The Milky Way halo population studied with LAMOST and Subaru

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The Milky Way halo population studied with LAMOST and Subaru
outline

- Background
- LAMOST survey and Subaru high-res spectroscopy for very metal-poor stars

➡Session 5, Haining Li

- Distributions of elemental abundance ratios
- Detailed abundance patterns of individual stars

➡Session 1, Yangming Lin

- Kinematics and elemental abundances
- Summary and extension of the project

Related publications

- Main sample:

Four-hundred Very Metal-poor Stars Studied with LAMOST and Subaru.

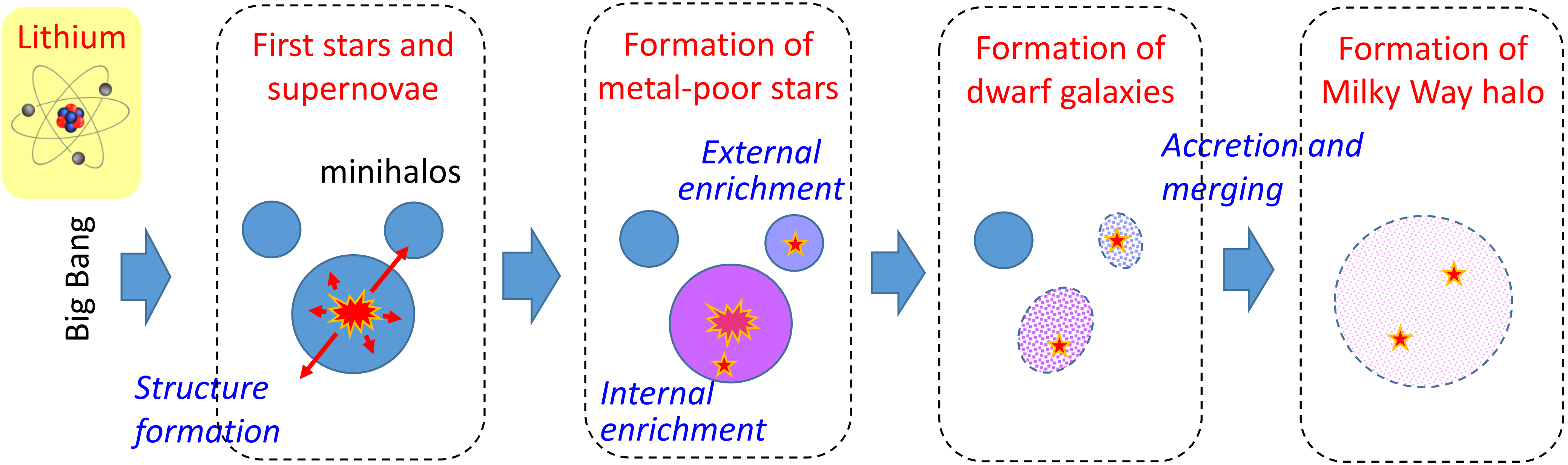
I. Survey Design, Follow-up Program, and Binary Frequency (Aoki et al. 2022, ApJ 931, 146)

II. Elemental abundances (Li et al. 2022, ApJ 931, 147)

III. Dynamically Tagged Groups and Chemodynamical Properties (Zhang, R. et al. 2024, ApJ 866, 174)

- α-poor star with r-process-excess (Xing et al. 2019, Nature Astronomy 3, 631; Xing et al. 2024, ApJ 965, 79)
- CEMP with large excess of Mg and Si (Aoki et al. 2018, PASJ 70, 94)
- CEMP-s star recording the products by the AGB progenitor (Zhang, S. et al. 2019, PASJ 71, 89)

Large sample of metal-poor stars in the Milky Way halo for studying process from first stars to early Galaxy



Chemical abundances of very metal-poor stars

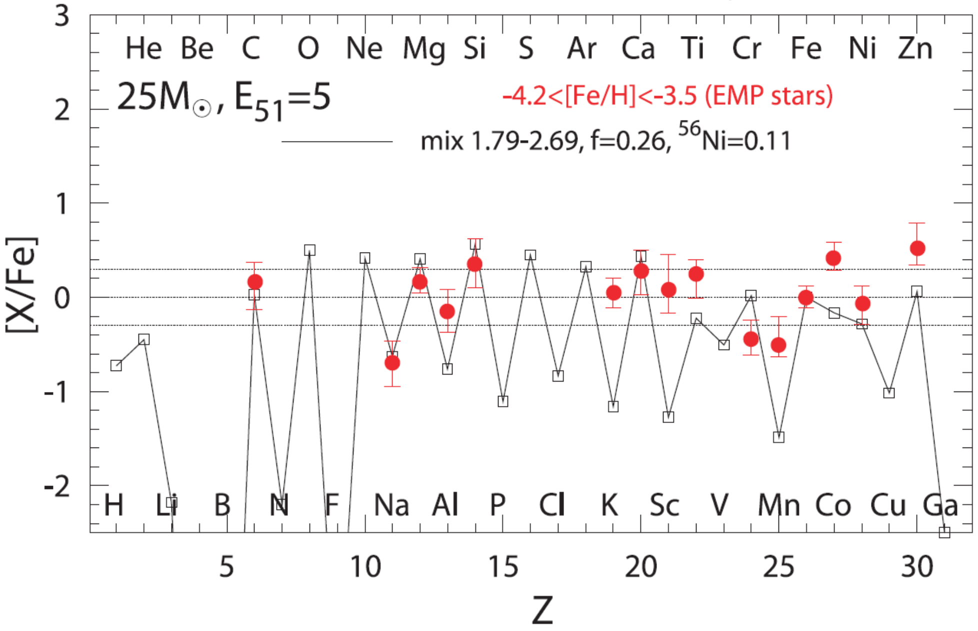
- ➡ Nucleosynthesis of first stars/supernovae
  - ➡ Masses of progenitor stars
- ➡ Accretion of low-mass stars into the halo structure

Abundance pattern and abundance distribution

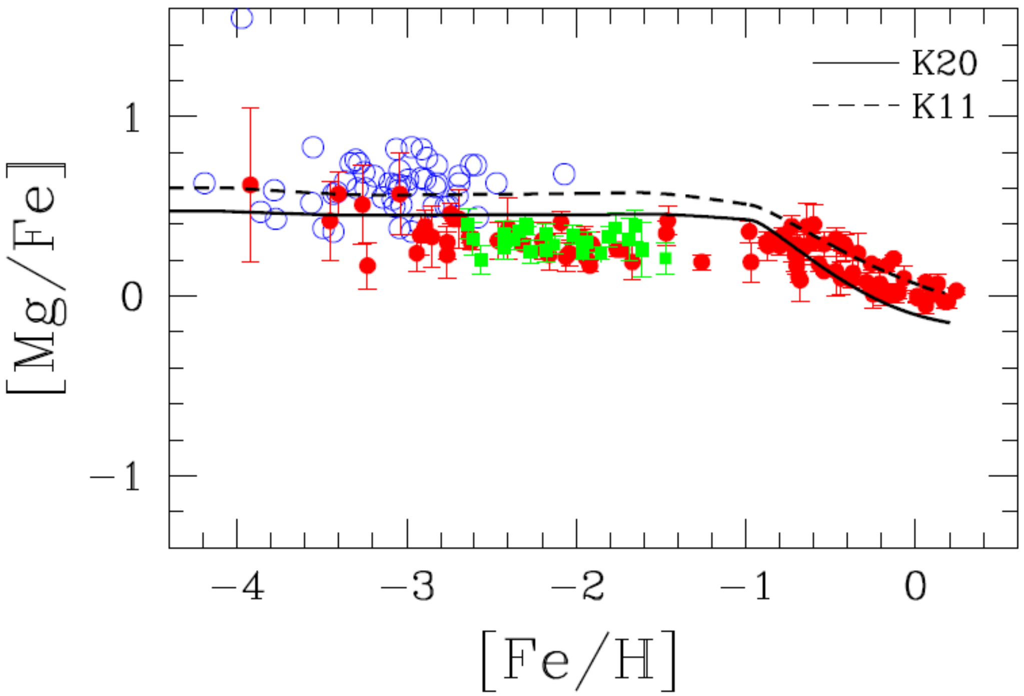
Abundances are determined for 10-20 elements from high-resolution spectra

- Elemental abundance pattern of individual stars (or their averages) are compared with supernovae and other nucleosynthesis models
- Distributions of abundance ratios of individual elements are compared with chemical-evolution models

Tominaga et al. 2007



Kobayashi et al. 2020



Searches for very metal-poor stars in the Milky Way halo and abundance measurements

- Abundance measurements for bright (nearby) stars ～1980s
  studies for high proper motion stars
- **Objective prism surveys**
  HK survey (1980s-)　Beers et al. 1985, 1992, etc.
  Hamburg/ESO survey (1990s-)　stellar content: Christlieb et al. 2001
  Abundance studies:
    McWilliam et al. 1995, Ryan et al. 1996
    Cayrel et al. 2004, Honda et al. 2004, Cohen et al. 2004, etc.
- **Large spectroscopic surveys** (2000s～)
  SDSS/SEGUE (Yanny et al. 2009), **LAMOST (Li, this symposium)**
  Abundance studies
    Aoki et al. 2013, Bonifacio et al. 2015, etc.
    Li et al. 2022
- **Photometric surveys**
  Skymapper (Keller et al. 2007), Pristine (Starkenburg et al. 2017)
  Abundance studies
    Jacobson et al. 2015, Yong et al. 2021, etc.
    Venn et al. 2020, etc.
- ***Gaia*** spectroscopy + astrometry + photometry

1980
Systematic searches

1990

2000
8-10m telescopes

Multi-object spectroscopy

2010
Photometric survey

2020

Searches for satellite dwarf galaxies

Studies of metal-poor stars in dwarf galaxies

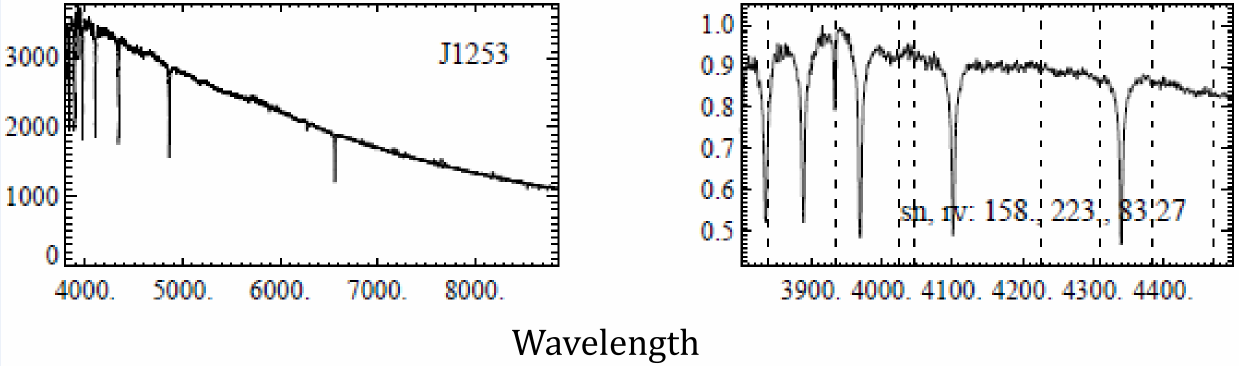
Searches for very metal-poor stars from LAMOST low-resolution spectra and abundance studies with Subaru/HDS

Selection of >1500 candidates with [Fe/H]<-2 from >5M spectra of LAMOST DR1-5

- Synthetic spectra fitting
- 27 line indices
- Visual inspection

Li, this symposium

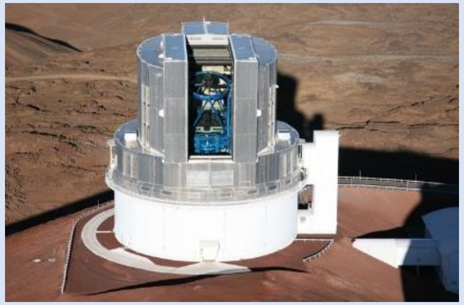
LAMOST
R=1800
3700-9100A
4000 fibers



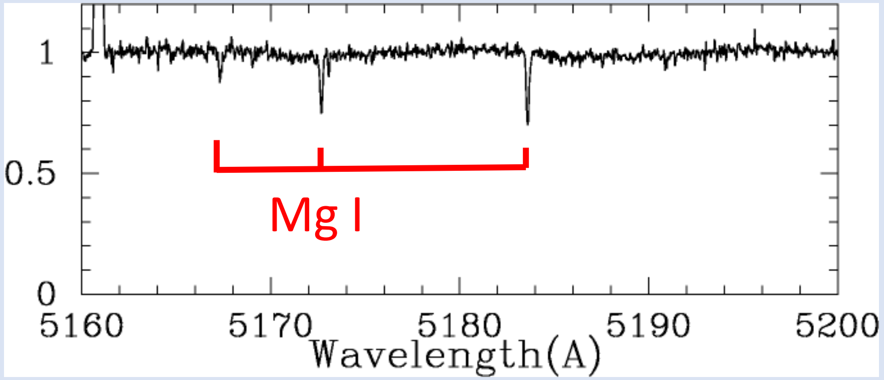
Follow-up spectroscopy since 2014

e.g., Subaru intensive program S16A-119I: LAMOST/Subaru study for 500 very metal-poor stars (2016-2018)

Aoki et al. (2022)



Subaru
R=36,000
4050-6800A
386 stars for the main sample

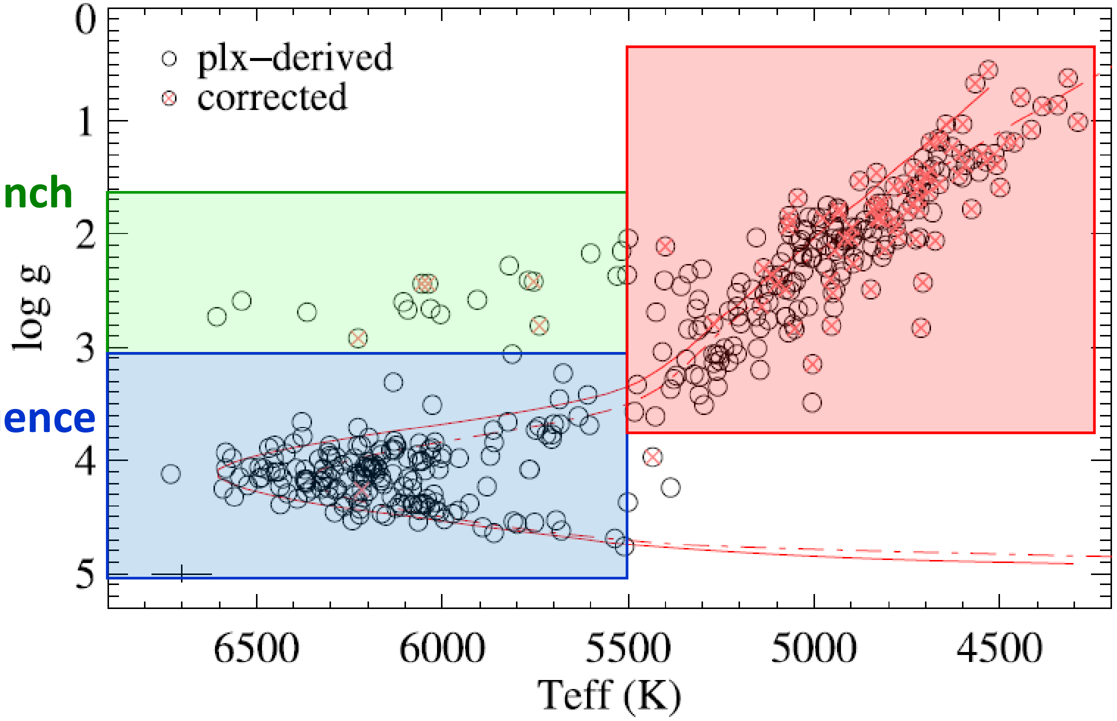


Sample of LAMOST/Subaru study: main-sequence turn-off stars and red giants

- The sample covers main-sequence turn-off, red giants, and horizontal branch stars.

Surface gravity is derived using the *Gaia* parallax data for >300 stars

Li et al. (2022)

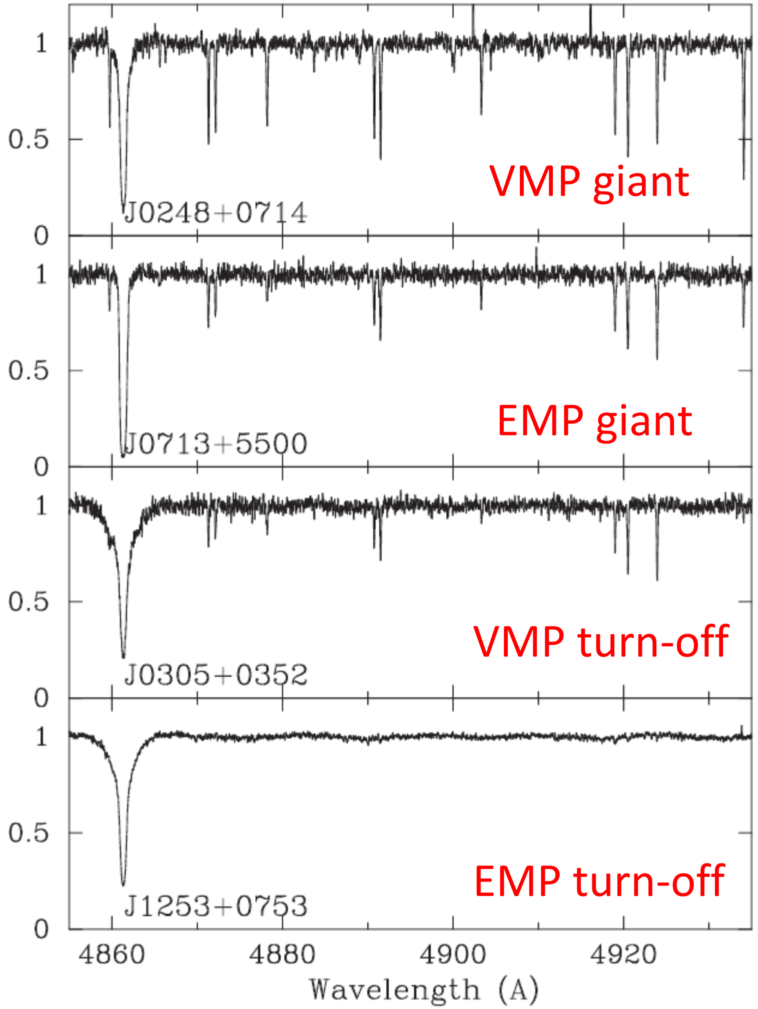


Horizontal branch

Red giants

Main-sequence turn-off

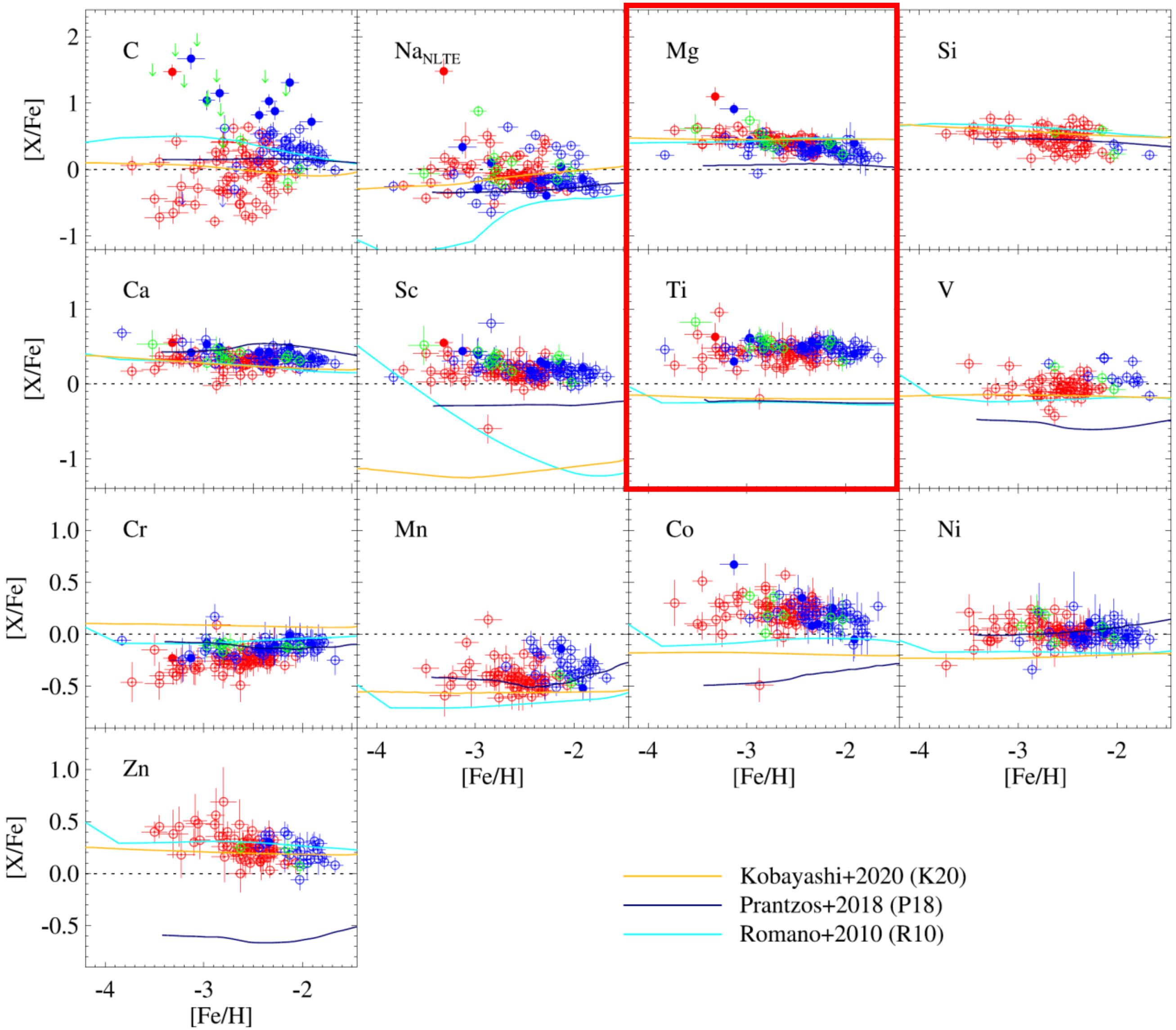
Examples of Subaru/HDS spectra



Distributions of elemental abundance ratios: constraints on the nucleosynthesis and accretion history

Distributions of abundance ratios compared with chemical evolution models

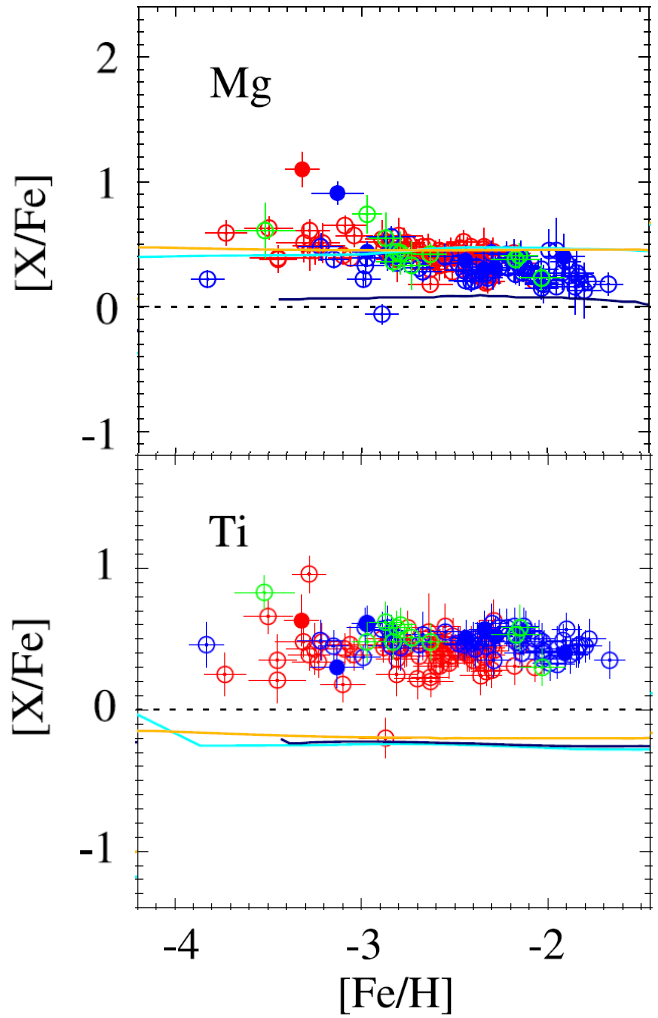
Trend and scatter of abundance ratios of α and Fe-peak elements examine chemical evolution models, including supernova yields and mixing in star-forming clouds/mini-halos.



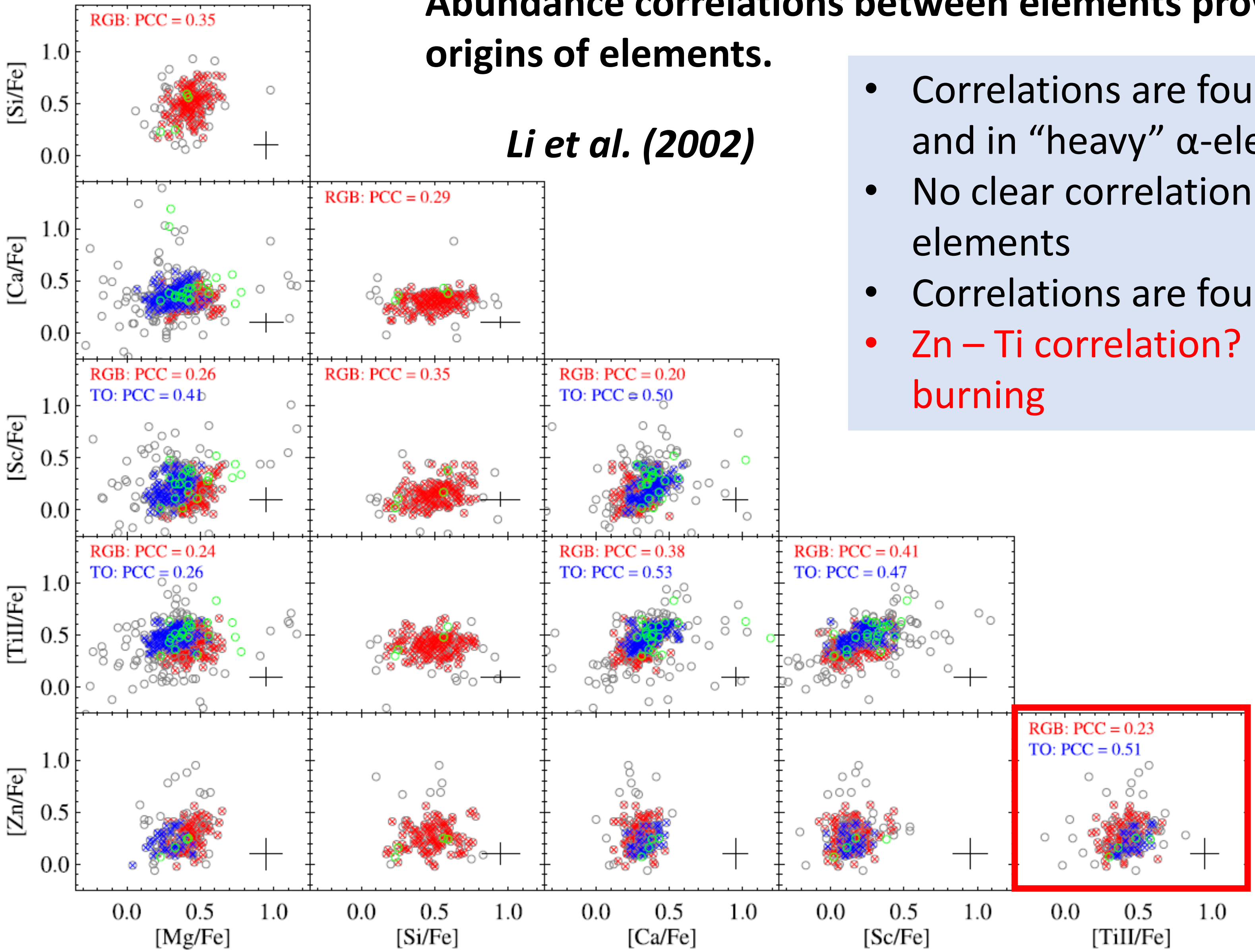
○● main-sequence turn-off stars

○● red giants

Li et al. (2022)



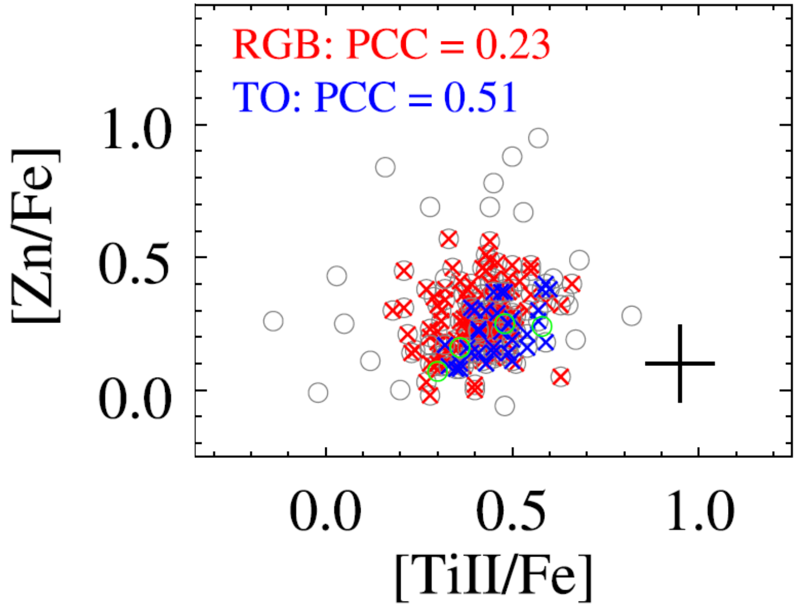
Distributions of abundance ratios: correlation between elements



Abundance correlations between elements provide hints for understanding the origins of elements.

Li et al. (2002)

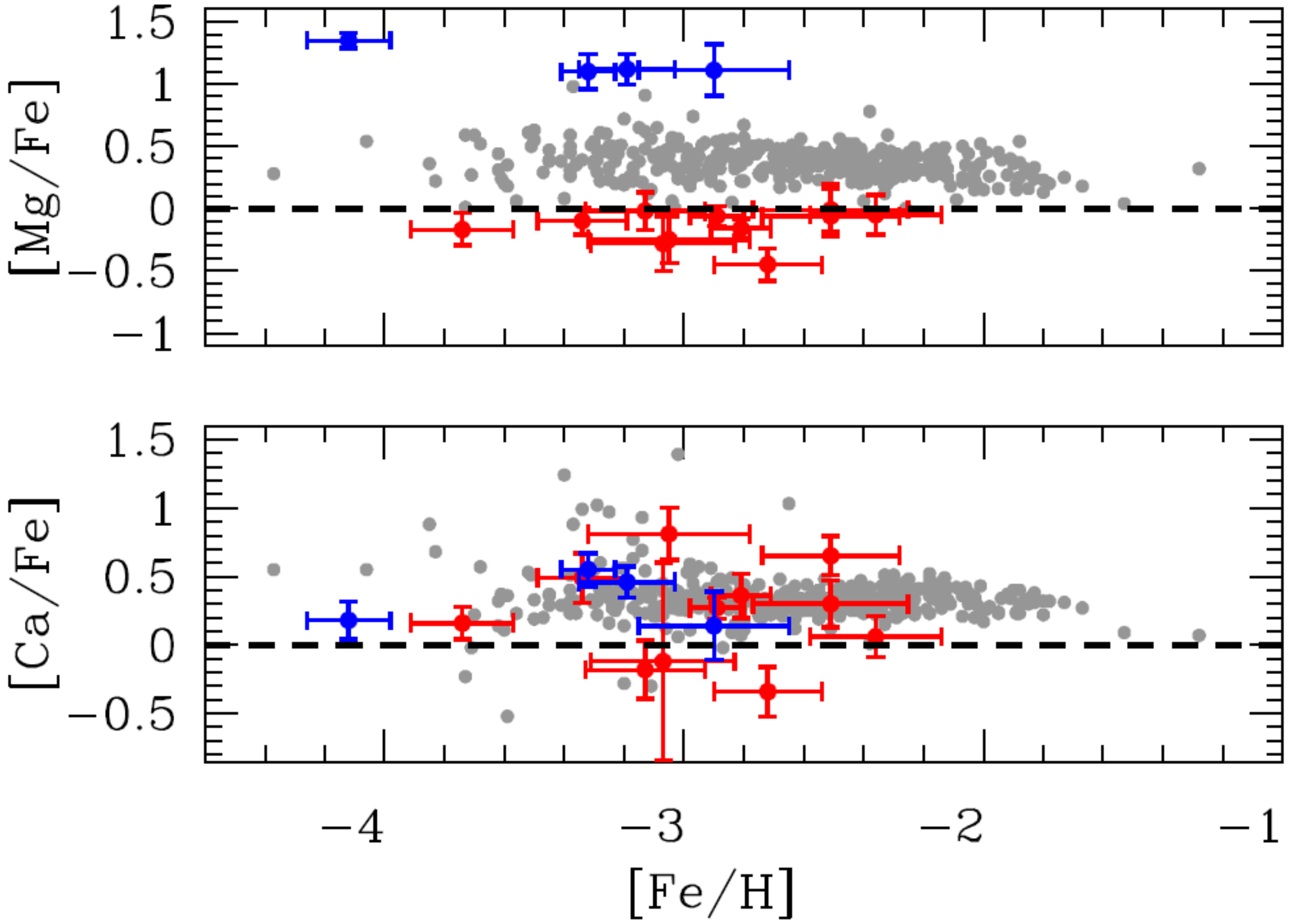
- Correlations are found in “light” α-elements (Mg-Si), and in “heavy” α-elements (Ca-Ti)
- No clear correlation between “light” and “heavy” α-elements
- Correlations are found odd-even pairs (e.g., Sc – Ca)
- Zn – Ti correlation? : Contribution of complete Si burning



Outliers: α/Fe ratios

A small fraction of VMP/EMP stars have high α/Fe or low α/Fe ratios

- “α-rich” stars are carbon-enhanced objects
- “α-poor” stars are explained by contributions of type Ia supernovae. The time scale of type Ia is a matter to be considered at very low metallicity



- “α-rich” and “α-poor” stars are identified by [Mg/Fe] ratios
- Their [Ca/Fe] are indistinguishable from other stars

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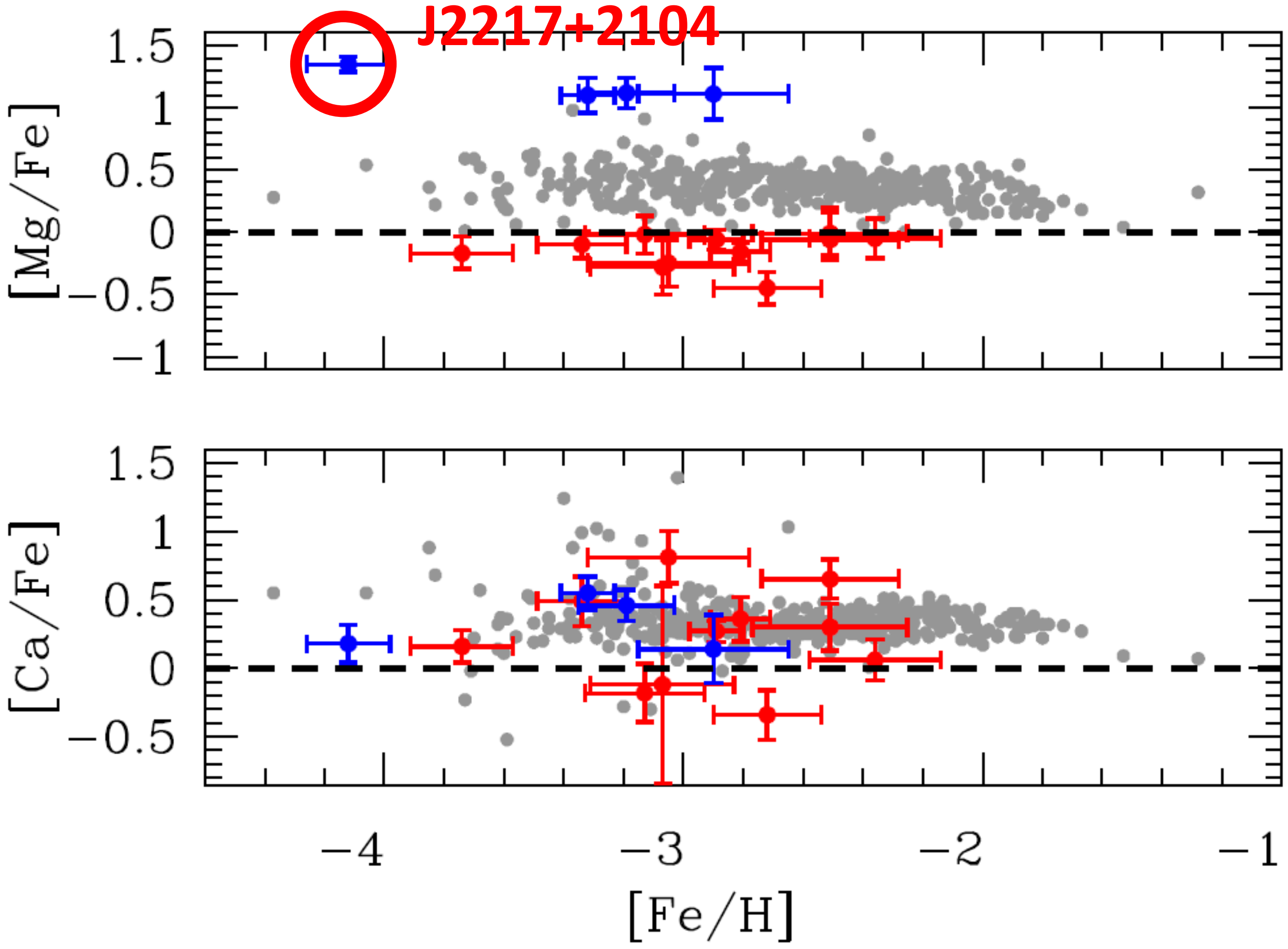

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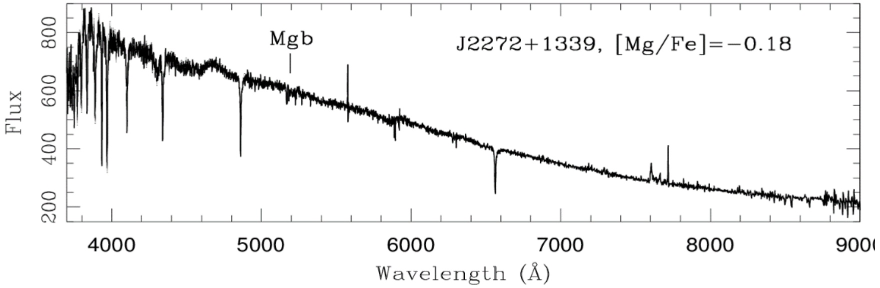
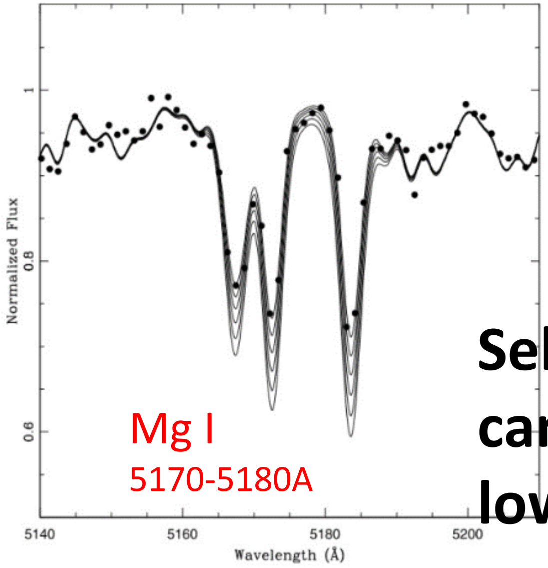
α-poor stars selected from LAMOST spectra

α-poor (low α) stars have been identified from the LAMOST low-resolution spectra using the Mg b lines (as a separate sample)

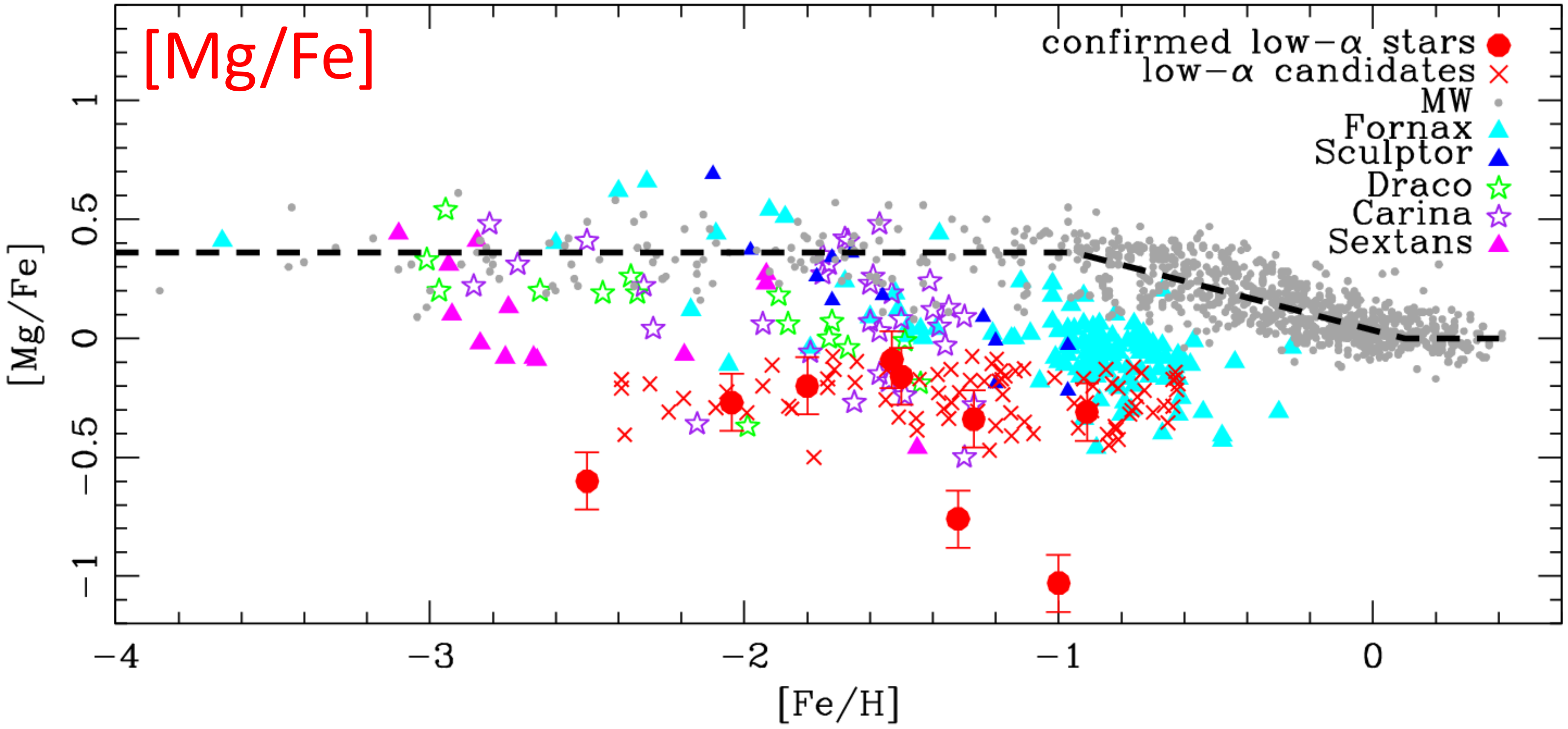
➡High-resolution spectra with Subaru/HDS confirm the low Mg/Fe ratios for several stars

LAMOST low resolution spectra





Selection of candidates of low α/Fe stars



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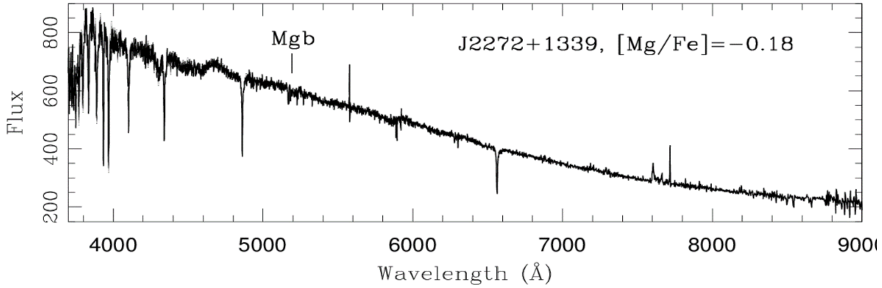

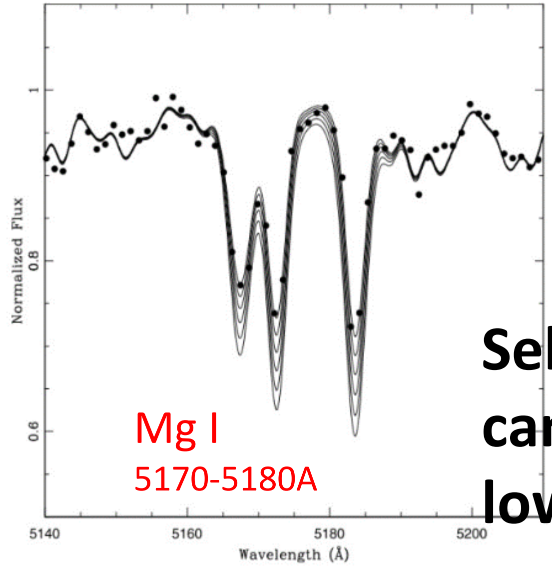

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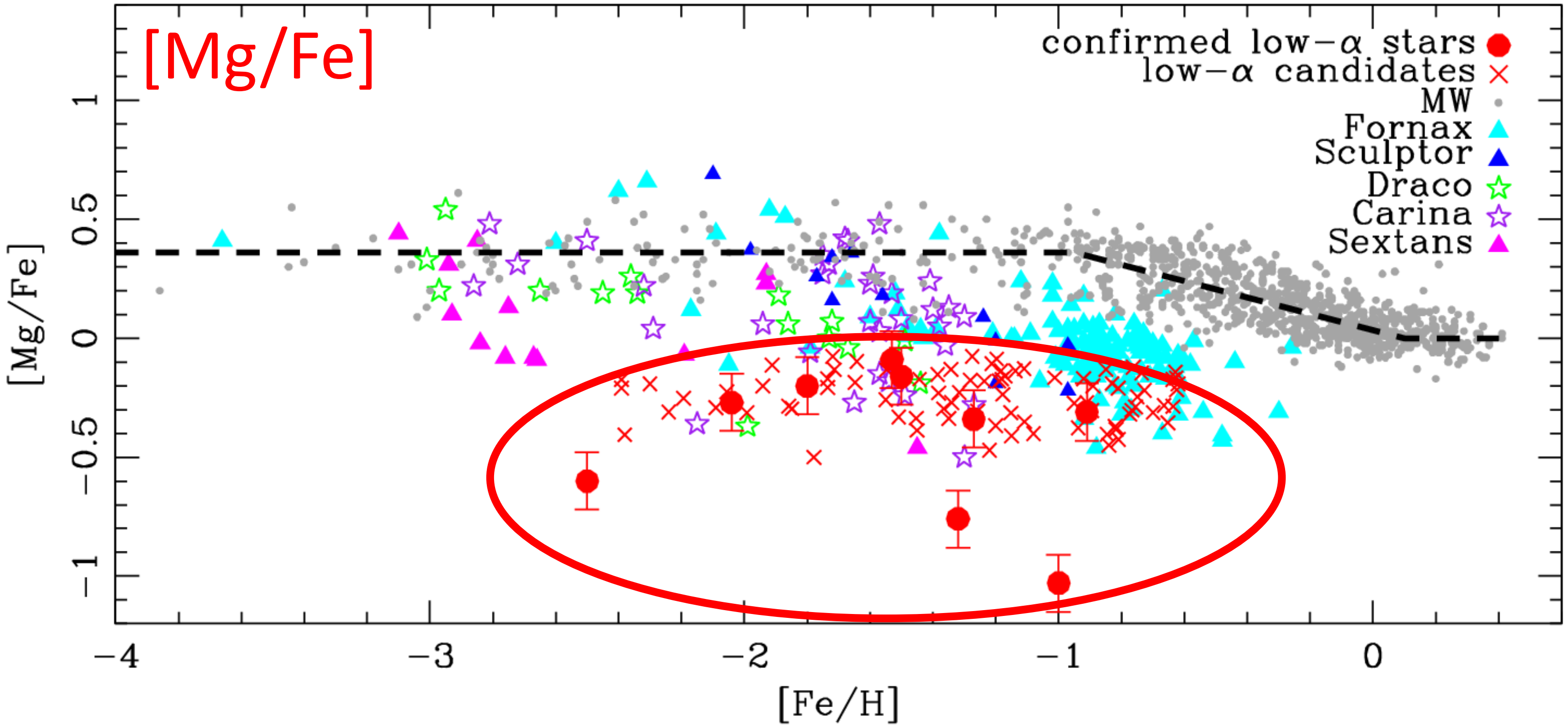

Detailed abundance patterns: constraints on the nucleosynthesis and progenitor mass

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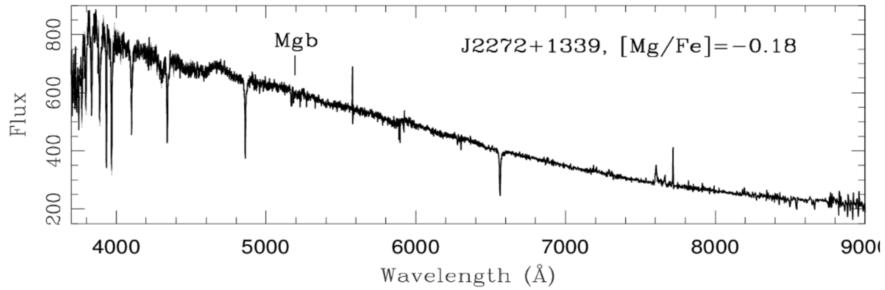

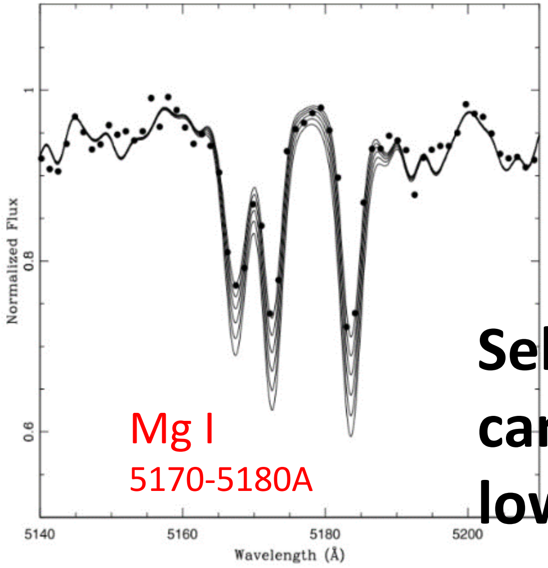

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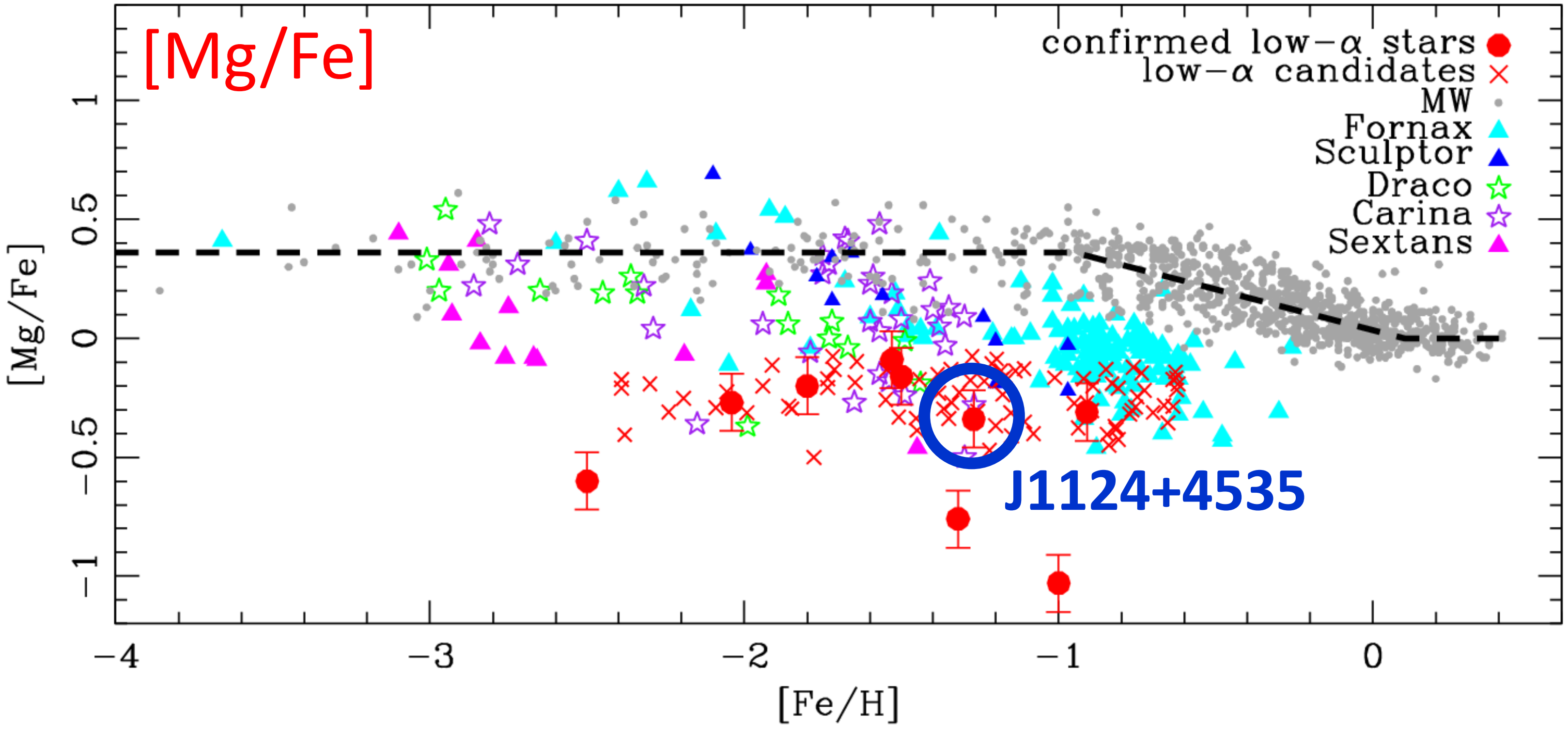


Discovery of an α-poor metal-poor star with r-process-excess

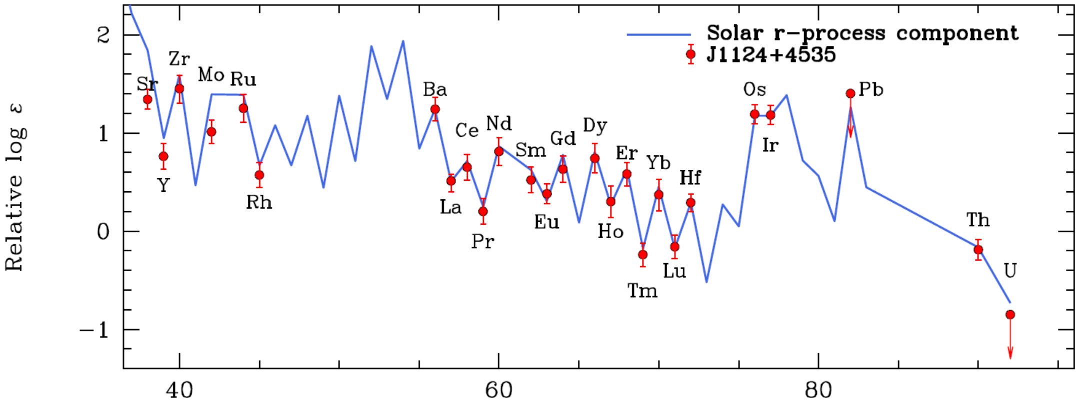
Among the α-poor stars found with LAMOST, an r-process-enhanced star (LAMOST J1124+4535) was identified by high-resolution spectra

➡ This is a unique star in the halo, but similar stars are found in dwarf galaxies (e.g. Ursa Minor COS 82).

➡ This star provides clear evidence of accretion of a dwarf galaxy similar to Ursa Minor.

Xing et al. (2019, Nature Astronomy)
Xing et al. (2024, ApJ)

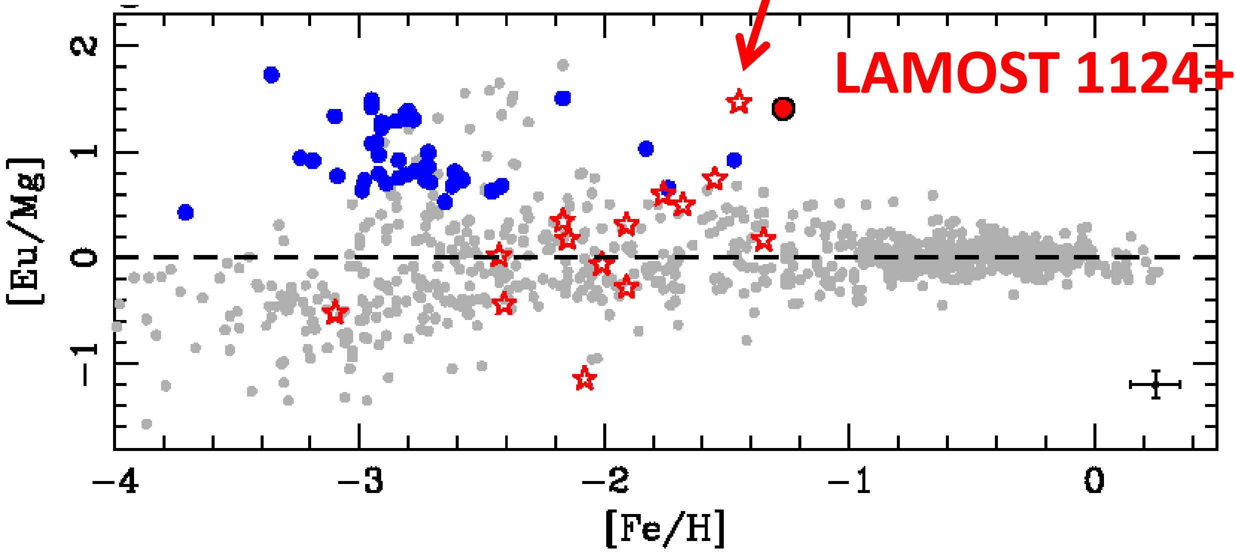
Origin of heavy elements is r-process



dwarf galaxy stars
(Ursa Minor COS82)

[Eu/Mg]

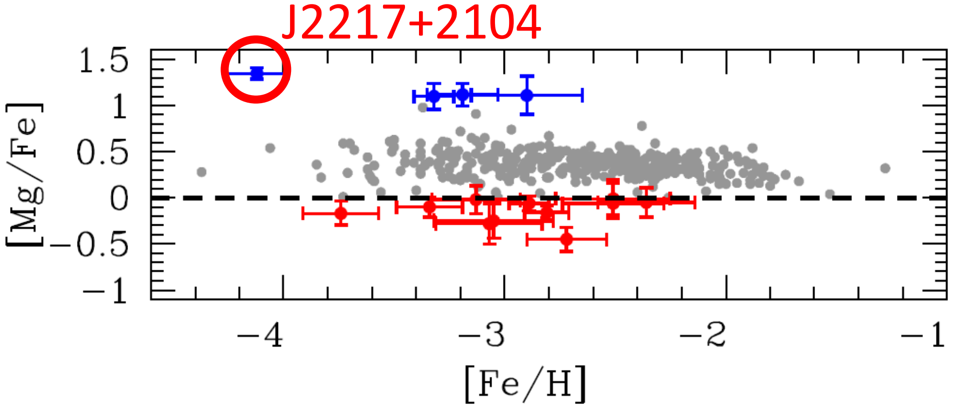
LAMOST 1124+4535



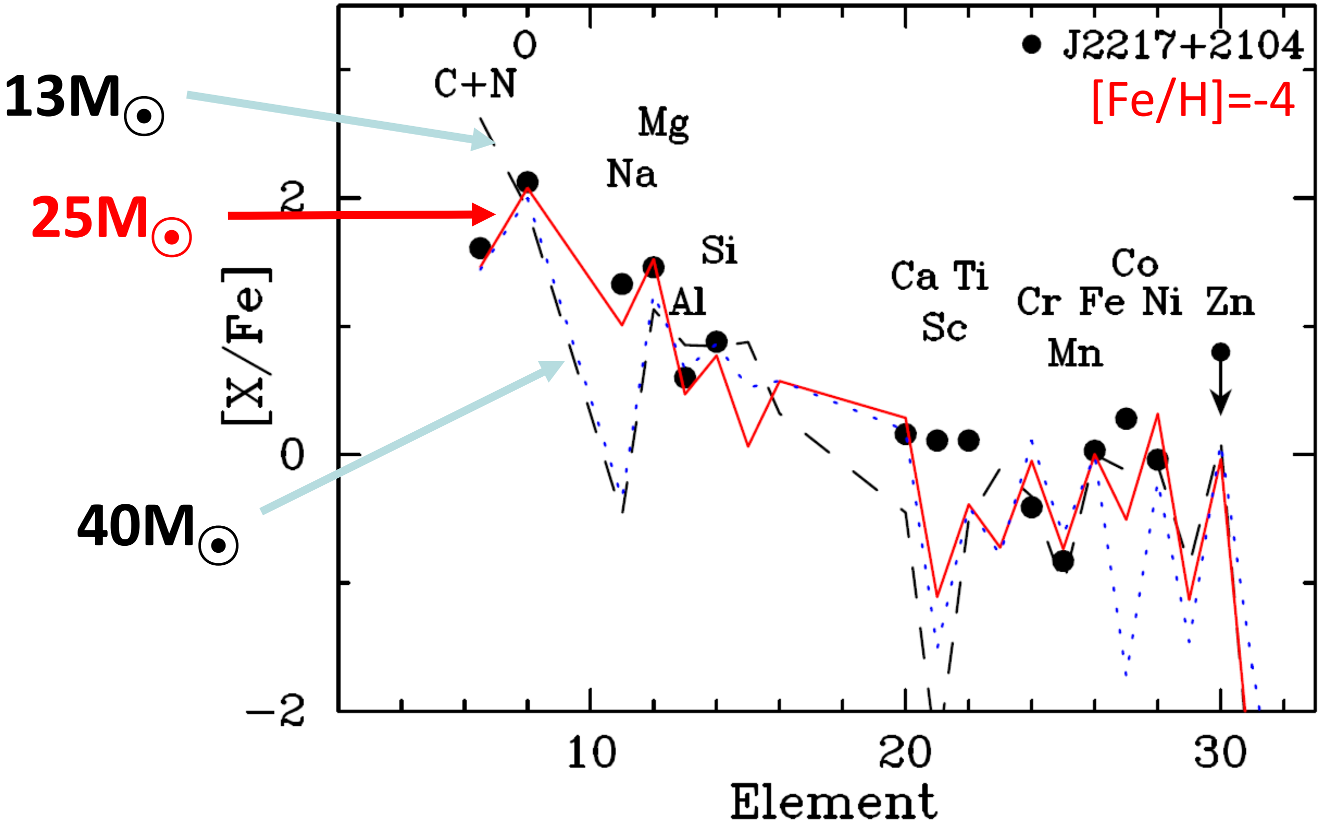
Carbon-enhanced (CEMP-no) star from a massive progenitor

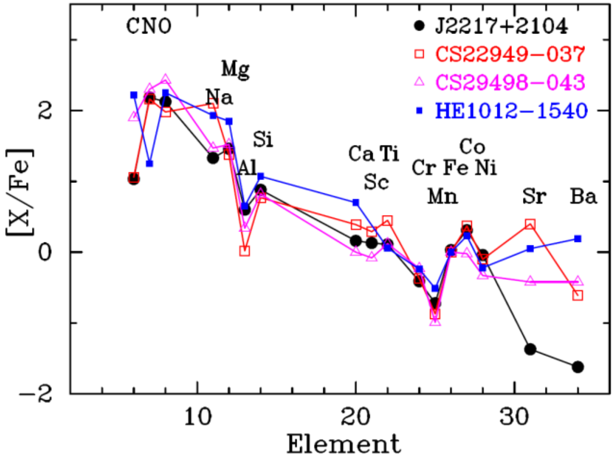
Ultra/Extremely metal-poor stars with C-excess could reflect first generation supernova yields

- (C+N)/O, Na/Mg ratios are sensitive to the progenitor mass (Ishigaki et al. 2018)
- Abundance patterns of metal-poor stars are usually explained by supernovae of progenitor mass of ~25 $M_\odot$



Aoki et al. (2018)





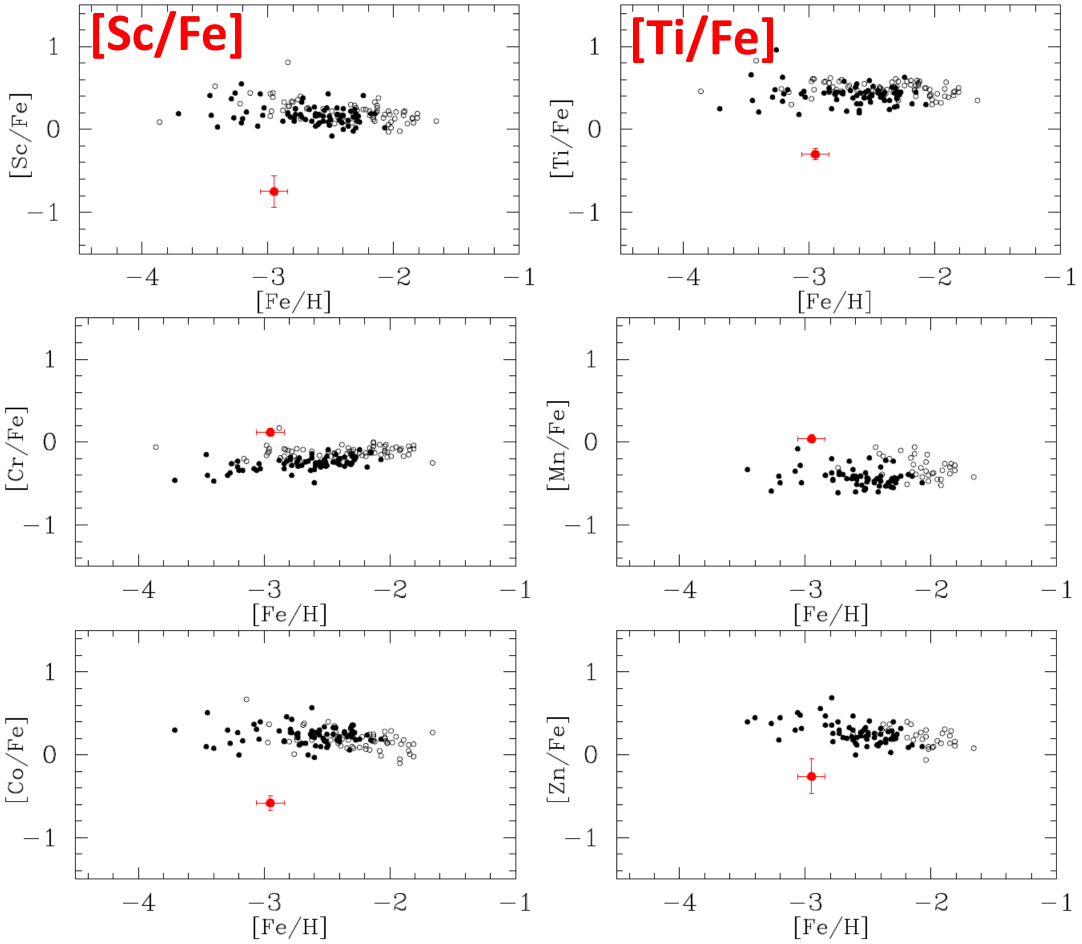
EMP outlier reflecting a faint supernova with spherical explosion?

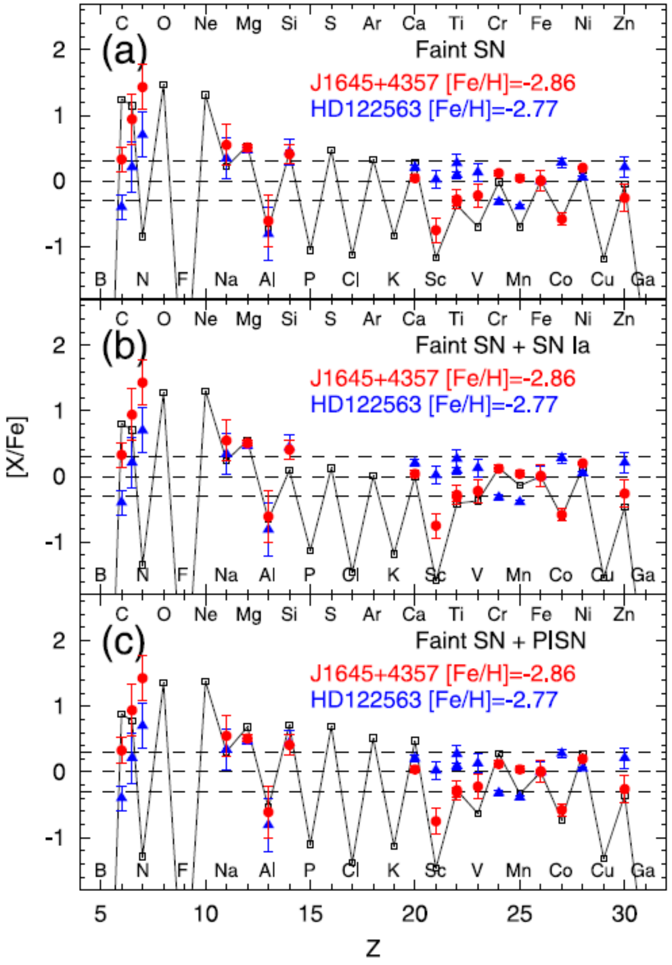
A unique star showing peculiar abundance ratios J1645+4357

Aoki et al. (2023)

➡The overall abundance pattern (moderate excess of C+N) is explained by faint supernova

➡The abundance ratios are better explained by special explosion than the patterns of other stars … why is this star peculiar?





A faint supernova model assuming spherical explosion well explains the pattern including Ti and Sc.

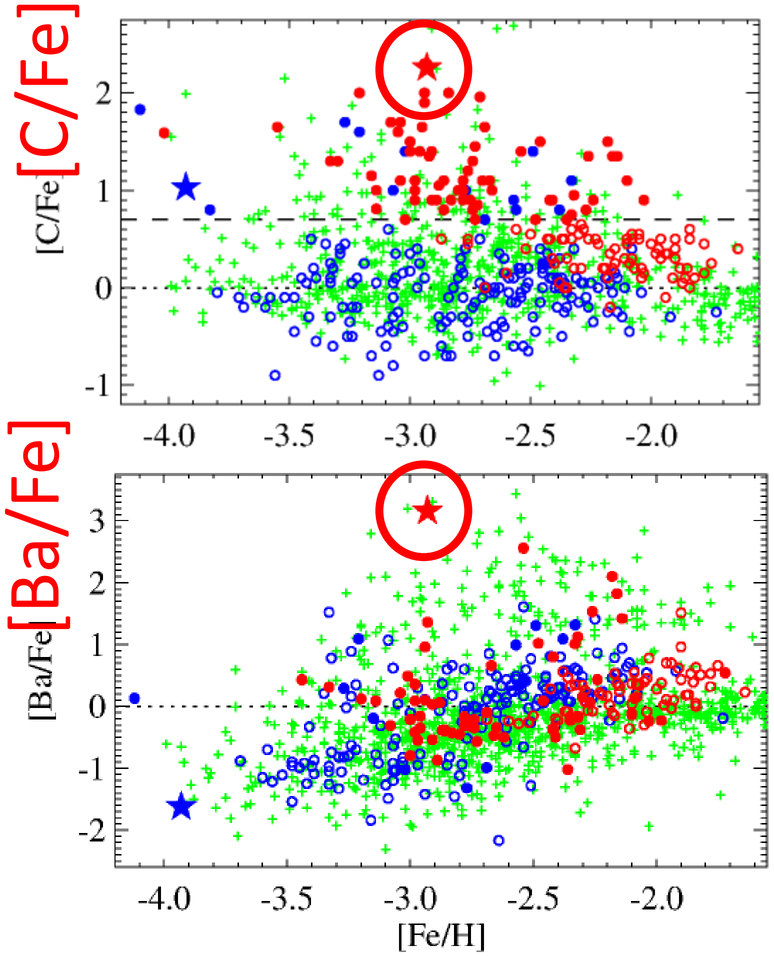
Assuming contribution by type Ia or pair-instability supernova better explains the pattern (e.g., Mn).

Carbon-enhanced (CEMP-s) star polluted by a low-mass AGB companion

LAMOST J0119-0121: **a main-sequence turn-off star with extremely large excess of C and s-process elements**

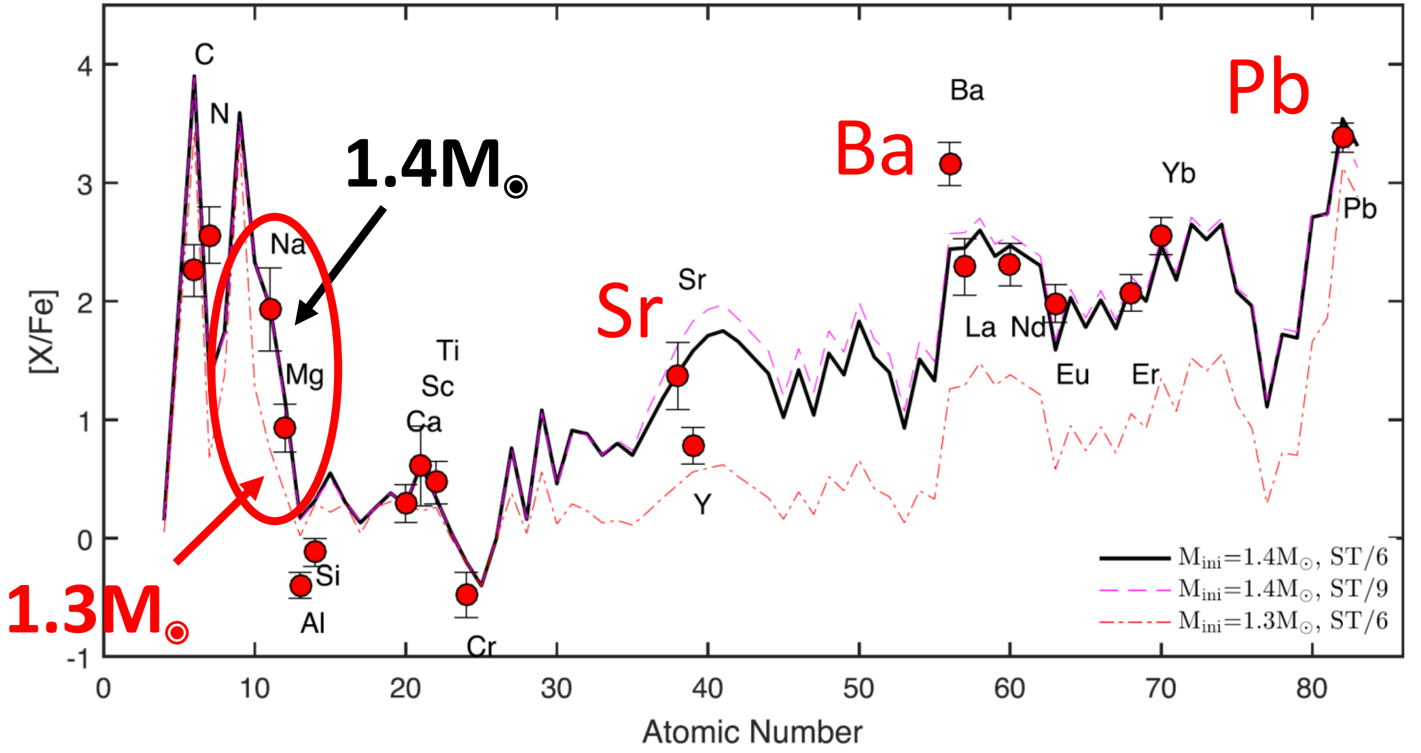
➡ The surface could be well covered by material transferred from the companion AGB star.

- Abundance pattern of heavy elements (Sr-Ba-Pb) are reproduced by models of s-process for low metallicity
- Na and Mg abundances are useful to constrain AGB mass ➡ 1.4M$_\odot$ model AGB star



Zhang et al. (2019)

Direct comparison of AGB models (e.g. Bisterzo et al. 2010)



Dynamically tagged groups

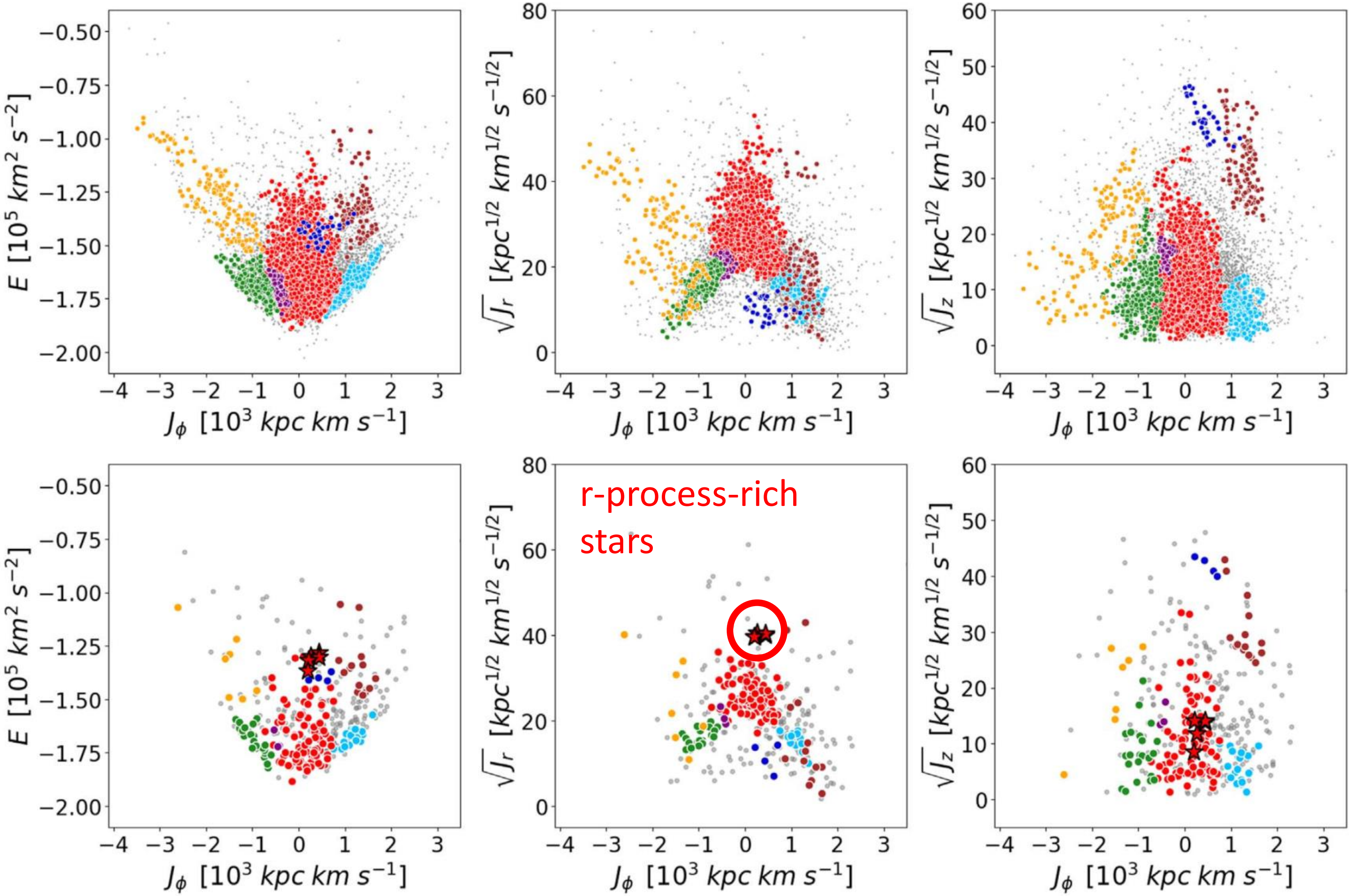
The VMP/EMP stars of our sample and candidates of the master catalog are separated into (known and unknown) groups by kinematics using *Gaia* and radial velocity data

- A subgroup in GSE exhibits a very high fraction of r-process enhanced stars

Zhang et al. (2014)

Low-resolution sample (master catalog)

High-resolution sample with abundance data



The Milky Way halo population studied with LAMOST and Subaru
Summary

- Elemental abundances are determined with Subaru/HDS for a large sample of very metal-poor stars (~400) identified by the LAMOST survey
- **Distributions of abundance ratios and correlations** between elements raise problems to be solved and some hints:
  - Ti and Sc abundances higher than predictions
  - Co (slight overabundant) and Zn (overabundant at lower metallicity)
    - Tight correlations between Ti and Sc, weak correlation between Ti and Zn
- **α-poor stars** could record the accretion history, though their origin is not well constrained for the lowest metallicity
  - An α-poor star with large excesses of r-process elements provide strong evidence of accretion
- **Detailed abundance pattern of individual stars** constrain the nucleosynthesis and mass of progenitors
  - α-rich stars: massive progenitors and their explosions
  - s-process: progenitor AGB mass
- **Dynamical tagging** of stars with detailed abundance data reveals the chemical features of substructures, and identifies groups of stars having particular features, e.g. r-process-excess.

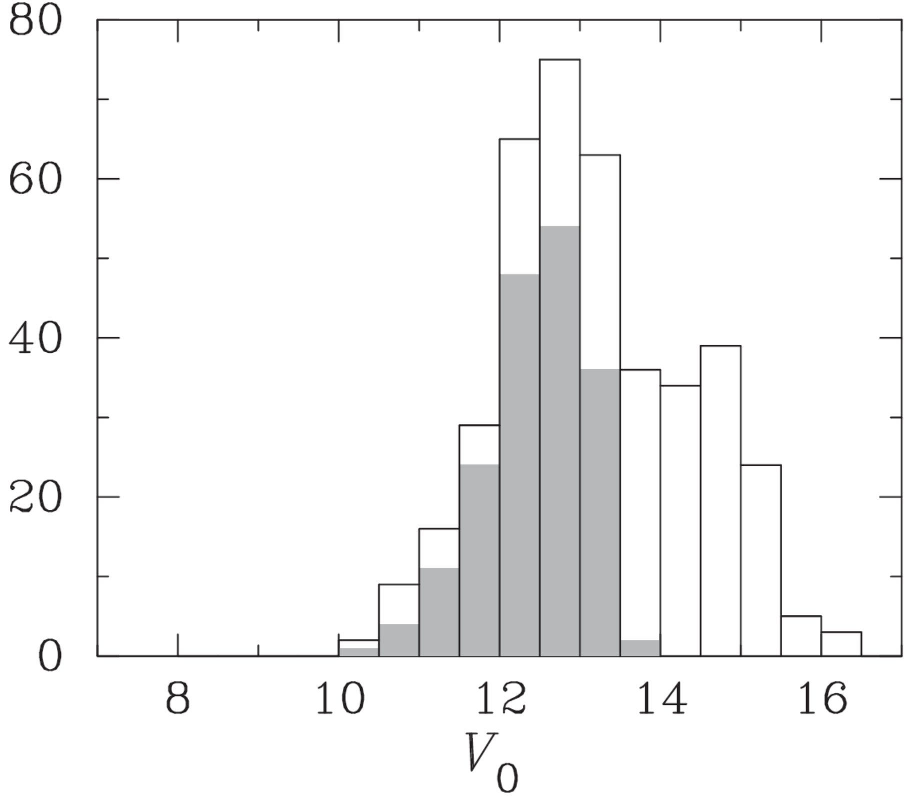
Future extension

The LAMOST/Subaru sample includes many bright VMP/EMP stars

➡ Follow-up observations with higher S/N, and extension to UV and NIR observations

➡ More complete and accurate abundance patterns for individual stars

Aoki et al. (2022)



Example: Si abundances determination using many Si I lines in the NIR range (>1um)

Aoki et al. (2022, PASJ), Aoki et al. (in prep)