Element production by supernovae across the cosmic time probed by metal-poor stars

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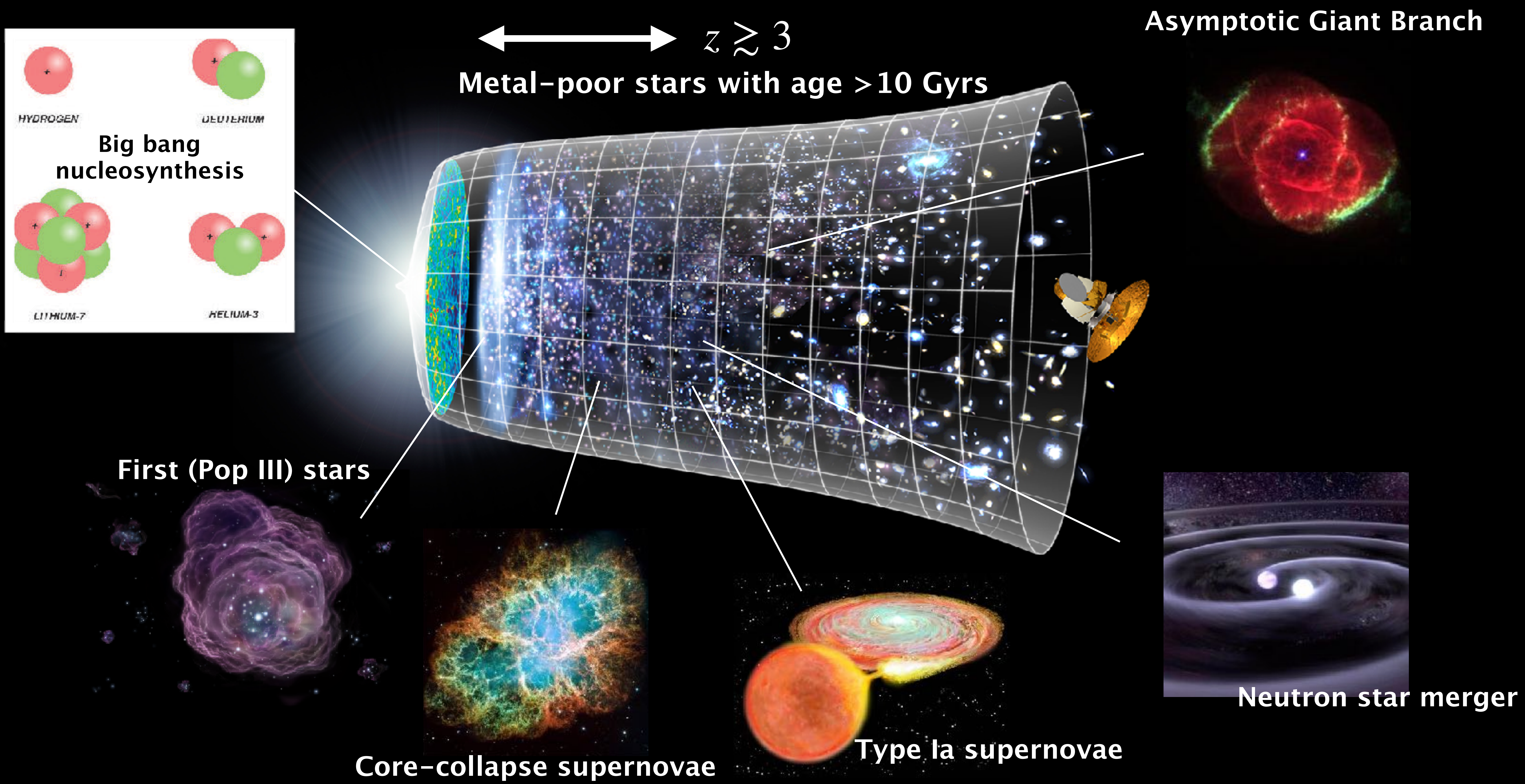
Outline

- Motivations of observing ancient metal-poor stars: supernova nucleosynthesis in the early Universe
- Comparison of a set of supernova yield models with:
  - Extremely metal-poor stars ➡ masses of the metal-enriching first stars
  - An age-selected sample of the Milky Way halo stars ➡ inhomogeneous metal-enrichment by the first stars
- Future prospects

Discussions between stellar observations and theoretical supernova yield calculations is essential to make full use of the big survey data of metal-poor stars

Cosmic chemical evolution probed by "stellar archaeology"



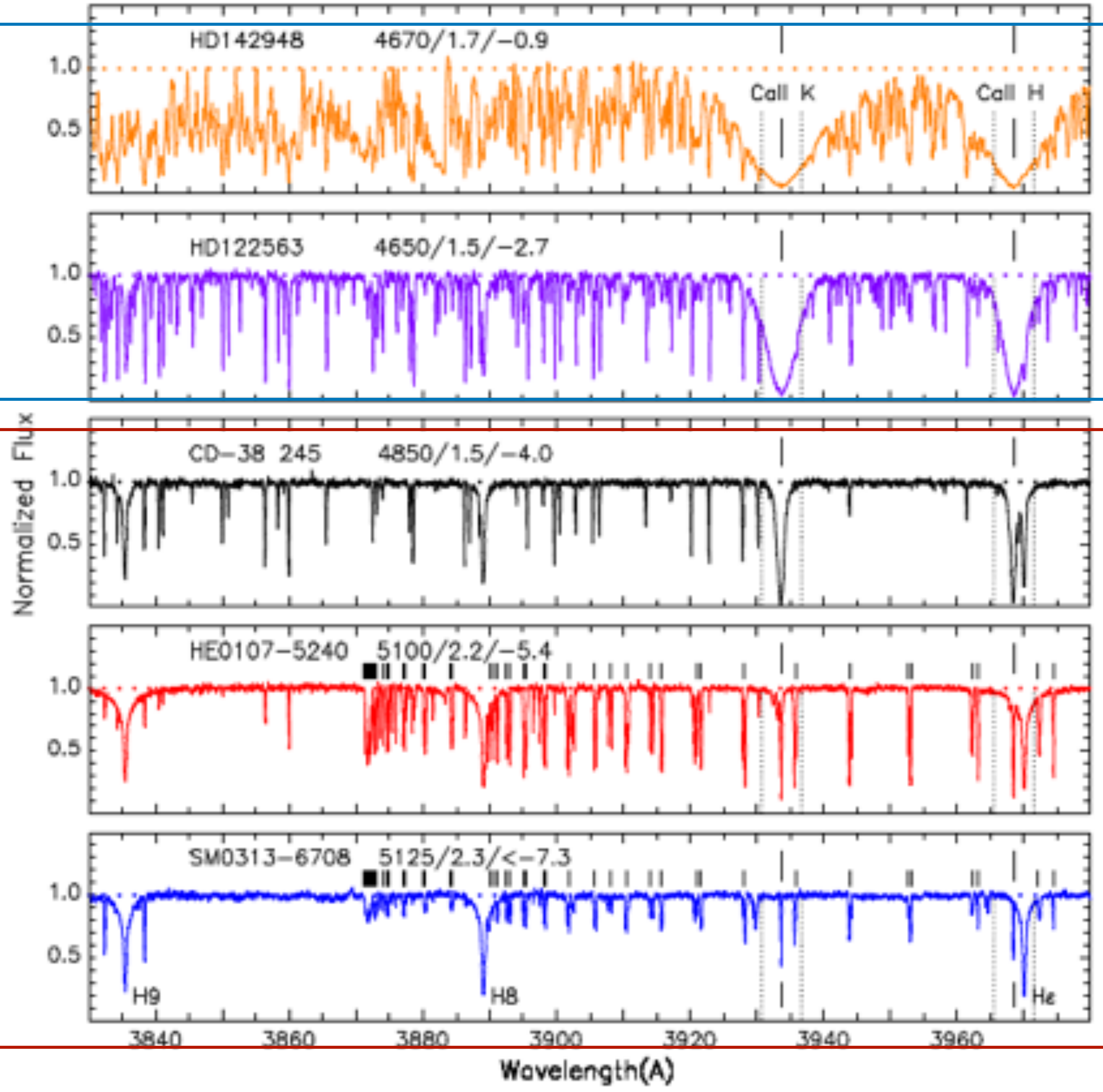
Metal–poor stars

$$[Fe/H](\text{metallicity}) = \log(N_{Fe}/N_H) - \log(N_{Fe}/N_H)_\odot$$

Frebel & Norris 2015

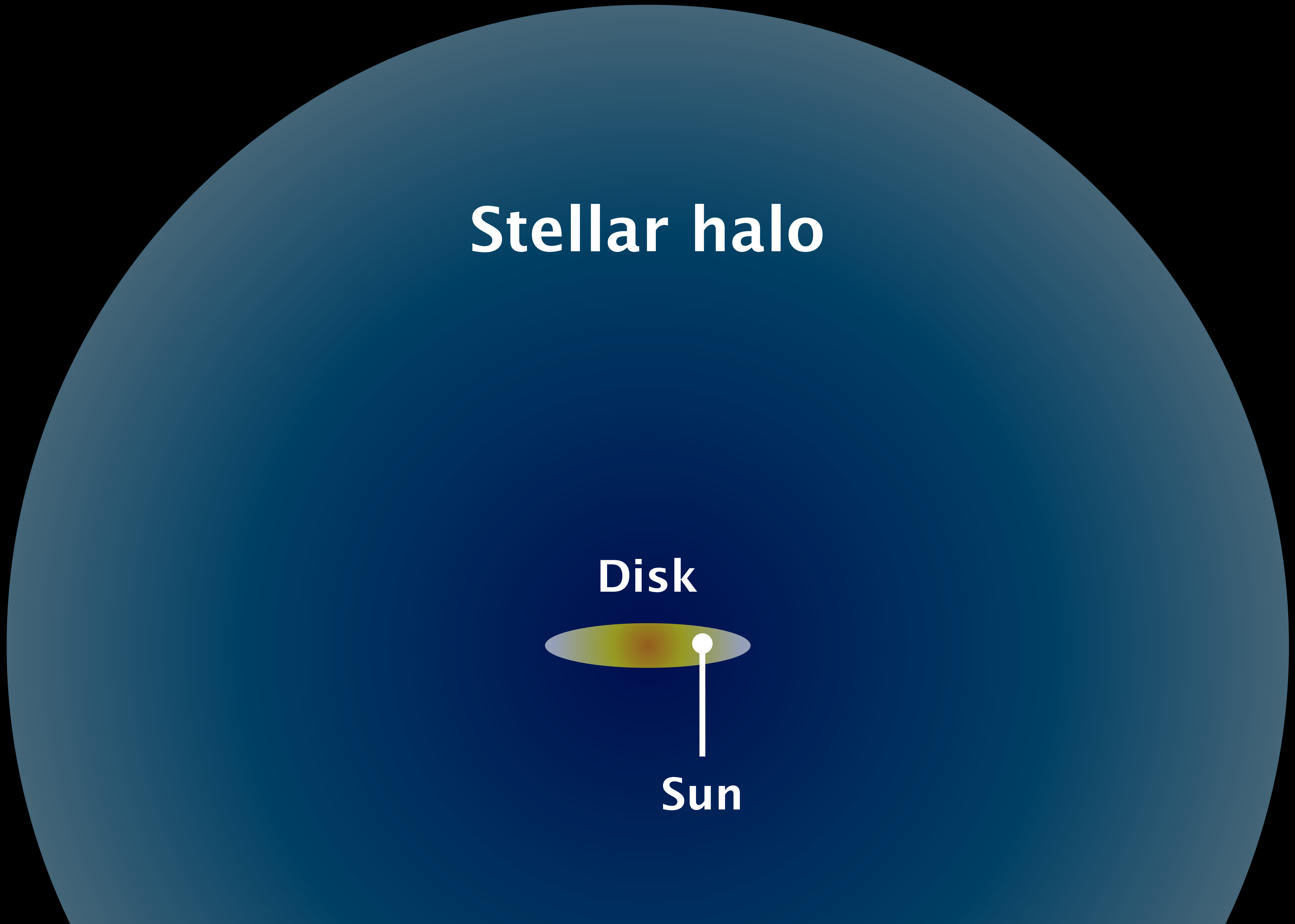
Numerous past supernovae

< 0.0	**Metal–poor**	
< -2.0	**Very metal–poor**	
< -3.0	**Extremely metal–poor (EMP)**	
< -4.0	**Ultra/Hyper metal–poor**	
< -6.0	**Mega metal–poor**	



Individual supernova(e)

The stellar halo in the Milky Way



Metal-poor stars are belonging to the diffuse stellar halo

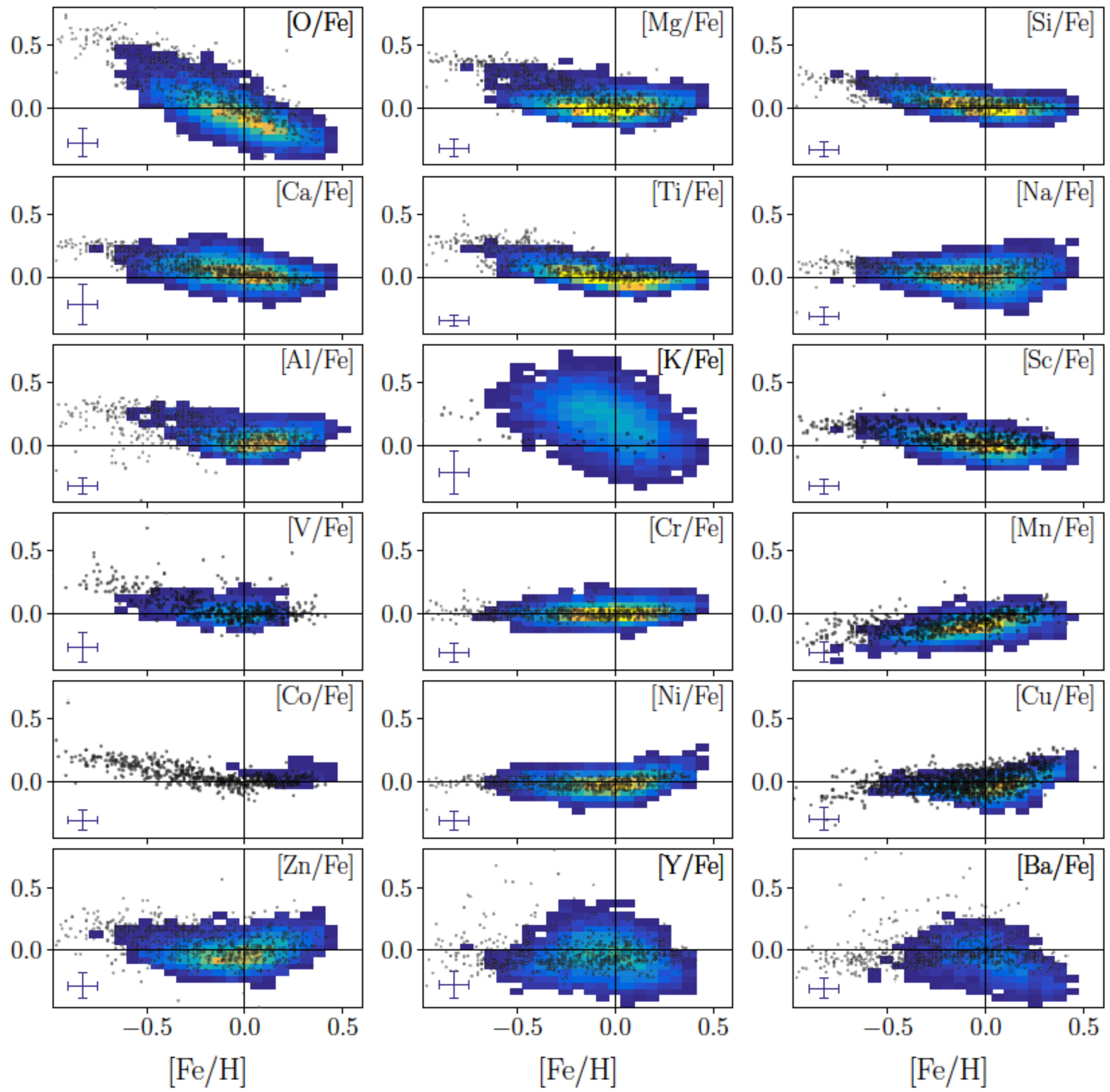
➡ Less than 1% in the solar neighborhood

➡ Difficult to build a statistical sample of metal poor stars with detailed elemental abundance measurements

Recent/ongoing surveys of stars the Milky Way

- High-resolution spectroscopic surveys
  - ➡ measurements of > 10 elemental abundances
    - Gaia-ESO survey: > 10^5 dwarf and giant stars
    - SDSS/APOGEE: > 10^5 giant stars
    - Galactic Archaeology with HERMES (GALAH) survey: ~ 10^6 dwarf and giant stars
- Low-resolution or photometric surveys
    - SDSS/SEGUE, LAMOST, PRISTINE, SkyMapper
- How to interpret these survey data of metal-poor stars?
    - Chemical evolution model
    - Compare supernova yields of the first (Pop III) stars with observed chemical abundance patterns of individual stars that are candidates of "the first metal-enriched stars"

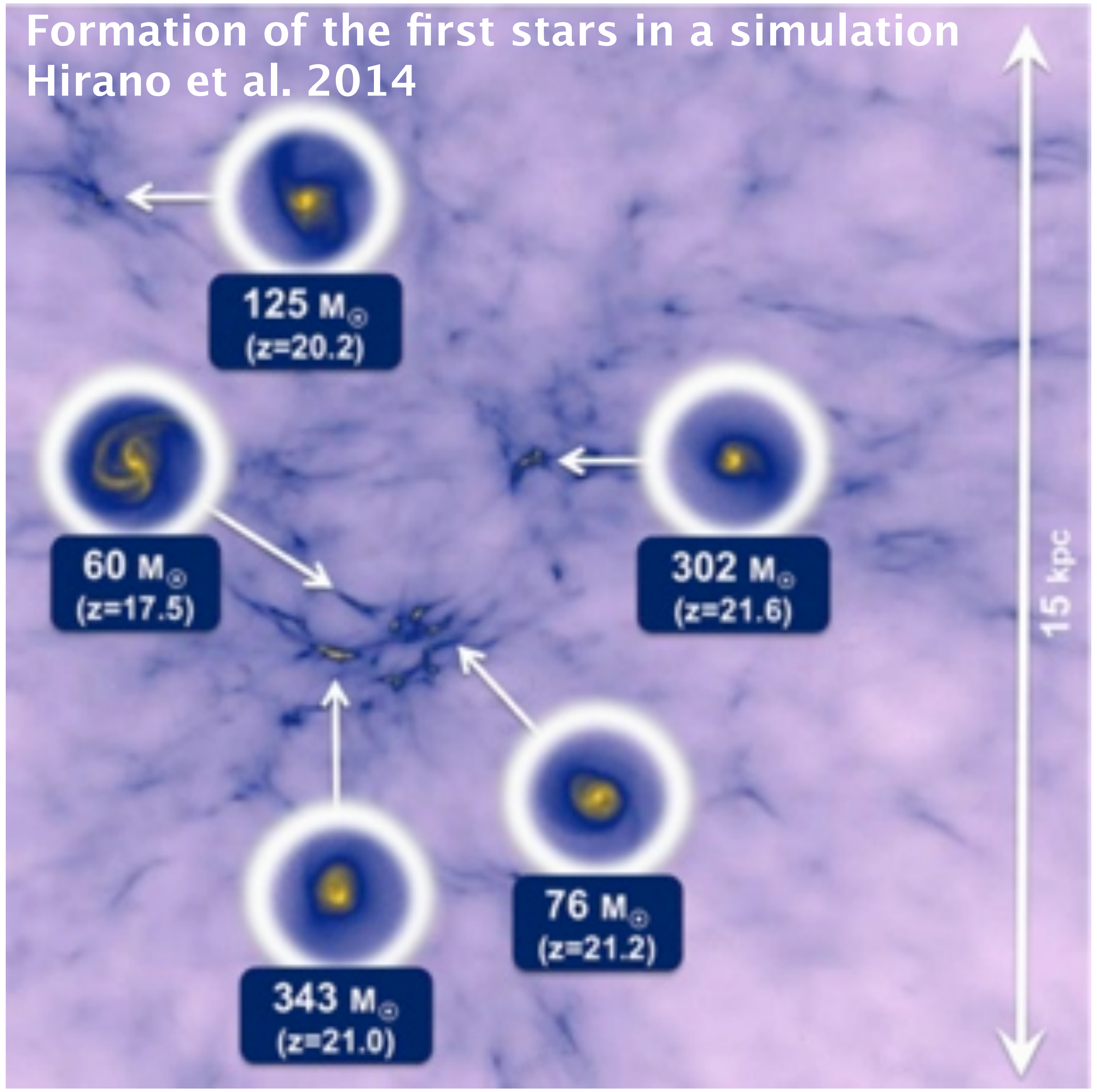
GALAH survey abundance results; Buder et al. 2019



1. Elemental abundances in extremely metal-poor stars

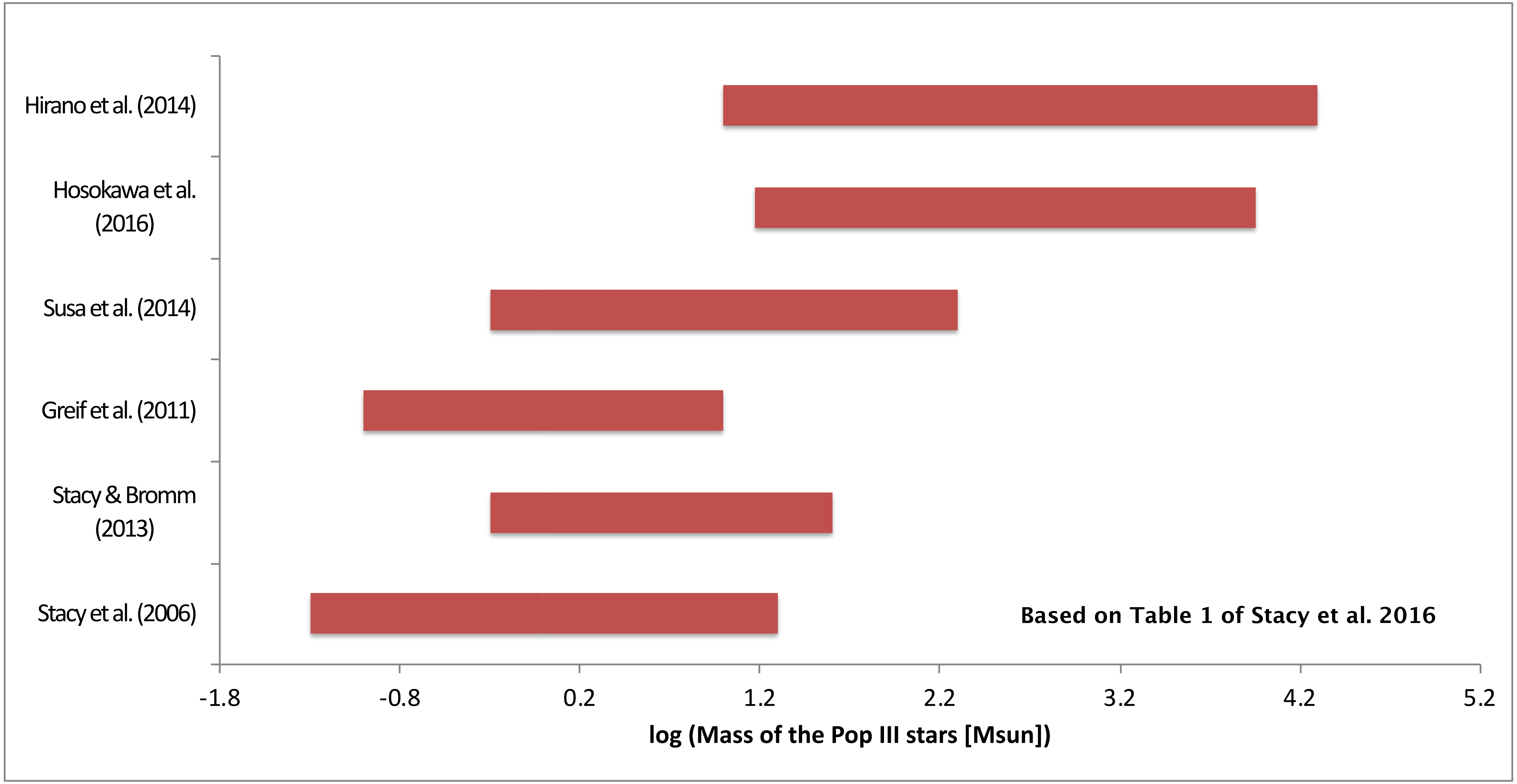
— Implications for the masses of the first stars —

The first (Population III) stars



- The first luminous objects in the Universe ➡ A source of ionizing photons
- Produce “metals” for the first time in the Universe ➡ the formation of low-mass stars and the first galaxies
- The physical properties (e.g., masses, supernovae) are largely uncertain

Theoretical predictions

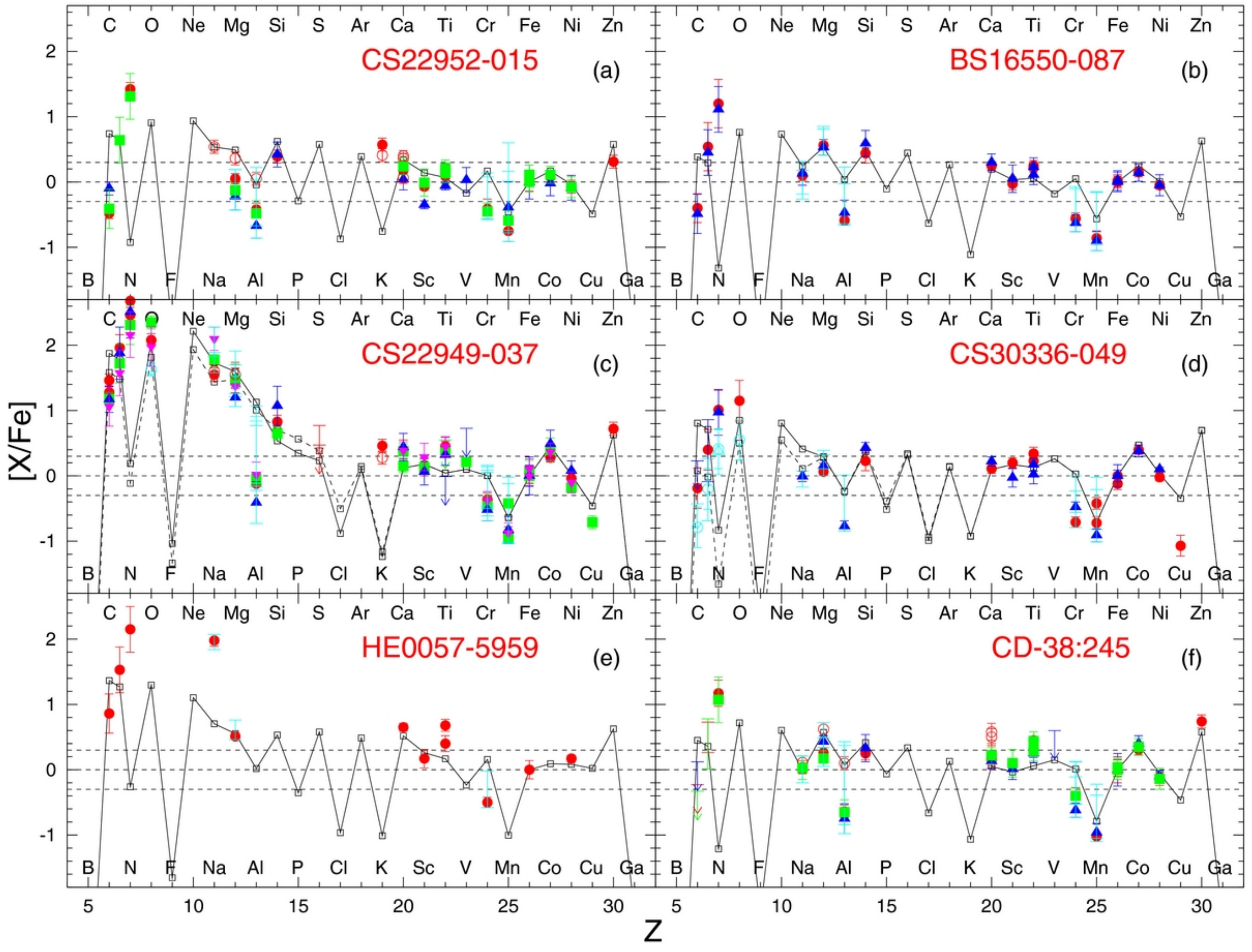


Observational constraints

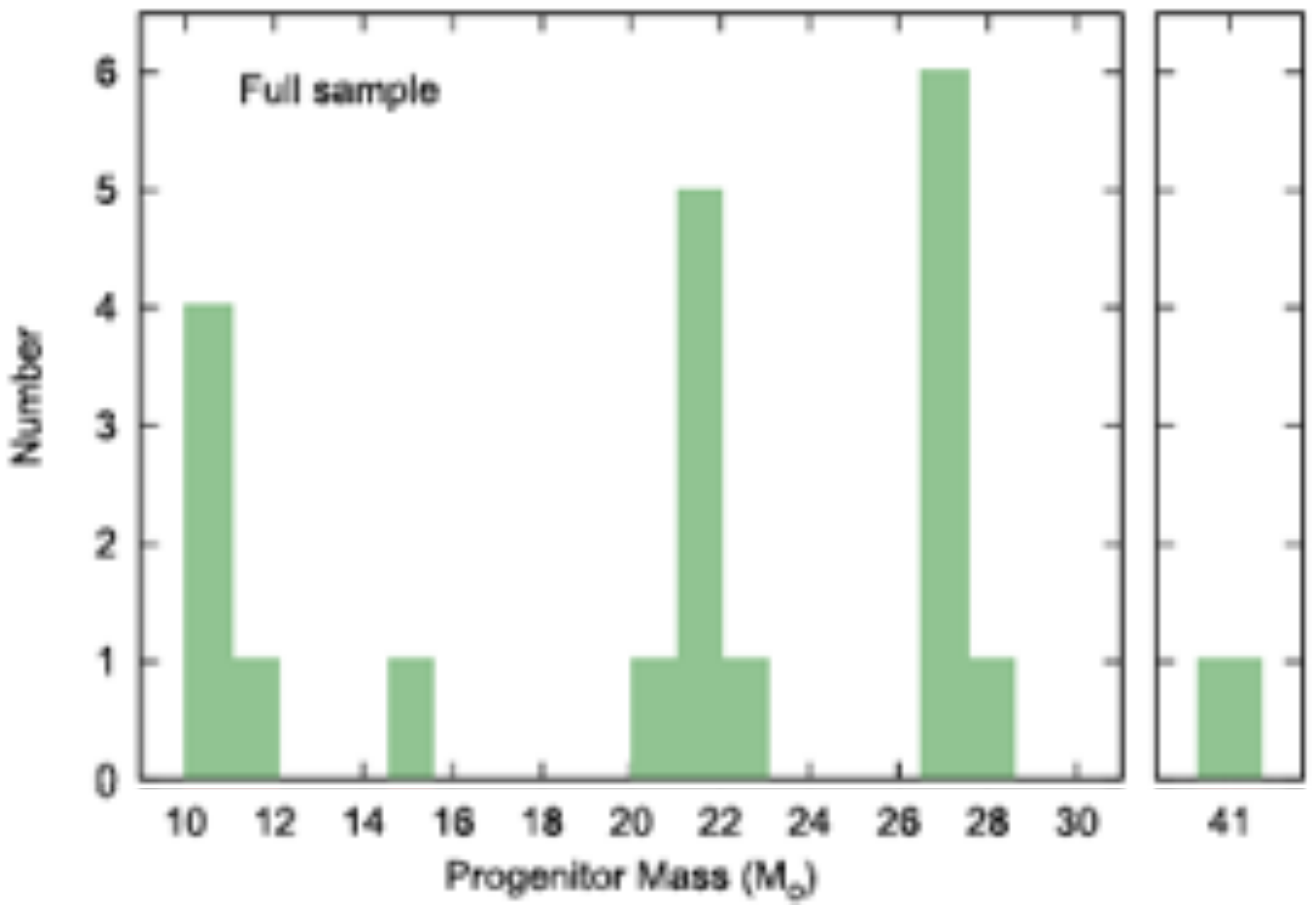
Pop III mass	Prediction	Constraints from metal-poor stars
$< 0.8\ M_\odot$	Survive until present day	Metal-free stars have not been discovered
$140\text{–}300 M_\odot$	Pair instability supernovae	A clear signature of their characteristic abundance patterns (e.g. high Si/O ratio) have not been found
$10\text{–}100 M_\odot$	**core-collapse supernovae**	**Chemical abundances in extremely metal-poor stars (Tominaga et al. 2014; Placco et al. 2015)**

Pop III yield models compared with observation

Abundance profiling (Tominaga et al. 2014)



Pop III masses inferred from 20 ultra-metal-poor stars (Heger & Woosley 2010; Placco et al. 2015)



<u>This study:</u>

- **Compile a sample of ~ 200 extremely metal-poor stars with high quality elemental abundance measurements and compare them with a set of Pop III supernova yield models to obtain typical masses and supernovae of the metal-enriching first stars**
- **Impacts of observational and theoretical uncertainties**

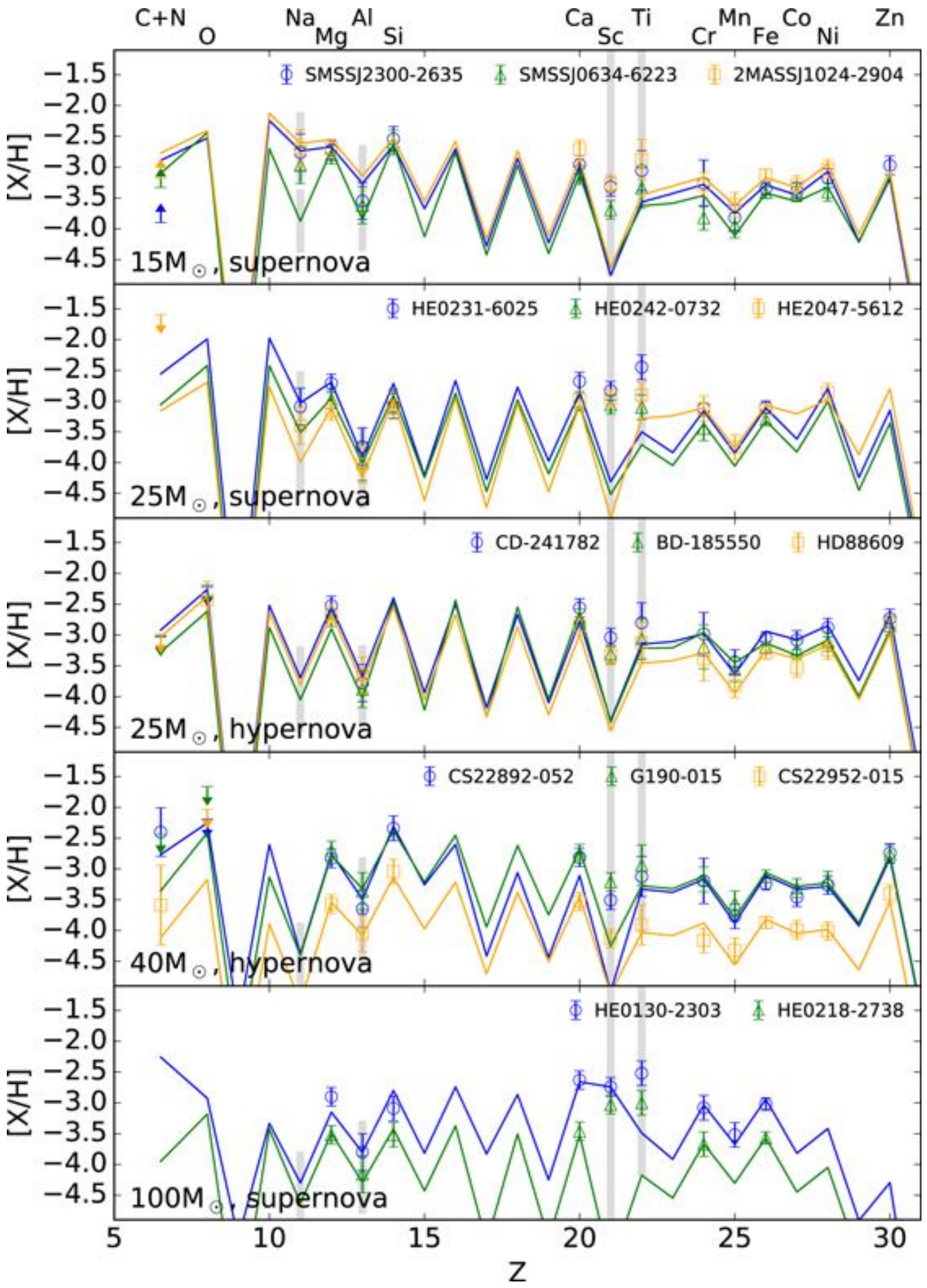
Calculation of supernova yields

- Progenitor model and explosive nucleosynthesis previously calculated by e.g., Tominaga et al. 2007.

- Analytic prescription for the mixing and fallback of elements to obtain the mass cut, so that ejected elemental abundances best explain the observation (mixing-fallback model; Umeda & Nomoto 2002)

- Fit the yield model to the data by varying (1) Pop III progenitor mass, (2)explosion energy, (3)radius of the mixing zone (M_{mix}), (4)ejected fraction (f_{ej}), and (5)Hydrogen dilution mass

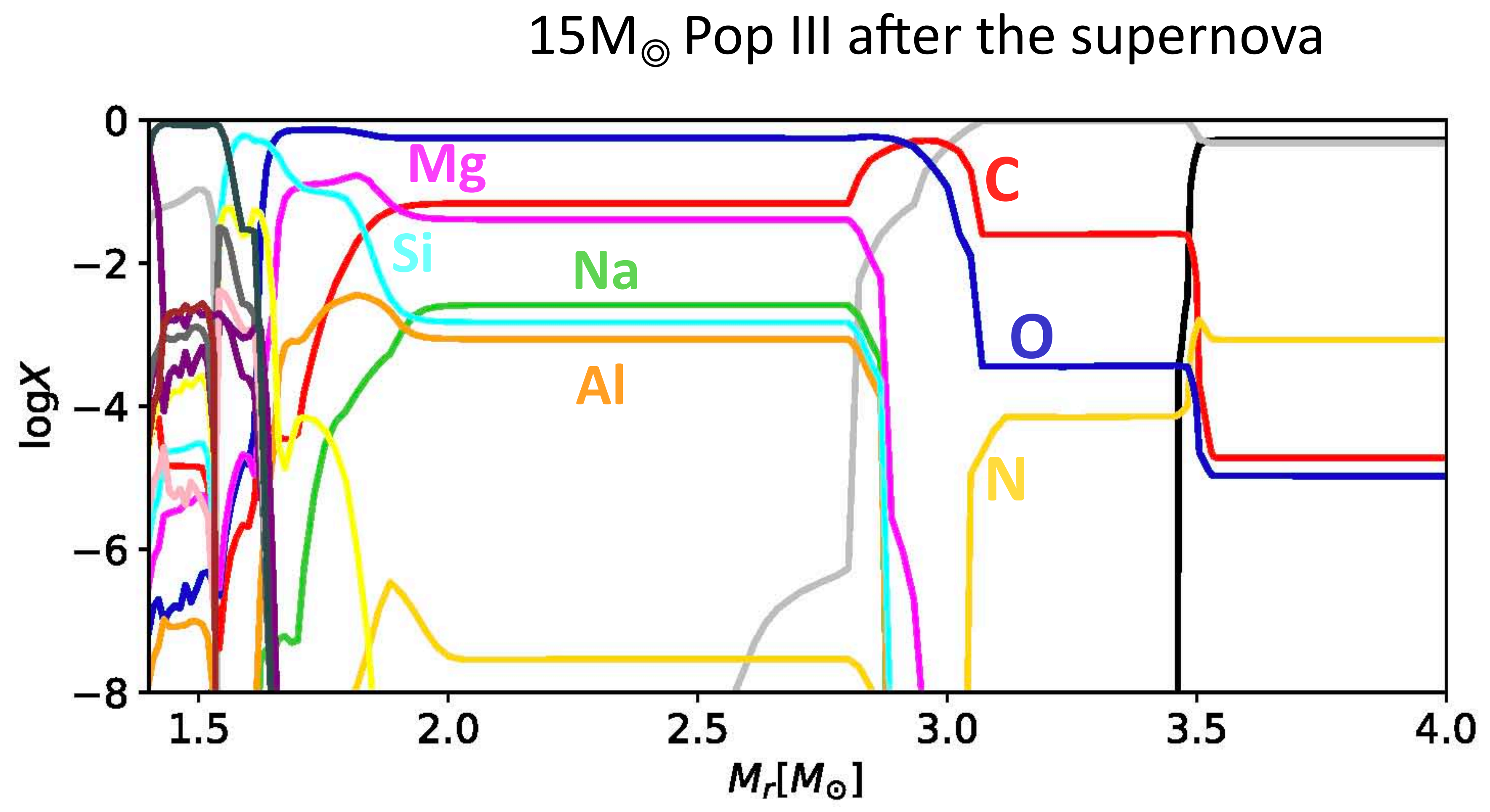
Fitting observed abundance with Pop III SN yields

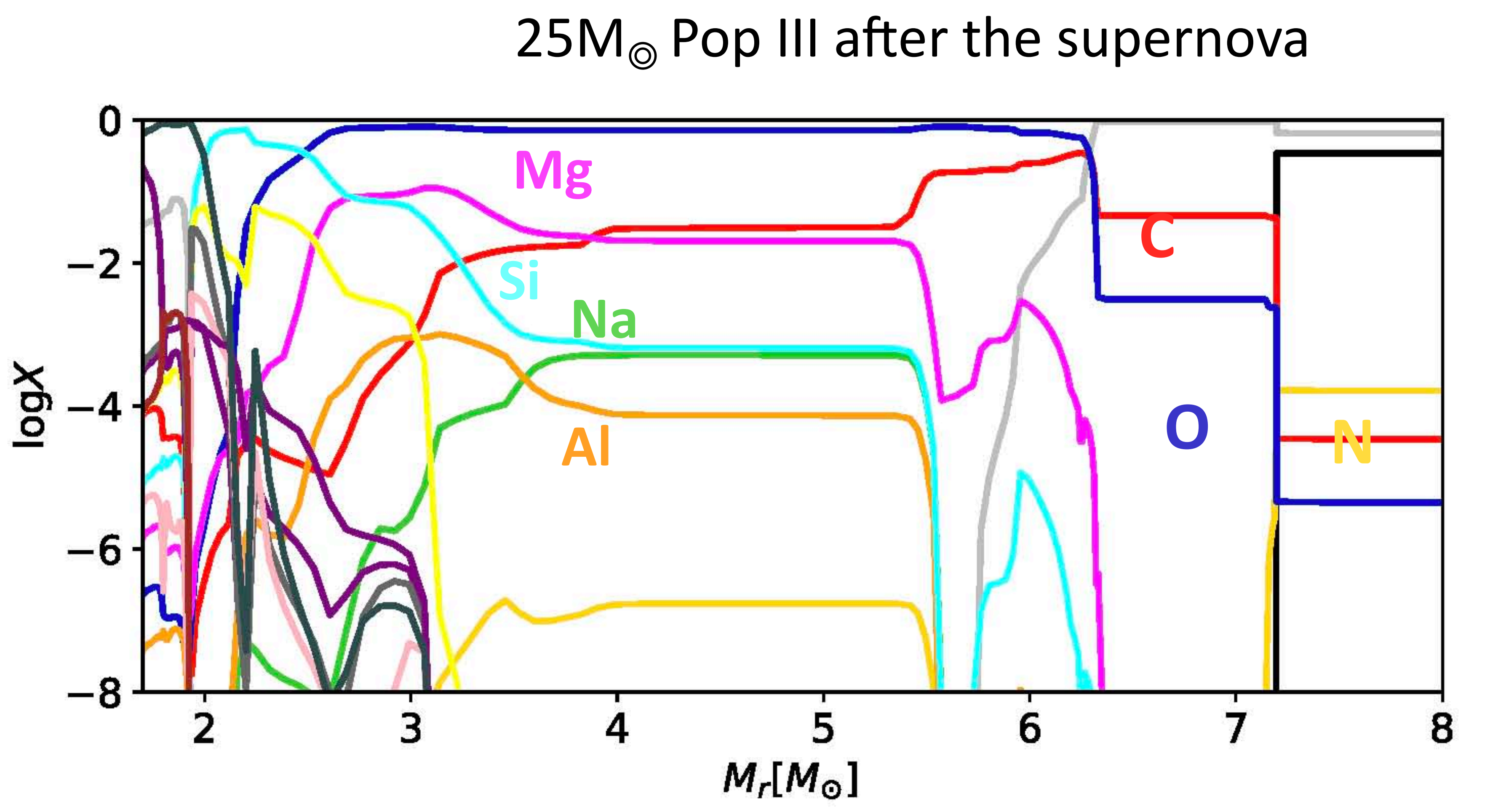


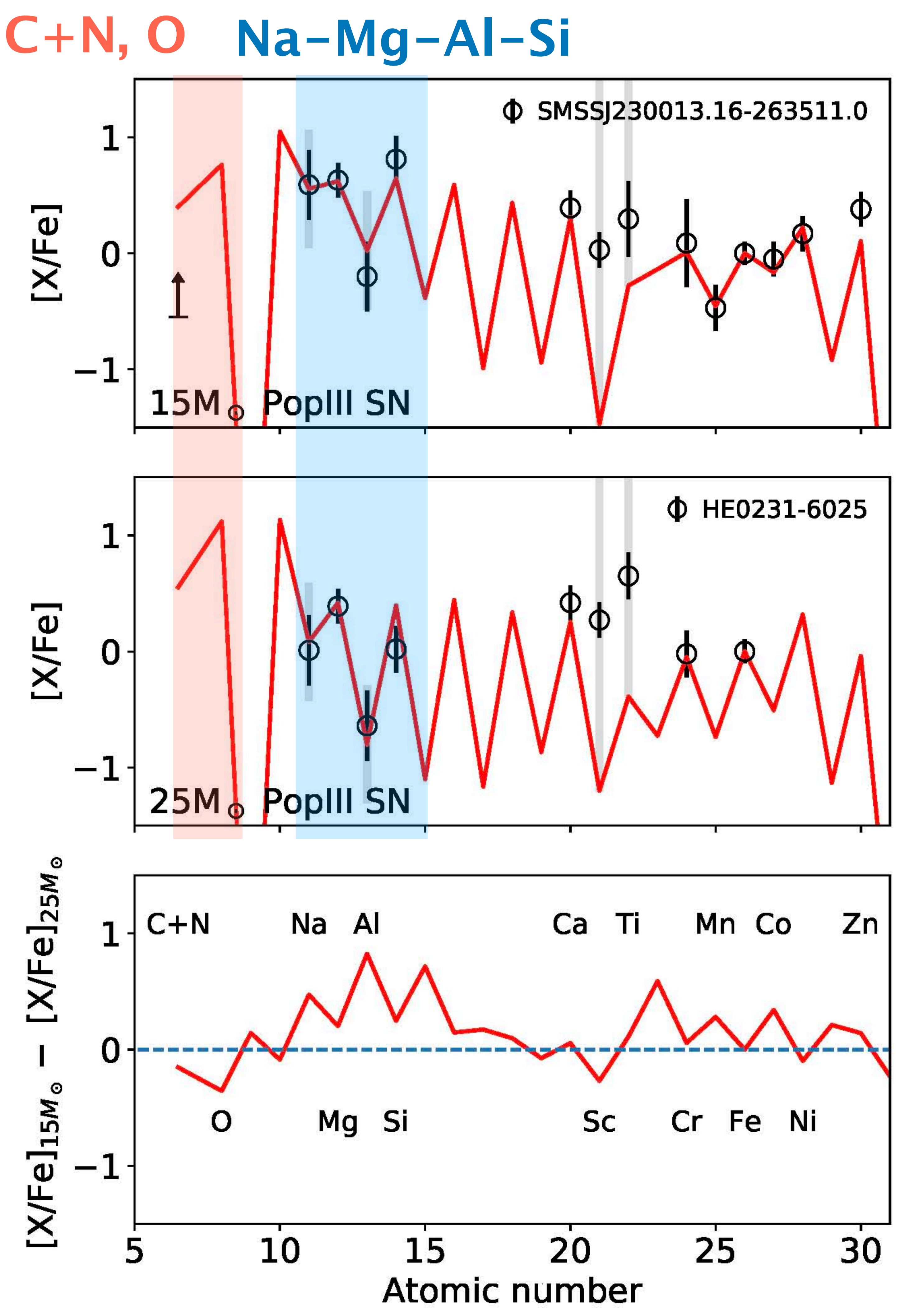
Ishigaki et al. 2018

- The model is fit to the high-quality elemental abundance measurements of 200 extremely metal-poor stars
- The observational uncertainties of 0.1-0.3 dex
- Theoretical uncertainties:
    - Large uncertainties of 0.4 dex is assigned to the Na and Al
    - Sc and Ti are treated as lower limits

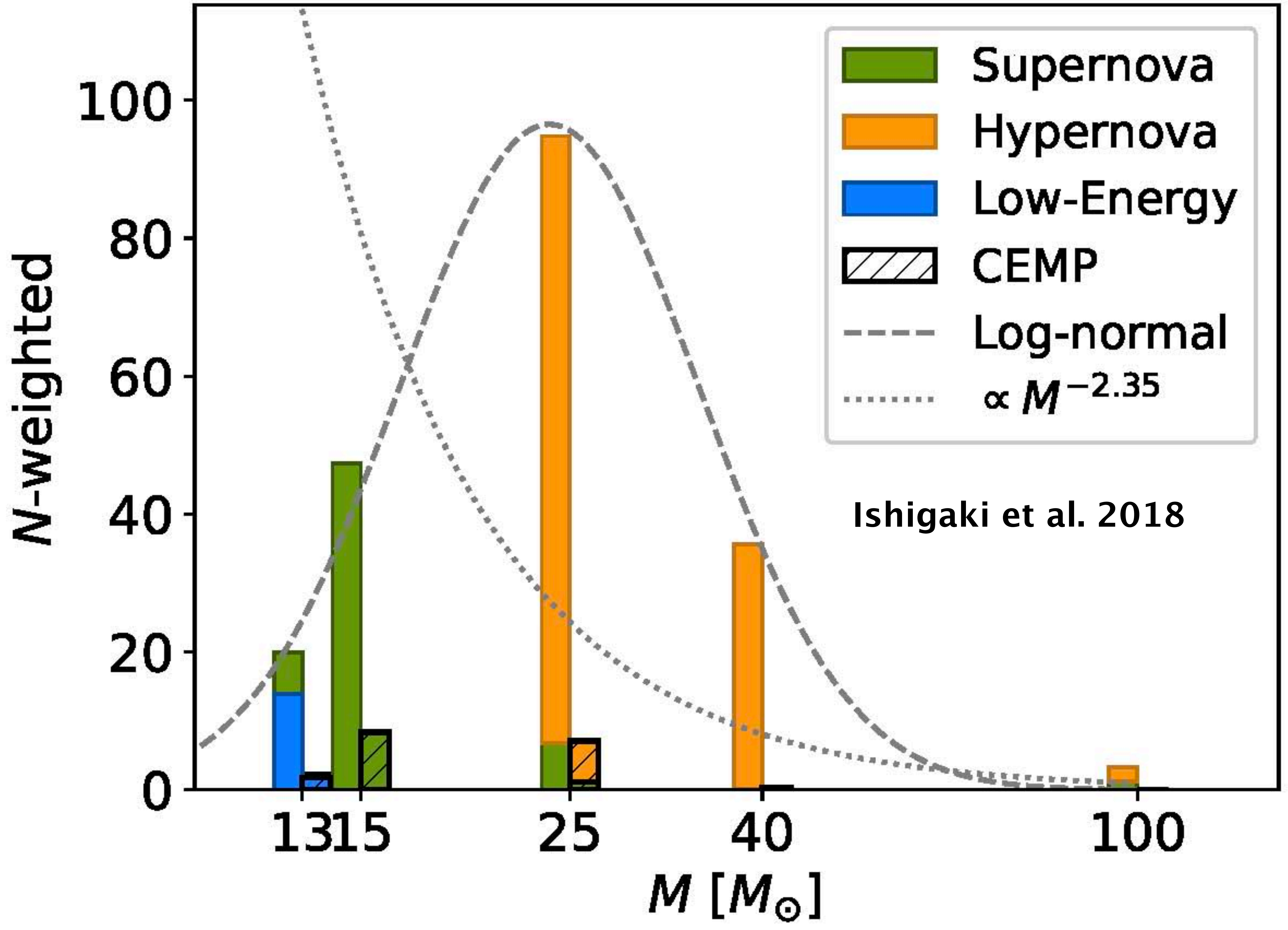
Diagnostic elements for the masses







The masses of the Pop III yield models

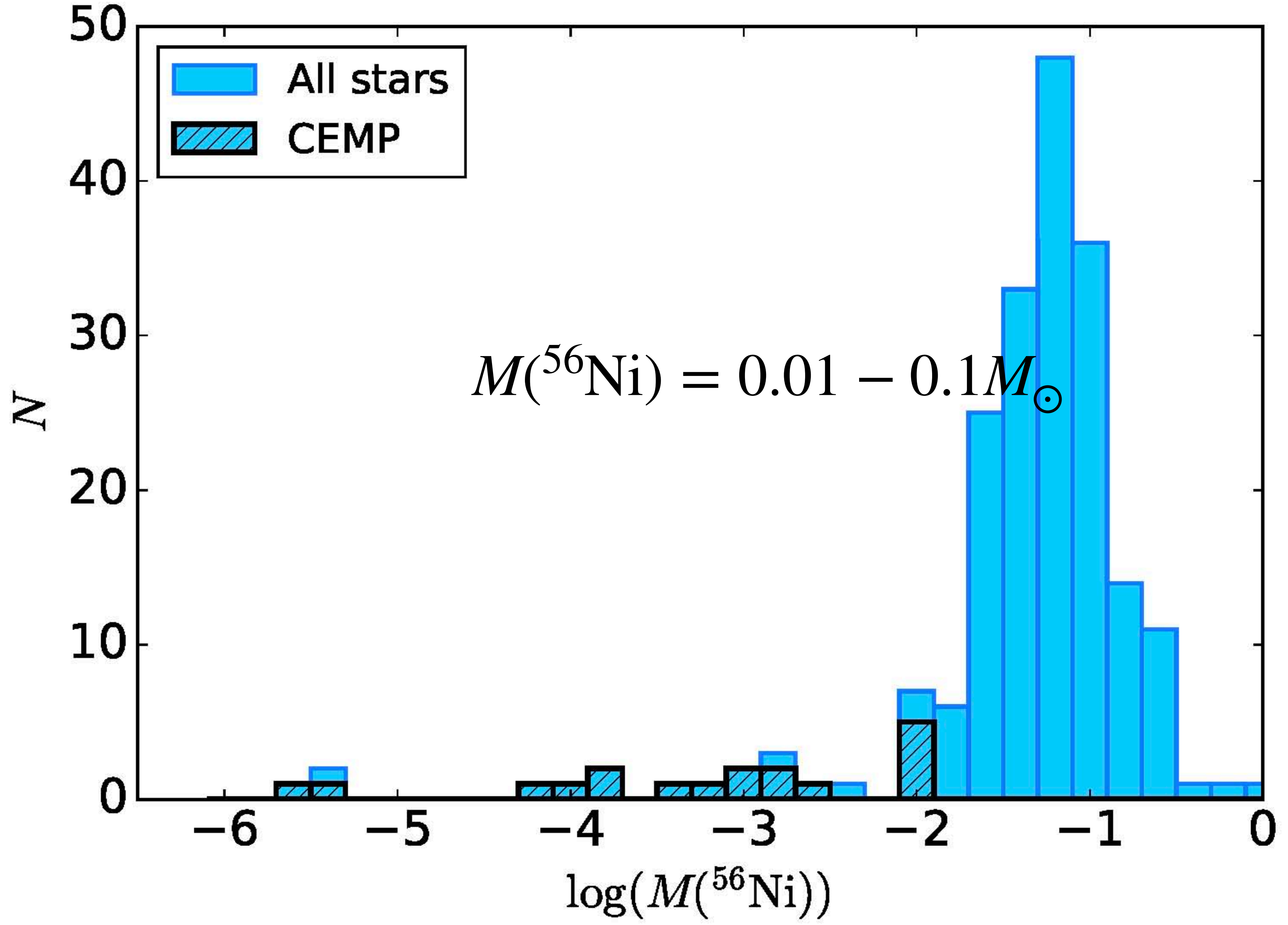


- The majority of the sample stars are best explained by 25M◎ Pop III supernova yields
- A large fraction of the data prefer energetic explosion of Pop III stars

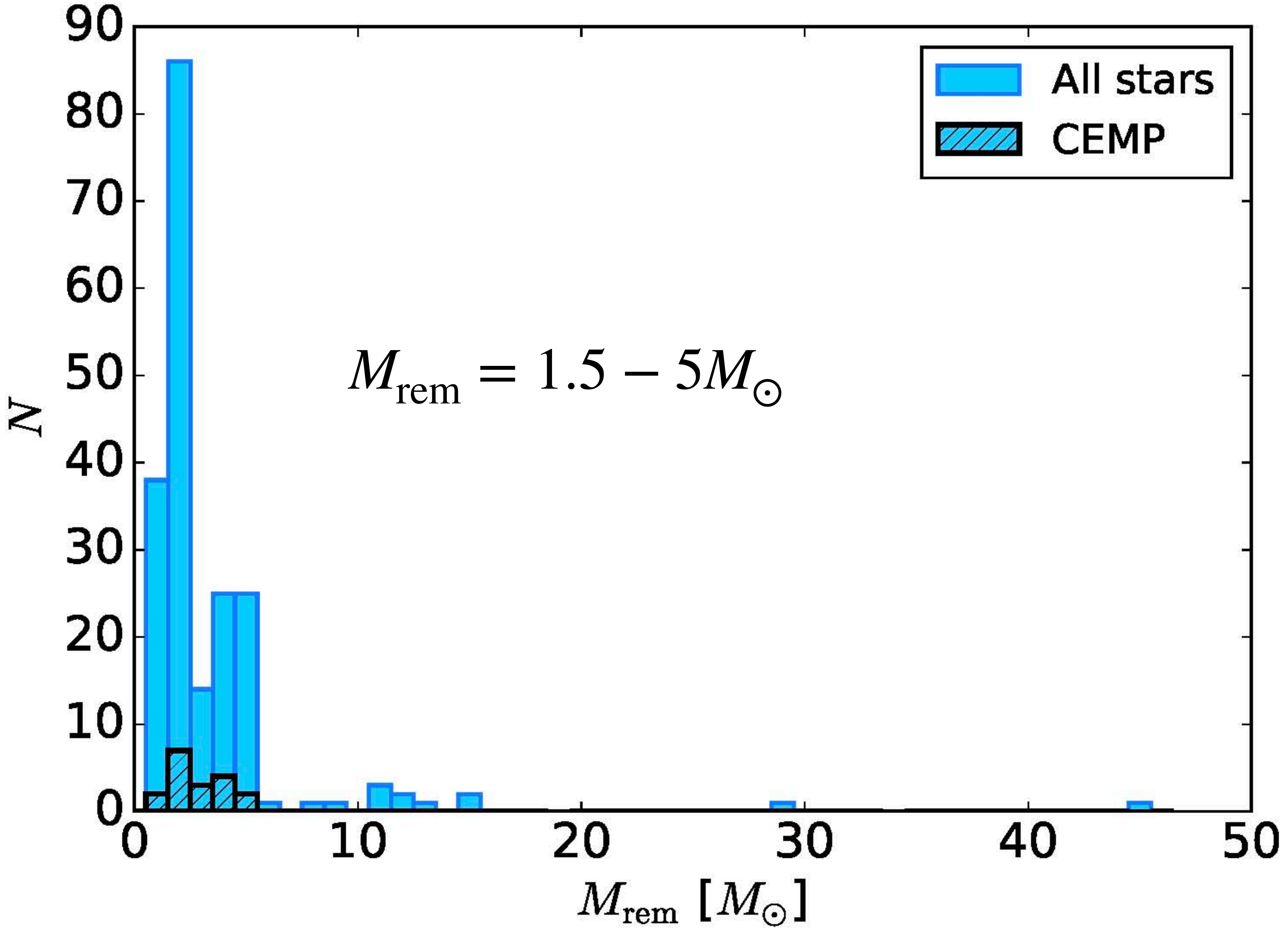
Properties of metal-enriching Pop III stars inferred from the current sample of extremely metal-poor stars

Masses of the ejected ^{56}Ni and compact remnants

Masses of ejected ^{56}Ni
➡ Luminosity of supernova



Masses of the compact remnant
➡ mass distribution of neutron stars and black holes



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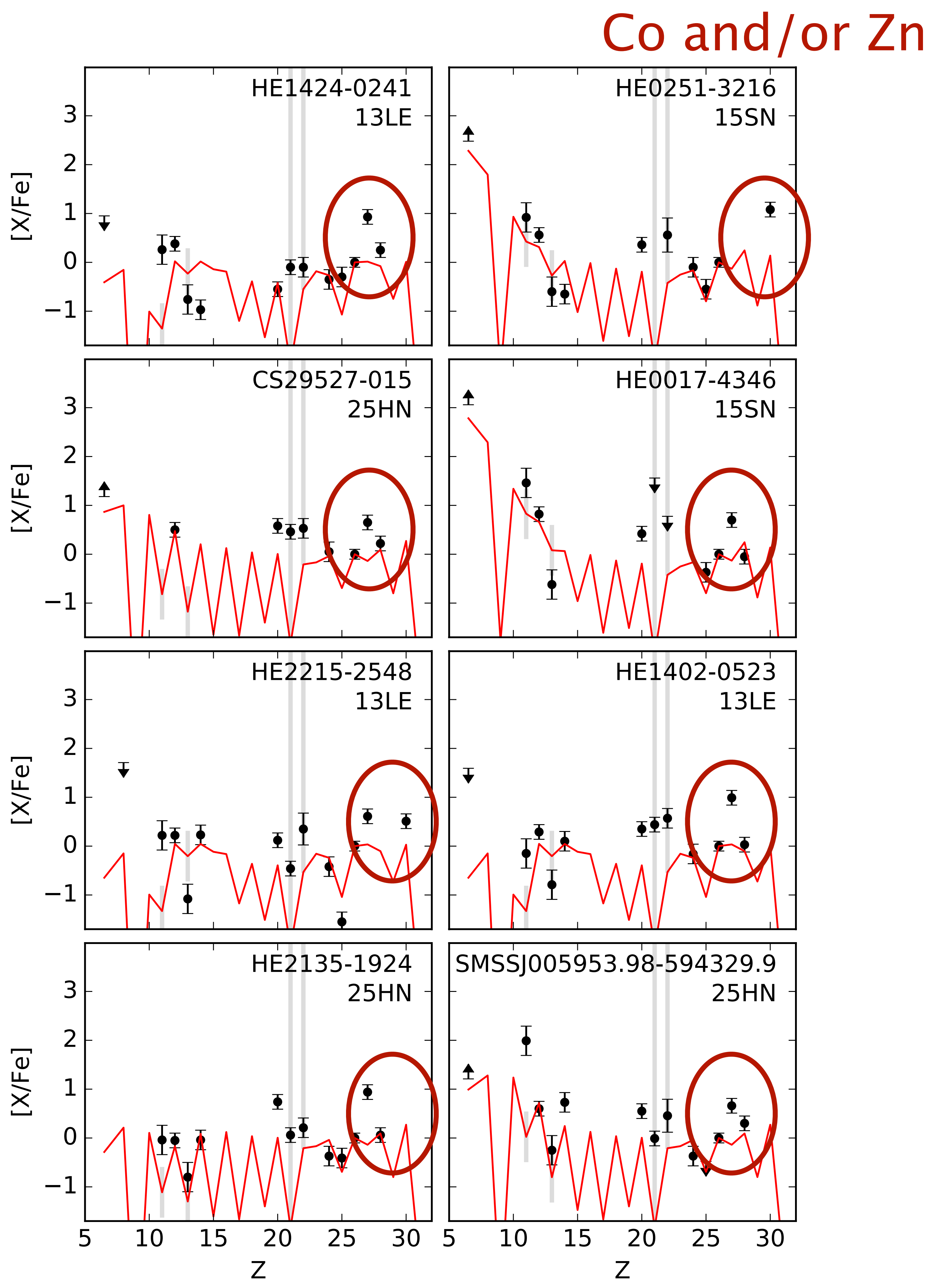
Open questions

The stars with large χ^2/DoF



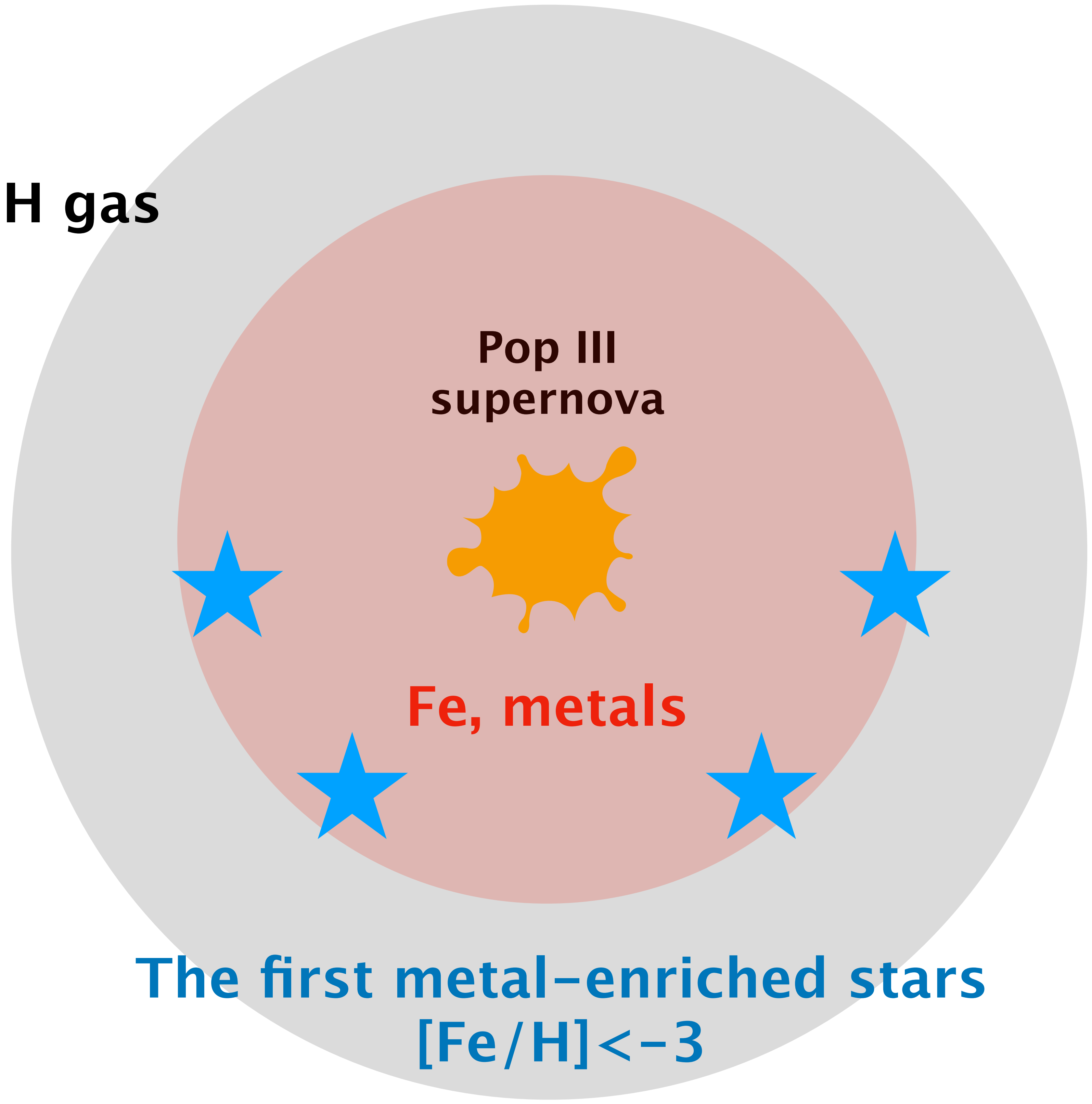
- Stellar evolution and supernova physics
  - The simple analytic prescription of the mixing and fallback
  - Ignorance of stellar rotation
  - Physics of aspherical supernovae
- Possibility of multi-enrichment (e.g. Hartwig et al. 2018)
- Limitation in the sample size
  - Only a small fraction of halo stars have been analyzed

2. Elemental abundances in age-selected Milky Way halo stars

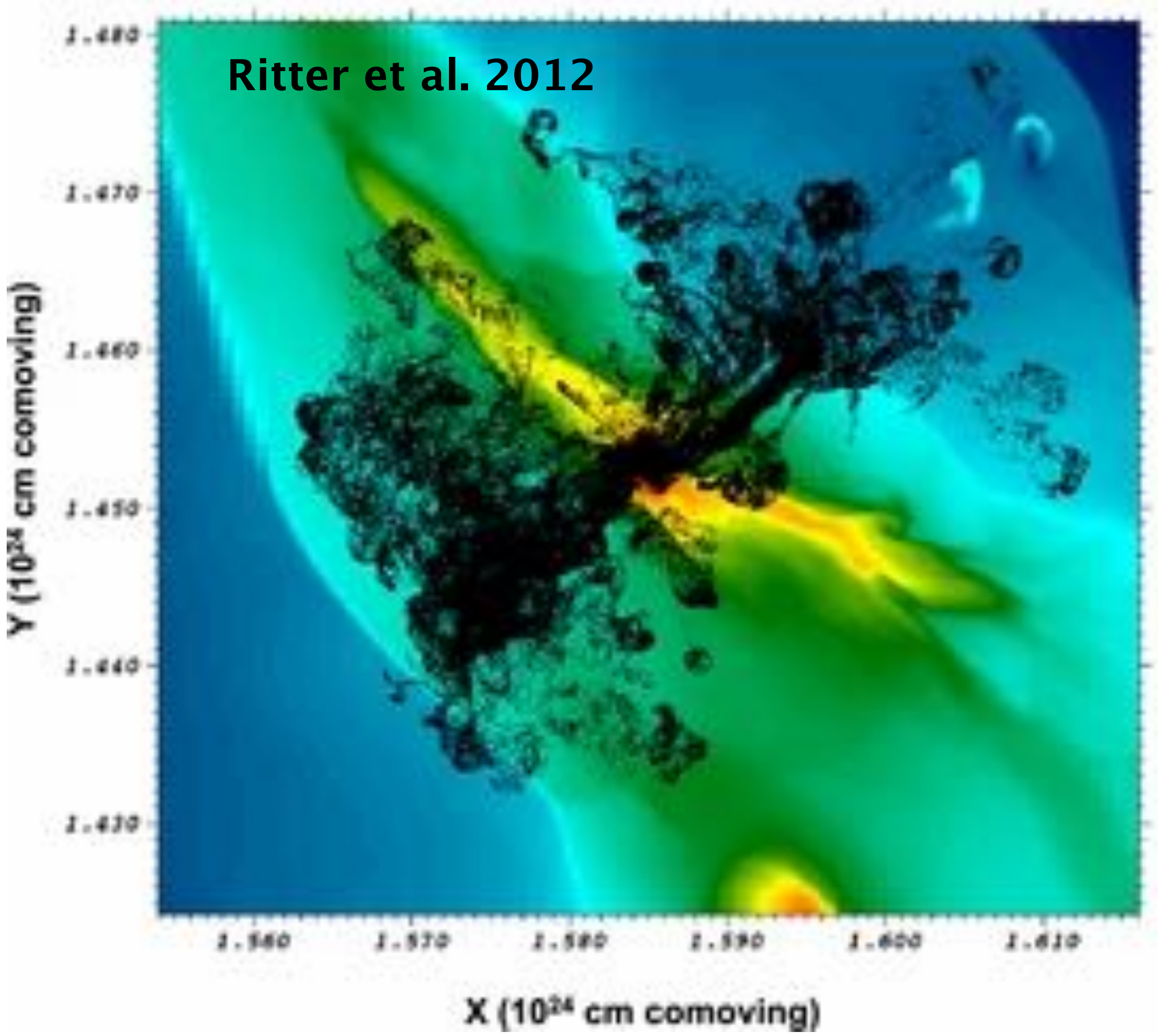
— Implication for inhomogeneous metal mixing in the early Universe —

The first metal-enriched stars

A simplified picture



Simulations

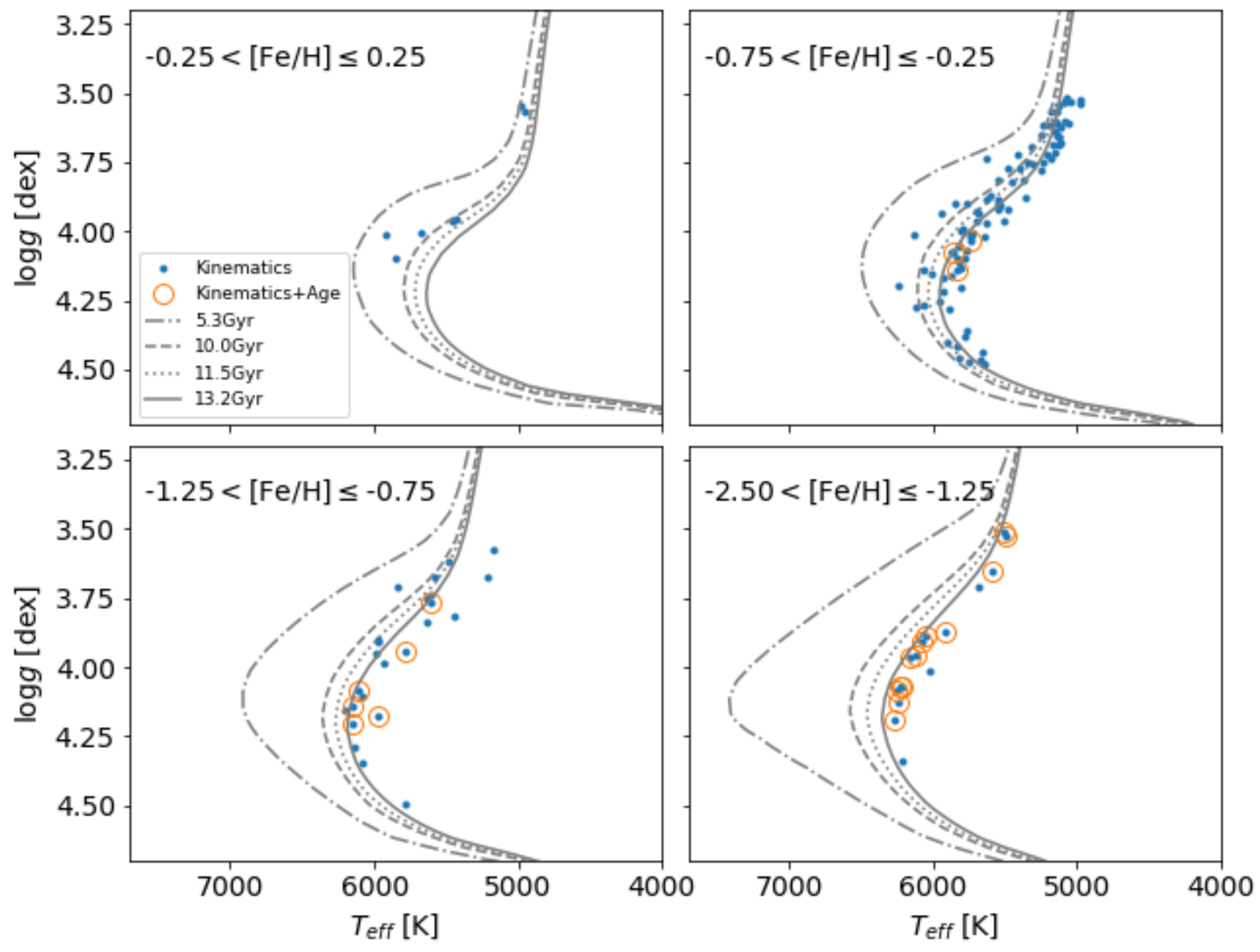


The first metal-enriched stars can have a wide range of [Fe/H]
as a result of the inhomogeneous metal mixing

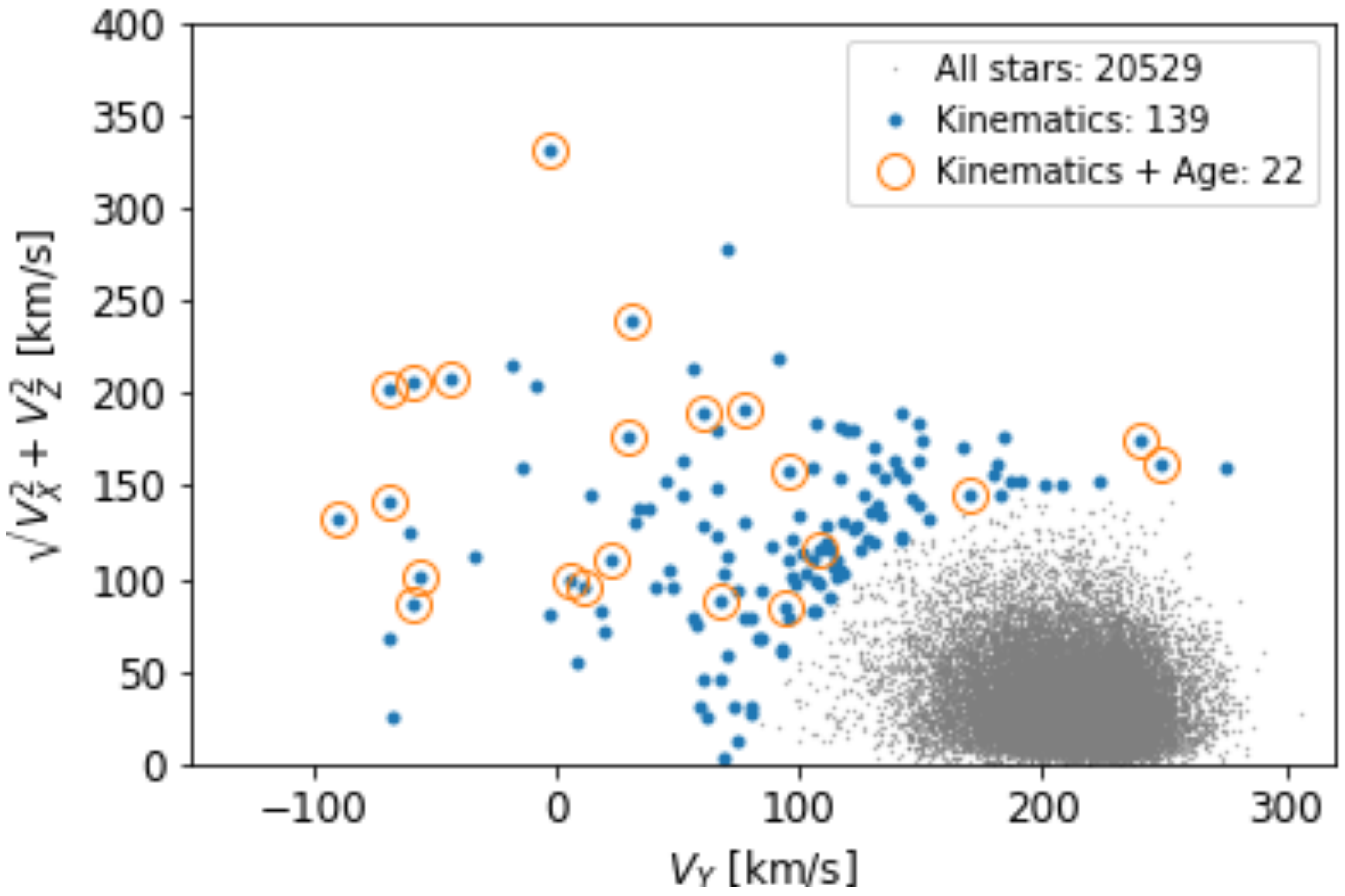
Selection of old halo stars

Based on the spectroscopic/astrometric data from Sanders & Das 2018

Color-magnitude diagram



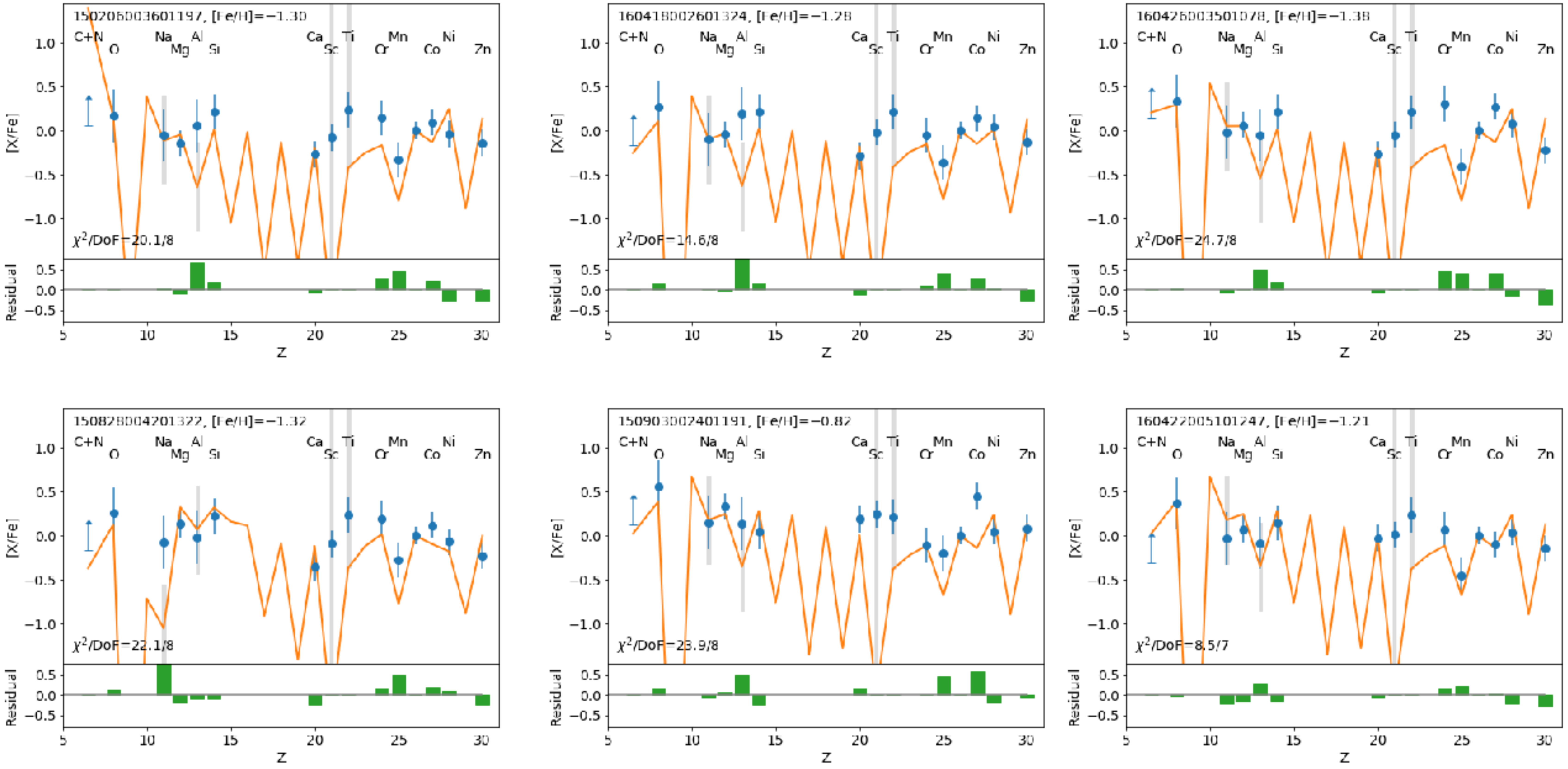
Velocity component based on the Gaia DR2



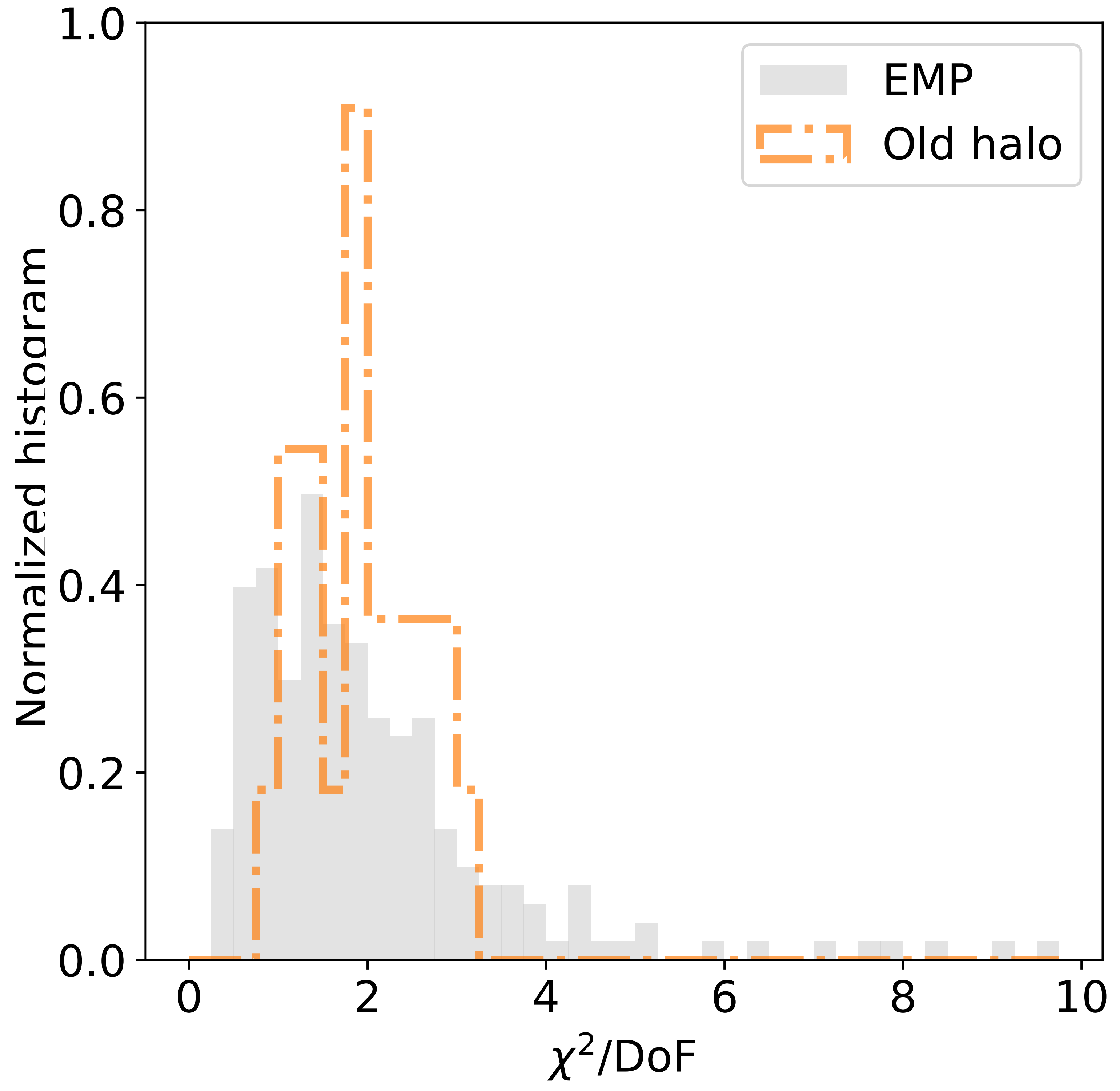
22 Main sequence turn-off stars with age estimated to be > 12 Gyrs
➡ -2.5<[Fe/H]<-0.5

Abundances measured by the GALAH survey

- **GALAH: A large high-resolution spectroscopic surveys of nearby stars conducted by HERMES instrument on AAT**
- **Fitting the Pop III supernova yield models to the observed elemental abundances from the GALAH DR2 (Buder et al. 2018)**



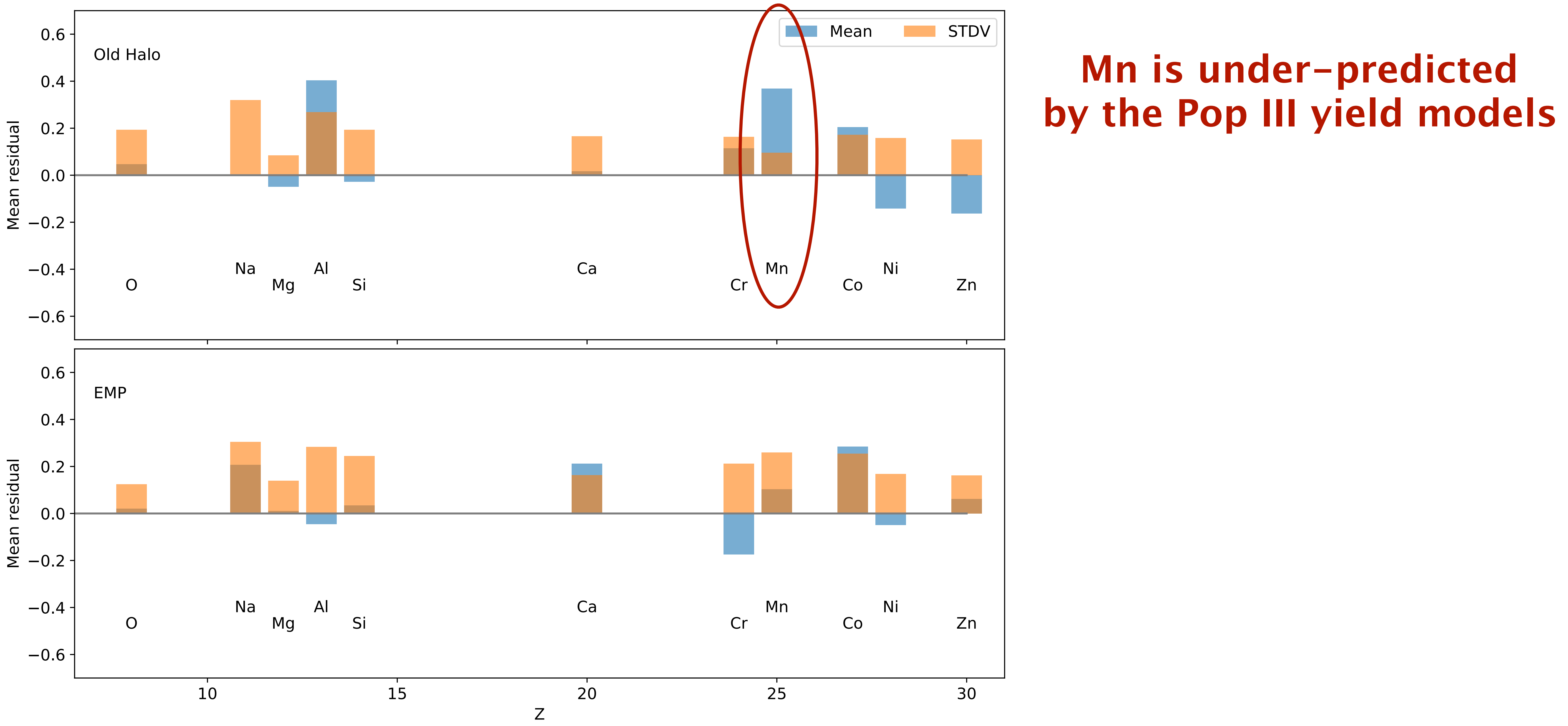
Chi square distributions



- Larger χ^2/DoF for the age-selected stars than the 200 EMP ([Fe/H]<−3) stars

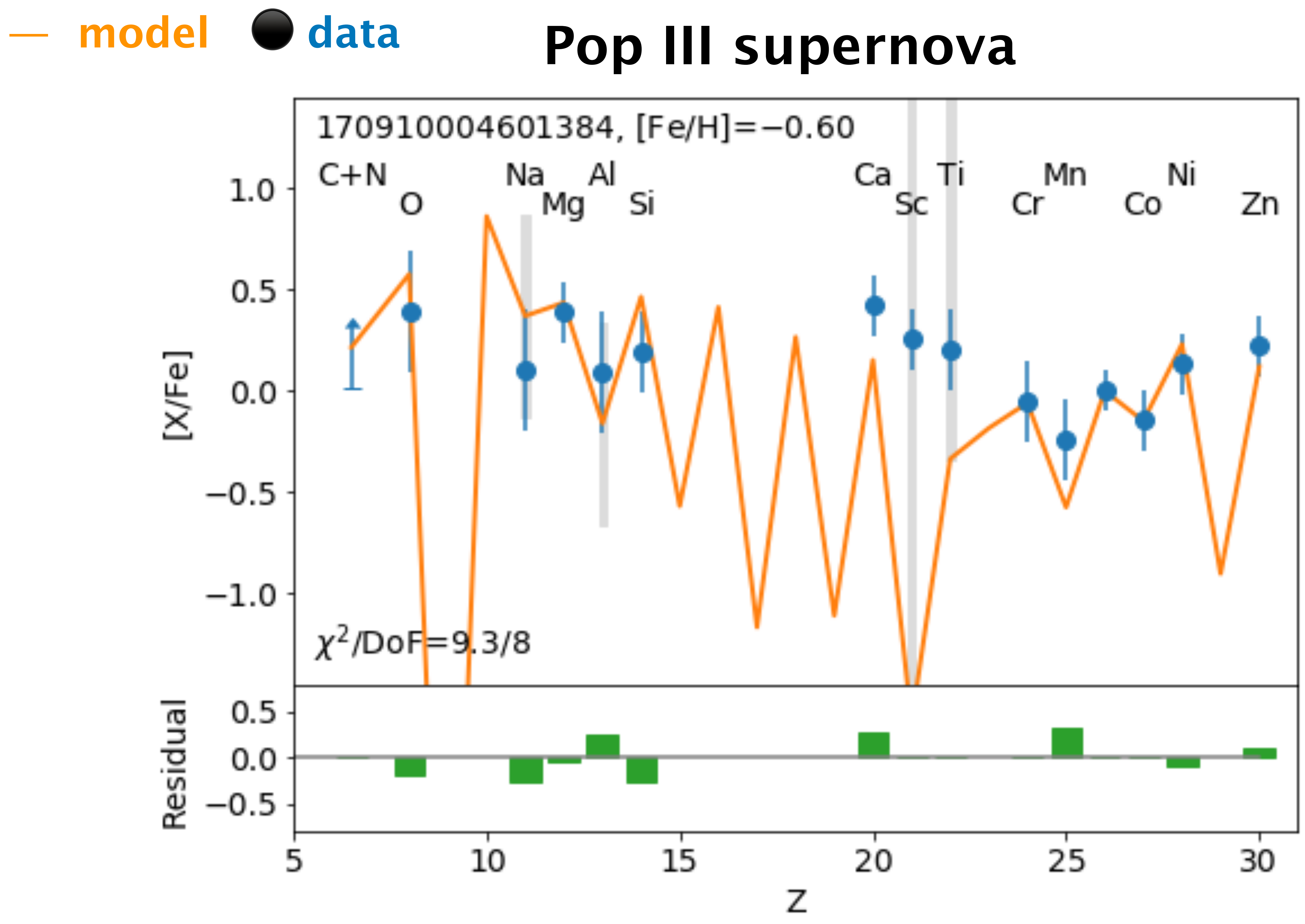
➡ Contributions from nucleosynthesis from sources other than Pop III supernovae

Mean residual



Contribution of Mn, probably from Type Ia supernovae at > 12 Gyrs ago

The abundances in old stars with [Fe/H]~−0.6



A simple prescription for the swept-up H mass
(e.g. Tominaga et al. 2007)

$$M(\mathrm{H}) = X(\mathrm{H})M_{\mathrm{SW}} = 3.93 \times 10^4 E_{51}^{6/7} n^{-0.24} M_\odot$$

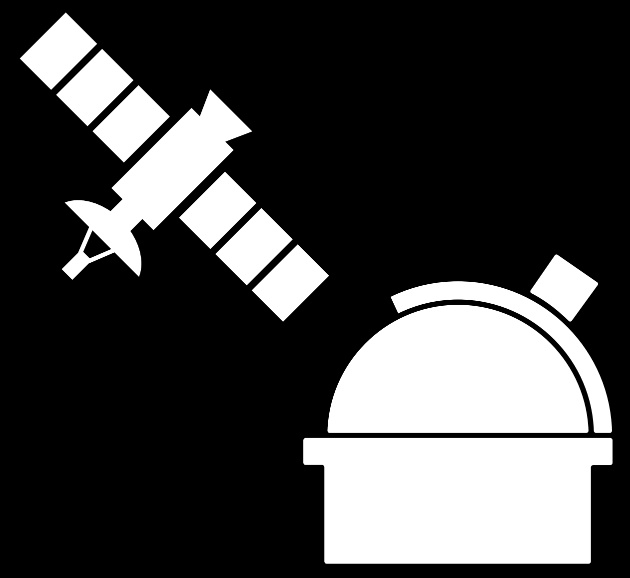
$$M(\mathrm{H}) \sim 10^5 M_\odot \quad (E_{51} = 1)$$

$$[\mathrm{Fe/H}] = -4 \sim -2$$

$$[\mathrm{Fe/H}] = -0.6 \quad ➡ \quad M(\mathrm{H}) \sim 10^2 M_\odot$$

The stars have been enriched by multiple, possibly primordial, core-collapse supernovae

A region with a rapid chemical enrichment timescale



3. Future prospects

Search for chemical signature of Pop III stars with wide-field surveys

- High-resolution spectroscopic surveys:

➡ Measuring detailed elemental abundances in most of the key elements: CNO, α-elements, Fe-peak elements

  - 4MOST @ VISTA telescope (4m): R>18000
  - MOONS @ VLT (8m): R~9000-20000
  - WEAVE @ WHT (4m): R~21000

- Low-resolution spectroscopic surveys:

➡ Distribution of chemical elements in the Milky Way halo

  - 4MOST, MOONS, WEAVE: R~4000-6000
  - DESI @ Mayall (4m): R~2000-5000
  - Prime-Focus Spectrograph (PFS) on the Subaru Telescope (8m, early 2022)

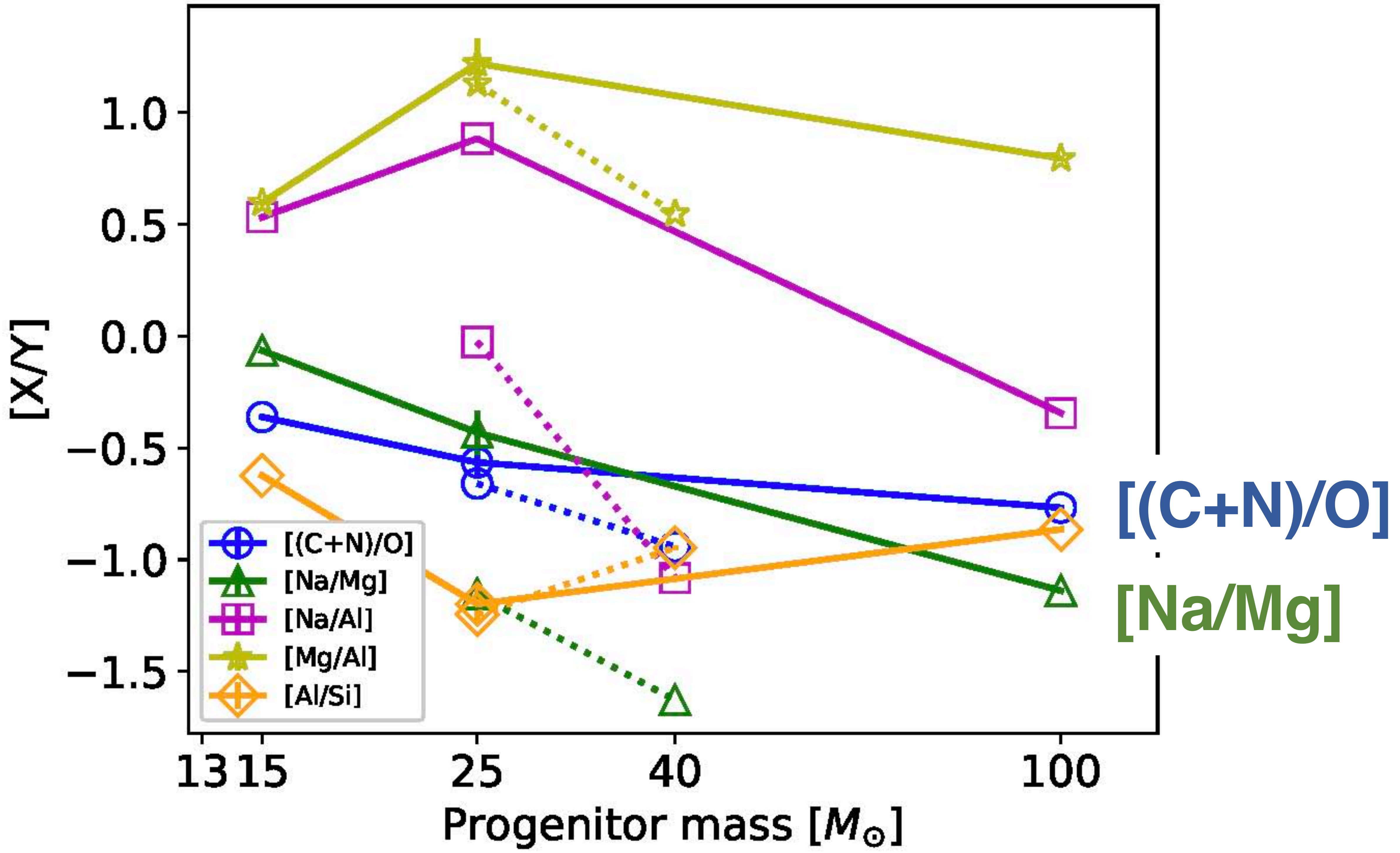
    ➡ Outer halo and dwarf satellites

High-resolution spectroscopy by large aperture telescopes

- Measurements of O abundances (e.g. [OI] forbidden line at 630nm, OH lines in UV) for a large sample of extremely metal-poor stars

High-resolution (R>30,000) spectroscopy with large-aperture telescopes (e.g. GMT/G-CLEF, TMT/HROS)

Elemental abundance ratios most sensitive to the Pop III progenitor masses



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Summary

- Chemical composition in metal-poor stars provide key information to make constraints on the chemical enrichment in the early Universe
- Comparison of a set of Pop III supernova yield models with observed elemental abundances in the two independent samples of stars, both of which could be candidates of the first metal-enriched stars:
  - 200 extremely metal-poor ([Fe/H]<-3) stars ➡ masses of the first stars
  - Stars selected based on estimated ages as well as kinematics ➡ Inhomogeneous chemical enrichment in the early Universe
- Future prospects
  - Identification of old/metal-poor stars in the Milky Way halo by wide-field surveys
  - Characterization of detailed elemental abundances with large aperture telescopes such as GMT/TMT

Discussions between stellar observations and theoretical supernova yield calculations is essential to make full use of the big survey data of metal-poor stars