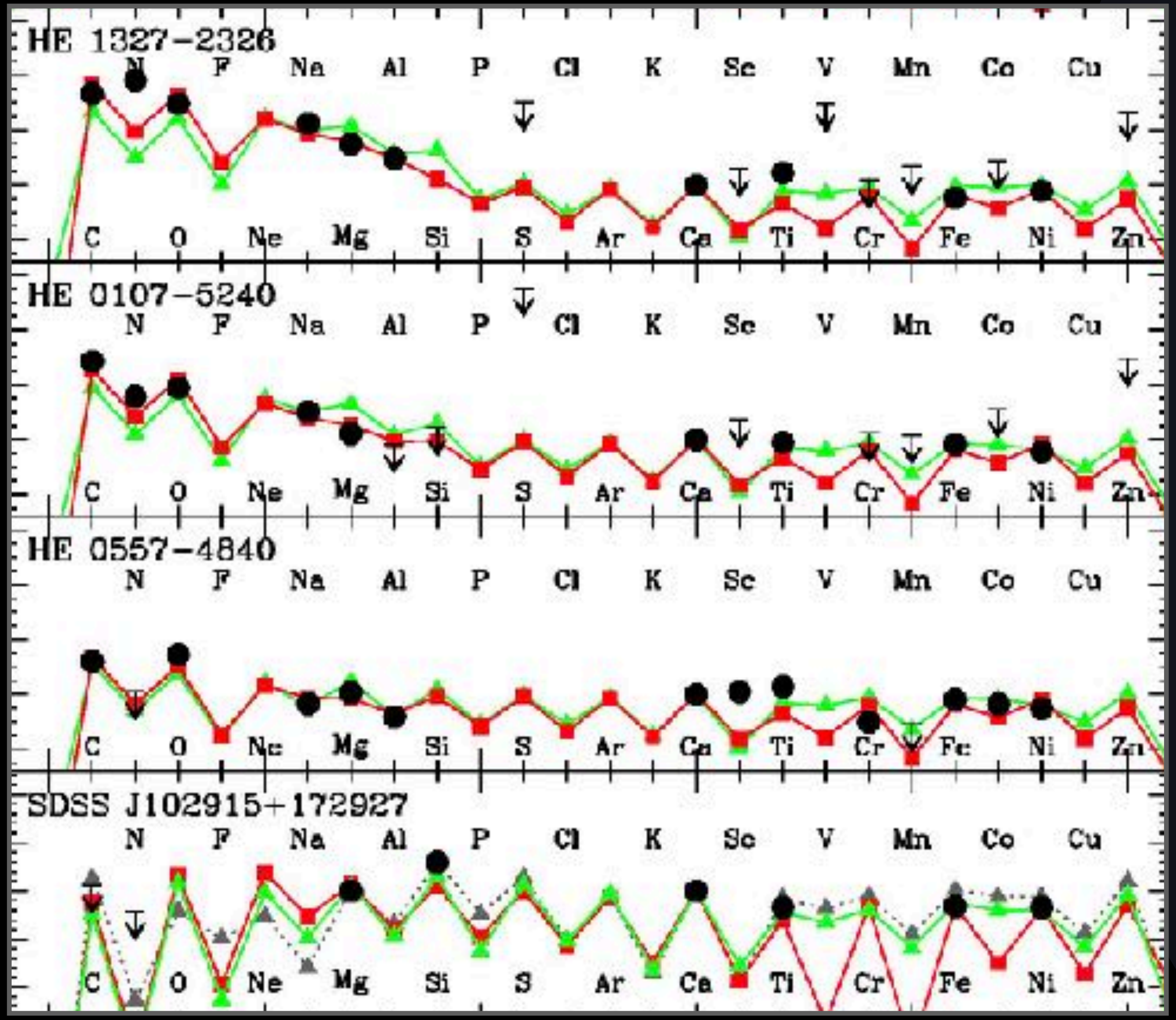
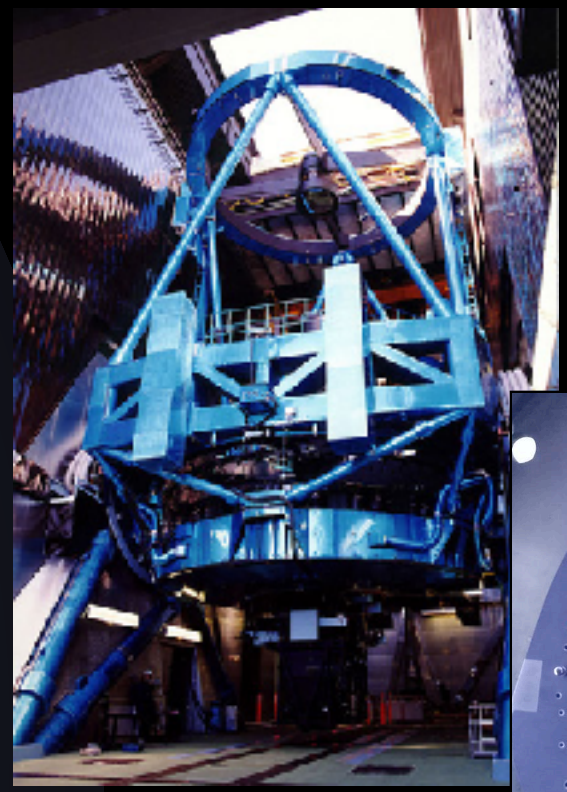
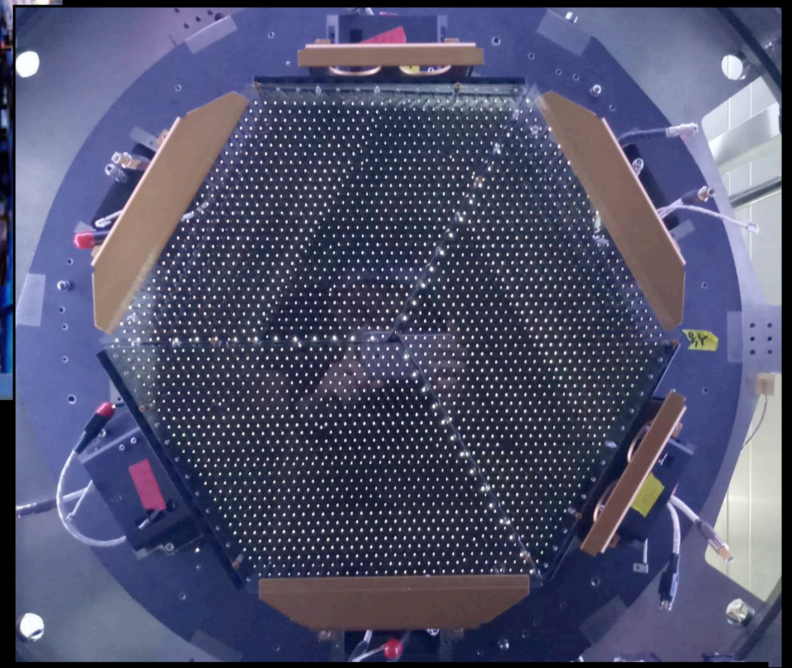
Elemental Abundances of Extremely Metal-Poor Stars

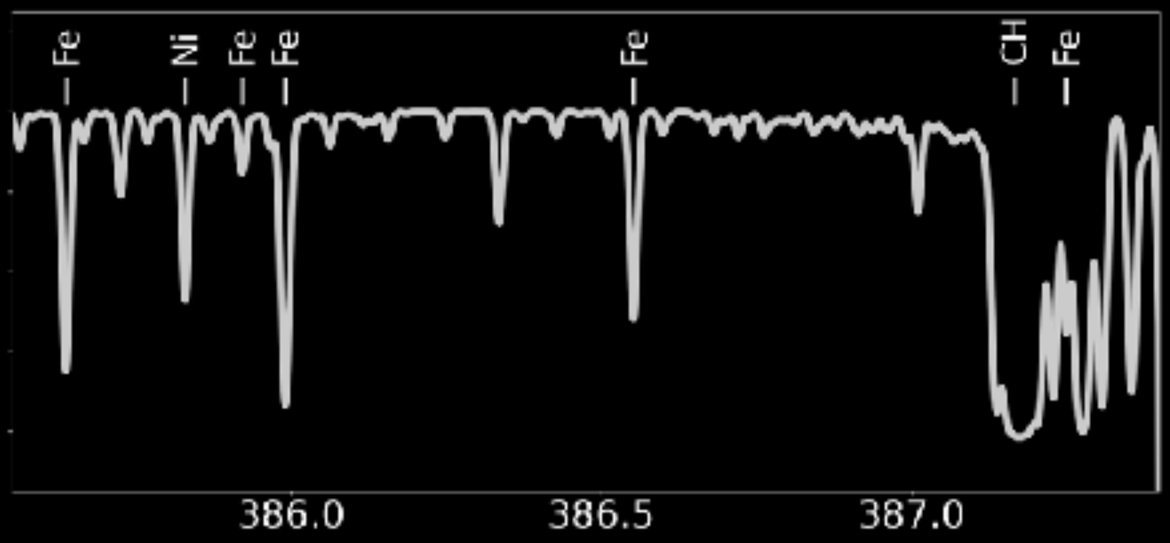


Miho N. Ishigaki
Subaru Telescope, NAOJ

Nuclei in the Cosmos XVIII
June 16-20th, 2025 Girona





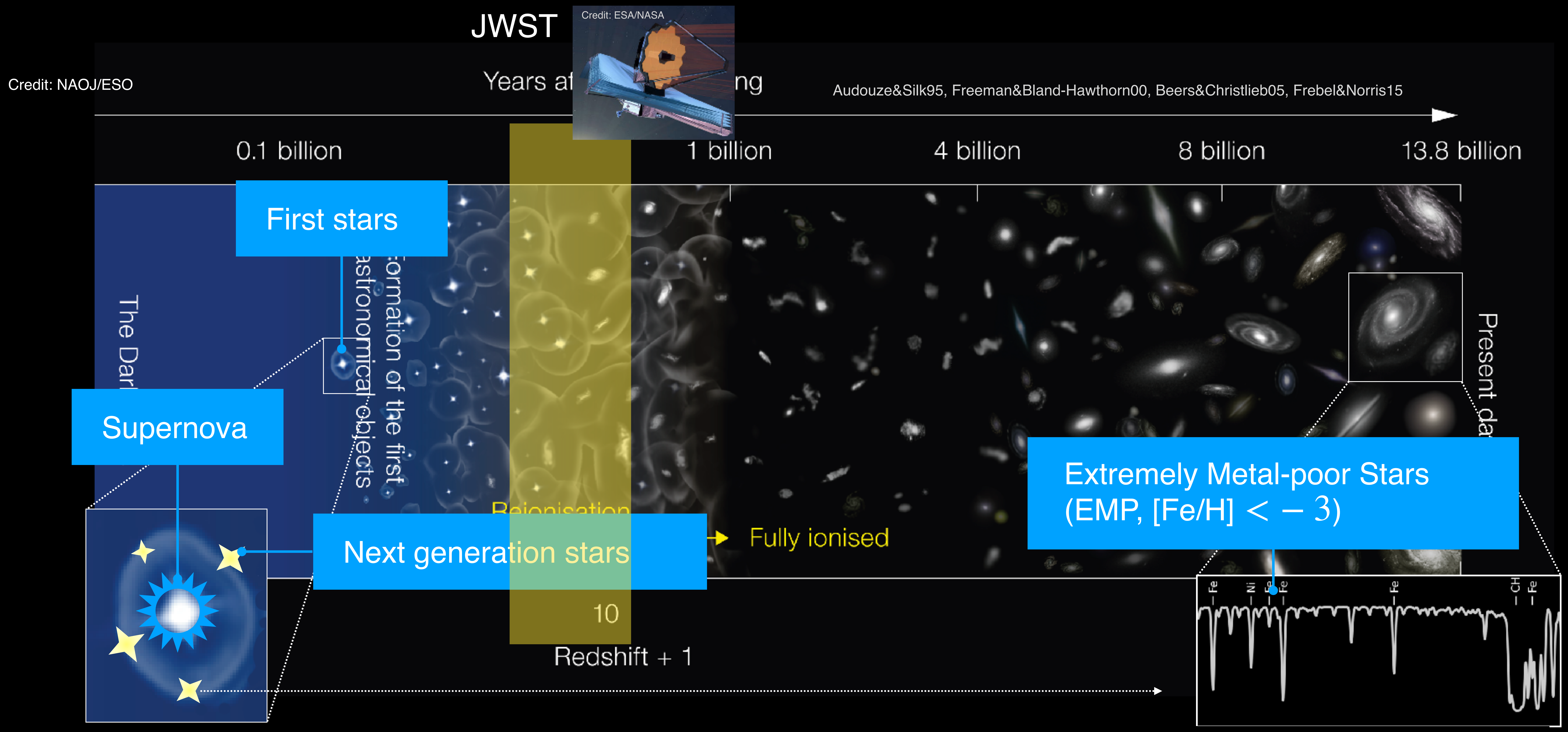


Collaborators: T. Hartwig, C. Kobayashi, N. Tominaga, K. Nomoto, S. Wanajo, T. Takiwaki, K. Nakamura, W. Aoki, Y. Takeda, PFS Galactic Archaeology science working group, inspiring discussion with many others!

Nucleosynthesis in the early universe:
What did we learn from the abundances of Extremely Metal-Poor (EMP) stars?

- The basic picture
  - EMP as a probe of the nature of the first stars and their supernovae
- Challenges in the abundance interpretation
  - “mono-” vs. “multi-” enriched EMPs
  - Abundances of odd-Z elements: the case of Potassium (K)
- Future Prospects - go beyond the solar neighborhood

Abundances of EMPs： A basic picture

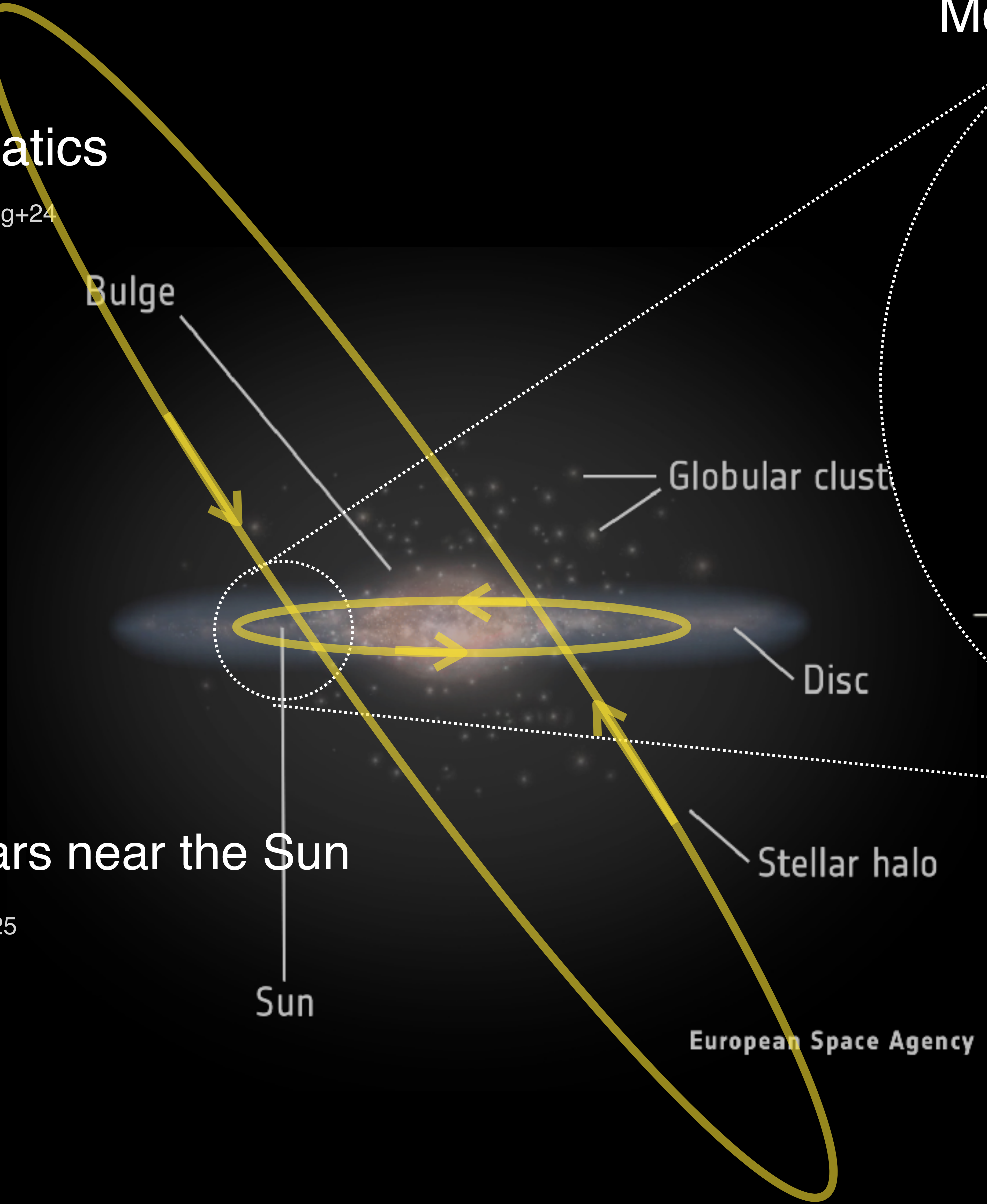


$$[\mathrm{Fe/H}] = \log\left(N_{\mathrm{Fe}}/N_{\mathrm{H}}\right) - \log\left(N_{\mathrm{Fe}}/N_{\mathrm{H}}\right)_{\odot}$$

EMP stars in our Galaxy

A wide range of orbital kinematics

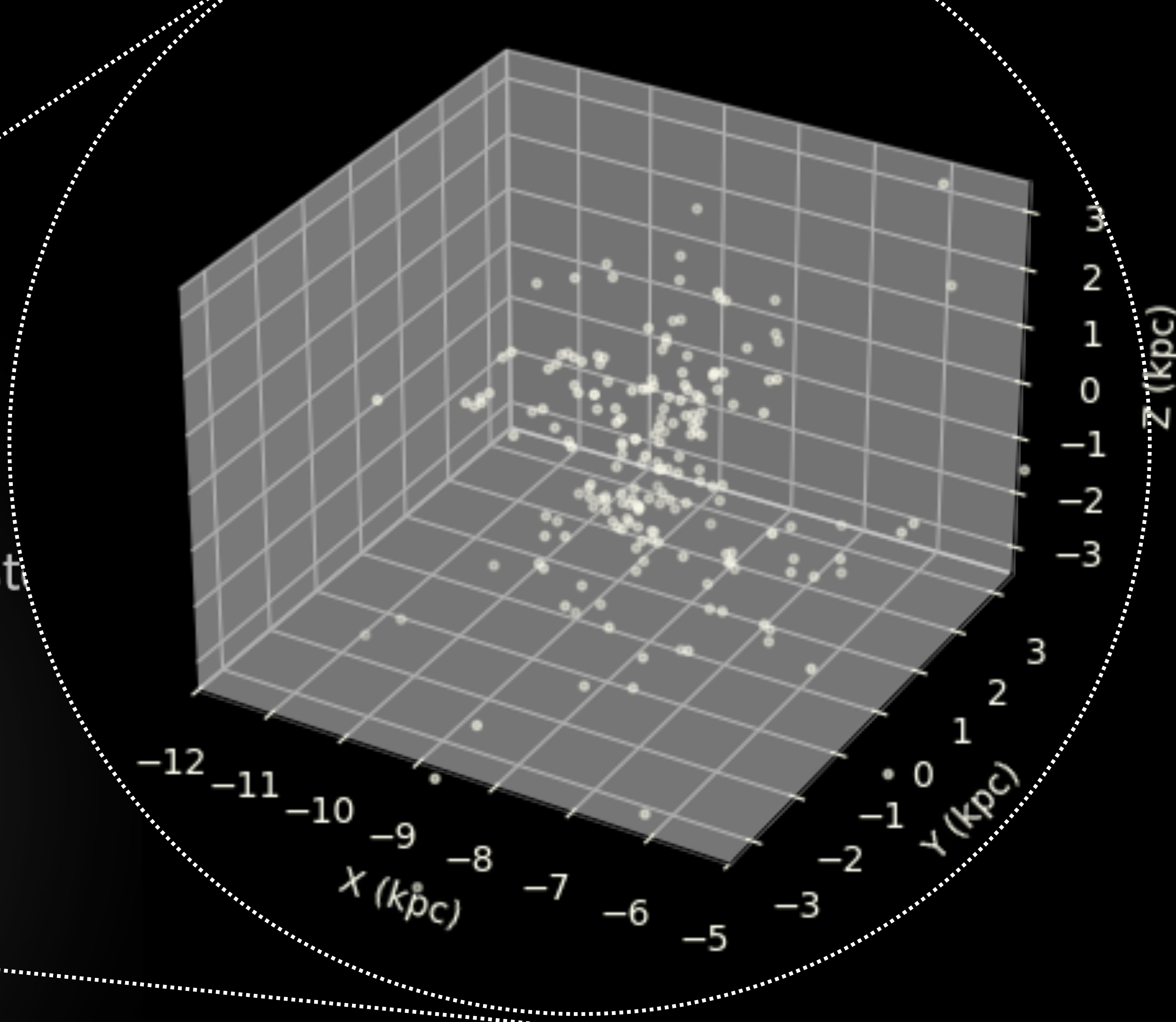
Sestito+19, 20; Carollo & Chiba21, Carollo+23, Zhang+24



Very rare: $10^{-4} - 10^{-5}$ of stars near the Sun

Shorck+09, Naidu+20, Youakim+20, Bonifacio+21, +25

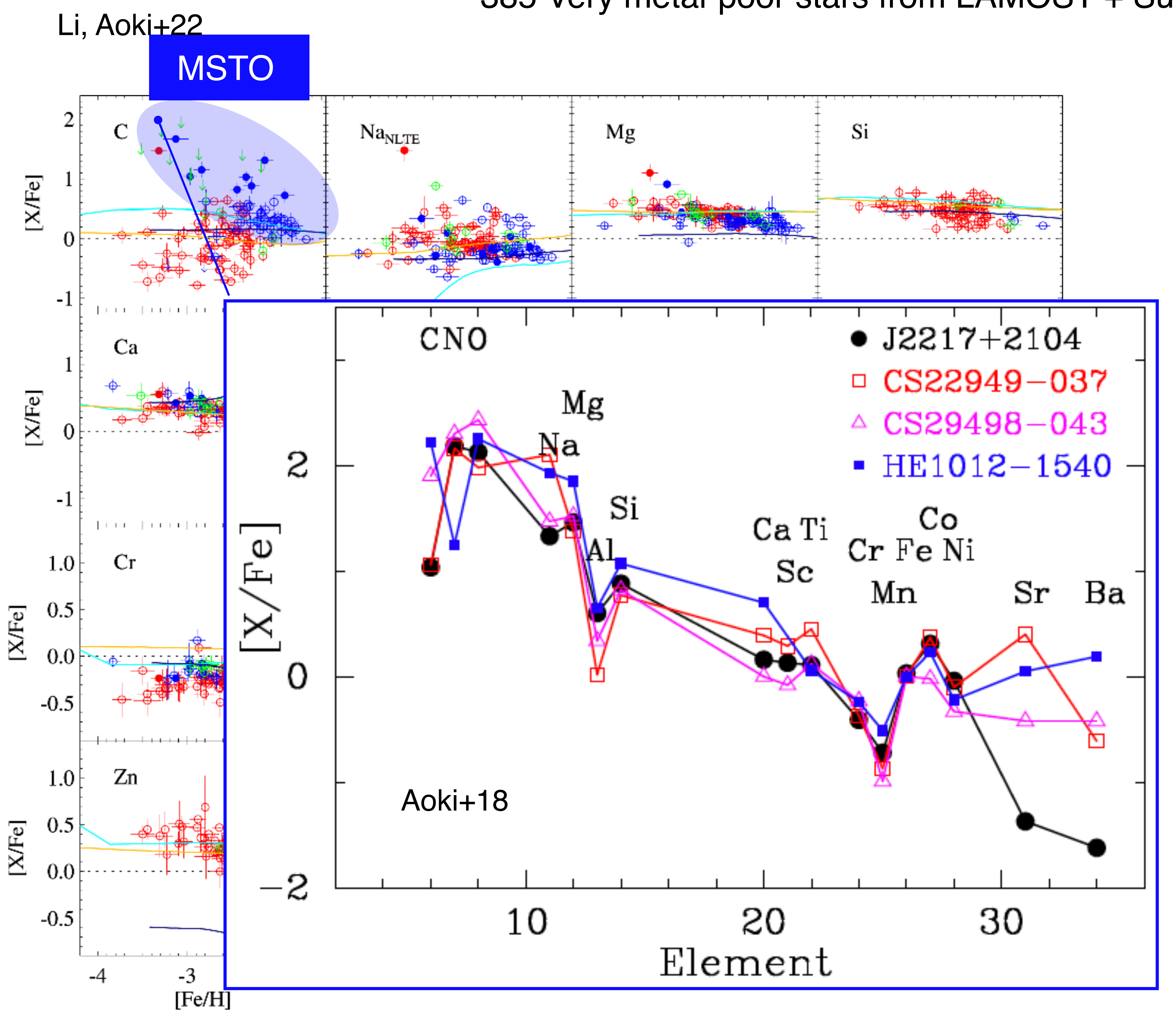
Mostly located within ~ 3 kpc



SAGA database (Suda+08)

Elemental abundance ratios from surveys

385 Very metal-poor stars from LAMOST + Subaru survey



A small scatter in Fe-peak elemental abundances

➡ the nucleosynthesis sources are independent of the birth environment

Cayrel+04, Cohen+13, Yong+13, Roederer+14

A few outliers hinting at unusual metal source in the early Universe

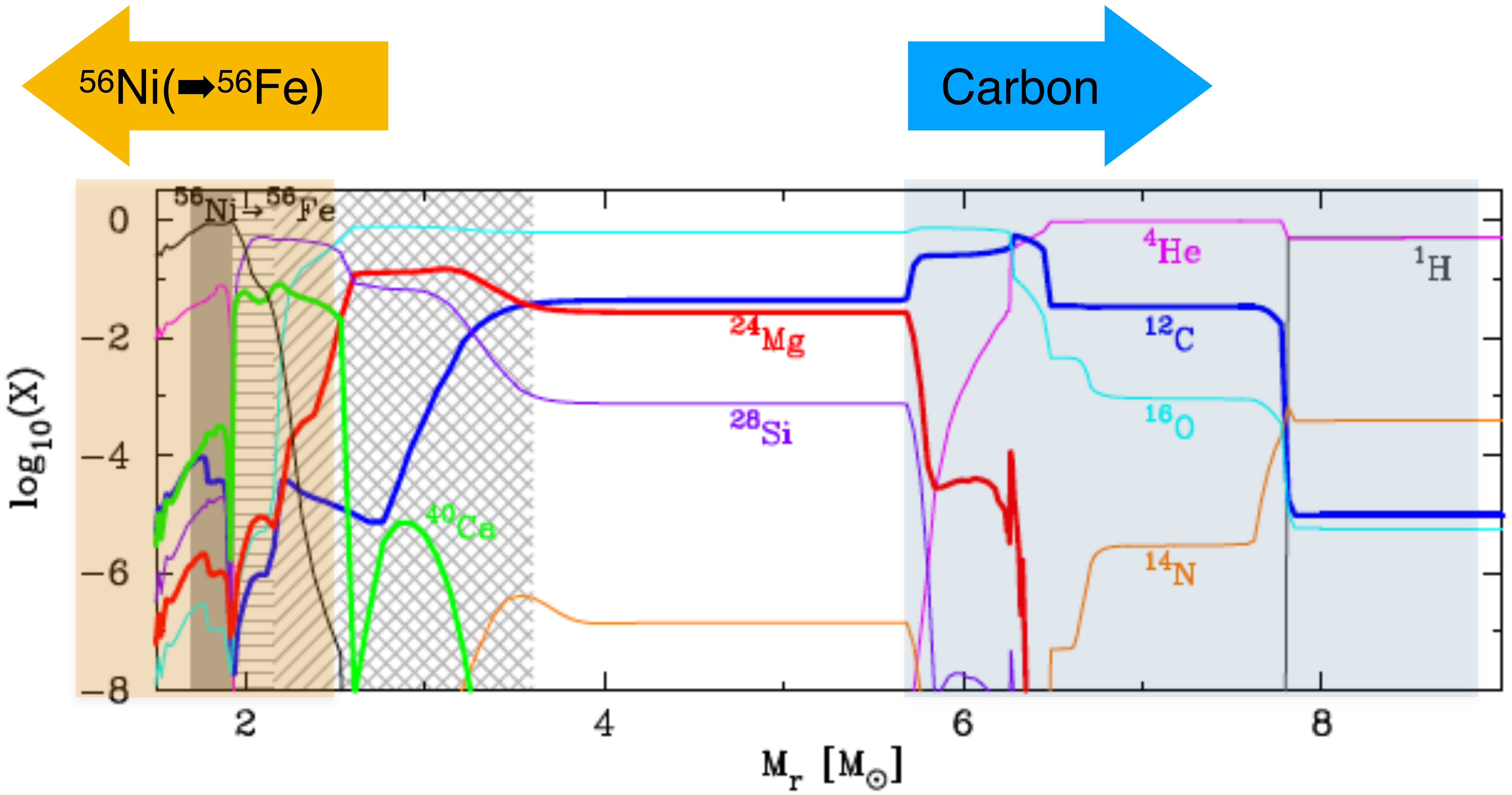
Xing+19, 23, Skúladóttir+24

About 30 % of the Main-Sequence Turn-Off stars are "CEMP", half of them are "CEMP-no"

First star's supernovae as a possible origin of CEMP-no

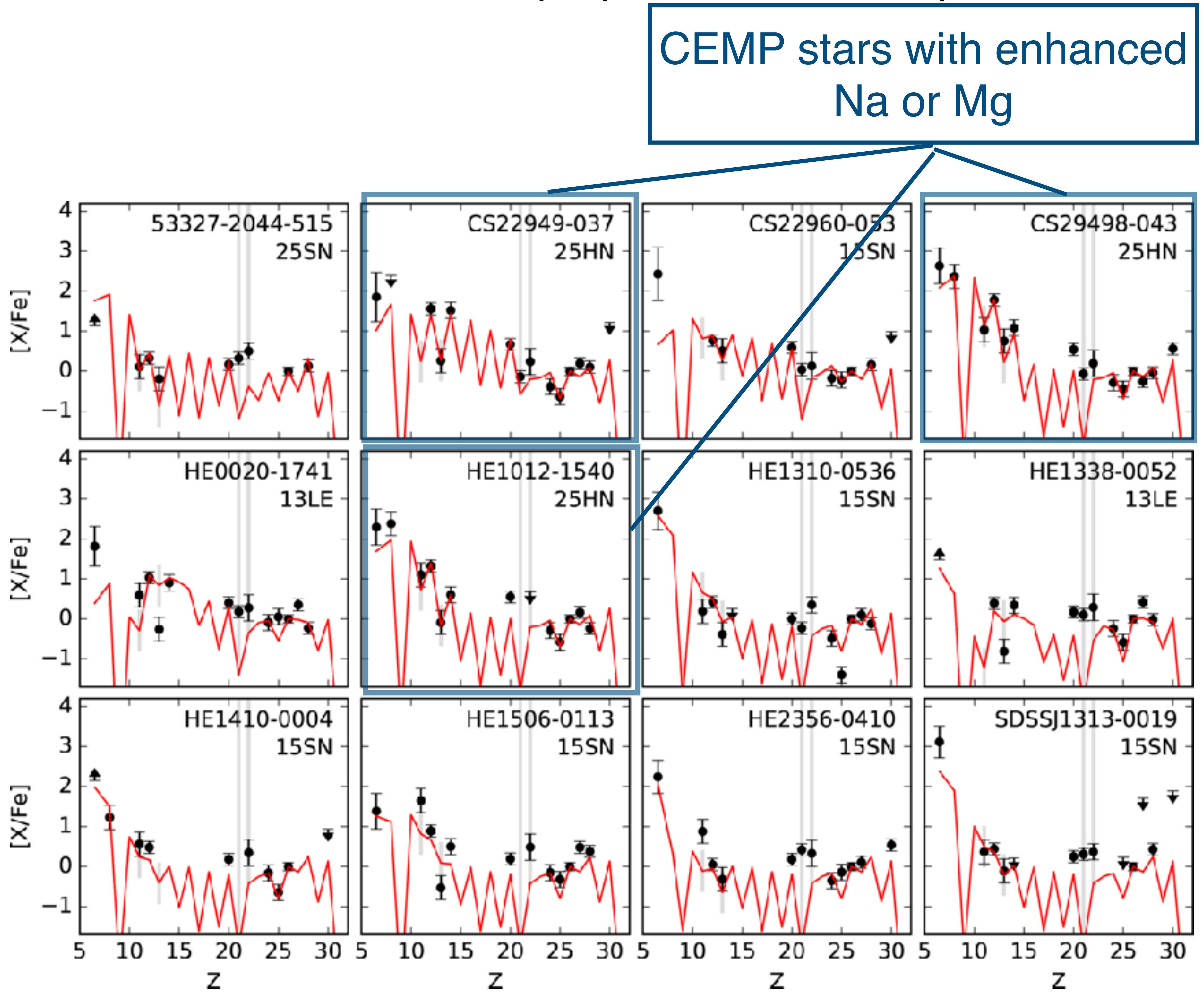
Abundance distribution after a first star's supernova

Umeda & Nomoto02,03; Tominaga+07



The variation in the CEMP abundances:

first star's masses or the properties of their supernovae



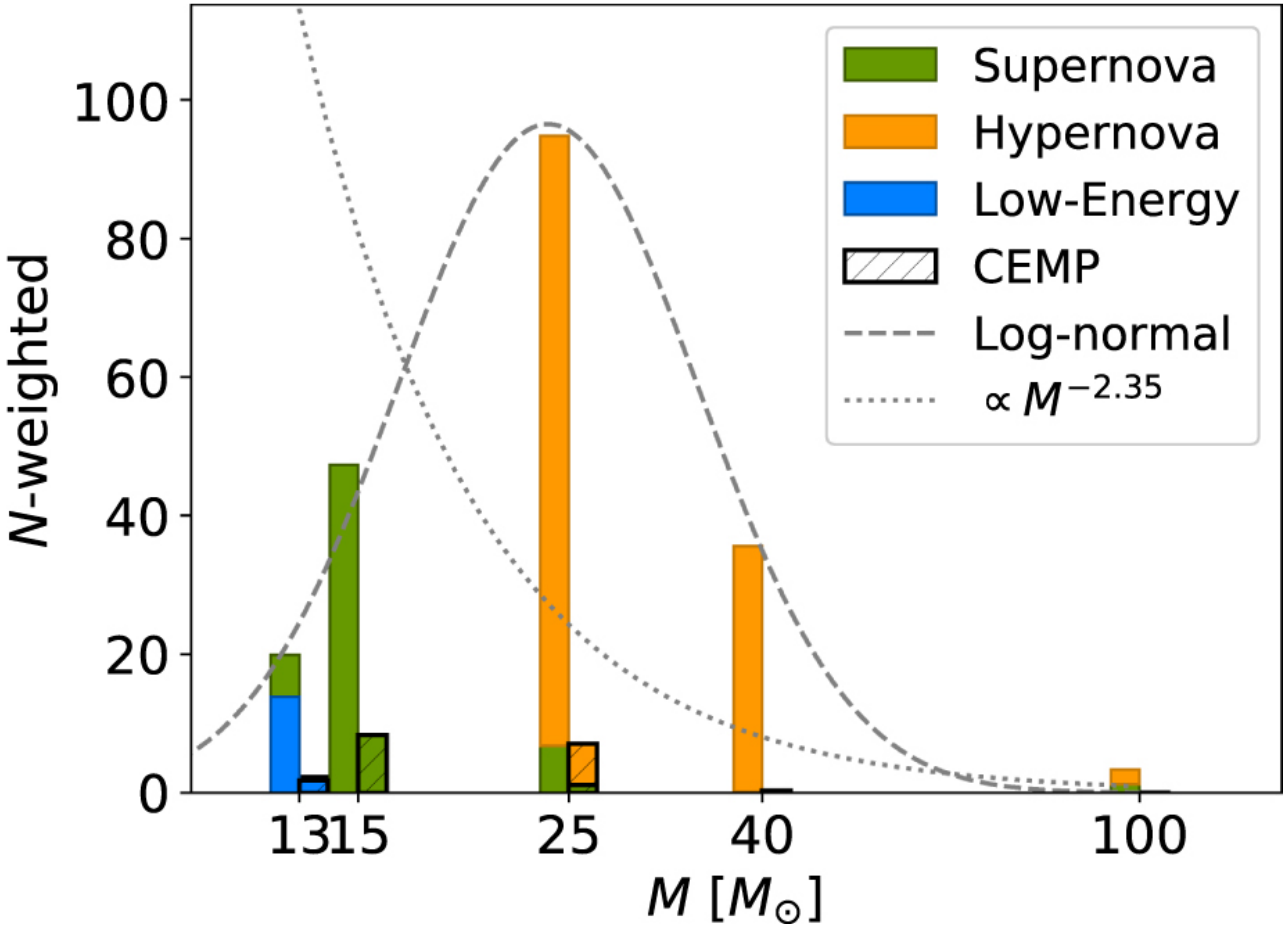
➡ Simultaneously reproduce the variation in Carbon enhancement and the small scatter in Fe-peak elements observed in the EMP stars MI+14

Iwamoto+05, Tominaga+06, Hansen+15; Aoki+18; MI+18

Properties of the first star's supernovae infered by the abundances of EMP stars

MI, Tominaga, Kobayashi & Nomoto18

The (χ^2-weighted) histogram of the progenitor masses of the best-fit first stsr's SN yield models



The observed abundances of EMPs are best explained by the first star's supernovae with a few tens of $M_\odot$, little contribution from more massive first stars

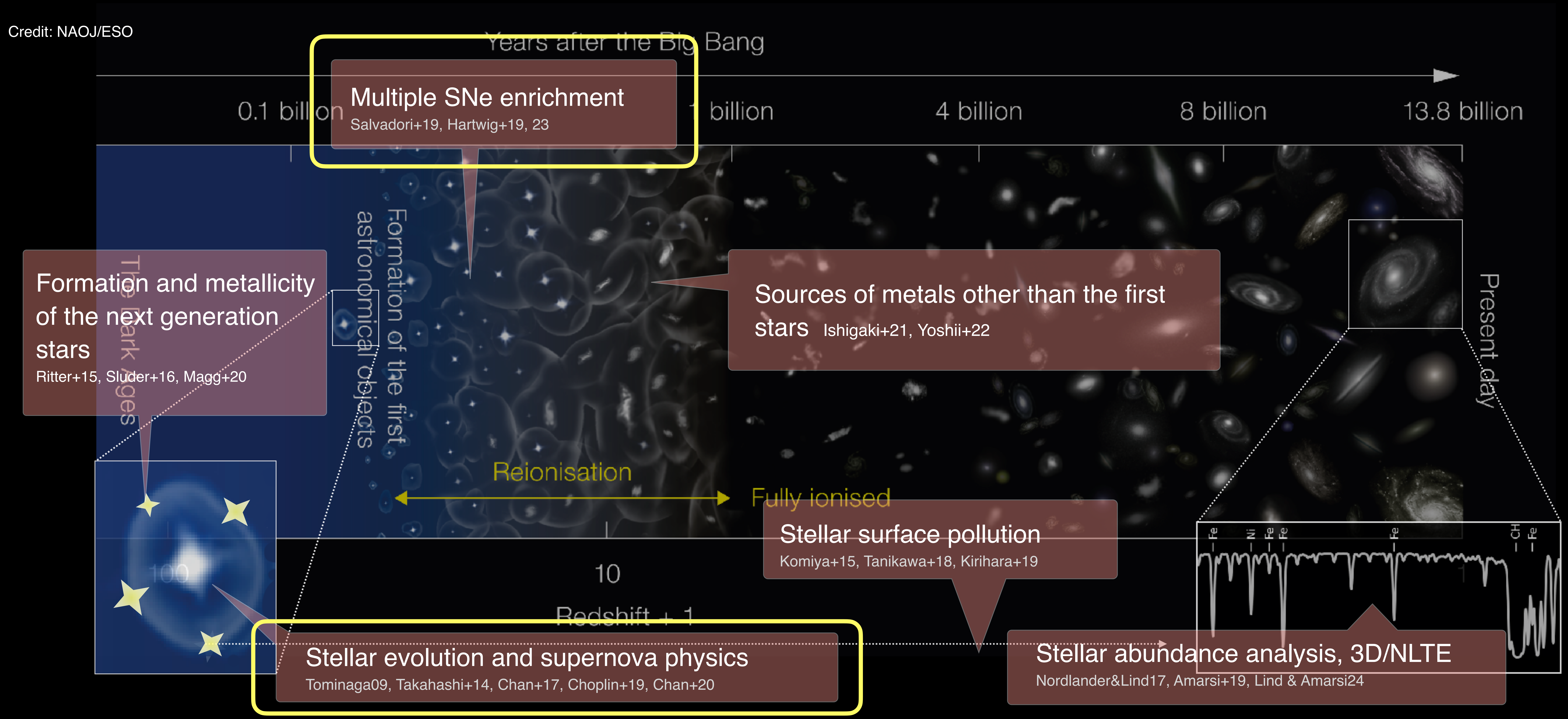
Tominaga+14, Placco+14, MI+18

A certain fraction of the stars are better explained by a supernova of high-explosion energy ("hypernova")

⬅ High [Zn/Fe] aundance ratios

Tominaga+09, Nomoto+13, Grimmett+21

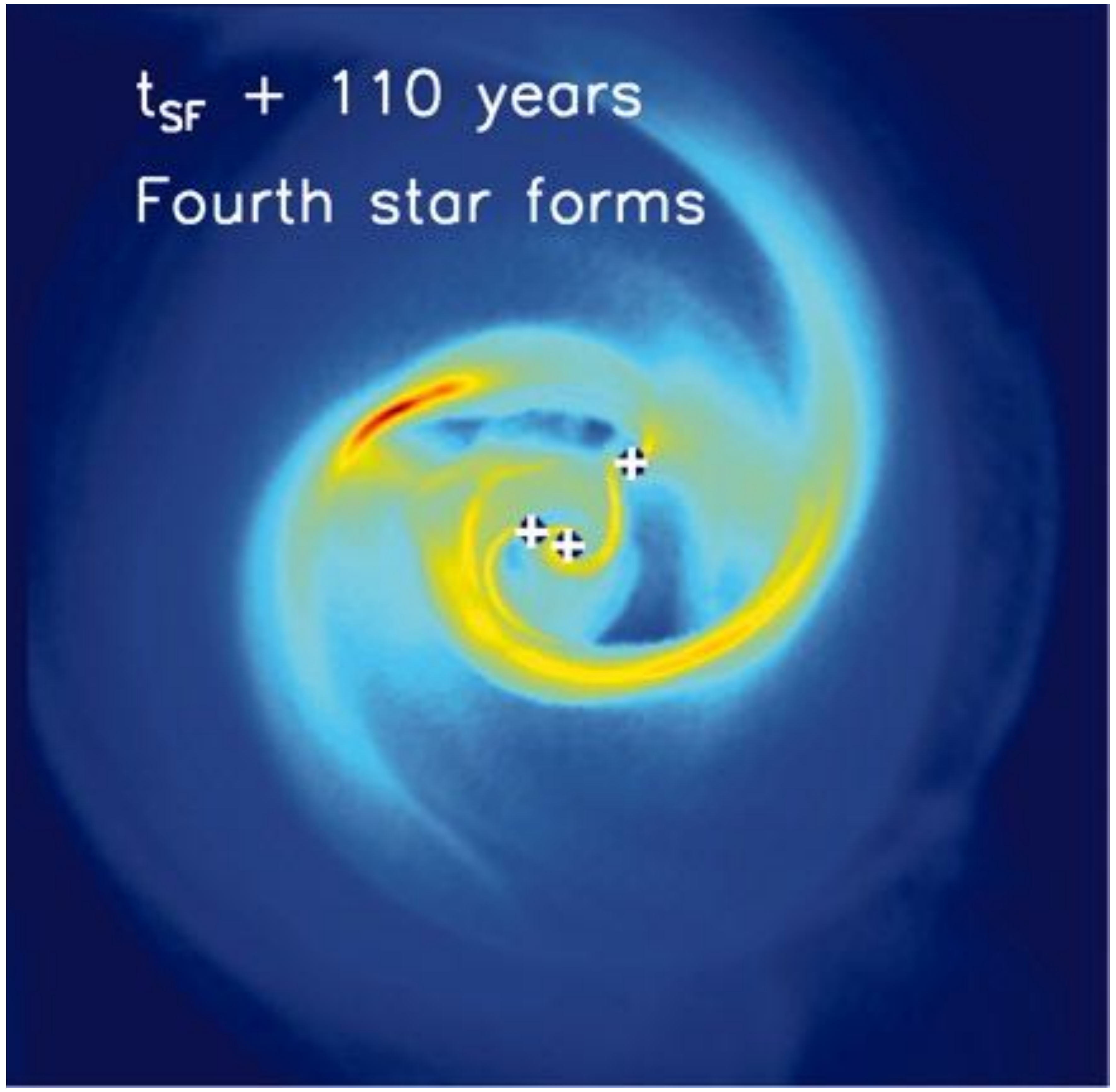
The abundances of EMP: realistic pictures



Multi-enrichment of the first star's supernovae

The first stars form in binaries/clusters

Clark+11, Greif+15, Hirano & Bromm+17, Susa+19, Sharda+20, Sugimura+20



Elements supplied by multiple first star's supernovae

The formation of 'multi-enriched' EMP stars

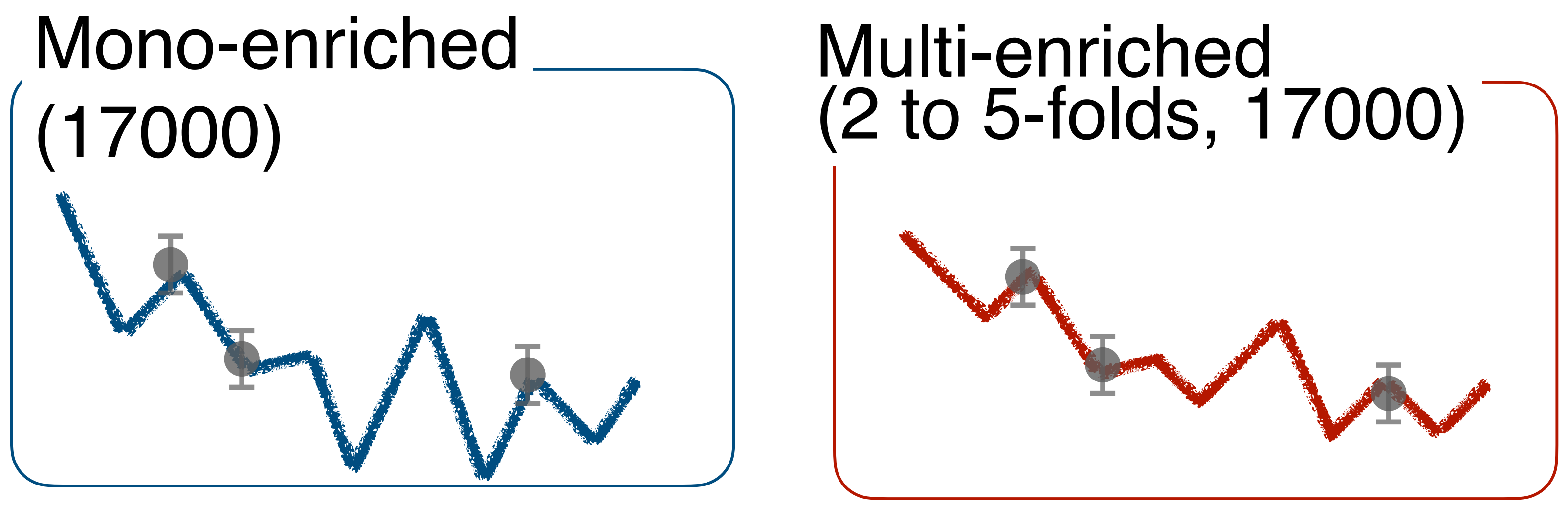
- The assumption about the 'mono-enrichment' may bias the inference on the properties of the first stars based on the abundances of EMP stars
- Challenging to constrain individual contributions (too many free parameters in the yield models, e.g., mass, explosion energy, fallback, mixing)

The classification of EMP stars into mono- and multi-enriched scenarios

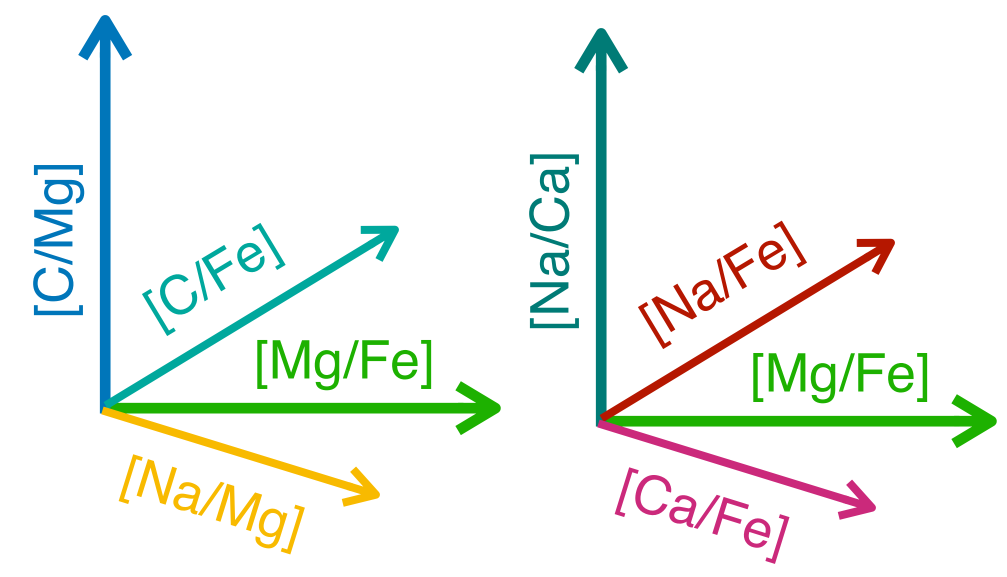
Hartwig, MI, Kobayashi, Tominaga, & Nomoto23

1. Create mock observation as a training set

539 yield models
Ishigaki+18



2. Training 10 Support Vector Machine (SVM) models based on 24 [X/Y] ratios (X, Y: C to Zn)



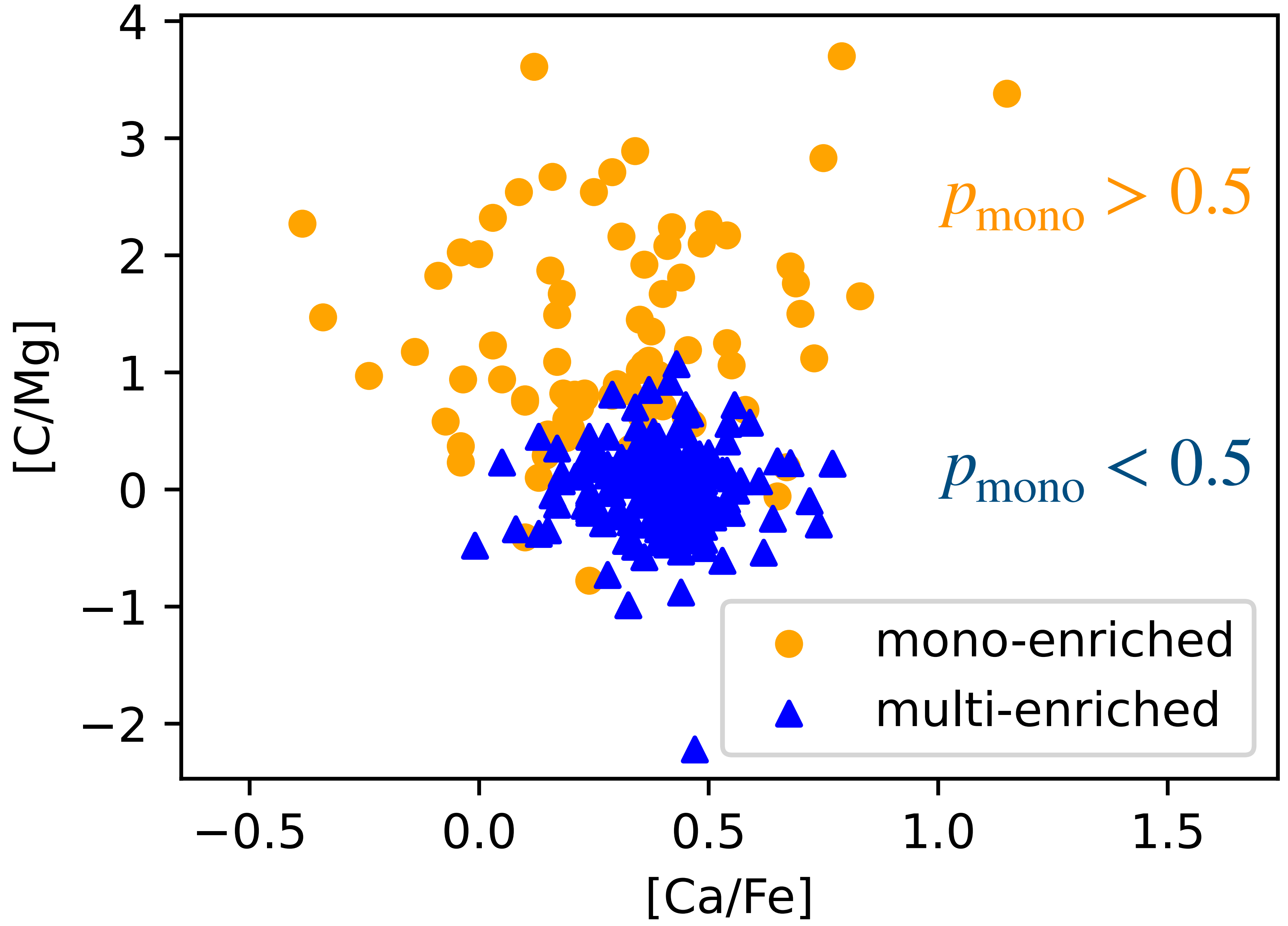
Average of 10 SVM predictions: $p_{\rm mono}$

3. Validation

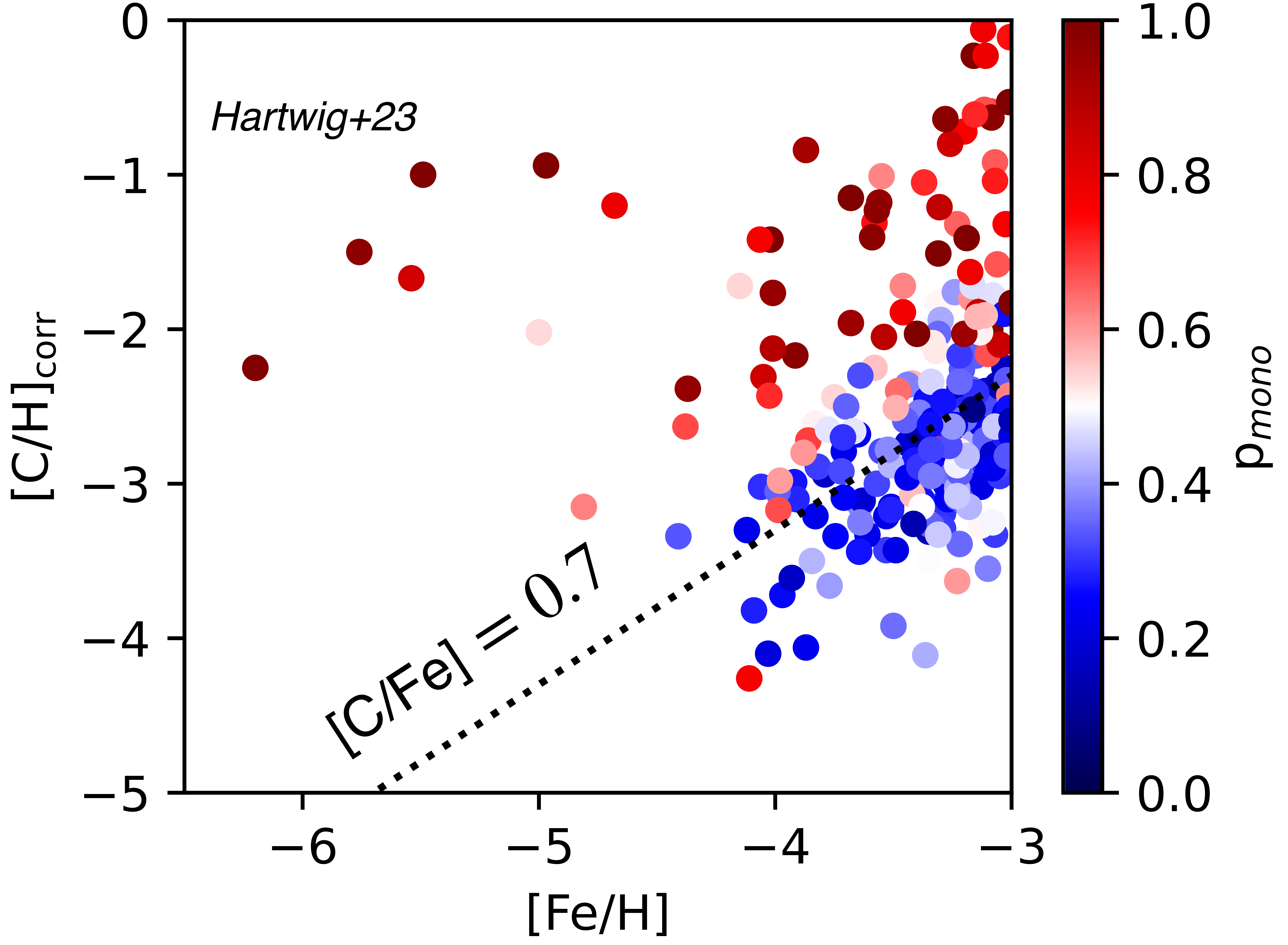
Ground Truth \ Prediction	N/A	mono	multi
mono	0.20%	34.20%	15.60%
multi	0.21%	13.84%	35.95%

Accuracy: $\sim 70\,\%$
(w/o errors: $\sim 79\,\%$)

4. Applying to observational data:
462 unique EMP stars SAGA database (Suda+08), Ishigaki+18



The origin of observed abundance patterns in EMPs



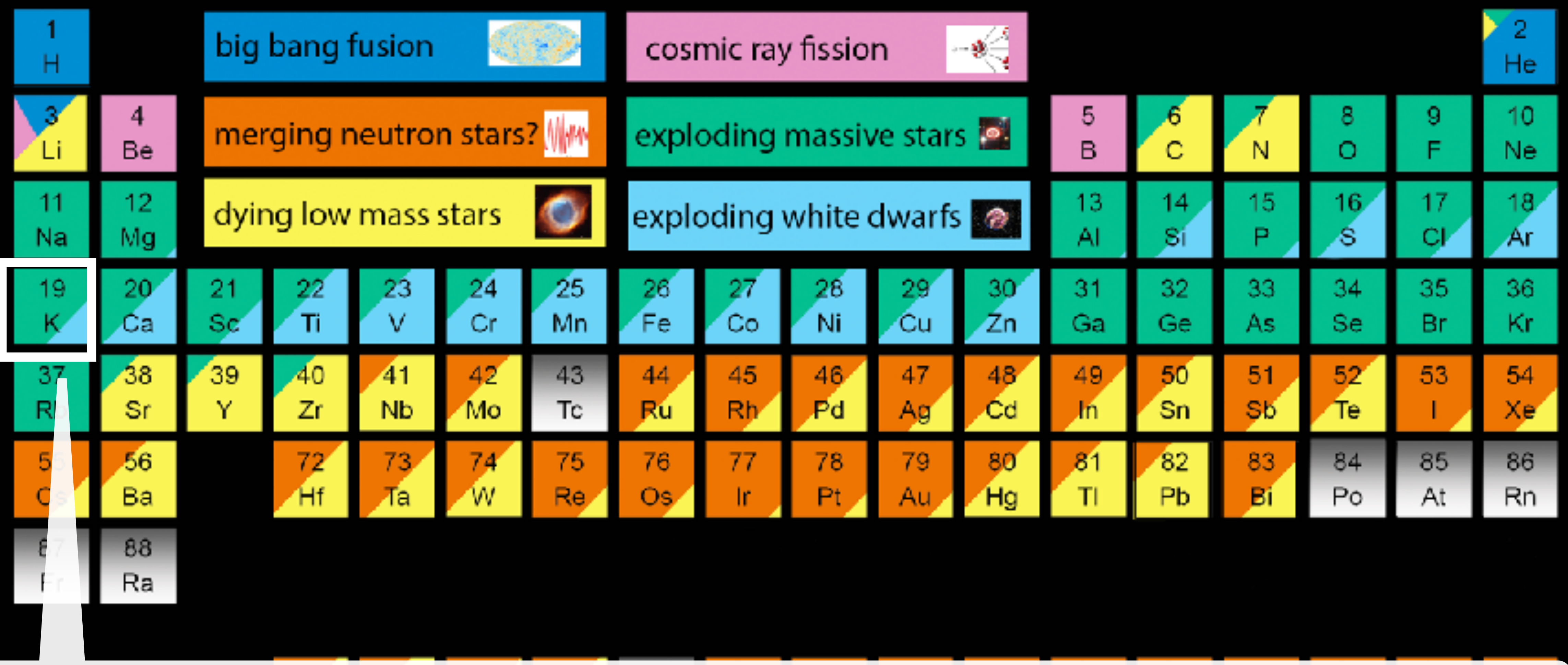
Carbon-enhanced ([C/Fe] > 0.7) stars ：more likely classified as mono-enriched stars

CEMP stars formed under the most pristine environment, e.g., very low star formation and/or low metal-mixing efficiency

The fraction of mono-enriched stars（$p_{\rm mono} > 0.5$）：$31.8\% \pm 2.3\,\%$

Abundances of odd-Z elements; Potassium

Credit: ESA/NASA/AASNova (created by Jennifer Johnson)



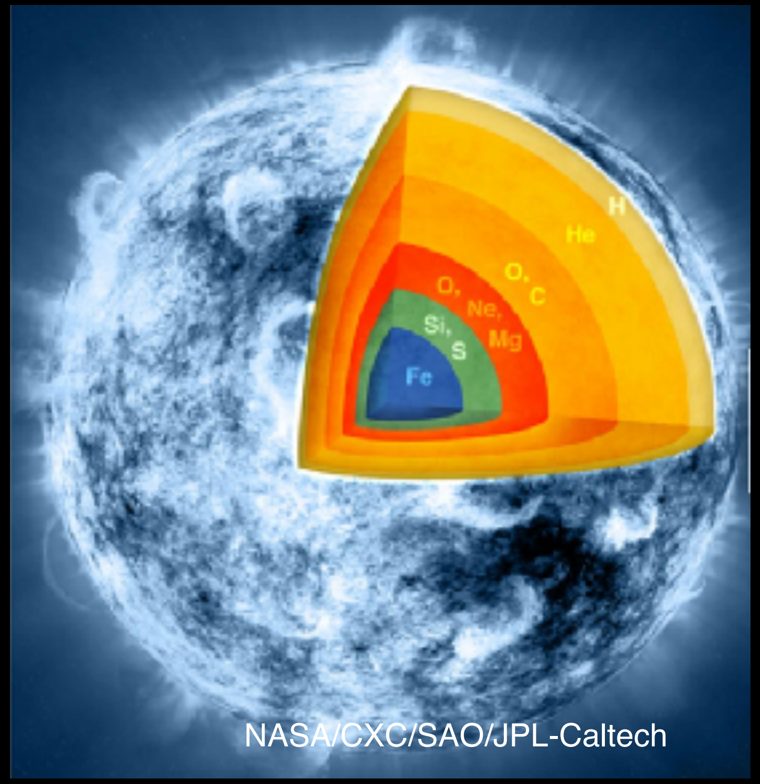
K $\left({}^{39}\mathrm{K}, {}^{40}\mathrm{K}, {}^{41}\mathrm{K}\right)$, Z=19

- An essential element for life, the Earth's crust, etc.
- Astrophysical origins and the chemical evolution are highly uncertain. Similar for other odd-Z elements such as Sc (Z=21) or V (Z=23)

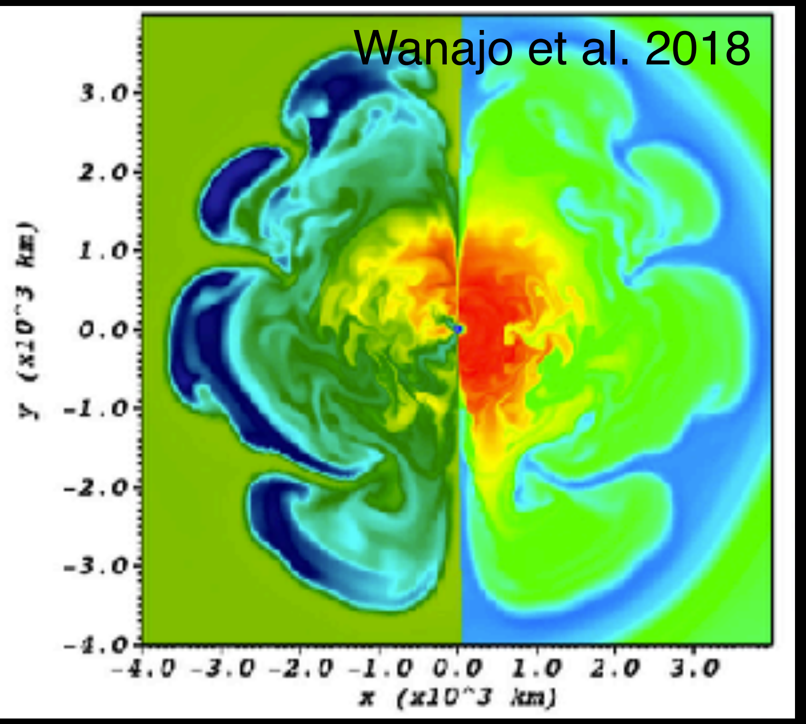
Nucleosynthesis sites

Woosley & Weaver 95, Thielemann+96, Nomoto, Kobayashi & Tominaga 13, Wanajo+18

Oxygen burning during the evolution of massive stars



Explosive nucleosynthesis at core-collapse supernovae

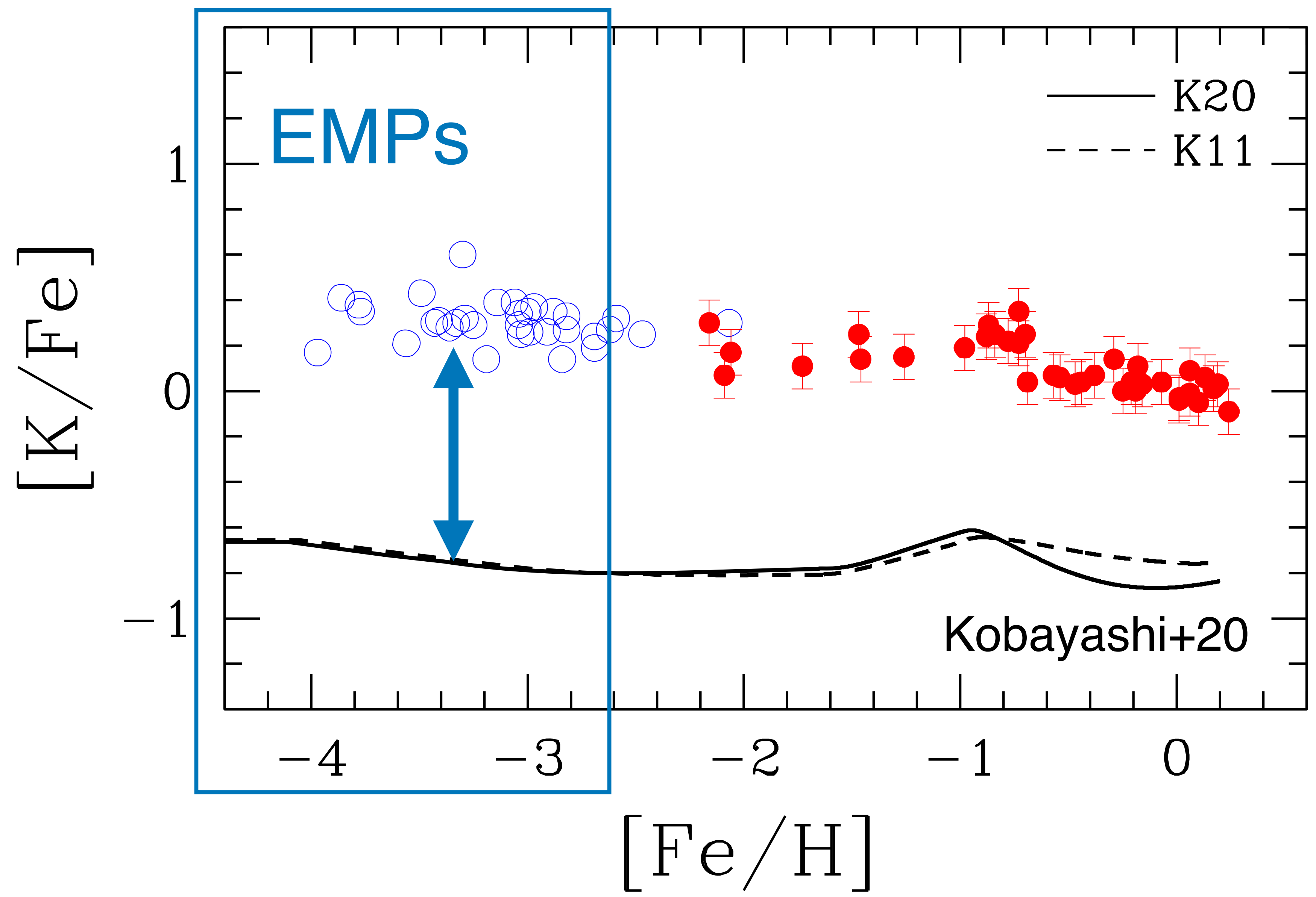


Open questions

Observations

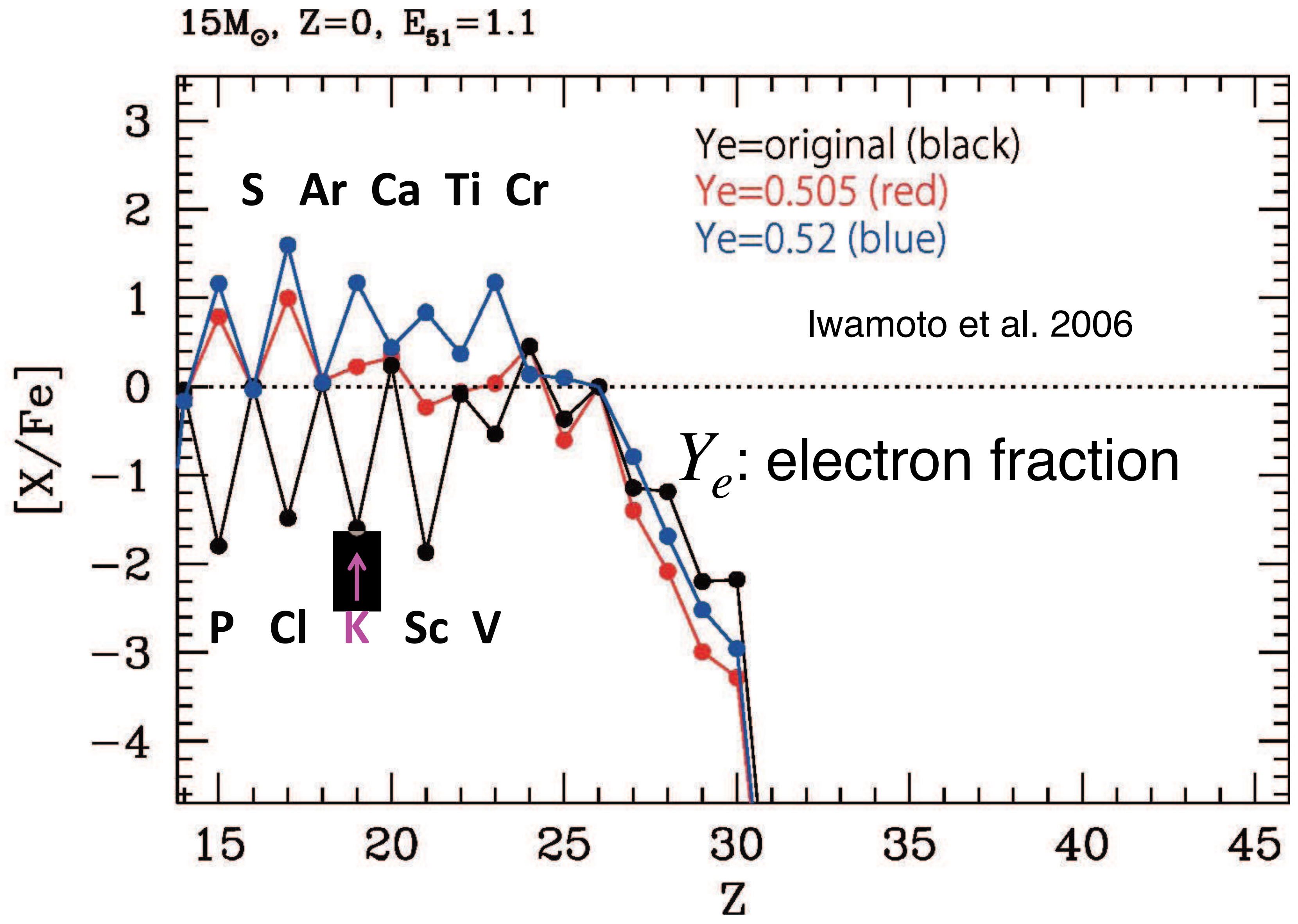
Takeda+02, 09, Andrievsky+10, Sneden+16, Zhao+16, Reggiani+19; Kobayashi+20

- Observed K abundances are one order of magnitude higher than the predictions of the chemical evolution model.
- The resonance doublet (7664Å, 7698Å) are very weak (< a few percent of the continuum) in the EMP stars
- Contamination of telluric O_2 lines
- Sensitive to NLTE effects

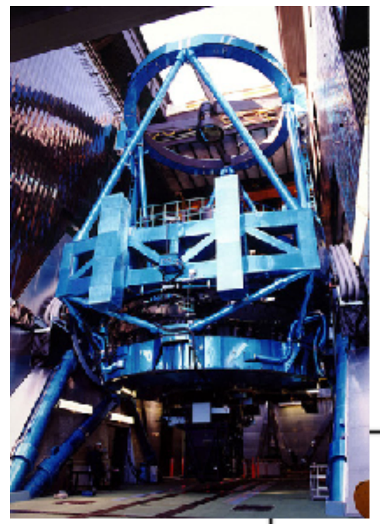


Theories

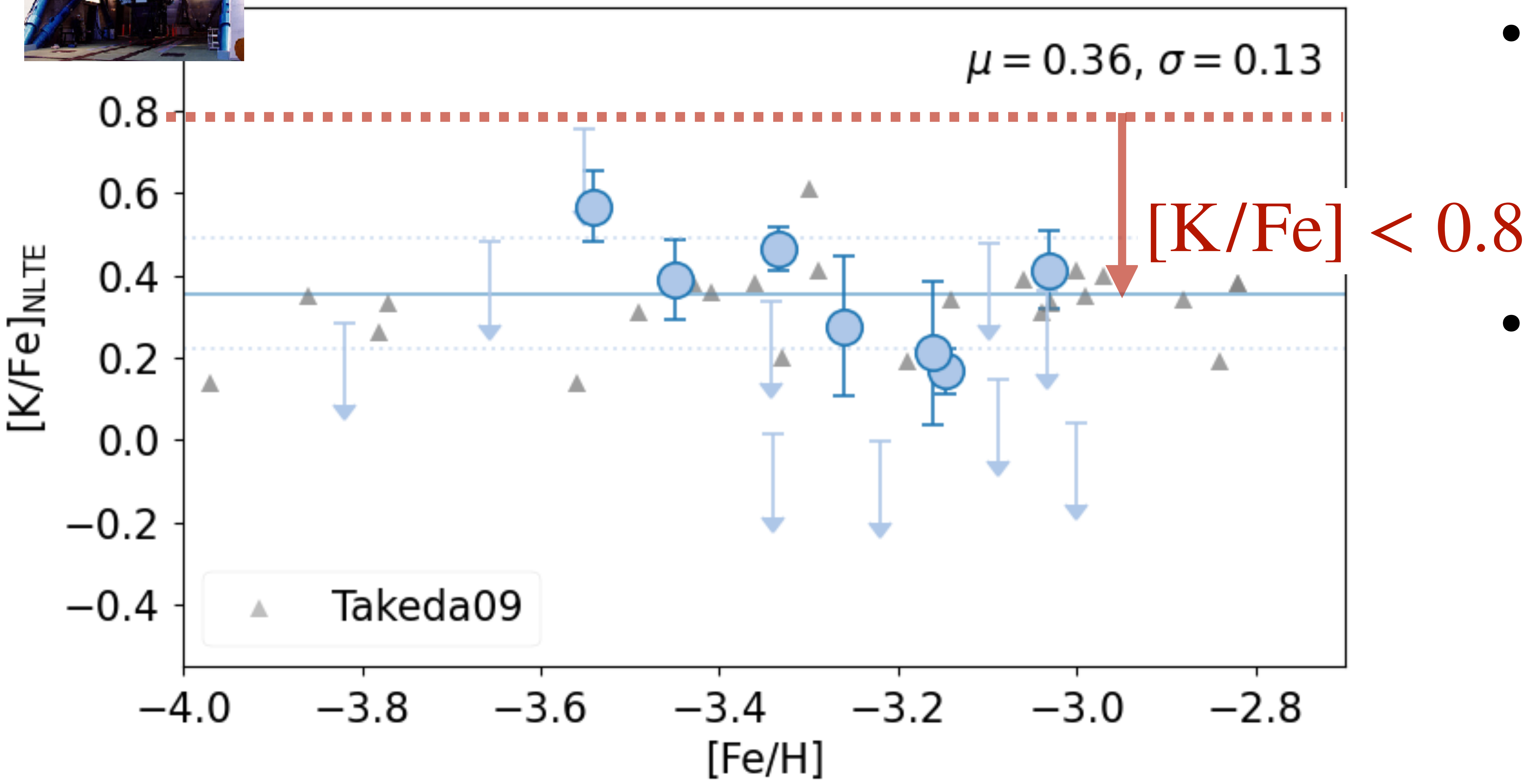
- Rotatational mixing in massive stars Limongi+18, Prantzos+18
- Interactive C-O shells in massive stars Ritter+18
- Jetted aspherical supernovae Tominaga+-09
- Neutrino process in supernovae Kobayashi+11, Wanajo+18



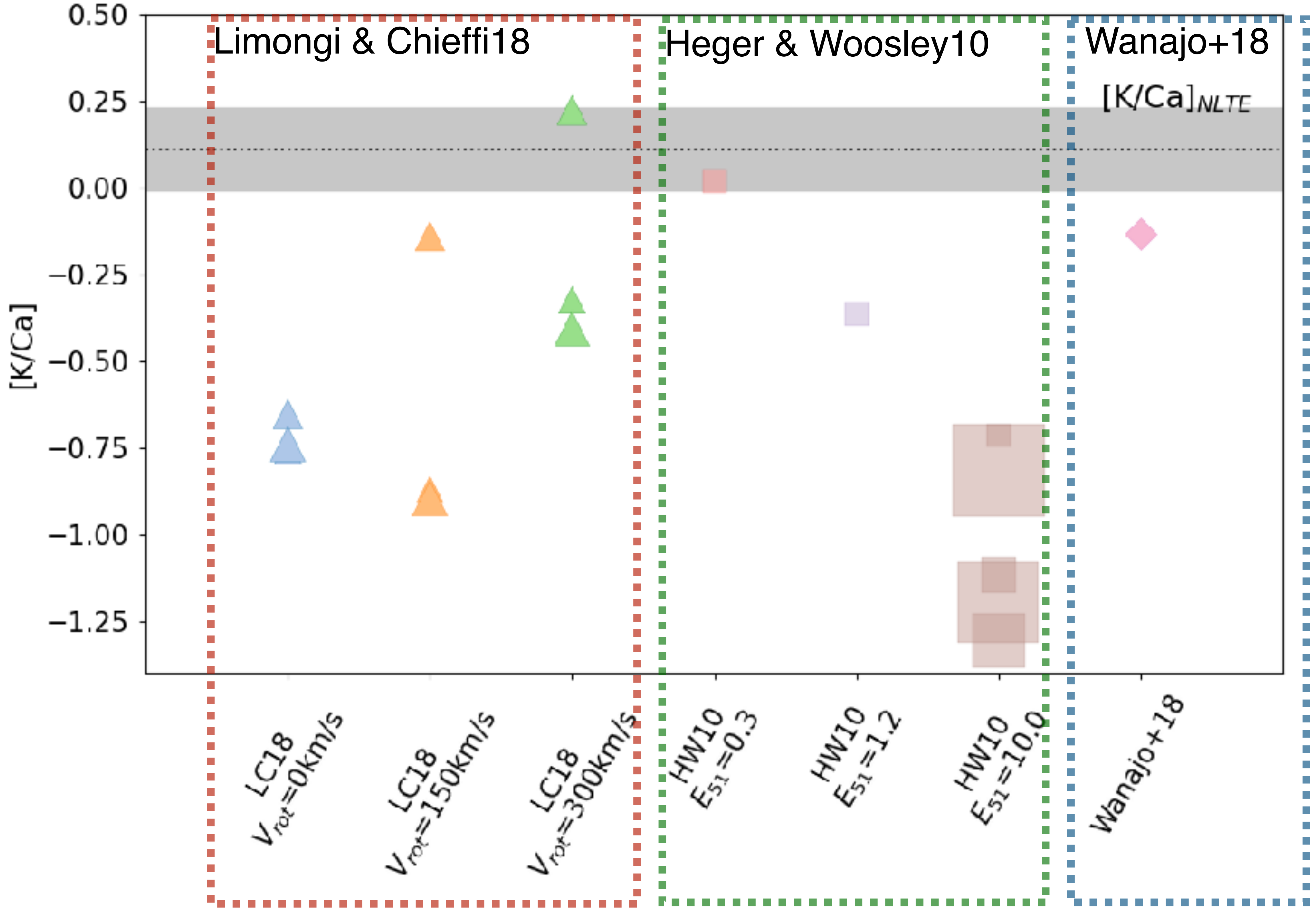
The [K/Fe] scatter, correlation with other elemental abundances in EMP need to be quantified.



K abundances in EMP stars with Subaru/HDS

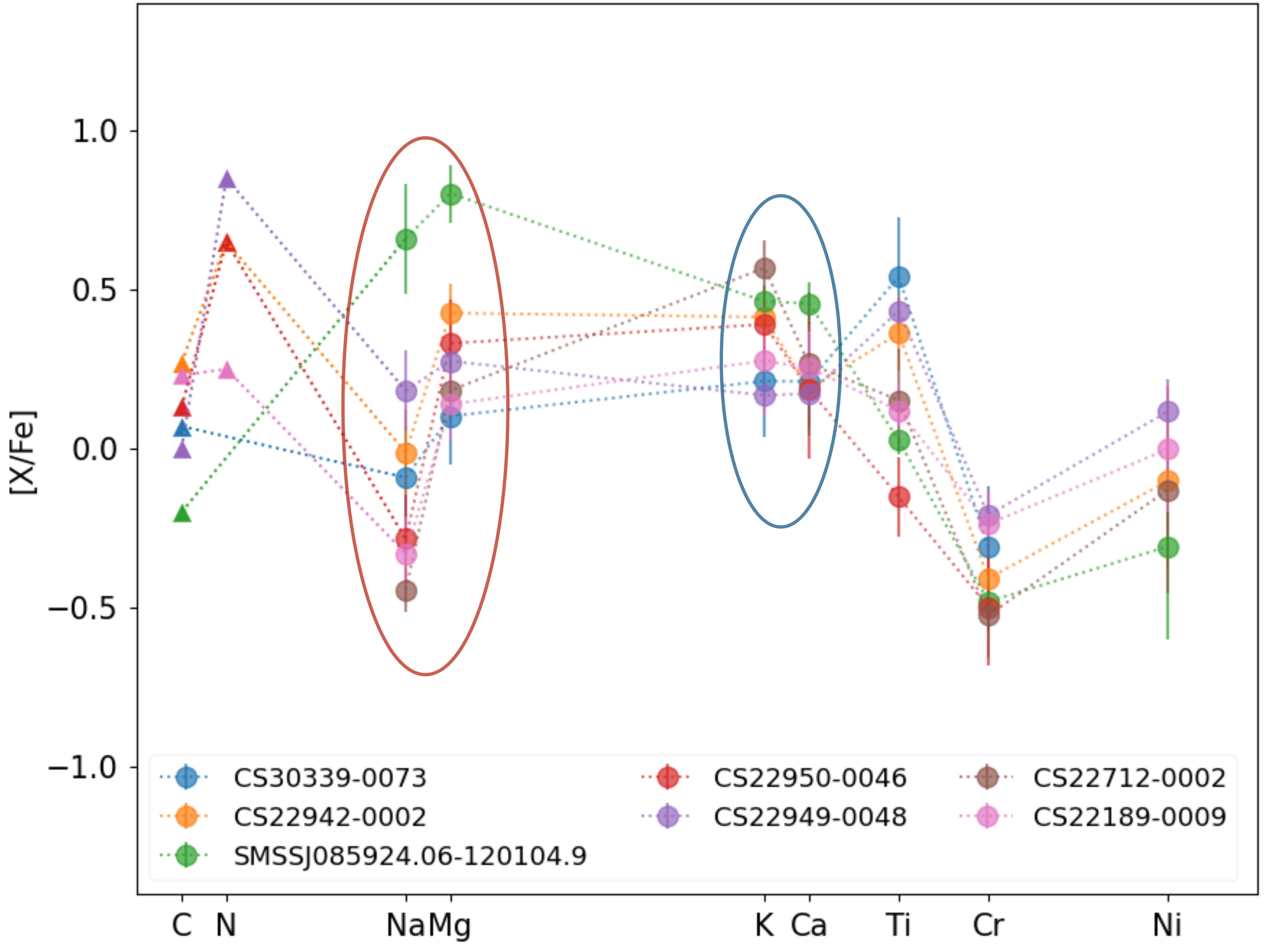


- High-resolution ($R \sim 60{,}000$) spectroscopy with the High Dispersion Spectrograph
- NLTE correction based on Reggiani+19



- All of the 18 stars show $[K/Fe]_{NLTE} \lesssim 0.8$ dex
- Among 7 stars with detected K lines:
  - The mean $[K/Fe]_{NLTE}$: 0.36 dex
  - The scatter: 0.13 dex (typical observational uncertainty ~ 0.15 dex)

K abundances in EMP stars with Subaru/HDS



[K/Ca] scatter: 0.11 dex

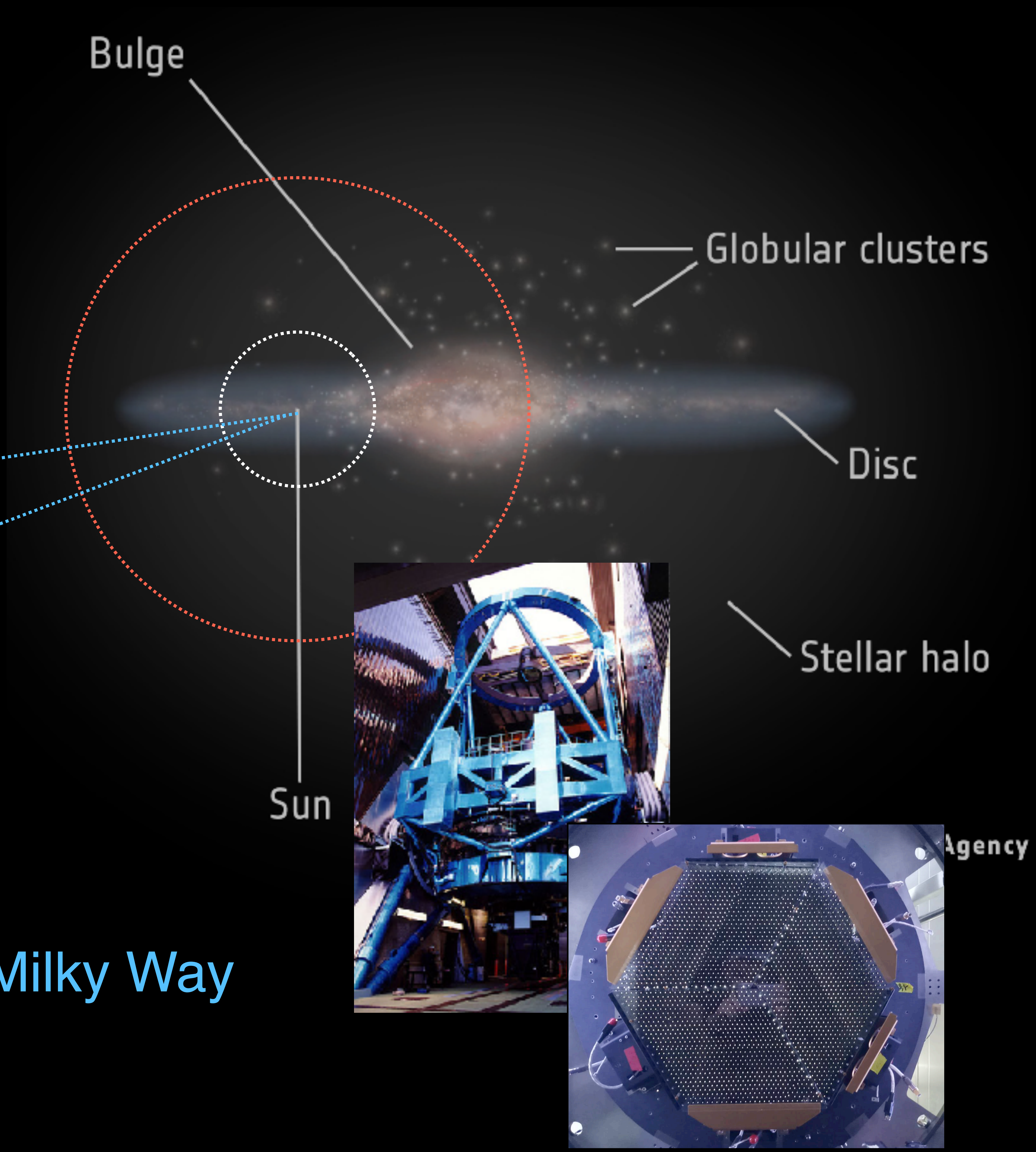
[Na/Mg] scatter: 1.49 dex

The K yield in massive stars or supernovae is *independent* of the mechanism that causes the variation in Na/Mg

Prospects with wide-field spectroscopic surveys

Identification and chemical characterization of the local halo

➡ H3, 4MOST, WEAVE, DESI, Milky Way Mapper



MSTO: ~ 50 kpc

Bright RGB: $\gtrsim 300$ kpc

Identification of EMPs in the Outer Milky Way

➡ MOONS (VLT), PFS (Subaru)

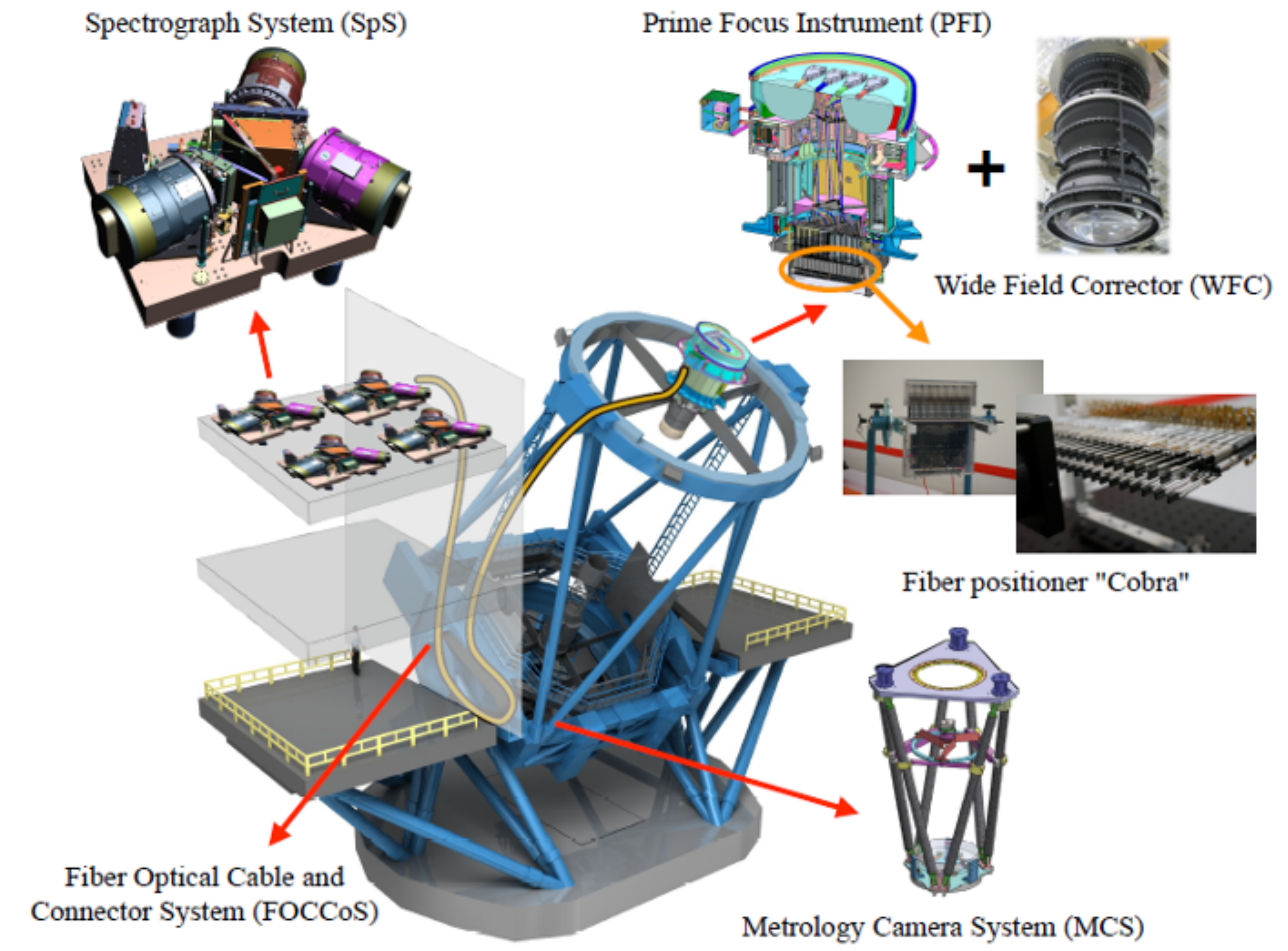
What is missing from the current sample of metal-poor stars

- Debris from merged dwarf galaxies, etc. Sharpe+22

Chemical abundances in the outer halo

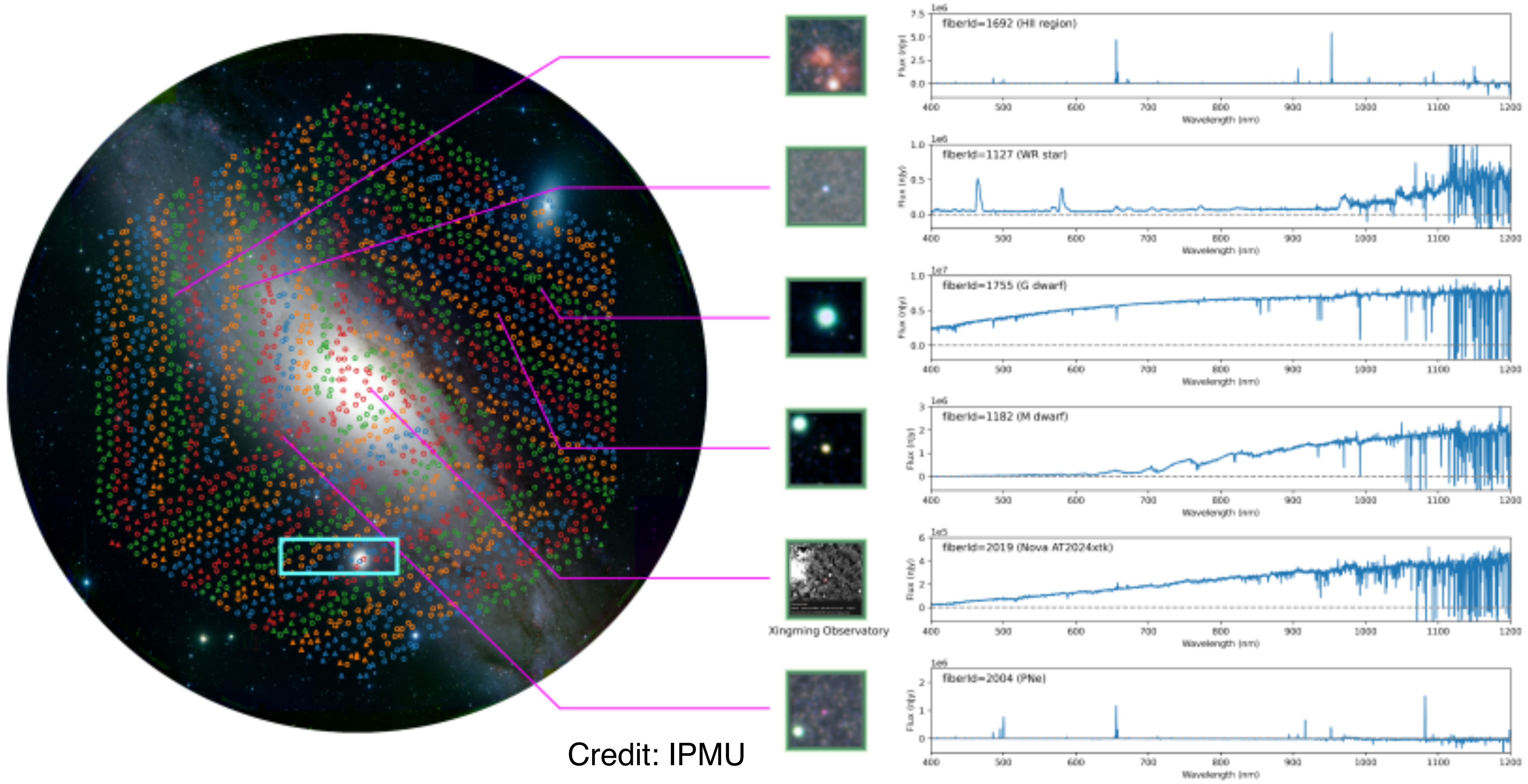
- Lower mean metallicity
  Carollo+10, Ivezic+12
- A larger fraction of CEMP
  Lee+17

Prime Focus Spectrograph (PFS) at Subaru Telescope



Instrument summary

- Field of view: 1.3 deg diameter
- 2386 reconfigurable fibers
- λ : 380-1260nm (3 channels: Blue, Red, IR)
- R: ~3000 (LR), ~5000 (MR)
- Scientific operation: March 2025 ~



Credit: IPMU

PFS-Galactic archaeology survey (~ 100 nights in 5-6 years) will observe classical dwarf satellites, M31 and the outer Milky Way disk and halo

Summary

Nucleosynthesis in the early universe: What did we learn from the abundances of EMP stars?

- The basic picture
  - EMP as a probe of the nature of the first stars and their supernovae
- Challenges in the abundance interpretation
  - “mono-” vs. “multi-” enriched EMPs
    - For a give set of theoretical yield models, we can purify the EMP stars with mono-enriched stars
  - Abundances of odd-Z elements: the case of Potassium (K)
    - The scatter of K abundances and their correlations with other elements constrain the physical condition of K synthesis beyond the conventional models
- Future Prospects - go beyond the solar neighborhood
  - The on-going wide-field spectroscopic surveys will chapture the abundance diversity in EMPs by exploring larger volumes and wider distance ranges