Tracing the Origins of Elements: Insights from AGB and Post-AGB Stars

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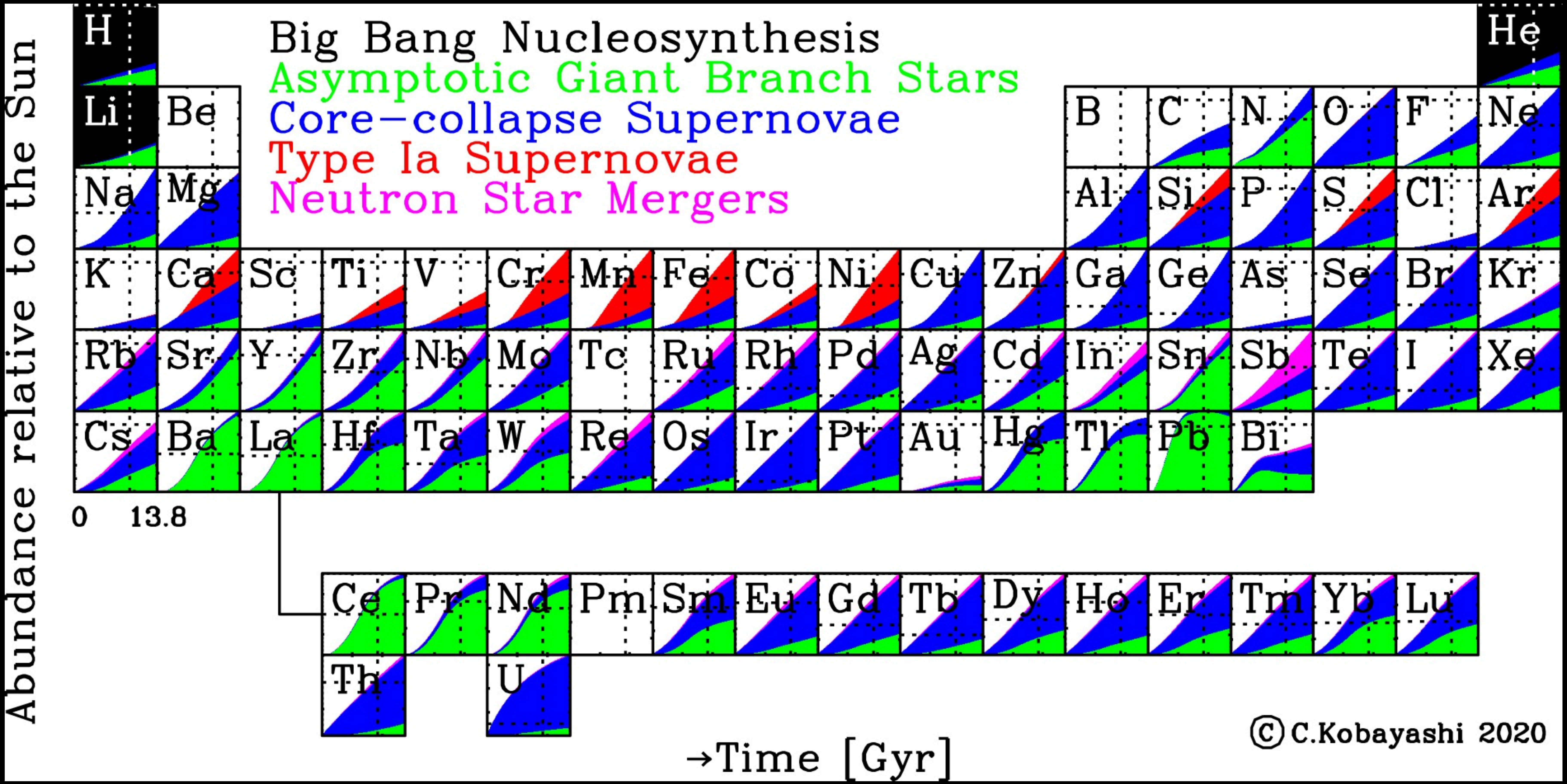
Big Bang Nucleosynthesis
Asymptotic Giant Branch Stars
Core-collapse Supernovae
Type Ia Supernovae
Neutron Star Mergers
Abundance relative to the Sun
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th U
0
13.8
→Time [Gyr]
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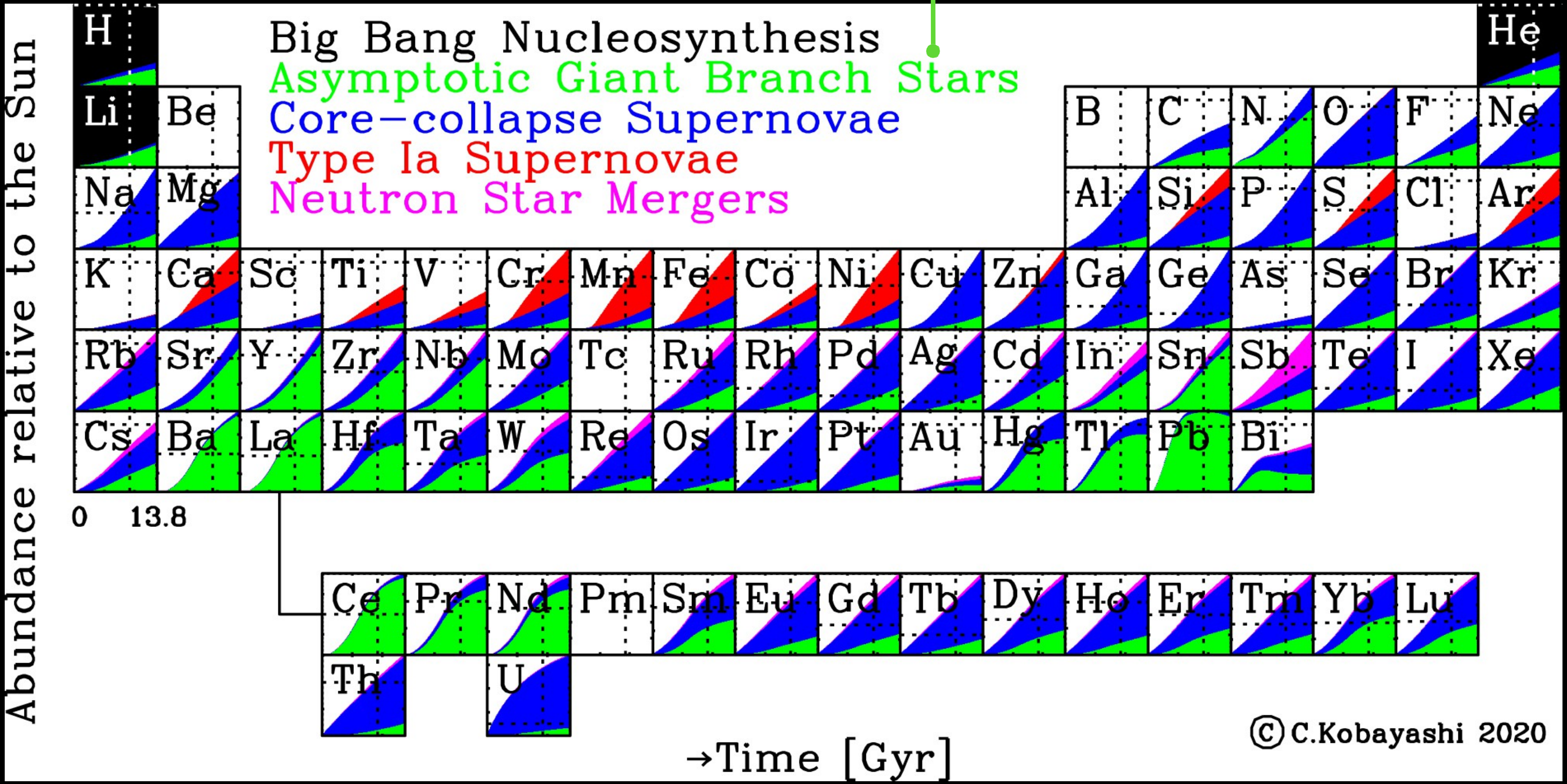
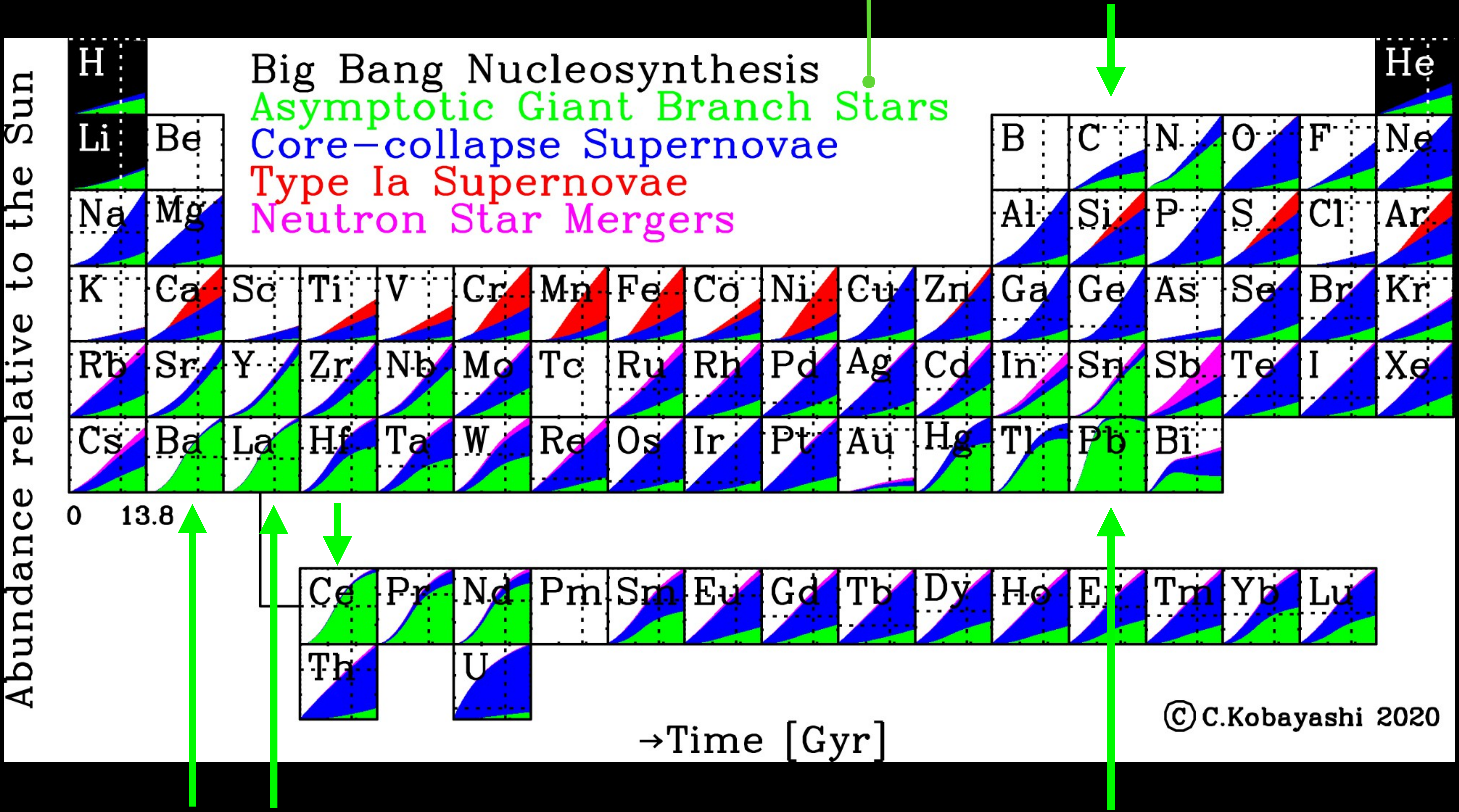
AGB Nucleosynthesis



AGB Nucleosynthesis



Conceptual origin: Burbidge, Burbidge, Fowler & Hoyle (1957), Rev. Mod. Phys., 29, 547 — "Synthesis of the Elements in Stars"

Theoretical Advances in s-Process Nucleosynthesis and AGB Evolution

- **Iben & Truran (1978), ApJ, 220, 980**
  First models of neutron-capture nucleosynthesis in AGB stars
- **Gallino, Busso & Lugaro (1998), ApJ, 497, 388**
  Role of the 13C pocket; modelling of the main s-process component
- **Busso, Gallino & Wasserburg (1999), ARA&A, 37, 239**
  Comprehensive review of AGB nucleosynthesis
- **Lattanzio & Wood (2003), in *Asymptotic Giant Branch Stars*, Habing & Olofsson (eds.)**
  AGB evolution, third dredge-up, hot bottom burning, structural evolution
- **Straniero, Gallino & Cristallo (2006), Nucl. Phys. A, 777, 311**
  Origin of the strong s-process component in low-metallicity AGB stars
- **Karakas & Lattanzio (2007), PASA, 24, 103**
  AGB yields of light and heavy elements; stellar evolution across mass and metallicity
- **Cristallo, Straniero & Gallino (2009), ApJ, 696, 797**
  First full AGB stellar models with detailed s-process yields
- **Karakas & Lattanzio (2014), PASA, 31, e030**
  Updated review of AGB nucleosynthesis and stellar evolution models

Modelling of Intermediate Mass AGB Stars and Hot Bottom Burning

- **Ventura & D'Antona (2005), A&A, 431, 279**
  Modelling of hot bottom burning in massive AGB stars
- **Ventura et al. 2013, MNRAS, 431, 3642)**
  Advanced models of HBB and nucleosynthesis in intermediate-mass AGB stars

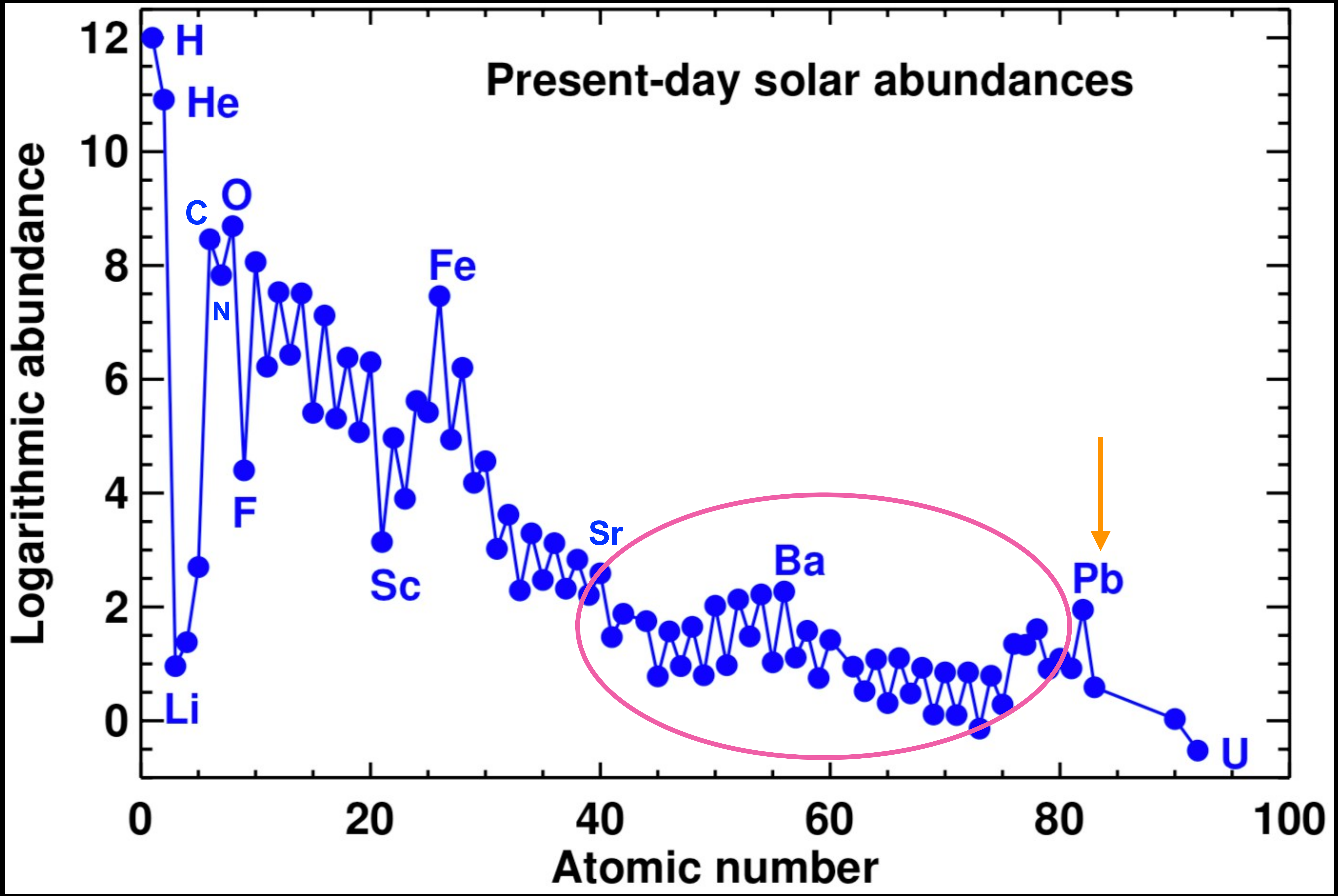
Extra Mixing Processes

- **Boothroyd & Sackmann (1999), ApJ, 510, 232**
  Cool bottom processing (CBP) in low-mass AGB stars
- **Nollett, Busso & Wasserburg (2003), ApJ, 582, 1036**
  Deep mixing and its impact on light-element abundances

Observational Pioneers of Post-AGB Stars as Tracers

- **Lloyd Evans (1985), MNRAS, 217, 493**
  Identification of post-AGB stars as IR-bright evolved objects
- **Waelkens et al. (1991), A&A, 242, 433**
  Spectroscopic studies of post-AGB stars; depletion phenomenon
- **Kwok (1993), ARA&A, 31, 63**
  Post-AGB evolution and chemical signatures in proto-planetary nebulae
- **Kwok & Hrivnak (early 1990s)**
  First systematic observations of post-AGB stars and dusty envelopes
- **Van Winckel (2003), ARA&A, 41, 391**
  Post-AGB stars as tracers of AGB nucleosynthesis and binarity

ORIGINS: CNO, IRON-PEAK, *S*-PROCESS ELEMENTS



Asplund et al., 2021

Weak component: Fe to Sr

- τ ≈ 0.06 mbarn−1
- Massive stars

Main component: Sr to Pb

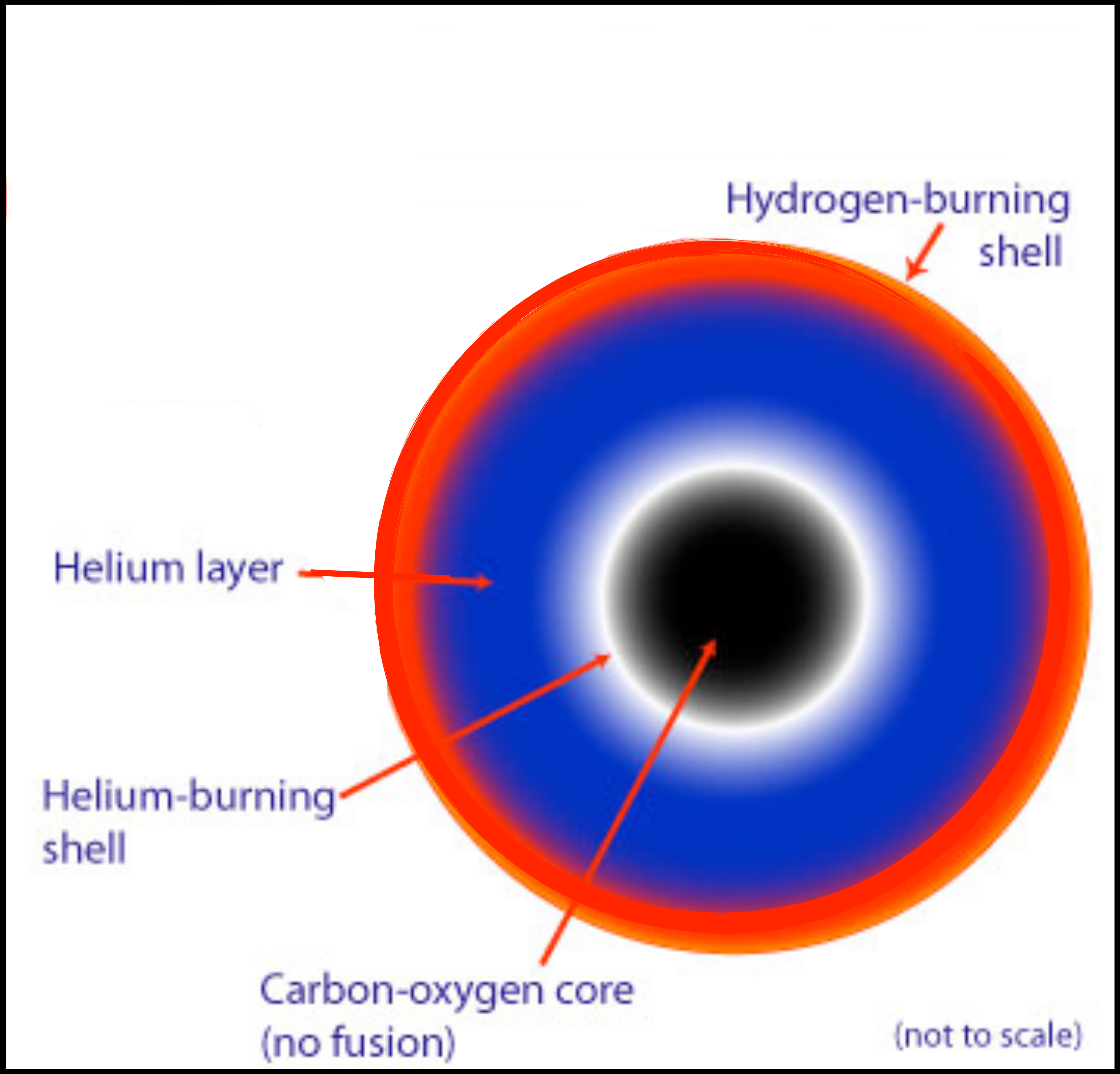
- τ ≈ 0.3 mbarn−1
- **Low-mass AGBs**

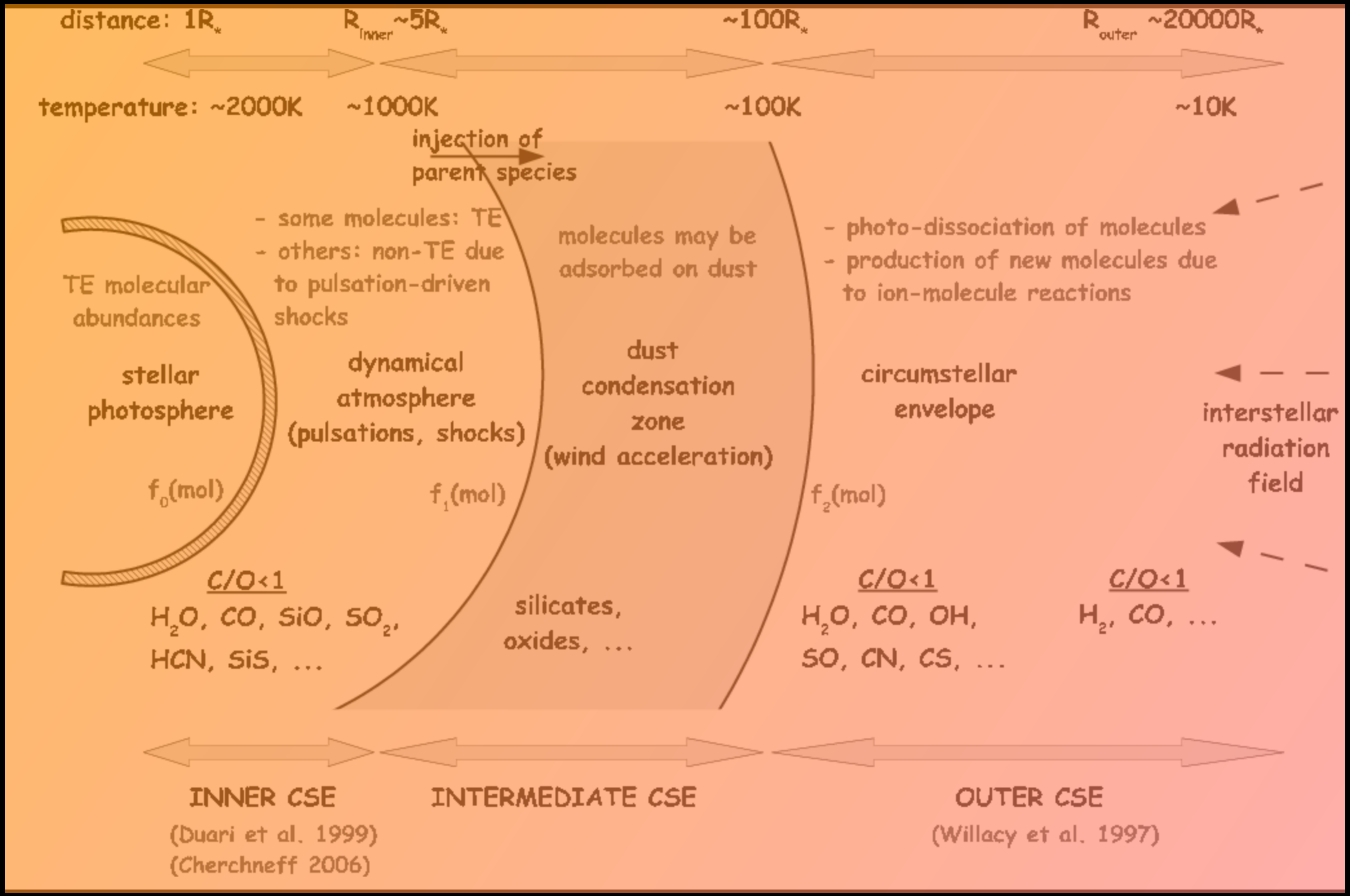
Strong component: Pb

- τ ≈ 7.0 mbarn−1
- **Low-mass, Low-metallicity AGBs**

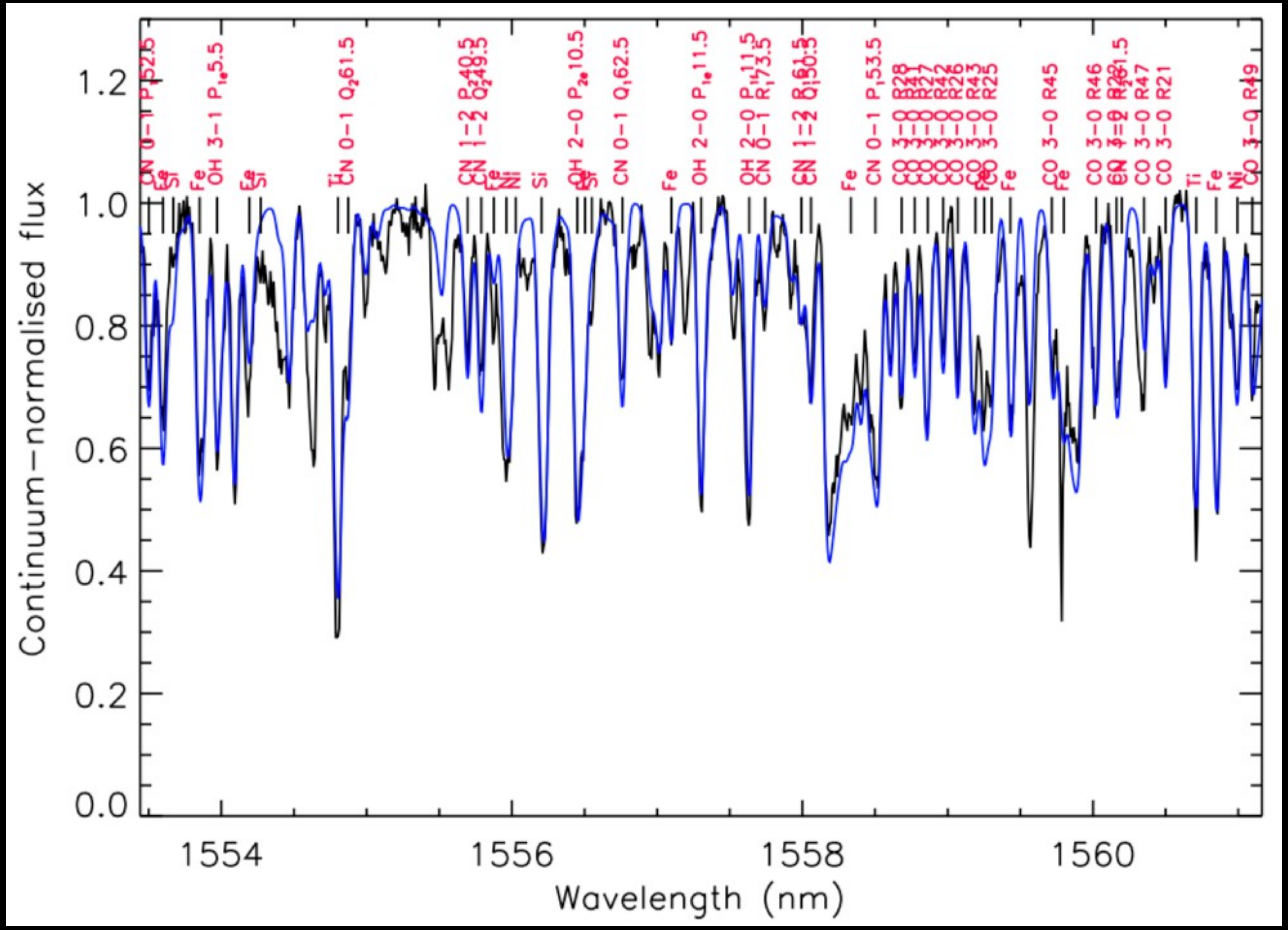
- Tracing AGB Nucleosynthesis Through Post-AGB Observations
- Revealing Chemical Diversity in AGB Nucleosynthesis
- Implications of the Observed Chemical Diversity

AGB Stars as Tracers of AGB Nucleosynthesis

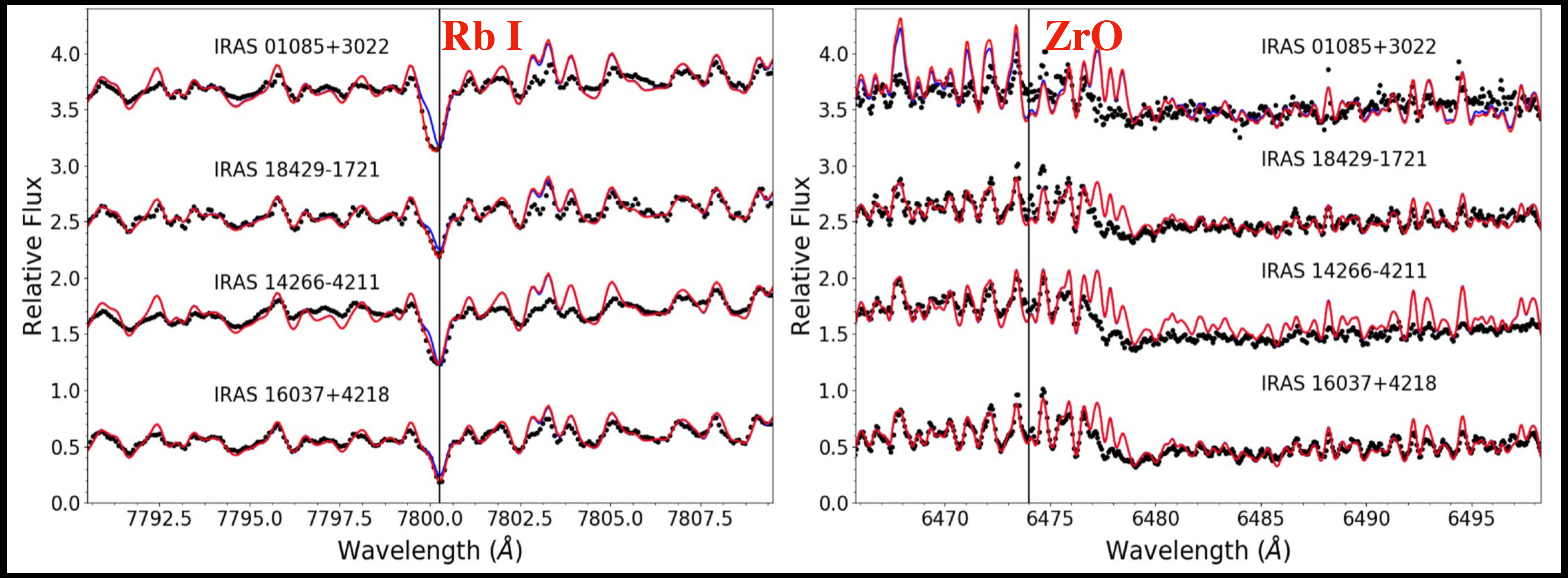




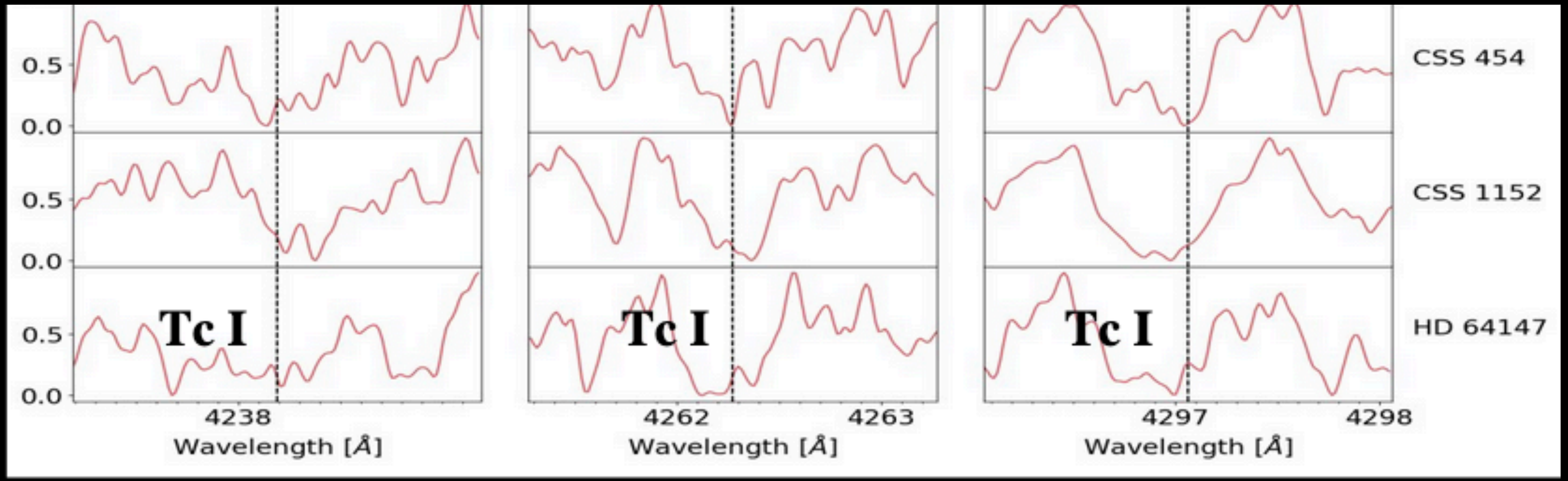
AGB Stars as Tracers of AGB Nucleosynthesis



Uttenthaler et al., 2011

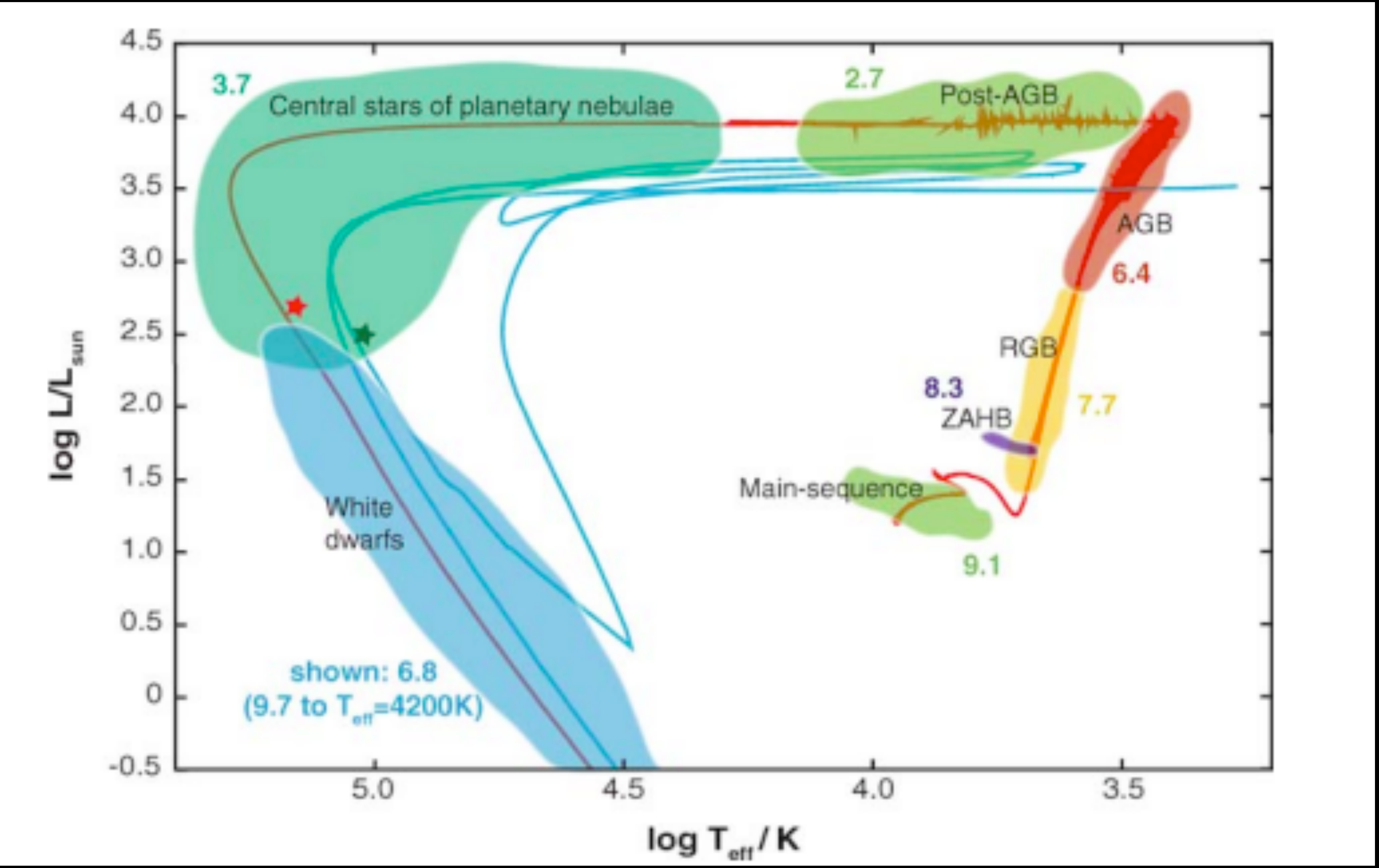


García-Hernández, D. A et al., 2011; 2017



Shyete et al., 2021

Post-AGB Stars as Tracers of AGB Nucleosynthesis

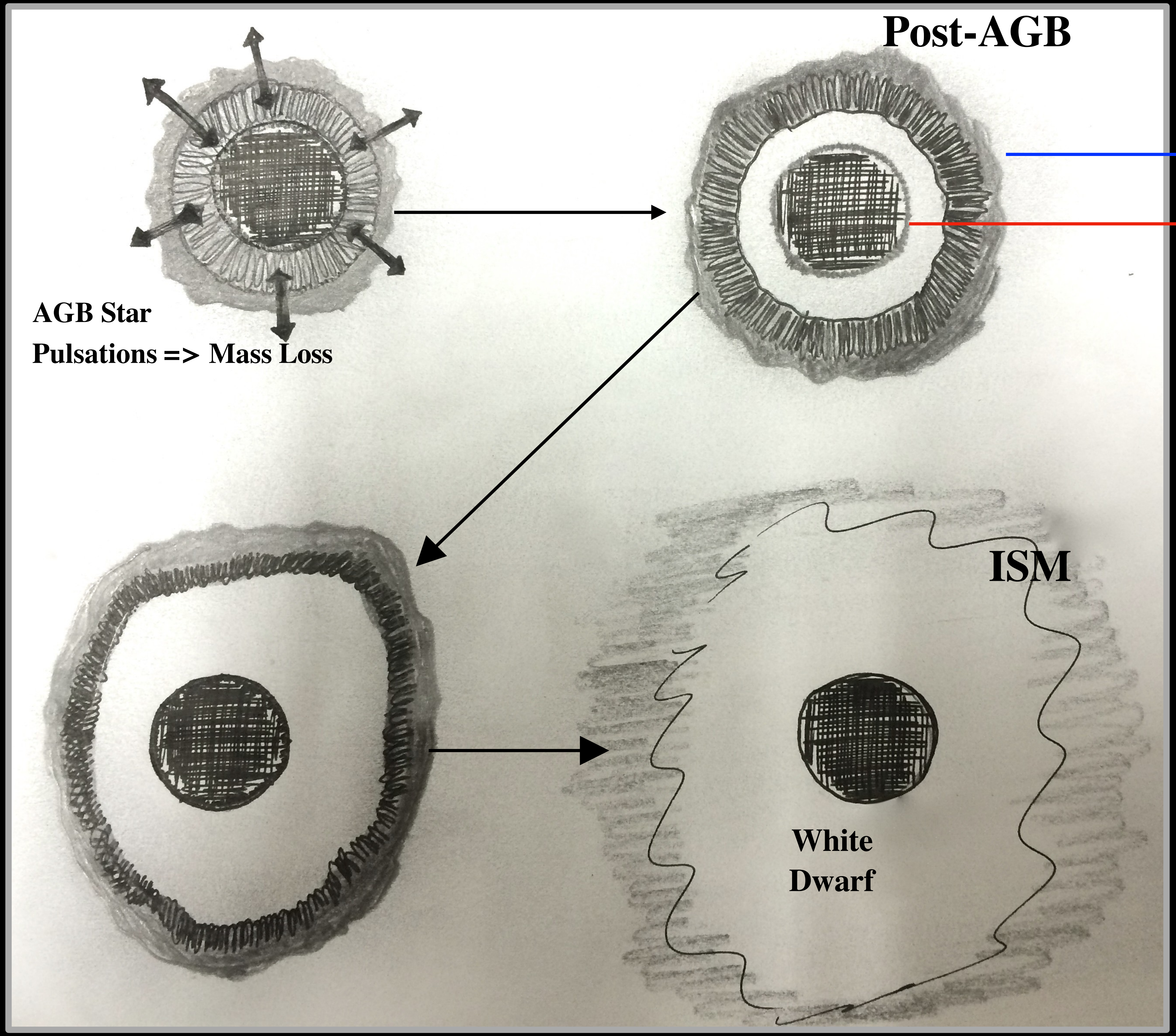


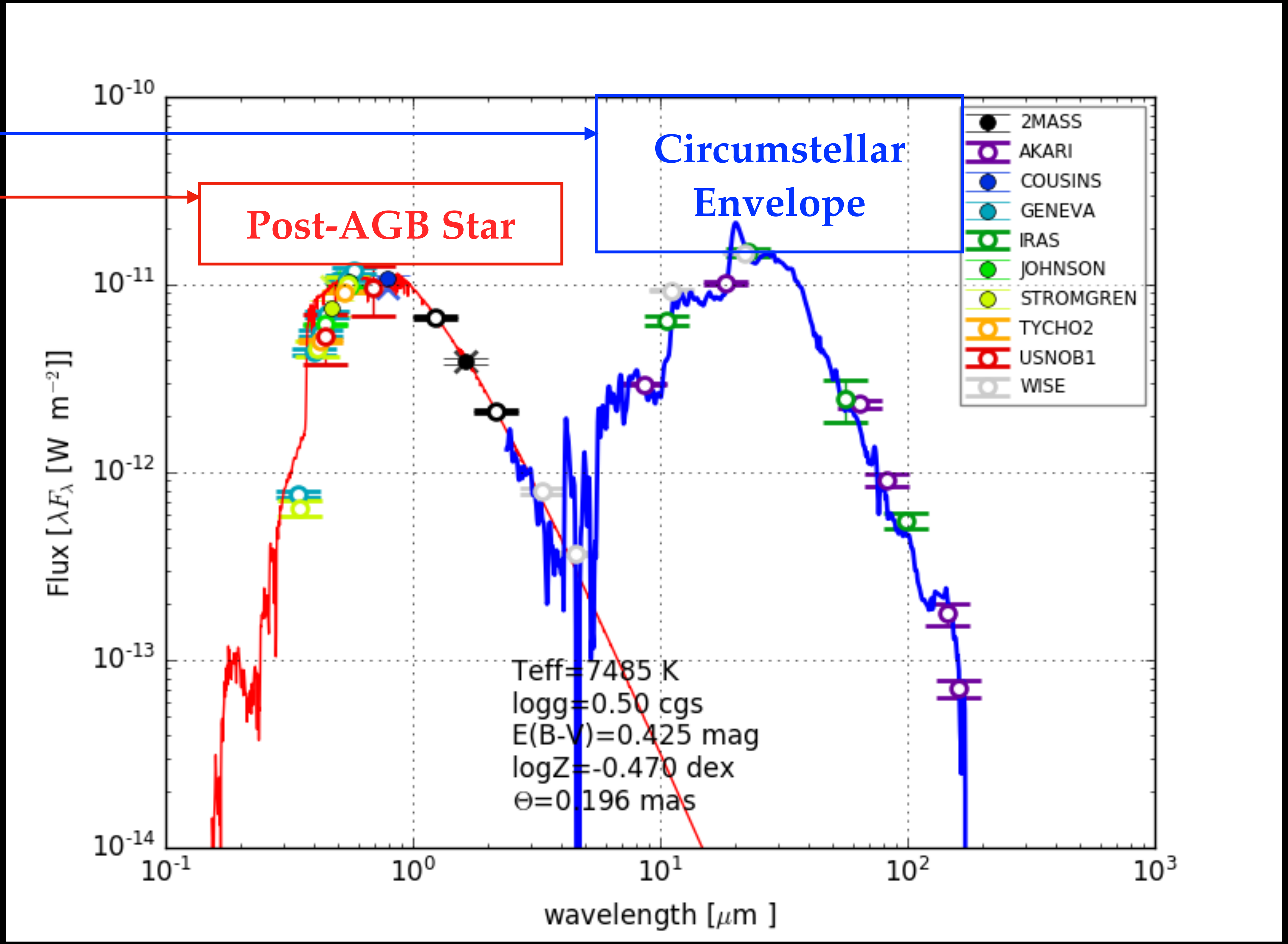
Herwig 2005

Post-AGB Stars as Tracers of AGB Nucleosynthesis

*A-K Spectral Types **
*Low Log g (0 to ~1.5 dex) **
*Low Metallicity **

Single Stars

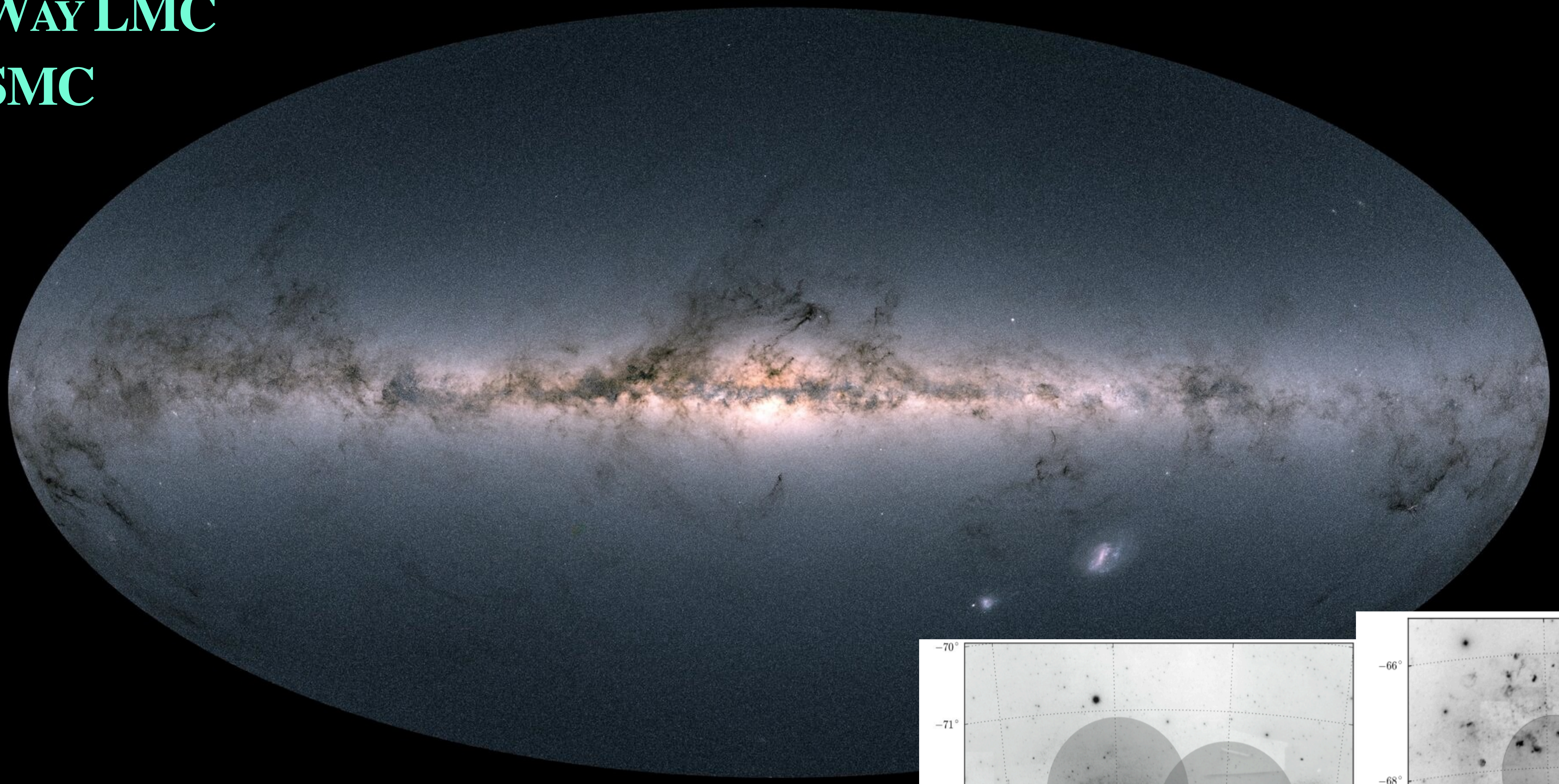


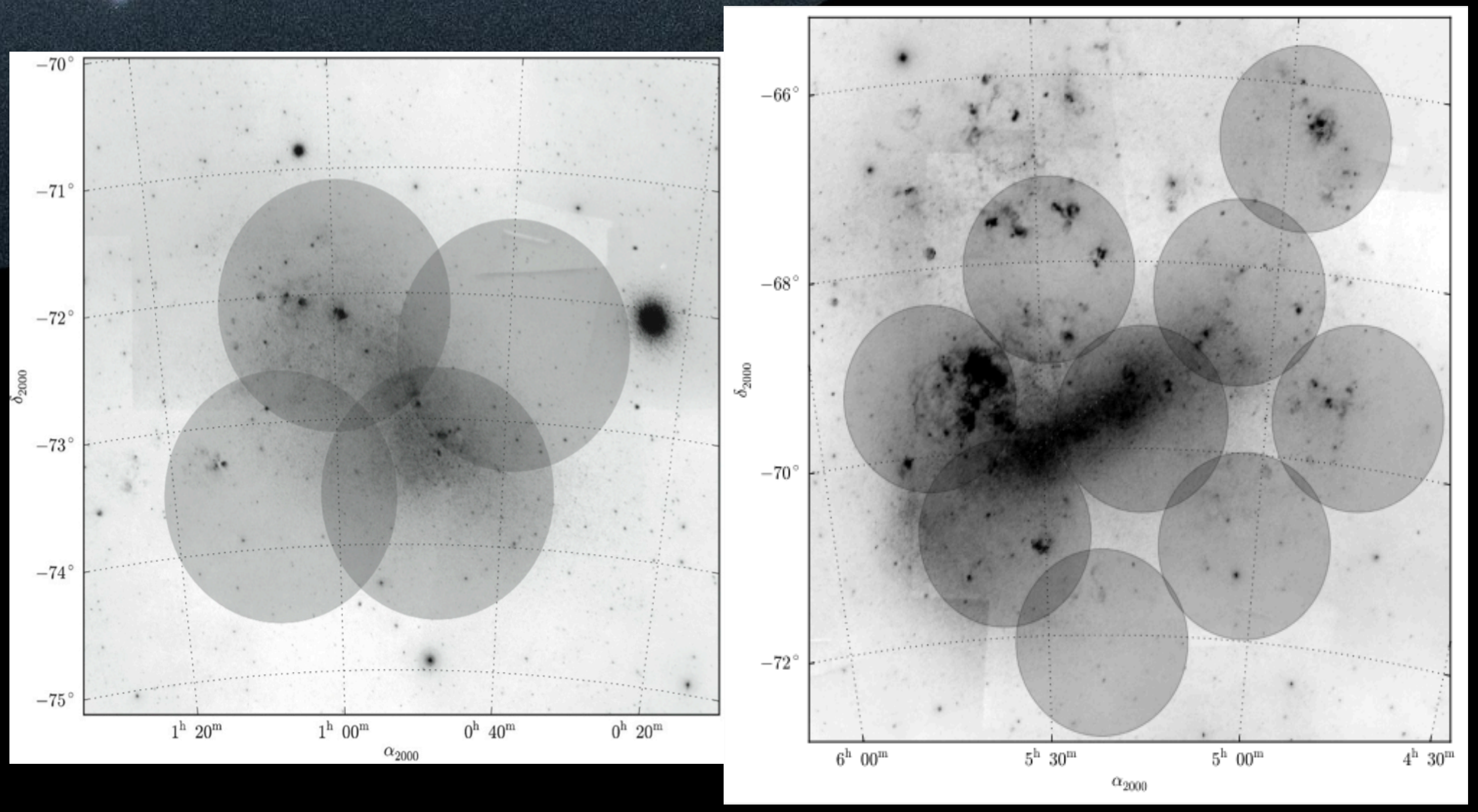


Kwok et al., 1980; Reddy et al., 1999; Bakker et al., 1997; Bakker & Lambert 1998; Van Winckel 2003; Van Winckel et al., 2009; Rao et al., 2012; Sczerba et al., 2009; Kamath et al., 2014, 2015; and all others…

The Hunt for Post-AGB Stars

Milky Way LMC SMC



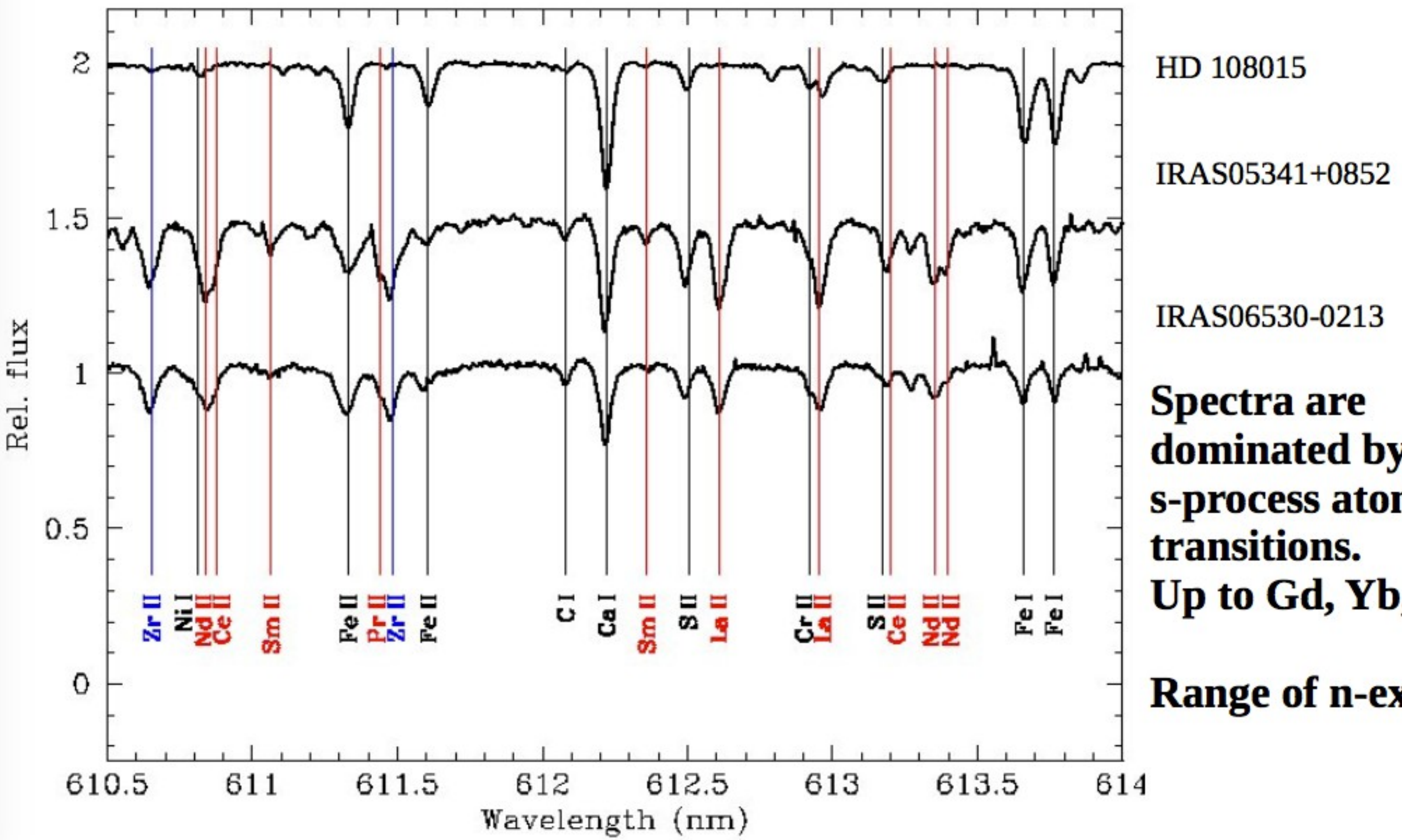


- **Initial Sample: Combination of UV, Optical and IR Photometry**
- **Candidate List: Low-Resolution Spectroscopic Analyses**
- **Final Catalogue: High-resolution Spectroscopic Analyses**

<u>Current Sample:</u>
Galaxy: 300 candidates
LMC: 35 post-AGBs; 120 post-RGBs
SMC: 20 post-AGBs; 30 post-RGBs

Galaxy: Kwok et al., 1980; Van Winckel 2003; Szczerba et al., 2007; Kamath et al., 2022; Kluska et al., 2022
LMC/SMC: Van Aarle et al., 2011; Kamath et al., 2014; 2015

POST-AGB STAR SPECTRA: TRACING SURFACE CHEMICAL SIGNATURES

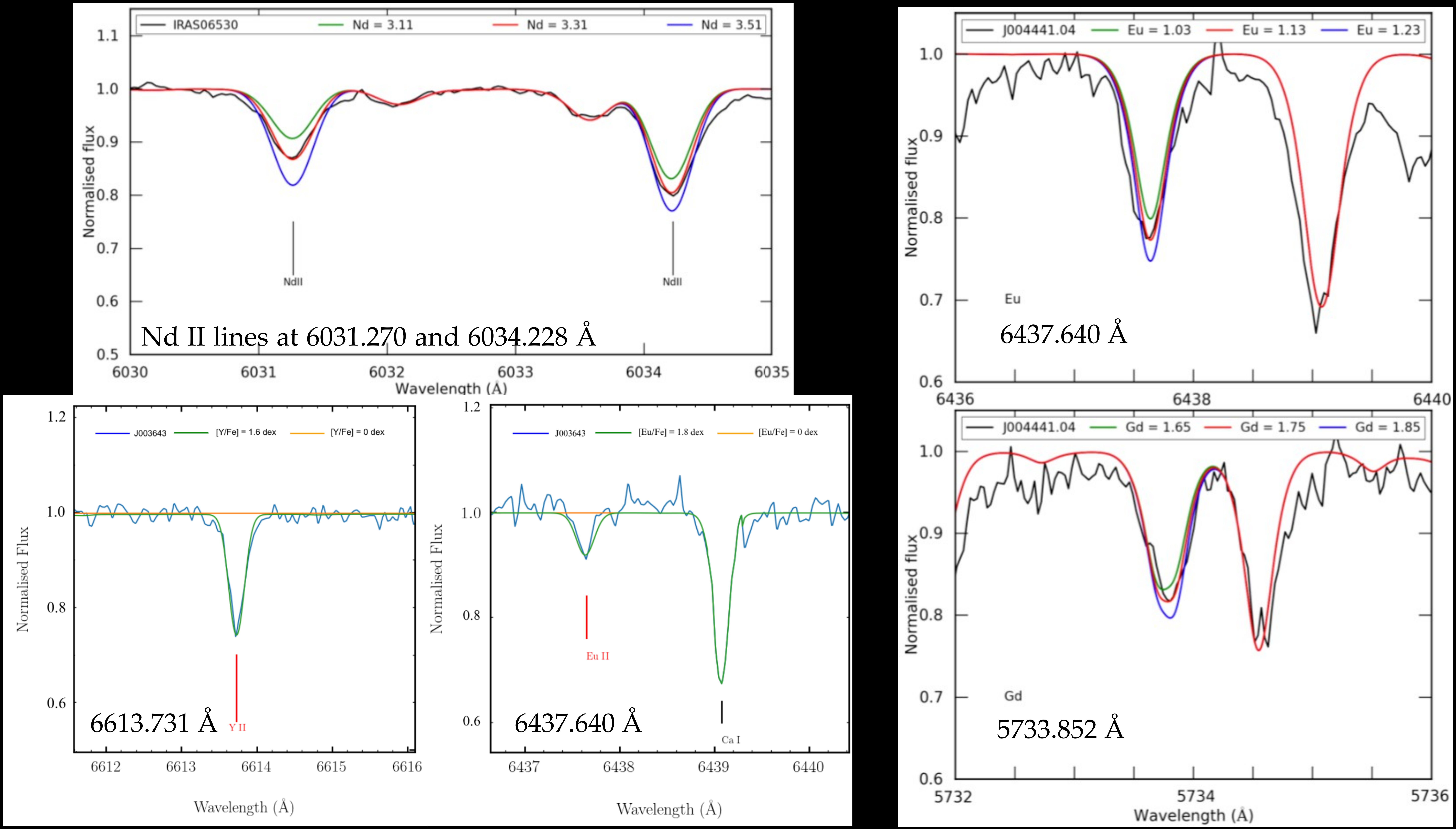


Spectra are dominated by s-process atomic transitions.
Up to Gd, Yb, Lu, W

Range of n-exposures

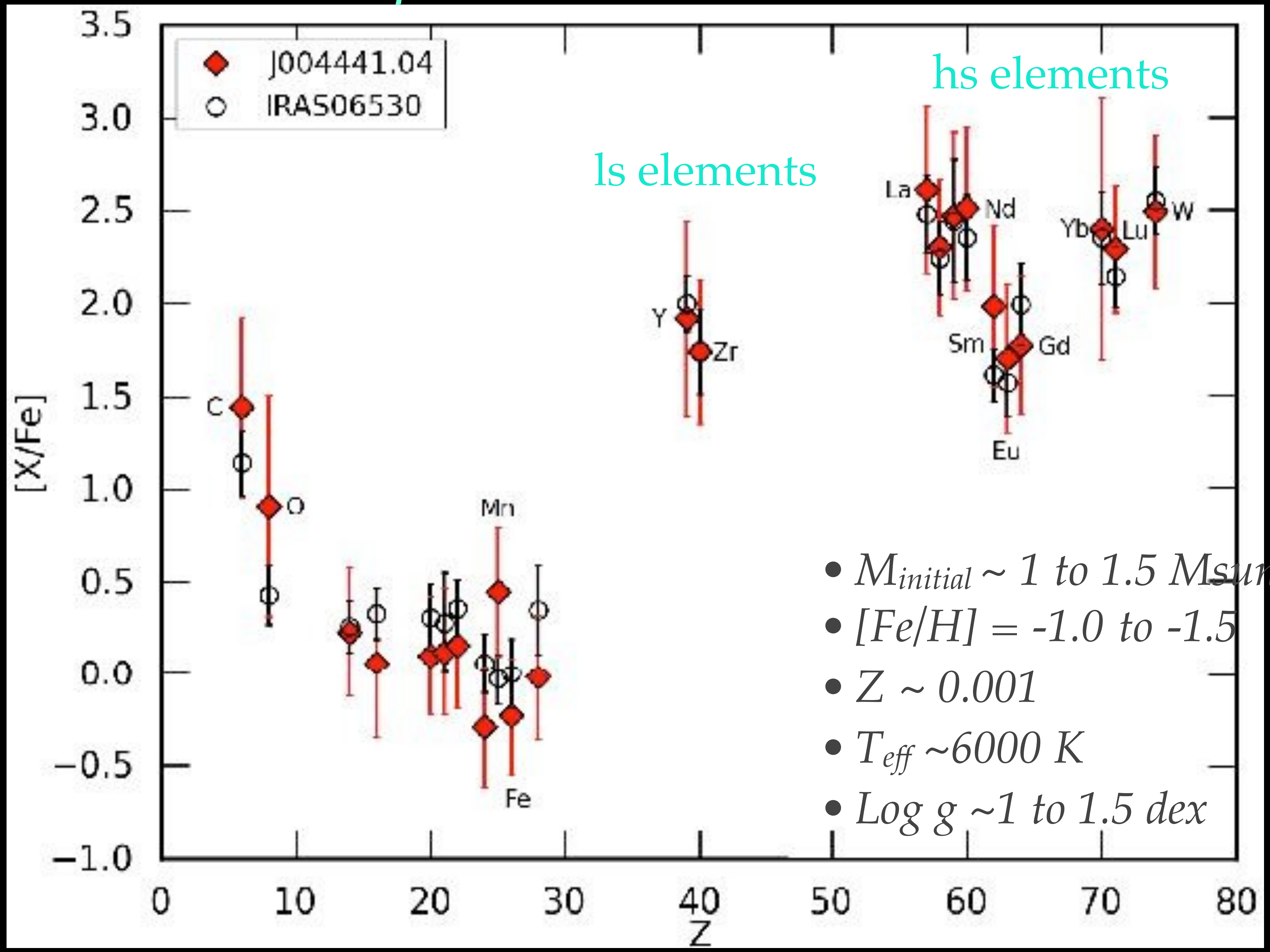
+ Luminosity → *Progenitor Mass*

Post-AGB Star Spectra: Tracing Surface Chemical Signatures

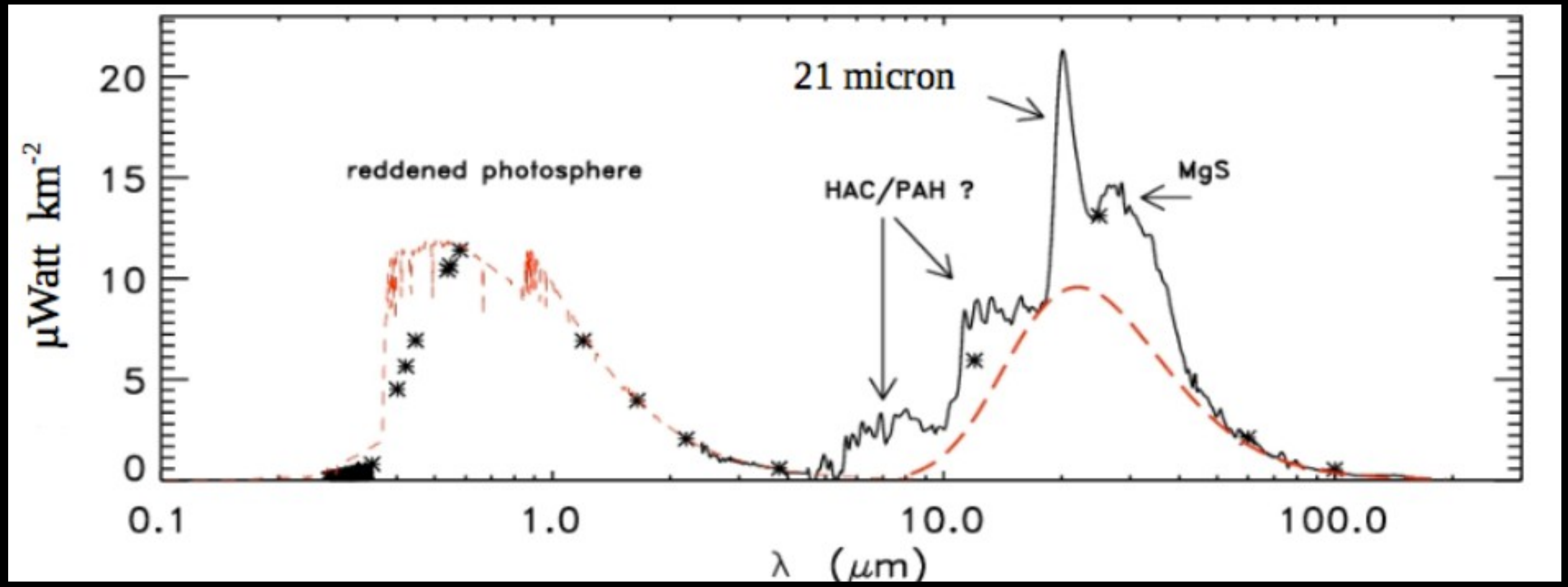


SINGLE POST-AGBS: EXQUISITE TRACERS OF CNO, FE-PEAK & *s*-PROCESS

Carbon and s-process rich stars:



- $M_{initial}$ ~ 1 to 1.5 Msun
- [Fe/H] = -1.0 to -1.5
- Z ~ 0.001
- T_{eff} ~6000 K
- Log g ~1 to 1.5 dex

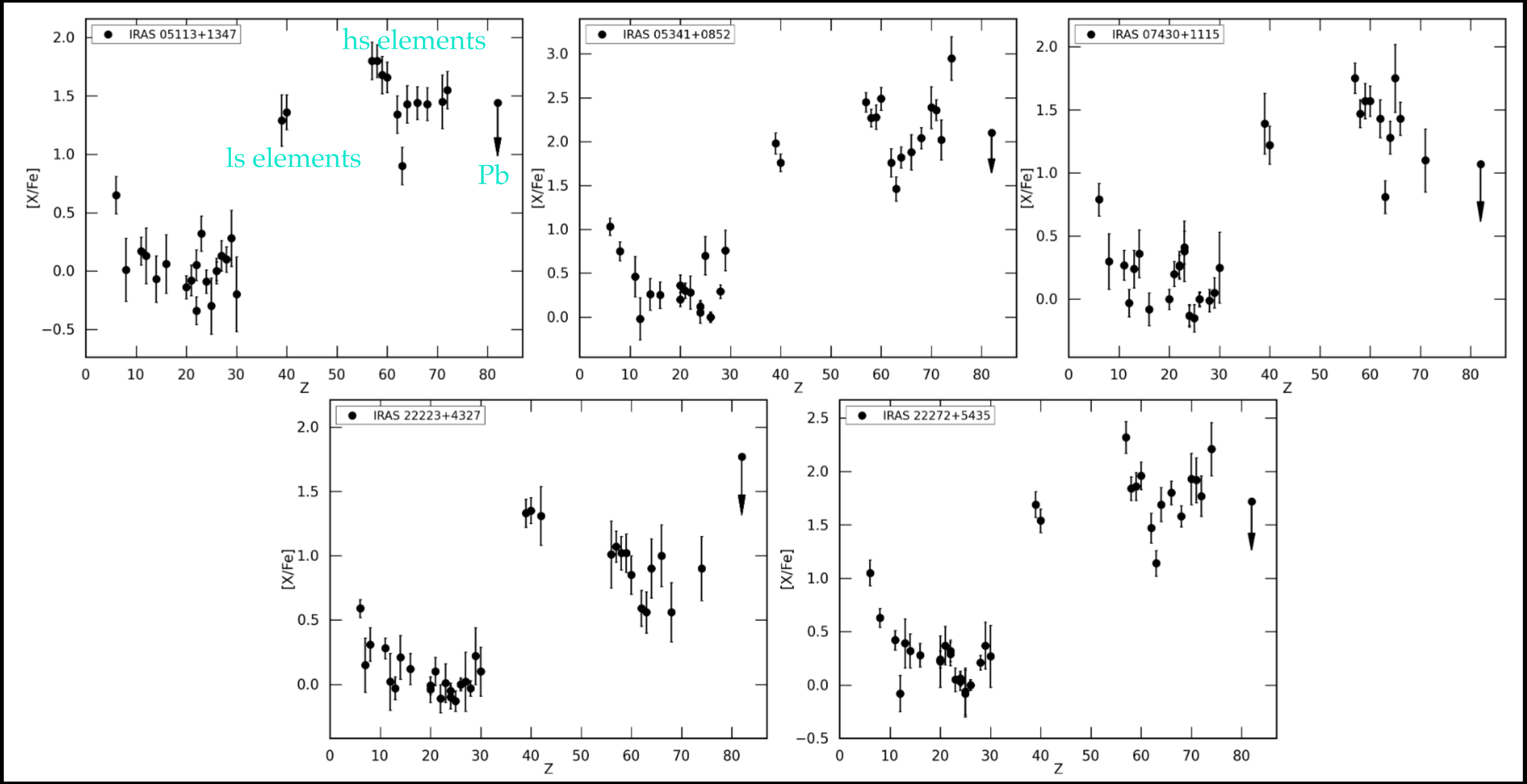


Van Winckel 2003

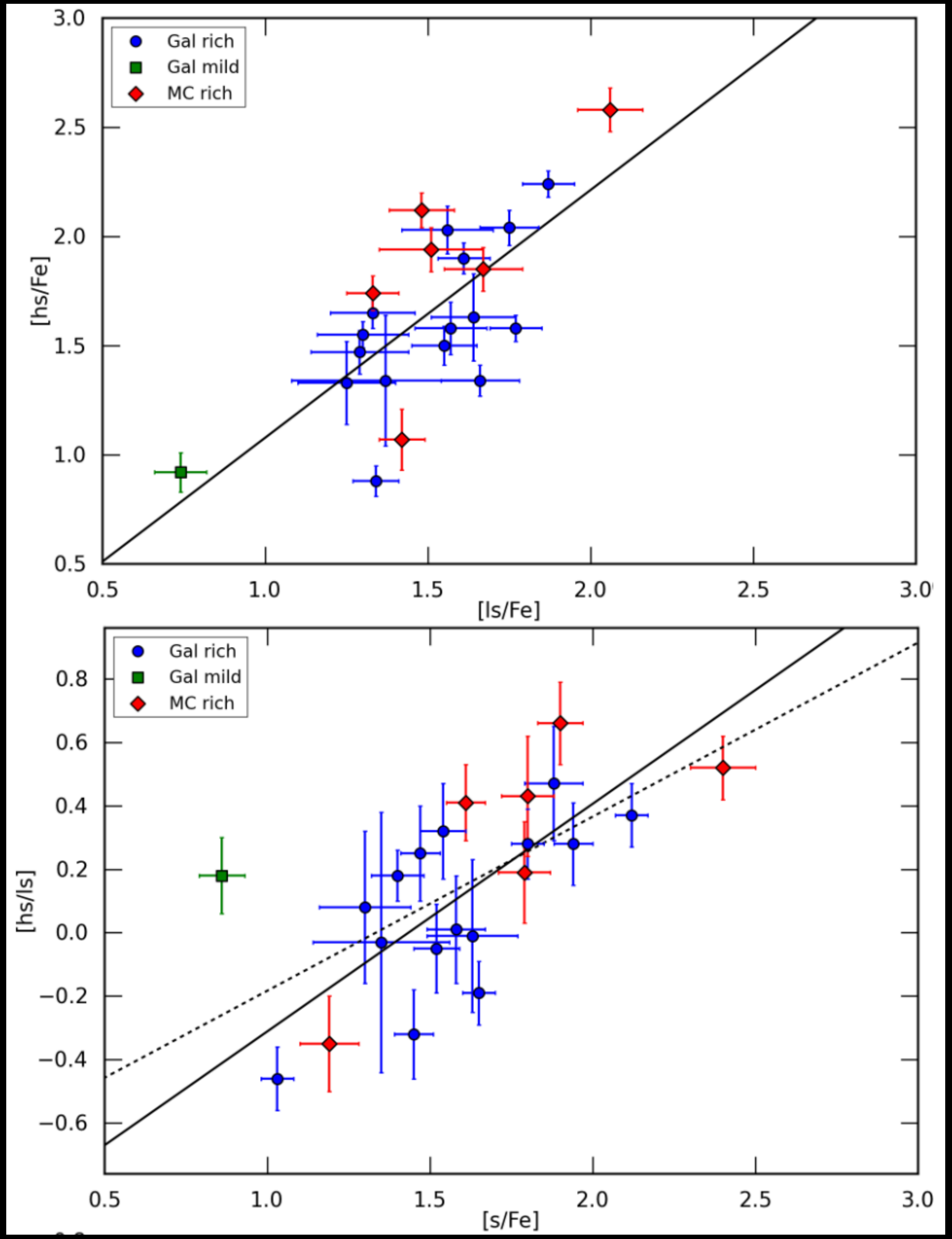
All C-rich and s-process rich post- AGB stars show the 21-micron feature!

e.g., De Smedt et al., 2012, 2015; Kamath et al., 2022; Menon et al., to-be-submitted

Single Post-AGBs: Exquisite Tracers of CNO, Fe-peak & *s*-process



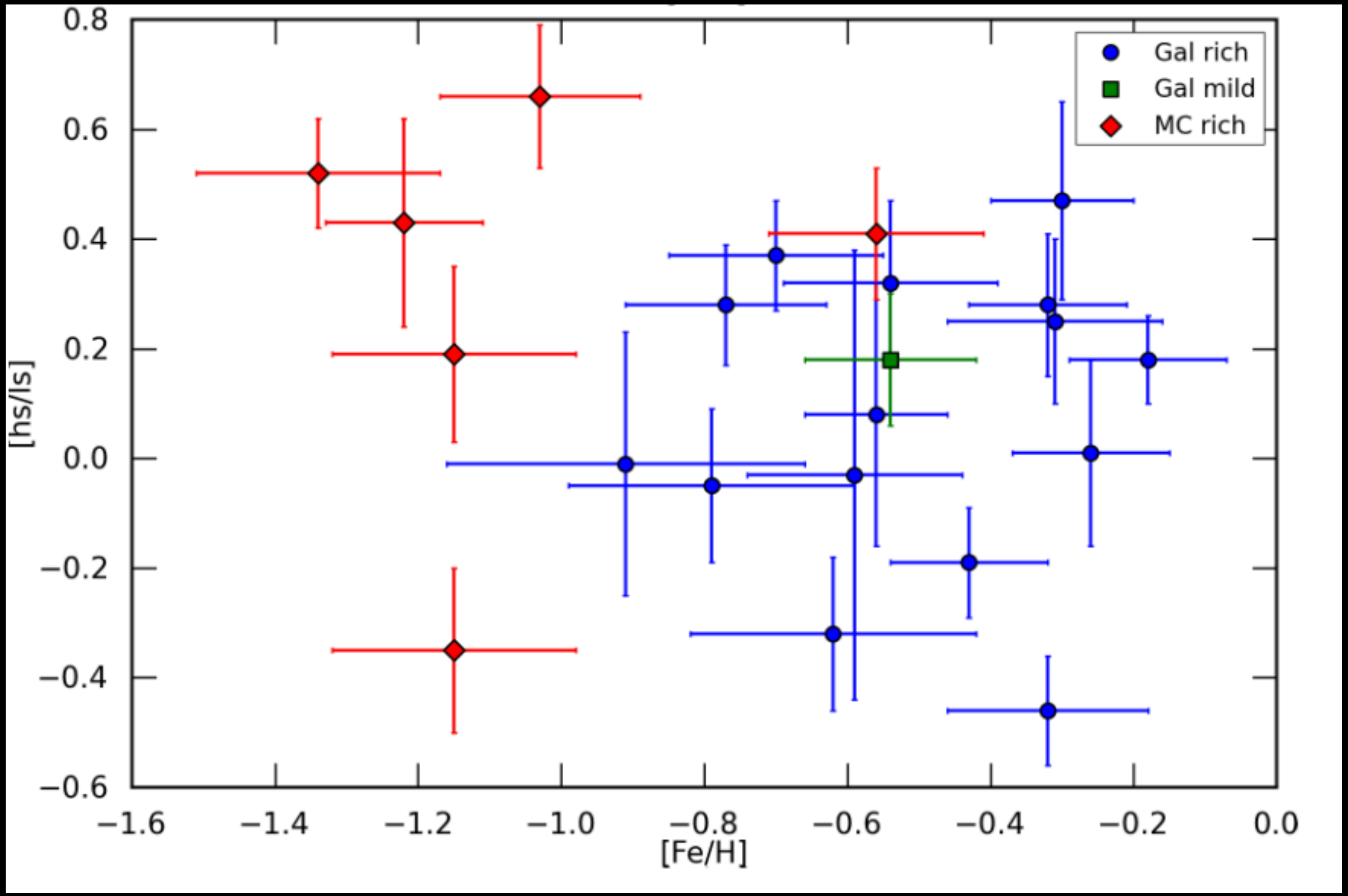
s-Process Trends Across Post-AGB Populations



- Strong positive correlation
- Higher overall s-process enrichment leads to greater production of heavy-s elements (consistent with increasing neutron exposure).

- Overall trend confirmed
- no systematic dependence on galactic environment (Galaxy, LMC, SMC).

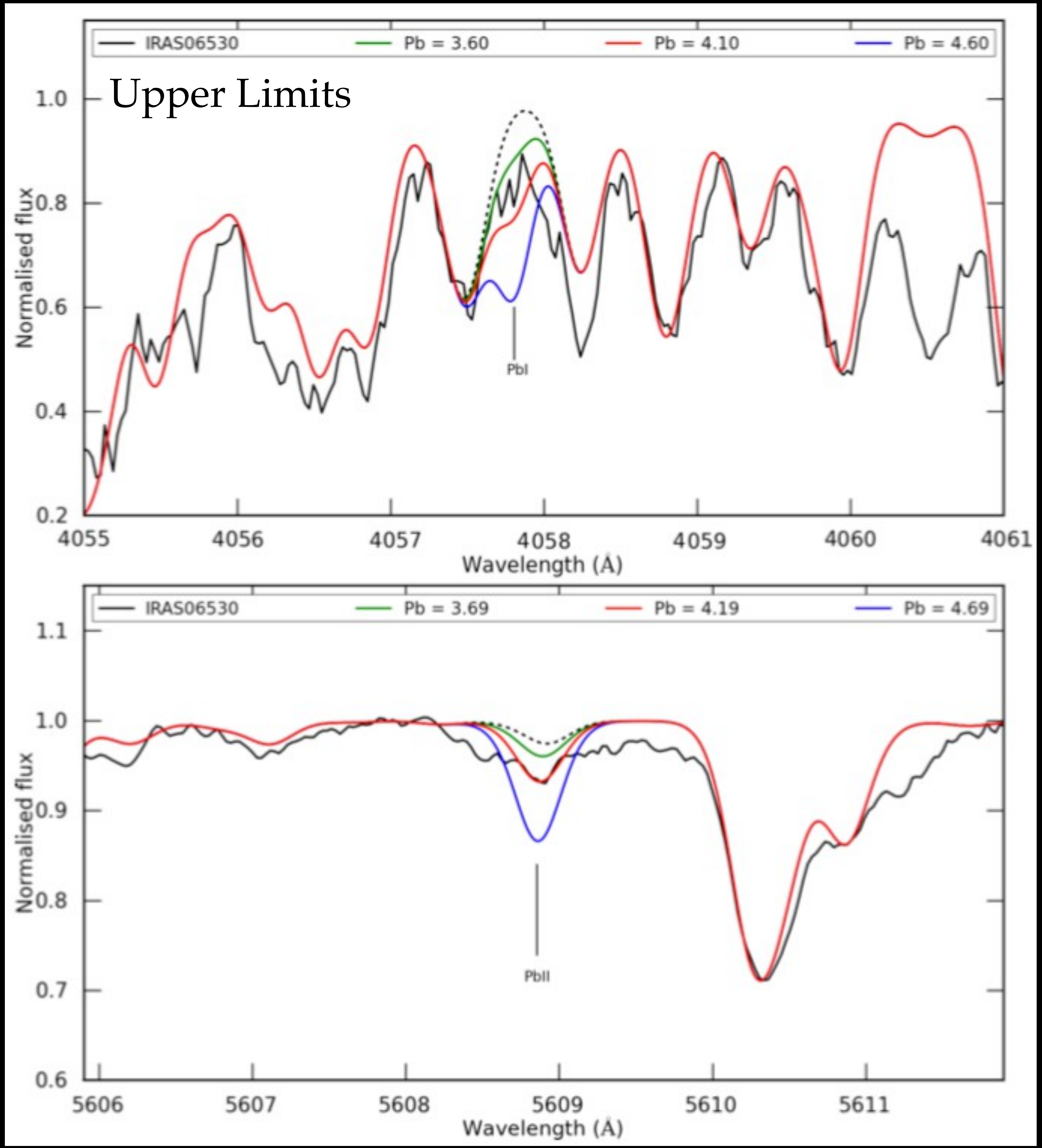
s-Process Efficiency and Metallicity Trends in Post-AGB Stars



- Lower-metallicity stars show higher neutron-to-seed ratios and higher [hs/ls].
- Deviations suggest additional factors beyond metallicity (e.g. initial mass, neutron source, TDU efficiency).

Complexities in s-process Nucleosynthesis

LEAD-ING US ASTRAY?

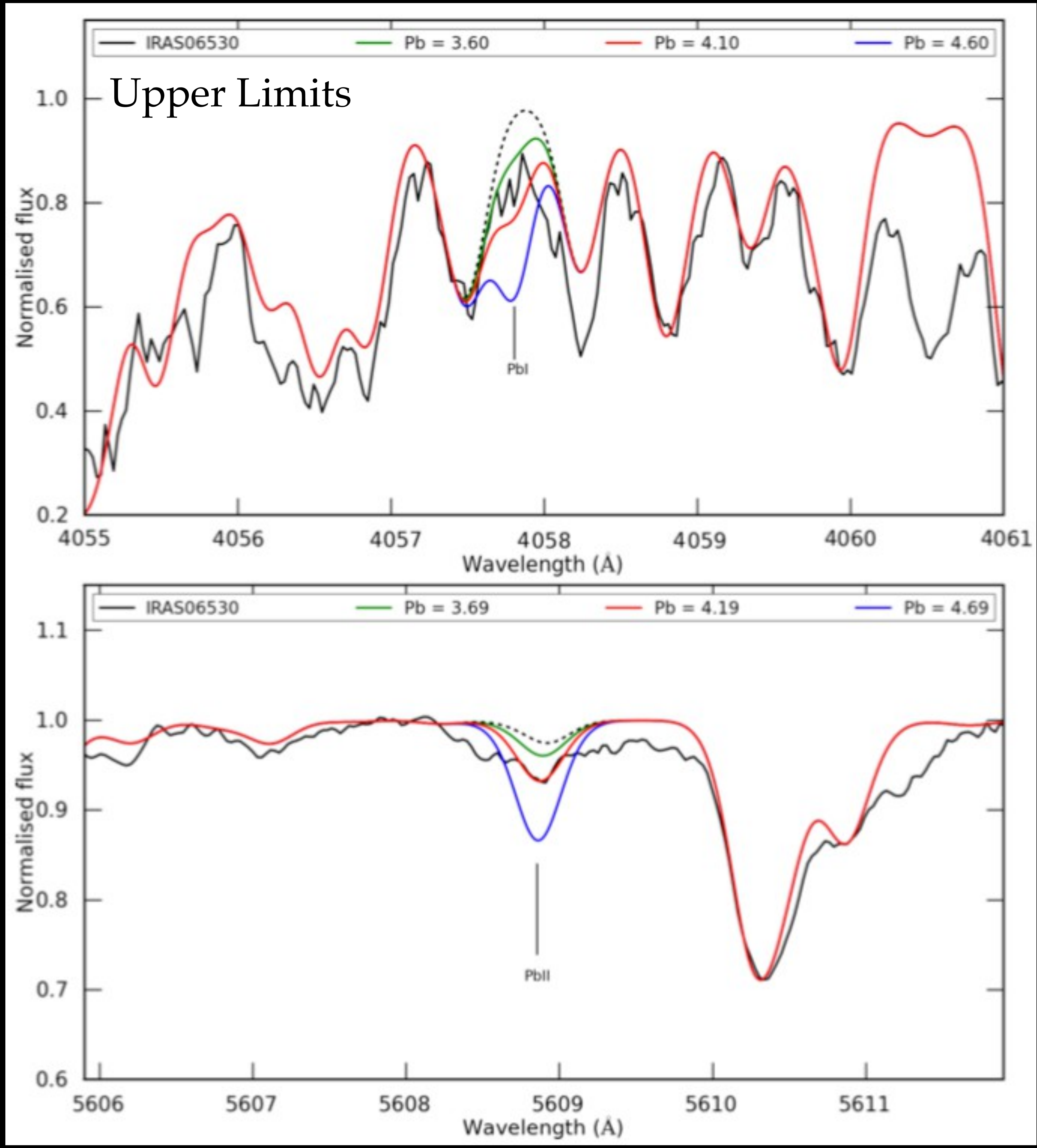


De Smedt et al., 2016

Strong component: Pb

- τ ≈ 7.0 mbarn−1
- Low-mass, Low-metallicity AGBs

LEAD-ING US ASTRAY?



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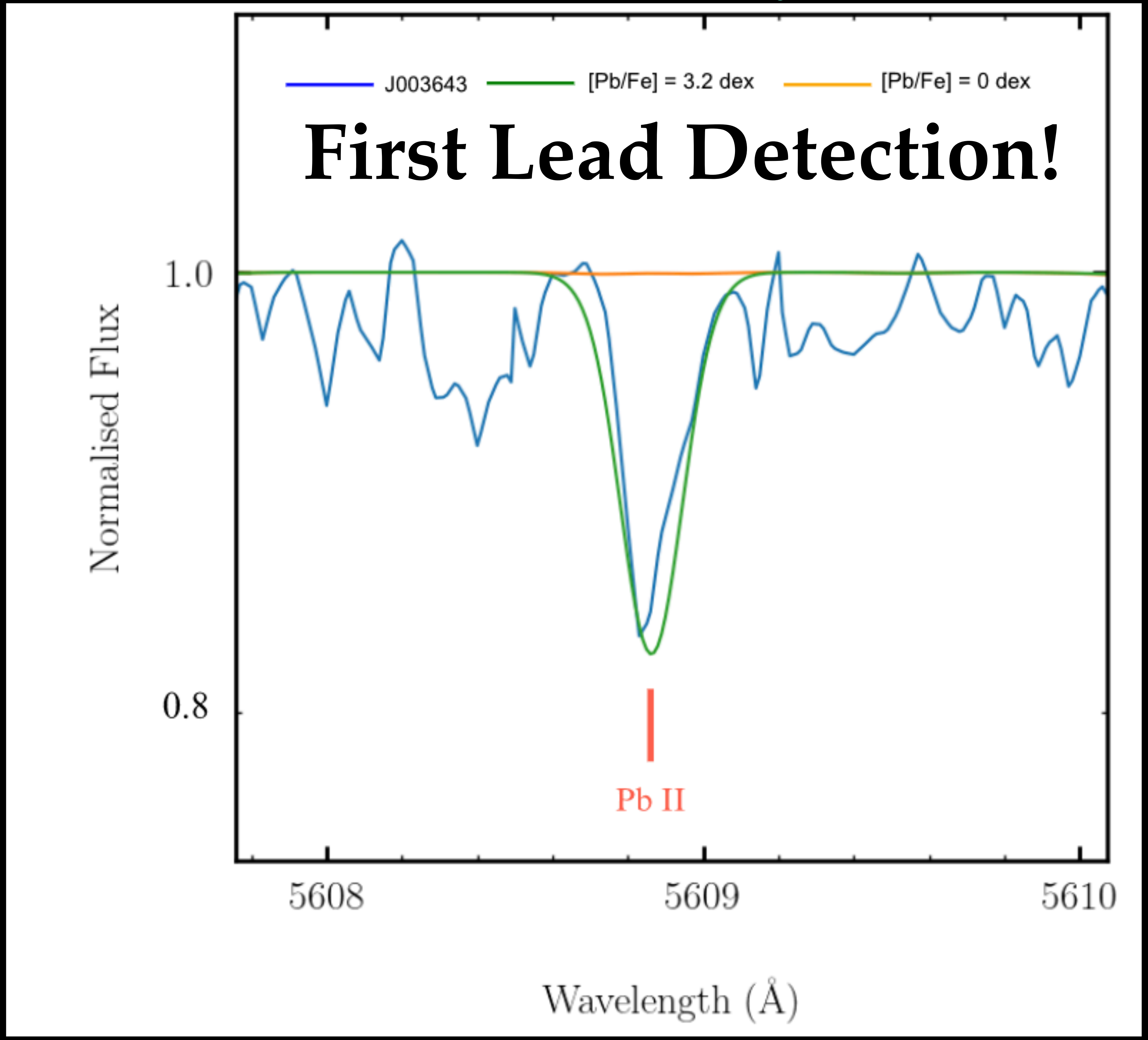
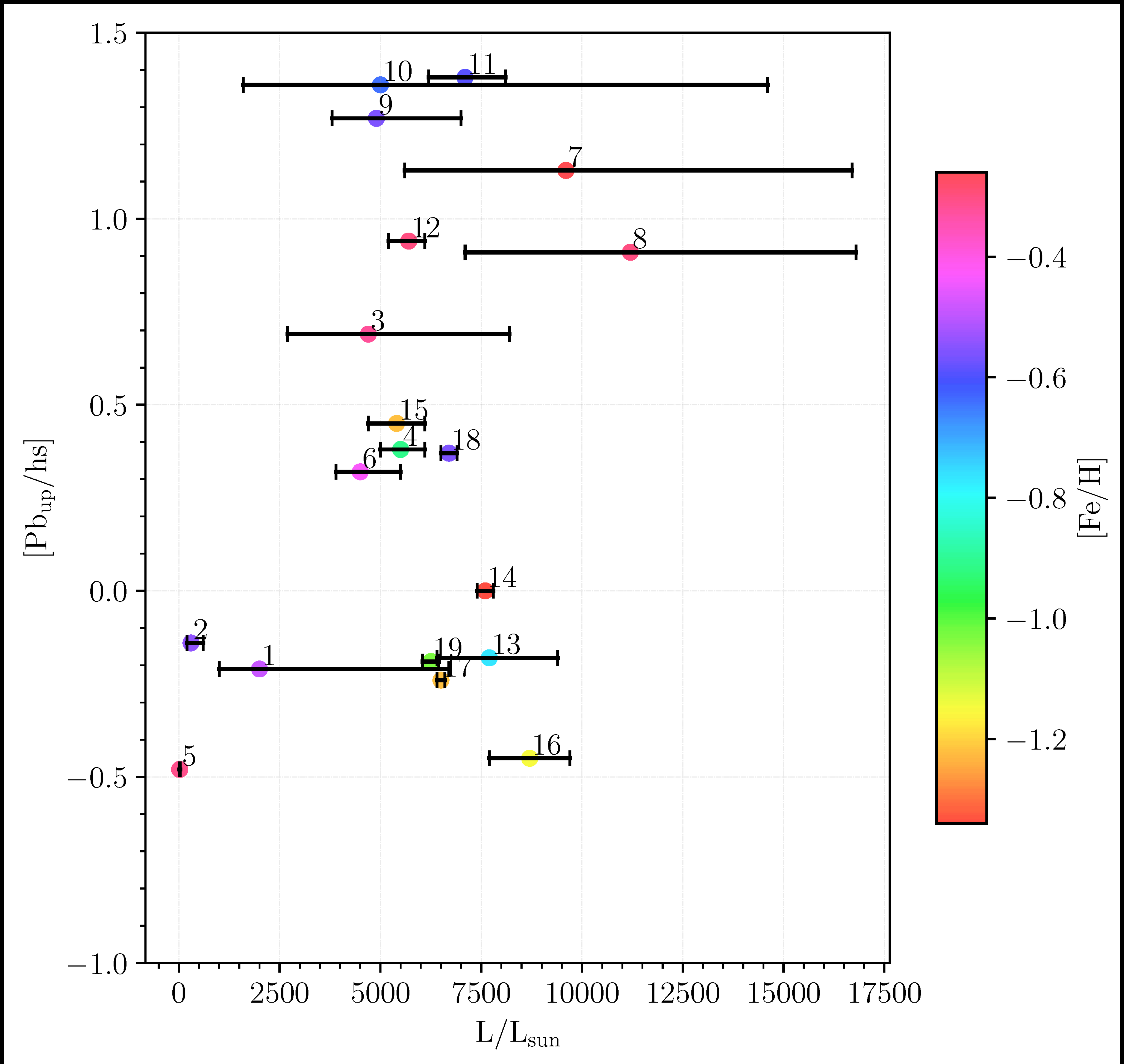


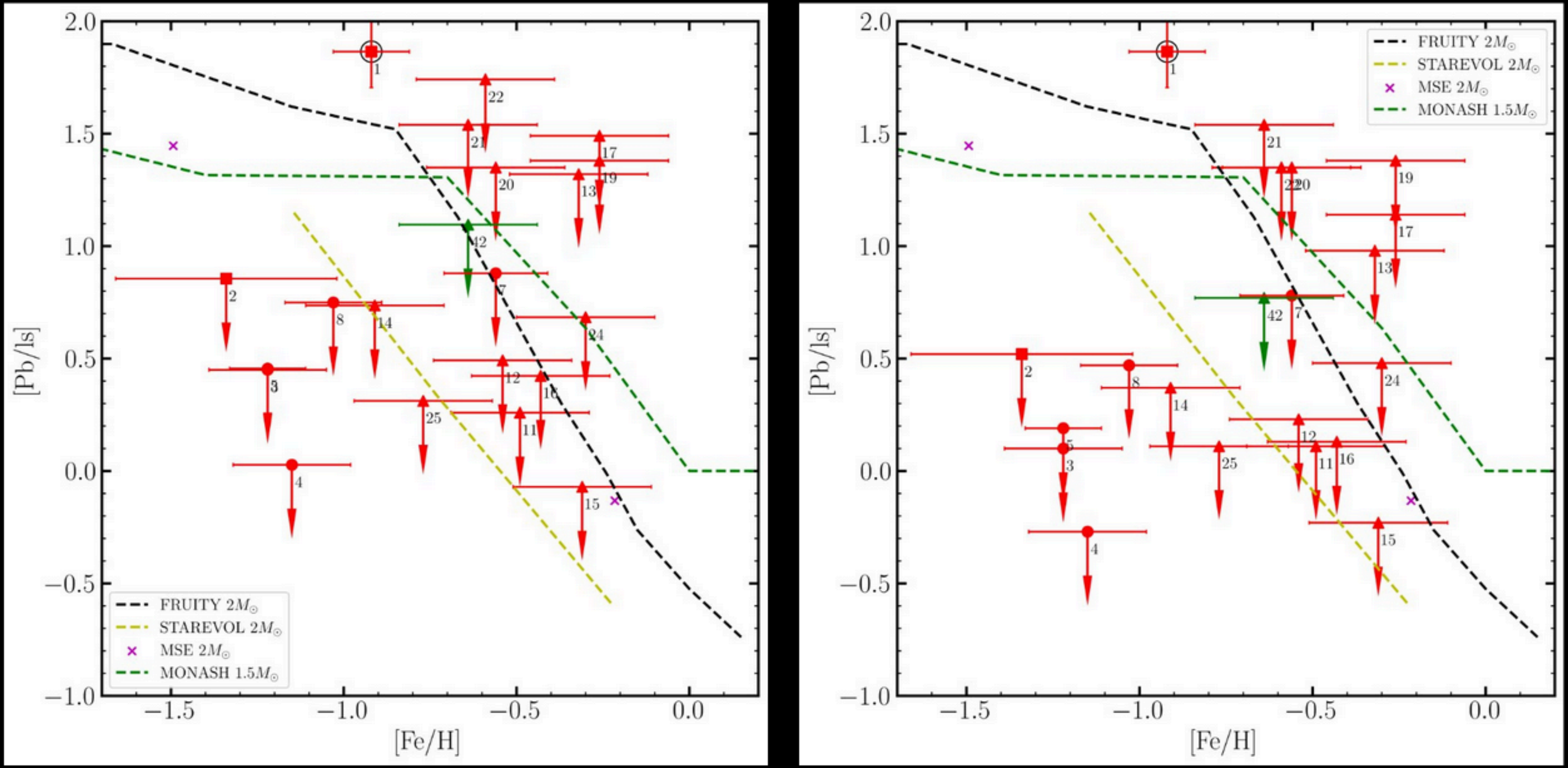
Menon et al., 2025 to-be-submitted

No Clear Luminosity (Progenitor MASS) Dependence in Lead Production



Kamath & Van Winckel 2021

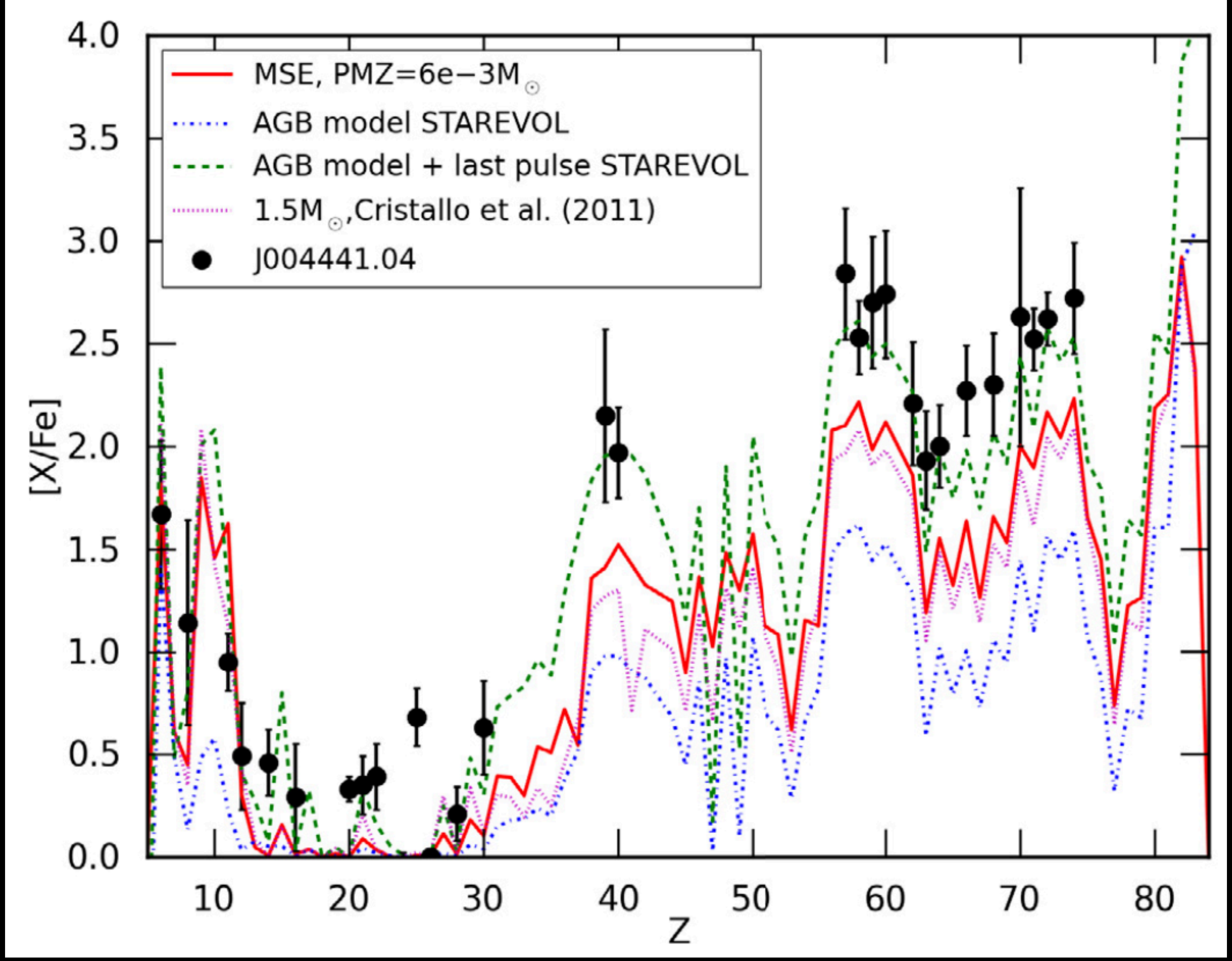
LEAD-ING US ASTRAY?



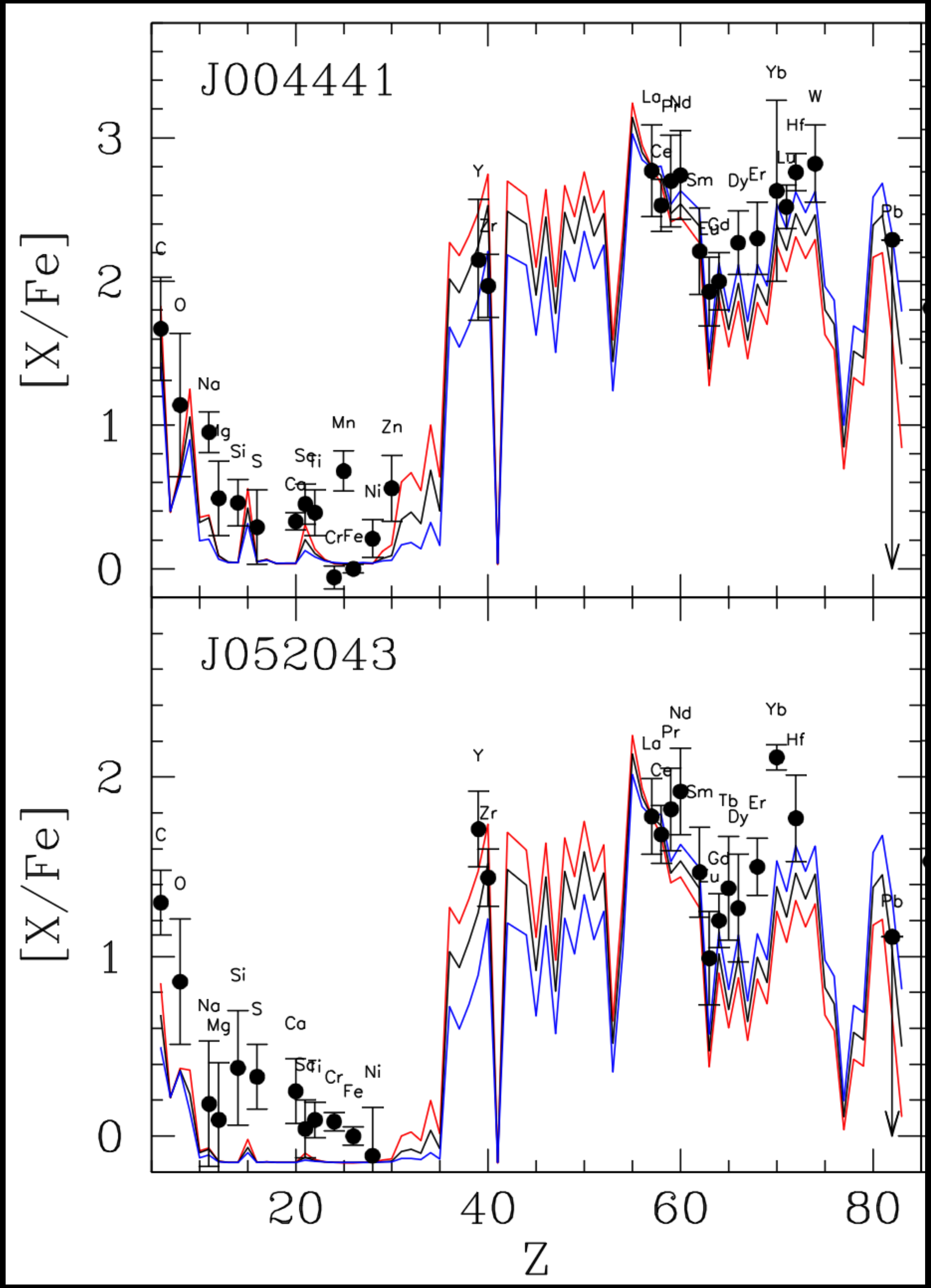
Menon et al., 2025 to-be-submitted

De Smedt et al., 2016; Kamath & Van Winckel 2021

CONSTRAINING AGB NUCLEOSYNTHESIS WITH POST-AGB STARS

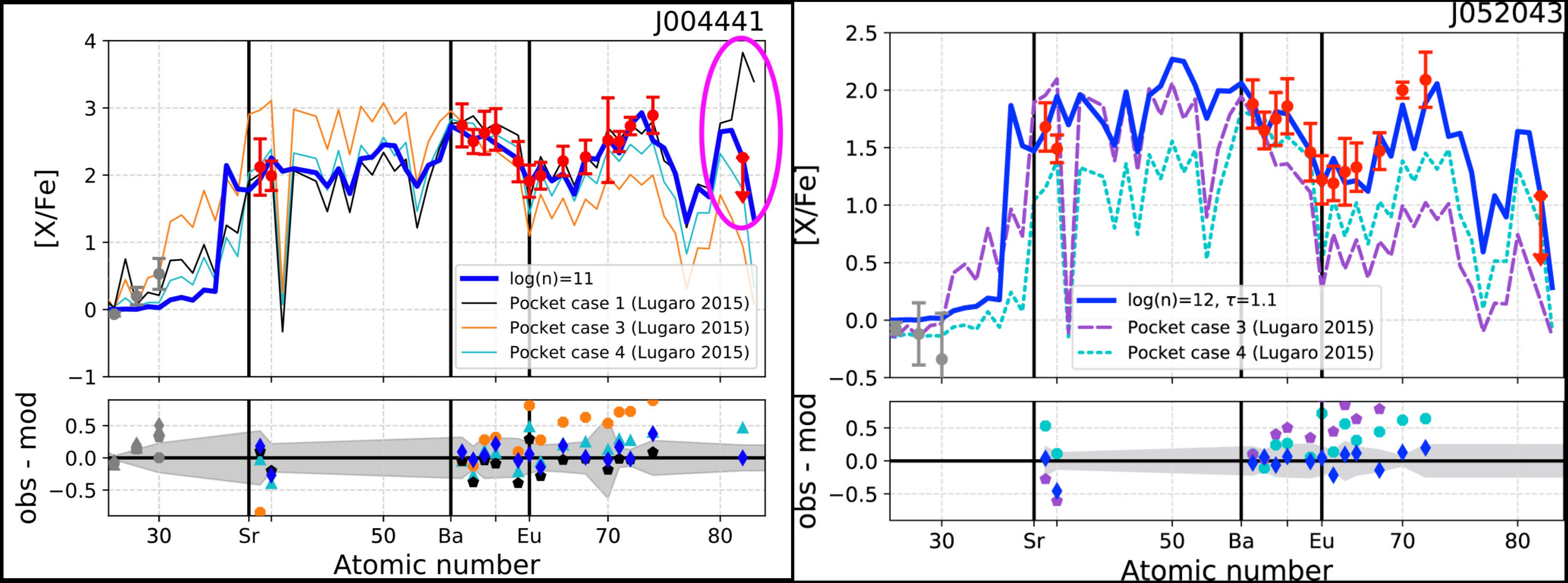


De Smedt et al., 2012



Lugaro et al., 2015

The Intermediate Neutron-capture Process and Lead Abundances



Hampel et al., 2019

THE INTERMEDIATE NEUTRON-CAPTURE PROCESS AND LEAD ABUNDANCES

Low-Pb Post-AGB stars require:

Moderate neutron exposures ($\tau \lesssim 1.0$ $mbarn^{-1}$)

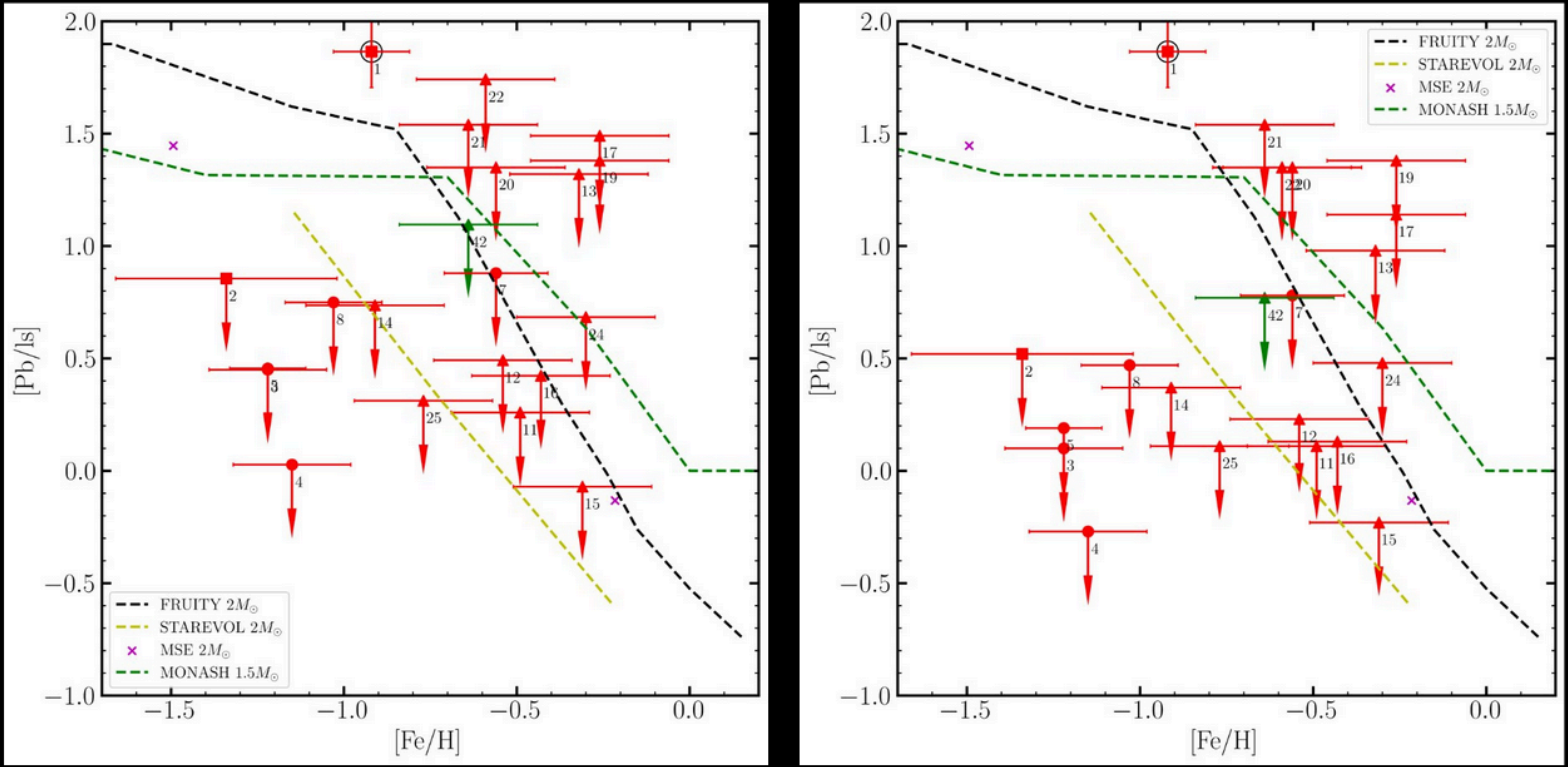
Low neutron densities $n \gtrsim 10^{11}$–10^{12} cm^{-3}

CEMP-i stars requires:

- Higher neutron exposures ($\tau > 2.0$ $mbarn^{-1}$)
- Higher neutron densities, typically at or above $n \gtrsim 10^{13}$–10^{15} cm^{-3}.

Hampel et al., 2019

LEAD-ING US ASTRAY?



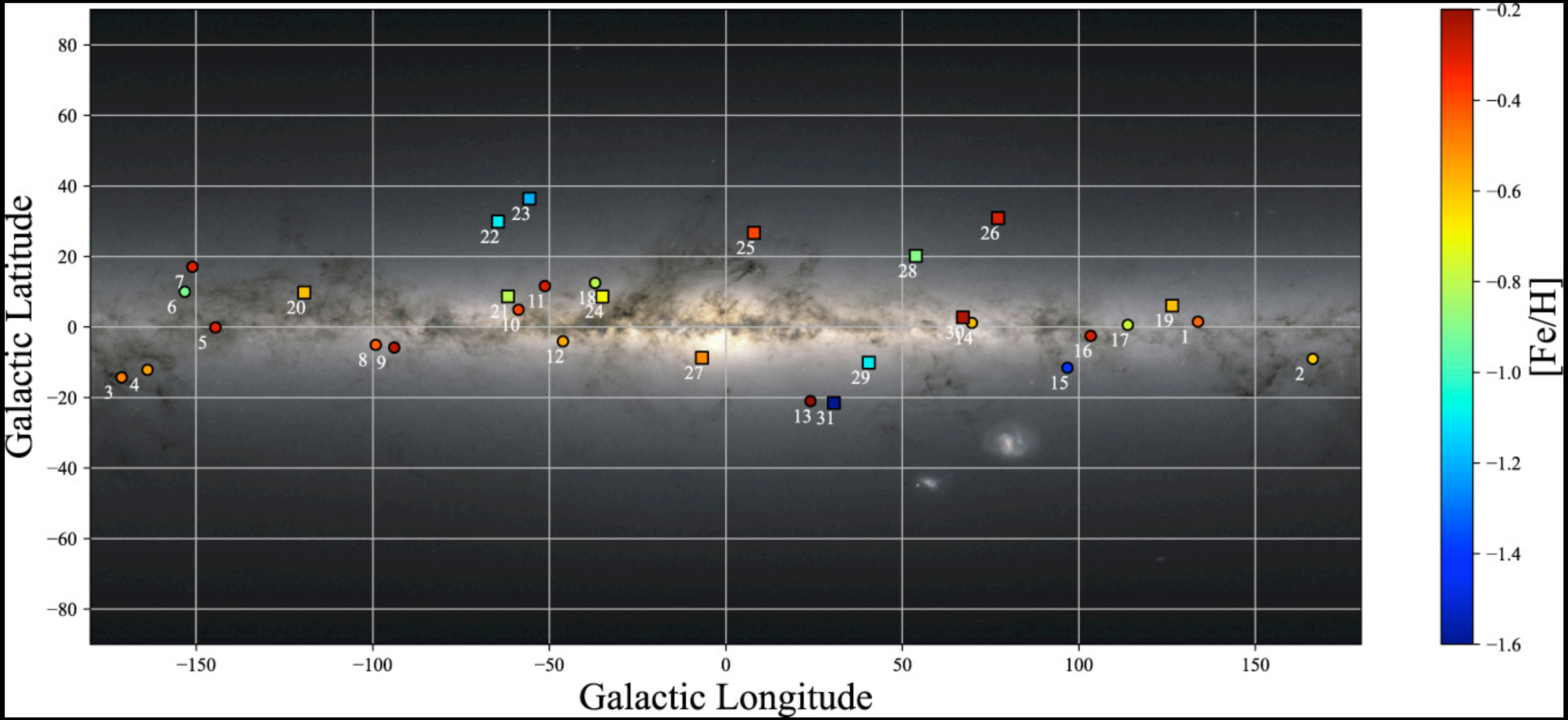
Menon et al., 2025 to-be-submitted

De Smedt et al., 2016; Kamath & Van Winckel 2021

The revelation of chemical diversities in AGB nucleosynthesis…

Van Winckel 2003; Kamath et al., 2017; 2020; 2022; 2023, Menon et al., 2023

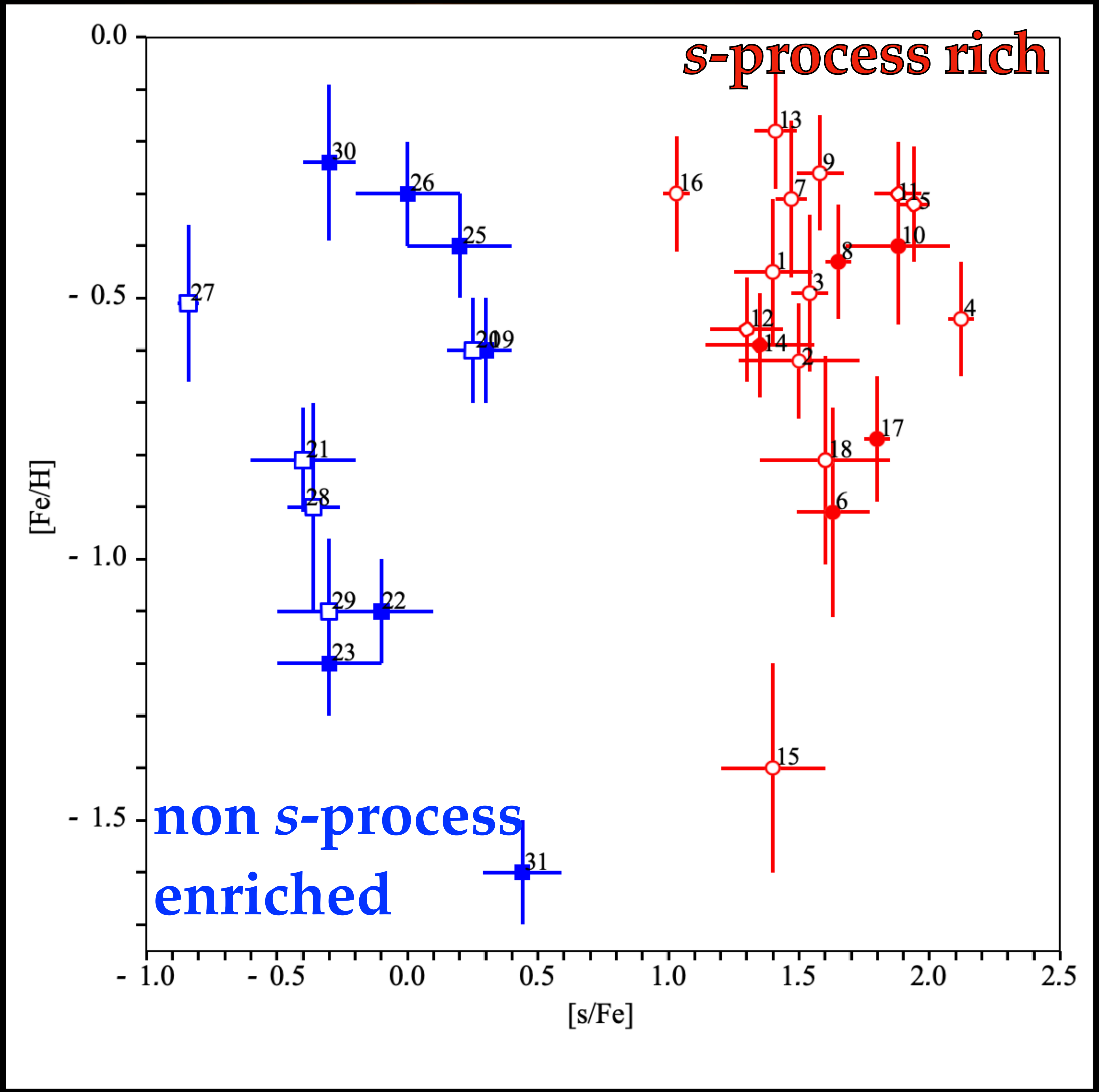
Chemical Diversities Within the Single Star Sample



Kamath et al., 2022

CHEMICAL DIVERSITIES **WITHIN THE SINGLE STAR SAMPLE**

s-process rich versus non-enriched:

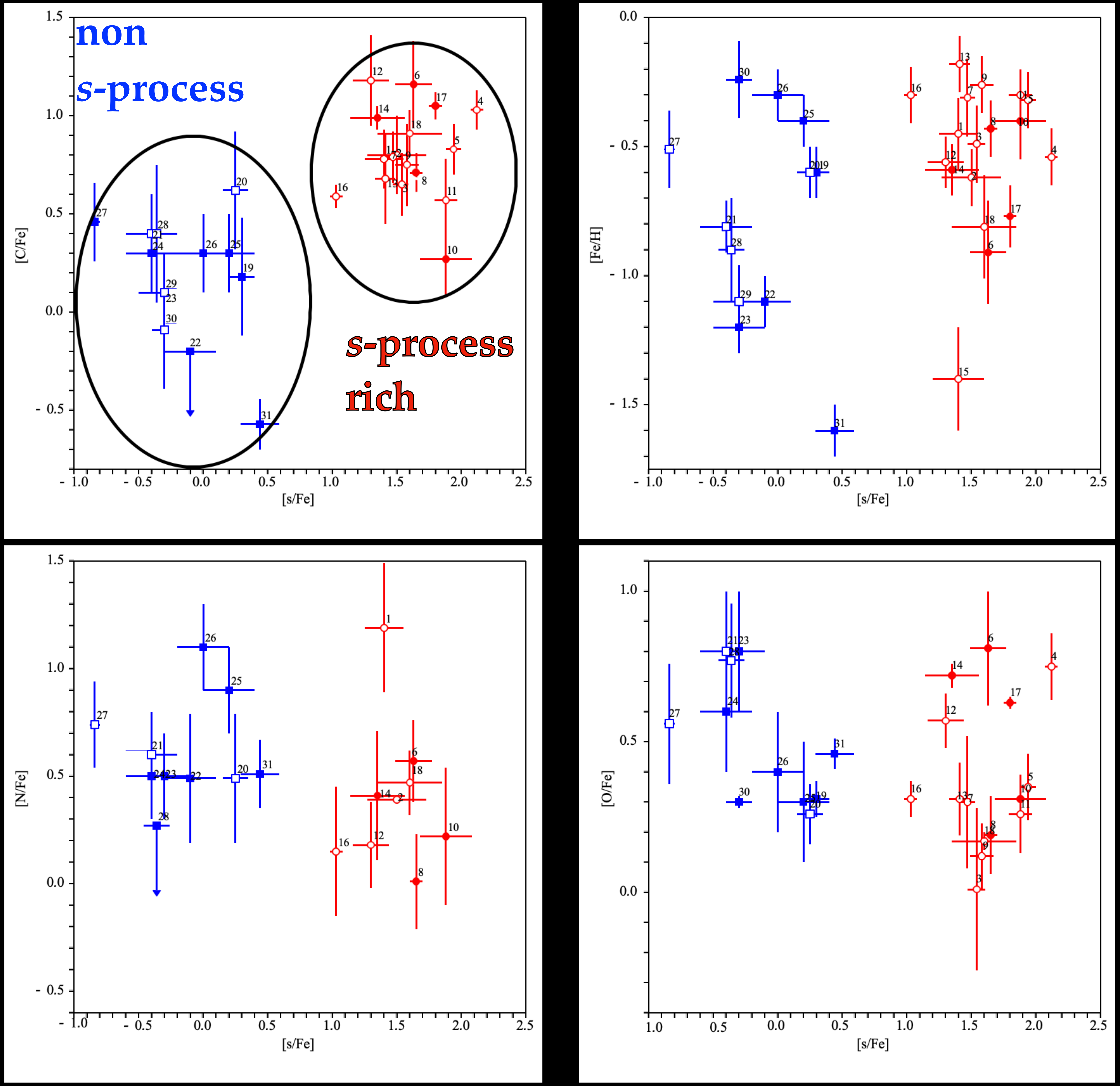


Kamath et al., 2022

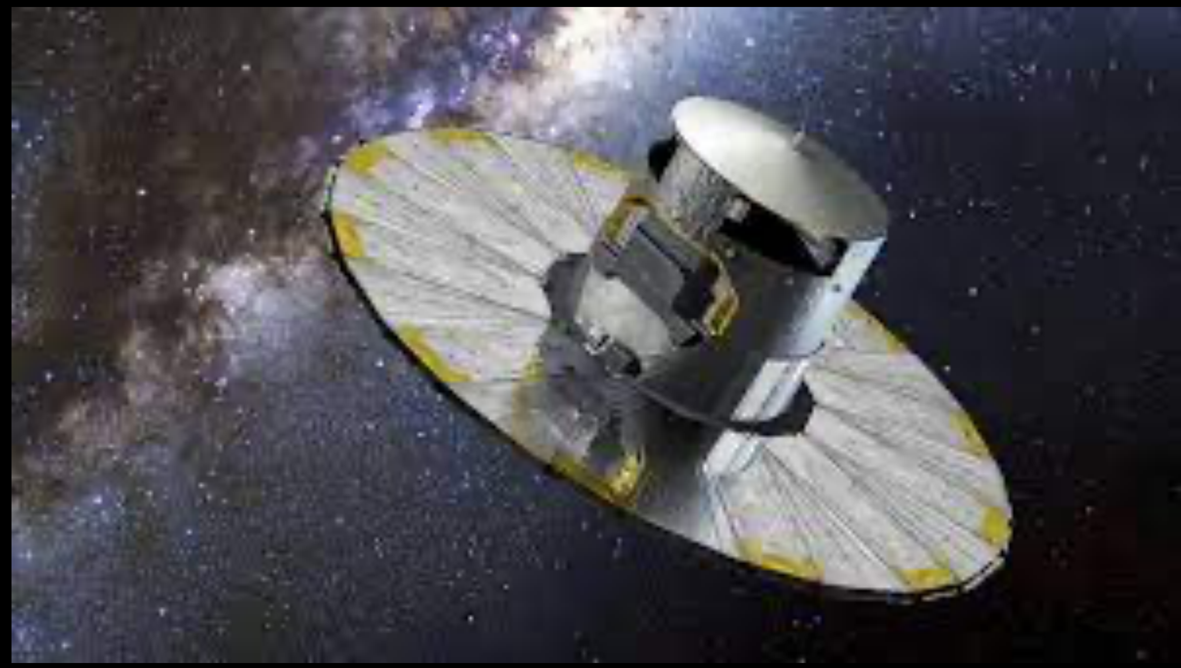
AGB Nucleosynthesis is NOT homogenous!

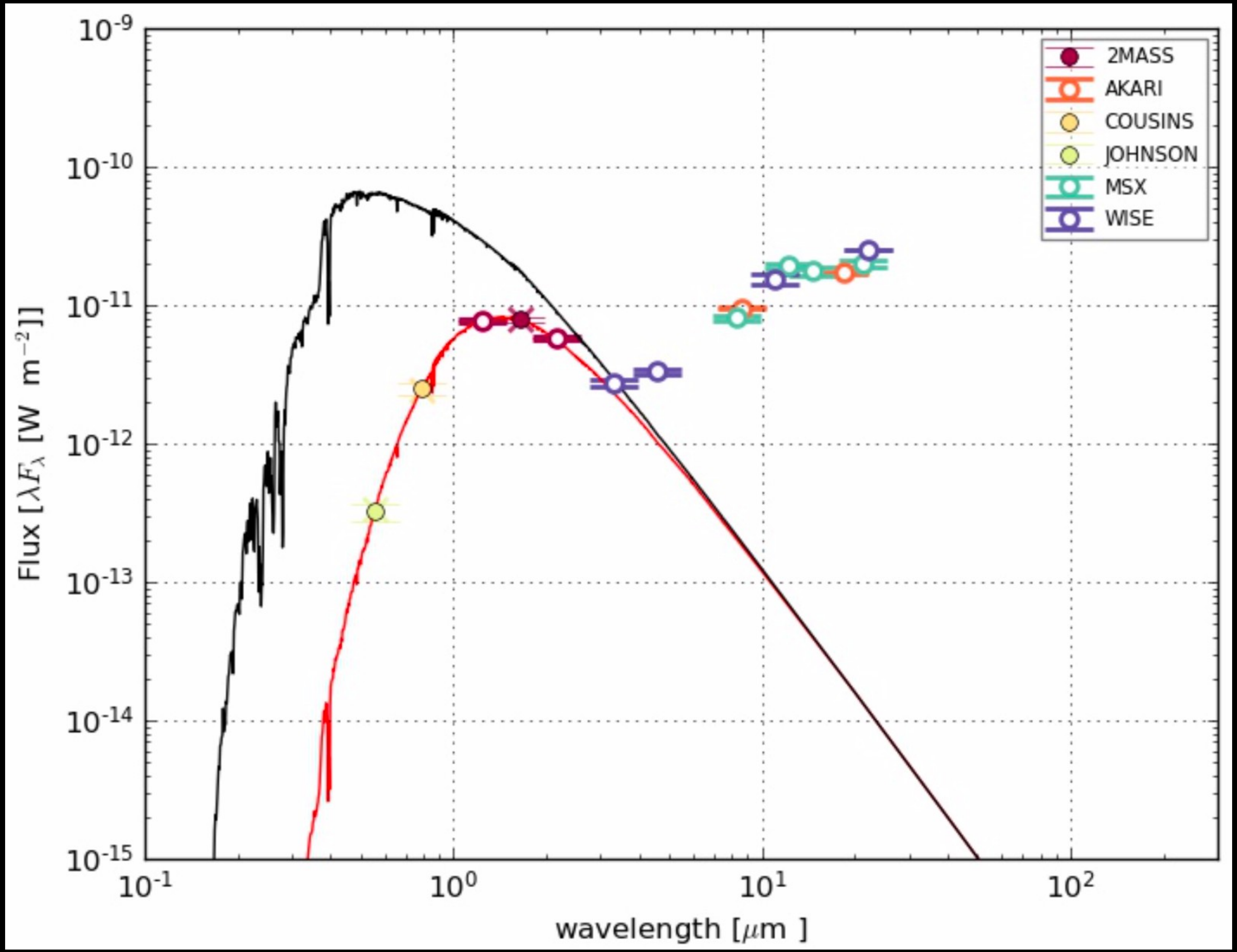
- A chemical dichotomy in the C and *s*-process abundances: enriched and non-enriched (in disagreement with models!)

- No obvious trends in O and N



LUMINOSITIES FOR SINGLE POST-AGB STARS WITH GAIA

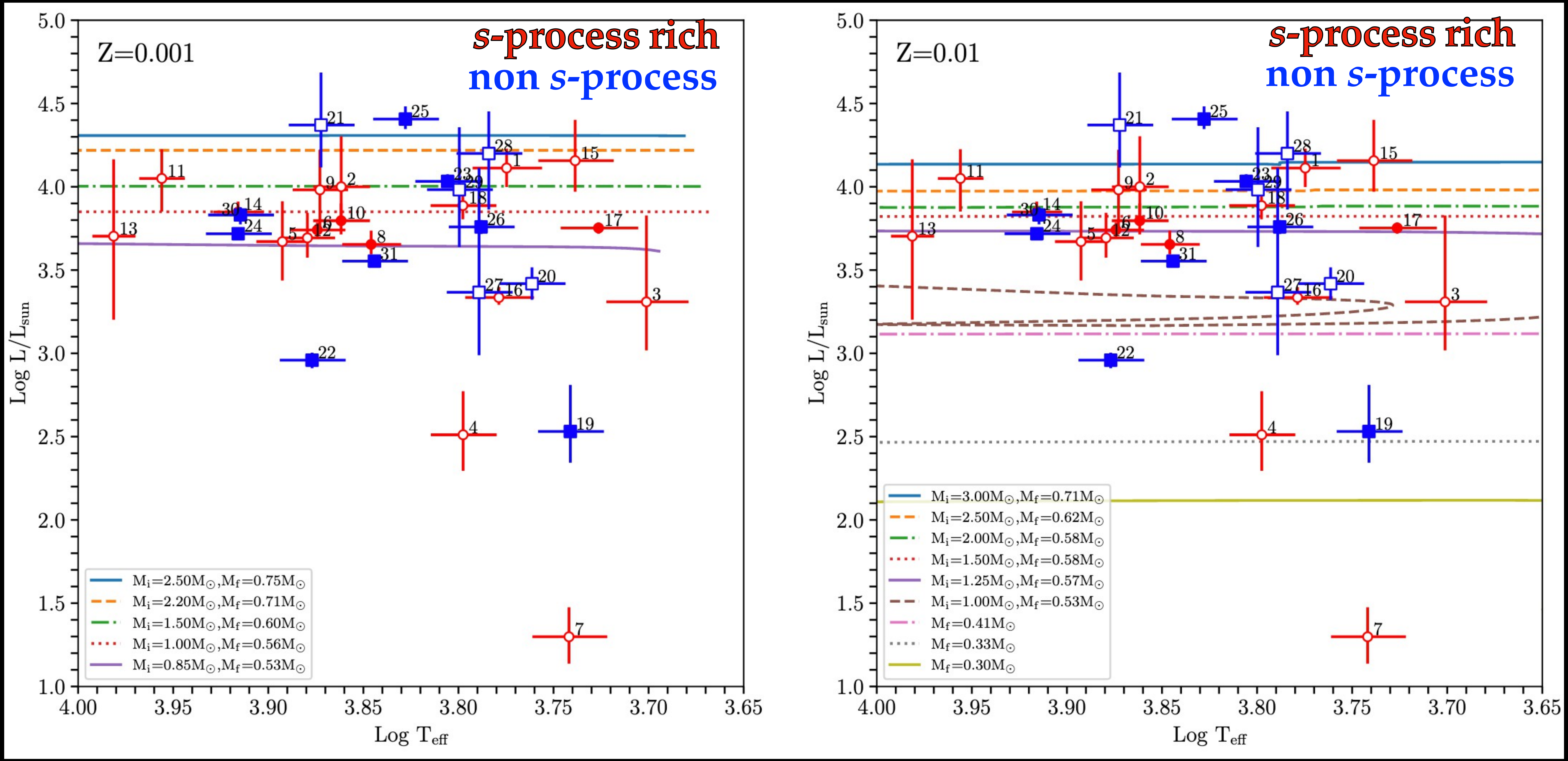




- Parallaxes from Gaia EDR3
- Geometric distances from Bailer Jones et al., 2021
- SED Fitting: E(B-V)

  ↓
- Luminosity ⟶ ***Progenitor Mass***

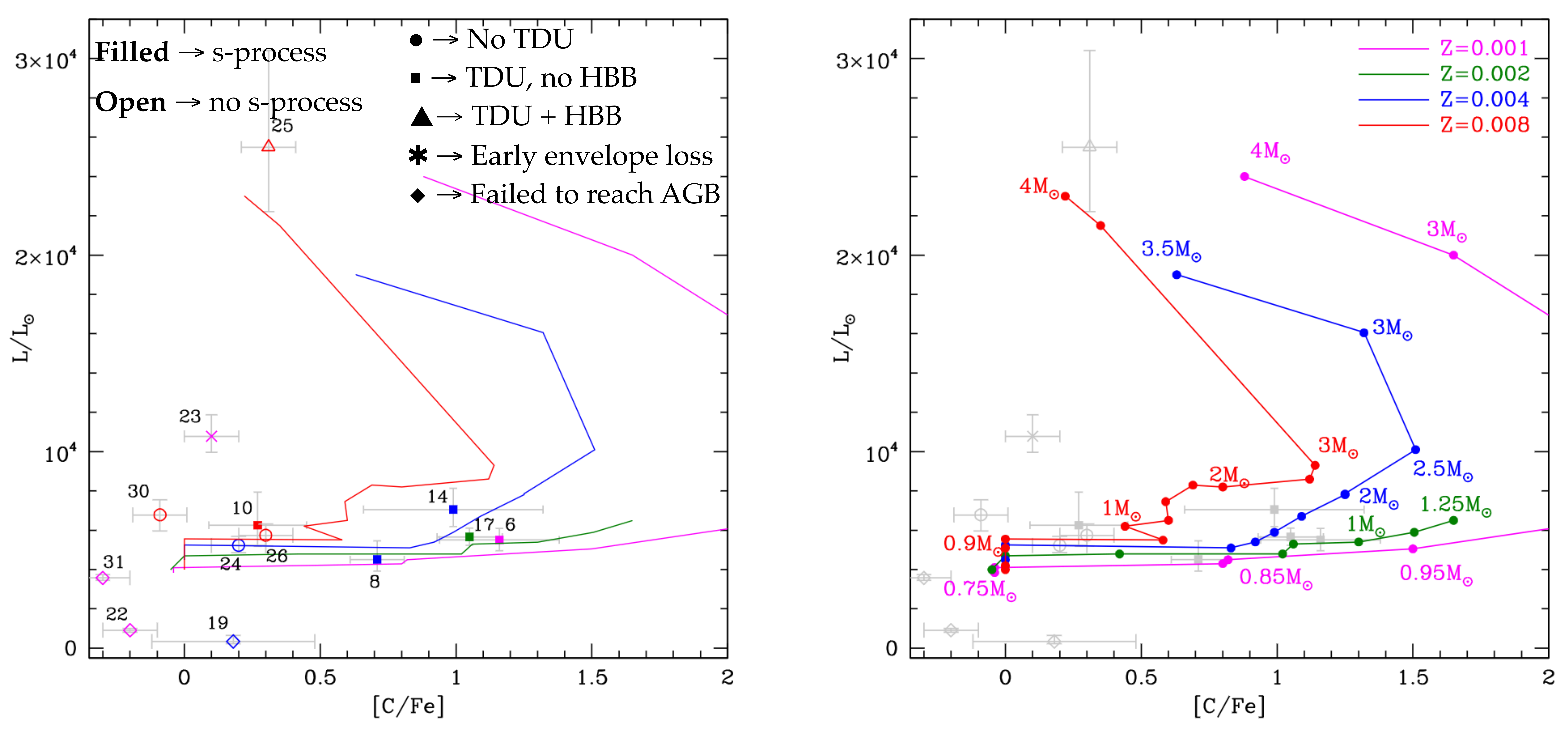
POSITIONS OF GALACTIC POST-AGB STARS IN THE HR-DIAGRAM



Kamath et al., 2022

Filled symbols: Quality 1
Open symbols : Quality 2
(based on GAIA astrometric data)

Using Post-AGB Modelling with **ATON** to Constrain AGB Evolution and Nucleosynthesis



Kamath et al., 2024; Ventura et al., 2015

A subset of post-AGB stars reflect a lack of carbon production during the AGB phase
efficiency of the third dredge-up

Non-uniform *s*-process production
AGB nucleosynthesis

Under-abundance of lead (b)
***s*-process nucleosynthesis**

Intrinsically enhanced s-process binaries
Impact of binary interactions

Current Challenges and the Road Ahead

Key Questions:

- What drives the chemical diversity among post-AGB stars?
  (s-rich vs. s-poor, Pb-rich vs. Pb-poor)
- Why do current s-process models systematically over-predict Pb abundances?
- What is the precise role of the i-process in shaping heavy-element abundances in post-AGB stars?
- How does binarity influence surface abundances and the chemical yields of AGB stars?

Critical Priorities Going Forward:

- Develop multi-phase studies — linking photospheric, circumstellar, and dust-phase tracers — to build a complete picture of nucleosynthesis and element transport.
- Conduct systematic observational studies to map chemical diversity across metallicities and evolutionary stages. (AGB → post-AGB → PN)
- Refine stellar yields — incorporating chemical diversity, binary evolution, and realisticcircumstellar effects — to improve Galactic Chemical Evolution models.