The s-process and Difficulties in the definition of the LEPP

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Nuclear Astrophysics

1957-2007

Beyond the First Fifty Years

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Background photo: Star-forming region in N90. NASA, ESA and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration.

The classical analysis of the s-process

- Definition of s-process: in B^2FH – [P. Merrill discovered Tc in 1952 in the spectrum of R And].

- Based on the σN_s curve in the Solar System for s-only isotopes of abundance N_s times the maxwellian average neutron capture cross section σ. The only available data needed are solar system isotopic abundances and experimental /theoretical cross sections.

Classical analysis of the s-process.
Three components: main-s, weak-s, strong-s

Kaeppeler, Beer, Wisshak, Clayton, Macklin, Ward, 1982, ApJ, 257, 821; Clayton & Rassbach, 1967

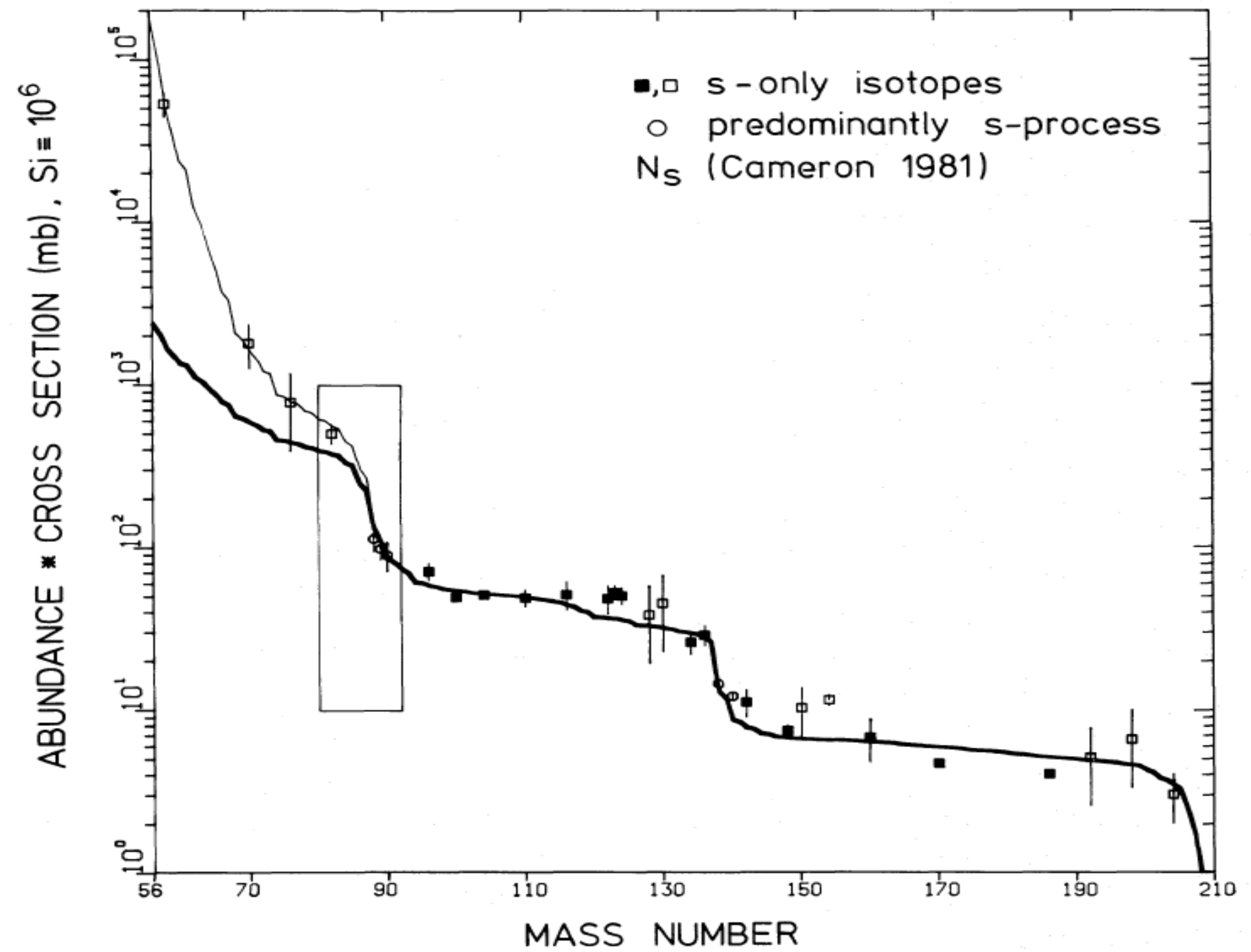


FIG. 2.—The product of *s*-process abundance times cross section as a function of mass number. The symbols correspond to empirical values for *s*-only isotopes (*squares*) or to neutron magic isotopes which are predominantly produced by the *s*-process (*circles*). The respective abundances are taken from the solar abundance table of Cameron (1981). Error bars include the cross section uncertainties only. The calculated solid lines correspond to the strong and weak component in the exponential neutron fluence distribution.

WARNING !

The s-process is far from being a unique process.

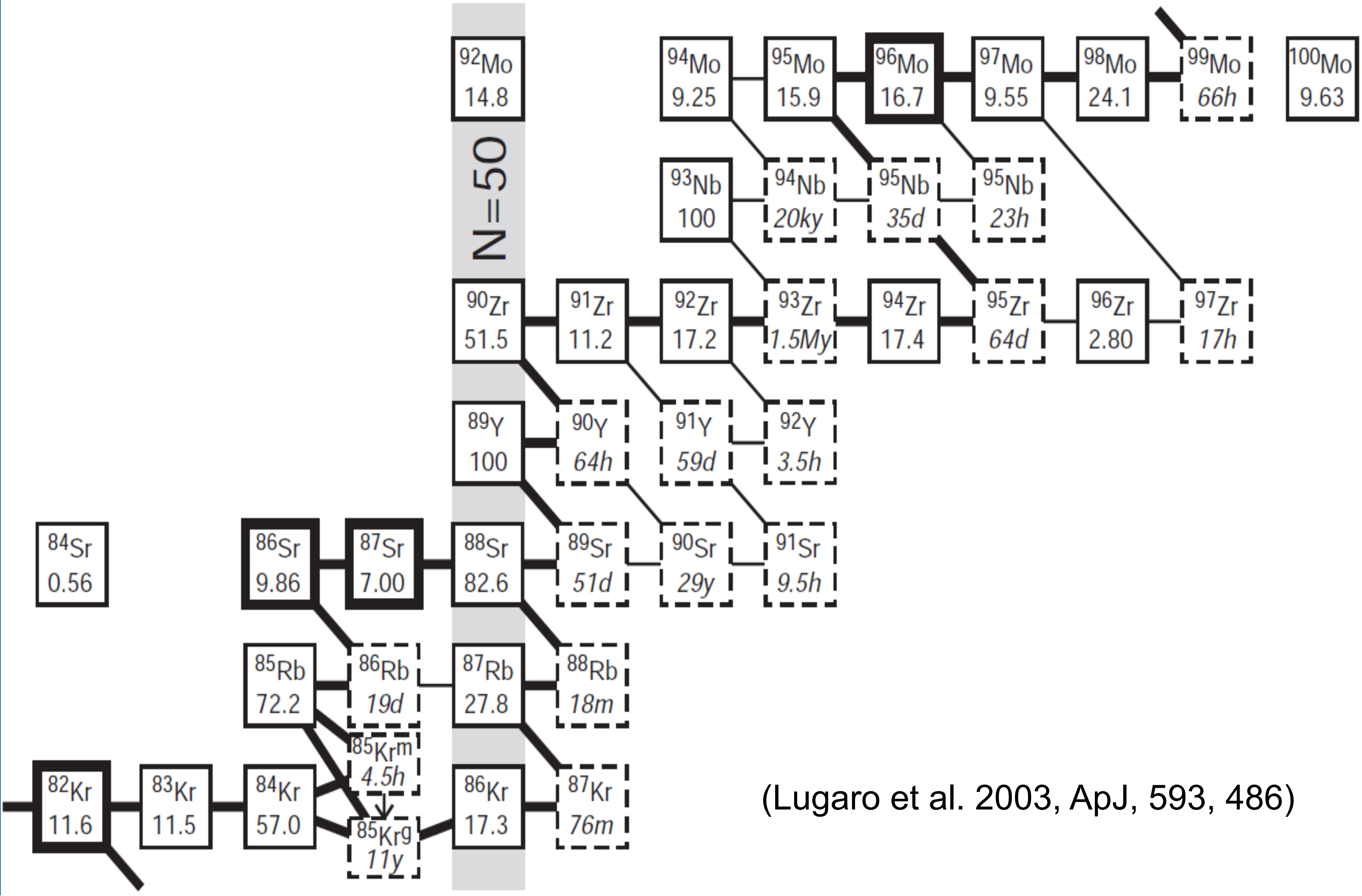
The solar s-process distribution is the outcome of many generations of stars polluting the interstellar medium before the formation of the solar system.

Fe Galactic nucleosynthesis

SNe of Type II evolve fast.
Their ejecta contribute to 1/3 of solar Fe and C, 100% of solar O, ~ 90% of the alpha-elements (Mg,Si,S, Ca,Ti).
SNII are considered the source of the r-process(es).
SNII are the source of the secondary-like weak-s component.

SNe of Type Ia explode at later times polluting the interstellar medium at [Fe/H] > -1.
SNIa ejecta are essentially made of radioactive ^{56}Ni that decays (half-life 6 days) to unstable ^{56}Co (half-life 77days) and then to stable ^{56}Fe.
SNIa contribute 2/3 of solar ^{56}Fe

How to make Sr, Y, Zr during the s-process



(Lugaro et al. 2003, ApJ, 593, 486)

The s-process in AGB stars

The two neutron sources

$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
Needs ^{13}C !	Abundant ^{22}Ne
Major neutron source	Minor neutron source
^{13}C-pocket	Neutron burst
Primary source!	Secondary source
$T_8 = 0.9\text{-}1$ (kT~8keV)	$T_8 = 3$ (kT~23keV)
Interpulse phase	Thermal pulse
Duration ~10,000 yr	Duration 6 yr
Radiative conditions	Convective conditions
$N_n = 10^7$ cm^{-3}	N_n (peak) = 10^{10} cm^{-3} followed by rapid decline (neutron freezout)

Straniero et al. 2006 , **Nucl. Phys. A 777, 311**

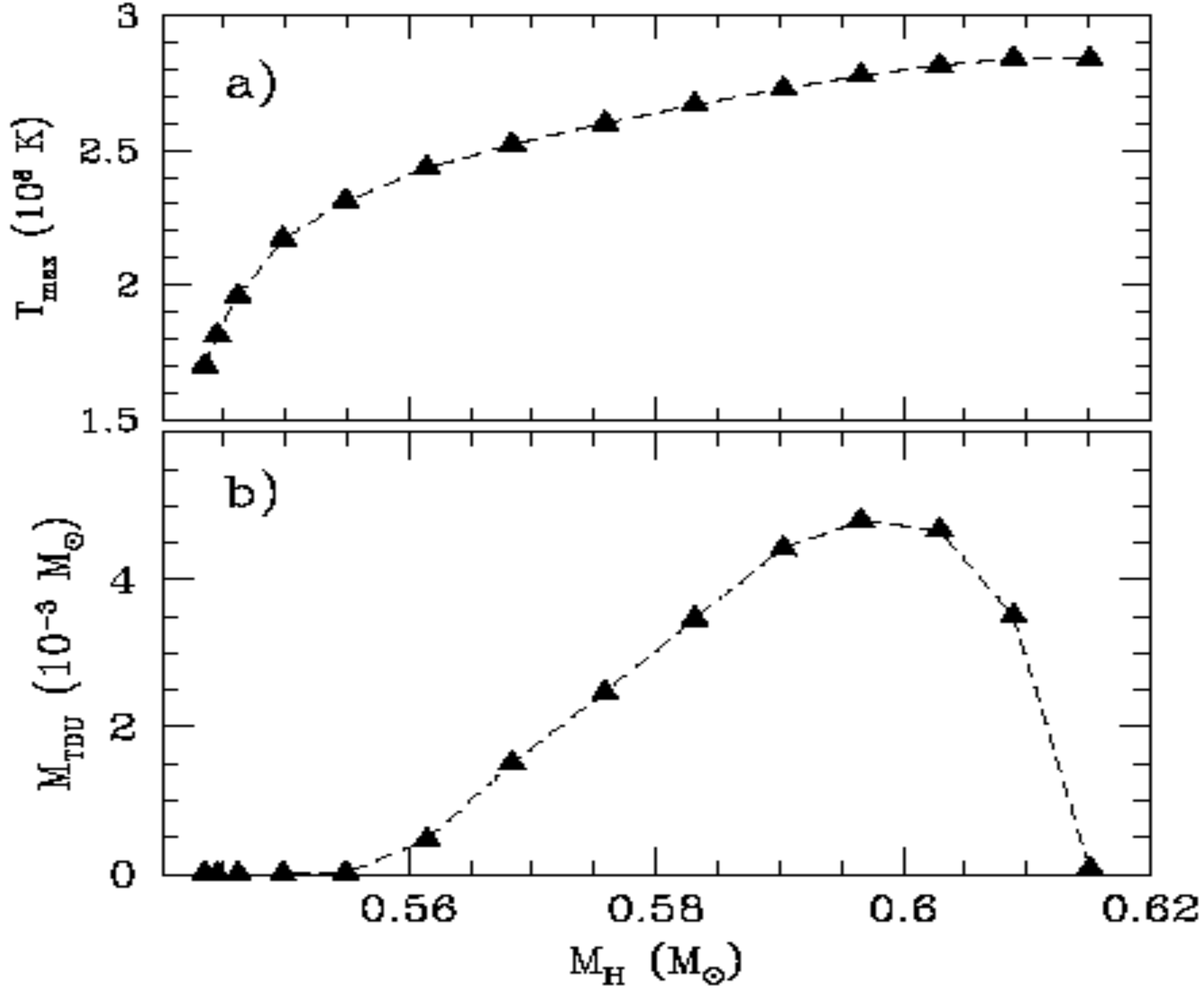
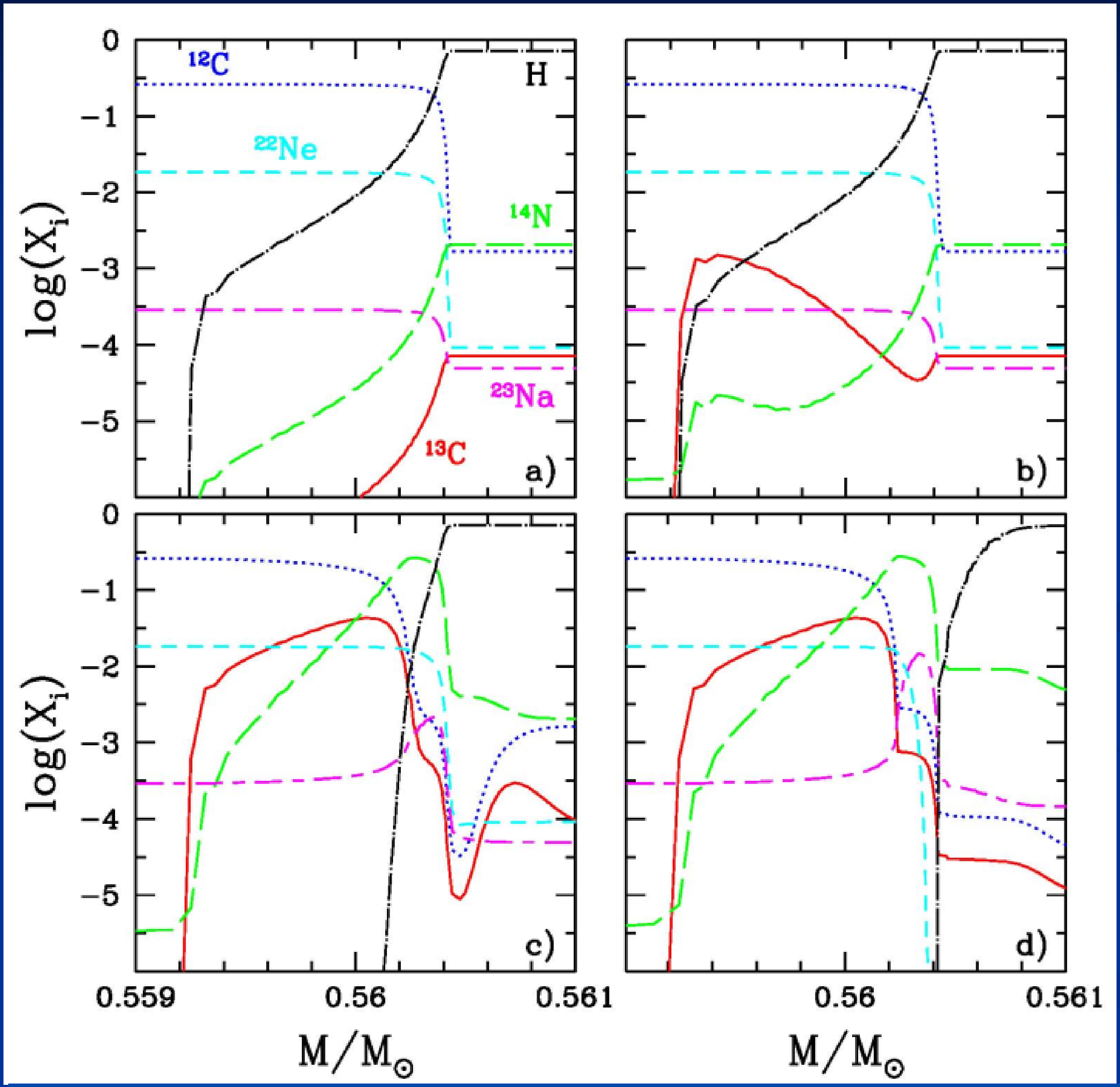


Fig. 8. Evolution of the maximum temperature at the base of the convective pulses (panel a) and dredged up mass per pulse (panel b) along the AGB phase.

Formation of the ^{13}C-pocket



Straniero et al. 2006,
Nucl.Phys.A 777, 311

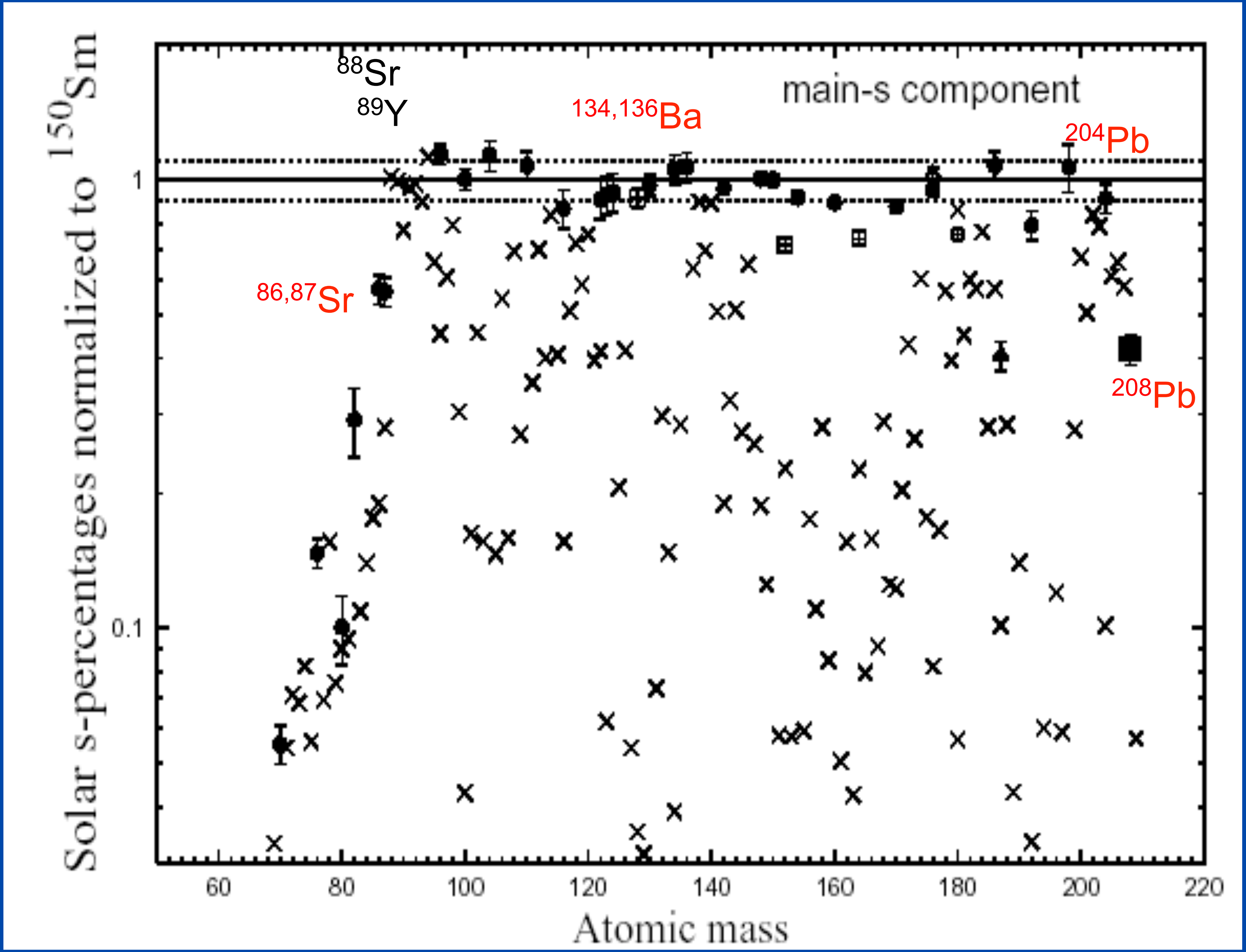
a) Maximum envelope penetration (during TDU);

b) $^{12}C(p,\gamma)^{13}N(\beta^-)^{13}C$ and $^{13}C(p,\gamma)^{14}N$ reactions;

c) $^{22}Ne(p,\gamma)^{23}Na$;

d) the envelope receeds.

Main component
Arlandini et al. 1999, updated Kaeppeler et al. 2011



13C pocket
Case ST

Average
M=1.5 - 3 Msun

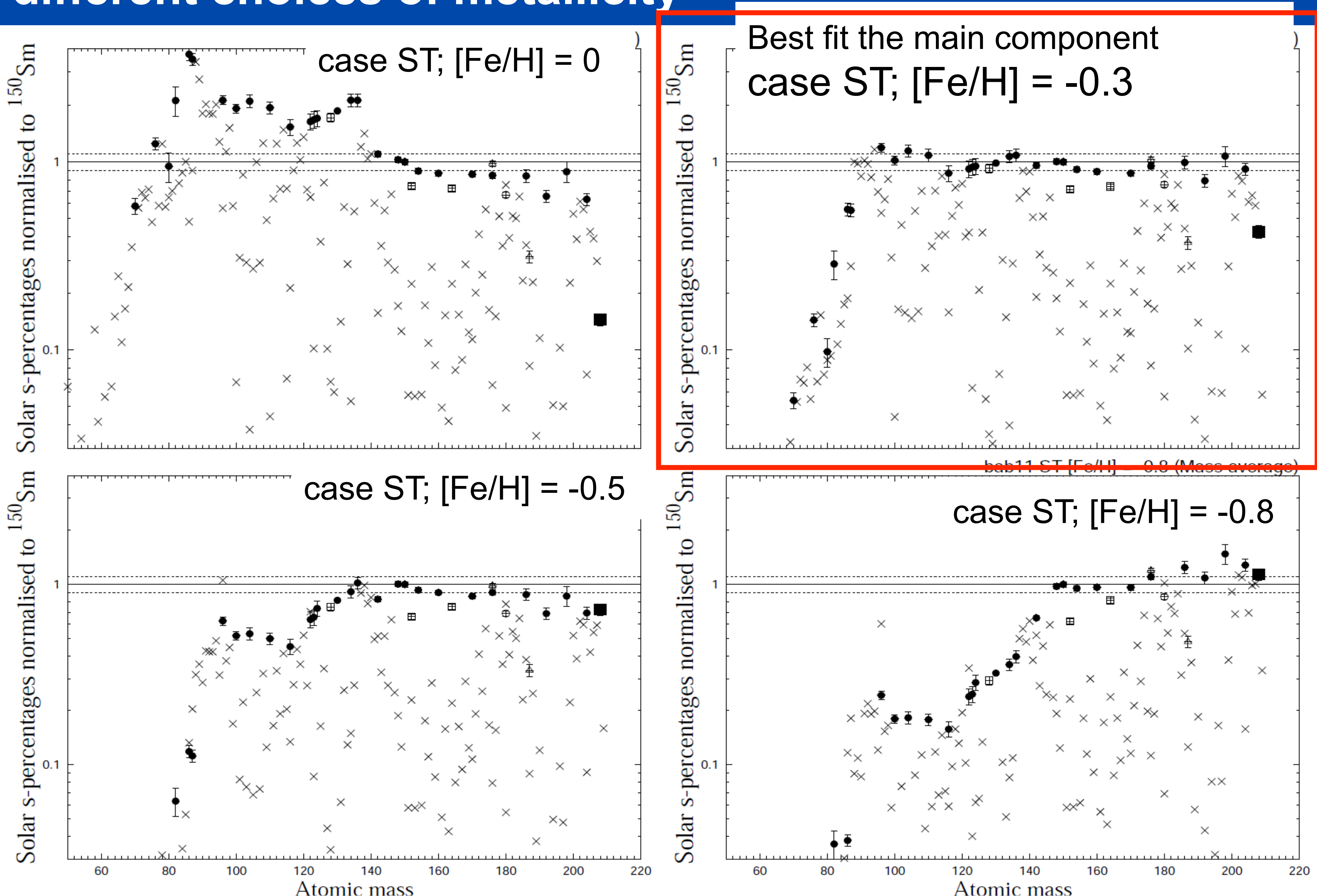
^{208}Pb

=43%solar

Pb

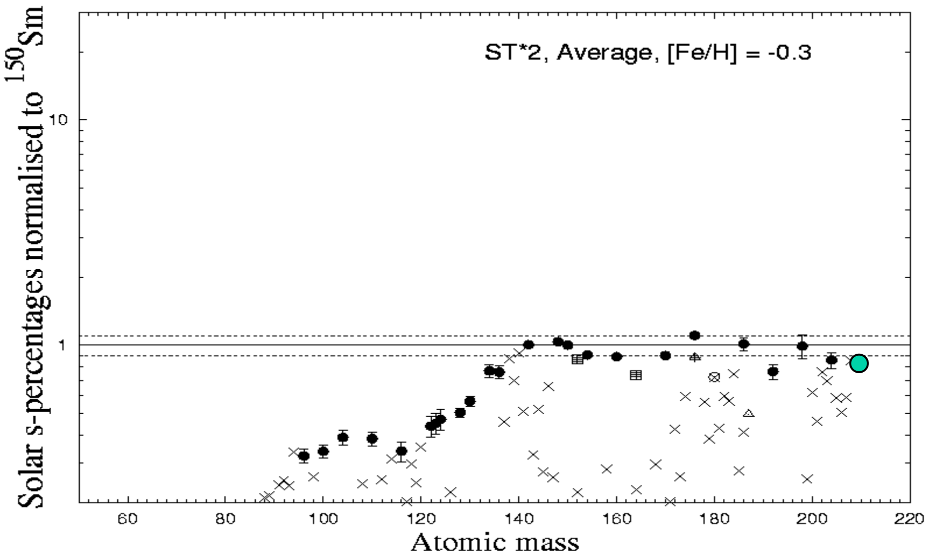
=51%solar

Solar s-percentage normalized to ^{150}Sm for case ST and different choices of metallicity



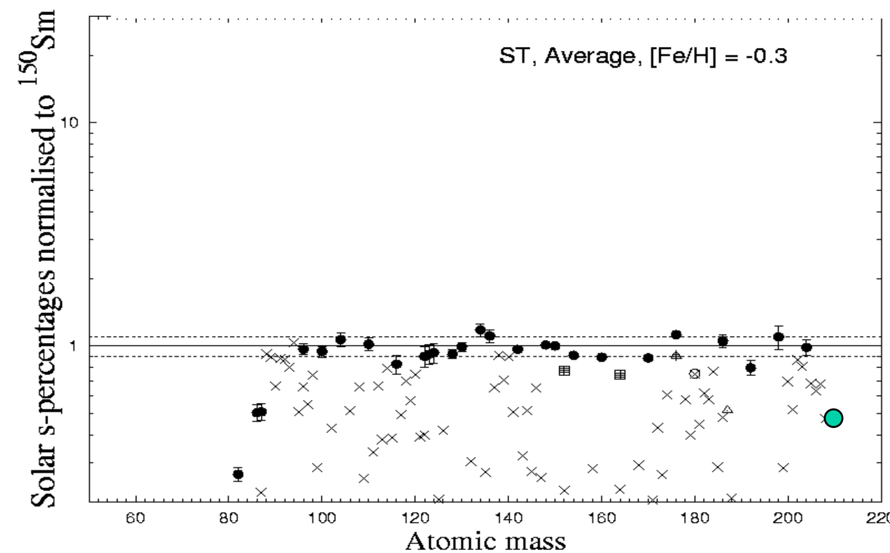
Solar s-percentage normalized to ^{150}Sm for [Fe/H] = -0.3 and different choices of the ^{13}C-pocket

case ST*2

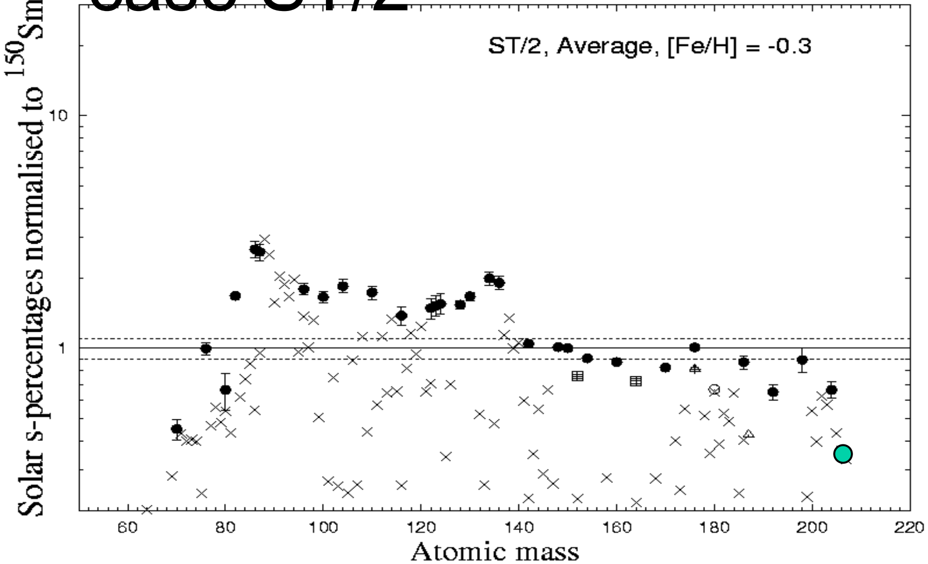


Best fit the main component

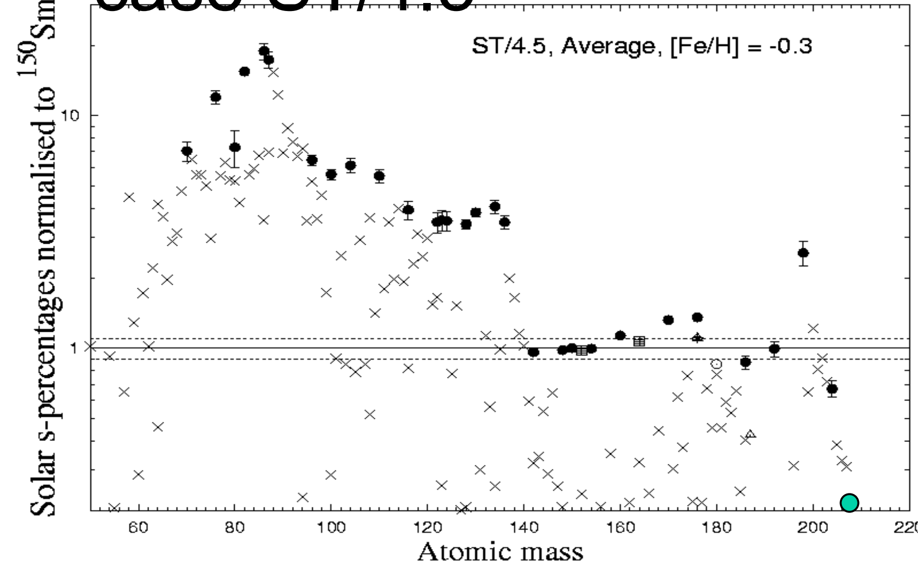
case ST



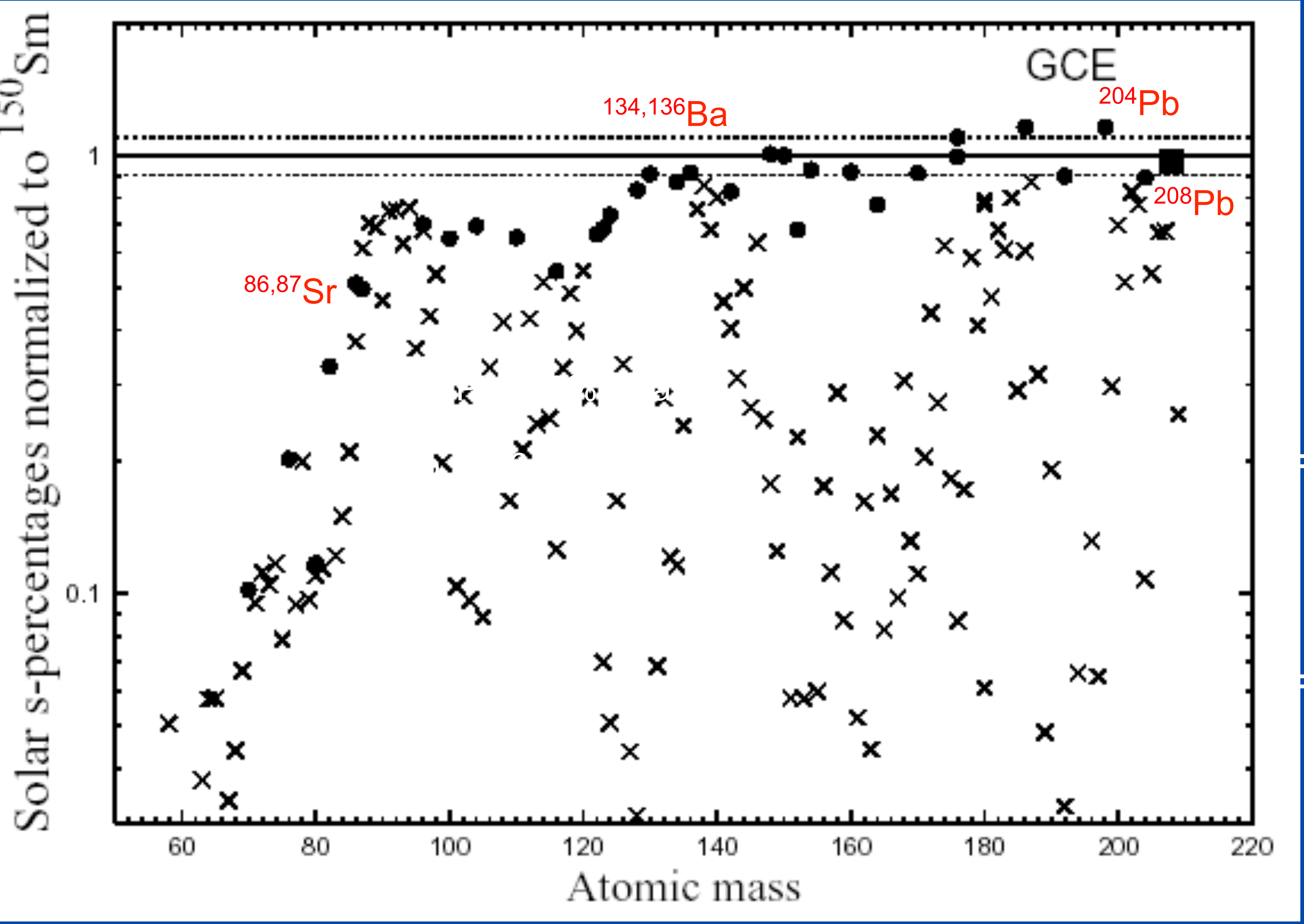
case ST/2



case ST/4.5



Galactic chemical evolution model (Travaglio et al. 1999, updated Bisterzo et al. 2010)



^{208}Pb

=95%solar

Pb

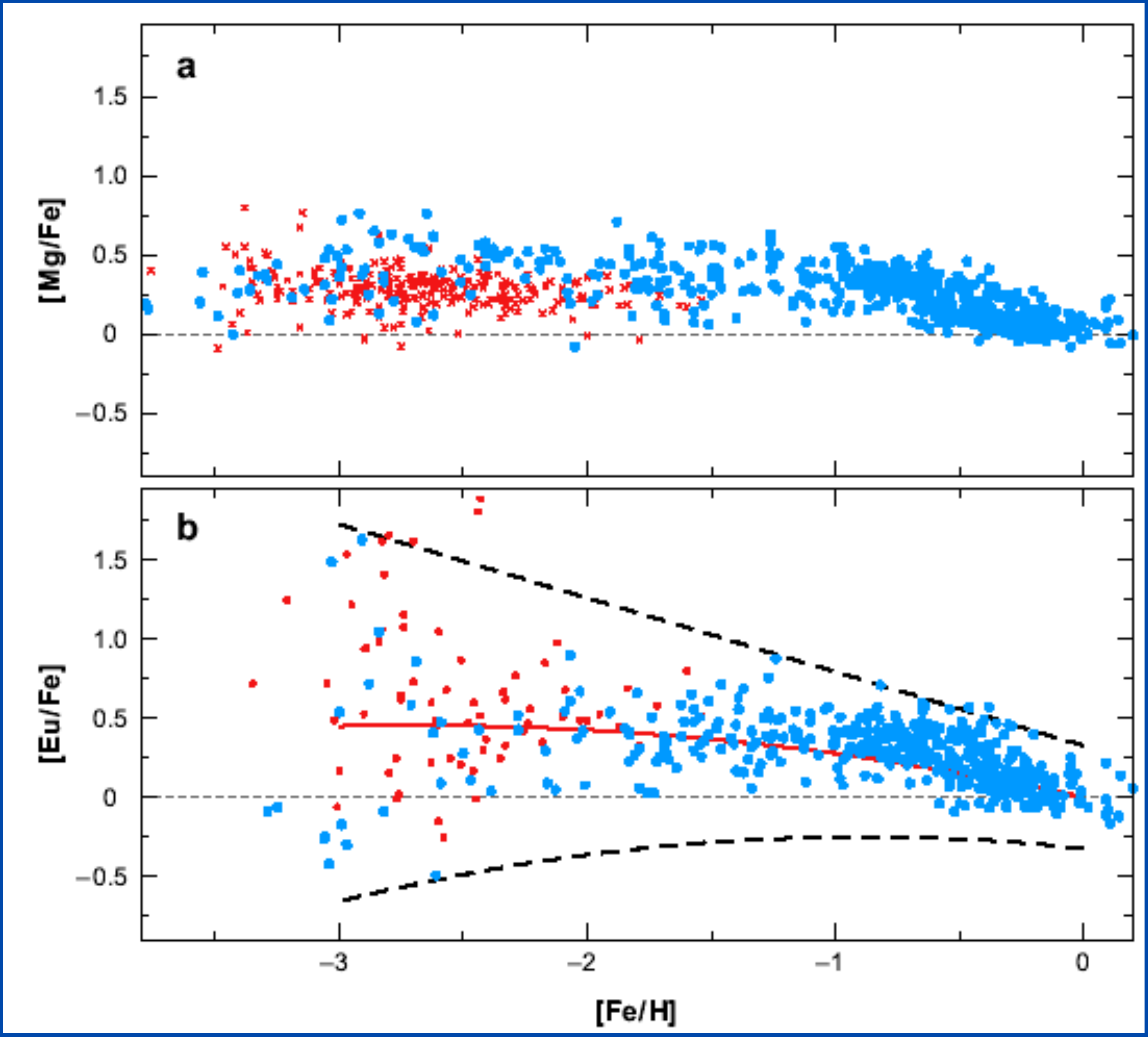
=87%solar

Kaeppeler et al. 2011, Rev.Mod. Phys. 83, 157

s- and r-process contributions CGE (Travaglio et al. 2004, updated Kaeppeler et al. 2010)

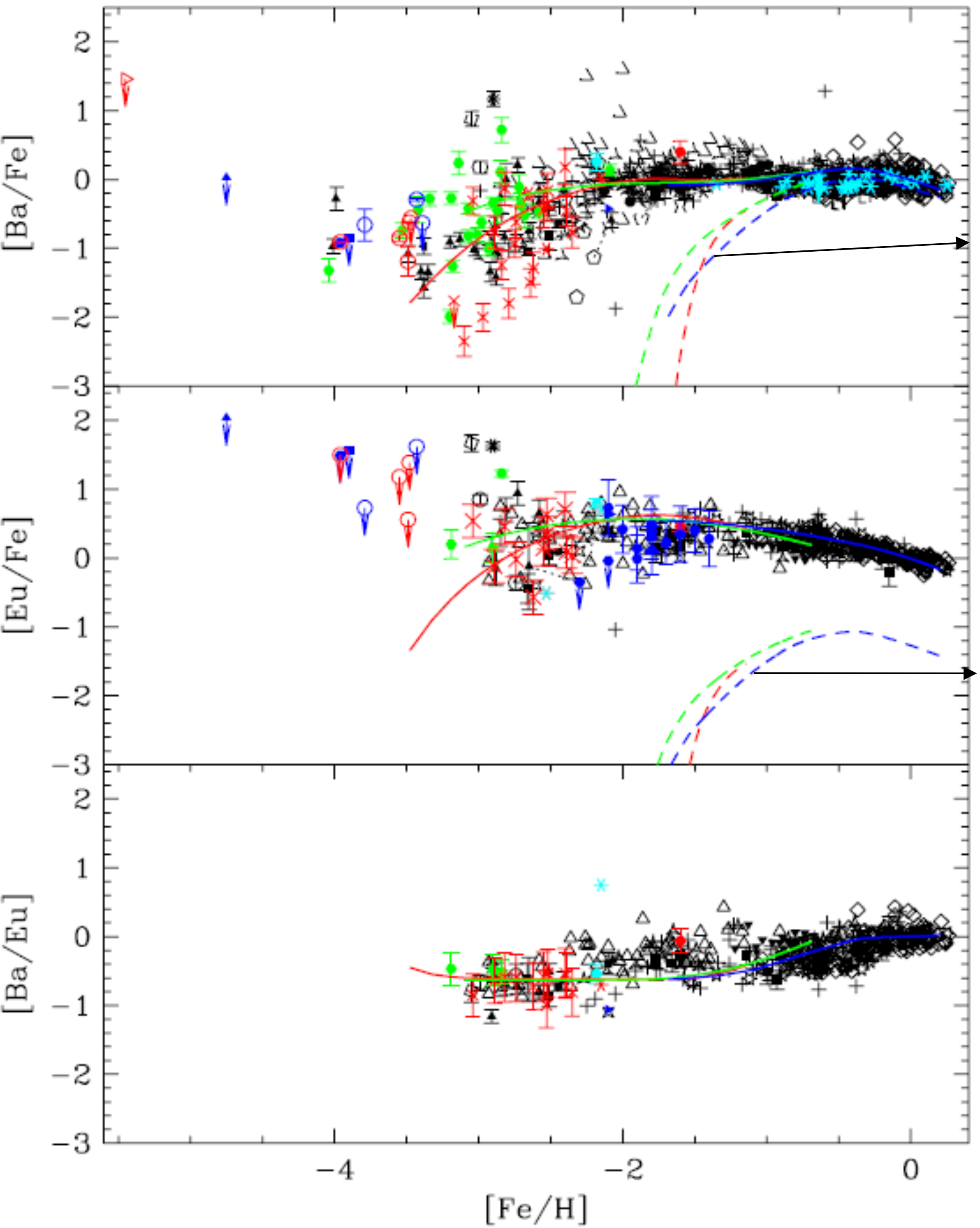
	N_s	N_r
Ba	80%	20%
La	70%	30%
Eu	6%	94%
Pb	87%	13%

where $N_r = N - N_s$



Sneden, Cowan, Gallino 2008, ARAA, 46, 241

Observational constraints



S+R-process contributions

S-process contribution only (halo, thick and thin disc)

S+R-process contributions

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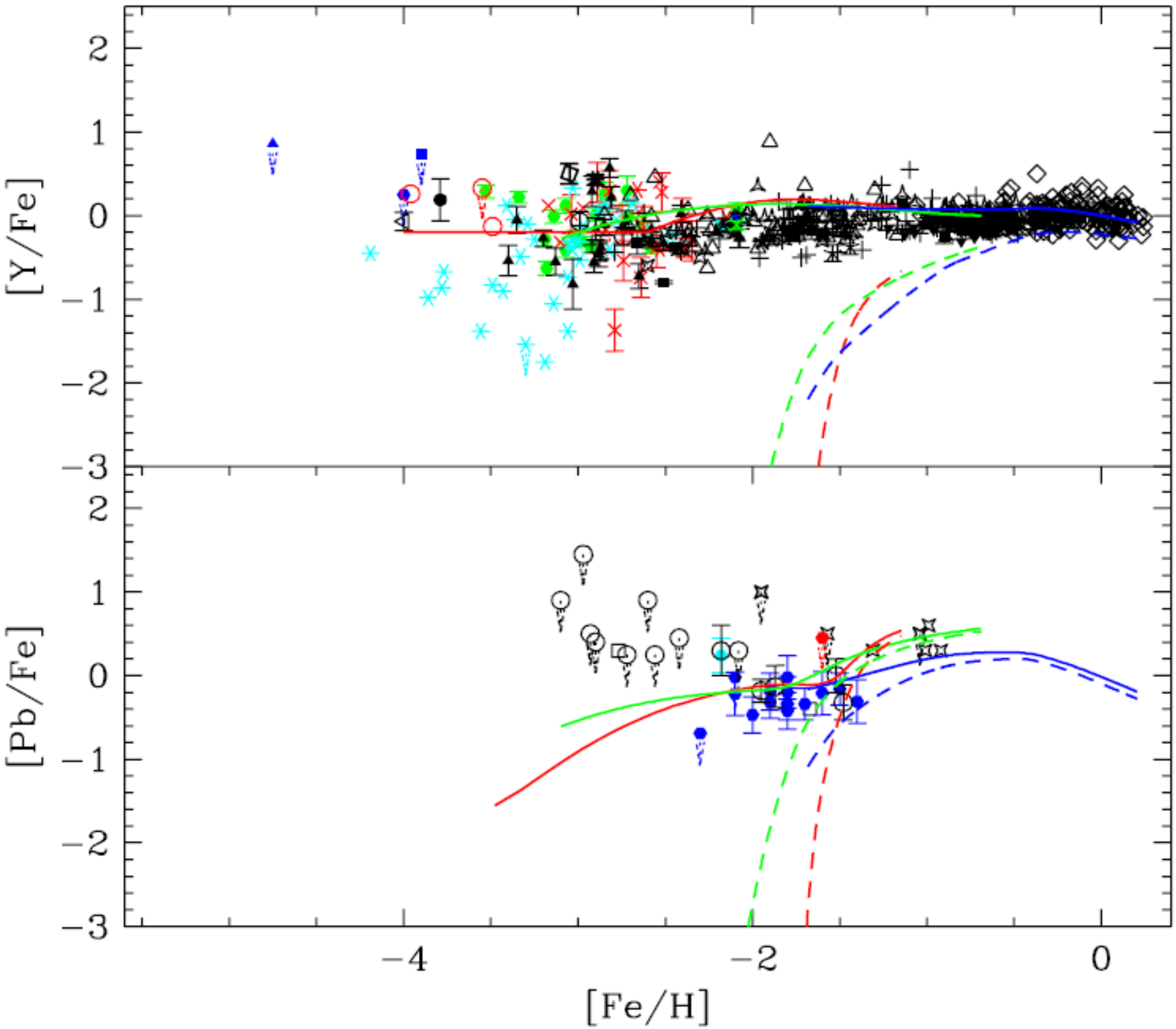
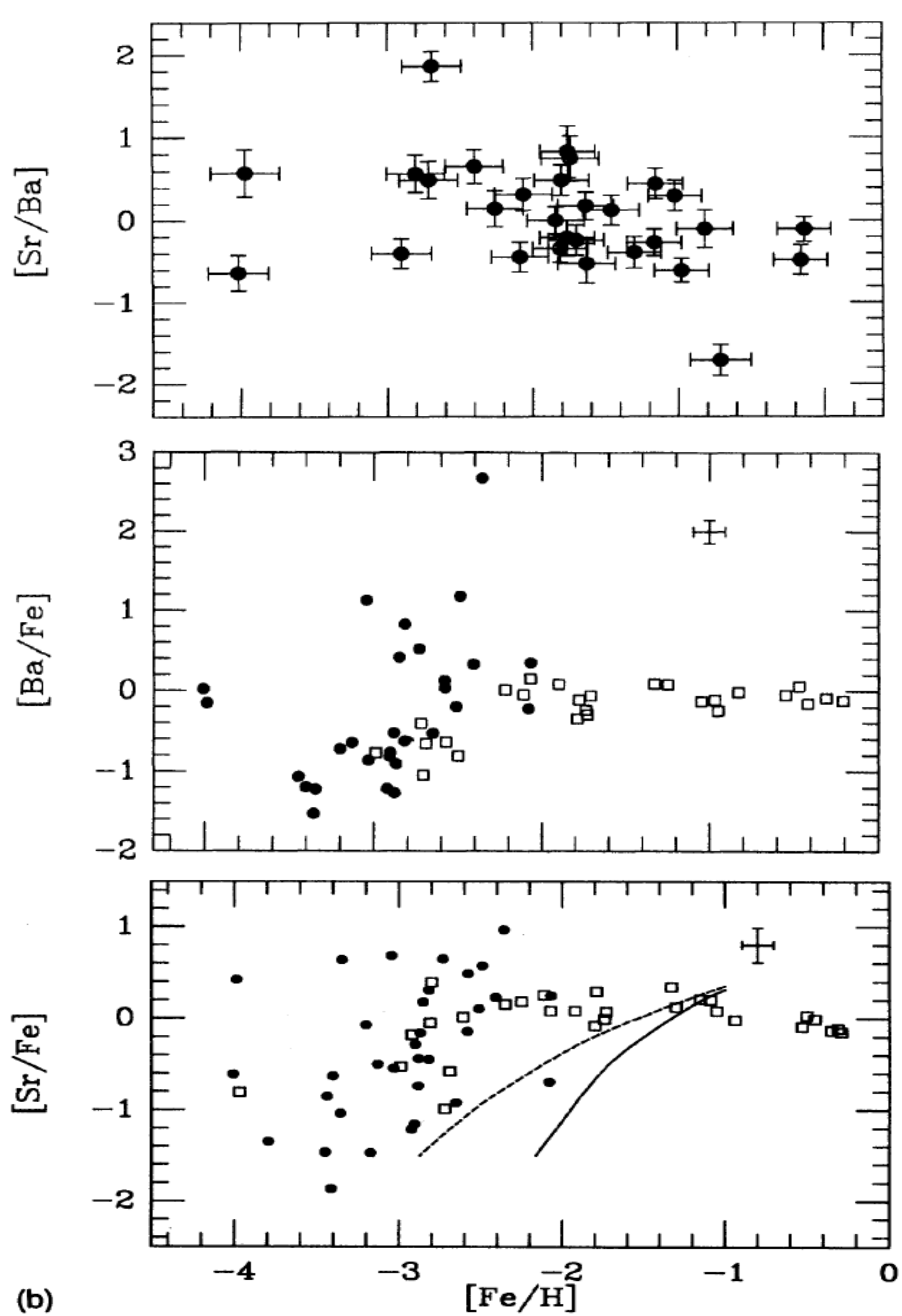
S+R-process contributions

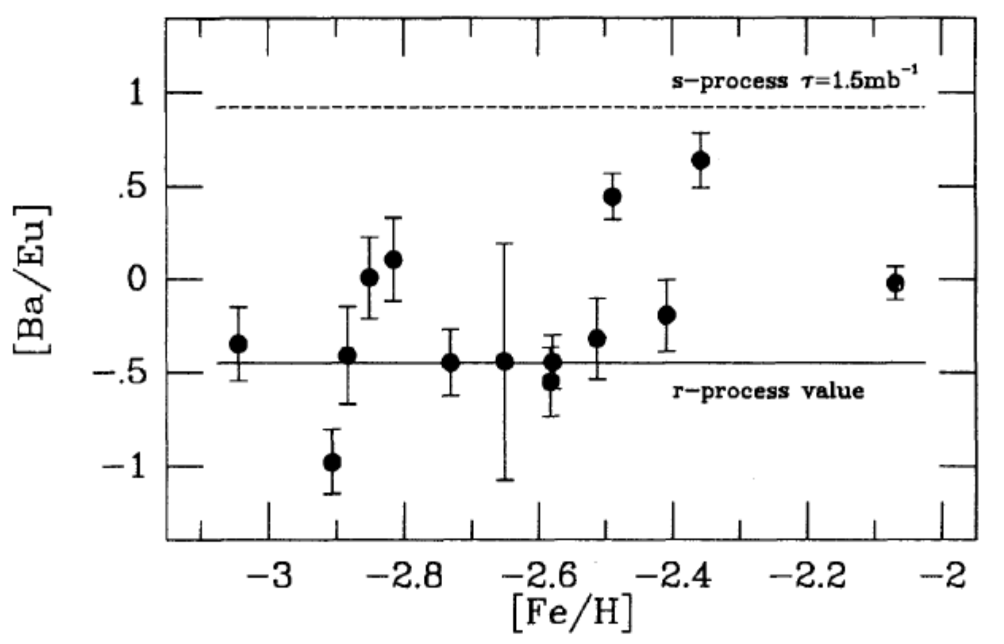
Kaeppeler et al. 2011, Rev.Mod. Phys. 83, 157



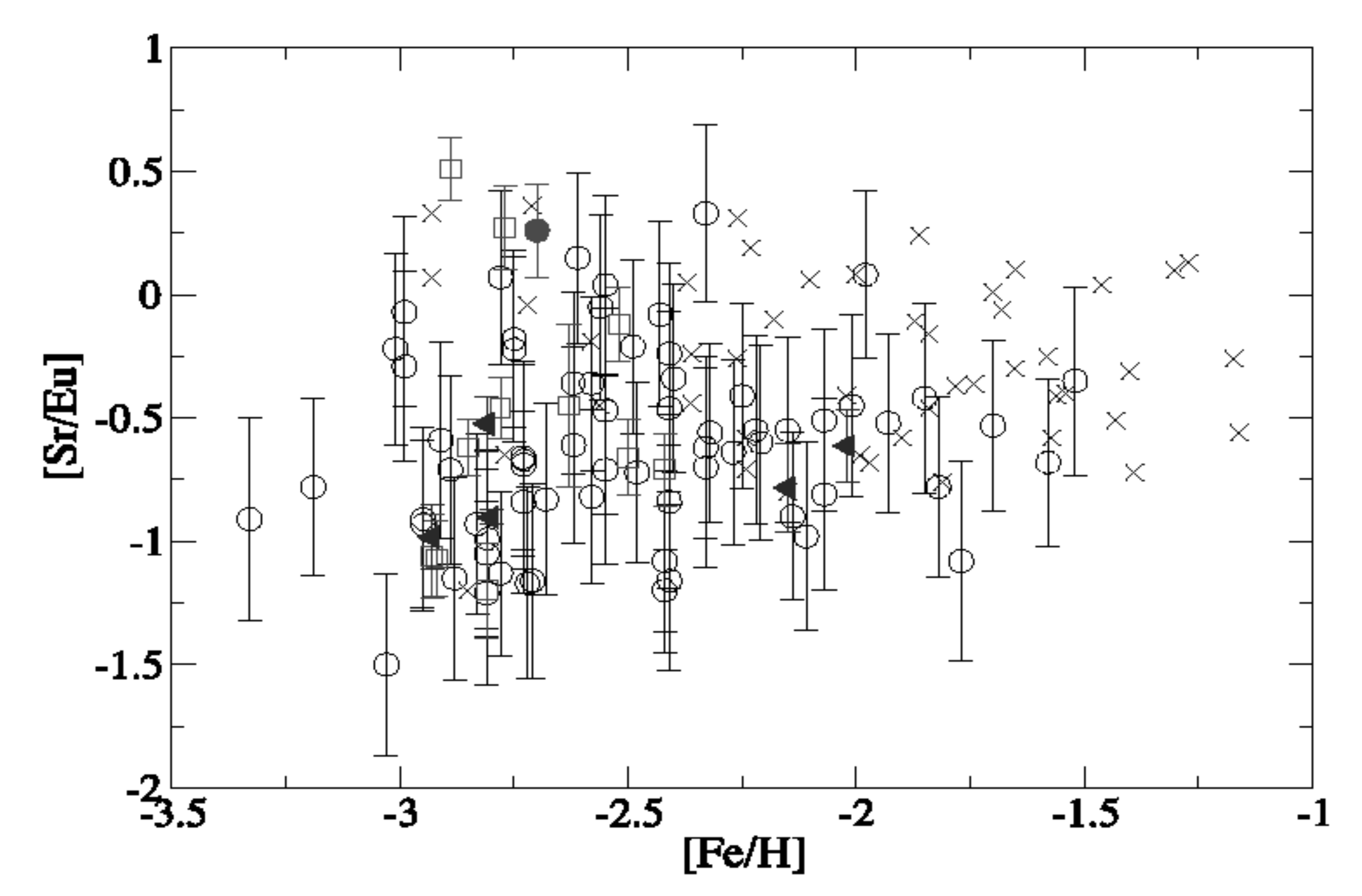
Kaeppeler et al. 2011, Rev.Mod. Phys. 83, 157

McWilliam et al. 1995, AJ, 109, 2757



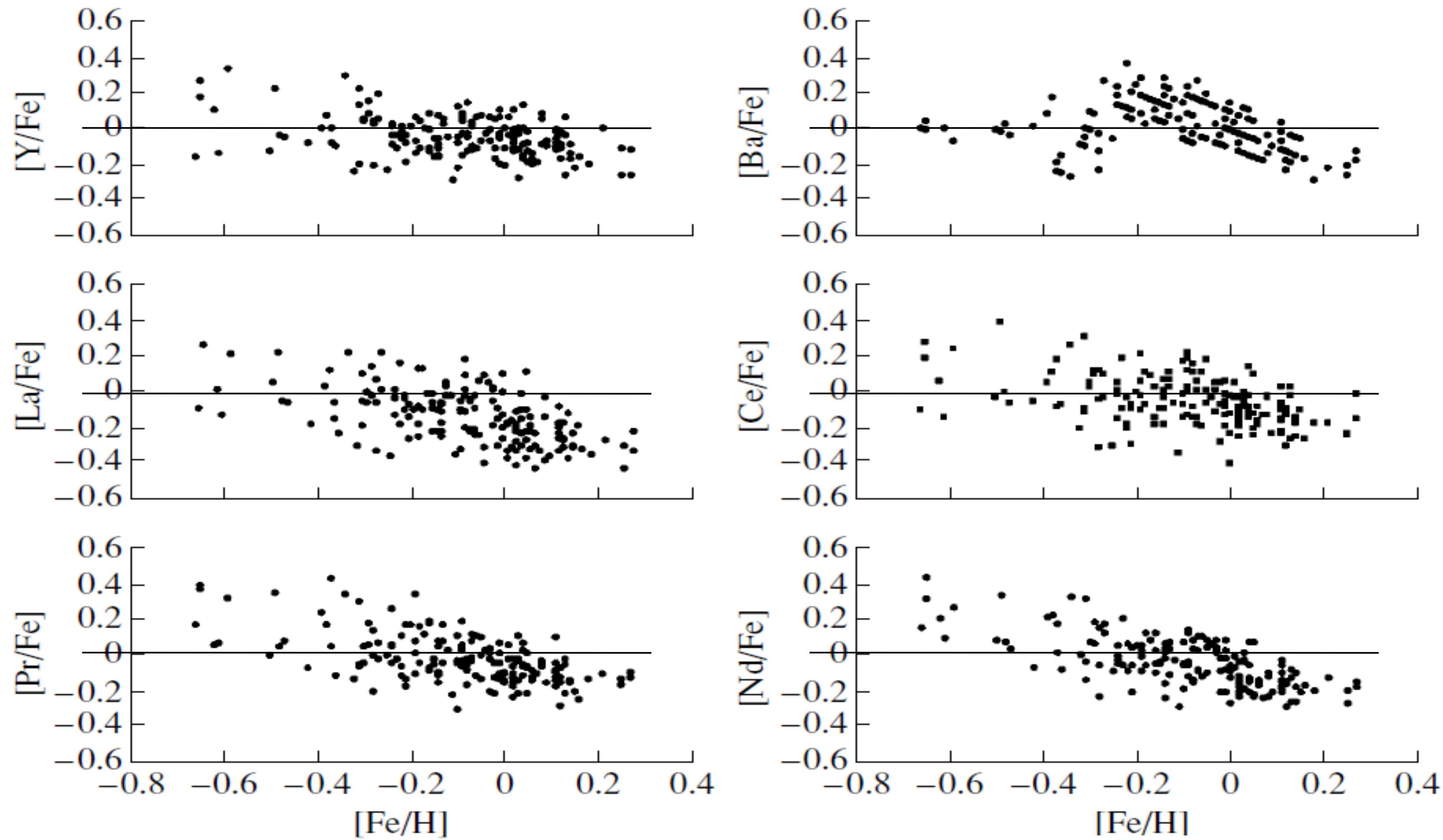


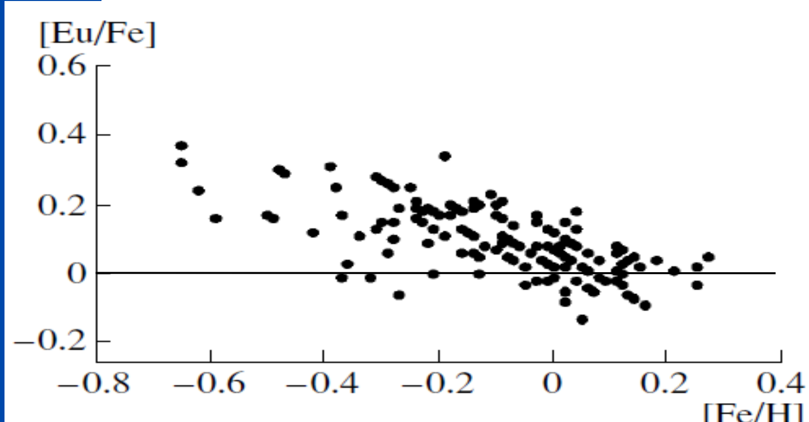
[Sr/Eu] vs [Fe/H]



Montes et al. 2007, ApJ, 671, 1685

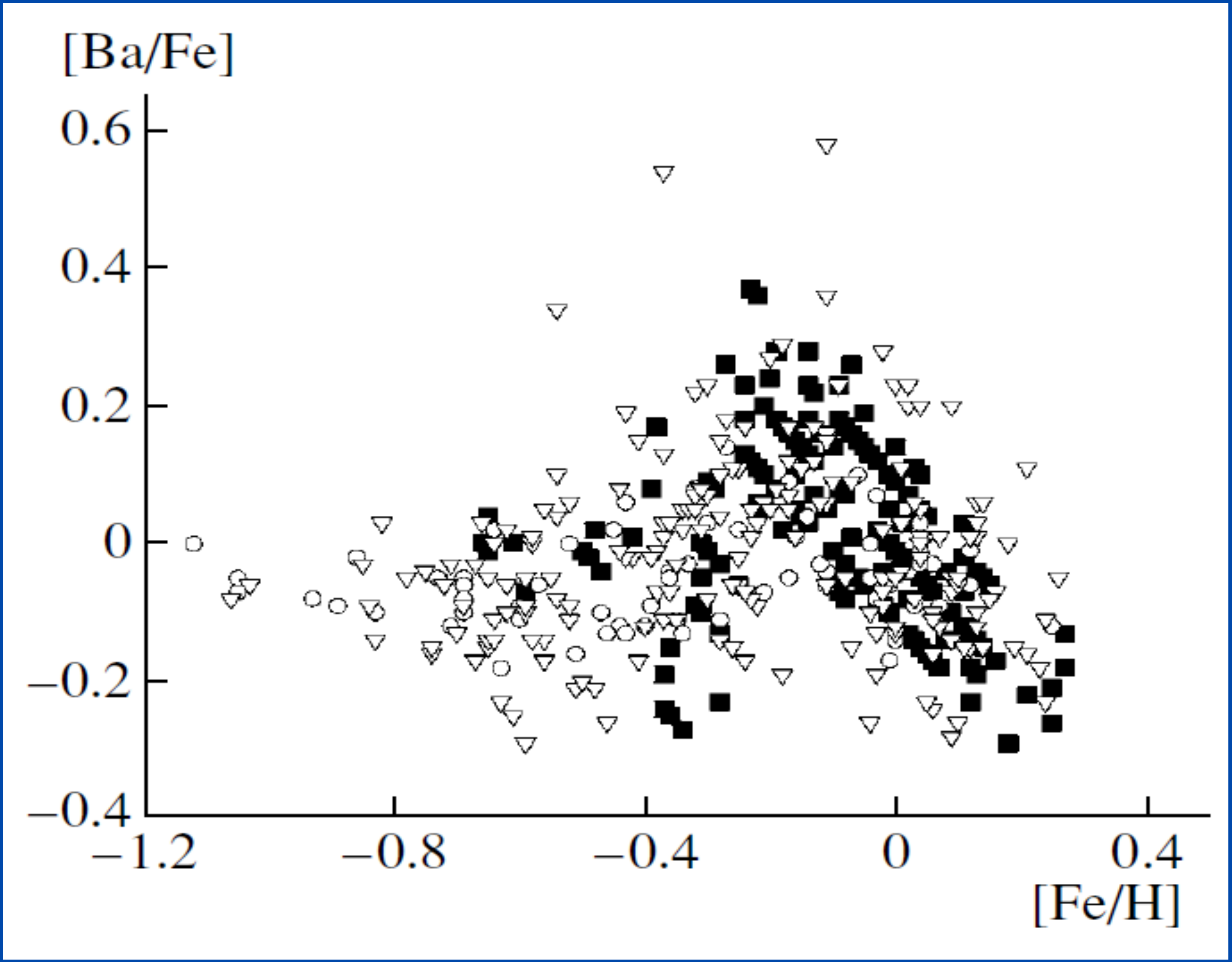
Mishenina et al. 2007, Astron. Rep. 51, 382





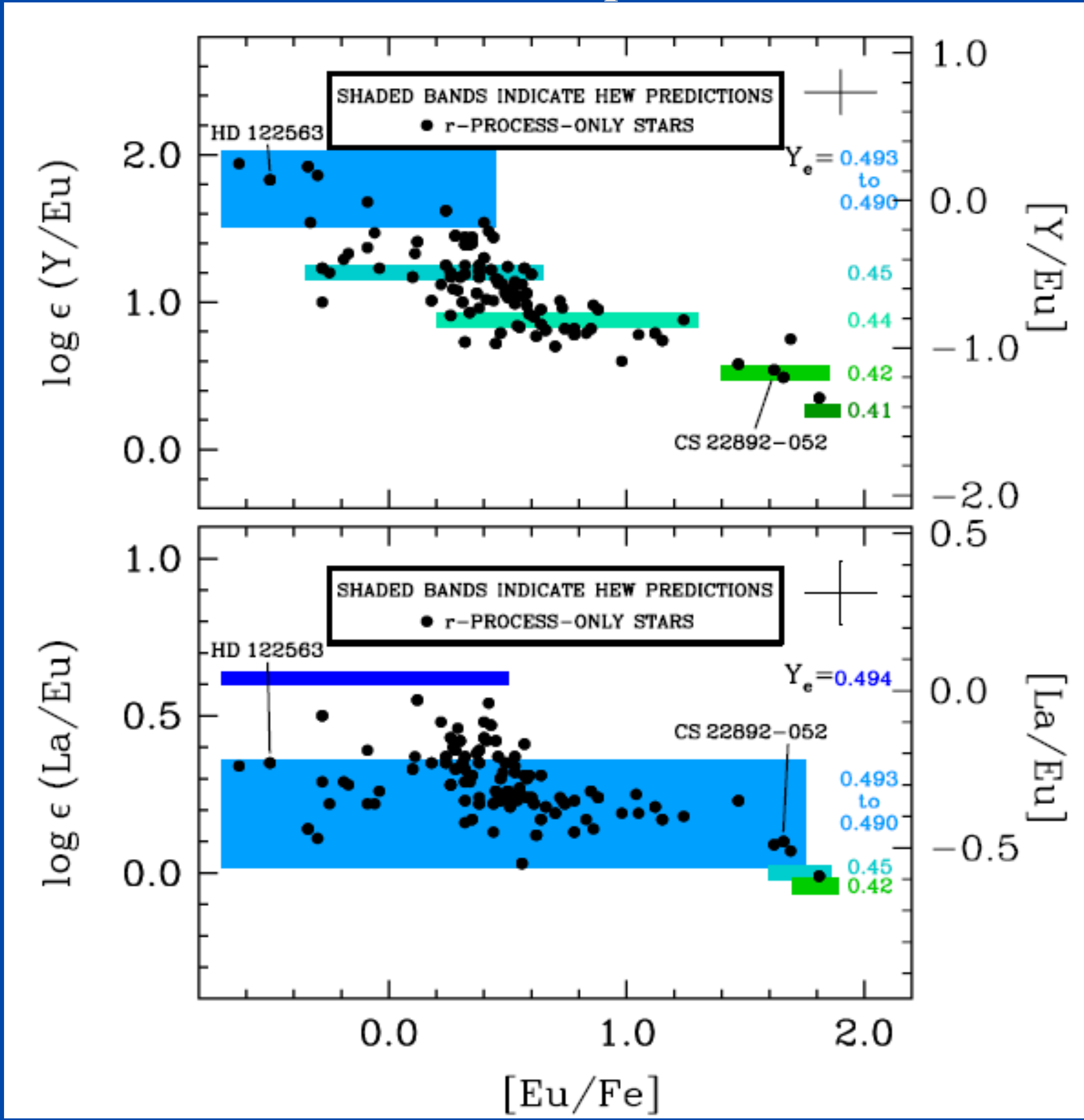
We observe a decrease in the Ba, La, Ce, Pr, Nd, and Eu abundances with increasing metallicity when [Fe/H] > 0, with the trend being stronger than for yttrium. This is consistent with the computations of the Galaxy's chemical evolution of Travaglio et al. 2004, and can be explained if the yield of these elements in low-mass AGB stars depends on the metallicity.

Mishenina et al. 2007, Astron. Rep. 51, 382



Symbols: Misheniina et al. 2007(filled squares);
Mashonkina & Gehren 2000, Astron. Astrophys. 364, 249 (open circles);
Edvarsson et al., 1993, Astron. Astrophys. 275, 101 (open triangles).

Roederer et al. 2010, ApJ 724, 975



MASSIVE STARS
Hydrostatic nucleosynthesis
in core He-burning
and in convective shell C-burning

Post-processing models

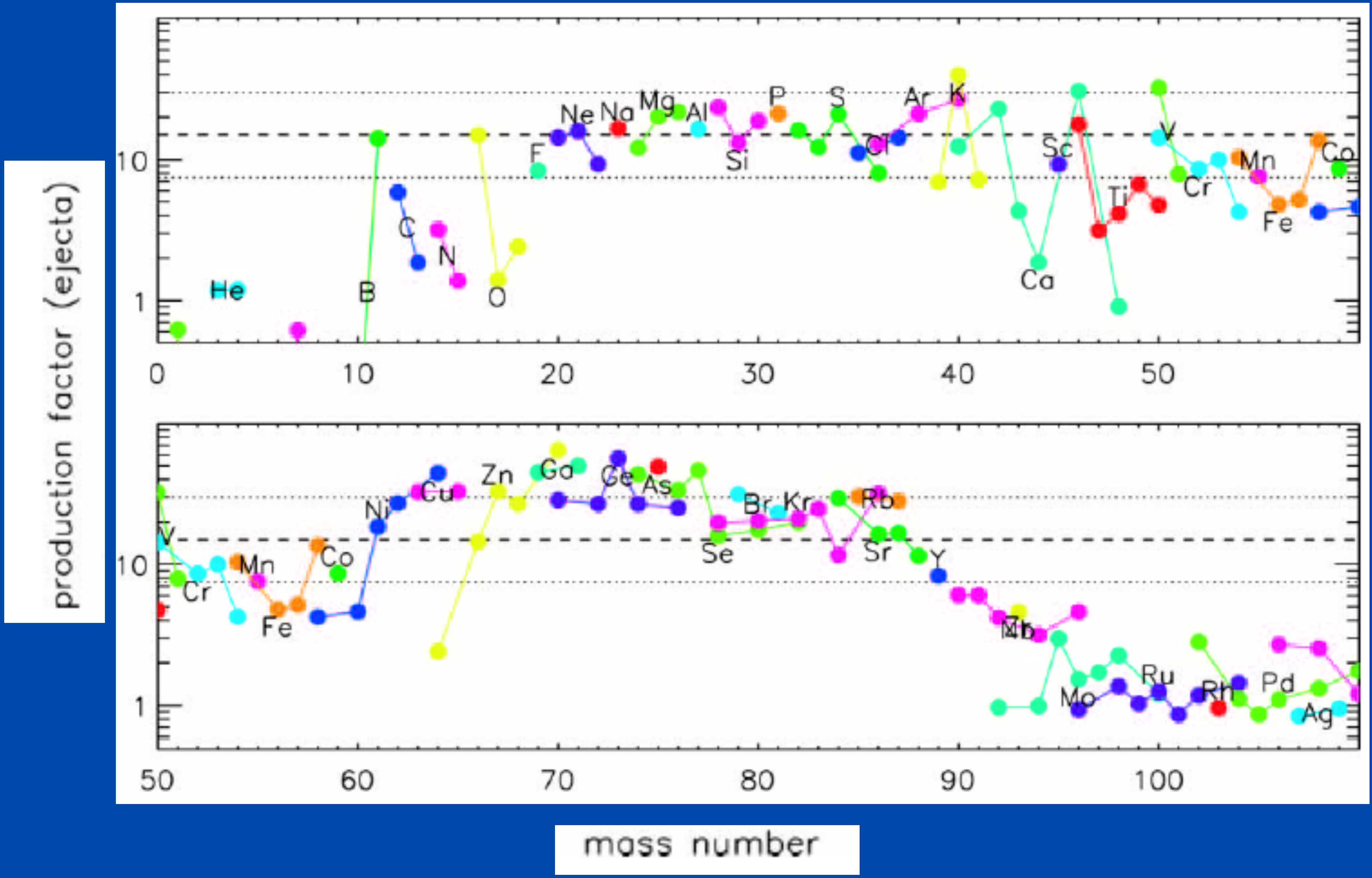
(Raiteri et al. 1991, 1993)

Updated network

Bao et al. 2000 for (n,γ) + more recent measures, or theoretical expectations (**KADoNiS** , I. Dillmann),

β decay rates from various sources,

(n,p) and (n,α) channels....



Rauscher , Heger, Hoffman, Woosley 2002, ApJ, 576, 323

The weak s-component is secondary-like

Convective Core He-burning

Low neutron density (~10^6 n/cm^3)
T~3-3.5 10^8 K
Classical s-process

Lamb et al. 1977,
Couch et al. 1974,
Prantzos et al. 1987,
Raiteri et al. 1991
……

Convective Shell C-burning

Peak neutron density
(10^{11}- 10^{12} n/cm^3)
T~ 1 10^9 K

The convective shell works on the ashes of core He-burning

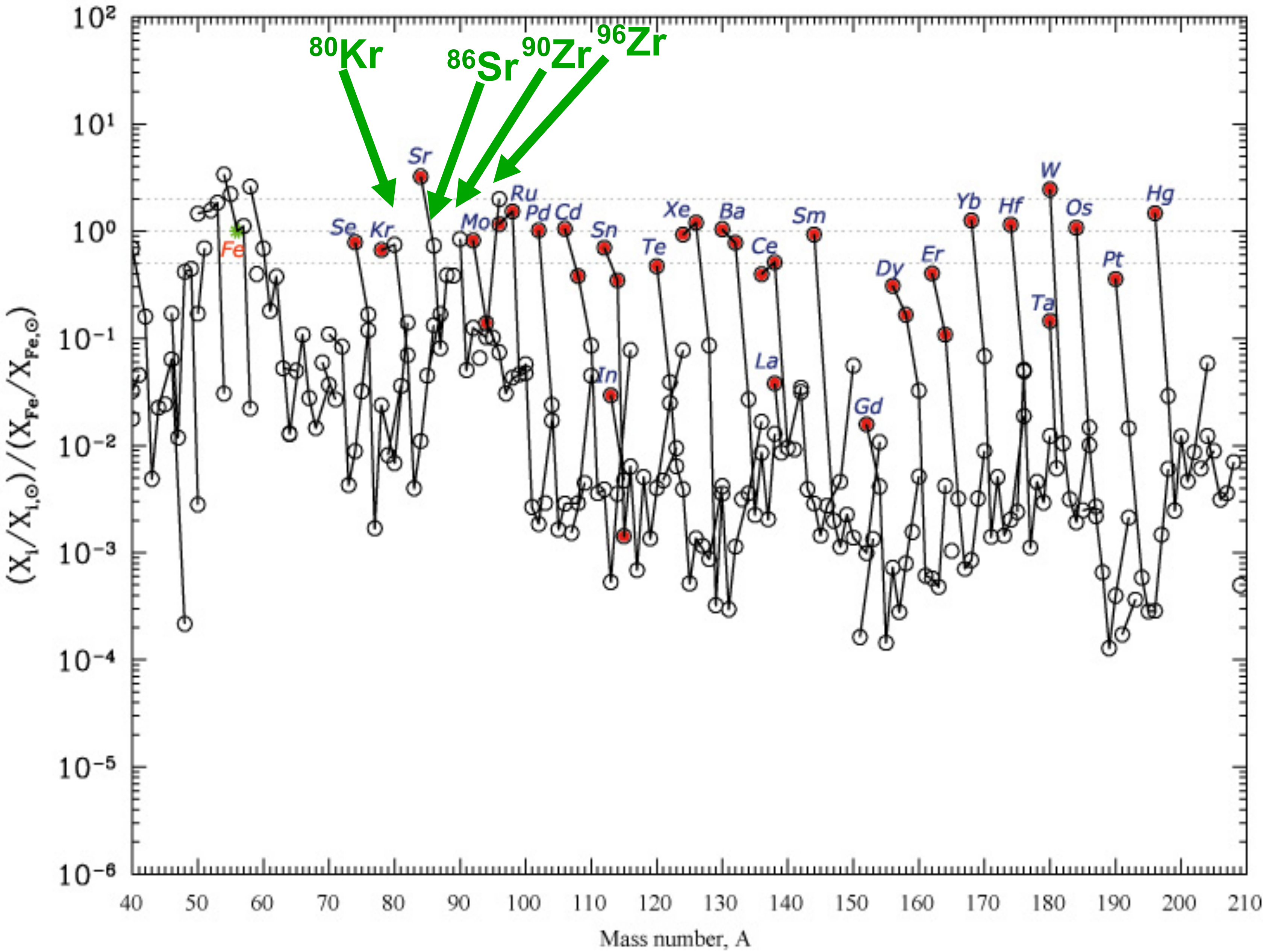
Raiteri et al. 1991
The et al. 2007 ….

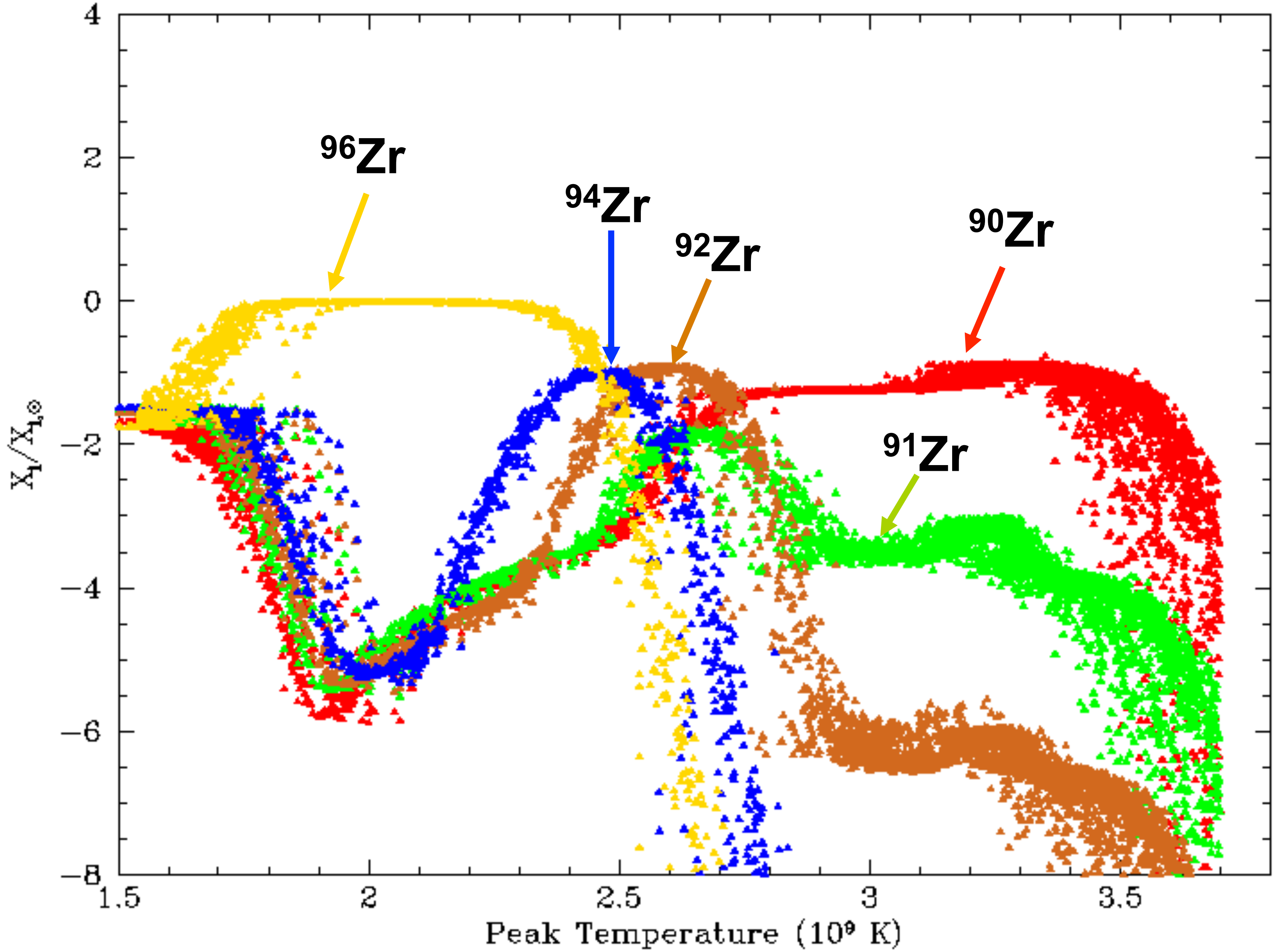
The final weak s component is an overposition of different components

Question:

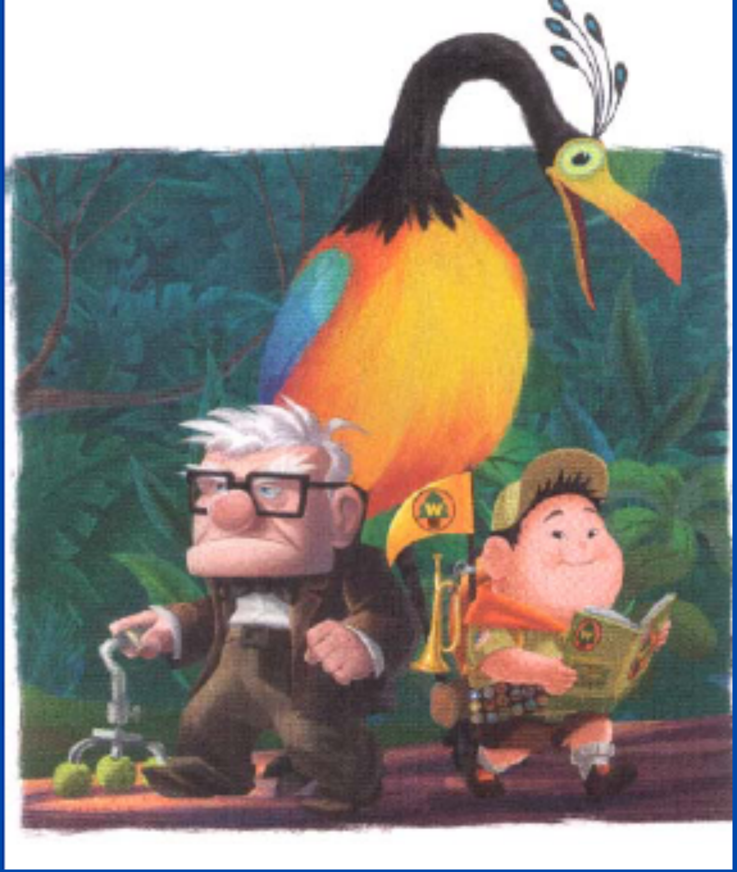
is ^{90}Zr of s-, r-, AND p-origin?

P-process in SNIa
Travaglio et al. 2011, ApJ, 739, 93





96Zr
94Zr
92Zr
90Zr
91Zr
4
2
0
−2
−4
−6
−8
1.5
2
2.5
3
3.5
X_i/X_i,⊙
Peak Temperature (10⁹ K)



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Mon. Not. R. Astron. Soc. 404, 1529–1544 (2010) doi:10.1111/j.1365-2966.2010.16369.x

s-Process in low-metallicity stars – I. Theoretical predictions

S. Bisterzo,[1★] R. Gallino,[1] O. Straniero,[2] S. Cristallo[2,3] and F. Käppeler[4]

The s-Process in Low Metallicity Stars. II. Interpretation of High-Resolution Spectroscopic Observations with AGB models.

MNRAS in press

S. Bisterzo[1★], R. Gallino[1,2], O. Straniero[2], S. Cristallo[3] and F. Käppeler[4]

s-Process in Low Metallicity Stars. III. Individual analysis of CEMP-s and CEMP-s/r with AGB models.

MNRAS submitted

S. Bisterzo[1★], R. Gallino[1,2], O. Straniero[2], S. Cristallo[3] and F. Käppeler[4]

Hubble Space Telescope:
Behind the Gas and Dust of Orion's Trapezium Cluster

Greetings, John, from the south part of the Alps