Spectroscopy of AGB and CEMP stars with ESO data

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In collaboration with
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Arthur Choplin, Lionel Siess, Stéphane Goriely, Hans Van Winckel

ESO 60 years

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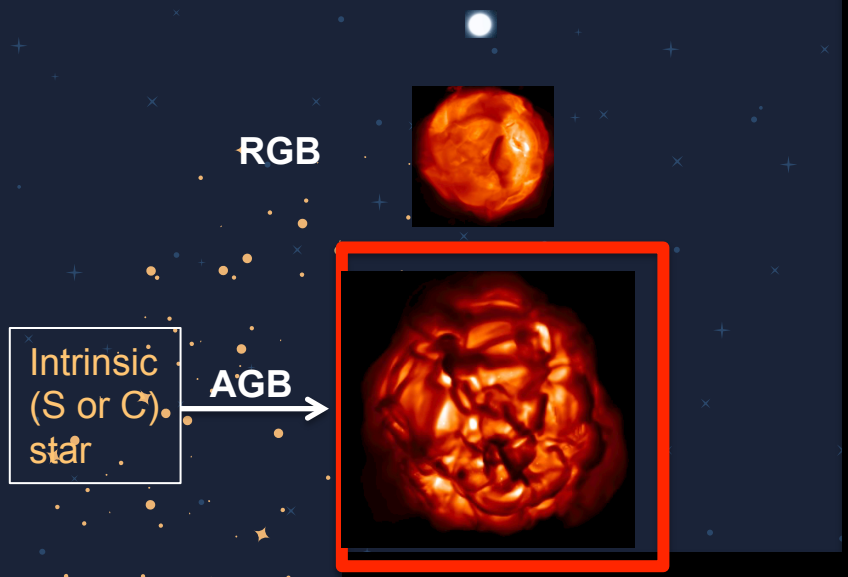
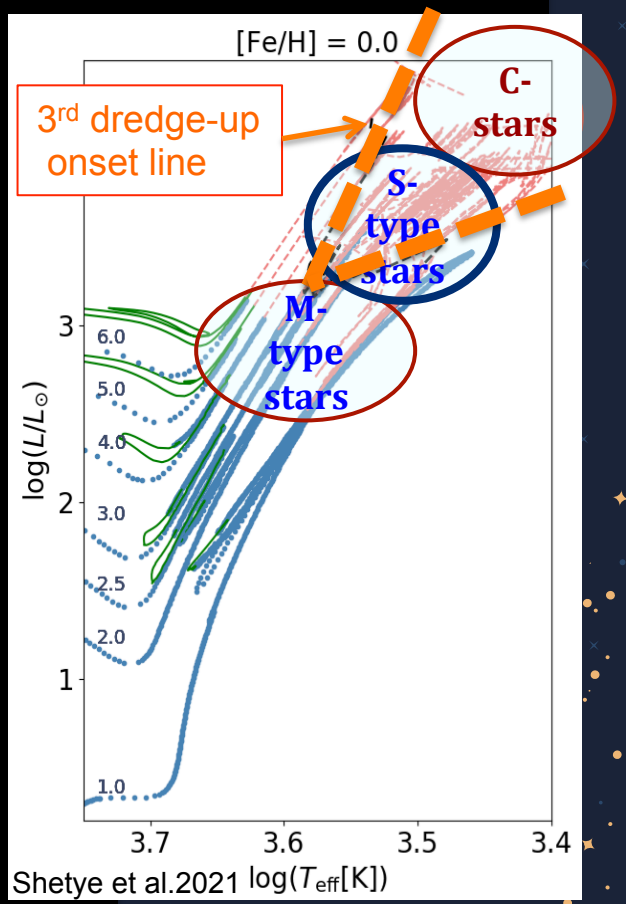
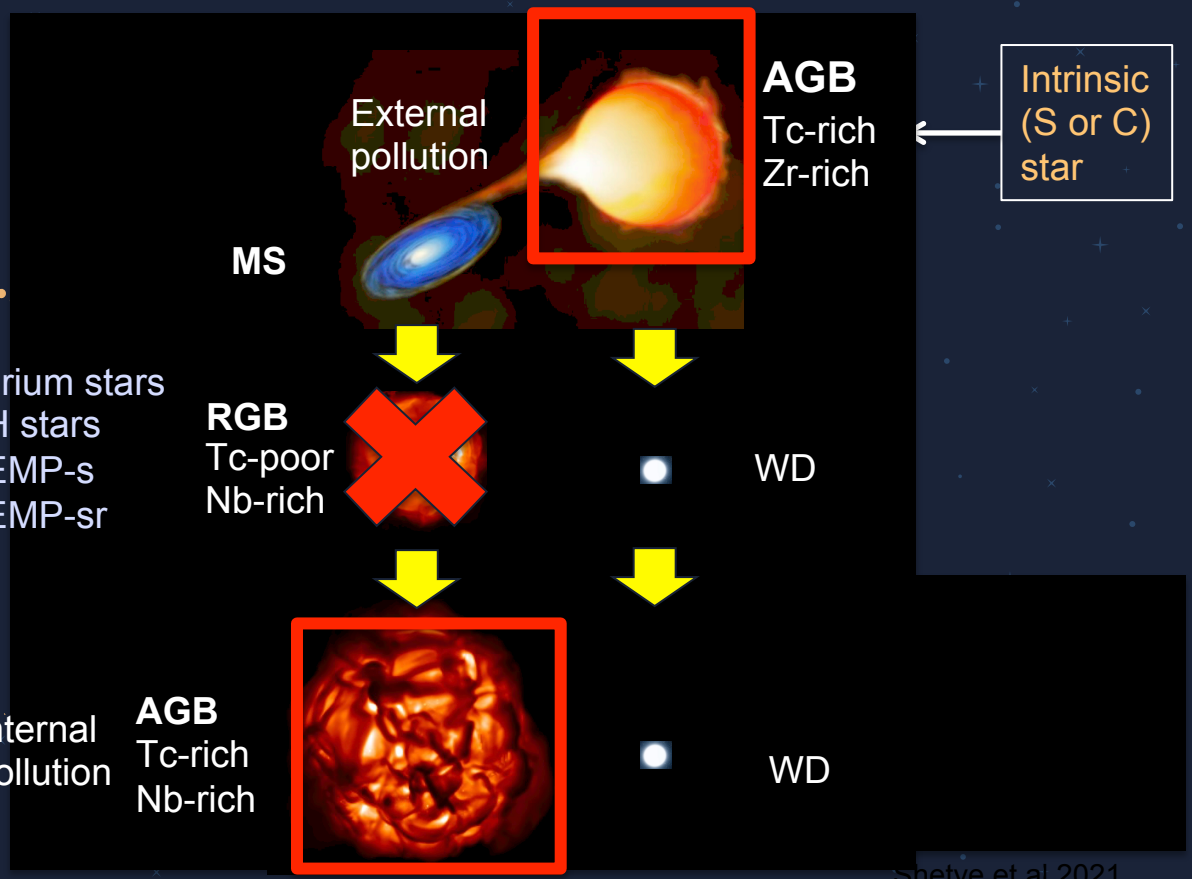
Technetium: where it should be detected





Shetye et al.2021

Technetium: where it should be detected



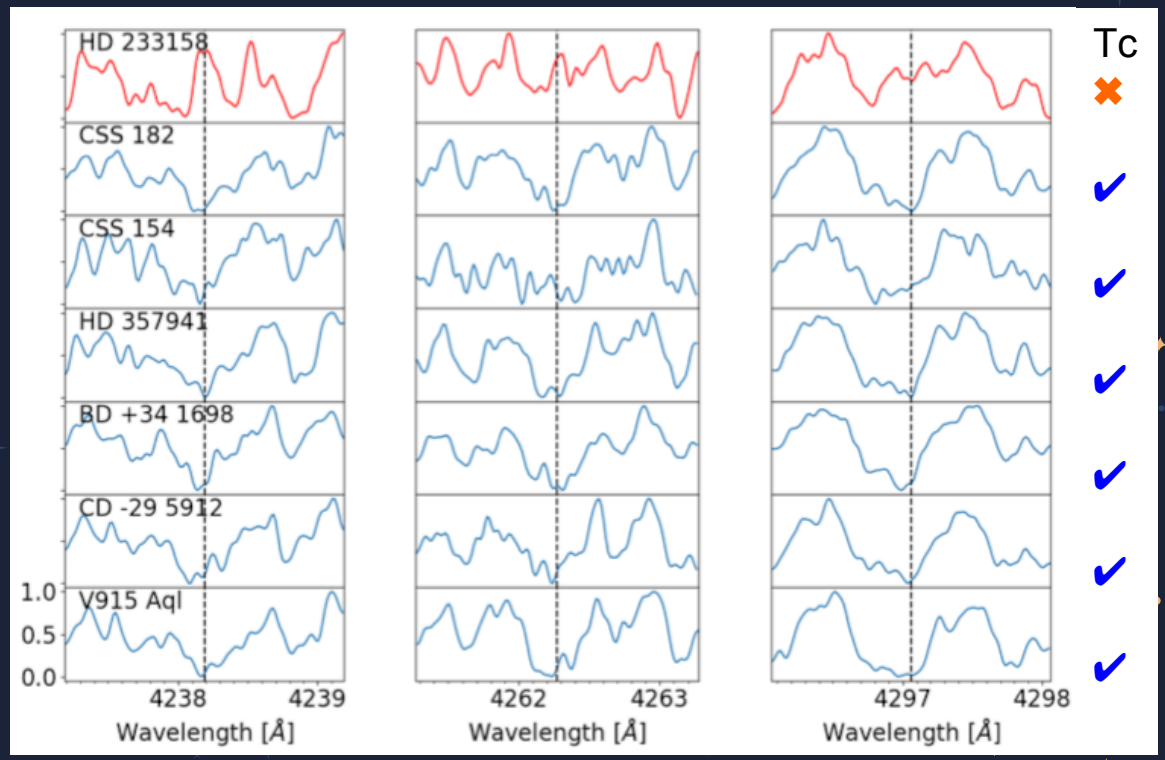
Shetye et al.2021

Technetium: where it is detected

Tc I searched in **TP-AGB stars** and detected (as expected):
Tc I: 3 resonance lines 4238, 4262, 4297A

Extrinsic (no-Tc) star shown for comparison

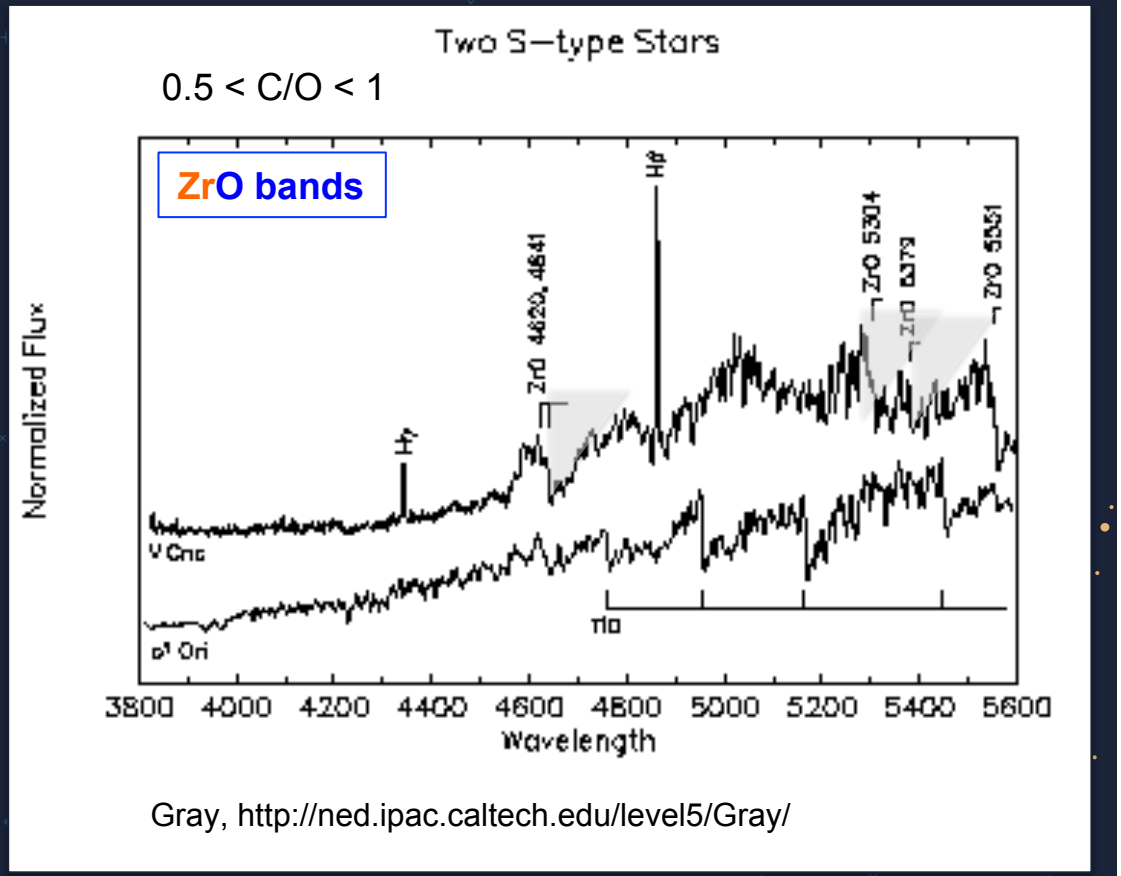
In TP-AGB S stars



Shetye et al. 2021

s-process along the AGB

S stars (intrinsic)



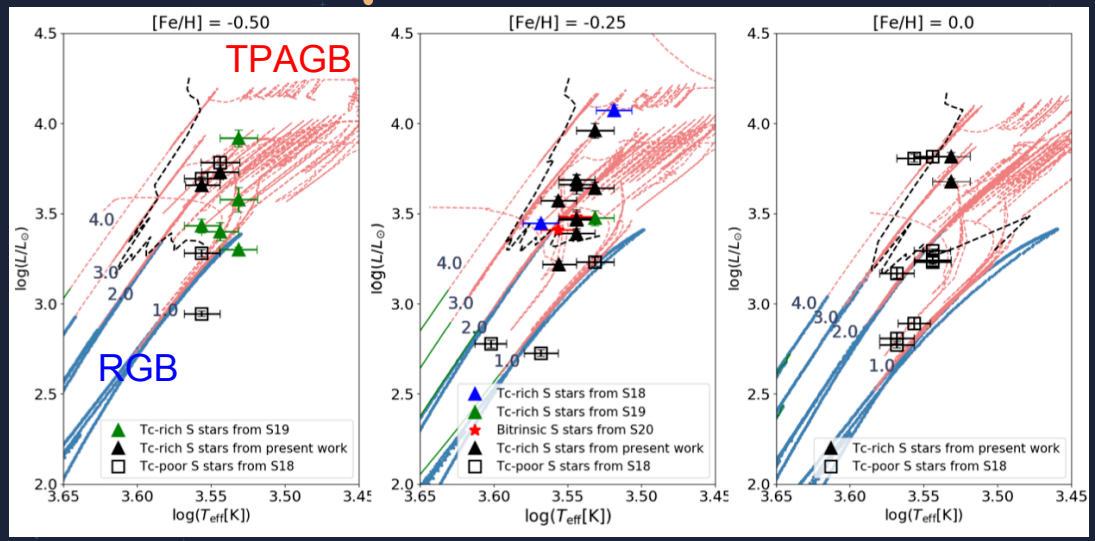
Gray, http://ned.ipac.caltech.edu/level5/Gray/

s-process along the AGB

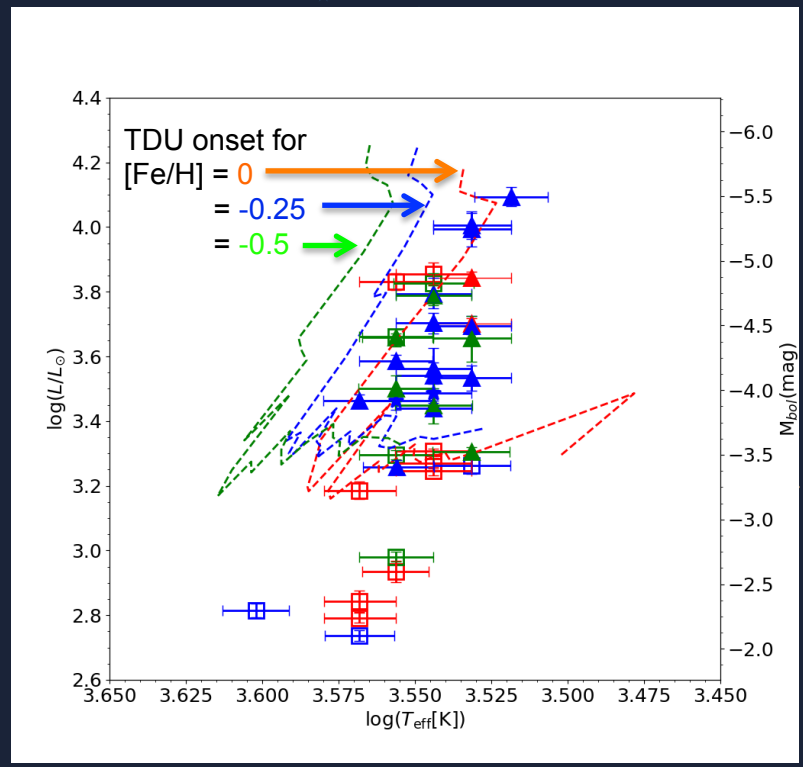
S stars (intrinsic)

- HR diagram (Gaia eDR3)

→ Good agreement between Tc detection and TP-AGB location (STAREVOL tracks)



Shetye et al. 2021

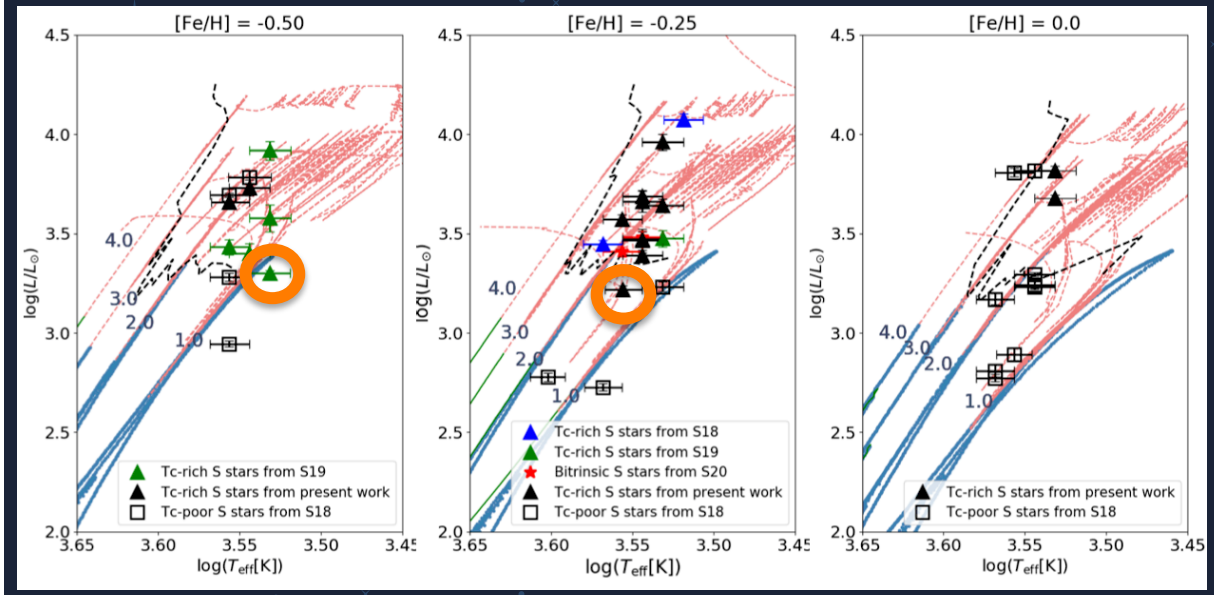


Van Eck, Shetye & Siess 2022

s-process along the AGB

S stars (intrinsic)

- Discovery **of low-mass Tc-rich S stars** (M<1.5) thanks to Gaia DR2 and eDR3 (Shetye et al. 2019)



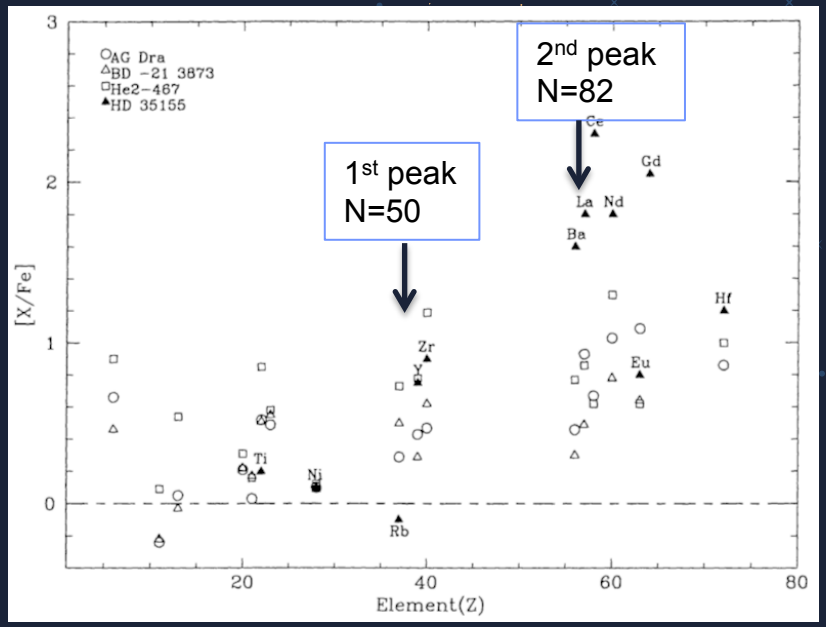
Name	$M_{current}$	M_{init}
CSS 154	1.4	1.6
BD +34 1698	1.2	1.4
V 915 Aql	0.8	1
CSS 182	1.1	1.3
BD-29 5912	1.3	1.5

→ Contribution to the galactic chemical evolution

s-process along the AGB

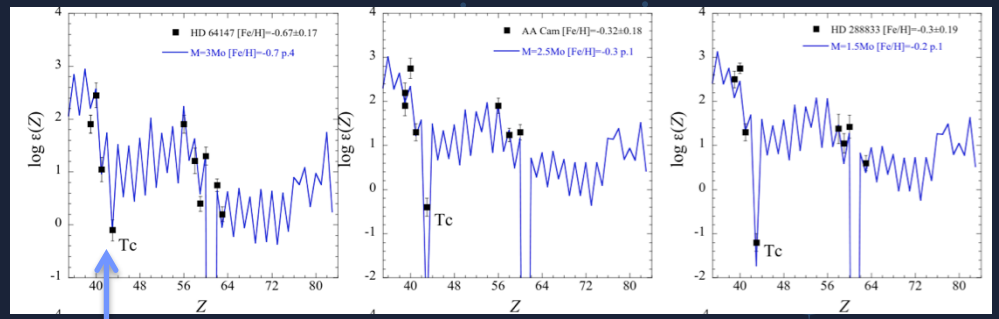
S stars (intrinsic)

- s-process overabundances:

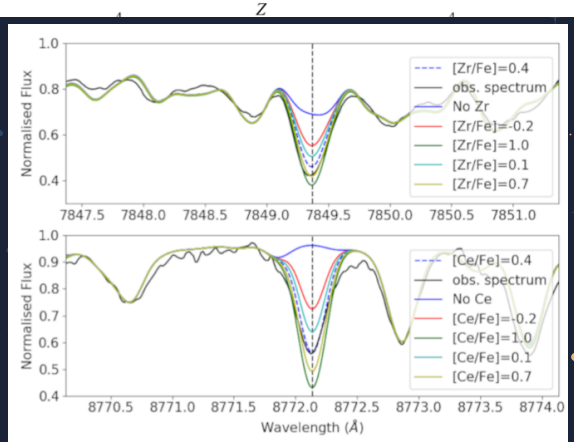


Wallerstein et al. 2003

MARCS model atmosphere of S stars (Van Eck et al. 2017)
→ Good agreement between s-process abundances and models



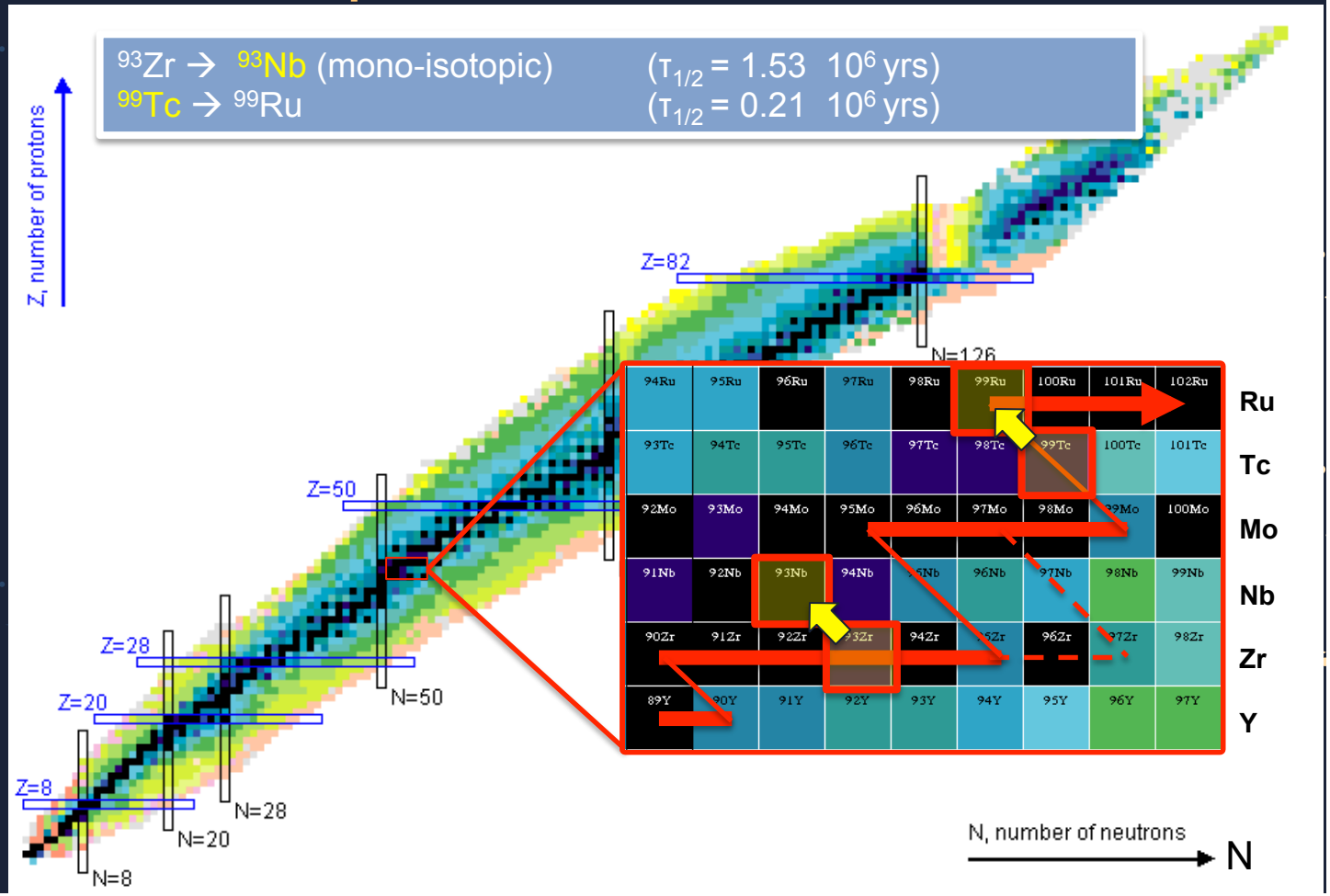
First Tc abundance measures



Shetye et al. 2019, 2021

s-process

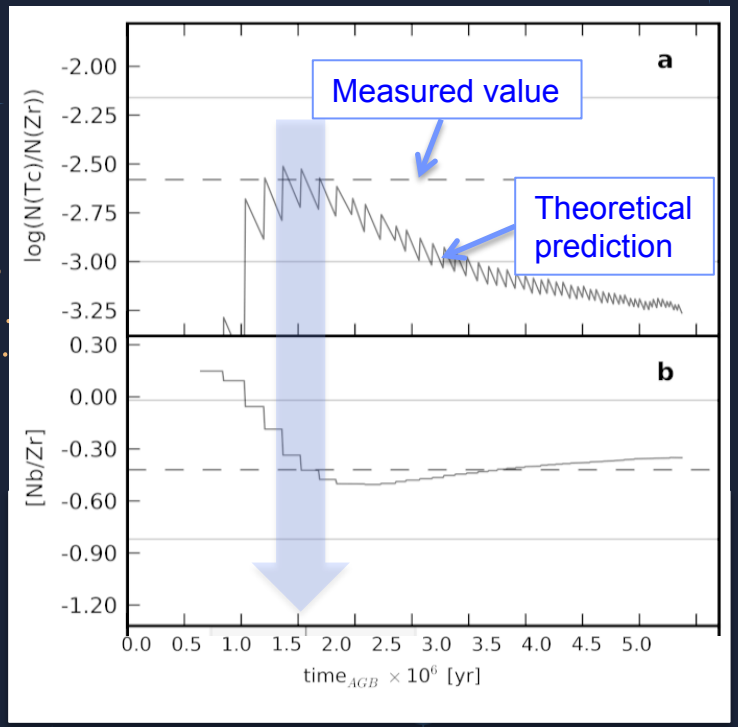
Radio-isotopes allowing to derive information on the timescales of the s-process

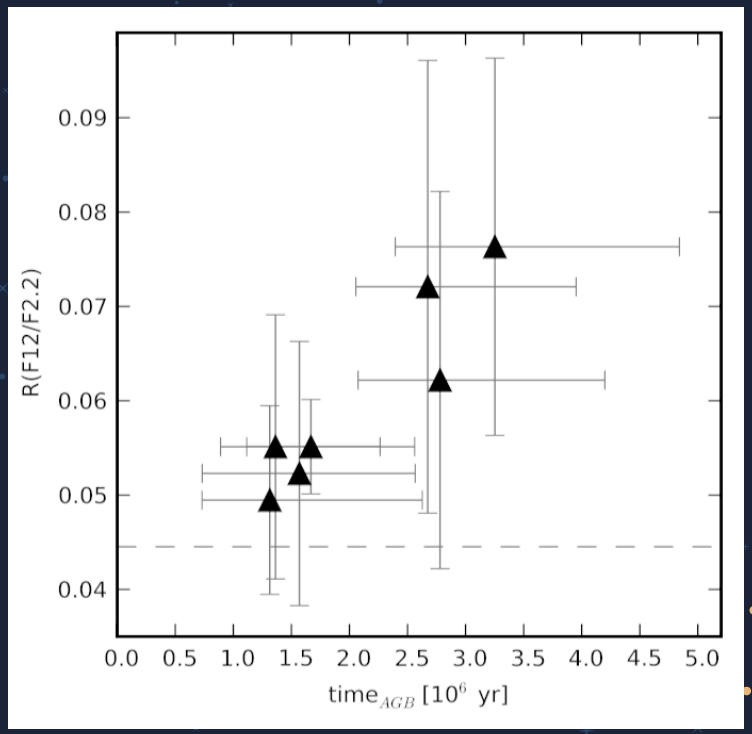


s-process along the AGB

Intrinsic S stars: Using the Zr→Nb and Tc→Ru chronometers,

- determination of ages since the s-process nucleosynthesis onset
- Constraint on s-process temperature operation in S stars: T< 250 10^6 K →^{13}C (α, n) neutron source





Neyskens et al. 2015

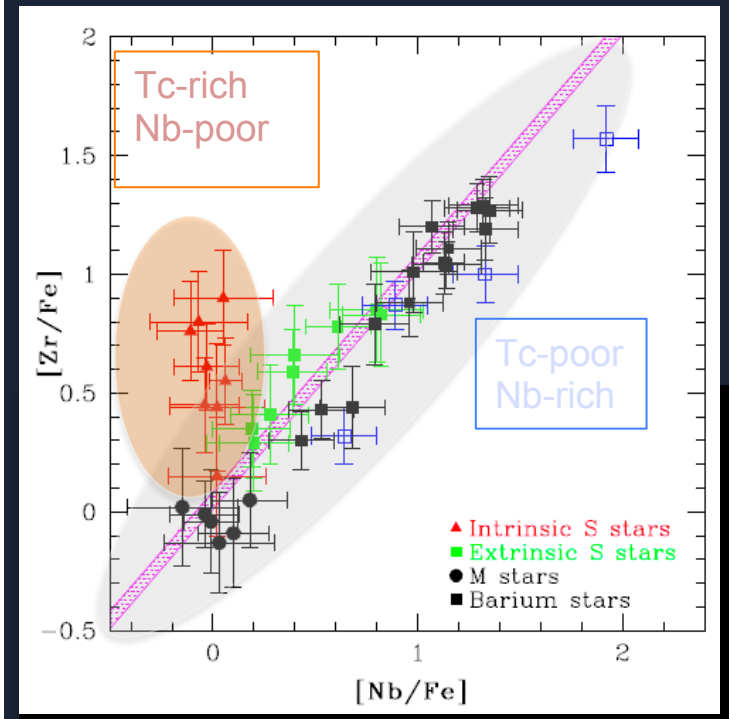
s-process: extrinsic stars

COLD CASES

Extrinsic S stars

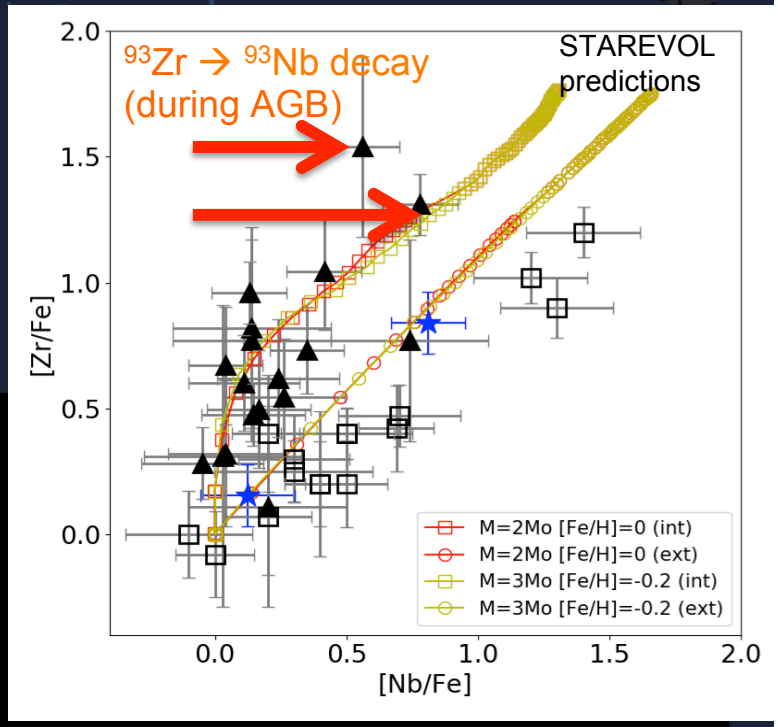
Validation in S-type stars, barium stars, CEMP-s stars:

- Nb and Zr follow the expected trends



Karinkuzhi, et al. 2018

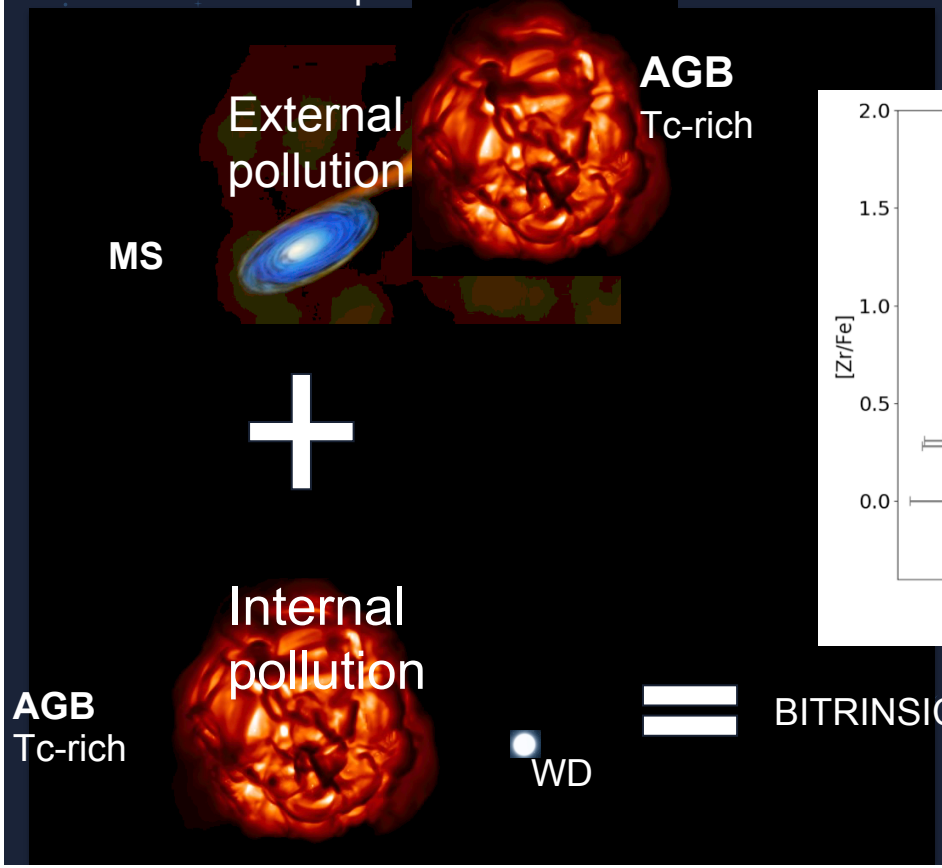
Shetye et al. 2021

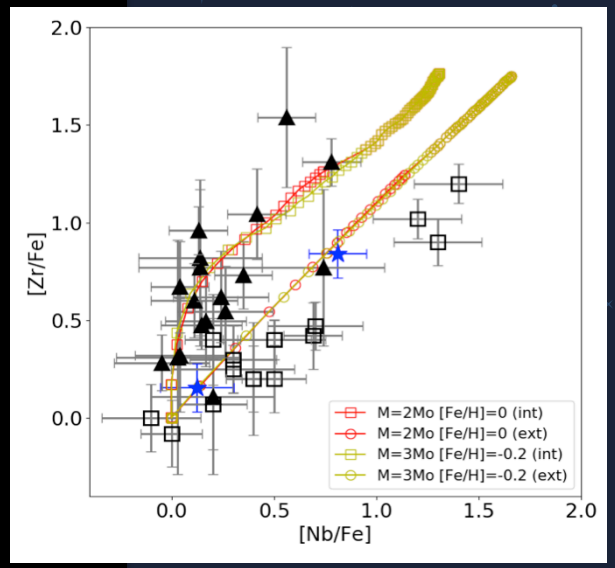


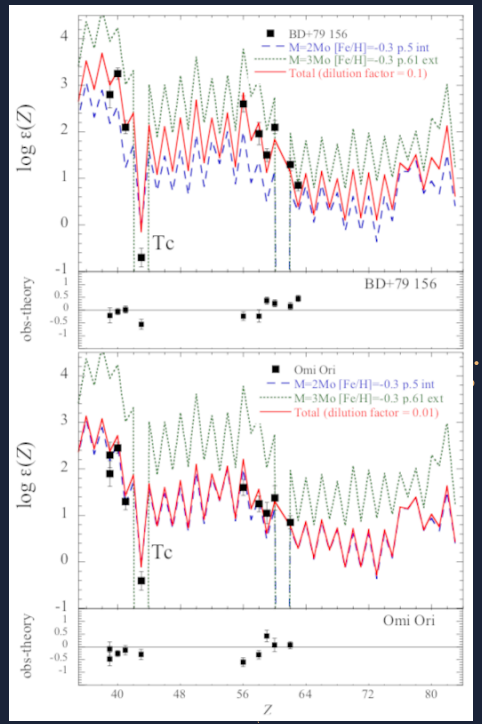
s-process: Bitrinsic stars

Reheated cold case

Discovery of bitrinsic stars:
Stars that have experienced 2 pollutions:







Shetye et al. 2021

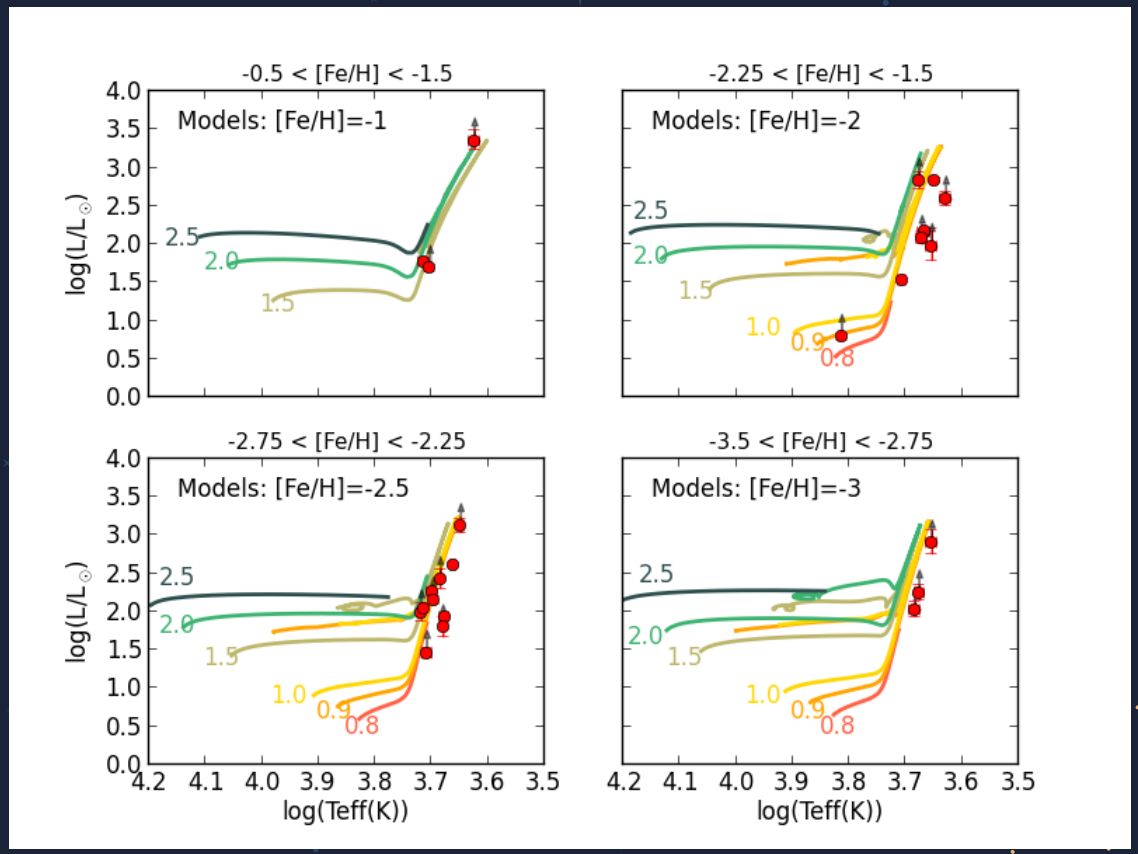
Two words of caution

1. HR diagrams: models vs measured stars

Non-solar chemical composition
→ **→impact photospheric opacities**
→ **→impact Teff**

Example: Comparison CEMP stars with Starevol (L. Siess)

Karinkuzhi et al. 2021



1. HR diagrams: models vs measured stars

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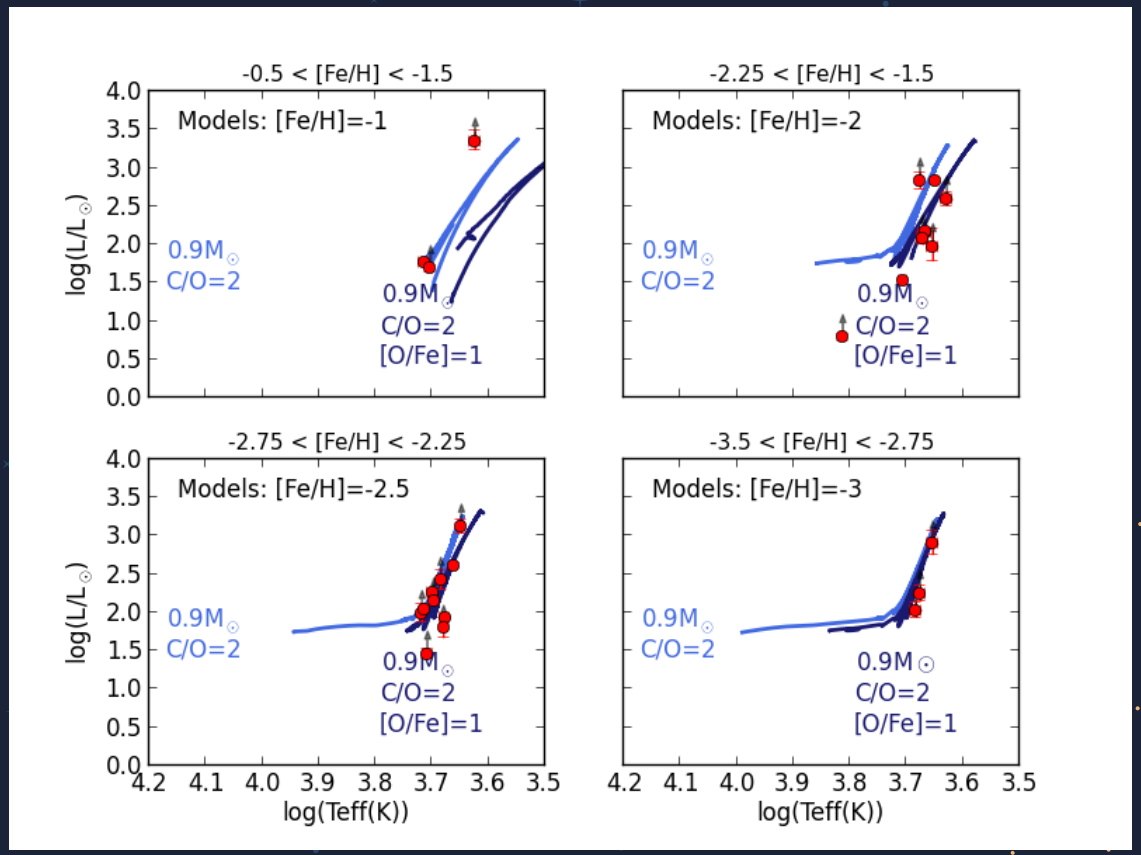
Karinkuzhi et al. 2021



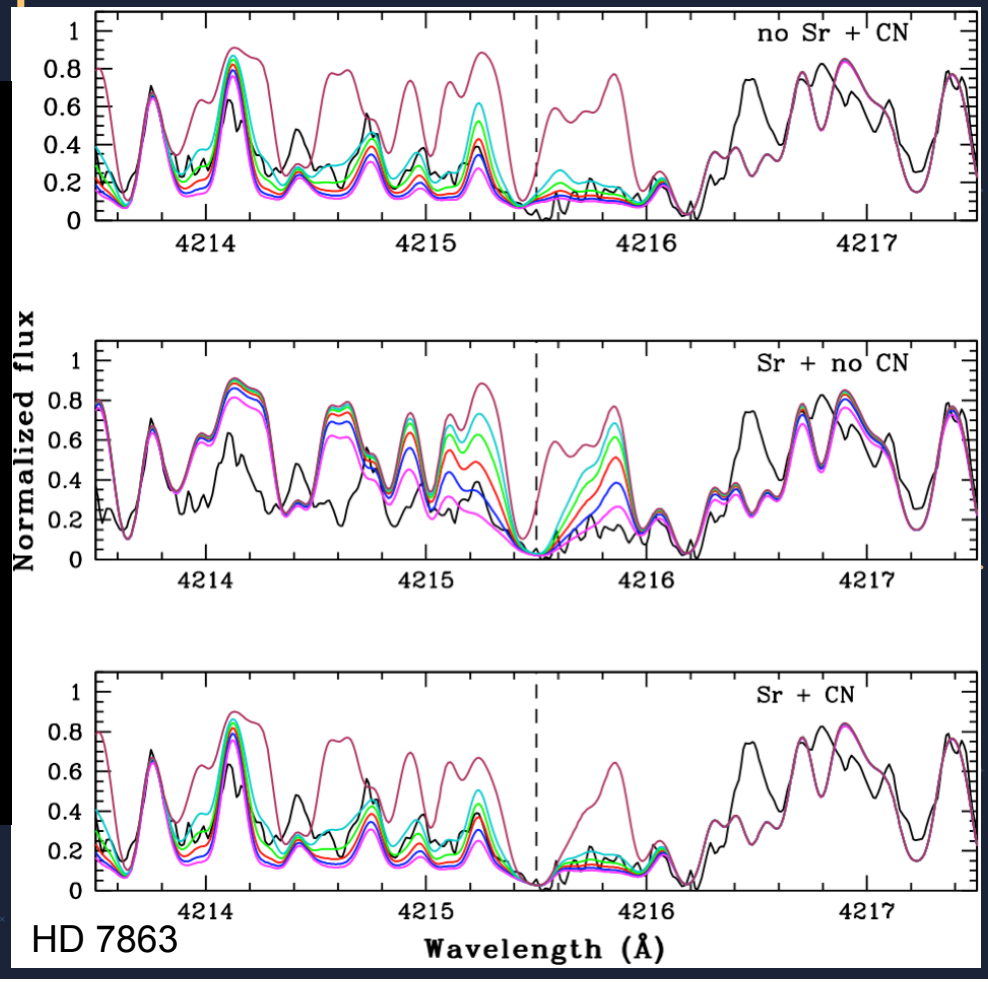
2. Machine-learning s-process line identification

Re-analysis of 15 bright Barium stars uncovered in LAMOST using machine-learning (Norfolk 2019)

3 strong barium stars
8 mild barium stars
4 non-enriched stars

→ 25% misclassification

Reasons: Sr II 4215.519Å line
- heavily saturated
- blended with CN 4216Å



HD 7863

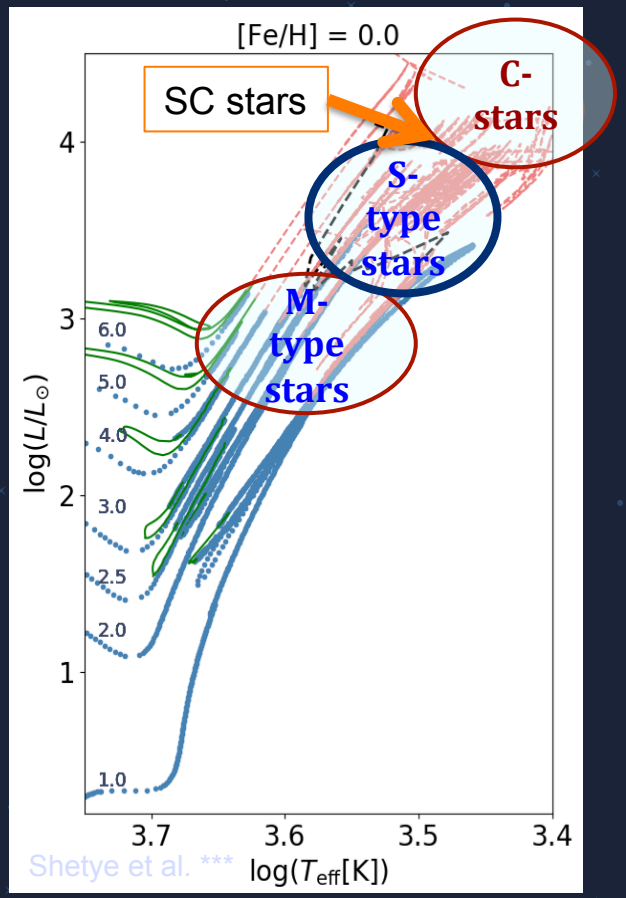
Karinkuzhi et al. 2021

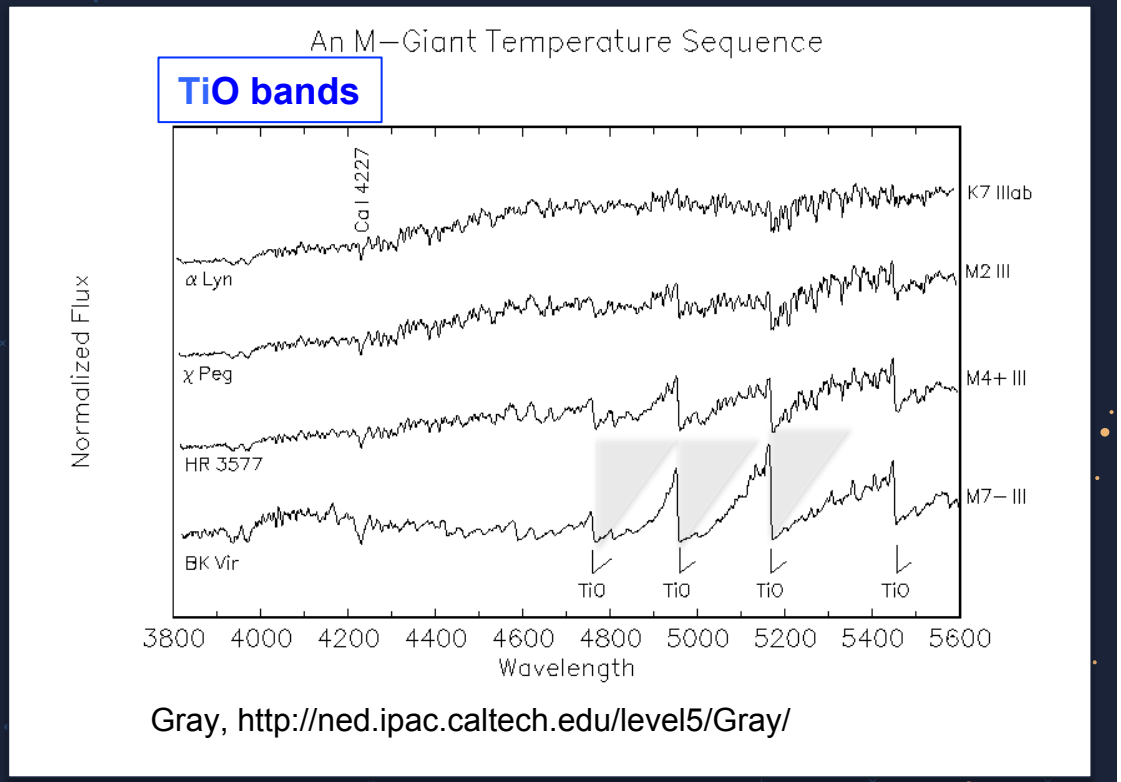
Some open questions

Tc-rich M stars

INTRINSIC STARS

Tc-rich M-type stars



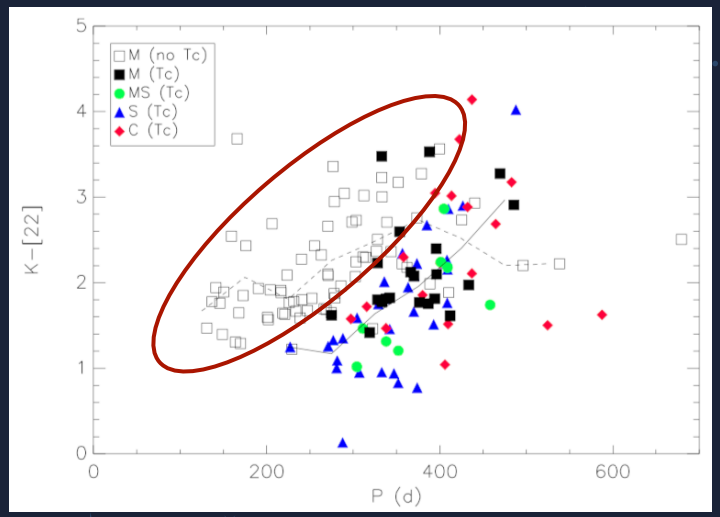


Gray, http://ned.ipac.caltech.edu/level5/Gray/

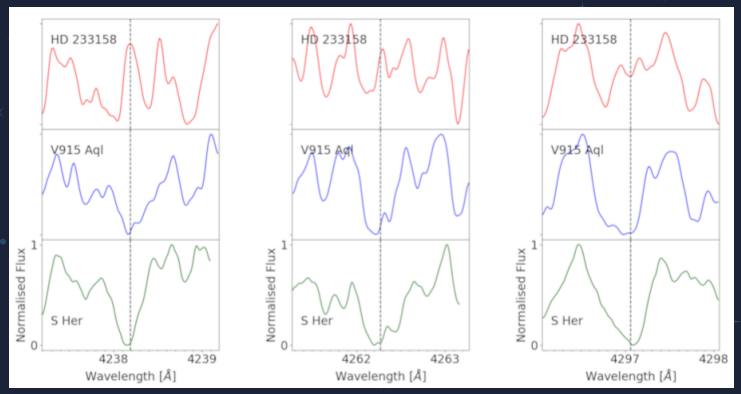
Tc-rich M stars

INTRINSIC STARS

- Uncovered by Little-Marenin & Little 1979
- No (prominent) s-process enrichment



Uttenthaler et al.2019



Shetye et al. 2021

No Tc S

Tc-rich S

Tc-rich M

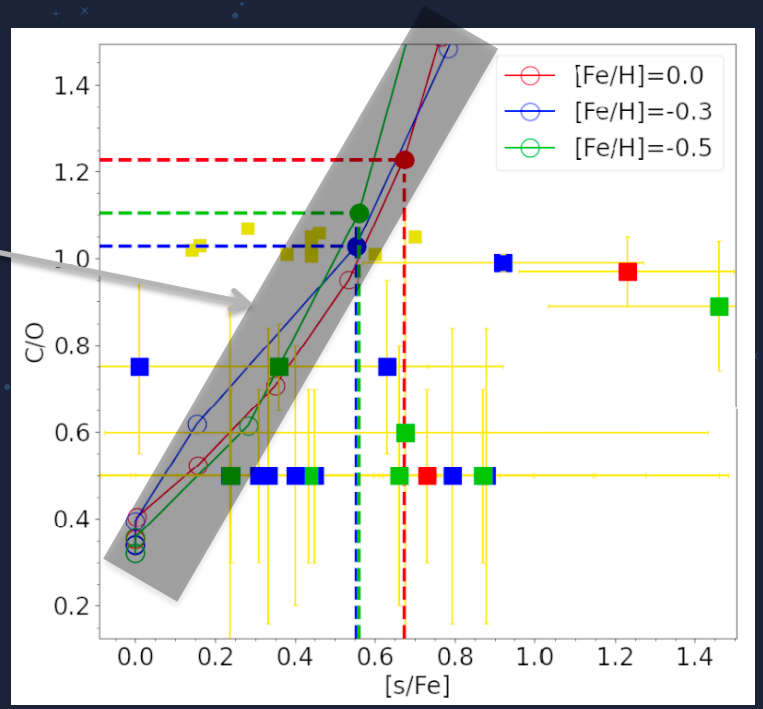
→Only a (few) thermal pulses?
→or a different s-process?

s and C increase

INTRINSIC STARS

- Simultaneous increase of s and C

Stellar evolution model (STAREVOL) predictions



s and C increase

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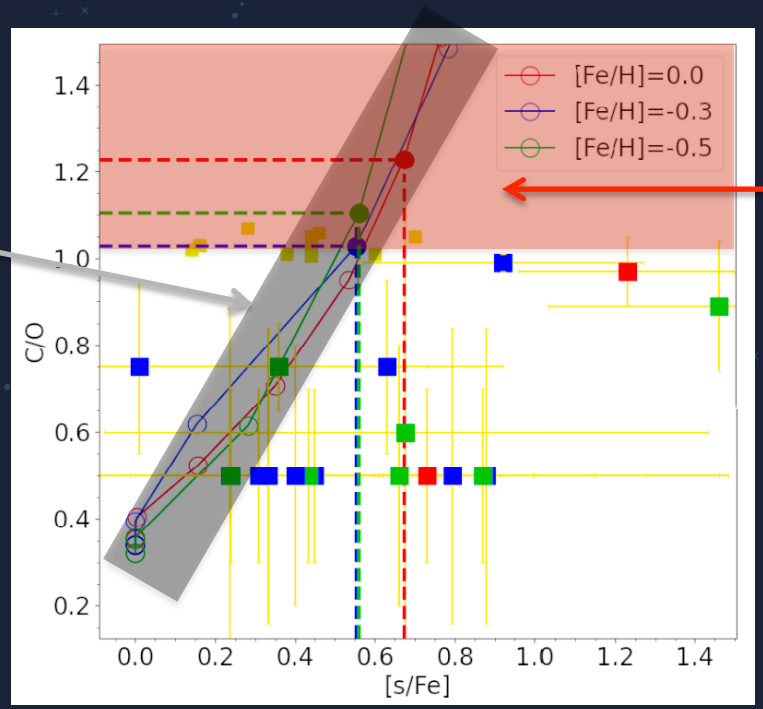


C/O>1

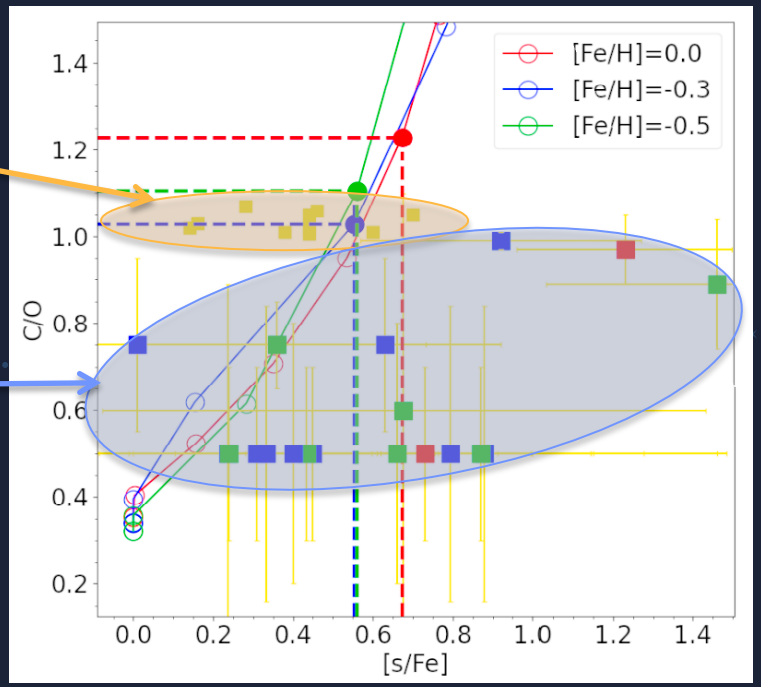
s and C increase

INTRINSIC STARS

- Simultaneous increase of s and C

C stars (Abia et al.)

S stars (Shetye et al.)
C/O<1



s and C increase

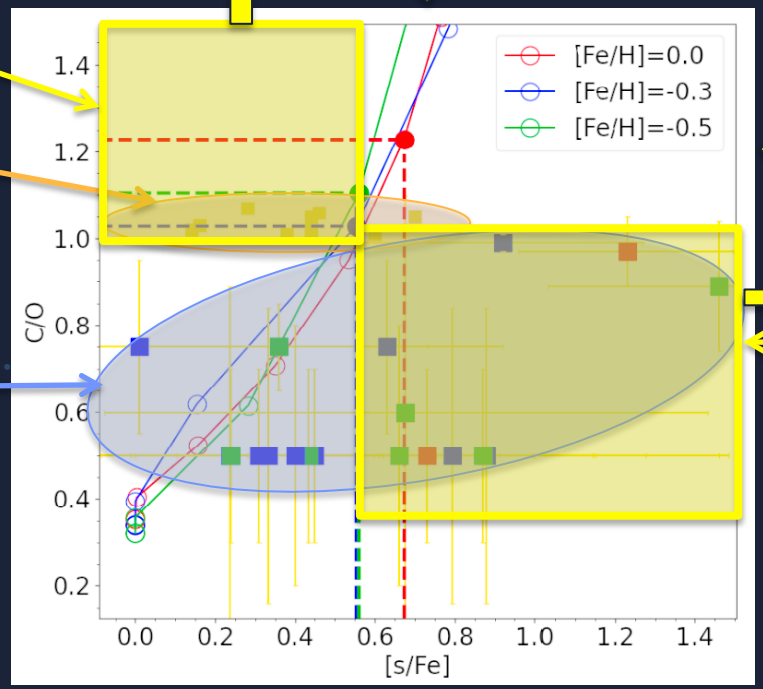
INTRINSIC STARS

- Simultaneous increase of s and C

Stars with such C/O should have [s/Fe]≥0.6

C stars (Abia et al.)

S stars (Shetye et al.) C/O<1



Stars with such [s/Fe] should have C/O>1

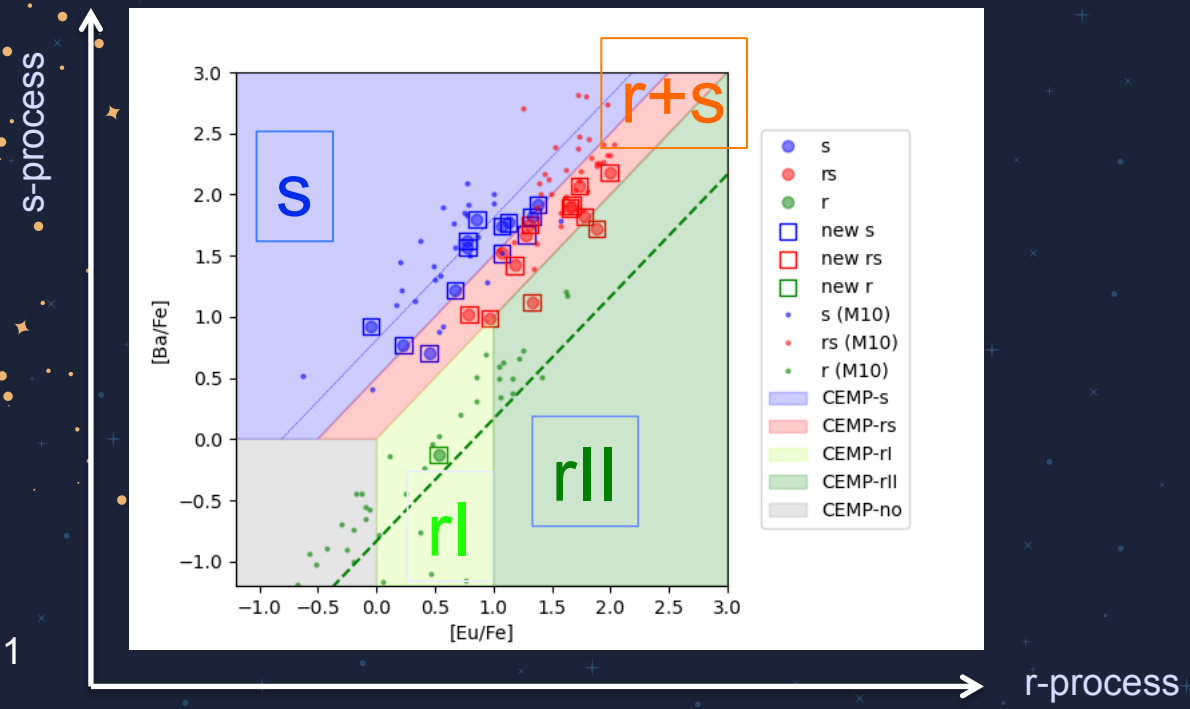
Shetye et al. 2020

More extrinsic stars

COLD CASES

CEMP-sr:

- Binaries
- Overabundances in s and r elements
- Classification

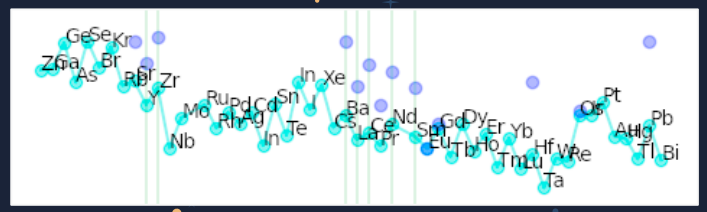


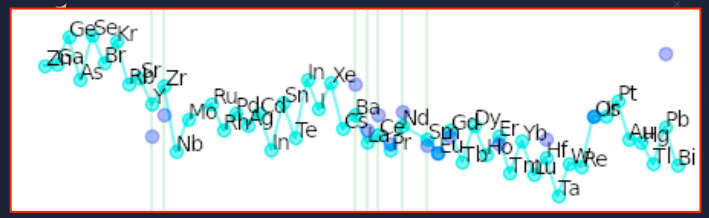
Karinkuzhi et al., 2021

4. More extrinsic stars

COLD CASES

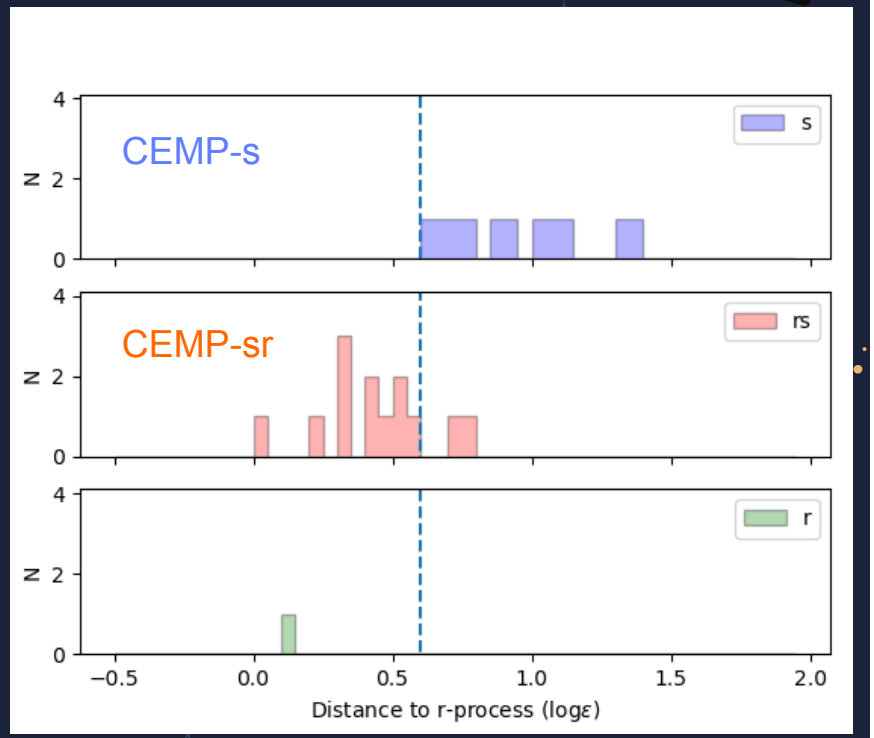
CEMP-sr:
- Classification





New classification scheme
Using Y, Zr, Ba, La, Ce, Nd, Sm, Eu

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



4. More extrinsic stars

CEMP-s

CEMP-sr

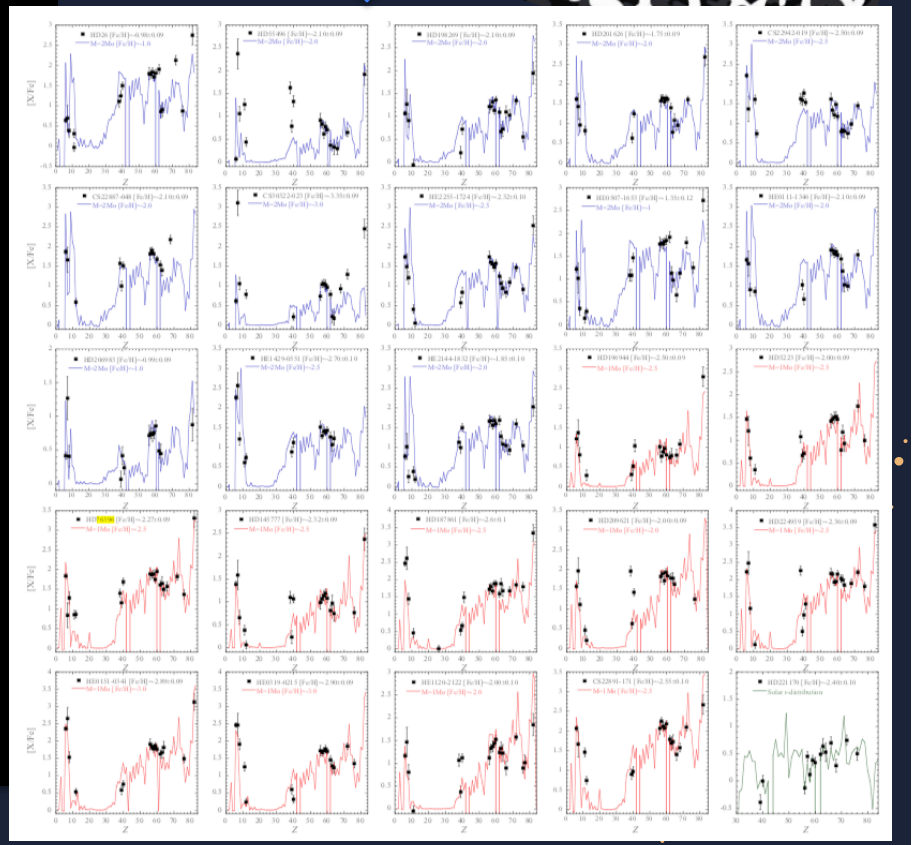
Double event scenario? (Gull et al. 2018)

Or

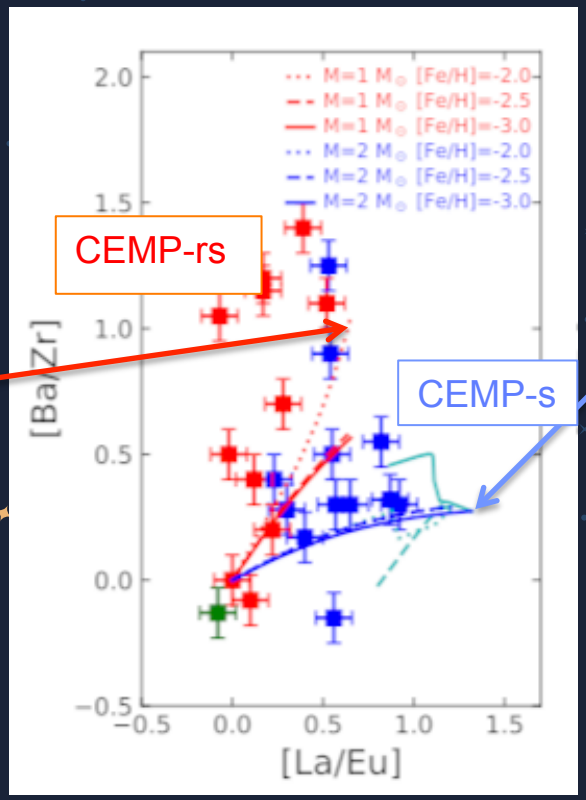
Low-metallicity and low- mass thermally-pulsing AGB stars
(Iwamoto et al. 2004; Lugaro et al. 2012, Choplin et al. 2021)

But: HD 100503: analog to CEMP-rs star
but at [Fe/H]=-0.7
Karinkuzhi et al. 2018

CEMP-rs



4. More extrinsic stars



1 $M_\odot$ models with proton ingestion

Radiative s-process during interpulse

Karinkuzhi D. et al., 2021, A&A 645, 61

- Particular manifestation of the s-process (at low [Fe/H])
- Easier to detect at low [Fe/H]
- HD100503: analog to CEMP-rs star at [Fe/H]=-0.7
- Mixed profile also found in V4334 Sagittarri (Sakurai's object)
- Some SC stars have a high Eu overabundance (0.5 to 1 dex) (Abia & Wallerstein 1998) as well as some Ba stars

Perspectives

Methods:
Non-LTE abundances (La, Ce, Sr, Y, Zr…)
3D abundances
Systematics from large surveys: to come

Targets: Mainly 5 types of s (and i ?) -process stars:

- Intrinsic TP-AGB (S, SC, C)
- Extrinsic (S, C, Ba, CH, CEMP-s and sr)
- Bitrinsic stars (S, SC?, C?)
- *Some* post-AGB objects
- GCE stars (Galactic Chemical Evolution) stars

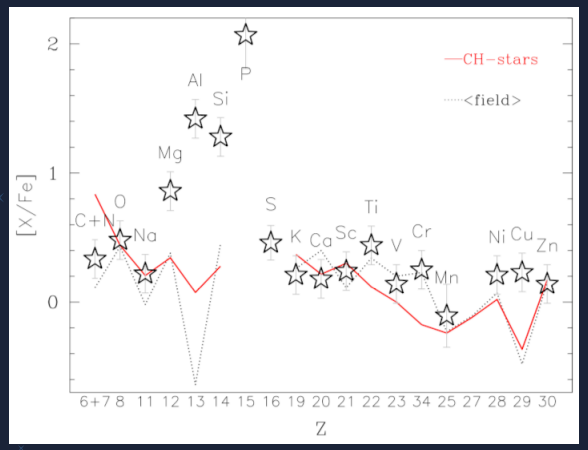
Looking forward

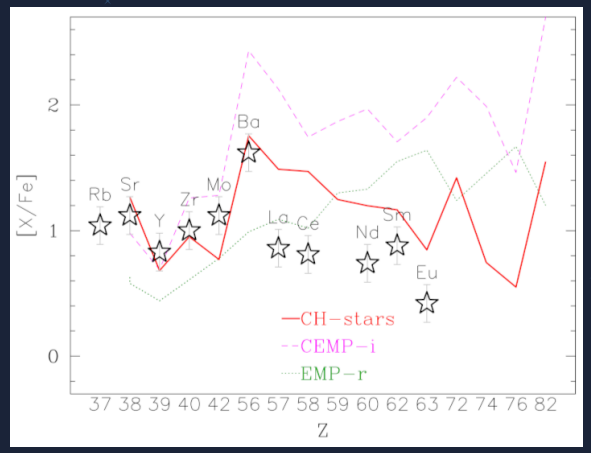

ESO
60
years
Happy anniversary ESO!
Looking forward
ESO
100
years

More puzzles to come from surveys

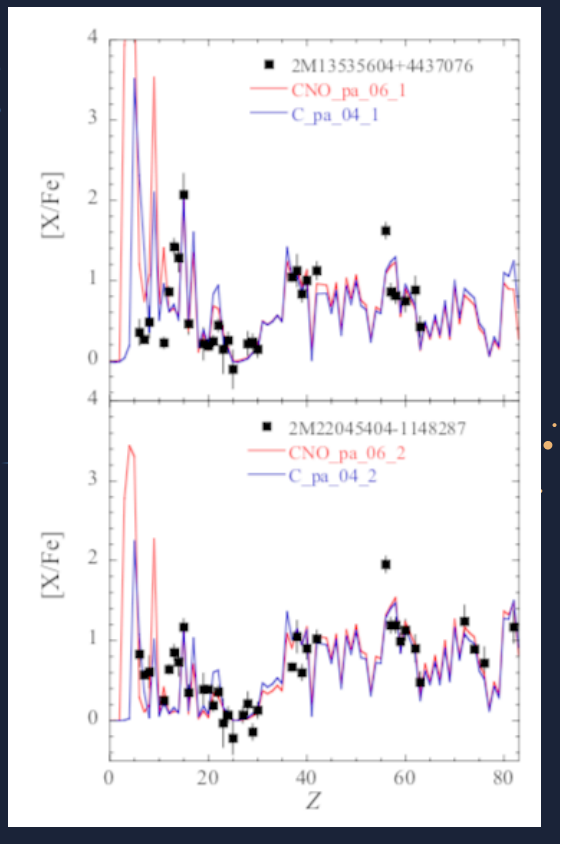
Phosphorus-rich stars

15 K giants
[Fe/H]~-1
Apparently single stars
1 shows C+N enhancement





Masseron et al. 2020



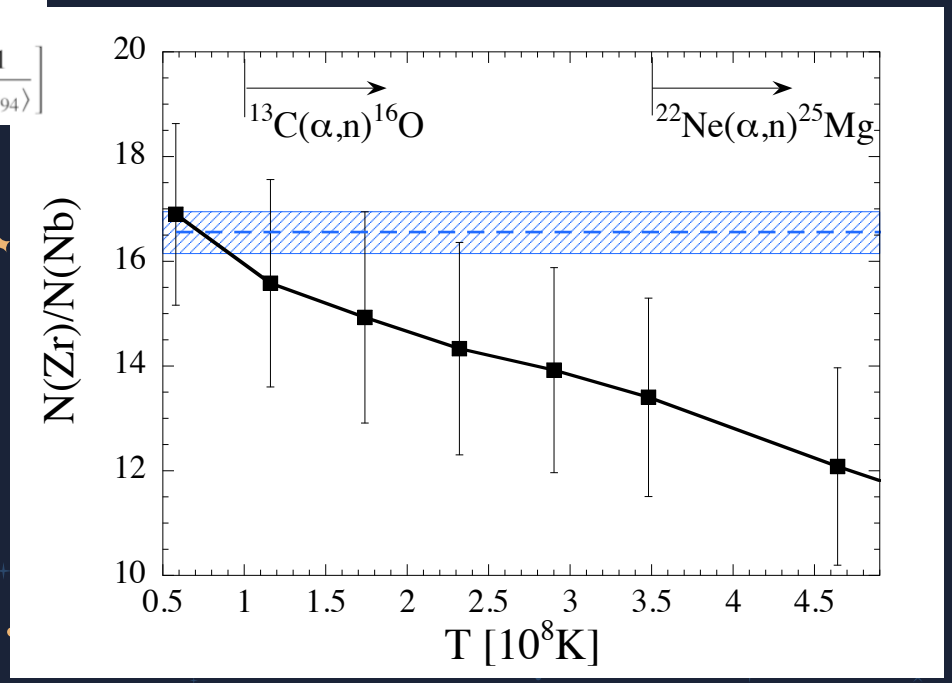
Spallation: non-thermal processes resulting from the interaction of C-rich or CNO-rich material with energetic protons and/or α-particles (Goriely 2022)

s-process: extrinsic stars

$$\left[\frac{\mathrm{Zr}}{\mathrm{Fe}}\right] = \left[\frac{\mathrm{Nb}}{\mathrm{Fe}}\right] + \log \omega^* - \log \frac{N_\odot(\mathrm{Zr})}{N_\odot(\mathrm{Nb})},$$

where

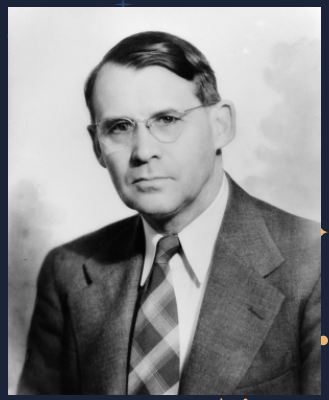
$$\omega^* = \langle \sigma_{93} \rangle \left[\frac{1}{\langle \sigma_{90} \rangle} + \frac{1}{\langle \sigma_{91} \rangle} + \frac{1}{\langle \sigma_{92} \rangle} + \frac{1}{\langle \sigma_{94} \rangle} \right]$$



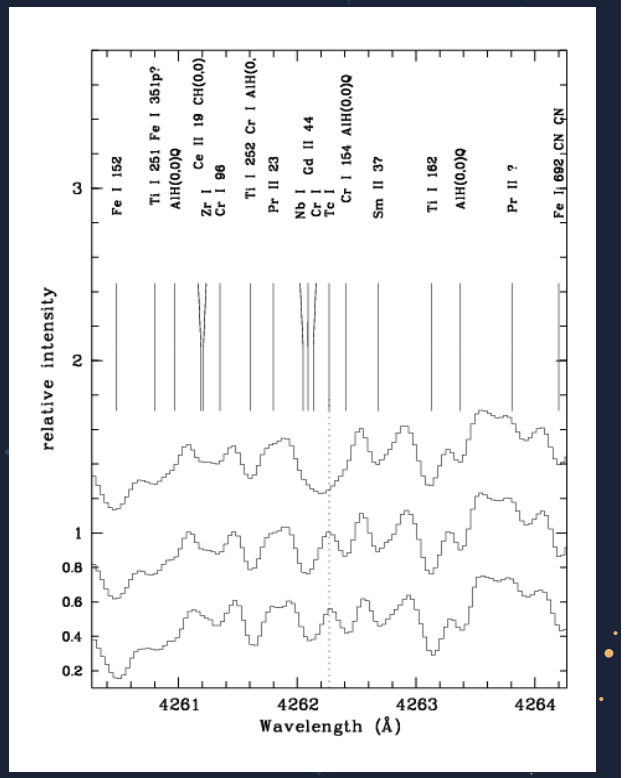
Neyskens et al. 2015

Constraint on s-process temperature operation in S stars: T< 250 10^6 K
→ ^{13}C (α, n) neutron source

Technetium



- 1952: Observation by Paul Merrill of Tc I lines in the photosphere of S stars (R And, R Gem, AA Cyg)



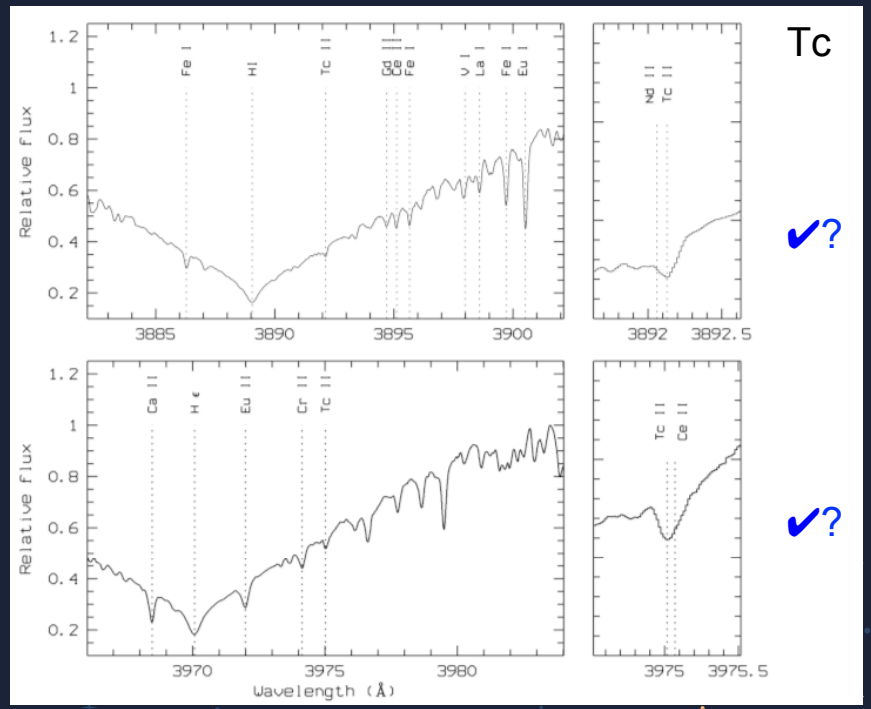
Lines of *Tc* I, an element believed to have no completely stable isotope, appear to be stronger in the stars with the more dominant S-type characteristics. This fact, together with others, might suggest that S-type stars represent a comparatively transient phase of stellar existence.

Technetium: where it should not be detected?

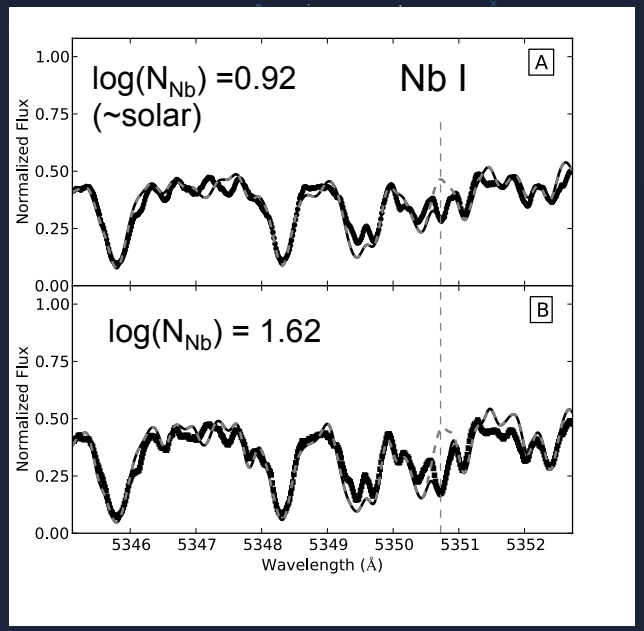
Searched in **Ap stars**: inconclusive results
Tc II: 3892.129 and 3975.017 A

- Eu–Cr A1 star HD 125248
  Palmeri et al. 2007

- See also Boyarchuk & Snow (1978): no Tc in Ap stars

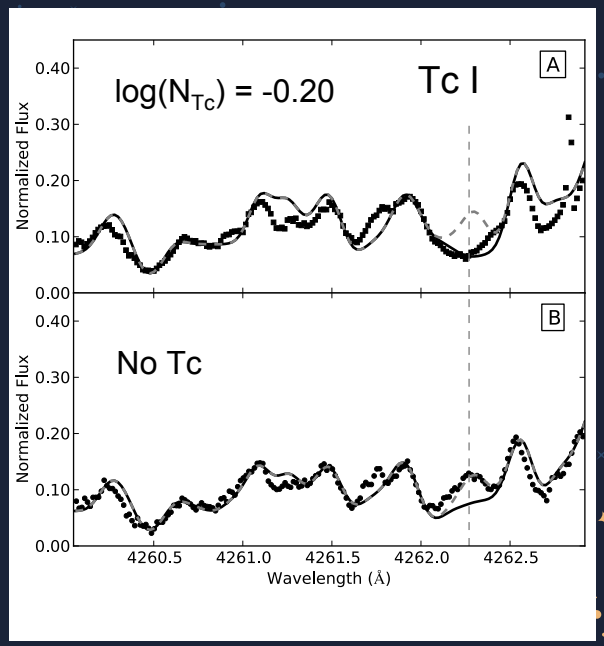


s-process: binary paradigm



Intrinsic:
Tc-rich →
← Nb-solar

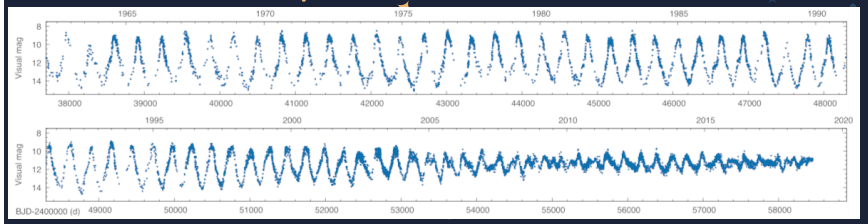
Extrinsic:
No Tc →
← Nb-rich



4. Real-time AGB evolution

INTRINSIC STARS

T Ursae Minoris
AGB M star (Mira→semi-regular)
Steep pulsation period decline
Pulsation mode switching
(also: RU Vul, R Dor, R Aql, R Hya, and W Dra)
Uttenthaler et al. 2016
→ Onset of a thermal pulse?



Molnar et al. 2019

BH Cru
SC → C
(Whitelock 1999, Uttenthaler et al.2011)

LX Cygni
S→ C spectral type
Uttenthaler et al. 2016

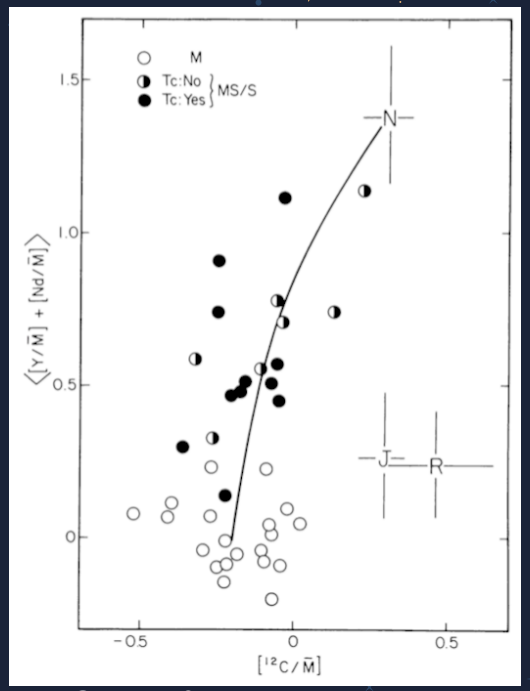
Table 3. Historic spectral type determinations of LX Cyg.

Date dd/mm/yyyy	Sp. type	Reference
22/10/1952	S LaO 3	Terrill (1969)
05/09/1954	S LaO 3	Terrill (1969)
20/08/1955	S	Cameron & Nassau (1956)
27/09/1956	S LaO 2–3	Terrill (1969)
05/10/1957	S LaO 2	Terrill (1969)
12/09/1958	S LaO 2:	Terrill (1969)
07/06/1962	S LaO 3	Terrill (1969)
03/10/1965	S LaO 1	Terrill (1969)
27/08/1975	S5.5e: Zr 1	Ake (1979)
14/11/1976	SC3e Zr 0.5	Ake (1979)
18/10/1977	SC8/8.5e	Keenan & Boeshaar (1980)
29/10/1978	SC7/9–e	Keenan & Boeshaar (1980)
02/08/1979	SC4:/8e	Keenan & Boeshaar (1980)

s-process along the AGB

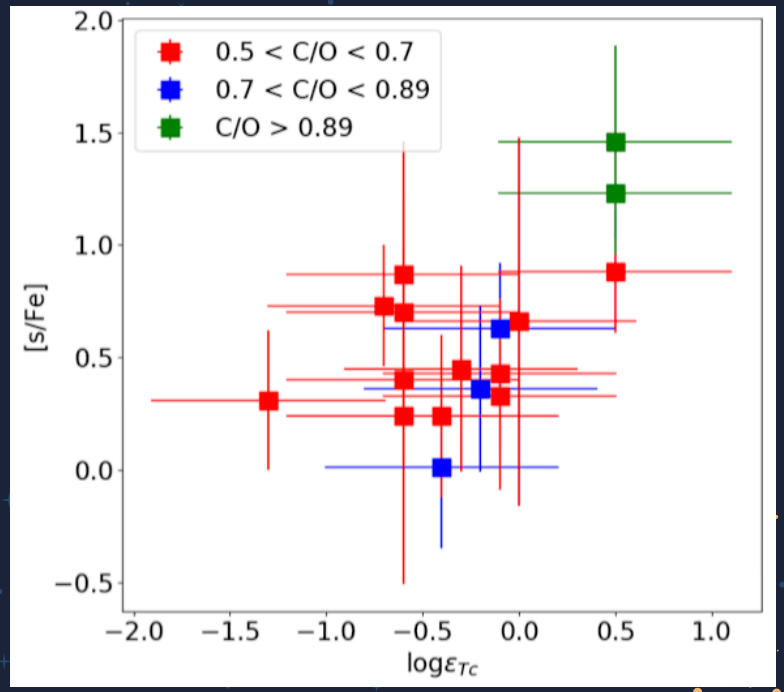
S stars

- Loose tendency to have largest [s/Fe] for largest C/O:



Smith & Lambert 1990

- Loose tendency to have largest Tc for largest C/O and largest [s/Fe]



Shetye et al. 2019, 2021