

CEMP Stars as Probes of First-Star Nucleosynthesis and Galaxy Assembly

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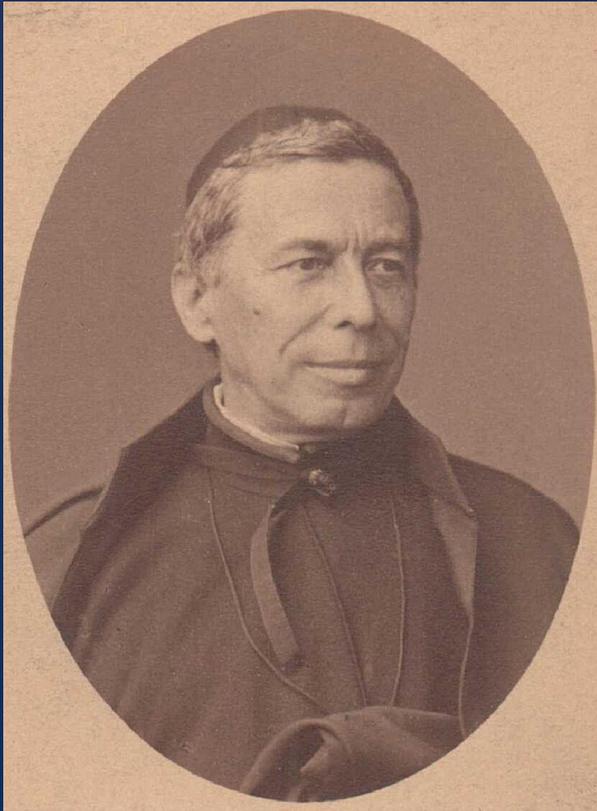
SDSS

What Are We Looking For ? Expected Signatures in the Early Universe

- First-generation objects of high mass presumably formed from metal-free gas
 - Lived short lives (**Myr not Gyr**)
 - Exploded
 - Distributed (pre or post explosion) their nucleosynthetic products
- Next-generation objects formed from the gas polluted by first-generation objects
 - A wider range of masses allowed, perhaps including stars with main-sequence lifetimes $>$ a Hubble time
 - Further star formation (Pop II) contributed additional material, and **diluted the signatures** of first/next-generation stars
- We should look for a characteristic set of abundance signatures **ONLY found** among the lowest metallicity stars

Discovery of Carbon Stars

Angelo Secchi and the Discovery of Carbon Stars



1818 – 1878

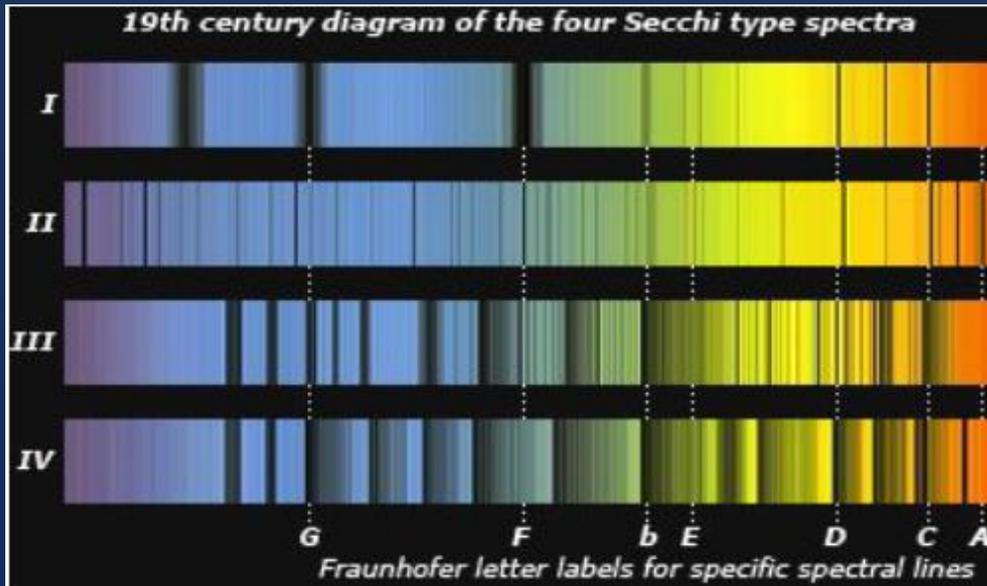
The year 1868 was a banner year for Father Angelo Secchi. In that year, after being disappointed at not being able to go to India to observe the great eclipse of 18 August 1868, he stayed at home in Rome and reported to the French Academie des Sciences in a rather tentative vein his suspicions that he had detected a new spectral type (Secchi 1868a). This would be a clear distinction among the red stars he had been observing from his observatory of the *Collegio Romano* located atop the Church of San Ignazio near the *Piazza Venezia* in downtown Rome. In January Secchi (1868a) announced his discovery as follows:

Stars which do not belong to the three established types are very rare. I have examined without success many hundreds of faint stars. I have just come across one very extraordinary star which is listed in Lalande's catalogue (RA = 4hr 54m 10s and Dec = + 0°59'). Its spectrum is very peculiar. The red region is divided into two bands by a very broad dark line. The golden yellow is reduced to a very clear and very sharp line. After a broad dark band comes a broad green-yellow band and, after another dark interval, a zone of blue... Although I have not examined the whole sky I believe that one will find very few of these stars and that they will belong to the family of red stars and of variable stars.

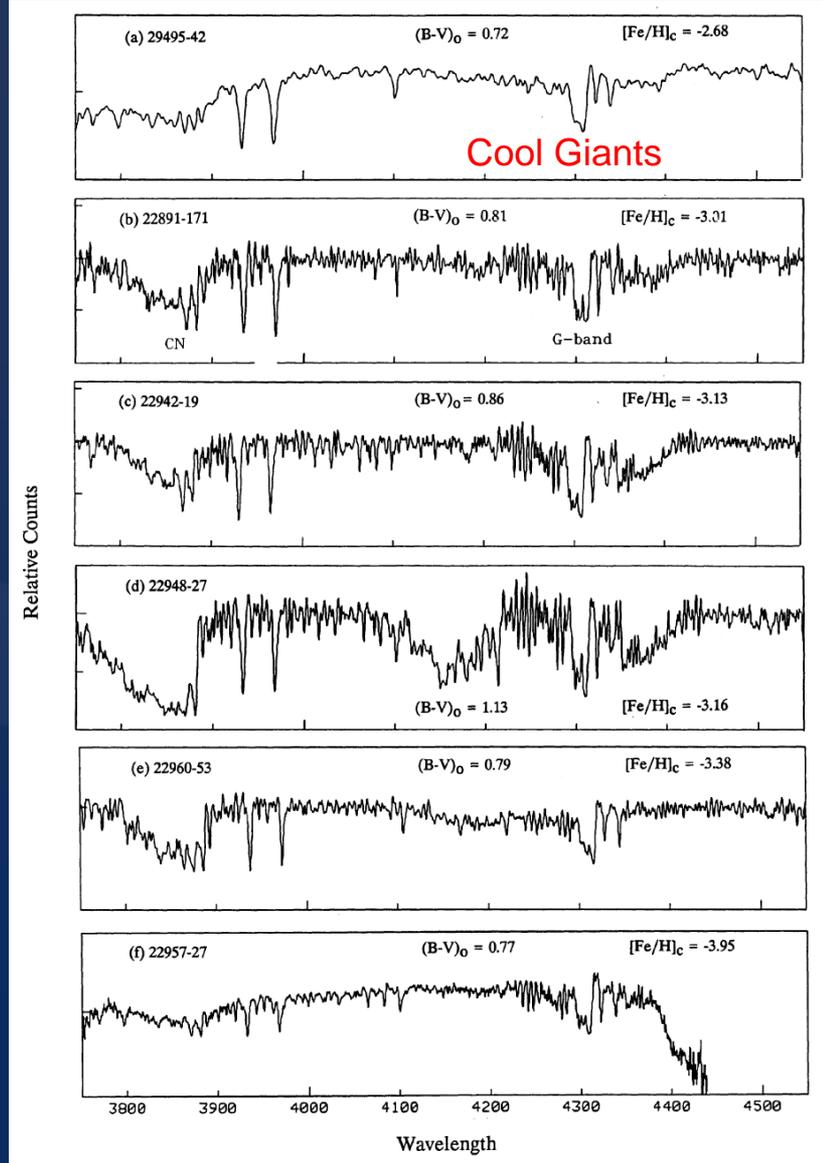
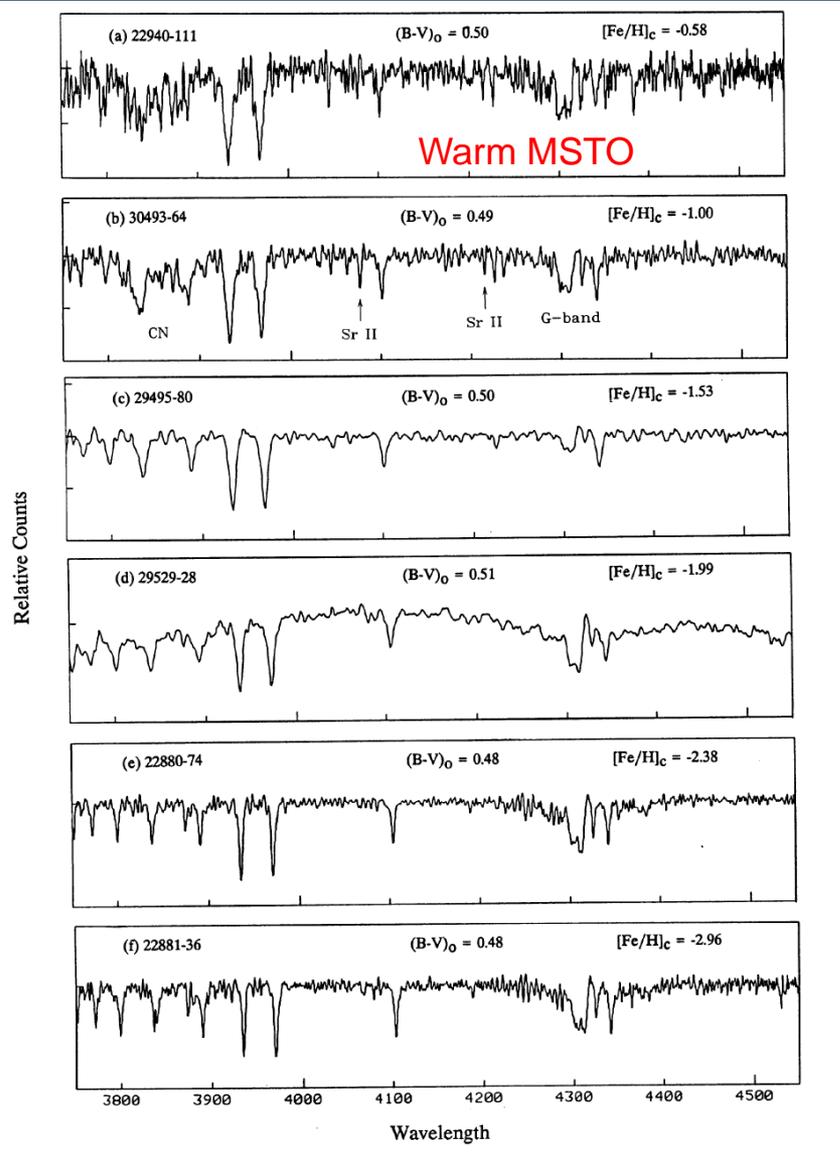
M.F. McCarthy, S.J. (1994)

What Did Father Secchi See ?

Angelo Secchi and the Discovery of Carbon Stars



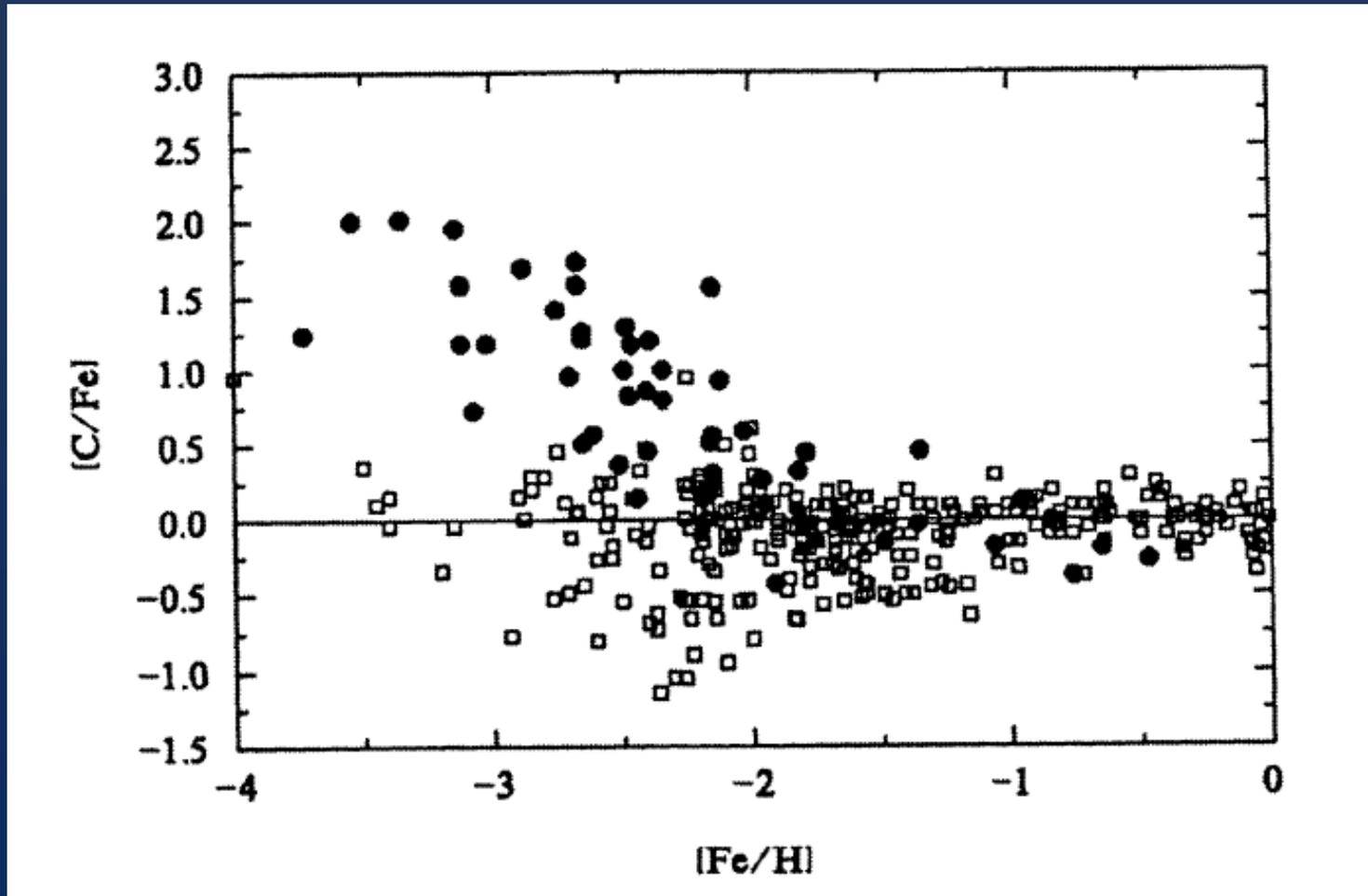
Discovery of CEMP Stars



$[Fe/H] < -2.0$; high velocity; unknown n-capture

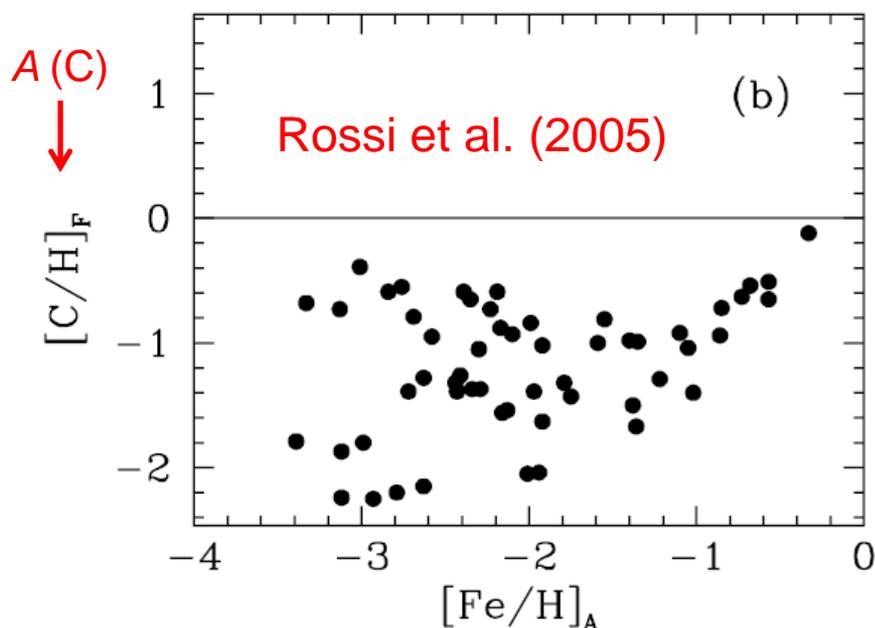
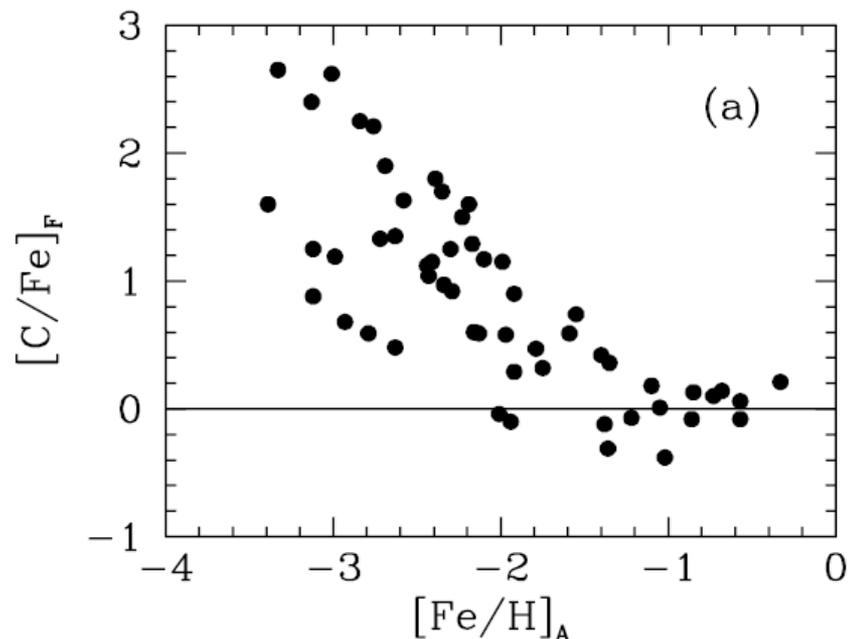
Beers et al. (1992)

CEMP Frequency / Level of [C/Fe]



Higher CEMP Frequency + Higher $[C/Fe]$ at lower $[Fe/H]$

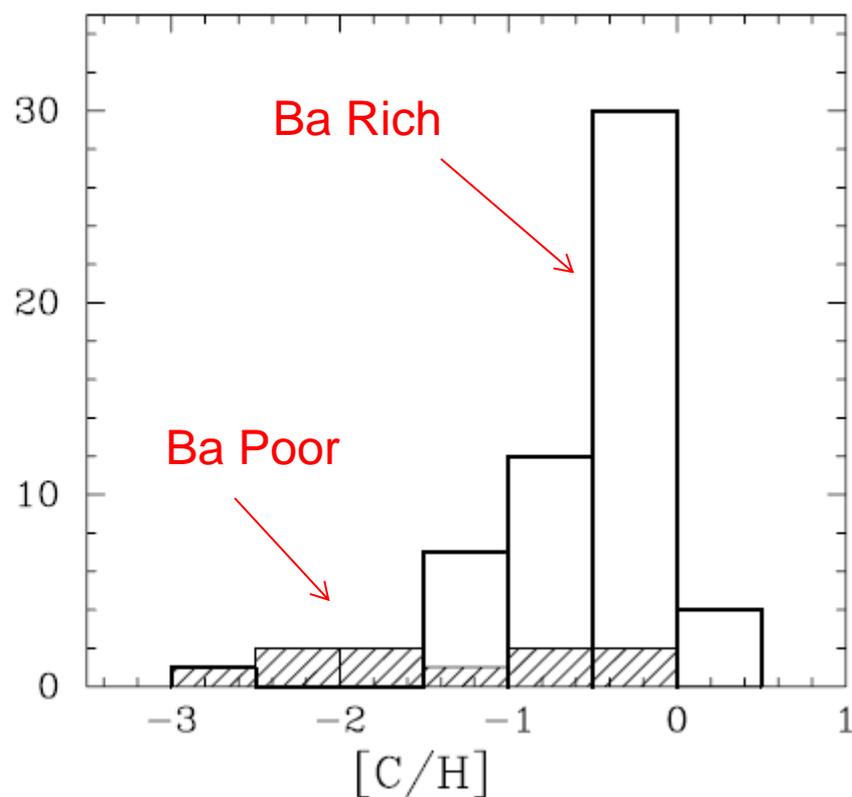
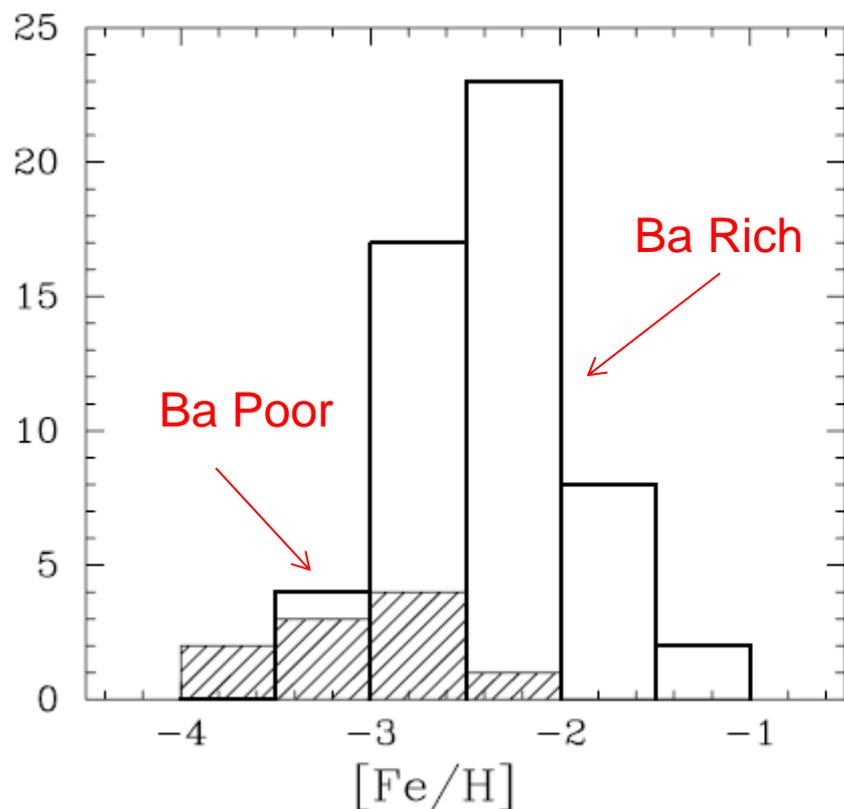
Refined Estimates of [C/Fe]



Apparent Split of [C/Fe] and [C/H] for [Fe/H] < -2.5

“ If all the CEMP stars obtained their carbon enhancement as the result of the transfer of AGB-processed material from a now-deceased companion, this result places a strong constraint on the level of carbon enhancement that must be accounted for by models of AGB evolution at low metallicity. However, we suspect that it may not be the case that all the CEMP stars can be accounted for by this single process. It is worth noting that, for metallicities in the range $Fe/H < -2.5$, the distribution of [C/H] for CEMP stars may be bimodal, which also suggests that several nucleosynthetic processes may be involved.”

Larger Samples of CEMP Stars with High-Resolution Abundances



Clear Distinctions Between Ba-poor and Ba-rich Stars

Exploration of Nature's Laboratory for Neutron-Capture Processes

Neutron-capture-rich stars

r-I	$0.3 \leq [\text{Eu}/\text{Fe}] \leq +1.0$ and $[\text{Ba}/\text{Eu}] < 0$
r-II	$[\text{Eu}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Eu}] < 0$
s	$[\text{Ba}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Eu}] > +0.5$
r/s	$0.0 < [\text{Ba}/\text{Eu}] < +0.5$

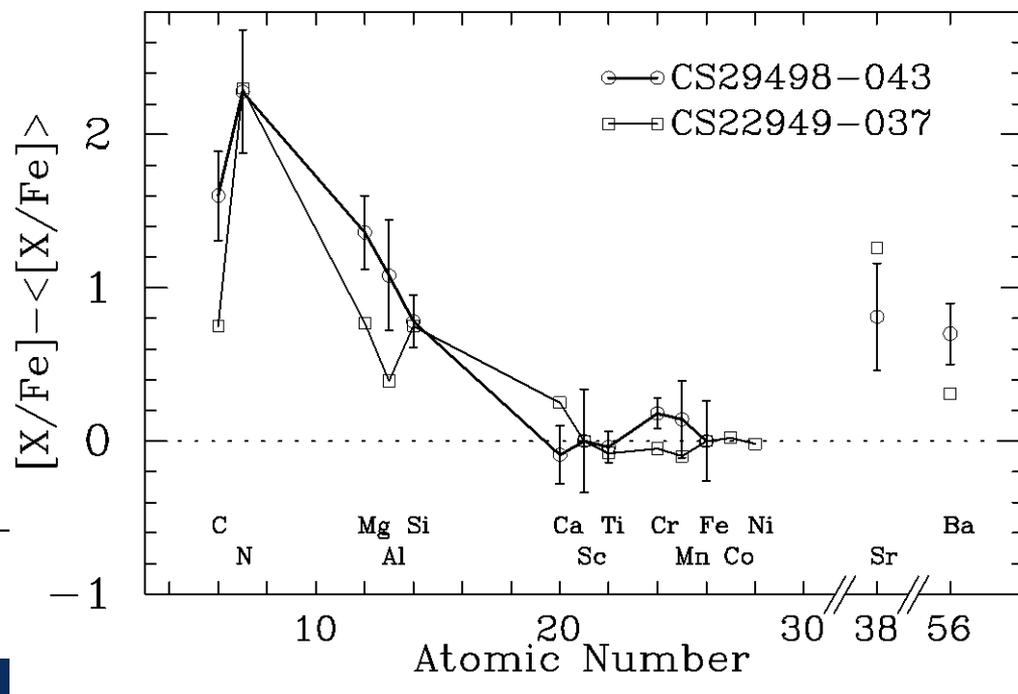
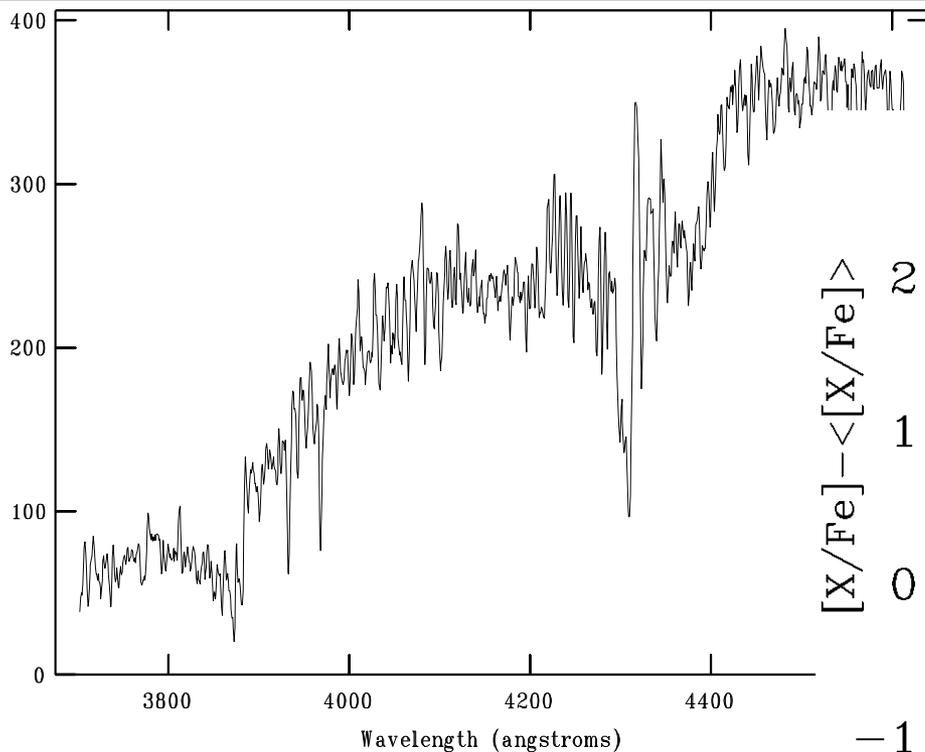
Carbon-enhanced metal-poor stars

CEMP	$[\text{C}/\text{Fe}] > +1.0$
CEMP-r	$[\text{C}/\text{Fe}] > +1.0$ and $[\text{Eu}/\text{Fe}] > +1.0$
CEMP-s	$[\text{C}/\text{Fe}] > +1.0$, $[\text{Ba}/\text{Fe}] > +1.0$, and $[\text{Ba}/\text{Eu}] > +0.5$
CEMP-r/s	$[\text{C}/\text{Fe}] > +1.0$ and $0.0 < [\text{Ba}/\text{Eu}] < +0.5$
CEMP-no	$[\text{C}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Fe}] < 0$

$[\text{C}/\text{Fe}] > +1.0$ later revised to $+0.7$ for CEMP status

CEMP-no Stars are Associated with UNIQUE Light-Element Abundance Patterns (Aoki et al. 2002)

CS 29498-043: $[\text{Fe}/\text{H}] = -3.8$; $[\text{C}/\text{Fe}] = +1.9$

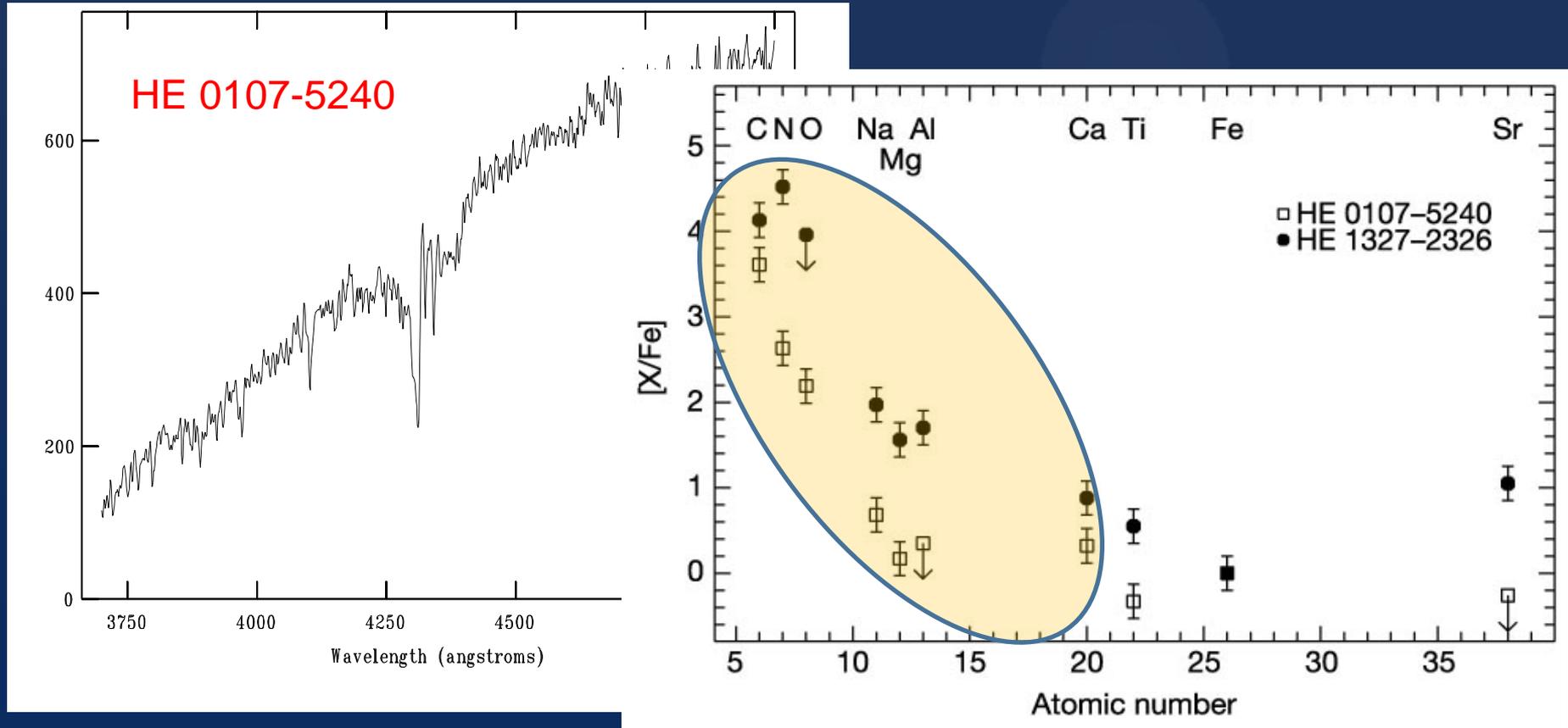


Harbingers of Things to Come!

CEMP-no Stars are Associated with UNIQUE Light-Element Abundance Patterns

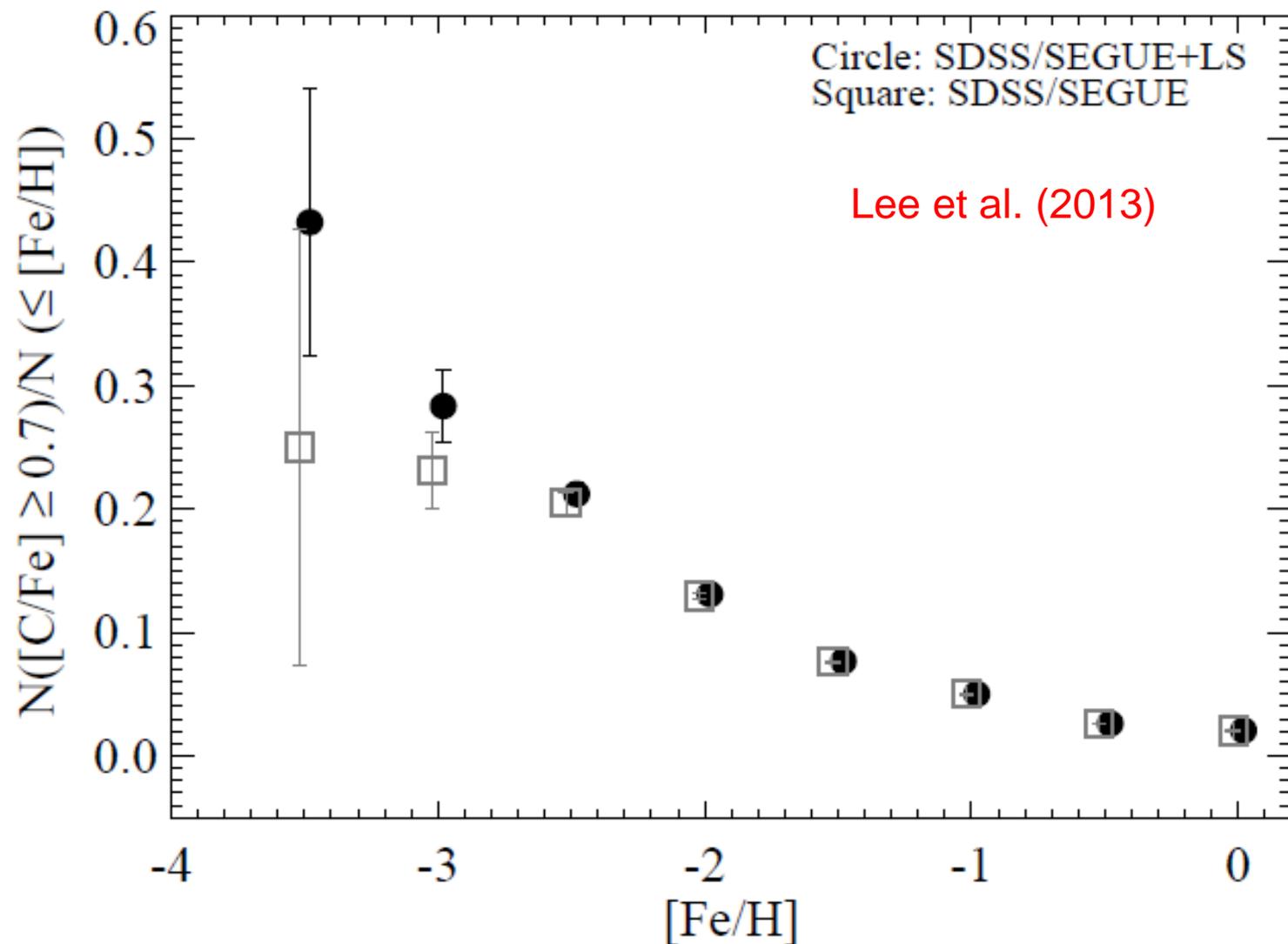
HE 0107-5240 $[\text{Fe}/\text{H}] = -5.3$, $[\text{C}/\text{Fe}] = +3.6$ (Christlieb et al. 2002)

HE 1327-2326 $[\text{Fe}/\text{H}] = -5.5$, $[\text{C}/\text{Fe}] = +4.2$ (Frebel et al. 2005)

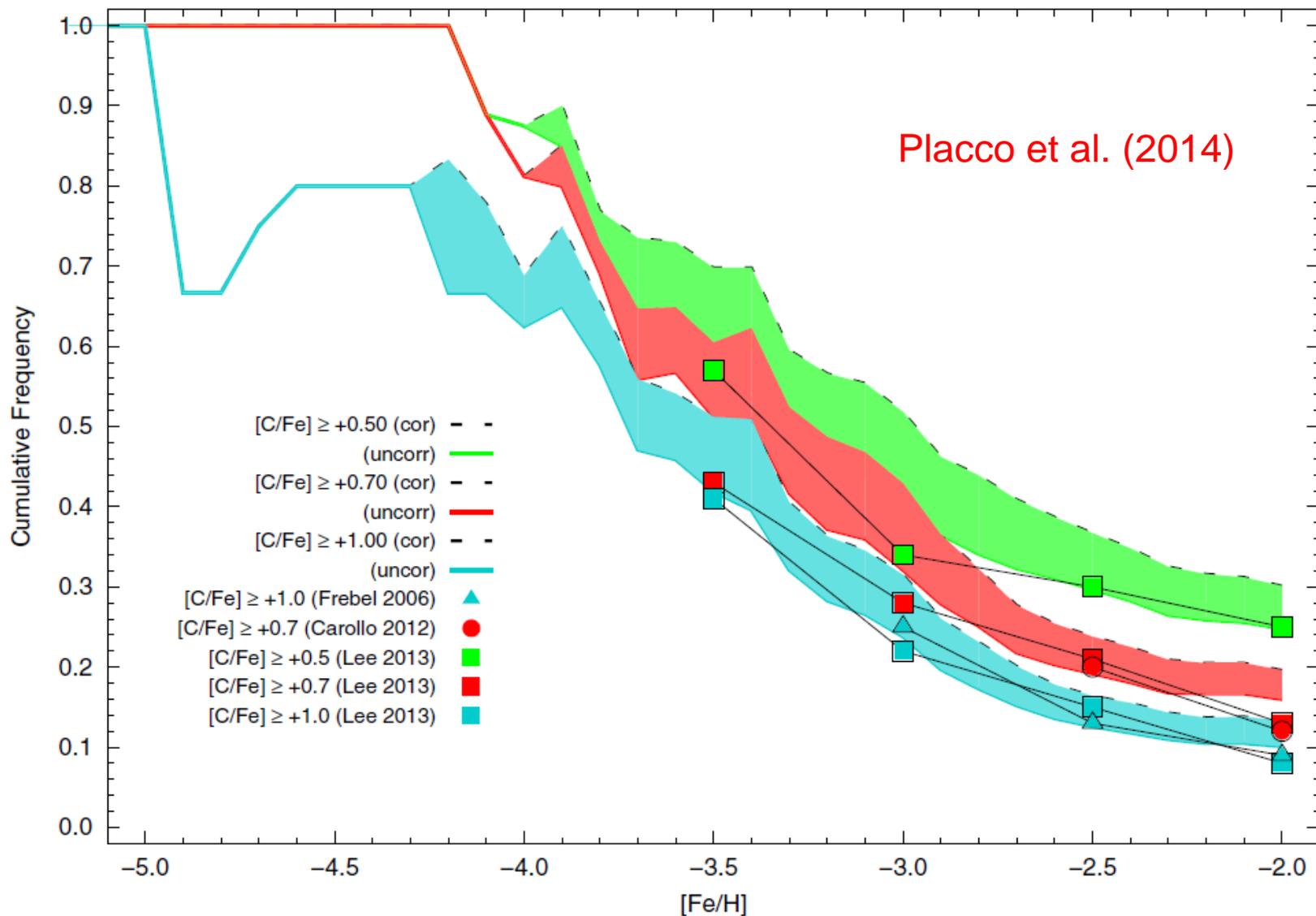


It is the SAME pattern among the light elements !

Learning How to Count – Cumulative Frequencies of CEMP Stars



Cumulative Frequencies of CEMP-no (ONLY) Stars from SDSS/SEGUE, with Luminosity Corrections



As If Right on Cue ...

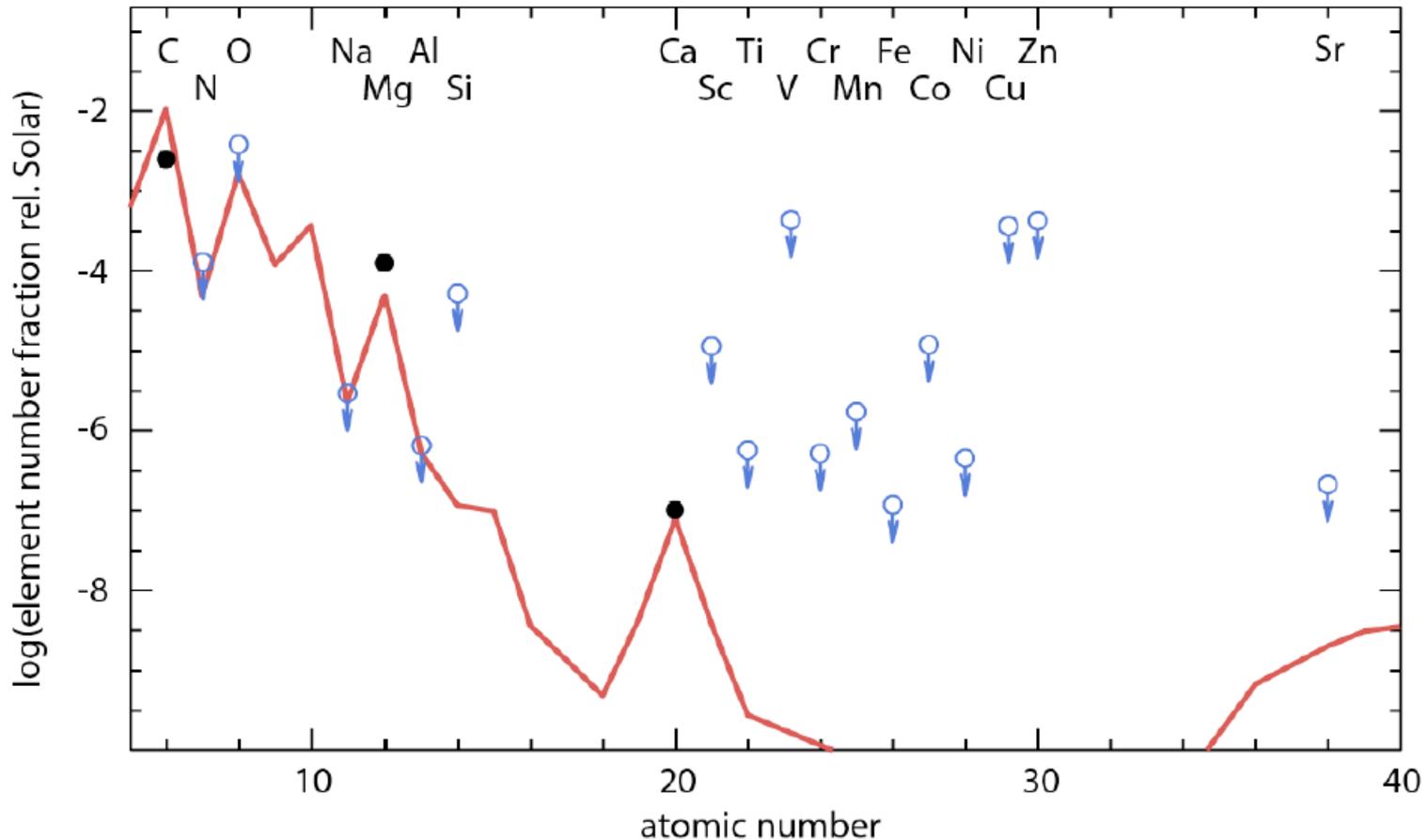
➤ Nature – March, 2014

A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3

S. C. Keller, M. S. Bessell, A. Frebel, A. R. Casey, M. Asplund, H. R. Jacobson, K. Lind, J. E. Norris, D. Yong, A. Heger, Z. Magic, G. S. Da Costa, B. P. Schmidt, & P. Tisserand

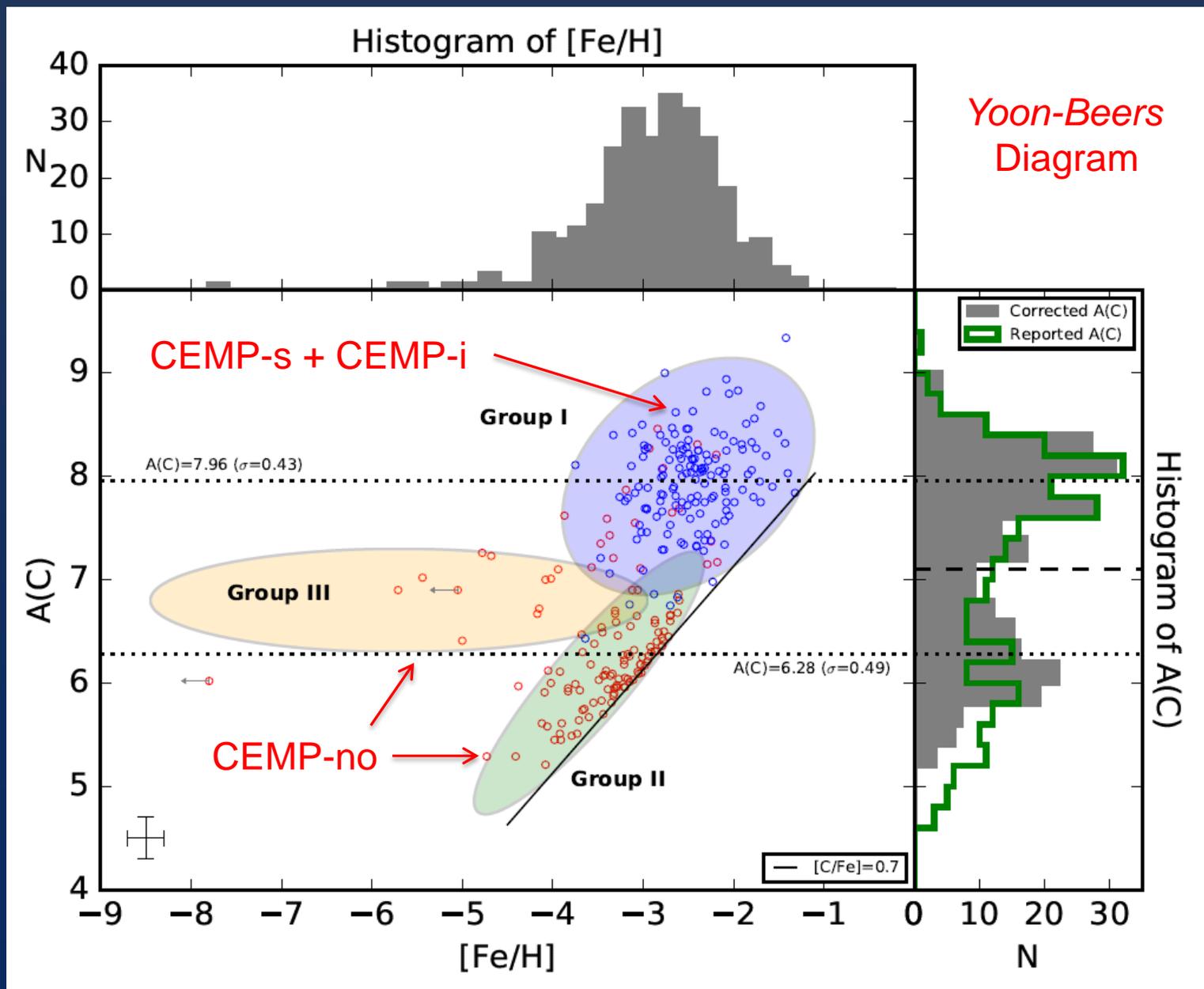
- Announcement of the discovery of a star with metallicity $[\text{Fe}/\text{H}] < -7.1$ -- more than 10,000,000 times lower than the Sun
- And of course, it is a **CEMP-no star**, with the same **light element** abundance pattern, and **detectable (but very low) Li**

Observed Elemental Abundance Pattern for SMSS J031300.36-670839.3 ($[Fe/H] < -7.8$)

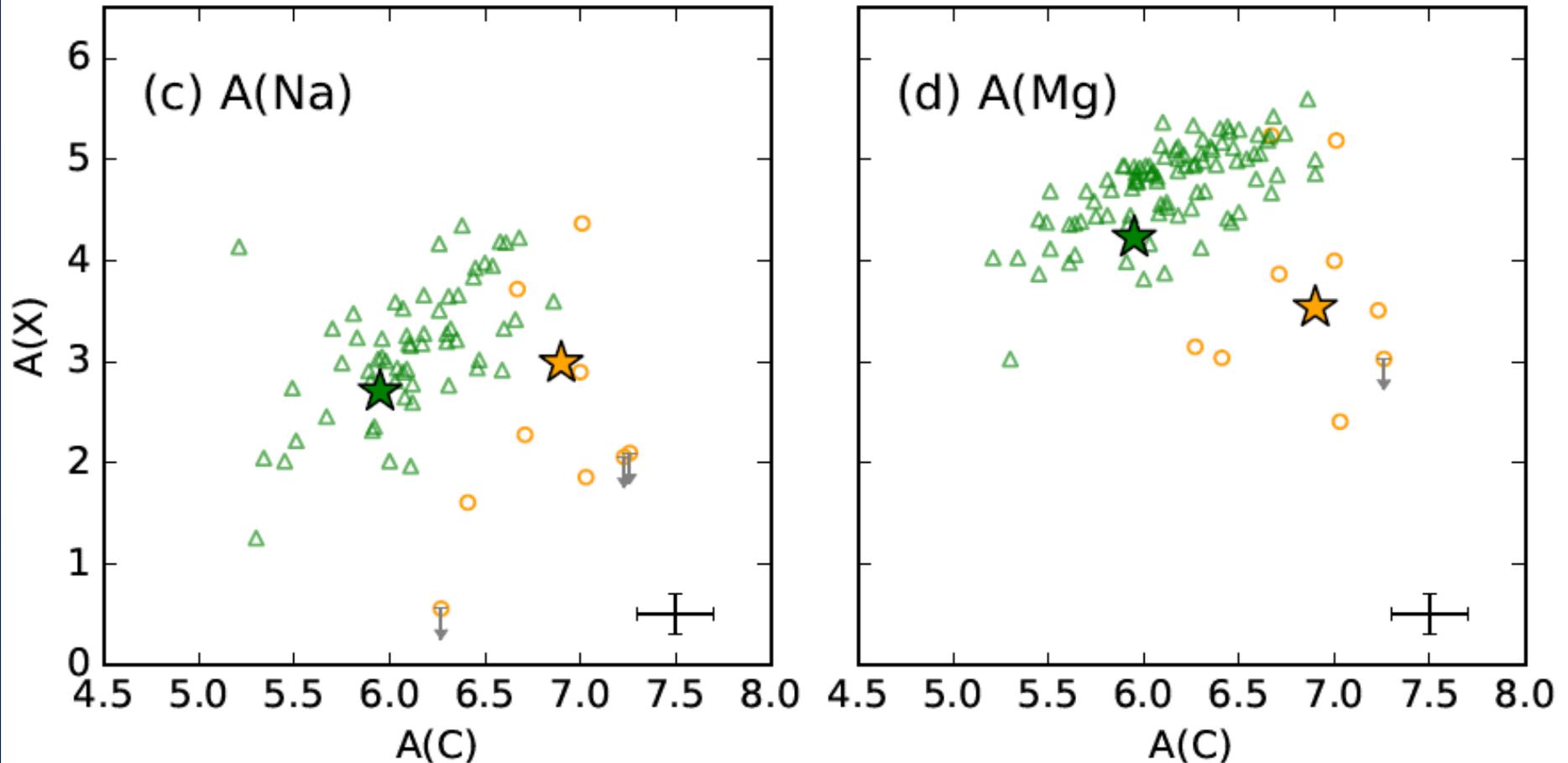


Note singular detections of C, Mg, and Ca – Everything else is an upper limit! (Keller et al. 2014)

Yoon et al. (2016) – Absolute Carbon A(C) vs. [Fe/H]



Yoon et al. (2016) – A(Na) and A(Mg) vs. A(C)



Group II CEMP-no: **Green**

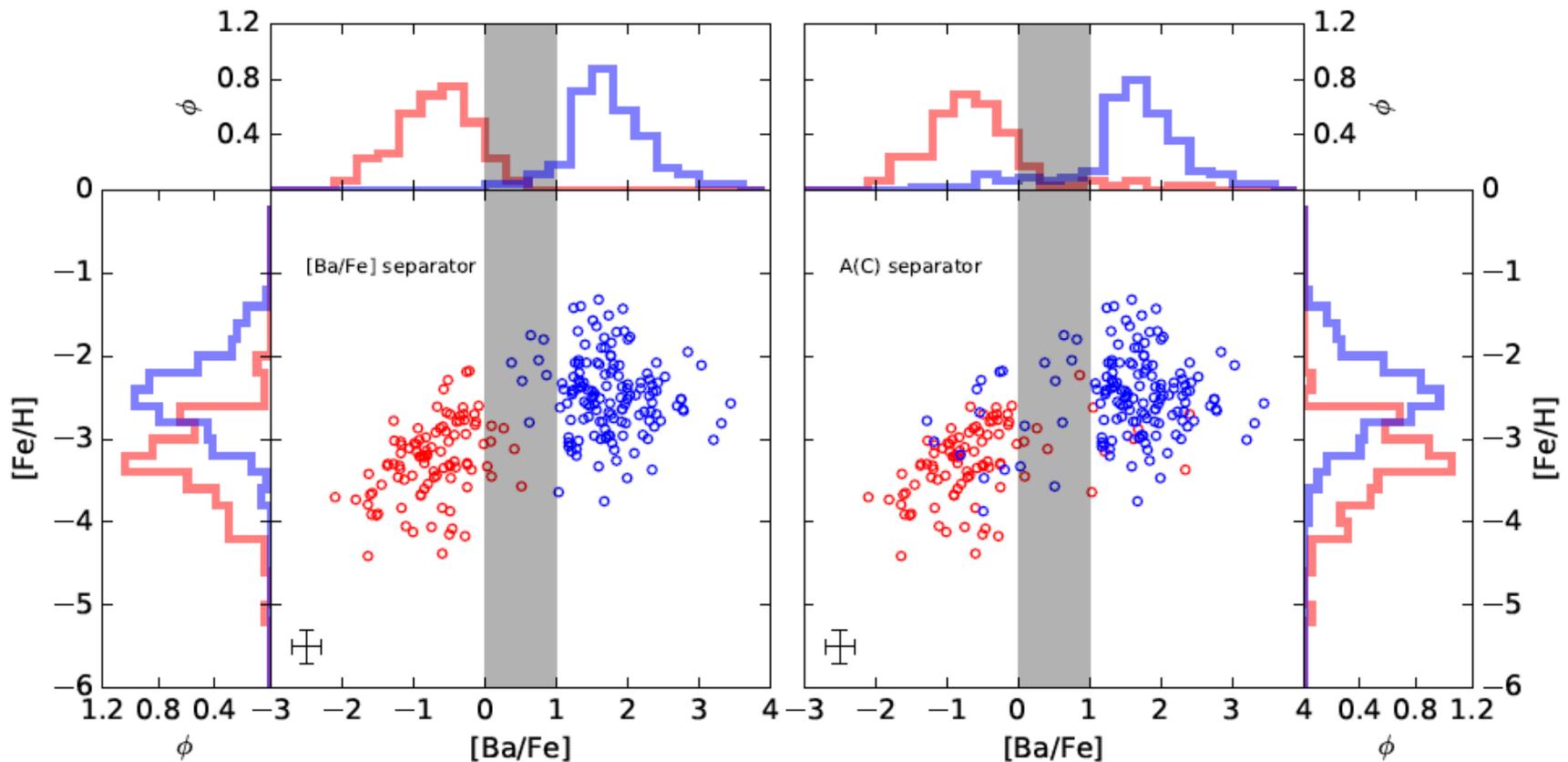
BD+44:493

/ Group III CEMP-no: **Orange**

HE 1327-2326

New Tools / New Techniques

- Separation of CEMP-s(i) stars from CEMP-no stars based on *Yoon-Beers* diagram (A(C) vs. [Fe/H]), opening identification from medium-resolution, rather than high-resolution spectroscopy



Hidden CEMP-no Stars

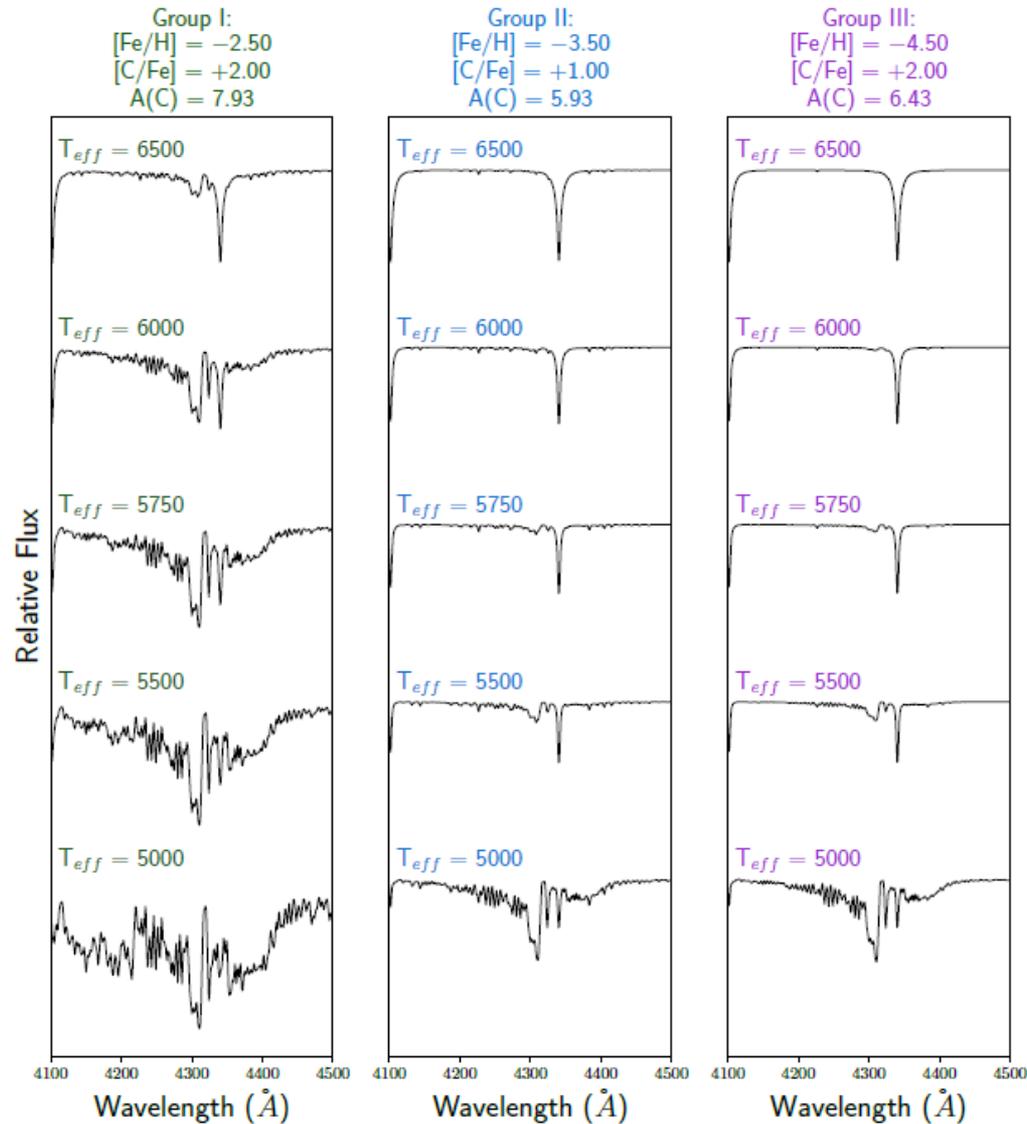


Figure courtesy
Kaitlin Rasmussen

Hidden CEMP-no Stars

G64–12 AND G64–37 ARE CEMP-NO STARS

VINICIUS M. PLACCO^{1,2}, TIMOTHY C. BEERS^{1,2},
HENRIQUE REGGIANI³, JORGE MELÉNDEZ³

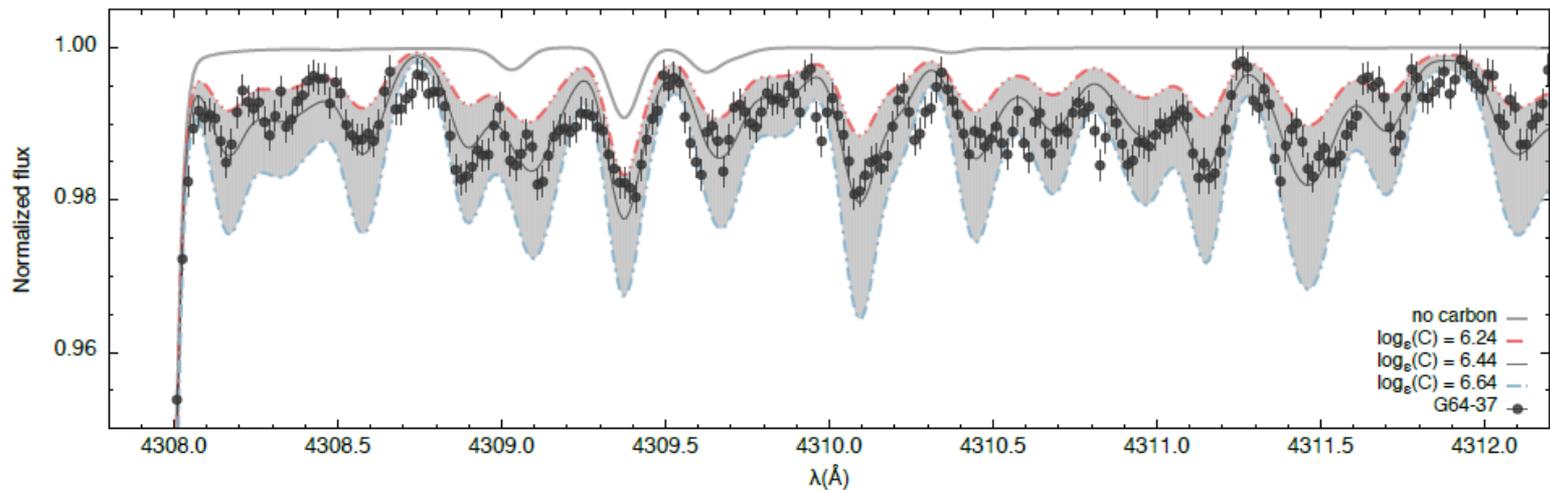
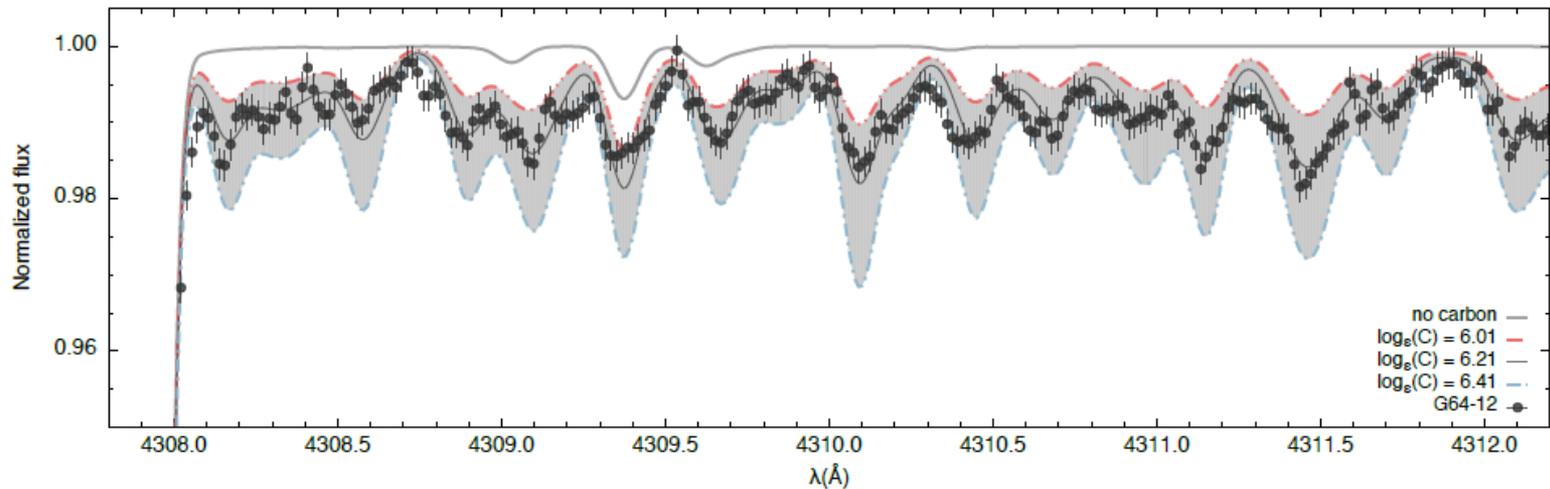
Draft version August 15, 2016

ABSTRACT

We present new high-resolution chemical-abundance analyses for the well-known extremely metal-poor, high proper-motion subdwarfs G64–12 and G64–37, based on very high signal-to-noise spectra ($S/N \sim 700/1$) with resolving power $R \sim 95,000$. These high-quality data enable the first *reliable* determination of the carbon abundances for these two stars; we classify them as CEMP-no Group-II stars, based on their location in the Yoon-Beers diagram of absolute carbon abundance, $A(C)$ vs. $[Fe/H]$, as well as on the conventional diagnostic $[Ba/Fe]$. The relatively low absolute carbon abundances of CEMP-no stars, in combination with the high effective temperatures of these two stars ($T_{\text{eff}} \sim 6500$ K) weakens their CH molecular features to the point that accurate carbon abundances can only be estimated from spectra with very high S/N . A comparison of the observed abundance patterns with the predicted yields from massive metal-free, supernova progenitors models reduces the inferred progenitor masses by factors of ~ 2 -3, and explosion energies by factors of ~ 5 -6, compared to those derived using previously claimed carbon abundance estimates. There are certainly many more warm CEMP-no stars near the halo main-sequence turnoff that have been overlooked in past studies, directly impacting the derived frequencies of CEMP-no stars as a function of metallicity, a probe that provides important constraints on Galactic chemical evolution models, the initial mass function in the early Universe, and first-star nucleosynthesis.

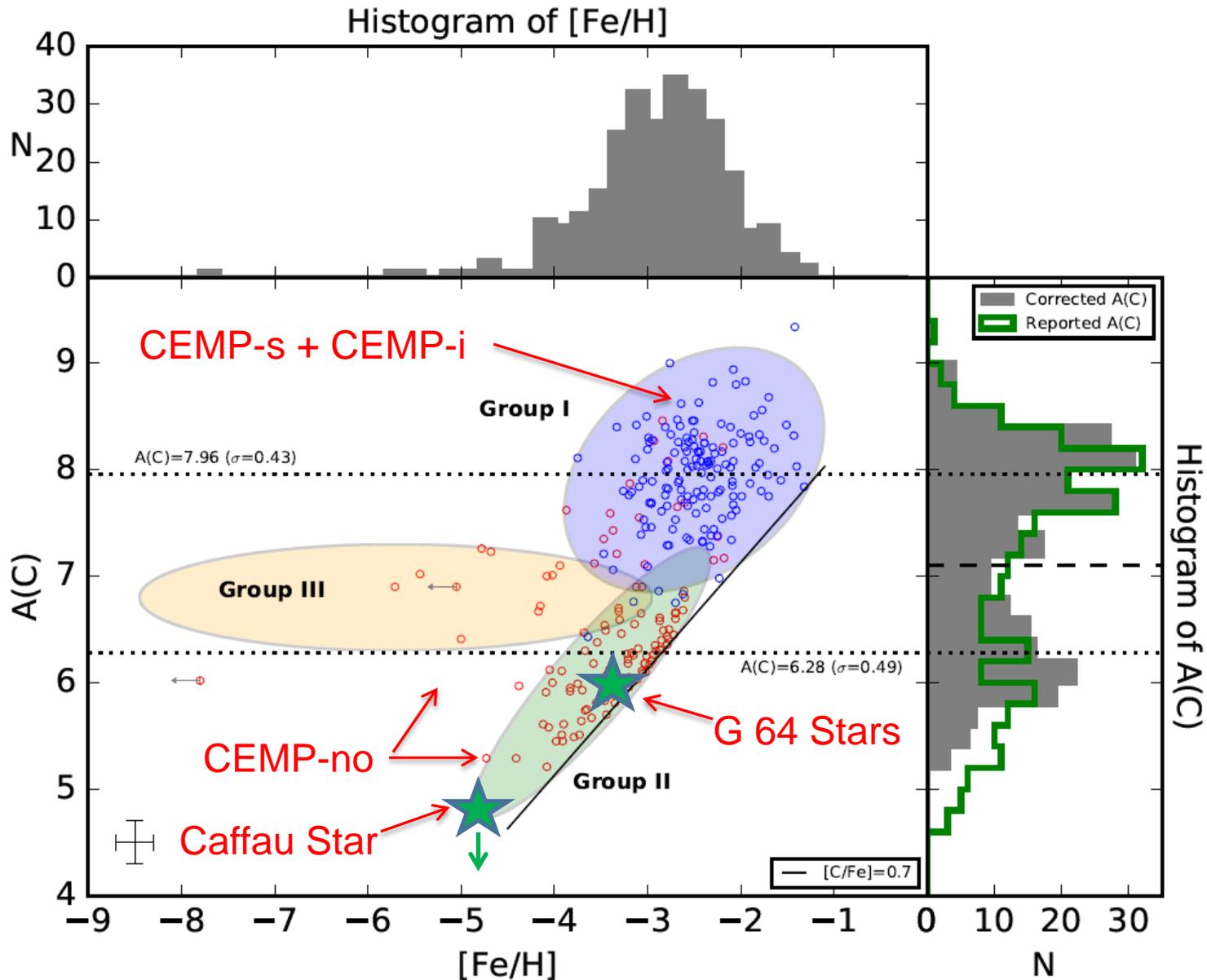
Keywords: Galaxy: halo—stars: abundances—stars: Population II—stars: individual (G64–12)—stars: individual (G64–37)

Hidden CEMP-no Stars



$T_{\text{eff}} \sim 6500 \text{ K}$ $[\text{Fe}/\text{H}] \sim -3.5$ $[\text{C}/\text{Fe}] = +1.1$ $A(\text{C}) = 6.2$

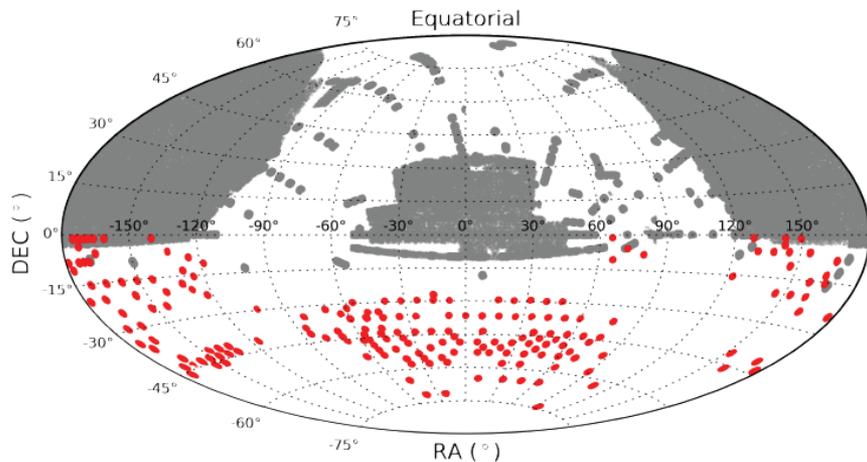
Yoon – Beers Diagram – Absolute Carbon A(C) vs. [Fe/H]



New Surveys / Using the New Tools – AEGIS Survey

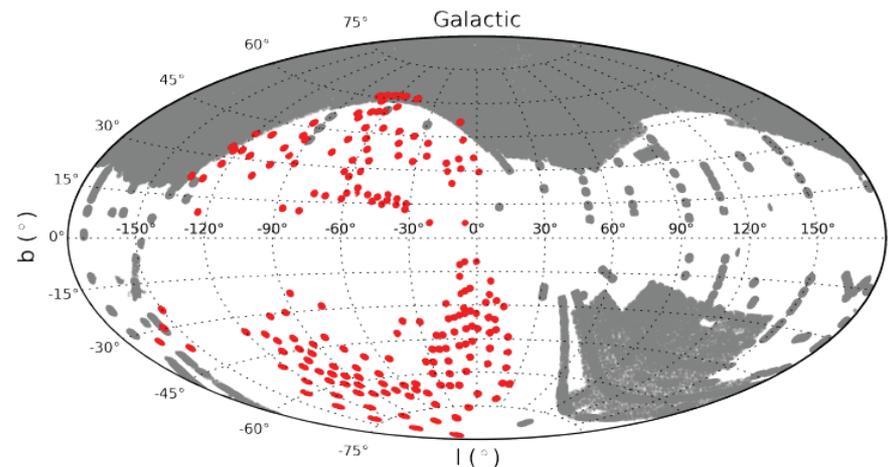
Galactic Archeology with the AEGIS Survey: The Evolution of Carbon and Iron in the Galactic Halo

JINMI YOON,^{1,2} TIMOTHY C. BEERS,^{1,2} SARAH DIETZ,^{1,2} YOUNG SUN LEE,³ VINICIUS M. PLACCO,^{1,2} GARY DA COSTA,⁴ STEFAN KELLER,⁴ CHRISTOPHER I. OWEN,⁴ AND MAHAVIR SHARMA⁵

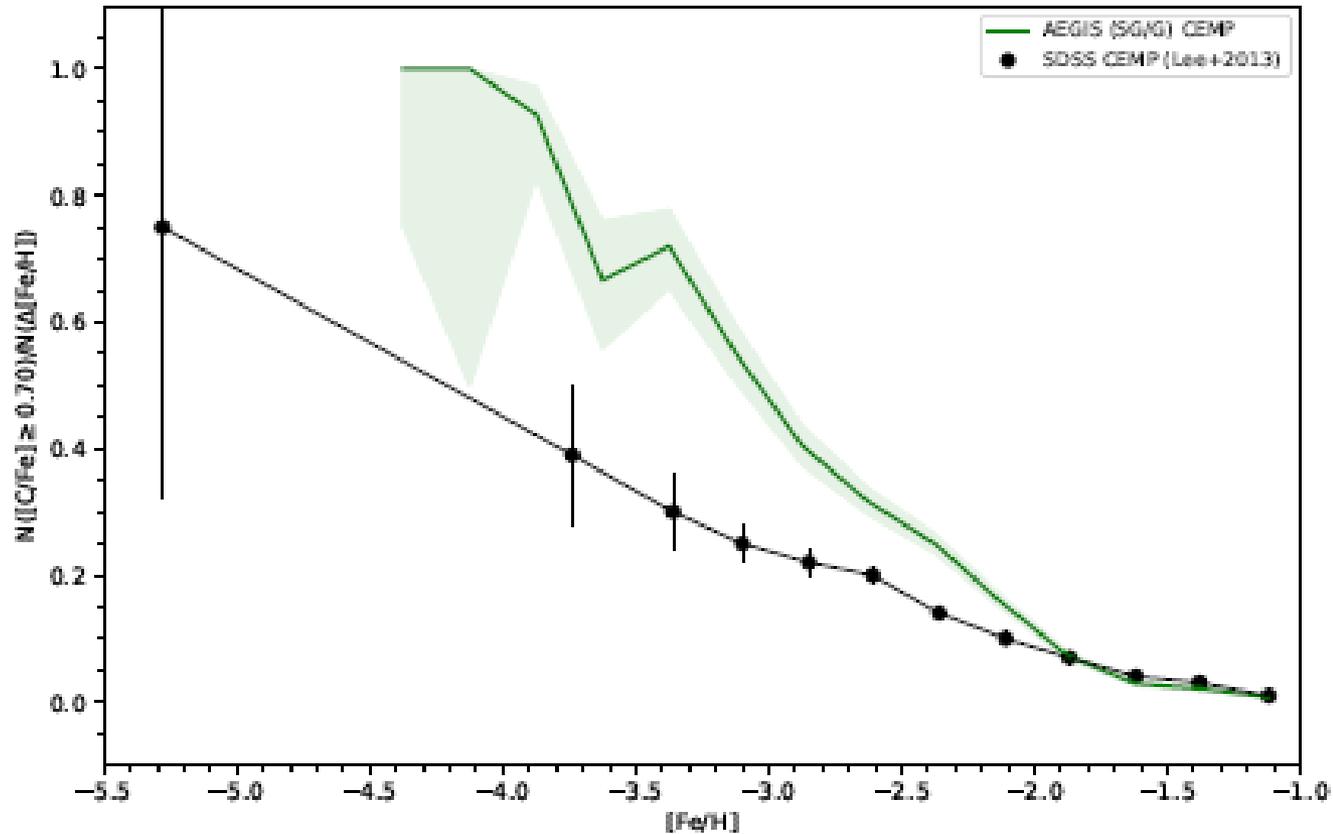


Equatorial Map

Galactic Map

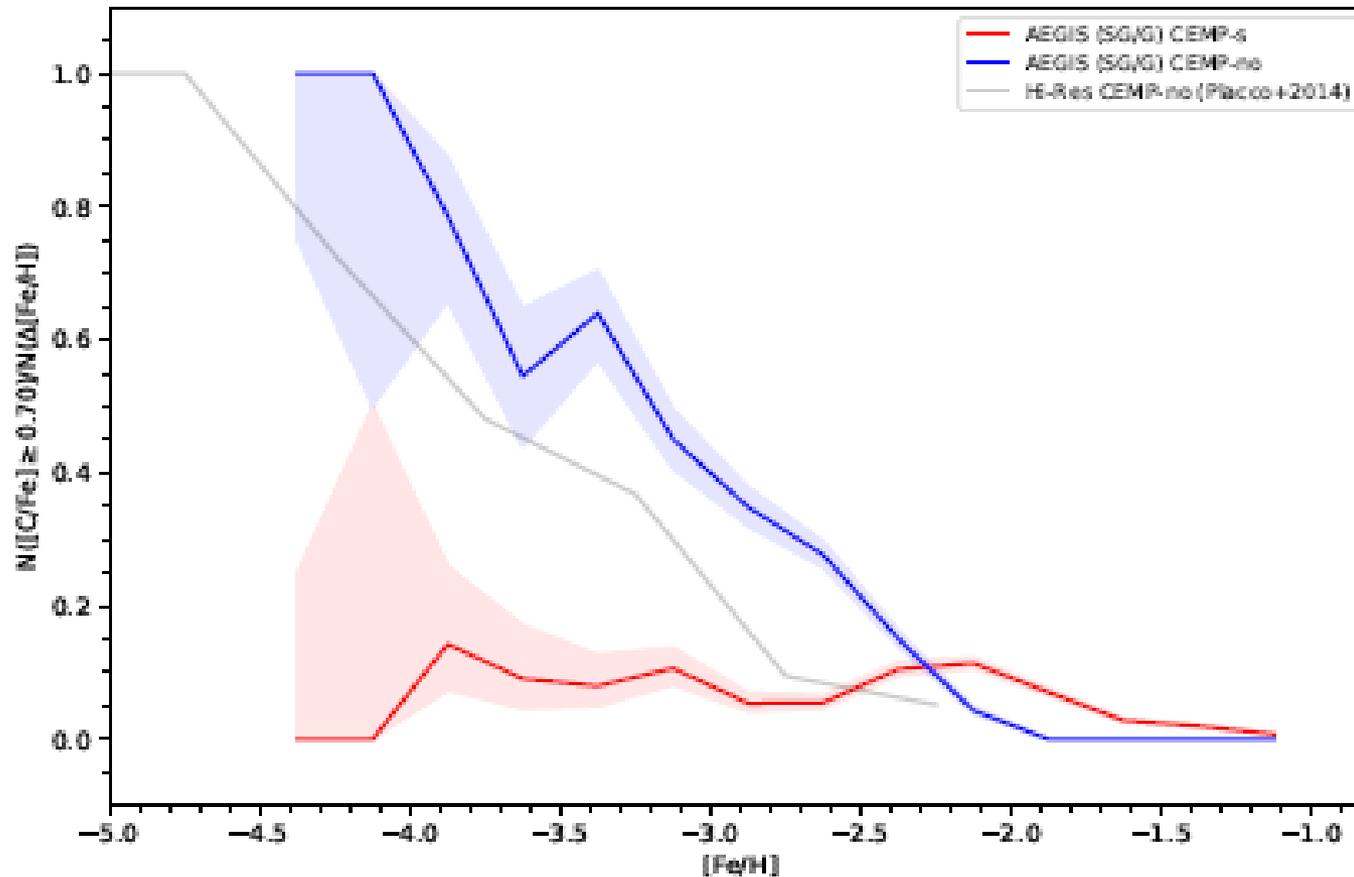


Cumulative Frequencies / Differential Frequencies of ALL (CEMP-no + CEMP-s with $T_{\text{eff}} < 5750$ K) for the AEGIS Sample



(b) Differential frequencies of all CEMP stars.

Cumulative Frequencies / Differential Frequencies of SPLIT (CEMP-no + CEMP-s with $T_{\text{eff}} < 5750$ K) for the AEGIS Sample



(d) Differential frequencies of the CEMP-no and CEMP-s stars.

Association of CEMP-no Stars with Outer Halo / CEMP-s Stars with Inner Halo

Consideration of different spatial regions --
The distribution of AEGIS SG + G sample reveals:

The IHR comprises: **47 +/- 4% CEMP-no**

The OHR comprises: **53 +/- 4% CEMP-s**

The OHR comprises: **78 +/- 7% CEMP-no**

The IHR comprises: **22 +/- 7% CEMP-s**

Dietz et al. (in prep) – Stellar Kinematics →

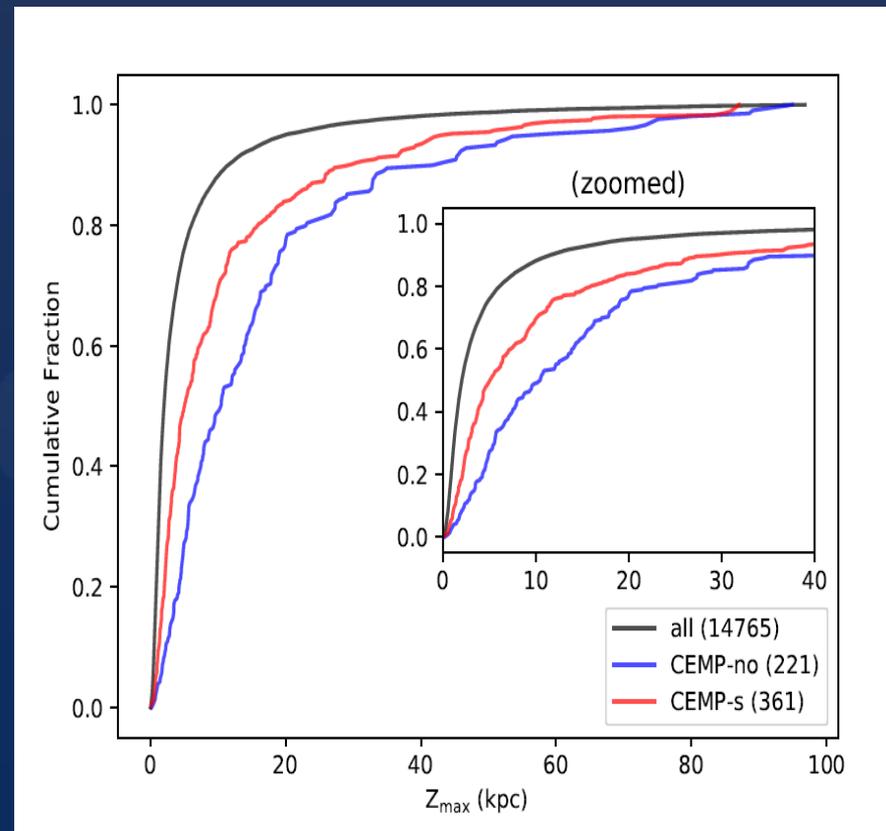
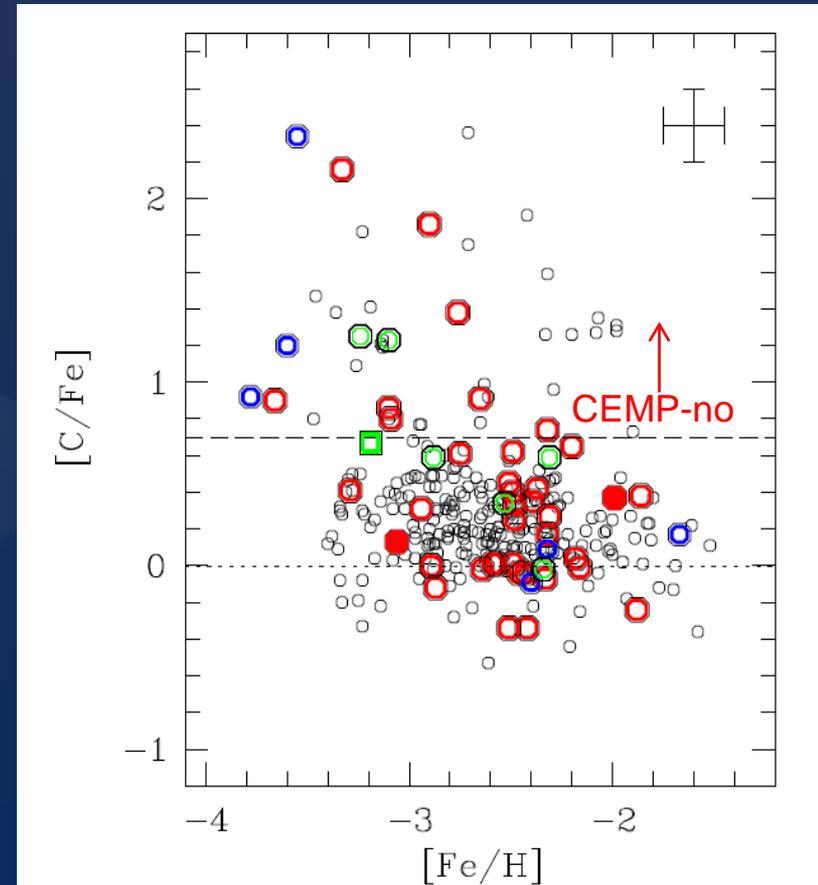
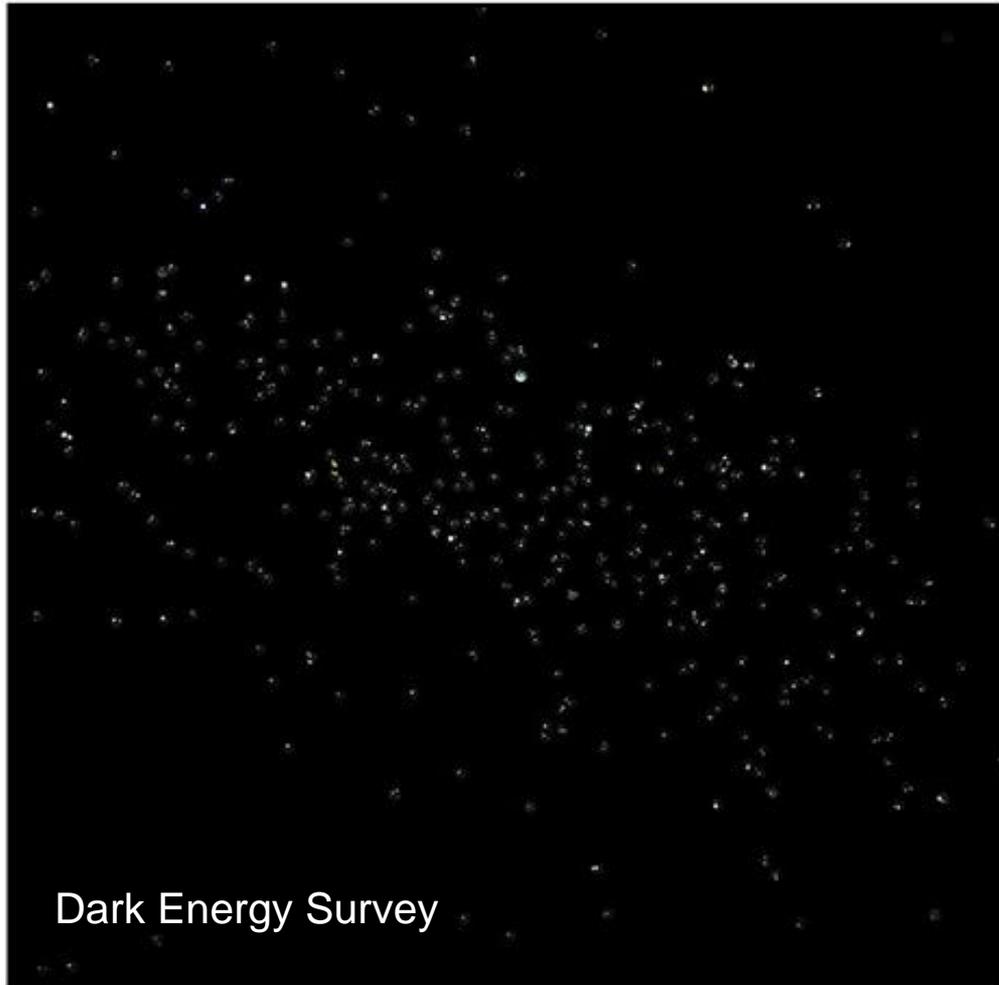


Figure courtesy Sarah Dietz

The Story So Far ...

- CEMP stars, in particular CEMP-no stars, appear **intimately related with documenting** the first generations of star formation in the early Universe
- CEMP stars may not be the full story, but perhaps a large part of it
 - Avenues for forming second-generation stars **without** large carbon over-abundances ?
- We need to learn how to **COUNT** better, as the frequency of CEMP-no vs. $[\text{Fe}/\text{H}]$ diagram is of **fundamental importance** for comparison with models of the early halo
- **The ENVIRONMENTS** in which CEMP-no stars formed can and probably DO provide **crucial constraining information** on the nature of the first star-forming entities in the Universe, perhaps something like currently observed UFD galaxies

But Where ? In the First Galaxies – The Ultra Faint Dwarfs



Frebel et al. (2016)

Attack of the Theoreticians - 2017/2018

Origins of carbon-enhanced metal-poor stars

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Metal-poor star formation triggered by the feedback effects from Pop III stars

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²*Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA*

CEMPLifying reionization

Mahavir Sharma^{*}, Tom Theuns & Carlos Frenk

Institute for Computational Cosmology, Department of Physics, Durham University,

Classification of extremely metal-poor stars: absent region in $A(C)$ - $[Fe/H]$ plane and the role of dust cooling

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Limits on Pop III star formation with the most iron-poor stars

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Descendants of the first stars: the distinct chemical signature of second generation stars

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Attack of the Theoreticians - 2017/2018

Seeding the second star: Enrichment from population III, dust evolution, and cloud collapse

Gen Chiaki^{1,2*} and John H. Wise¹

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New Neutron-Capture Site in Massive Pop III and Pop II Stars as a Source for Heavy Elements in the Early Galaxy

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s-Process in massive carbon-enhanced metal-poor stars

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⁵*Tsung-Dao Lee Institute, Shanghai 200240, China*

The neutron star merger GW170817 points to collapsars as the main r-process source

Daniel M. Siegel^{1;2}, Jennifer Barnes^{1;2}, Brian D. Metzger¹

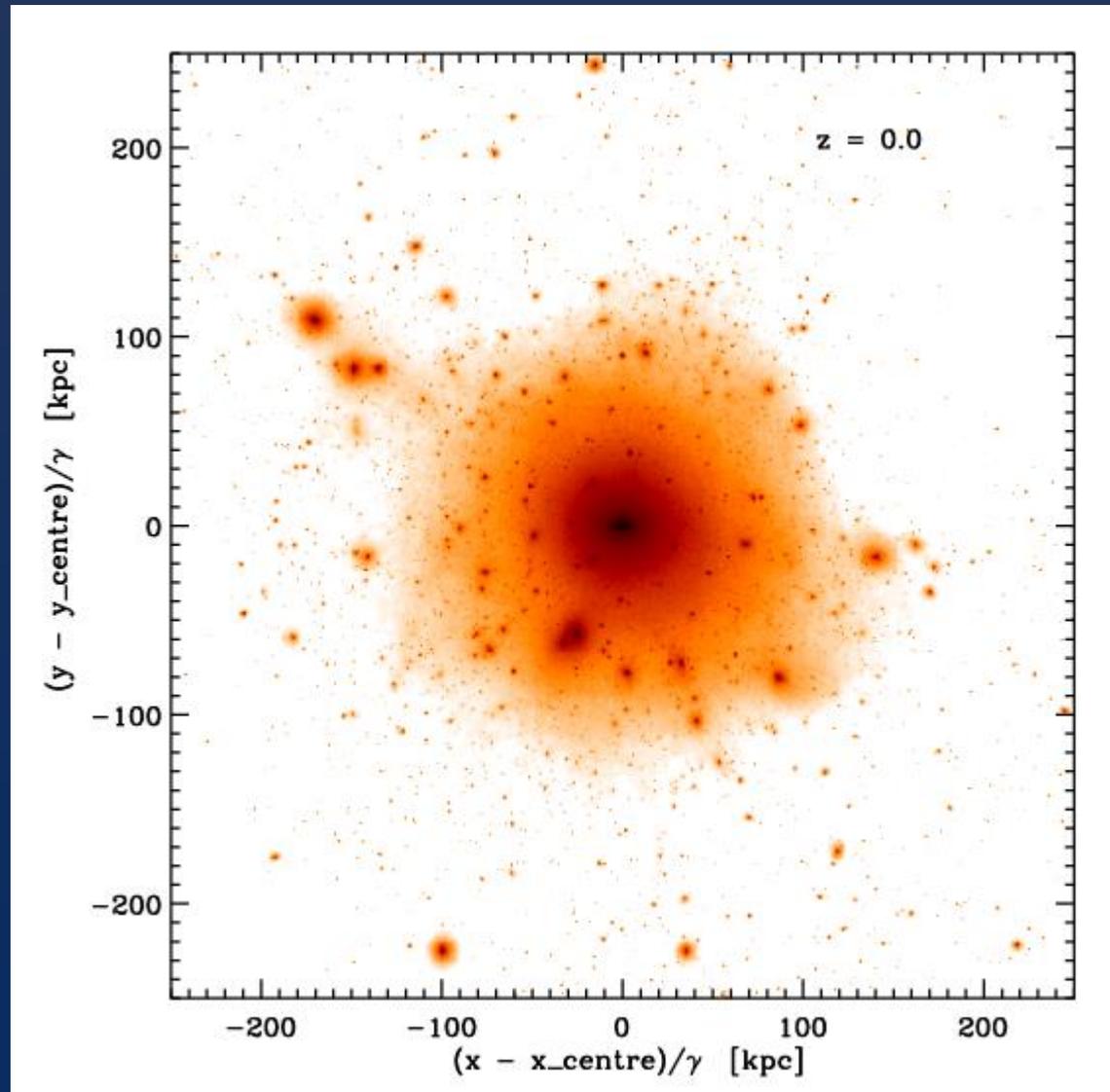
¹Department of Physics and Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

What Comes Next ?

- Large (unbiased) samples of CEMP stars observed with high-resolution spectroscopy (SALT -- ~200 so far, ~ 250 soon)
 - Sub-classification of CEMP stars – CEMP-r, CEMP-s, CEMP-i, CEMP-no
 - Frequencies of various sub-classes of CEMP stars
- Large (unbiased) samples of CEMP stars observed with medium-resolution spectroscopy (LAMOST / DESI / PFS / WEAVE / 4MOST)
 - Refined maps of spatial distribution of CEMP-s / CEMP-no stars
 - Refined frequency distributions of CEMP-s / CEMP-no stars
- Large (unbiased) samples of CEMP stars identified with photometric surveys (J-PLUS / S-PLUS)
 - Distant maps of spatial distribution of CEMP-s / CEMP-no stars
 - Matches with Gaia astrometry for kinematics
- Long-term radial-velocity monitoring of ALL subsets of CEMP stars (SOAR/STELLES would be ideal).

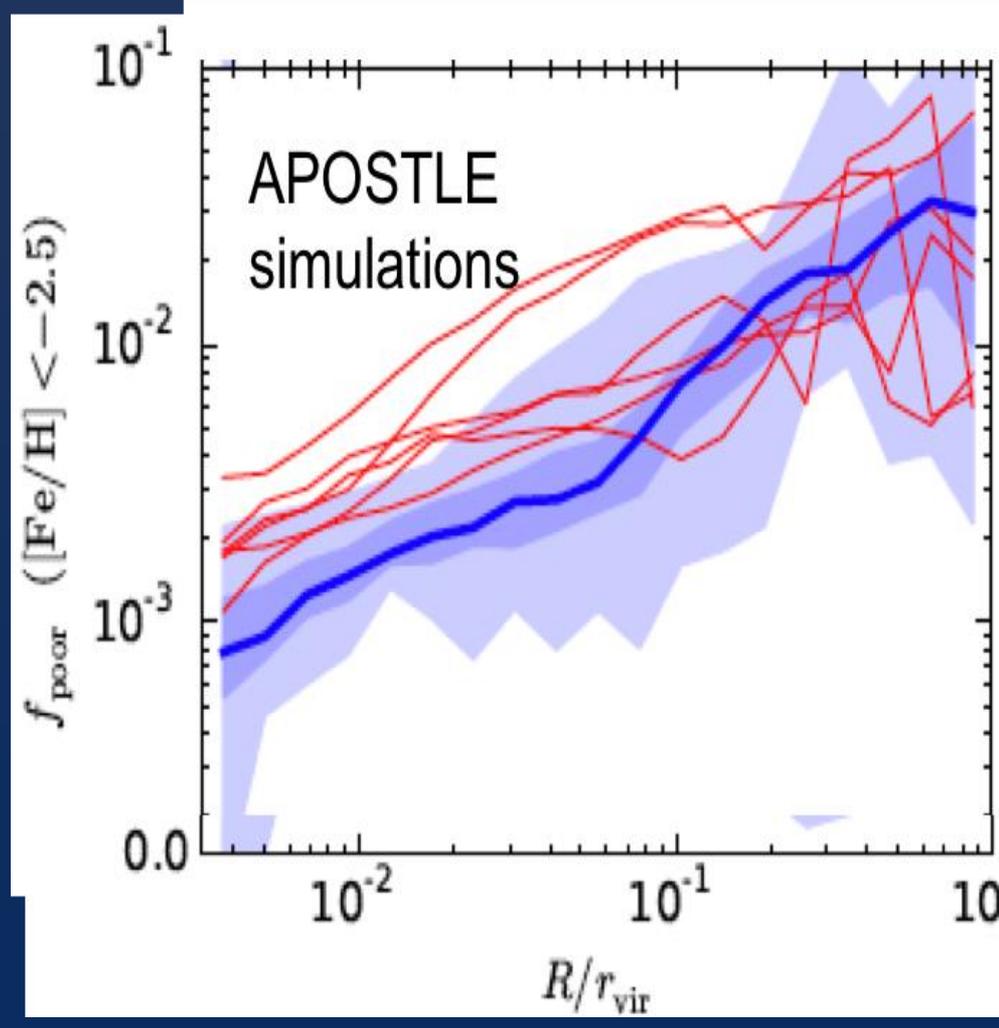
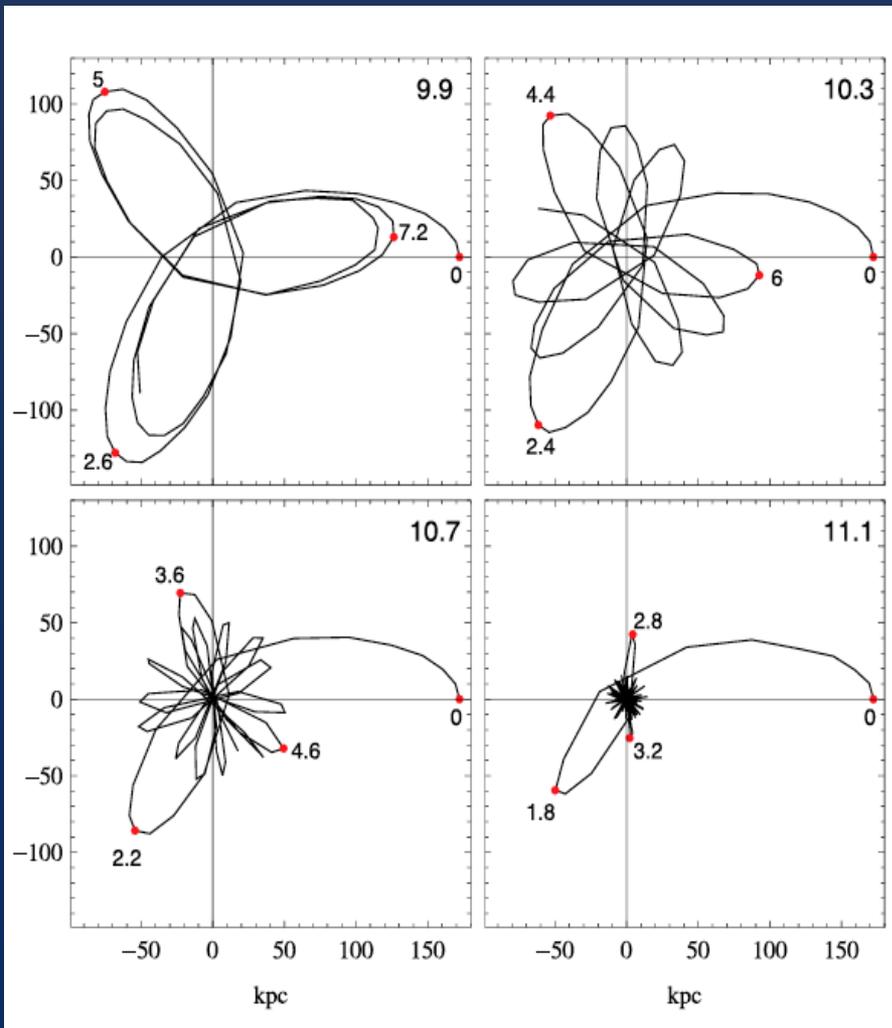
Assembly History of the Milky Way

- Initial collapse of a few high-mass mini-halos → **Inner Halo (G-E)**
- Prolonged accretions of lower mass mini-halos → **Outer Halo**
- Stars initially in bound mini-halos are disrupted → **distributed throughout the halo system**



Where are the UMP Stars Hiding?

Starckenburg+2016



Low-mass mini-halos **never penetrate** to deep inside the halo

Spectroscopic Surveys of the Halo

- HK Survey

$B_{\text{lim}} \sim 15.5$

Reach for giants

~ 15-20 kpc

- Hamburg/ESO

$B_{\text{lim}} \sim 17$

Reach for giants

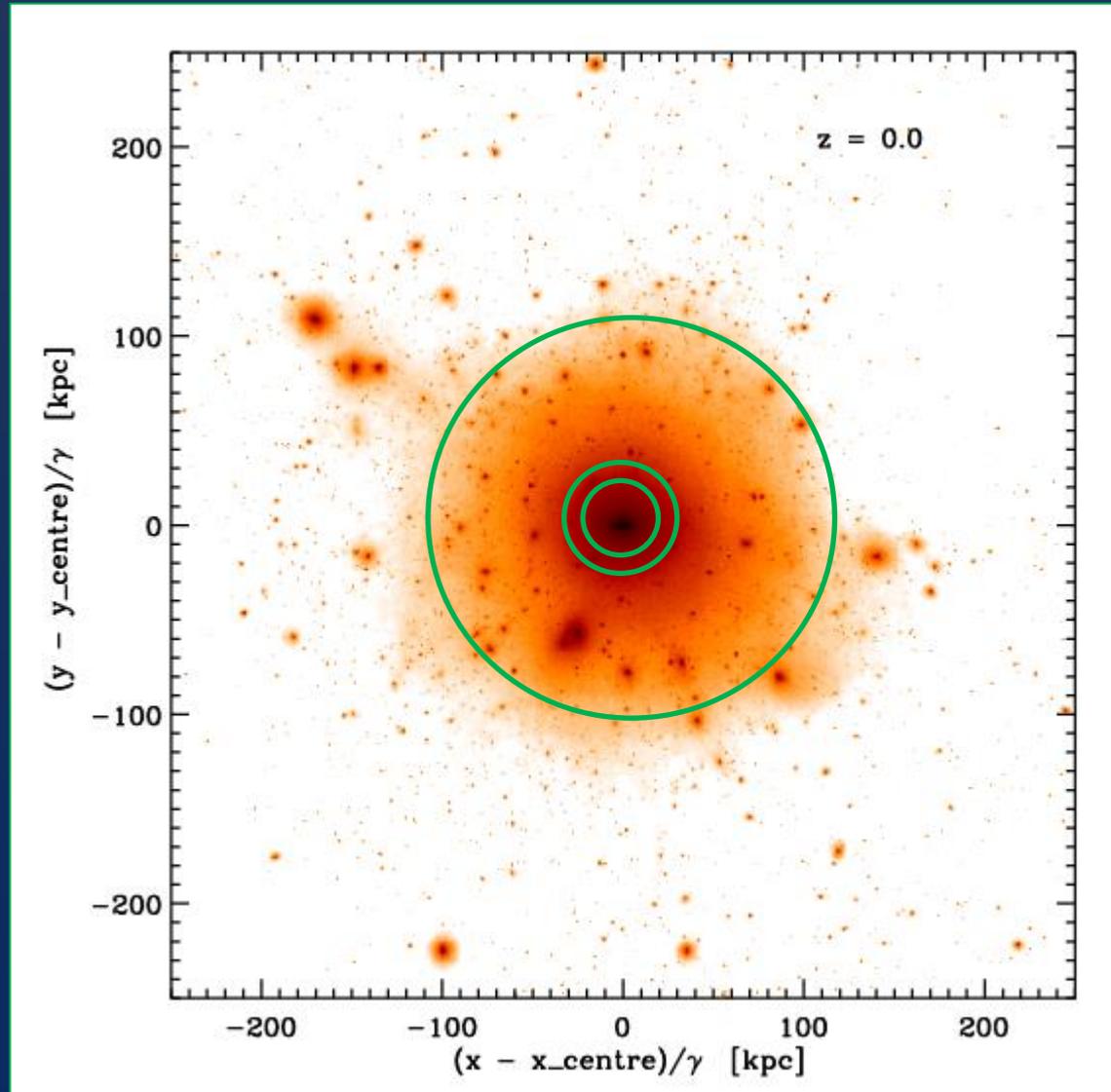
~ 25-30 kpc

- SDSS/SEGUE

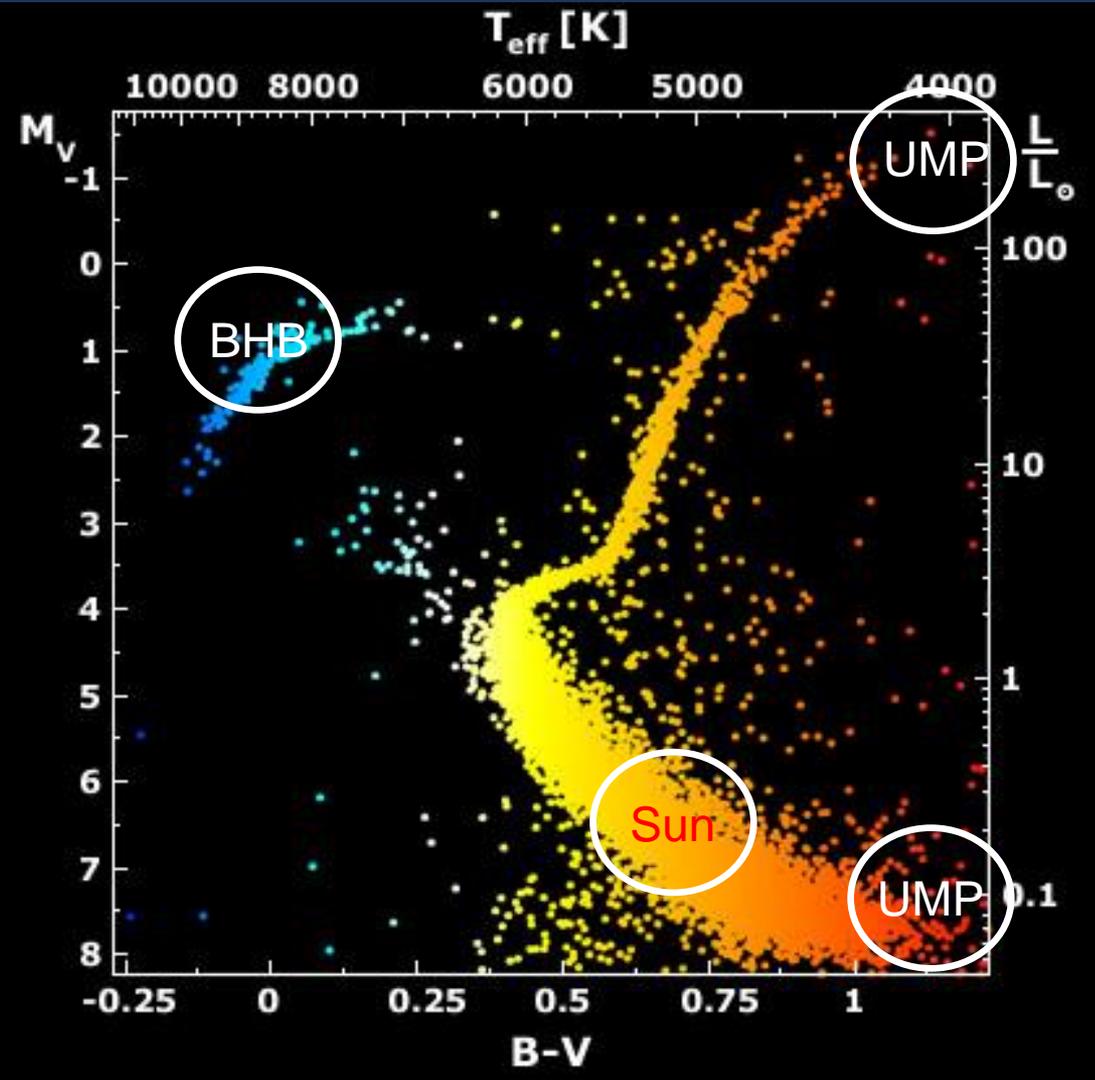
$B_{\text{lim}} \sim 20-22$

Reach for giants

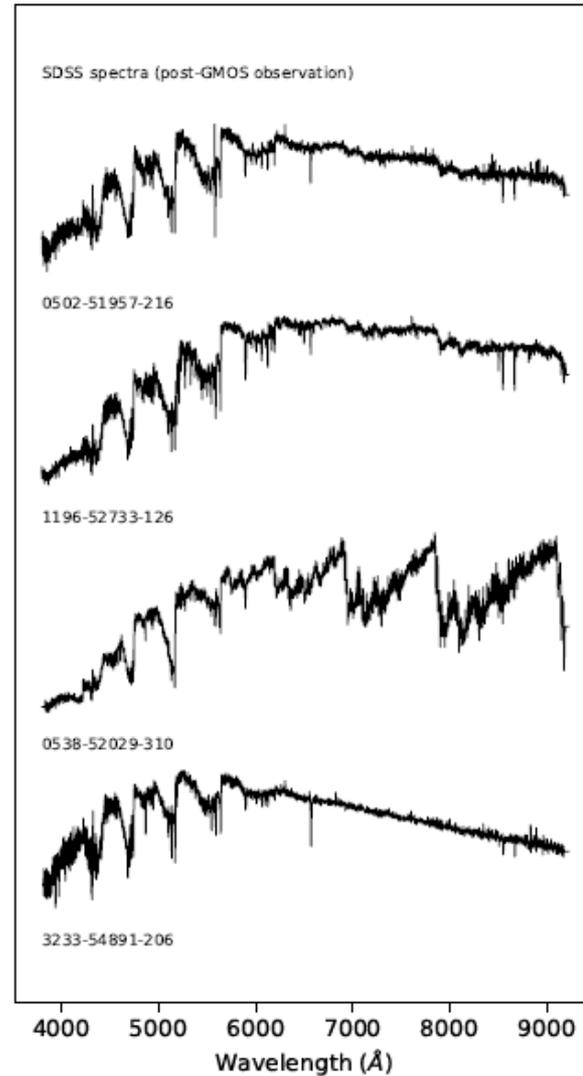
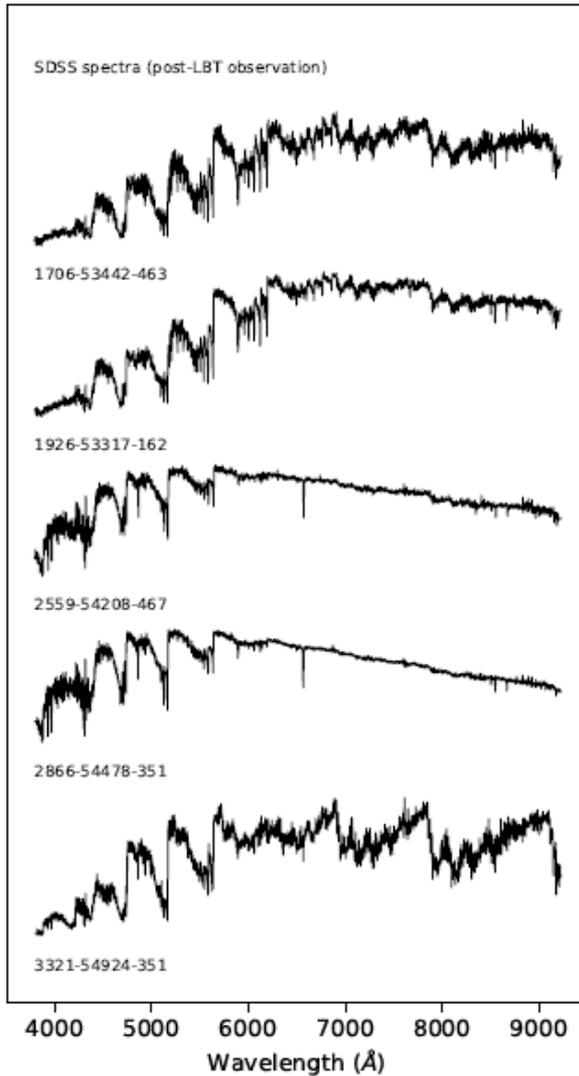
~ 100-150 kpc



Reality of the Color-Magnitude Diagram

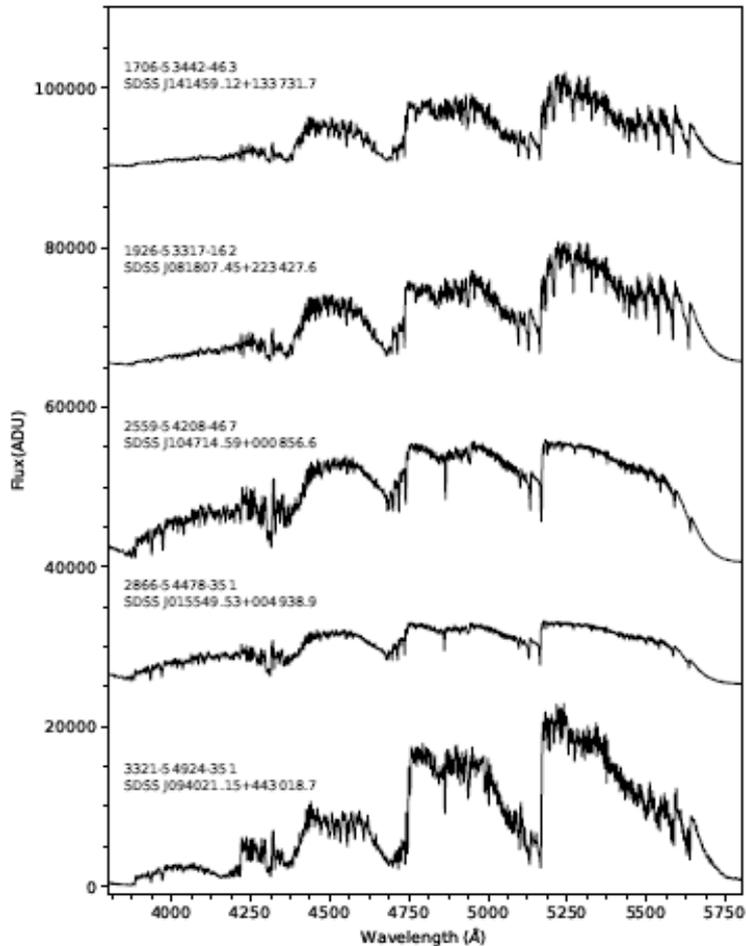


CEMP Stars , Near and Far

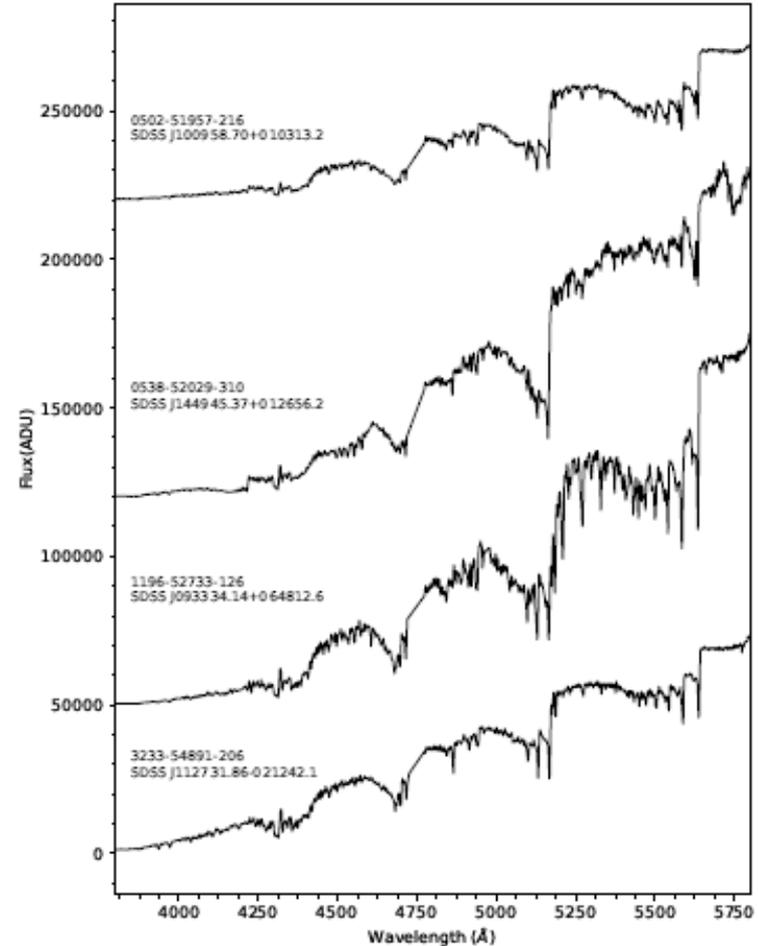


SDSS spectra of stars from Green (2013) – dCs or CEMP giants?

CEMP Stars, Near and Far

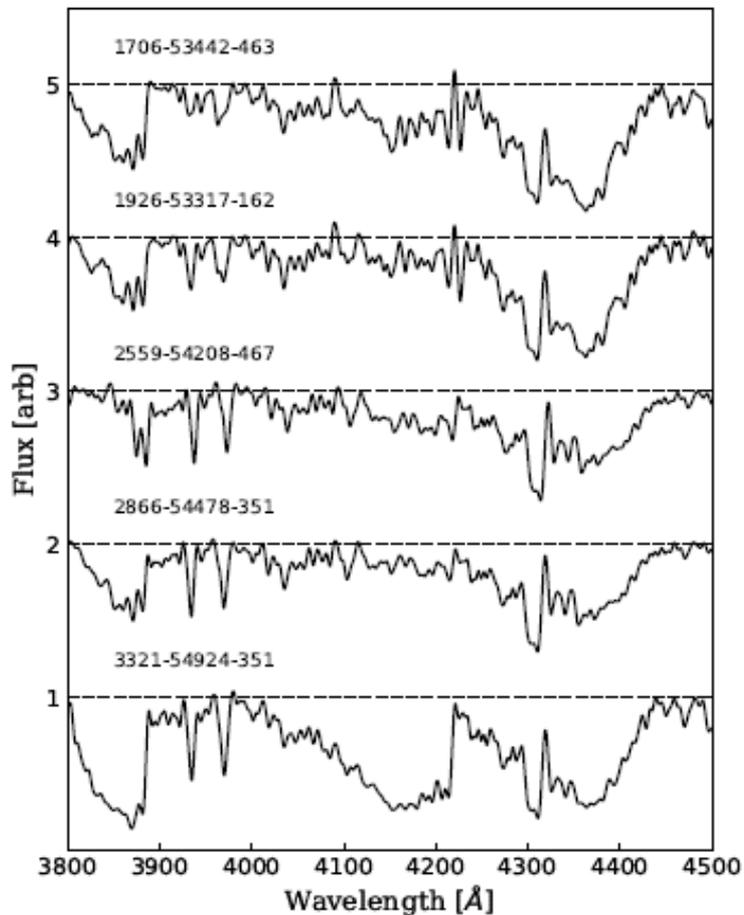


LBT/MODS Spectra

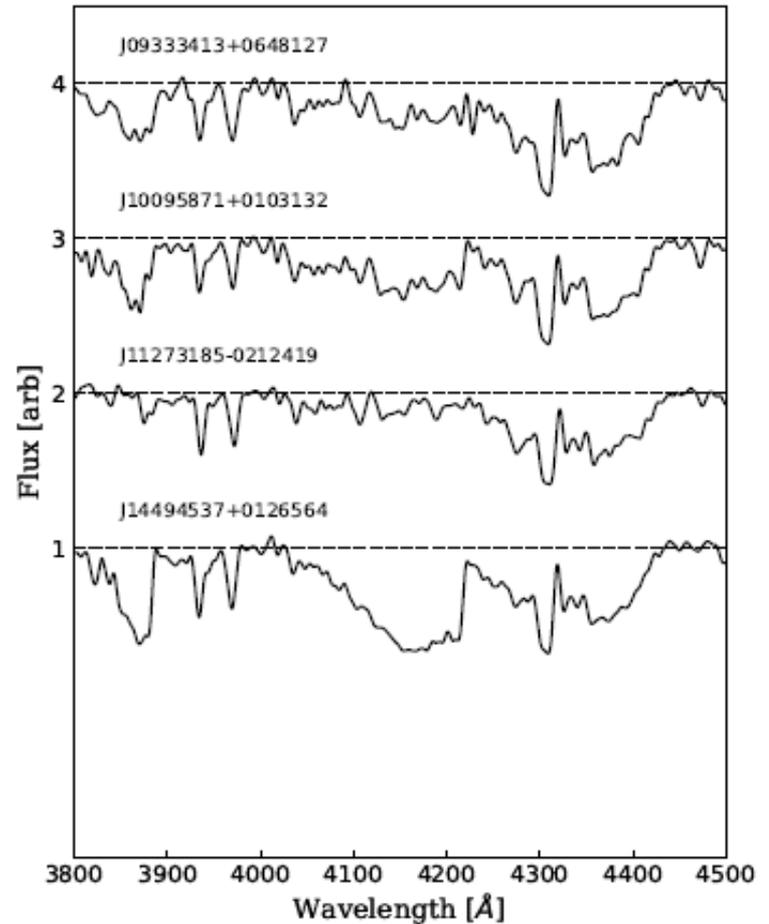


Gemini/GMOS Spectra

CEMP Stars, Near and Far



LBT/MODS Spectra



Gemini/GMOS Spectra

Yoon et al. (in prep)

CEMP Stars, Near and Far

	PID-MJD-FIBER	T_{eff} (K)	$\log g$ (cm/s^2)	[Fe/H]	[C/Fe]	A(C) ^a	Subclass ^b
★	0502-51957-216	4870	4.8	-4.03	2.84	7.24	Group III
★	0538-52029-310	4086	0.0	-4.00	2.78	7.21 (7.55)	Group III
★	1196-52733-126	4450	5.0	-3.82	2.66	7.27	Group III
★	1706-53442-463	3872	4.0	-4.50	2.80	6.23	Group II/III
★	1926-53317-162	4400	5.1	-5.00	4.14	7.57	Group III
★	2559-54208-467	4836	1.4	-3.82	3.41	8.02 (8.15)	Group I/III
★	2866-54478-351	4984	5.0	-4.02	3.37	7.78	Group I/III
★	3233-54891-206	4880	5.0	-3.59	2.48	7.32	Group I/III
★	3321-54924-351	4128	0.1	-3.80	2.56	7.19 (7.53)	Group III

Present best estimates of stellar parameters – stay tuned
Yoon et al. (in prep)

CEMP Stars as Probes of First-Star Nucleosynthesis, the IMF, and Galactic Assembly

September 9-13, 2019

University of Geneva
Geneva, Switzerland

Organizers: Georges Meynet
Raphael Hirschi
Timothy Beers

Joint Workshop: Univ. of Geneva,
ChETEC, JINA-CEE

EXTRA SLIDE – Group II, III Patterns

