


Exploring the early chemo-dynamic history of the Milky Way with LAMOST and Subaru

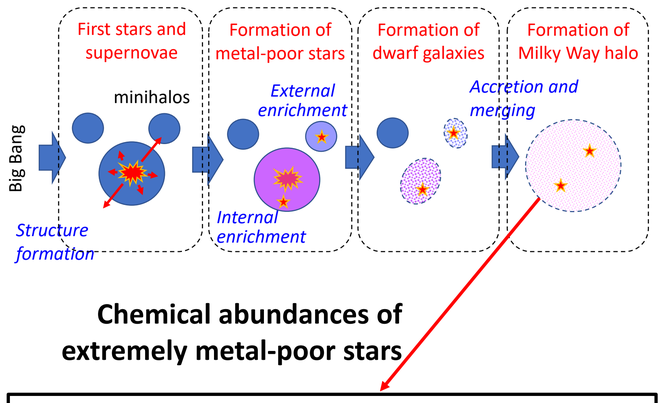


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- **Measurements of elemental abundances of stars in the Milky Way provides useful constraints on the nucleosynthesis and chemical evolution in the early universe.**
- **Large spectroscopic surveys combined with studies on dynamical motions of stars in the Milky Way reveal connections between chemical enrichment and galaxy formation.**
- **We have determined elemental abundances based on high-resolution spectra obtained with the Subaru Telescope for more than 400 very metal-poor stars found with LAMOST.**
- **This poster provides a brief overview of this program and results:**
  1. **Substructures identified from abundance and kinematics**
  2. **Mass and nucleosynthesis of first stars**
  3. **Neutron-capture element-enhanced stars and their accretion history**
- **Revising abundance analysis including NLTE effects is ongoing.**

Constraints from metal-poor stars on first stars and early chemical evolution



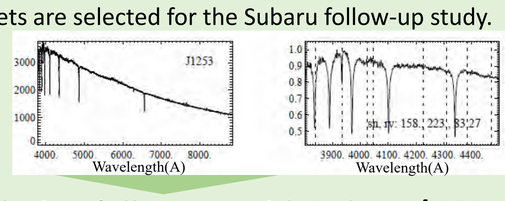
Chemical abundances of extremely metal-poor stars

- **Nucleosynthesis of the first generation of massive stars and supernovae**
- **Early chemical enrichment including r-process**

Survey and study of very metal-poor stars

● Low-resolution survey with LAMOST

Metal-poor stars have been found from millions of stars observed with LAMOST (*R*=1800, 4000 fibers) (Li et al. 2018, ApJS 238, 16). About 1000 targets are selected for the Subaru follow-up study.

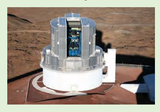
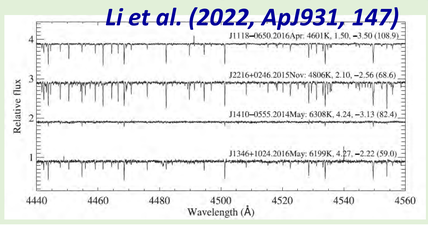



● High-resolution follow-up with Subaru/HDS

Elemental abundances are determined from high-resolution spectra obtained with Subaru/HDS (R=36,000).

- Main sample: 386 stars with [Fe/H]≲-2
- Small samples that have specific features

Aoki et al. (2022, ApJ 931, 146)
Li et al. (2022, ApJ931, 147)

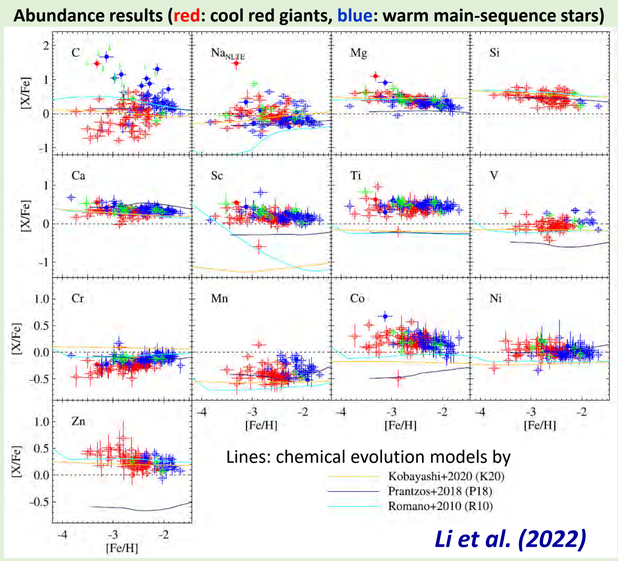
Overall abundance trends and correlations

Elemental abundances of very metal-poor stars are primarily determined by first and early generations of massive stars and supernova nucleosynthesis. Comparisons with chemical evolution models indicate:

- **Mg, Ca** (**Si** to be confirmed): overabundant as expected from models. Decreasing trend with increasing metallicity in [Fe/H]>-2 is found for Mg.
- **Ti** and **Sc** are overabundant (or close to the solar value). Models predict underabundance. The discrepancy needs to be resolved.
- **Cr** (solar value), **Mn** (underabundant) and **Ni** (solar value) are well explained by models.
- **Co** (slight overabundant) and **Zn** (overabundant at lower metallicity) needs sources of these elements (e.g., jet-like supernova explosions).

Abundance trends

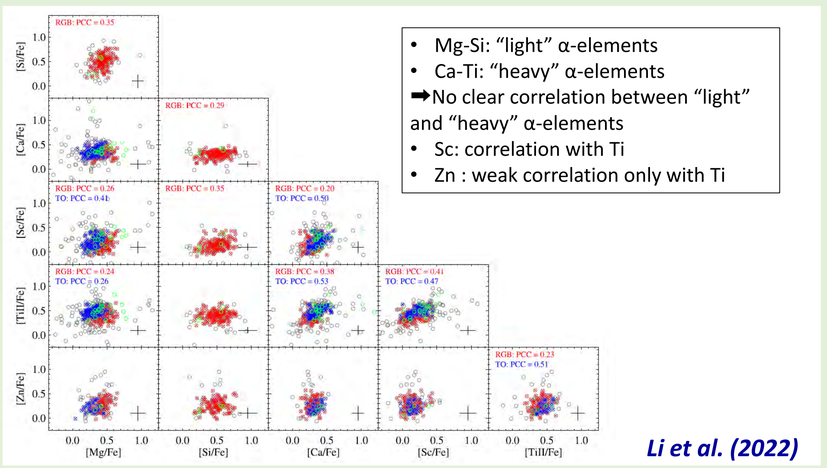
Abundance results (red: cool red giants, blue: warm main-sequence stars)



Li et al. (2022)

Abundance correlations

- **Mg-Si** and **Ca-Ti** both show correlations, but the correlation between them is not clear. Sc shows correlations with α-elements, in particular with Ti.
- **Zn** shows a correlation only with **Ti** among α-elements.



Li et al. (2022)

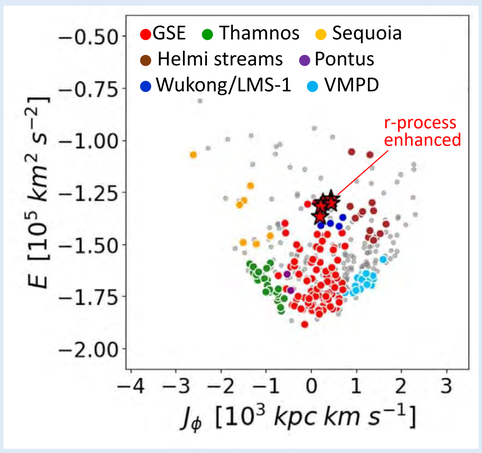
1. Dynamically Tagged Groups and Chemodynamical Properties

Zhang et al. (2024, ApJ 966, 174)

We conduct a chemodynamical analysis of 352 VMP stars among the sample of our LAMOST/Subaru study. 131 dynamically tagged groups with 89 known substructures (e.g., Gaia-Sausage-Enceladus (GSE), Helmi streams) are identified from to the master catalog of this high-resolution sample (5778 stars). The chemical nature of main substructures among them are investigated from the 352 VMP stars with detailed abundance information.

Key findings:

- the **Very Metal-Poor Disk (VMPD)** shows lower Zn abundances, indicating that it could be a relic of small stellar systems
- **Sequoia** shows moderately high r-process abundances
- **Helmi streams** show deficiencies in carbon and light neutron-capture elements
- The fraction of carbon-enhanced stars with no enhancement in heavy elements (CEMP-no stars) seems low in the **VMPD** and the **Helmi streams**
- A subgroup in GSE exhibits a very high fraction of r-process enhanced stars, with four out of five showing [Eu/Fe]>+1.0.



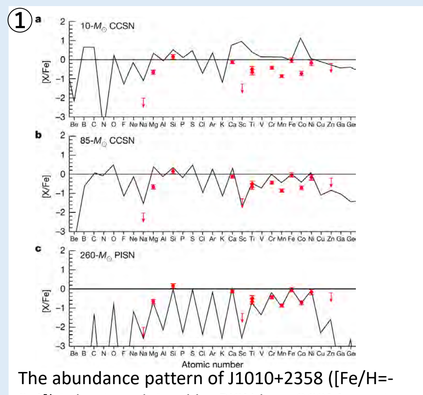
The distributions of groups associated with known substructures in energy and action phase space.

2. Mass of first generations of stars

Elemental abundances of bulk of very metal-poor stars are determined by core-collapse supernovae of several tens solar-mass stars (see above).
However, a small number of stars show peculiar abundance patterns, which could be evidence for specific supernova explosions.

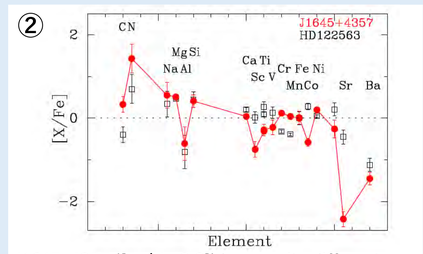
① **Signature of a pair-instability supernova (PISN)**
Existence of **very massive (>140M$_\odot$) stars that explode as PISNe** is predicted from first star formation models.
The abundance pattern of a very metal-poor star, J1010+2358 showing low α/Fe ratio is the clearest signature of PISN obtained to date.

② **Signature of a non-rotating faint supernova?**
A very metal-poor star, J1645+4357, shows quite different abundance pattern from typical metal-poor stars (e.g., high C, N, Cr and Mn, low Ti, Sc, Co, and Zn). The overall pattern is explained by a **“faint supernova model” (ejecting small amount of Fe) with no rotation**. A question is why such stars are so rare.



The abundance pattern of J1010+2358 ([Fe/H=-2.4]) is best explained by PISN by a 260Msun star.

Xing et al. (2023, Nature, 618, 712)



J1645+4357 ([Fe/H=-2.9]) has a quite different abundance pattern from a typical star (HD122563).

Aoki et al. (2023, ApJ 955, 28)

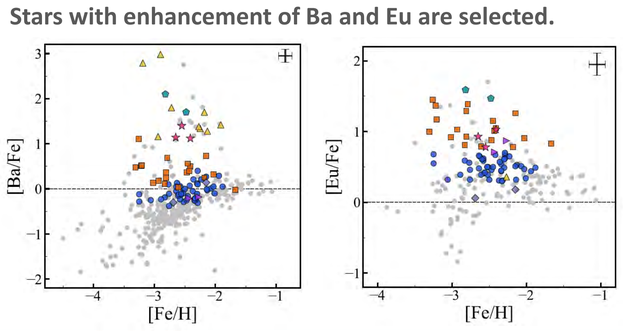
3. Heavy elements enhanced stars

Lin et al. (in prep)

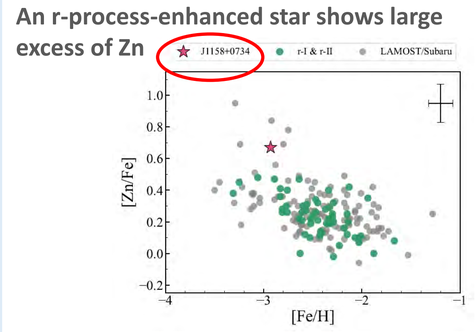
Homogeneous analysis focusing on heavy neutron-capture elements is conducted for **83 heavy-element-enhanced stars** among the LAMOST/Subaru sample.

- 65 stars exhibit r-process-enhancement. Combined with dynamical evidence, **r-process-enhanced stars likely formed in low-mass dwarf galaxies**
- The extremely metal-poor **r-process-enhanced star J1158+0734** ([Fe/H] =-2.93) with significant Zn enrichment is identified. The origin could be Magneto-rotationally driven jet supernovae with high explosion energy from a massive progenitor.
- **Three "r+s" stars** exhibiting abundance patterns consistent with combined r- and s-process contributions and **two r/s stars** whose origin could be the i-process are identified among 16 carbon-enhanced stars (CEMP).

Stars with enhancement of Ba and Eu are selected.



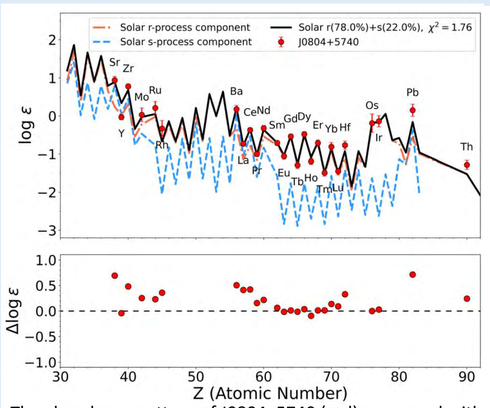
An r-process-enhanced star shows large excess of Zn



LAMOST J0804+5740,: an Actinide-boost Star Discovered in the Gaia-Sausage-Enceladus ([Fe/H] = -2.38, [Eu/Fe] = 0.80)

Lin et al. (2025, ApJ, 984, L43)

- Abundance pattern of heavy elements is explained by the r-process and possible small contribution of the s-process.
- An excess of Th indicates that this is a new example of actinide-boost star.
- Kinematic analysis indicates that this star belongs to Gaia-Sausage-Enceladus (GSE).

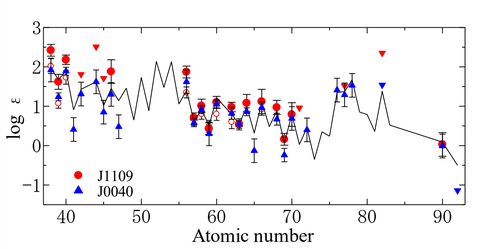


The abundance pattern of J0804+5740 (red) compared with the solar r- and -process patterns and the mixture.

LAMOST J1109+0754: one of the most metal-poor example of Eu-enhanced stars ([Fe/H]=-3.4,[Eu/Fe]=0.8)

Honda et al. (in prep)

- Abundance pattern of heavy elements agrees very well with the solar r-process pattern.
- The extremely low metallicity may prefer magnetrotational supernova as the source of heavy elements.



The abundance pattern of J1109+0754 (red), as well as of another r-process-enhanced star (J0040+2729: [Fe/H]=-2.9,[Eu/Fe]=1.1), compared with the solar r-process pattern.