# The Discovery and Importance of Carbon-Enhanced Metal-Poor Stars

Timothy C. Beers
University of Notre Dame

JINA–CEE

UNIVERSITY OF NOTRE DAME

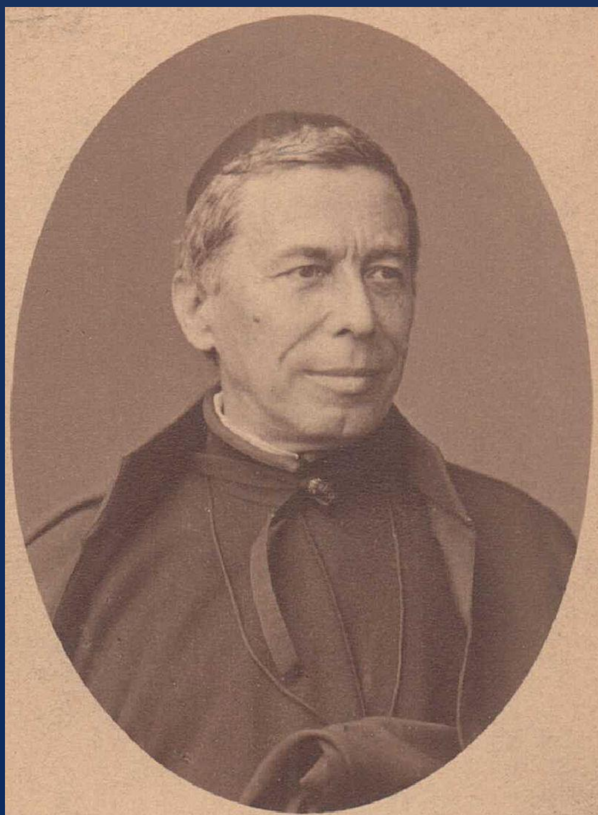
SDSS

# 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 (Myrs not Gyrs)
  - 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)

# Discovery of Carbon Stars

**The Carbon Stars—An Astrophysical Enigma**

WILLIAM P. BIDELMAN

This paper discusses our present knowledge of the objects which define the "carbon star problem". It is shown that these stars do not comprise a homogeneous group; the characteristics of three different types of "non-typical" carbon stars are summarized. Following a general discussion of the problem of the classification of the "typical" carbon stars, a number of special problems are considered, several of which present profitable fields for further research.

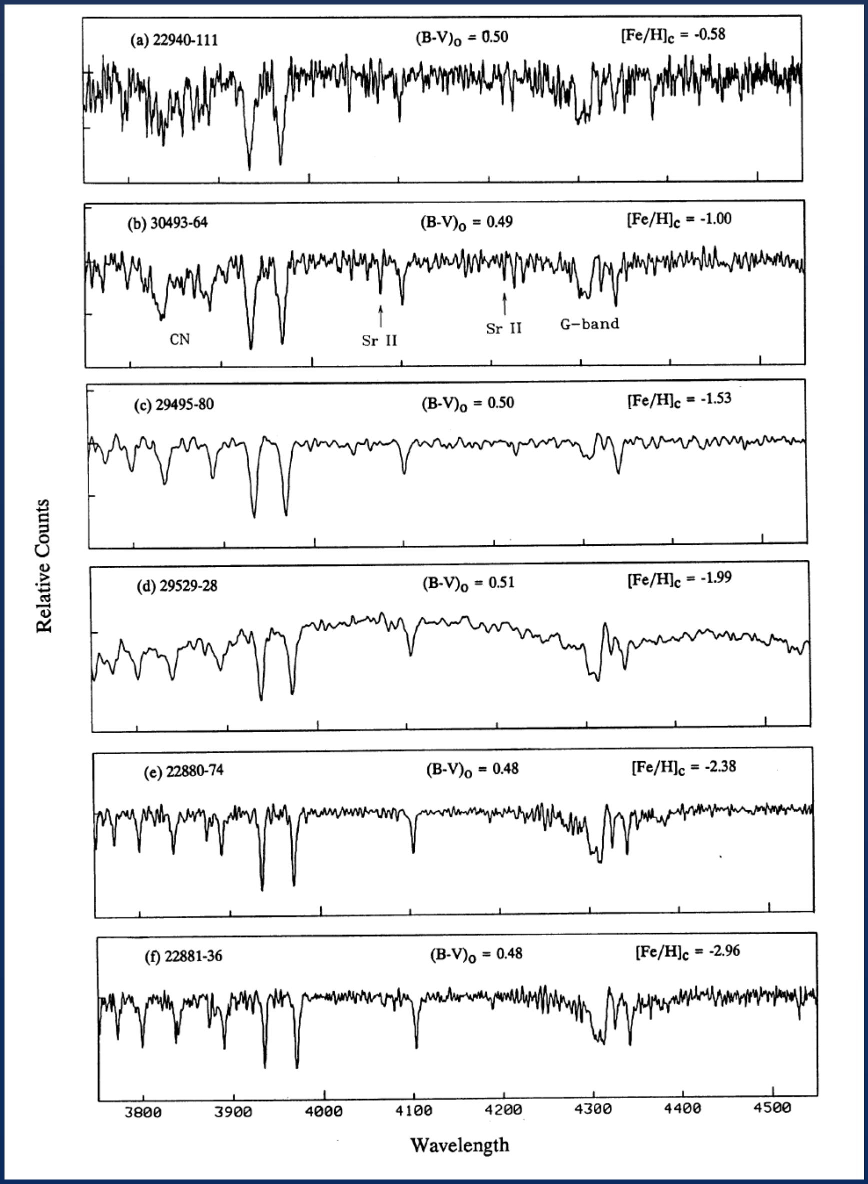
*(a) Carbon Stars Apparently Deficient in Hydrogen*

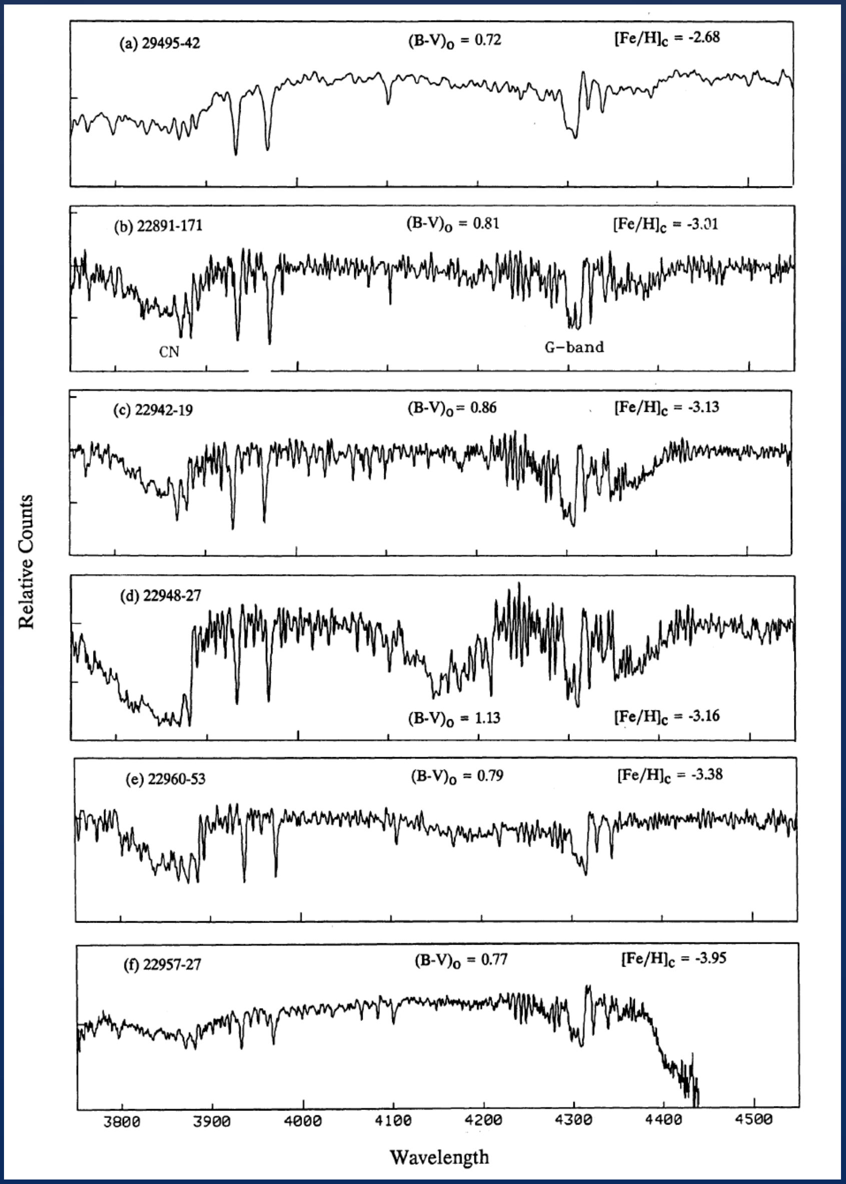
*(b) CH Stars* –1.5 < [Fe/H] < 0.0; high velocity; s-process elements

*(c) Ba* II *Stars* –0.5 < [Fe/H] < 0.0; low velocity; s-process elements

W.P. Bidelman (1956)

# Discovery of CEMP Stars

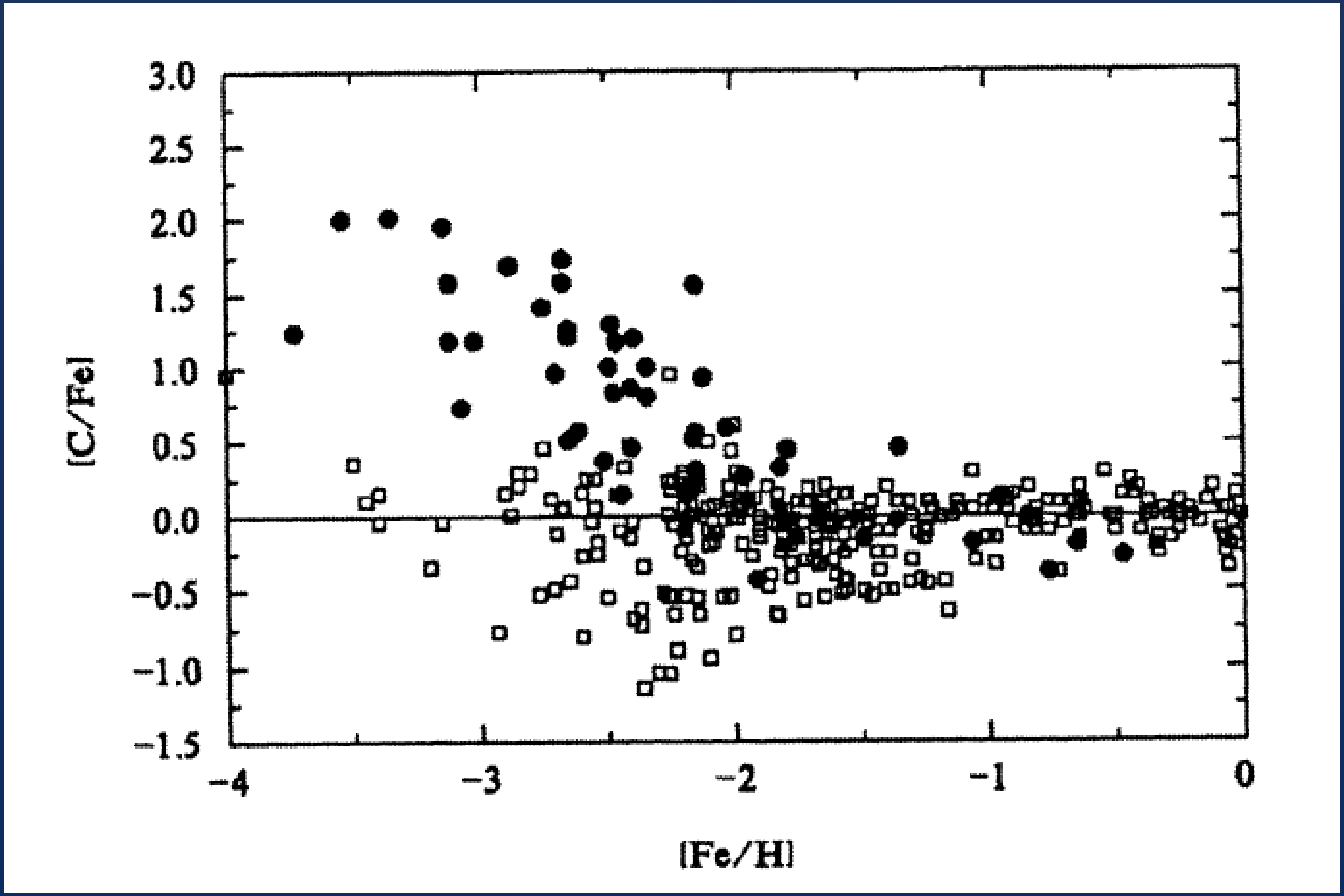



[Fe/H < -2.0; high velocity; unknown n-capture

Beers et al. (1992)

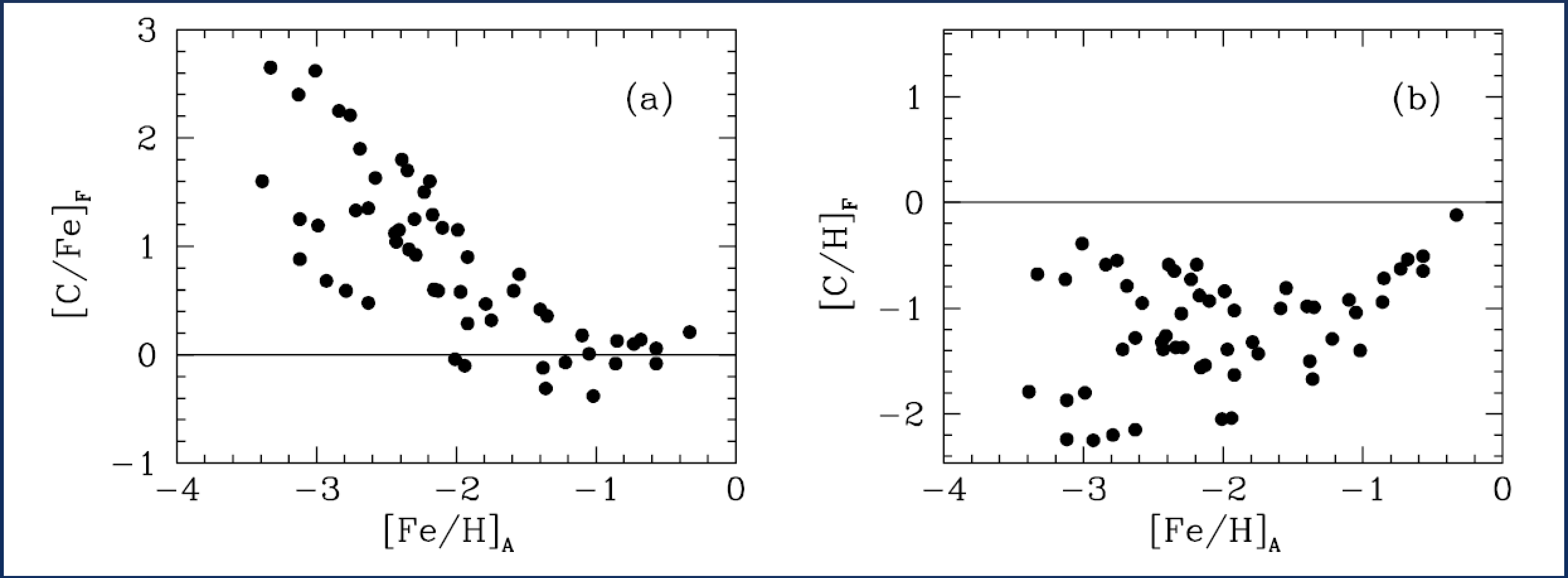
# CEMP Frequency / Level of [C/Fe]




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

Rossi et al. (1999)

# Refined Estimates of [C/Fe] for BPS Strong G-band Stars




Apparent Split of [C/Fe] and [C/H] for [Fe/H] < -2.0

Rossi et al. (2005)

# The Plot Thickens – Early High-Resolution Abundances

THE CHEMICAL COMPOSITION OF CARBON-RICH, VERY METAL POOR STARS: A NEW CLASS OF MILDLY CARBON RICH OBJECTS WITHOUT EXCESS OF NEUTRON-CAPTURE ELEMENTS

Wako Aoki,[1] John E. Norris,[2] Sean G. Ryan,[3] Timothy C. Beers,[4] and Hiroyasu Ando[1]

*Received 2001 September 14 ; accepted 2001 November 16*

EXTREMELY METAL-POOR STARS. IX. CS 22949-037 AND THE ROLE OF HYPERNOVAE

John E. Norris
Research School of Astronomy and Astrophysics, Australian National University, Mount Stromlo Observatory, Cotter Road, Weston ACT 2611, Australia; jen@mso.anu.edu.au
Sean G. Ryan
Department of Physics and Astronomy, Open University, Walton Hall, Milton Keynes MK7 6AA, UK; s.g.ryan@open.ac.uk
Timothy C. Beers
Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1116; beers@pa.msu.edu
and
Wako Aoki and Hiroyasu Ando
National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan; aoki.wako@nao.ac.jp, ando@optik.mtk.nao.ac.jp
*Received 2002 February 5; accepted 2002 March 13; published 2002 March 21*

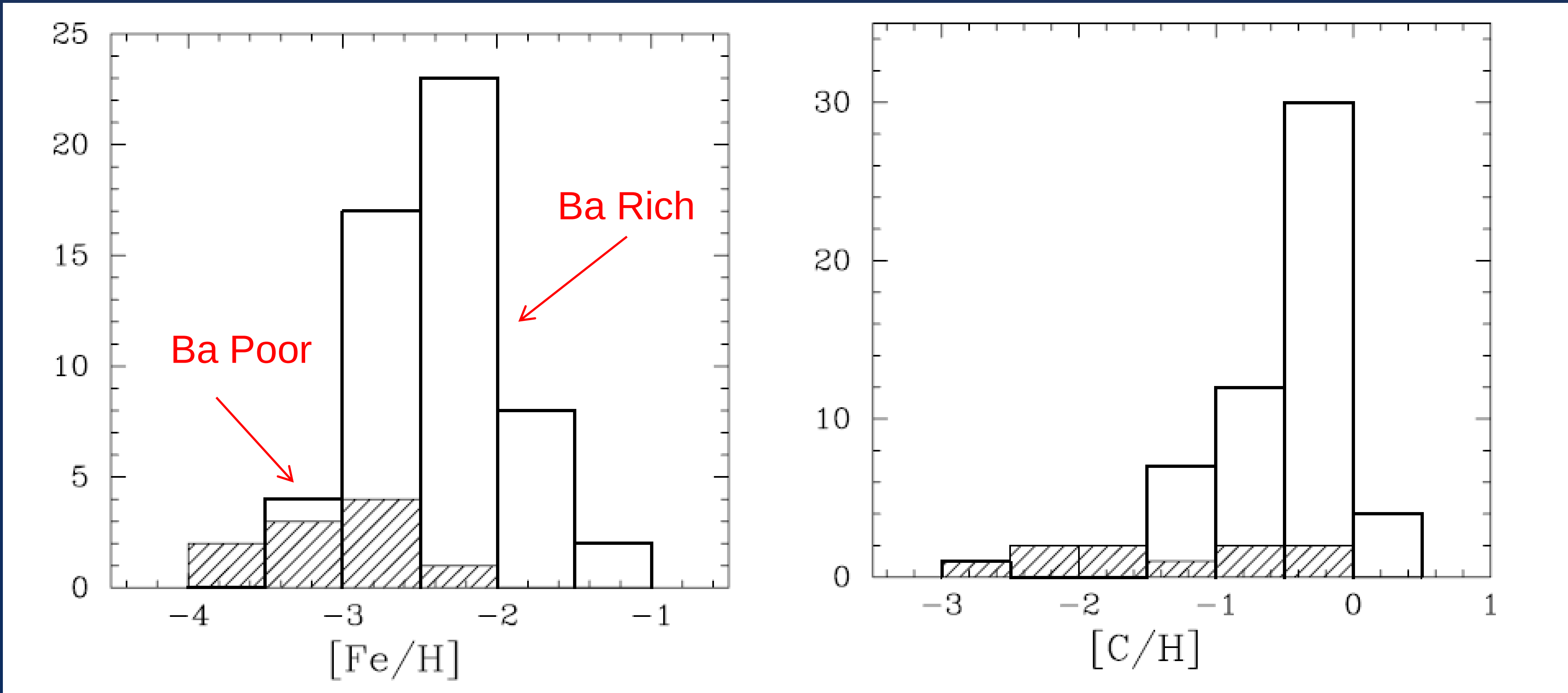
THE ORIGINS OF TWO CLASSES OF CARBON-ENHANCED, METAL-POOR STARS

Sean G. Ryan,[1] Wako Aoki,[2] John E. Norris,[3] and Timothy C. Beers[4]

*Received 2003 September 18; accepted 2005 August 17*

Aoki et al. (2002); Norris et al. (2002); Ryan et al. (2005)

# Larger Samples of CEMP Stars with High-Resolution Abundances




Clear Distinctions Between Ba-poor and Ba-rich Stars

Aoki et al. (2007)

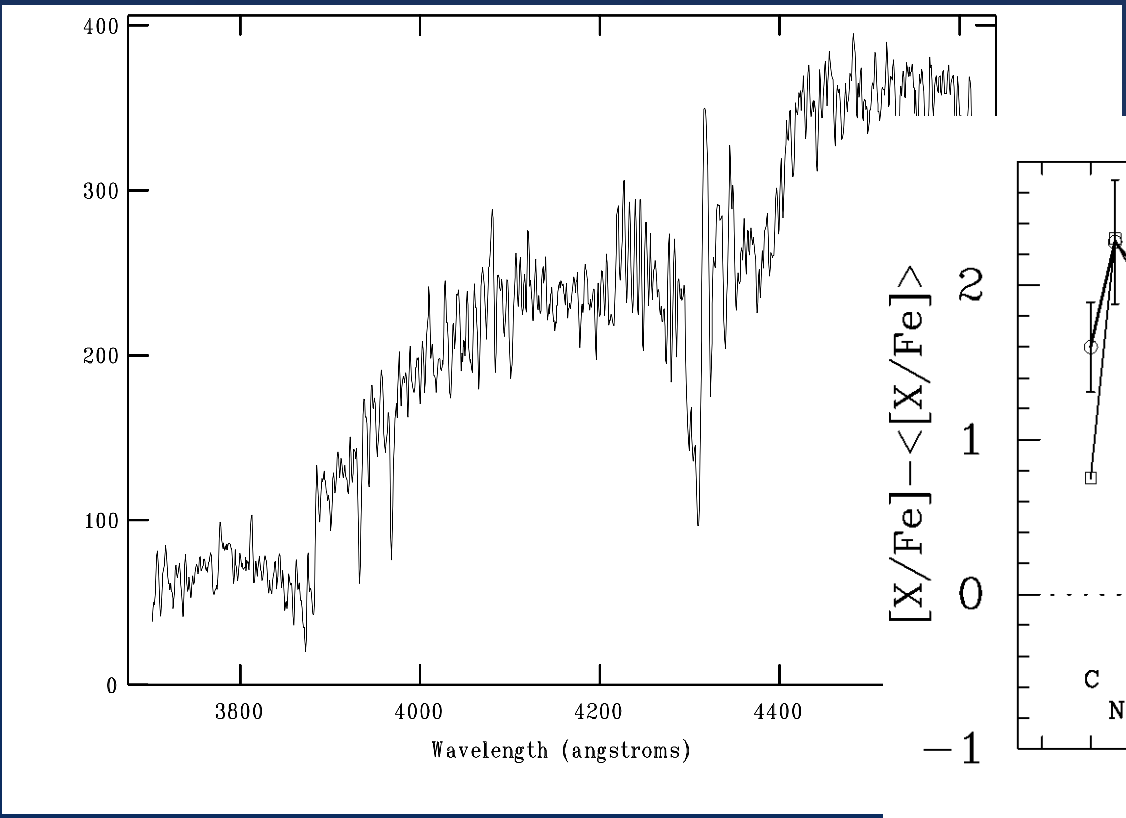
# Exploration of Nature's Laboratory for Neutron-Capture Processes

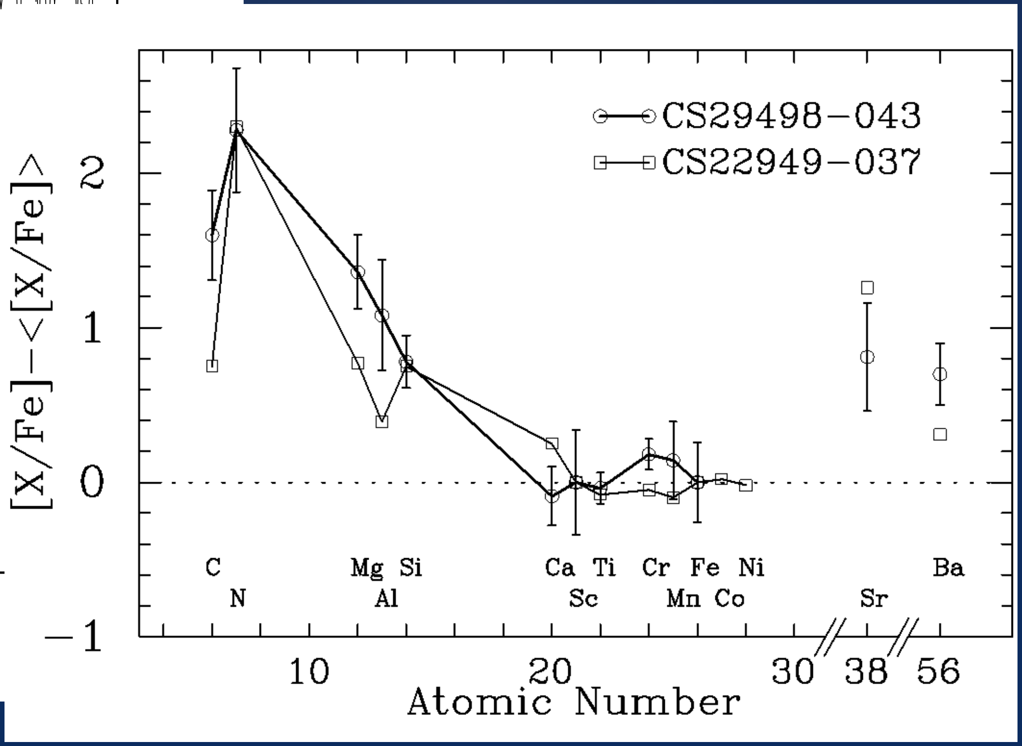
| | |
|---|---|
| **Neutron-capture-rich stars** | |
| r-I | $0.3 \leq [Eu/Fe] \leq +1.0$ and $[Ba/Eu] < 0$ |
| r-II | $[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0$ |
| s | $[Ba/Fe] > +1.0$ and $[Ba/Eu] > +0.5$ |
| r/s | $0.0 < [Ba/Eu] < +0.5$ |
| **Carbon-enhanced metal-poor stars** | |
| CEMP | $[C/Fe] > +1.0$ |
| CEMP-r | $[C/Fe] > +1.0$ and $[Eu/Fe] > +1.0$ |
| CEMP-s | $[C/Fe] > +1.0$, $[Ba/Fe] > +1.0$, and $[Ba/Eu] > +0.5$ |
| CEMP-r/s | $[C/Fe] > +1.0$ and $0.0 < [Ba/Eu] < +0.5$ |
| CEMP-no | $[C/Fe] > +1.0$ and $[Ba/Fe] < 0$ |

Beers & Christlieb ARAA (2005)

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

CS 29498-043: [Fe/H] = -3.8; [C/Fe] = +1.9

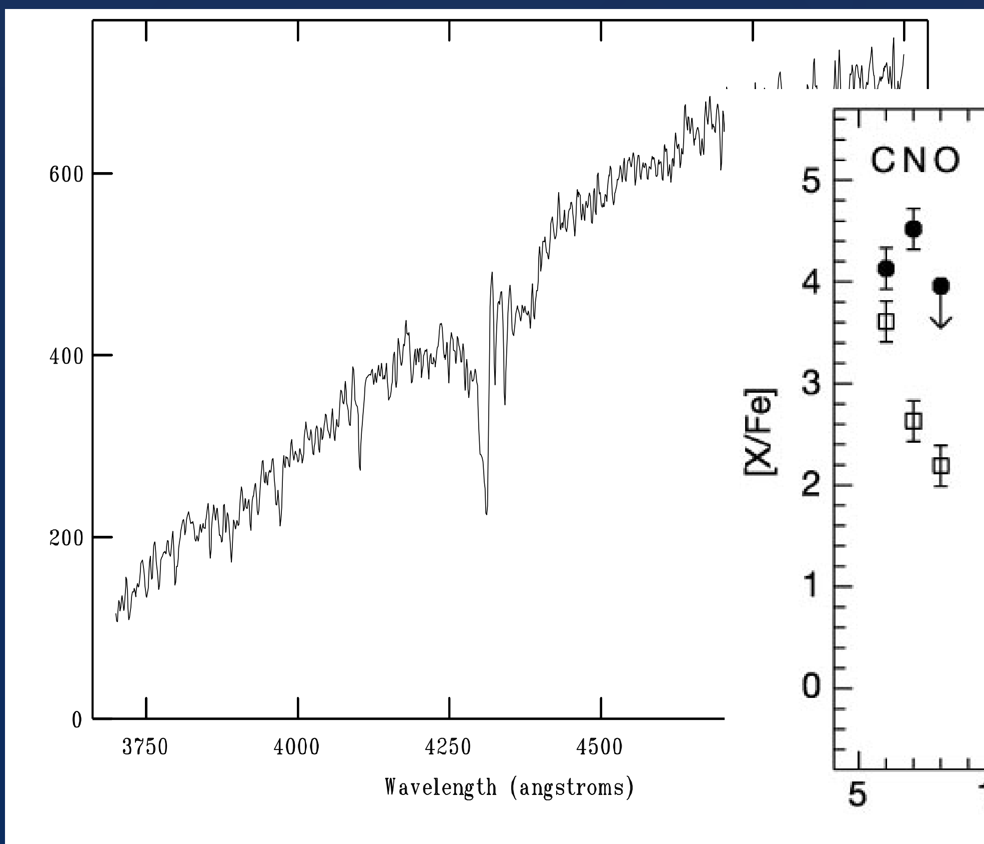


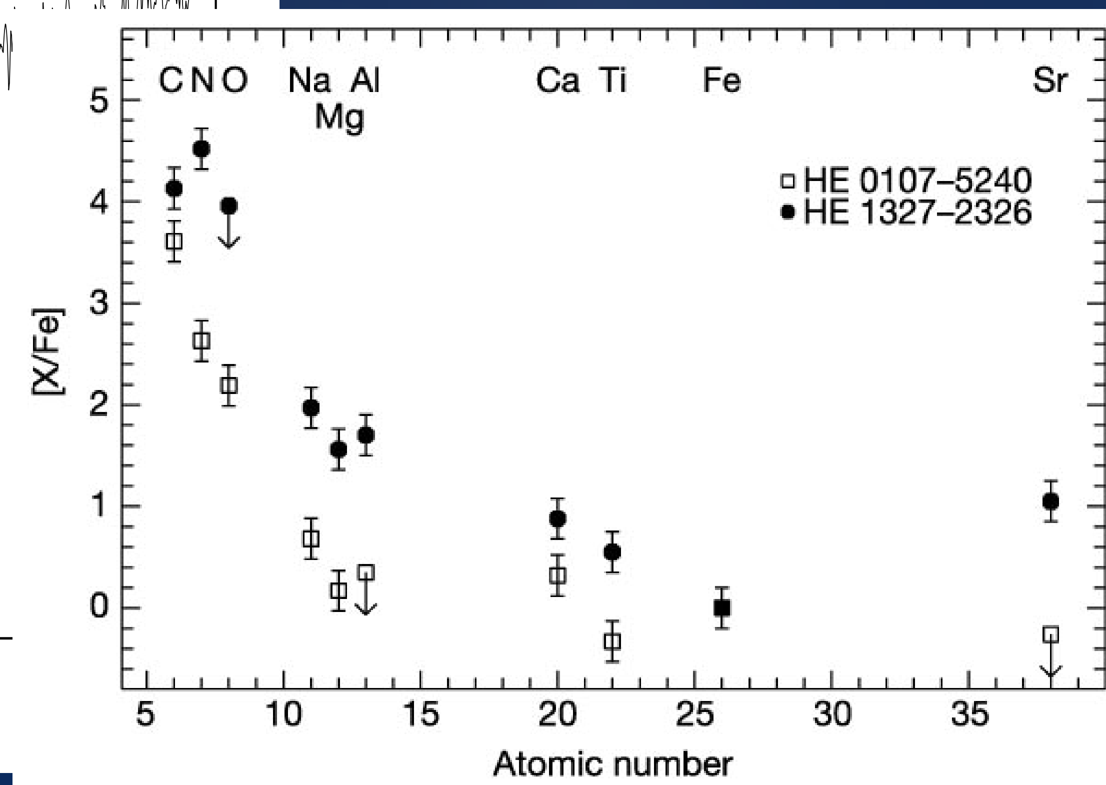




Harbingers of Things to Come!

# Last but Definitely NOT Least… (Christlieb et al. 2002; Frebel et al. 2005)

HE 0107-5240 [Fe/H] = -5.3 [C/Fe] = +3.9




It is the SAME pattern among the light elements !

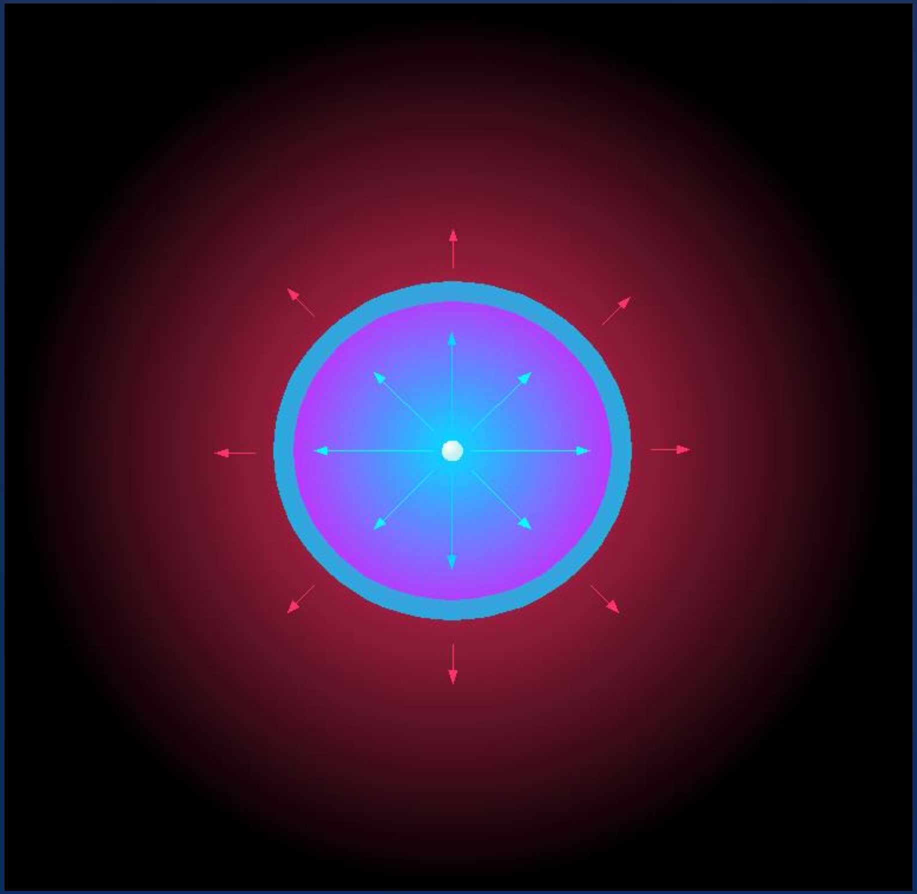
# RV Monitoring – Hansen et al. (2016): CEMP-s and CEMP-r/s (i) → Binary Fraction ~ 82%

| Stellar ID | $N_{obs}$ | Template | $RV_{mean}$ (km $s^{-1}$) | $\sigma$ (km $s^{-1}$) | $\Delta T$ (Days) | $P(\chi^2)$ | Binary |
|---|---|---|---|---|---|---|---|
| CEMP-*s* | | | | | | | |
| HE 0002−1037 | 10 | Co-add | −31.295 | 5.957 | 1066 | 0.000 | Yes |
| HE 0111−1346 | 9 | Strongest | +40.920 | 8.404 | 1044 | 0.000 | Yes |
| HE 0151−0341 | 11 | Co-add | −35.685 | 9.136 | 1012 | 0.000 | Yes |
| HE 0206−1916 | 9 | Co-add | −199.536 | 0.121 | 1044 | 0.233 | No |
| HE 0319−0215 | 16 | Co-add | −225.782 | 2.357 | 2207 | 0.000 | Yes |
| HE 0430−1609 | 16 | Co-add | +231.821 | 1.727 | 1184 | 0.000 | Yes |
| HE 0441−0652 | 16 | Co-add | −30.647 | 2.655 | 2371 | 0.000 | Yes |
| HE 0507−1430 | 11 | Strongest | +44.802 | 7.920 | 1064 | 0.000 | Yes |
| HE 0507−1653 | 15 | Co-add | +348.280 | 4.859 | 2124 | 0.000 | Yes |
| HE 0854+0151 | 15 | Co-add | +138.297 | 7.798 | 1757 | 0.000 | Yes |
| HE 0959−1424 | 17 | HE 0507−1653 | +343.379 | 0.655 | 2736 | 0.000 | Yes |
| HE 1031−0020 | 22 | Co-add | +68.660 | 1.157 | 2923 | 0.000 | Yes |
| HE 1045+0226 | 6 | HE 0507−1653 | +131.498 | 0.280 | 803 | 0.223 | No |
| CS 30301−015 | 18 | Co-add | +86.607 | 0.077 | 2234 | 0.883 | No |
| HE 1046−1352 | 12 | Strongest | +79.471 | 21.250 | 1812 | 0.000 | Yes |
| HE 1523−1155 | 9 | Co-add | −42.607 | 3.781 | 502 | 0.000 | Yes |
| HE 2201−0345 | 27 | Co-add | −55.927 | 3.525 | 2943 | 0.000 | Yes |
| HE 2312−0758 | 11 | Co-add | +32.981 | 3.176 | 1066 | 0.000 | Yes |
| HE 2330−0555 | 17 | Co-add | −235.124 | 0.231 | 2573 | 0.543 | No |
| CEMP-*r/s* | | | | | | | |
| HE 0017+0055 | 28 | Strongest | −80.219 | 1.168 | 2943 | 0.000 | Yes |
| HE 0039−2635 | 2 | Strongest | −47.739 | 6.136 | 278 | 0.000 | Yes |
| LP 625−44 | 28 | Co-add | +35.036 | 3.348 | 2667 | 0.000 | Yes |

# RV Monitoring – Hansen et al. (2016): CEMP-no → Binary Fraction ~ 17%

| Star | N obs | Delta T | Template | mean Rv | $\sigma$ | Binary |
|---|---|---|---|---|---|---|
| BD+44°493 | 18 | 1190 | Coadd | −150.08 | 0.05 | No |
| BS 16292−005 | 9 | 769 | Delta | −50.62 | 0.56 | No |
| CS 22166−016 | 7 | 765 | Coadd | −209.77 | 0.16 | No |
| CS 22877−001 | 16 | 2923 | Coadd | +166.30 | 0.11 | No |
| CS 22878−027 | 5 | 952 | BD+44°493 | −91.32 | 0.84 | No |
| CS 22949−037 | 7 | 765 | BD+44°493 | −125.56 | 0.27 | No |
| CS 22957−027 | 19 | 1567 | Coadd | −67.30 | 5.74 | Yes |
| CS 29498−043 | 18 | 2602 | Delta | −32.48 | 0.70 | No |
| CS 29502−092 | 21 | 2602 | Coadd | −67.21 | 0.09 | No |
| CS 29527−015 | 6 | 751 | BD+44°493 | +47.08 | 0.48 | No |
| HE 0020−1741 | 8 | 794 | Coadd | +93.02 | 0.24 | No |
| HE 0219−1739 | 15 | 2207 | Coadd | +106.69 | 5.09 | Yes |
| HE 0405−0526 | 12 | 828 | Coadd | +165.66 | 0.04 | No |
| HE 1012−1540 | 8 | 802 | Delta | +226.36 | 0.74 | No |
| HE 1135−0800 | 5 | 836 | Delta | +106.70 | 0.75 | No |
| HE 1146−1126 | 4 | 456 | BD+44°493 | +241.02 | 0.76 | No |
| HE 1150−0428 | 14 | 2220 | Strongest | +48.04 | 8.35 | Yes |
| HE 1201−1512 | 5 | 420 | Delta | +239.45 | 1.85 | No |
| HE 1300−0641 | 2 | 381 | Delta | +68.82 | 0.09 | No |
| HE 1300+0157 | 4 | 386 | BD+44°493 | +74.63 | 0.76 | No |
| HE 1302−0954 | 3 | 386 | BD+44°493 | +32.54 | 0.04 | No |
| HE 1327−2326 | 12 | 2577 | Delta | +64.34 | 1.17 | No |
| HE 1410+0213 | 22 | 2923 | Coadd | +81.14 | 0.17 | Yes |
| HE 1506−0113 | 6 | 339 | BD+44°493 | +83.92 | 2.01 | Yes |
| HE 2318−1621 | 6 | 766 | BD+44°493 | −41.67 | 0.29 | No |

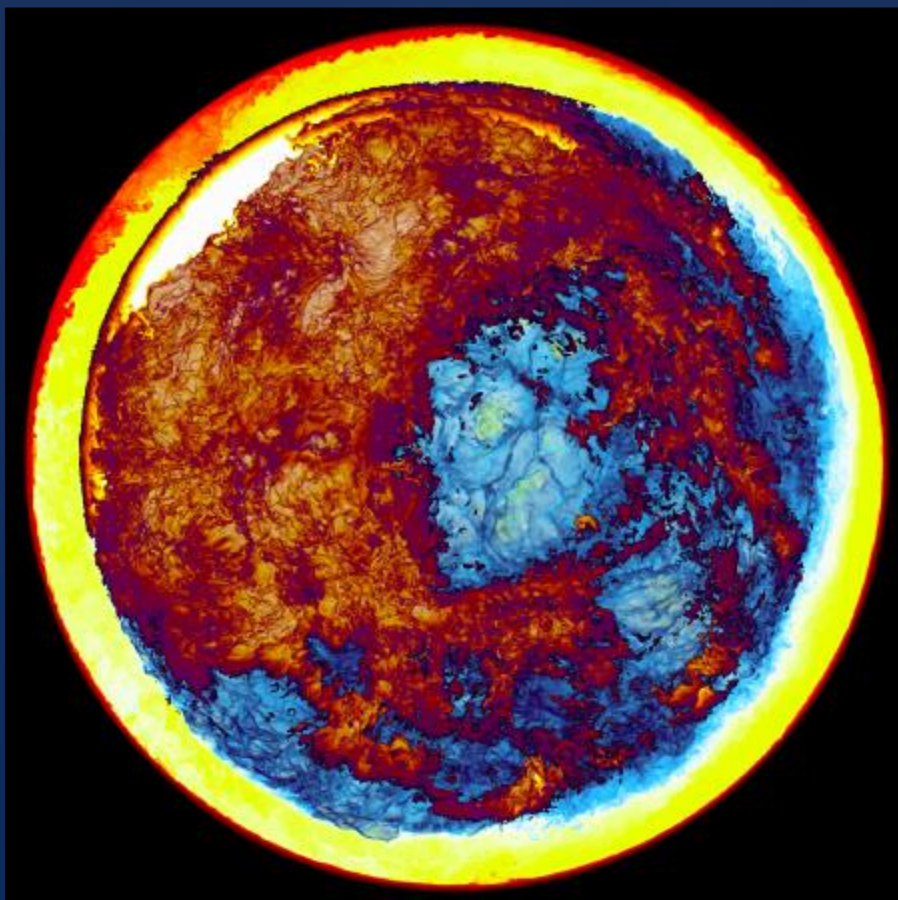
# In Pictures – Low to Intermediate Mass AGB Stars and Mass Transfer → CEMP-s



1 < M/Mo < 4

Receiving Star

# In Pictures – High Mass AGB Stars? and Mass Transfer → CEMP-i



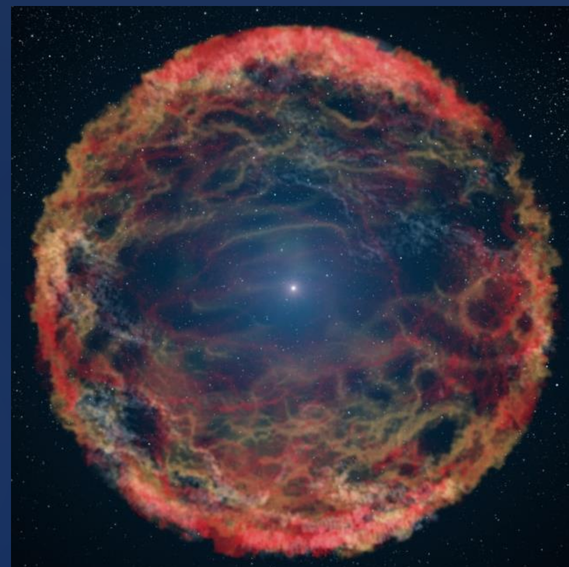
4 < M/Mo < 9

Receiving Star

# In Pictures – Moderate Mass Type II SNe with Mixing and Fallback → CEMP-no

Umeda
Tominaga
Nomoto

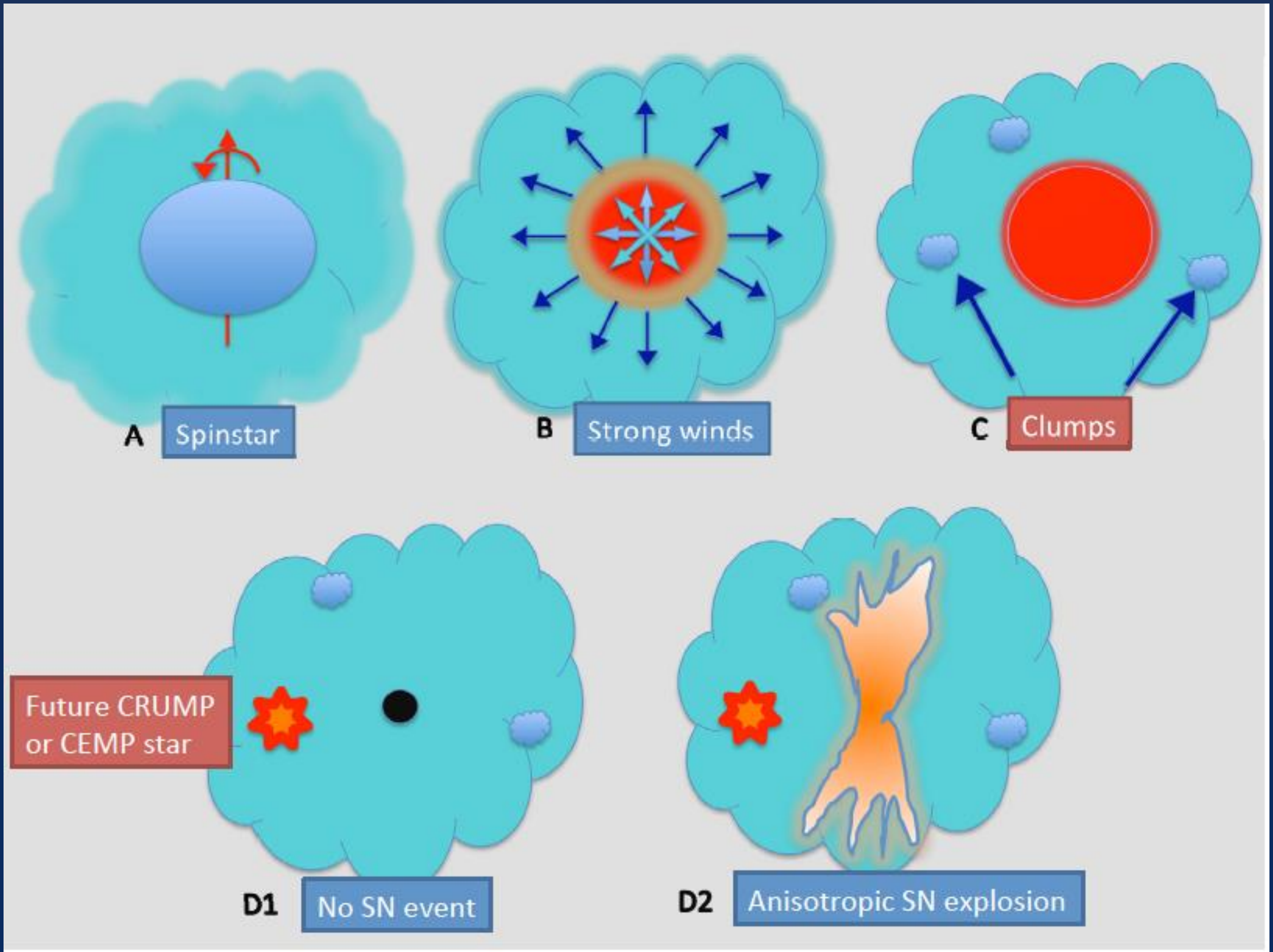
15 < M/Mo < 50



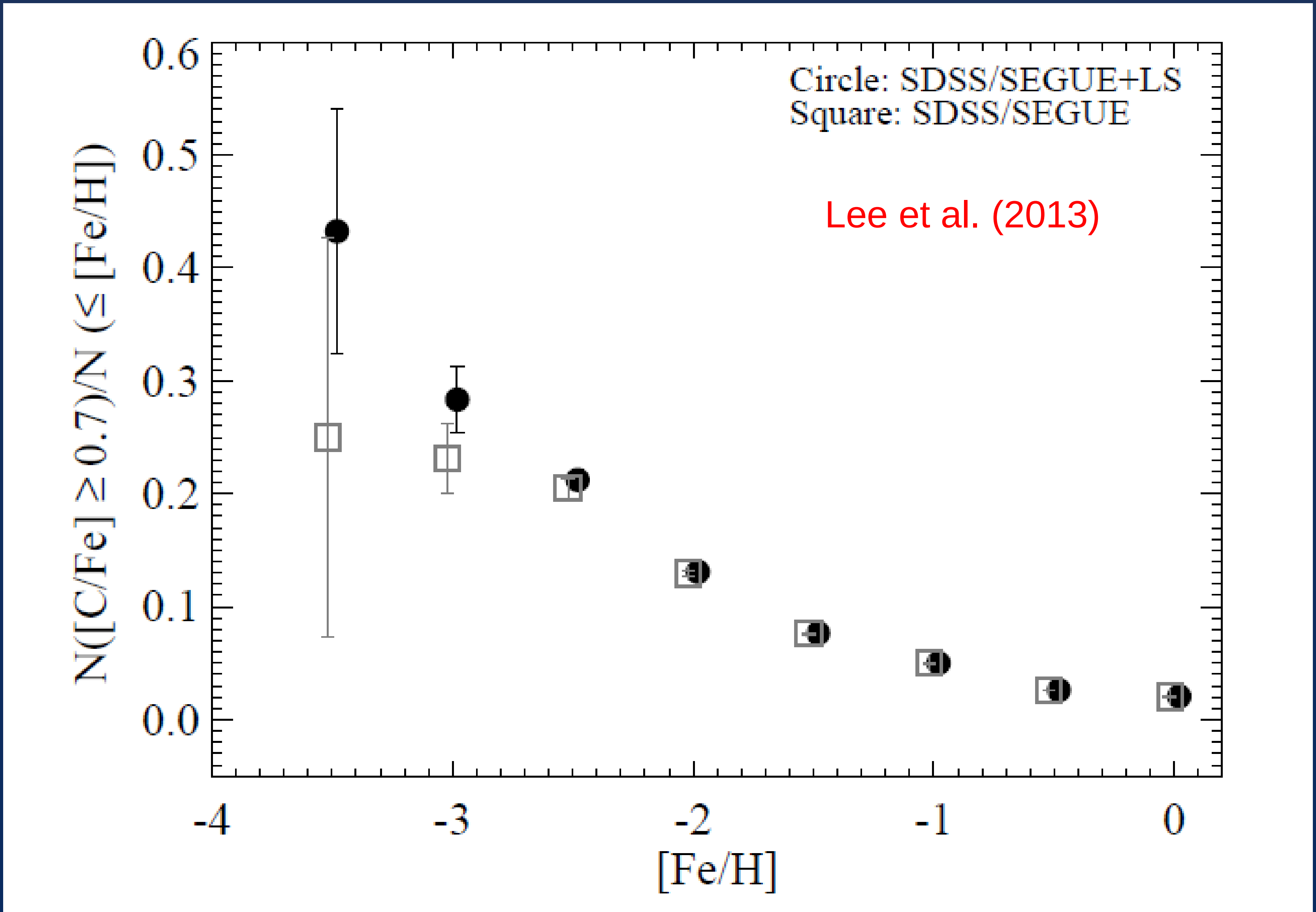
C, N, O gets out but Fe and other heavy elements do not

# In Pictures – Spinstars → CEMP-no

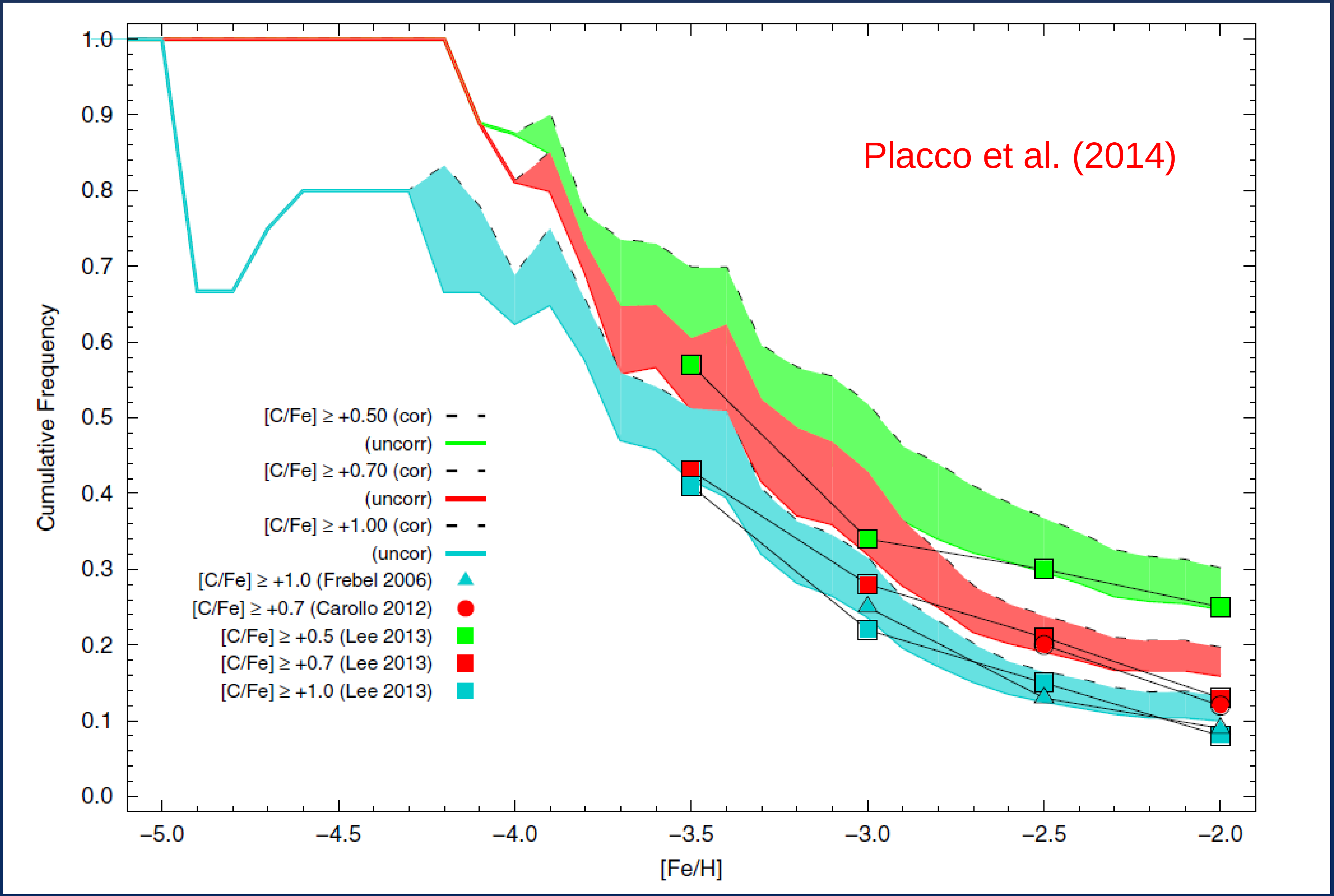
50 < M/Mo < 300



# 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

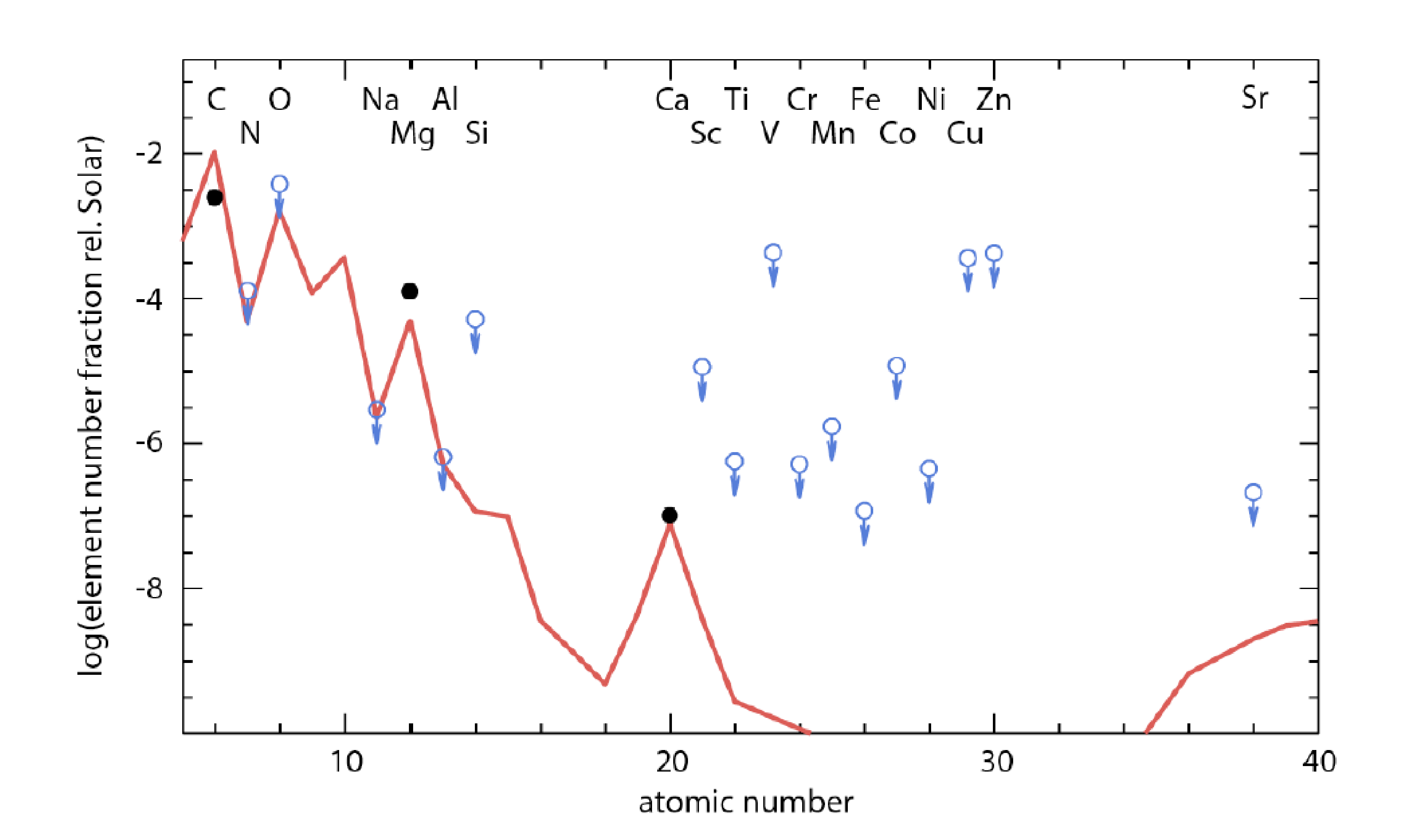
**A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3**

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 [Fe/H] < -7.1 -- more than 10,000,000 times lower than the Sun

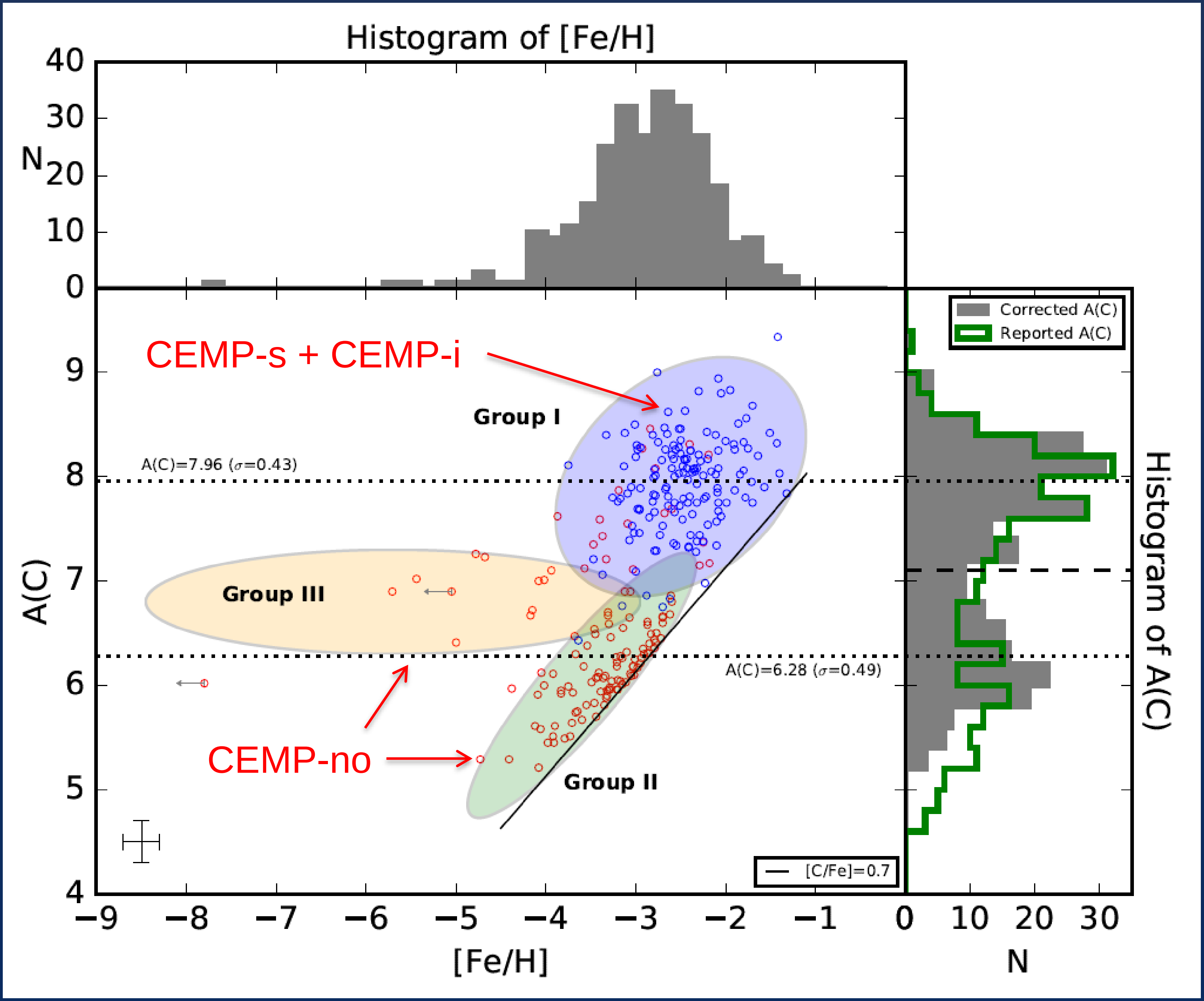
- And of course, it is a CEMP-no star, with the same light element abundance pattern, and detectable (but very low) Li

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

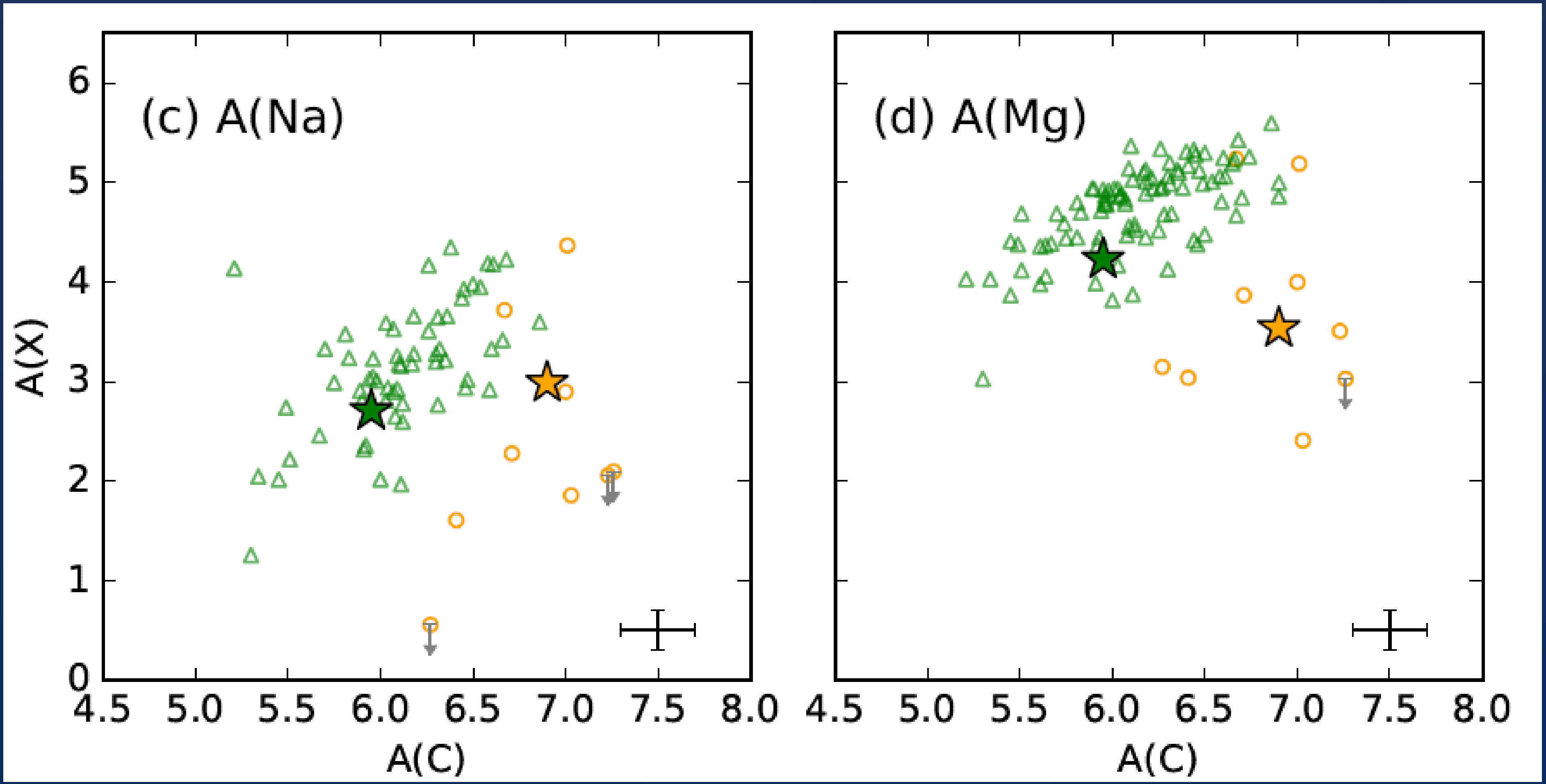



Note singular detections of C, Mg, and Ca – Everything else is an upper limit ! (Keller et al. 2014)

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



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



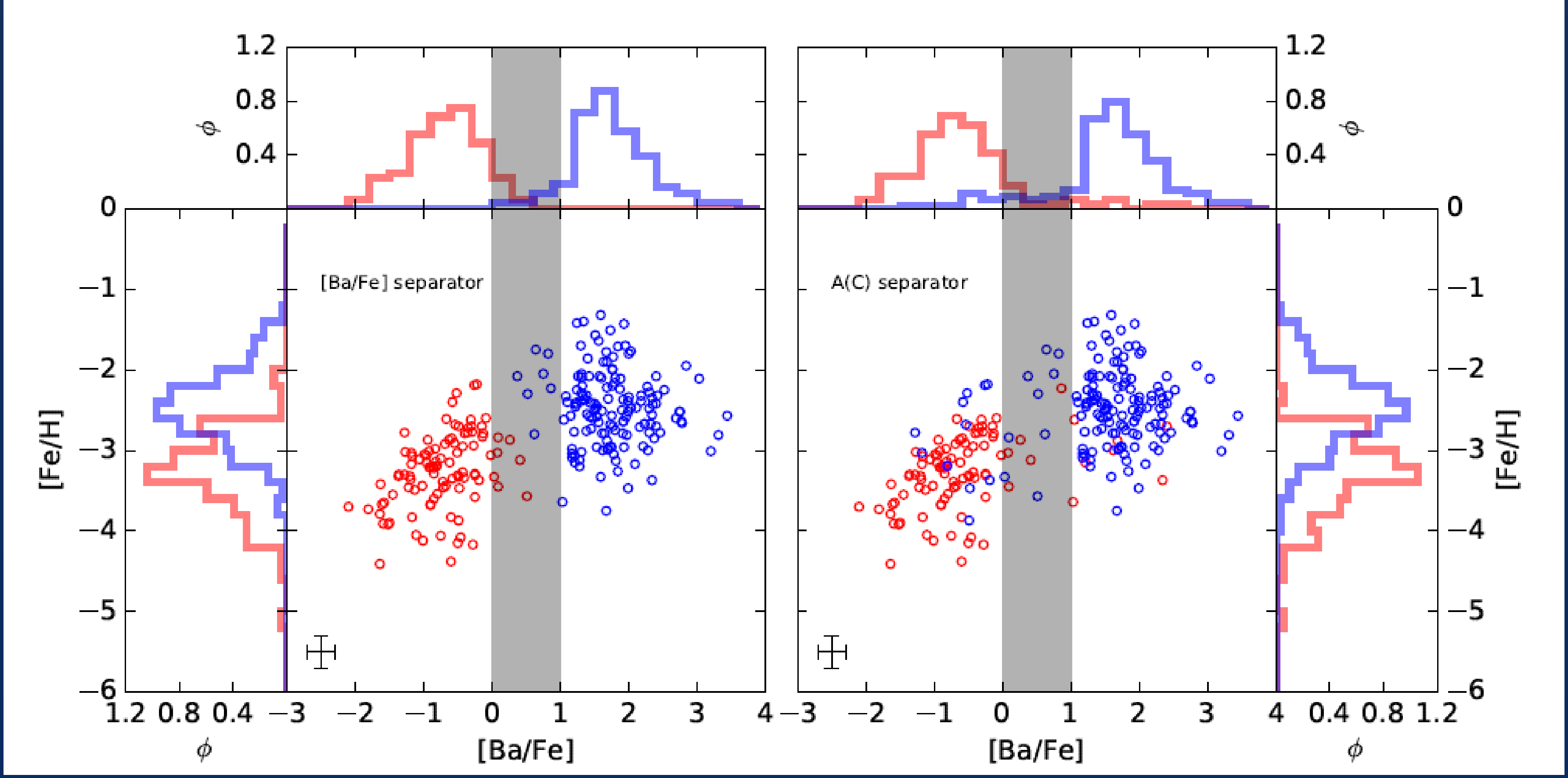

Group II CEMP-no: **Green** / Group III CEMP-no: **Orange**

BD+44:493

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

## G64–12 AND G64–37 ARE CEMP-NO STARS

Vinicius M. Placco[1,2], Timothy C. Beers[1,2],
Henrique Reggiani[3], Jorge Meléndez[3]

*Draft version August 15, 2016*

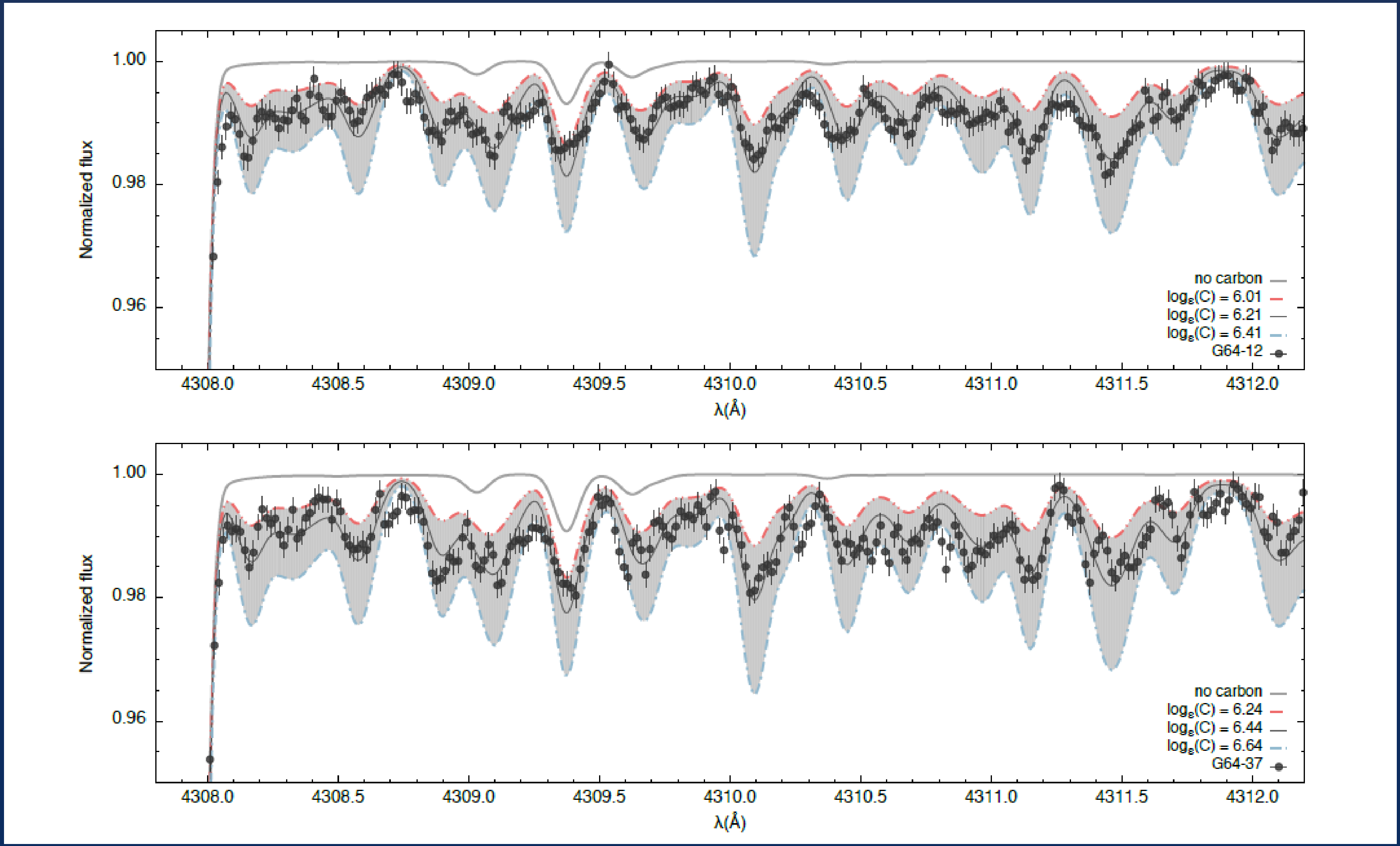
### ABSTRACT

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 ($T_{\rm eff} \sim 6500$ 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)

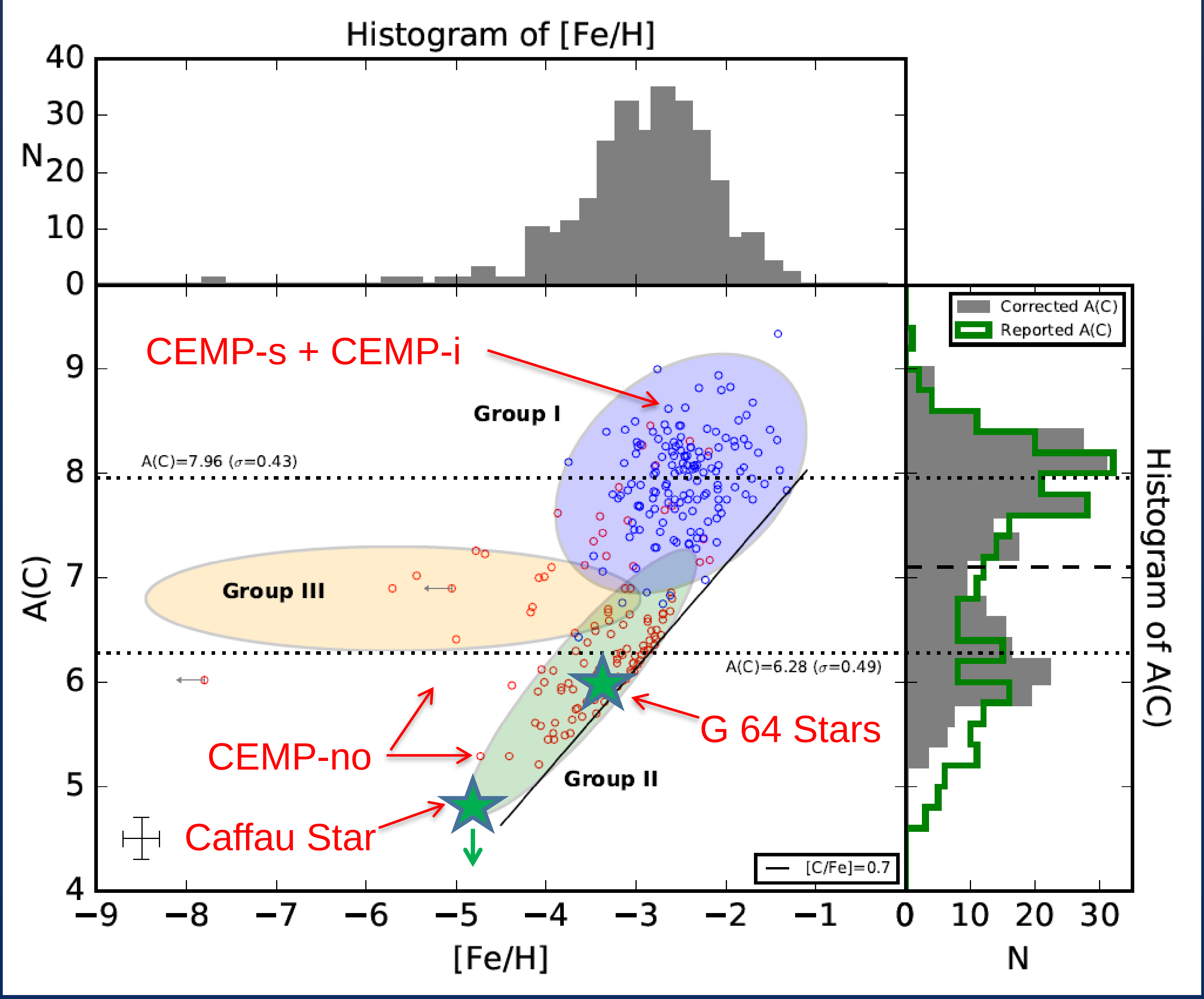
Placco et al. (2016)

# Hidden CEMP-no Stars




Teff ~ 6500 K [ Fe/H] ~ –3.5 [C/Fe] = +1.1 A(C) = 6.2

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



# Associations of CEMP-s / CEMP-no with Inner/Outer Halo Populations

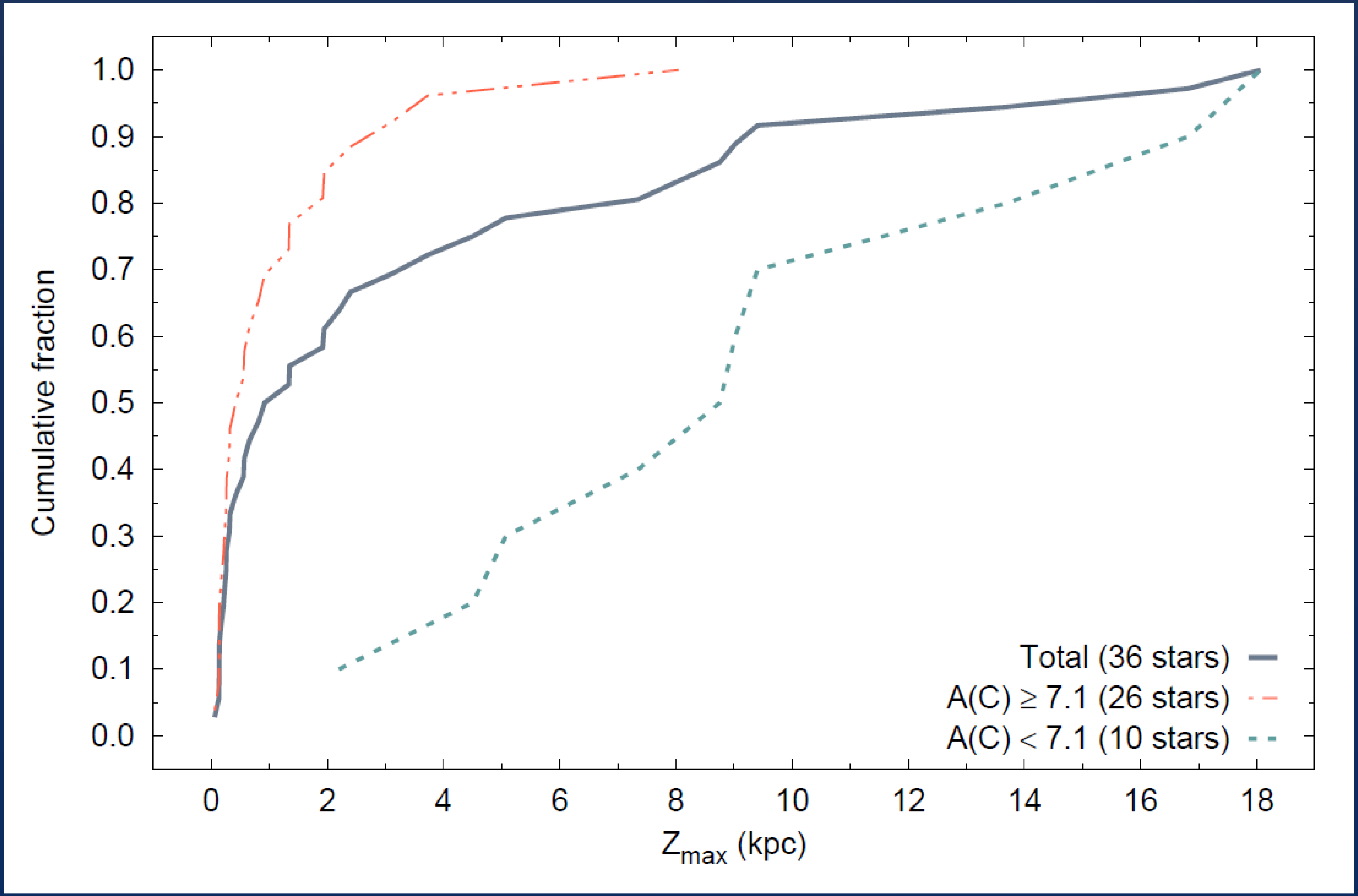
CARBON-ENHANCED METAL-POOR STARS: CEMP-*s* and CEMP-no SUBCLASSES IN THE HALO SYSTEM OF THE MILKY WAY

DANIELA CAROLLO[1,8], KEN FREEMAN[2], TIMOTHY C. BEERS[3,4], VINICIUS M. PLACCO[5], JASON TUMLINSON[6], AND SARAH L. MARTELL[7]

We explore the kinematics and orbital properties of a sample of 323 very metal-poor stars in the halo system of the Milky Way, selected from the high-resolution spectroscopic follow-up studies of Aoki et al. and Yong et al. The combined sample contains a significant fraction of carbon-enhanced metal-poor (CEMP) stars (22% or 29%, depending on whether a strict or relaxed criterion is applied for this definition). Barium abundances (or upper limits) are available for the great majority of the CEMP stars, allowing for their separation into the CEMP-*s* and CEMP-no subclasses. A new method to assign membership to the inner- and outer-halo populations of the Milky Way is developed, making use of the integrals of motion, and applied to determine the relative fractions of CEMP stars in these two subclasses for each halo component. Although limited by small-number statistics, the data suggest that the inner halo of the Milky Way exhibits a somewhat higher relative number of CEMP-*s* stars than CEMP-no stars (57% versus 43%), while the outer halo possesses a clearly higher fraction of CEMP-no stars than CEMP-*s* stars (70% versus 30%). Although larger samples of CEMP stars with known Ba abundances are required, this result suggests that the dominant progenitors of CEMP stars in the two halo components were different; massive stars for the outer halo, and intermediate-mass stars in the case of the inner halo.

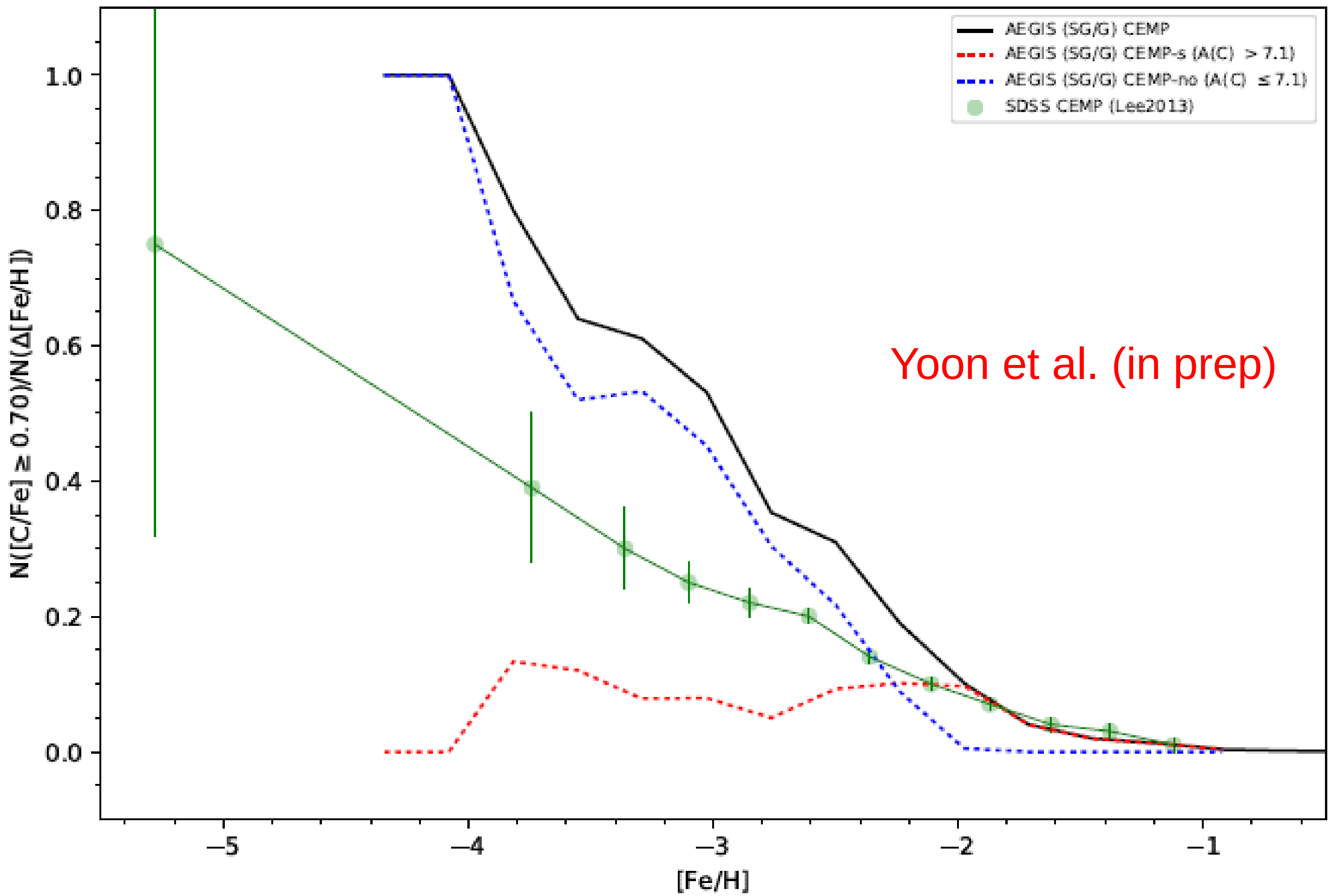
Carollo et al. (2014)

# Associations of CEMP-s / CEMP-no with Inner/Outer Halo Populations




Beers et al. (2017)

# Cumulative Frequencies / Differential Frequencies of CEMP-no + CEMP-s for AEGIS Sample




(b) Differential fraction based on only Giants

# What Comes Next ? Hopefully This Meeting Will Have Something to Say about That … A Few Already Clear

- CEMP stars, in particular CEMP-no stars, appear intimately related with documenting the first generations of star formation in the 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 abundances ?
- We need to learn how to COUNT better, as the frequency of CEMP-no vs. [Fe/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