BINARY STARS AS FOSSILS OF PAST NUCLEOSYNTHESIS

Sophie Van Eck

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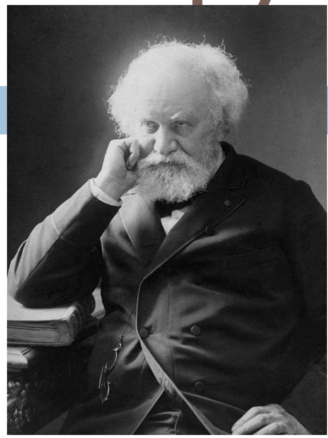
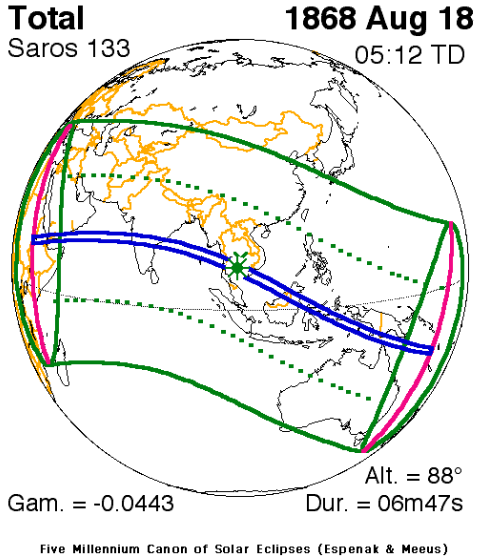
The Periodic Table Through Space and Time


ROARrr

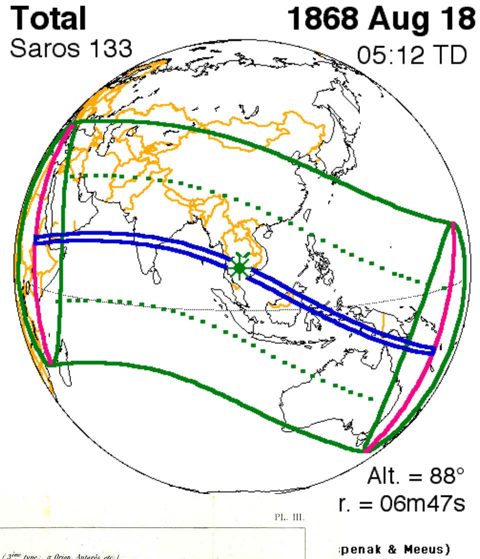
The rise of spectroscopy

- August 18, 1868: Jules Janssen, total eclipse in eclipse in Guntur (India): mesurement of He lines (587.49 nm)





The rise of spectroscopy



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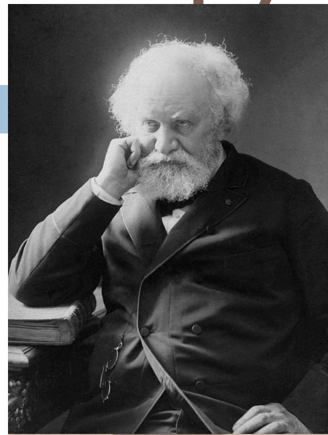
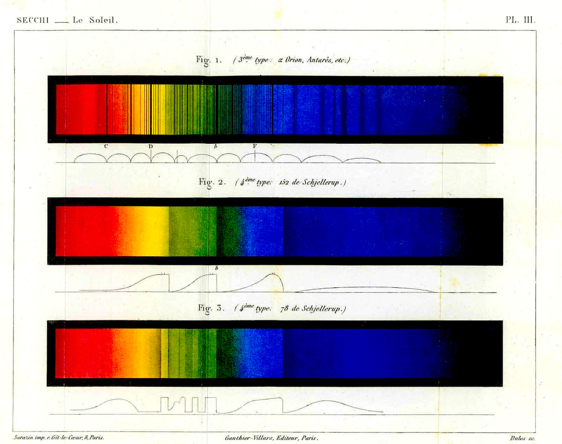
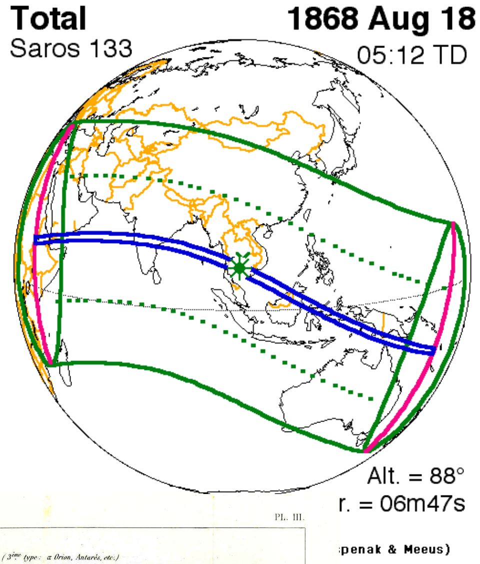
- 1868: Father Angelo Secchi: discovery of carbon stars





"Marked analogy with the reversed spectrum of C"

The rise of spectroscopy



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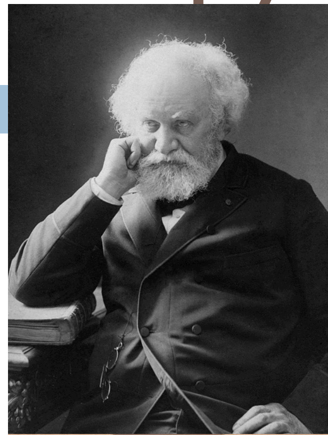

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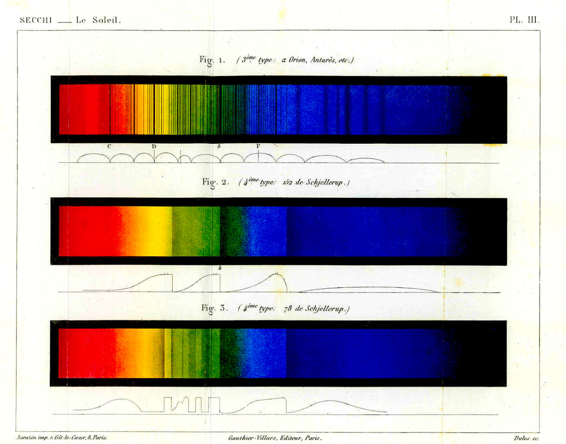
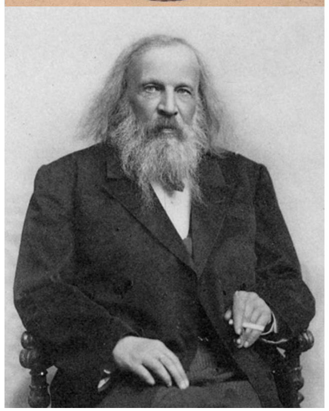


"Marked analogy with the reversed spectrum of C"

- 1869: Mendeleev formal presentation to the Russian Chemical Society, titled "*The Dependence between the Properties of the Atomic Weights of the Elements*"



Including Carbon, but without Helium till 1902

Carbon enrichment is ubiquitous

(especially at low-Z)

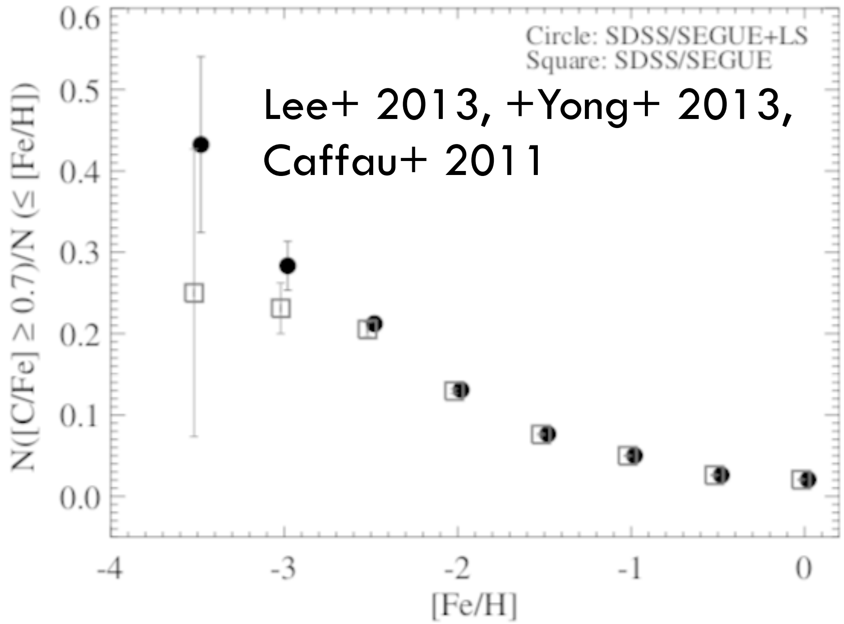
- CEMP (Carbon-enriched metal-poor)

Different definitions:

- [C/Fe]>1 (Beers & Christlieb 2005)
- [C/Fe]>0.7 if log L/Lsun<2.3

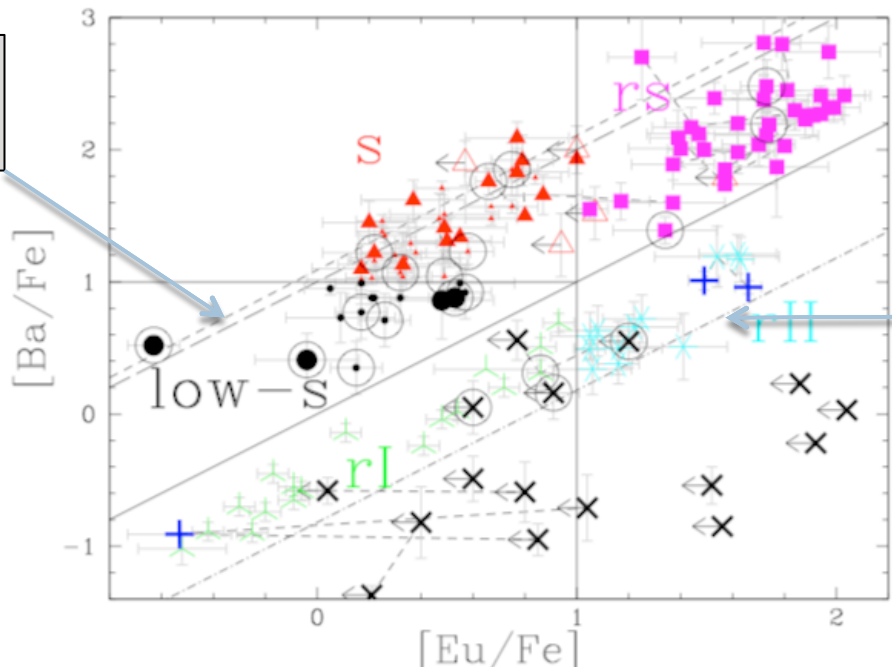
  [C/Fe]=3-log(L/Lsun) if log L>2.3 (Aoki+2007)

Fraction of C-enriched objects:



See also Placco+ 2014

Carbon enrichment at low-Z



Pure s-process 3M$_\odot$

Masseron+ 2010

Pure r-process

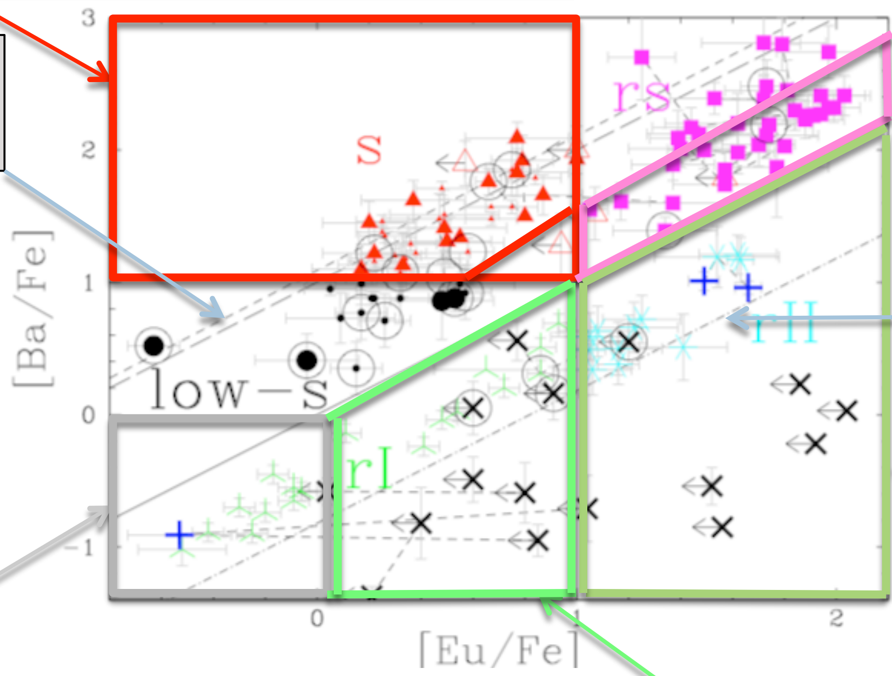
Carbon enrichment at low-Z

CEMP-s:
- [Ba/Fe]>1; [Ba/Eu]>0.5 or 0; [Eu/Fe<1] (Beers & Christlieb 2005, Aoki 2010, Lugaro 2012)
- 80% of all CEMP

CEMP-rs:
[Ba/Fe]>1; [Eu/Fe]>1
0 < [Ba/Eu] < 0.5

Pure s-process
3M$_\odot$

Masseron+ 2010



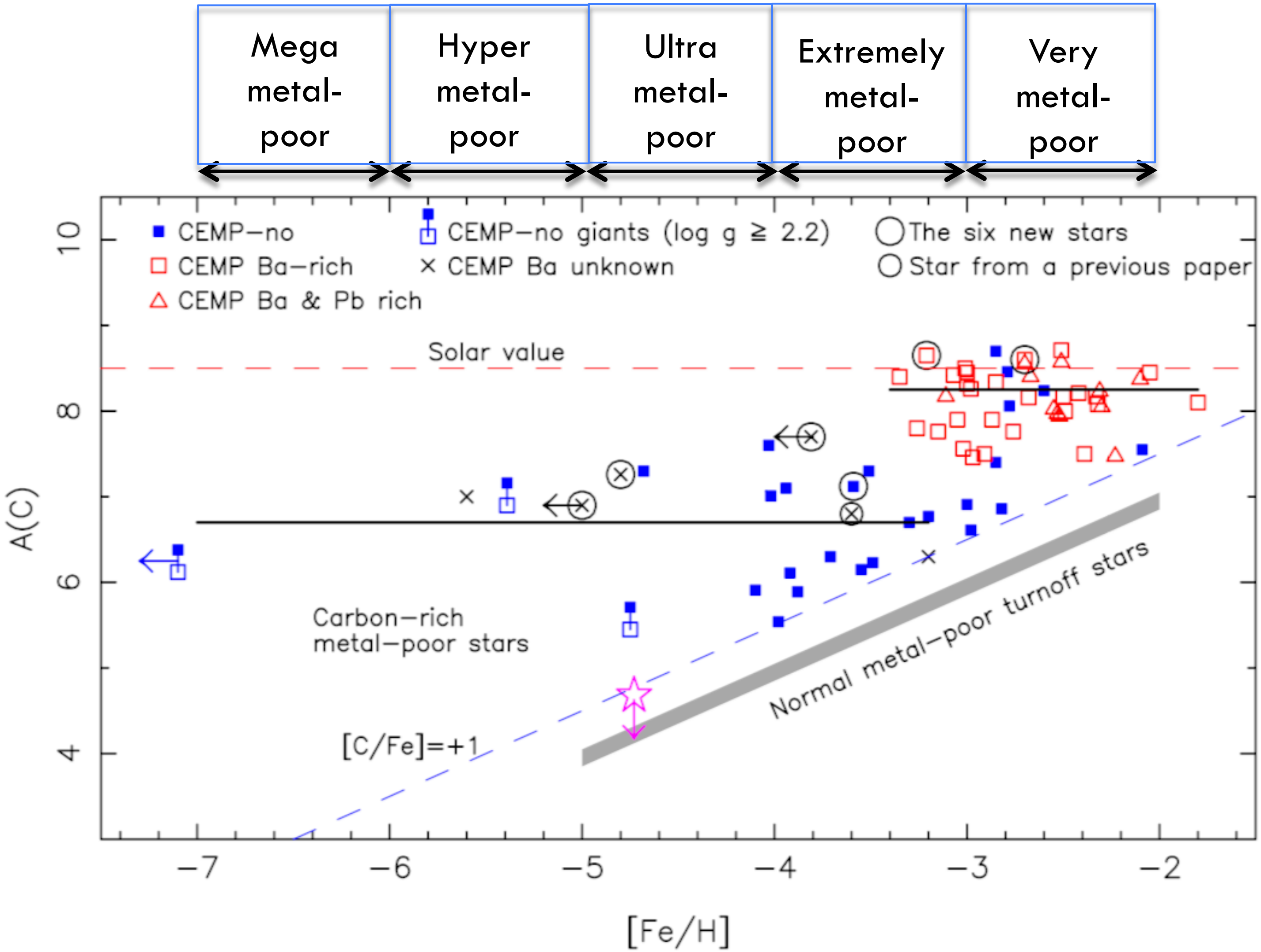
Pure r-process

CEMP-rII:
[Ba/Eu]<0
[Eu/Fe] > 1
(Beers & Christlieb 2005

CEMP-no:
[Ba/Fe]<0; [Eu/Fe]<0

CEMP-rI: [Ba/Eu]<0
0.3 < [Eu/Fe] < 1

Carbon enrichment at low-Z

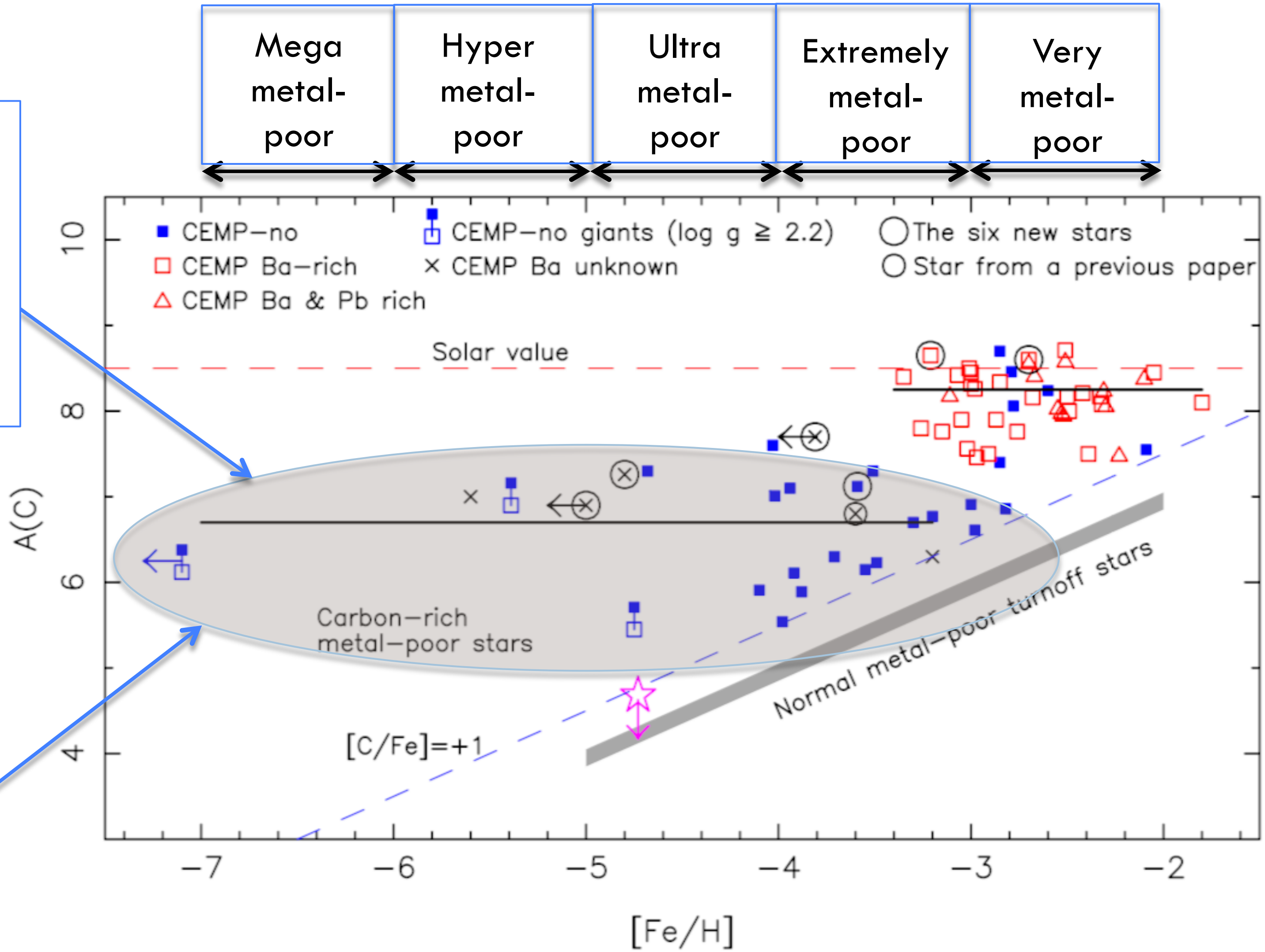


Spite+ 2013, Bonifacio+2015

Carbon enrichment at low-Z

Alternative scenario: massive, rapidly rotating, mega-metal-poor stars ([Fe/H]<-6 Meynet+ 2006, 2010; Hirschi+ 2006)

Fossile records from an ISM enriched by a few zero-metallicity faint SN (Umeda & Nomoto 2003)



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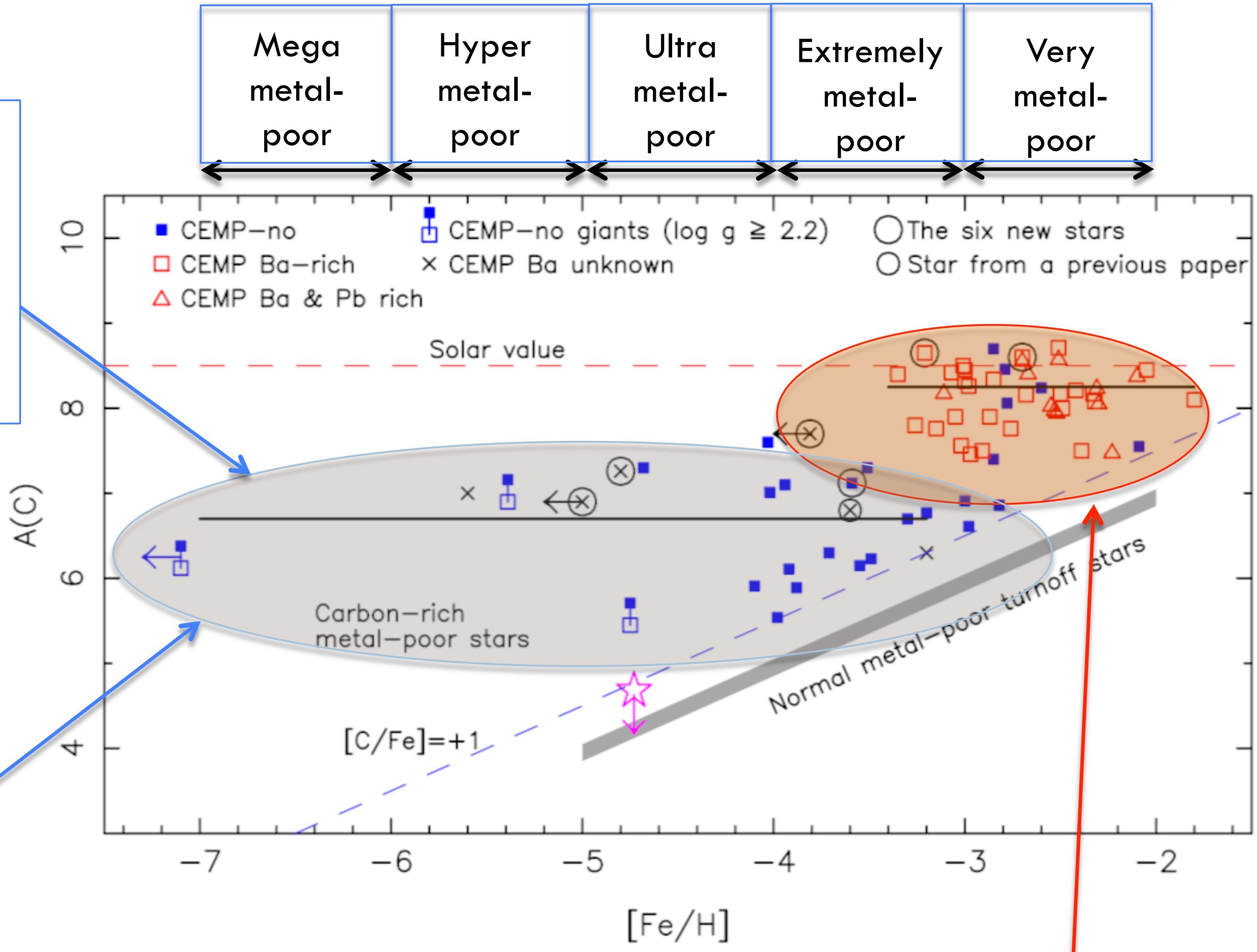
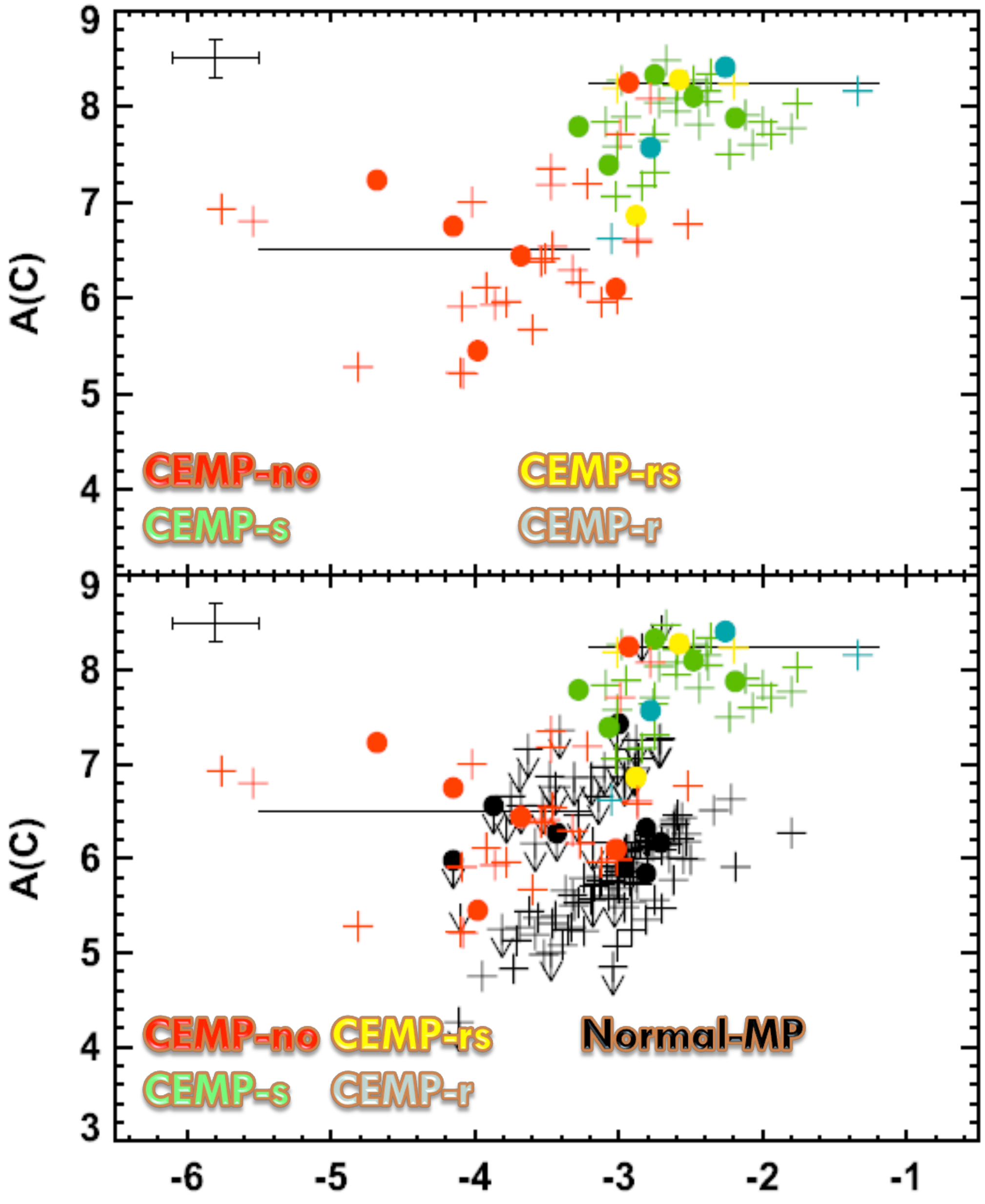


Spite+ 2013, Bonifacio+2015

Mass transfer

Carbon enrichment at low-Z

- Smoother transition between the high-C band and the low-C band
- CEMP-no in the high-C band, challenging the AGB pollution scenario



Hansen+ 2015

Binarity is ubiquitous
(especially at low-Z)

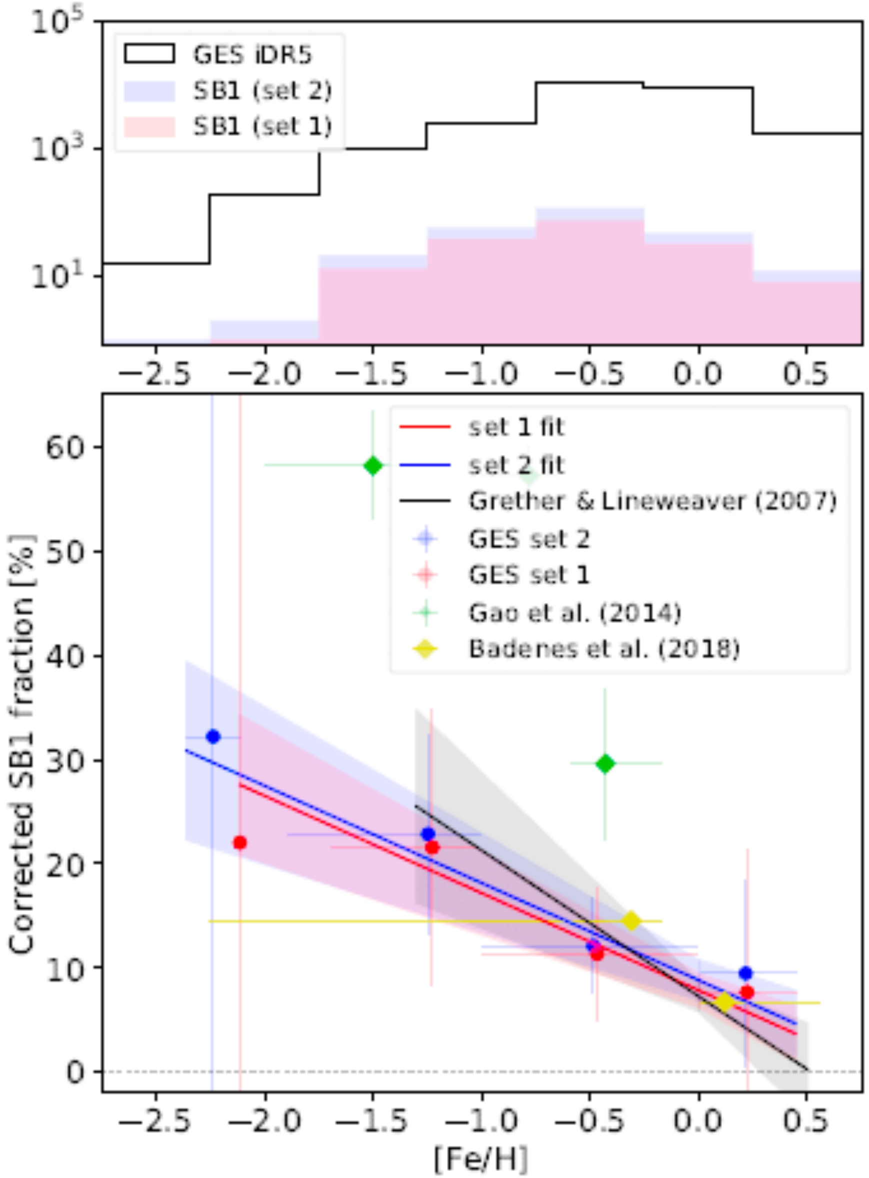
The SB1 fraction decreases with increasing metallicity

→ By **- 14% +- 6%** per metallicity dex in the range -1.2 < [Fe/H] < 0 (FGK, Grether & Lineweaver 2007)

→ By **~ - 14%** per metallicity dex (APOGEE, Badenes+ 2018)

→ by **- 9% +- 3%** per metallicity dex in the range -2.5<[Fe/H]<+0.5 (FGK, Gaia-ESO Survey, Merle, Van der Swaelmen, Van Eck+, submitted)

See also meta-analysis of Moe & Di Stefano 2017



Merle+ , submitted

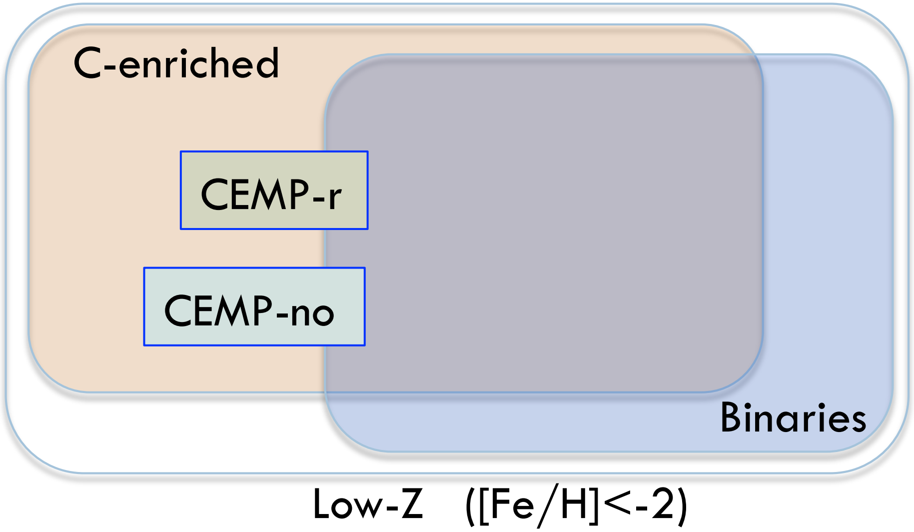
Intersection: C-enrichment and binarity

At low Z

- **CEMP-no** have normal binarity rate

→ fossile record from a C-enriched ISM

(Arentsen+ 2018, A&A 621, A108)



- **CEMP-rI and –rII** have normal binarity rate

3/17=17%

(T. T. Hansen+ 2015 A&A 583, A49, 2015)

Consistent with binary frequency of other metal-poor giants in the halo ~16% (Carney+ 2003)

Intersection: C-enrichment and binarity

At low Z

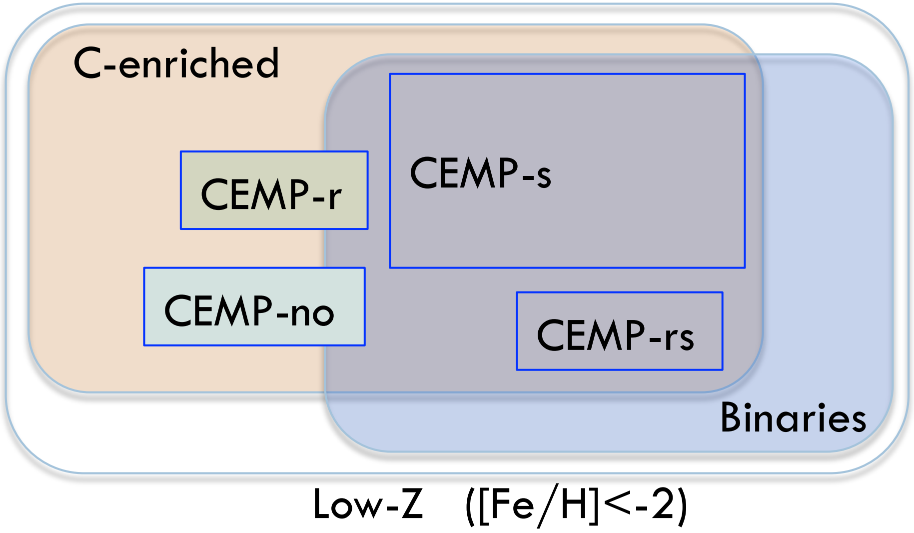
- **CEMP-s** and **CEMP-rs** are compatible with 100% binaries

(Arentsen+ 2019, Hansen+ 2016, Starkenburg+ 2014, see also Lucatello+ 2005)

→ **CEMP-s:** past pollution by companion AGB

→ **CEMP-rs:**

  - 1st scenario: r from former neutron star merger, s from pollution by AGB companion
  - 2nd scenario: i-process, producing r- and s-mixture, in AGB companion



CEMP r+s

CEMP r+s

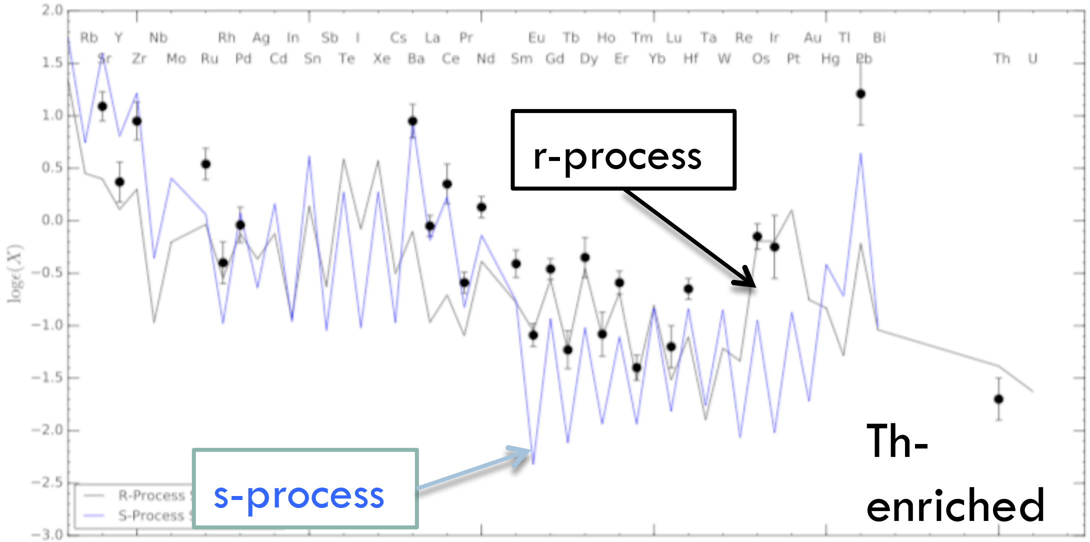
1st scenario:

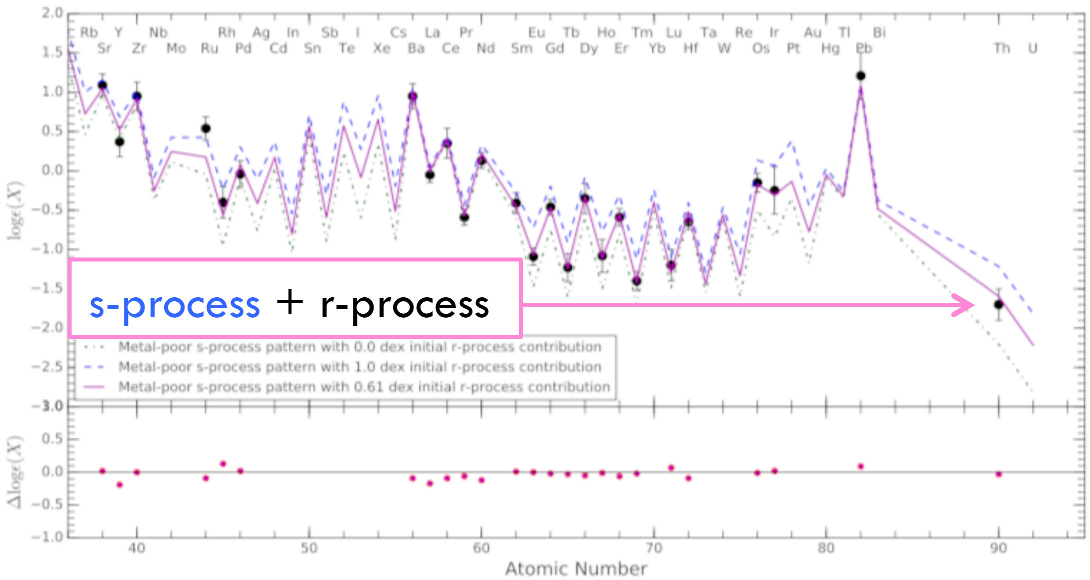
CEMP-s star (AGB pollution) initially formed from

r-process-enriched gas:

r-I profile from former neutron star merger, s from pollution by AGB companion

- RAVE J094921.8-161722
- [Fe/H]=-2.2
- Age (Th/Eu) 13.1 Gyr
- Gull+ 2018, ApJ 862, 174





CEMP r+s

CEMP r+s

Successive contribution from r- and s- processes seem to fail in several cases (Cohen+ 2003; Ivans+ 2005; Jonsell+2006; Abate+ 2016)

- **2^{nd} scenario:**

→ i-process (Cowan & Rose 1977) which also operates in AGB stars

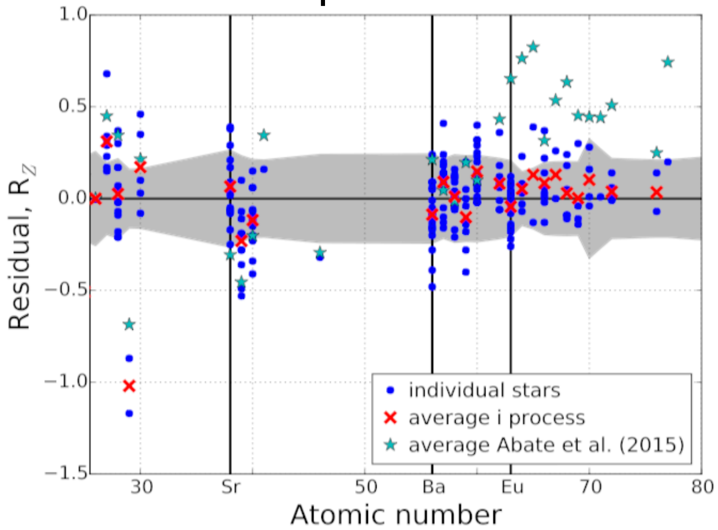
s-process: $T \sim 10^8$K, $N_n = 10^7$-10^{11} cm^{-3}

r-process: $T > 10^9$K, $N_n > 10^{20}$ cm^{-3}

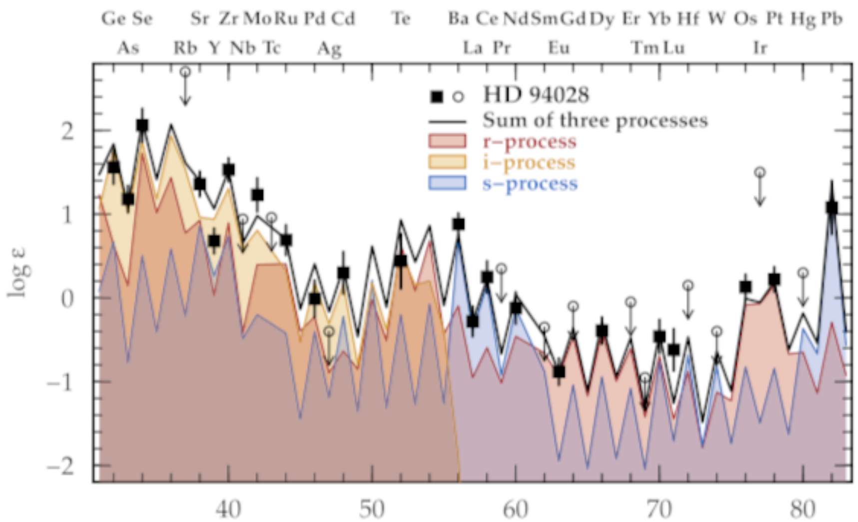
i-process: $N_n \sim 10^{15}$ cm^{-3}

→ this n burst is reachable (at least) in low-Z AGB stars

Hampel+ 2016

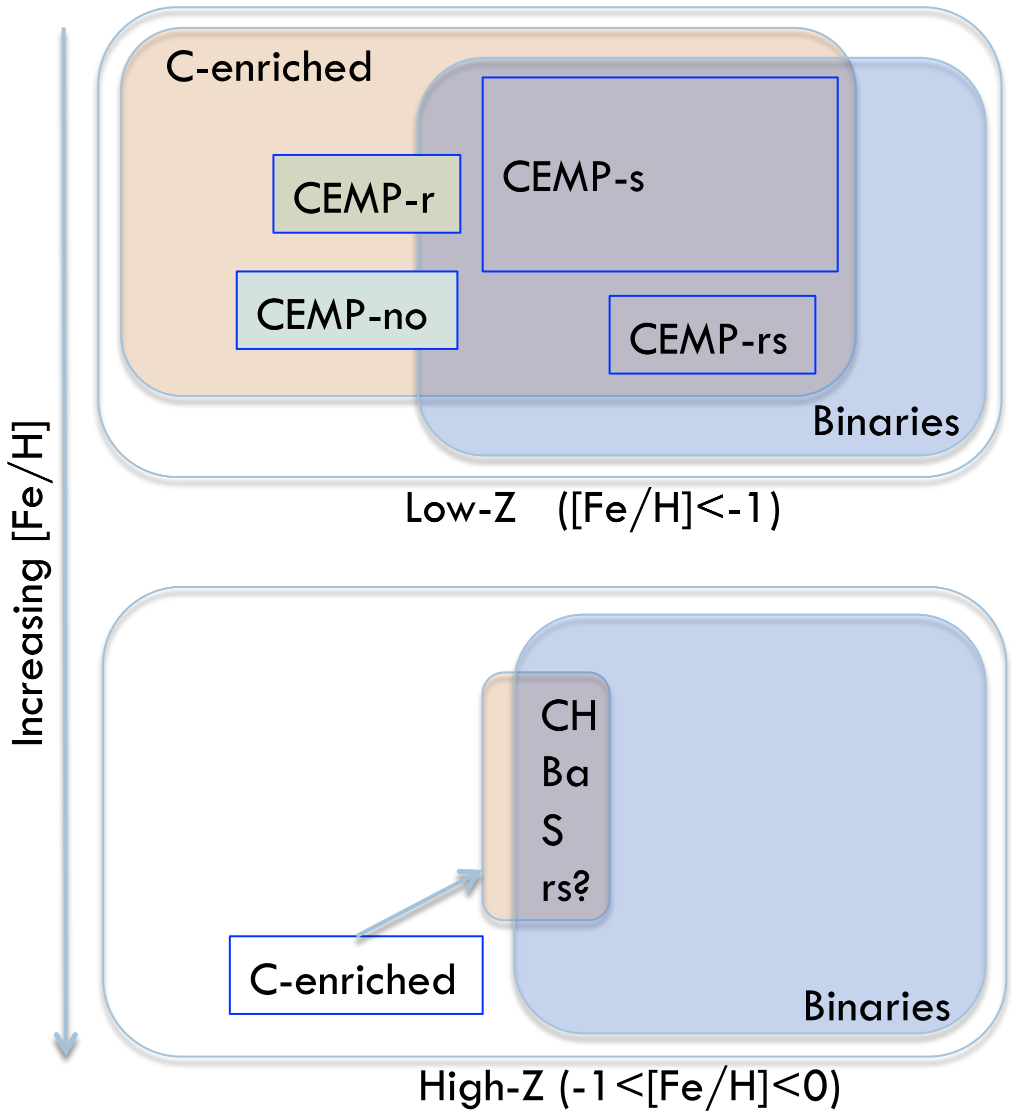


Roederer+ 2016.



Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars



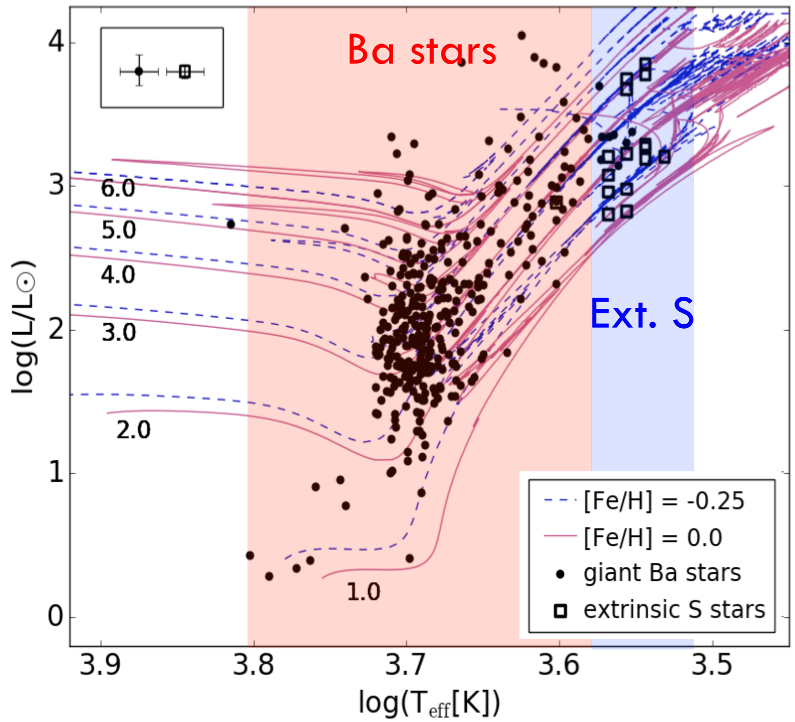
- **CH, Barium and extrinsic S** stars are all binaries, polluted by s-process from former AGB companion

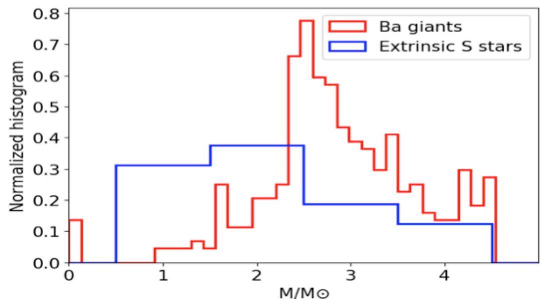
  (Mc Clure 1990, Jorissen+ 1998, Van Eck+ 1999, 2000)

Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

Gaia DR2
HR diagram
of Ba and
extrinsic S stars





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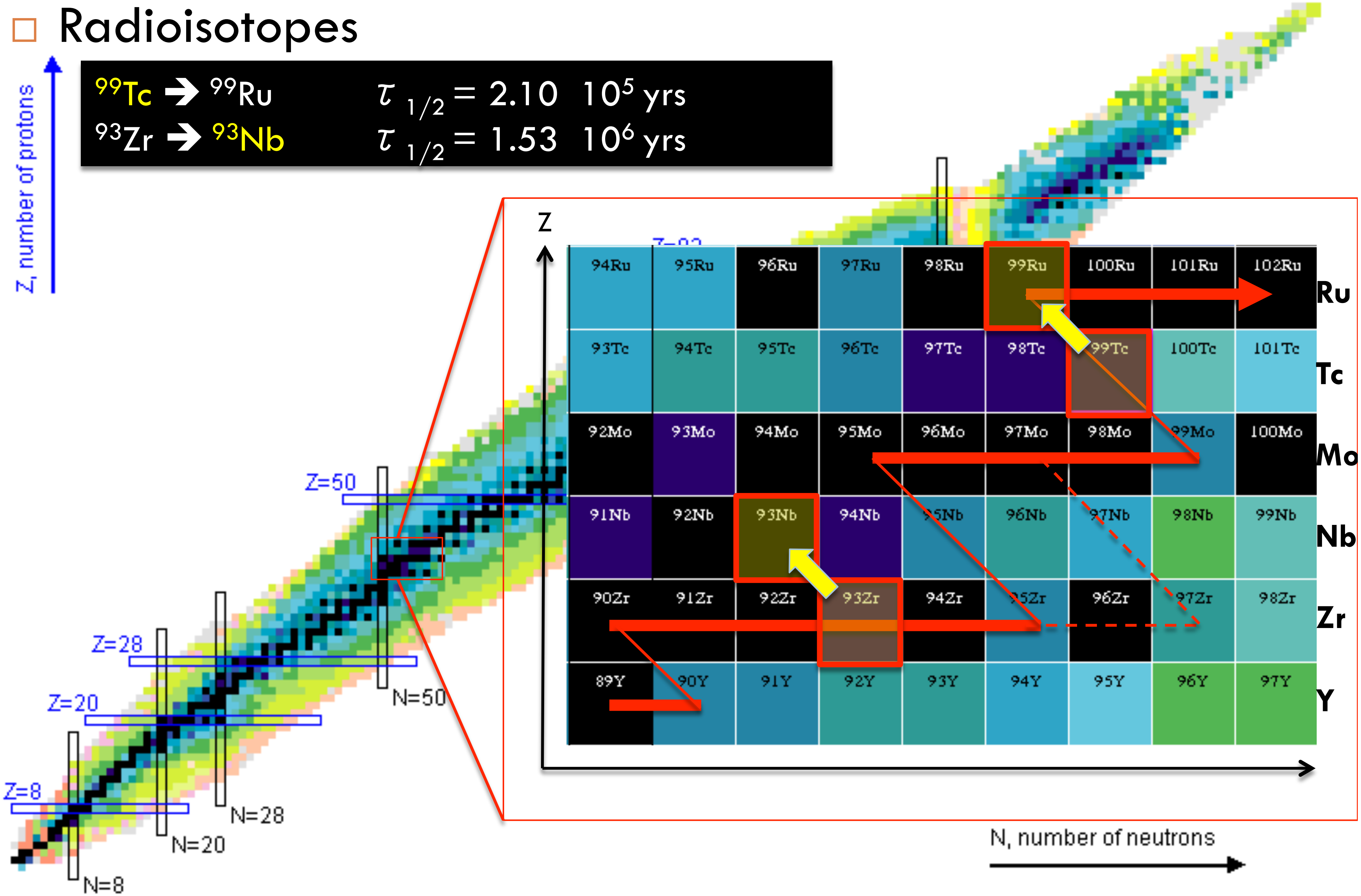
Ba stars from Escorza et al., 2017
S stars from Shetye, Van Eck et al., in prep.

Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

- Radioisotopes

$^{99}Tc \rightarrow {}^{99}Ru$		$\tau_{1/2} = 2.10 \ \ 10^5$ yrs
$^{93}Zr \rightarrow {}^{93}Nb$		$\tau_{1/2} = 1.53 \ \ 10^6$ yrs



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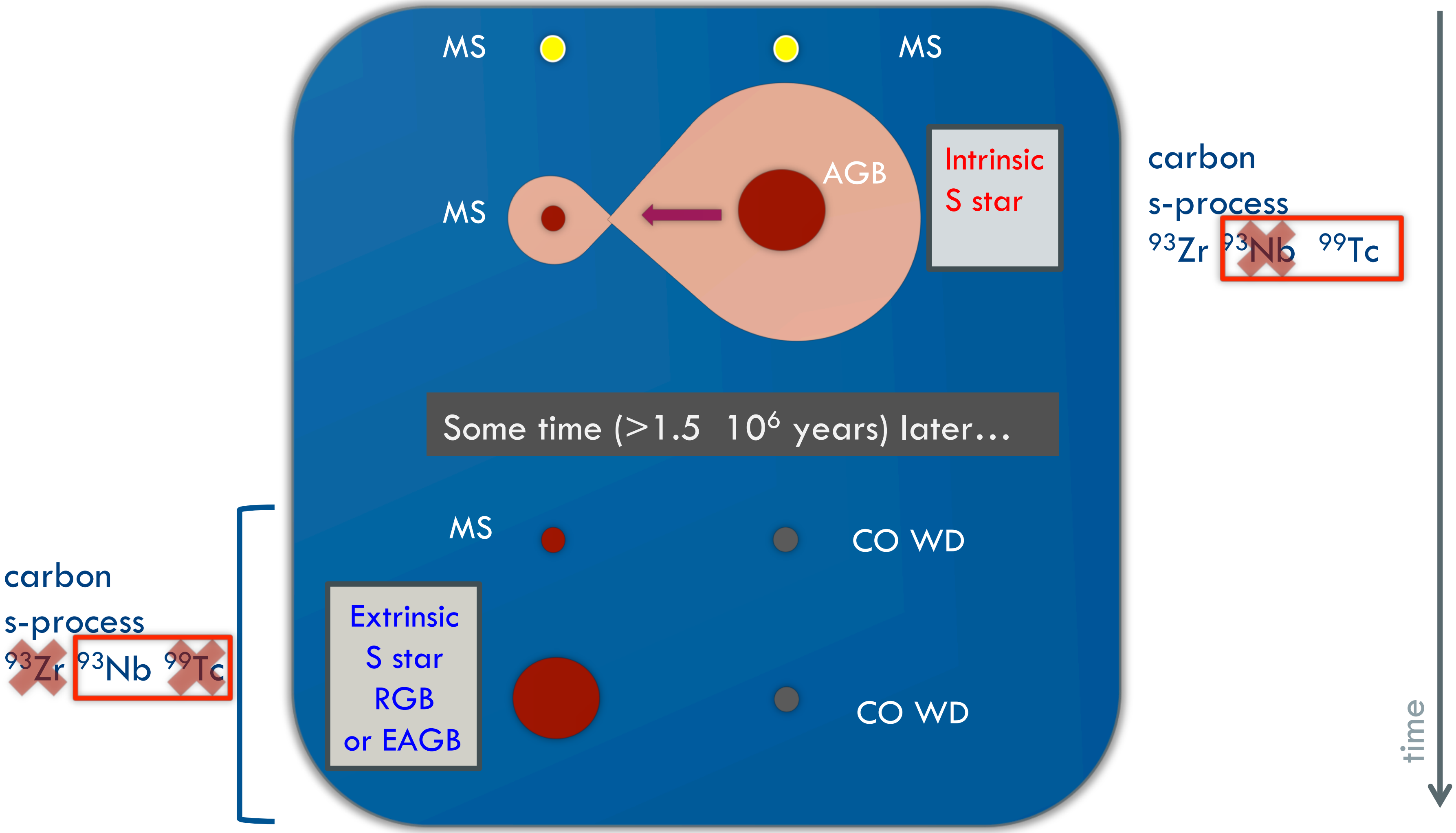
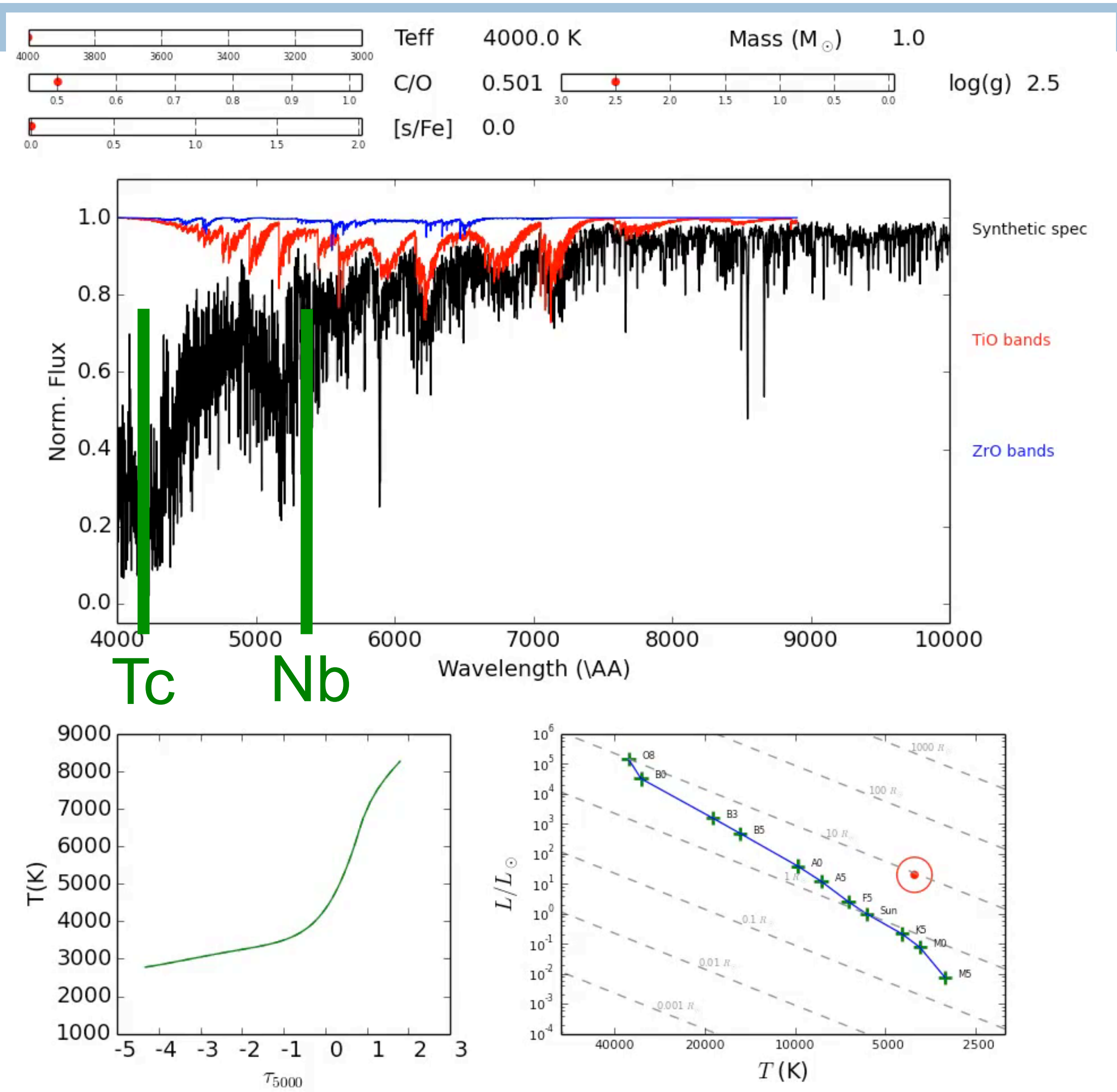


Nb dichotomy: Bisterzo+ 2010

Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

- Radioisotopes



Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

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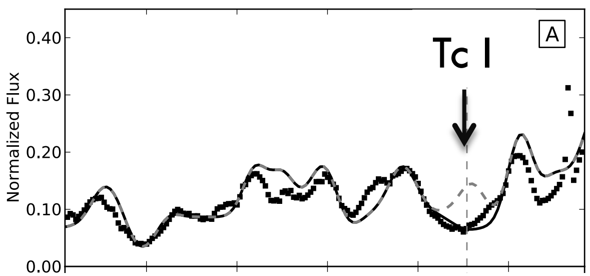
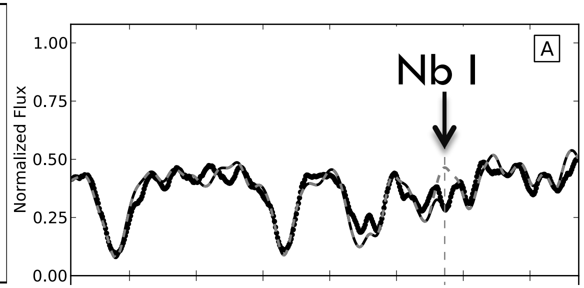


Tc-rich

- Intrinsic
- Genuine AGB

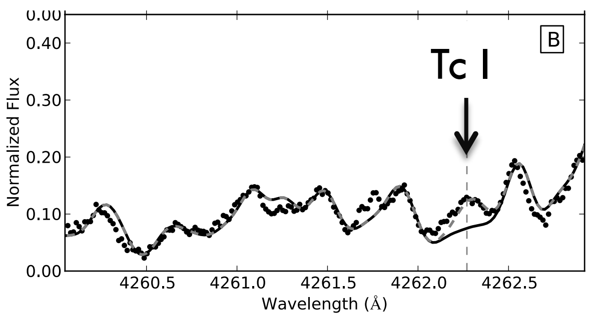


Nb-poor (~solar)

$^{99}\text{Tc} \rightarrow {}^{99}\text{Ru}$

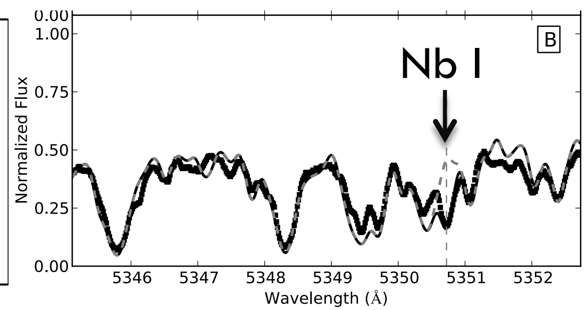
If binary, may pollute its companion which (after some time) will turn into:

$^{93}\text{Zr} \rightarrow {}^{93}\text{Nb}$



Tc-poor

- Extrinsic
- RGB, earlyAGB



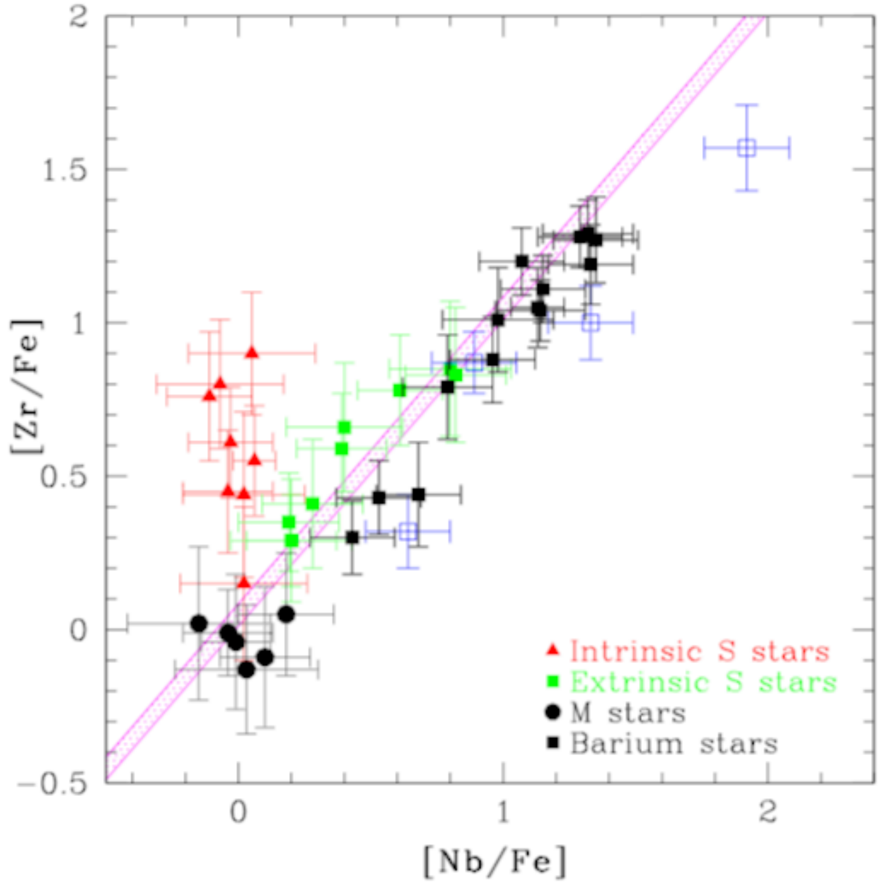
Nb-rich

Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

- Radioisotopes

Diagnostic from the ^{93}Zr radio-isotope



Karinkuzhi+ 2018, A&A 618, A32

Parameters from BACCHUS (Masseron+ 2016)

Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

□ Radioisotopes

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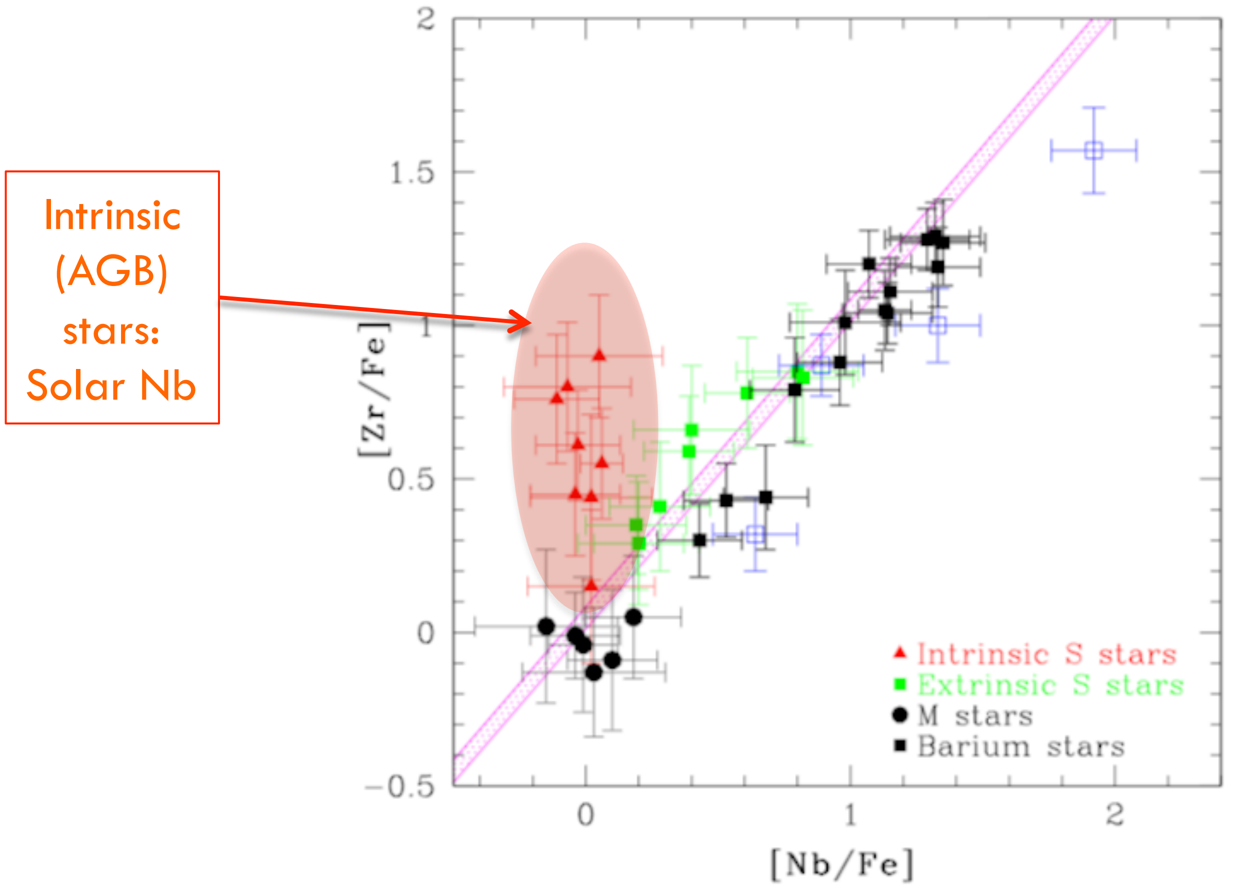

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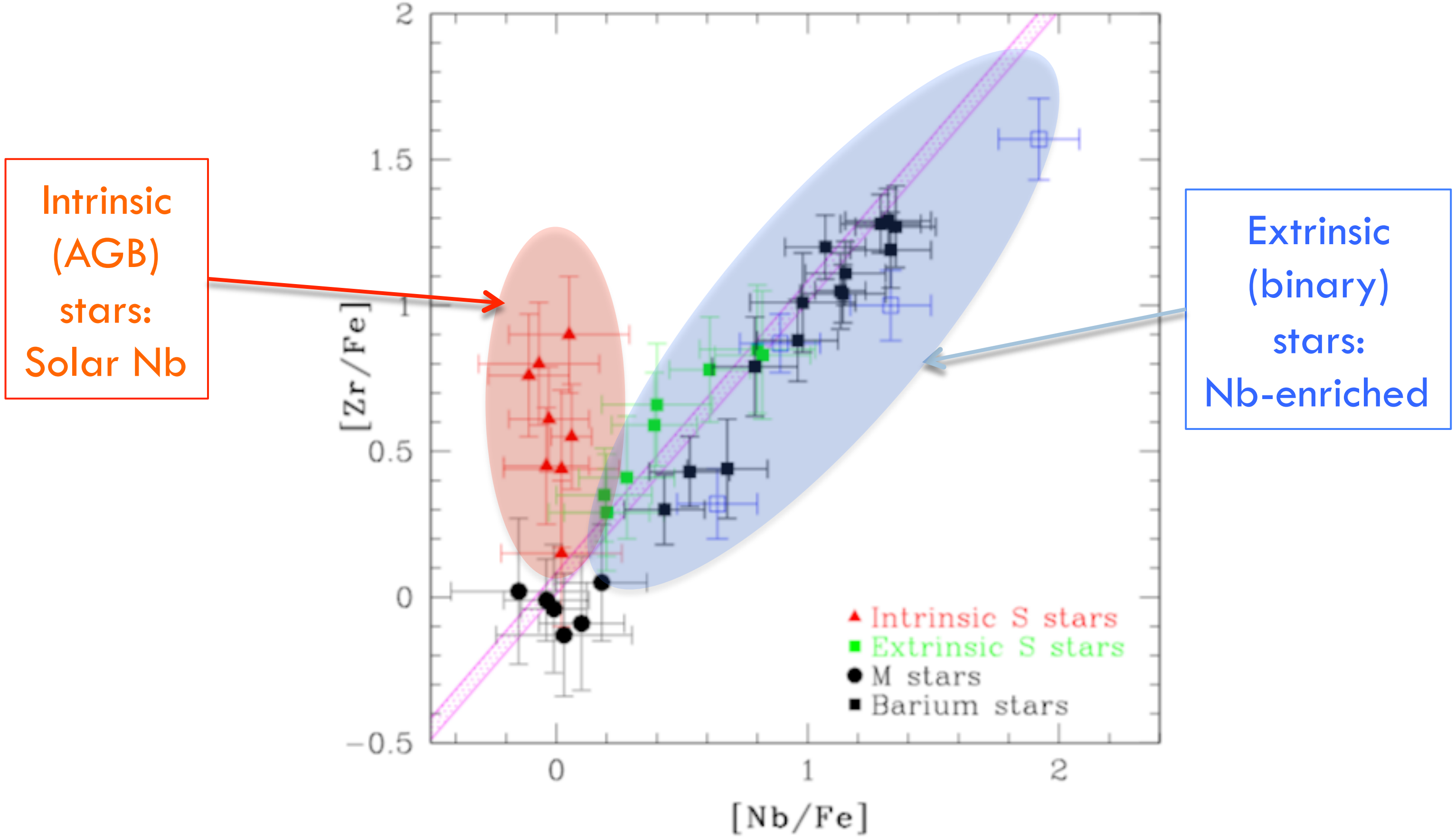

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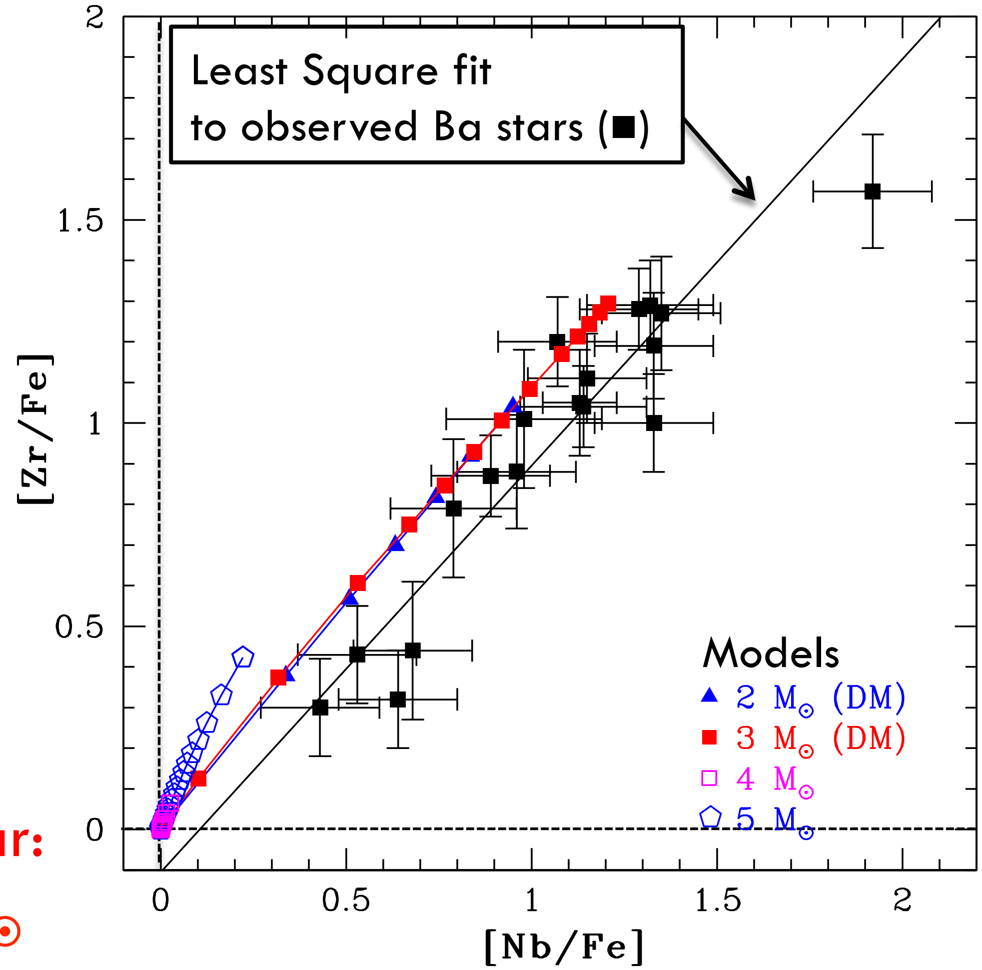


→All extrinsic stars analysed so far:

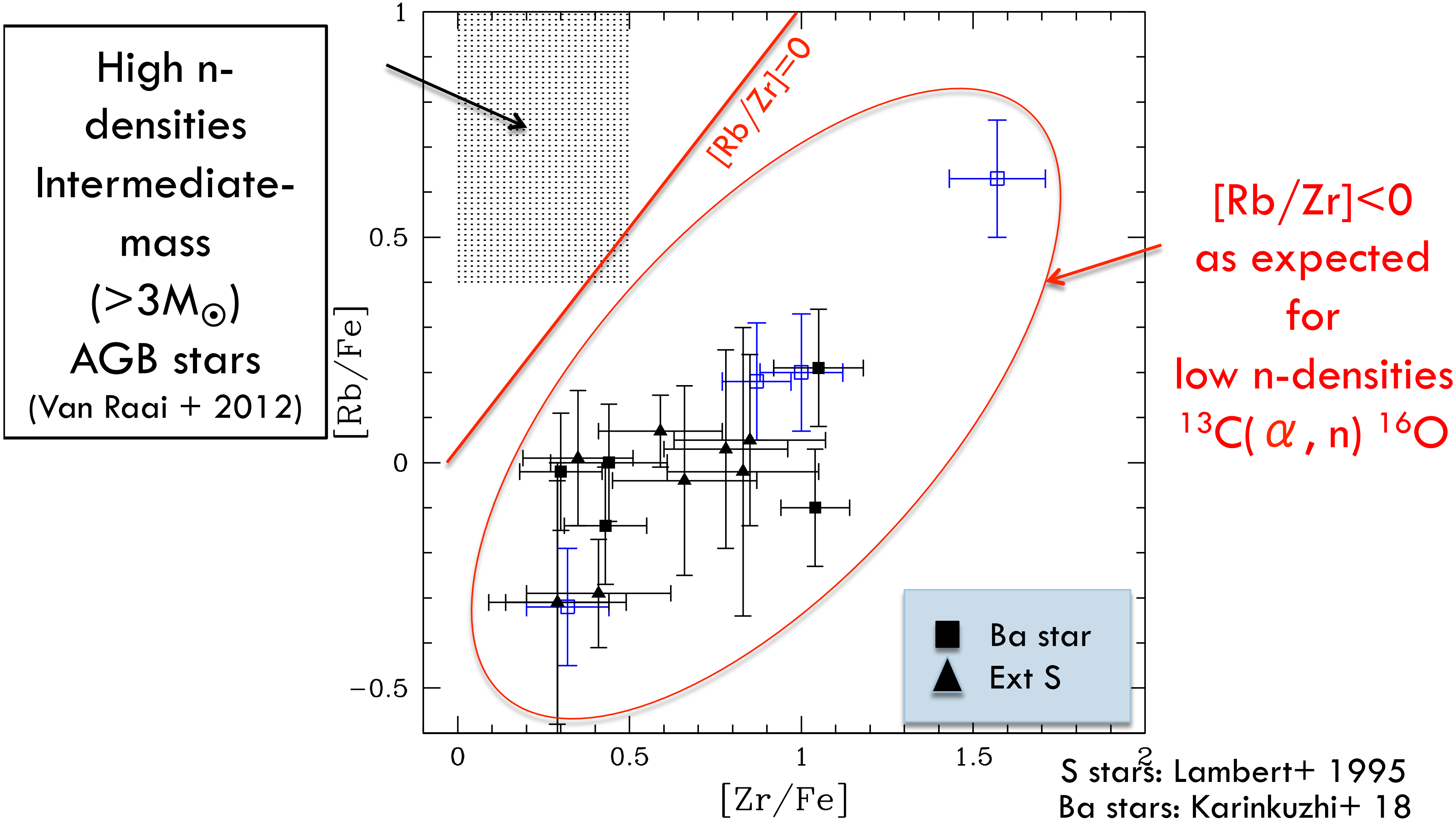
- Polluted by AGB stars of 2-3M⊙
- $^{13}C(\alpha, n)\,^{16}O$ neutron source

Karinkuzhi, Van Eck et al., 2018

Binary fossils at higher metallicity (-1<[Fe/H]<0)

CH, Barium and extrinsic S stars

- Rubidium



S stars: Lambert+ 1995
Ba stars: Karinkuzhi+ 18

Extrinsic, Intrinsic and ... Trinsic stars

S stars

□ Radioisotopes

2 peculiar objects:

- Nb-rich, binaries

→Extrinsic

- But: Tc-rich

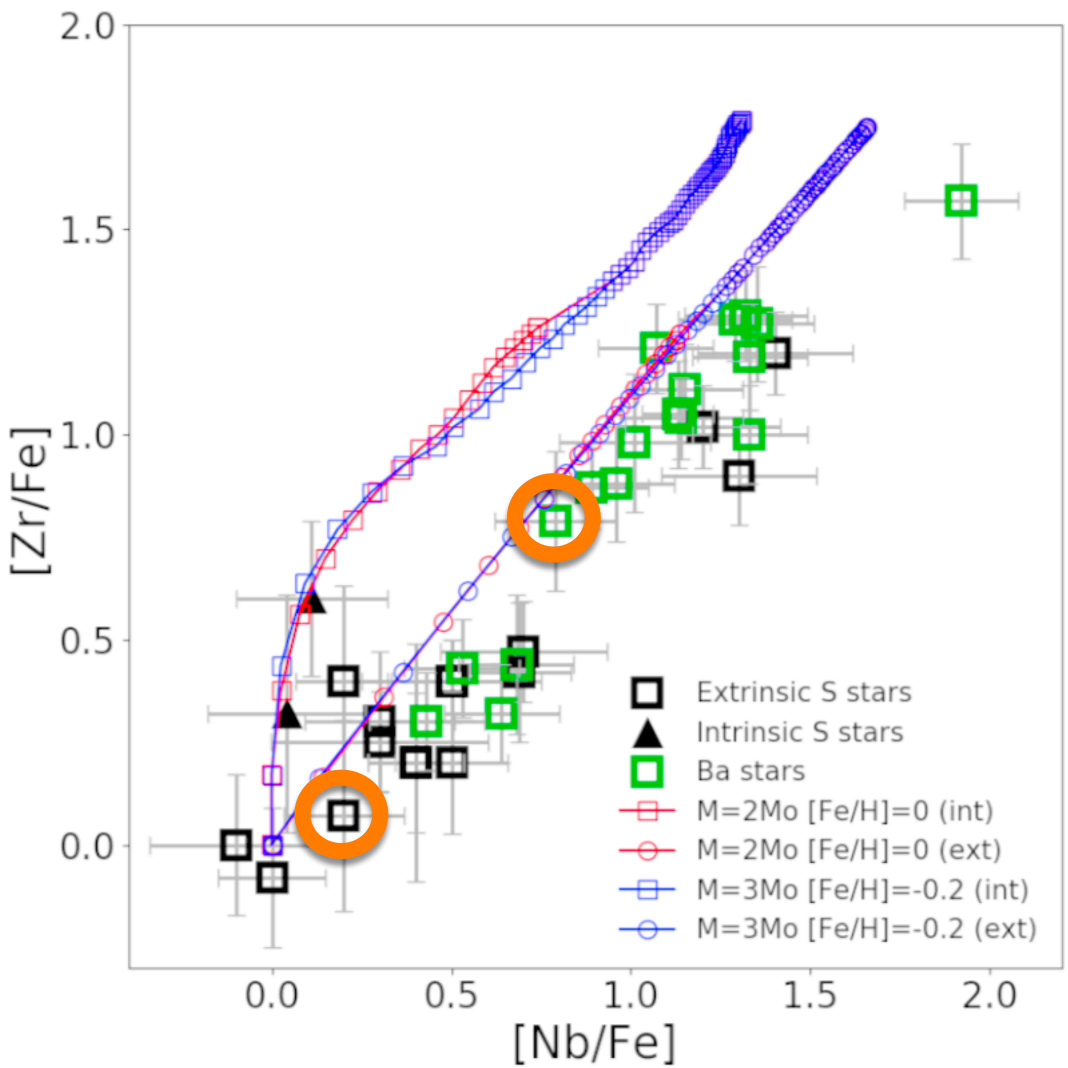
→ Also Intrinsic

BD +79 156

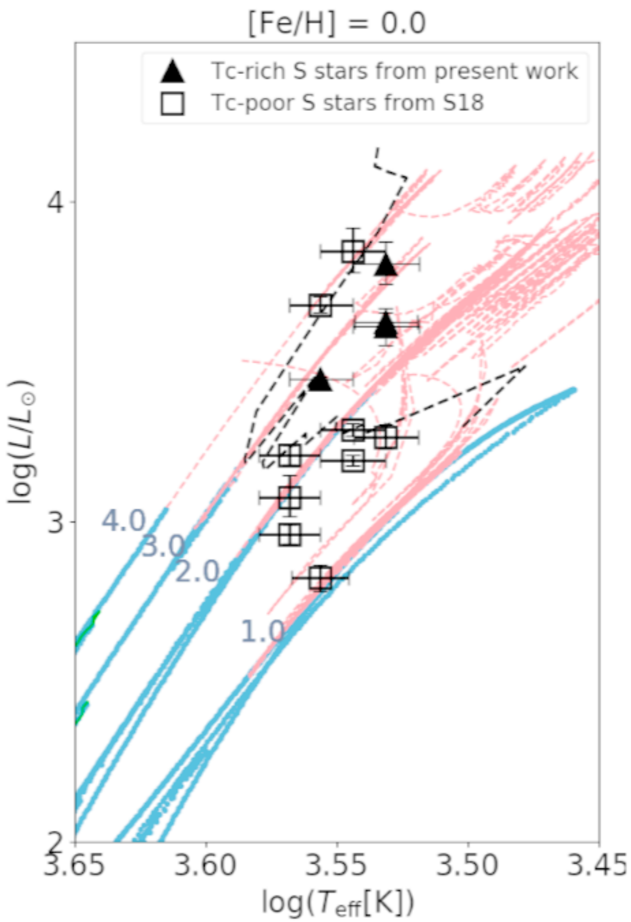
O[1] Ori

“Trinsic” stars

Shetye, PhD thesis 2019



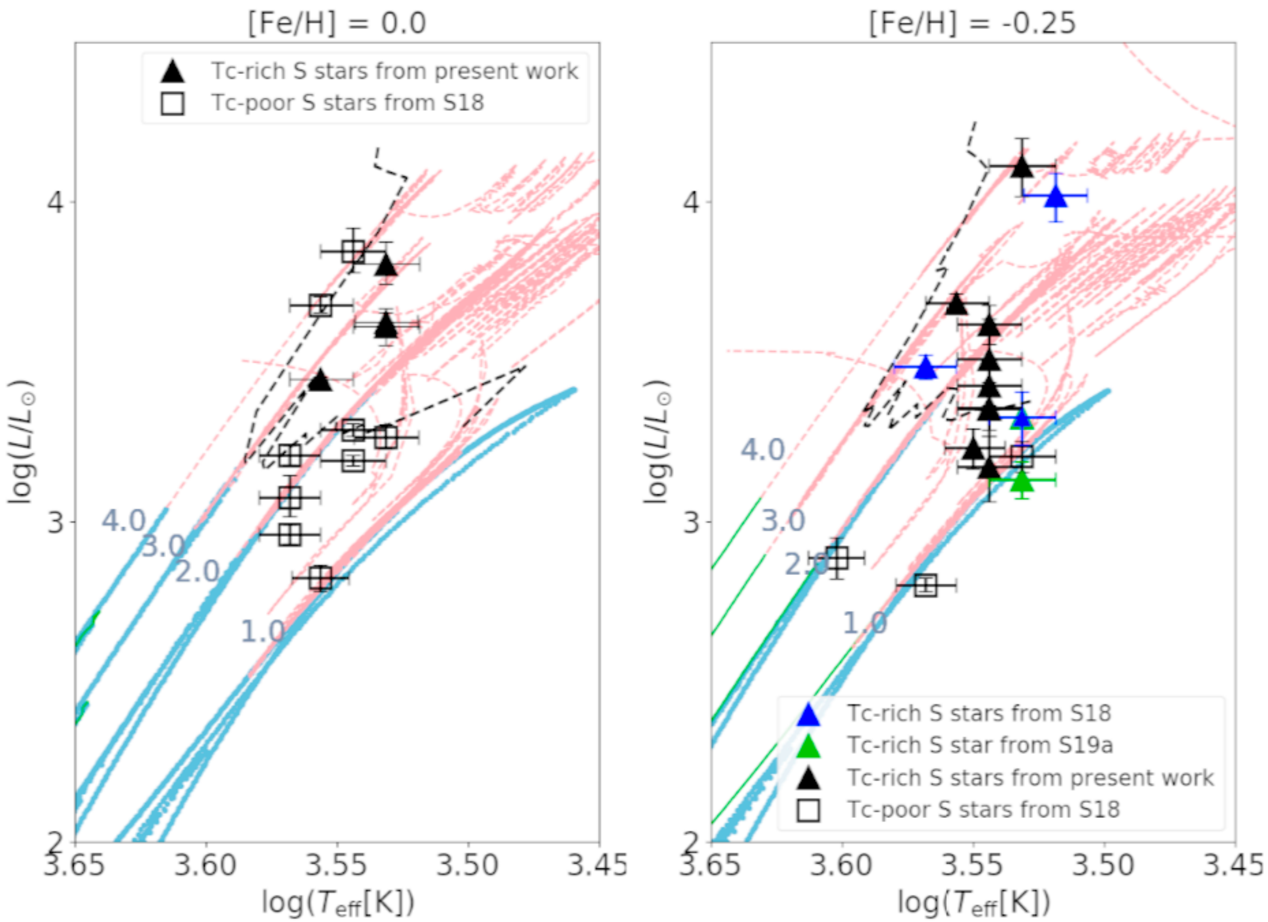
Fossil vs on-going nucleosynthesis
Extrinsic vs intrinsic stars



Predicted (L. Siess) vs observed (Gaia DR2) location of S stars in the HR diagram

Shetye+ 2018, 2019

Past vs on-going nucleosynthesis
Extrinsic vs intrinsic stars



Shetye, Van Eck et al., 2018, 2019

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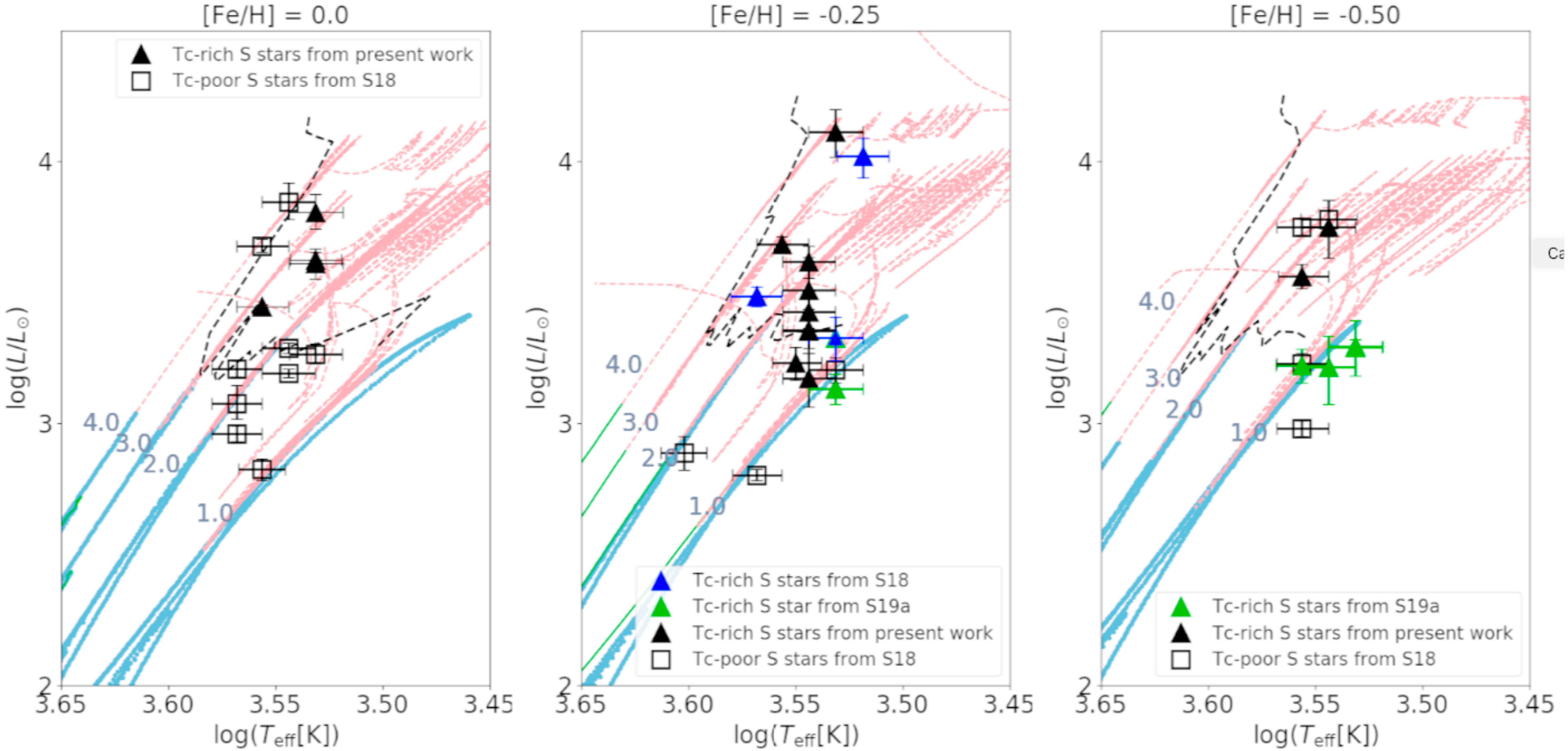
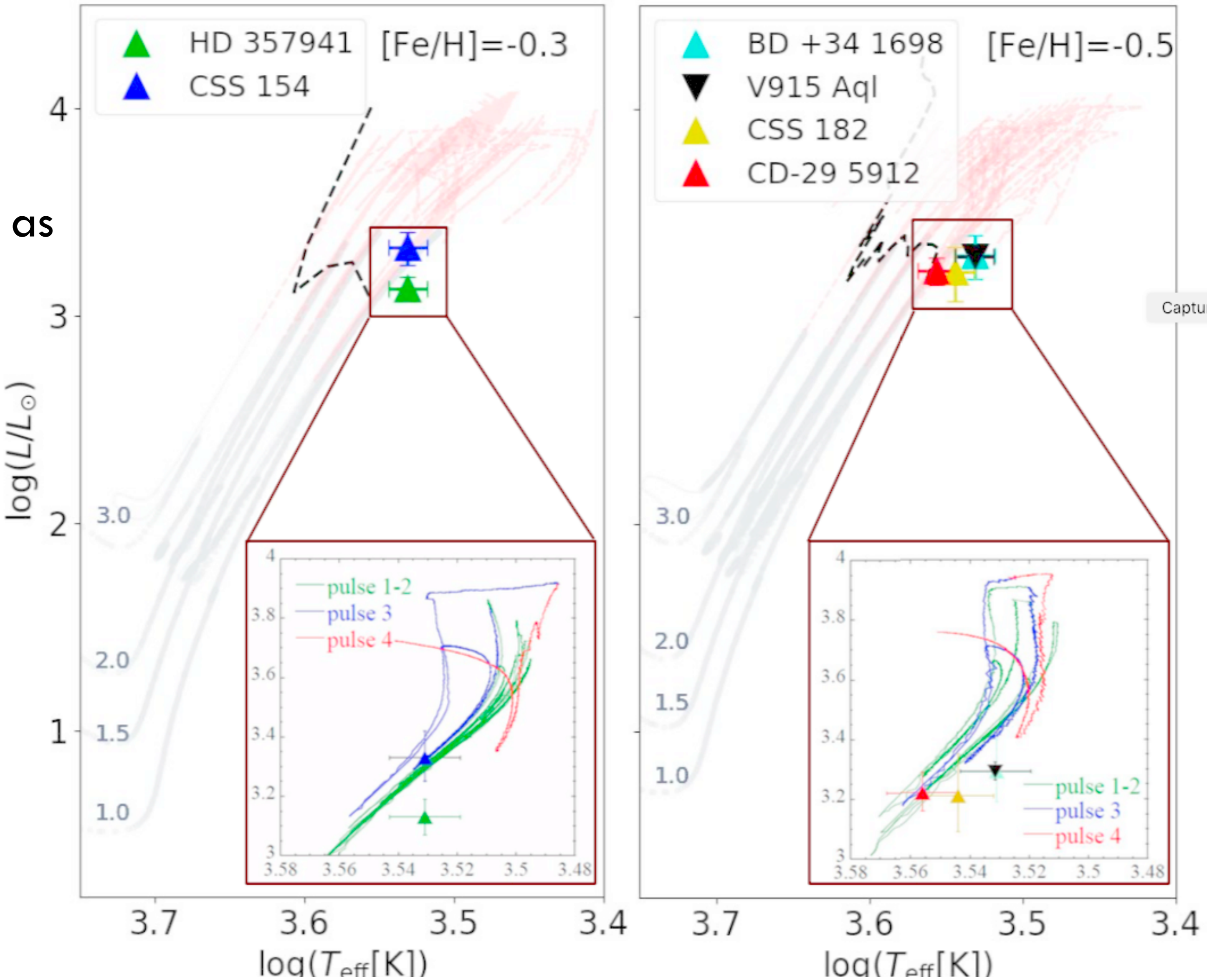


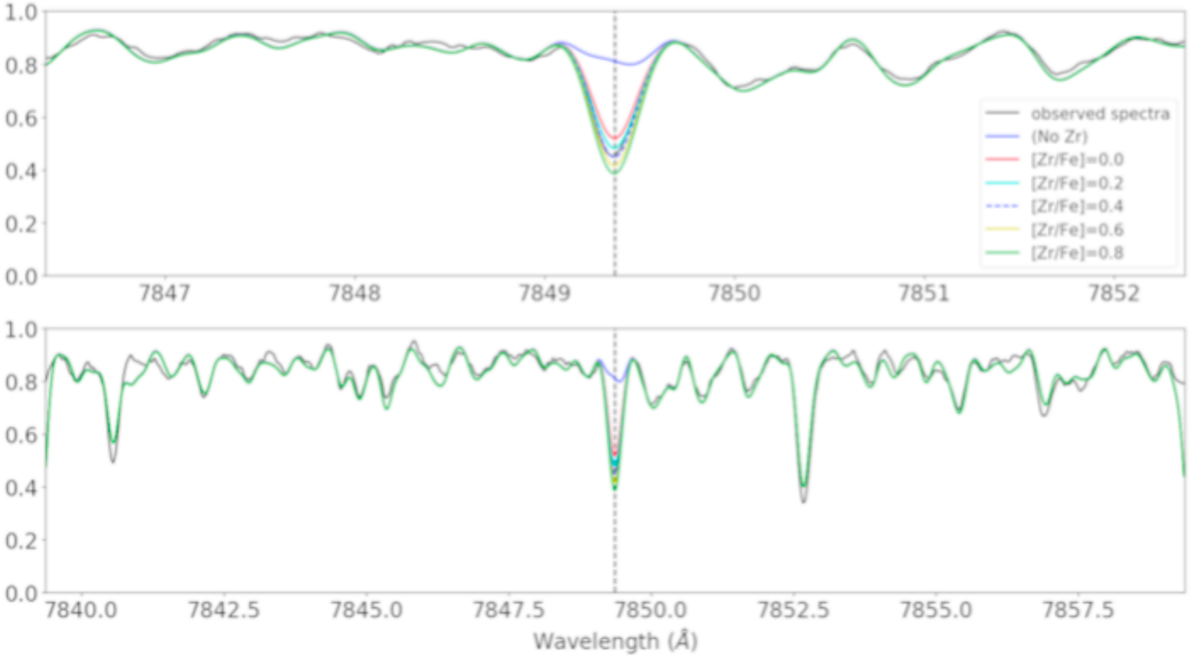
Shetye, Van Eck et al., 2018, 2019

Dredge-up from 1Msun mass stars

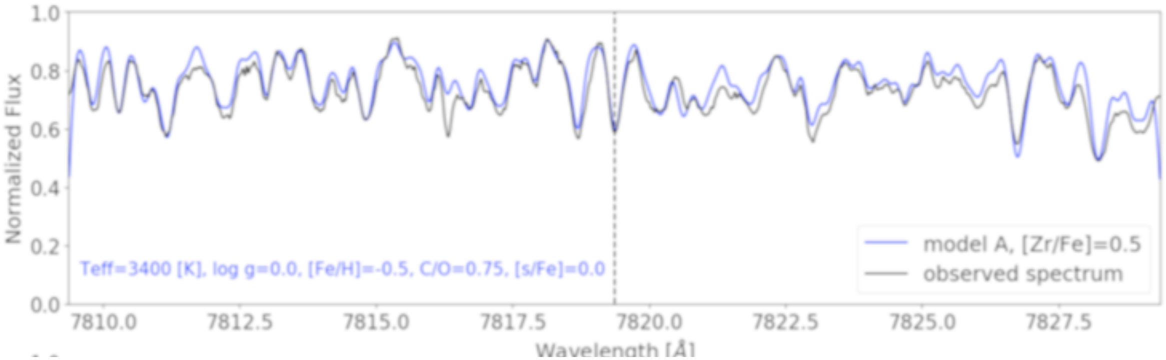
Efficient third dredge-up
 in stars with masses as low as
1 – 1.2 Msun
with [Fe/H] in the range
-0.3 to -0.5.



Examples of spectral fitting



HD 191226

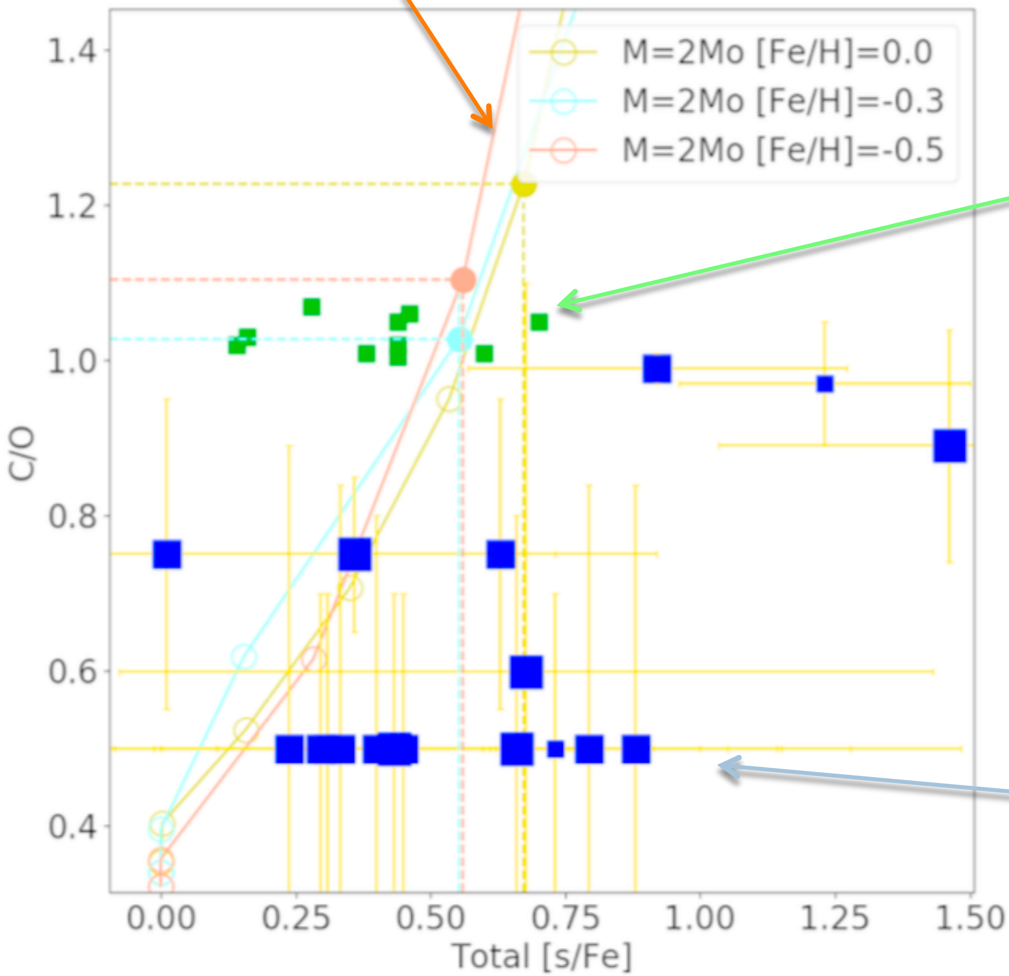


V915 Aql

Shetye + 2018

On-going nucleosynthesis

Model predictions (L. Siess, S. Goriely)



C stars (C. Abia)

S stars

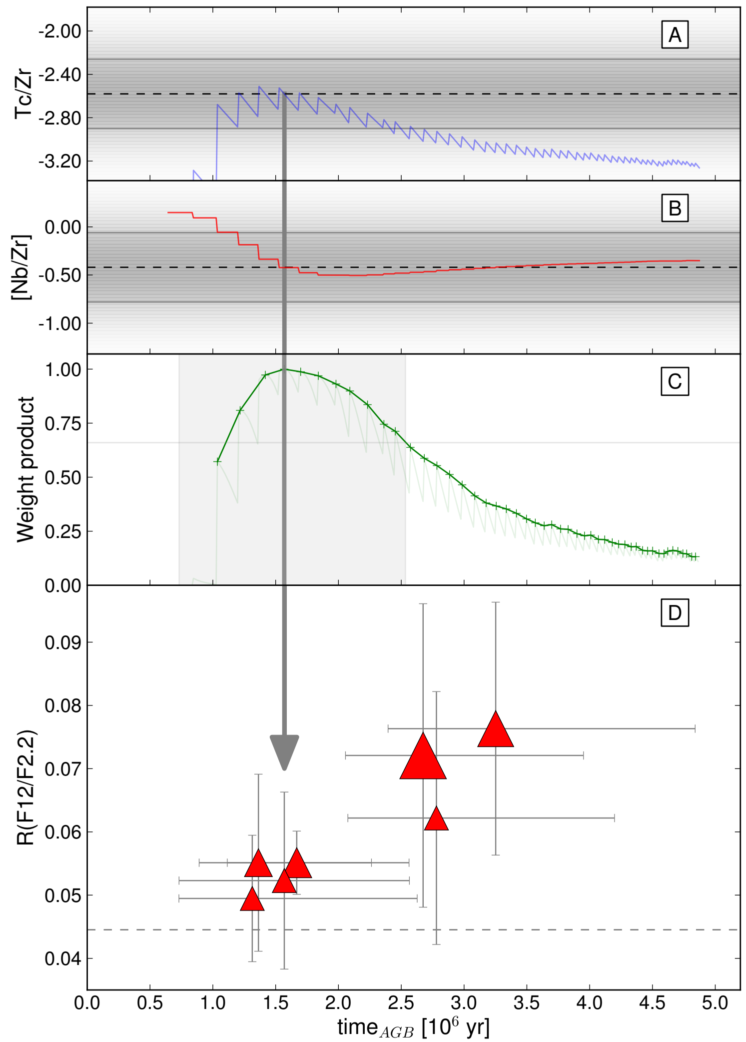
At ~solar metallicity and at a given s-process enrichment, the **predicted** C/O is much **too high** with respect to the **measured** one

S. Shetye, PhD thesis

s-process cosmo-chronology

$^{99}Tc \rightarrow ^{99}Ru$ ($\tau_{1/2} = 0.21 \quad 10^6$ yrs)

$^{93}Zr \rightarrow ^{93}Nb$ ($\tau_{1/2} = 1.53 \quad 10^6$ yrs)

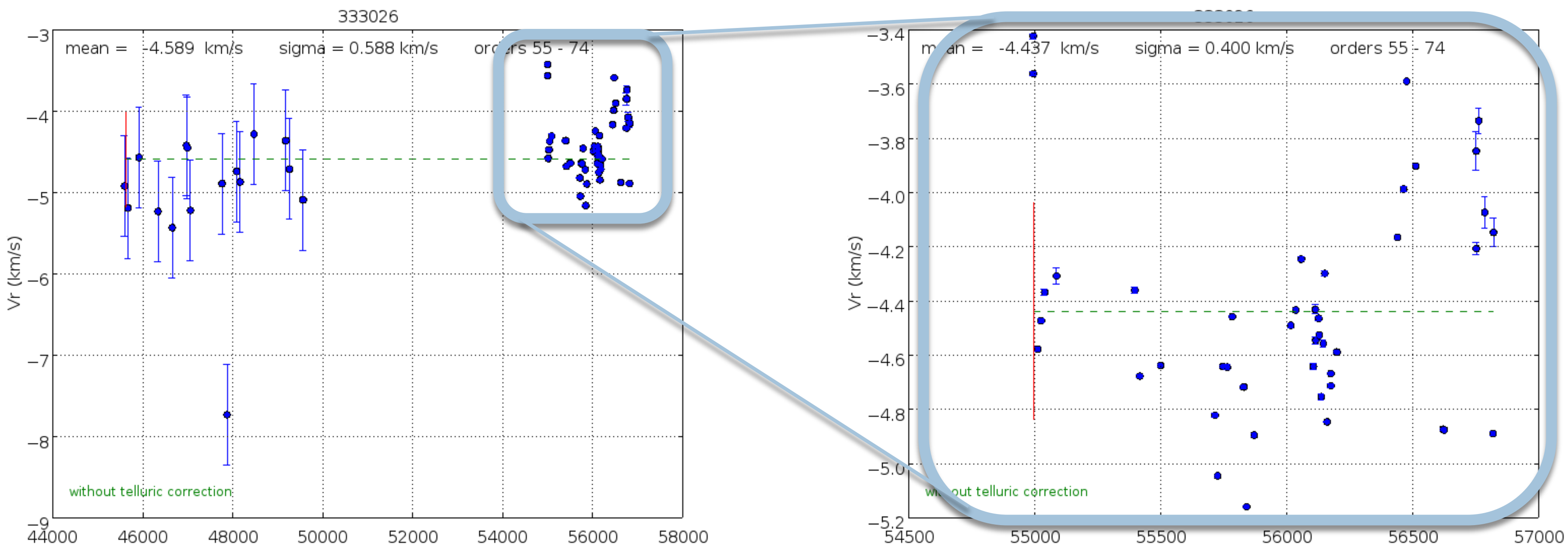


The derived ages correlate with the infrared excess:

R = F(12 μ m)/F(2.2 μ m)

Merger stars as fossils of past nucleosynthesis

- **(Early-) R stars:**
  - Solar metallicity, K-type giants
  - enriched in C- and N, low $^{12}C/^{13}C$
  - No s-process enrichment
  - Core-He burning
  - 0% of binaries (McClure 1997)
- Possible explanation:
  - Merging RGB+WD, common envelope and He-flash in a rotating core, mixing C to the surface (Izzard 2007)



HERMES (KULeuven, ULB, ROB) monitoring of R-type stars

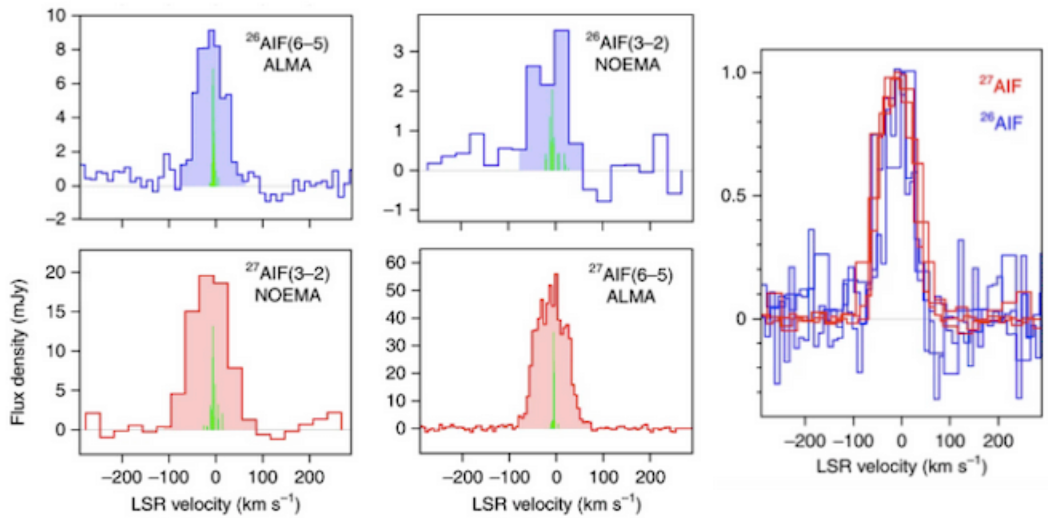
Merger stars as fossils of past nucleosynthesis

- CK Vul: remnant of stellar merger
- Millimeter wave detection of a radioactive molecule ^{26}AlF in a remnant of an ancient explosion

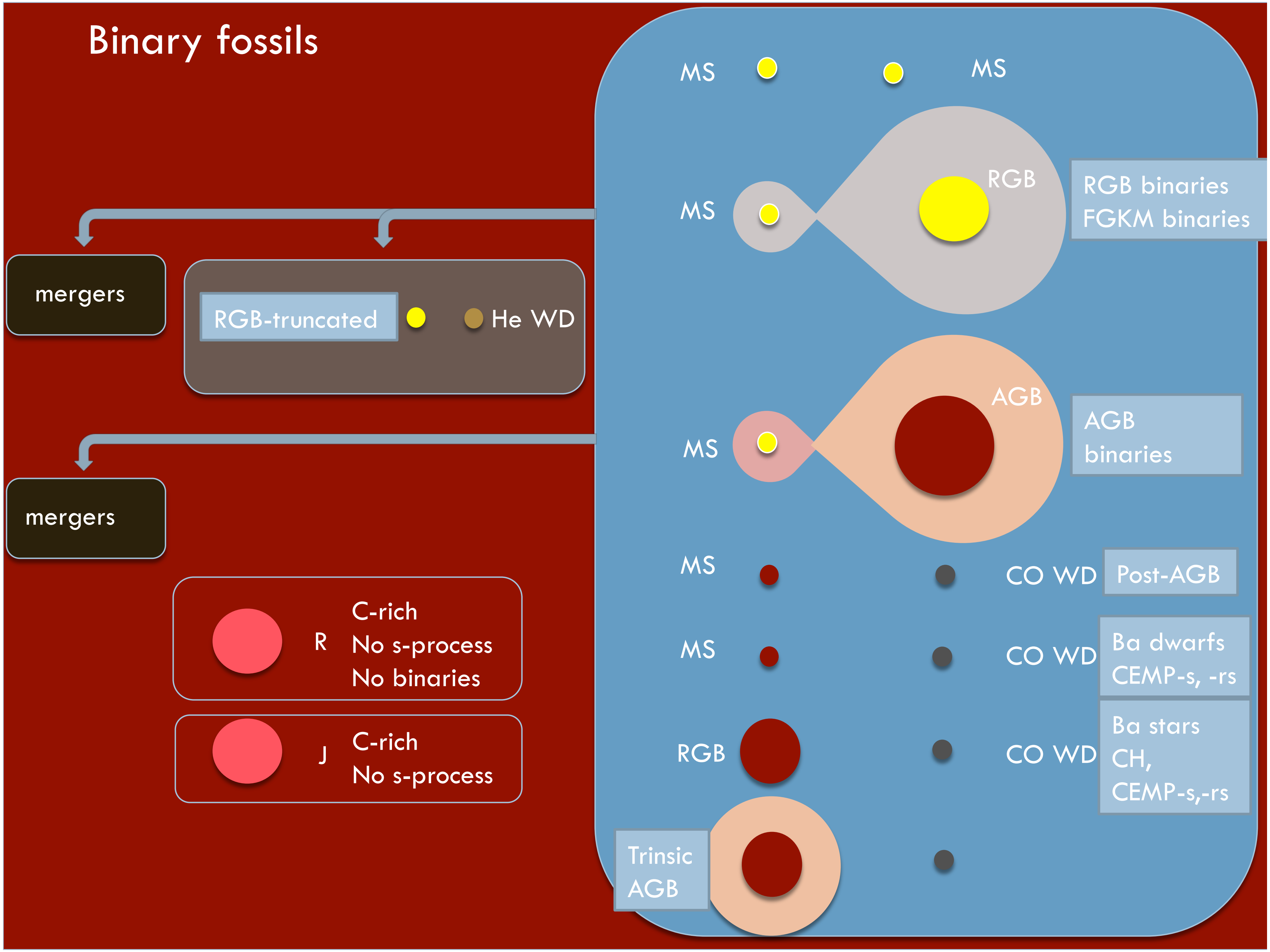
Kaminski et al., accepted to Nature Astronomy

https://arxiv.org/abs/1807.10647

- ^{26}Al synthesis on the RGB and ejected during coalescence



Binary fossils



Conclusions

- Binary fossils (extrinsic stars) bear signatures of a past nucleosynthesis, helping to *directly* trace nucleosynthesis at various epochs
- C-enrichment + binarity reveal a diverse zoo (CEMP-s, -rs, CH, Ba, S, etc)
- Key-diagnostic (Tc, Nb, Rb…) provide s-process conditions (for example thermometer and chronometer)

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