Neutron-capture signatures in a large sample of Ba stars

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s, i & r Element Nucleosynthesis (sirEN) Conference
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introduction

- peculiar G–K spectral type, [Fe/H] > –1 dex
- not yet evolved to the AGB phase
- strong spectral features: carbon molecular bands + s-process elements (e.g. Ba)
  → synthetised inside AGB stars
- RV variation (McClure+ 1983, ...), UV excess (Böhm-Vitense+ 2000, ...)
  → binary systems, now WD companion

introduction

- origin of overabundance: extrinsic!
- pollution from a former AGB companion
  → mass transfer
- type of mass transfer still under debate...
- test: AGB s-process nucleosynthesis
- precise abundances, atomic data

s-process enhancement

- s-process: peaks at Sr (1.), Ba (2.), Pb (3.)
- s-process efficiency: ratio of heavy (2. peak, hs) and light (1. peak, ls) s- elements: [hs/ls]
  → s=? hs=? ls=?
- ls: Sr, Y, Zr
  hs: Ba, La, Ce, Nd
- ratio: elimination of dilution effects in the Ba star's envelope
- what dilution factor is reliable?

Ba star sample

- 169 Ba stars with elemental abundances from:
  de Castro+ (2016), Roriz+ (2021a,b), Roriz+ (2024)
- FEROS (R ~ 48000)
- [Fe/H]~ −1 dex – solar, Teff ~4100–5400 K
- Ba star: if [s/Fe] ≥ 0.25 (s = Y, Zr, La, Ce, Nd)
  - light elements: Na, Mg, Al, Si, Ca, Ti, Cr, Ni
  - heavy: Rb, Sr, Y, Zr, Nb, Mo, Ru, La (new), Ce, Nd, Sm, Eu, W

comparison: AGB models

- final surface abundances, [s/Fe] ≥ 0.25 dex
- different ^{13}C pocket size: to produce s-process elements
- FRUITY + Monash: most extended in mass and metallicity

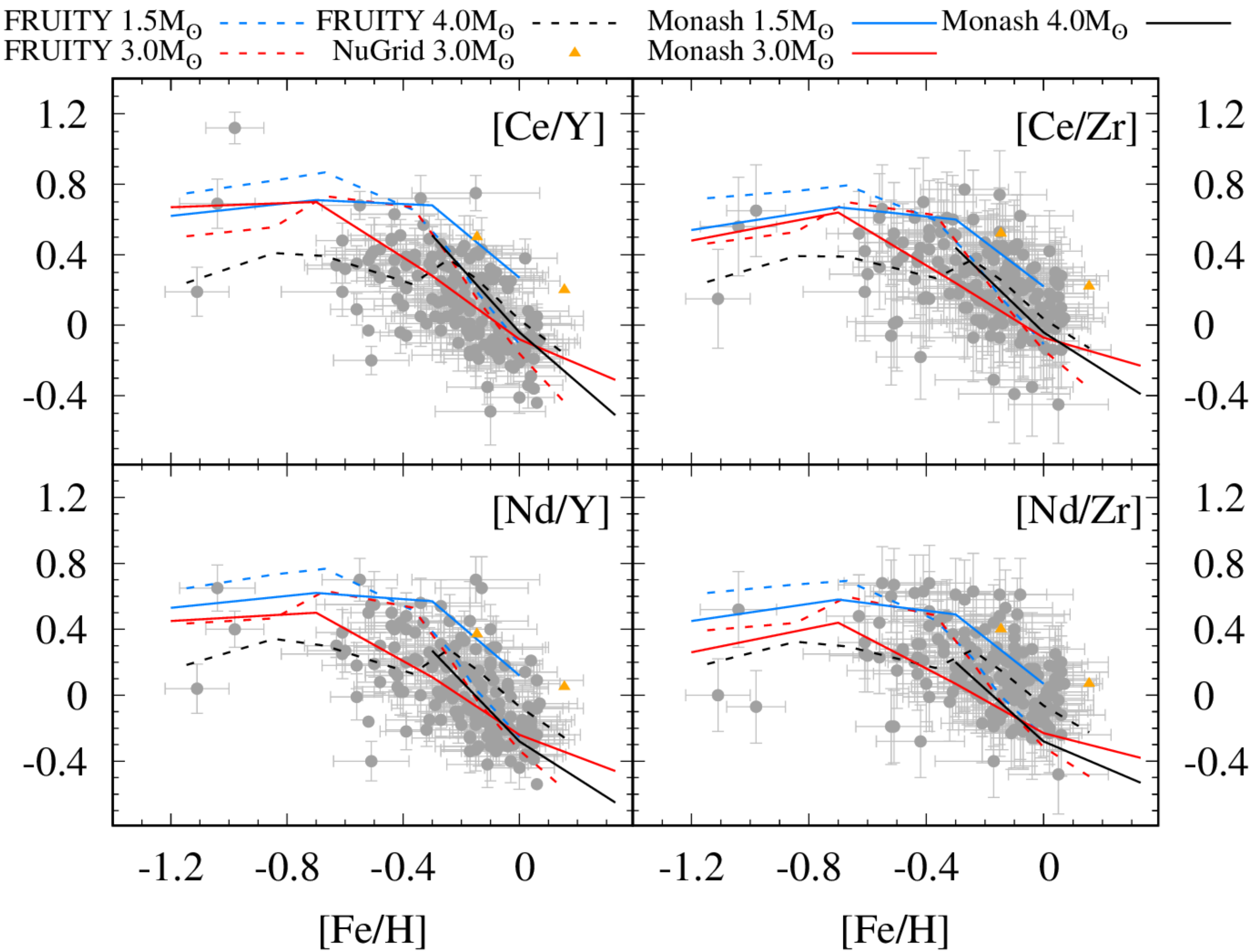
FRUITY → Cristallo+ 2016, Cristallo+ 2015, Straniero+ 2014, Piersanti+ 2013, Cristallo+ 2011, Cristallo+ 2009

Monash → Karakas+ 2018, Karakas & Lugaro 2016, Fishlock+ 2013, Lugaro+ 2012

model & data comparison

Ba star data:
de Castro+ (2016)

trend agrees with
<4 M_{Sun} non-rotating
models



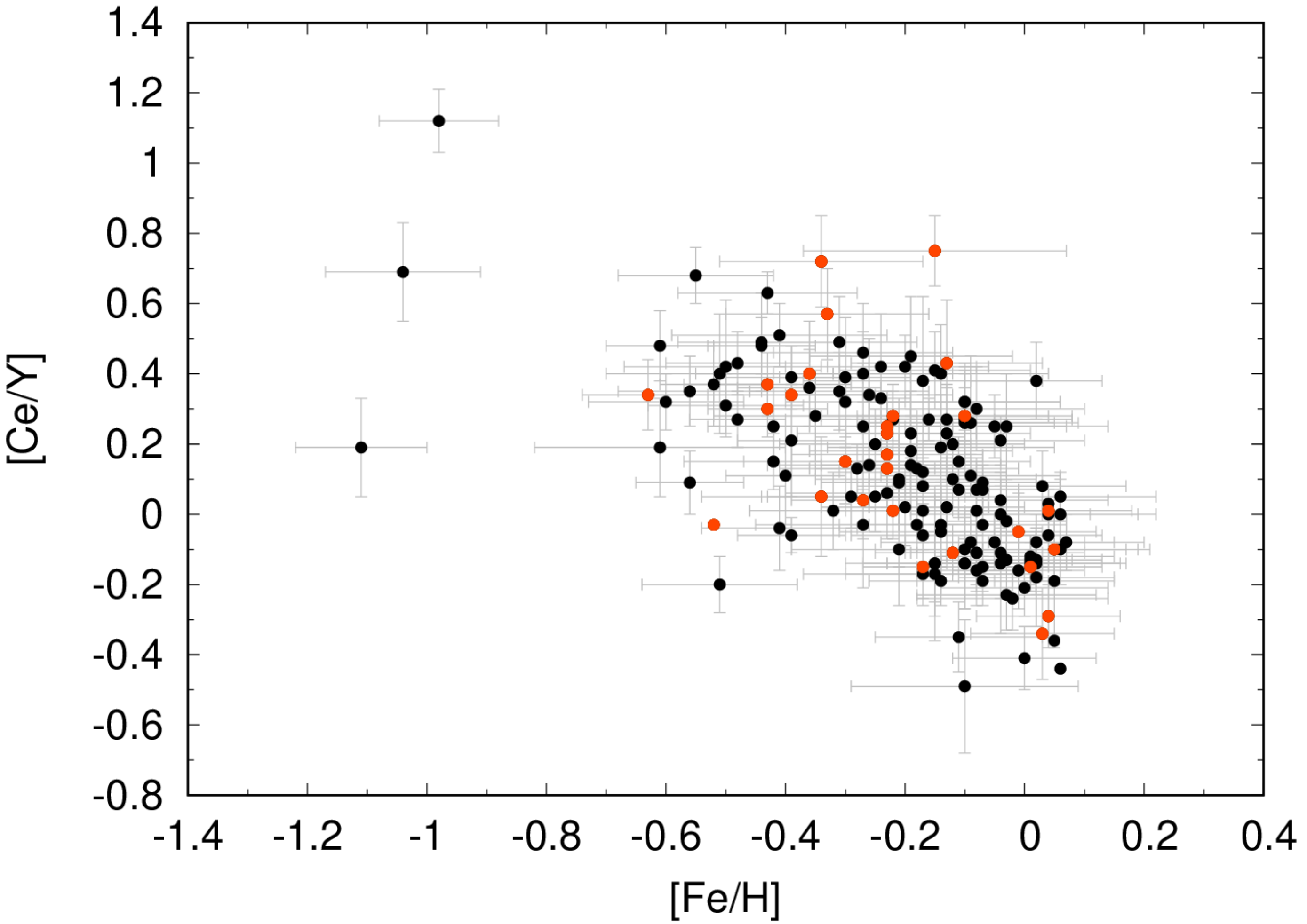
Cseh+ (2018)

individual stars

- 28 stars from the large sample in Jorissen+ (2019) → orbits + masses (Ba + initial AGB)
- all giants → model comparison with dilution (δ)
→ part of the AGB mass is carried to the secondary and mixed due to convective envelope
- “manual” analysis (Cseh+ 2022): closest in mass (AGB_{ini}) and metallicity

individual stars

spanning the
whole [Fe/H]
and [Ce/Y] range



“manual” analysis

- metallicity range: Ba star’s [Fe/H] +/- err
- δ: to match [Ce/Fe] ($\delta < 0.9$), Rb: strong mass indicator
- 3 groups:
  1: stars matching well the s-process peaks: most of the sample stars (3 subgroups → depending on overabundance after the s-process peaks)

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  2: low estimated mass ($< 2\ M_{Sun}$) + high first peak: 4 stars

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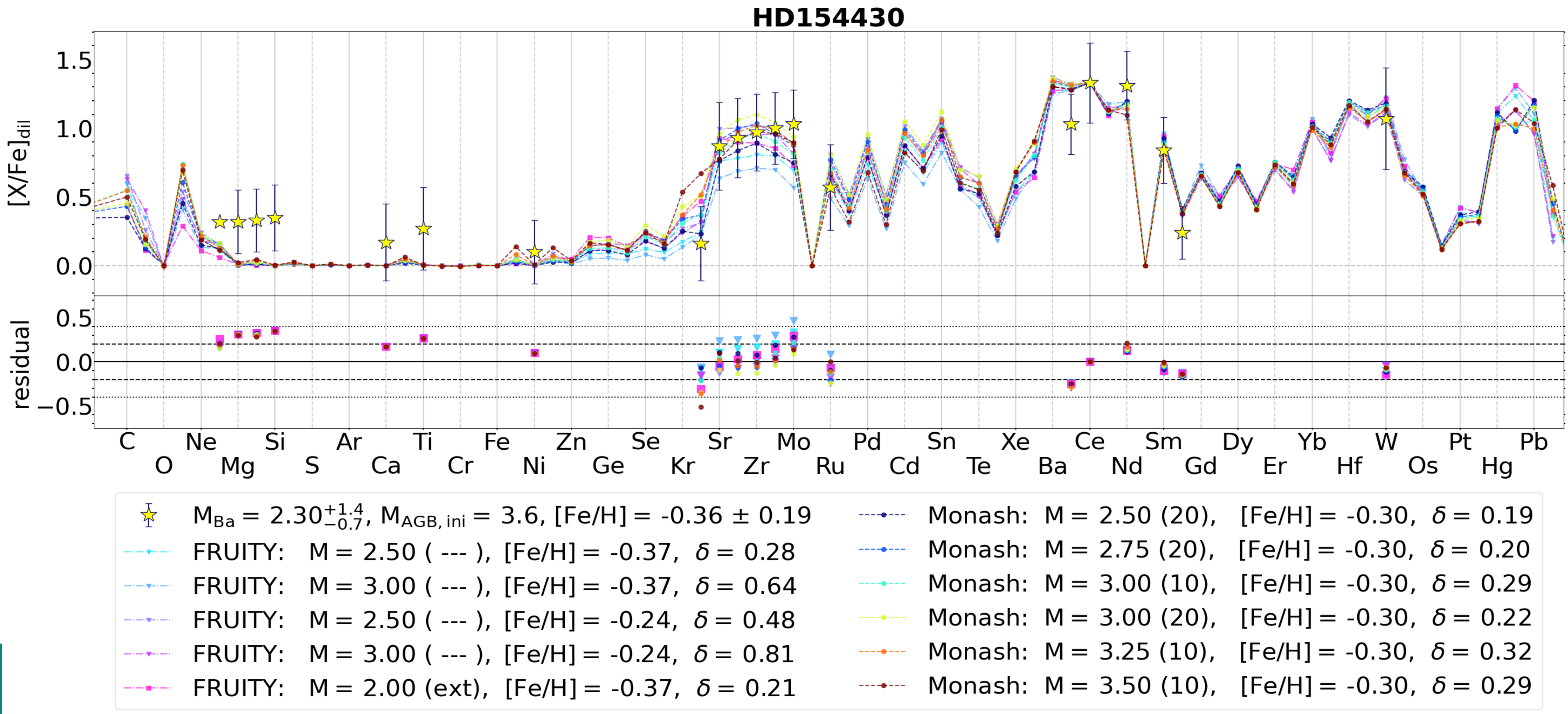
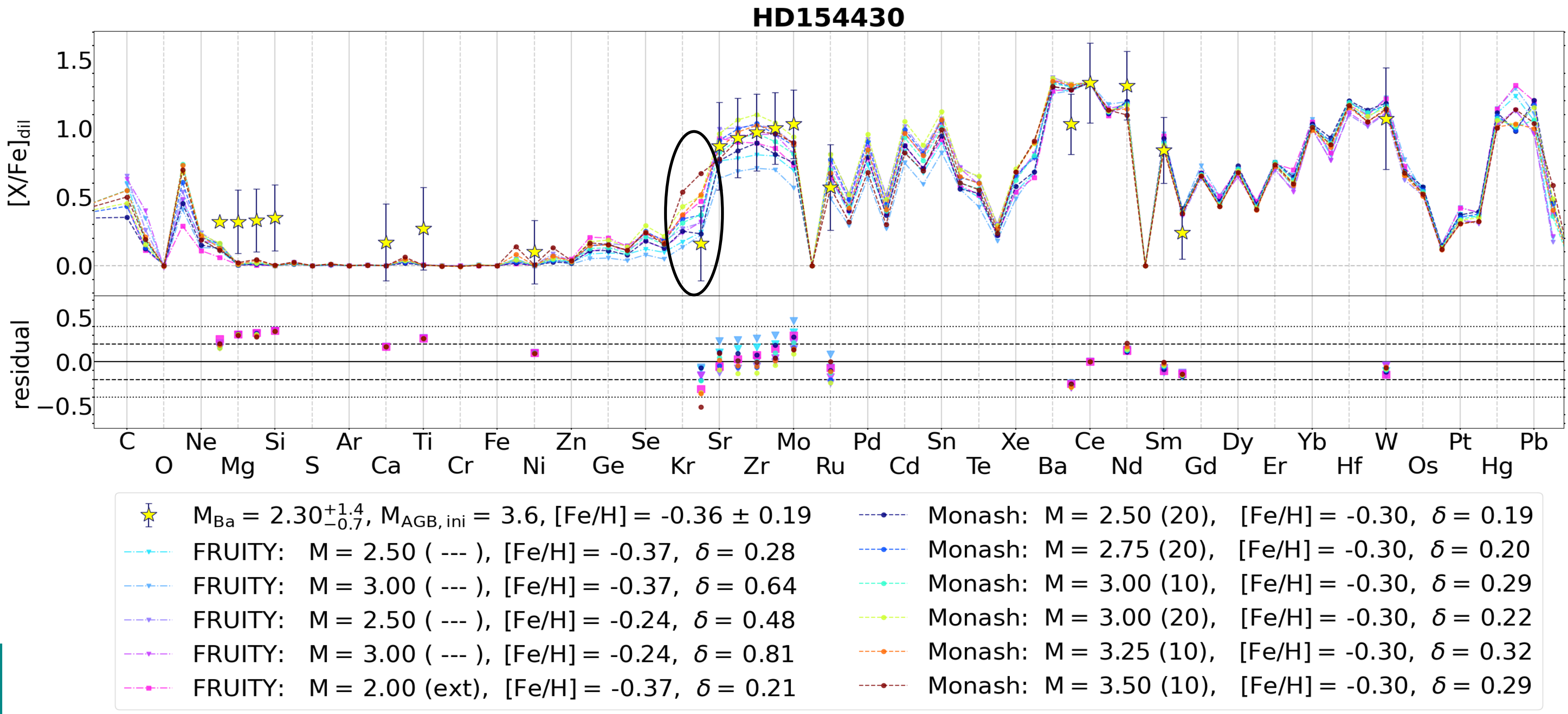
  3: higher AGB_{ini} mass (> 3.8 M_{Sun}): 3 stars, match with lower mass models

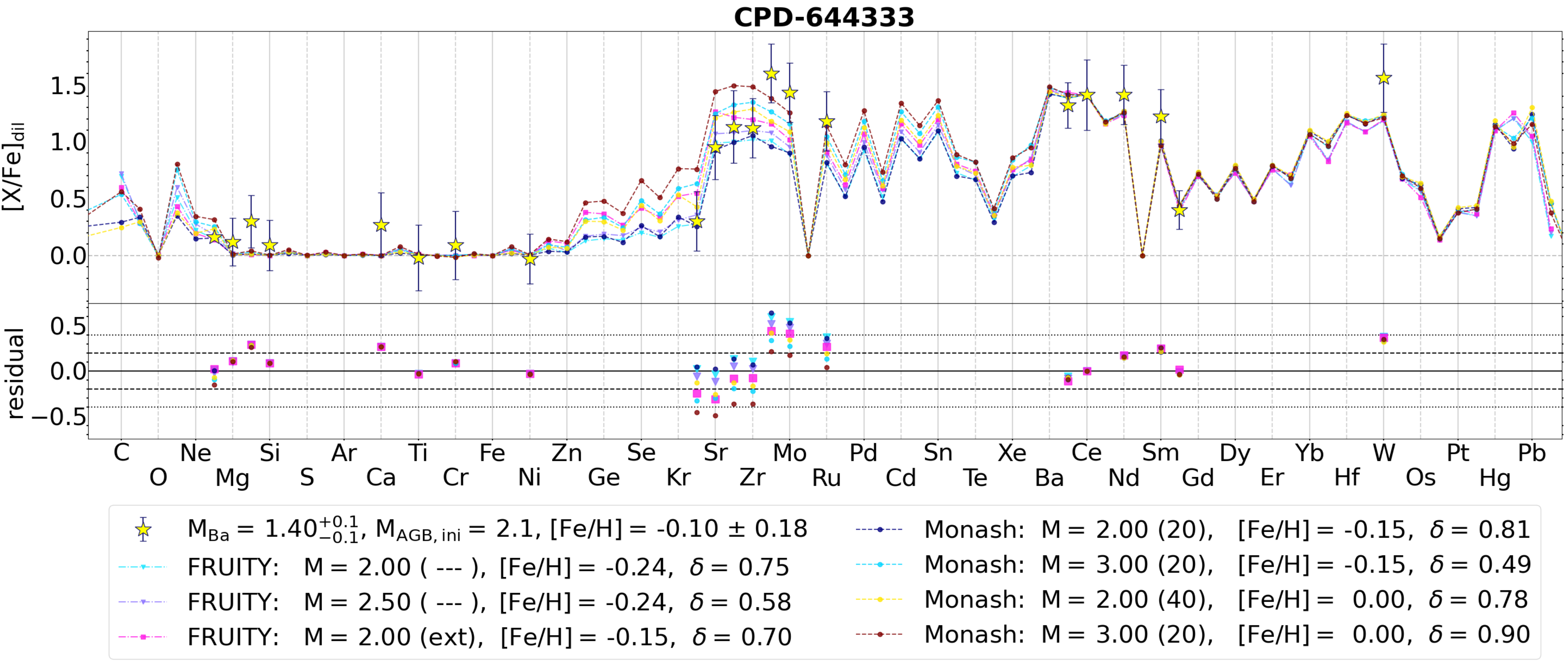
group 1a: all OK



group 1a: all OK

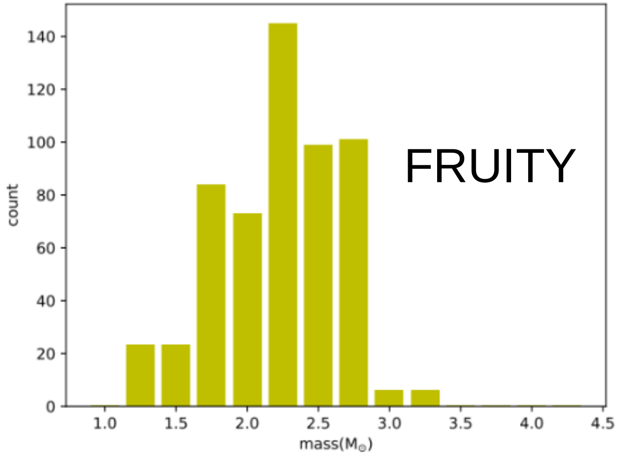


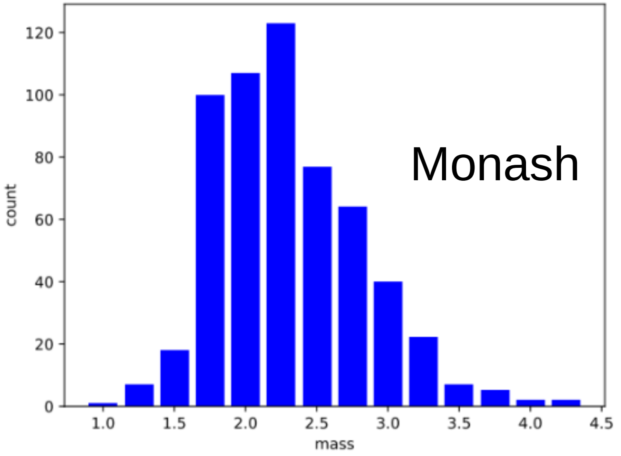
group 1c: OK, high Nb,Mo,Ru,Nd,Sm + W

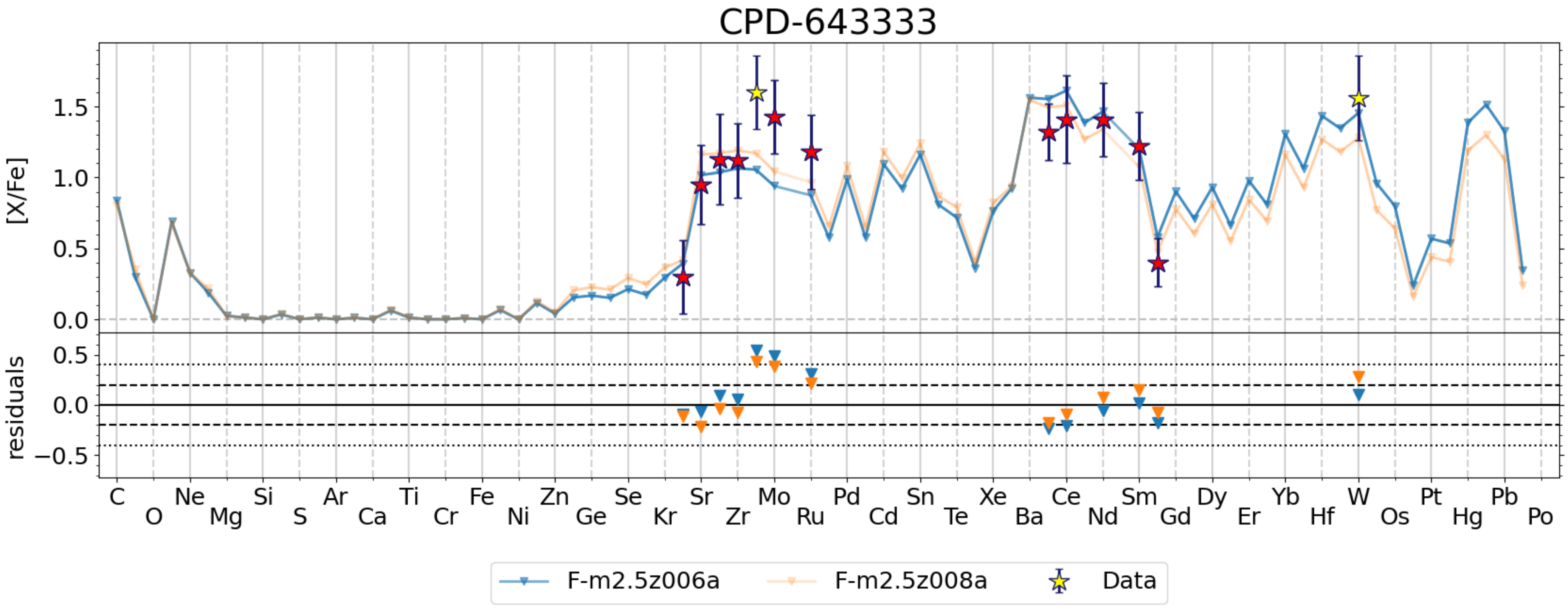


whole sample analysis

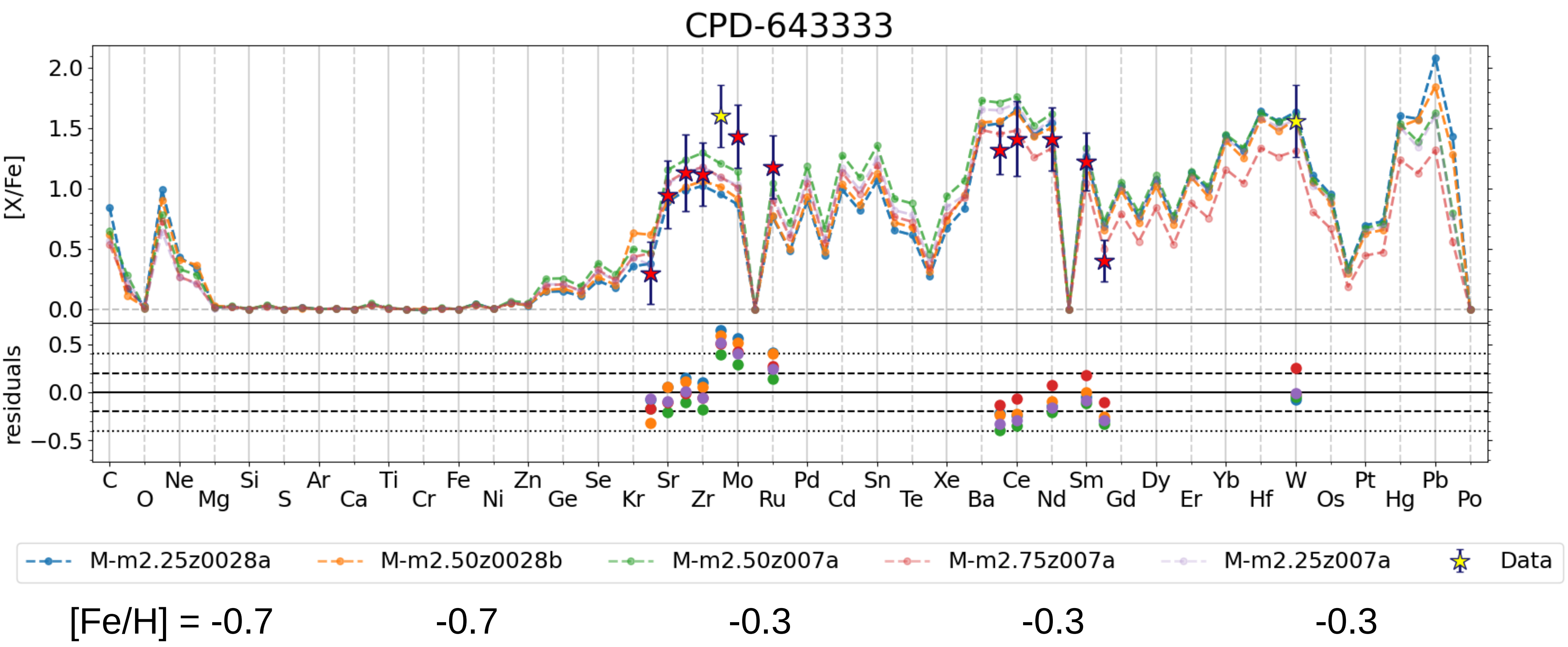
- only abundances, no masses → machine learning methods (den Hartogh+ 2023, Világos+ 2024)
- $\delta < 0.9$, best match, more than one model/star
- anomalous abundance patterns at first peak in 43/169 stars (25%) + Sm
- mass distribution: supported by different ML techniques







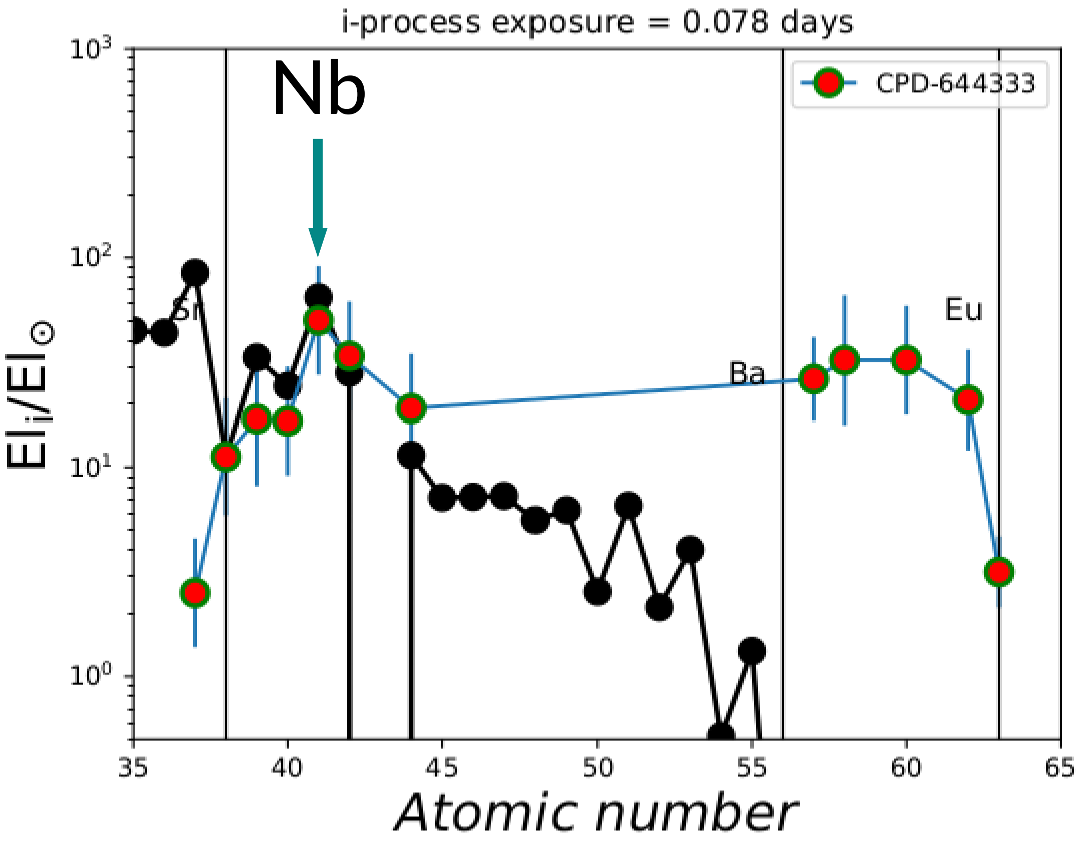
[Fe/H] = -0.368 -0.243


CPD-643333
[X/Fe]
residuals
C O Ne Mg Si S Ar Ca Ti Cr Fe Ni Zn Ge Se Kr Sr Zr Mo Ru Pd Cd Sn Te Xe Ba Ce Nd Sm Gd Dy Er Yb Hf W Os Pt Hg Pb Po
M-m2.25z0028a
M-m2.50z0028b
M-m2.50z007a
M-m2.75z007a
M-m2.25z007a
Data
[Fe/H] = -0.7
-0.7
-0.3
-0.3
-0.3

test: i-process signature?

i-process signature? →
 test (4 stars): simplified
 i-process trajectory,
 NuGrid codes

reproduction of the
 pattern between Sr and Ru



den Hartogh+ (2023)

s process temperatures – Nb vs Zr

- Nb: one stable isotope (^{93}Nb), decay product of ^{93}Zr (half-life ~1.5 Myr)
  → s process thermometer (Neyskens+ 2015)
- steady state: line with slope 1, intercept: ω* (T dependence)
- ^{13}C neutron source: below ~250 MK
- ^{22}Ne: at most ~350–400 MK
- δ → Ba star abundances reversed into AGB original abundance

Világos+ (2024)

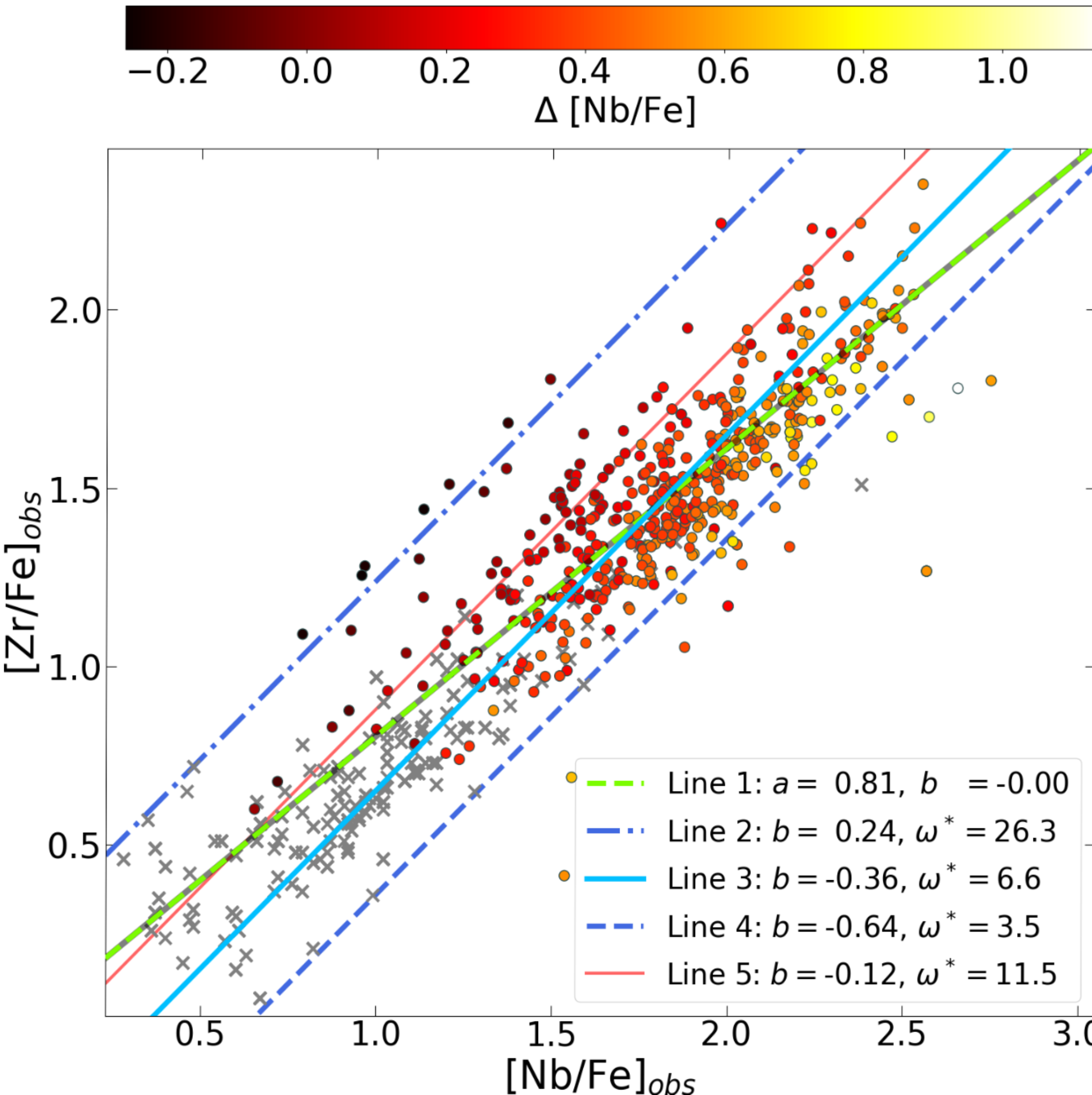
grey crosses:
Ba star abundances

color points: AGB

Line 3: isothermal line
(slope fixed to 1)

Line 1: fit to the data
(slope: free parameter)

AGB temperatures:
90 – 450 MK → ω* ~10 – 17



Világos+ (2024)

summary

- 1,75–3 M_{Sun} AGB s-process models with ^{13}C pocket (Cseh+2018, 2022, den Hartogh+ 2023)
- no Rb enhancement (Roriz+ 2021)
- ~25% Ba stars with higher Nb, Mo, Ru, Nd, and/or Sm abundances → reproduced with i-process calculations (den Hartogh+ 2023)
- some elements might not be produced in a steady-state s process (Világos+ 2024)

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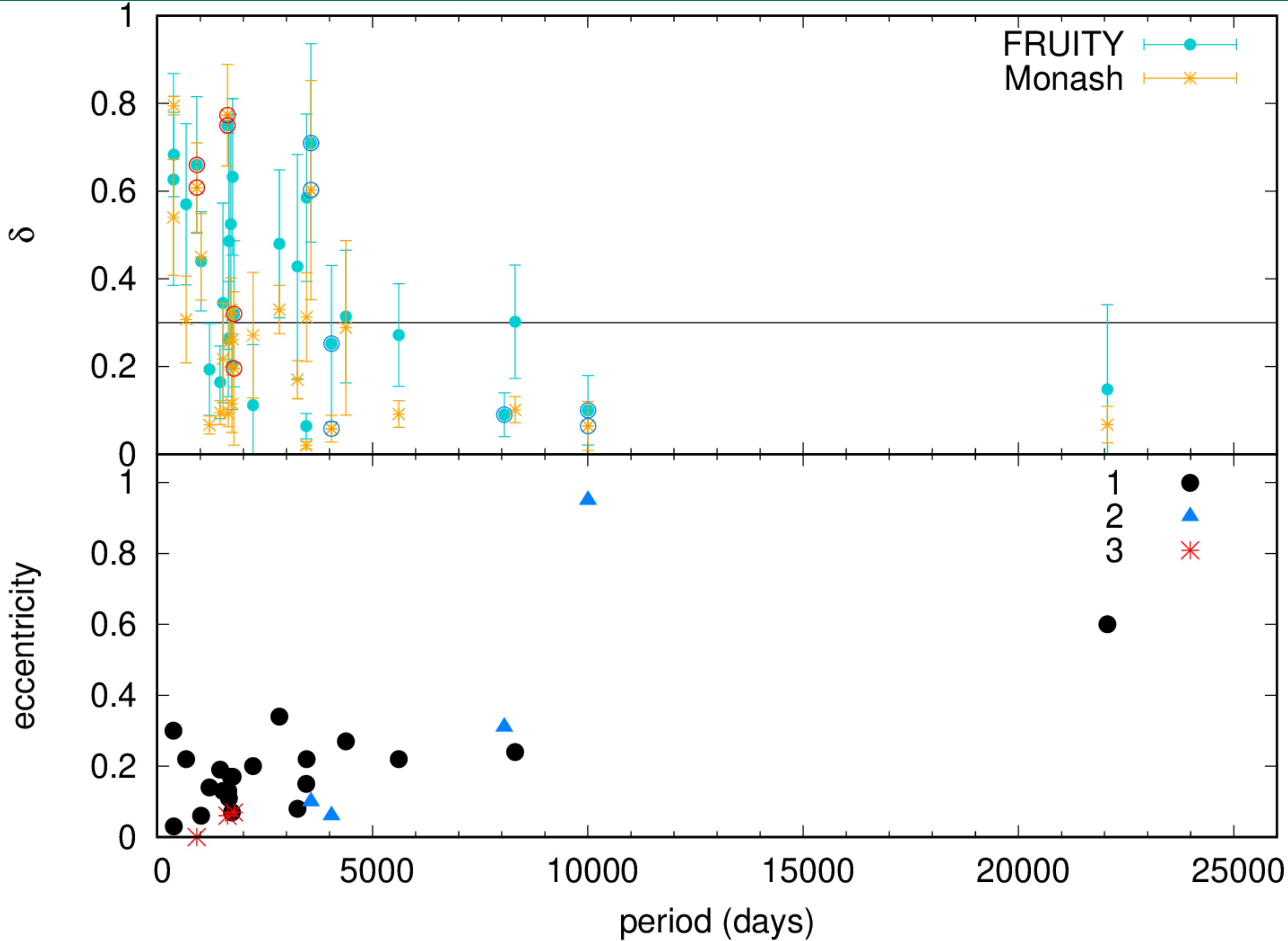
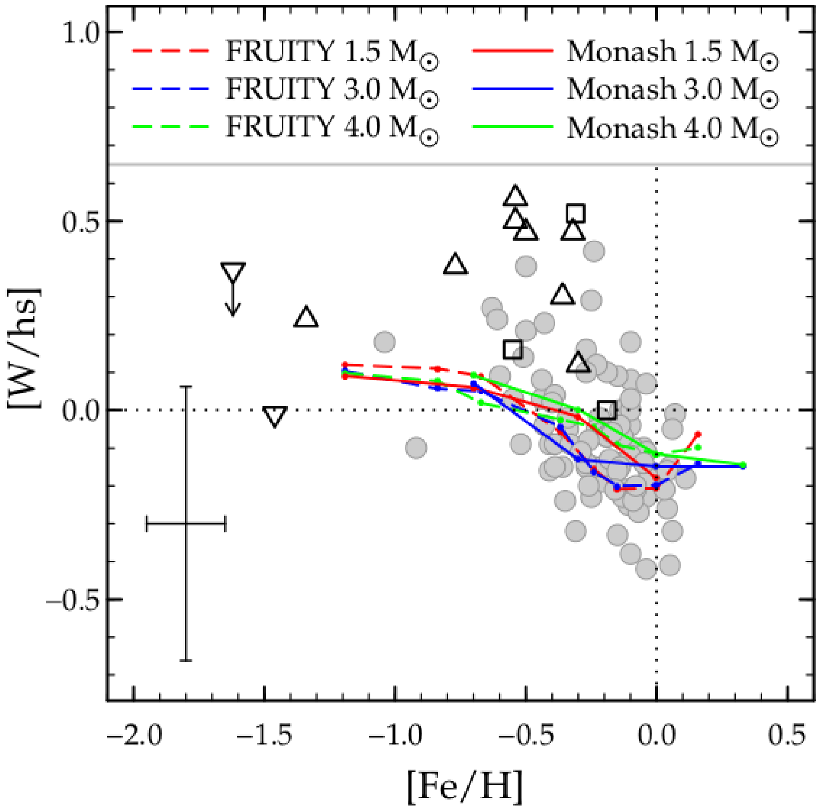
Thank you for your attention!

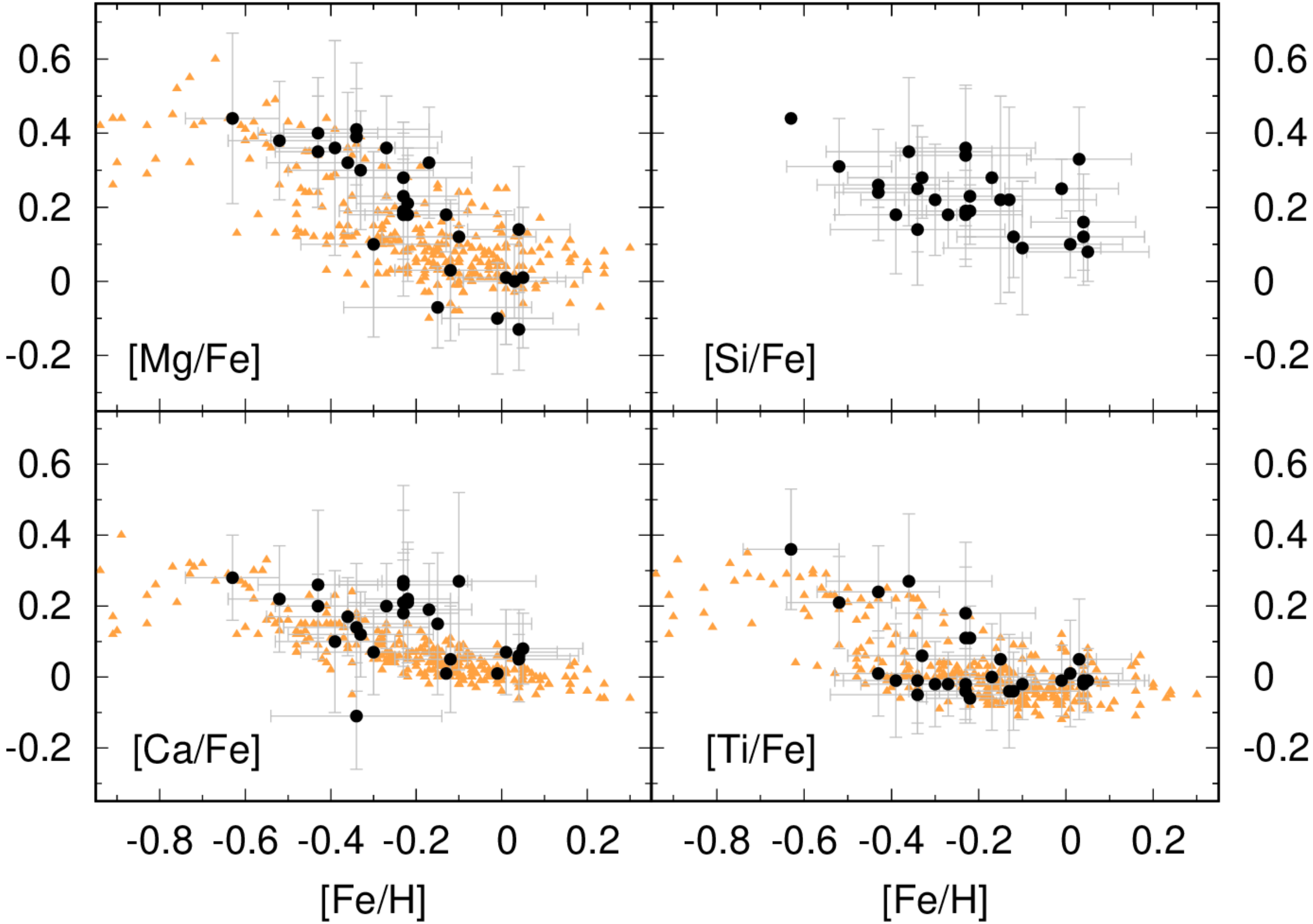
long period
→ low δ



new abundance: tungsten

- W: Roriz+(2024)
- upward triangles: post-AGB stars
  squares: other chemically peculiar stars
- group of W enhanced stars?




[Mg/Fe]
[Si/Fe]
[Ca/Fe]
[Ti/Fe]
0.6
0.4
0.2
0
-0.2
-0.8
-0.6
-0.4
-0.2
0
0.2
[Fe/H]
[Fe/H]