The Future of Carbon-Enhanced Metal-Poor (CEMP) Studies

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Importance of Studies of CEMP Stars

- Nature of the first-generation stars
  - ✓ Nucleosynthesis process of the first stars

What can we do further?

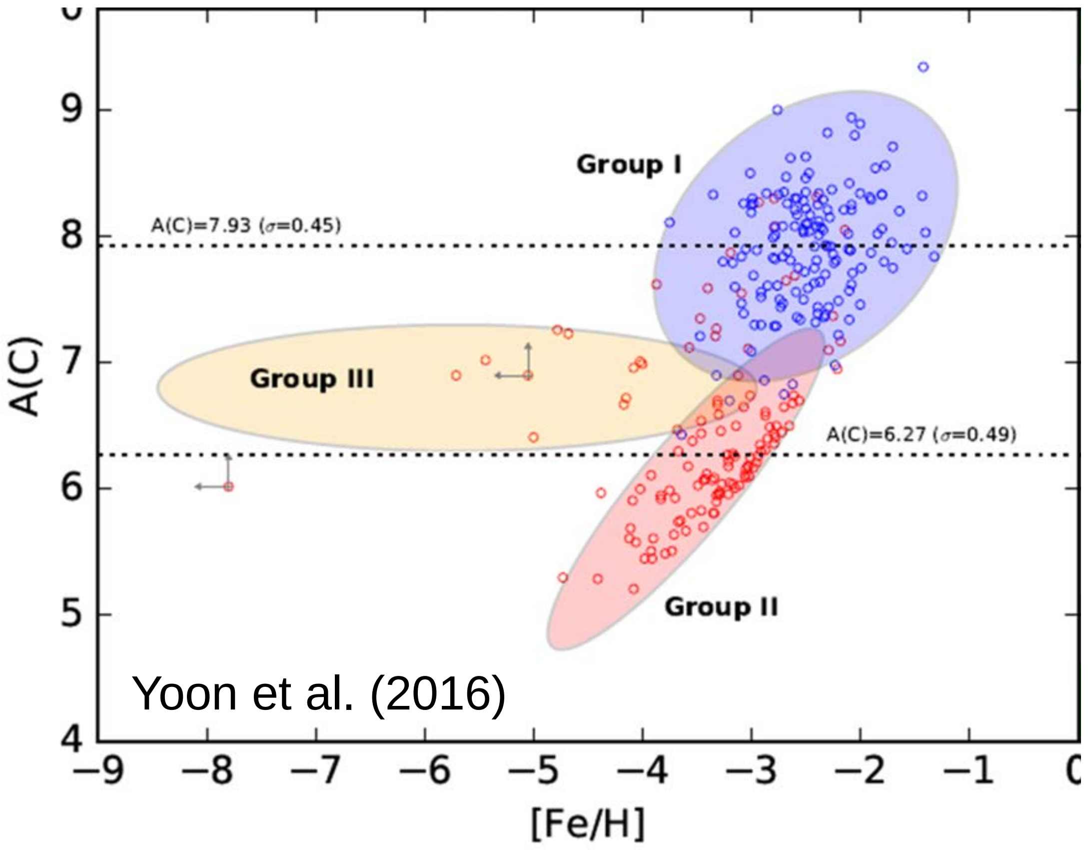
- Nature of the Milky Way halo system
  - ✓ Increasing frequency of CEMP stars in the Galactic inner/outer halo

How can we do?

  - •CEMP frequency from AGB binary population synthesis model

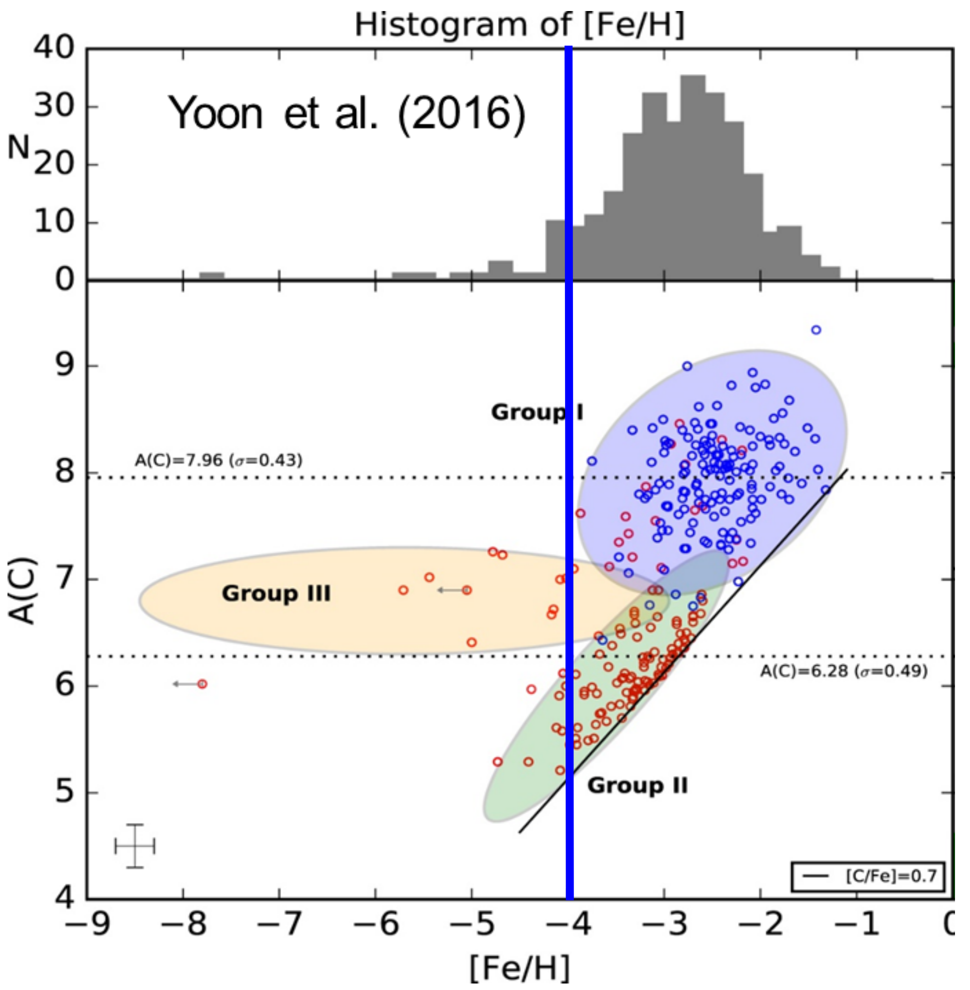
Understanding the Nature of Pop III Stars

- ❑Three groups
  - ✓Group I – CEMP-s, -r, and –r/s (i)
    - •Associated with Pop II AGB stars
  - ✓Group II – CEMP-no
    - •Correlation between A(C) and [Fe/H]
  - ✓Group III – CEMP-no
    - •No correlation of A(C) with [Fe/H]
- ❑This division means different progenitor mass range and different mixing history !
- ❑Progenitors on the CEMP-no stars are still unknown



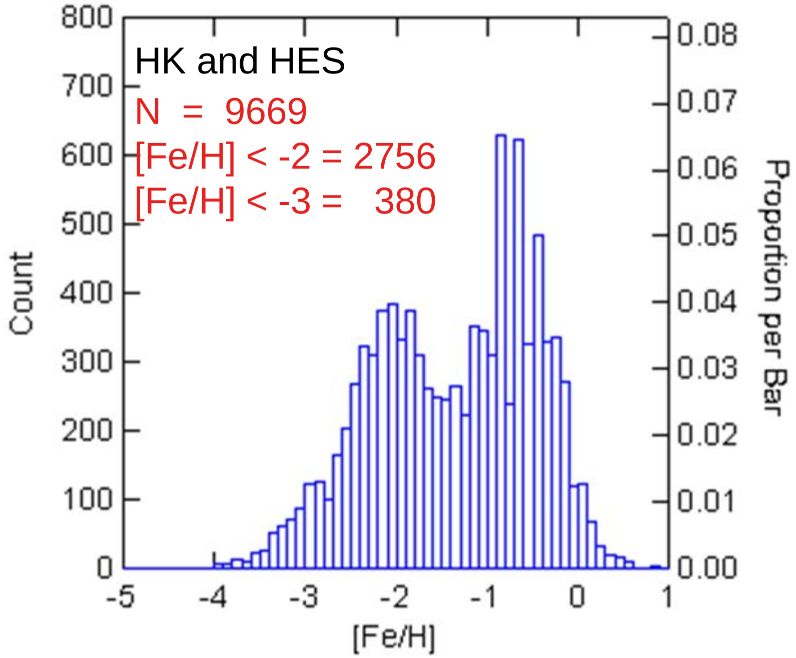
Understanding the Nature of Pop III Stars

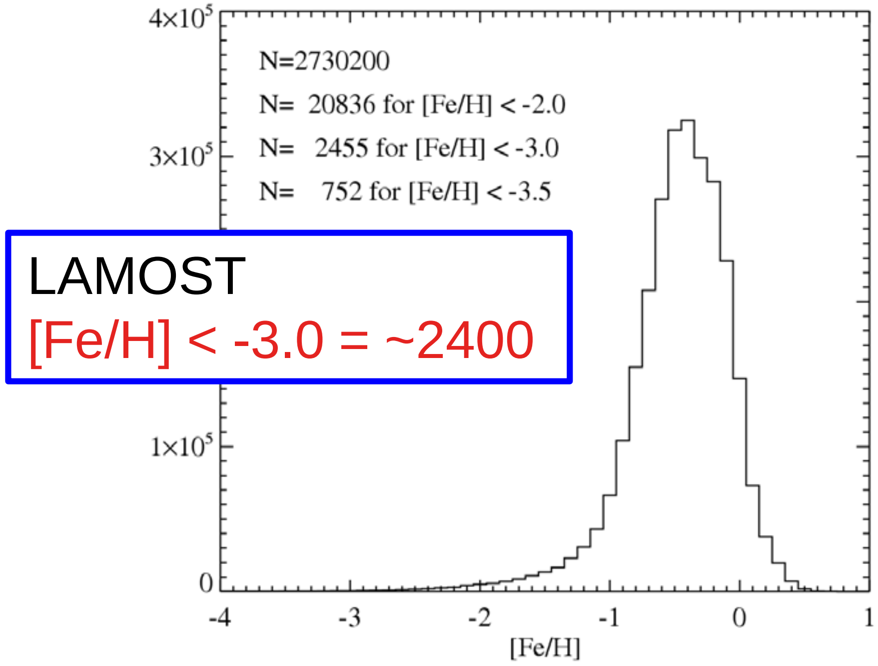
- ❑Characterization of progenitors for Group II and Group III
  - ✓Require understanding of the nucleosynthetic products
  - ✓Need a larger number of UMP ([Fe/H] < -4.0) stars, about 25 UMP stars known presently
  - ✓Necessary to carry out systematic search and high-resolution spectroscopy
  - ✓Also require further elaborate theoretical models to explain abundance patterns and characterize the progenitors

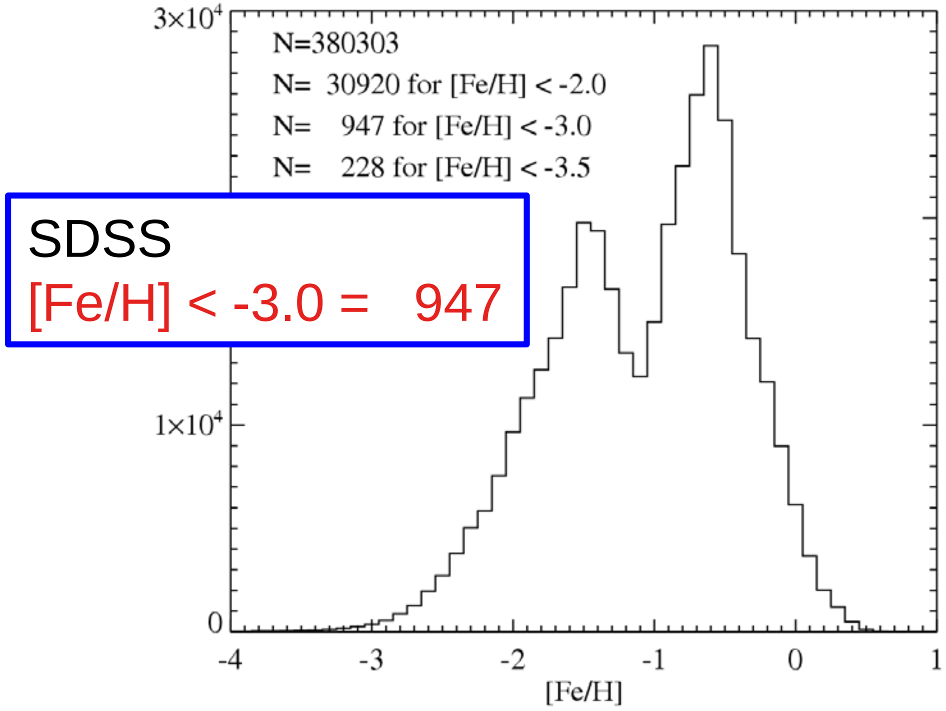


Search for UMP Stars

- ❑EMP stars are good candidates
  - ✓HK and HES: ~380 EMP ([Fe/H] < -3.0) stars
  - ✓SDSS & SEGUE: ~950 EMP stars
  - ✓LAMOST: ~2400 EMP
    - •Need to carefully inspect these, though

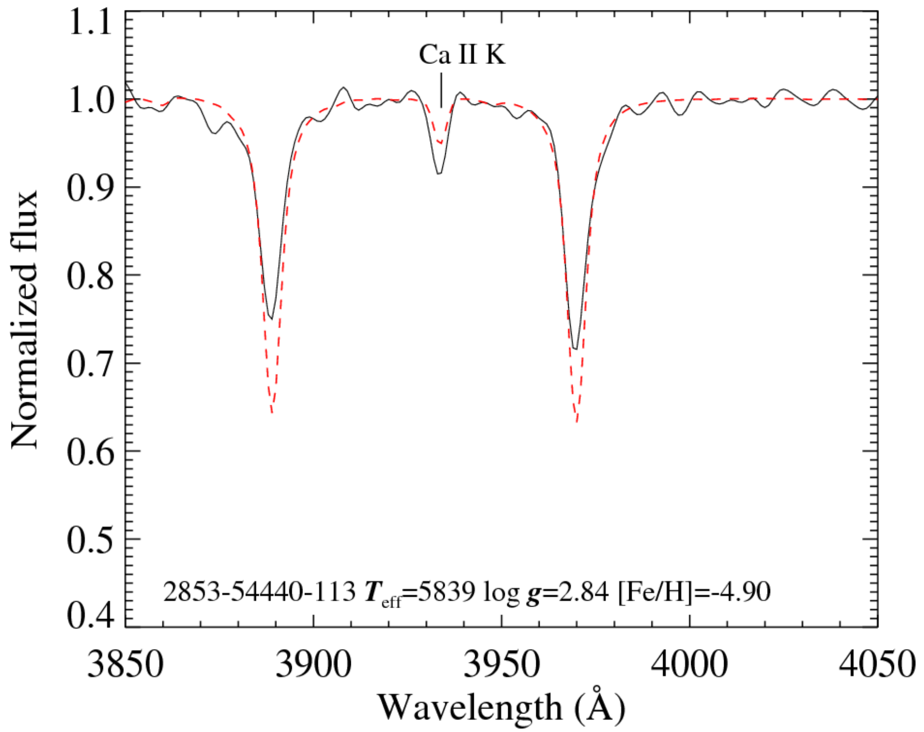


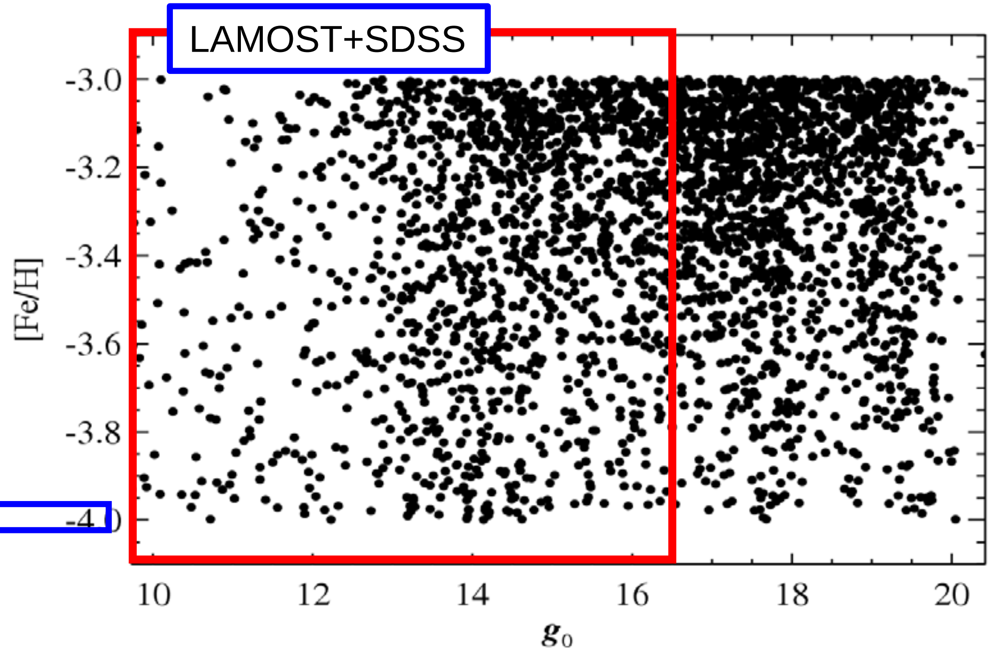




Search for UMP Stars

- UMP targets can be reliably selected from low-resolution of the SDSS and LAMOST spectra using Ca II K line
- Selection criteria
  - ✓ [Fe/H] < -3.5 measured from Ca II K line
  - ✓ 4000 < T_{eff} < 6500 K, g_0 < 16.5

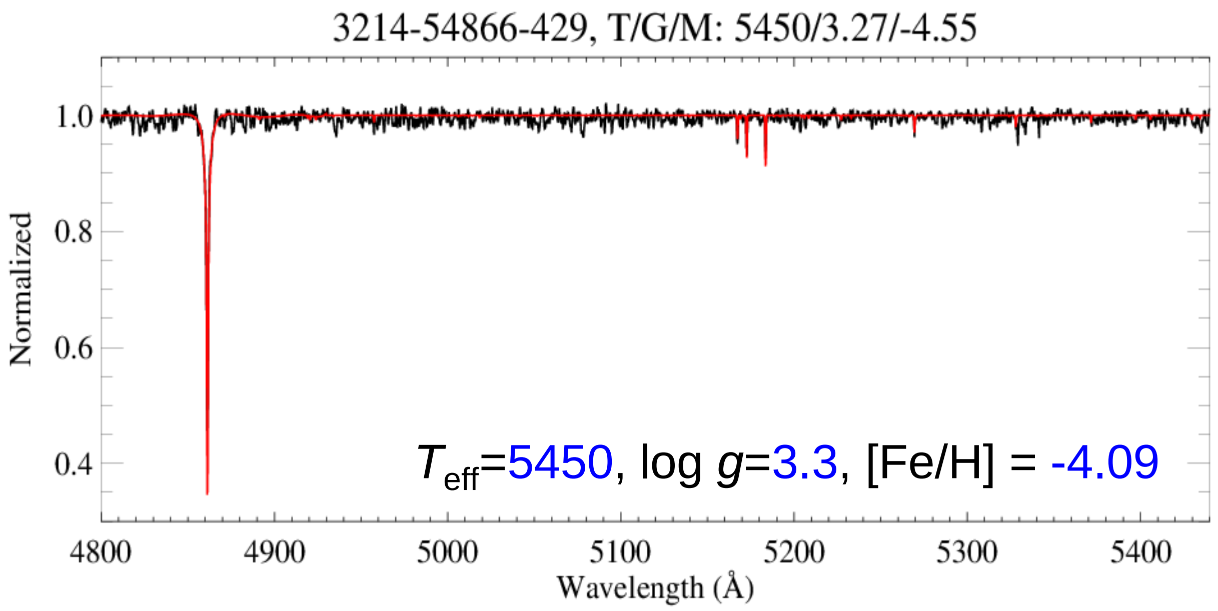


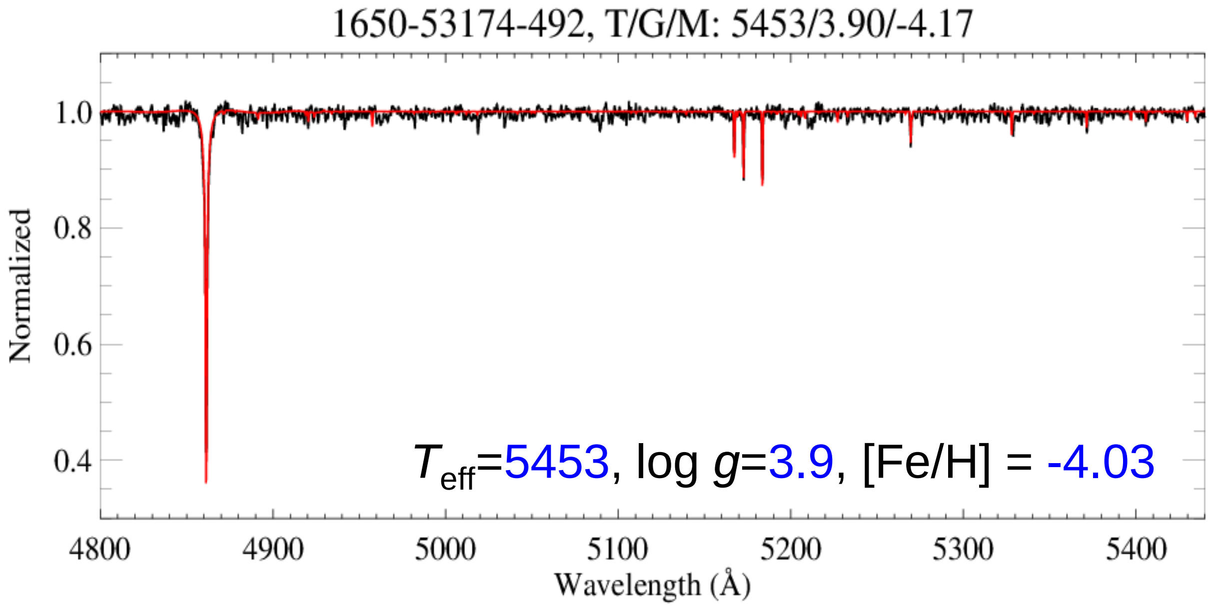


Possible to obtain high-resolution spectra with larger telescopes

Search for UMP Stars

- ❑ Observation of six UMP candidates with Gemini/GRACES
  - ✓ Reference star: 3214-54866-429
    - • T_{eff}=5467, log g=3.2, [Fe/H] = -4.34 (Placco et al. 2015)





Search for UMP Stars

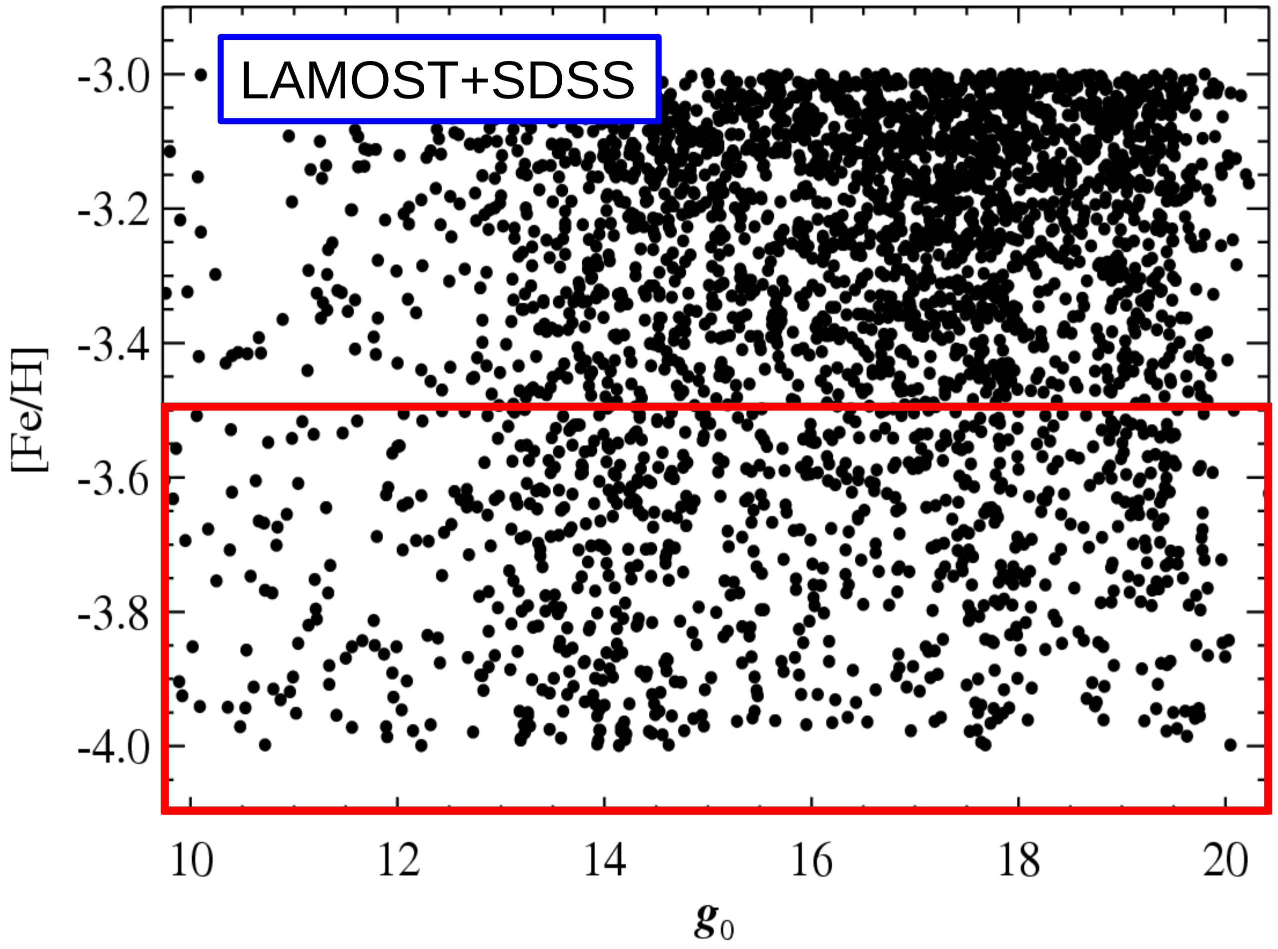
- Observation of UMP candidates with Gemini/GRACES
  - ✓ Identified four out of six stars as near UMP stars
  - ✓ Abundance patterns can be used to constrain the progenitor masses

Measured abundances of Ultra Metal-poor Stars

Name	[Fe/H]	[Ba/Fe]	[Ca/Fe]	[Cr/Fe]	[Mg/Fe]	[Na/Fe]	[Ti I /Fe]	[Ti II /Fe]	[C/Fe]*
SDSS 3214-54866-429	-4.09	-0.22	0.76	-0.02	-0.06	-0.04	0.75	···	1.10
SDSS 1650-53174-492	-4.03	···	0.23	···	0.52	···	1.08	0.77	1.33
SDSS 2901-54652-464	-3.97	0.41	0.63	···	0.47	-0.08	1.19	···	1.46
SDSS 3264-54889-032	-3.82	···	0.16	-0.23	0.31	···	···	···	2.61
SDSS 6377-56245-0382	-3.94	···	0.53	-0.25	0.12	···	···	···	0.97

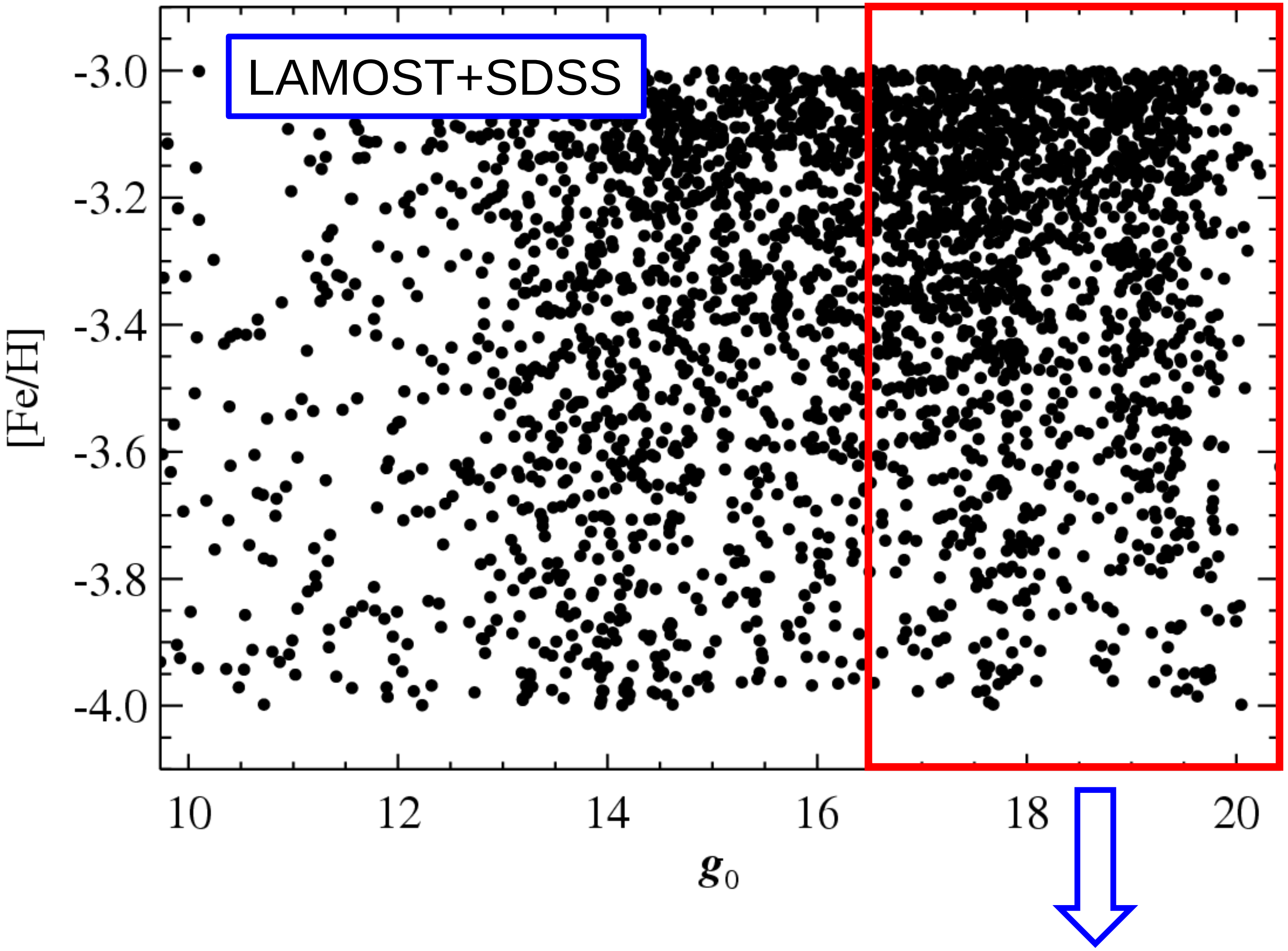
What is Ahead? – Nature of Pop III Stars

- ❑Need to discover more UMP stars
- ❑Low-resolution spectroscopic surveys such as LAMOST and SDSS provide lots of good UMP candidates for high-resolution follow-ups



What is Ahead? – Nature of Pop III Stars

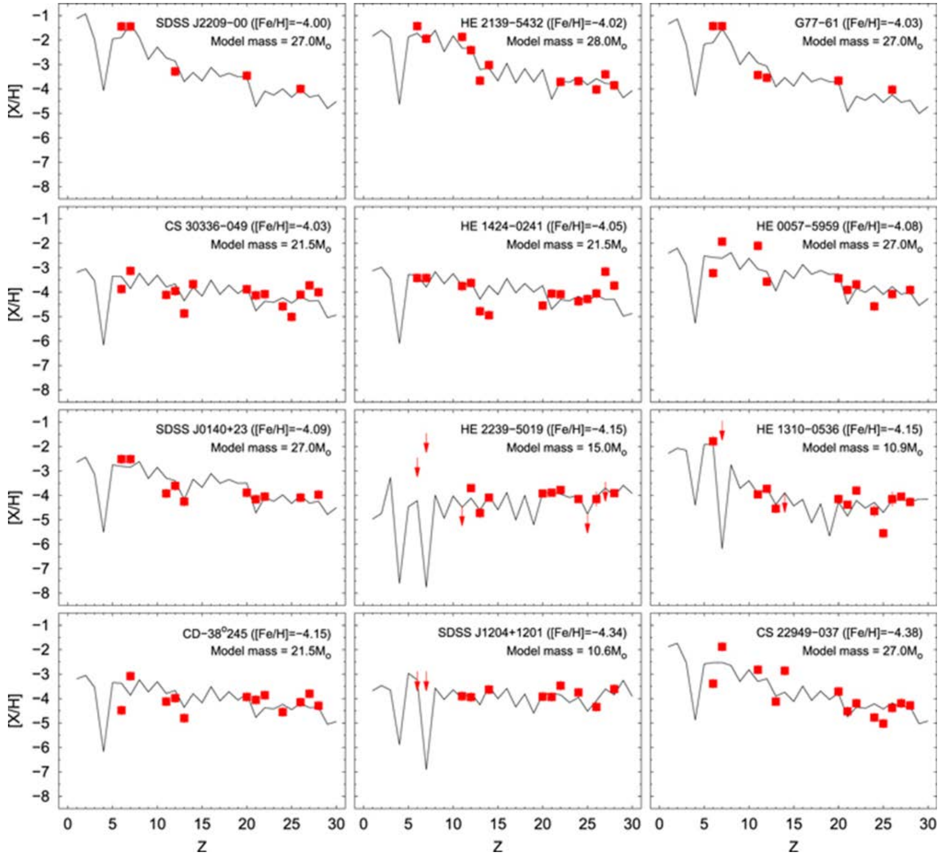
- Stars fainter than g_0 > 16.5 are really good targets for GMT, TMT, and ELT
  - ✓ Obtain high S/N medium resolution spectra for those objects
  - ✓ Confirm the UMP and CEMP status

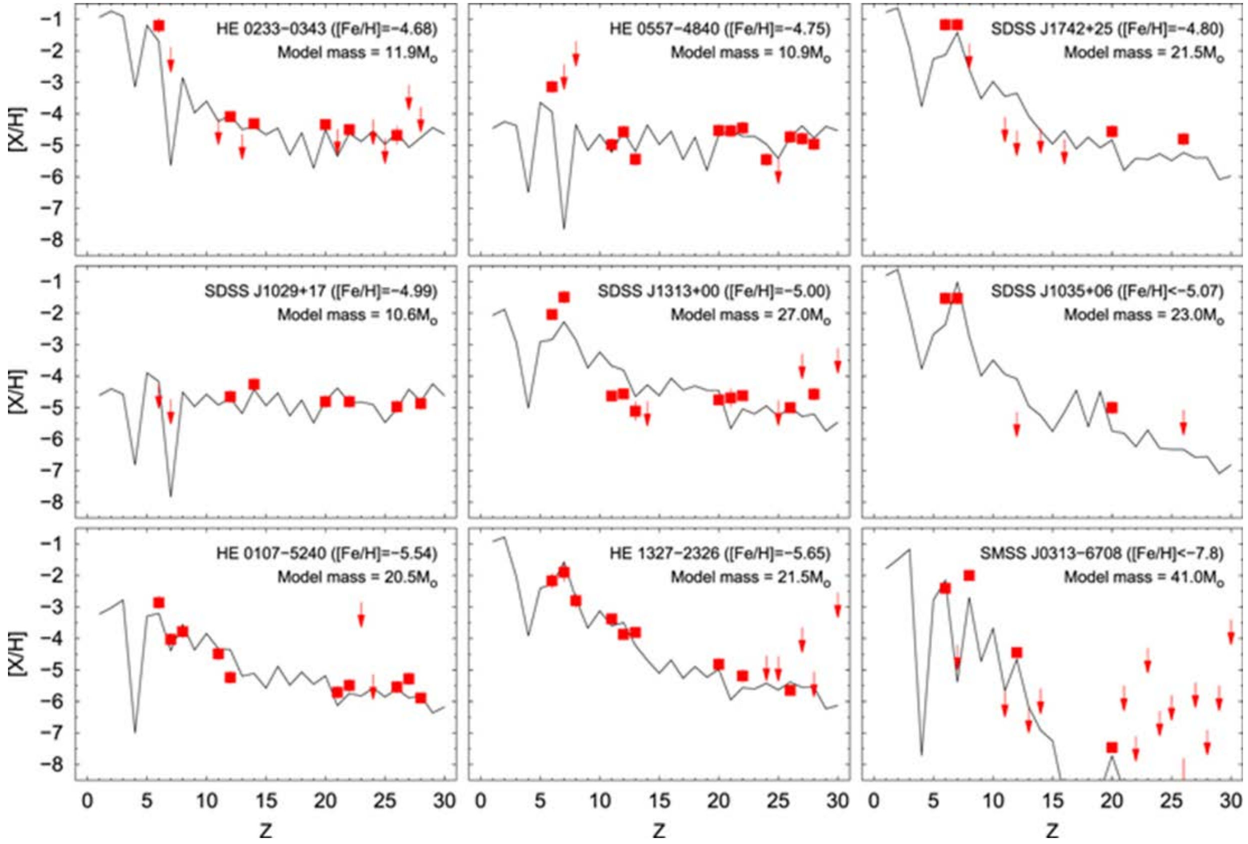


These targets will be able to reach by next generation telescopes

What is Ahead? – Nature of Pop III Stars

- ❑ More sophisticated SN models for CEMP-no stars
  - ✓ Provide stringent constraints on the mass range of the Pop III stars
  - ✓ Mass range of 21 UMP star progenitor is 10~40 $M_\odot$ (Placco et al. 2015)





Understanding the Nature of the Galactic Halo with CEMP Stars

Dichotomy of the Galactic Halo

- The Galactic halo
  - ✓ An important component to understand the assembly history of the MW
  - ✓ New results from about 30,000 SDSS calibration stars (Carollo et al. 2007, 2010)

	Inner Halo (IH)	Outer Halo (OH)
Distance (R)	< 10–15 kpc	> 15–20 kpc
Rotational Velocity (V_φ)	~0–50 km/s	-40 to -70 km/s
Distribution	Oblate shape (high *e*)	More spherical shape
[Fe/H]	-1.6	-2.2
Origin	Dissipative collapse	Accreted

  - ✓ But, local sample (d < 4 kpc) and kinematics involved for population separation

Contrast in Other Elements?

- The dichotomy should be expected in other chemical elements
- Can we use other element such as C?

Implications of CEMP Contrast in the Halo

- The variety of the CEMP stars indicates that there is likely to be more than one source of carbon production mechanism at low metallicity
  - ✓ If different progenitors (or subclasses) of CEMP stars can be associated with each halo population, this implies that each halo had different initial mass function and experienced different chemical evolution and assembly history

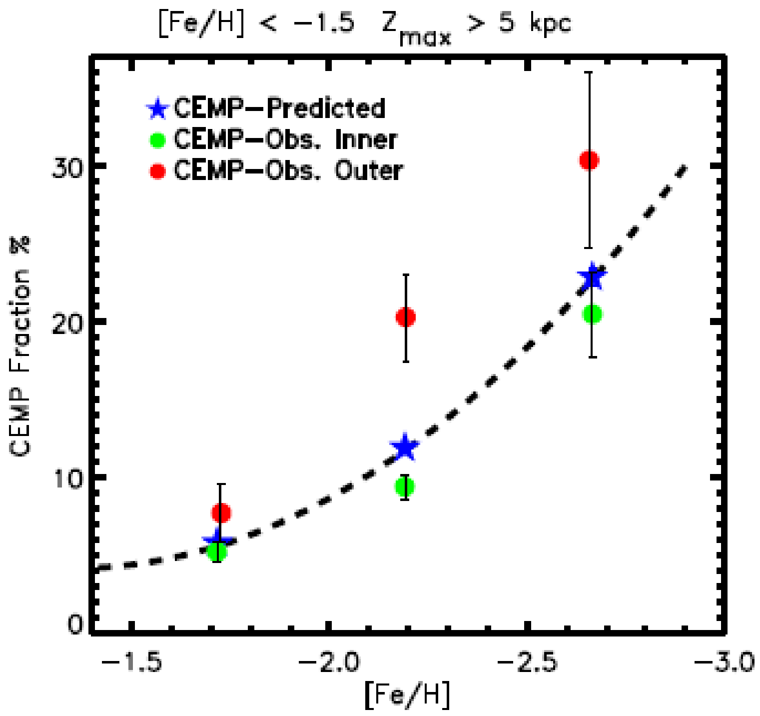
Implications of CEMP Contrast in the Halo

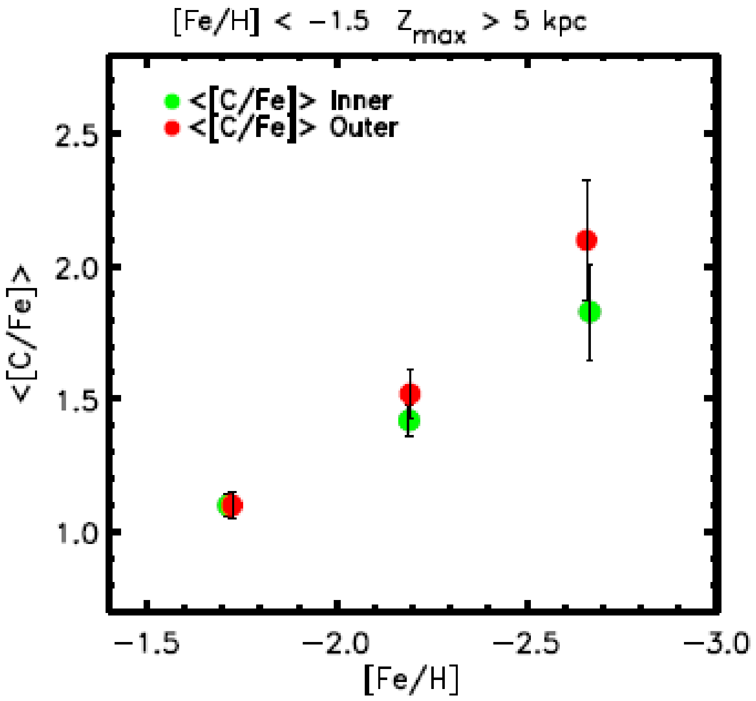
- Questions to ask
  - ✓Does the metallicity distribution function (MDF) differ between the two halos separated by the level of [C/Fe]?
  - ✓Does the kinematic feature differ between the two halos?
  - ✓Does the ratio of CEMP-s to CEMP-no stars in the inner halo differ from that of the outer halo? If so, does the kinematics also show different characteristics?

➔ Let us find out !

Inner/Outer Halo CEMP Fractions

- ❑Local sample (d < 4 kpc) of ~13,000 SDSS calibration stars
  - ✓ f (CEMP)$_{OH}$ ~ 2 x f (CEMP)$_{IH}$
  - ✓ The average [C/Fe] appears to be higher for the outer halo



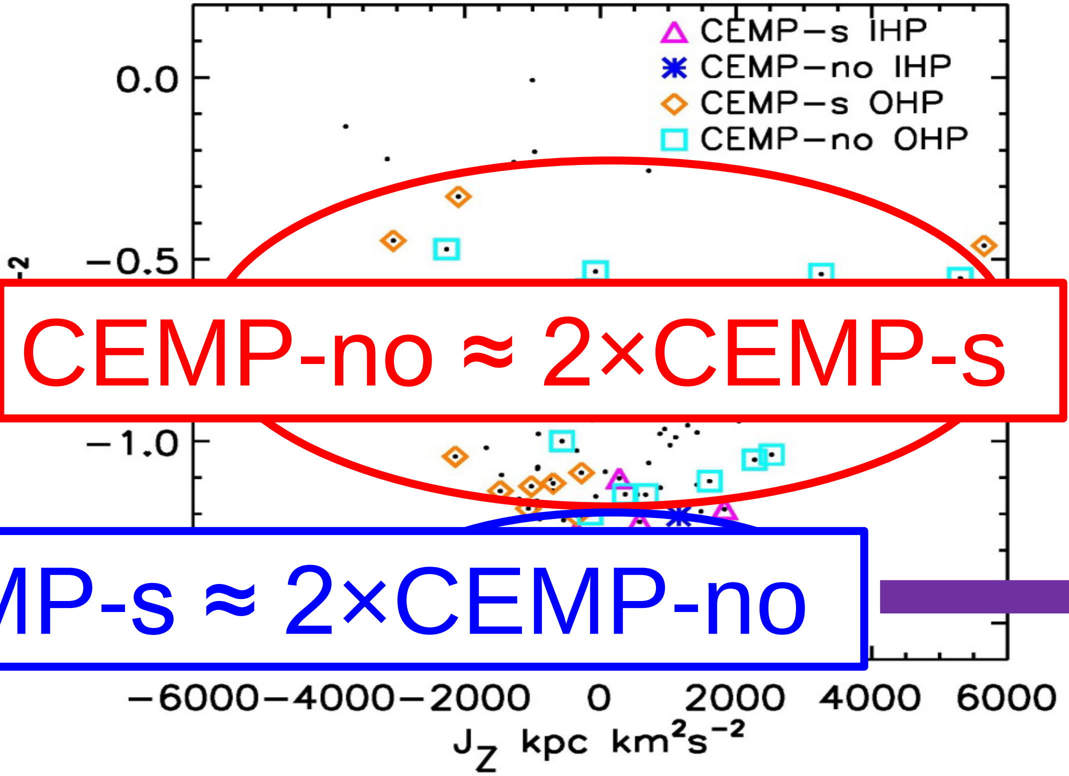


Carollo et al. (2012)

➔ Need to confirm with a much larger sample

Ratio of CEMP-no to CEMP-s in the IH/OH

- Derived ratio of CEMP-no to CEMP-s stars among 50 CEMP stars out 183 stars with high-resolution spectroscopy (Carollo et al. 2014)



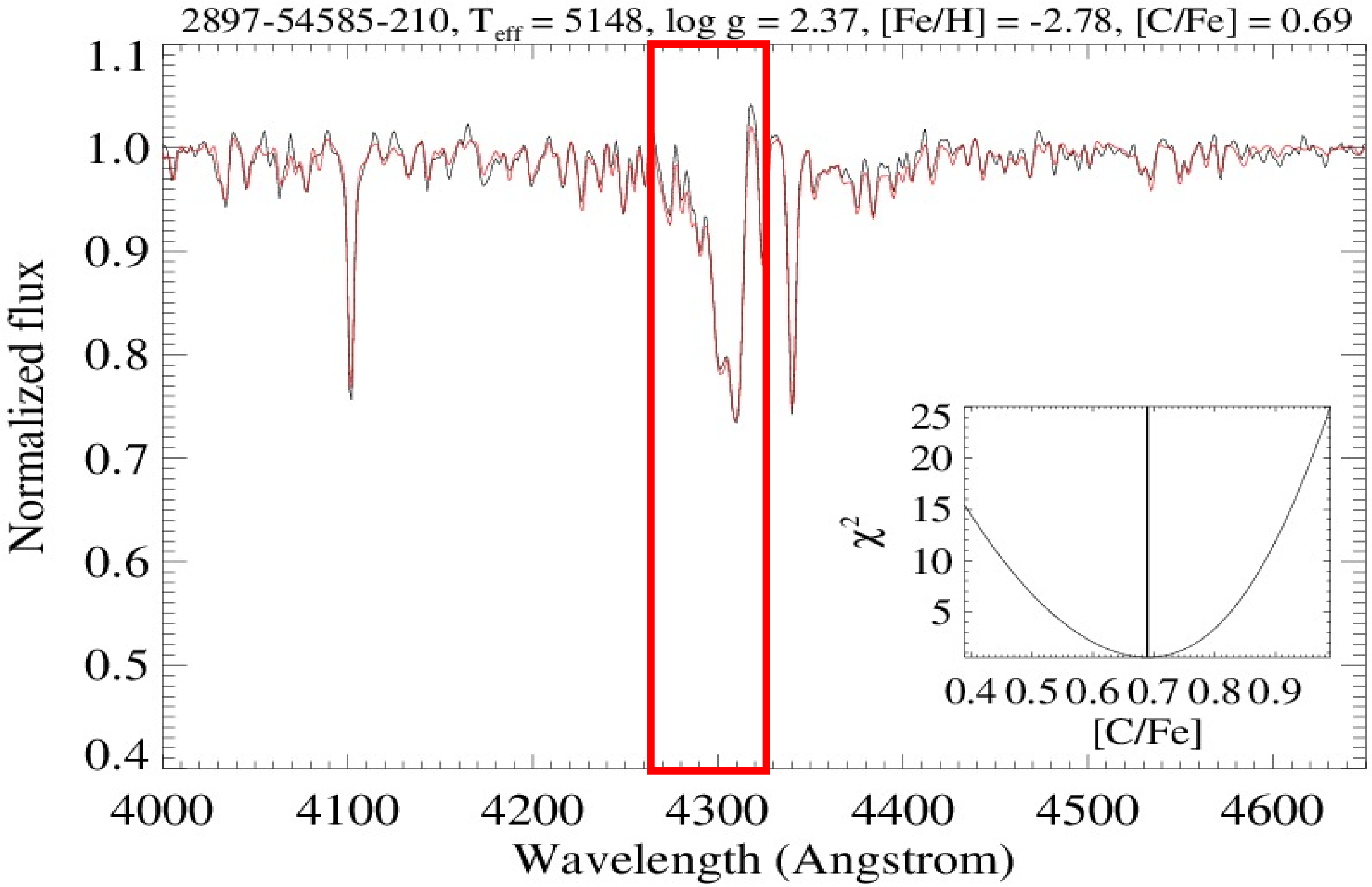
CEMP-no ≈ 2×CEMP-s → Outer halo

CEMP-s ≈ 2×CEMP-no → Inner halo

To confirm this, obviously more sample with high-resolution spectroscopy needed !

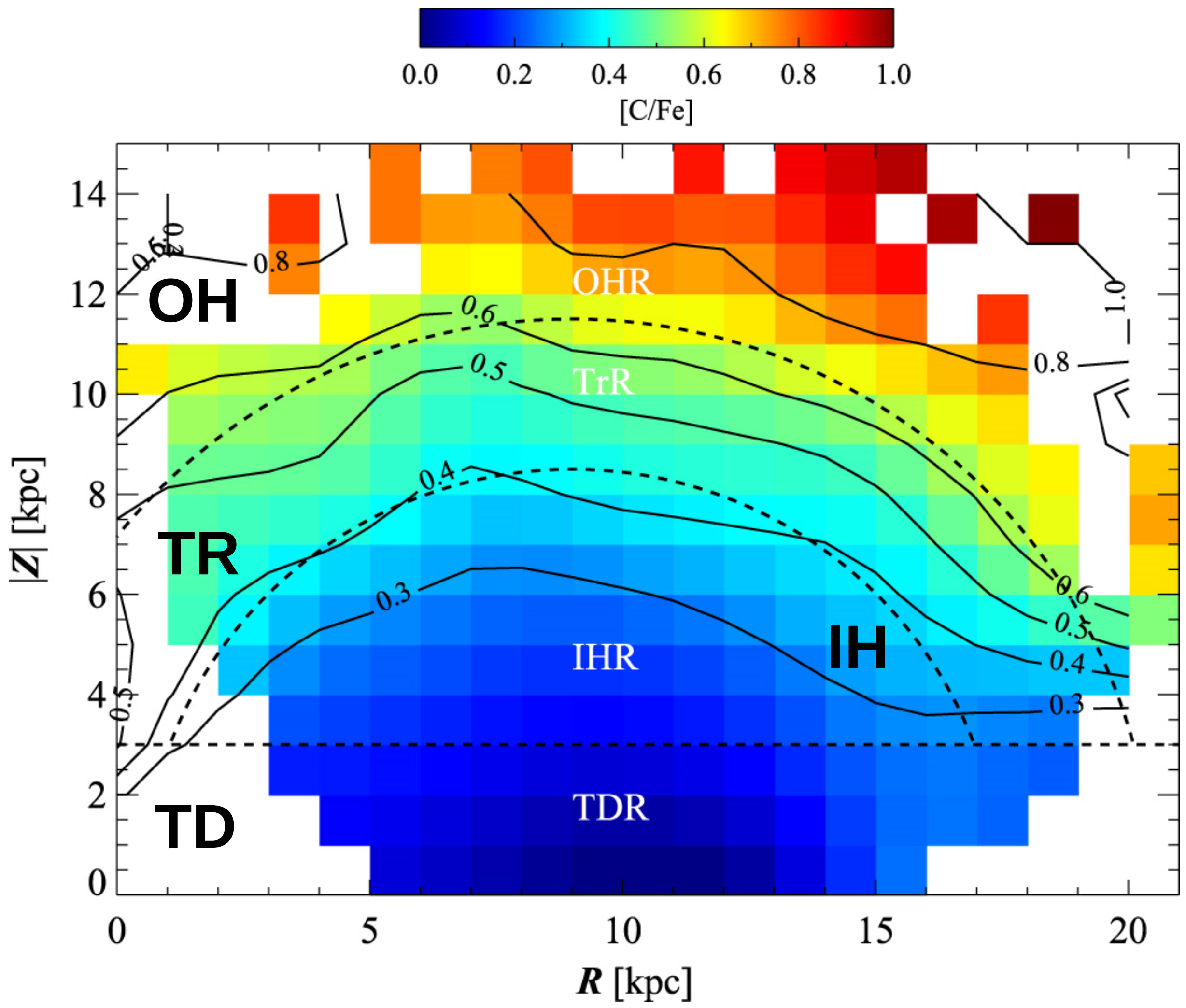
Identification of More CEMP Stars

- Attempted to estimate [C/Fe] from about 600,000 SDSS/SEGUE stellar spectra using CH *G* band (Lee et al. 2013)



Contrast in the Distribution of [C/Fe]

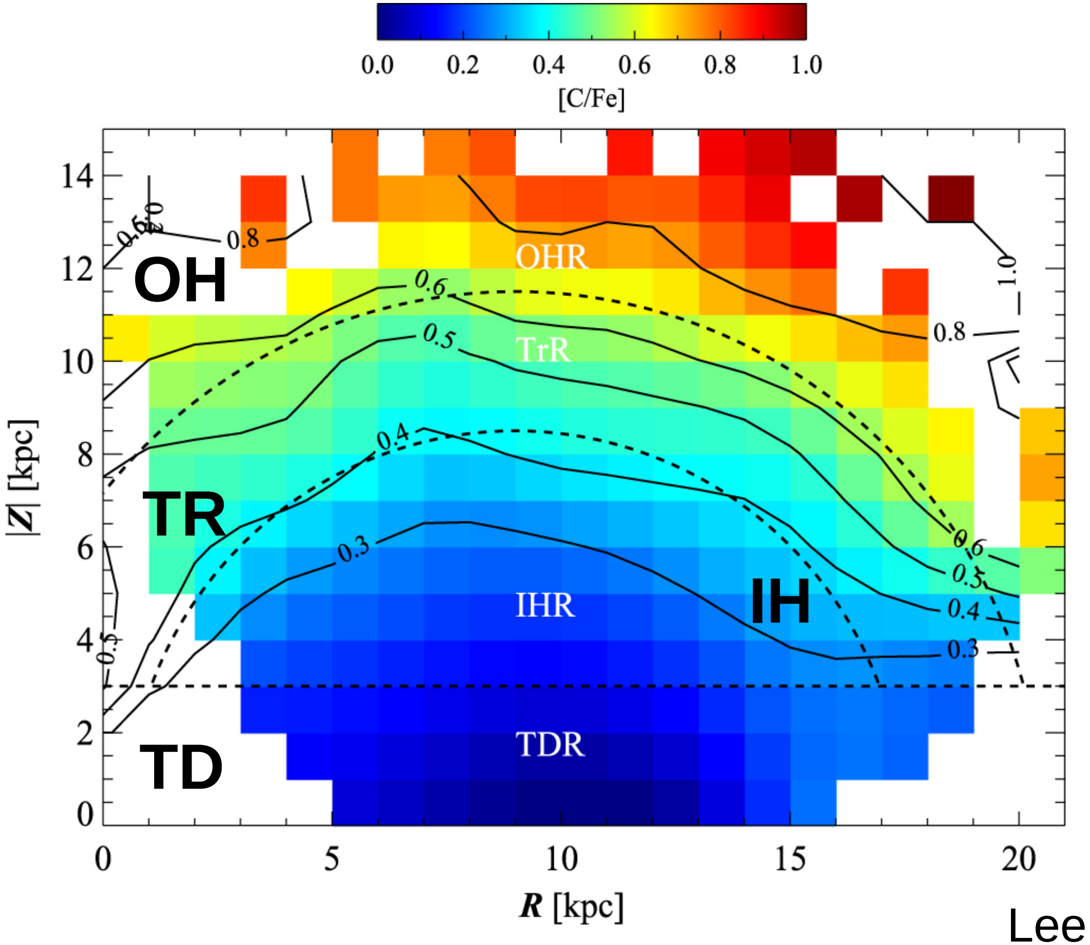
- Constructed a carbonicity ([C/Fe]) map from ~100,000 SDSS MSTO stars
- Separated into thick-disk region (TDR), inner-halo region (IHR), transition region(TrR), and outer-halo region (OHR) based on the level of [C/Fe] and spatial distribution



Lee et al. (2017)

Metallicity Distribution Functions

- Metallicity distribution function (MDF)s for the IHR and OHR



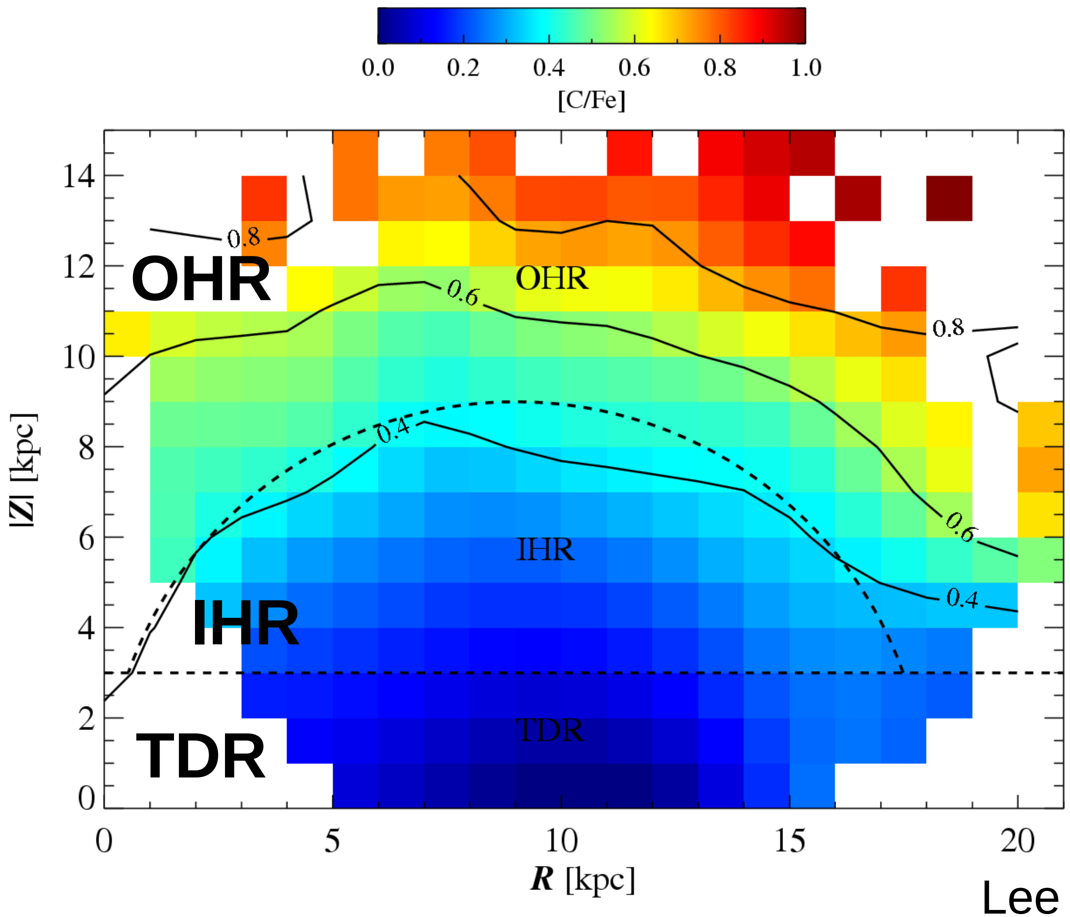
Lee et al. (2017)

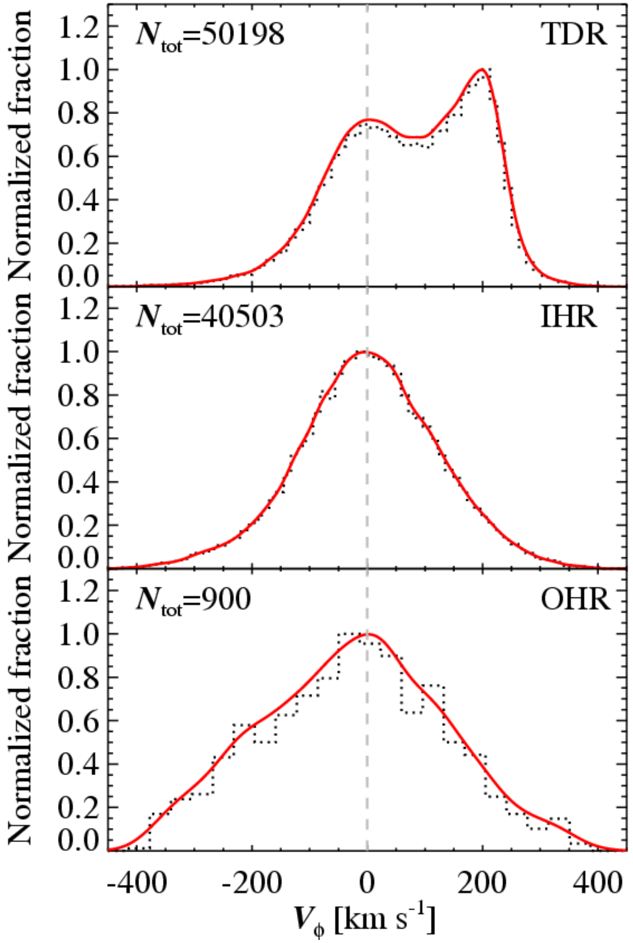
[Fe/H] peaks at -1.5

[Fe/H] peaks at -2.2

Rotation Velocity Distributions

- Considering only the inner- and outer-halo regions, the OHR shows a slightly retrograde motion, but weaker than the previous study (-80 km/s)





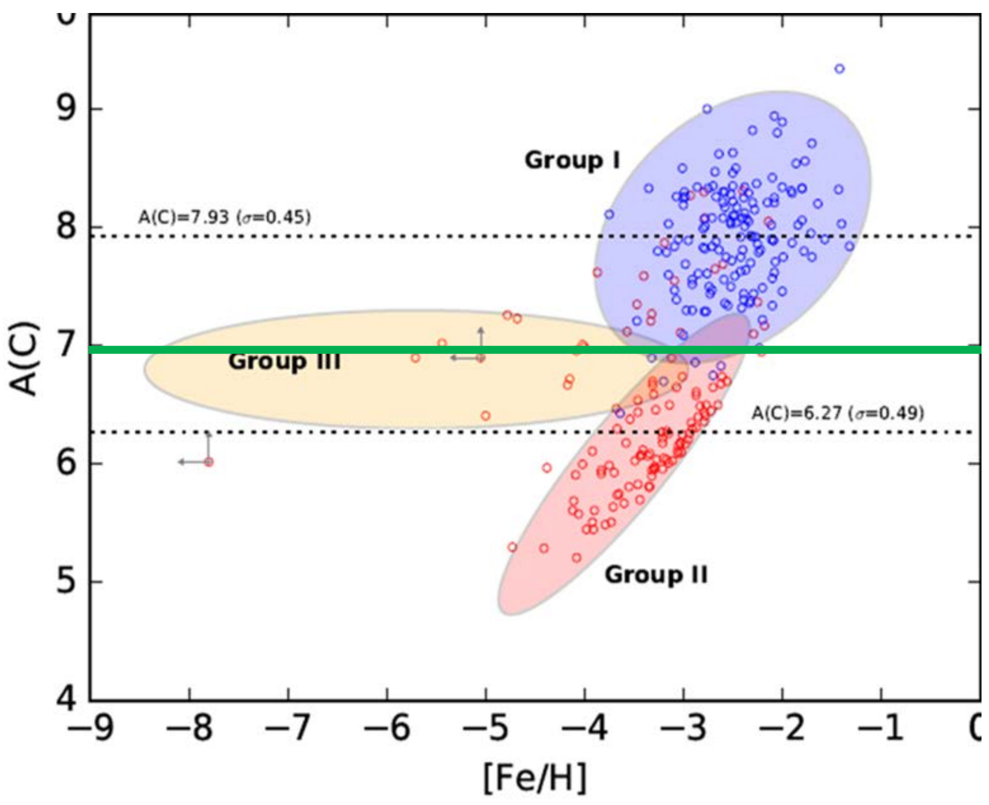
$<V_\varphi>=2.0$ km/s

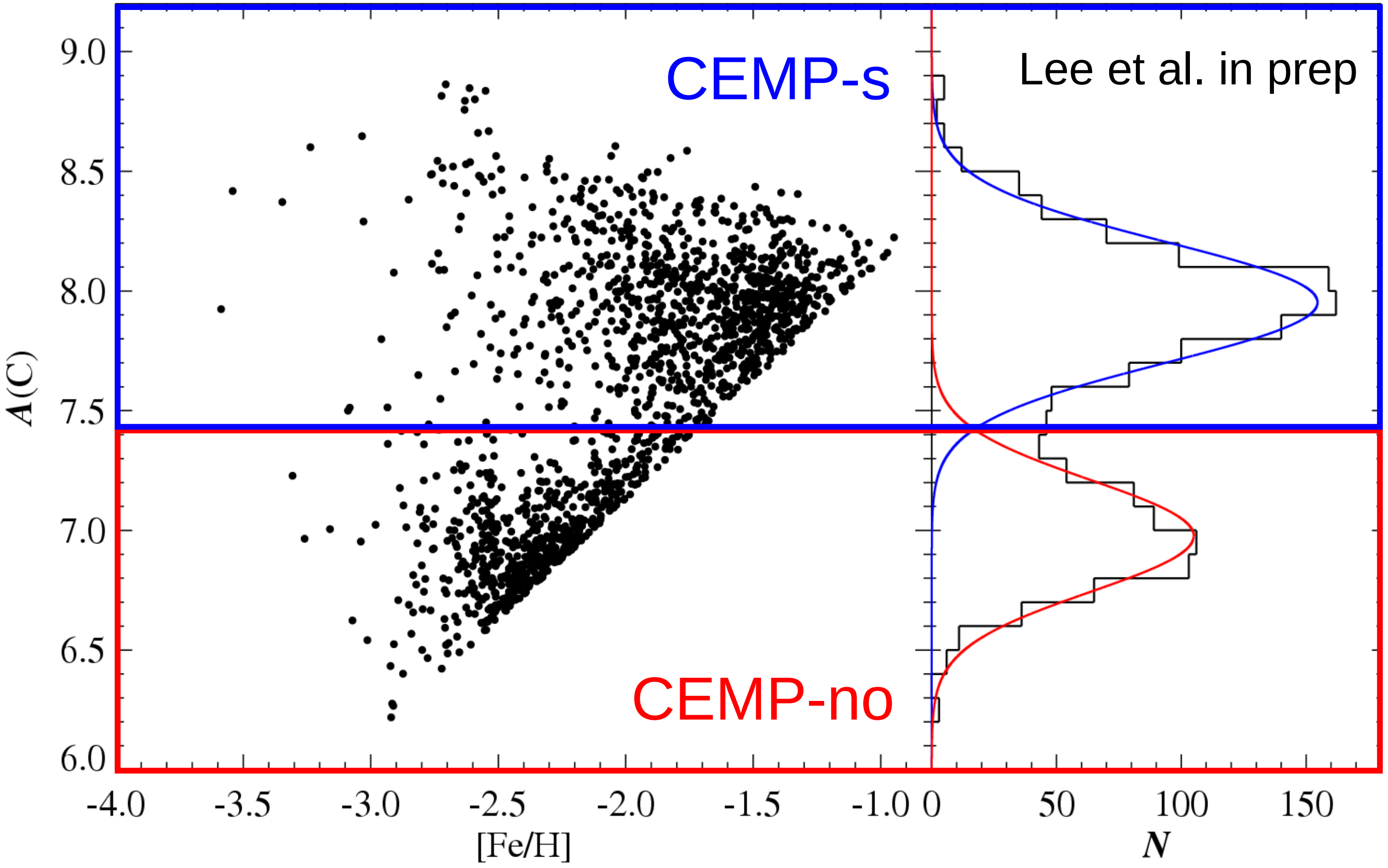
$<V_\varphi>=-25$ km/s

Lee et al. in prep.

Separation of CEMP-no and CEMP-s

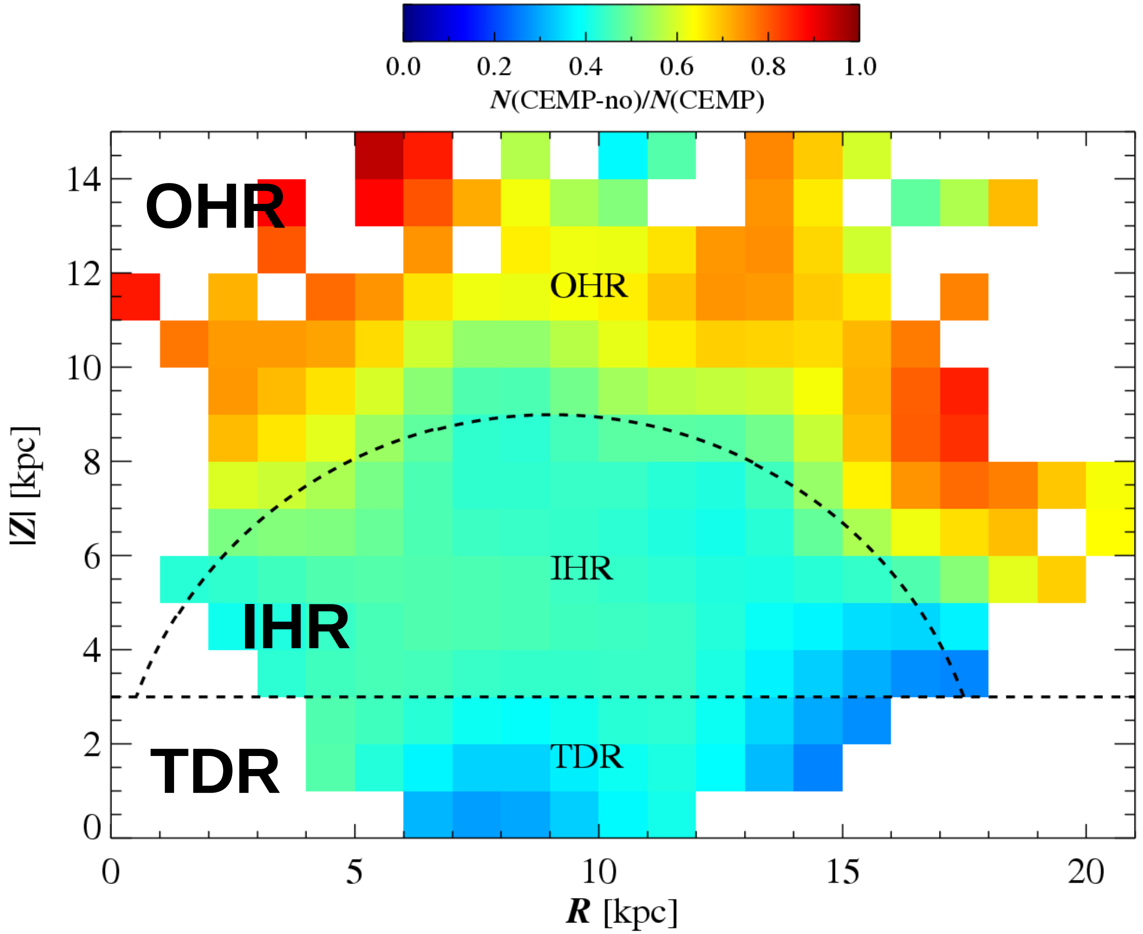
- Motivated by the work by Yoon et al. (2016)
  - ✓ Low *A*(C) stars are associated with CEMP-no, while high *A*(C) with CEMP-s





Fraction of CEMP-on and CEMP-s Stars

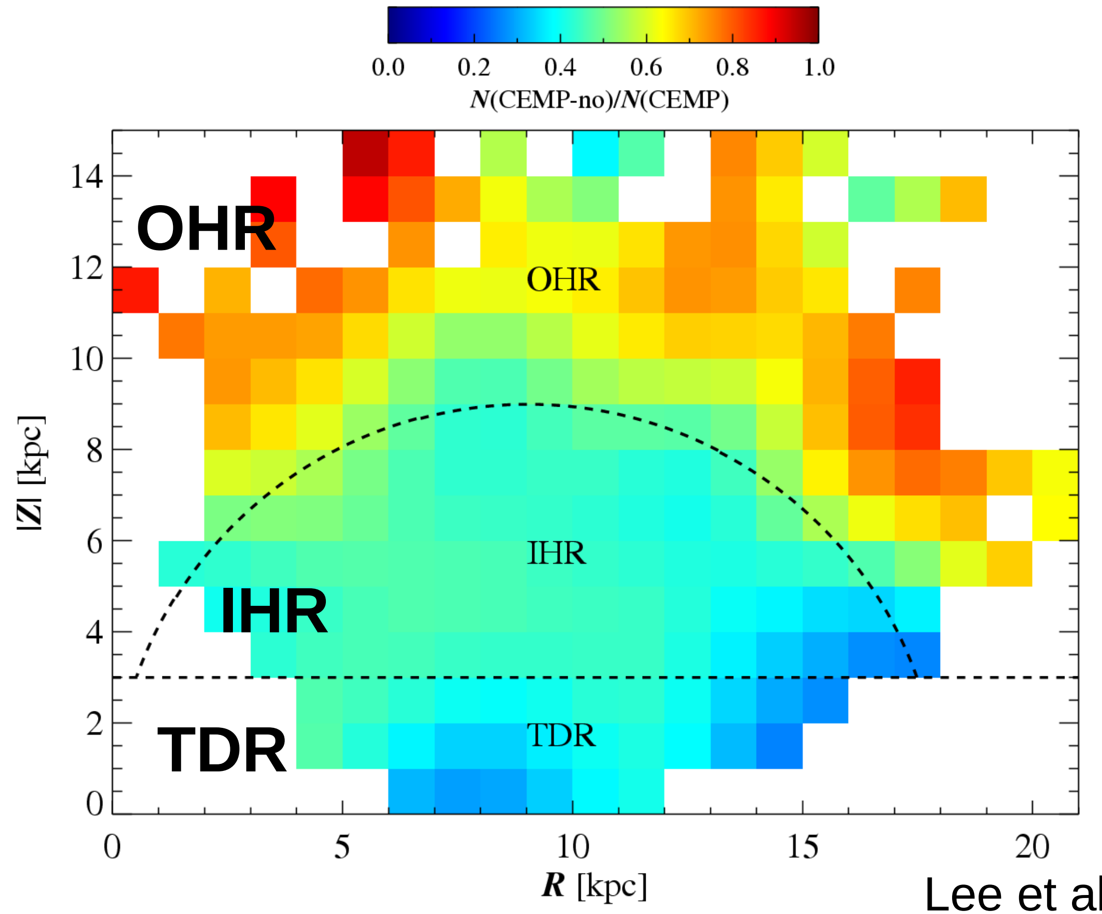
- The outer-halo region shows higher fractions of CEMP-no stars, indicating that dominant progenitors associated with each halo differ



Lee et al. in prep

Kinematics Between CEMP-no and CEMP-s

- ❑Rotation velocity differs between CEMP-no and CEMP-s stars in the outer halo → Numerous accretion history?



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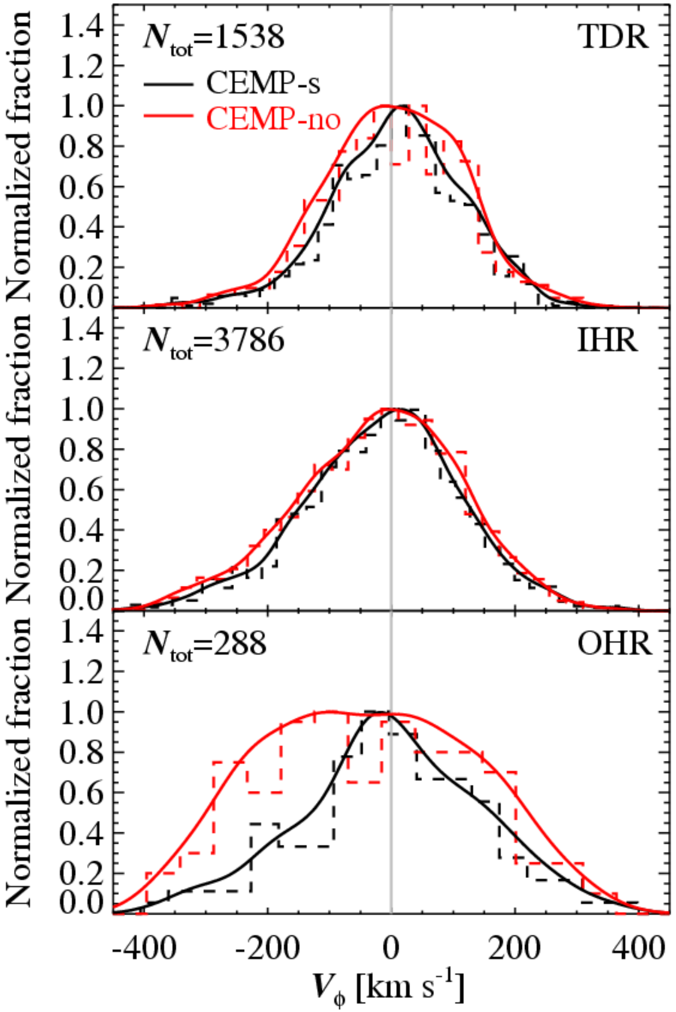


$\langle V_\varphi \rangle$=-14 km/s

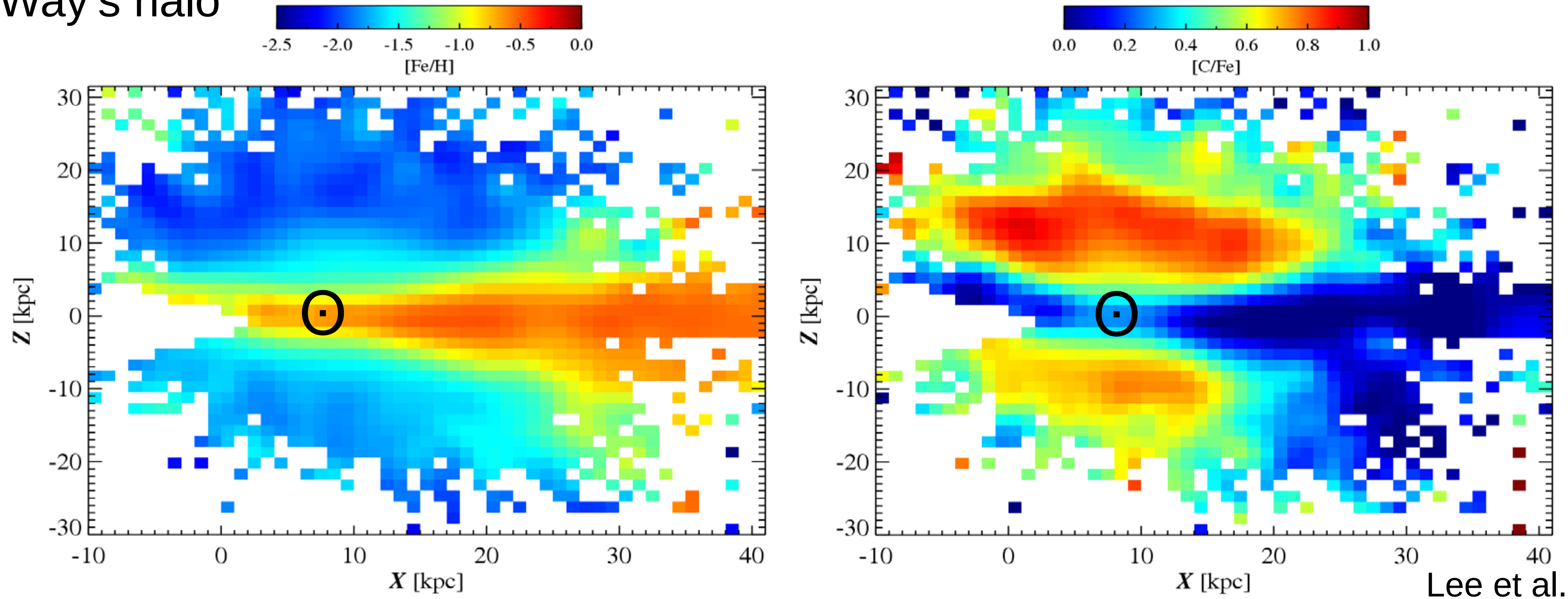
$\langle V_\varphi \rangle$=-20 km/s

$\langle V_\varphi \rangle$=-4 km/s

$\langle V_\varphi \rangle$=-41 km/s

What is Ahead? – The Galactic Halo

- Combined sample from various spectroscopic surveys (e.g., SDSS + LAMOST) allows to construct more detailed abundance map with kinematics from Gaia proper motions and parallaxes ➔ Eventually can reveal the formation process of the Milky Way's halo



Lee et al. in prep.

What is Ahead? – Galactic Archeology

- High-resolution spectroscopic surveys such as GAIA-ESO, GALAH, 4MOST, WEAVE, etc.
  - ✓ Determine abundances of many chemical elements based on high-resolution spectra for millions of stars
  - ✓ Find some interesting stars to explain the variety of CEMP-r, CEMP-r/s, CEMP-no, CEMP-s stars
  - ✓ Possible to depict detailed chemo-dynamic assembly history of the Milky Way with Gaia

➔ Will help disentangle the contributions of various nucleosynthesis processes to the chemical enrichment of the MW as well as the building blocks of the MW