Constraining a pure r-process Ba/Eu ratio from observations of halo stars

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Outline of this talk

- ✶ Introduction: why Ba/Eu is important?
- ✶ HFS effects on derived Ba abundances.
- ✶ Non-LTE modelling for Ba II and Eu II.
- ✶ Ba/Eu of r-II stars.

Origin of heavy elements (Z > 30)

✓ Slow (*s*-) process:

- main component (A=90-208), AGB stars of 2-4 M_{sun},

  calculations: *Arlandini et al.* (1999, **A99**), updated by *Bisterzo et al.* (2011, **B11**).
- weak component (A < 90), He burning core of $M > 10\ M_{sun}$.

✓ Rapid (*r*-) process: SNeII, neutron star mergers ??

Solar System matter, Ba and Eu isotopes

	Lodders2009 (%)	*s*-process (%) A99	*s*-process (%) B11		Lodders2009 (%)	*s*-process A99	*s*-process B11
^{134}Ba	2.4	100	100	^{151}Eu	47.8	6	6
^{135}Ba	6.6	26	30	^{153}Eu	52.2	5	6
^{136}Ba	7.9	100	100				
^{137}Ba	11.2	66	67				
^{138}Ba	71.7	86	94				
Total Ba:		81	88.7	Total Eu		6	6

Significant discrepancy!

Introduction: why Ba/Eu is important?

- Solar system matter: log Ba/Eu = 1.66
- *r*-residuals = SS abundance – *s*-contribution

  log $(Ba/Eu)_r$ = 0.96, $[Ba/Eu]_r$ = -0.70 (**A99**),

  0.74 -0.92 (**B11**).

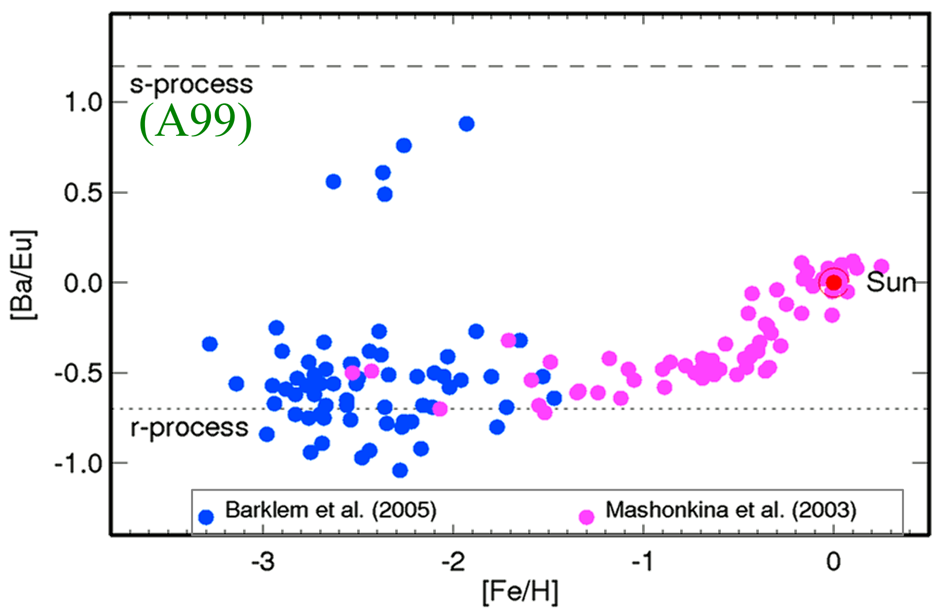
  Due to different predictions for Ba!

- *r*-process models

  log $(Ba/Eu)_r \approx 1$, WP approximation (*Kratz et al.* 2007),

  0.8, HEW (*Farouqi et al.* 2010)

Ba/Eu is sensitive to whether s- or r-process dominated heavy element production



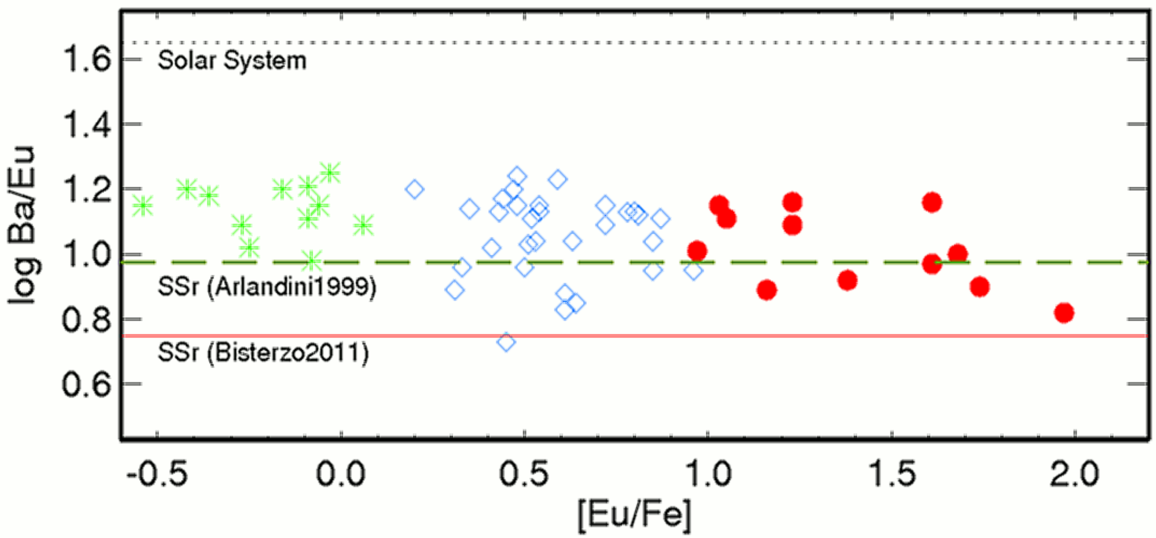
- Most MP stars are enriched in *r*-process elements

  Spite & Spite (1978),
  McWilliam (1998),
  Mashonkina&Gehren (2000),
  Barklem et al. (2005),
  Francois et al. (2007).

- *s*-process contributes to Ba at [Fe/H] > -1.

Ba/Eu in [Fe/H] < -1.5 stars with [Ba/Eu] < -0.4

(based on literature data, in total, 14 sources)



r-I: [Eu/Fe] = 0.3 - 1;
[Ba/Eu] < 0
r-II: [Eu/Fe] > 1;
[Ba/Eu] < 0

(*Beers & Christlieb*, 2005)
for [Fe/H] < -1 stars

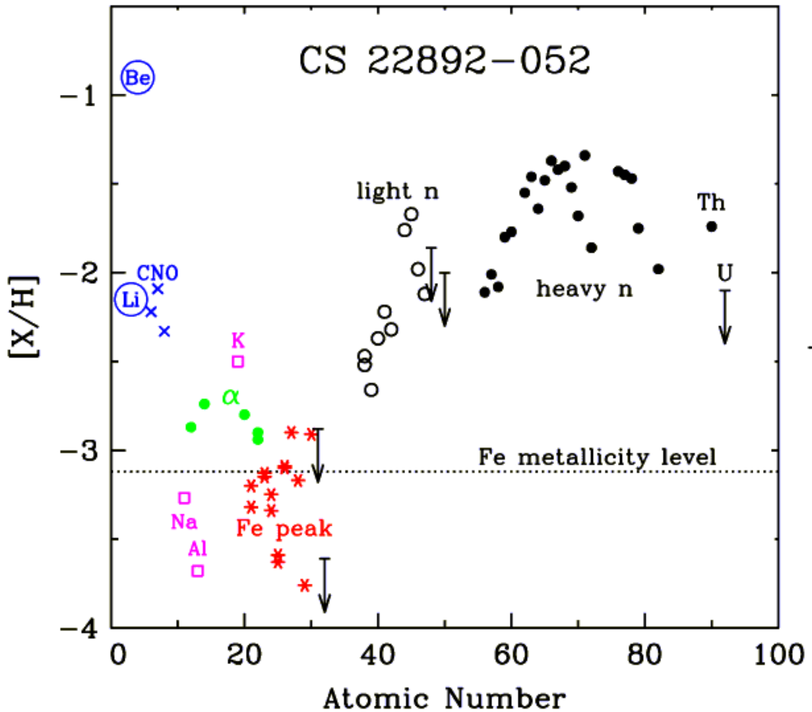
● r-II: mean log Ba/Eu = 1.03
◊ r-I: 1.08
* Eu-poor ([Eu/Fe] < 0): 1.14

log Ba/Eu ≈ 1,
independent of [Eu/Fe]

Why do *Arlandini*1999's and WP models reproduce observations better than those of *Bisterzo*2011 and HEW?

r-II stars are best candidates for learning r-process

✓ First discovery: CS 22892-052 [Fe/H] = -3.1, [Eu/Fe] = 1.63.

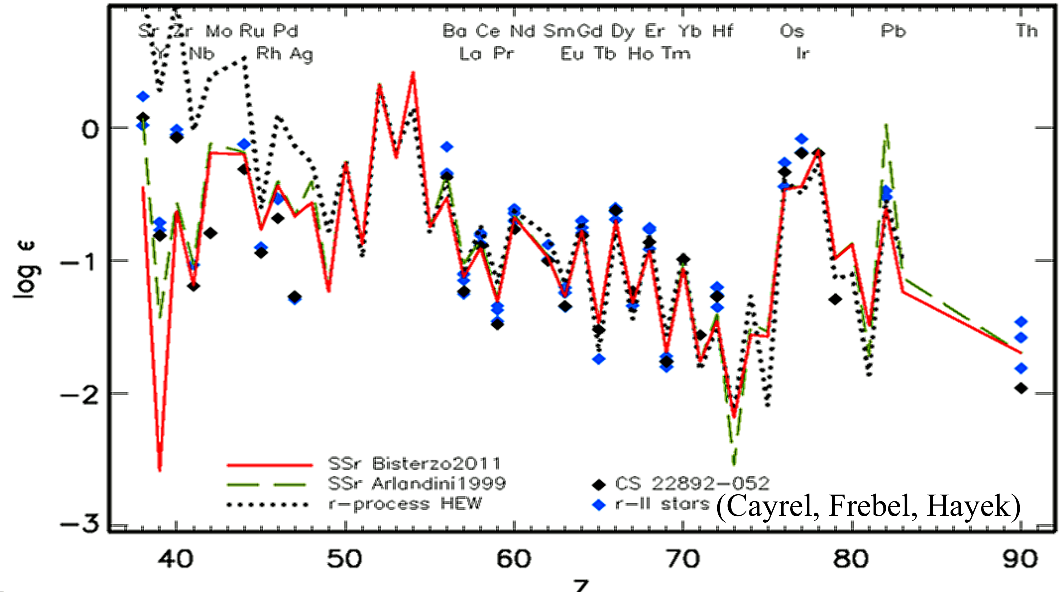


In total, 30 elements from Sr to Th were measured.

(Sneden et al. 1994, 1996, 2003)

✓ r-II: ~ 5 % of stars at [Fe/H] < -2.5. 12 stars are known:

-3.4 ≤ [Fe/H] ≤ -2.8, [Eu/Fe] = 1.0 - 1.9.



✓ Sr-Hf (-Ir?) abundance patterns of r-II stars are very similar.

✓ Ba-Hf abundance patterns match the SS r-process. Ba?

This study aims to improve observational data on Ba and Eu abundances of the r-II stars

- ✓ by using an appropriate Ba isotope mixture,
- ✓ taking the departures from LTE for Ba II and Eu II into account.

HFS effects on derived Ba and Eu abundances

- In odd-atomic mass isotopes, nucleon-electron spin interactions lead to hyper-fine splitting (HFS) of the energy levels.

- Each line of Ba II and Eu II consists of isotopic and HFS components. They make the line broader resulting in larger absorbed energy.

- HFS effects depend on isotope mixture.

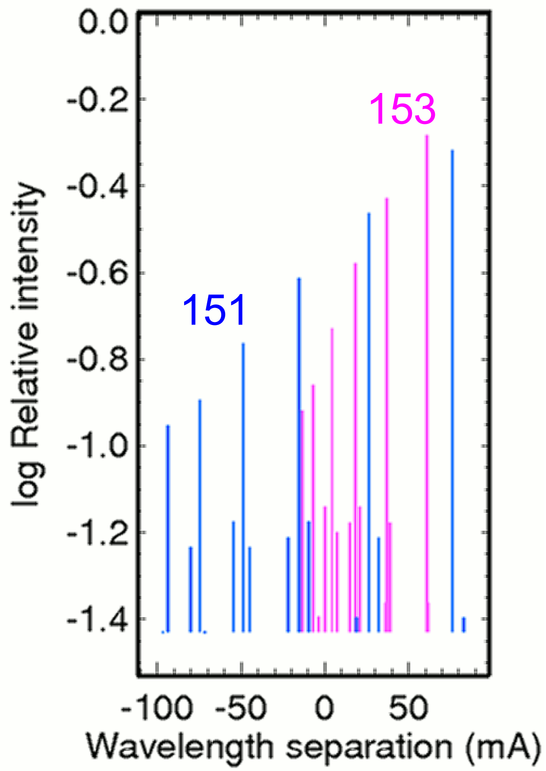
- Eu: two odd-A isotopes, strong HFS effects.

  SS: ^{151}Eu:^{153}Eu = 48:52,

  r-process: 39:61.

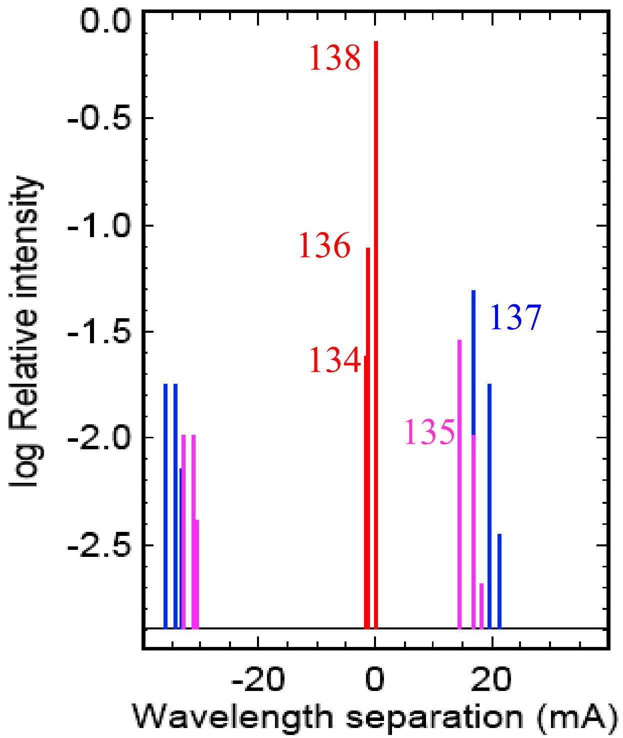
  Minor change in derived abundances between using two isotope mixtures.

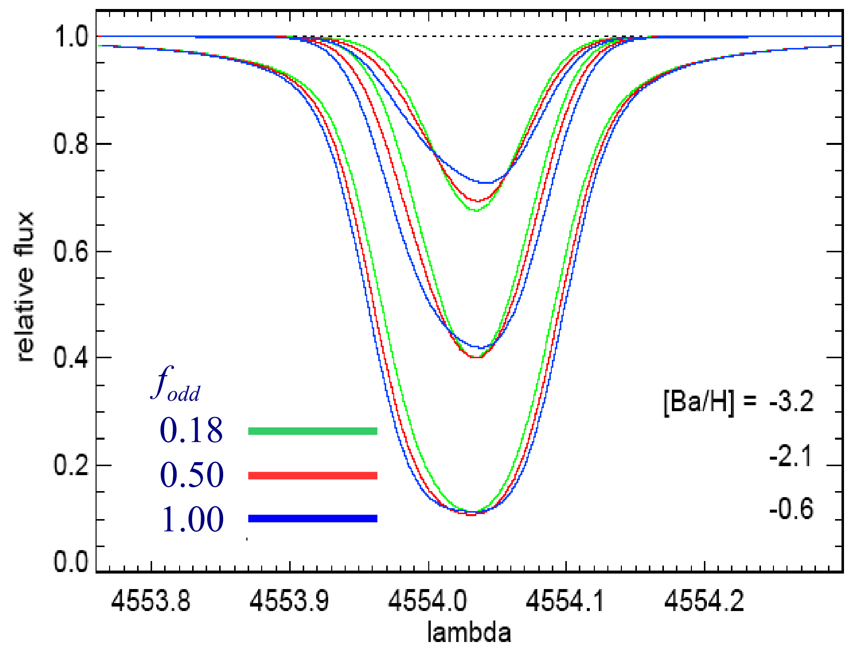
- Ba: isotope mixture is different for SS matter and r-process.



Eu II 4129: isotopic and HFS components. Relative intensities correspond to ^{151}Eu:^{153}Eu = 48:52

Ba II 4554, 4934 Å are strongly affected by HFS





- ✓ Ba II 4554: isotopic and HFS components. Relative intensities correspond to the SS Ba isotope mixture, with $f_{odd} = 0.18$.

- ✓ The greater f_{odd}, the stronger Ba II 4554 is. Ba abundances derived from resonance lines depend on adopted f_{odd}

- ✓ HFS is negligible for subordinate lines of Ba II.

Ba II 4554, 4934 Å are strongly affected by HFS

Effect of different Ba isotope mixtures for Sneden"s star CS 22892-052, 4800/1.5/-3.1

Mean non-LTE abundance	f_{odd}	
(Ba II 4554, 4934 Å)		
0.03	0.18	(Solar System)
-0.18 ± 0.01	0.46	(A99)
-0.28 ± 0.03	0.66	(B11)
-0.30	0.72	(*McWilliam*, 1998)
-0.20	0.52	(*Sneden et al.* 1996)
(Ba II subordinate lines)		
-0.15 ± 0.02		

f_{odd}: Arlandini1999 or Bisterzo2011 ?

Caution against firm conclusion, when the resonance lines are strong.

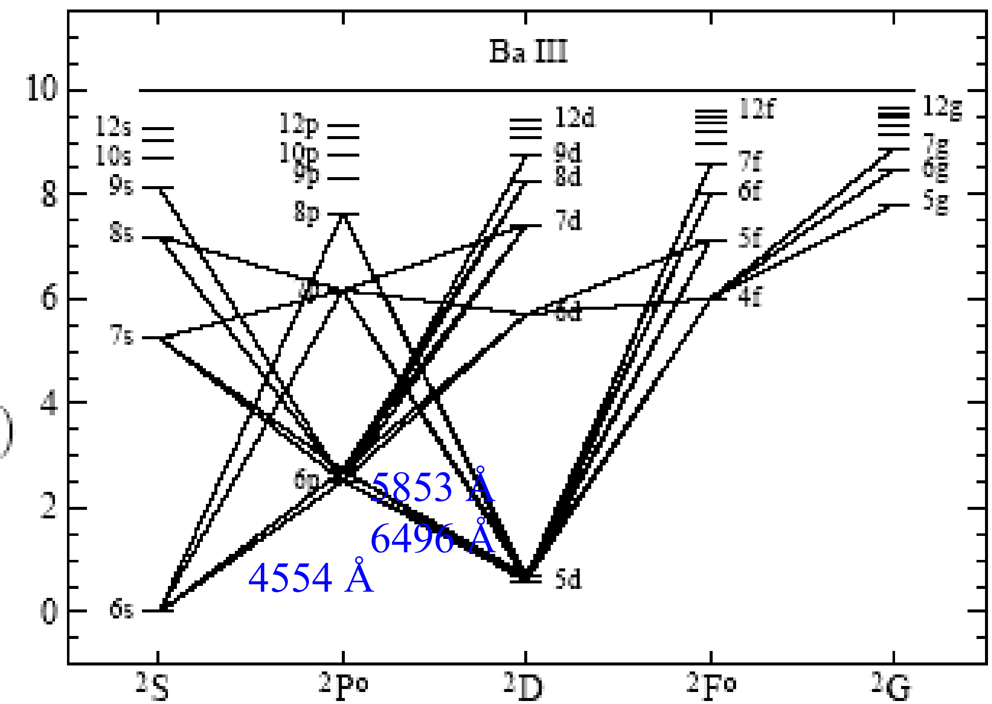
$\Delta\xi_t = -0.2$ km/s $\rightarrow$ $\Delta\log\varepsilon = +0.15$ dex.

What is meant by *non-local thermodynamic equilibrium* (non-LTE) ?

- Atomic level number densities n_i from balance between various population and de-population processes, i.e., statistical equilibrium (SE) equations.
- Maxwellian velocity distribution, $T_e = T_A = T_i$
- Model atom represents real atomic term structure.
- Solution of combined SE and radiation transfer equations:

$$
\left\{
\begin{aligned}
& n_i \sum_{j \neq i} (R_{ij} + C_{ij}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) \\
& \mu \frac{dI_\nu(z,\mu)}{dz} = -\chi_\nu(z) I_\nu(z,\mu) + \eta_\nu(z)
\end{aligned}
\right.
$$

Excitation and ionization state of the matter at any depth point depends on physical conditions throughout the atmosphere.



Atomic term structure for Ba II

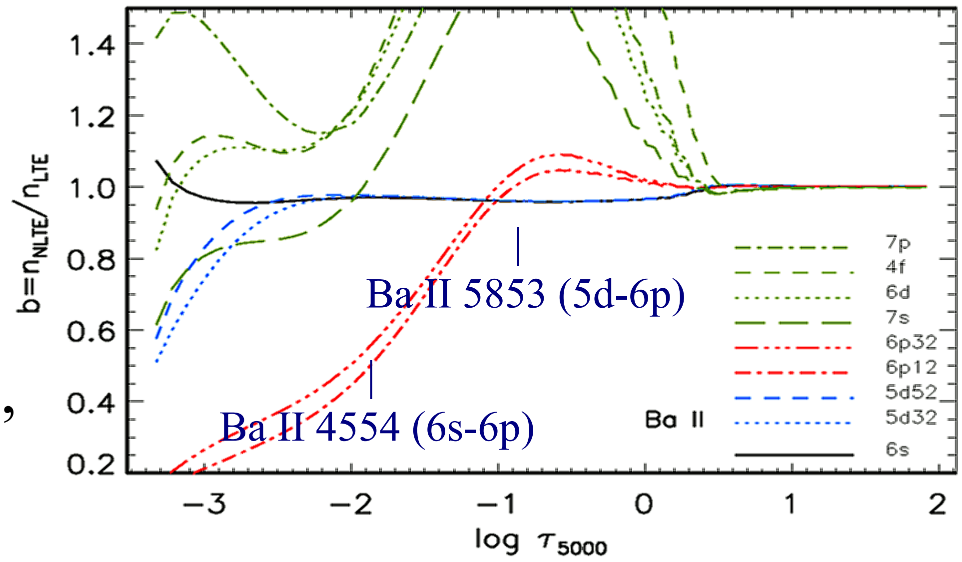
Method of calculations

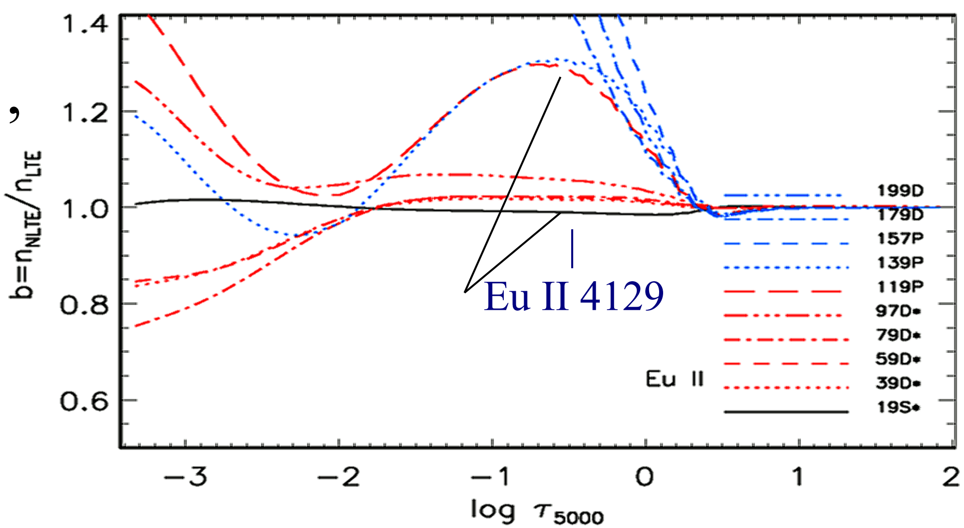
- Non-LTE populations for Ba II and Eu II:
  - model atoms and atomic data from *Mashonkina et al.* (1999), *Mashonkina* (2000, updated)
  - code DETAIL by *Butler & Giddings* (1985) with updated opacity package.
- Spectral line synthesis: code SIU by *Reetz* (1991).
- Model atmospheres: MARCS (*Gustafsson et al.* 2008)

Non-LTE modelling for Ba II and Eu II

Departure coefficients
$b = n_{NLTE}/n_{LTE}$
for Ba II and Eu II
in 4800/1.5/-3 model

- Ba II 4554: b(6s) ≈ 1, b(6p) < 1, line is strengthened, with non-LTE abundance correction Δ_{NLTE} = -0.14 dex.
- Ba II 5853: b(5d) ≈ 1, b(6p) ≈ 1, Δ_{NLTE} = -0.03 dex.
- Eu II 4129: $b_{low} \approx 1$, $b_{up} > 1$ line is weakened, Δ_{NLTE} = +0.10 dex.





Mashonkina et al. (2013, in prep)

Non-LTE effects depend on stellar parameters and the line.

$$\Delta_{NLTE} = \log \varepsilon_{NLTE} - \log \varepsilon_{LTE}$$

T_{eff}/log g/[Fe/H]/[Ba/Fe]		Ba II 4554	5853	6497	[Eu/Fe]	Eu II 4129
4800/1.5/-3/	1.1	-0.13	-0.14	-0.35	1.8	0.06
4800/1.5/-3/	0.7	-0.14	-0.02	-0.22	1.6	0.08
5050/2.3/-3/	0.7	-0.15	0.02	-0.11	1.5	0.10
5010/4.8/-3/	0.7	-0.01	0.01	0.01	1.5	0.03

- ✓ r-II stars are mostly VMP cool giants.
  Non-LTE leads to *lower* Ba, but *higher* Eu abundances.
- ✓ Exception is VMP dwarf with [Eu/Fe] = 1.9 (*Aoki et al*. 2010).
  Non-LTE effects are minor.

Ba/Eu of r-II stars

Sources of observational data (spectra, EWs, LTE abundances):

Sneden et al. (1996); *Christlieb et al.* (2004); *Honda et al.* (2004); *Andrievsky et al.* (2009); *Aoki et al.* (2010); *Mashonkina et al.* (2010).

Ba non-LTE abundances:

- from subordinate lines of Ba II (CS 22892-052, HE 1219-0312, HE 2327-5642, SDSS J2357),
- from two resonance lines available, with f_{odd} = 0.46 and 0.66 (CS 22183-031, CS 29497-004),
- taken from *Andrievsky et al.* (2009) (CS 31082-001, CS 22953-003, subordinate and resonance lines, f_{odd} = 0.5).

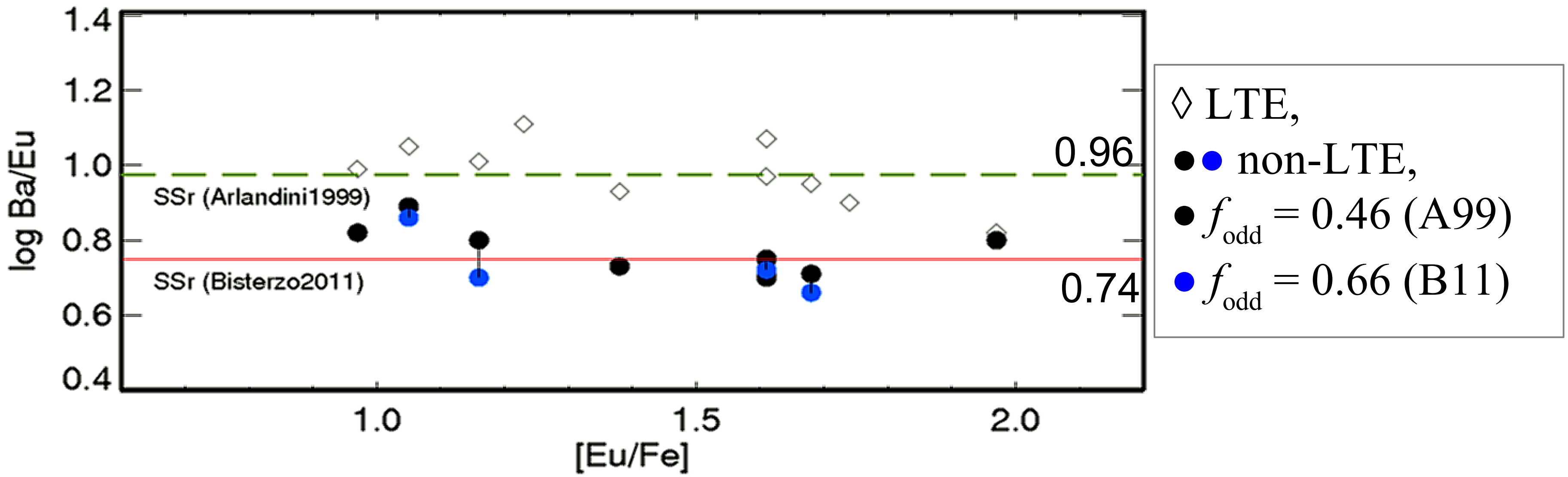
Eu non-LTE abundances: 8 stars, in total.

Non-LTE effects on Ba abundances of Sneden"s star CS 22892-052, 4800/1.5/-3.1

Mean abundance	LTE	non-LTE
Ba II 4554, 4934 (f_{odd} = 0.46, A99)	0.02±0.07	-0.18±0.01
(f_{odd} = 0.66, B11)	-0.05±0.08	-0.28±0.03
Ba II subordinate lines	0.02±0.11	-0.15±0.02

Note dramatic reduction of statistical error when moving from LTE to non-LTE.
This favours non-LTE line formation for Ba II.

Ba/Eu of r-II stars



LTE, mean log Ba/Eu =	0.99 (10 stars)
non-LTE, A99	0.78 (8 stars)
non-LTE, B11	0.75

For 4 stars, Ba abundances depend on used Ba isotope mixture.

Non-LTE Ba/Eu ratios of the r-II stars support

- ✓ updated solar r-process log $(Ba/Eu)_r = 0.74$ (*Bisterzo et al.* 2011)
- ✓ HEW r-process model log $(Ba/Eu)_r = 0.8$ (*Farouqi et al.* 2010)

Concluding remarks

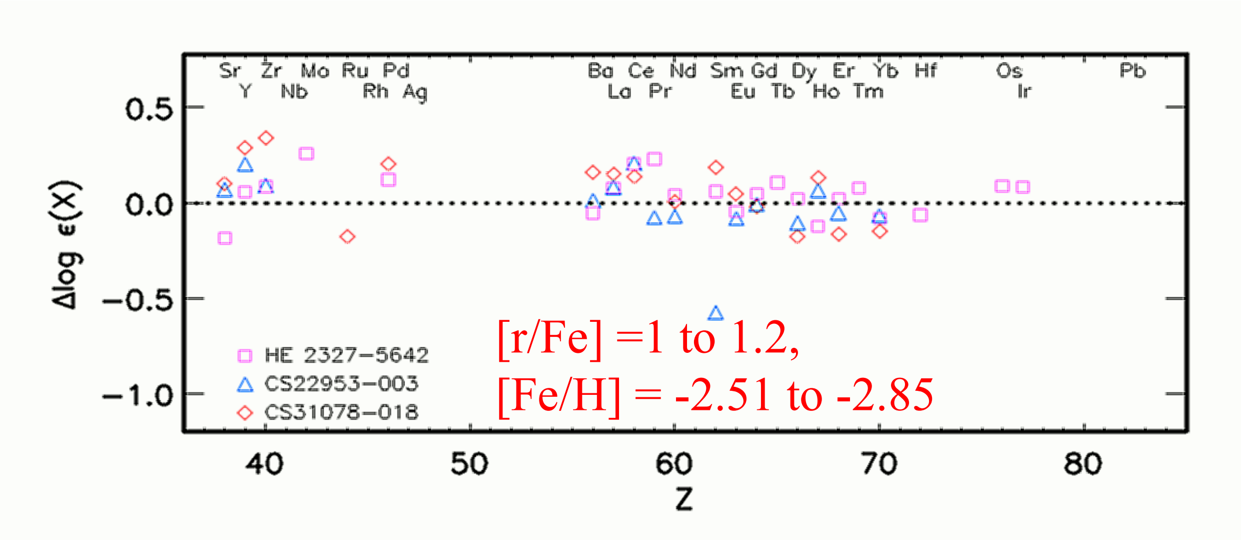
- Adequate line-formation modelling is important for accurate determination of heavy element abundances of VMP stars, in particular, giants.
  Δ_{NLTE} can be of different sign for (Sr,Ba) and (Eu,Nd,Pr,...).

- Revised Ba/Eu abundance ratios of the r-II stars support chemical evolution calculations of *Bisterzo et al.* (2011) and HEW r-process model by *Farouqi et al.* (2010).

- For constraining r-process models, it would be important to determine fraction of the odd isotopes of Ba in the r-II stars.

(See tomorrow talk on proposed project).

Abundance difference between “moderate” and “extreme” r-II stars



r-II stars:

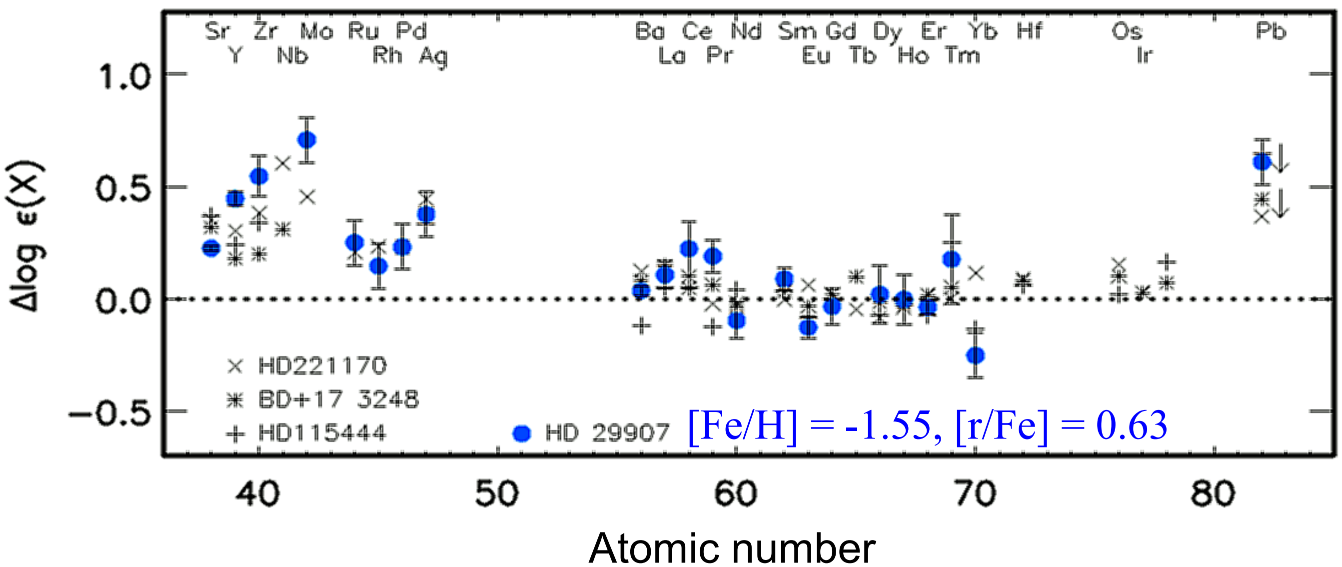
☺ similar abundance pattern in the Sr-Ir range.

☺ Ba-Hf match the Solar r-process pattern very well.

☹ Sr-Ag: no conclusion due to uncertainty in the Solar r-process abundances.

Stellar abundances: *Mashonkina* 2010; *Francois* 2007; *Lai* 2008.

Abundance difference between r-I and “extreme” r-II stars



Four r-I stars: [Fe/H] = -1.55 to -2.99, [r/Fe] = 0.63 to 0.86.

☺ Ba-Ir: abundance pattern is similar to that of r-II stars,
pure r-process synthesis up to [Fe/H] = -1.55.

? Sr-Ag: extra-production, how, where ?

Stellar abundances: *Ivans* 2006; *Cowan* 2002; *Westin* 2000; *Sitnova & Mashonkina* 2011.