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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INAF

C-MetaLL project: High-resolution spectroscopy of Classical Cepheids as tracers of the Milky Way Disc

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Classical Cepheids in a nutshell

Young

- Mass 3-13 $M_\odot$
- Central Helium-burning phase

Bright

- 10^3-10^4 $L_\odot$

Pulsating variables

- Periods 1.5-70 days
- Famous for the Period-Luminosity relation

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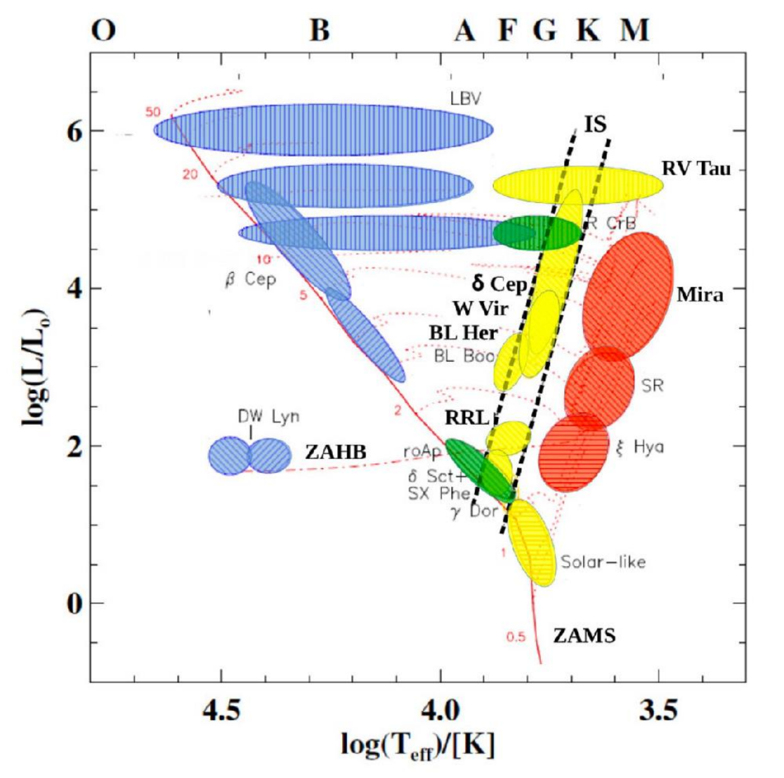

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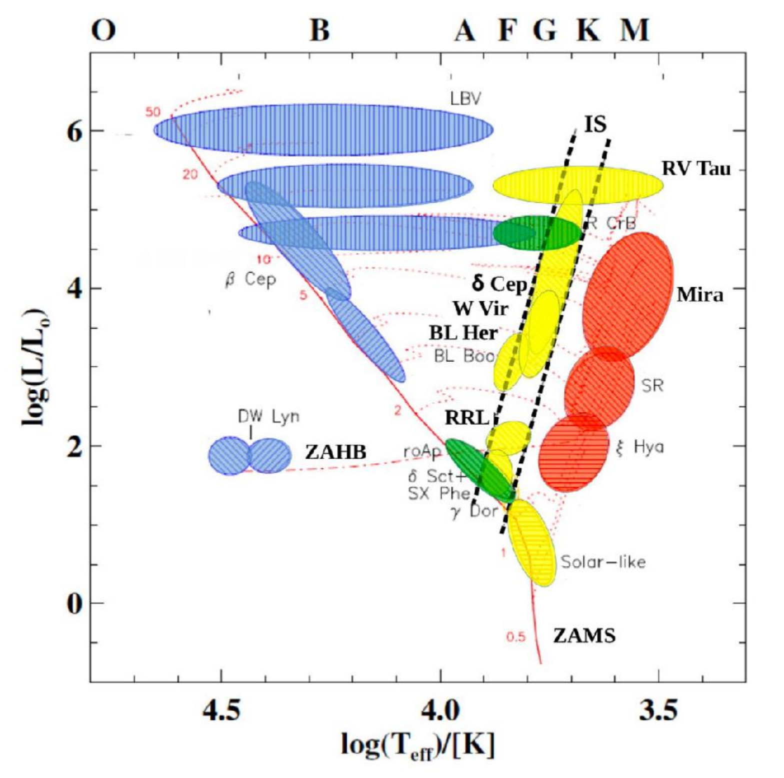
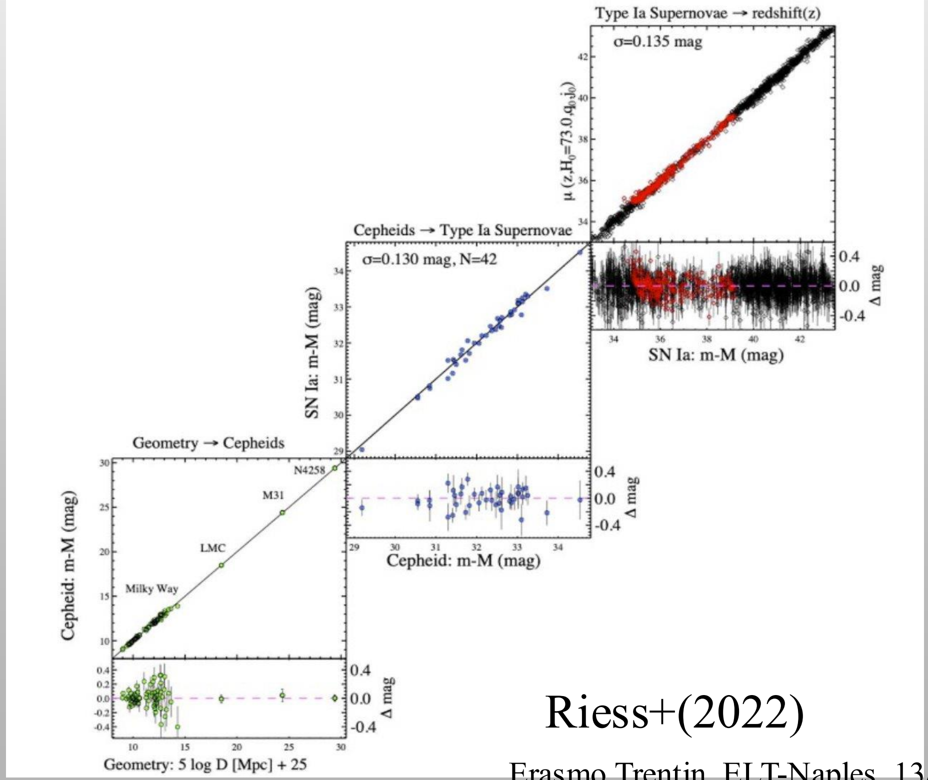




Riess+(2022)

C-MetaLL

Cepheids-Metallicity in the Leavitt Law

1. Significantly enlarge (+~300 objects) the sample of Cepheids with metallicity measured from high-resolution spectroscopy (*HARPS-N@TNG; GIANO-B@TNG; UVES@VLT; PEPSI@LBT; ESPADONS@CFHT)*.

2. Enlarge the range of [Fe/H] adopted in the determination of the PLZ/PWZ relations up to values typical of the SMC or more metal poor.

3. Obtain multiband g,r,i,z,J,H,Ks photometry for a large sample of Cepheids to obtain precise average magnitudes and individual reddening measurements.

https://sites.google.com/inaf.it/c-metall/home

Spectroscopic sample

Published in previous papers:

- 50 stars from HARPS-N@TNG (Ripepi+2021a) (C-MetaLL I)
- 65 observed with UVES@VLT (Trentin+2023) ((C-MetaLL II)

Published in Trentin+(2024b) (C-MetaLL VI):

- 111 spectra (101 stars) with UVES@VLT (R= 47.000)
- 90 spectra (42 stars) with ESPaDOnS@CFHT (R= 81.000)
- 130 spectra (37 stars) with HARPS-N@TNG (R=115.000)

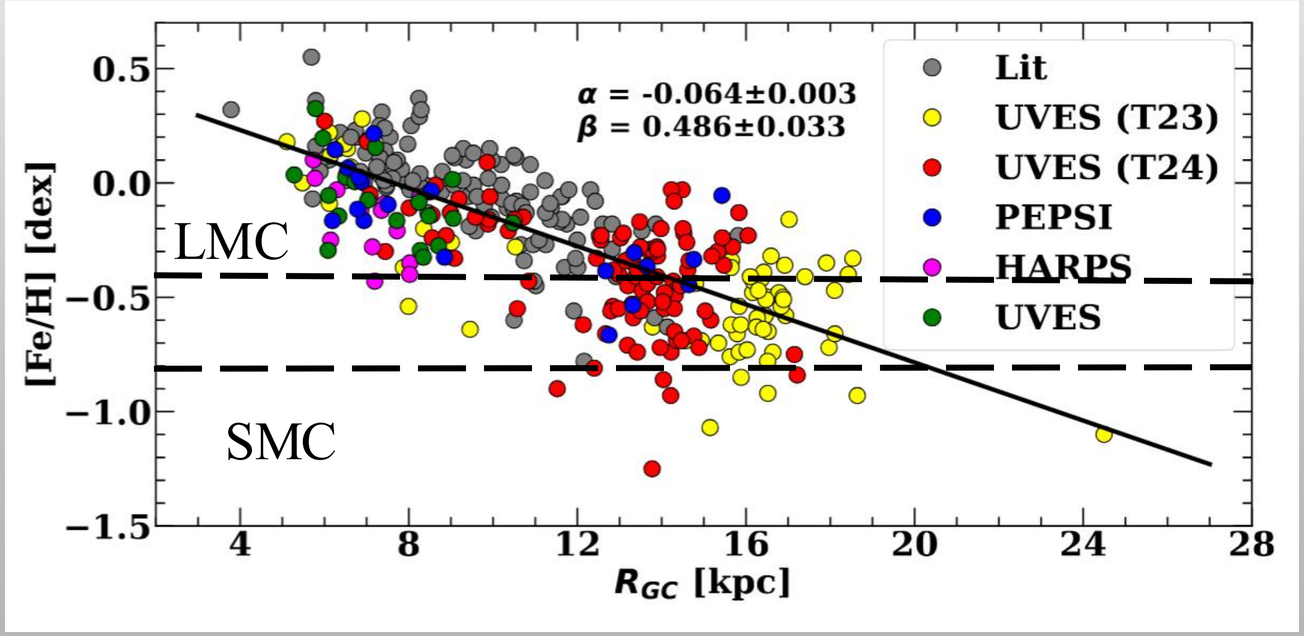
Published in Trentin+(2026) (C-MetaLL VIII):

- 29 spectra (23 stars) with UVES
- 44 spectra (15 stars) with HARPS-N
- 63 spectra (22 stars) with PEPSI@LBT (R = 50.000)

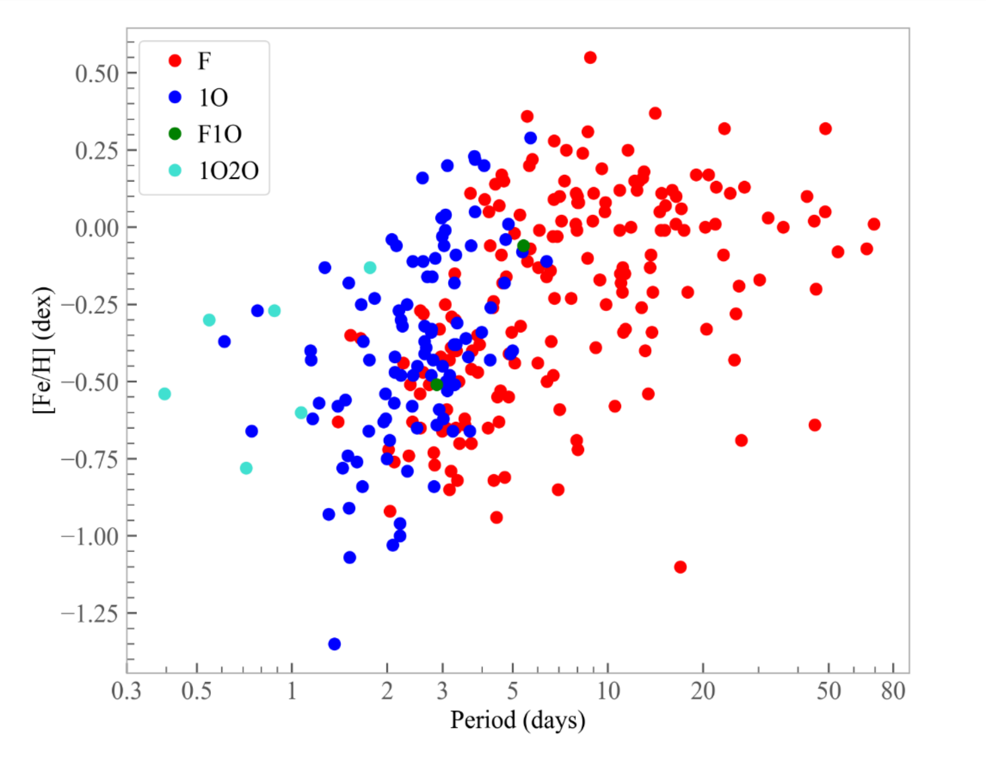
Total: 340 individual DCEPs, SNR ~ 80, up to 33 chemical species

Radial metallicity gradient….

- Homogeneous and robust sample composed of HiRes metallicities
- Homogeneous distribution in both metallicities and distances
- Periods from 0.4 to 70 days



Trentin+(2026)



Ripepi+(2026)

Radial metallicity gradient….and polar distribution

- Homogeneous and robust sample composed of HiRes metallicities
- Homogeneous distribution in both metallicities and distances
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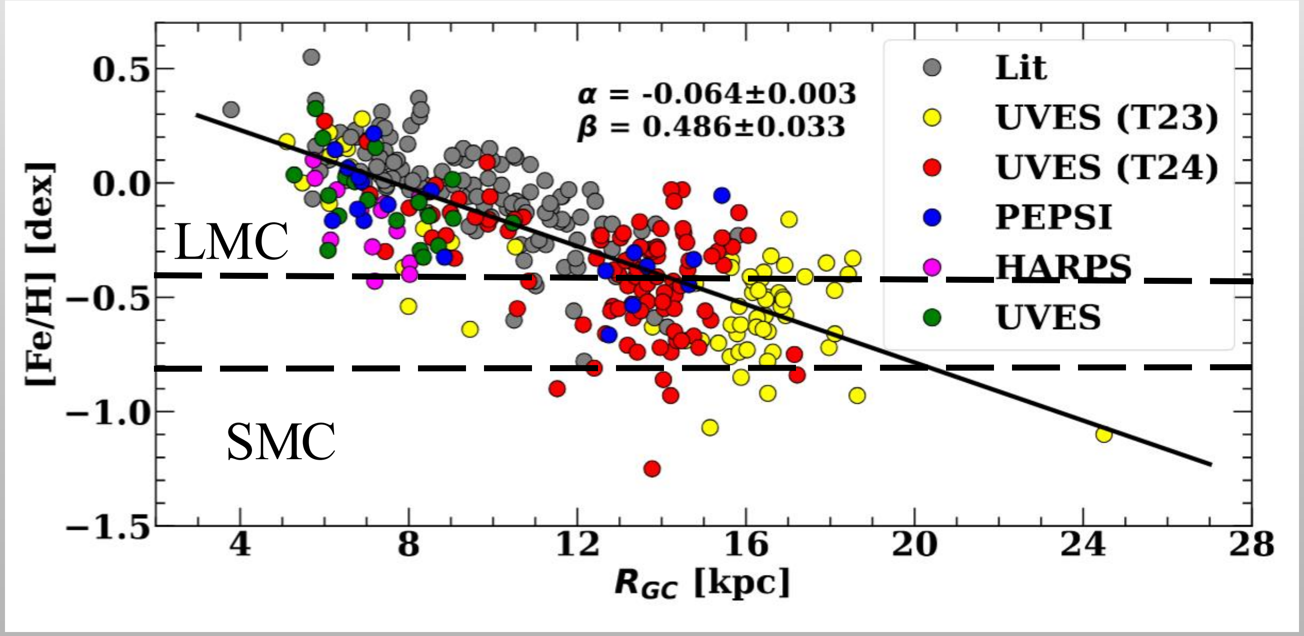

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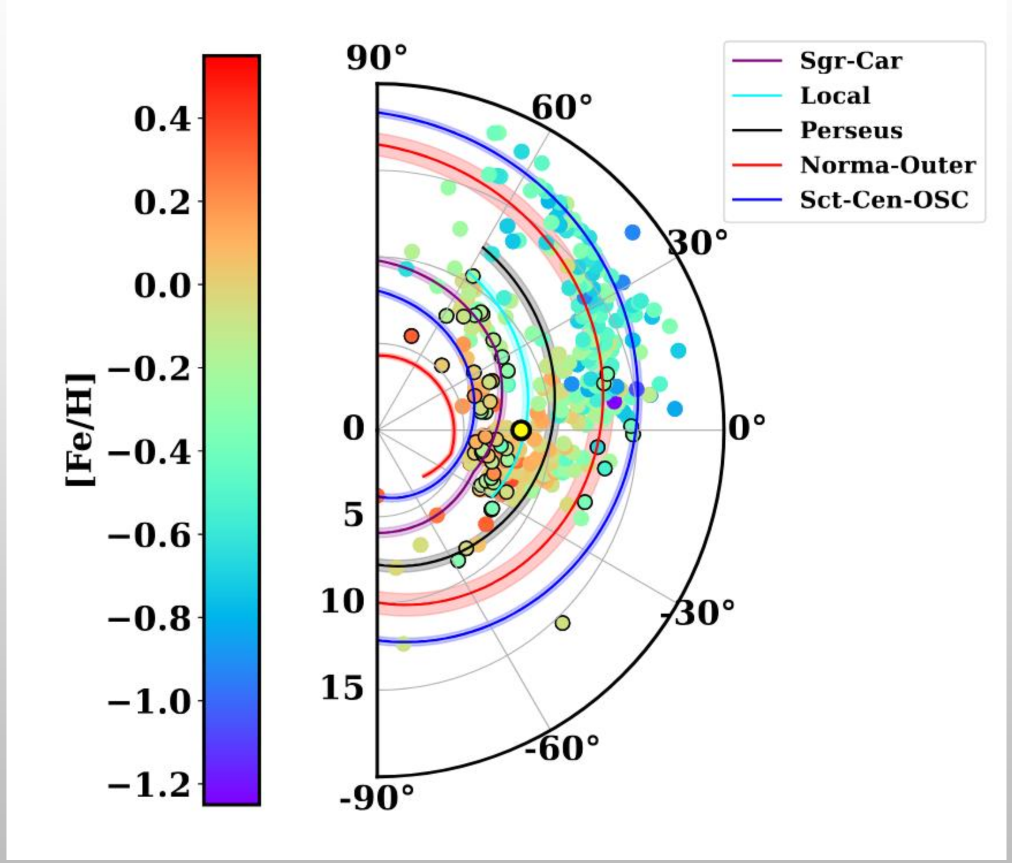
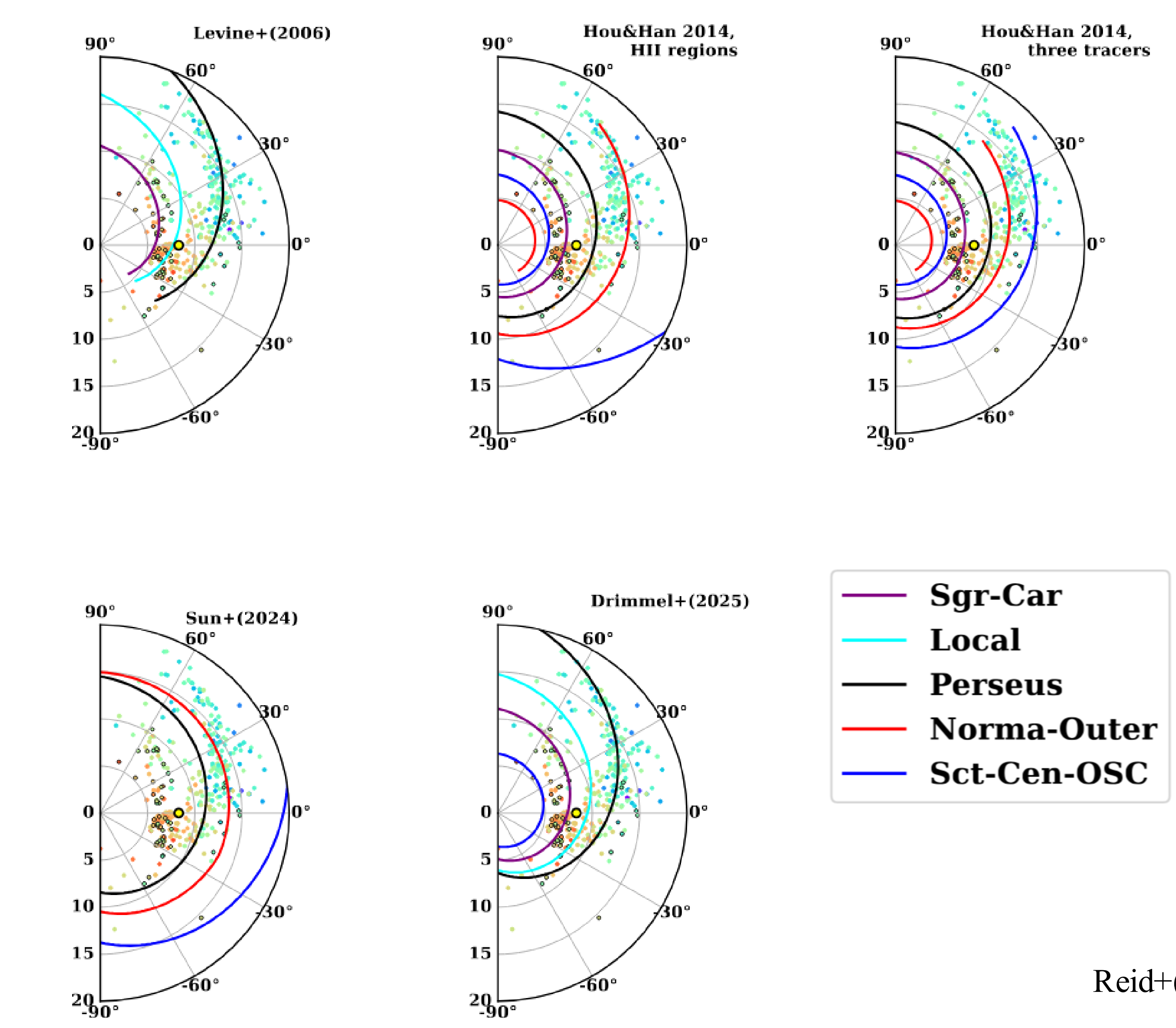


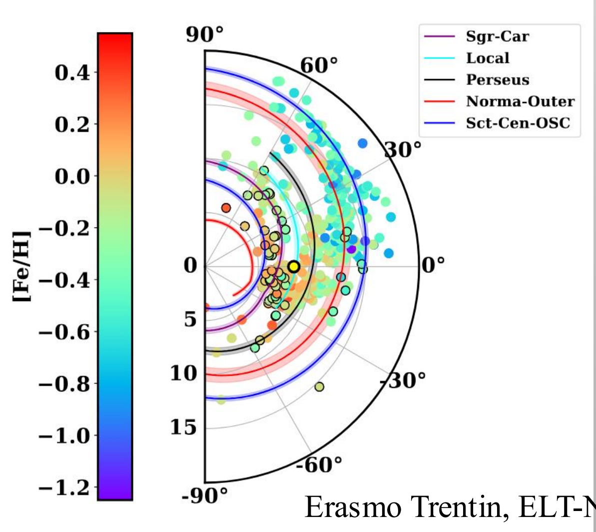
Adapted from Reid+(2019)

A journey among several spiral models



Depending on the model (tracers used and/or analytic function) the stars between 10 and 20 kpc from the Galactic Centre are tracing either the Outer, Perseus or OSC arms.

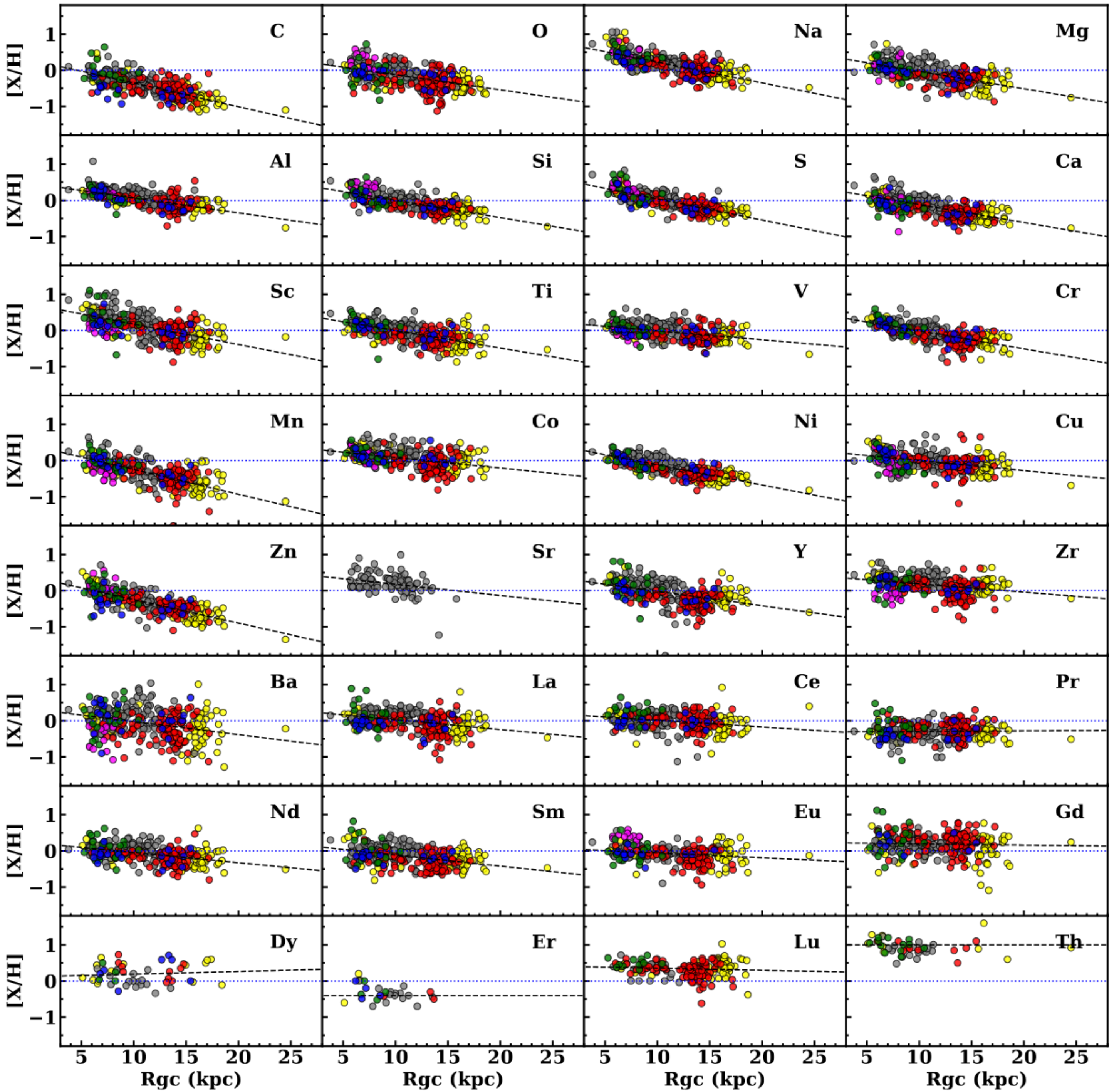
Reid+(2019)



All models collected in SpiralMap tool (Prusty+2025)

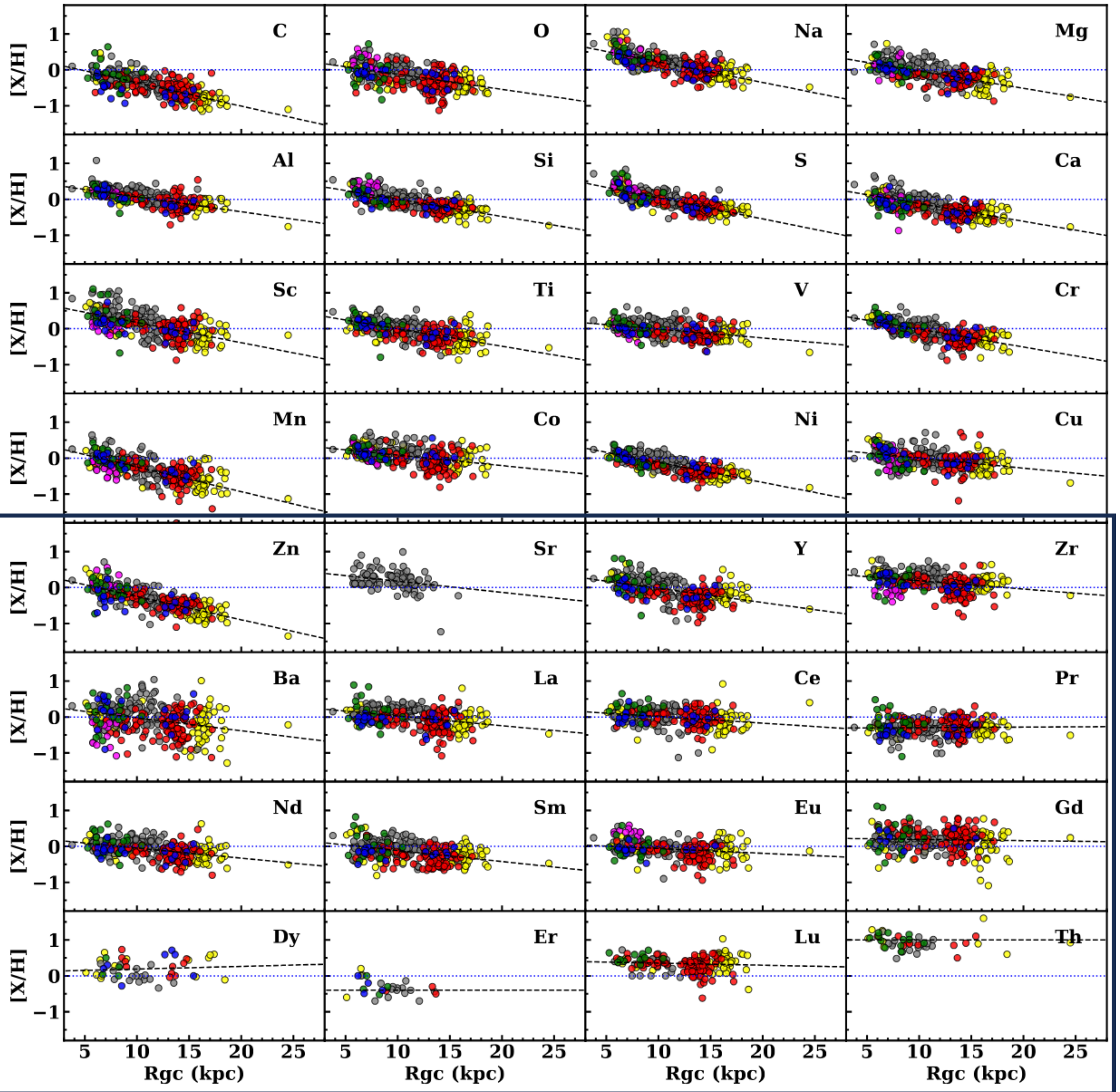
Radial gradient for the other elements

- Light, α and iron-peak elements have clear negative radial slopes;
- Neutron capture elements have shallower or null slopes;



Radial gradient for the other elements

- Light, α and iron-peak elements have clear negative radial slopes;
- Neutron capture elements have shallower or null slopes;
- Four new elements have been estimated in Trentin+(2026):
  - Dy (Z=66)
  - Er (Z=68)
  - Lu (Z=71)
  - Th (Z=90)



Neutron capture elements: slow (s-) processes

- Elements formed from lighter elements, by capturing one or more neutrons

- The difference between s- and r- processes lies in the neutron density, which influences the rate of capture on a timescale which competes with that of the radioactive decay.

- The traditional main s-processes:
  - For elements from Fe to Sr:
    Massive stars for solar metallicity (Pignatari et al. 2010)
    1. Low-metallicity stars with high rotational rates (Frischknecht et al. 2016, Limongi & Chieffi 2018)
  - For elements from Sr to Pb, low-mass AGB stars (see e.g. Karakas & Lattanzio 2014, Cescutti & Matteucci 2022)

Neutron capture elements: rapid (r-) processes

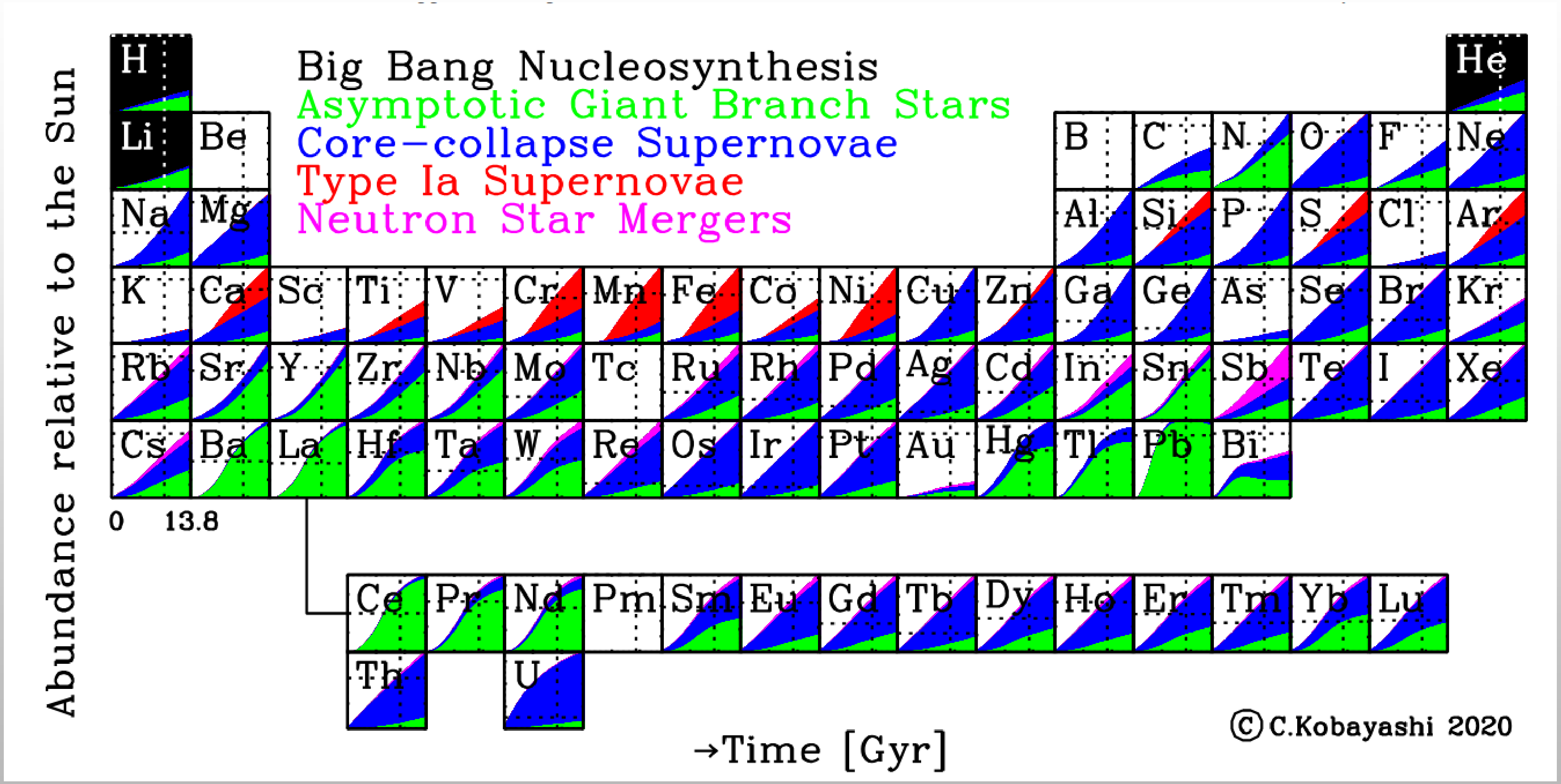
- The astrophysical nature of r-processes is still under debate.

- Several sites of formation of r-proces elements contribute differently and might depend on the metallicity.

- The most famous production channels:
    - Electron-capture Supernovae (ECSNe) (Hoffman+2008,Wannajo 2013)
    - Neutrino-driven winds (Arcones&Montes 2011, Wannajo 2013)
    - Neutron star mergers, whose events were confirmed by the recent gravitational wave detection of GW170817 (Abbott+2017a)
    - Magneto-rotational Supernovae (MRSNe, Cameron 2003, Nishimura+2015)

- In the Sun, 98% of Eu, 82% Gd and 88% of Dy are produced by r-processes.

Kobayashi, Karacs and Lugaro 2020: The Rosetta stone



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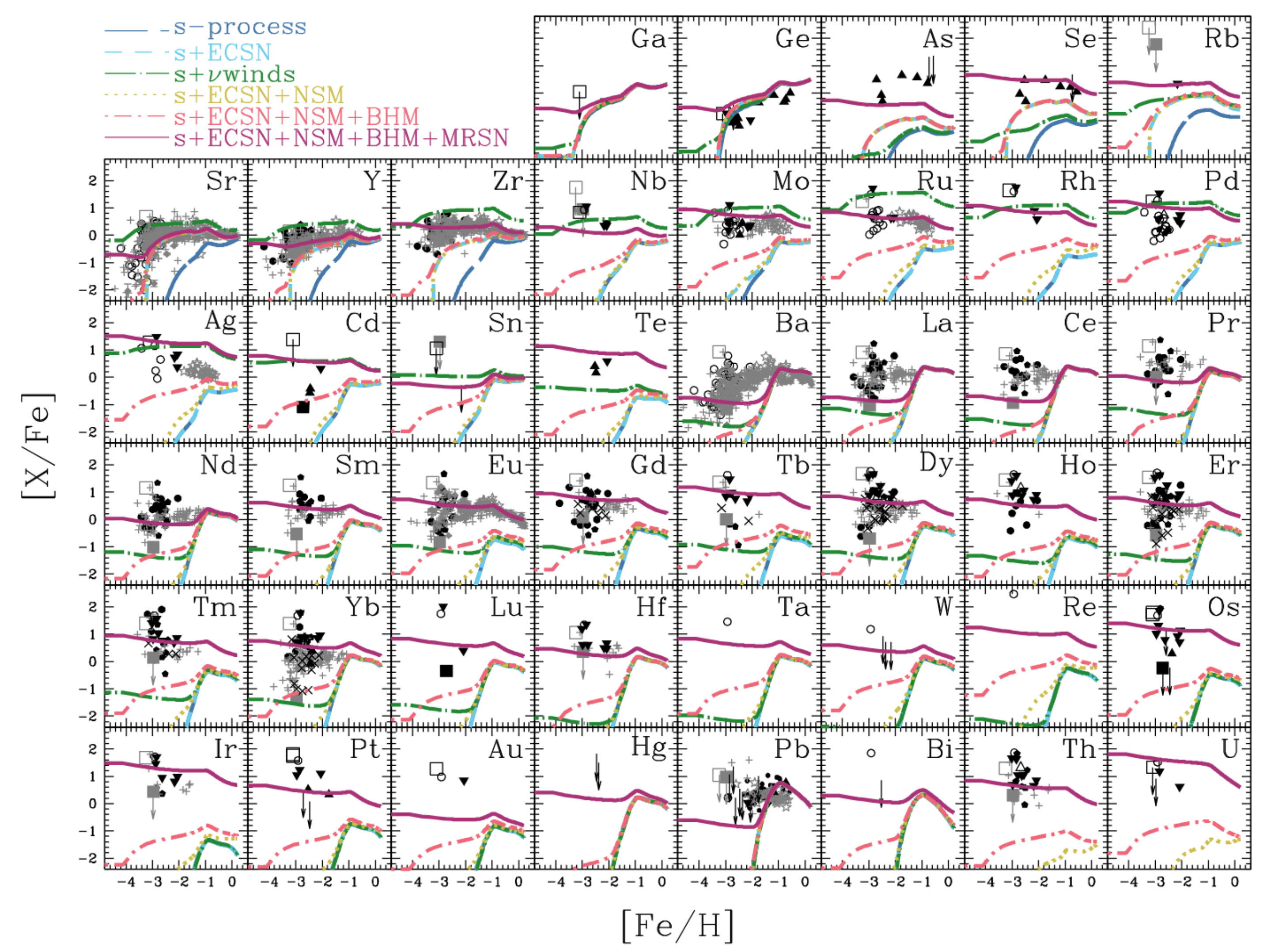

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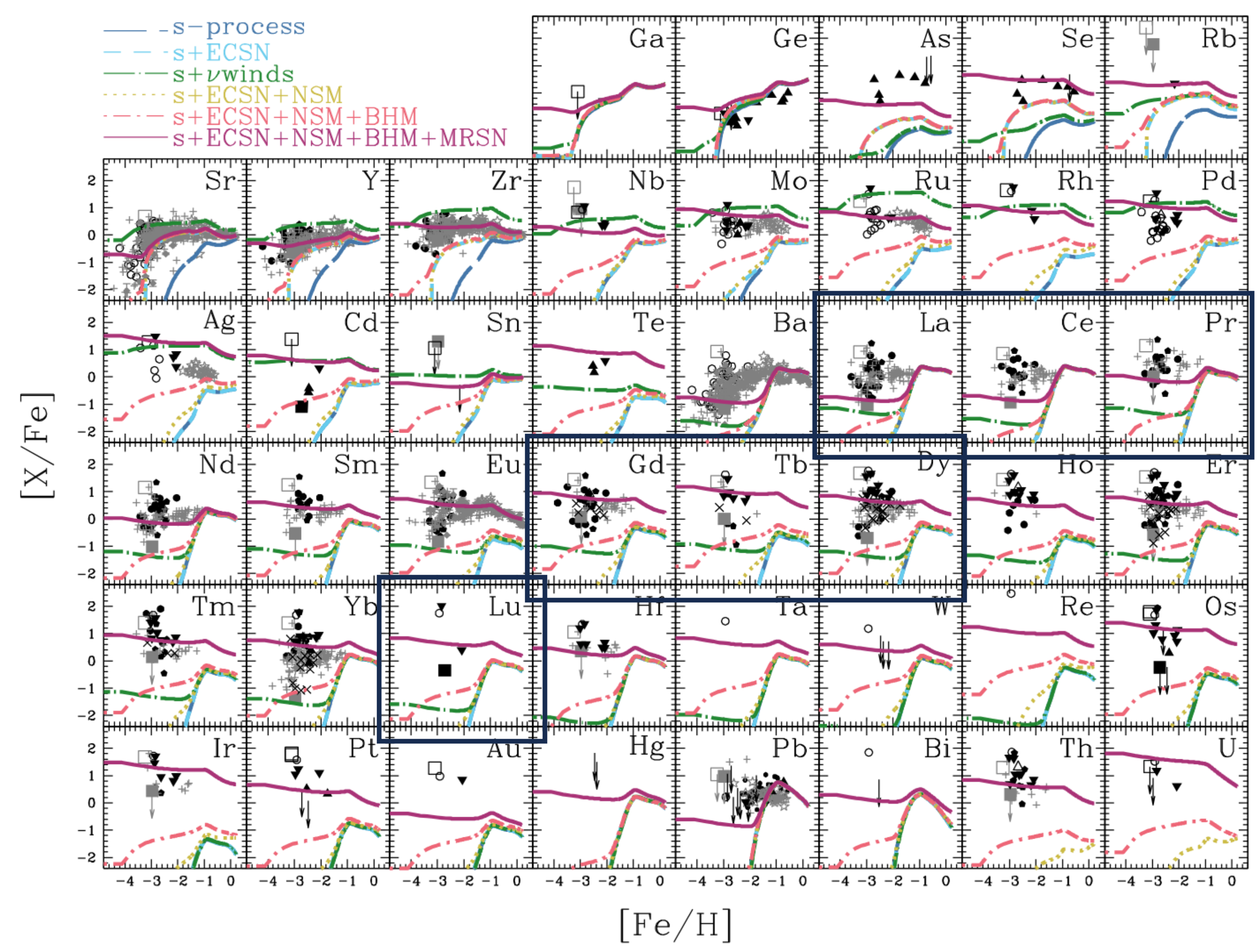

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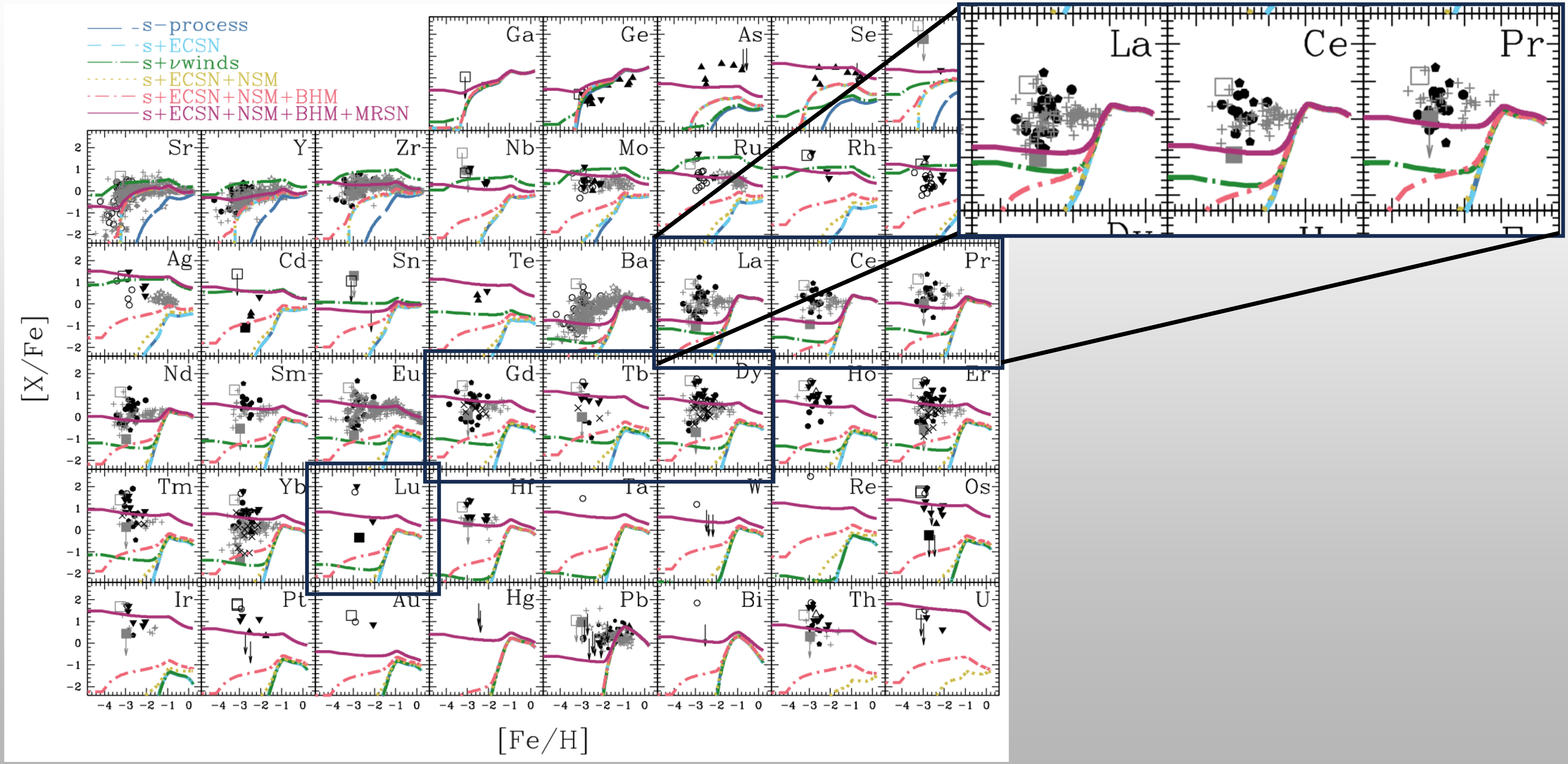

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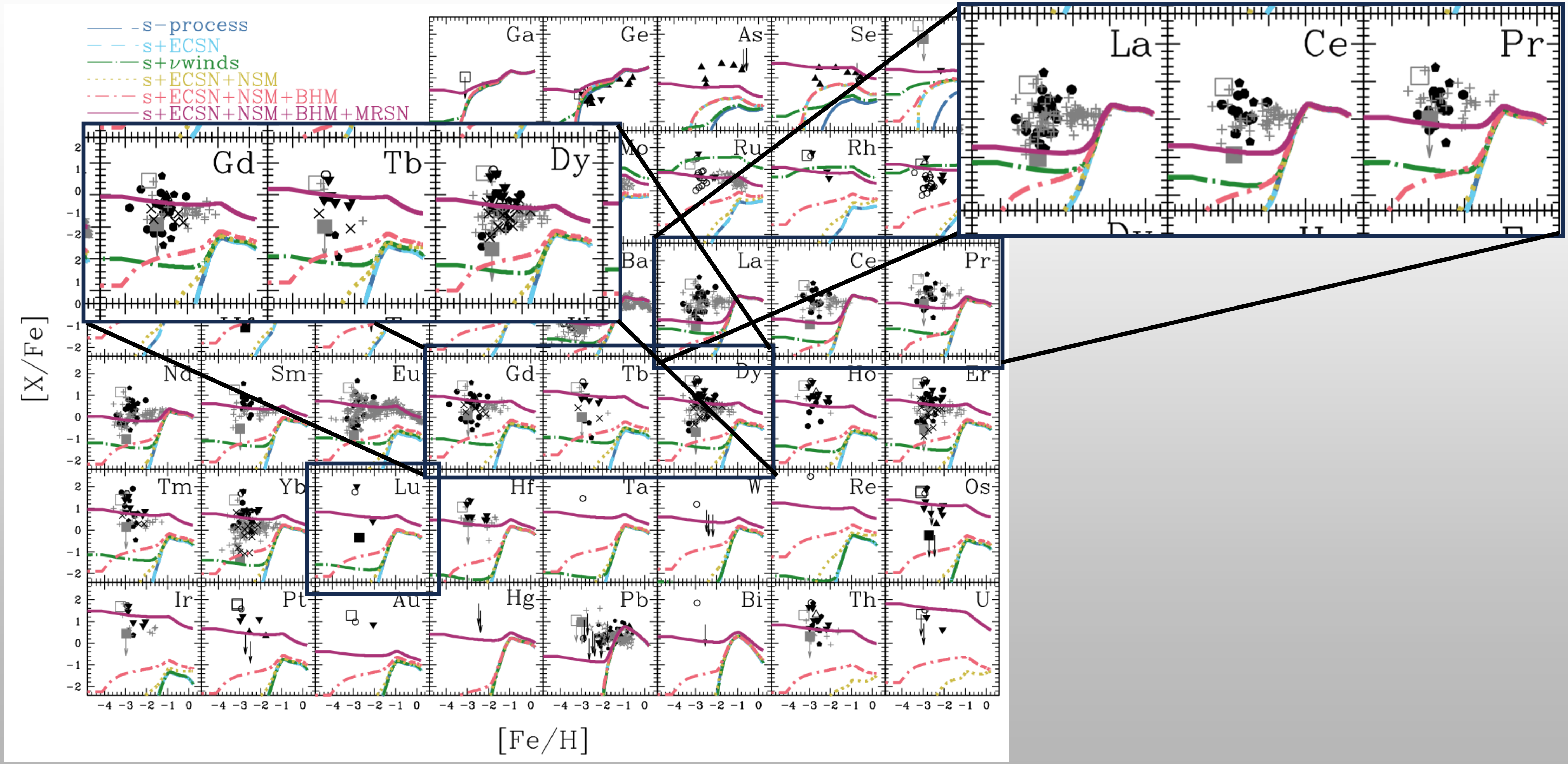

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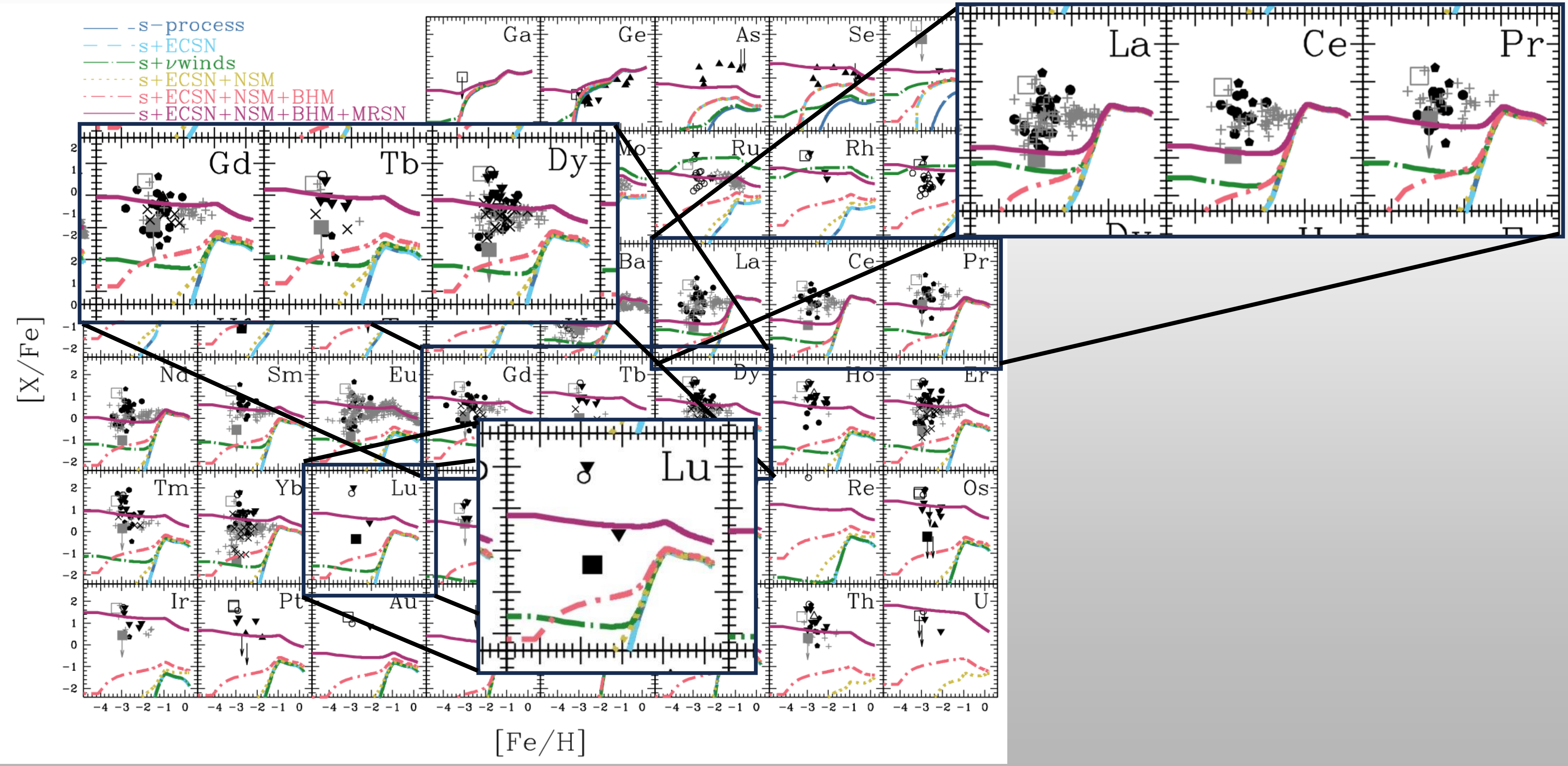

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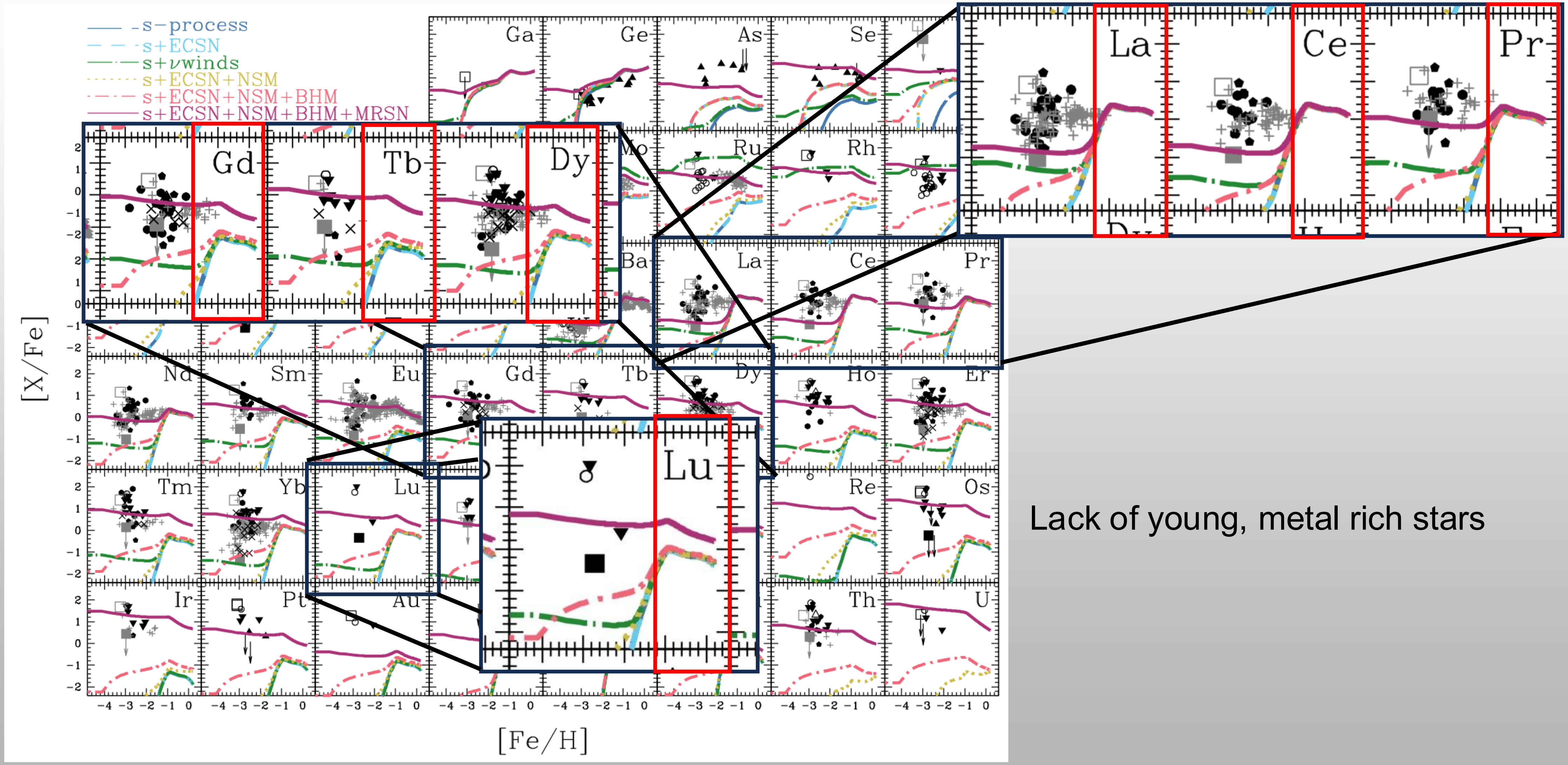

Lack of young, metal rich stars

A brief and incomplete summary of recent measurements of r-process elements abundances

- The AMBRE project (de Laverny+2013, Guiglion+2018, Mishenina+2022) :FGK dwarf stars;

- R-Process Alliance (RPA, Hansen+2018,2025): metal poor stars ([Fe/H] < -1);

- Lyubimkov+(2022a,b) more than 20 red giant stars with strong magnetic fields;

- Several other studies with estimation from metal poor stars: Saraf+2023, Lin+2025, Silva&Smiljanic 2025;

- Kovtyukh et al. (2023) analysed a Classical Cepheid already included in our sample;

Towards ELT and ANDES

- Significant advantage in observational time: in order to obtain the same SNR (>50) at high magnitude (G~14), we pass from ~ 1h for VLT to ~10 minutes for ELT
  - Reduced effect of pulsation on the atmosphere and spectral lines
  - Possibility to build a statistical solid sample, homogeneously analysed

- With a resolution of 100.000, abundances errors will be lower than present ones (below 0.1 dex, coming from spectral line statistics and error propagation from atmospheric parameters) and weak lines will be relevant

- In combination with more precise distance information (e.g. Gaia DR4) study of chemical enrichment and chemical characterisation of spiral arms

Conclusions

- Classical Cepheids represent a powerful tool to study both the structure, dynamics and recent chemical evolution history of the MW disc;

- They are textbook objects for optical spectroscopy of FGK stars, with a broad range of chemical elements that can be estimated: light elements, odd-Z, α, iron-peak, neutron capture (up to 33 in the context of the C-MetaLL project);

- ANDES@ELT will offer a great opportunity to significantly improve the determination of both atmospheric parameters and chemical abundances, breaking the current "wall" of error at ~0.1 dex;

- Unique chance of explore chemical formation channels, evolutional and pulsational models