New clues for heavy element nucleosynthesis

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In collaboration with
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Workshop in honour of Maurizio M. Busso

New clues for heavy element nucleosynthesis

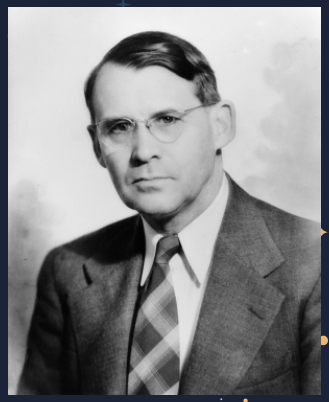
- s-process along the AGB:
  - Technetium detection
  - s-process abundances
- “Cold cases”: extrinsic stars
- Some open problems

THE 13TH TORINO WORKSHOP ON AGB STARS
PERUGIA, 19TH-24TH JUNE 2022

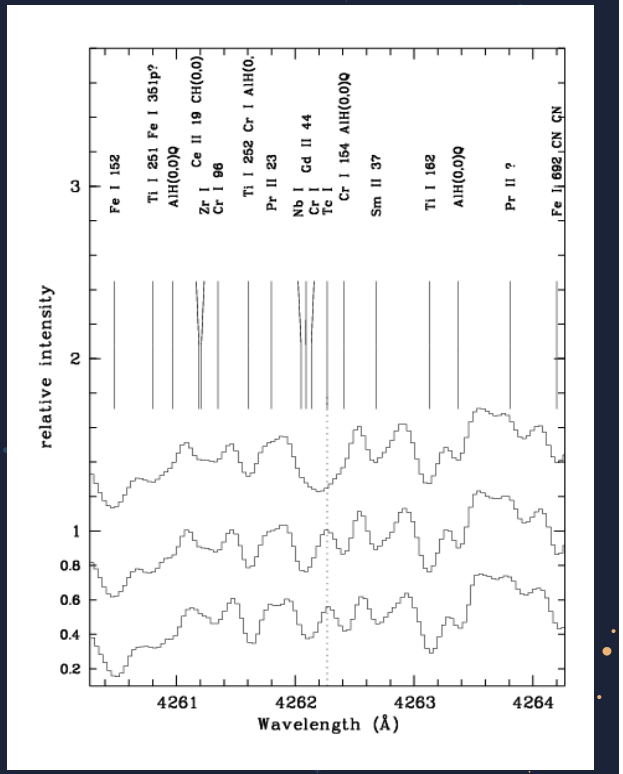
ULB UNIVERSITÉ LIBRE DE BRUXELLES

Workshop in honour of Maurizio M. Busso

Technetium

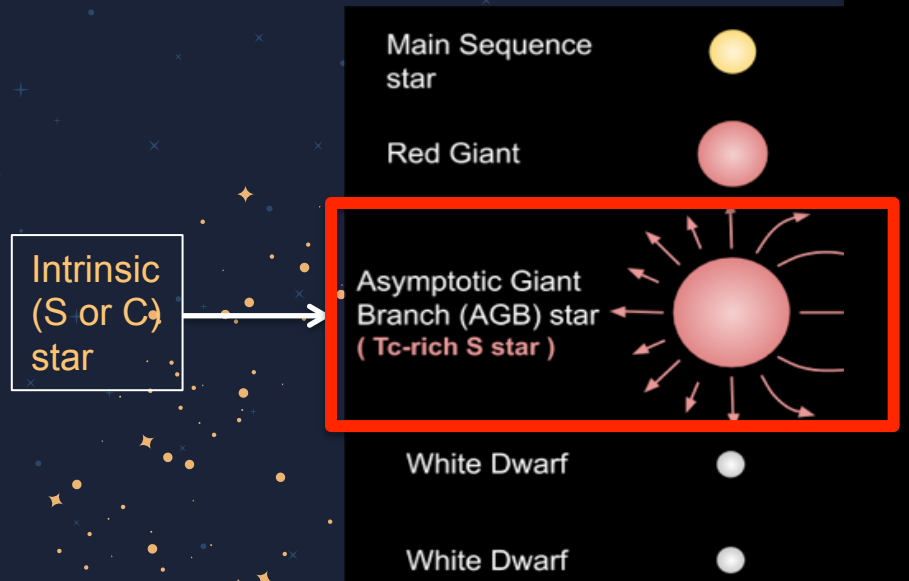


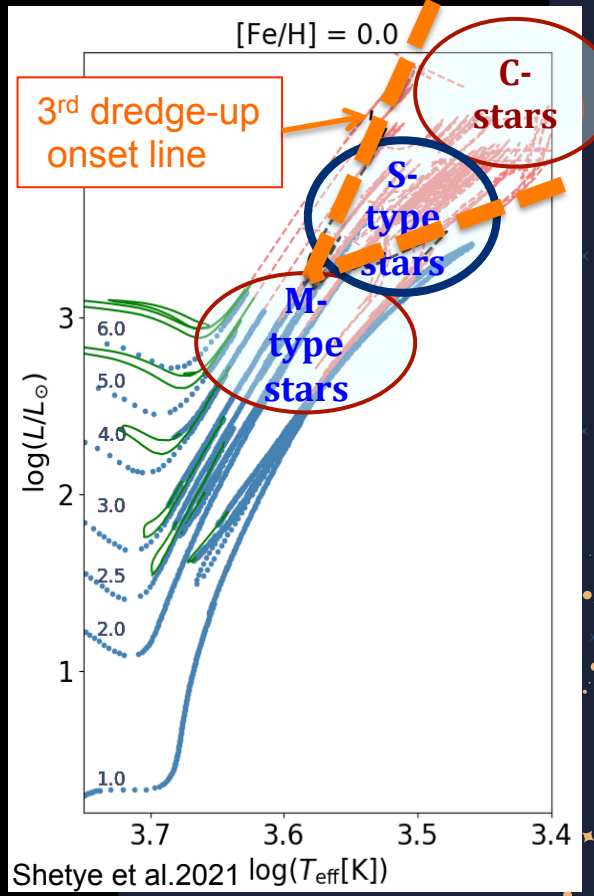
- 1952: Observation by Paul Merrill of Tc I lines in the photosphere of S stars (R And, R Gem, AA Cyg)



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.

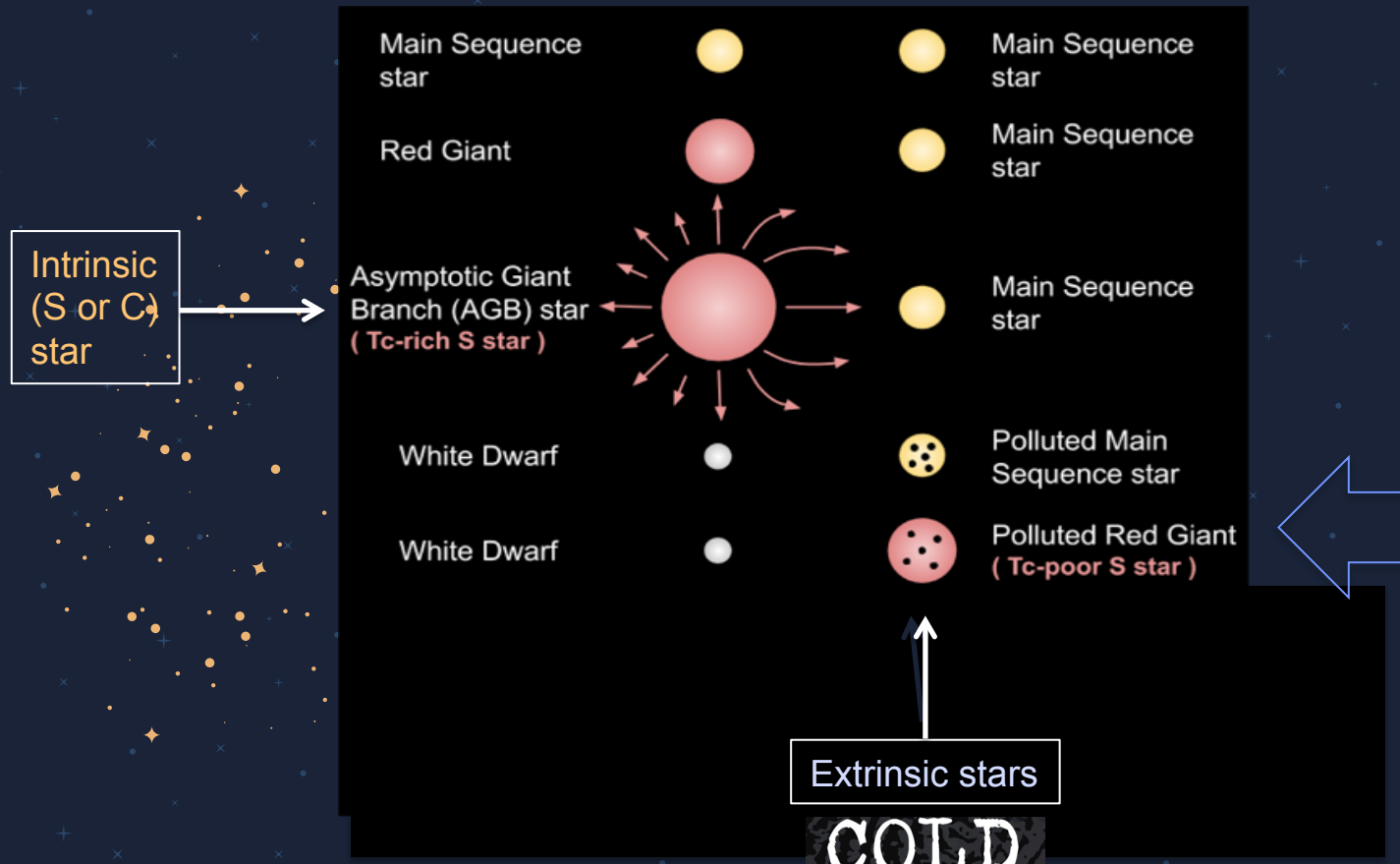
Technetium: where it should be detected





Shetye et al.2021

Technetium: where it should be detected



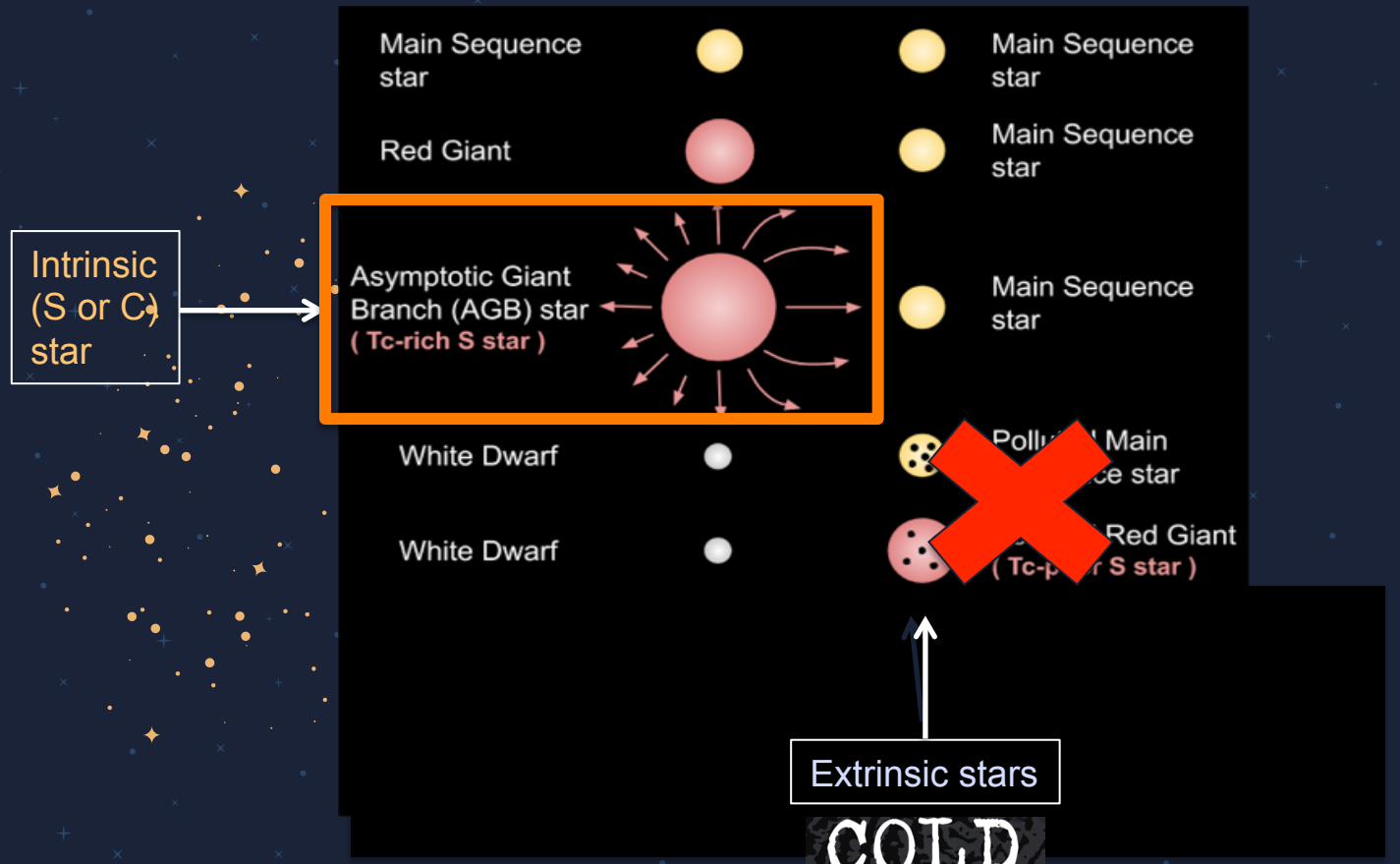
Intrinsic (S or C) star

Barium stars
CH stars
CEMP-s
CEMP-sr

Extrinsic stars

COLD CASES

Technetium: where it should be detected



Barium stars
CH stars
CEMP-s
CEMP-sr

Shetye et al.2021

Technetium: where it is detected

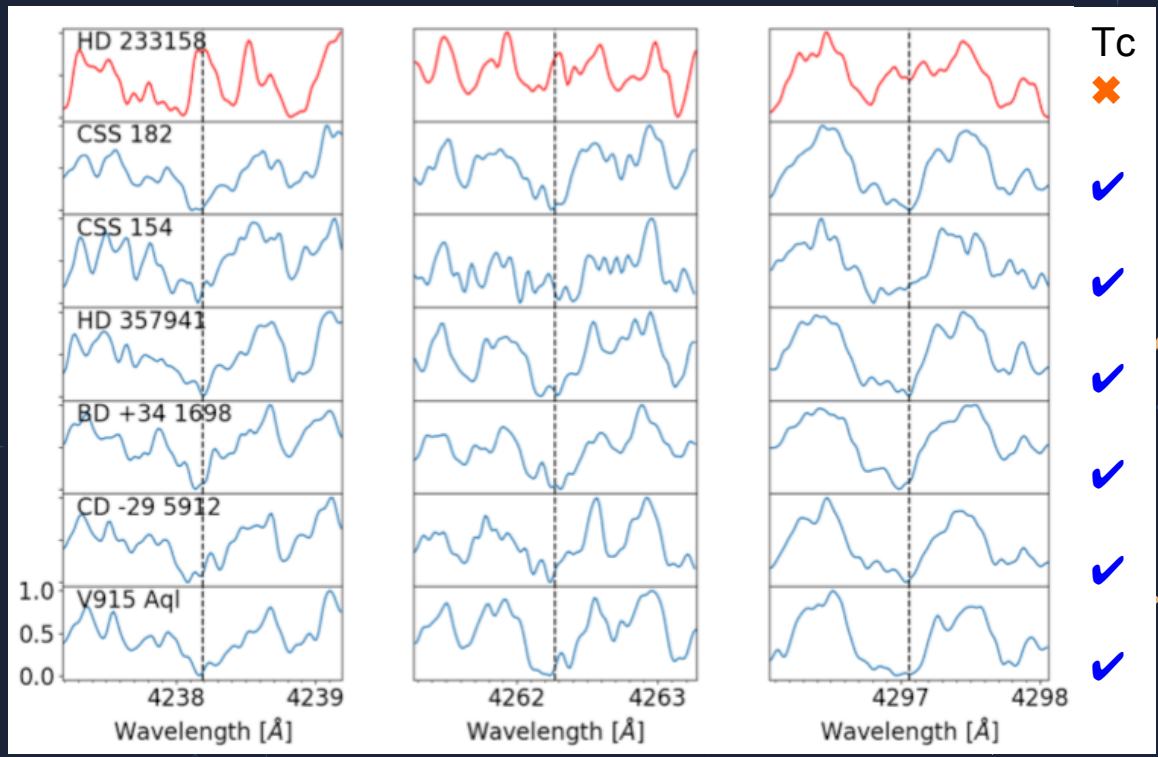
Tc I searched in **TP-AGB stars** and detected (as expected):
Tc I: 3 resonance lines 4238, 4262, 4297A

Extrinsic (no-Tc) star shown for comparison

In TP-AGB S stars

HERMES@Mercator spectra

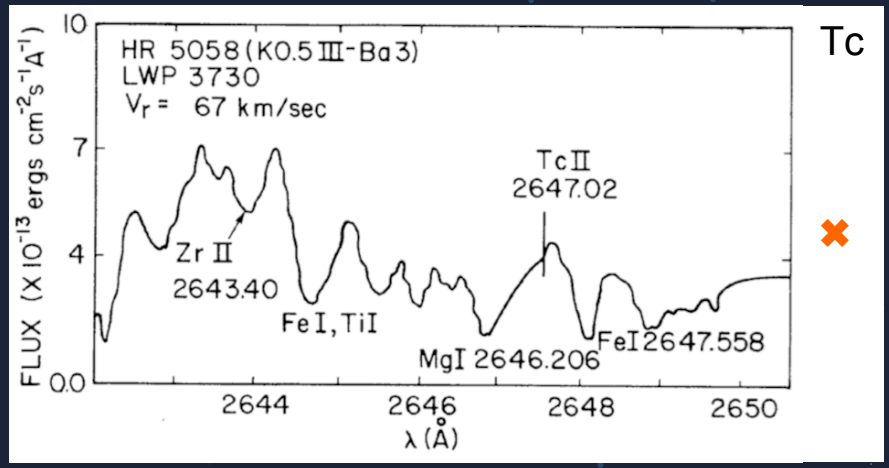
Shetye et al. 2021



Technetium: where it is not detected

Tc II searched in **Barium stars**: no detection (as expected)
Tc II: 2647.02, 2610.00 and 2543.24 (IUE spectra)

Little-Marenin & Little (1987)

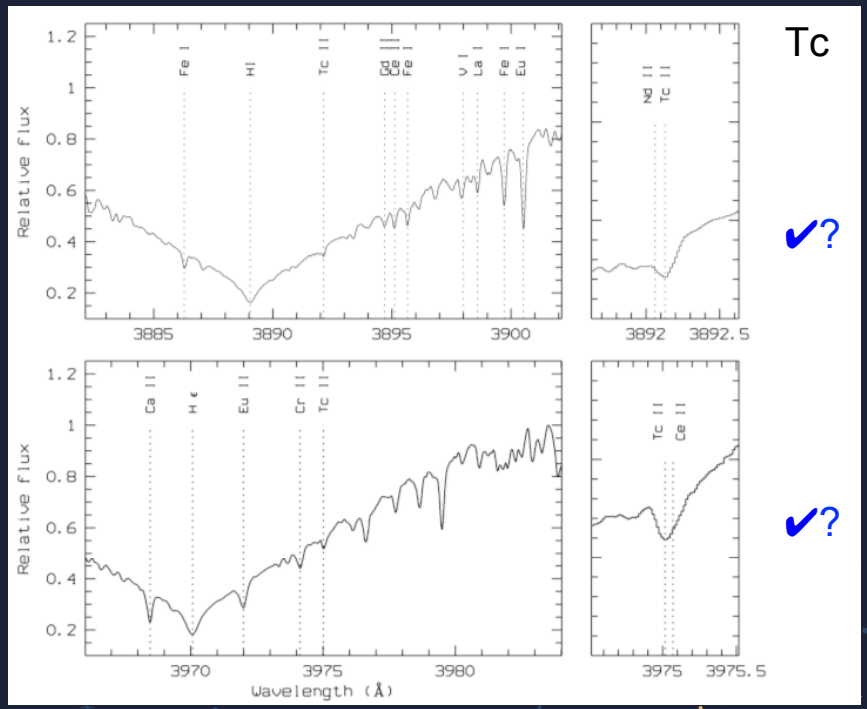


Technetium: where it should not be detected

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

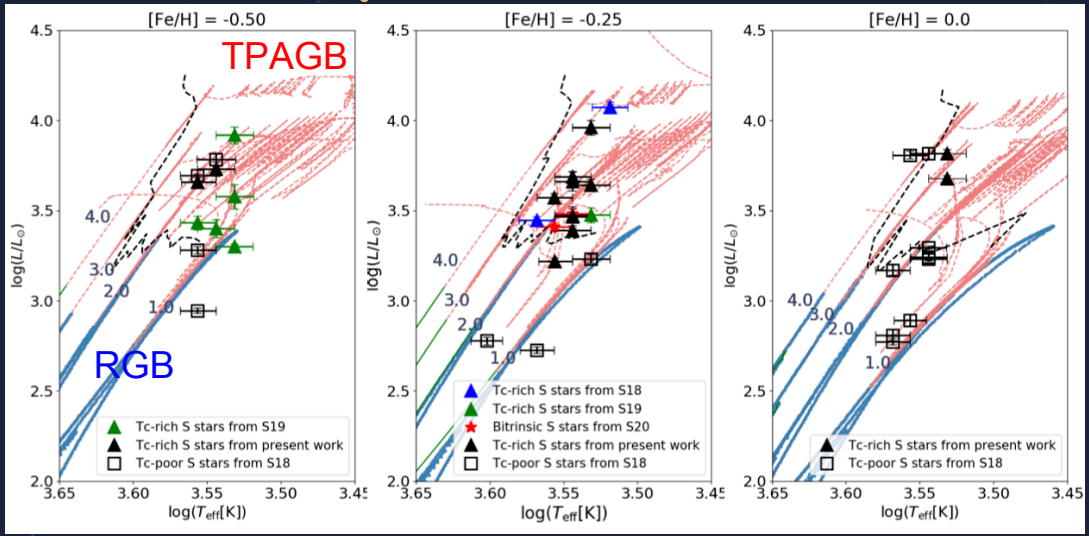


s-process along the AGB

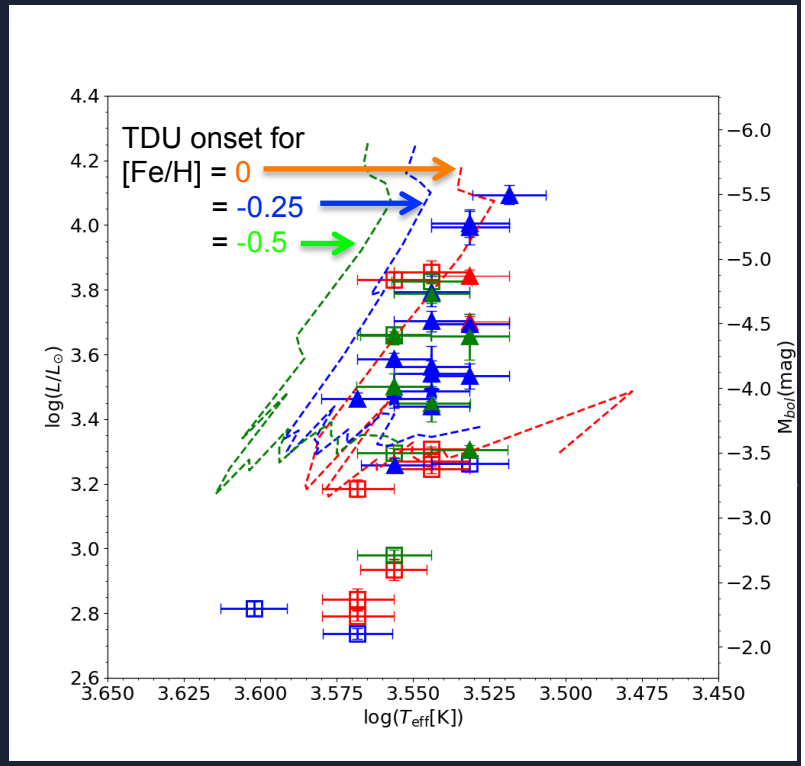
S stars

- HR diagram (Gaia eDR3)

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



Shetye et al. 2021



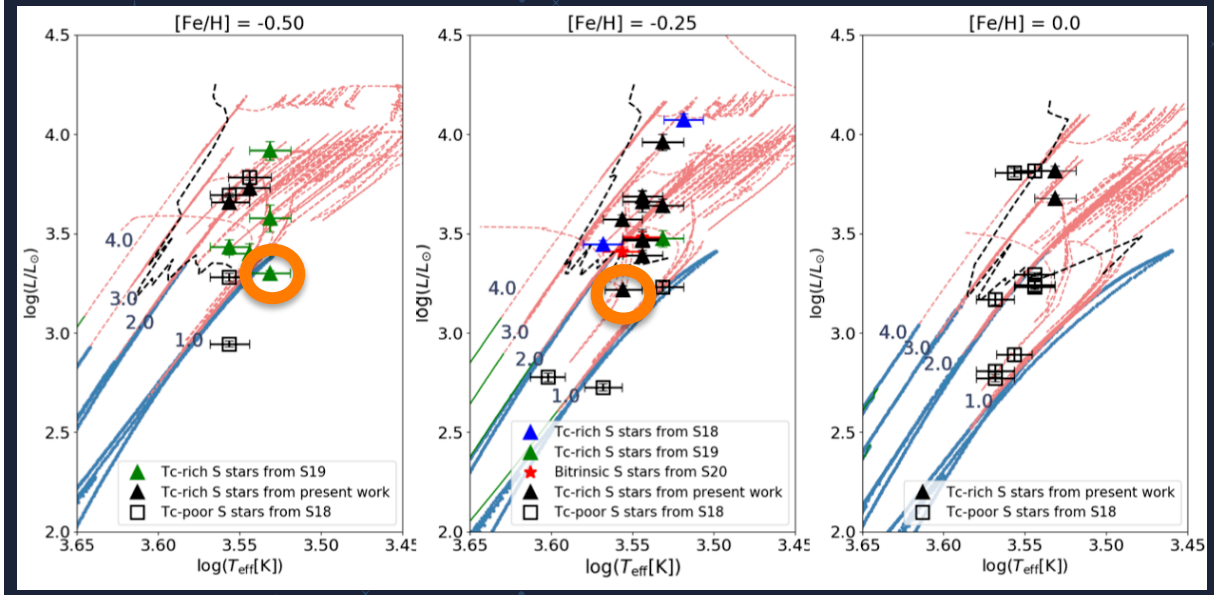
Van Eck, Shetye & Siess 2022

s-process along the AGB

S stars

- Contribution of low-mass AGB stars (M<1.5)

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



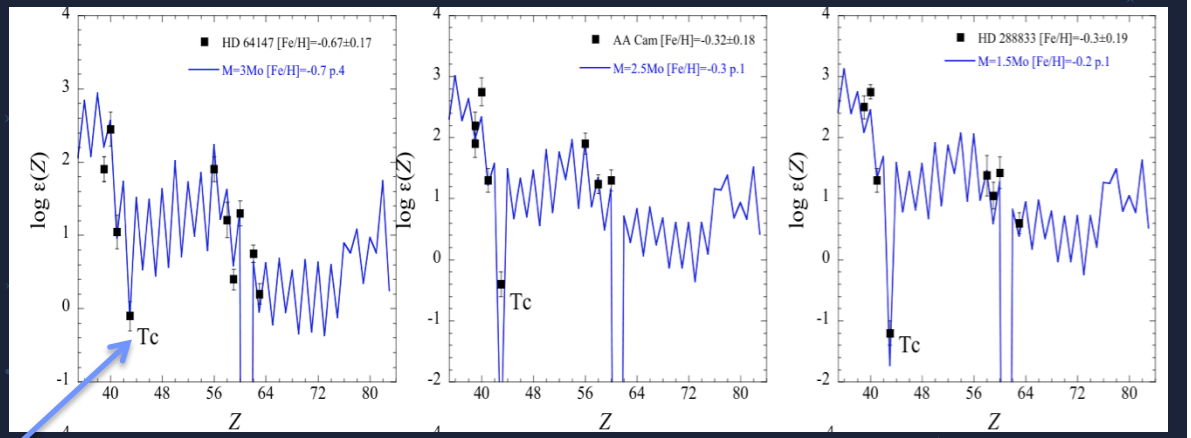
Name	$M_{current}$	M_{init}
CSS 154	1.4	1.6
BD +34 1698	1.2	1.4
V 915 Aql	0.8	1
CSS 182	1.1	1.3
BD-29 5912	1.3	1.5

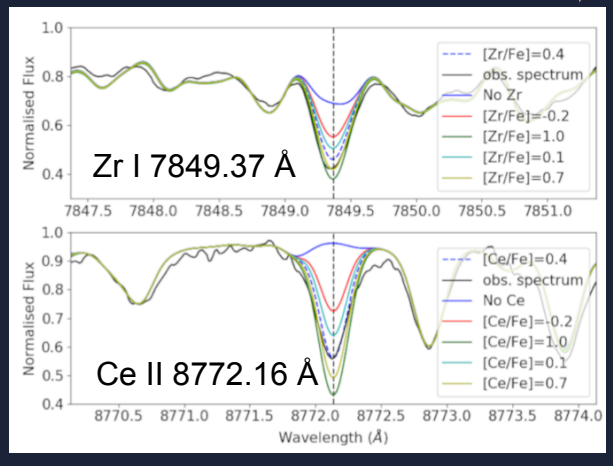
s-process along the AGB

S stars:

MARCS model atmosphere of S stars (Van Eck et al. 2017)

- Good agreement between s-process abundances and s-process models
- First measurement of Tc abundances



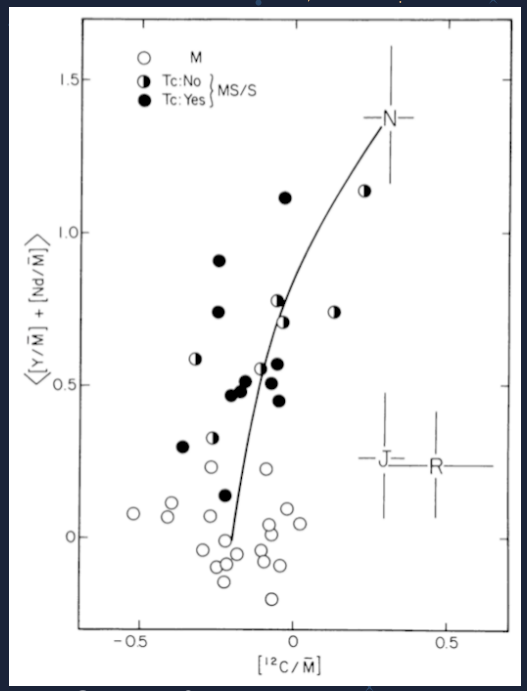


Shetye et al. 2019, 2021

s-process along the AGB

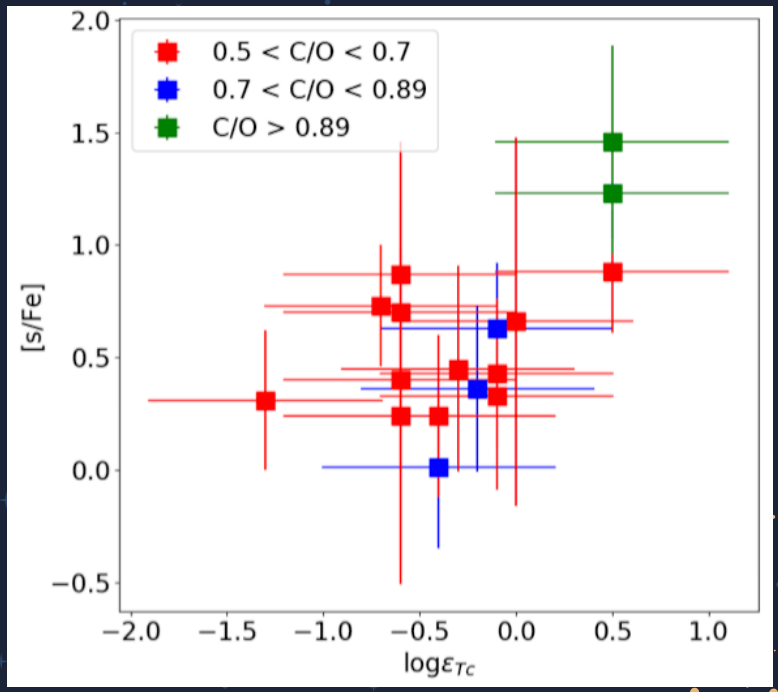
S stars

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



Smith & Lambert 1990

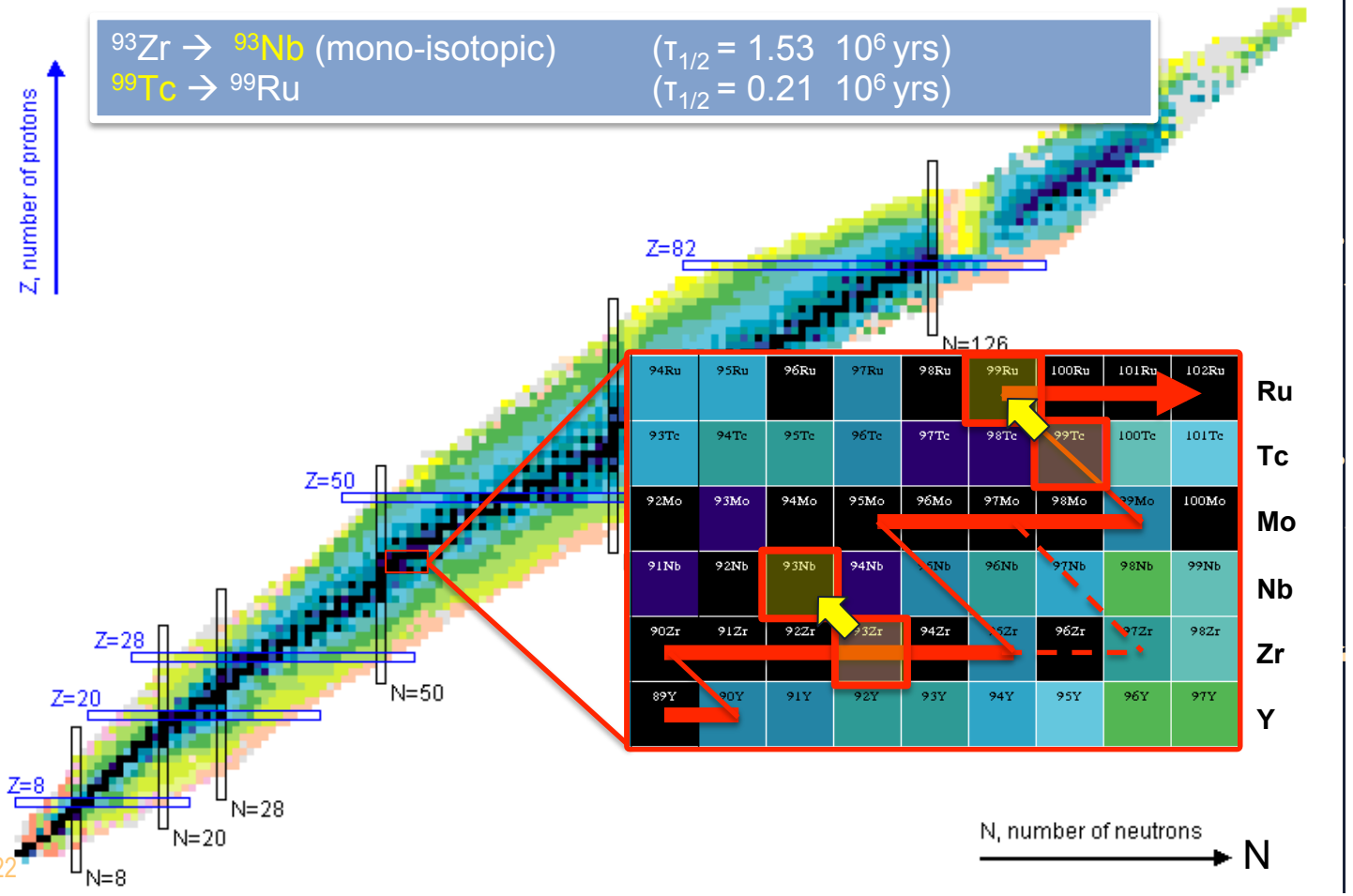
- Loose tendency to have largest Tc for largest C/O and largest [s/Fe]



Shetye et al. 2019, 2021

s-process

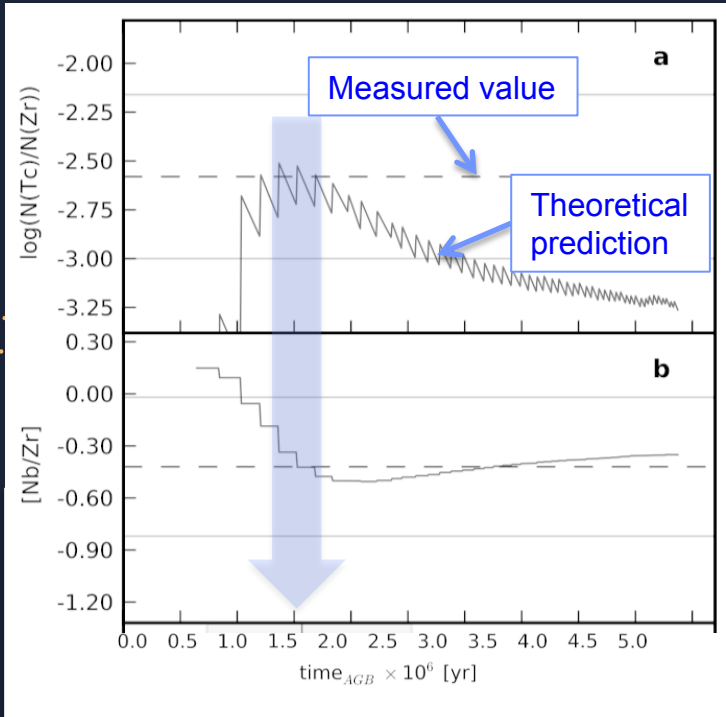
Radio-isotopes allowing to derive information on the timescales of the s-process

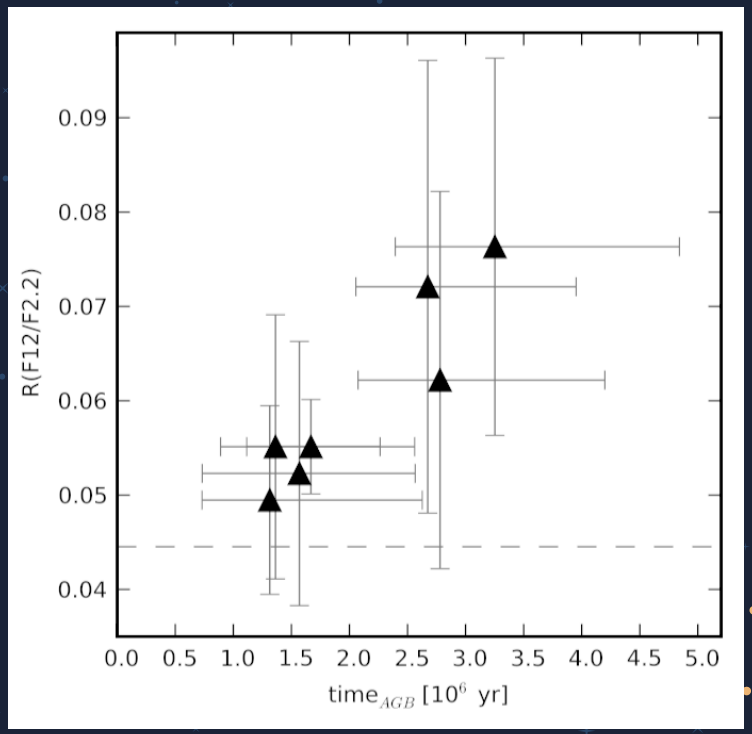


s-process along the AGB

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

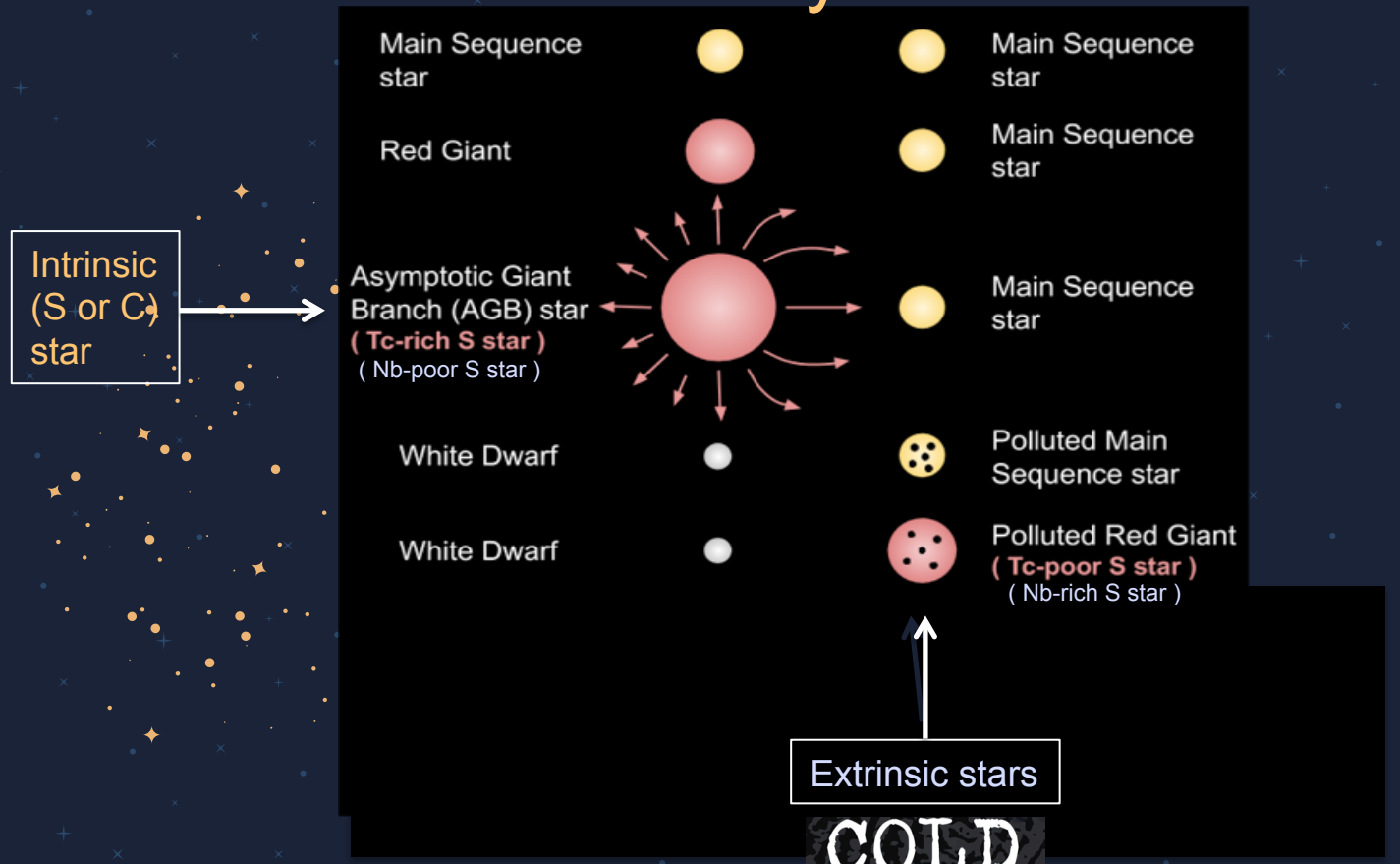
- determination of ages since the s-process nucleosynthesis onset
- Constraint on s-process temperature operation in S stars: T< 250 10^6 K →^{13}C (α, n) neutron source





Neyskens et al. 2015

The binary scenario



Intrinsic (S or C) star

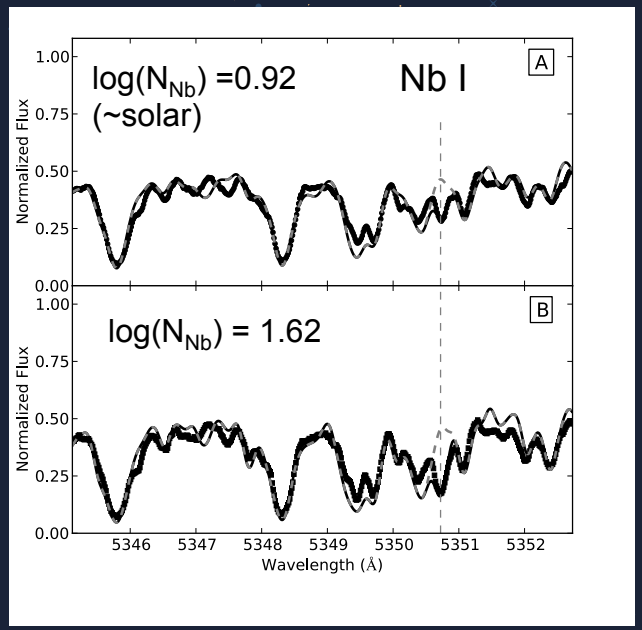
Extrinsic stars

COLD CASES

Barium stars
CH stars
CEMP-s
CEMP-sr

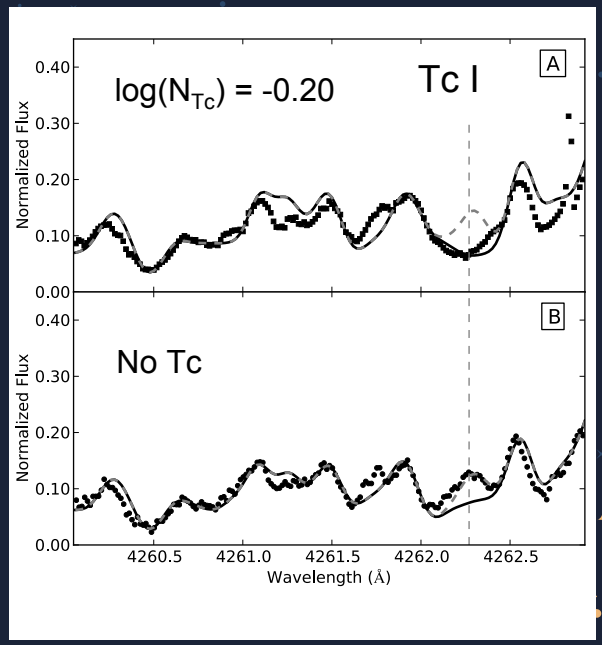
Shetye et al.2021

s-process: binary paradigm



Intrinsic:
Tc-rich
Nb-solar

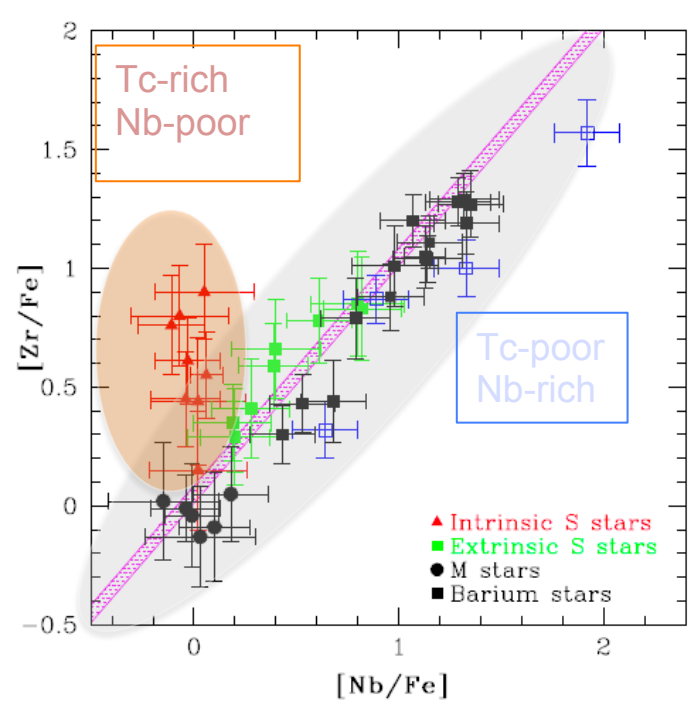
Extrinsic:
No Tc
Nb-rich



s-process: extrinsic stars

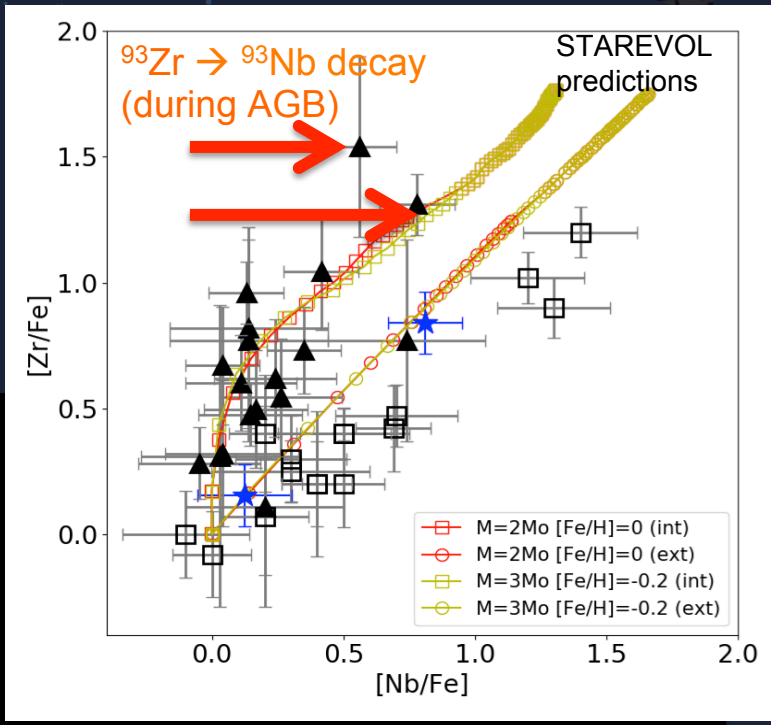
Extrinsic S stars

Validation in S-type stars, barium stars, CEMP-s stars:
- Nb and Zr follow the expected trends



Karinkuzhi, et al. 2018

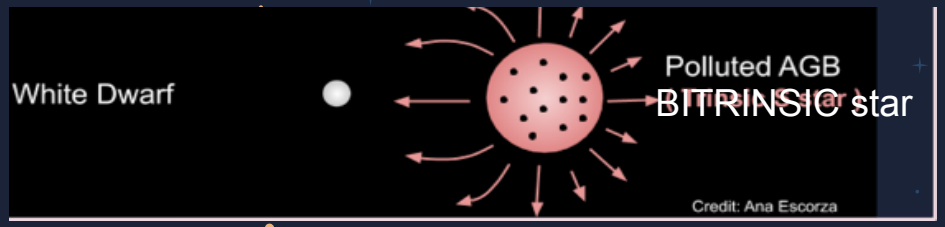
Shetye et al. 2021

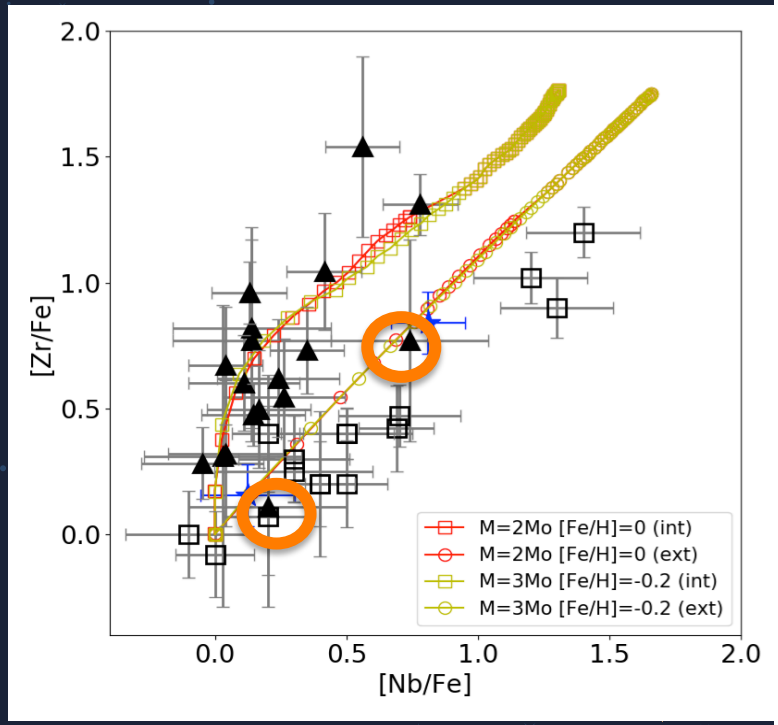


s-process: Bitrinsic stars

Reheated cold case

Discovery of bitrinsic stars:
Stars that have experienced 2 pollutions:
One external, one internal





Shetye et al. 2021

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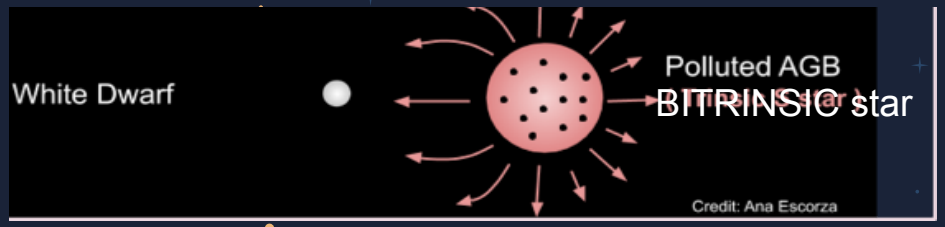
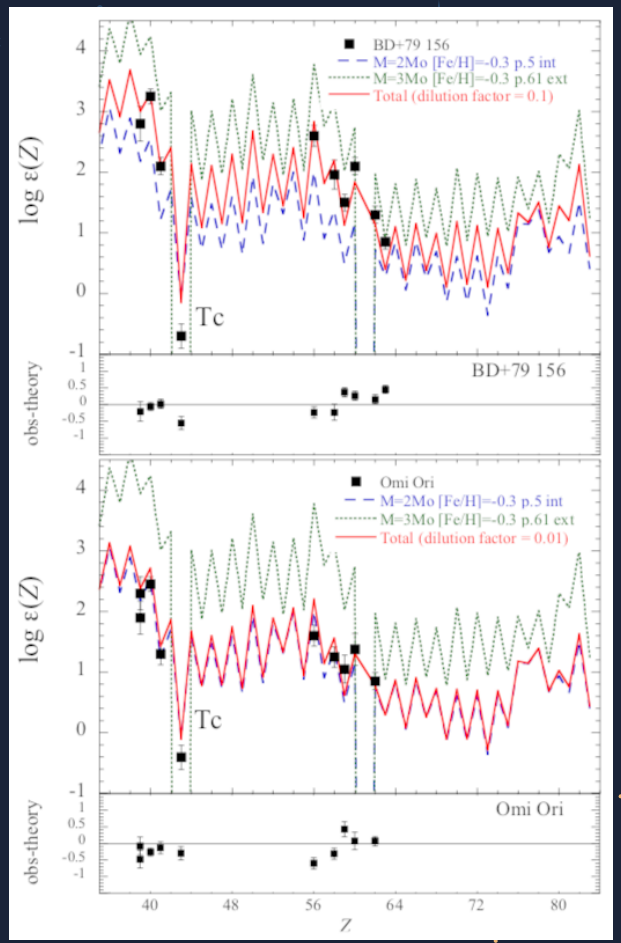




Shetye et al. 2021

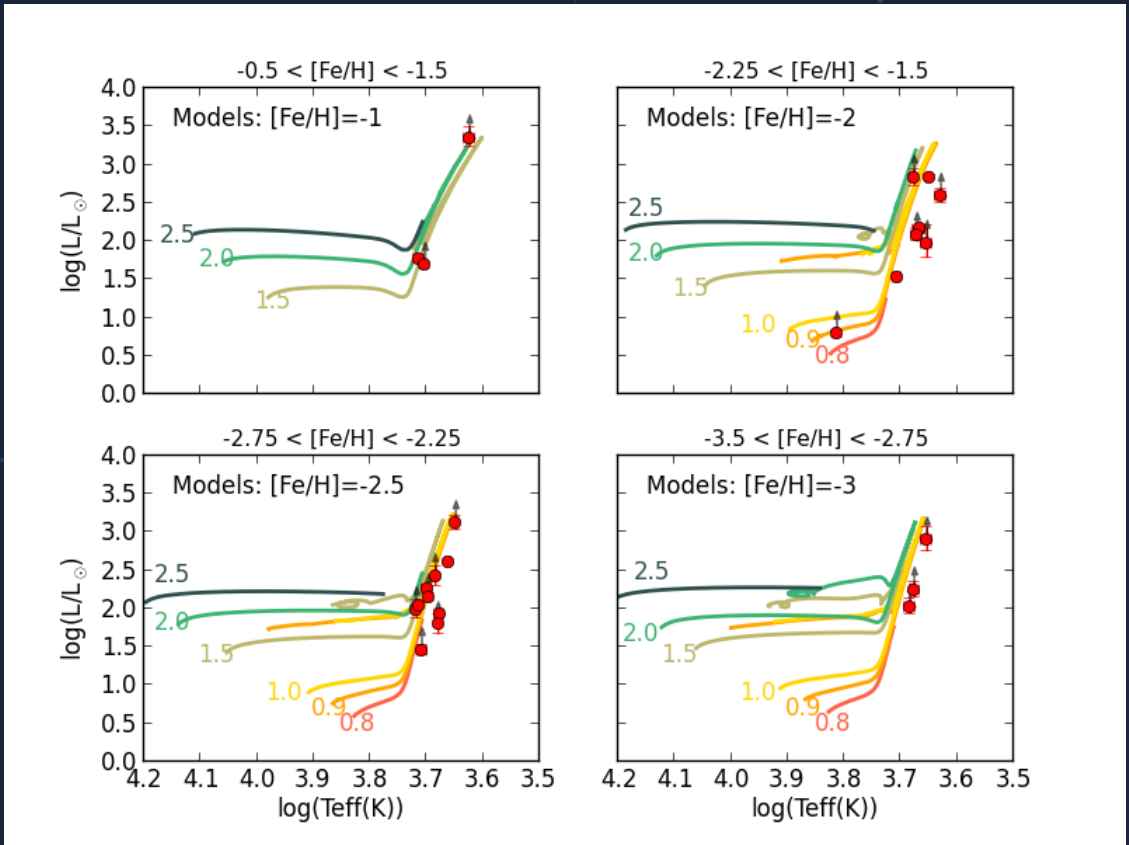
Two words of caution

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



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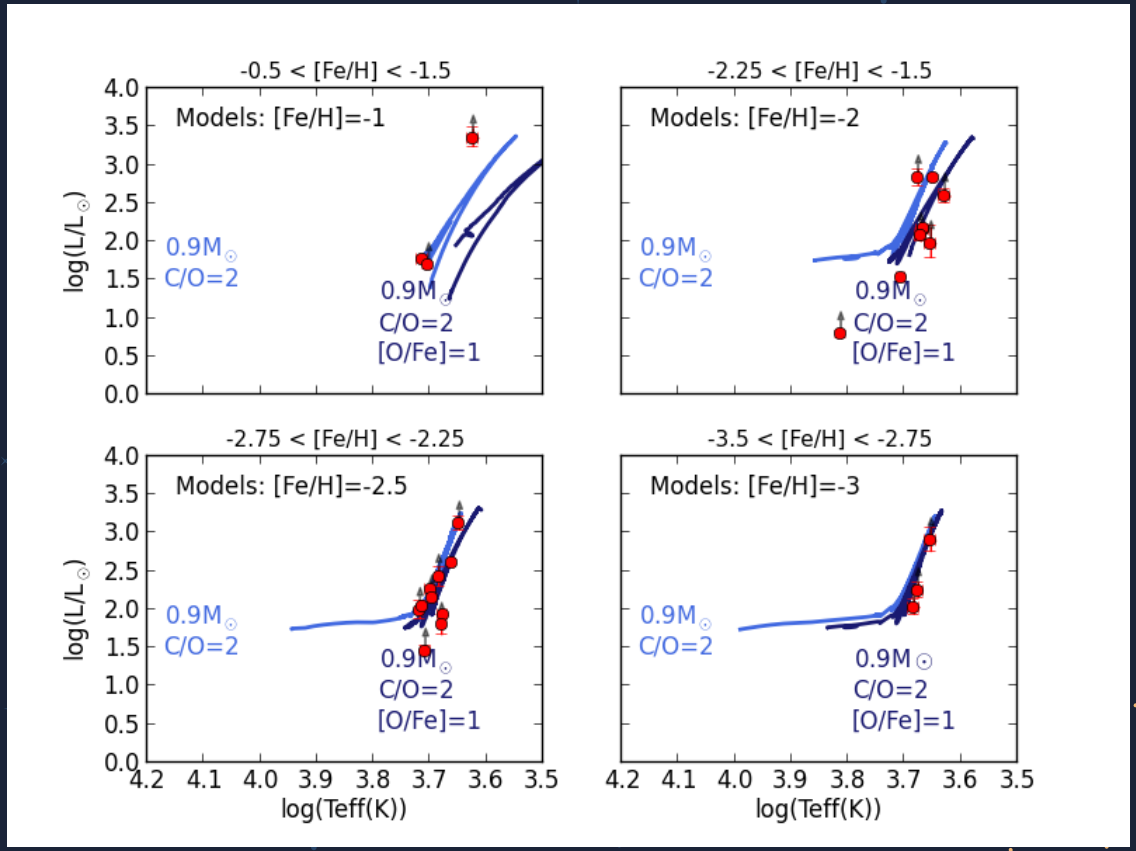


2. Machine-learning s-process line identification

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

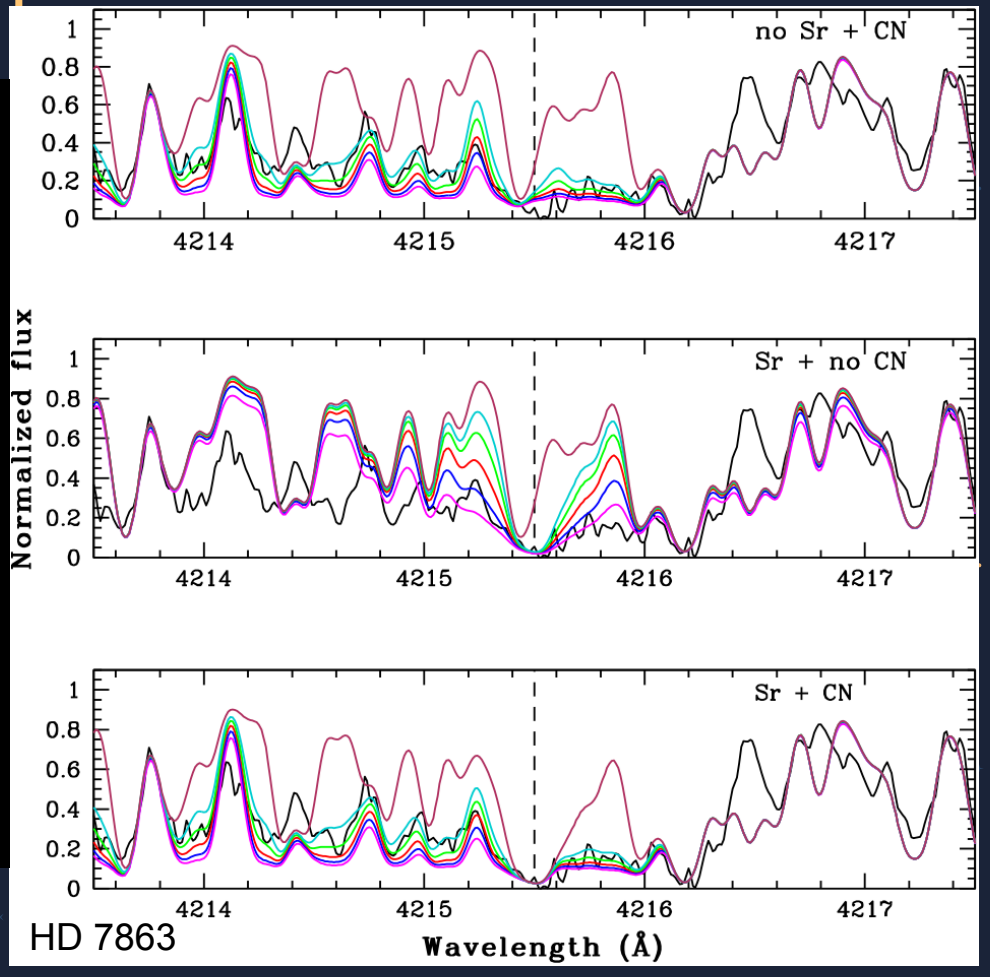
HERMES@Mercator spectra

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

Karinkuzhi et al. 2021

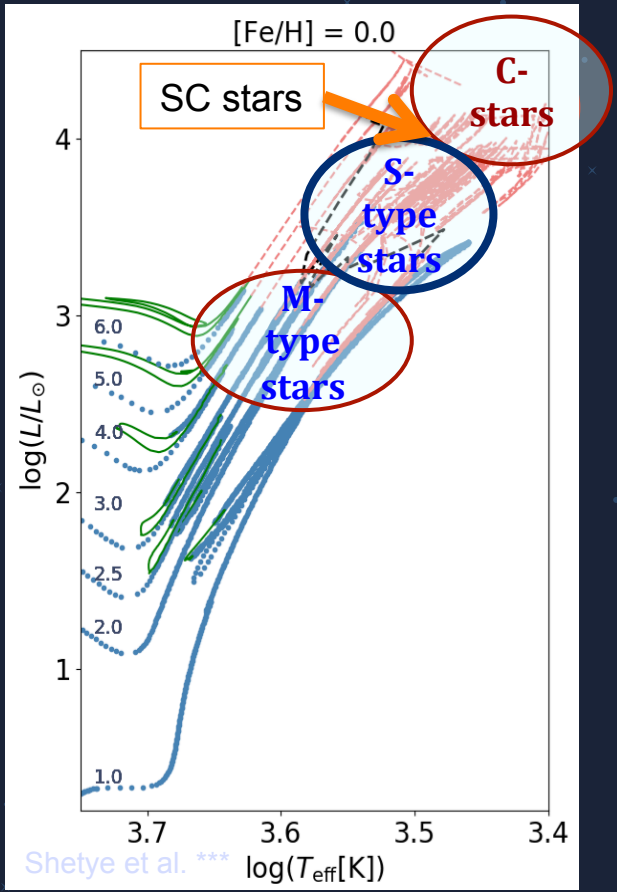


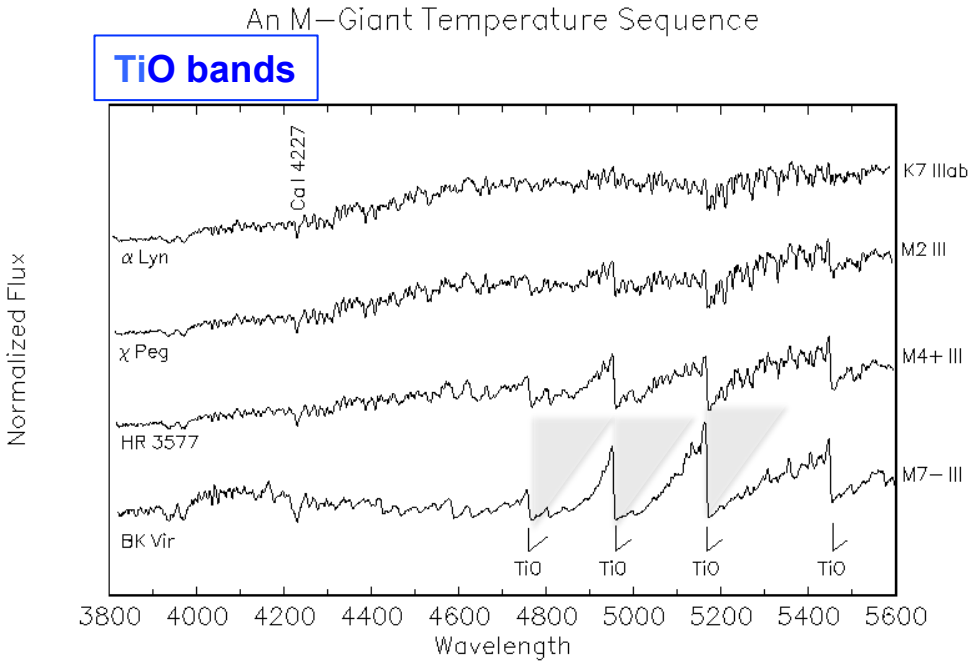
Some open questions

1. Tc-rich M stars

INTRINSIC STARS

Tc-rich M-type stars



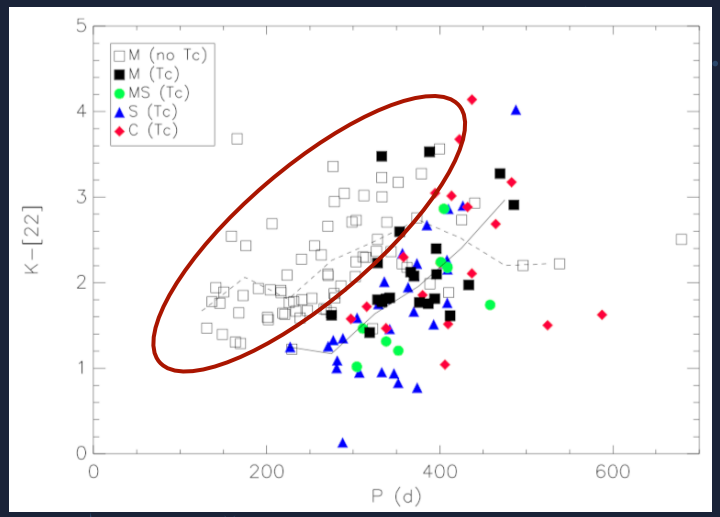


Gray, http://ned.ipac.caltech.edu/level5/Gray/

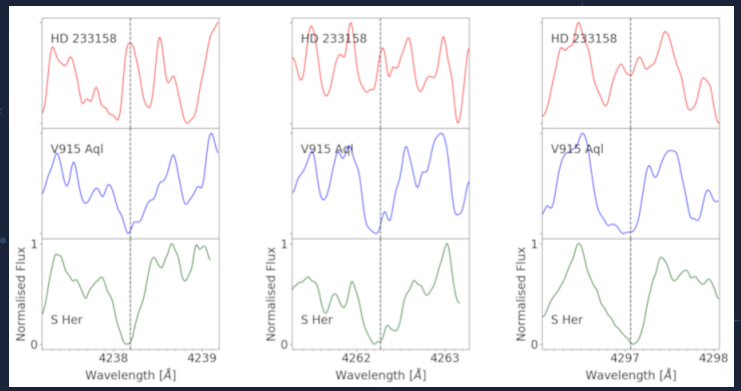
1. Tc-rich M stars

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

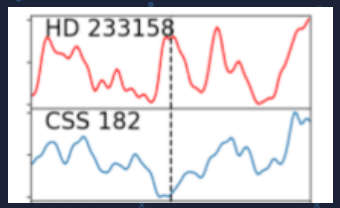
→Only a (few) thermal pulses?
→or a different s-process?

2. Technetium in C stars

Mystery of J-type stars (=^{13}C-rich C stars):

Abia et al. 2020: J-type stars have TP-AGB luminosities →

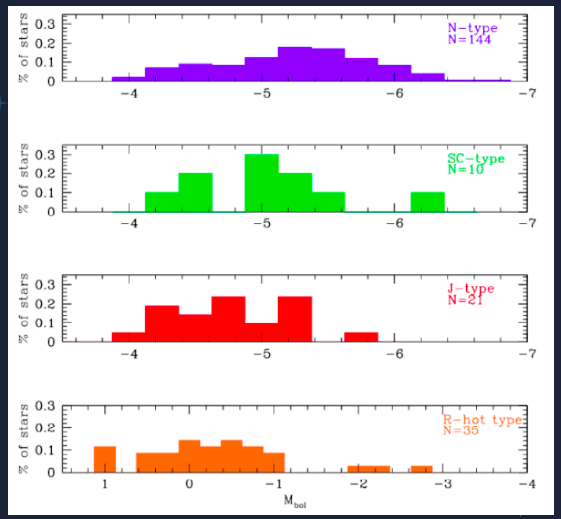
Abia & Isern 2000: 5924A lines: UV Cam, Y CVn, RX Peg: no Tc



No Tc

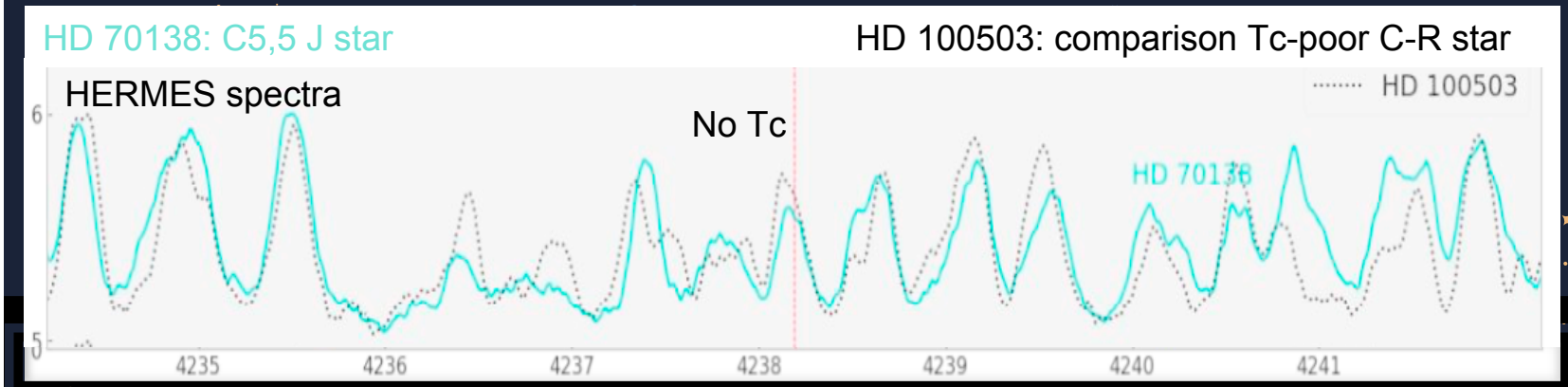
Tc

Shetye 2021



HD 70138: C5,5 J star

HD 100503: comparison Tc-poor C-R star

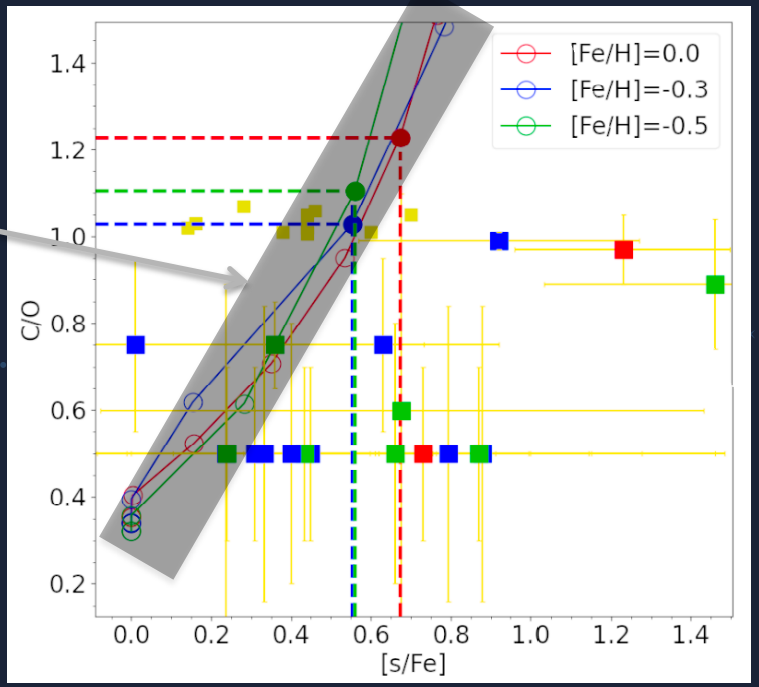


3. s and C increase

INTRINSIC STARS

- Simultaneous increase of s and C

Stellar evolution model (STAREVOL) predictions



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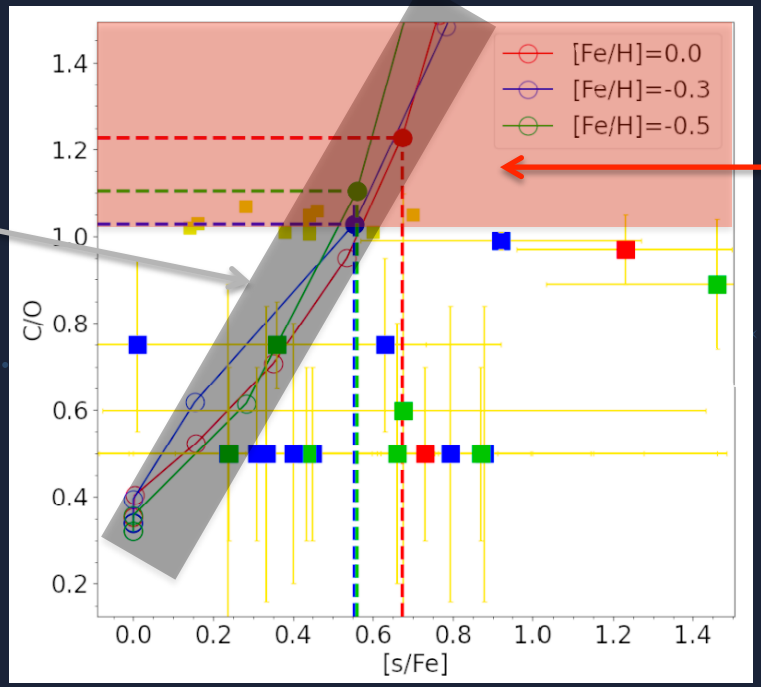


C/O>1

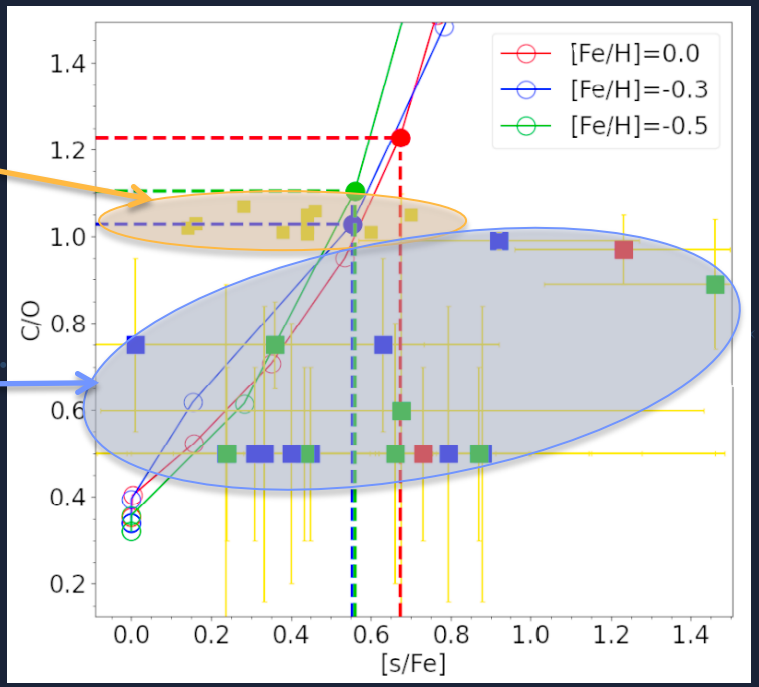
3. s and C increase

INTRINSIC STARS

- Simultaneous increase of s and C

C stars (Abia et al.)

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



3. s and C increase

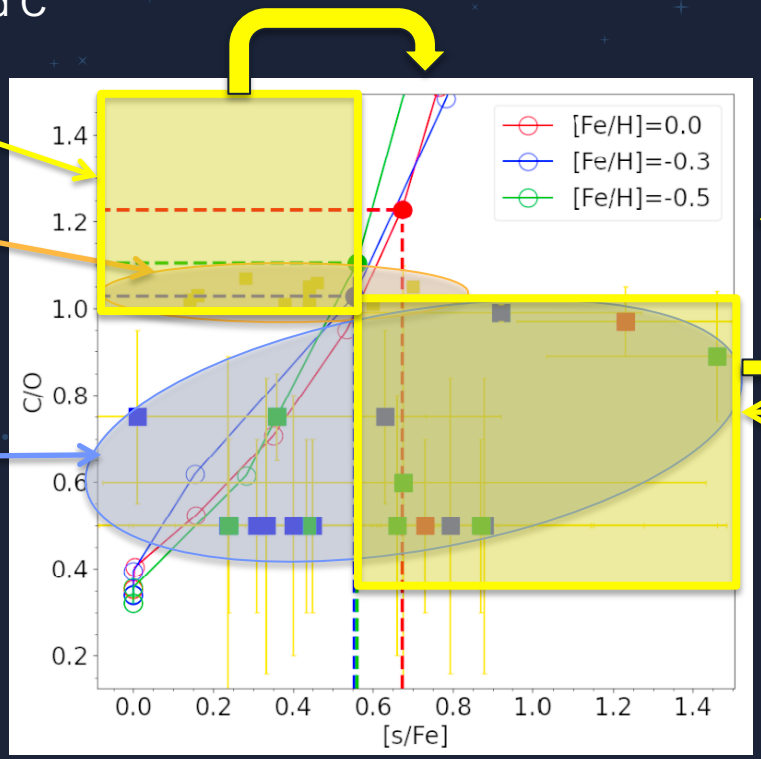
INTRINSIC STARS

- 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

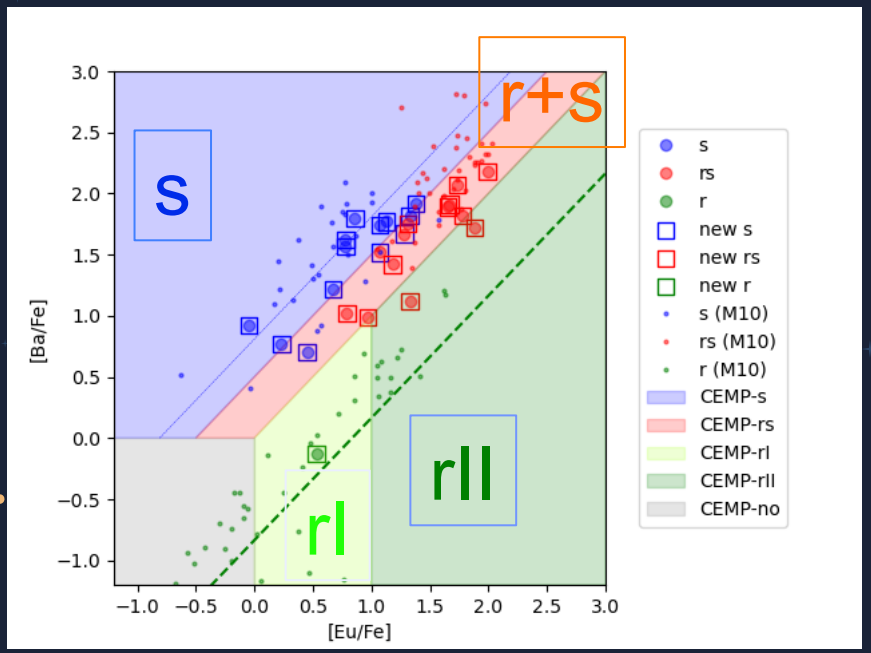
Shetye et al. 2020

4. More extrinsic stars

COLD CASES

CEMP-sr:

- - Binaries
- - Overabundances in s and r elements
- - Classification



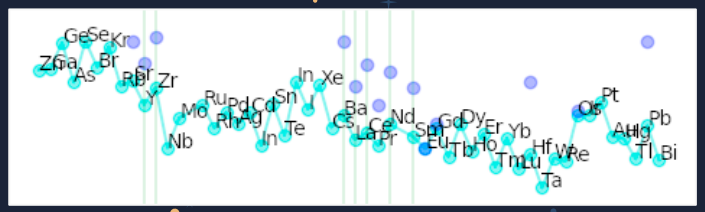
s-process

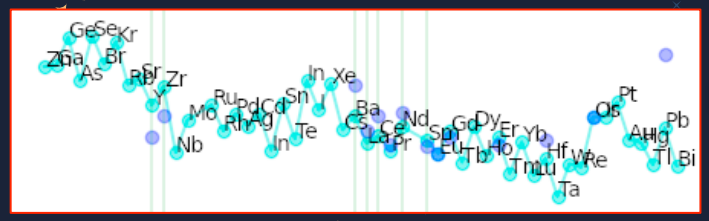
r-process

Karinkuzhi et al., 2021

4. More extrinsic stars

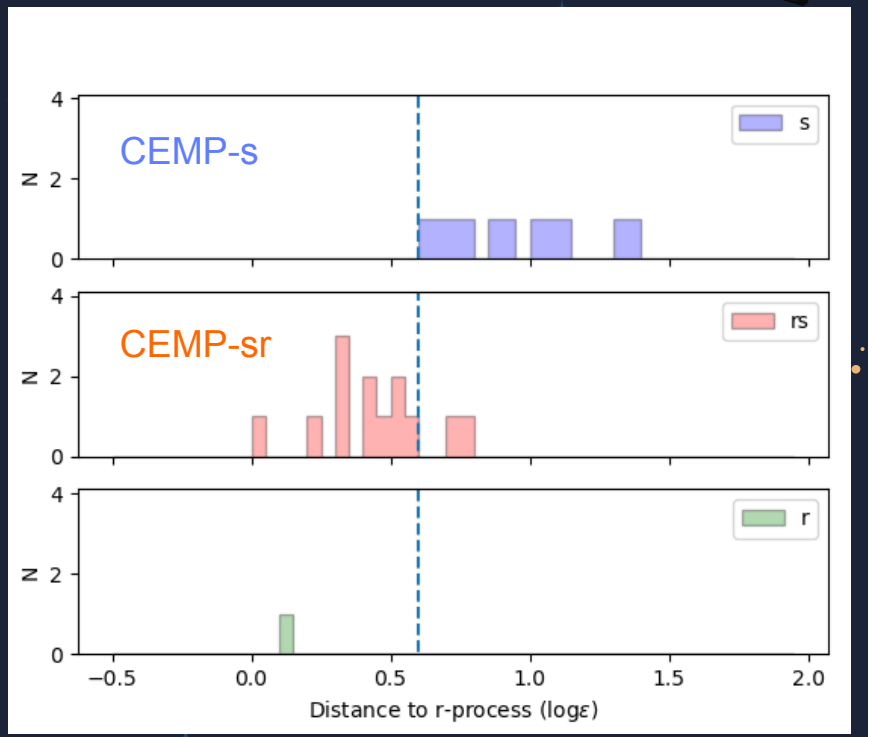
CEMP-sr:
- Classification





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

COLD CASES

CEMP-sr

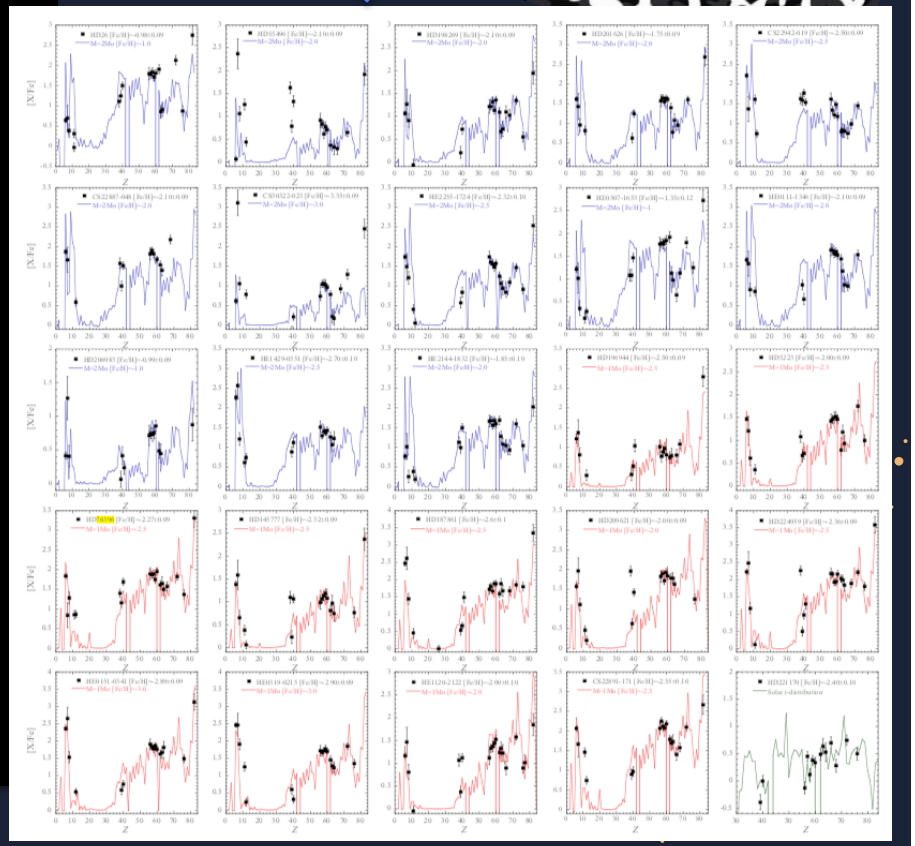
Double event scenario? (Gull et al. 2018)

Or

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

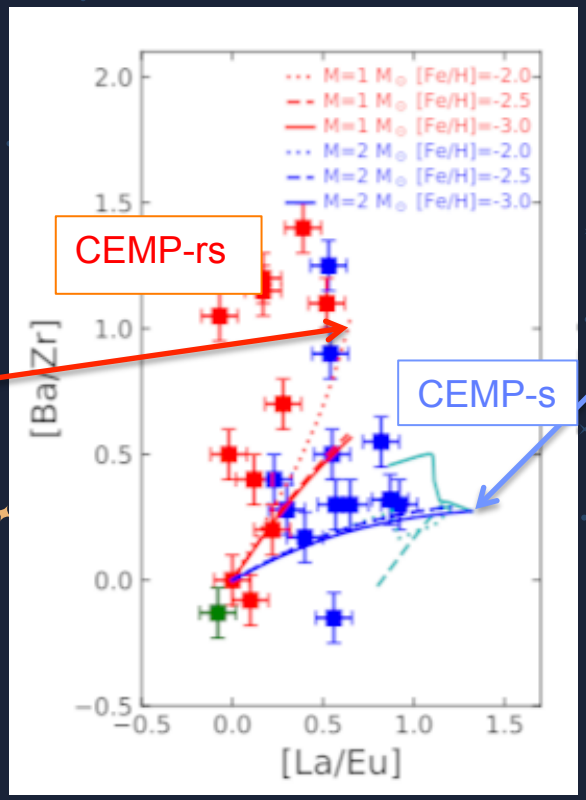
HD 100503: analog to CEMP-rs star
but at [Fe/H]=-0.7
Karinkuzhi et al. 2018

CEMP-rs



4. More extrinsic stars

COLD CASES



CEMP-rs

1 $M_\odot$ models with proton ingestion

CEMP-s

Radiative s-process during interpulse

- 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

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

Perspectives

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

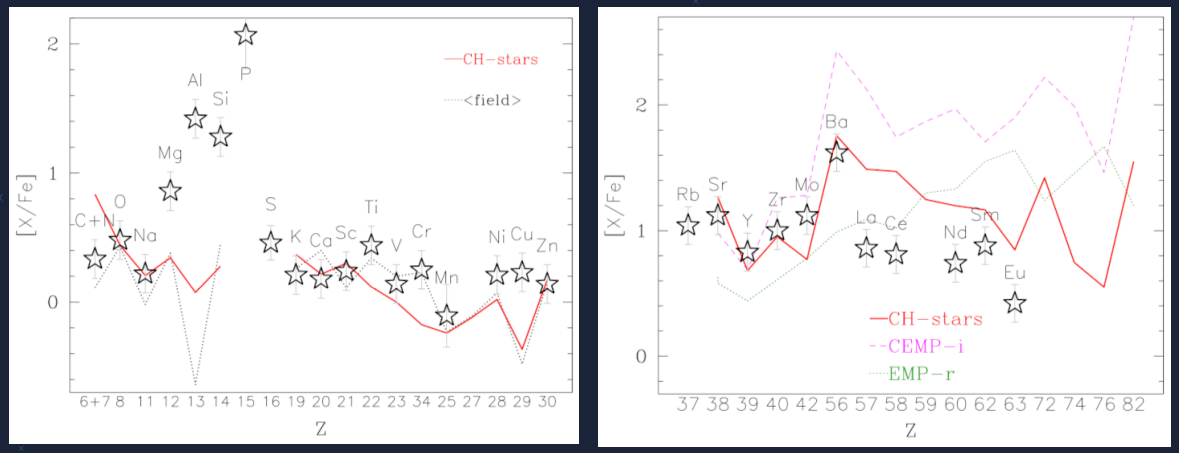
Targets: Mainly 5 types of s (and i ?) -process stars:

- 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

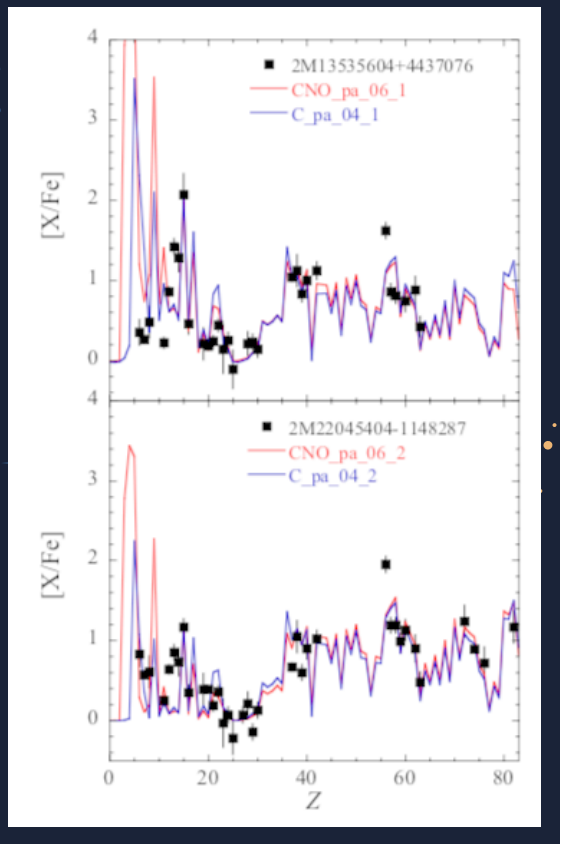
More puzzles to come from surveys

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)