

# Abundance distribution of neutron-capture elements in very metal-poor stars

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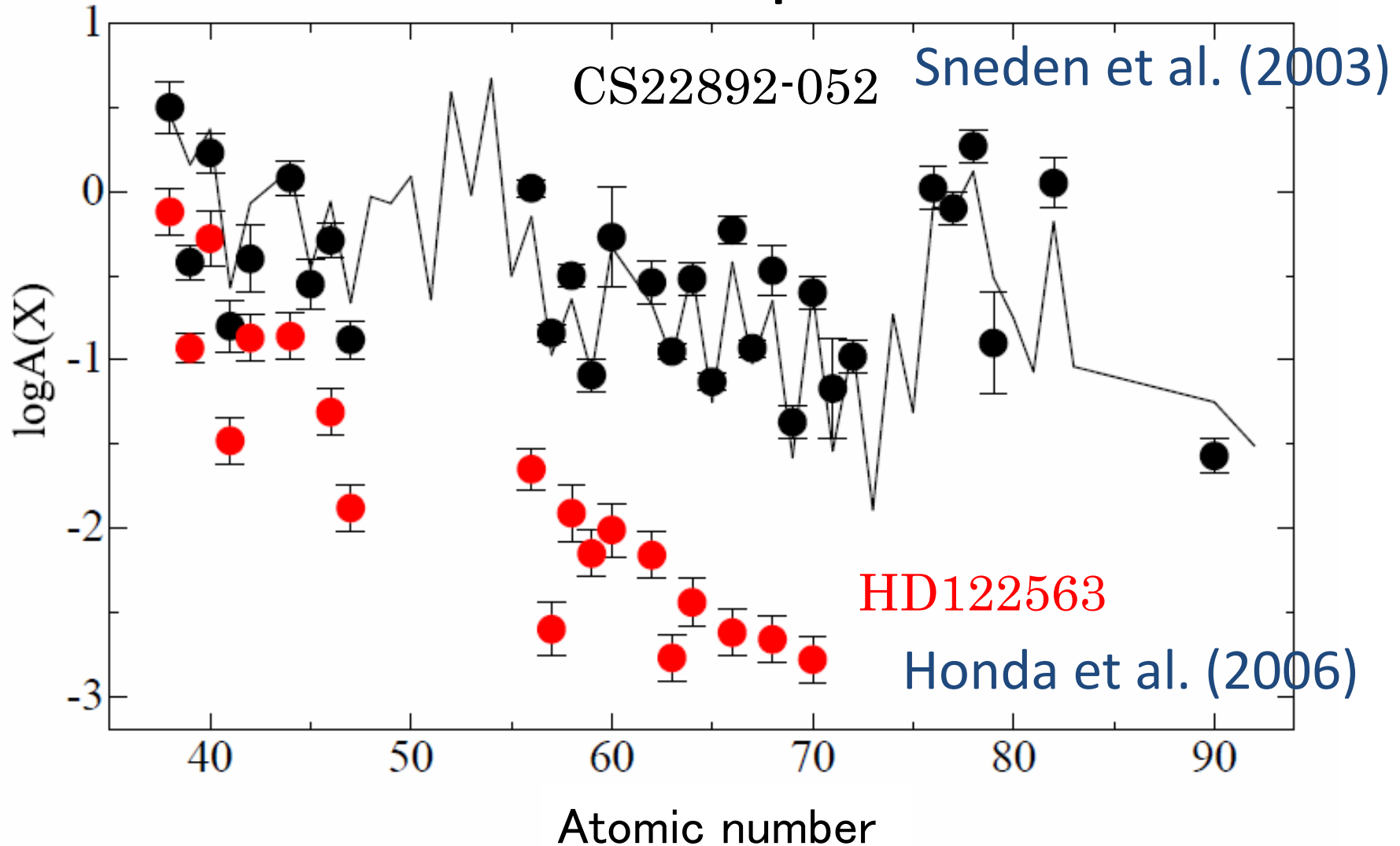
# Abundance distribution of neutron-capture elements in very metal-poor stars

- Sr/Ba ratios
- Ba isotope ratios
- Diversity of the weak r-process

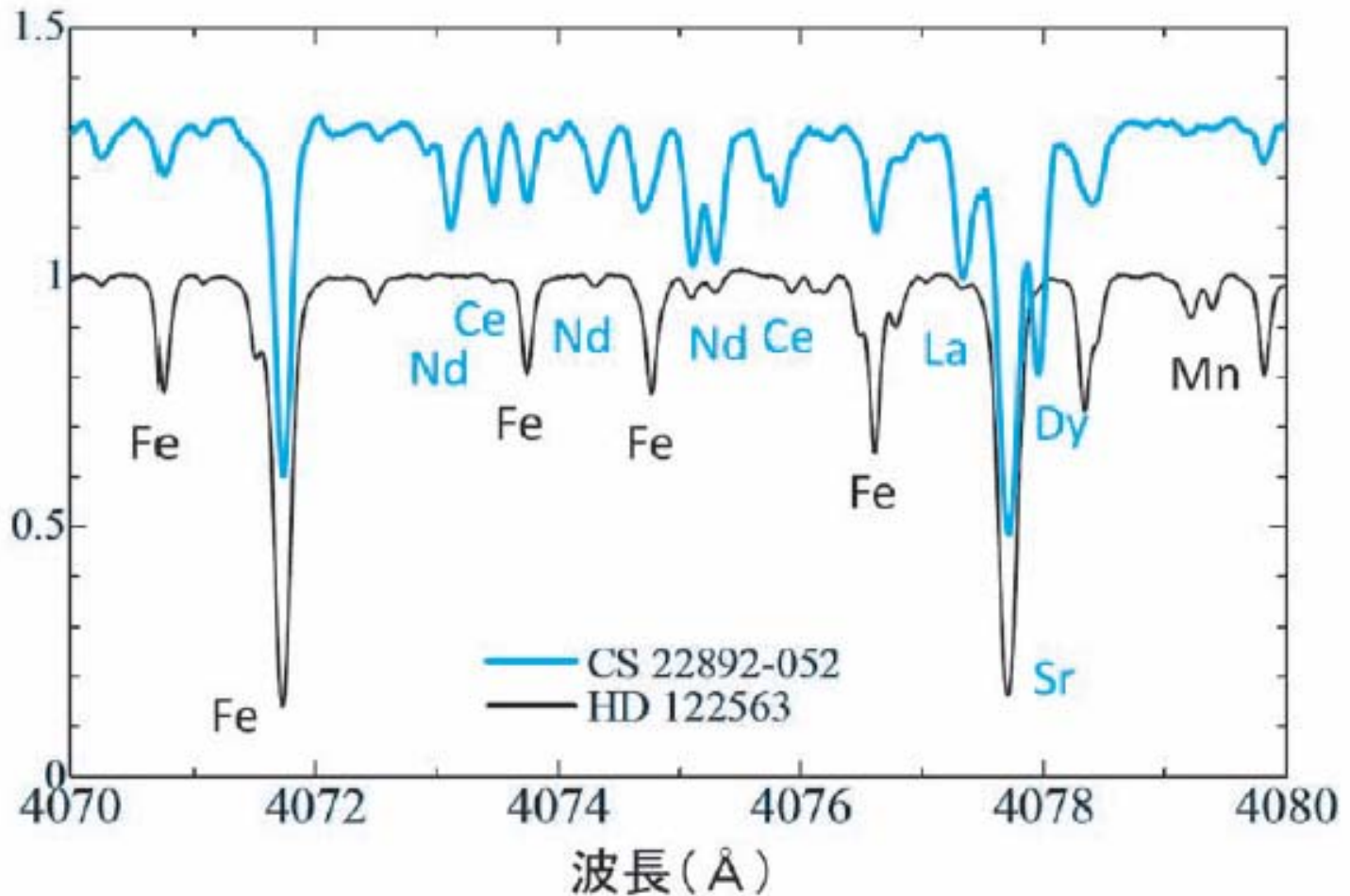
# Definition

- Chemical abundance: abundance ratio with respect to H  
 $\log \epsilon(X)$  or  $\log A(X) = \log(X/H) + 12$   
ex.  $\text{Fe}/\text{H} = 10^{-4.5} \rightarrow \log \epsilon(\text{Fe}) = 7.5$   
 $[X/Y] = \log(X/Y) - \log(X/Y)_{\text{sun}}$   
ex.  $[\text{Fe}/\text{H}] = -2.0 \rightarrow 1/100$  of the solar Fe/H ratio
- Metallicity: total abundance of heavy elements (elements heavier than boron)  
important for stellar structure and evolution  
sometimes presented as mass ratio  
ex. Solar metallicity = 0.02 (2%) or slightly lower  
usually represented by  $[\text{Fe}/\text{H}]$

# “main” and “weak” r-process abundance pattern



# Spectral features of “Snedden star” and “Honda star”



# HD122563, the “Honda star”

Wallerstein et al. 1963, ApJ

## RED GIANTS WITH EXTREME METAL DEFICIENCIES\*

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*Received July 23, 1962*

### ABSTRACT

The three field stars, HD 122563, HD 165195, and HD 221170, similar to giants in metal-poor globular clusters, which we have studied, show decreases in the average metal/hydrogen ratios by factors of 800, 500, and 500, respectively, compared with the sun. The abundance ratios of other elements to iron resemble those in the sun, with important exceptions. Manganese and vanadium are deficient with respect to iron, by a factor of 3. In HD 122563 all elements heavier than zinc are deficient compared with iron by a factor of 50, yielding a total deficiency of about 50000 for the heavy elements.

We interpret these observations by assuming that the elements were synthesized from hydrogen early in the history of our Galaxy. These stars were formed when the interstellar medium was almost entirely hydrogen, between  $10^7$  and  $10^8$  years after star formation began. Their metallic constituents were formed

# HD122563, the “Honda star”

Sneden & Parthasarathy 1983, ApJ

THE *r*- AND *s*-PROCESS NUCLEI IN THE EARLY HISTORY OF THE GALAXY: HD 122563

CHRISTOPHER SNEDEN AND M. PARTHASARATHY

Department of Astronomy, University of Texas at Austin

*Received 1982 July 26; accepted 1982 October 7*

## ABSTRACT

New high-resolution, high signal-to-noise spectra in the blue and ultraviolet spectral regions have been obtained for the extremely metal-poor giant star HD 122563. A complete model atmosphere, spectrum synthesis analysis of this star has been performed, employing a large number of weak iron-peak species lines and laboratory oscillator strengths. Spectral features of many rare earth elements have been detected in the ultraviolet. The large overdeficiency of nearly a factor of 10 for the *s*-process element barium is confirmed and is shown to extend to the other *s*-process elements La, Ce, Pr, Nd, and Sm. The *r*-process elements Eu, Gd, Dy, and possibly Er and Yb are less deficient than the *s*-process elements but do exhibit lower ratios with respect to iron-peak elements than in the Sun. A supplementary differential analysis of HD 122563 with respect to the Sun shows that the heavy-element abundances are not very model-atmosphere dependent. The heavy-element abundances can be understood with nucleosynthesis models in which the progenitors of this star produce mainly *r*-process isotopes. A small contribution of the *s*-process to the creation of the elements Sr, Y, Zr, and possibly Ba is not ruled out, but such traditional *s*-process elements as La, Pr, and Nd appear to have been made in the *r*-process in stellar generations prior to the formation of HD 122563.

# HD122563, the “Honda star”

Sneden & Parthasarathy 1983, ApJ

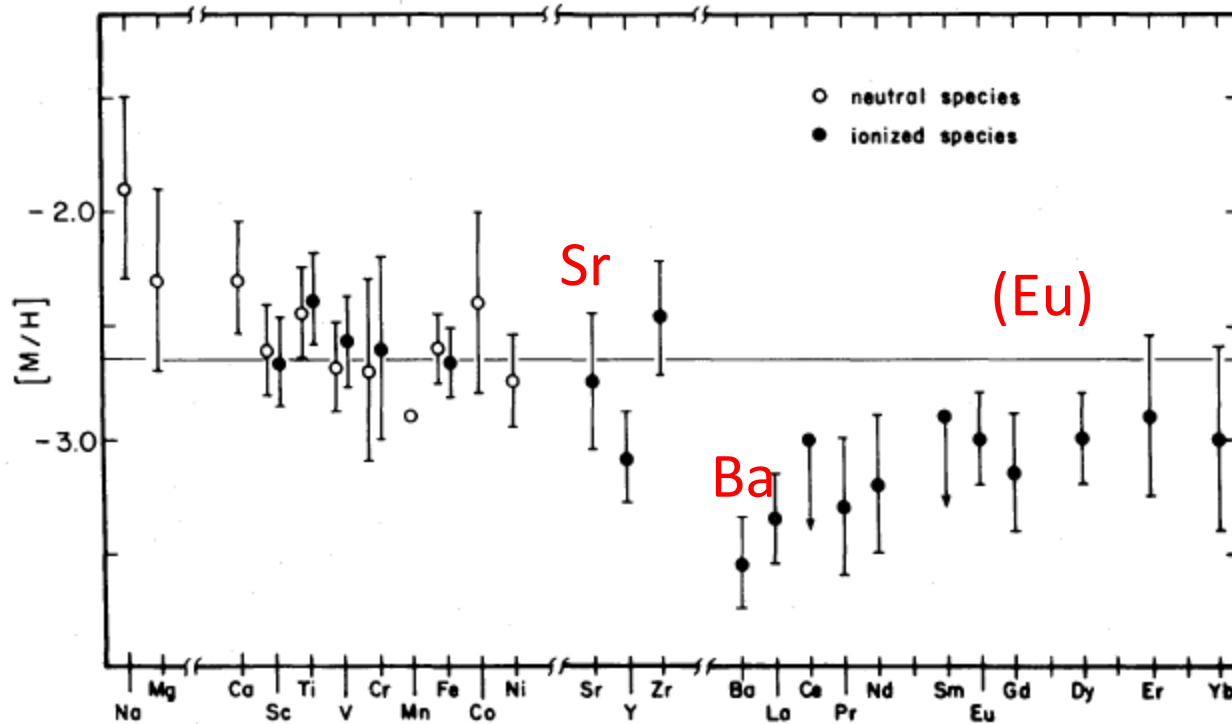


FIG. 6.—Element abundances in HD 122563. The lower temperature model was employed for these abundances.



# HD122563, the “Honda star”

Honda, Aoki, Ishimaru, Wanajo, Ryan 2006, ApJ

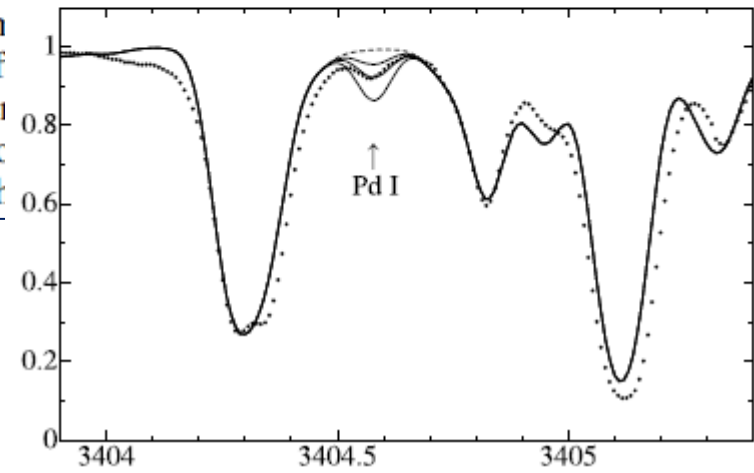
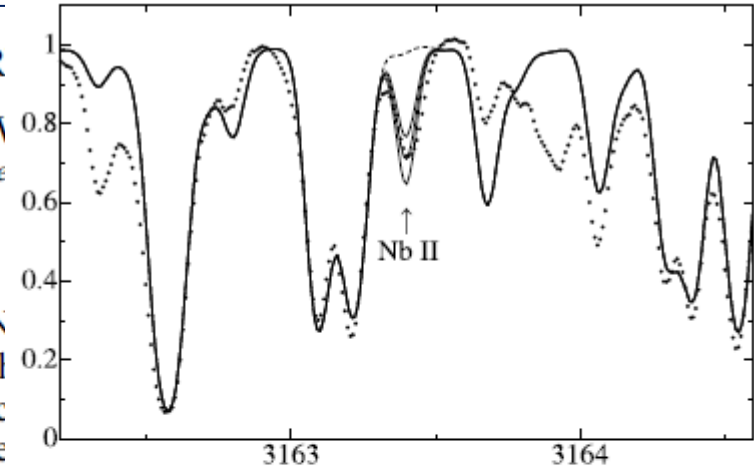
## NEUTRON-CAPTURE ELEMENTS IN THE VER

S. HONDA,<sup>2</sup> W. AOKI,<sup>2</sup> Y. ISHIMARU,<sup>3</sup> S. V

*Received 2005 December 23; accepte*

### ABSTRACT

We obtained high-resolution, high signal-to-noise ratio (S/N) spectra of HD 122563 with the Subaru Telescope High Dispersion Spectrograph. We found excesses of light neutron-capture elements, while its abundance pattern shows a gradually decreasing trend, as a feature quite different from those in stars with excesses of *r*-process elements. The abundance pattern provides new strong constraints on the models of nucleosynthesis with excesses of light neutron-capture elements but without en



Wavelength (A)

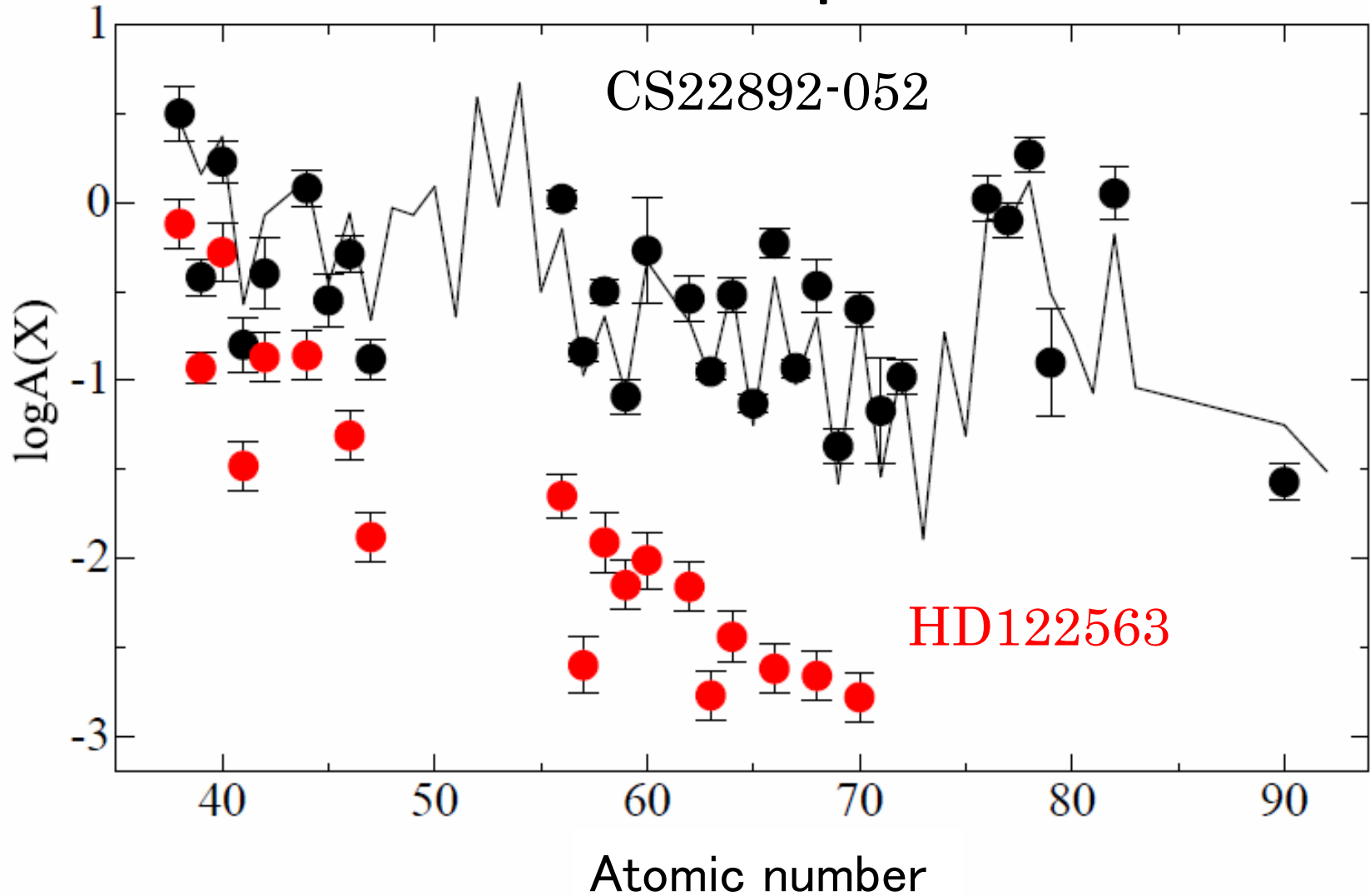
Subaru Telescope

90 minutes exposure

R=90,000

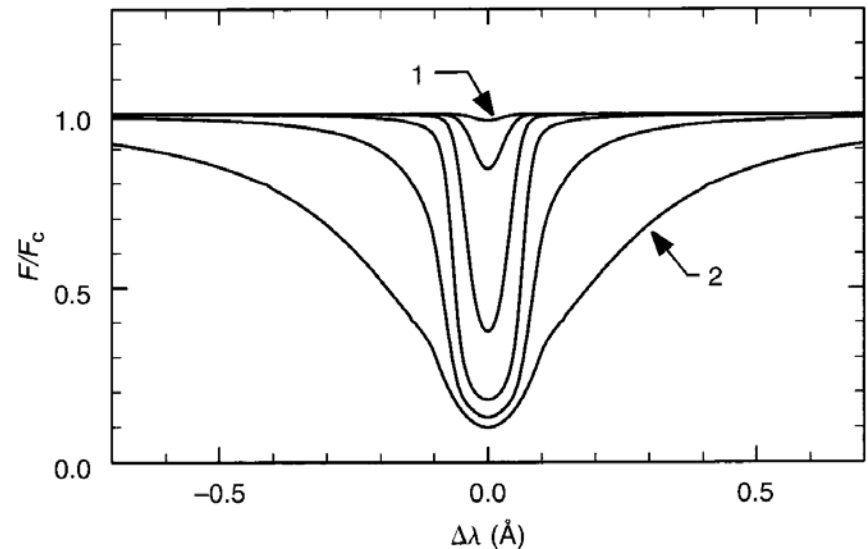
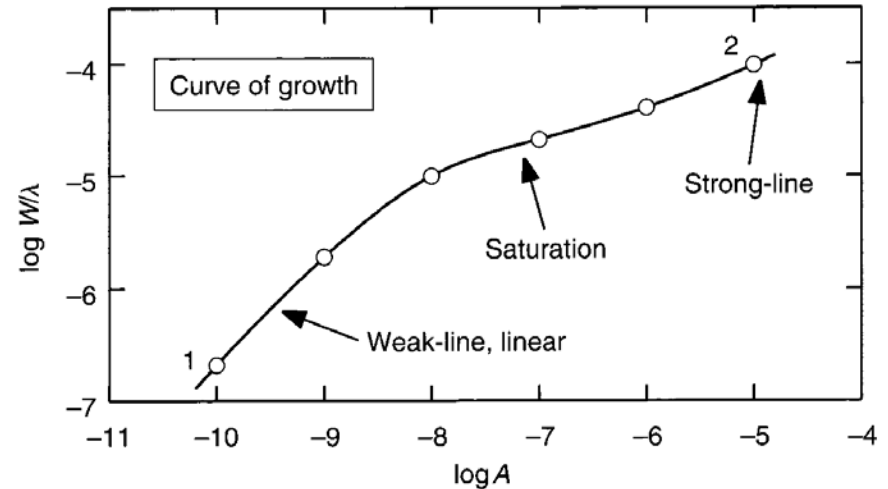
S/N~1000@4000A, 140@3100A

# “main” and “weak” r-process abundance pattern



# Abundance measurements from spectral lines

- Weak lines are preferable for abundance measurements, because they are sensitive to abundance change.
- Strong lines are useful to study whole sample covering a wide abundance range.



Gray (2005)

# Sr and Ba in periodic table

Singly ionized Sr and Ba have strong resonance lines

Periodic Table of the Elements © www.elementsdatabase.com

Legend:

- hydrogen (green)
- alkali metals (yellow)
- alkali earth metals (light blue)
- transition metals (orange)
- poor metals (blue)
- nonmetals (white)
- noble gases (red)
- rare earth metals (grey)

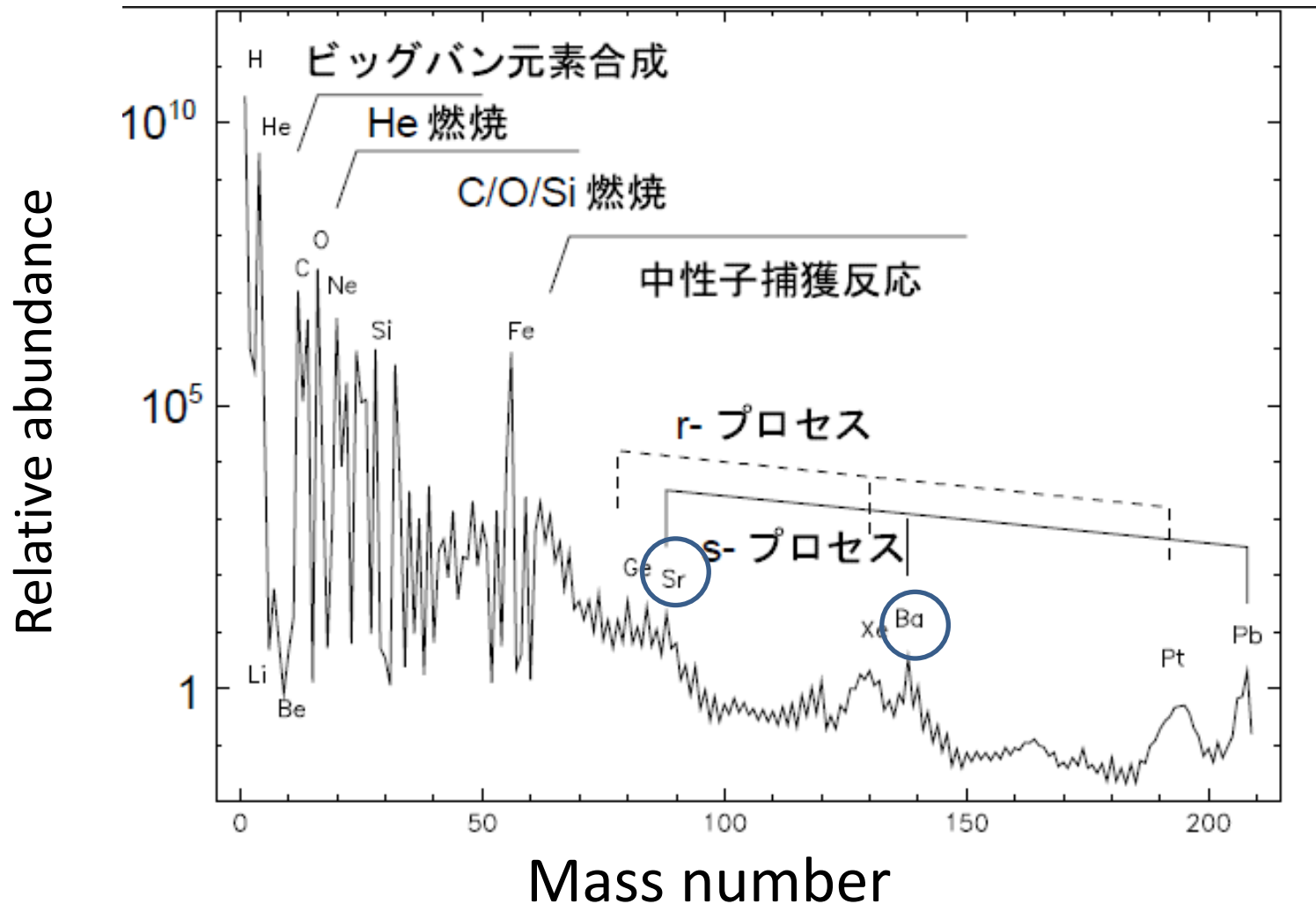
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

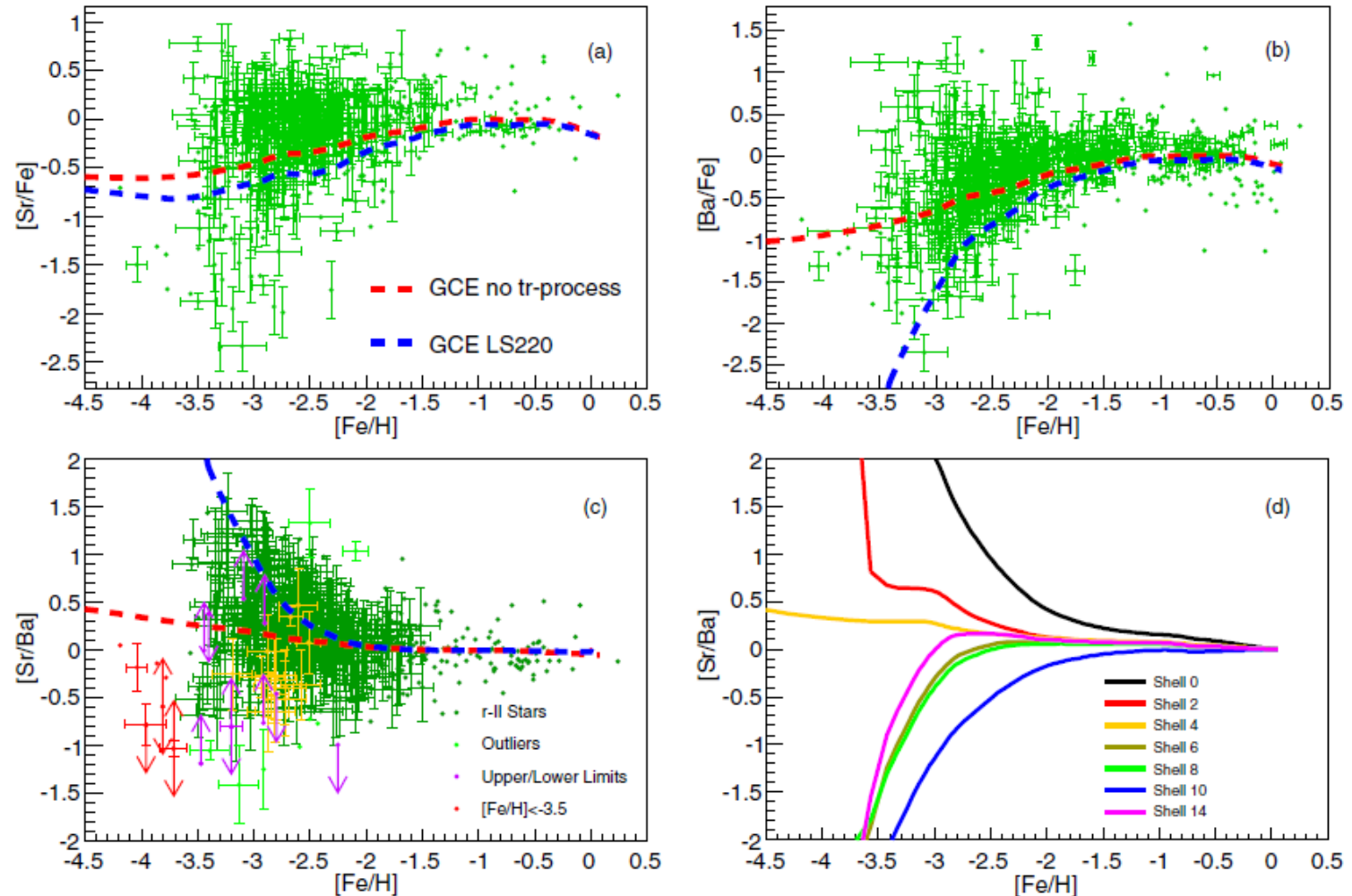
# Chemical abundances of solar-system material

Sr and Ba are the 1<sup>st</sup> and 2<sup>nd</sup> peak elements corresponding to the neutron magic numbers 50 and 82, respectively.



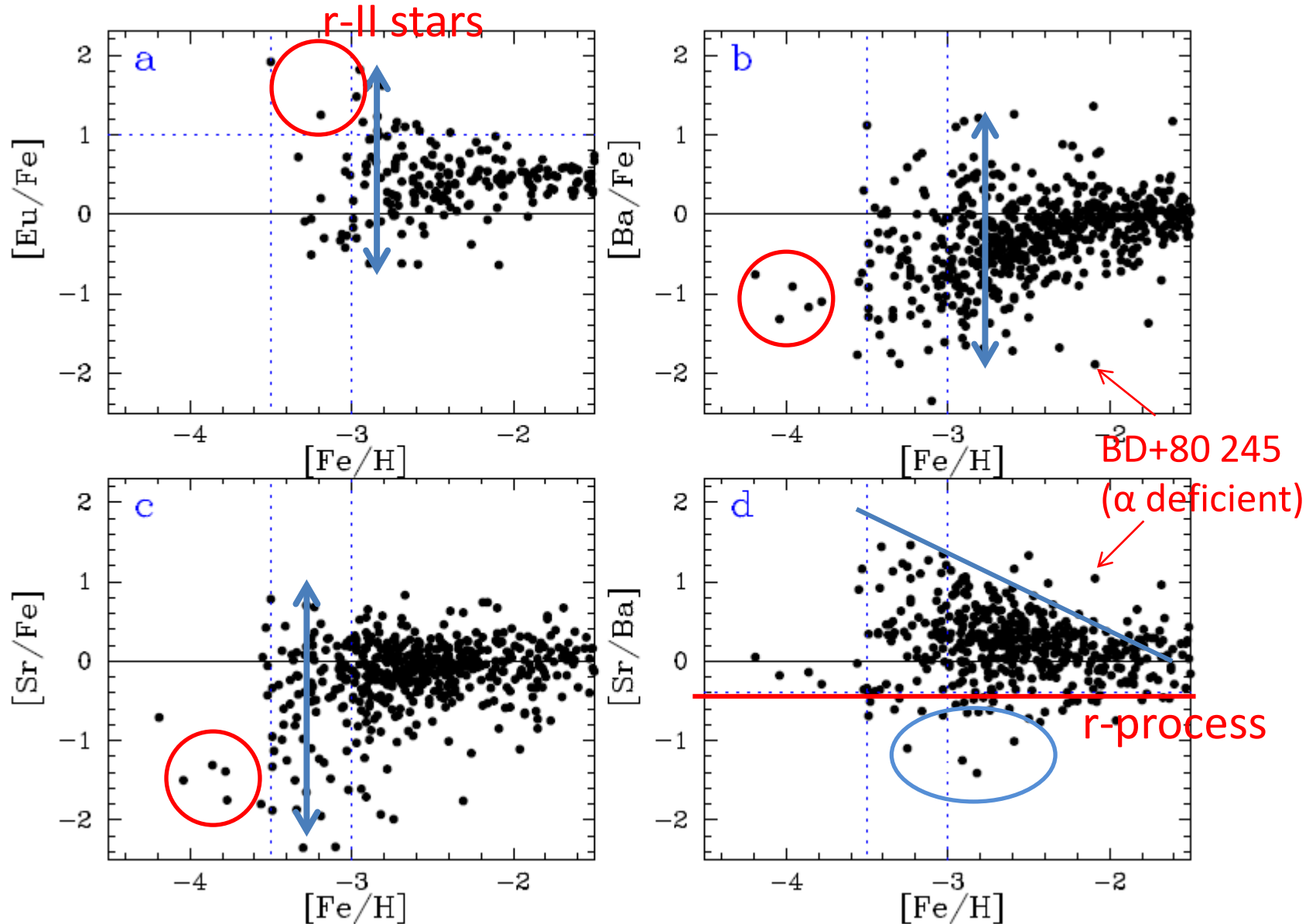
# Sr and Ba abundance ratios

Aoki, Suda, Boyd, Kajino, Fmiano 2013, ApJL

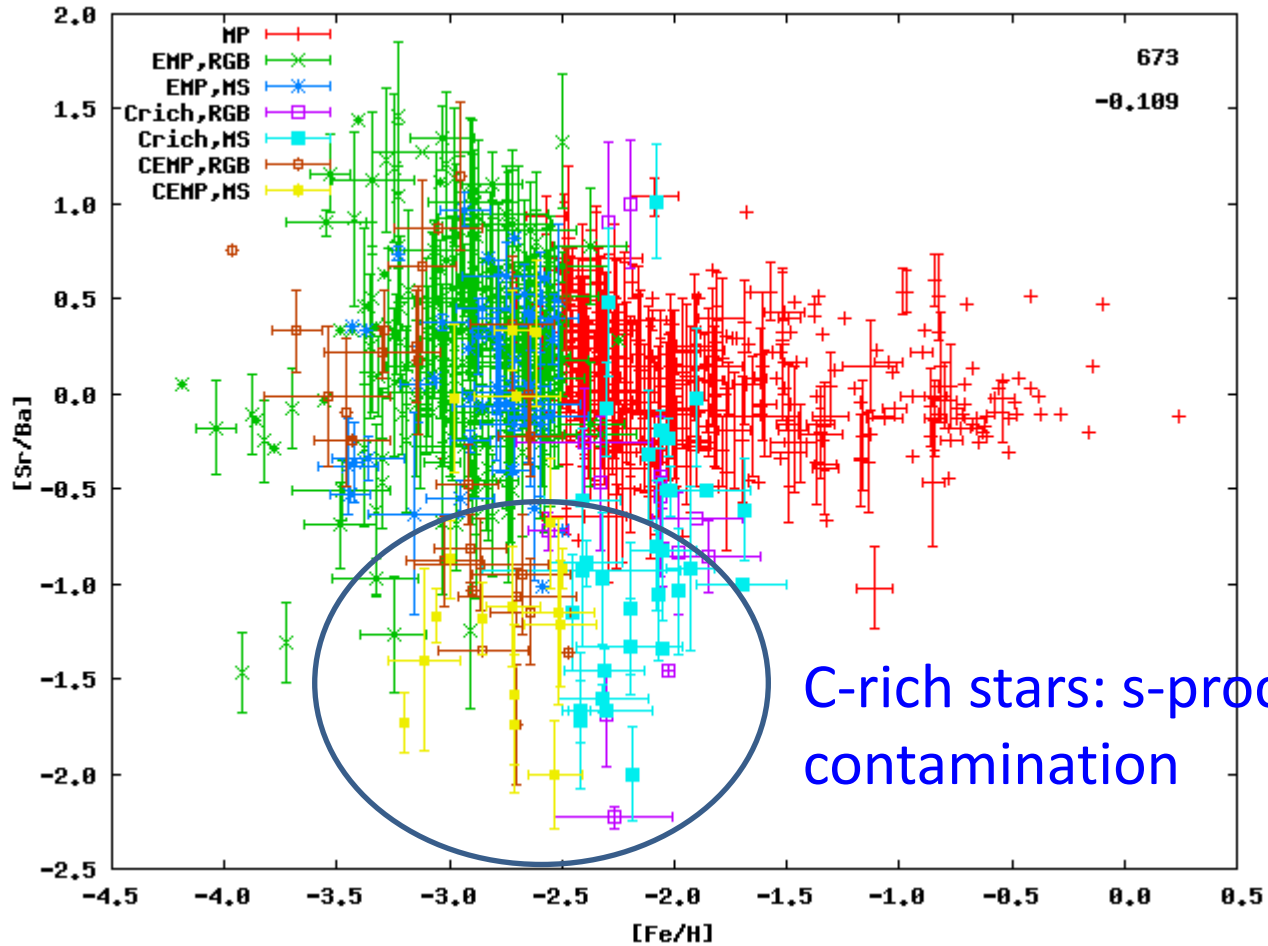


**Figure 1.** Results for (a)  $[Sr/Fe]$ , (b)  $[Ba/Fe]$ , and (c)  $[Sr/Ba]$  assuming a *tr*-process. The red dashed line corresponds to a GCE model with no production in a *tr*-process, and the blue dashed line corresponds to a GCE model with a primary production from a *tr*-process for all stars with  $M \geq 20 M_{\odot}$ . Plot (d) shows GCE results for single-site *tr*-process production for turbulent ejection of specific shells assuming only those shells are ejected.

# Sr and Ba (and Eu) abundance distributions

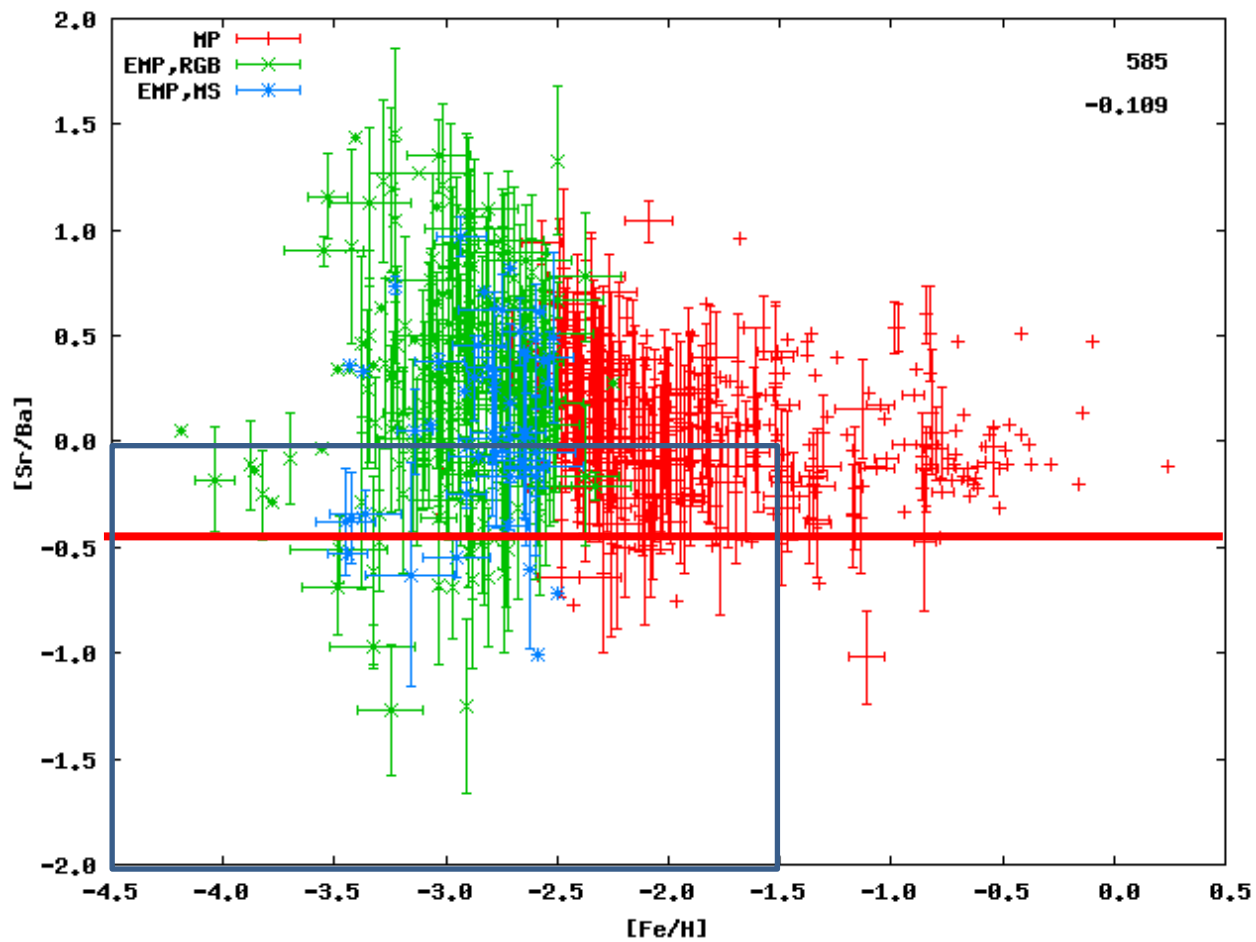


# Low Sr/Ba stars

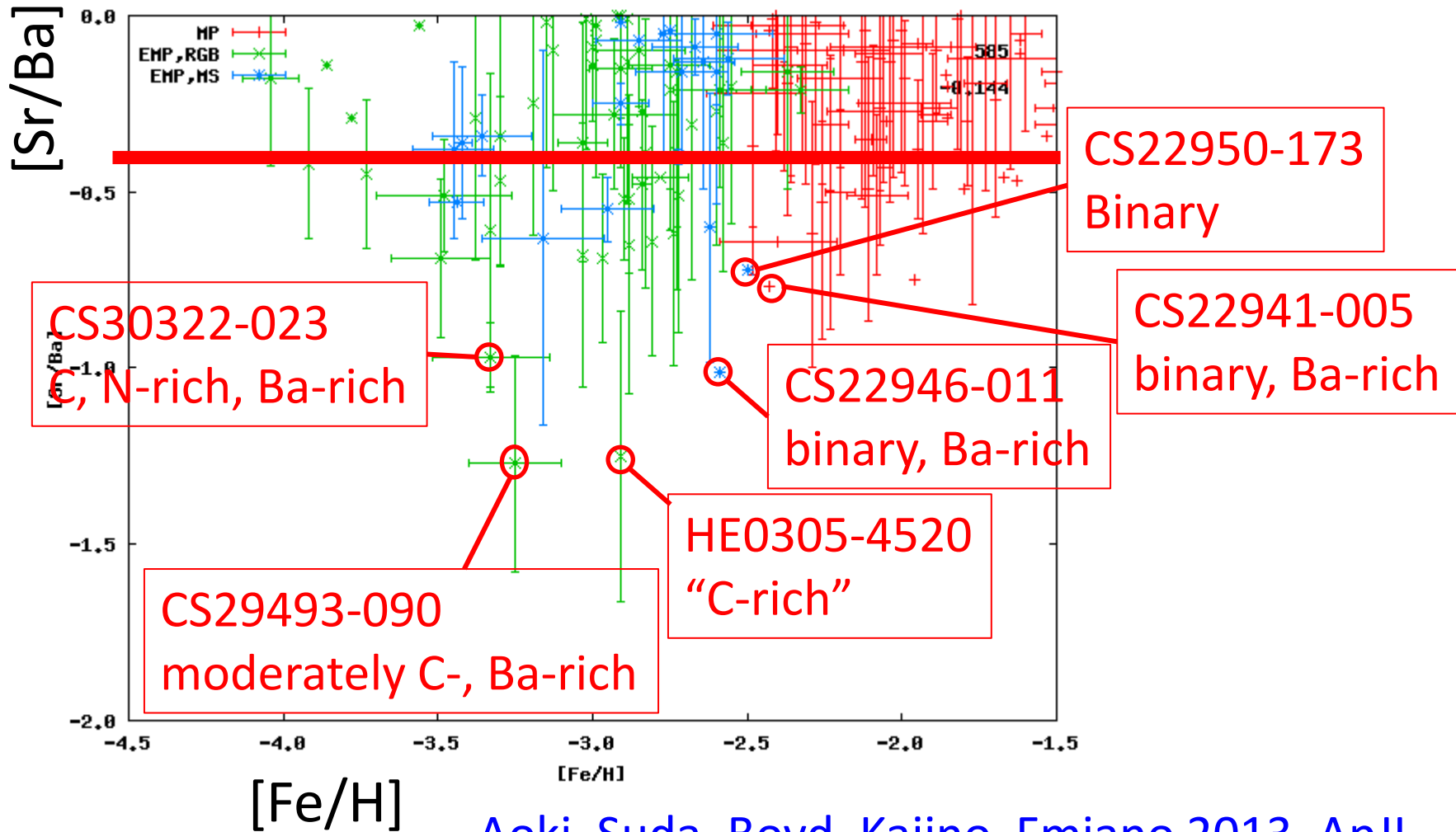




# Low Sr/Ba stars



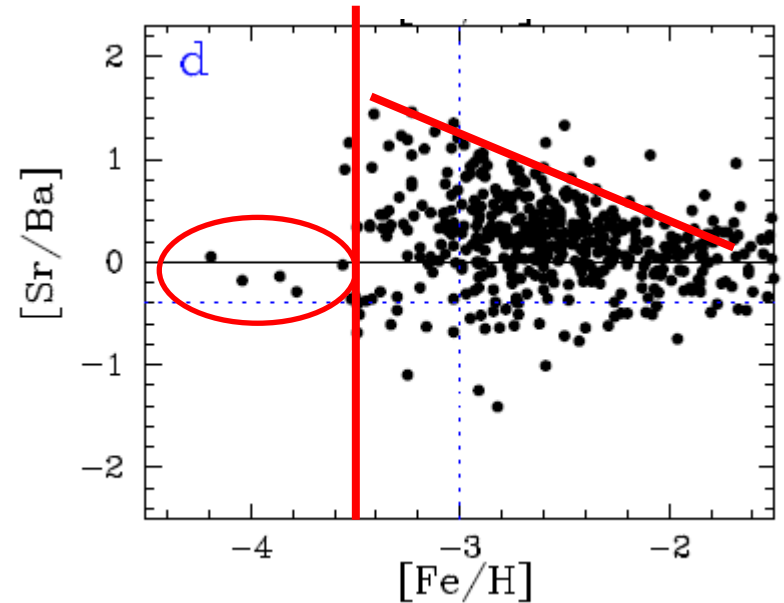
# Low Sr/Ba stars



Aoki, Suda, Boyd, Kajino, Fmiano 2013, ApJL

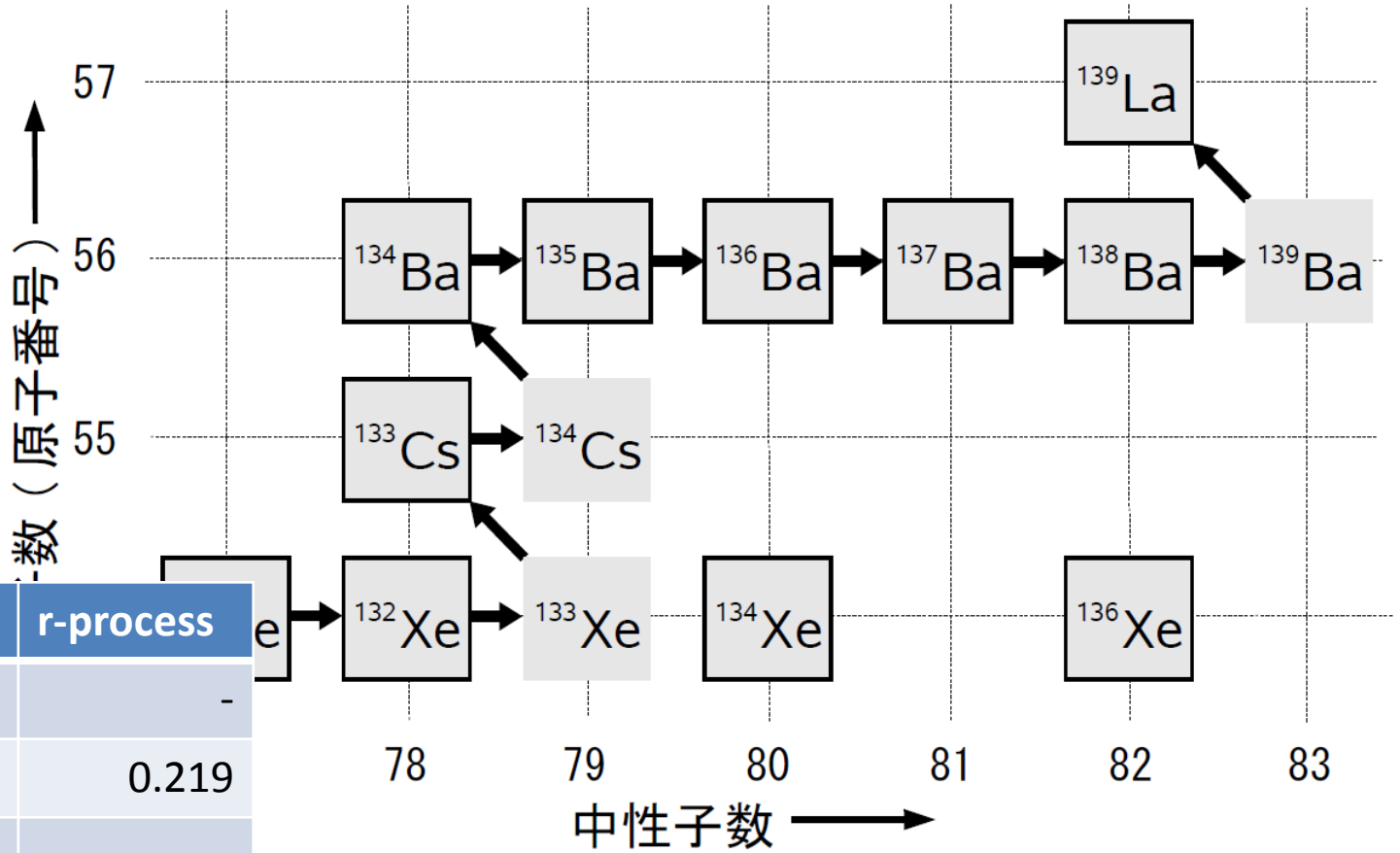
# Questions about Sr and Ba abundances in very metal-poor stars

1. Existence (or absence) of the cut-off at  $[\text{Fe}/\text{H}]=-3.5$ , below which Sr and Ba abundance scatter is small.
2. Origin of (the small amount of) Sr and Ba in stars with  $[\text{Fe}/\text{H}]=-3.5$ : small yields by CCSN?
3. Reason for the upper bound in Sr/Ba distribution ( $[\text{Sr}/\text{Ba}] \sim -1.5 - [\text{Fe}/\text{H}]$ )



Ba isotope ratios

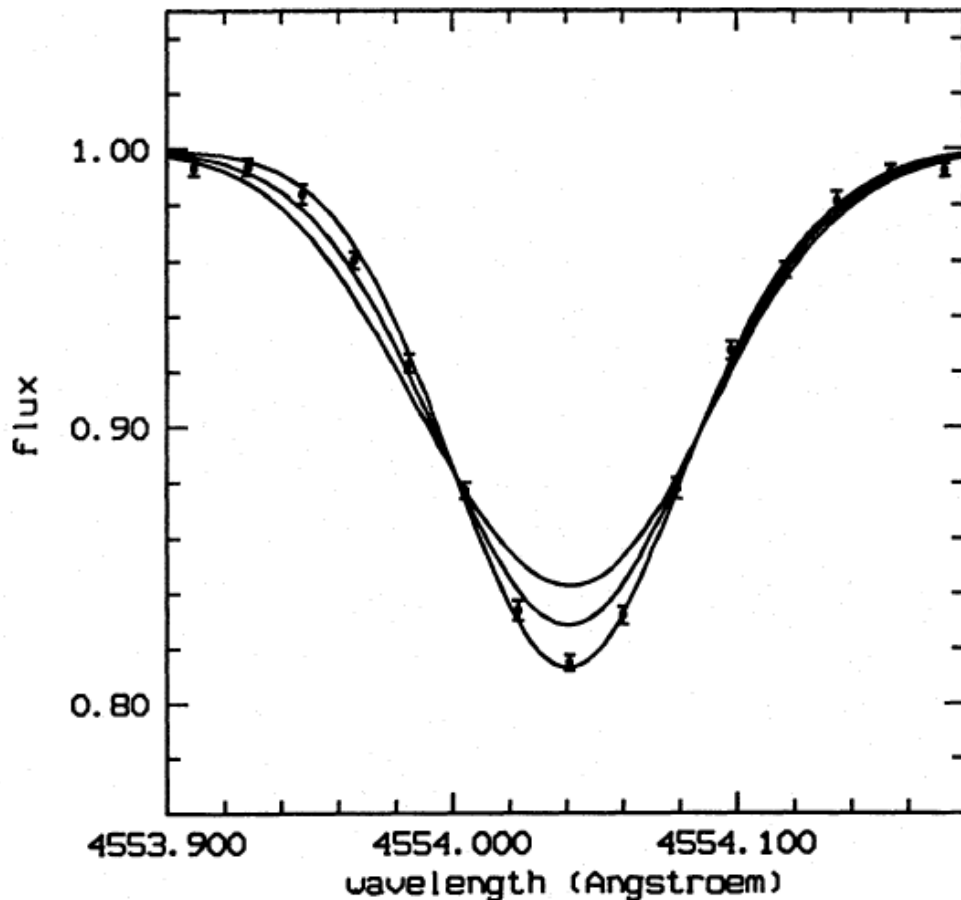
# Ba isotopes



	s-process	r-process
134	0.107	-
135	0.0775	0.219
136	0.353	-
137	0.330	0.174
138	2.76	0.459

Solar-system abundances  
Arlandini et al. (1999)

# Ba isotope ratios in the very metal-poor star HD140283: $f_{\text{odd}} = (^{135}\text{Ba} + ^{137}\text{Ba}) / \text{Ba}$

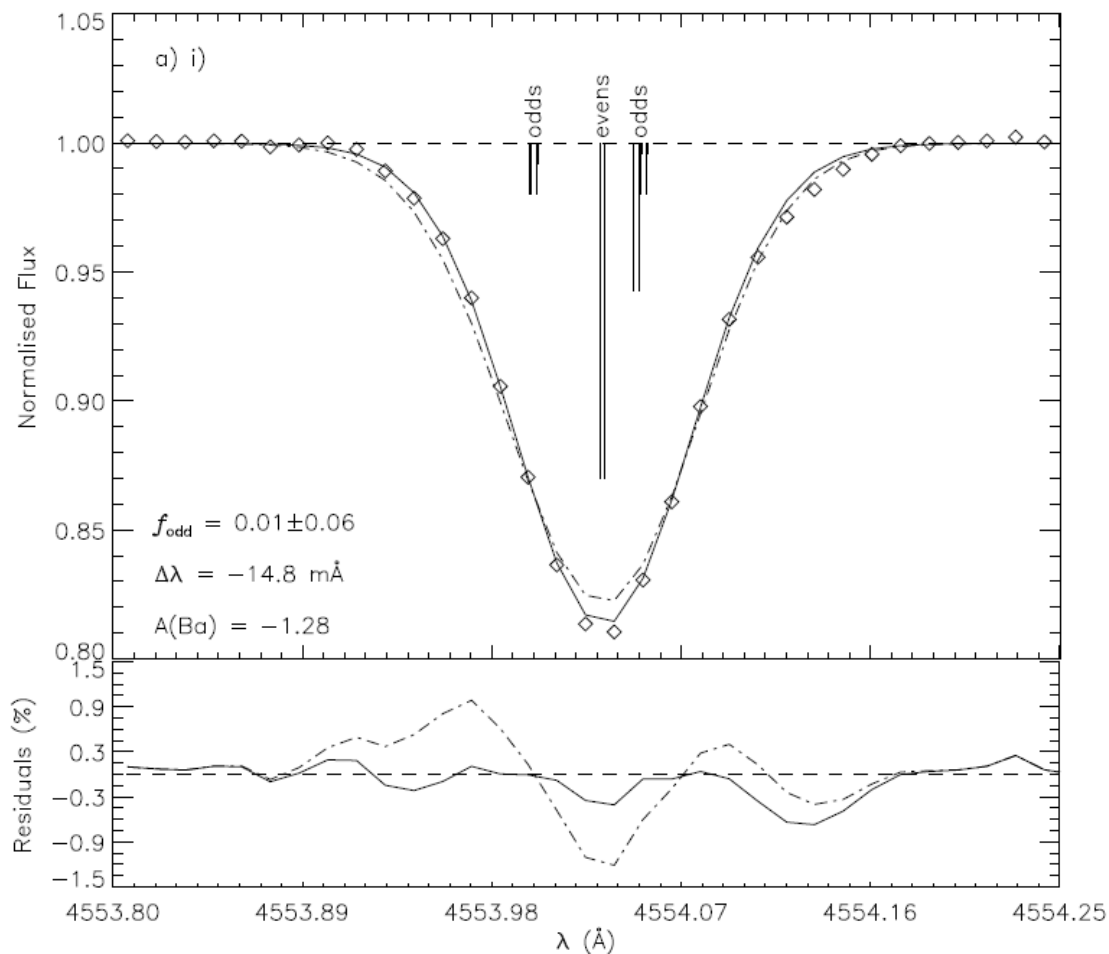


No detection of odd  
Ba isotopes in  
HD140283  
([Fe/H]=-2.5)  
→ Is Ba originated  
from s-process at  
this metallicity?

Fig. 9. Synthetic Ba II line profiles computed with  $f_{\text{odd}} = 1.0, 0.5$  and  $0.0$  (curves) compared with the average data

# Ba isotope ratios in the very metal-poor star HD140283: $f_{\text{odd}} = (^{135}\text{Ba} + ^{137}\text{Ba}) / \text{Ba}$

Gallagher et al. (2010)

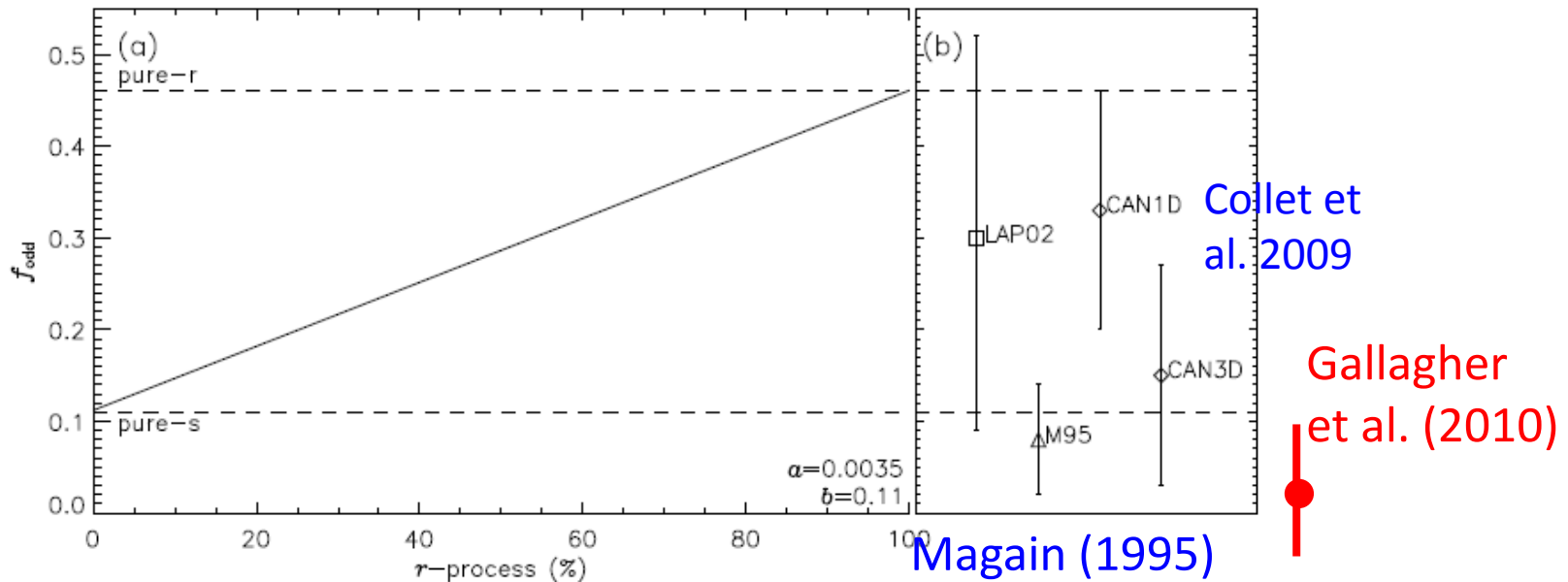


# Ba isotope ratios

Gallagher, Ryan, Garcia-Perez, Aoki 2010, A&A

$$f_{\text{odd}} = ({}^{135}\text{Ba} + {}^{137}\text{Ba}) / \text{Ba}$$

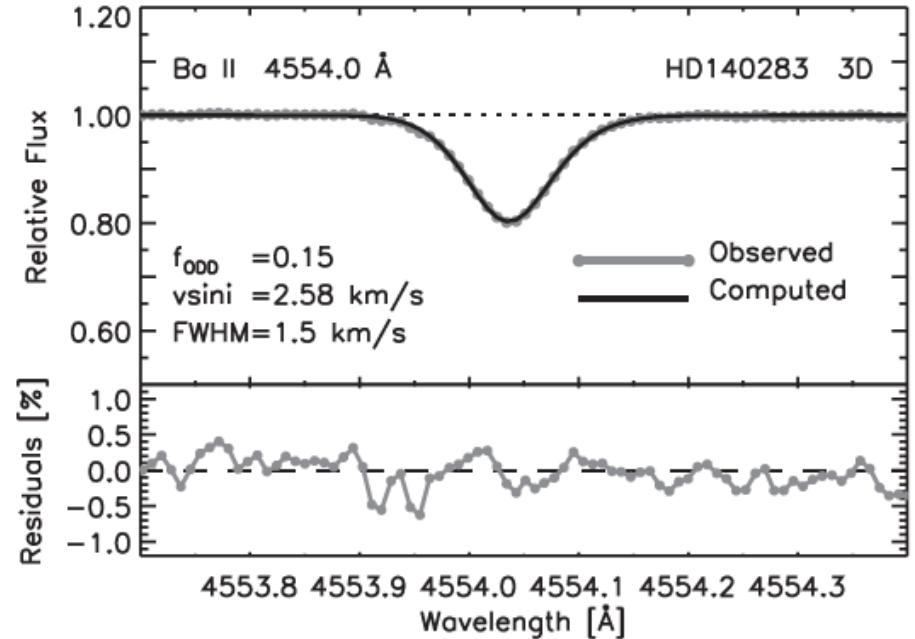
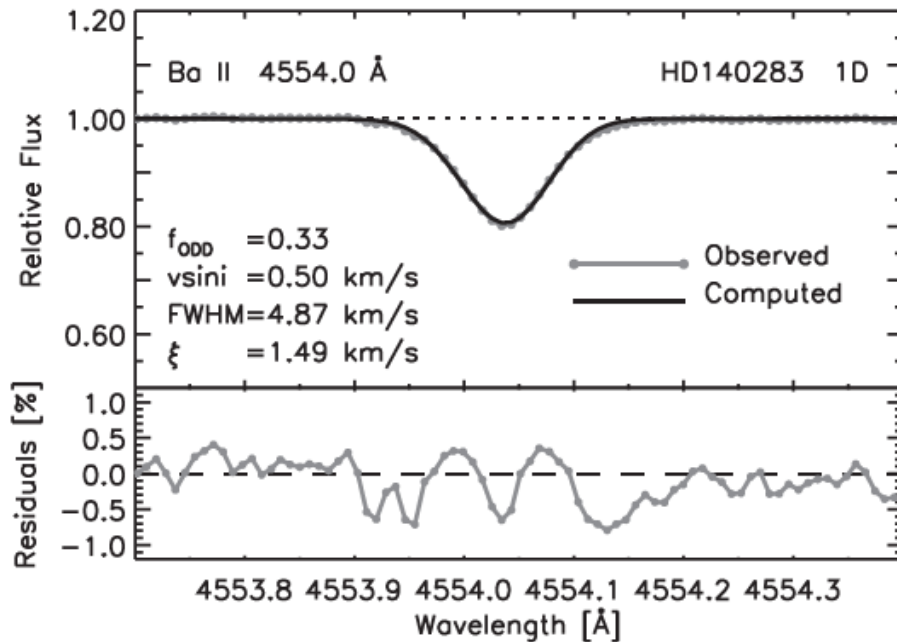
Lambert & Allende-Prieto (2002)



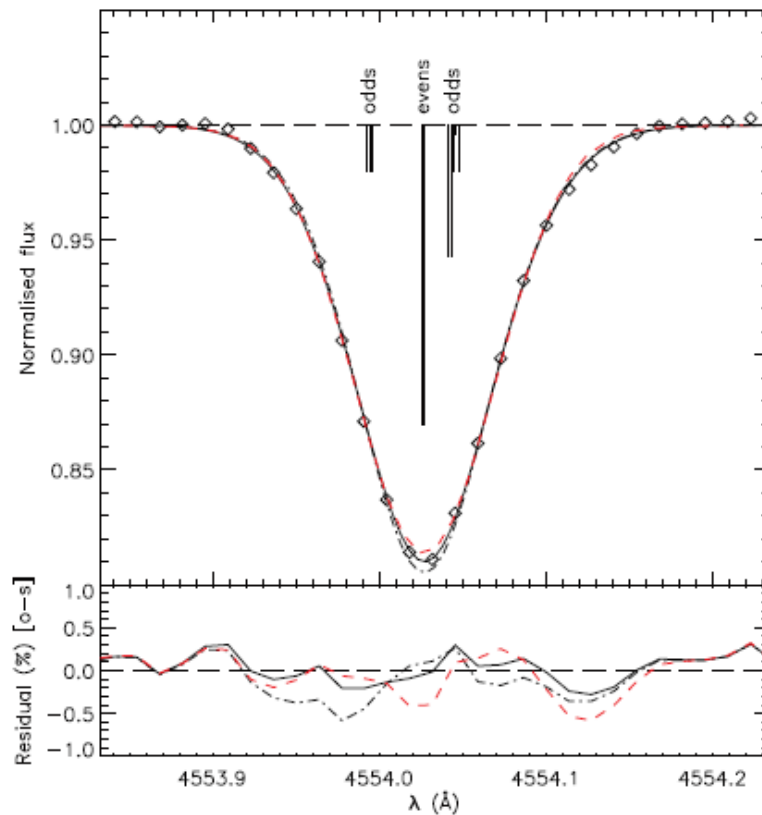
**Fig. 1.** a) Relation between  $f_{\text{odd}}$  and the  $r$ -process contribution calculated from Arlandini et al. (1999). Coefficients are given where  $f_{\text{odd}} = a \times r\text{-process} (\%) + b$ . b) LAMP02: the Lambert & Allende Prieto (2002) result for  $f_{\text{odd}}$ . M95: the Magain (1995) result for  $f_{\text{odd}}$ . CAN1D: the Collet et al. (2009) 1D LTE result for  $f_{\text{odd}}$ . CAN3D: the Collet et al. (2009) 3D hydrodynamical result for  $f_{\text{odd}}$ .



# Ba isotope ratios based on 3D model atmosphere



# New result on Ba isotope ratios based on 3D model atmosphere



**Fig. 10.** The best fit 3D (solid black line –  $f_{\text{odd}} = 0.38$ ) and 1D (dashed red line –  $f_{\text{odd}} = 0.02$  from PAPER1) fits to the observed Ba II 4554 Å profile (black diamonds). A residual plot is presented in the bottom panel. We have also included a lower isotope ratio fit to the observed profile (dashed-dot line) for  $f_{\text{odd}} = 0.25$ , i.e. 40%, for the same  $v \sin i$  and  $A(\text{Ba})$  values used in the best fit.

Gallagher et al. (in prep)

Re-analysis of Ba isotope ratios based on 3D model atmosphere

# Ba isotope ratios

Gallagher, Ryan, Garcia-Perez, Aoki 2010, A&A

$$f_{\text{odd}} = ({}^{135}\text{Ba} + {}^{137}\text{Ba}) / \text{Ba}$$

Lambert & Allende-Prieto (2002)

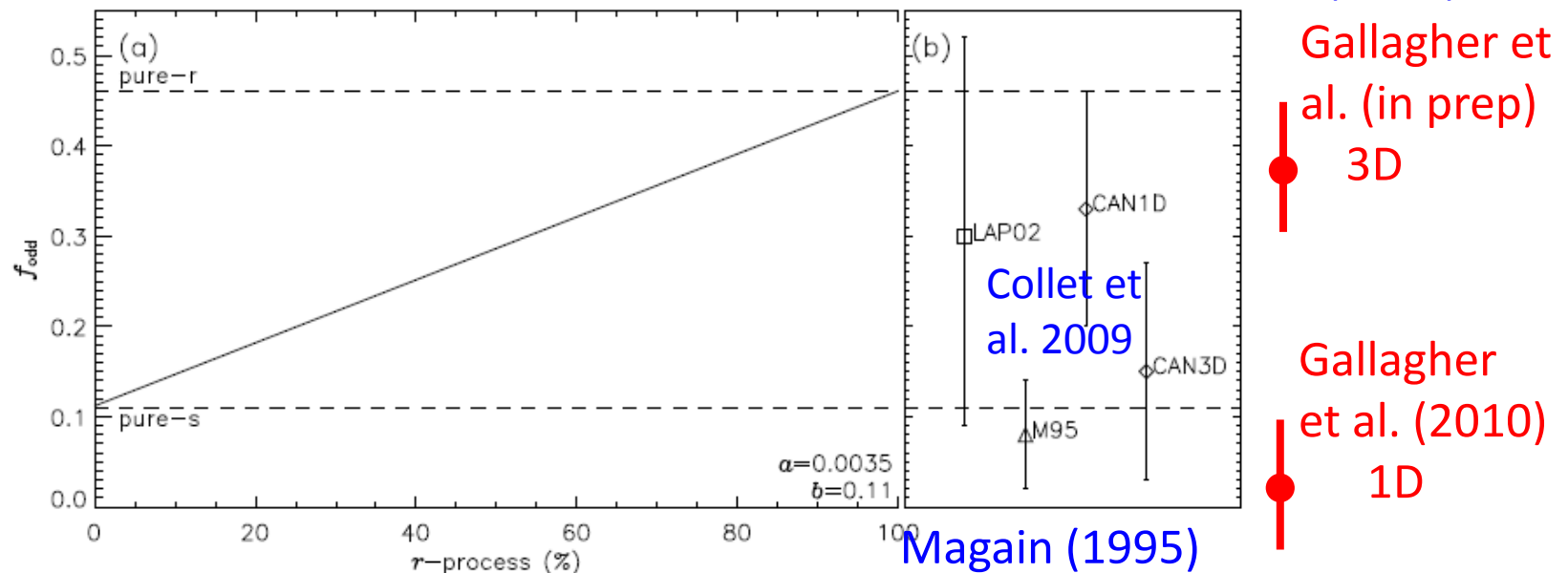


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