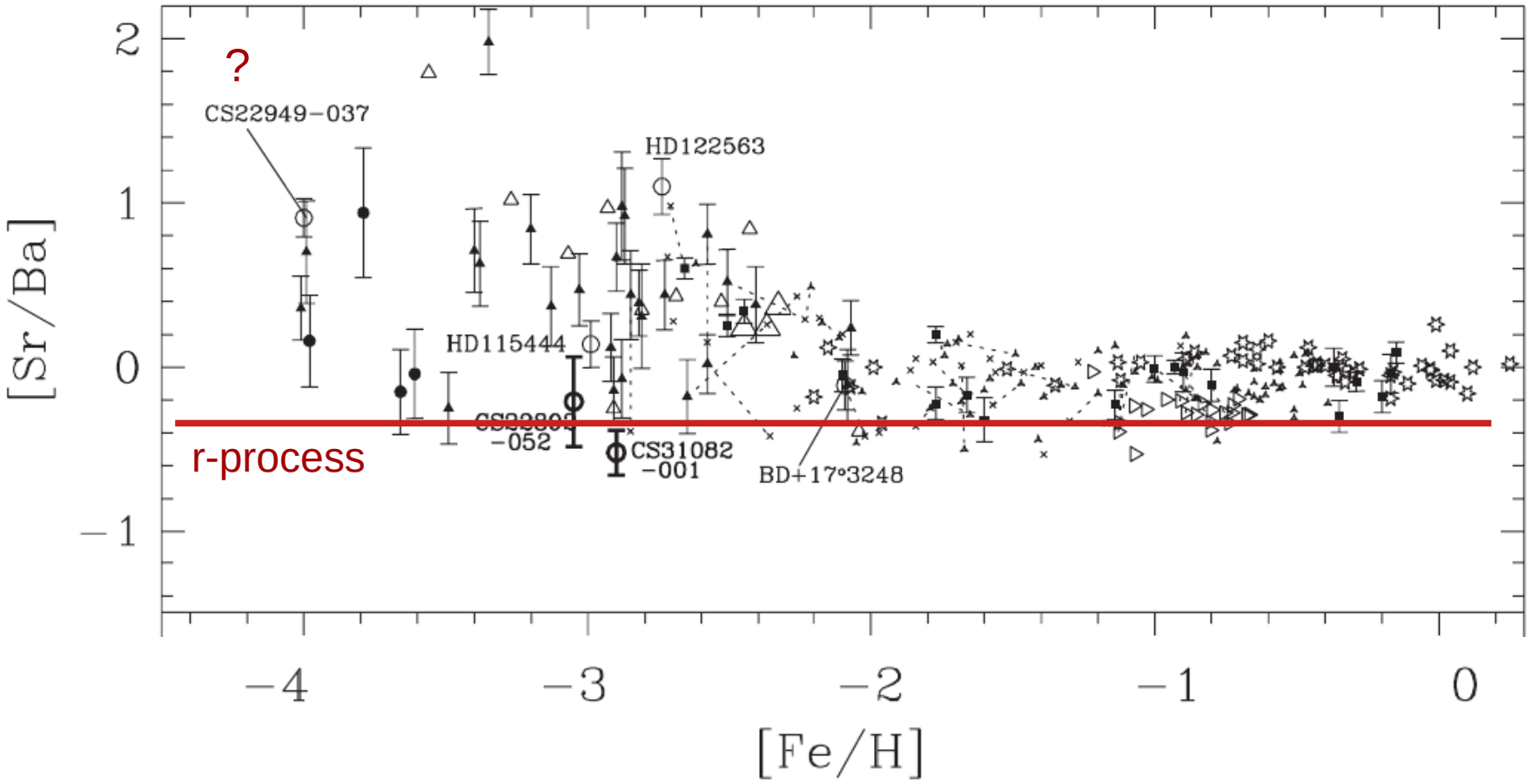
Barium isotope ratio in very metal-poor stars as a key to a puzzle of light neutron-capture element synthesis at the earliest epoch

Tatyana Sitnova
sitamih@gmail.com

L. Lombardo, L. I. Mashonkina, F. Rizzuti,
G. Cescutti, C. J. Hansen, P. Bonifacio, E. Caffau,
A. Koch-Hansen, G. Meynet, R. Fernandes de Melo

Light n-capture elements (Sr, Y, Zr) overabundances

Travaglio et al. (2004): LEPP is required



LEPP candidates

- weak s-process
Z < 45
- weak r-process
Z < 45
- s-process in VMP fast rotating massive stars
- i-process
- charged particle reactions
- νp-process
- something else...

What can we learn about LEPP properties from observations:

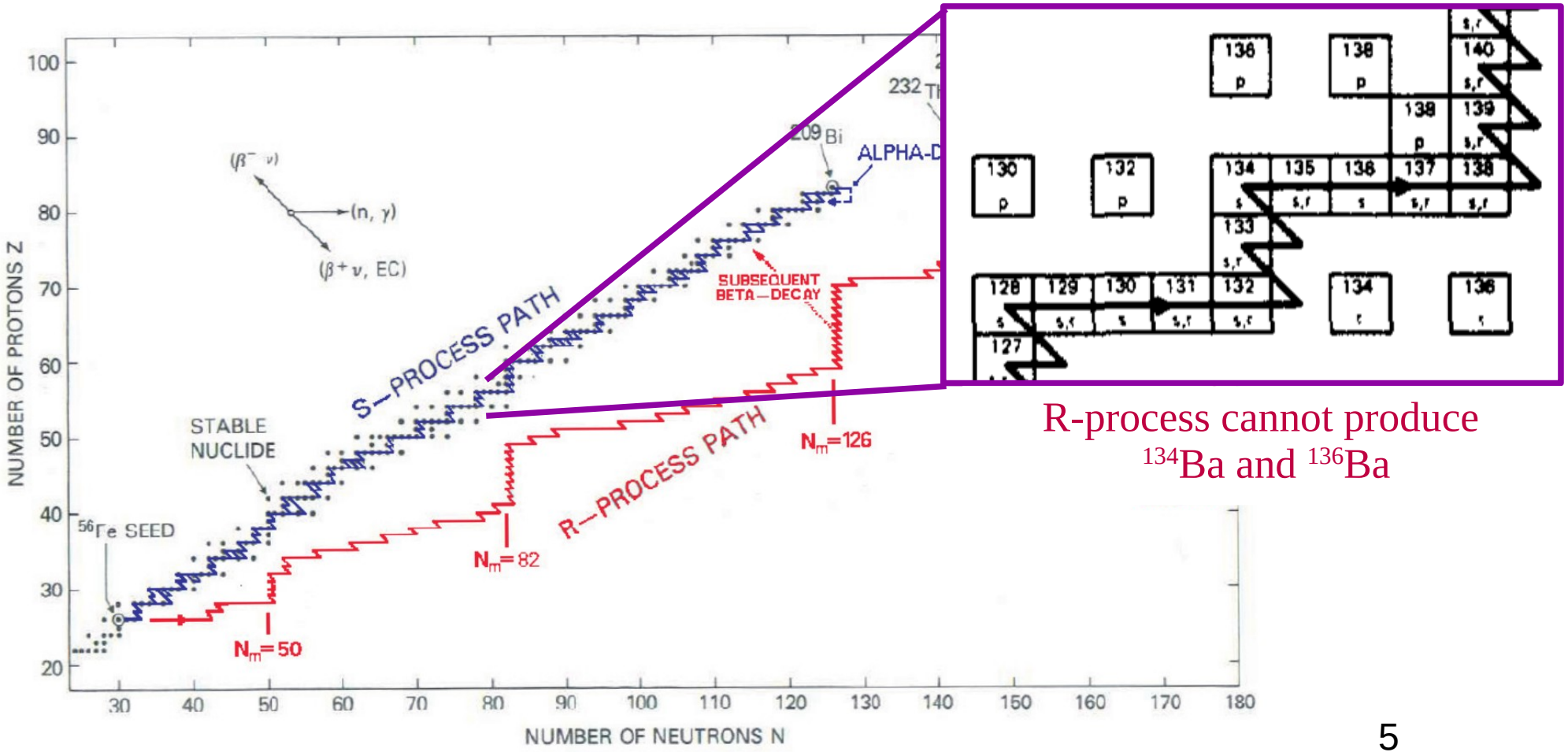
Could it be classified as an r- or s- process?

Does it produce the second peak n-capture elements (Ba)?

If so, which Ba isotopes are formed?

what [Sr/Ba] ratio does it produce?

Why do we need Ba isotope ratio?



R-process cannot produce ^{134}Ba and ^{136}Ba

Rolfs et al. (1987)

Stellar sample

- 16 VMP stars -3.10 < [Fe/H] < -2.15
  (CERES sample, Lombardo et al. 2022)
- Accurate stellar atmosphere parameters
- High-resolution spectra (VLT/UVES, Keck/HIRES) R > 40000, S/N > 100

Selection criteria

- [Ba/H] < -2.2 → sample stars formed before the main s-process
- The Ba II resonance lines with 40 mA < EW < 130 mA

Abundance determination method

- MARCS model atmospheres (Gustafsson et al. 2008)

- NLTE calculations: DETAIL (Giddings 1981; Butler 1984; Mashonkina et al. 2011)

model atoms:
Sr II: Mashonkina et al. (2022)
Ba II: Mashonkina & Belyaev (2019)
Eu II: Mashonkina & Gehren (2000)
NLTE corrections database https://spectrum.inasan.ru/nLTE2/
(Mashonkina et al. 2023)

- synthetic spectra synthV_NLTE (Tsymbal et al. 2019)

- spectral line fitting: binmag (Kochukhov 2018)

- line list: VALD (Pakhomov et al. 2019; Ryabchikova et al. 2015)

Ba isotope ratio determination method

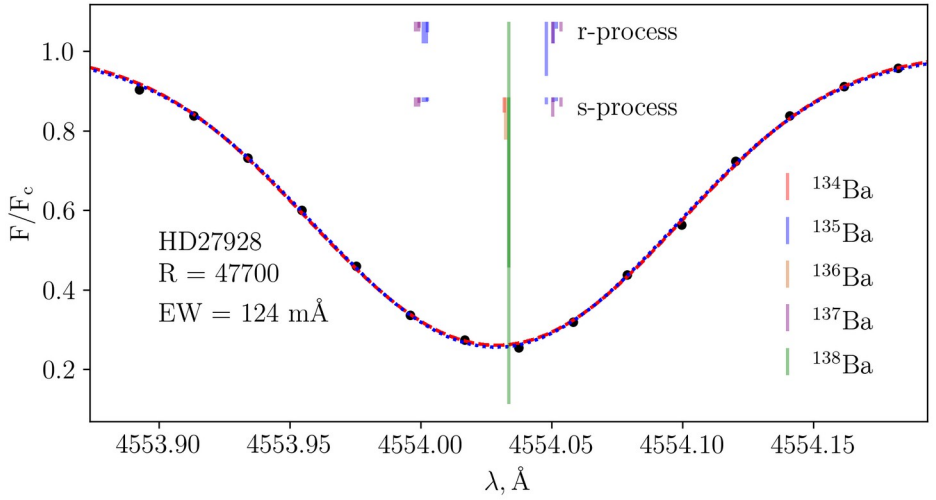
Subordinate (weak): Ba II 5853 A, 6141, 6496 A → Ba abundance

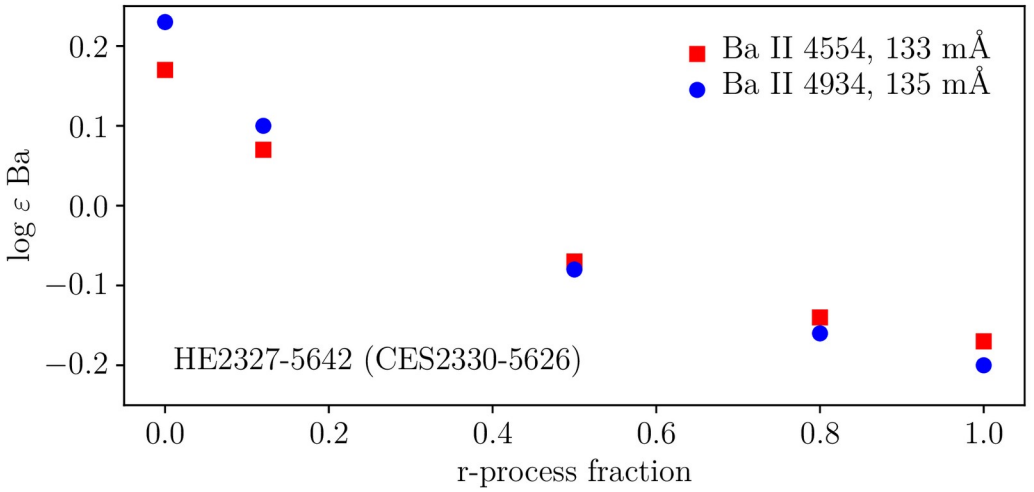
Resonance (strong): Ba II 4554 A, 4934 A → $F_{odd} = N(^{135}Ba+^{137}Ba)/N(Ba)$

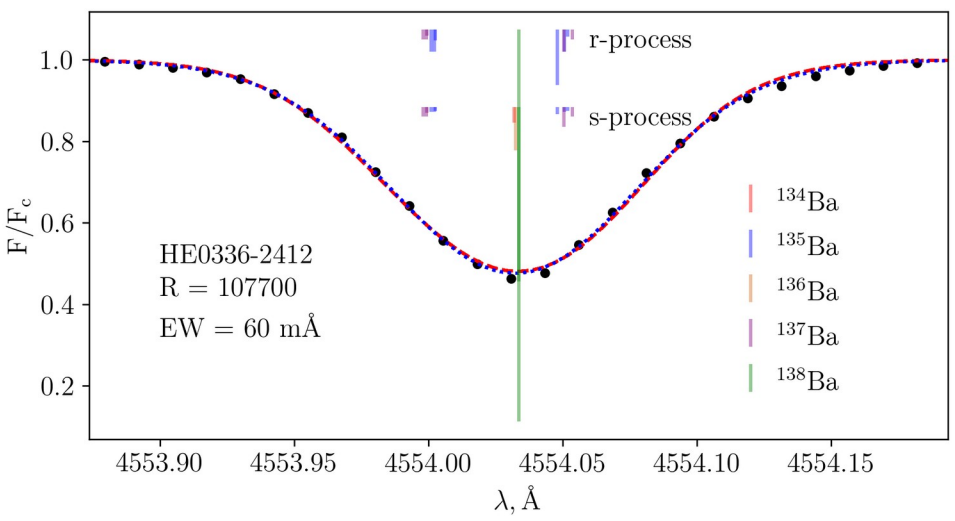
Line profile depends on the adopted Ba isotope ratio.

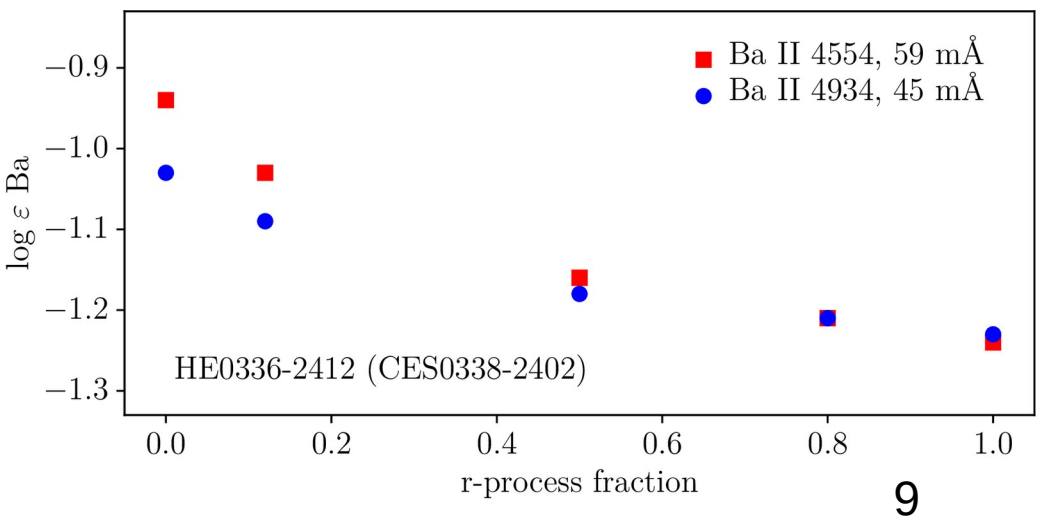
Abundances are calculated for
r/s: 100/0, 80/20, 50/50, 12/88, 0/100
F_{odd}: 0.75, 0.60, 0.43, 0.18, 0.10
Prantzos et al. (2020)

The Ba II resonance lines: profiles and abundances





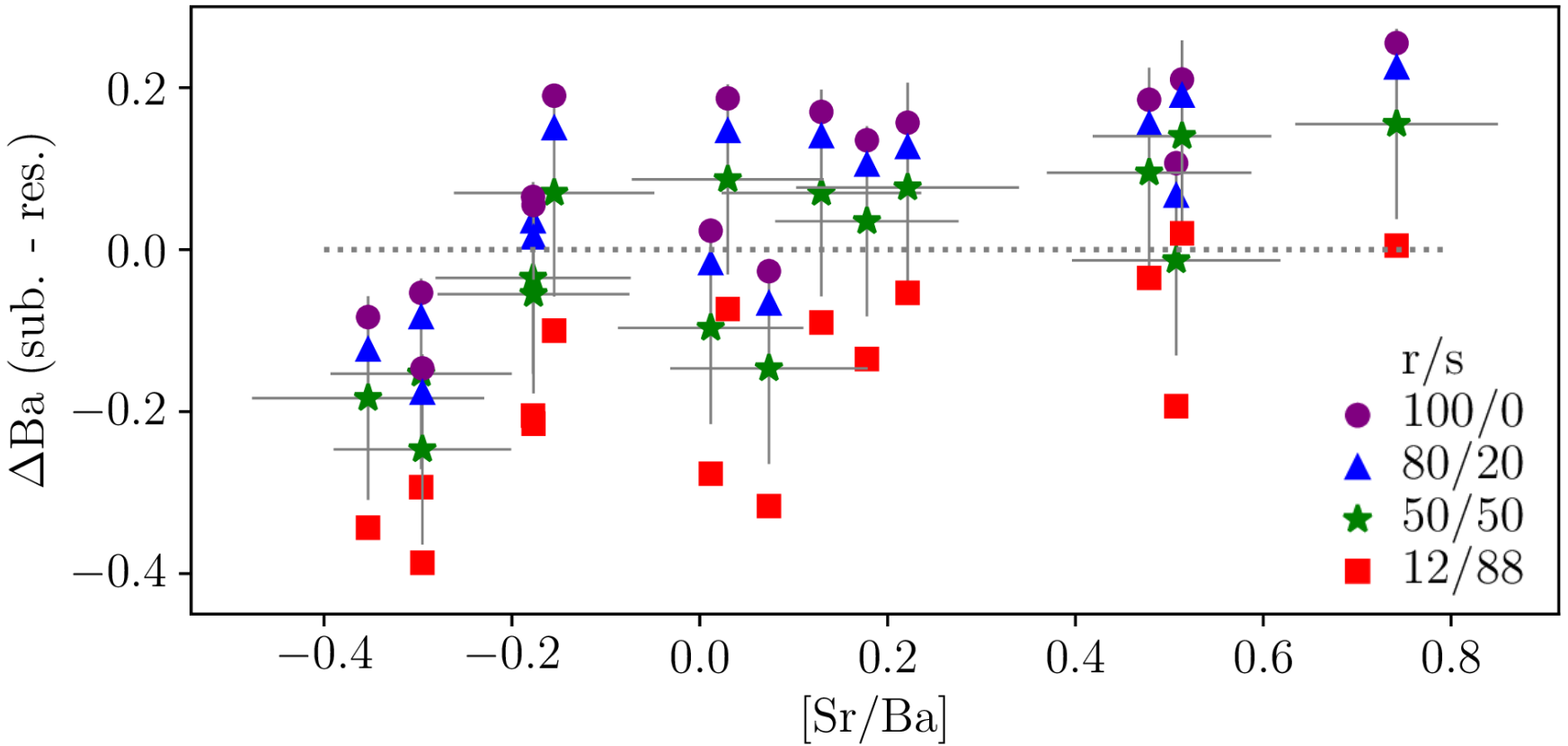




s-process contribution to Ba isotopes increases with [Sr/Ba] (and [Sr/Eu], [Ba/Eu])

- LEPP candidate is an **s-process**
- it produces Sr and Ba

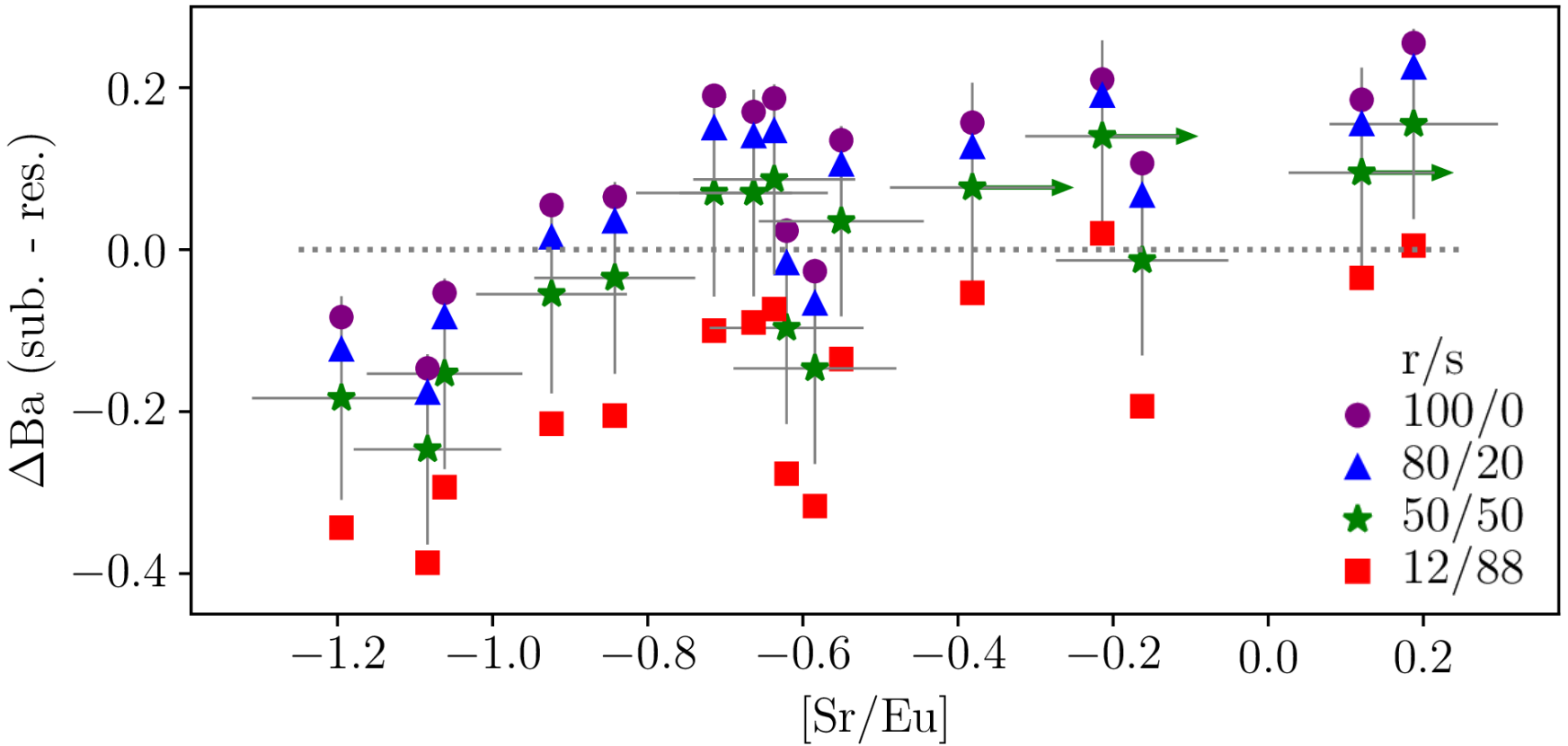
Early s-process in
VMP massive stars



s-process contribution to Ba isotopes increases with [Sr/Ba] (and [Sr/Eu], [Ba/Eu])

- LEPP candidate is an **s-process**
- it produces Sr and Ba

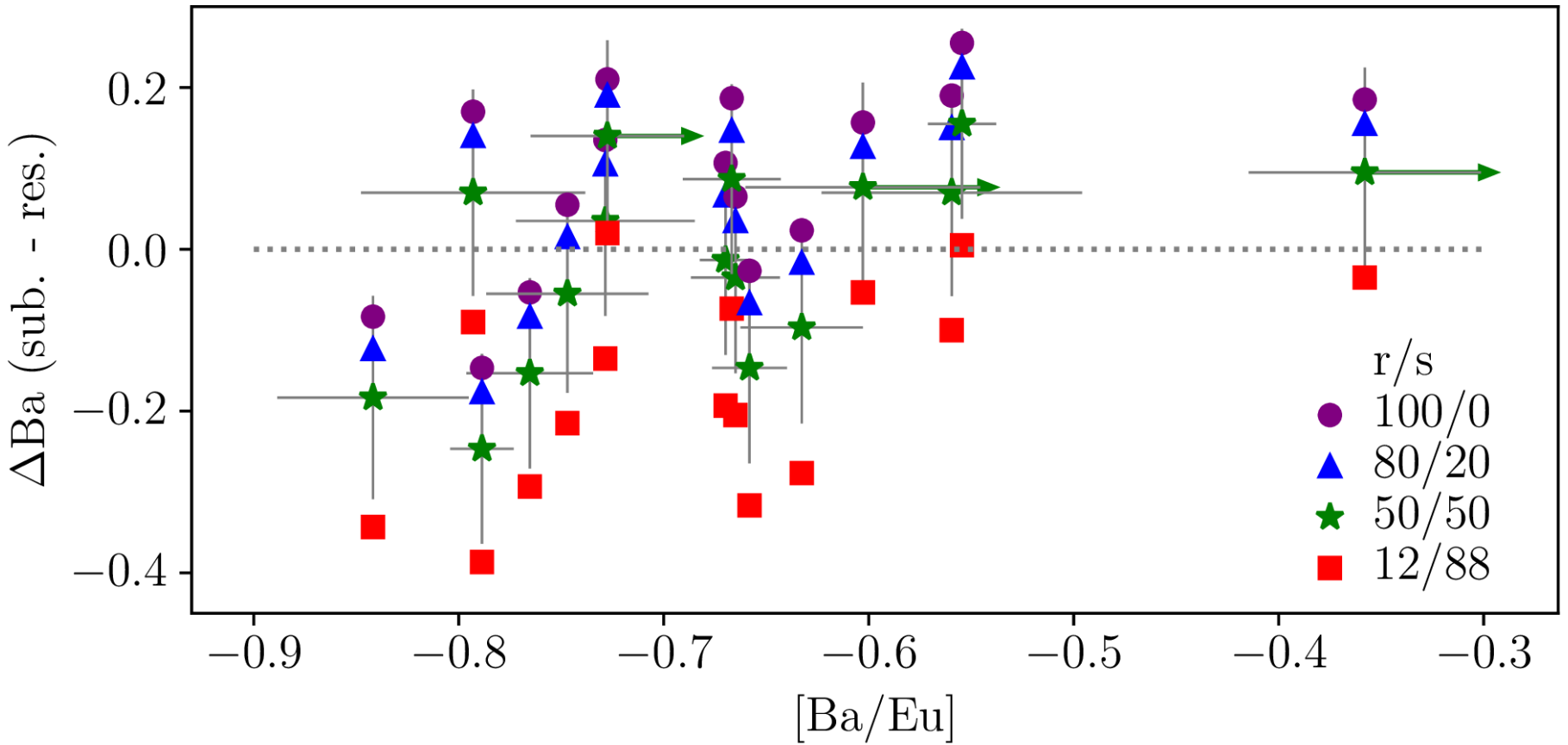
Early s-process in
VMP massive stars



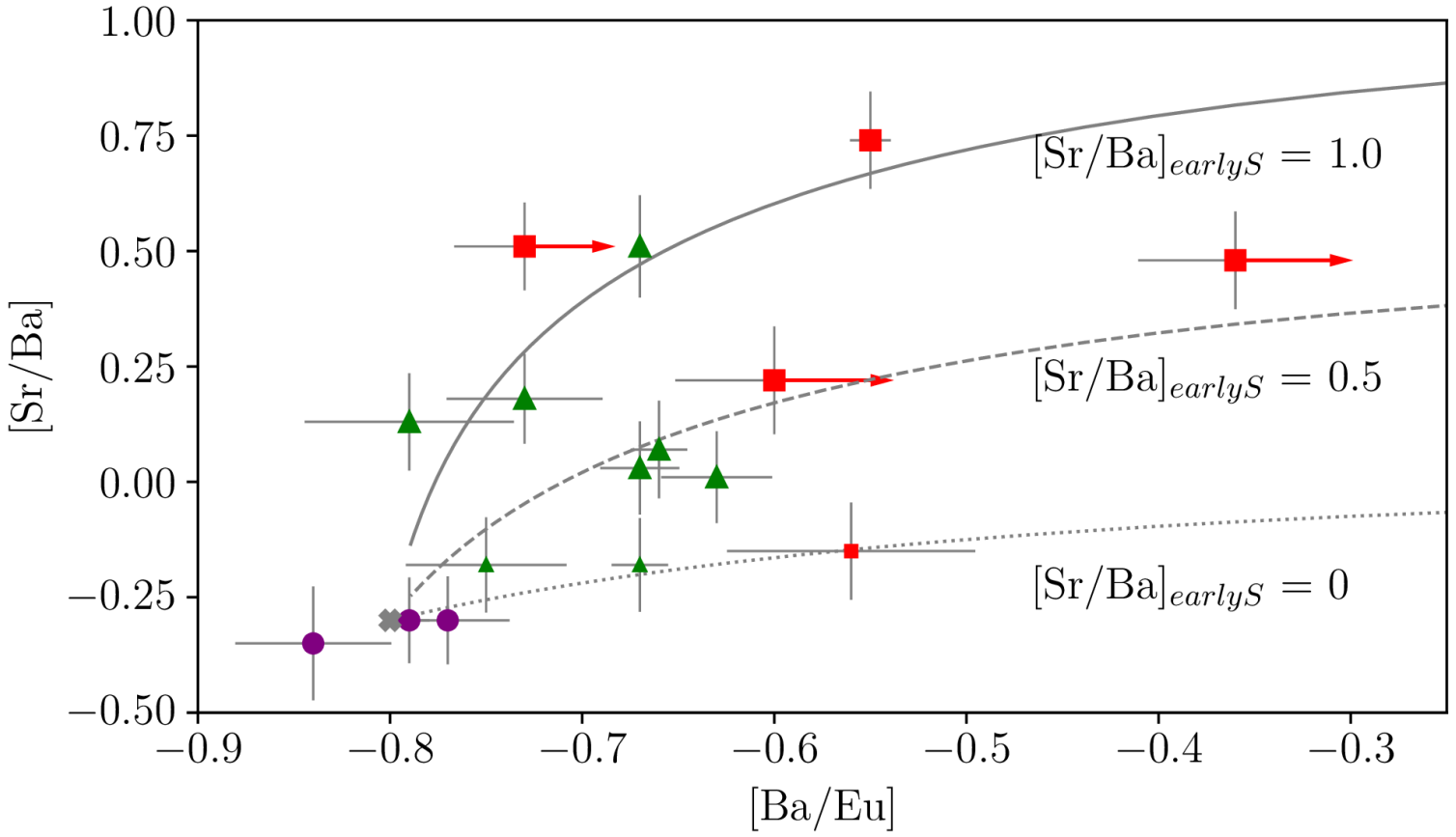
s-process contribution to Ba isotopes increases with [Sr/Ba] (and [Sr/Eu], [Ba/Eu])

- LEPP candidate is an **s-process**
- it produces Sr and Ba

Early s-process in
VMP massive stars

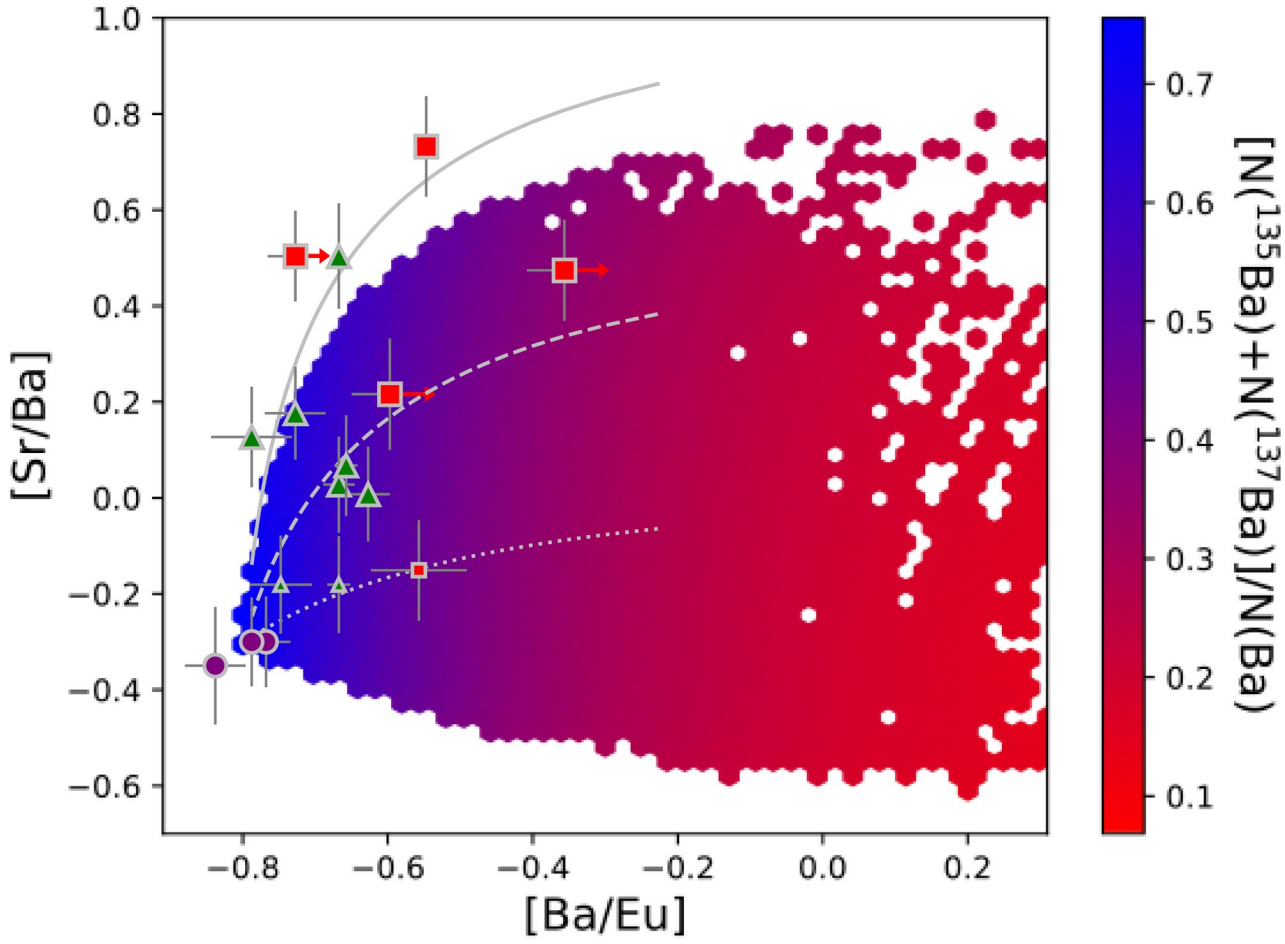


[Sr/Ba] ratio in the early s-process

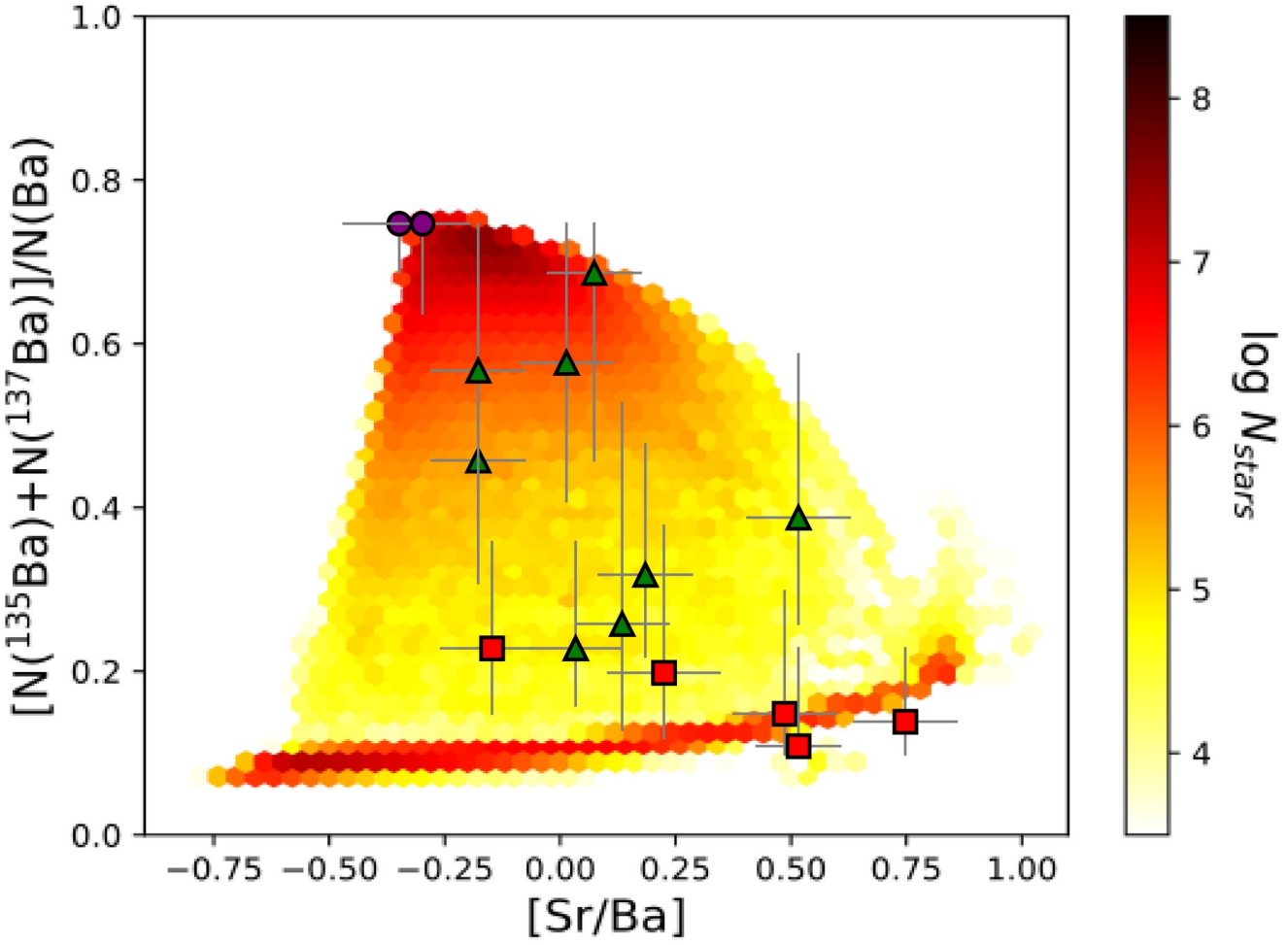


$[Sr/Ba]_{early\ s}$ estimation by subtracting r-process from stellar abundances

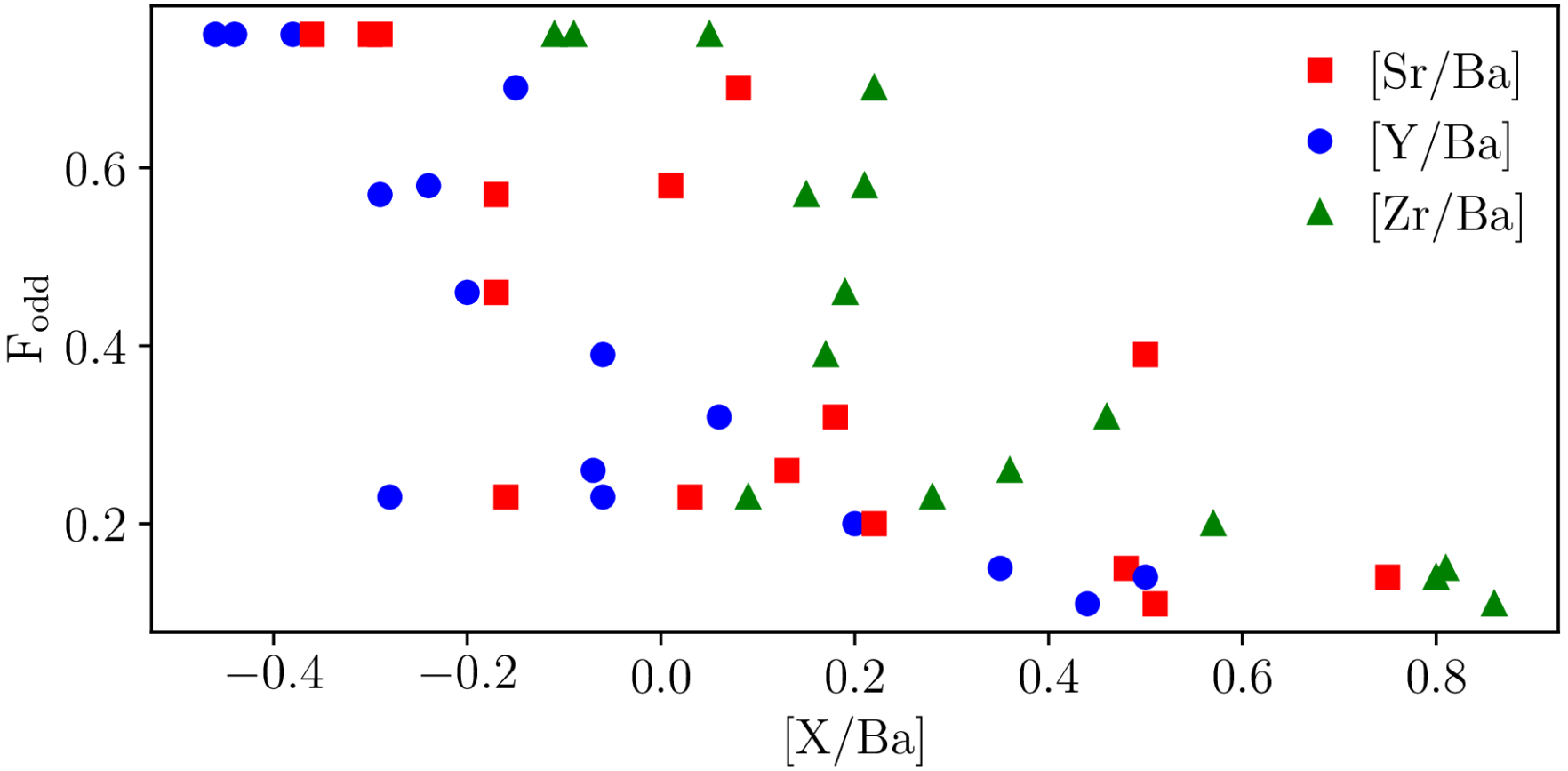
Comparison with the GCE model of Rizzuti et al. (2025)



Comparison with the GCE model of Rizzuti et al. (2025)



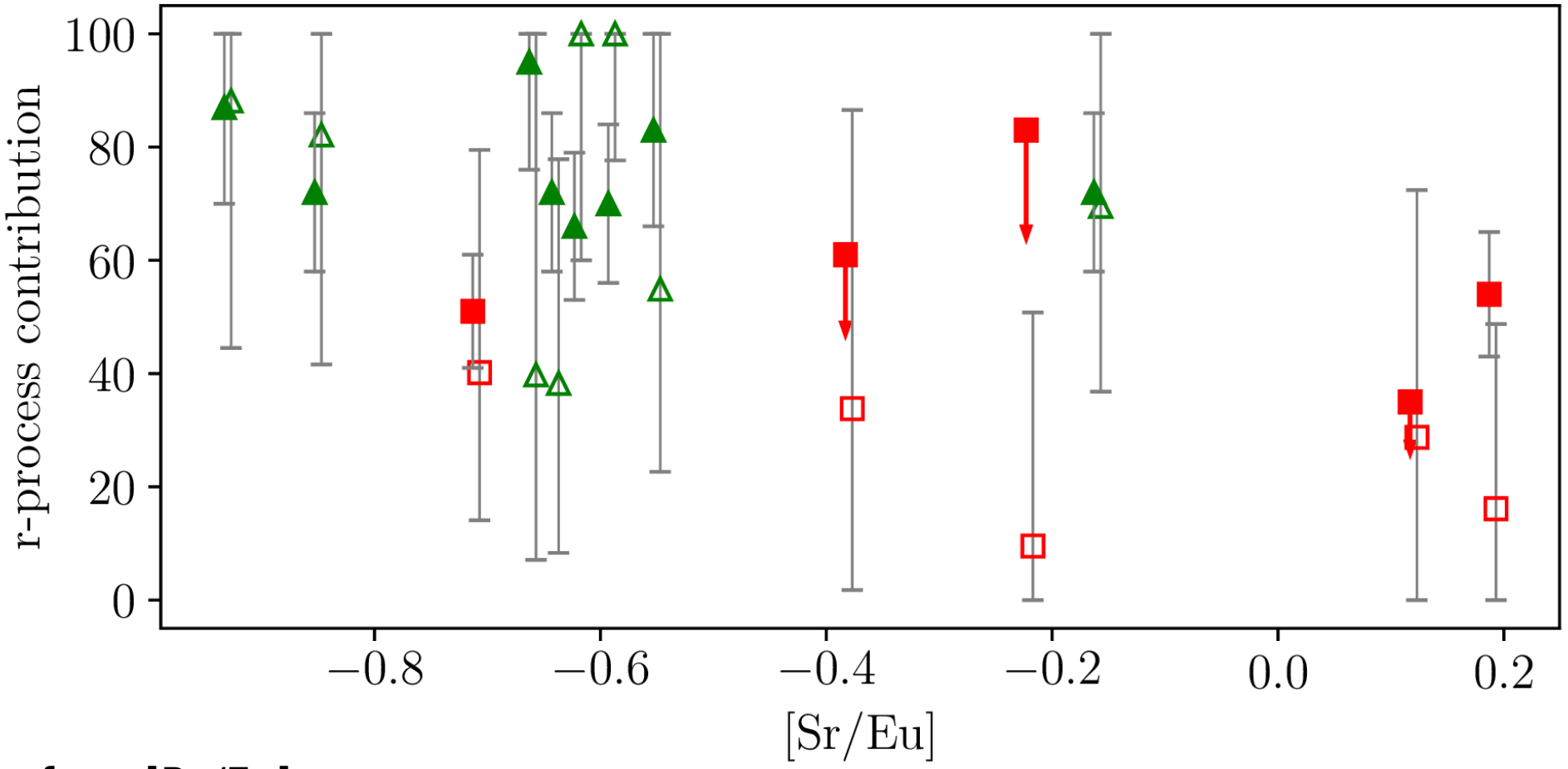
Other light n-capture elements - Y and Zr



Conclusion

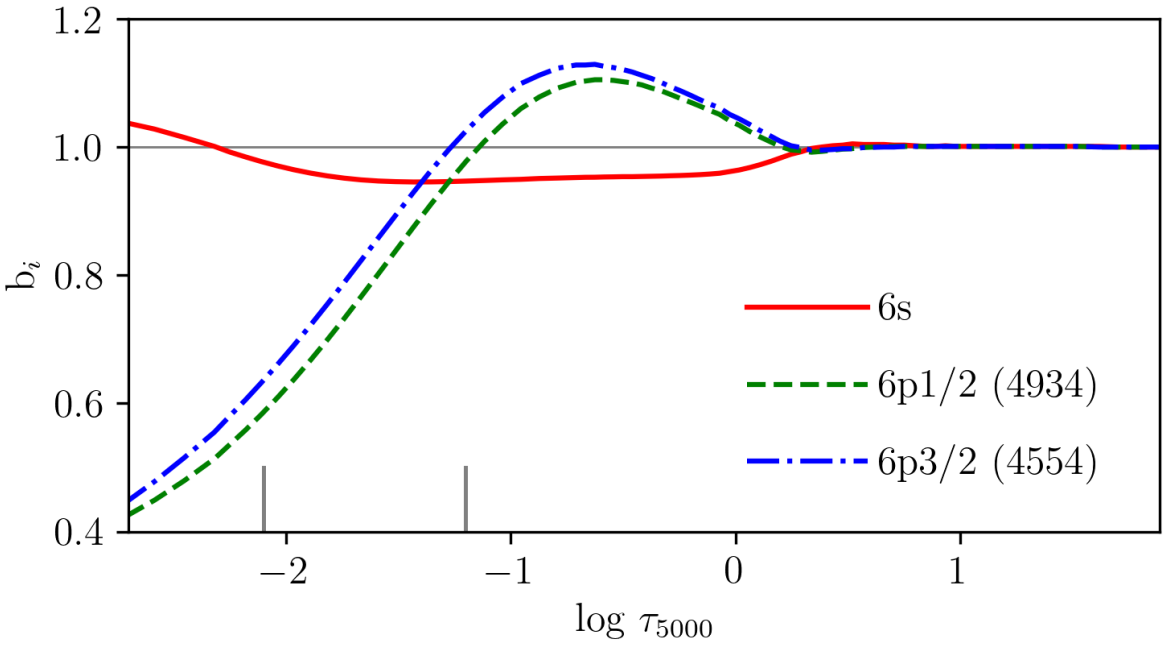
The additional source of Sr, Y, and Zr in the early Galaxy is the early s-process occurring in massive stars.


Thank you!



▲ from [Ba/Eu]
Δ from Ba isotopes

Paradox of the Ba II resonance lines

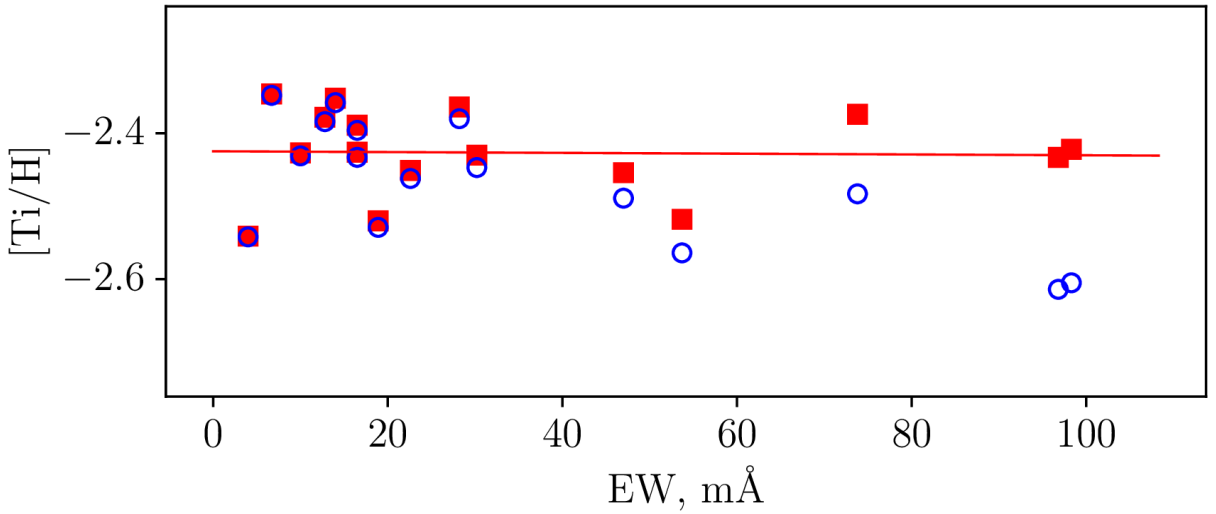


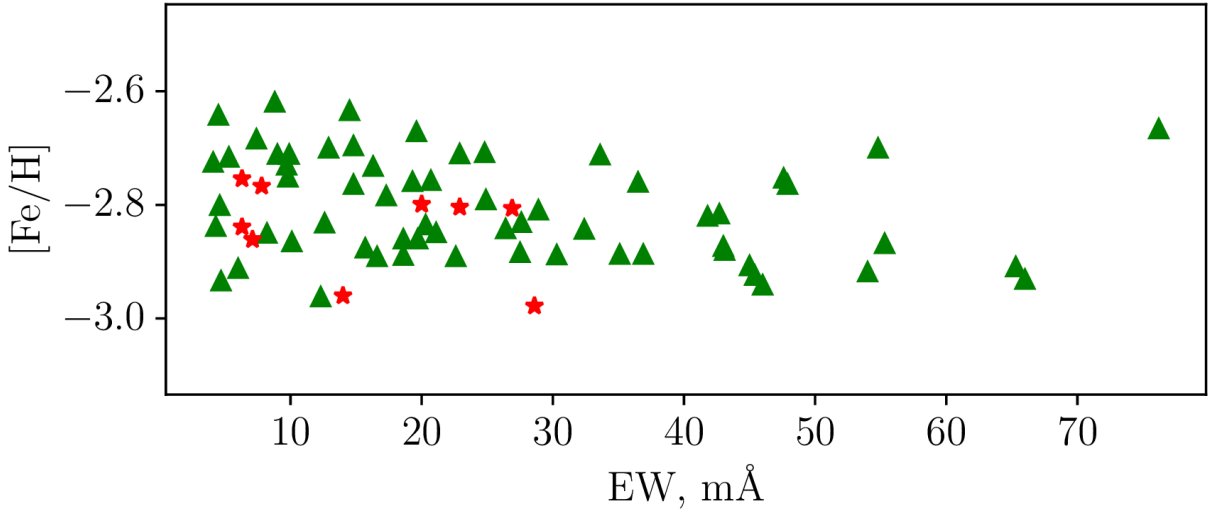
$(f_{4934}\ 4934)/(f_{4554}\ 4554) = 0.60$

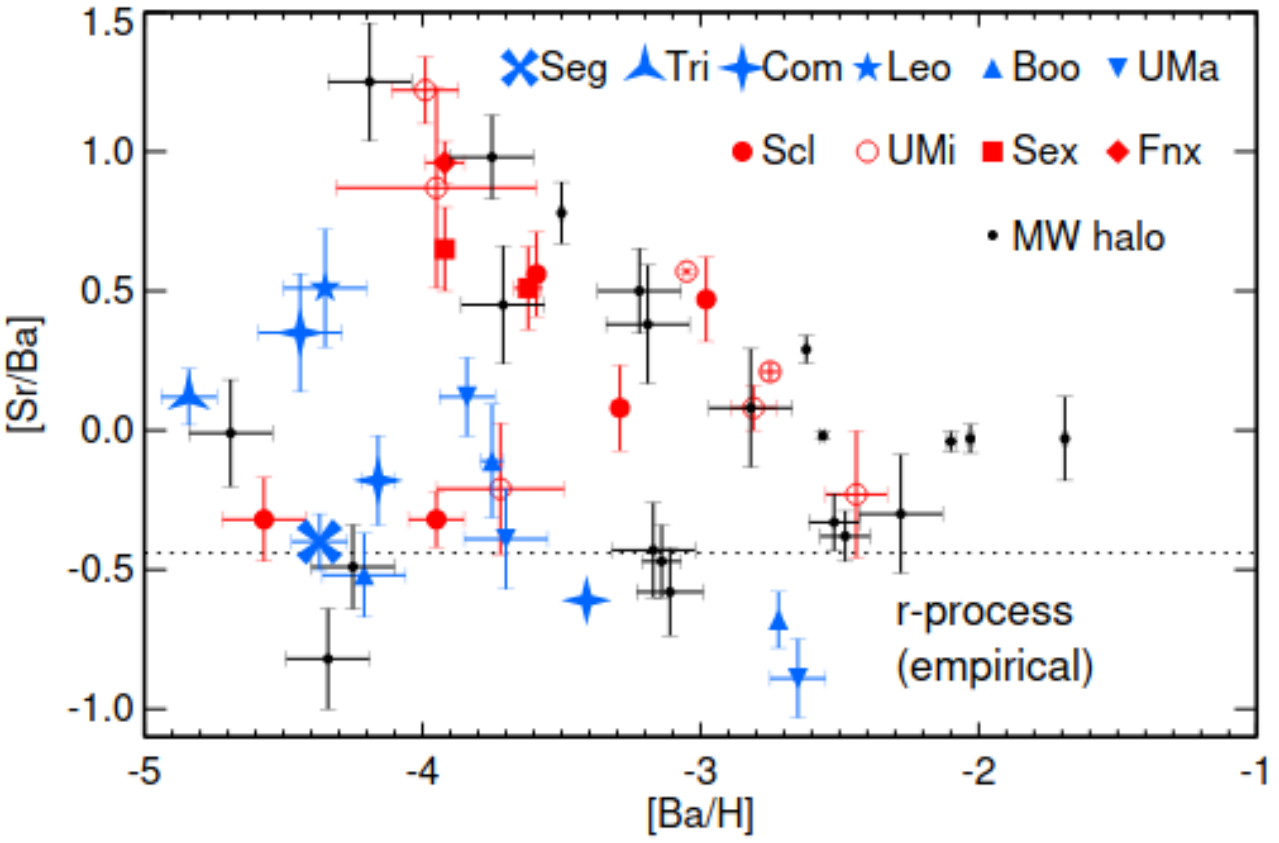
Stars with $EW_{res} > 110$ mA may exhibit $EW_{4934} > EW_{4554}$

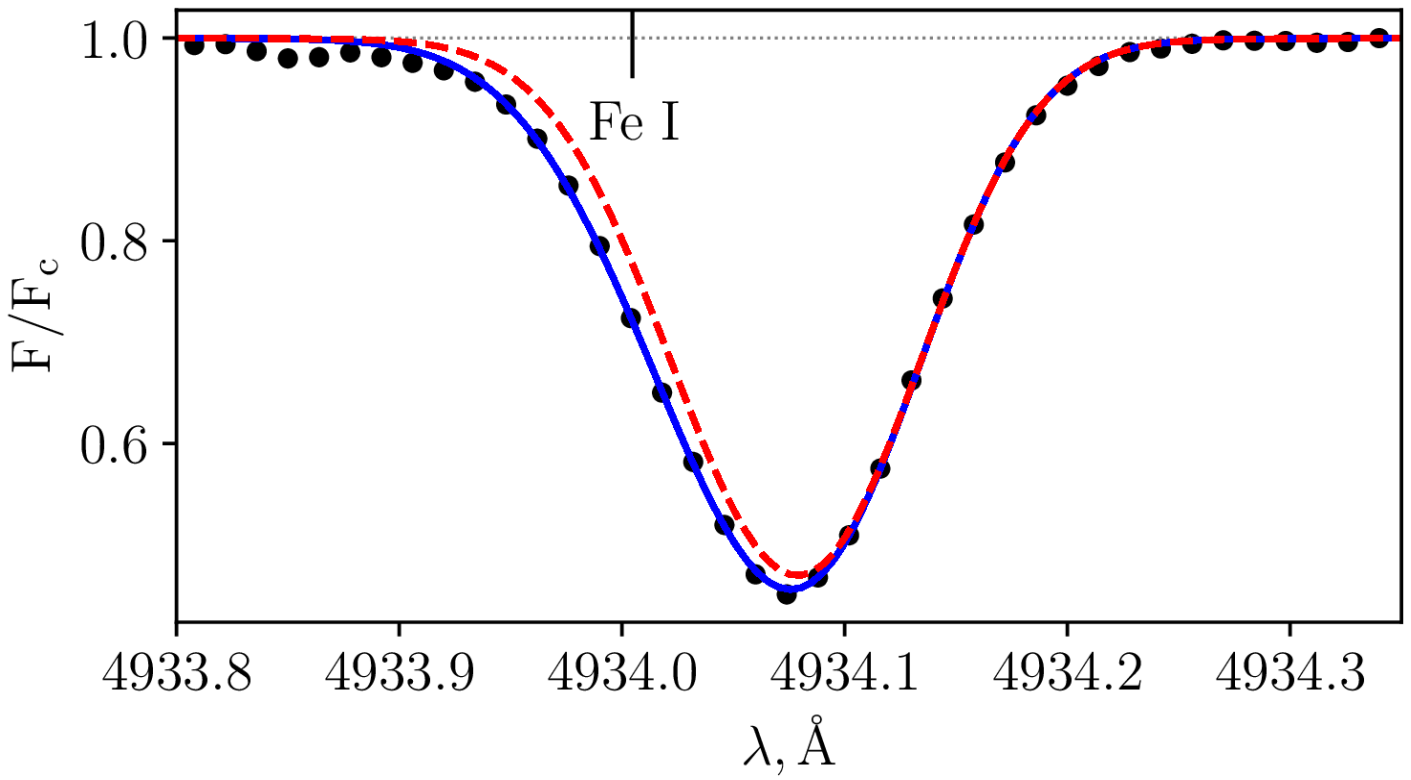
S/B ~ b_u/bl	< 1	> 1
Line	stronger	weaker

Due to the reduced line weakening in the deep layers, the Ba II 4934 A line may ultimately appear stronger than the Ba II 4554 A line!


[Ti/H]
−2.4
−2.6
0
20
40
60
80
100
EW, mÅ


[Fe/H]
−2.6
−2.8
−3.0
10
20
30
40
50
60
70
EW, mÅ


Seg
Tri
Com
Leo
Boo
UMa
Scl
UMi
Sex
Fnx
MW halo
r-process
(empirical)
[Sr/Ba]
[Ba/H]
1.5
1.0
0.5
0.0
-0.5
-1.0
-5
-4
-3
-2
-1


1.0
0.8
0.6
F/F$_c$
Fe I
4933.8
4933.9
4934.0
4934.1
4934.2
4934.3
λ, Å