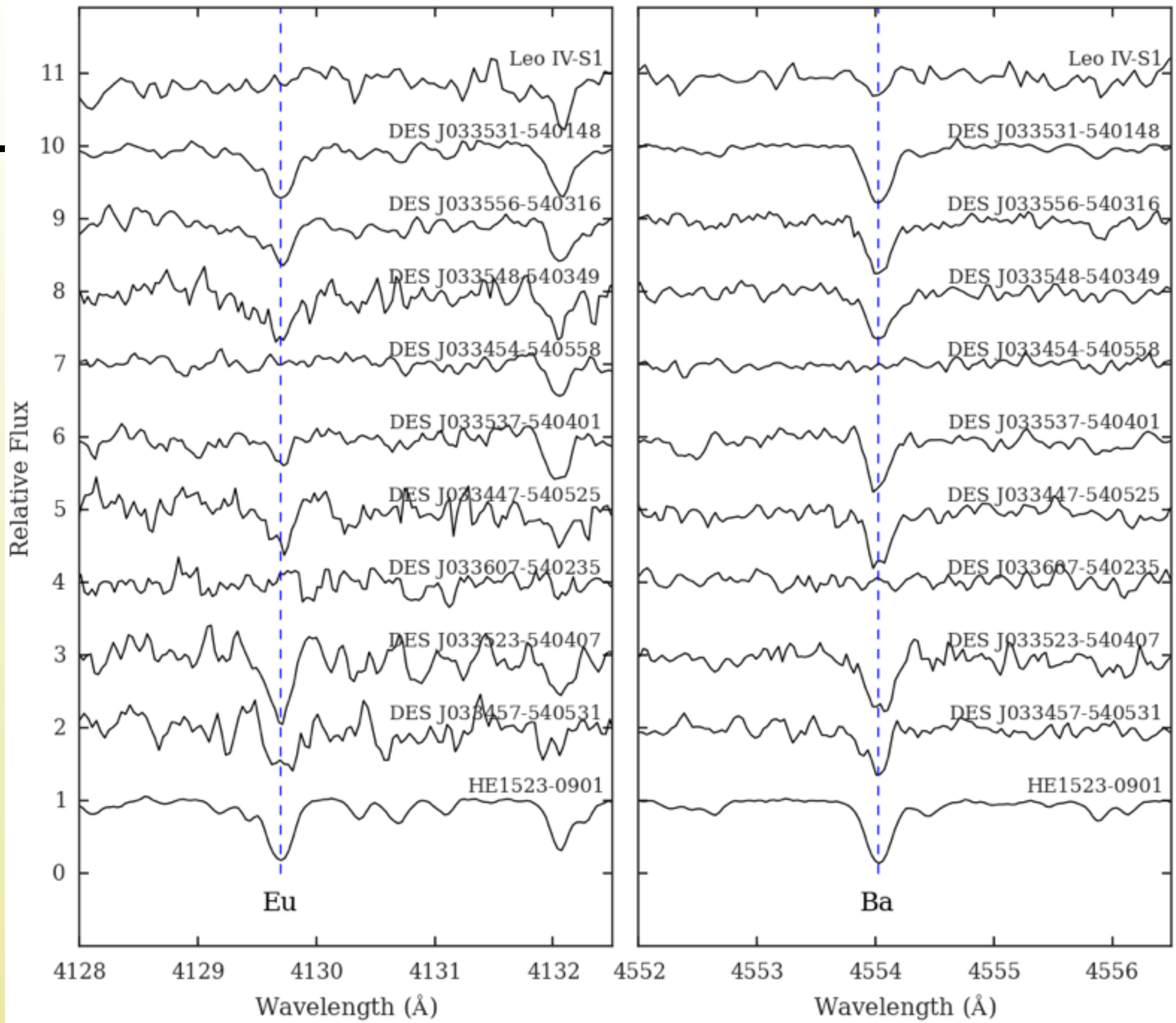
Reticulum II stars have same abundances as typical metal-poor halo stars



Core-collapse supernovae are primary light element source

gray dots metal-poor halo stars

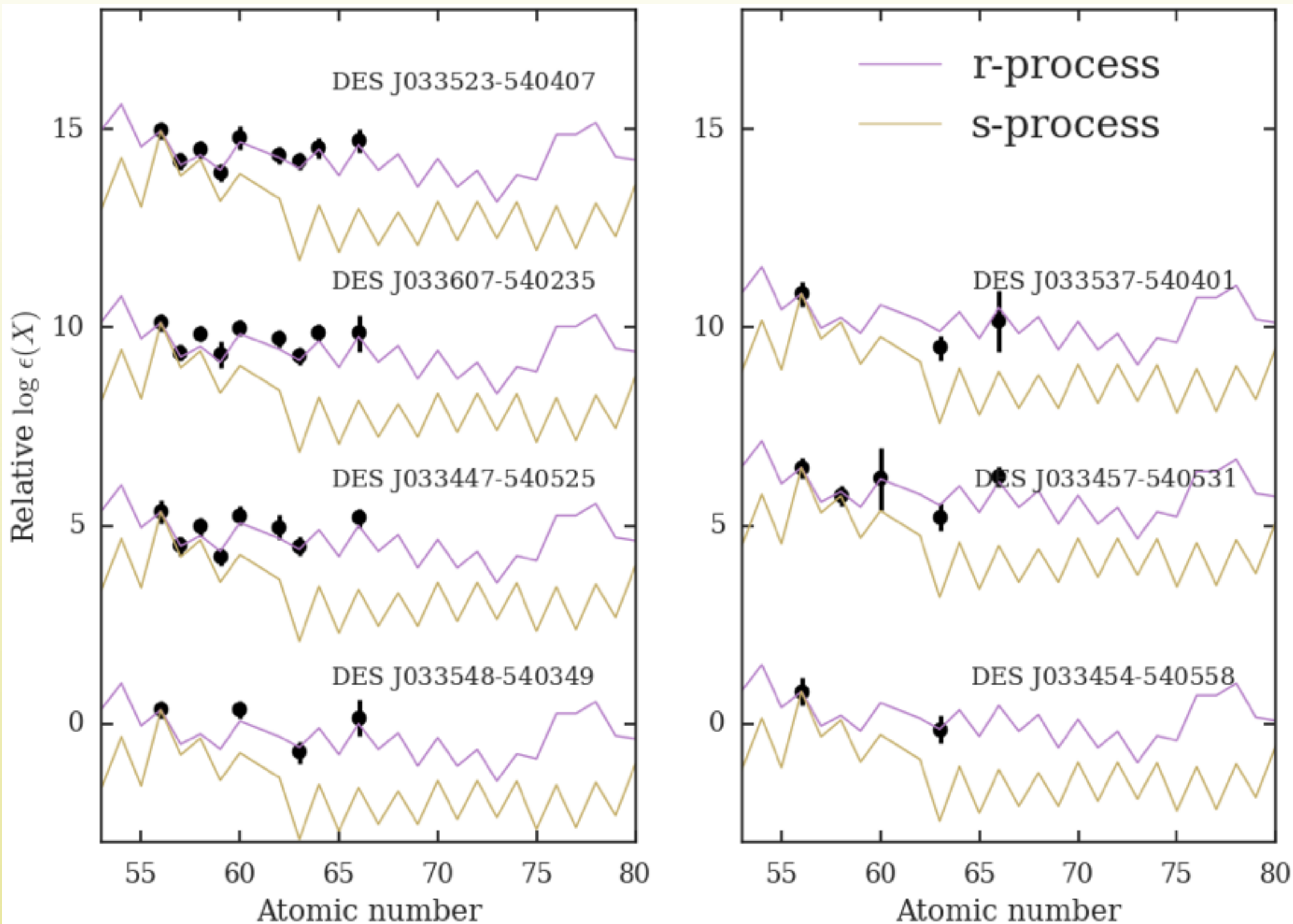
Ji et al 2016, *Nature*, 531, 610



Relative Flux
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
Wavelength (Å)
Wavelength (Å)

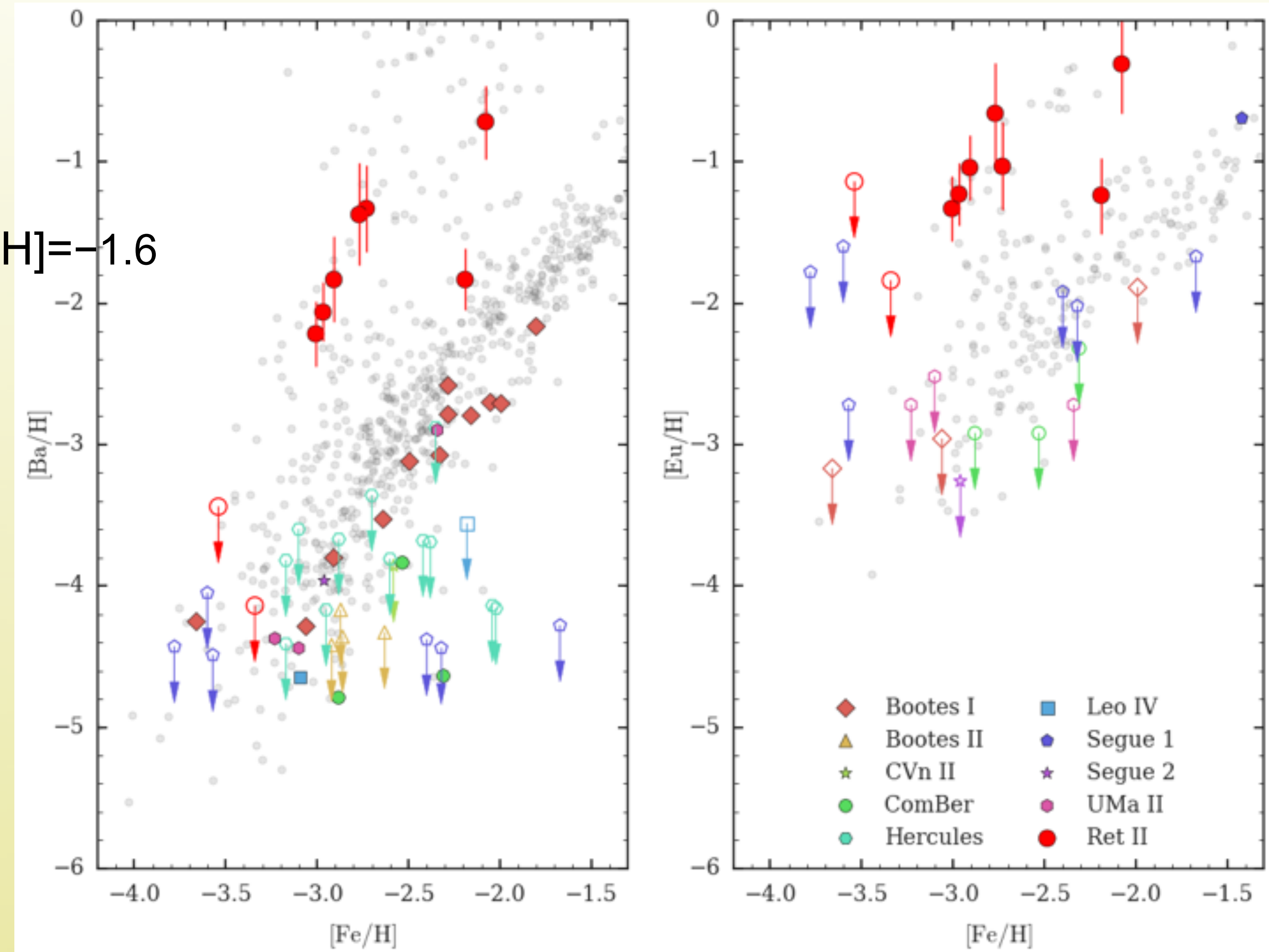
All seven Ret II stars display the r-process pattern

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?

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: ~10^7 M_{sun}

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

➡Min. dilution mass: ~10^5 M_{sun}

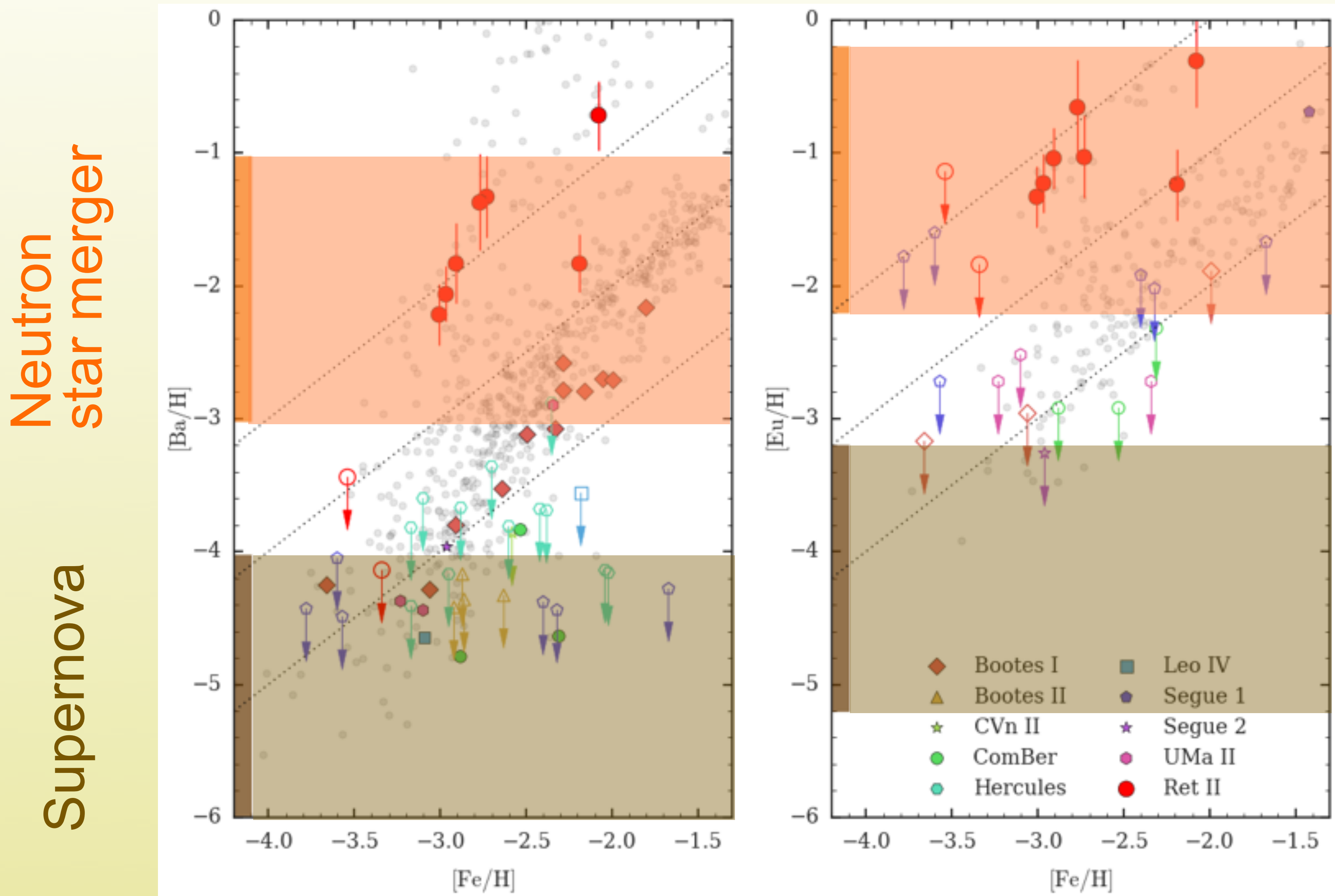
Back-of-the-envelope calculation

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

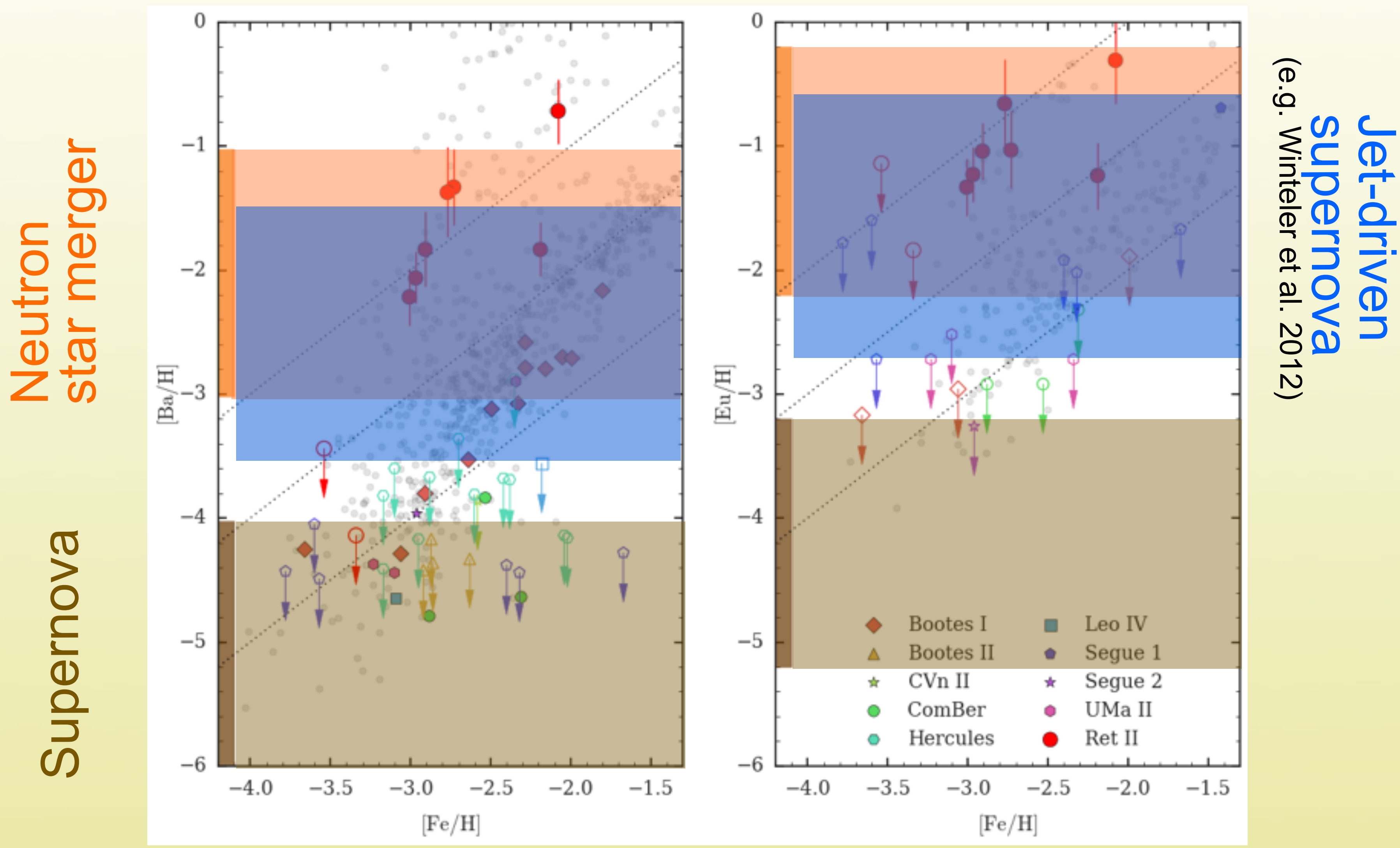
=> Agrees with Ret II abundance results!

Ret II abundances consistent w/ neutron-star merger yield



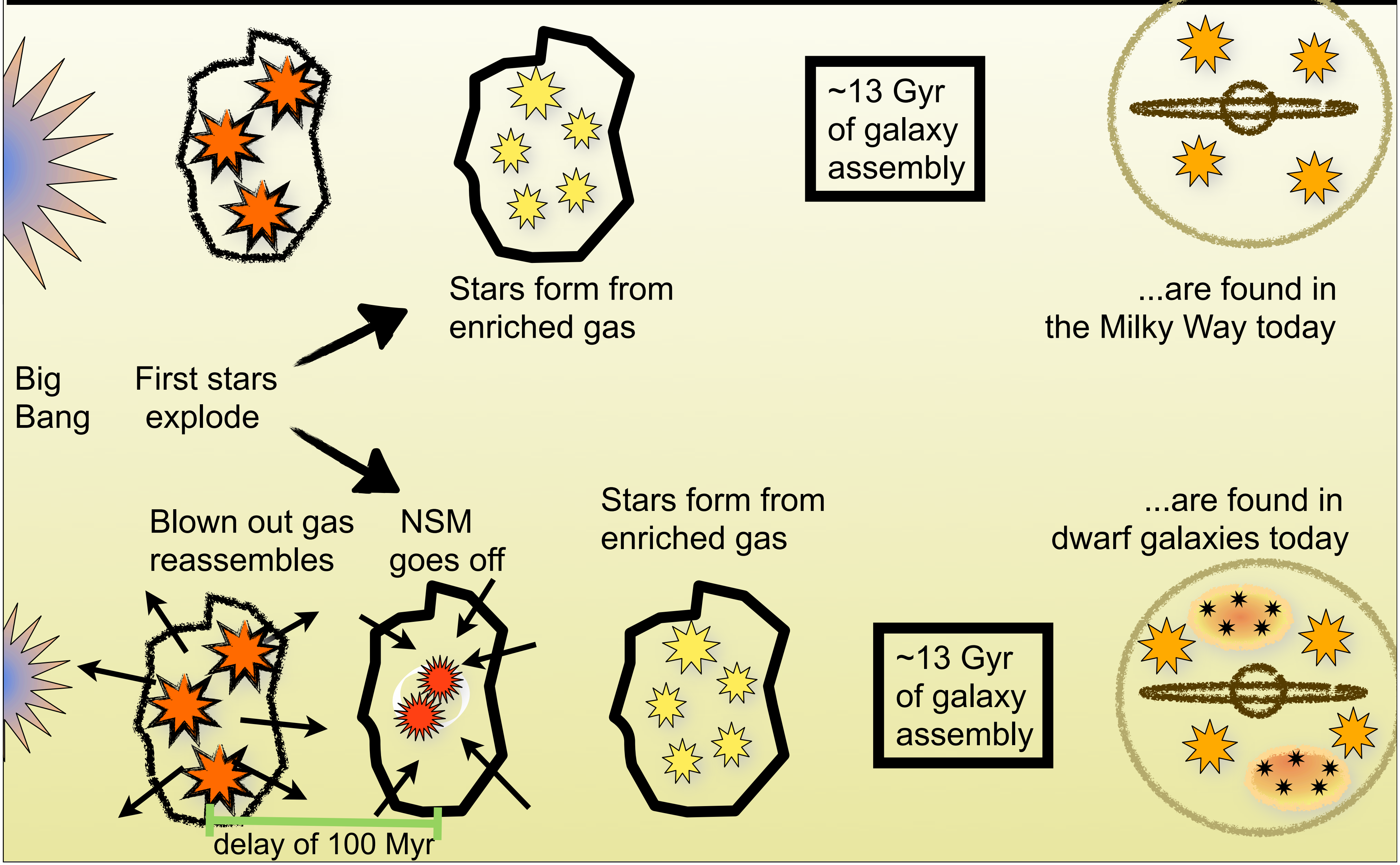
Ji et al 2016, *Nature*, 531, 610

Rare and prolific jet-driven supernova remains possibility



...but ordinary supernovae remain ruled out!

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.)

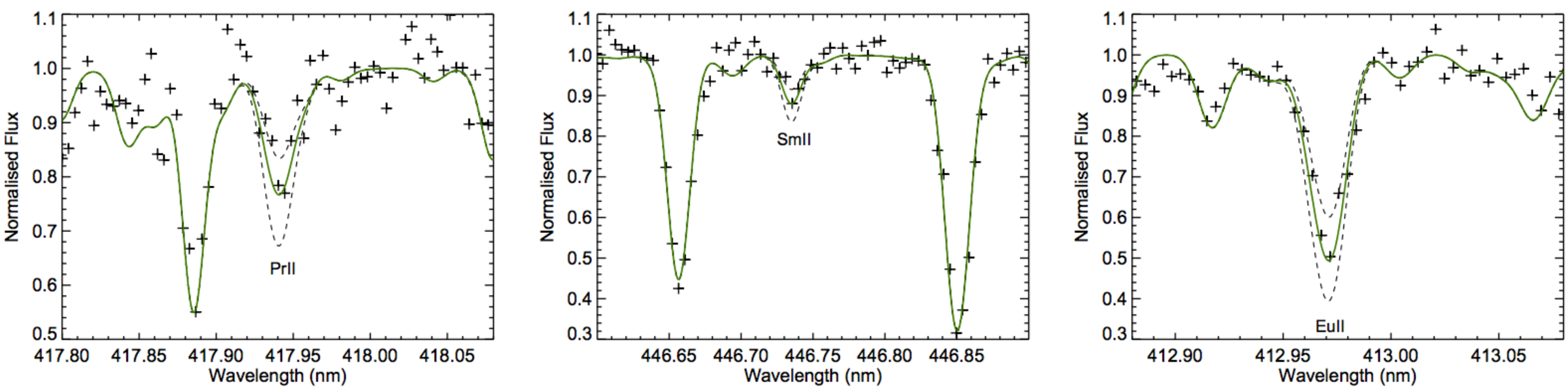
Ideal system to model given all these obs constraints!

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



Anna Frebel

Implications

R-PROCESS OPERATES IN DWARF GALAXIES

20 rI stars in

- Tucana III
- Ursa Minor
- Draco
- Sculptor
- Fornax
- Carina

-2.5 < [Fe/H] < -0.8

0.3 < [Eu/Fe] < 1.0

13 r II stars in

- Reticulum II
- Ursa Minor
- Draco
- Fornax

-3.0 < [Fe/H] < -2.1

1.0 < [Eu/Fe] < 2.1

-2.6 < [Fe/H] < -0.8

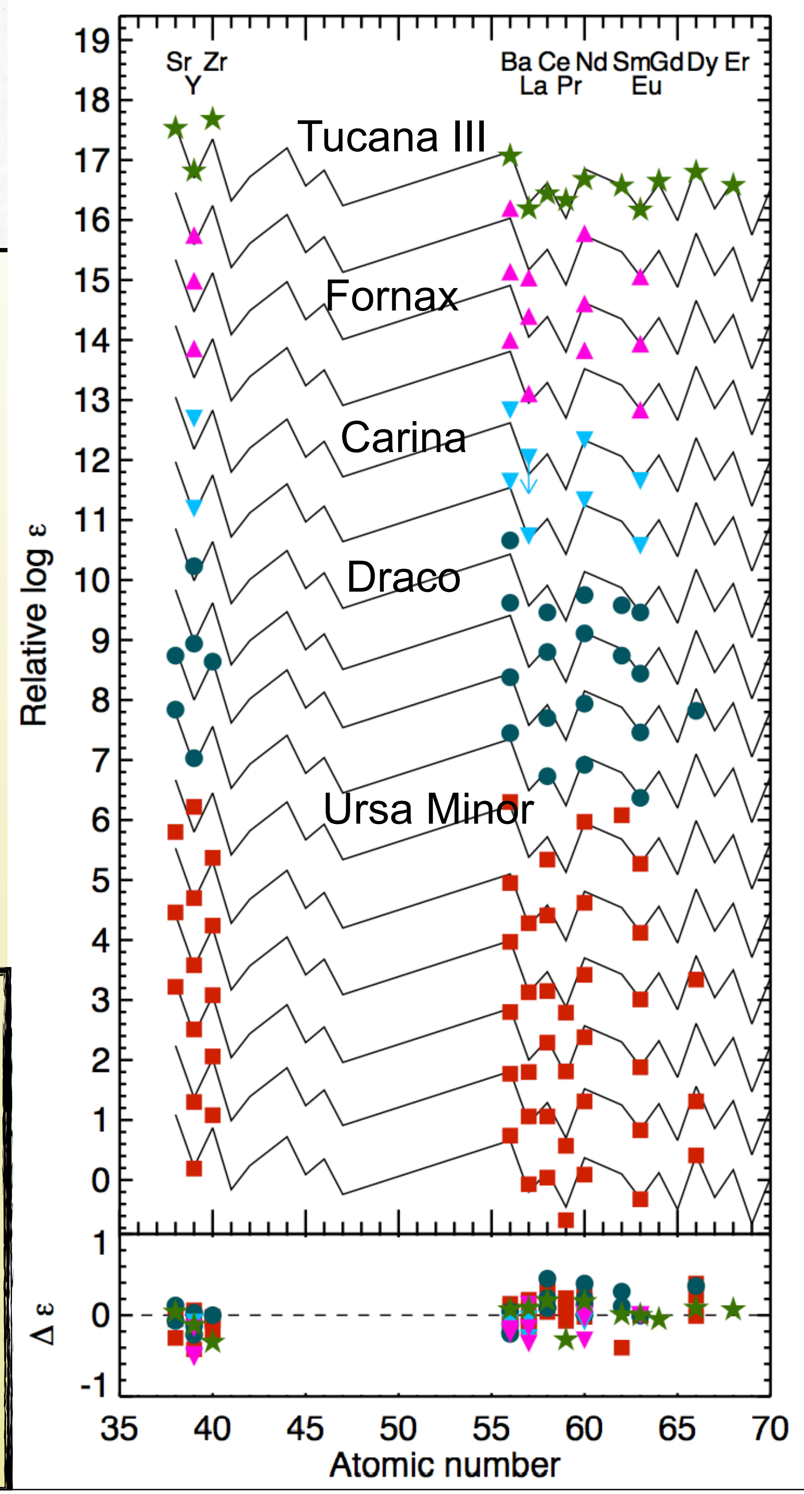
1.1 < [Eu/Fe] < 1.7

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)?

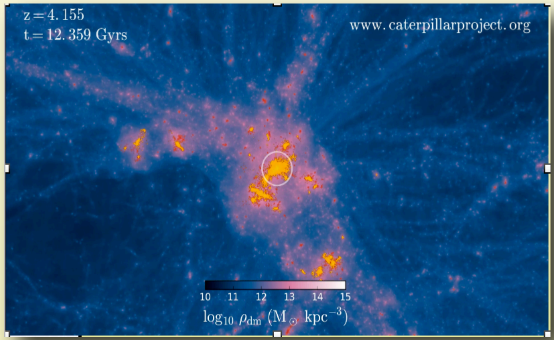


A new kind of chemical tagging

Tracing galaxy assembly w/ r-process stars & r-process galaxies

- Recall: The halo formed from accreted systems:
- r-process stars trace that assembly process: i.e., they trace the fraction of r-process dwarfs! -- we can determine that fraction

- Significant r-process enrichment in
- 2/12 ultra-faint dwarf galaxies: **~15%** of all UFD
- 5/12 classical dwarf galaxies: **~40%** of all dSph

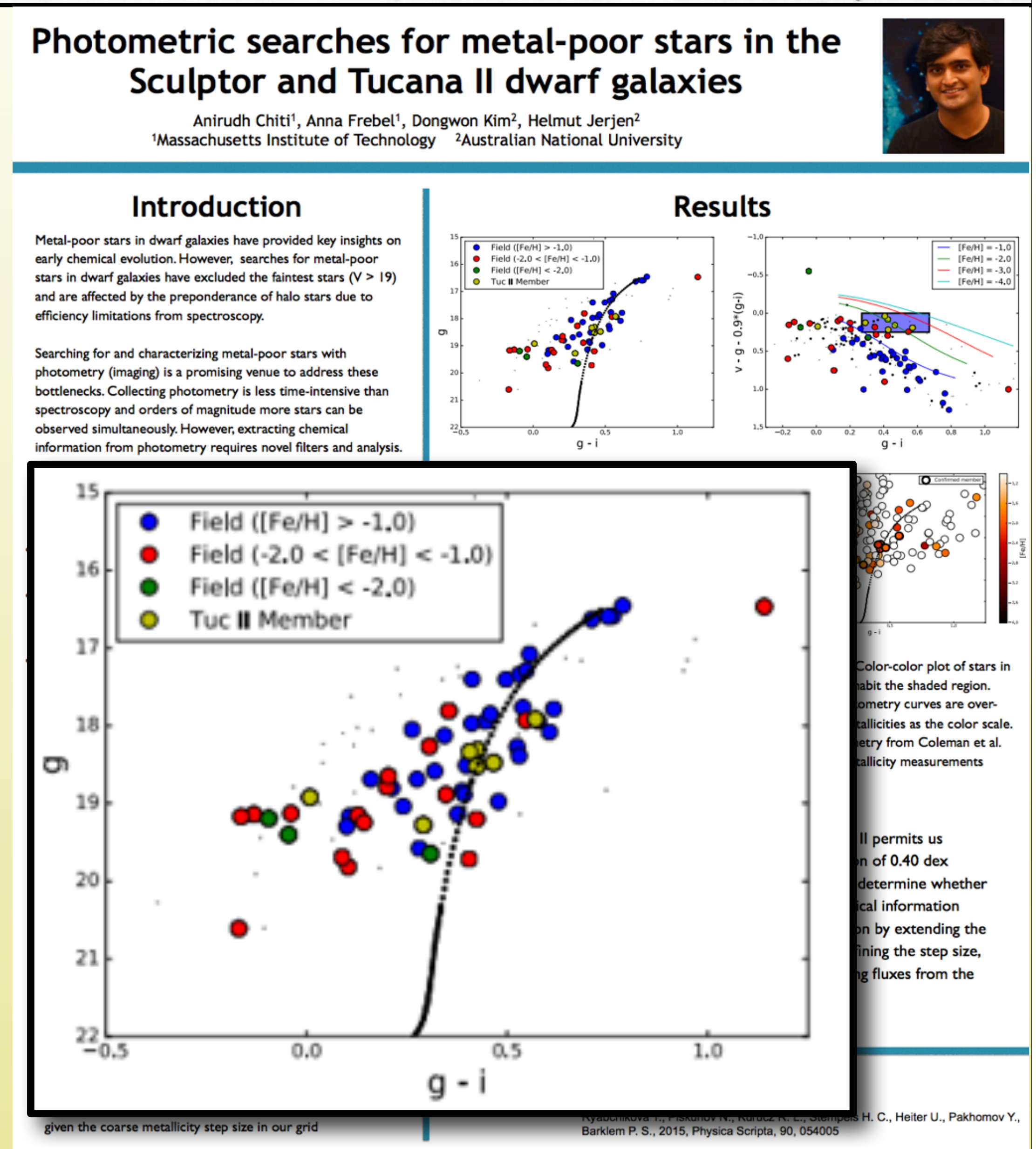


- In the halo:
- ~25-30 rII stars (published): **~5%** of metal-poor stars
- ~40 rI stars (publ) + dozens (unpubl.): **~20-30%** of metal-poor stars

Use existence of r-process pattern as a tag

Finding stars in dwarf galaxies

- Photometric searches more efficient than spectroscopic ones, but get less information
- => Get metallicities along the RGB
- Pilot study: deep SkyMapper observations of Tucana II & Sculptor:
- u, g, i, and Ca K v filter
- Chiti et al. 2017, in prep.



Abdu Abohalima

JINABASE

A NEW DATABASE OF METAL-POOR STARS

JINA-CEE

The Joint Institute for Nuclear Astrophysics

EMP Database

Home | Query/Plot | Search | References | Contact

Query data from database!

Data for axes

x-axis Fe / H From To

y-axis Ba / Fe From To

Solar abundance for normalization Asplund 2009

User defined criteria

+ Add criteria | Remove criteria −

Filters

Location of stars	Stellar phase	Specific element signatures
Select/Deselect All	Select/Deselect All	Select/Deselect All
MW Halo	Giants	no signatures
Bulge	Subgiants	r-I rich
Classical Dwarfs	Dwarfs	r-II rich
Ultra-faint Dwarfs	Horizontal branch	s-rich
		r/s stars
		CEMP
		CEMP-no

References

Select by Author and year: First Author/s Frebel, Roederer Year range: From 1990 To 2017

Select/Deselect All	Cohen & Huang(2009)	Ji et al. (2016a)	Ren et al. (2012)
Afsar et al. (2016)	Cohen et al. (2013)	Ji et al. (2016b)	Rich et al. (2009)
Allen et al. (2012)	Collet et al. (2006)	Johnson & Bolte(2002a)	Roederer et al. (2008)
Andrievsky et al. (2009)	Cowan et al. (2002)	Johnson & Bolte(2002b)	Roederer et al. (2009)
Andrievsky et al. (2010)	Cui et al. (2013)	Johnson & Bolte (2004)	Roederer et al. (2010)
Aoki et al. (2001)	Feltzing et al. (2009)	Jonsell et al. (2005)	Roederer et al. (2012a)
Aoki et al. (2002a)	Francois (2016)	Jonsell et al. (2006)	Roederer et al. (2012b)

Customize output table

+ Add element | Remove element −

Select/Deselect All	Science key	Radial velocity	I mag	Z
ID	CEMP key	RV bibcode	J mag	Vmic
Priority key	Location	Umag	H mag	Upper limits key
Reference	Stellar type	B mag	K mag	
Star name	RA	V mag	Teff	

Customize plot

Plot/Show duplicate stars | Plot upper limits | Show legend for plot

Plot | Show data table

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

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