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Europe/Berlin timezone

Unraveling the mysteries of Carbon-Enriched Metal-Poor (CEMP) stars

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ROARrr

CEMP classification (Carbon-Enriched Metal-Poor)

Classification based on carbon…

Different definitions:

- [C/Fe]>1 (Beers & Christlieb 2005)
- [C/Fe]>0.7 if log L/Lsun<2.3
  [C/Fe]=3-log(L/Lsun)
  if log L>2.3 (Aoki+2007)

N.B. Varying limits for external system.
e.g. Sgr, Dra, Umi, Scl (Sestito+ 2024)

… and on heavy elements : Ba, (La), Eu

Table 1
CEMP Subclass Definitions

Subclasses	Definition
CEMP	[C/Fe] $>+0.7$
CEMP-*r*	[C/Fe] $>+0.7$, [Eu/Fe] $>+0.7$, [Ba/Eu] <0.0
CEMP-*s*	[C/Fe] $>+0.7$, [Ba/Fe] $>+1.0$, [Ba/Eu] $>+0.5$
CEMP-*i* (*r*/*s*)	[C/Fe] $>+0.7$, $0.0<$ [Ba/Eu] $<+0.5$ or
	[C/Fe] $>+0.7$, $0.0\leqslant$ [La/Eu] $\leqslant+0.6$
CEMP-no	[C/Fe] $>+0.7$, [Ba/Fe] <0.0

Zepeda+ 2023

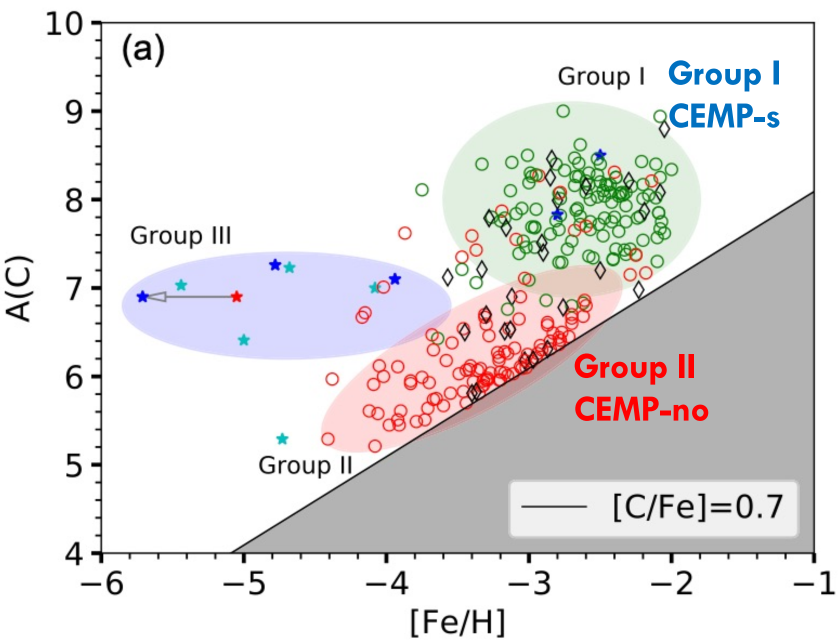
r-I:	0.3 < [Eu/Fe] <= 0.7 and [Ba/Eu]<0
r-II:	[Eu/Fe] > 0.7 and [Ba/Eu]<0
r-III :	[Eu/Fe] >2

Christlieb et al. 2004; Beers & Christlieb 2005; Holmbeck et al. 2020

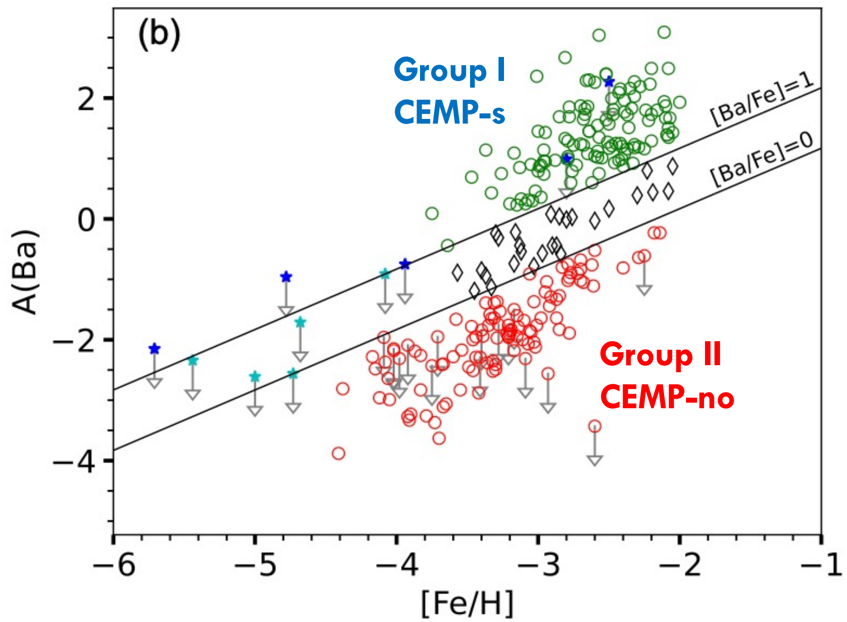
CEMP classification

From the C-metallicity diagram

Talk by E. Caffau



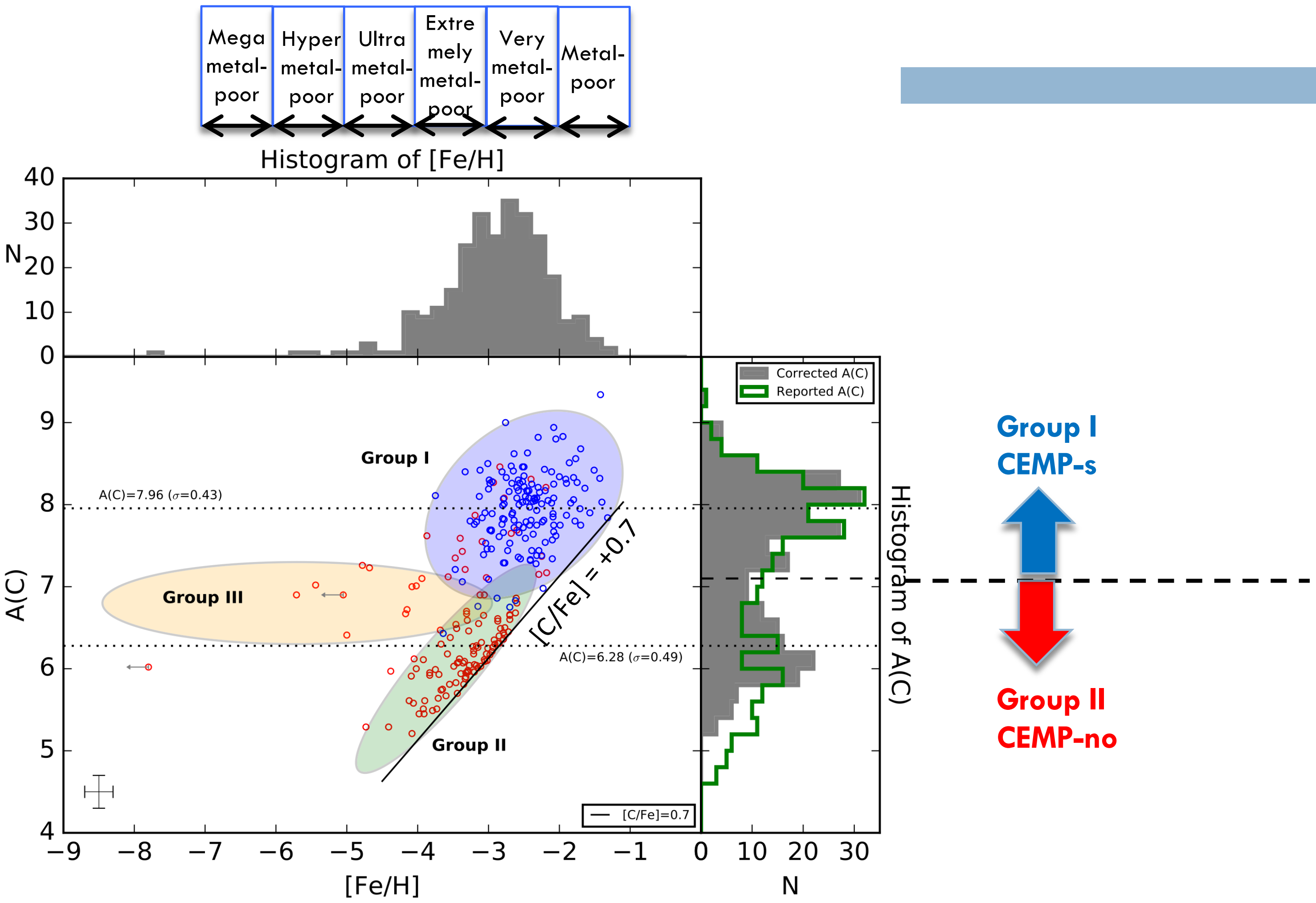
… to A(Ba)



Jeena+ 2023

CEMP classification

A(C) easier to measure than [s/Fe]

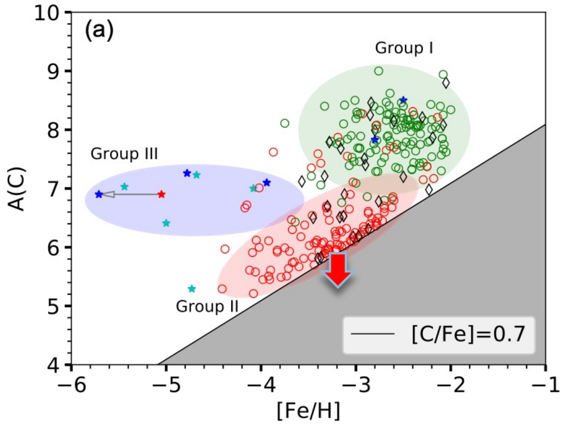


Yoon+ 2016

Impact of Non-LTE and 3D modelling on CEMP classification

C abundances:

- CH bands
- C I lines



Collet+ 2006; Amarsi+ 2019a,b;
Norris & Yong 2019, Gallagher 2016

- Effect of **3D** on **CH G band**:
  $\Delta_{3D-1D} \approx -0.3$ dex for group II (=CEMP-no)
  No effect on Group I (=CEMP-s)

Impact of Non-LTE and 3D modelling on CEMP classification

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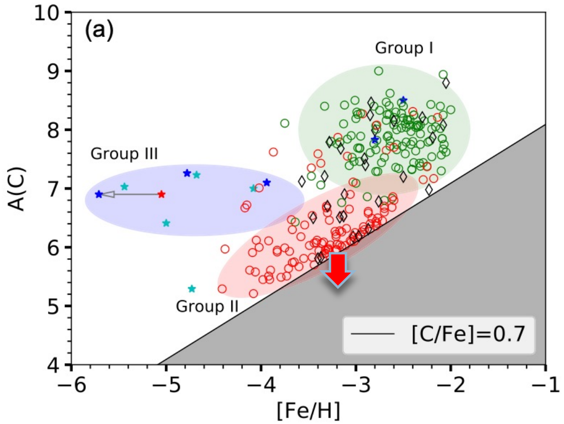

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Barium abundances:

Anish Amarsi talk
Jonas Klevas talk
Steffen+ 2018

3D CO5BOLD models + **non-LTE** MULTI on **Ba lines** (M.Steffen poster)
Largest corrections for giants at [M/H]= -1
$+0.25 < \Delta_{3D} - \Delta_{1D} < +0.4$

→ Higher 3D NLTE Ba abundances
- CEMP-s classification safe
- CEMP-no could turn to CEMP-s !

Carbon enrichment is ubiquitous (especially at low-Z)

Using this new definition:

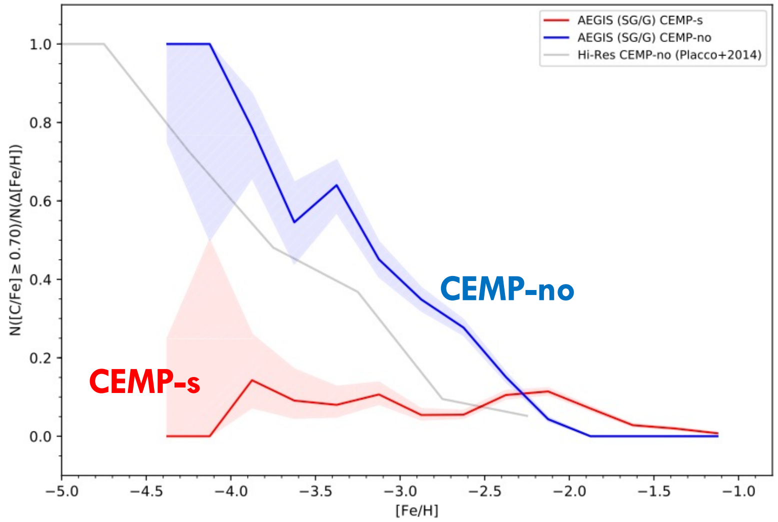
- **CEMP : [C/Fe]>0.7**
- **CEMP-s: A(C)> 7.1**
- **CEMP-no: A(C)< 7.1**

- Fraction of CEMP-no (among all stars) ↑ with decreasing metallicity, reaching 1 at [Fe/H]<-4
- Fraction of CEMP-s: 10% (independent of metallicity)
- CEMP-no dominate over CEMP-s below [Fe/H]=-2.3:

  Transition between:

  FIMF (First Initial Mass Function, more massive stars)

  and IMF (low and intermediate-mass stars)



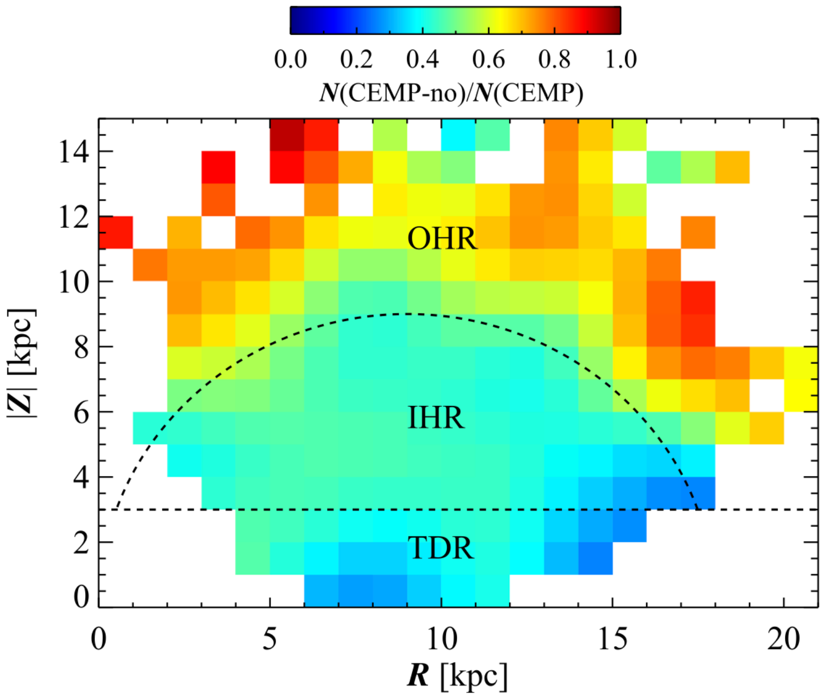
(d) Differential frequencies of the CEMP-no and CEMP-*s* stars.

Yoon + 2018

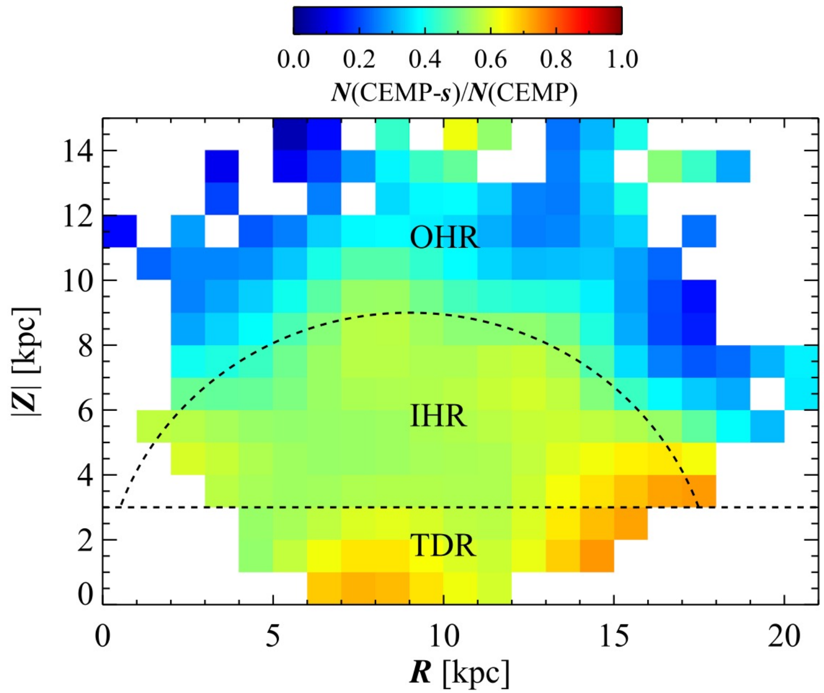
Lee+ 2013; Placco+ 2014; Yoon+ 2018, Arentsen+ 2021

Carbonicity galactic map for CEMP-no and -s

- CEMP-no: outer halo region (OHR)



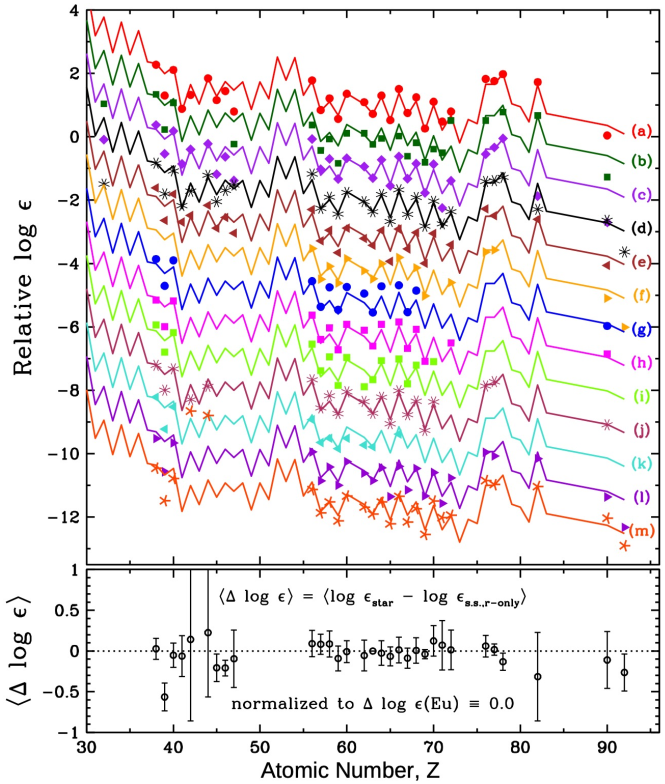
- CEMP-s: predominantly metal-weak thick disk (TDR) and inner-halo regions (IHR)



Lee+ 2019

CEMP-r

r-process: universal…



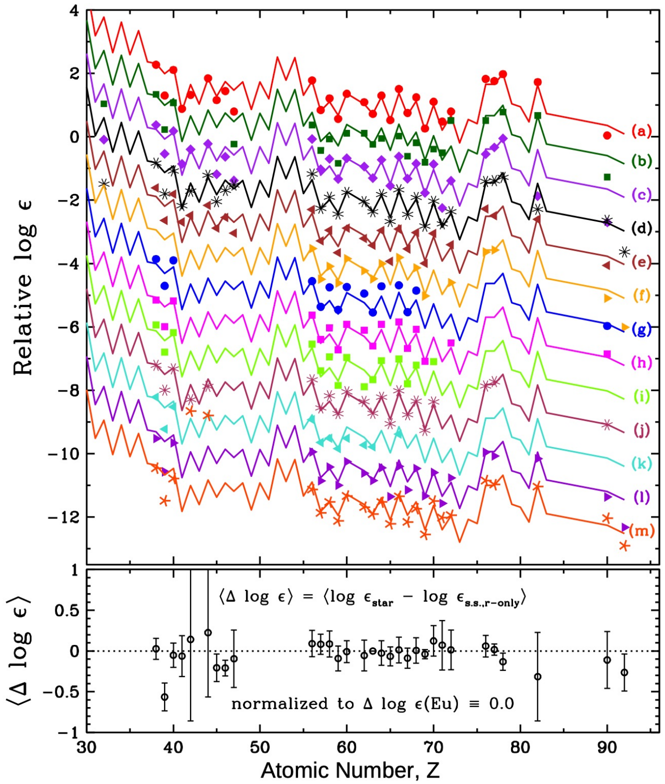
Cowan+ 2021

Possible interpretations:

- r-process elements are well-mixed into the interstellar medium after production
- Or: whatever the site, the r-process is uniform
- Or: a unique site is responsible for the r-process

CEMP-r

r-process: universal…



Cowan+ 2021

Possible r-process sites:

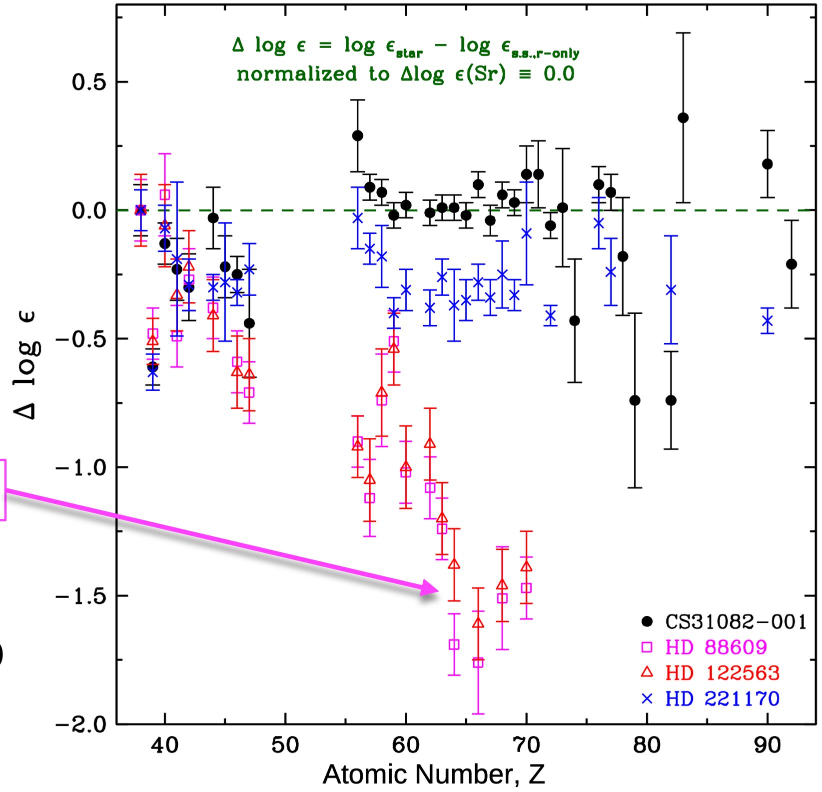
- Neutron star mergers
- Neutron-star – BH mergers
- Collapsars (fast rotating massive stars → SNe)
- Magneto-rotational core-collapse supernovae (MR-SNe)
- Quark deconfinement SNe
- Neutrino-driven winds in CCSN

CEMP-r: 32 < Z < 56

See posters by
L. Lombardo
T. Mishenina
M. Racca
V. Placco

r-process: universal…

… or not so? "truncated" "incomplete" "limited" r-process



Honda+ 2006, 2007

[Eu/Fe] < +0.3,
[Sr/Ba] > +0.5
and [Sr/Eu] > 0.0

Frebel+ 2018
Cowan+ 2021

CEMP-r: 32 < Z < 56

r-process: universal…

… or not so? "truncated" "incomplete" "limited" r-process

Truncated-r stars:

- Present more often disk-like kinematics than r-I and r-II stars
- Appear to belong to the MW thick disk more often than r-I and r-II
- Are on prograde orbits

→ Born in-situ (in the MW)

Xylakis-Dornbusch + 2024
Roederer+ 2018
Gudin+ 2021
Shank+ 2023

r-I and r-II stars:

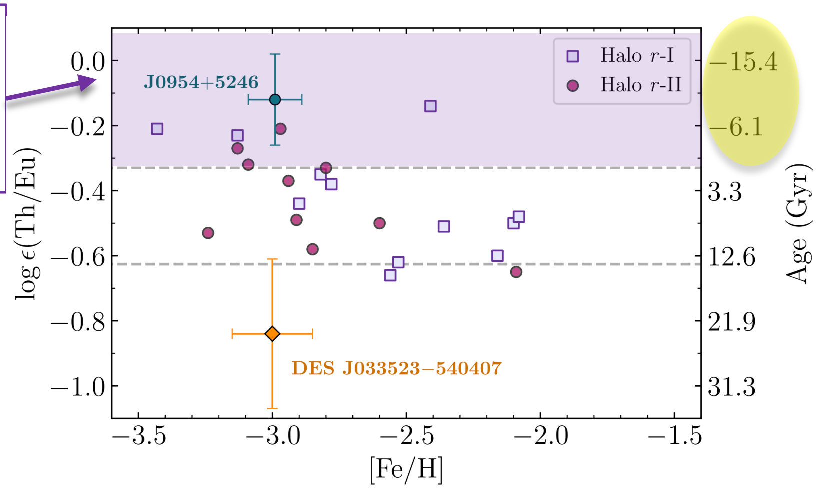
→ accreted by the MW from ultrafaint dwarf galaxies

CEMP-r: Z ≥ 90

r-process: universal…

… or not so? "actinide-boost" stars

Actinide-boost
Holmbeck+ 2018
Hill+ 2017



Negative ages!

30% of CEMP-r

Cowan+ 2021

CEMP-r: U-Th cosmochronometry

To be updated
(talk by T. Hansen)

The 8 stars with Th and U abundance measurements

2MASS J22132050−5137385	Roederer+ 2024	13.6 ± 2.6 Gyr
SMSS J200322.54−114203.3	Yong+ 2021	-
2MASS J09544277+5246414	Holmbeck+ 2018	13.0 ± 4.7 Gyr
RAVE J203843.2−002333	Placco+ 2017	13.0 ± 1.1 Gyr
CS 29497-004	Hill+ 2017	13.7 ± 4.4 Gyr
HE 1523-0901	Frebel+ 2007	13.2 Gyr
BD +17°3248	Cowan+ 2002	13.8 ± 4 Gyr
CS 31082-001	Cayrel+ 2001, Hill+ 2002	14.0 ± 2.4 Gyr
Solar system	Connelly+ 2017	4.56730 ± 0.00016 Gyr

CEMP stars: binarity

CEMP-r

- Binary frequency 18±6% (Hansen+ 2015), similar to the one of normal metal-poor field giants (16±4%, Carney+ 2003)

CEMP stars: binarity

CEMP-r	CEMP-no
Binary frequency 18±6% (Hansen+ 2015), similar to the one of normal metal-poor field giants (16±4%, Carney+ 2003)	Binary frequency 32 ± 10% Arentsen+ 2019 See also Starkenburg 2014; Hansen 2016b

CEMP stars: binarity

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Arentsen+ 2019

See also Starkenburg 2014; Hansen 2016b

CEMP-s

- Compatible with 100% binaries

Lucatello+ 2005, Starkenburg+ 2014,

Hansen+ 2016, Jorissen, Van Eck+ 2016, Arentsen+ 2019

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CEMP-s

- Compatible with 100% binaries

Lucatello+ 2005, Starkenburg+ 2014,

Hansen+ 2016, Jorissen, Van Eck+ 2016, Arentsen+ 2019

CEMP-rs

- More binaries than among CEMP-s

Hansen T.T. + 2016

Karinkuzhi, Van Eck+ 2021

CEMP stars: binarity & scenarii

CEMP-r

→fossile record from a C- and r-enriched ISM
Or
Stars polluted by nearby C and r-process source

CEMP-no

→fossile record from a C-enriched ISM
Or
Stars polluted by nearby C source

CEMP-s

→Polluted by an AGB companion

CEMP-rs

→Polluted by an AGB companion
(+ by a possible other source ?)

CEMP-no stars: binarity & scenarii: not so clear

- High-C CEMP-no have a large binary fraction (47%)

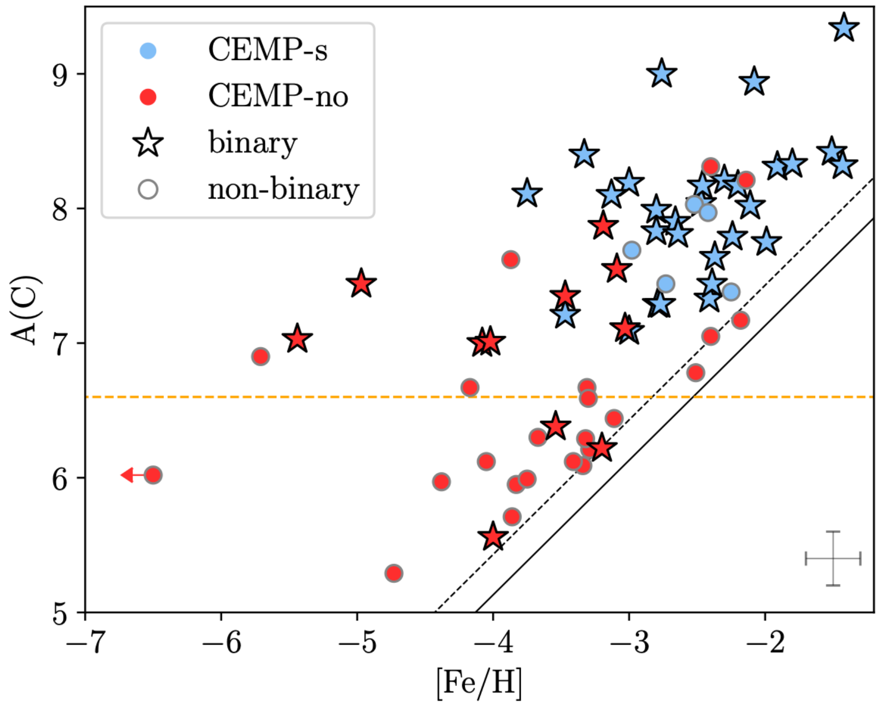
→ Polluted binaries?

- Low-C CEMP-no have a smaller binary rate (18%) similar to the one of CEMP-r

  - binary stars form more easily in a carbon-enhanced environment?

    Or:

  - they have been polluted with C-rich, s-normal material ejected from a nearby AGB?



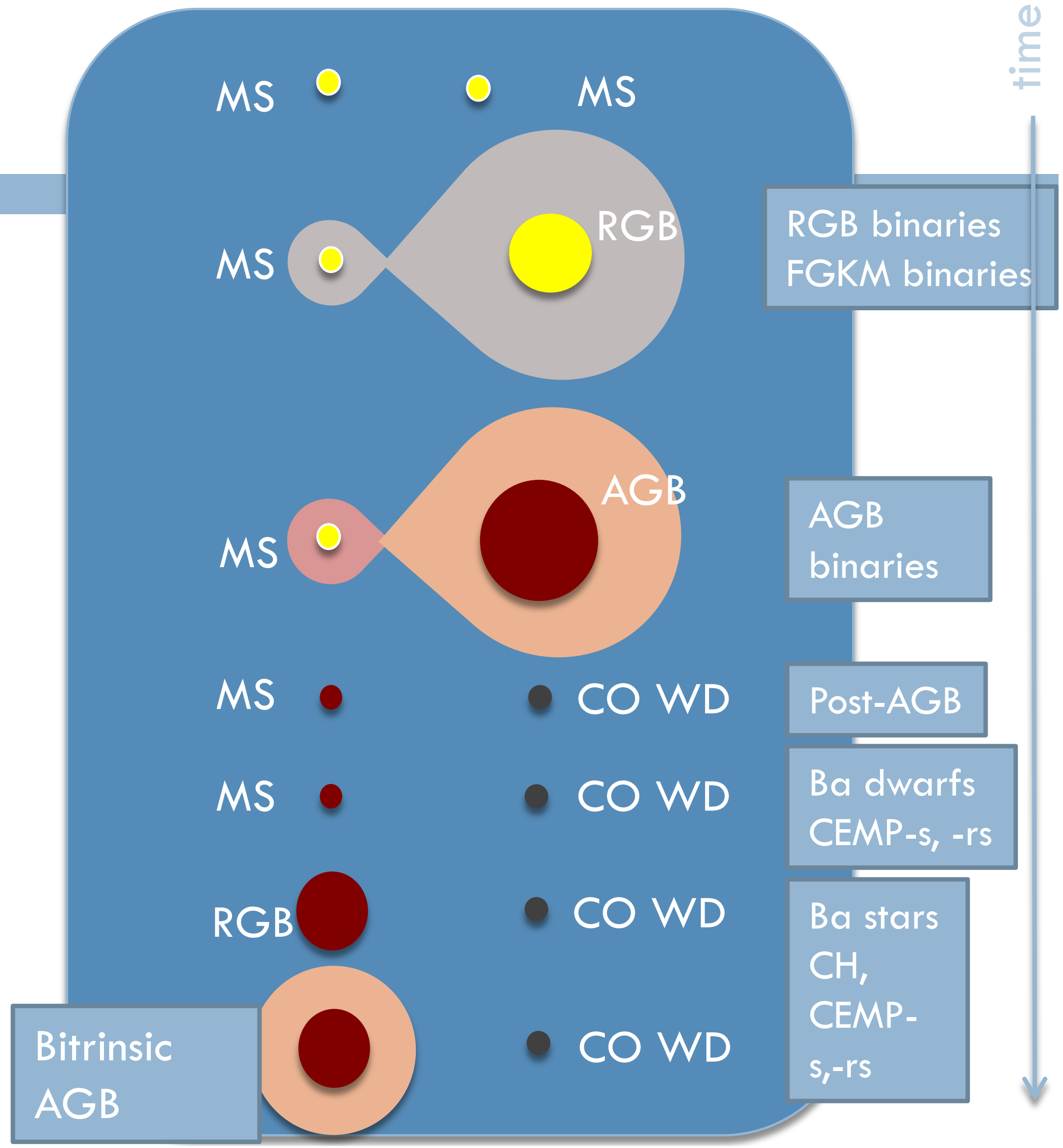
Hansen T.T., 2016; Arentsen+ 2018, 2019

Scenario for CEMP-s

Members of a large famous family: the extrinsics

Low-metallicity counterparts of:

- Extrinsic S stars (-0.5<[Fe/H]<0)
- Barium stars (-0.5<[Fe/H]<0)
- CH stars (-1<[Fe/H]<-0.5)
- All binaries
- WD companion:
  - direct detections in a few instances
  - Mass distribution of the companions compatible with WD



CEMP-rs and –s: Zr/Nb anti-correlation

Intrinsic stars
Tc-rich
Nb-poor

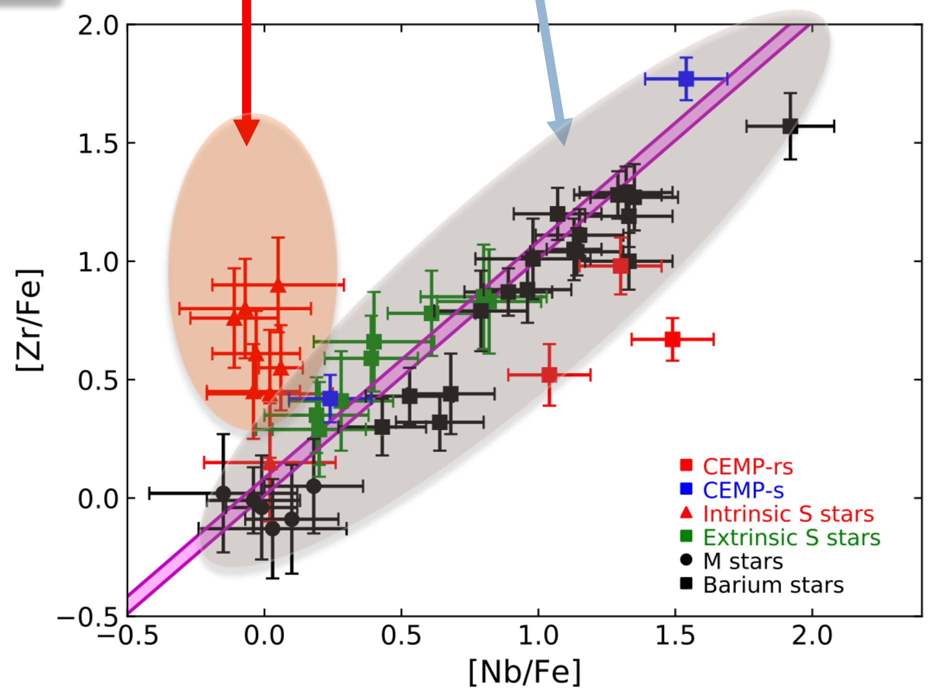
Extrinsic stars
No Tc
Nb-rich

^{93}Zr → ^{93}Nb (mono-isotopic) $\tau_{1/2} = 1.53\ \ 10^6$ yrs
^{99}Tc → ^{99}Ru $\tau_{1/2} = 0.21\ \ 10^6$ yrs

- Tc – Nb anti-correlation

in S stars, Ba stars, CEMP-s, CEMP-rs

Karinkuzhi+ 2018 2021 2023



Also see
B. Cseh poster

Scenarios for CEMP-rs

- Double event (r+s):

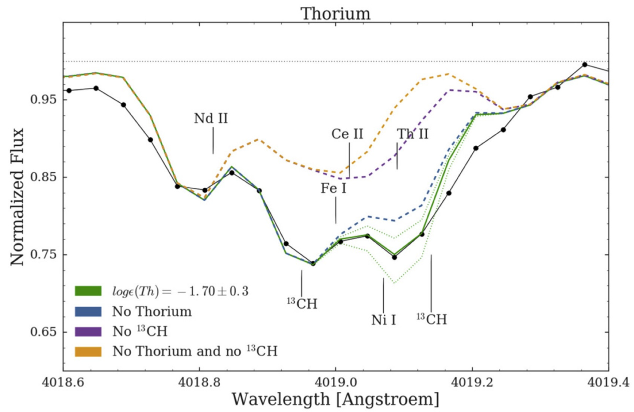
  Interstellar (r)

  or

  Kilonova (r)

Kilonova

AGB



Gull+ 2018; see however Choplin+ 2022

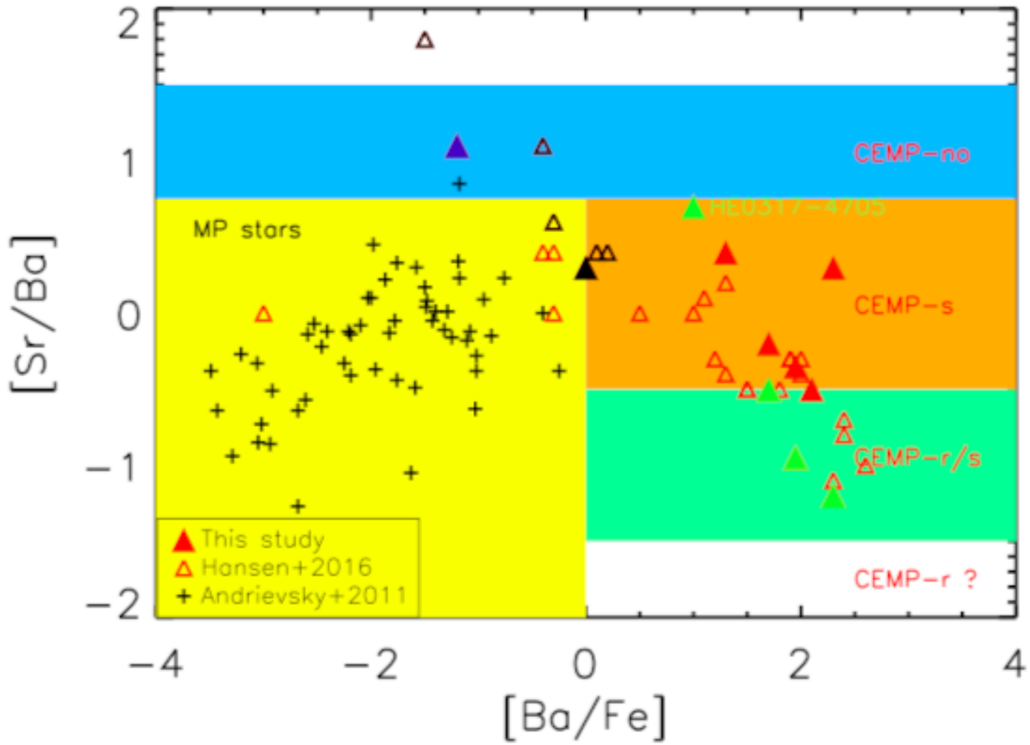
- i-process in a single astrophysical site
  - Proton injection event (Hampel+ 2019; Karinkuzhi+ 2021; Choplin+ 2021)

    Favoured in Mashonkina+ 2023, Karinkuzhi+ 2023

  - He shell flash of rapidly accreting WD (Denissenkov+ 2016)

Abundance profiles

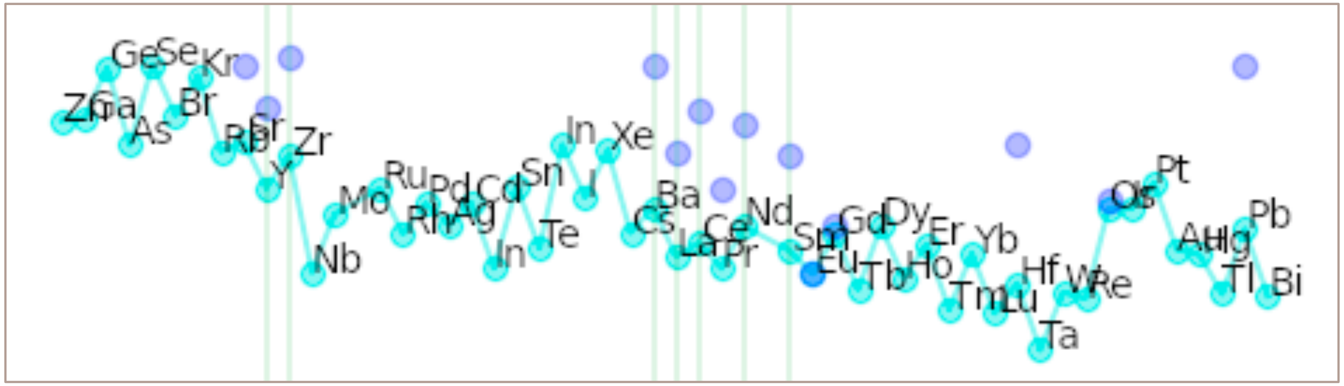
Abundance ratio : C.J. Hansen et al. A&A 623, A128 (2019)



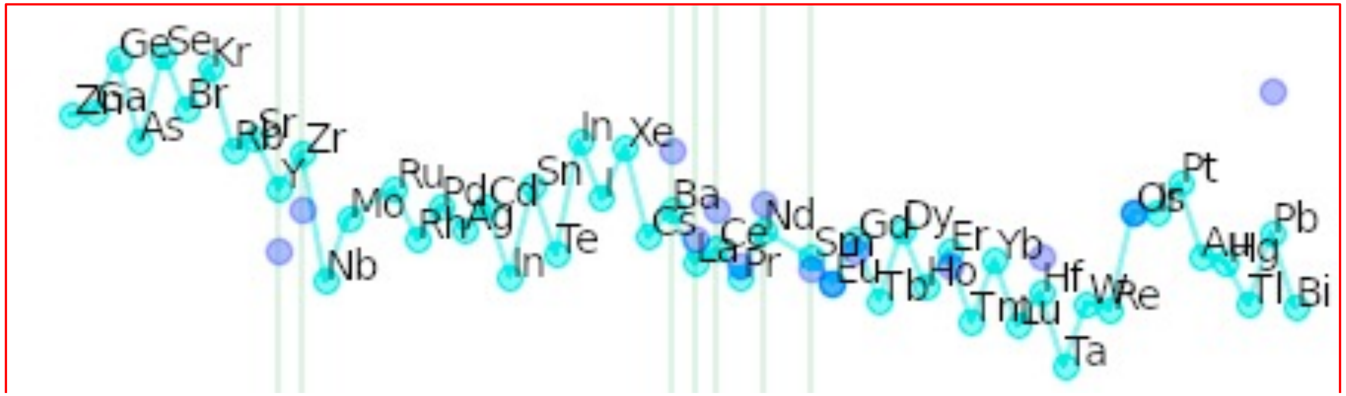
Abundance profiles

Signed distance to the r-process
Karinkuzhi+ 2023

$$d_S = \frac{1}{N}\sum_{x_i}(\log_{10}\epsilon_{x_i,*} - \log_{10}\epsilon_{x_i,\mathrm{norm(r,*)}})$$



CEMP-s

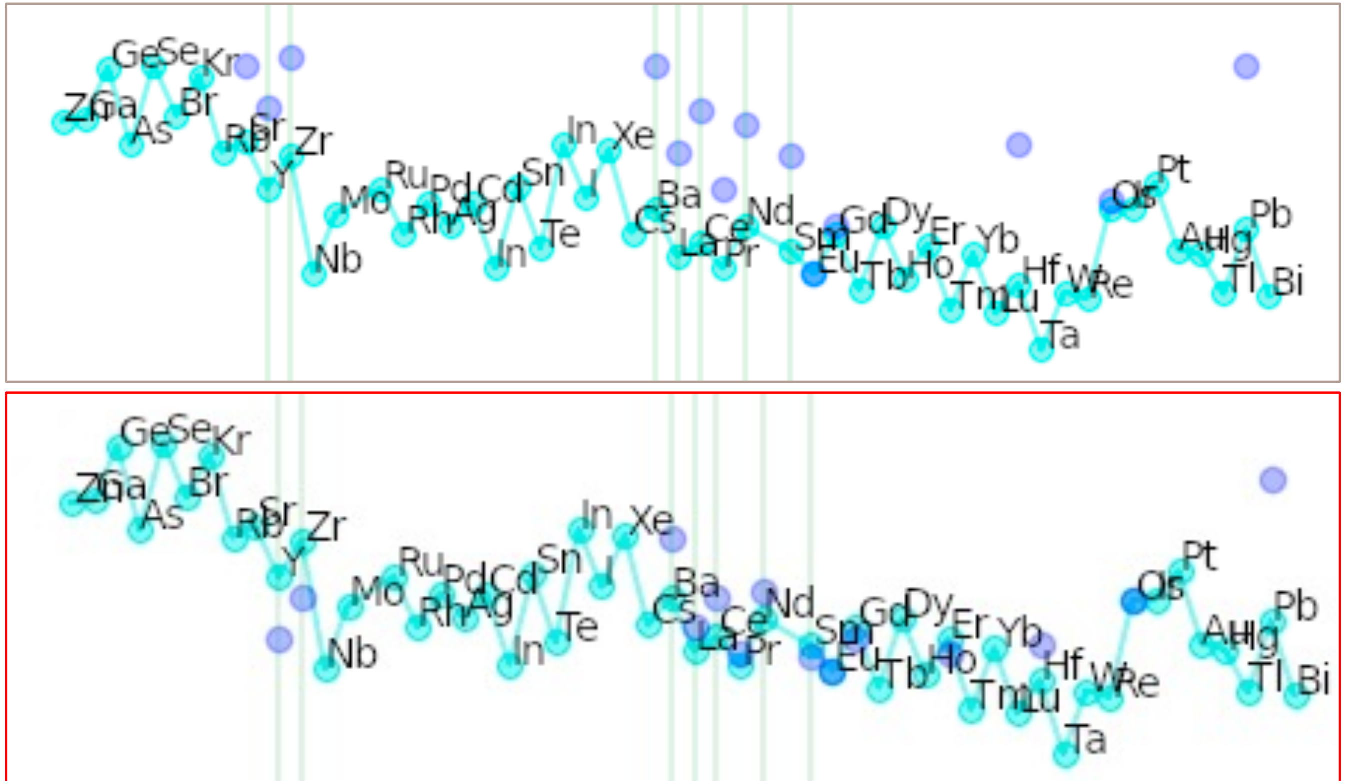


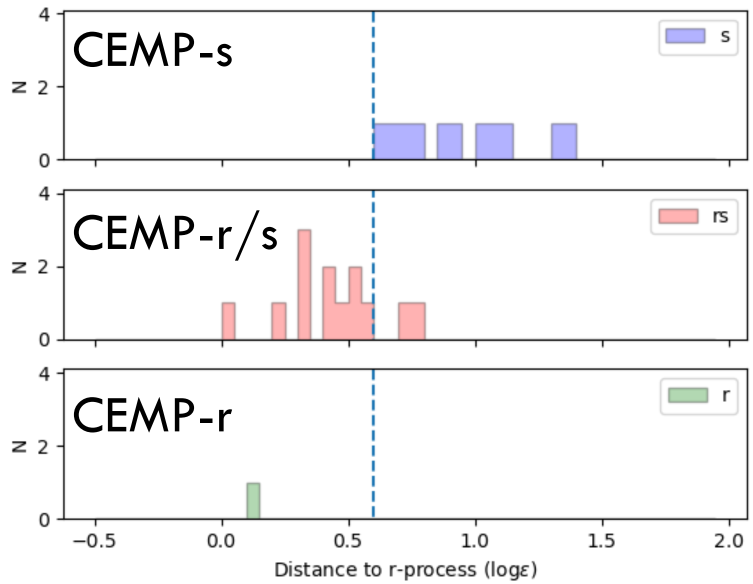
CEMP-r

Abundance profiles

Signed distance to the r-process
Karinkuzhi+ 2023

$$d_S = \frac{1}{N} \sum_{x_i} (\log_{10} \epsilon_{x_i,*} - \log_{10} \epsilon_{x_i,\mathrm{norm(r,*)}})$$

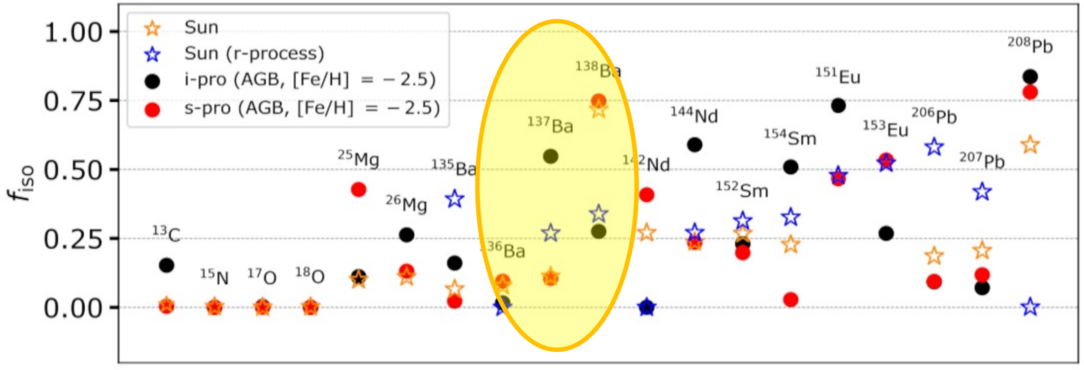




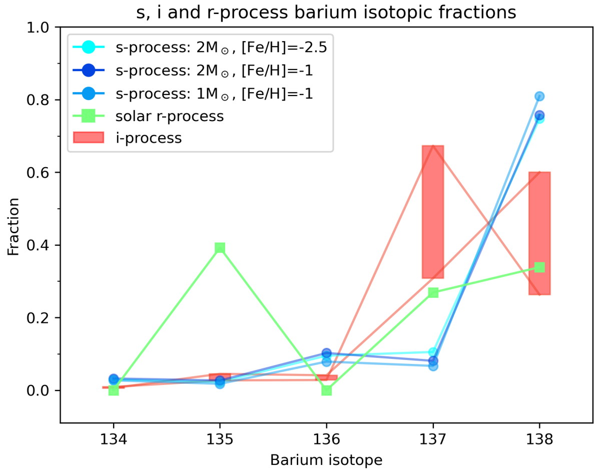
Ba Isotopic ratio

r,i and s-processes predict distinct isotopic mixtures

Choplin, Siess & Goriely 2021



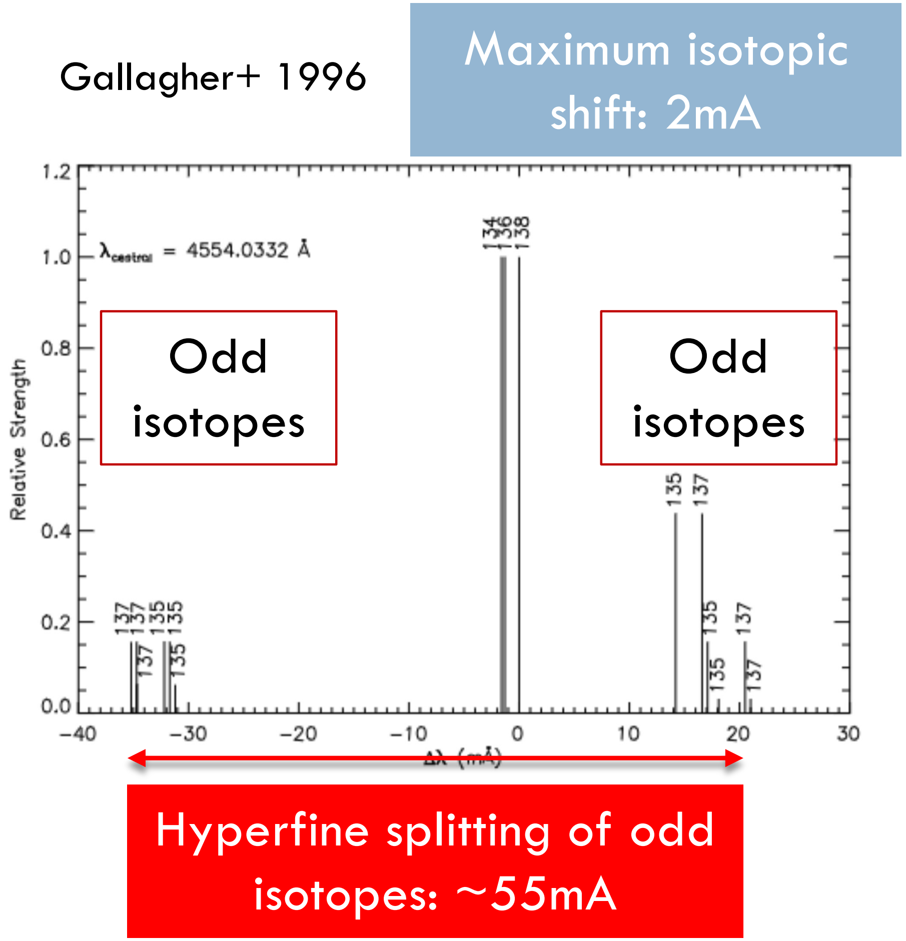
Martinet, Choplin+ 2024



Ba Isotopic ratio

- Isotopic shifts are too tiny to be detected
- But hyperfine splitting is not!

Gallagher+ 1996



Ba Isotopic ratio

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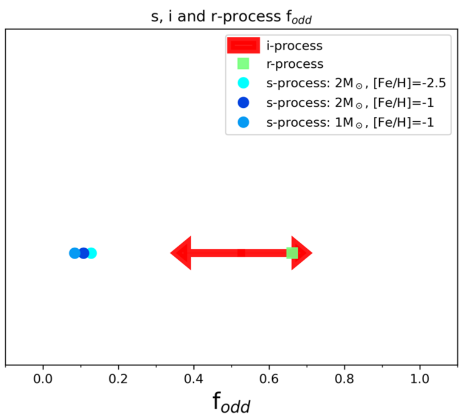
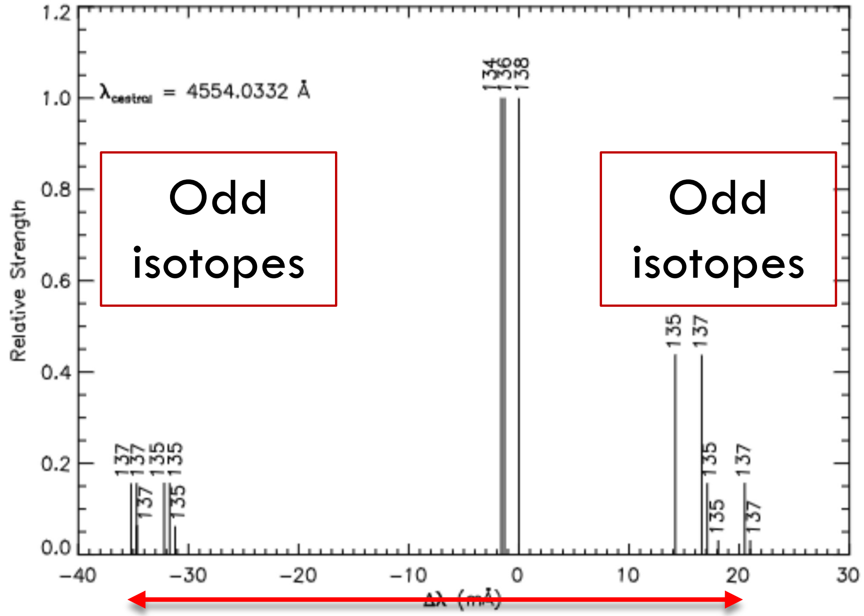
$$f_{Ba,odd} = \frac{N(^{135}Ba) + N(^{137}Ba)}{N(Ba)}$$



Gallagher+ 1996

Maximum isotopic shift: 2mA

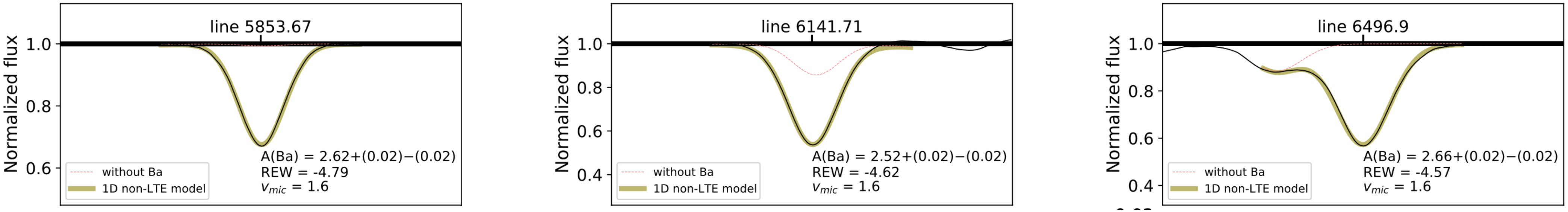


Hyperfine splitting of odd isotopes: ~55mA

Ba Isotopic ratio

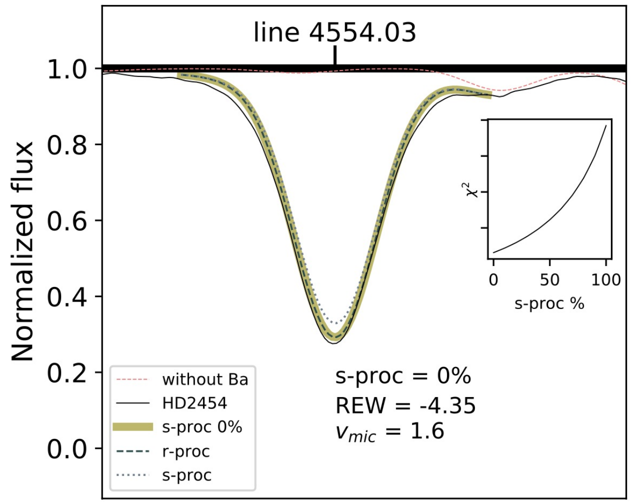
Subordinate lines:

Giribaldi+, in prep.



Resonance lines:

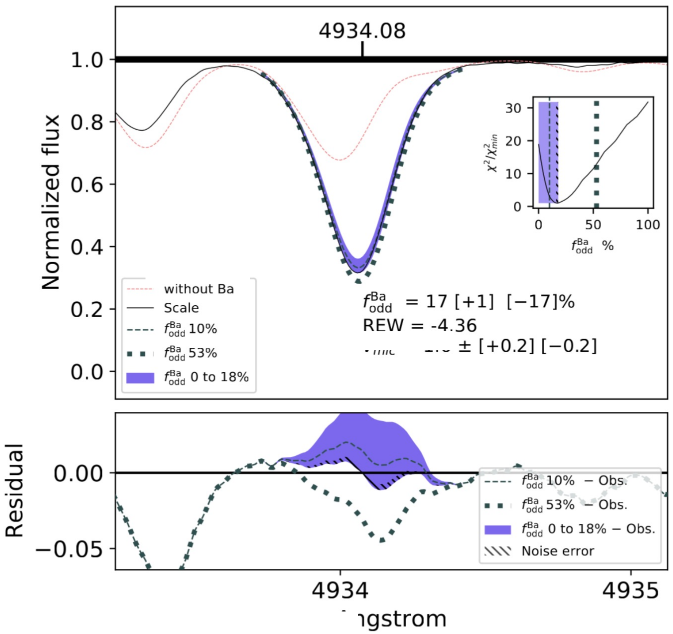
Problem: Abundance offset between resonance and subordinate lines (0.7 dex higher)



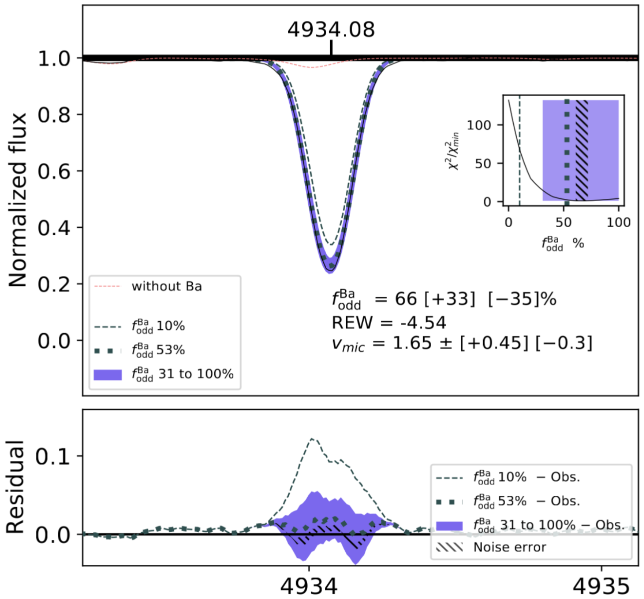
Hypothesis: A(Ba)=A(Ce)

Ba Isotopic ratio

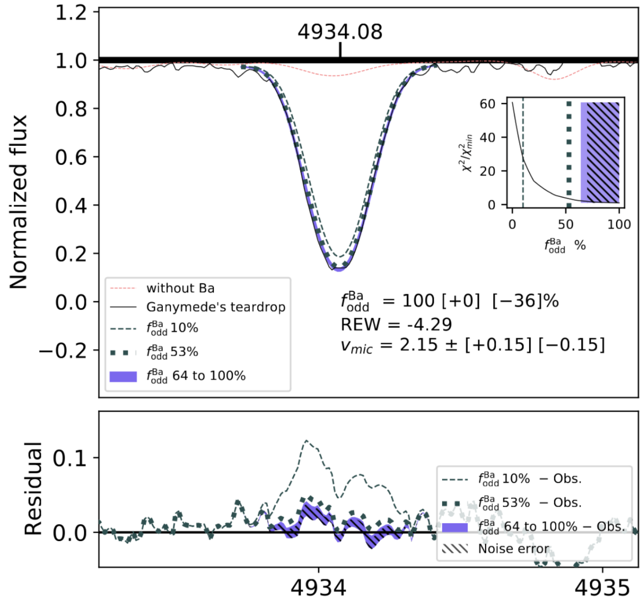
HD 2454	HD 115444	HE 2208-1239
s-process (Tomkin+89)	r-process (Sneden+2009)	CEMP-rs (Hansen+2015)



→ s-process



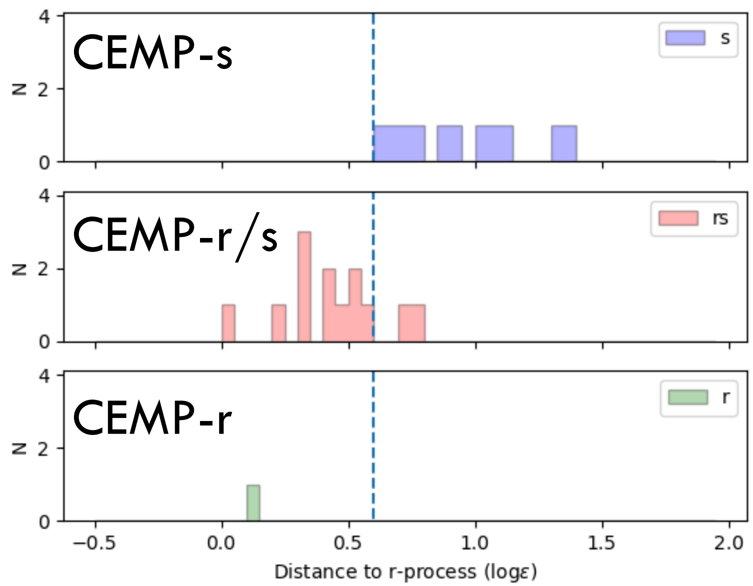
→ r or i process

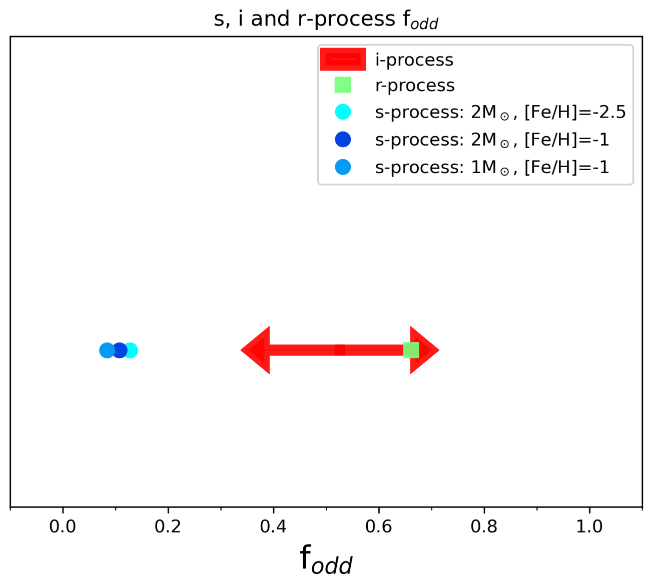


→ i or r-process

Giribaldi+, in prep.

CEMP-rs classification attempts: Ba isotopic ratio





s-process (Tomkin+89)
r-process (Sneden+2009)
CEMP-rs (Hansen+2015)

Star	Signed distance	χ^2_{s-pro}	χ^2_{i-pro}	χ^2_{r-pro}	f^{Ba}_{odd} x100
HD 2454	0.83	1.38	1.56	4.47	17^{+1}_{-17}
HD 115444	0.00	4.46	2.35	0.79	66^{+33}_{-35}
HE 2208-1239	0.56	13.14	2.05	7.37	100^{+0}_{-36}

s-process
r or i-process
i or r-process

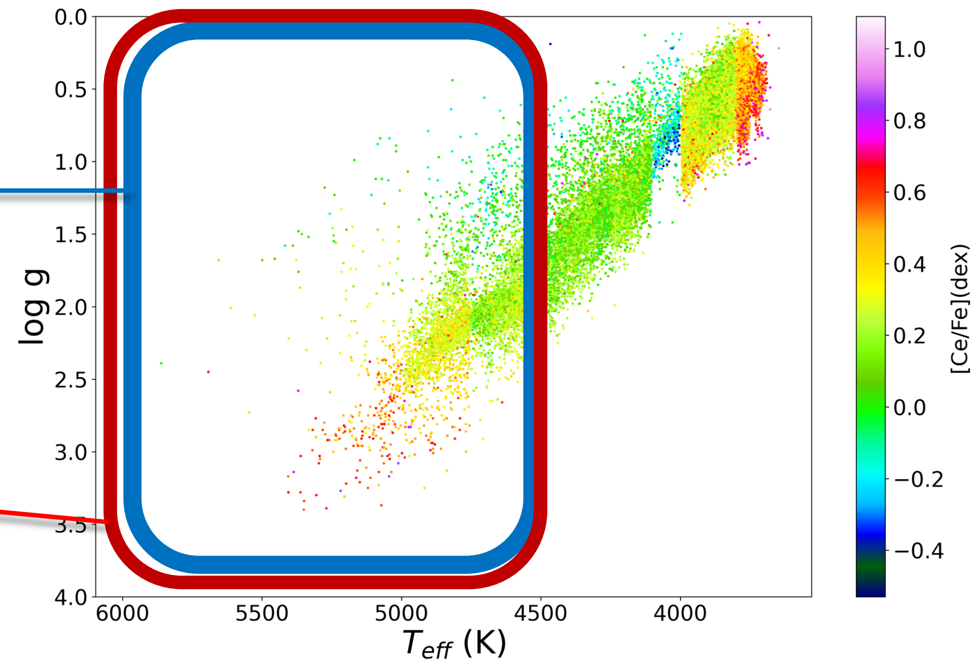
In conclusion: diamonds in large homogeneous surveys

[Ce/Fe] from Gaia RVS spectra (Contursi+ 23)

Kiel diagram for 28 613 stars with the recommended flag selection

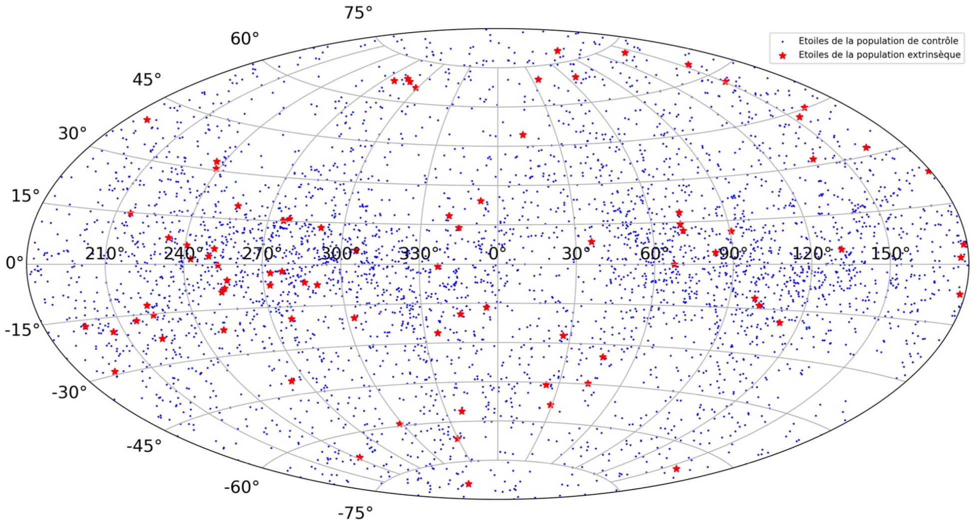
Reliable Cerium and 4500K < T_{eff} < 6000K	
« Extrinsic »	Control
[Ce/Fe]>0,6 dex	[Ce/Fe]<0,3 dex
82 stars	4161 stars

Detected binaries:
52.4 ± 5.5% 21.7 ± 0.6%



In conclusion: diamonds in large homogeneous surveys

Identification of 82 new candidate extrinsic stars



High-resolution checks

Lambotte+, in prep.