“Connection to dwarf galaxies”

or

Carbon enhancement is everywhere

Massachusetts Institute of Technology

Anna Frebel

ICRAR International Centre for Radio Astronomy Research

Fe and Ca Abundances in a Human Being

from
Evan
Kirby

$$[\mathrm{Fe/H}] = \log\left(\frac{n(\mathrm{Fe})}{n(\mathrm{H})}\right) - \log\left(\frac{n(\mathrm{Fe})}{n(\mathrm{H})}\right)_\odot$$

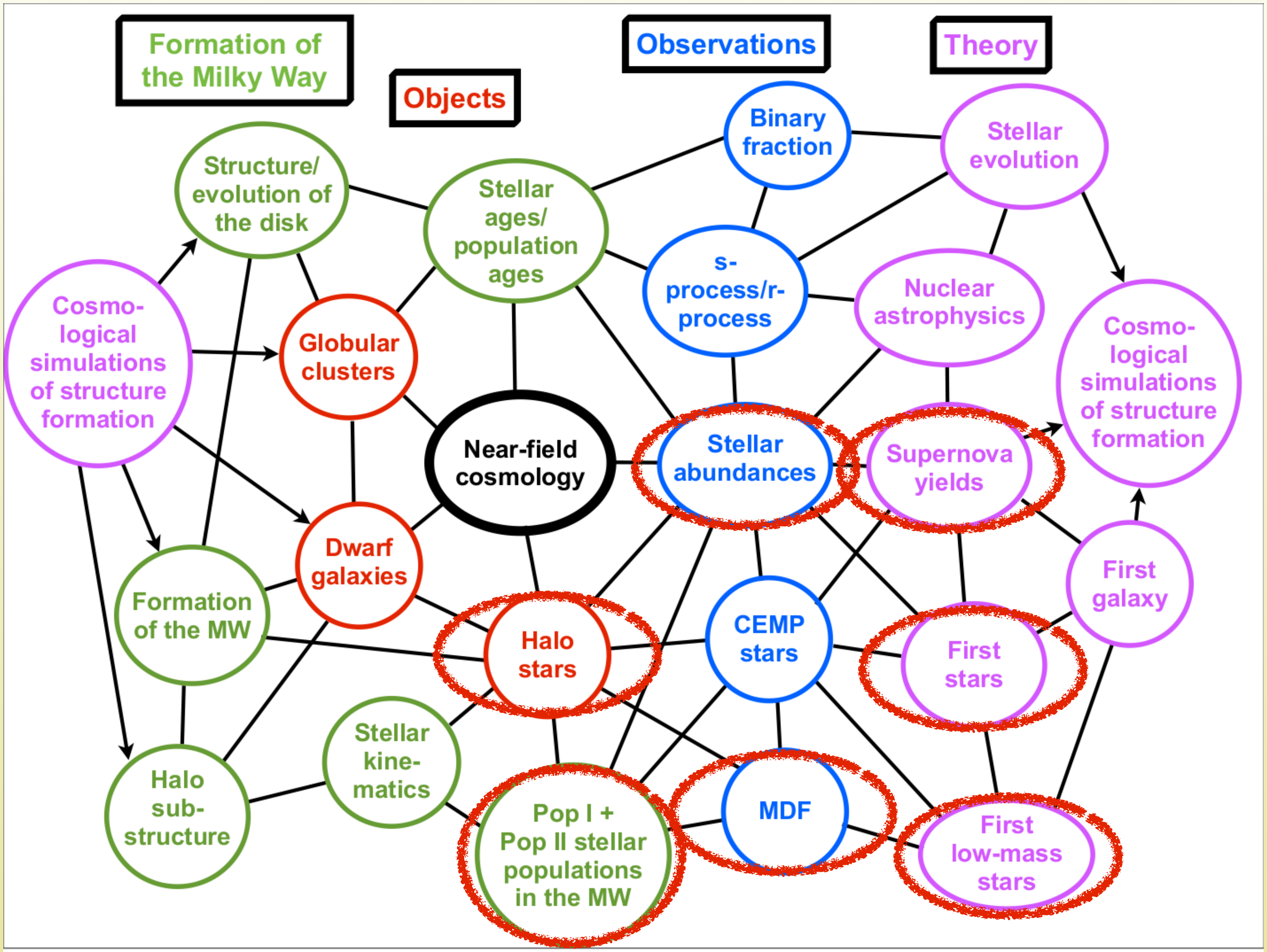
human being

[Fe/H] = –1.66
[Ca/Fe] = +5.88

12 + log(O/H) = +11.61
[O/H] = +2.68
[Mg/Fe] = +2.40
[Mg/H] = +0.74
[C/H] = +2.62
[N/H] = +2.28
[Ca/H] = +4.22
[P/H] = +4.06
[K/H] = +3.84
[S/H] = +1.69
[Na/H] = +2.49
[Cl/H] = +3.13
[I/H] = +2.99

[C/Fe] ~ 4 for humans
[C/Fe] ~ 4 for HE1327-2326

Importance of CEMP stars



The ubiquity of carbon enhancement

Nuclear Astrophysics

First r+s star discovered: CEMP star

Stellar archaeology

CEMP star HE1327-2326: constraints on first stars

Dwarf Galaxy Archaeology

Classical dwarfs: Sculptor

Ultra-faint dwarfs: Segue 1, Ret II

Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

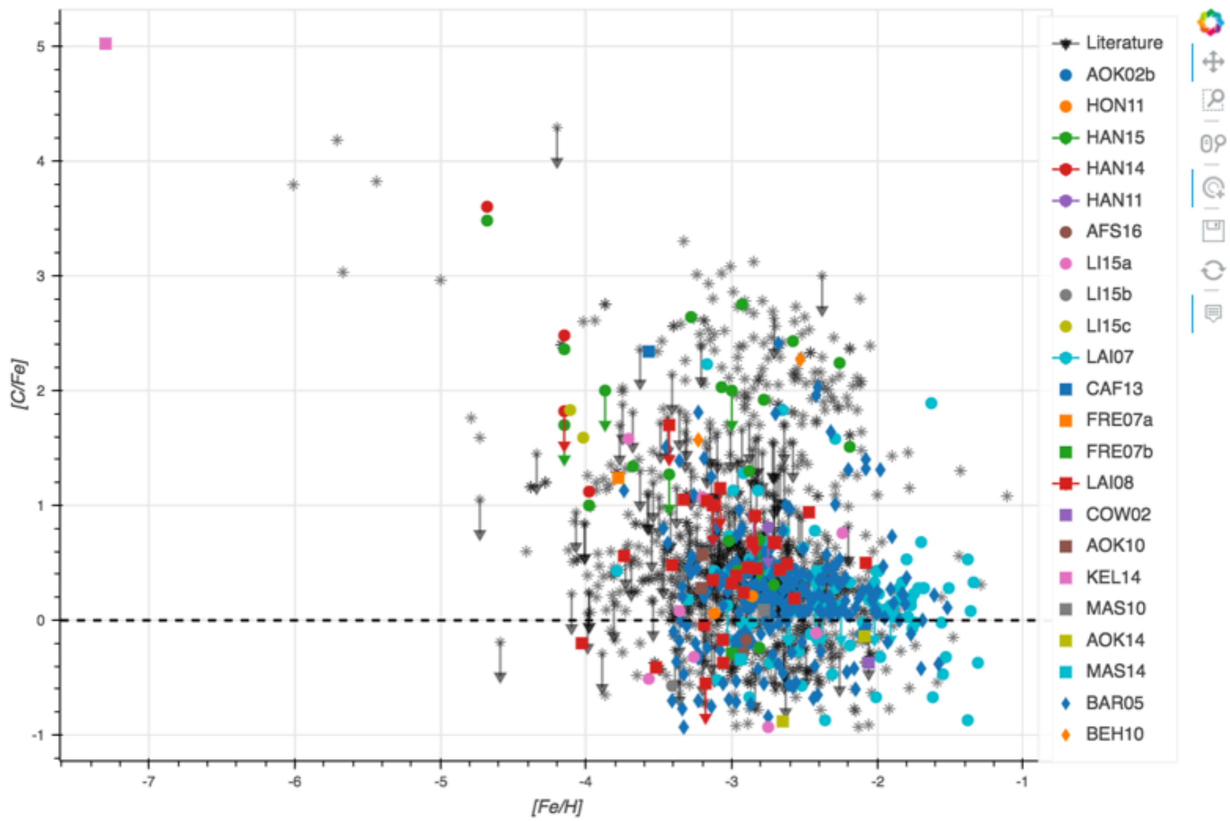
A NEW DATABASE OF METAL-POOR STARS

Note: The list of references on the query page will be updated to include only those studies that fulfill your selection criteria.

Upper limits are shown as inverted triangles when the option is selected on the query page.

Try hovering over the data points!

Click on entries in the legend to remove them from the plot.



Statistics of plotted data:

Number of stars: 1341,

Number of upper limits: 133

Total number: 1474

Abdu Abohalima

Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

JINA-CEE

JINAbase

- Home
- Query/Plot
- Search
- References
- User Page
- Logout

Flask powered

Welcome to JINAbase!

The admins need to assign you a role to access the internal pages of JINAbase. If it has been longer than 48 hours since you registered, please contact one of the admins below.

JINAbase: A database for metal-poor stars

This web application enables you to easily access the database. The different tabs in the navigation bar guide you through the website.

To get access to the user interface to upload your data and help maintain the database, please sign up using the form on this page.

If you find JINAbase useful for your work/plots, please do the following:

1. Cite the original papers where the data comes from. (We've made that easy for you, just head to the references tab and you'll find a link to the bibtex entry.)
2. Cite our paper (Abohalima & Frebel 2018, submitted). Find it here on arxiv.

Updates:

The web application is still under development, if you face any errors or have any suggestions please contact us.

Query/Plot

This tab has options to query the database for a customized sample of stars, it includes several options to customize your sample. After you select your preferences, the queried sample could then be retrieved as an ascii table (for now) or plotted in an interactive plot.

Search

In this tab you can search for a star in JINAbase. There are two options; 1) diplay user selected information for a star or list of stars, 2) plot the abundances as a function of the atomic number(the option to plot scaled solar values will be added soon).

References

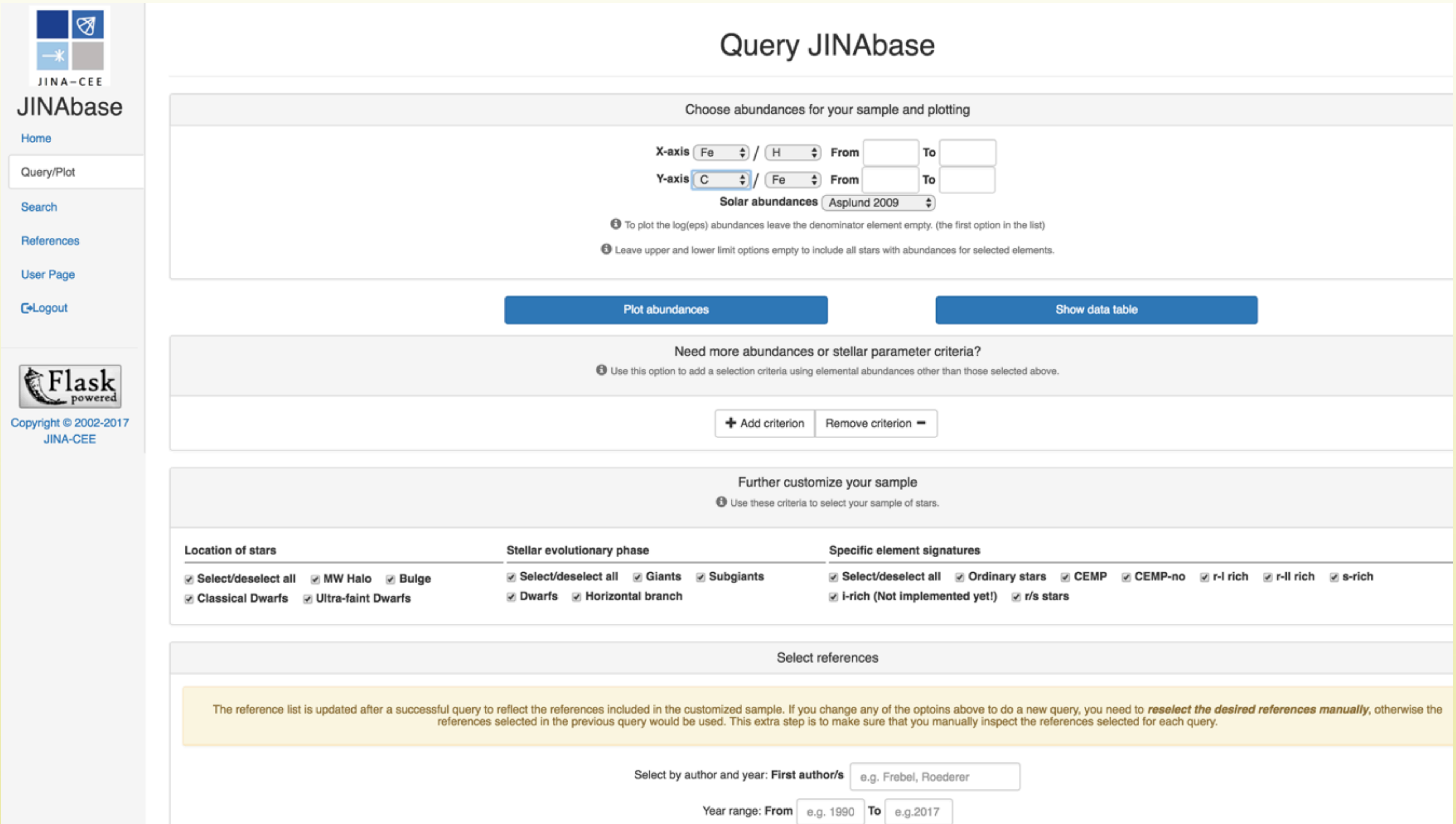
Here you can find all the original papers where the data comes from. You can also find a link to the paper on ADS as well as a direct link to the bibtex entry.

Abdu Abohalima

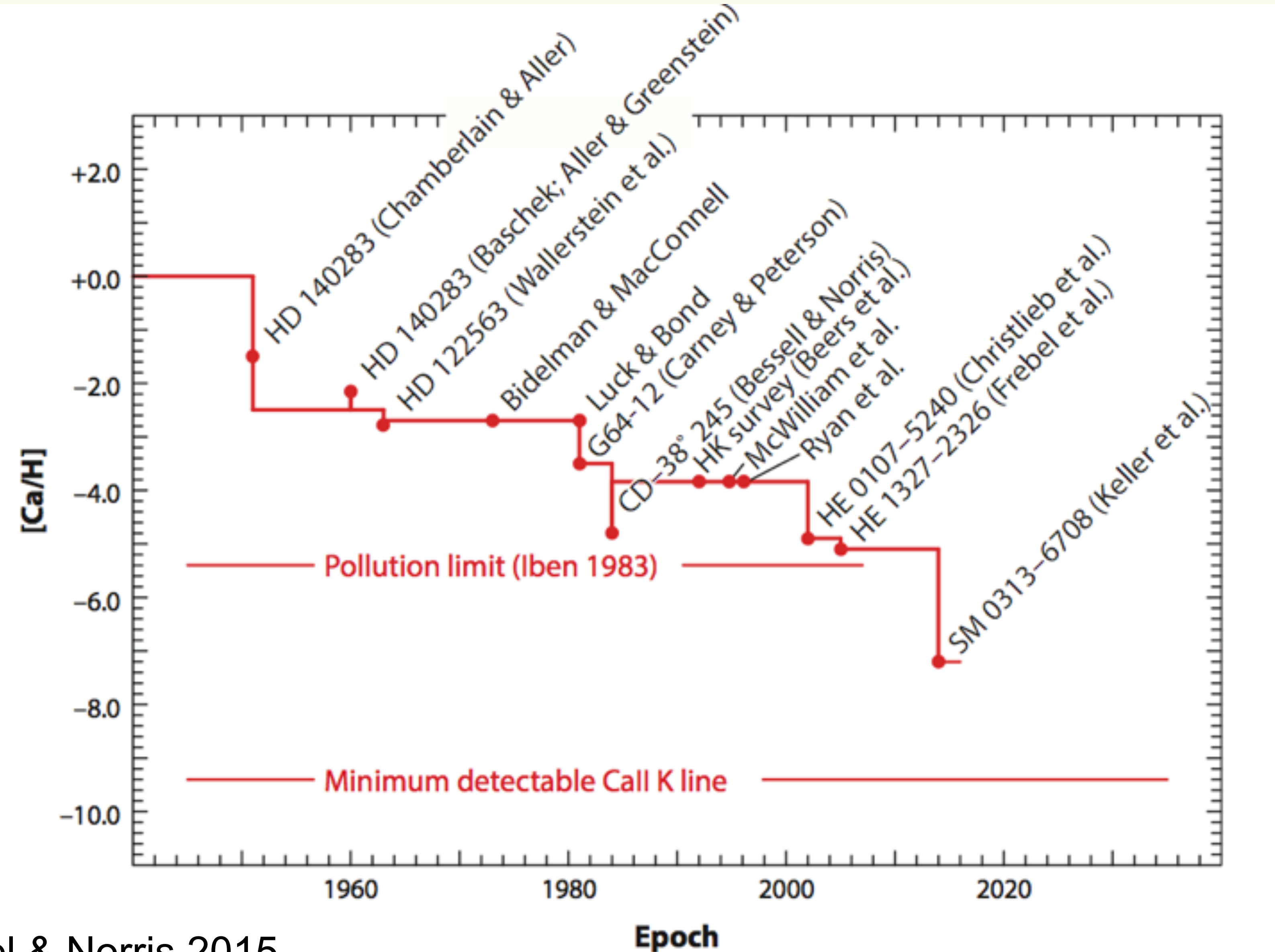
Abohalima & Frebel 2018, arxiv/1711.04410

JINABASE

A NEW DATABASE OF METAL-POOR STARS

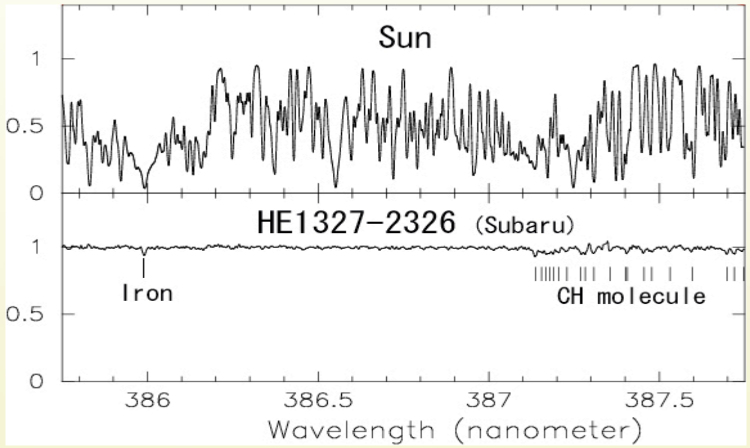


Record holders over time: Lowest [Ca/H] stars



Frebel & Norris 2015

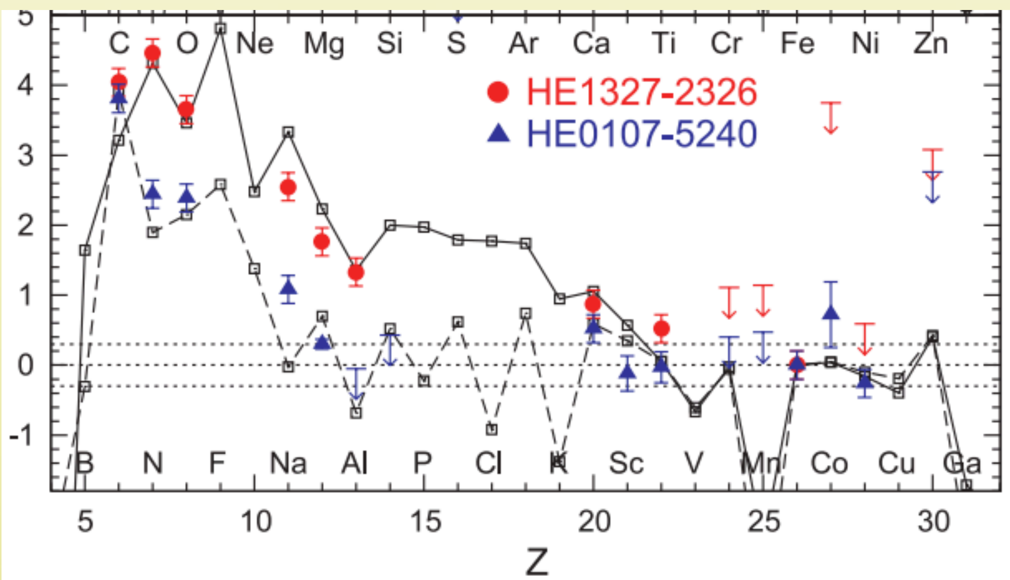
The story of HE 1327-2326



optical spectrum, taken with Subaru

On the most Fe poor stars (e.g., Frebel et al. 2005)
[Fe/H] = -5.7; [C/Fe] = 4.5

Lines of 11 elements could be detected in the optical



Iwamoto et al. 2005

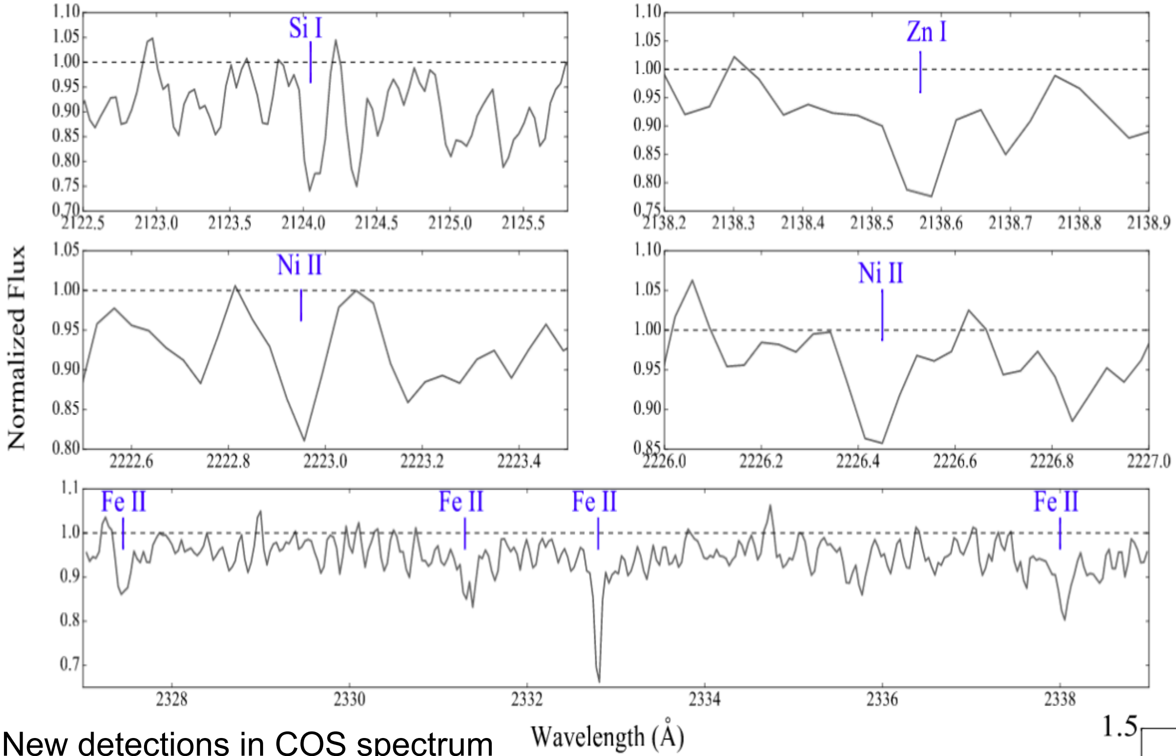
Second star whose abundance pattern was reproduced with the yields of a supernova with a **mixing and fallback mechanism** (to explain high [C/Fe])

Indicated a **progenitor with a faint explosion energy** (w/ 25Msun)

No zinc measurement from optical spectra, only a useless upper limit
=> **Zn constraints explosion mechanism and energy!**

New UV COS spectrum

Ezzeddine, Frebel, Roederer et al. 2018, in prep



New detections in COS spectrum

Detection of 4 Fe II lines and Si, Zn, Ni lines!

=> Now 13 elements measured
=> New stellar parameters

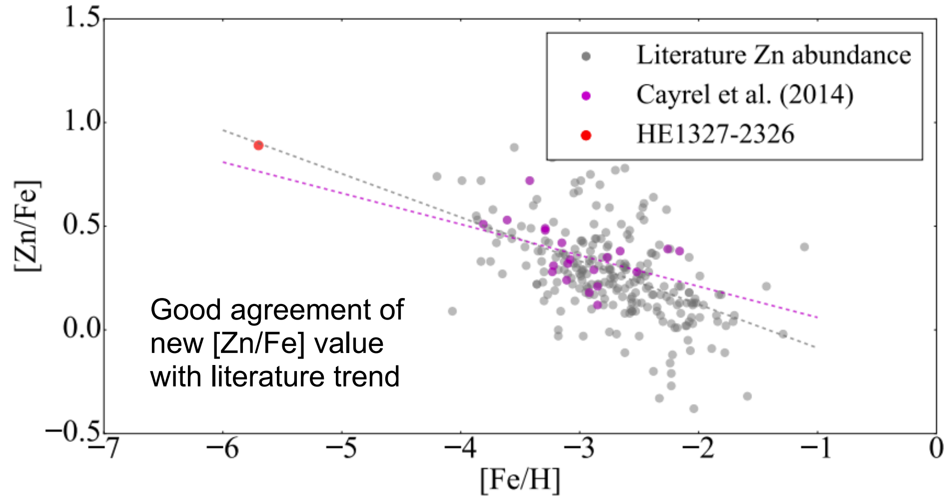
Teff = 6180K (photometric value)

[FeII/H] ~ -6.0 (subgiant case)
[FeII/H] ~ -5.7 (dwarf case)

More elements
=> Better constraints on nucleosynthetic yields of first stars!

[Si/Fe] ~ 0.9
[Ni/Fe] ~ 0.9
[Zn/Fe] ~ 0.9

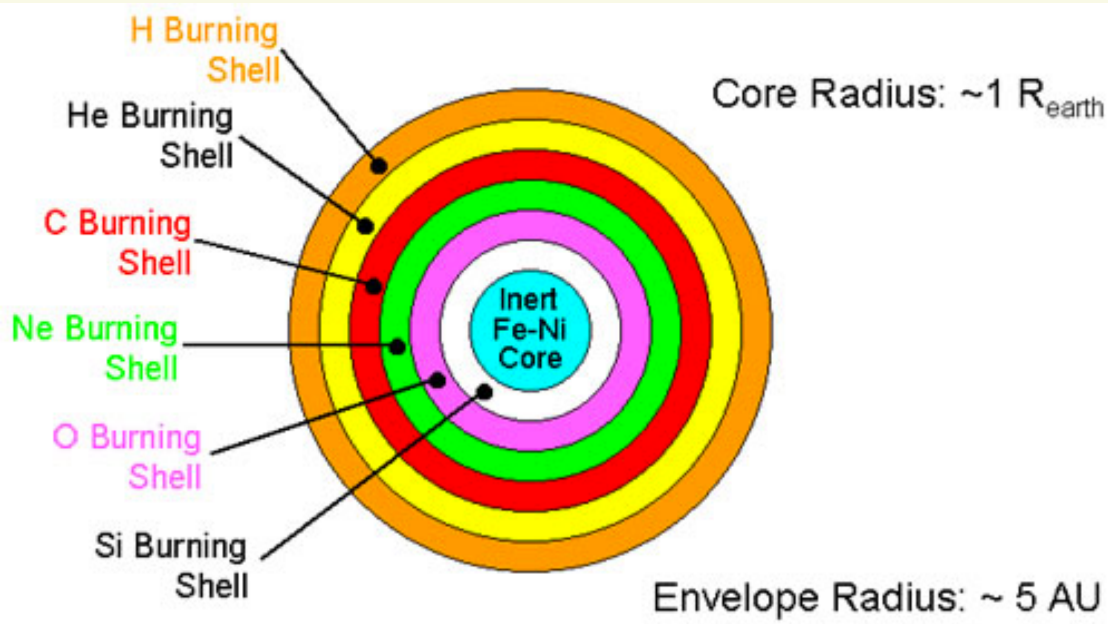
=> [Zn/Ni] ~ 0.0



Zinc nucleosynthesis

a little refresher...

After oxygen burning, **silicon burning** begins at 2.7 billion K



Si burning:

$^{28}Si + {}^{4}He \leftrightarrow {}^{32}S$ + photon;
$^{32}S + {}^{4}He \leftrightarrow {}^{36}Ar$ + photon;
$^{36}Ar + {}^{4}He \leftrightarrow {}^{40}Ca$ + photon;
$^{40}Ca + {}^{4}He \leftrightarrow {}^{44}Ti^{*}$ + photon;
$^{44}Ti + {}^{4}He \leftrightarrow {}^{48}Cr^{*}$ + photon;
$^{48}Cr + {}^{4}He \leftrightarrow {}^{52}Fe^{*}$ + photon;
$^{52}Fe + {}^{4}He \leftrightarrow {}^{56}Ni^{*}$ + photon;
$^{56}Ni + {}^{4}He \leftrightarrow {}^{60}Zn^{*}$ + photon
$^{60}Zn + {}^{4}He <=> {}^{64}Ga^{*}$ + photon

* radioactive!!

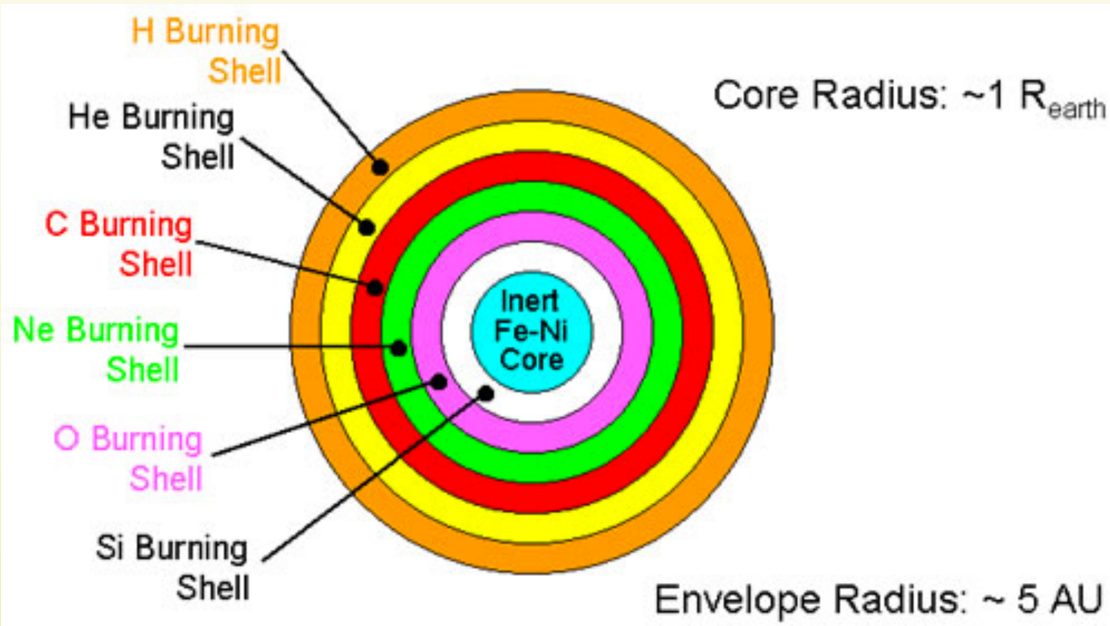
*(Mn (25), Cr (24) form in **incomplete** Si burning)*
***Fe (26)** forms in **complete and incomplete** Si burning*
*(Co (27) forms in **complete** Si burning)*
***Zinc (30)** forms in **complete** Si burning*

<u>To make [Zn/Fe] >0:</u> Need ejection of inner materials like Zn, fallback of Fe
=> Mcut should be located at the bottom of the complete and incomplete Si burning layers

ZINC NUCLEOSYNTHESIS

a little refresher...

After oxygen burning, **silicon burning** begins at 2.7 billion K



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$^{36}Ar + ^{4}He \leftrightarrow ^{40}Ca$ + photon;

$^{40}Ca + ^{4}He \leftrightarrow ^{44}Ti^{*}$ + photon;

$^{44}Ti + ^{4}He \leftrightarrow ^{48}Cr^{*}$ + => Ti

$^{48}Cr + ^{4}He \leftrightarrow ^{52}Fe^{*}$ + => Cr

$^{52}Fe + ^{4}He \leftrightarrow ^{56}Ni^{*}$ + => Fe

$^{56}Ni + ^{4}He \leftrightarrow ^{60}Zn^{*}$ + => Ni

$^{60}Zn + ^{4}He \Leftrightarrow ^{64}Ga^{*}$ => Zn

* radioactive!!

*(Mn (25), Cr (24) form in **incomplete** Si burning)*
***Fe (26)** forms in **complete and incomplete** Si burning*
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<u>To make [Zn/Fe] >0:</u> Need ejection of inner materials like Zn, fallback of Fe
=> Mcut should be located at the bottom of the complete and incomplete Si burning layers

What does this all mean?

Ezzeddine, Frebel, Roederer et al. 2018, in prep

HST UV observation of HE 1327-2327 yield a first [Zn/Fe] for star w/ [Fe/H] < -4

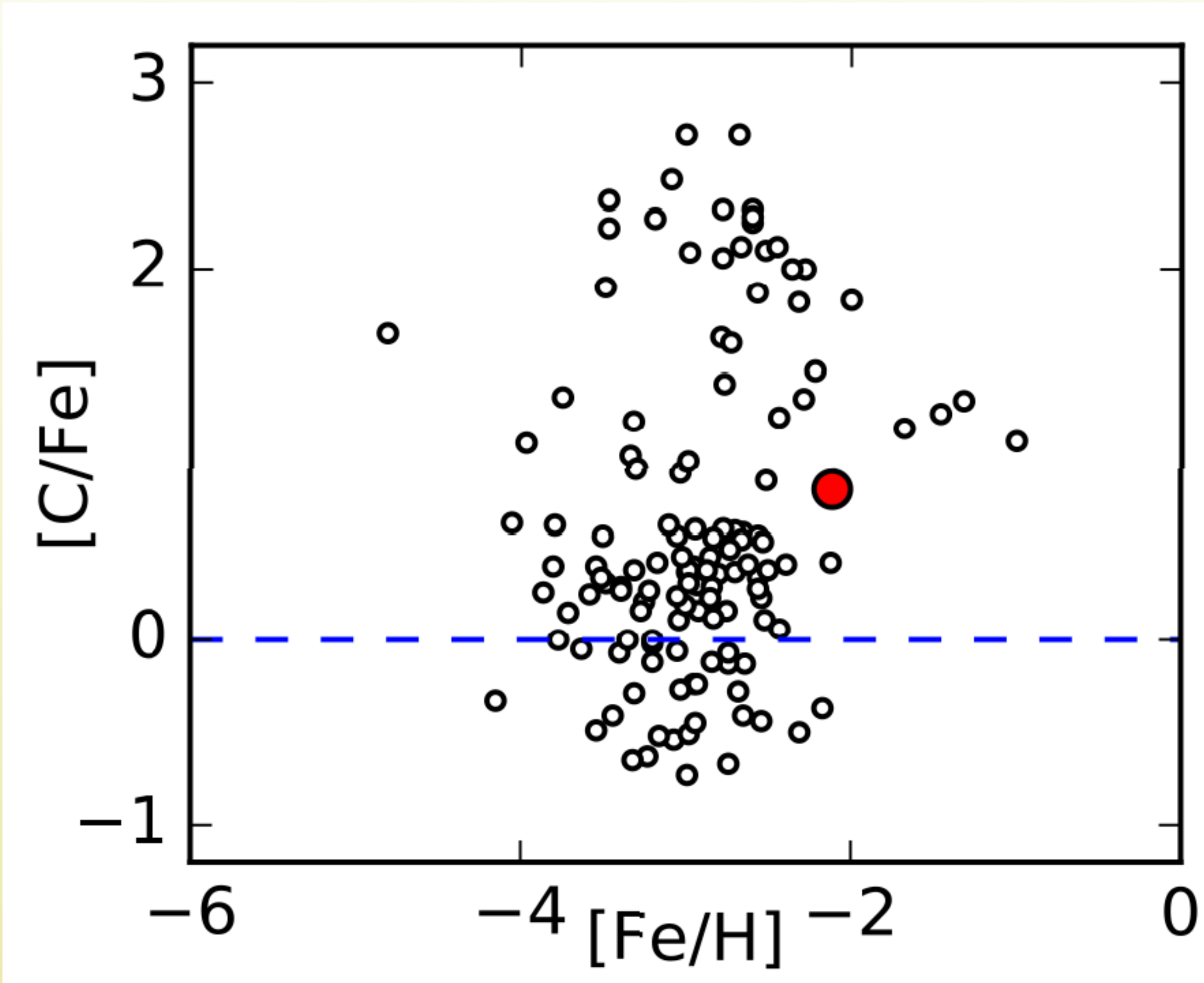
High [Zn/Fe]=0.9 (derived from just UV Zn and Fe measurements) **can only be reproduced in explosions w/ high entropy environment**

A high entropy environment is only realized in a jet-like explosion due to the concentration of explosion energy towards the opening-angle of the jet (confirmed with multi-D calculations);
1D mixing and fallback scenario naturally models aspherical effects

First evidence that Pop III first stars died in aspherical jet explosions!

=> Many implications for chemical enrichment and metal mixing processes

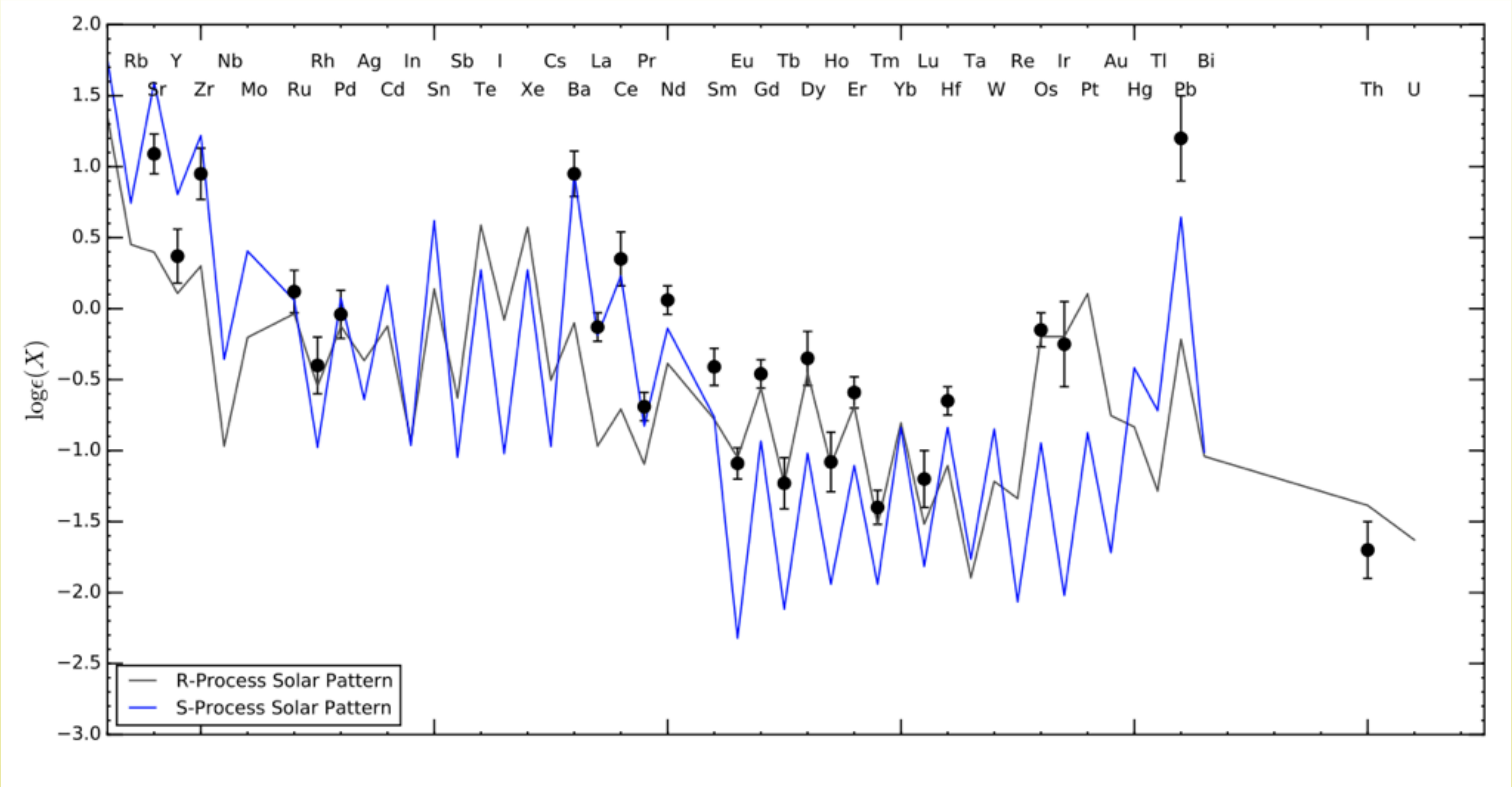
We found a CEMP halo star...!



Gull, Frebel et al. 2018, in prep

The first true r+s star!

An s-process star with [Fe/H] = -2.3 that formed from r-process enhanced gas!



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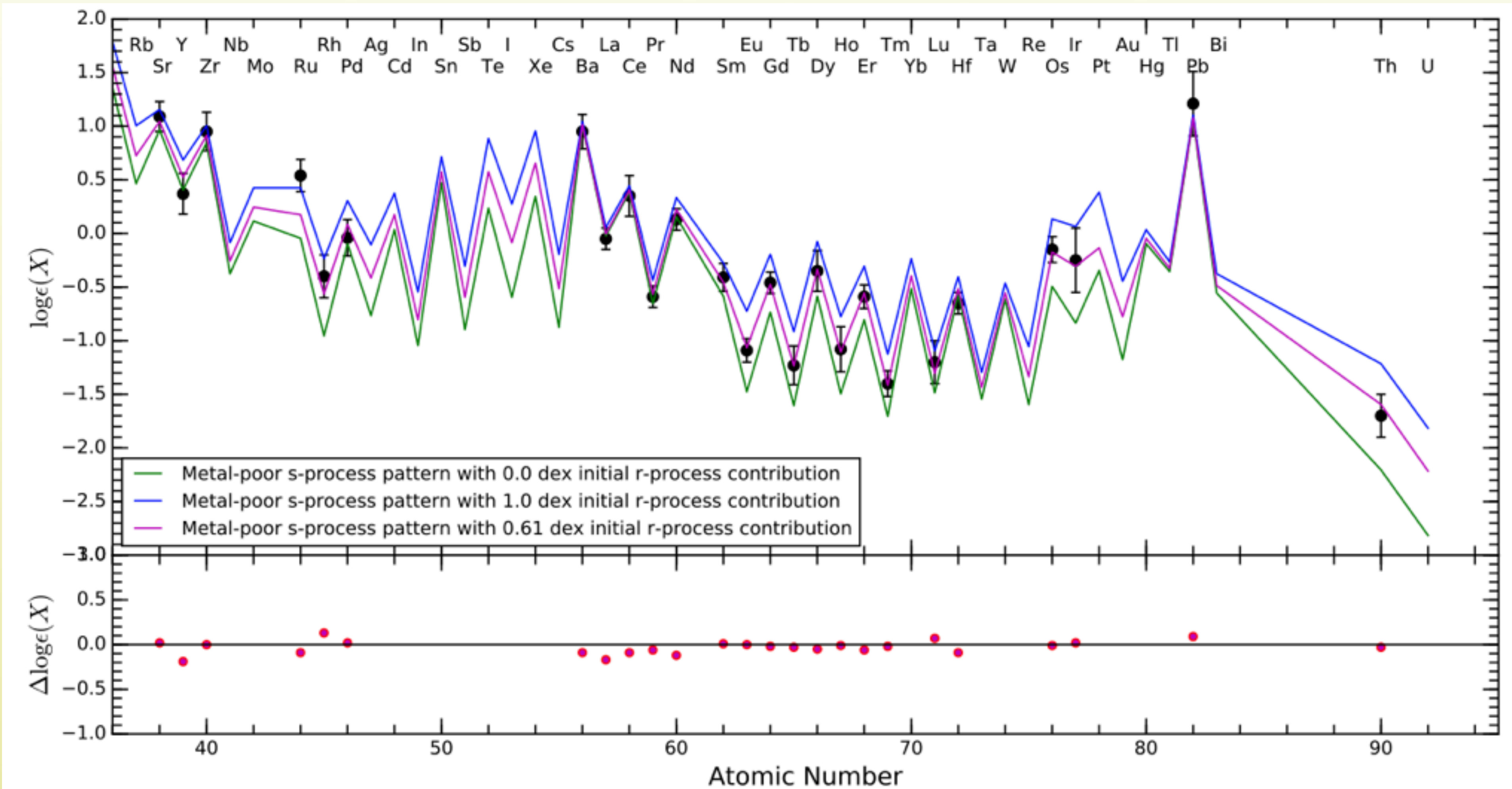

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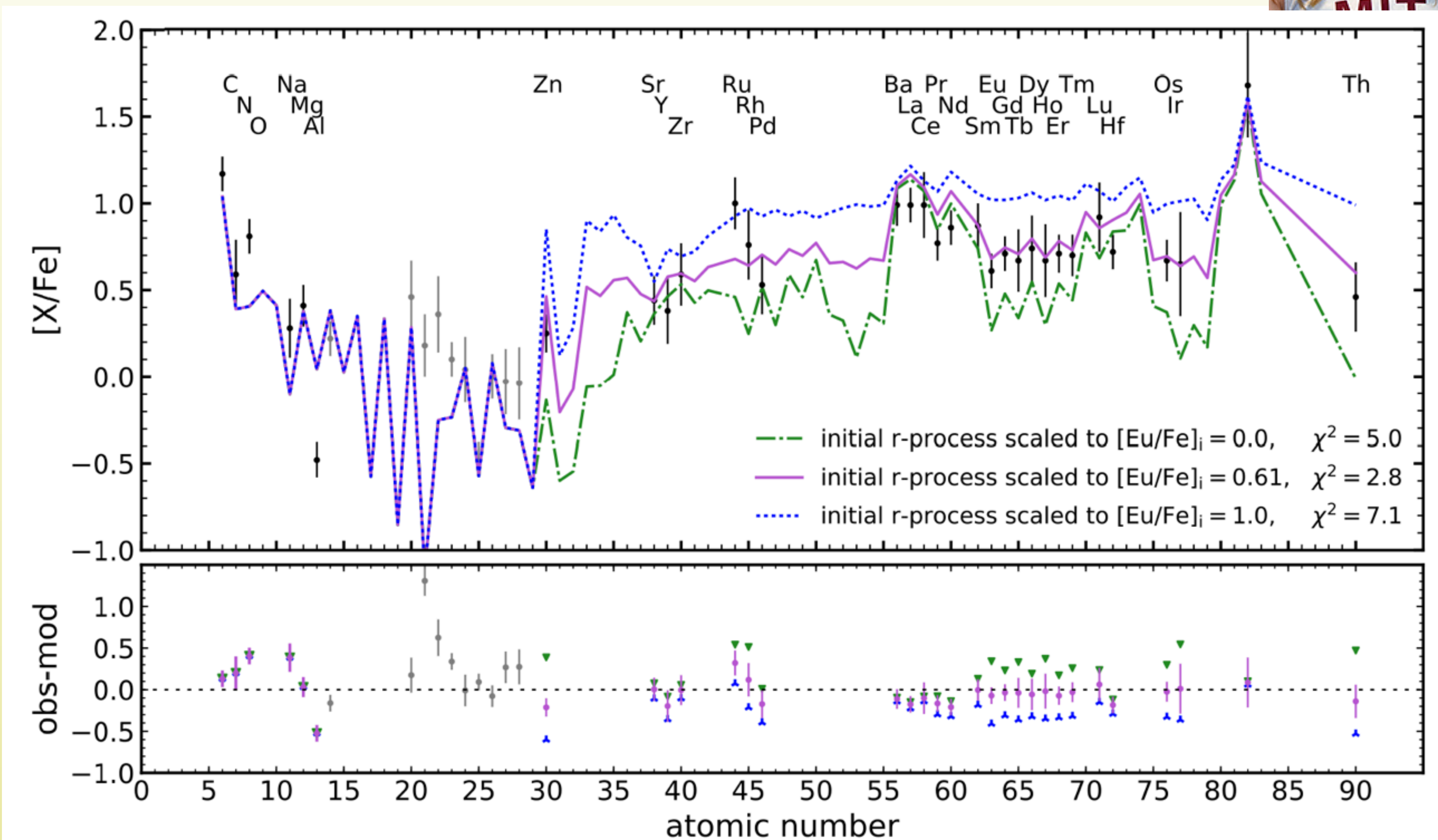


Gull, Frebel et al. 2018, in prep

CEMP STARS IN DWARF GALAXIES

Classical dwarfs:

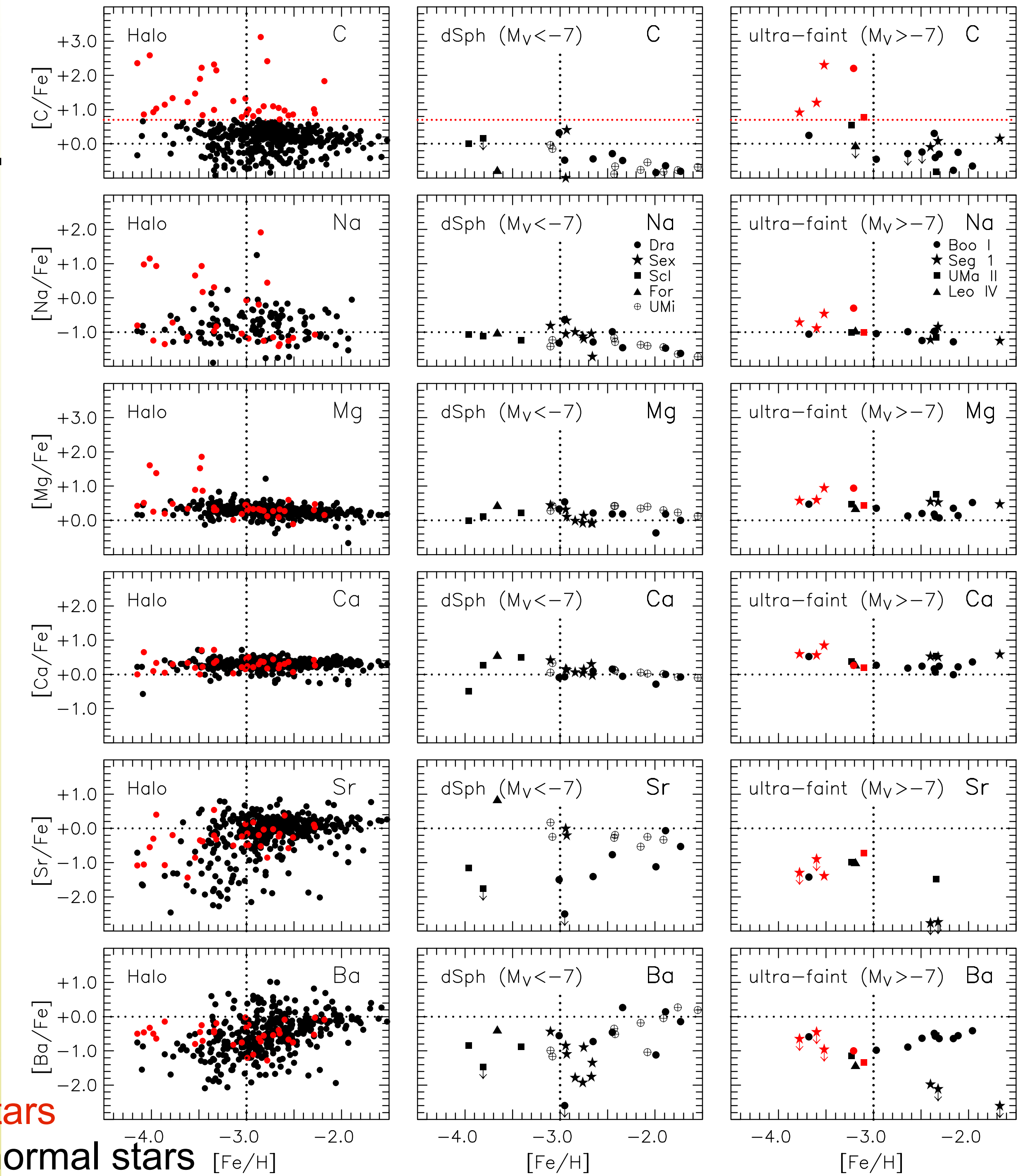
not so (m)any in 2015

Ultra-faint dwarfs:

5/21 => 23% (in 2015)

10/35 => 28% (2016)

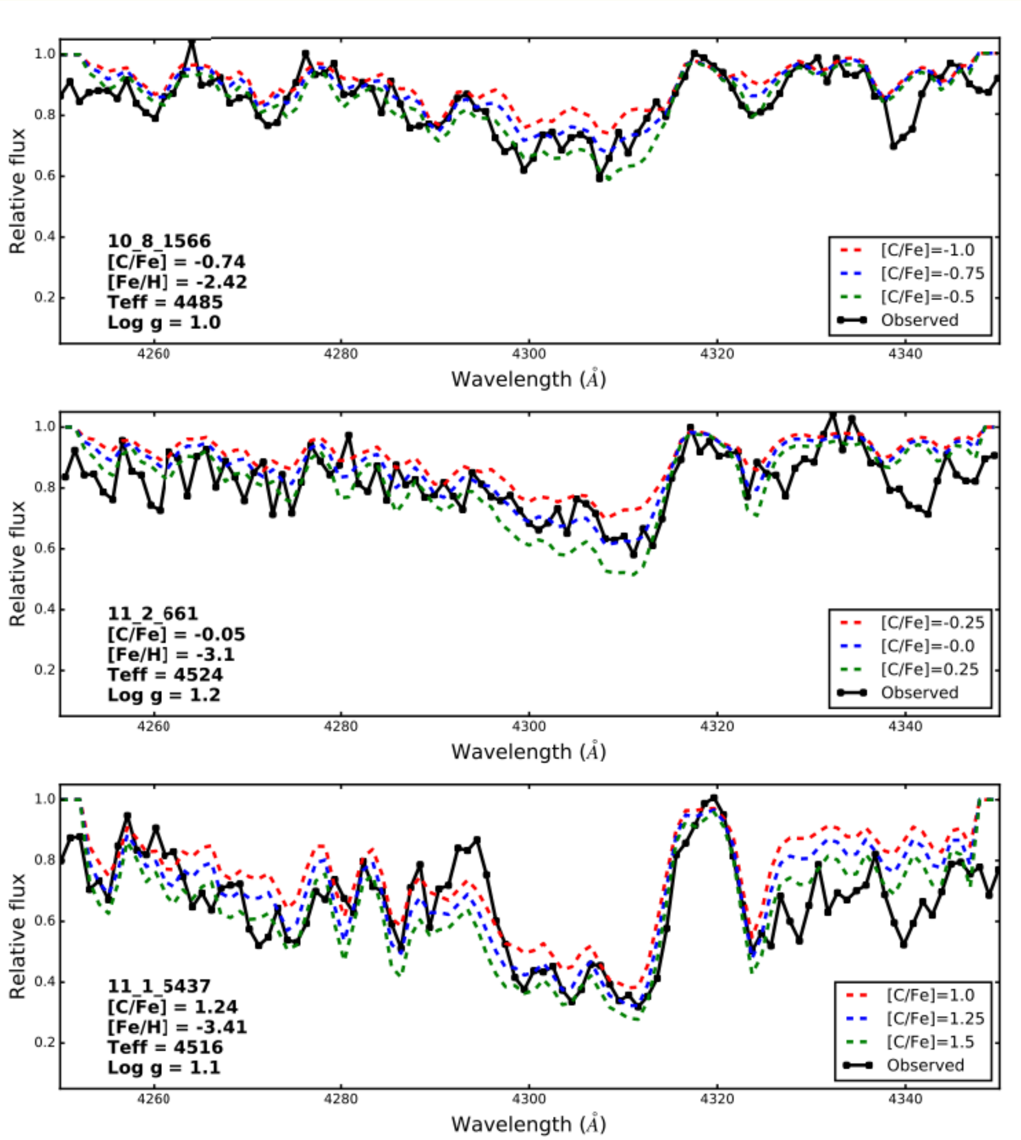
Halo: 25% ([Fe/H]<-2.5)

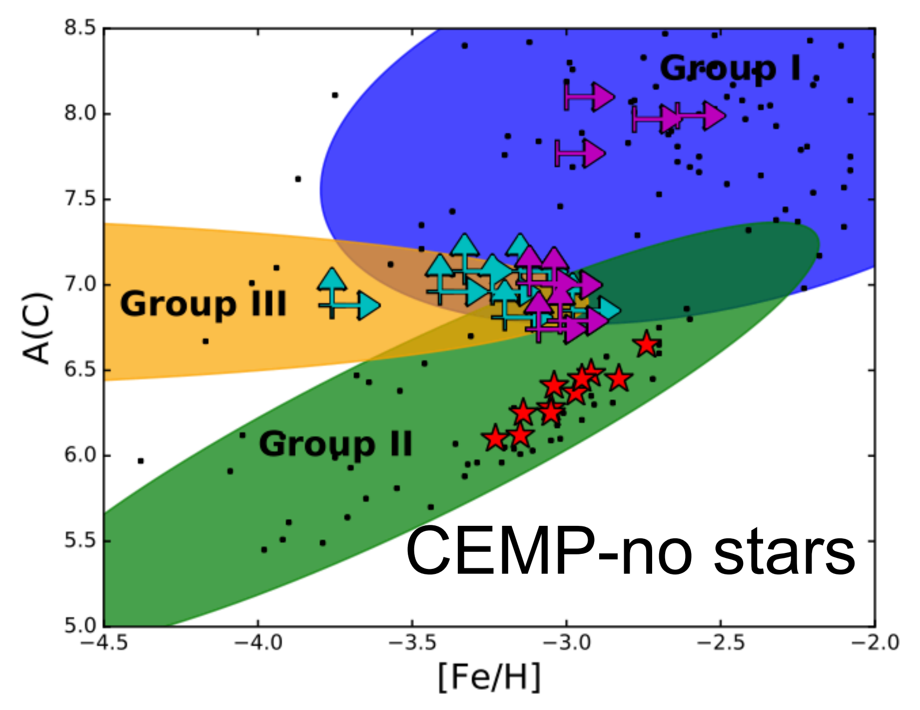


CEMP stars

carbon-normal stars

CEMP stars in Sculptor





Chiti et al. 2018, subm

CEMP fraction in Sculptor

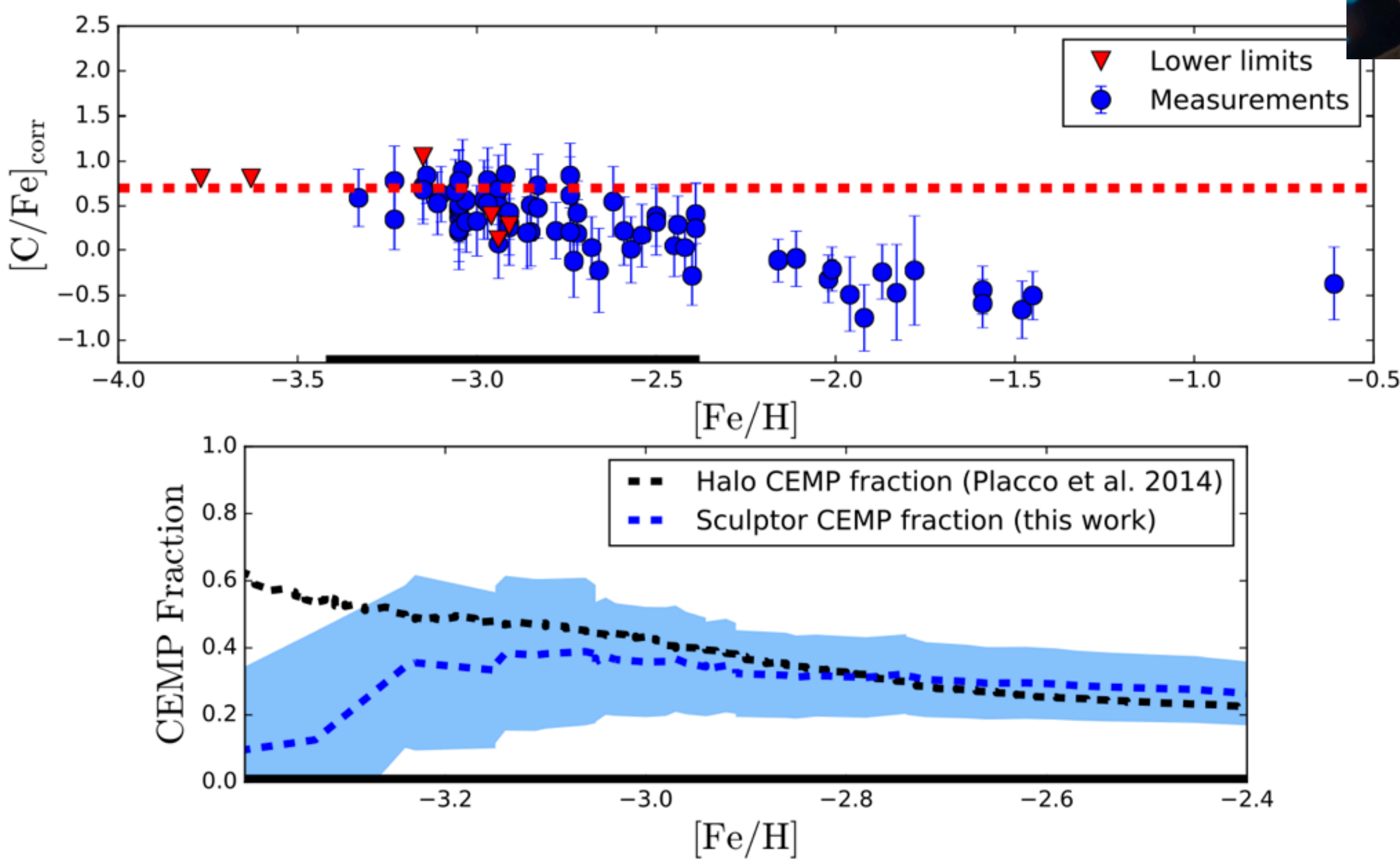
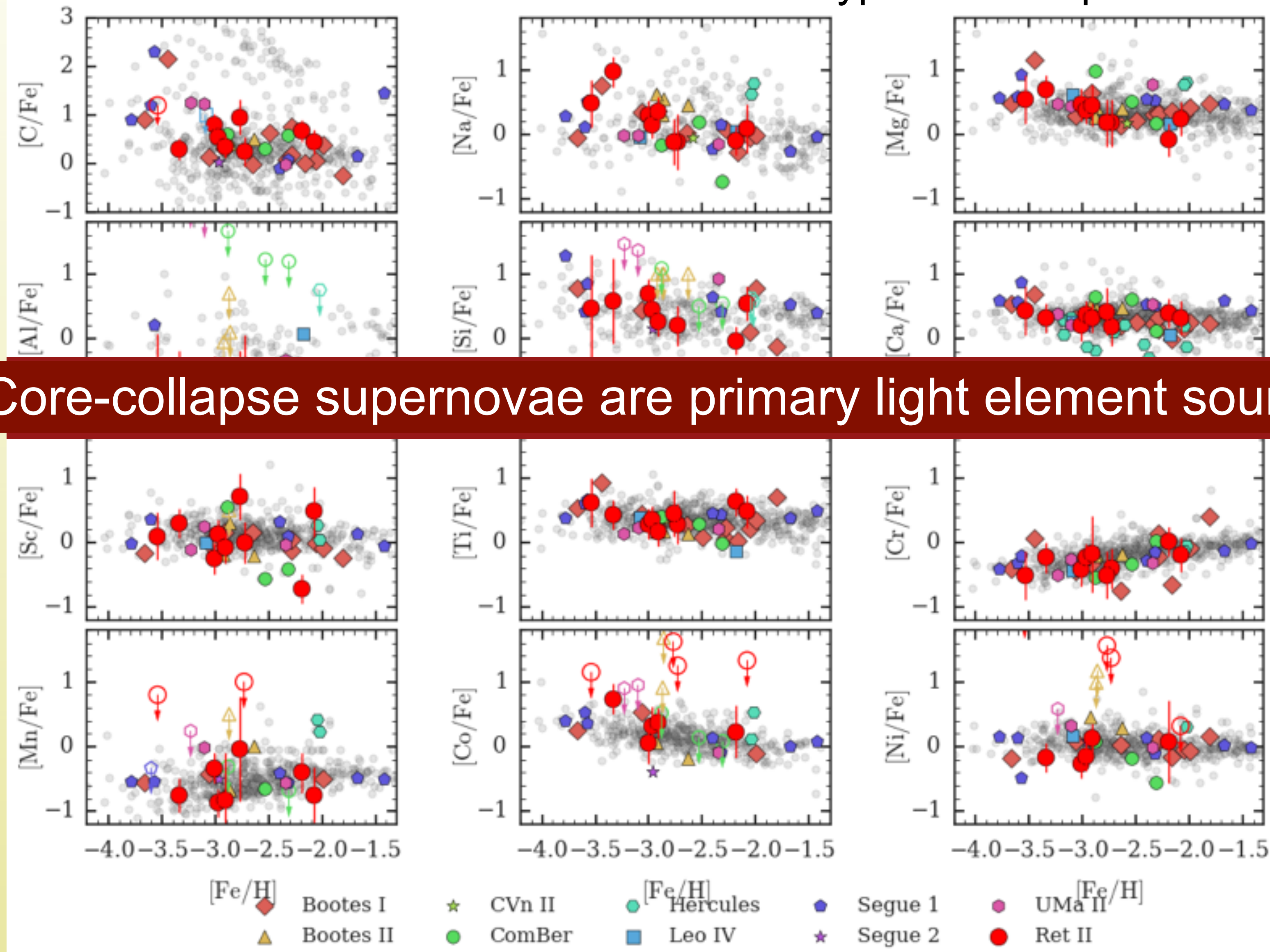


FIG. 12.— Top: [C/Fe] as a function of [Fe/H] for RGB stars in our M2FS Sculptor sample. CH strong, Ba strong, and CEMP-s candidates are not displayed in the upper panel of the plot. The displayed [C/Fe] measurements have been corrected for the evolutionary state of each star following Placco et al. (2014). The dashed red line marks the cutoff for a star to be considered a CEMP star ([C/Fe] > 0.7). Red downward-facing triangles are upper limits on [C/Fe] from non-detections of the G-band. Bottom: Measured cumulative CEMP fraction as a function of [Fe/H] for our Sculptor sample (blue) and the Milky Way halo from Placco et al. (2014) (black). The shaded blue region corresponds to the 95% confidence interval of our measured CEMP fraction.

Chiti et al. 2018, subm

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

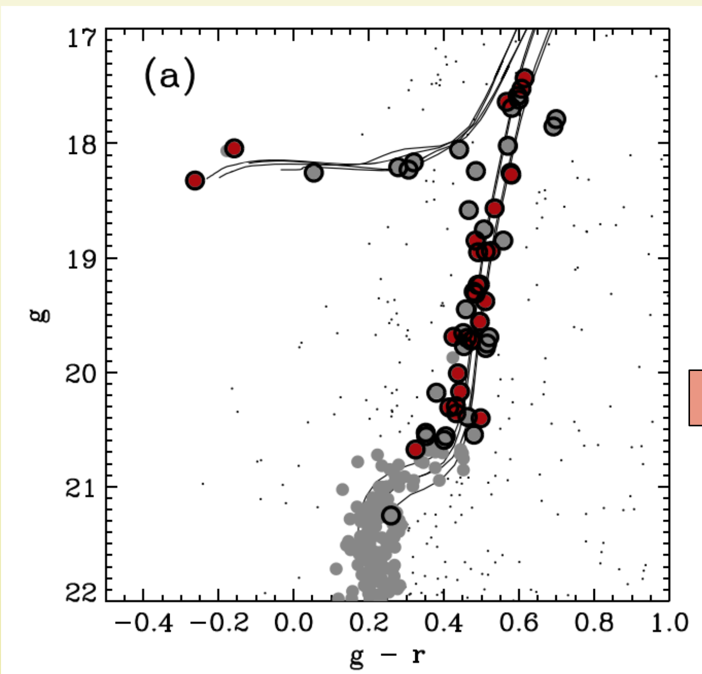
Ji et al 2016, *Nature*, 531, 610

Magellan observations of Reticulum II stars

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

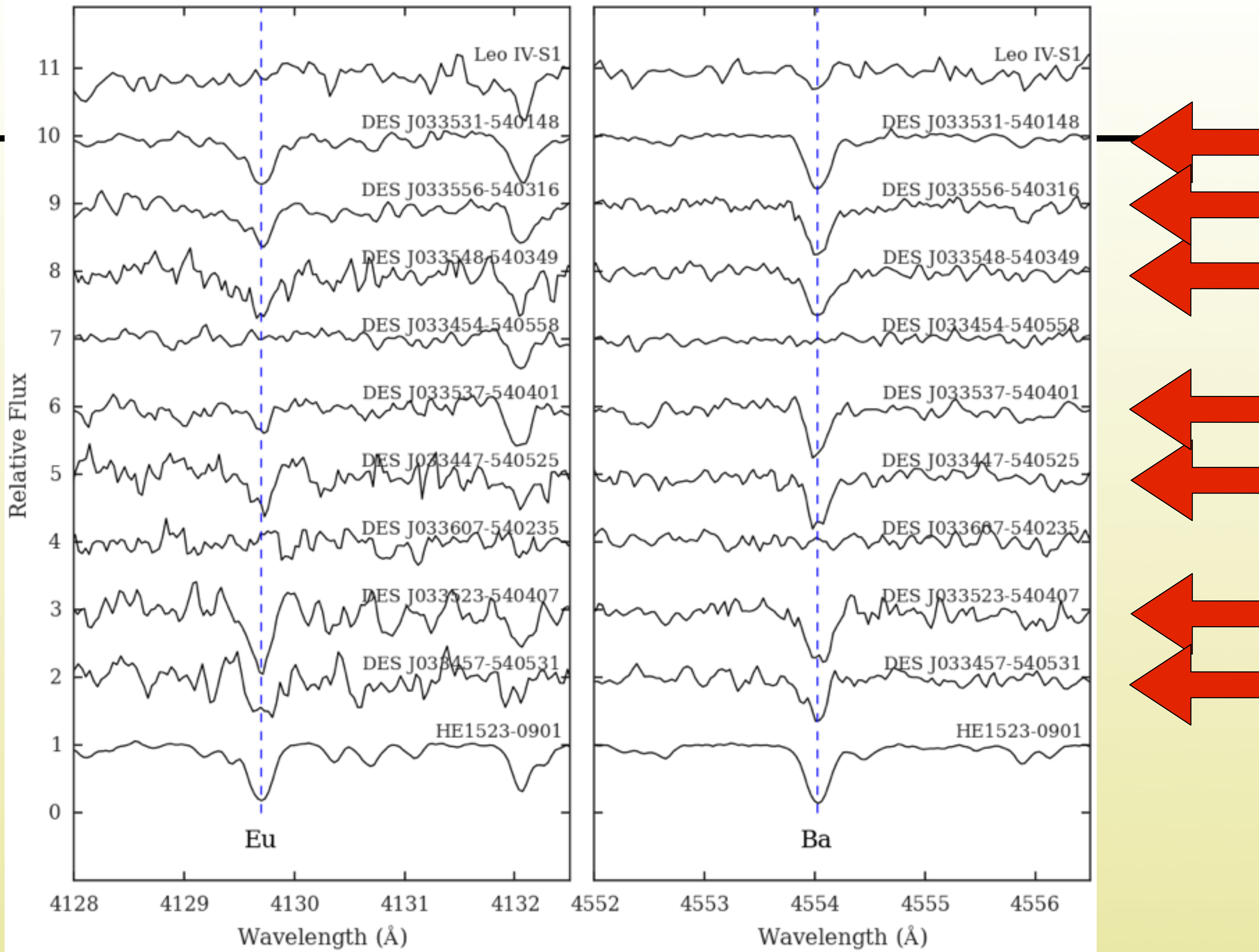
Brightest members (V=17-19) observable with high-resolution spectroscopy

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

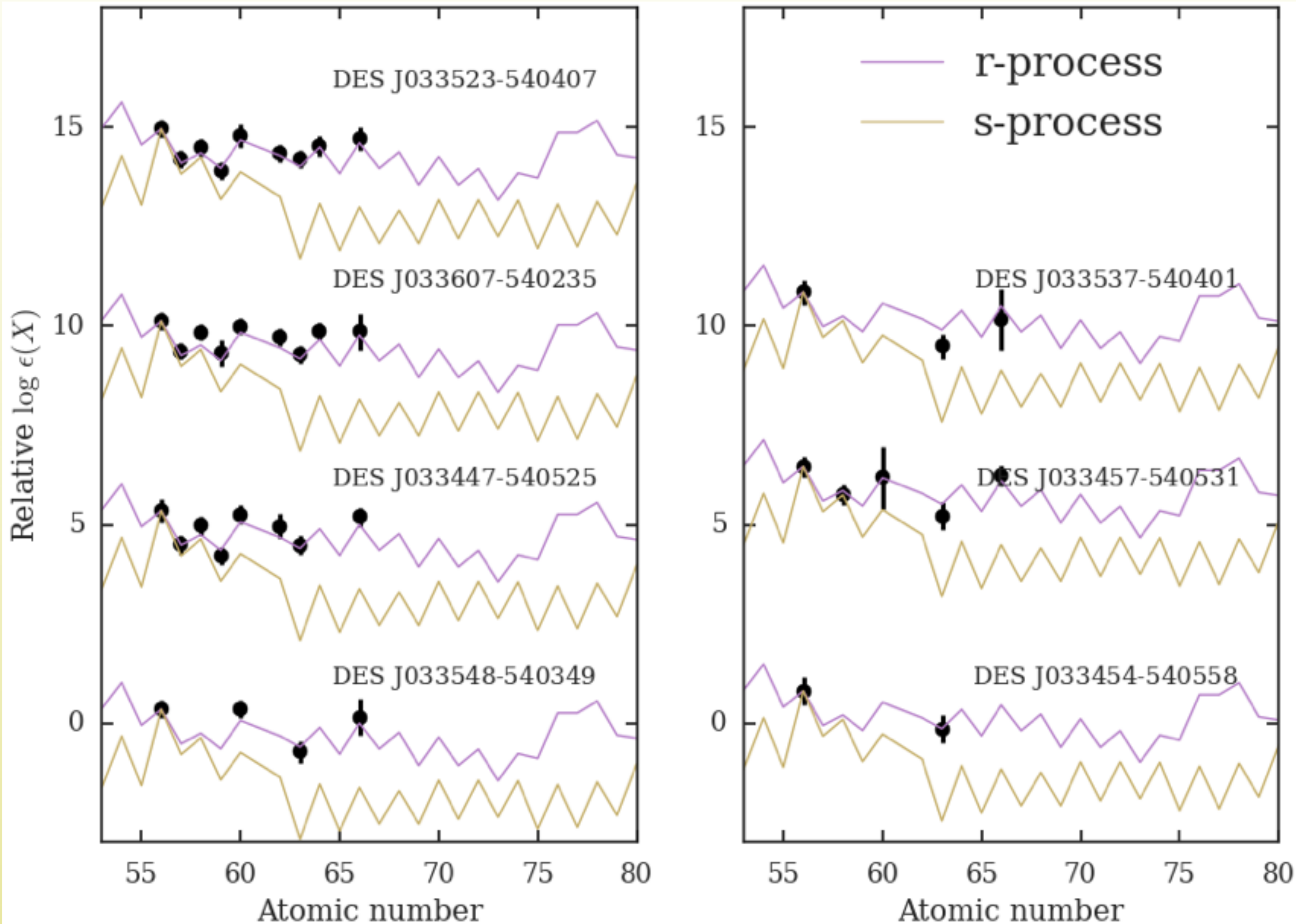


Color-magnitude-diagram of Ret II
(red = confirmed members)

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


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)
11
10
9
8
7
6
5
4
3
2
1
0
4128
4129
4130
4131
4132
4552
4553
4554
4555
4556

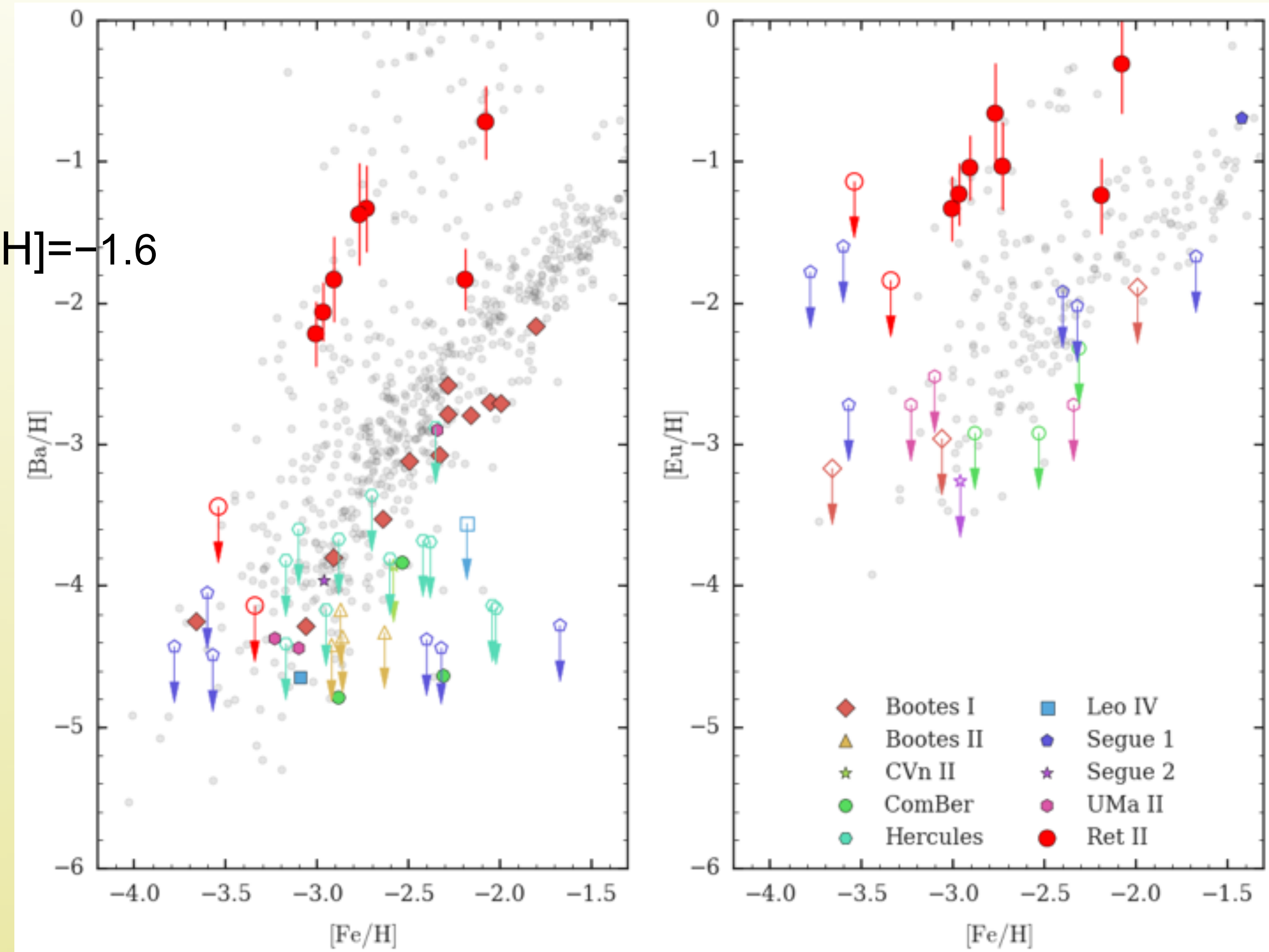
All seven Ret II stars display the r-process pattern



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

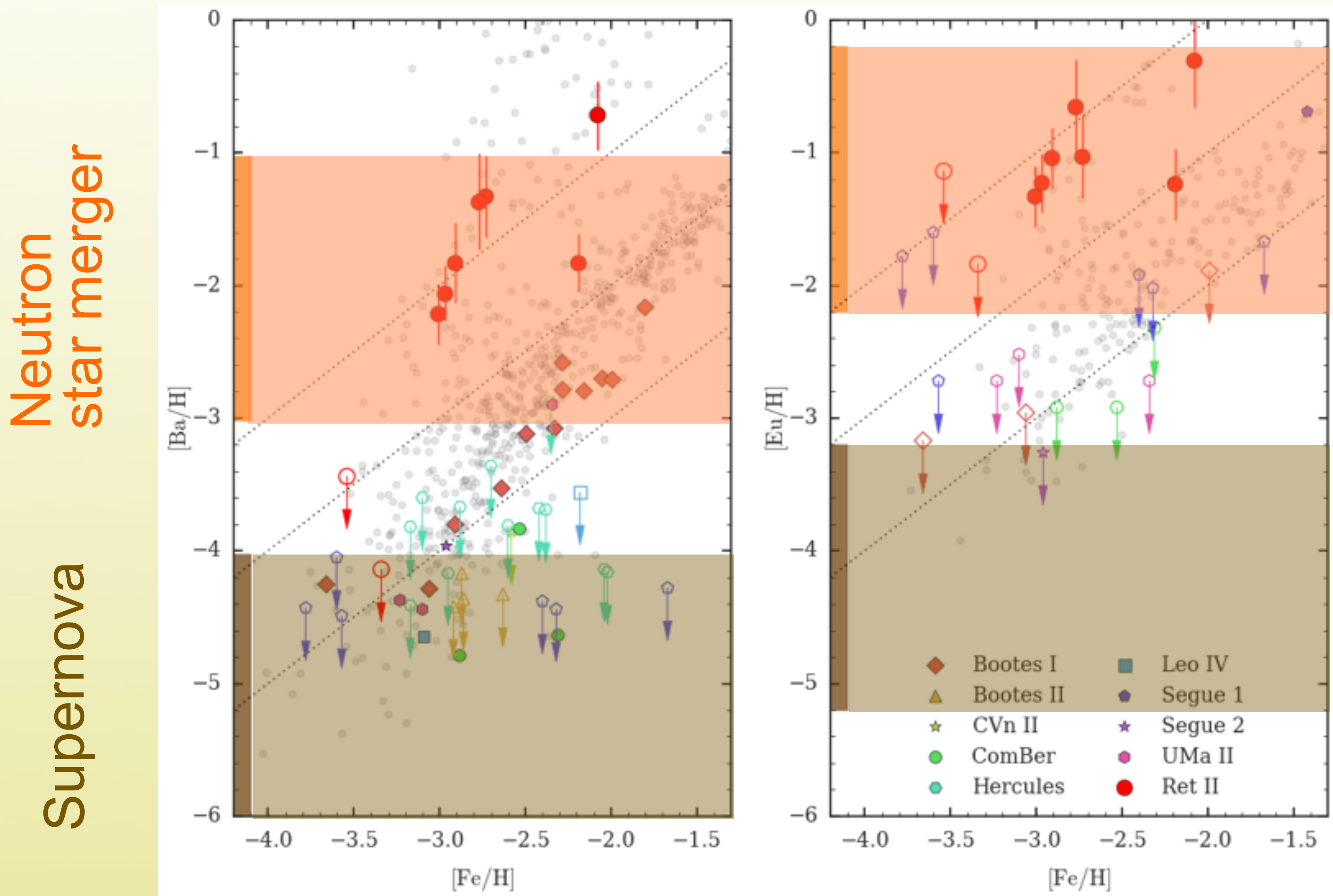
Ret II stars: <u>> 100x higher</u> n-capture element abundances than other UFDs

[Ba/H]=−1.6



[Eu/H]=−1

Ret II abundances consistent w/ neutron-star merger yield

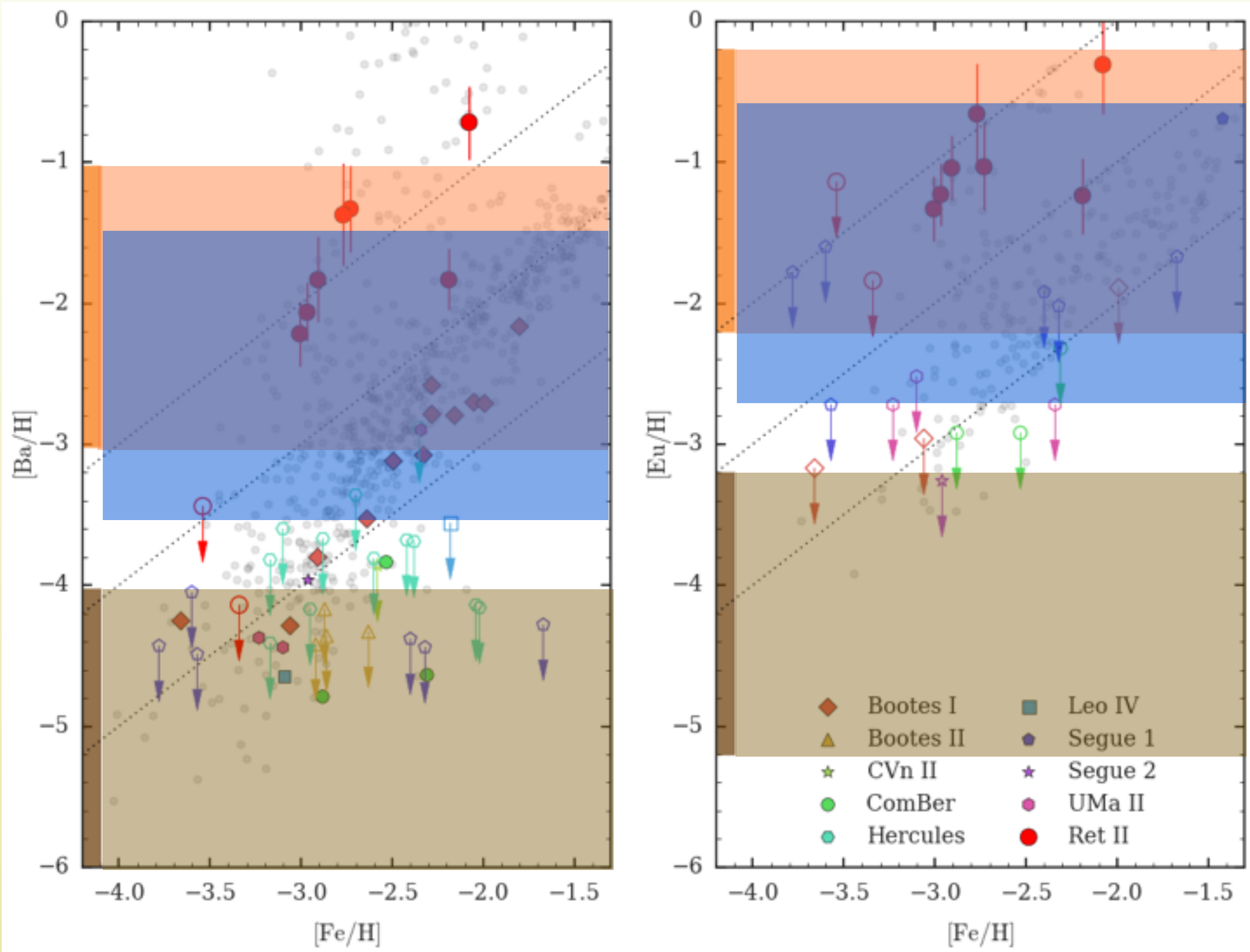


Ji et al 2016, *Nature*, 531, 610

Rare and prolific jet-driven supernova remains possibility

Neutron star merger

Supernova

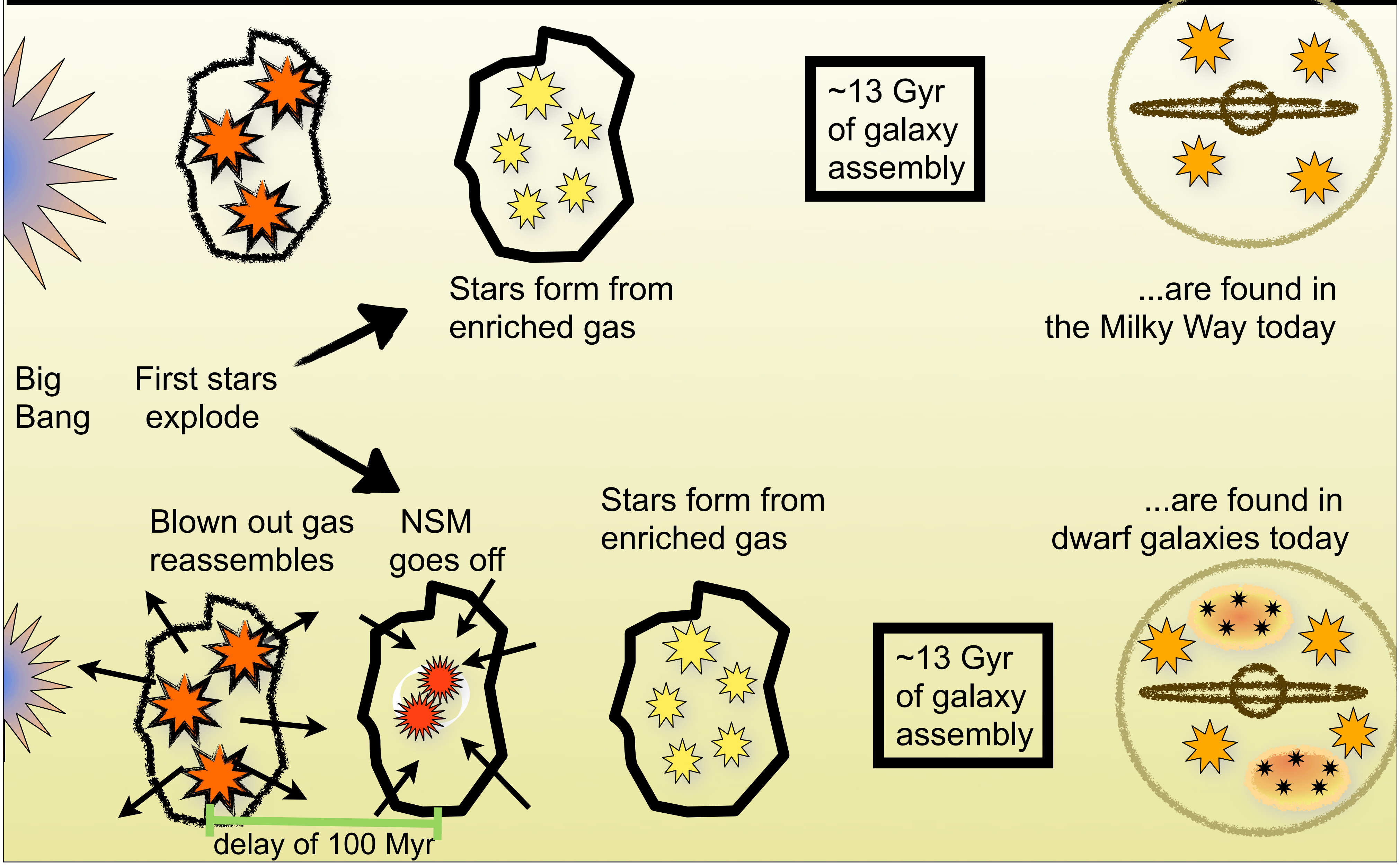


Jet-driven supernova

(e.g. Winteler et al. 2012)

...but ordinary supernovae remain ruled out!

ENRICHMENT AND STAR FORMATION TIMELINE



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?**

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; $\sim 10^{-2.5}$ M_{sun} of r-process

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

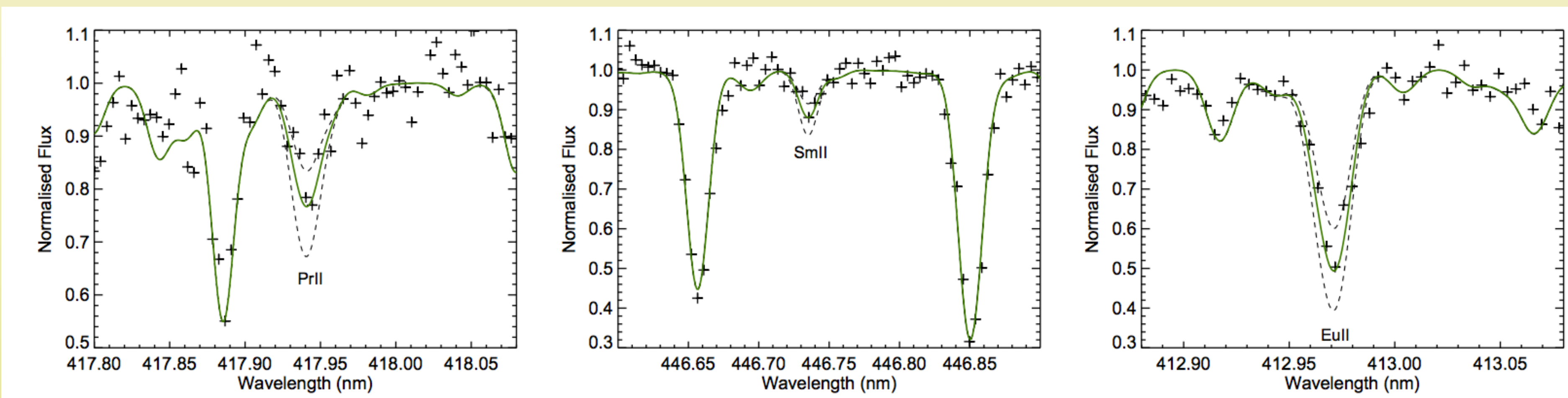
➡Probably not!

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



WHAT DO WE KNOW ABOUT THE FIRST STARS?

No, my darling -- but you can read about our recent progress here:

Near-Field Cosmology with Metal-Poor Stars

A. Frebel & J. E. Norris

2015, ARA&A

No, my darling -- but we now have a first clue where they might be hiding:

Predicting the locations of possible long-lived low-mass first stars: Importance of satellite dwarf galaxies

Magg et al. 2017, MNRAS

Is anybody out there...?

IF there were any **low-mass first stars**, e.g. 0.6-0.8 Msun, they would have a current age of ~13 billion years

=> They would *principally* be observable!

Big questions

Do they actually exist??

Are there enough left??

Where are they located??

All very speculative...

but that has never stopped theorists to explore it anyway!

Formation of Low-Mass First Stars

Fragmentation of accretion disk during massive first star formation (in 20% of cases Clark+11, Stacy +14)

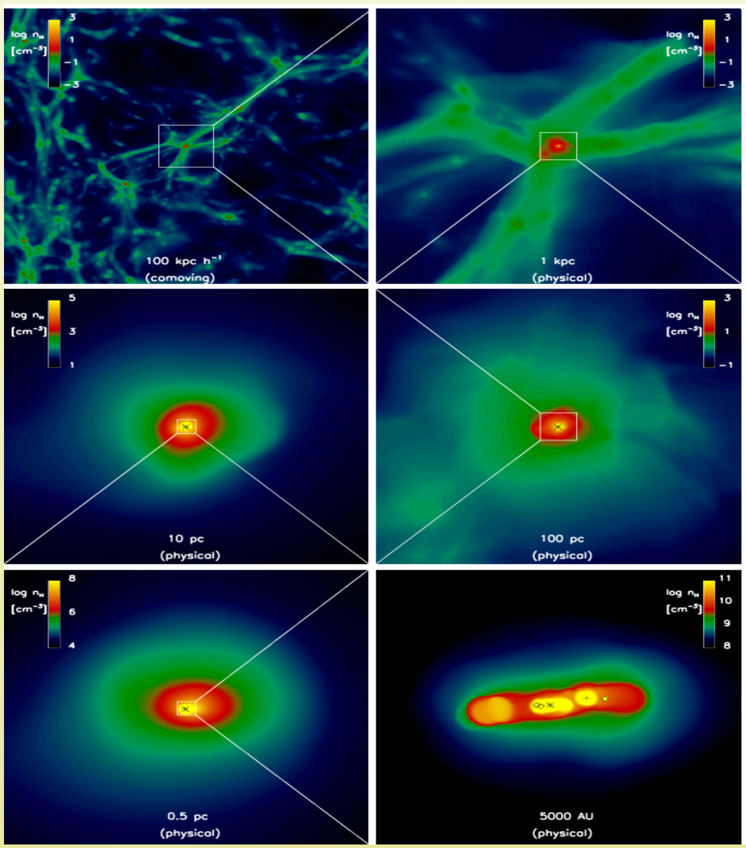
=> Clumps form which collapse under gravity

=> Evolve into low-mass stars smaller than Sun

Table 1. Formation times, final masses and distances from the main sink.

Sink	t_{form} (yr)	$M_{final}(M_{\odot})$	r_{init} (au)	r_{final} (au)
1	0	43	0	0
2	300	13	60	700
3	3700	1.3	930	1110
4	3750	0.8	740	890
5	4400	1.1	270	240

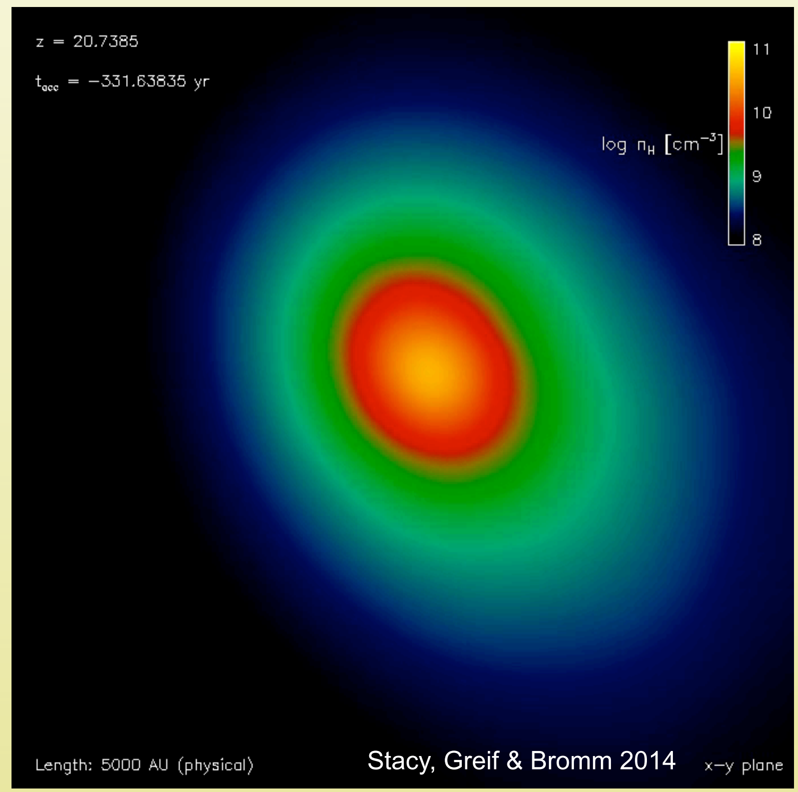
Note. We include all sinks still present at the end of the simulation.



Asterisks: location of most massive sink

Crosses: location of second most massive sink

Diamonds: locations of another sink



Stacy, Greif & Bromm 2014

Where would they be located?

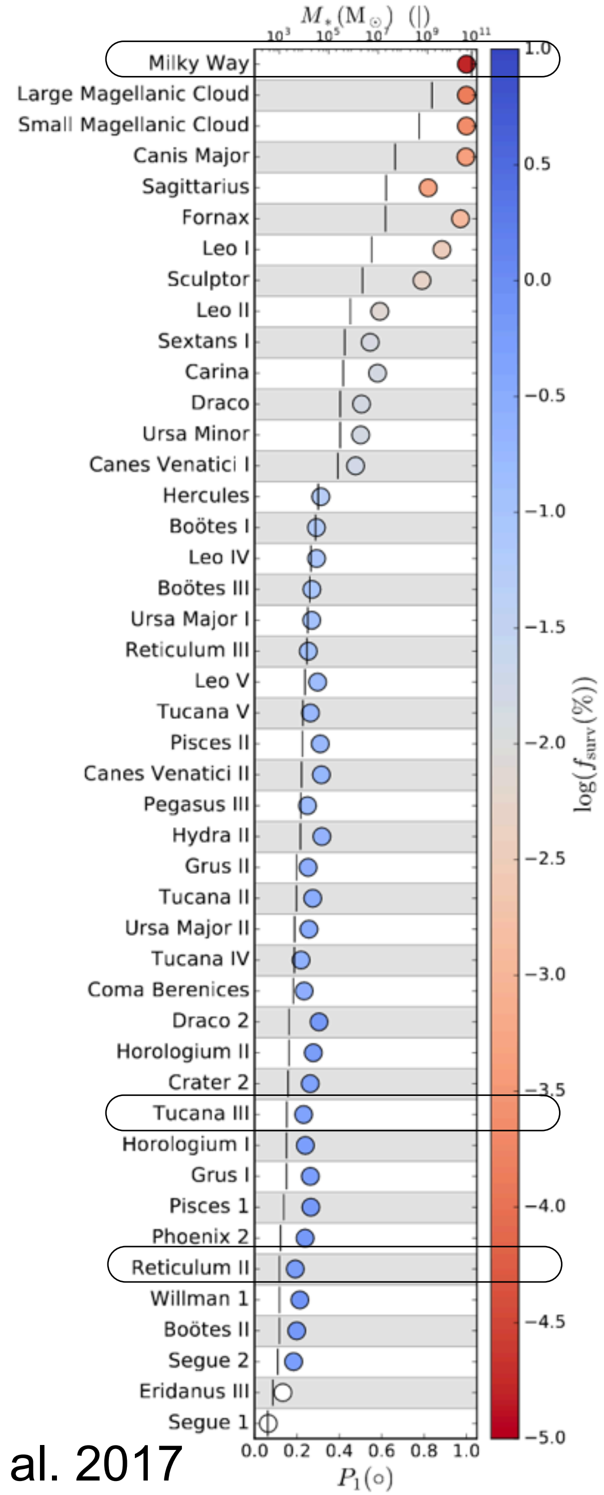
Milky Way: 93 red giant first stars

Dwarf galaxies: 0.1-0.6 red giant first stars per galaxy

<u>Best way forward:</u> Dwarf galaxies

But observationally extraordinarily challenging because dwarf galaxy stars are very faint -- need to push to unprecedented levels to catch all red giant stars in system :(

However, with the *Giant Magellan Telescope* this would be a piece of cake!



Magg et al. 2017

Conclusions

CEMP stars are found in all populations!

Sculptor has a CEMP-no fraction of 30-40%, likely similar to halo

UFD population has ~25%

=> Origin of CEMP stars might lay in dwarf galaxies but more data is needed to confirm this. Light element abundance have already suggested, though.

In other news:

- r+s stars do exist!

- The first stars may have all exploded aspherically => inhomogeneous metal mixing

... get all your abundance needs from JINAbase!