Neutron-capture Nucleosynthesis in Relics of the First Galaxies

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In collaboration with:
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Ji et al. 2016
Nature, 531, 610
arxiv:1512.01558

Ji & Frebel 2018
ApJ 856, 138
arxiv:1802.07272

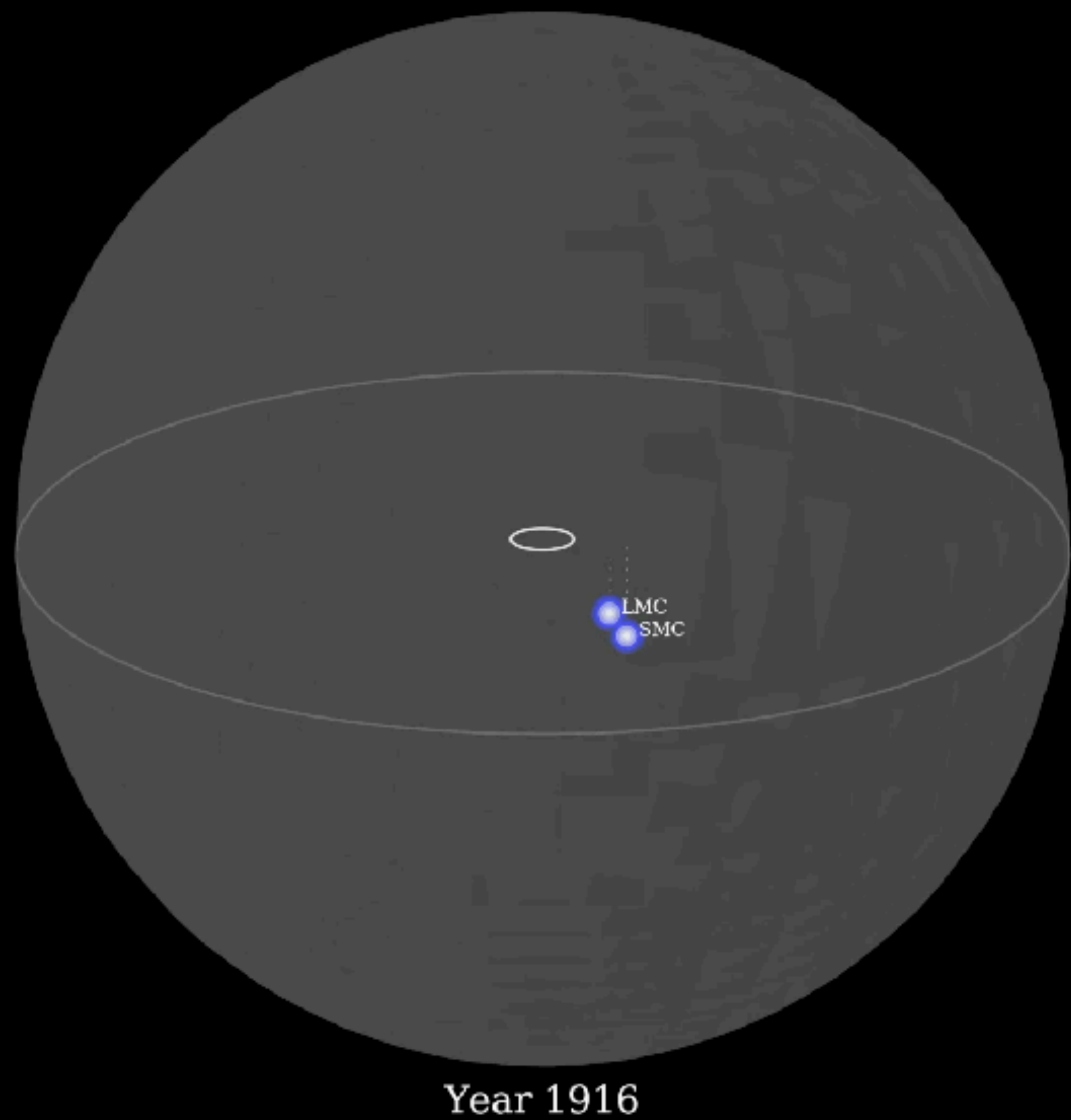
Ji et al. 2018
ApJ accepted
arxiv:1809.02182

Brauer, Ji et al. 2018
ApJ submitted
arxiv:1809.05539

Outline

- Ultra-faint dwarf galaxies
- Neutron-capture nucleosynthesis
- UFDs with large amounts of r-process
- UFDs with low neutron-capture elements
- Connection to Milky Way's halo

History of Milky Way Satellites



Movie by Marcel Pawlowski

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No overdensity in 2D

All stars

0.3 x 0.3 sq deg

(~1/3 the size of the moon)

Yes overdensity in 2+2D

Ret II Stars

Fermilab/Dark Energy Survey

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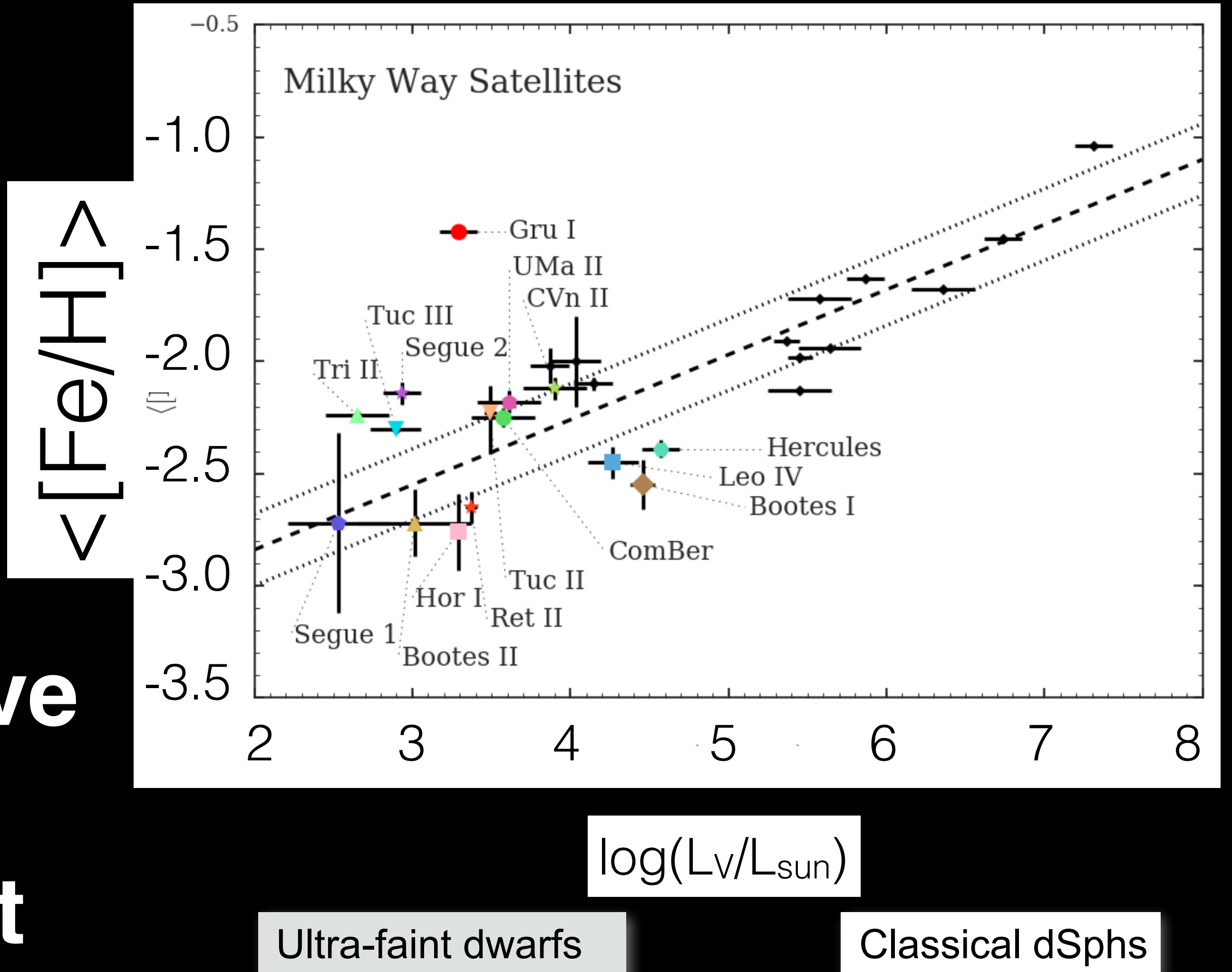
Ultra-faint dwarf galaxies

(UFDs)

- Low luminosity (~300 - 30,000 L_{sun})
- Dark-matter-dominated (M/L > 100)
- Metal-poor (Mean [Fe/H] < -2)
- Old (Mean stellar age 13.3 +/- 1 Gyr)
- Solve the missing satellite problem



The stars in each UFD preserve a short, independent burst of early chemical enrichment with a *known environment*!

The ideal place to study metal-poor stars.
Look at a *sample* of UFDs!

McConnachie 2012 + recent data
L-Z relation: Kirby+2013

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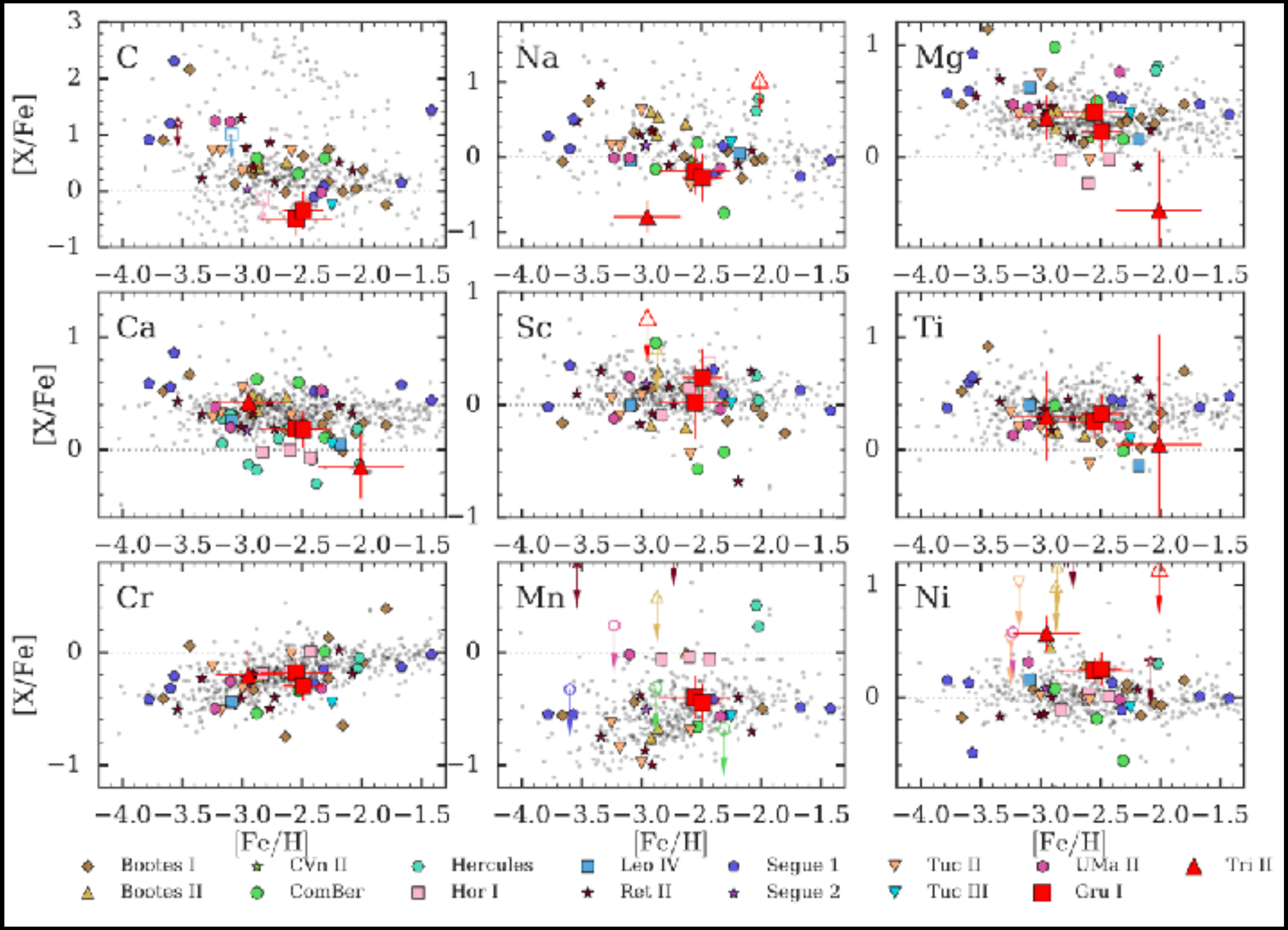
Light elements in UFDs



Now with 15 UFDs!

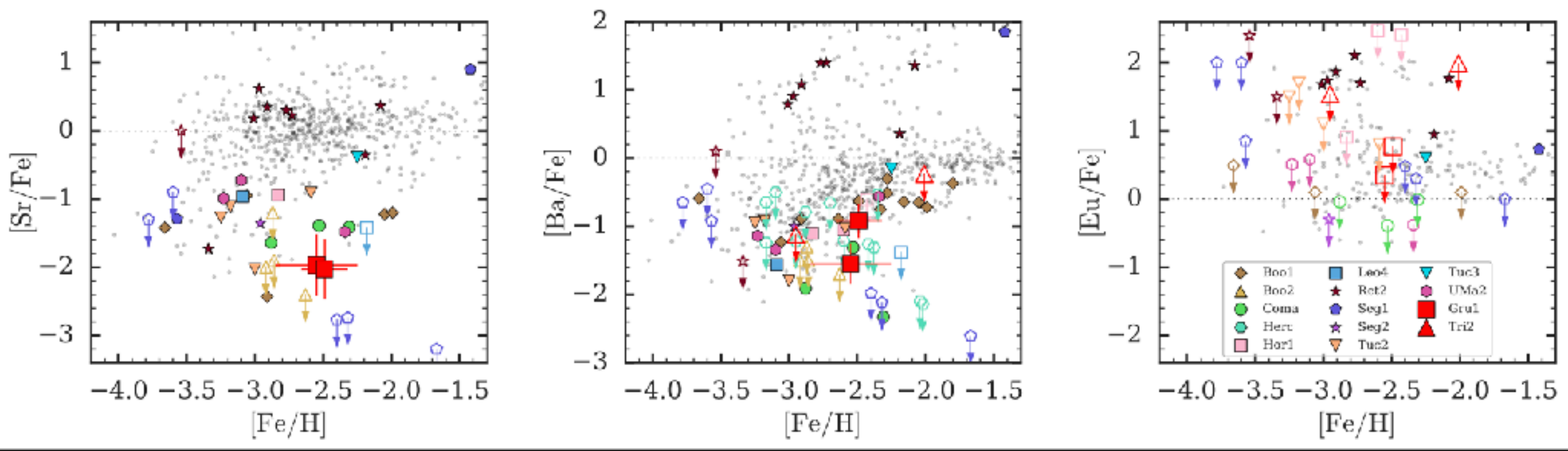
References here: Feltzing+09, Norris+10, Gilmore+13, Ishigaki+14, Frebel+16, Ji+16acd, Francois+16, Frebel+10, Koch+08/13, Nagasawa+18, Simon+10, Frebel+14, Roederer+Kirby 14, Chiti+18, Hansen+17, Ji+18

A complete homogeneous reanalysis is desperately needed

Ji et al. 2018

Neutron-capture elements in UFDs

Sr Ba Eu



UFDs obviously different than halo stars

Neutron-capture elements are the defining abundance feature of UFDs

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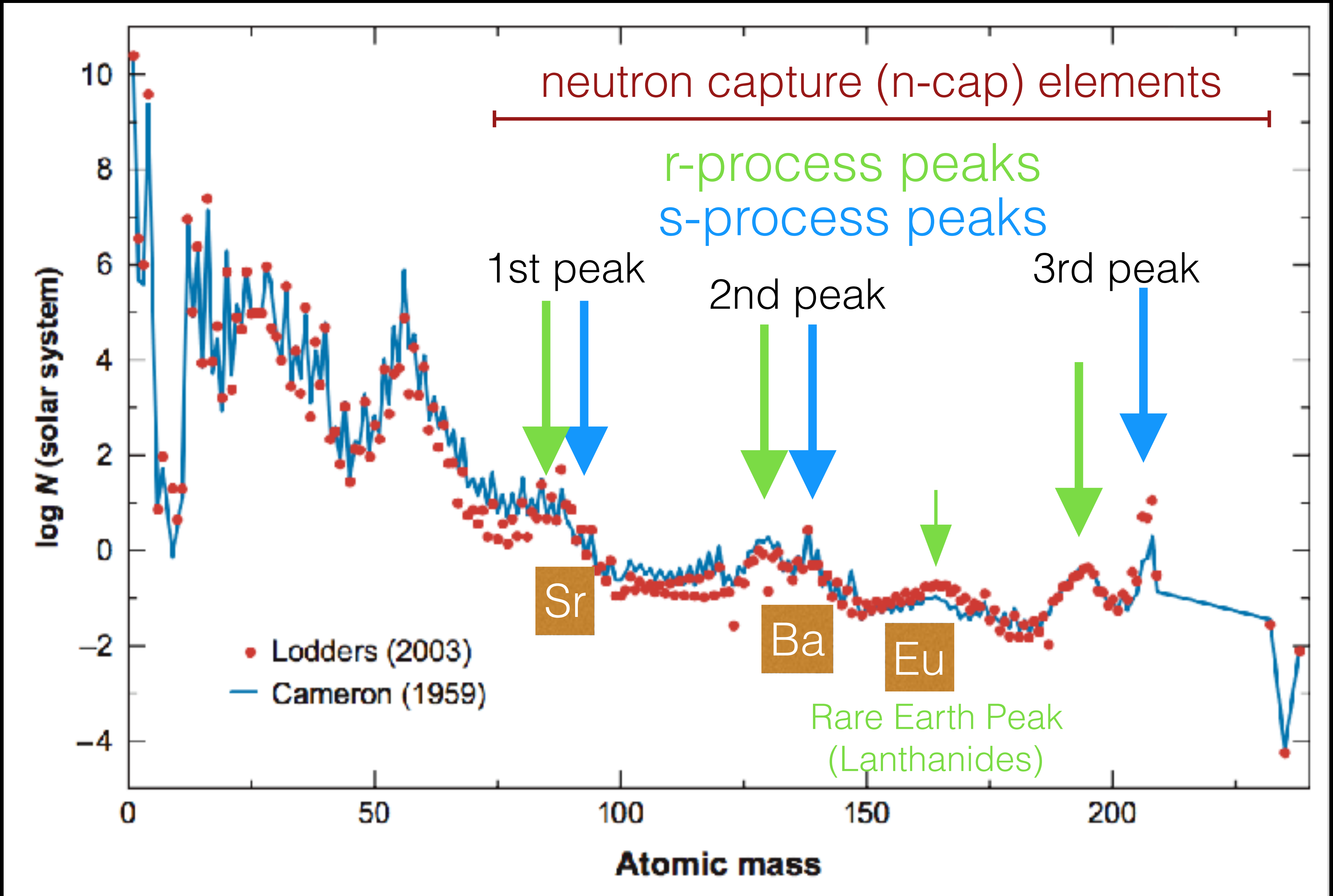
Ji et al. 2018

Solar System Abundances



Sneden et al. 2008

s-process: AGB stars

r-process: neutron star mergers (NSMs) and/or supernovae (SNe)

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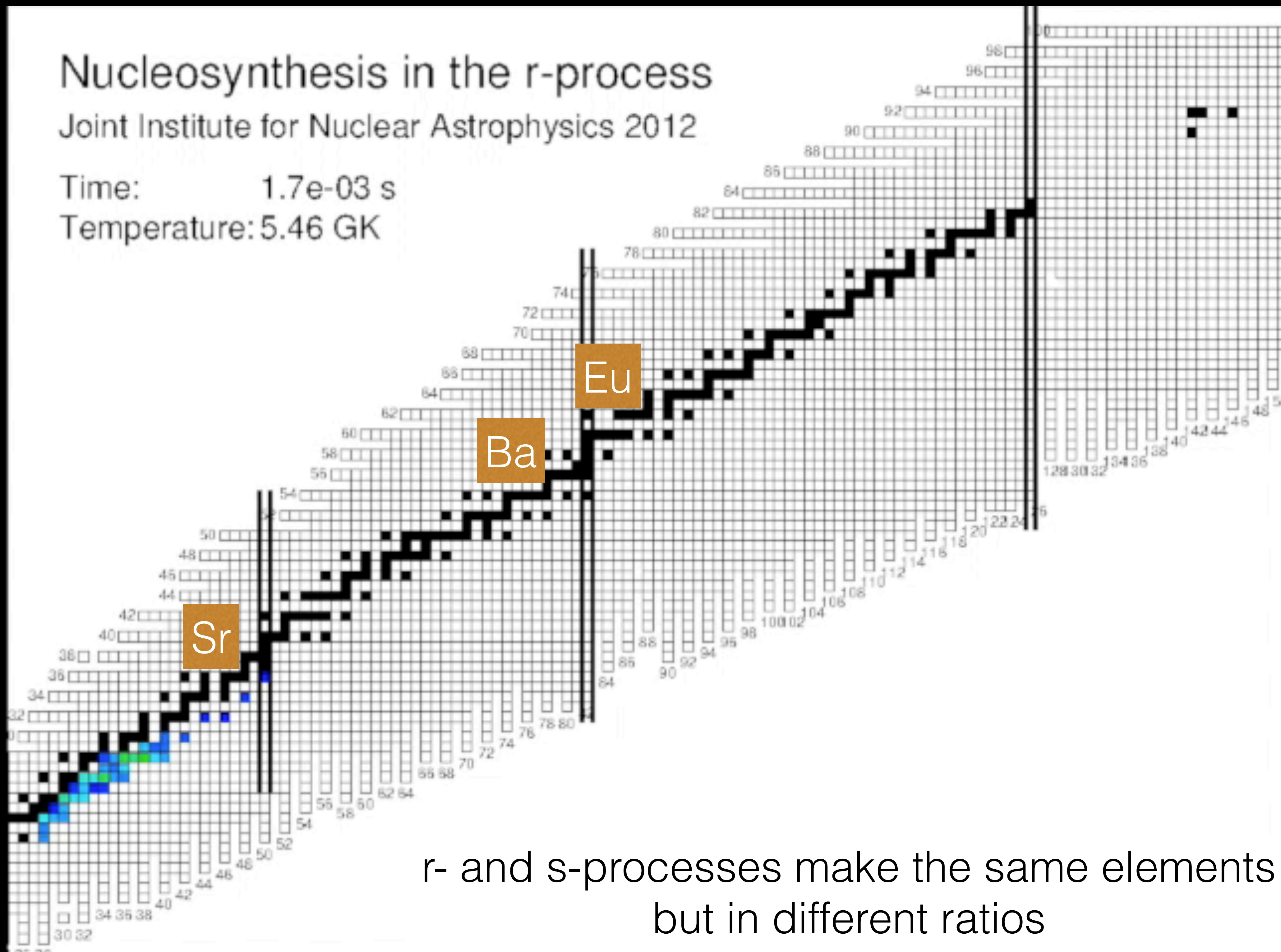
Z (number of protons)



N (number of neutrons)

Video: JINA-CEE
Meyer and Surman

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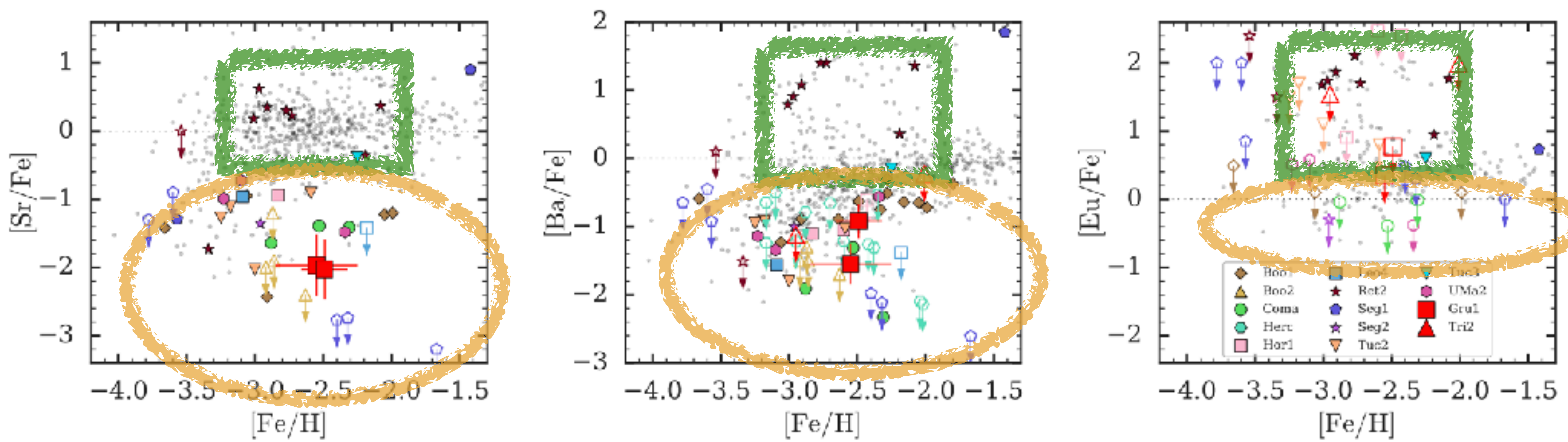
Neutron-capture elements in UFDs

Sr Ba Eu



Two UFDs are r-process enriched!

The others have very low neutron-capture

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Ji et al. 2018

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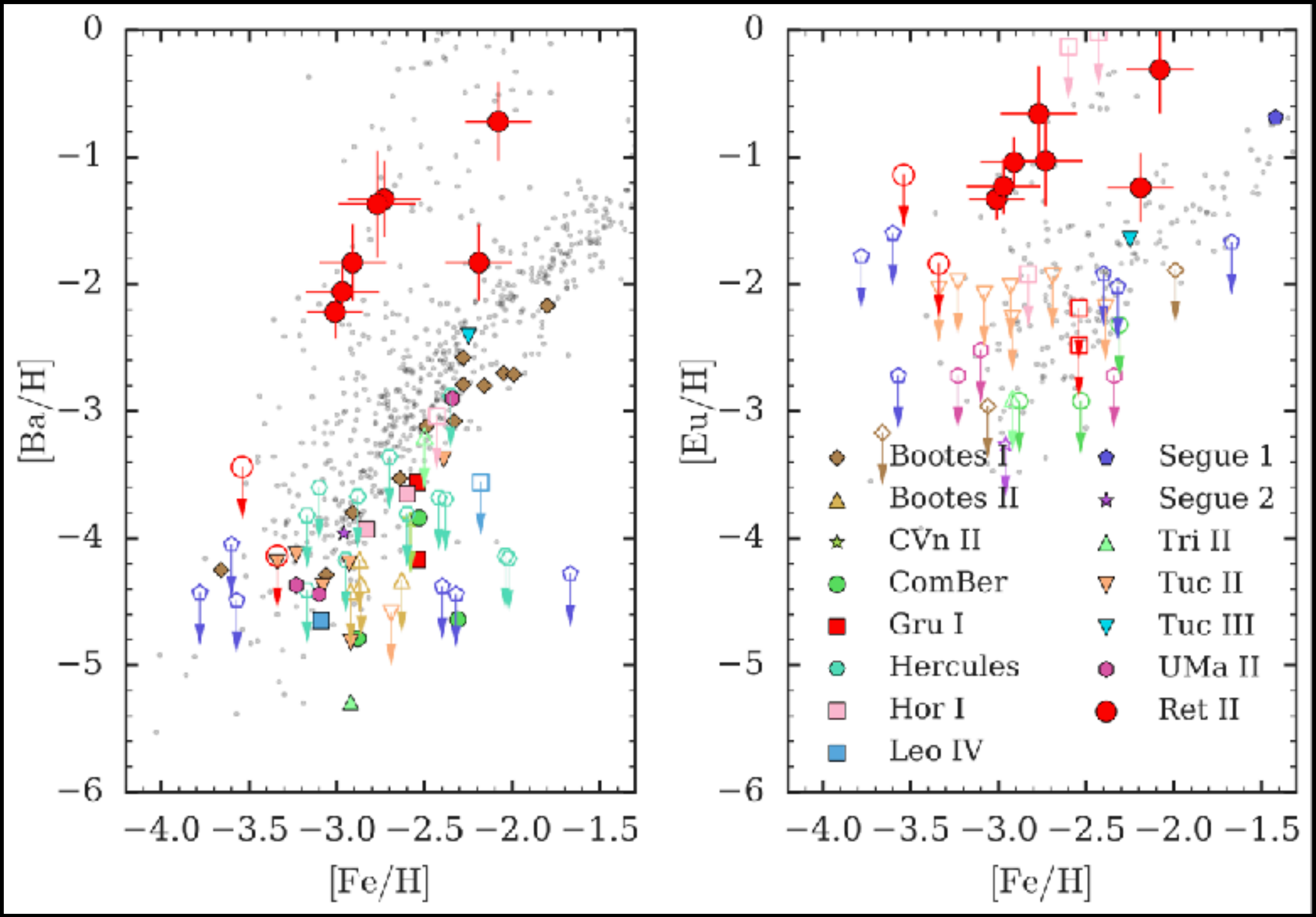
Ret II stars >100x higher neutron-capture element abundances than other UFDs



gray points: Milky Way halo stars

Halo stars: Frebel 2010. UFDs: Francois+ 2016; Frebel+ 2010, 2014, 2016; Hansen+17, Ji+2016, 2018; Koch+2013; Roederer+Kirby 2014; Simon+2010; Nagasawa+2018; Venn+2017, Kirby+2017

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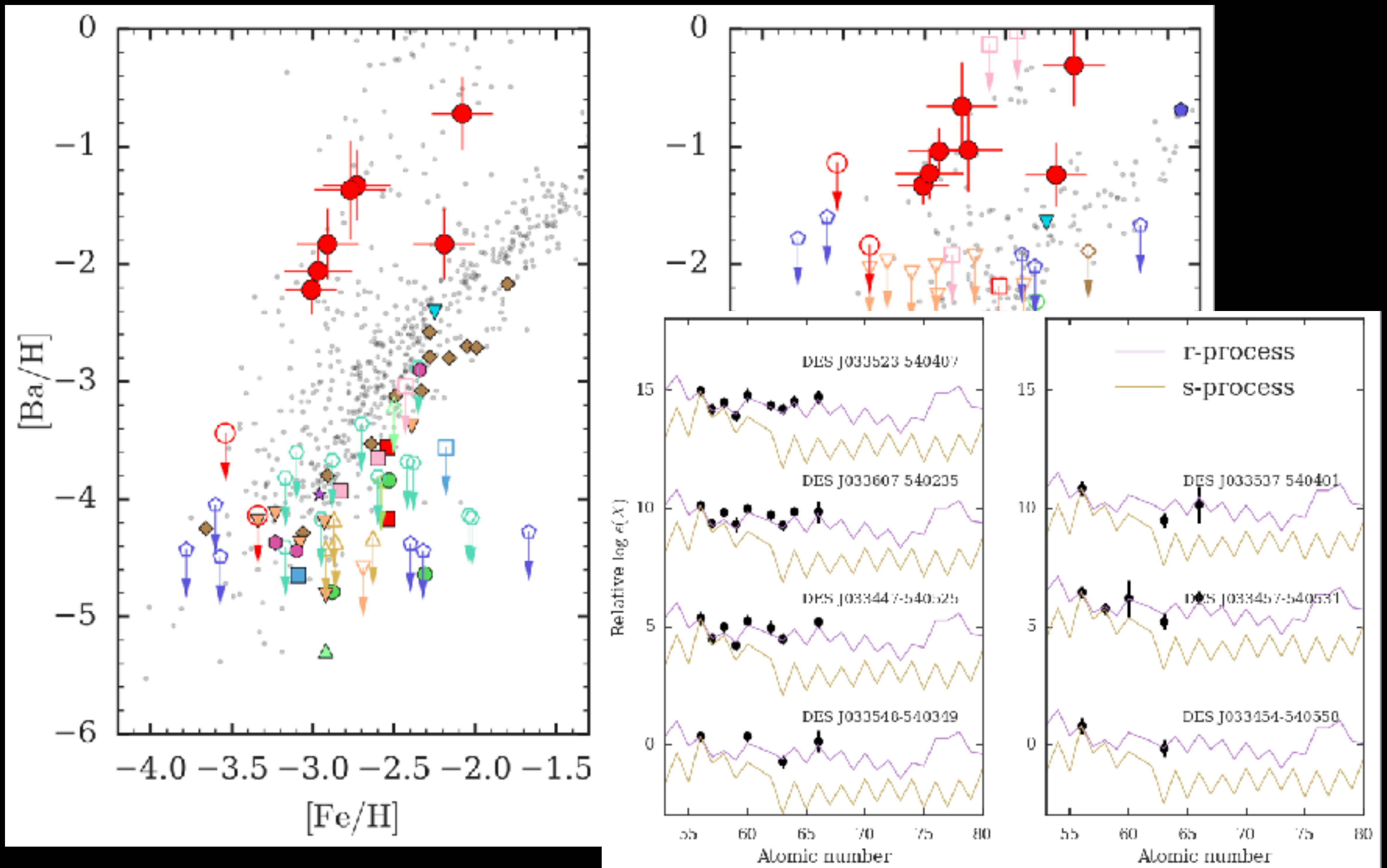
Ret II stars >100x higher neutron-capture element abundances than other UFDs



A pure r-process pattern! <1% contamination

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The Rare and Prolific r-process event in Ret II

- Rate: 1-2 r-process events out of 15 UFDs
  → 1 event per ~1000-2000 CCSNe

Population synthesis: ~1 event per 1000 CCSNe
GW170817: ~1 event per ~200 CCSNe

Ask me about the delay time problem in questions

- Yield: measure [Eu/H] ~ -1.3, estimate gas dilution mass 10^{5}-10^{7} M_{sun}
  → $10^{-4.5\pm1}$ M_{sun} Eu

NSM simulations: ~$10^{-4.3\pm1}$ M_{sun} Eu
GW170817: ~$10^{-4.7\pm0.5}$ M_{sun} Eu

GW170187 estimates: Côté et al. 2018

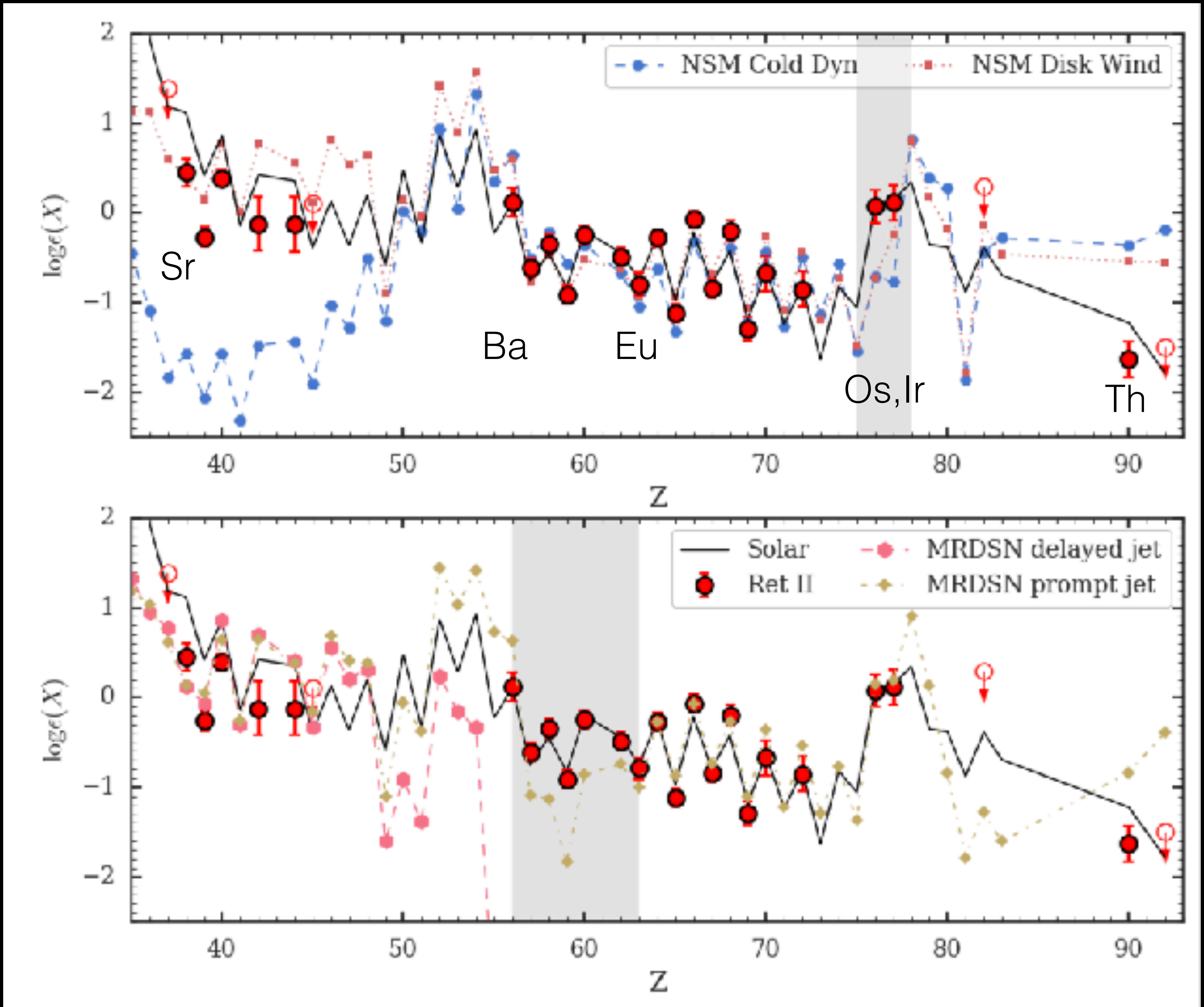
Broadly consistent with a neutron star merger

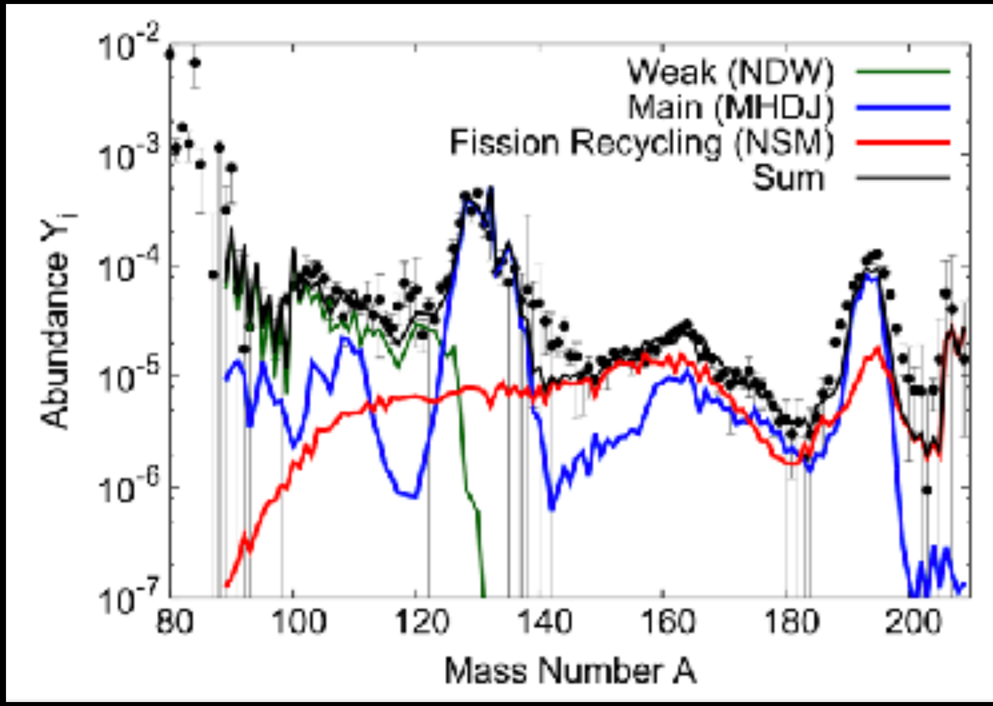
Other rare and prolific r-process sites

- Magnetorotationally driven jets
  Winteler et al. 2012, Nishimura et al. 2015, Tsujimoto et al. 2017, Moesta et al. 2018, …
- Disk winds in collapsars
  Siegel et al. 2018
- Common-envelope jets supernovae
  Grichener & Soker 2018
- Dark matter-induced implosions
  Bramante & Linden 2016
- And probably many others…

It is very hard to tell the difference with stellar archaeology

All three peaks are made in one r-process event





Shibagaki et al. 2016

The solution is NOT adding up ejecta from multiple sites! But, all three processes can occur in the same site

22h with Magellan/MIKE

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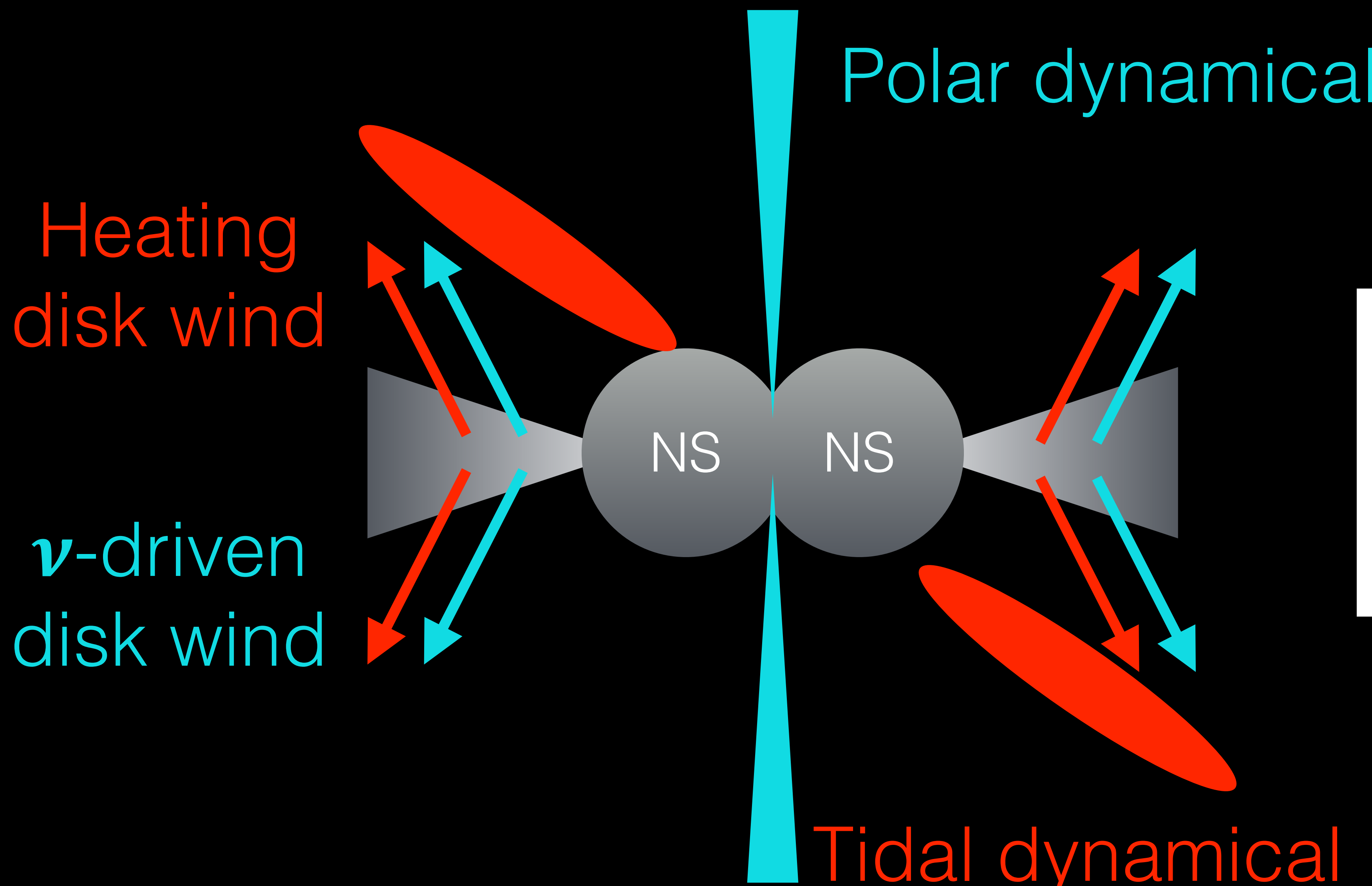
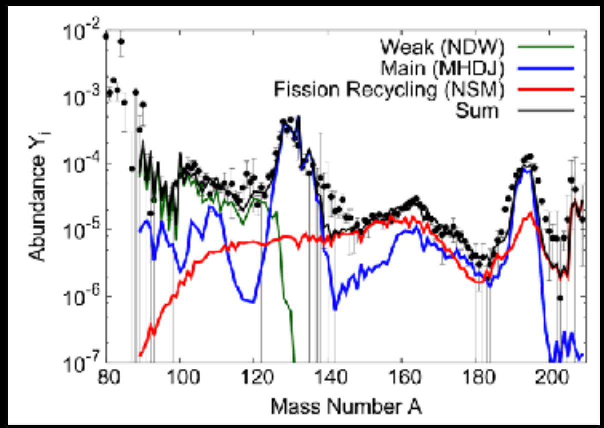
Models: Eichler et al. 2015, Wu et al. 2016, Nishimura et al. 2015/2017; Ji + Frebel 2018

Neutron star merger components





Shibagaki et al. 2016

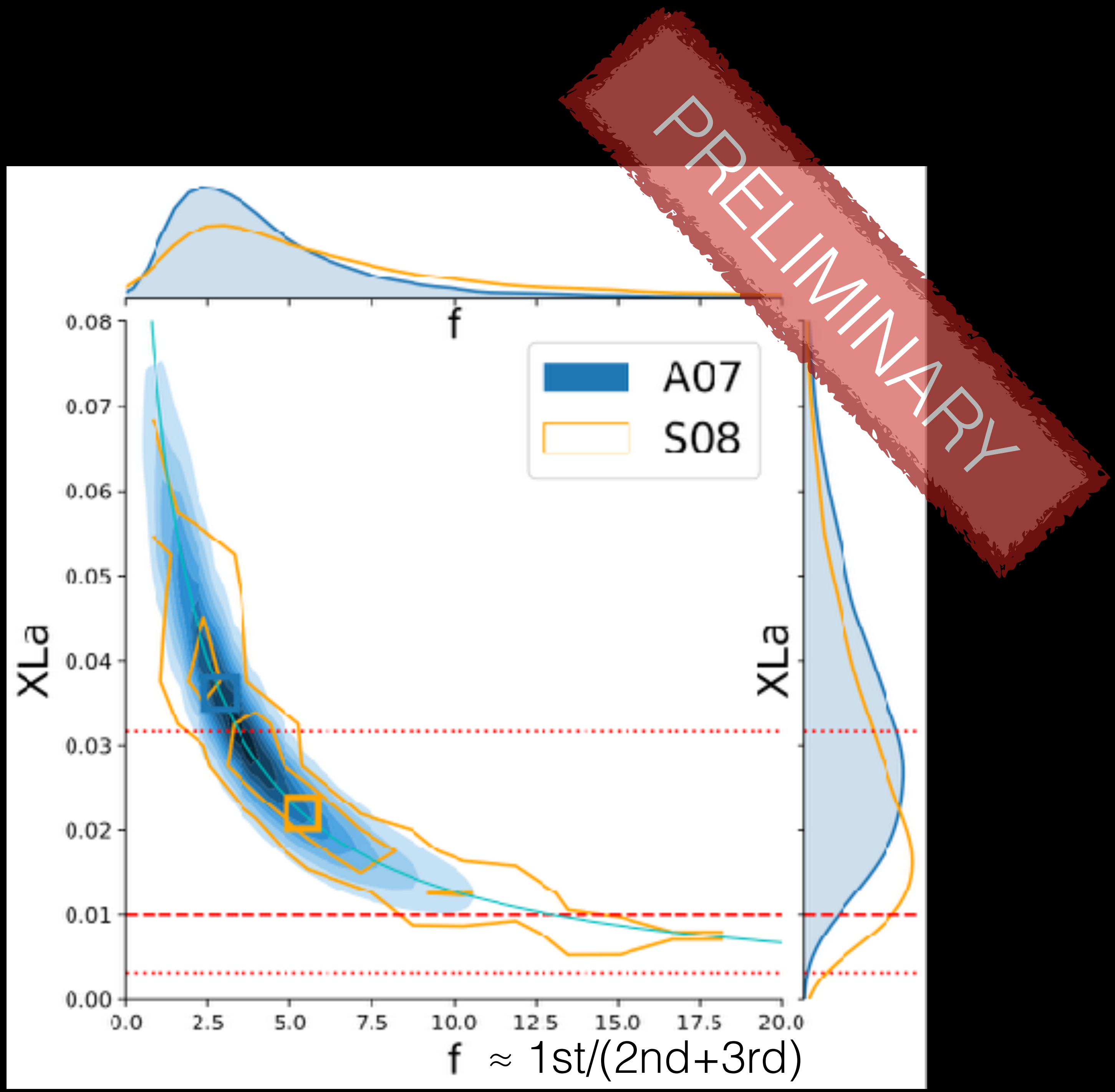
Blue: high Y_e, n-poor, 1st peak elements

Red: low Y_e, n-rich, 2nd-3rd peak elements

Also see e.g. Metzger 2017

A kilonova-based solution?

- If NSMs enrich metal-poor stars: r-process halo stars and kilonovae have same composition
- Gravitational waves guarantee a NS-NS
- Future KNe X_{La} distribution should match halo star composition



X_{La} from GW170817 ~ $10^{-2\pm0.5}$ (Kilpatrick et al. 2017)

Ji, Drout, & Hansen in prep

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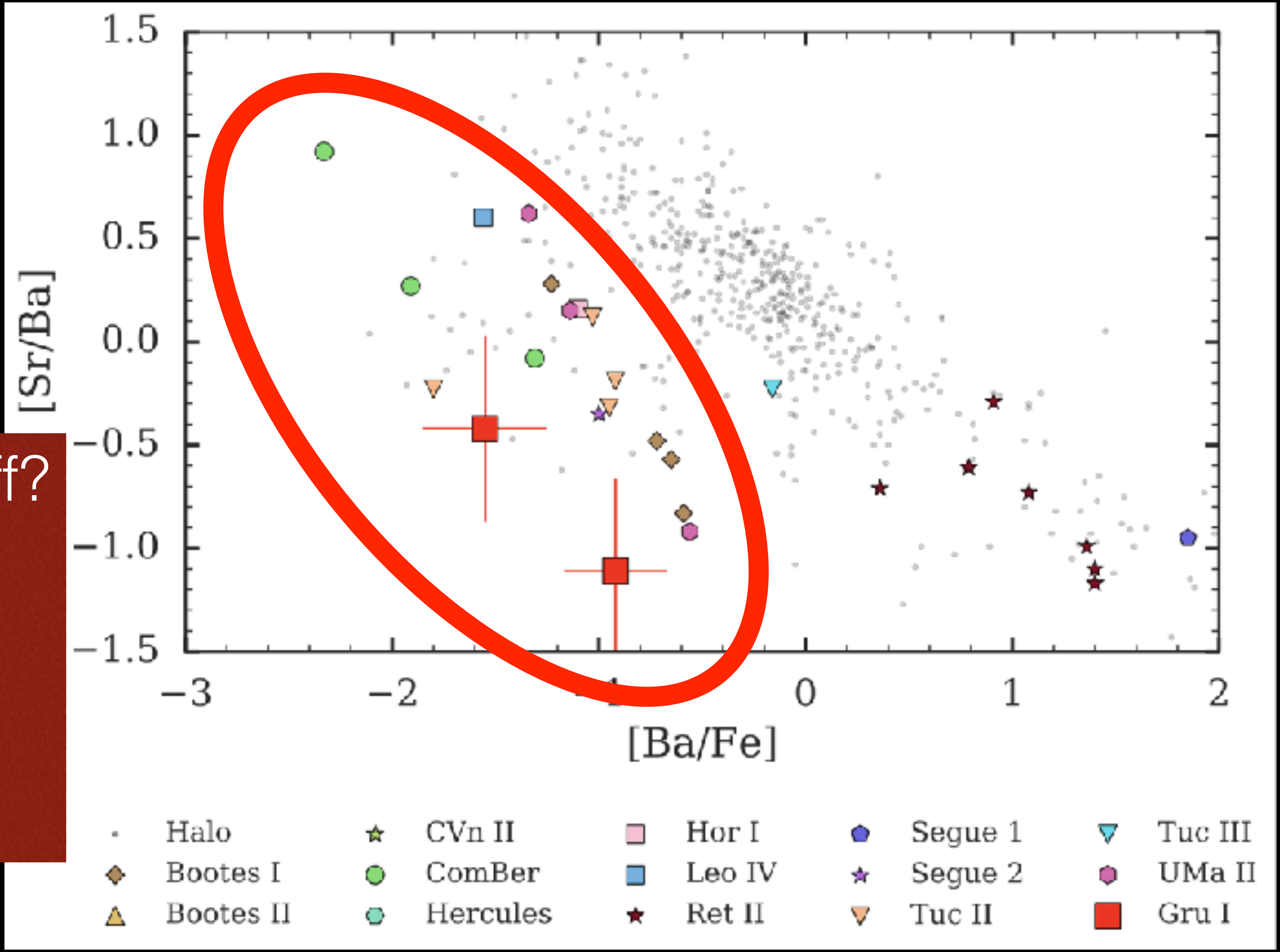
Neutron-capture elements in most UFDs



What makes this stuff?

* Low but nonzero yield
* [Sr/Ba] varies ~2 dex
* Source of Sr and Ba can be different
* Does NOT dominate n-cap production

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Ji et al. 2018

Possible origins of neutron-capture elements in most UFDs

- Neutrino-driven wind in CCSNe

  e.g., Wanajo 2013

- “Failed” MRD jets

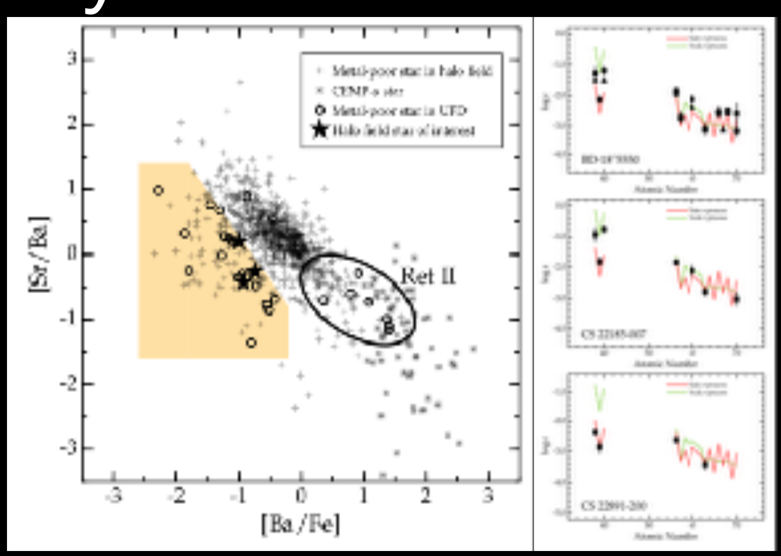
  e.g., Nishimura et al. 2015, Moesta et al. 2018

- Spinstars or proton ingestion in Pop III stars

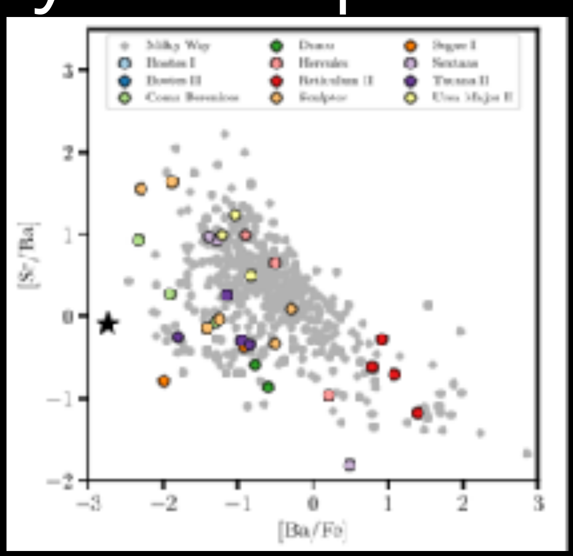
  e.g., Cescutti et al. 2013, Clark et al. 2018, Banerjee et al. 2018

- A yet-unknown low-yield r-process source

* Low but nonzero yield
* [Sr/Ba] varies ~2 dex
* Source of Sr and Ba can be different
* Does NOT dominate n-cap production



Roederer 2017



Casey & Schlaufman 2017

Halo stars with low n-cap prefer r-process

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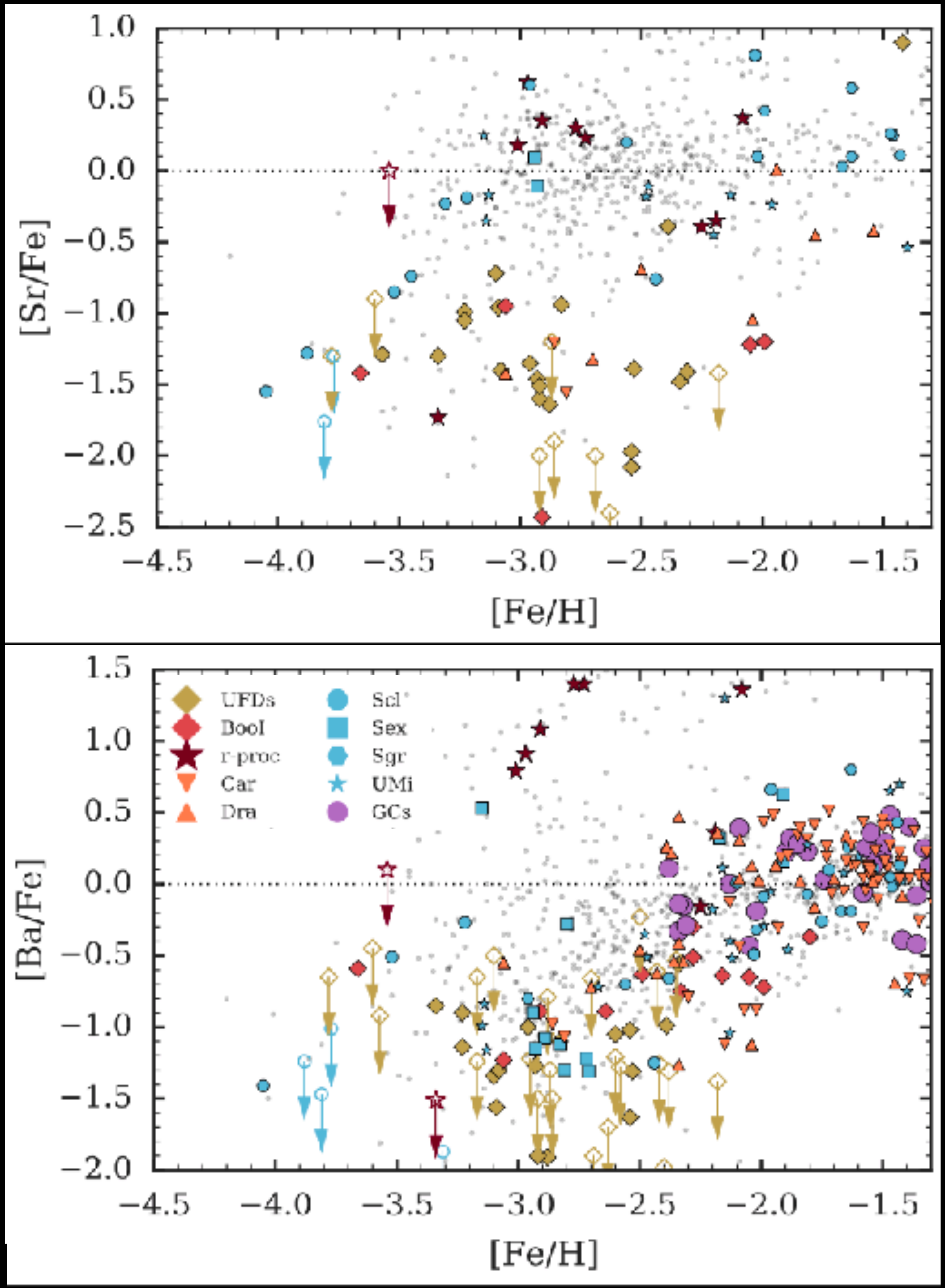
Ji et al. 2018



What about larger dSphs?

Categorize dwarf galaxies by neutron-capture behavior

Blue: high Sr, high Ba
Orange: low Sr, high Ba
Yellow: low Sr, low Ba

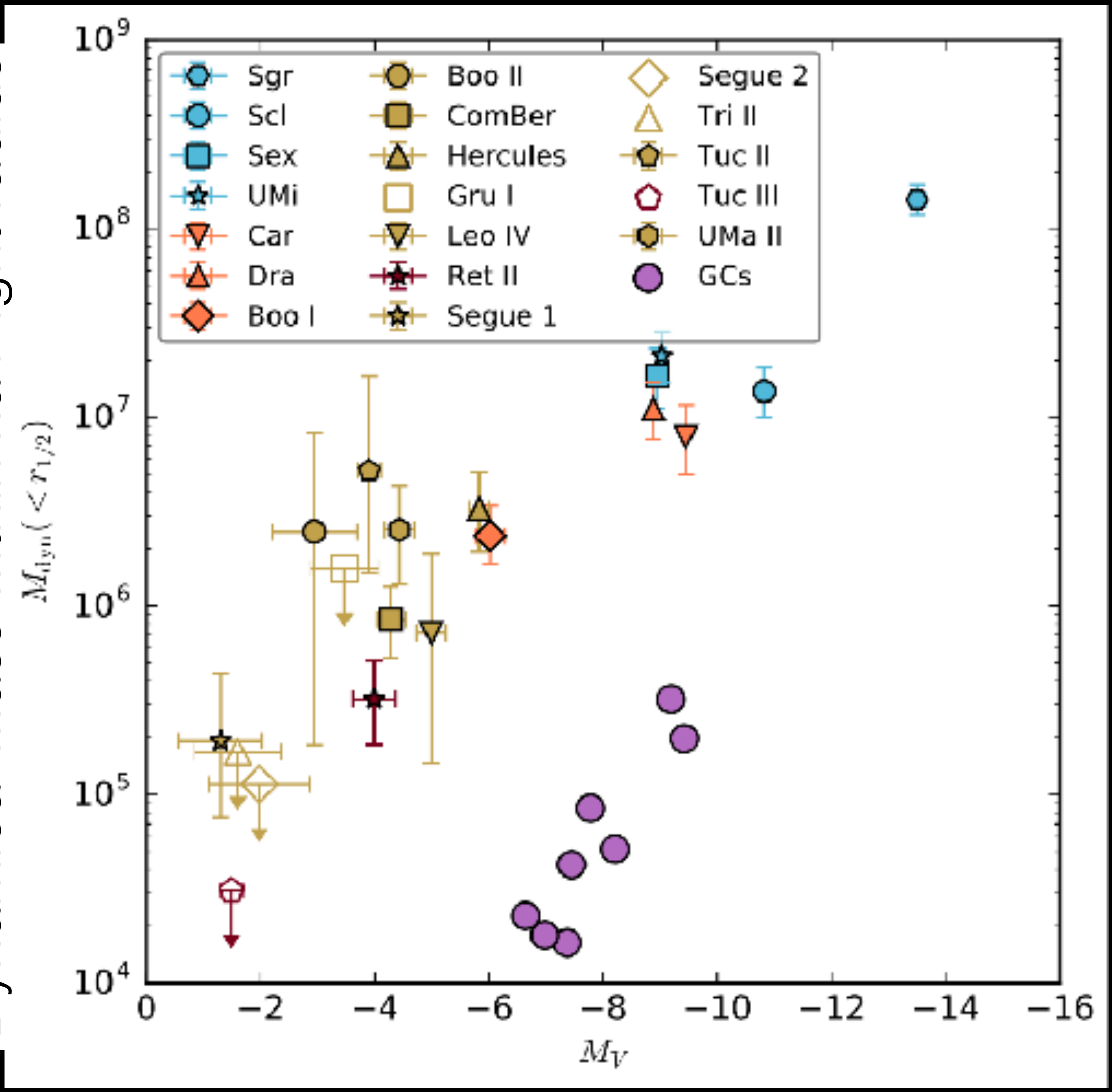
(Dark red: r-process)

Classical dSph references:
Aoki+09, Cohen+Huang 09/10, Frebel+10, Fulbright+04, Geisler+05, Hansen+18, Jablonka+15, Kirby+Cohen 12, Norris+17, Shetrone+01/03, Simon+15, Skuladottir+15, Tafelmeyer+10, Tsujimoto+15/17, Ural+15, Venn+12

Ji et al. 2018

Neutron-capture element evolution correlates with galaxy stellar and dynamical mass

Dynamical Mass within half light radius



Luminosity

Categorize dwarf galaxies by neutron-capture behavior

Blue: high Sr, high Ba
Orange: low Sr, high Ba
Yellow: low Sr, low Ba

(Dark red: r-process)

Stochastic sampling of rare sources?
Preferential n-cap loss from small DM halo?
Time delayed sources?

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Ji et al. 2018

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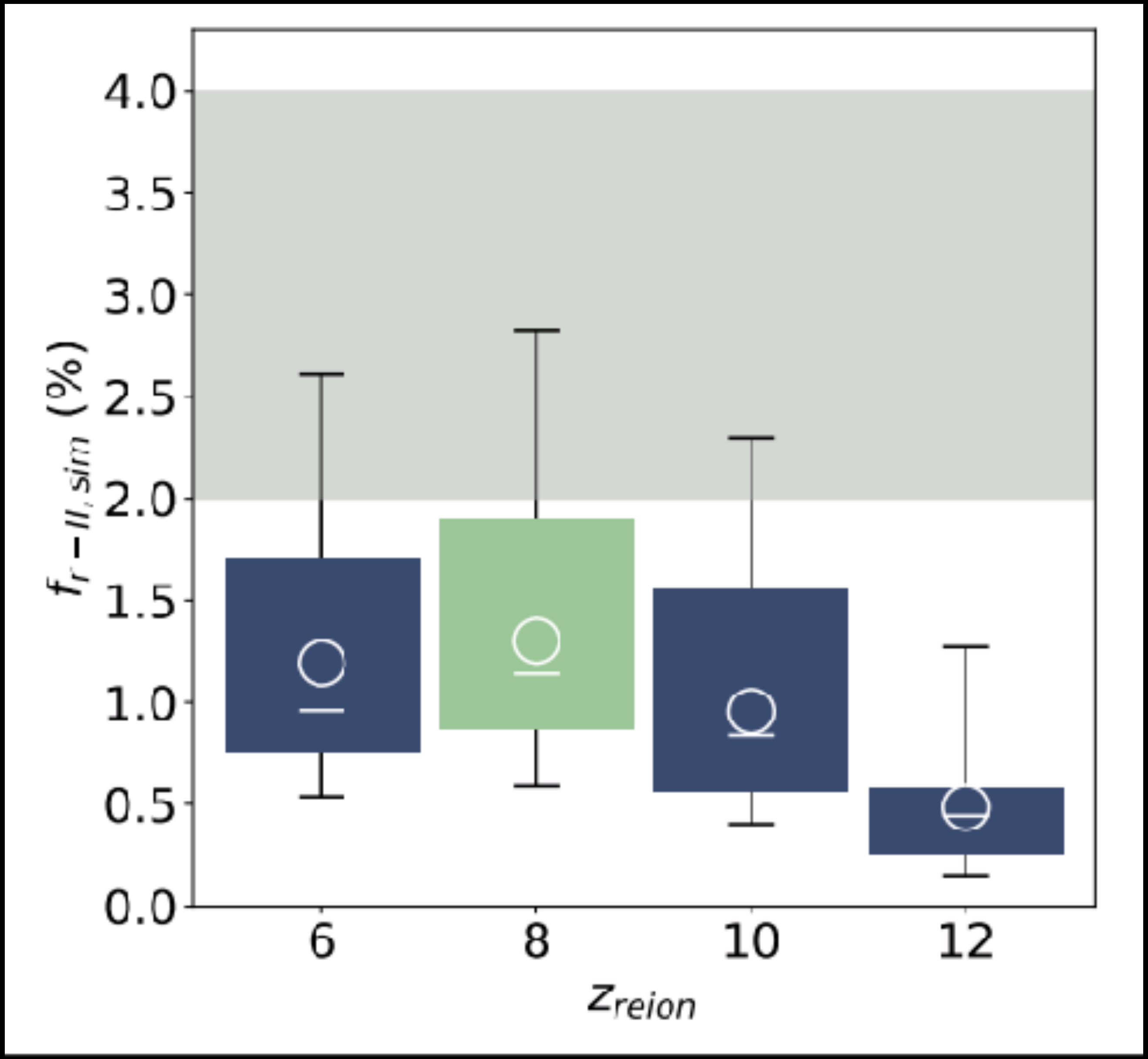
~Half of r-process enhanced halo stars come from destroyed UFDs

Kaley Brauer
MIT



Observed fraction

Modeled fraction

Assuming 10% of UFDs are r-process enhanced
Looking at accreted halo with [Fe/H] < -2.5

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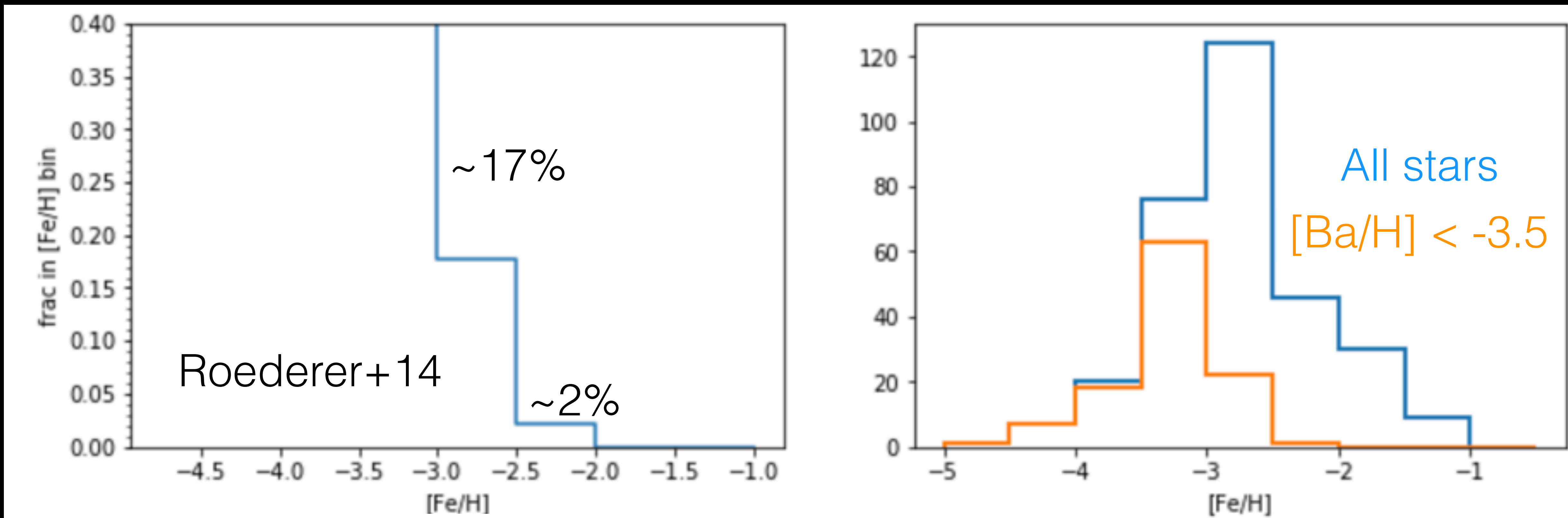
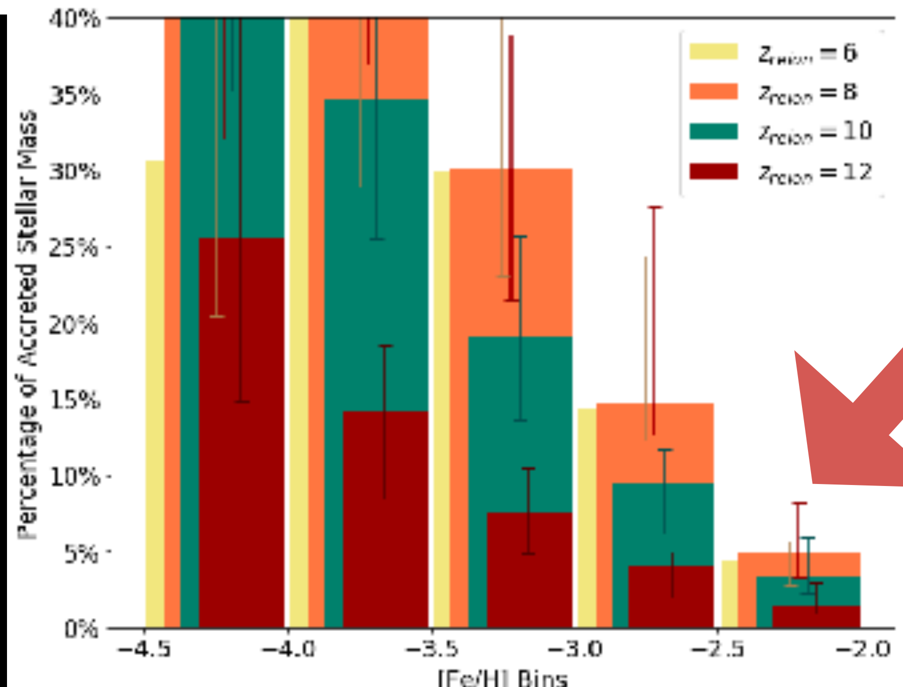
“High”-Fe, low-n-cap: the best UFD chemical tag
And they exist!





Expect ~2-5% from our model

At this [Fe/H], low-n-capture stars are as rare as r-process enhanced stars

Large (high-res?) spectroscopic surveys needed to look for this!

Brauer et al. 2018
Ji et al. 2018

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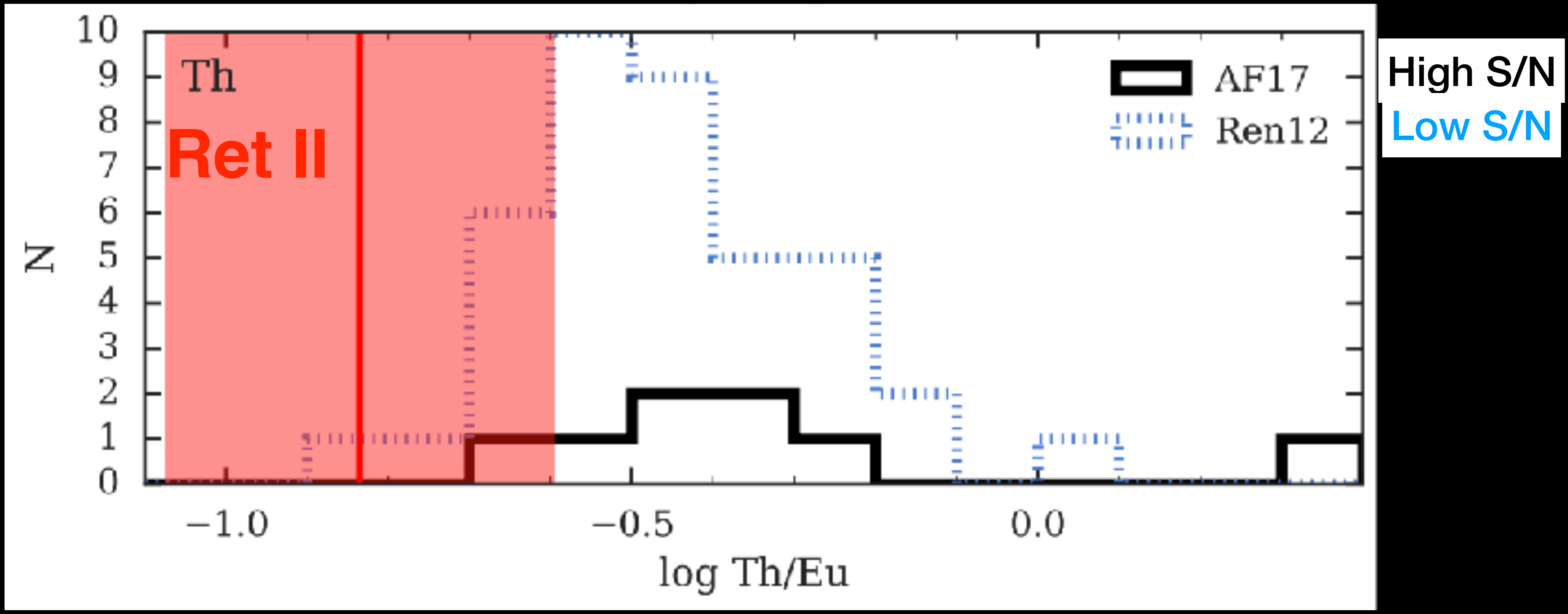
Summary

- Neutron-capture elements are the defining abundance feature of the faintest dwarf galaxies
- The r-process is dominated by a rare, prolific source: neutron star mergers most plausible
- The origin of neutron-capture elements in most UFDs remains unknown
- Neutron-capture elements encode something about galaxy mass
- Halo stars with extreme neutron-capture elements can be chemically tagged to the faintest building blocks of our MW halo

Extra Slides

Ret II has unusually low Th



Naive application of literature production ratios:

Age = 24.9 ± 2.8 ± 10.3 ± 3.2 Gyr

(stat) (sys, obs) (sys, PR)

More likely explanation: variable initial production ratios

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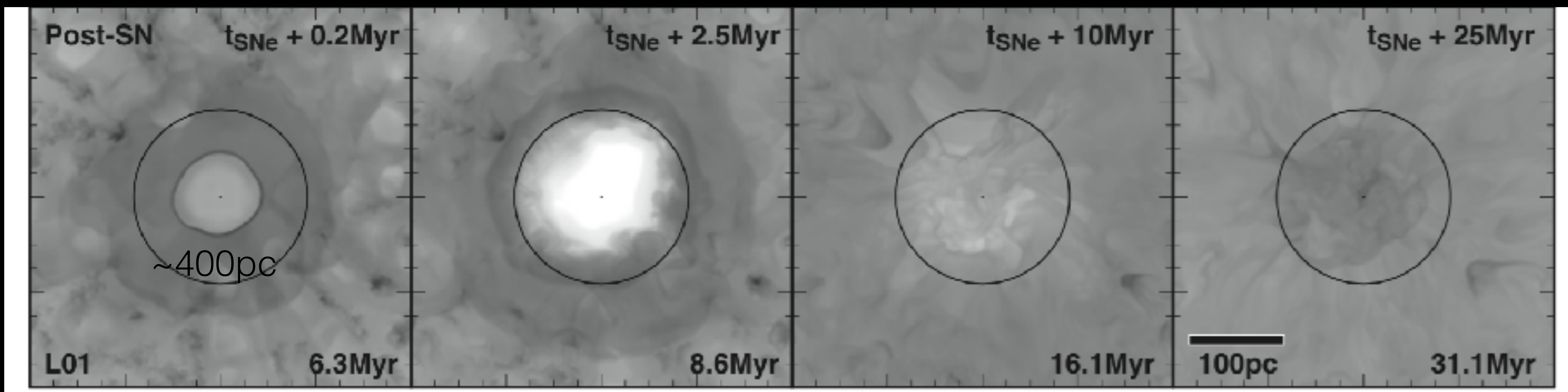
Ji + Frebel 2018

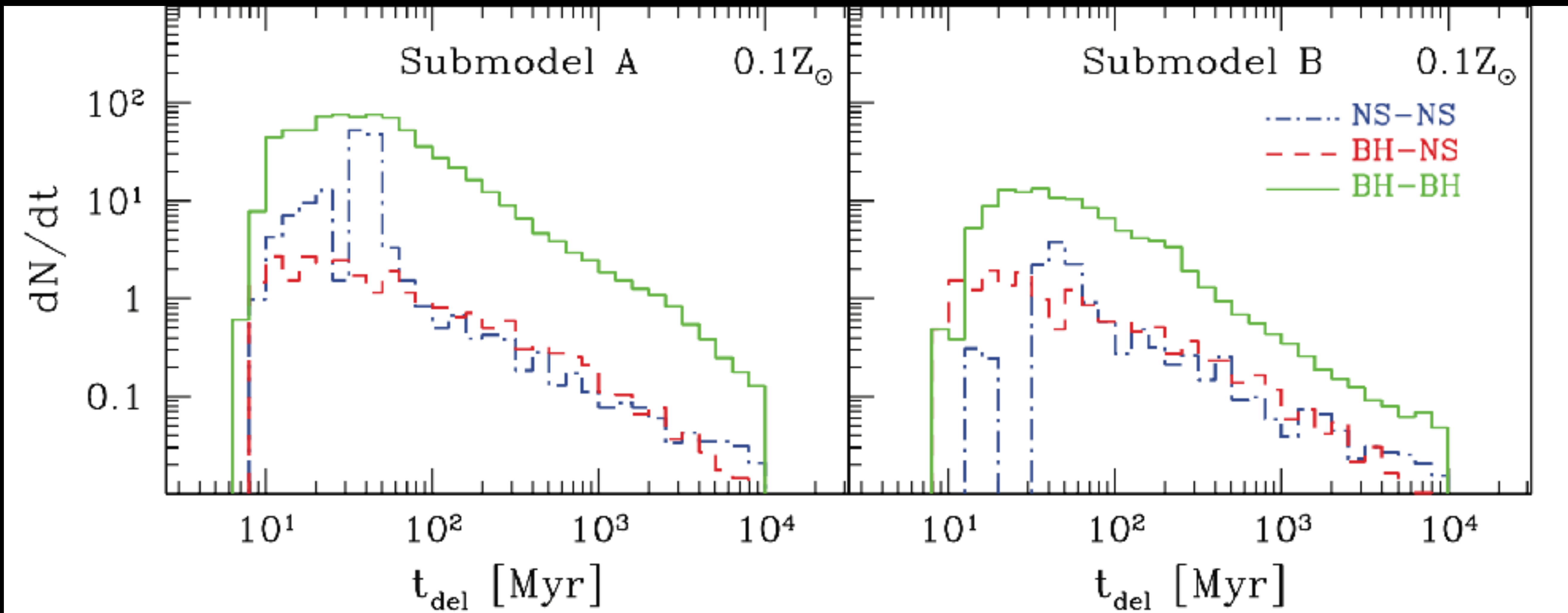
UFD Environment Mitigates Delay Time Problem for NSMs



Single supernova can delay star formation for 25 Myr
Very inefficient star formation

Figure: Bland-Hawthorn et al. 2015
Also see Jeon et al. 2015, Ishimaru et al. 2015, Chiaki et al. 2017, …

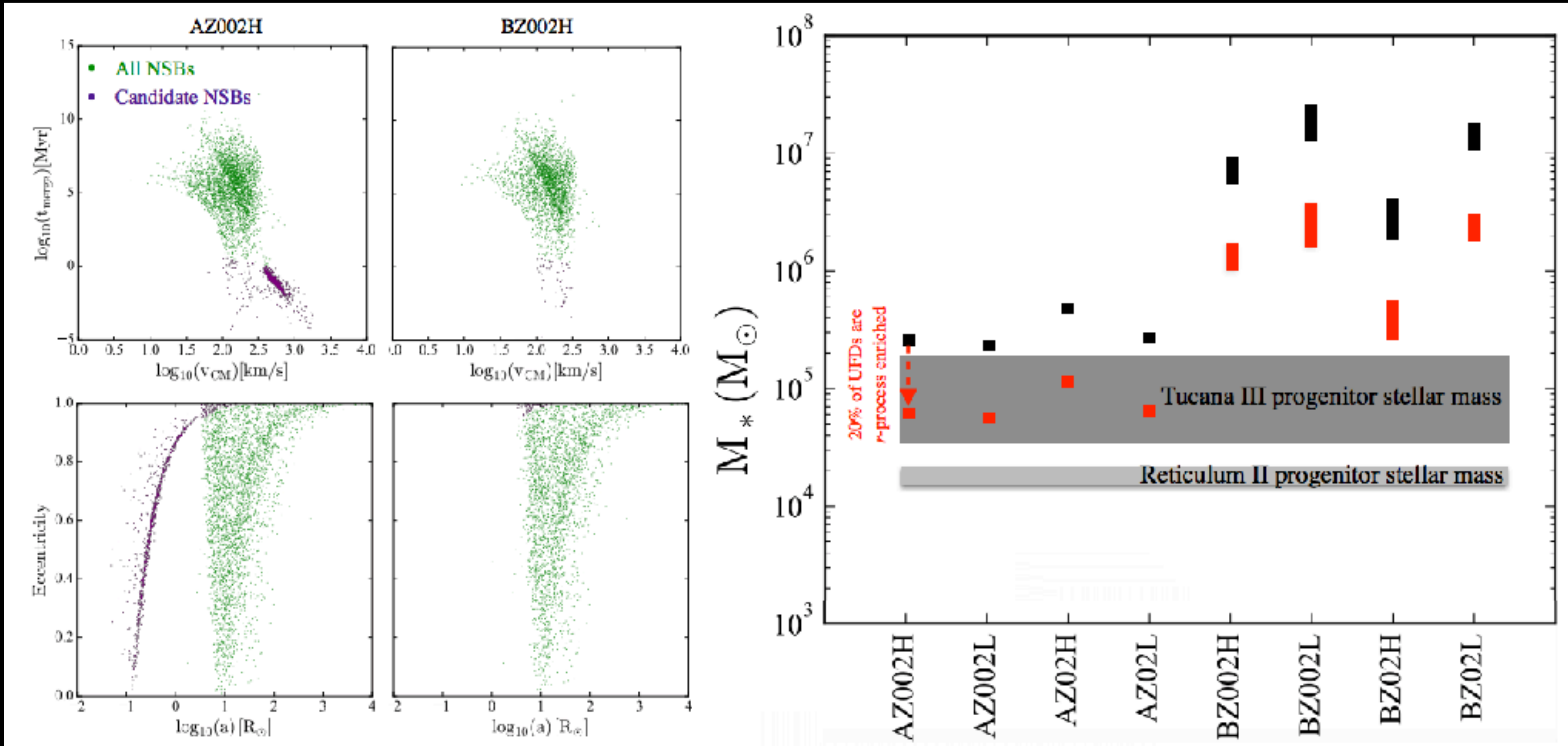
Neutron star merger delay time



20% from 10-100Myr

Dominik et al. 2012

Fast-merging neutron stars



Submodel A:
requires binaries to survive
"unstable BB" mass transfer

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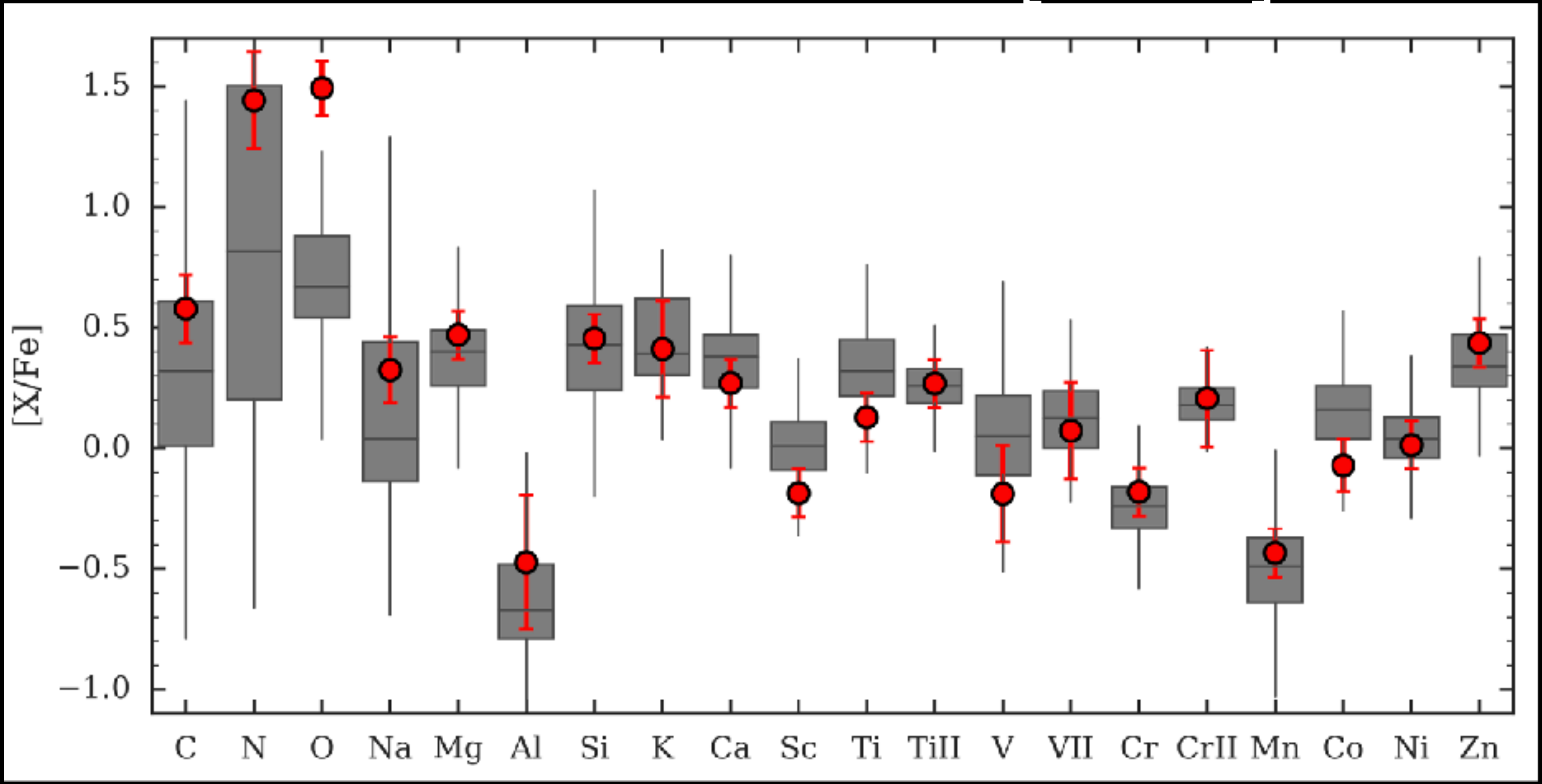
Safarzadeh et al. 2018

Carbon through Zinc similar to halo stars at [Fe/H] ~ -3

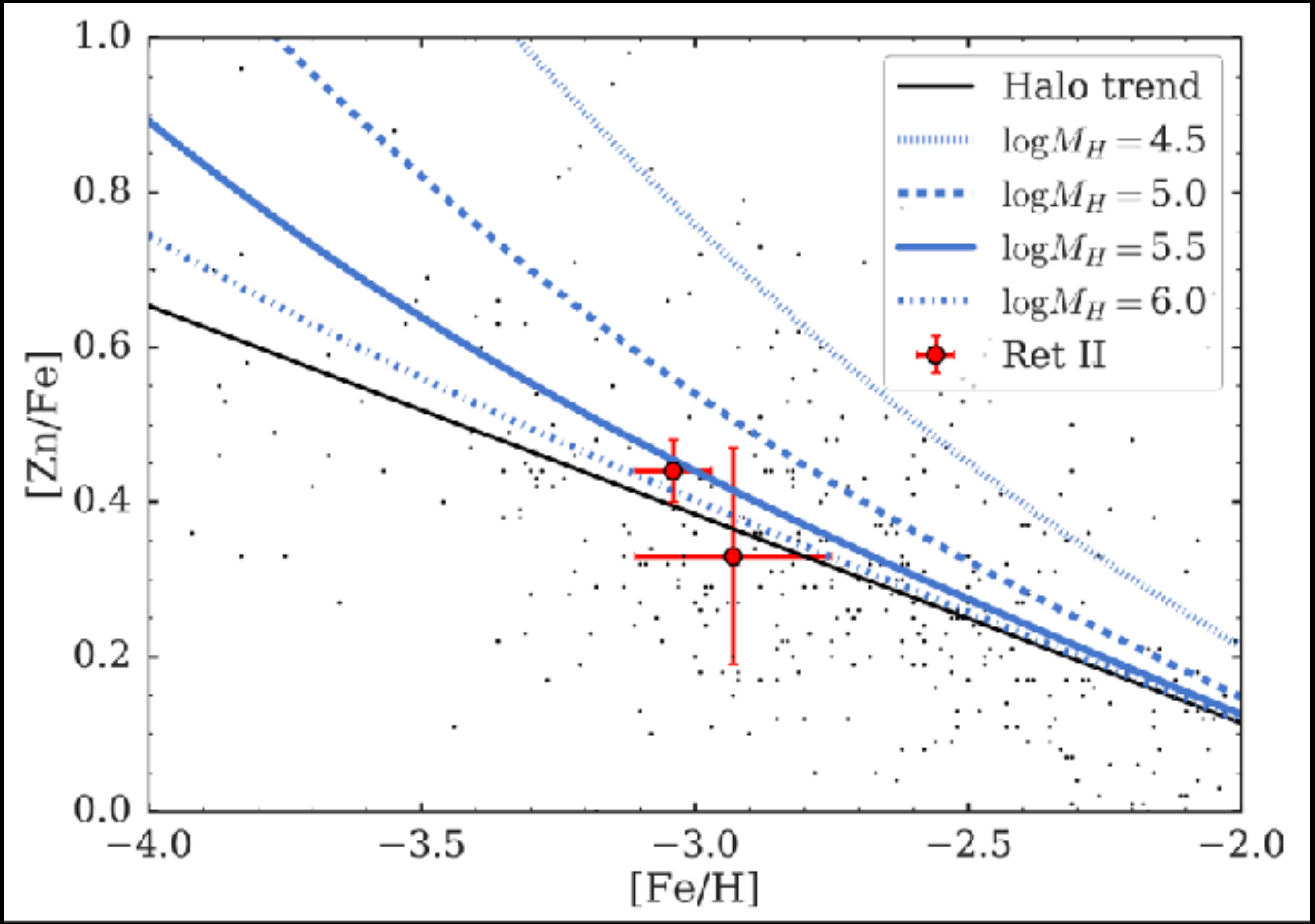


r-process not correlated with light elements

see Roederer et al. 2014, MNRAS, 445, 2970

Ji + Frebel 2018

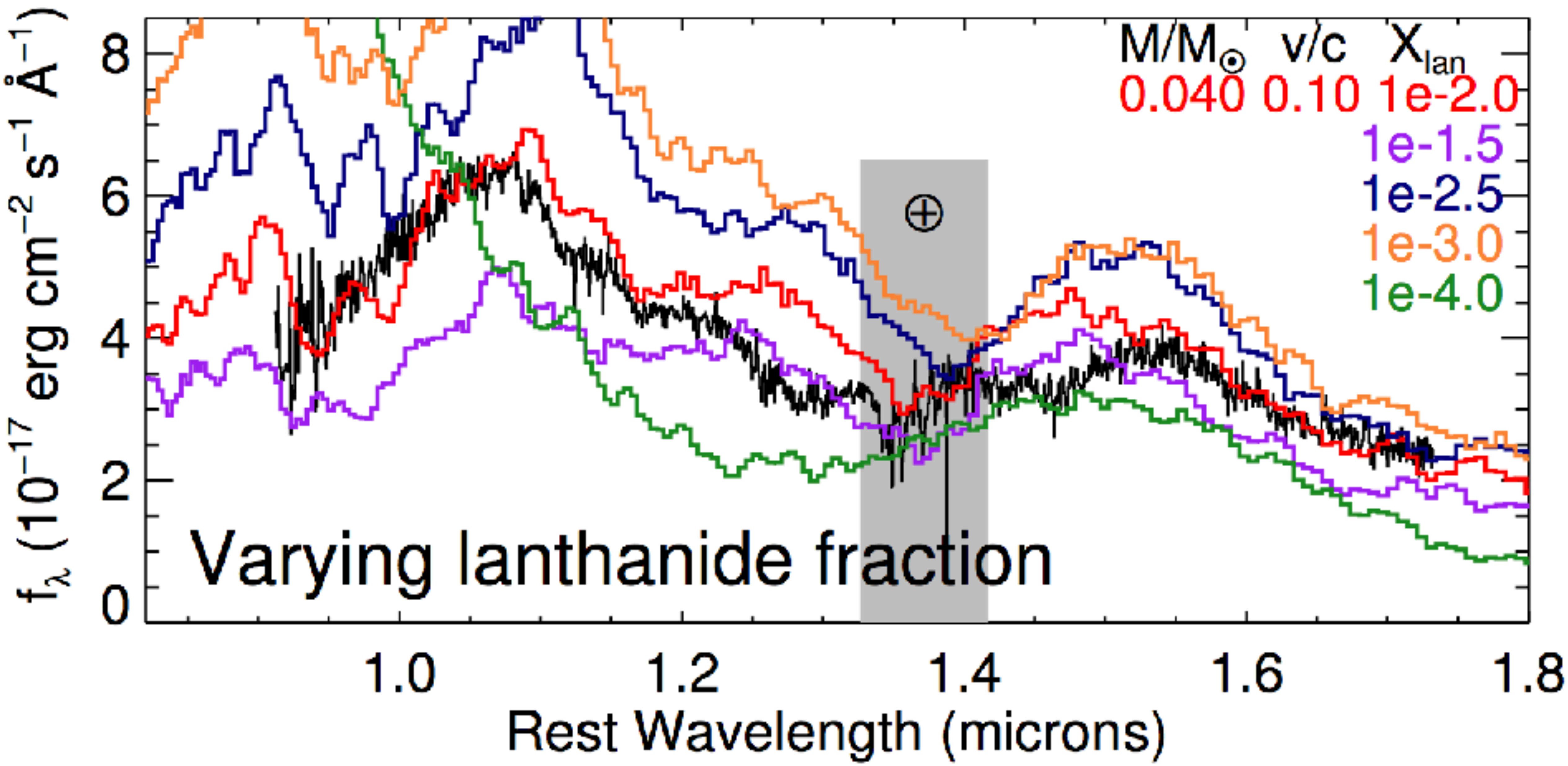
Zinc and MRD Jet SNe



Nishimura et al. 2017 predicts [Zn/Fe] > +1.5 for MRD Jet SN

Zn chemical evolution in Ret II could constrain the r-process site if we know the dilution mass

Ji + Frebel 2018



Chornock et al. 2017

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