Observational Constraints on First-Star Nucleosynthesis

Timothy C. Beers
University of Notre Dame

JINA–CEE

UNIVERSITY OF NOTRE DAME

SDSS

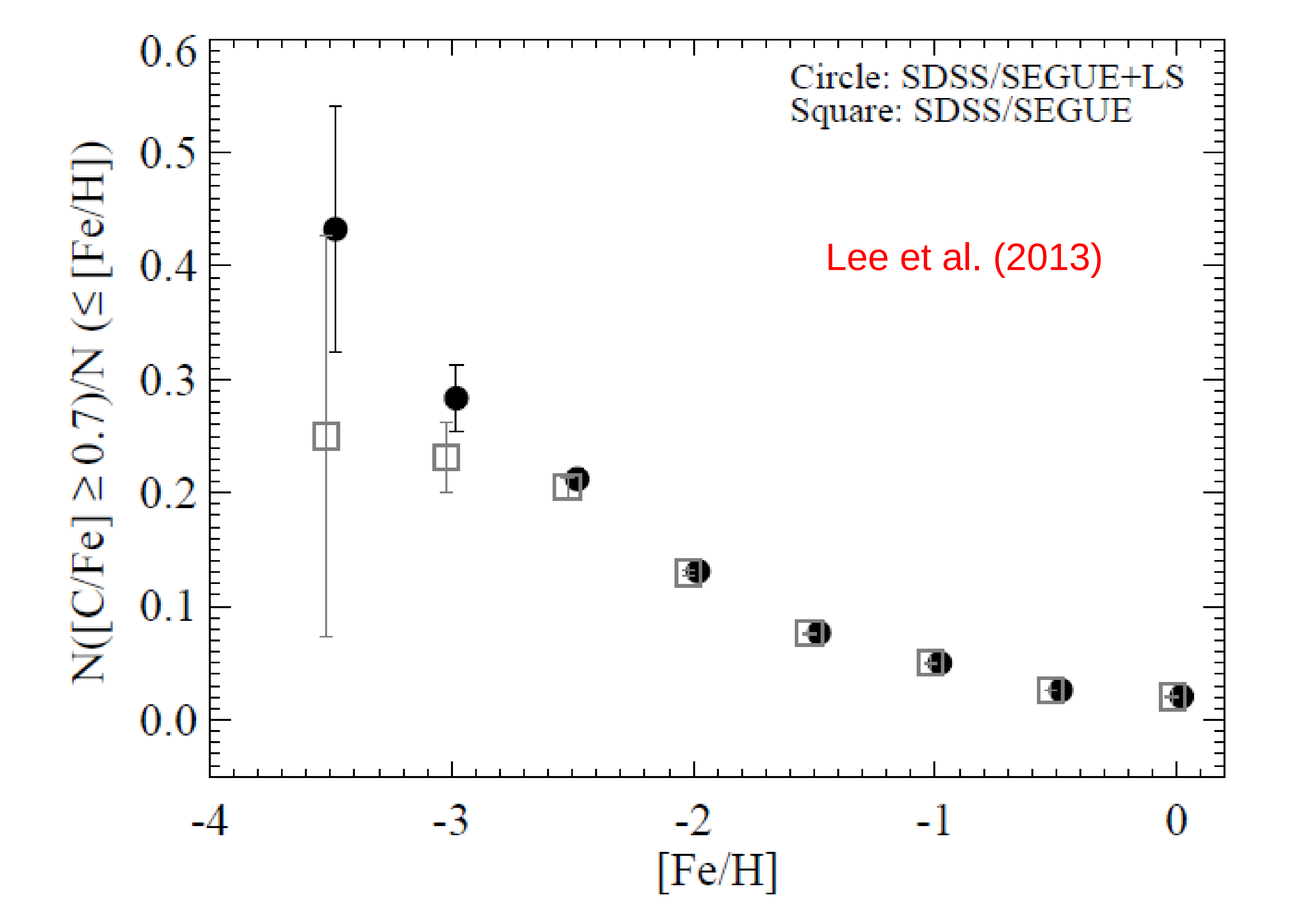
Expected Signatures

- 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

Frequencies of CEMP Stars Based on Stellar Populations

- Carbon-Enhanced Metal-Poor (CEMP) stars have been recognized to be an important stellar component of the halo system
- CEMP star frequencies are:
  - 20% for [Fe/H] < -2.5
  - 30% for [Fe/H] < -3.0 EMP
  - 40% for [Fe/H] < -3.5
  - 75% for [Fe/H] < -4.0 UMP
  - 100% for [Fe/H] < -5.0 HMP
- But Why ? – Atmospheric/Progenitor or Population Driven ?
- Carollo et al. (2012, 2014) suggest the latter

Cumulative Frequencies of CEMP Stars

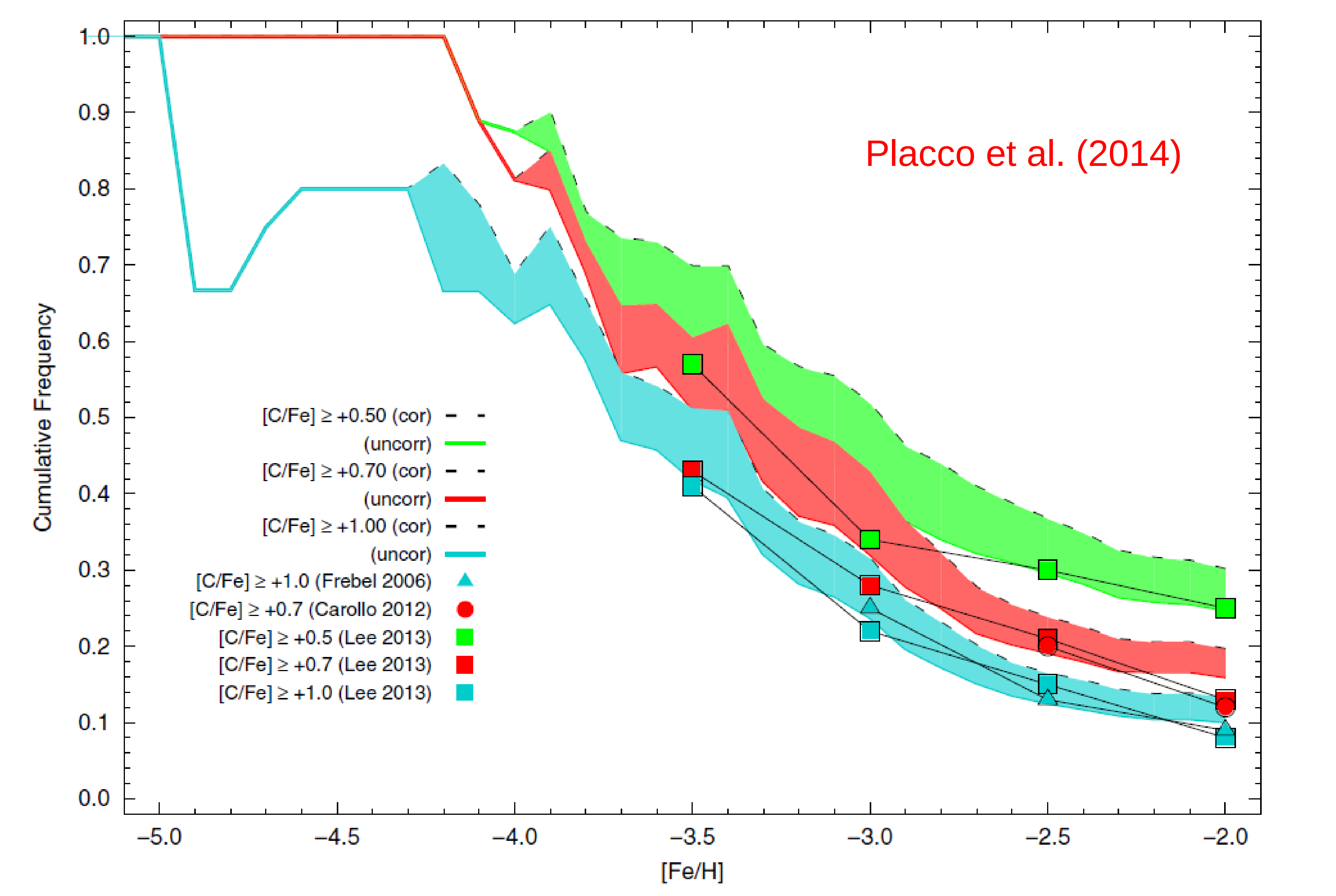


Exploration of Nature's Laboratory for Neutron-Capture Processes

Neutron-capture-rich stars	
r-I	$0.3 \le [Eu/Fe] \le +1.0$ 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 $[Ba/Fe] < 0$

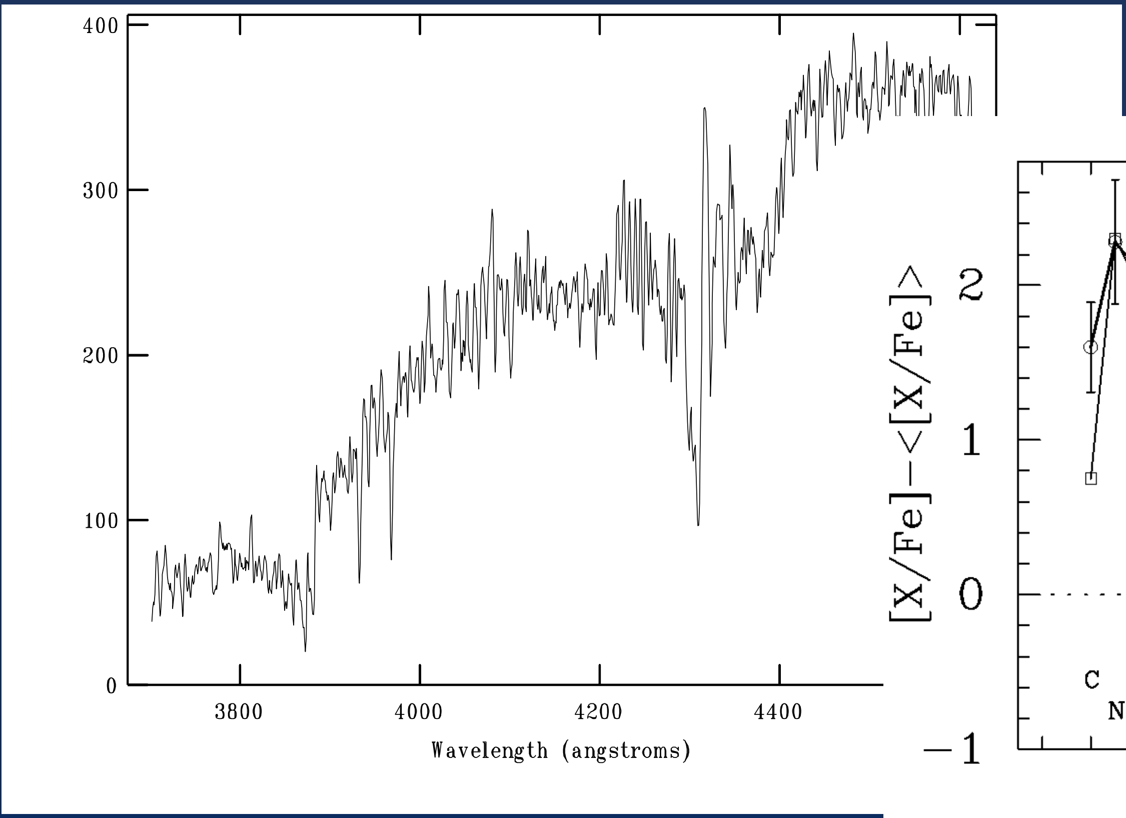
Beers & Christlieb ARAA (2005)

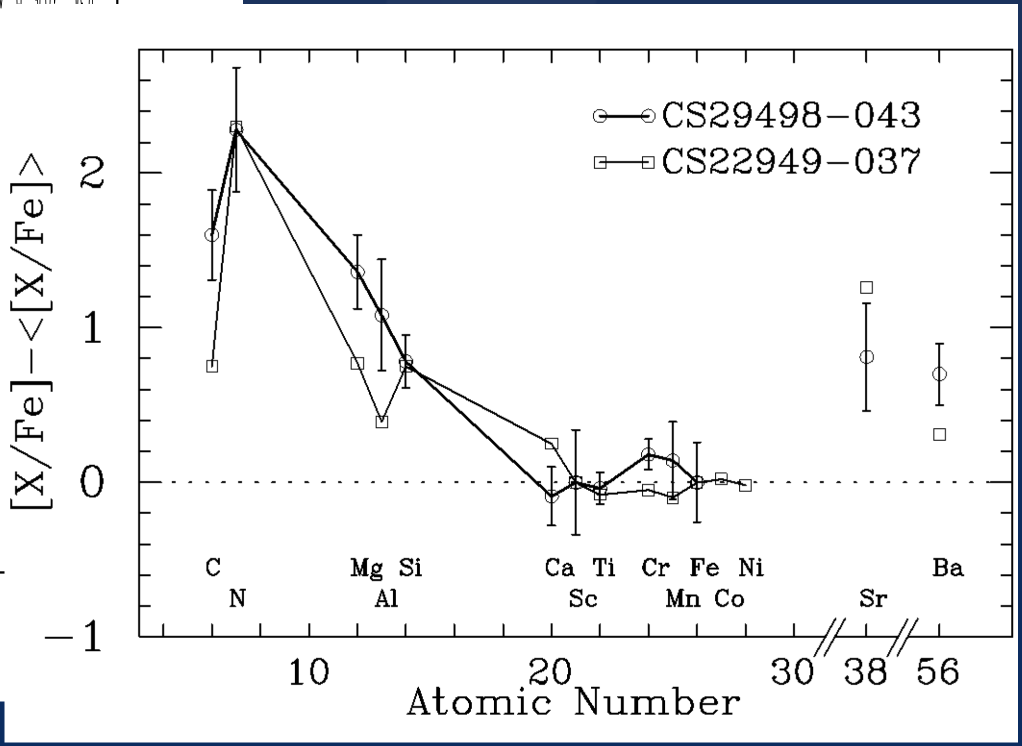
Cumulative Frequencies of CEMP-no (ONLY) Stars from SDSS/SEGUE, with Luminosity Corrections



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

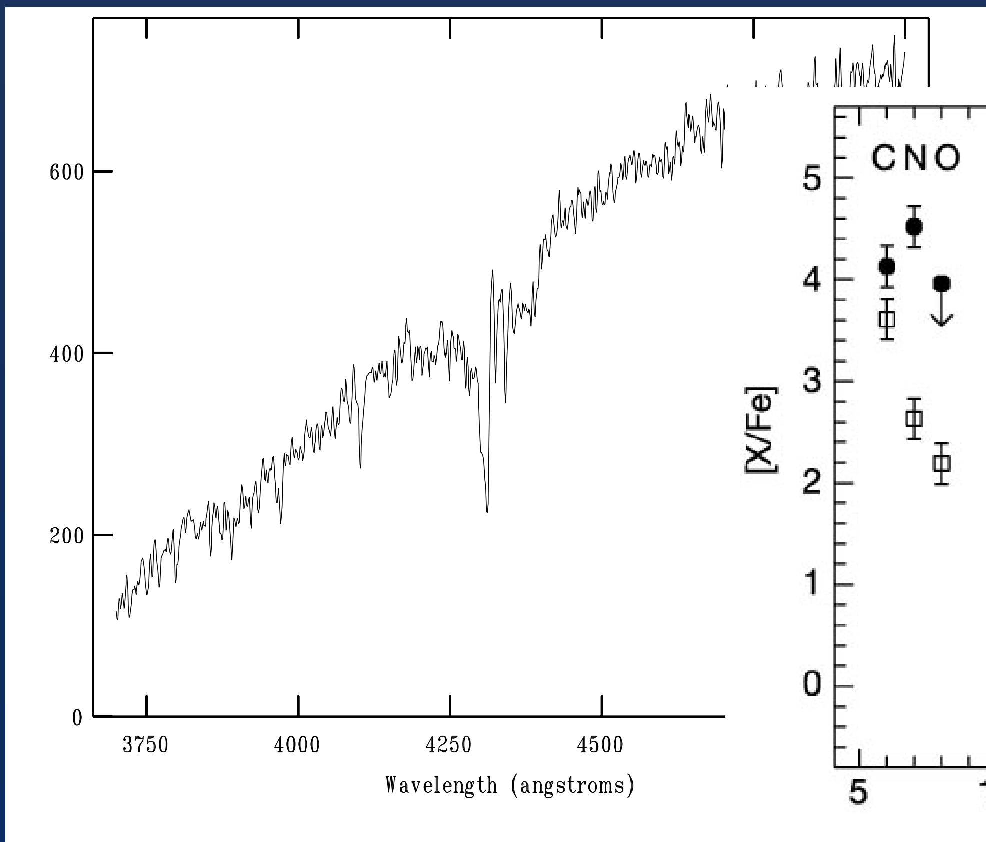


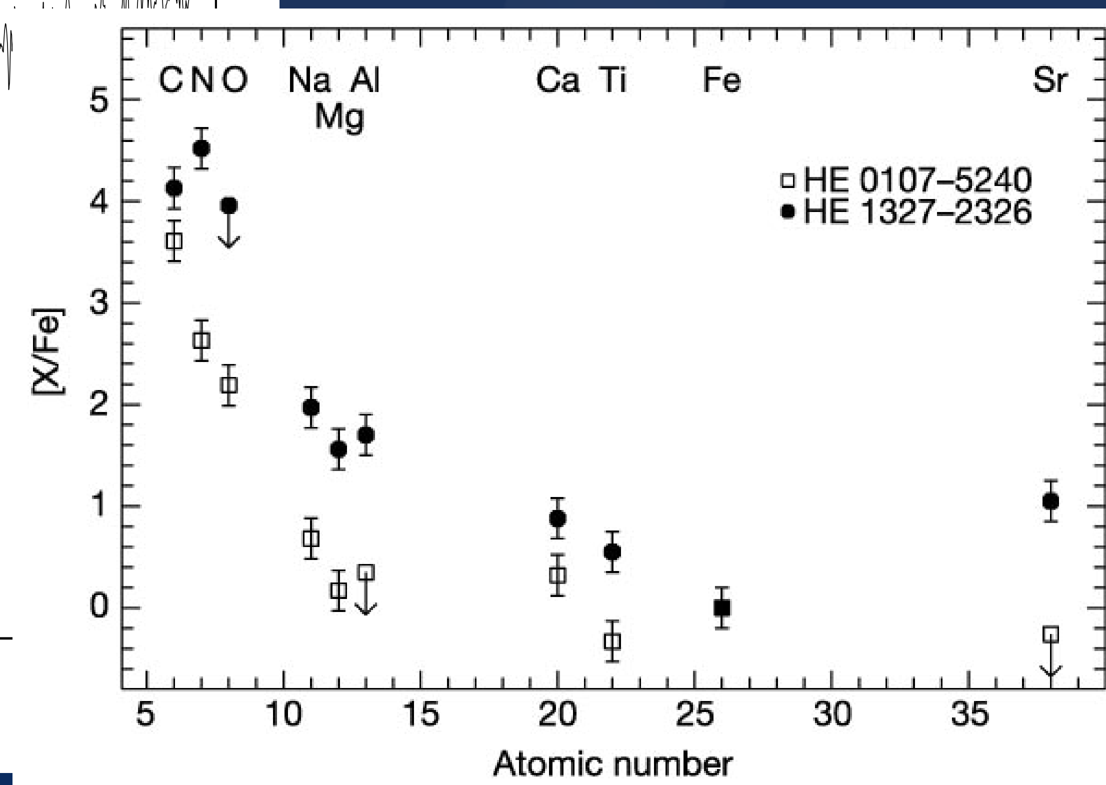


Harbingers of Things to Come!

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 !

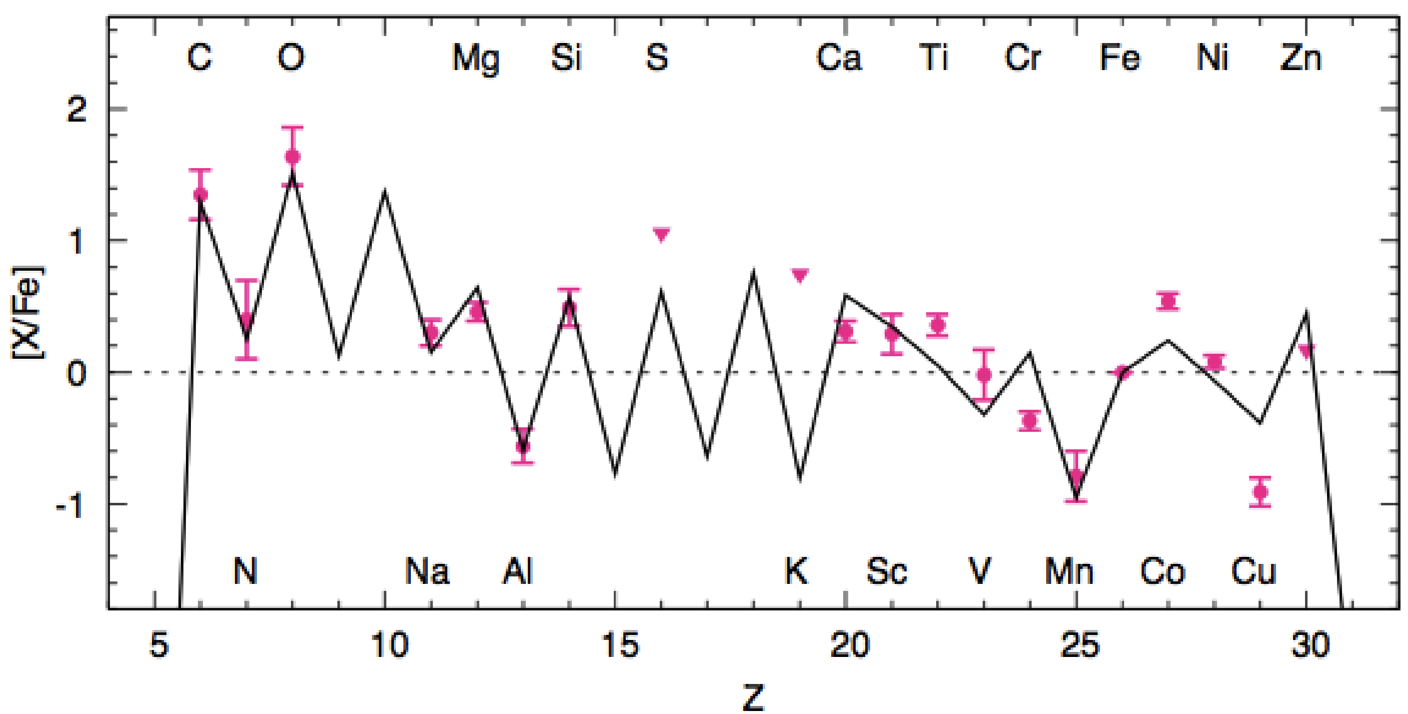
BD+44:493 – A 9th Magnitude Messenger from the Early Universe

- Ito et al. (2009) report on discovery that BD+44 is an [Fe/H] = -3.8, CEMP-no star; more detailed observations by Ito et al. (2013)
- Light-element abundance patterns similar to those for other CEMP-no stars
- Previous RV monitoring by Carney et al. indicate no variation at levels > 0.5 km/s over past 25 years
- The same is true for other CEMP-no stars with available RV monitoring (Hansen et al. 2013, 2016)

Something You Don't Often See

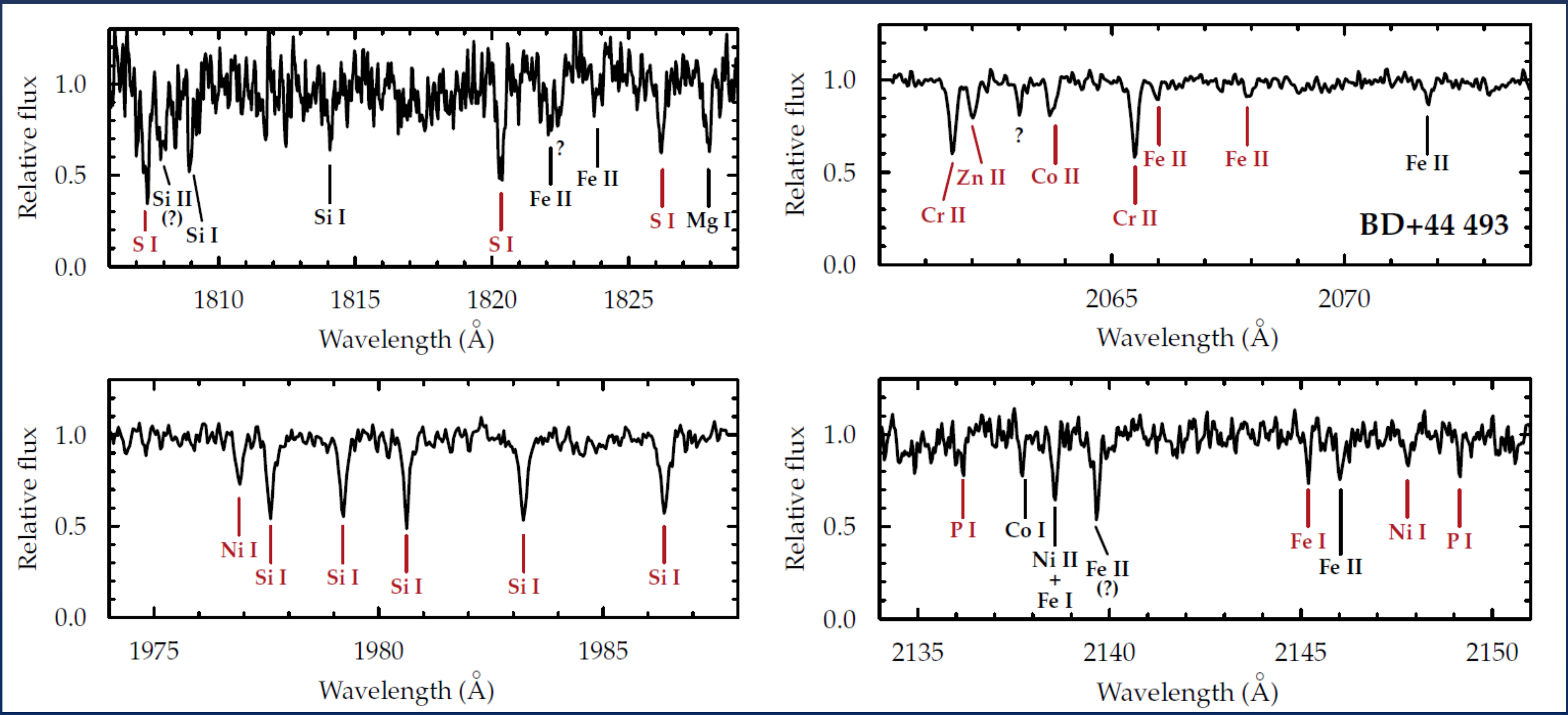
An Object of COSMOLOGICAL Significance with Diffraction Spikes

Abundance Pattern Compared to 25 M_o Mixing/Fallback Model



Ito et al. (2013) : Note the low N, compared with some other CEMP-no stars with enhanced N

HST/COS Observations of P, S, Si, and Zn in BD+44:493 (Roederer et al. 2016)



First Detection of Phosphorus (P) and Sulphur (S) in any CEMP-no Star
Note accurate measurement of Si (difficult in the optical)

As If Right on Cue …

- Nature – March, 2014

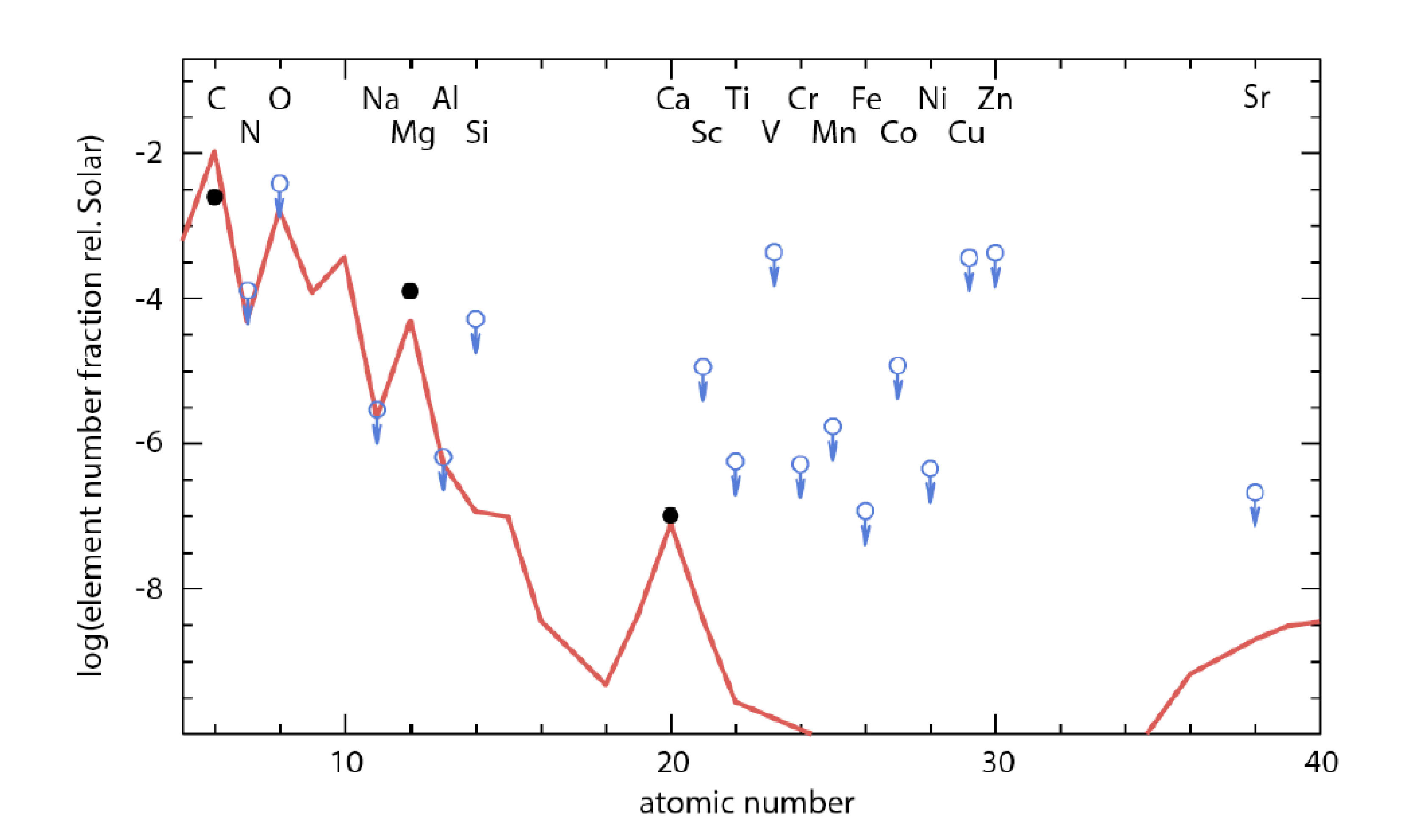
A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3

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)

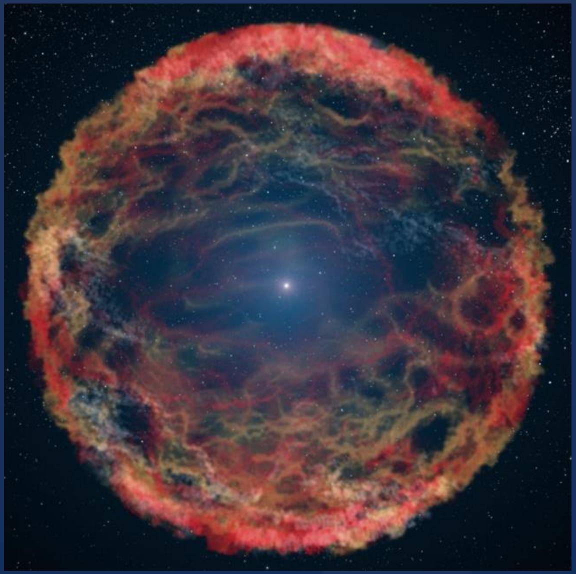


Note singular detections of C, Mg, and Ca – Everything else is an upper limit ! (Keller et al. 2014)

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

Umeda
Tominaga
Nomoto

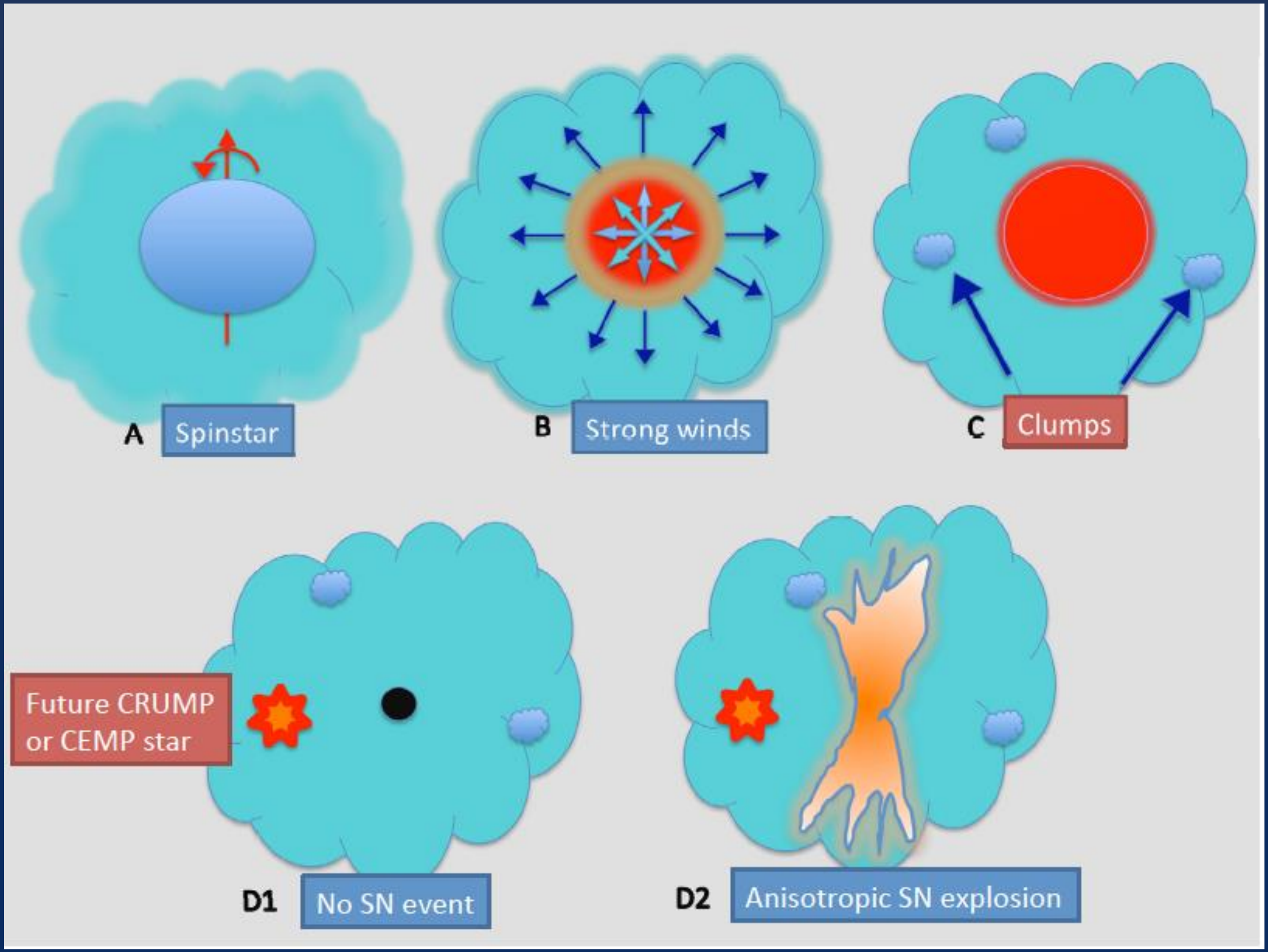
15 < M/Mo < 50



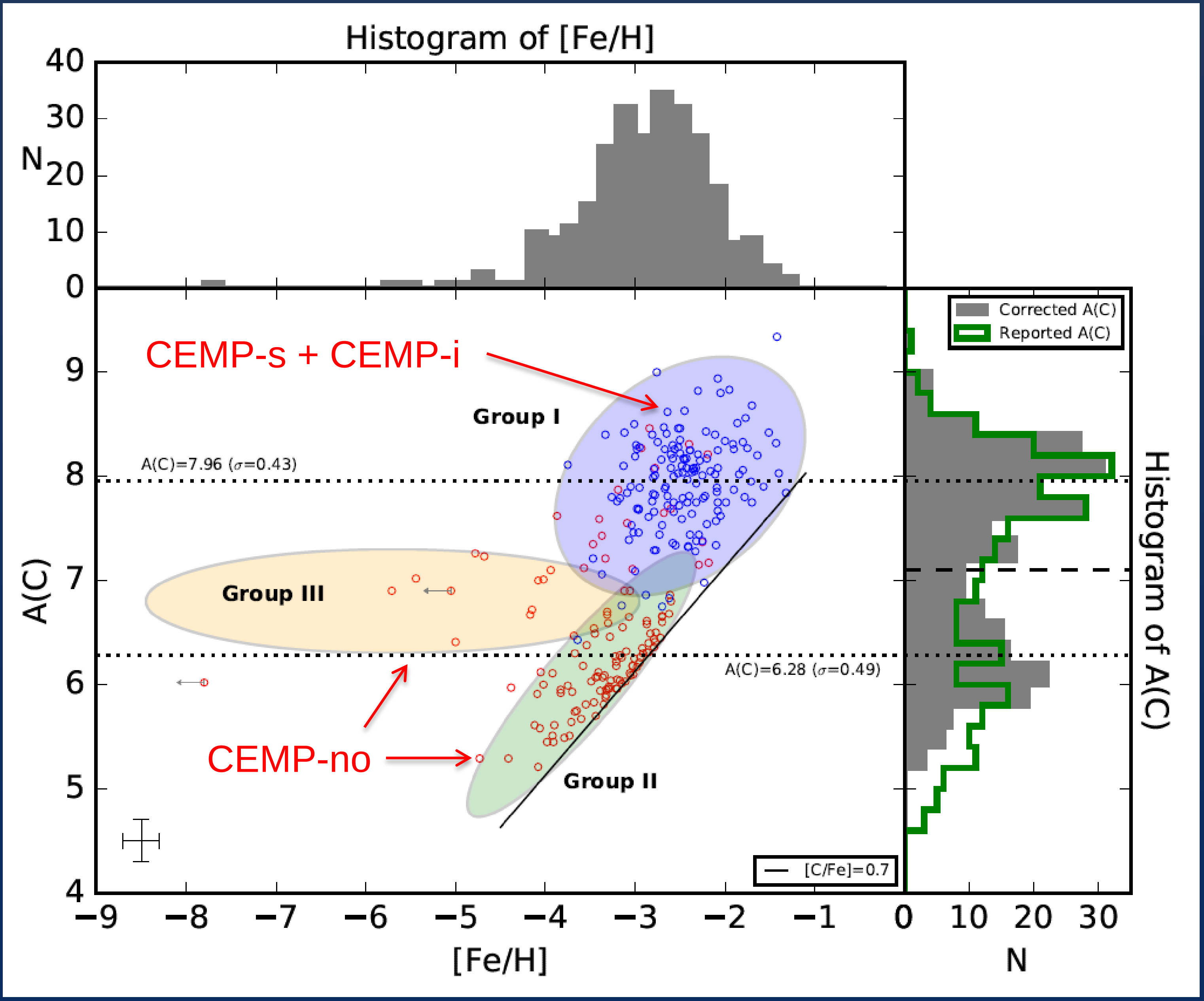
C, N, O gets out but Fe and other heavy elements do not

In Pictures – Spinstars → CEMP-no

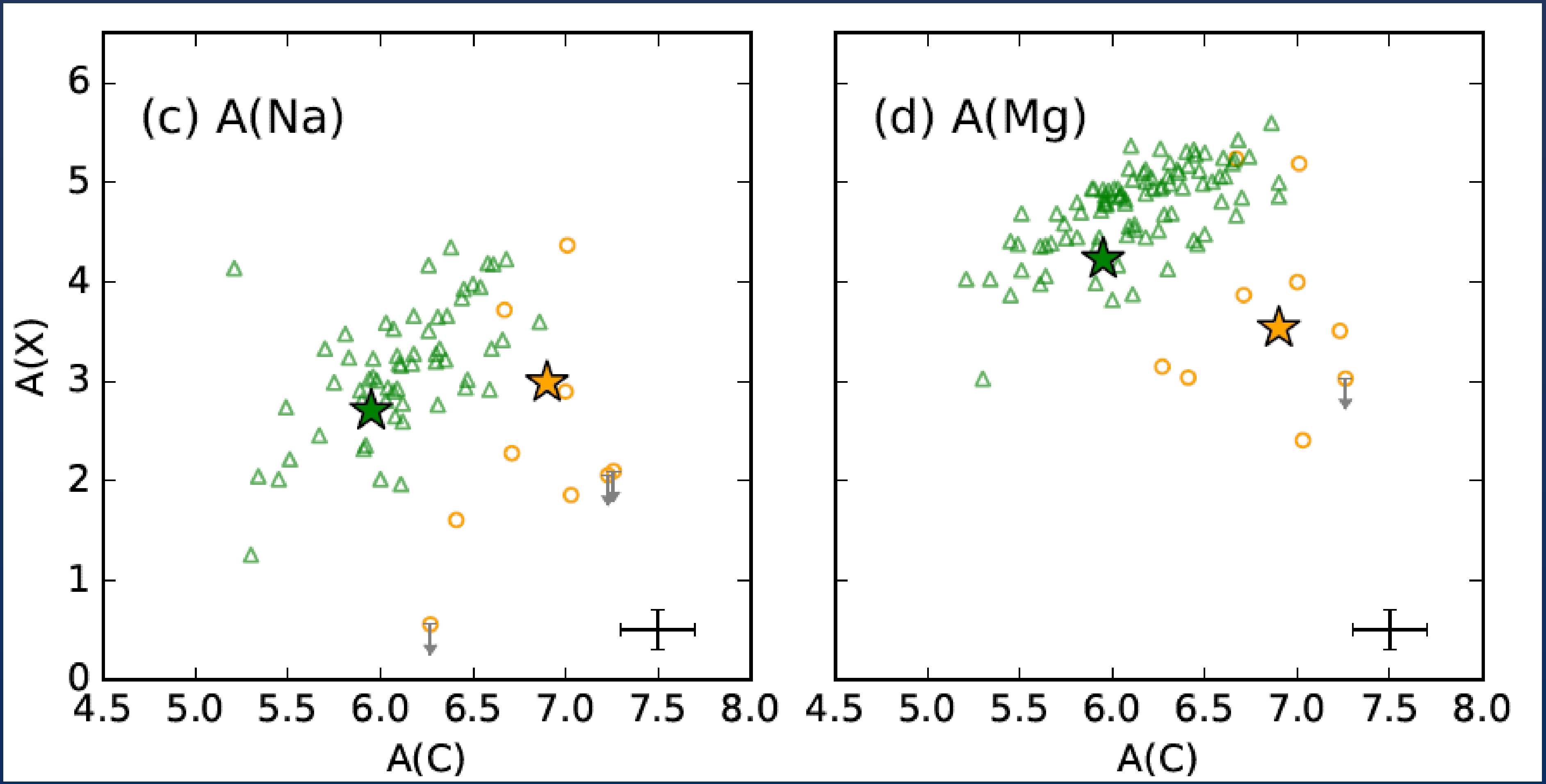
50 < M/Mo < 300



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

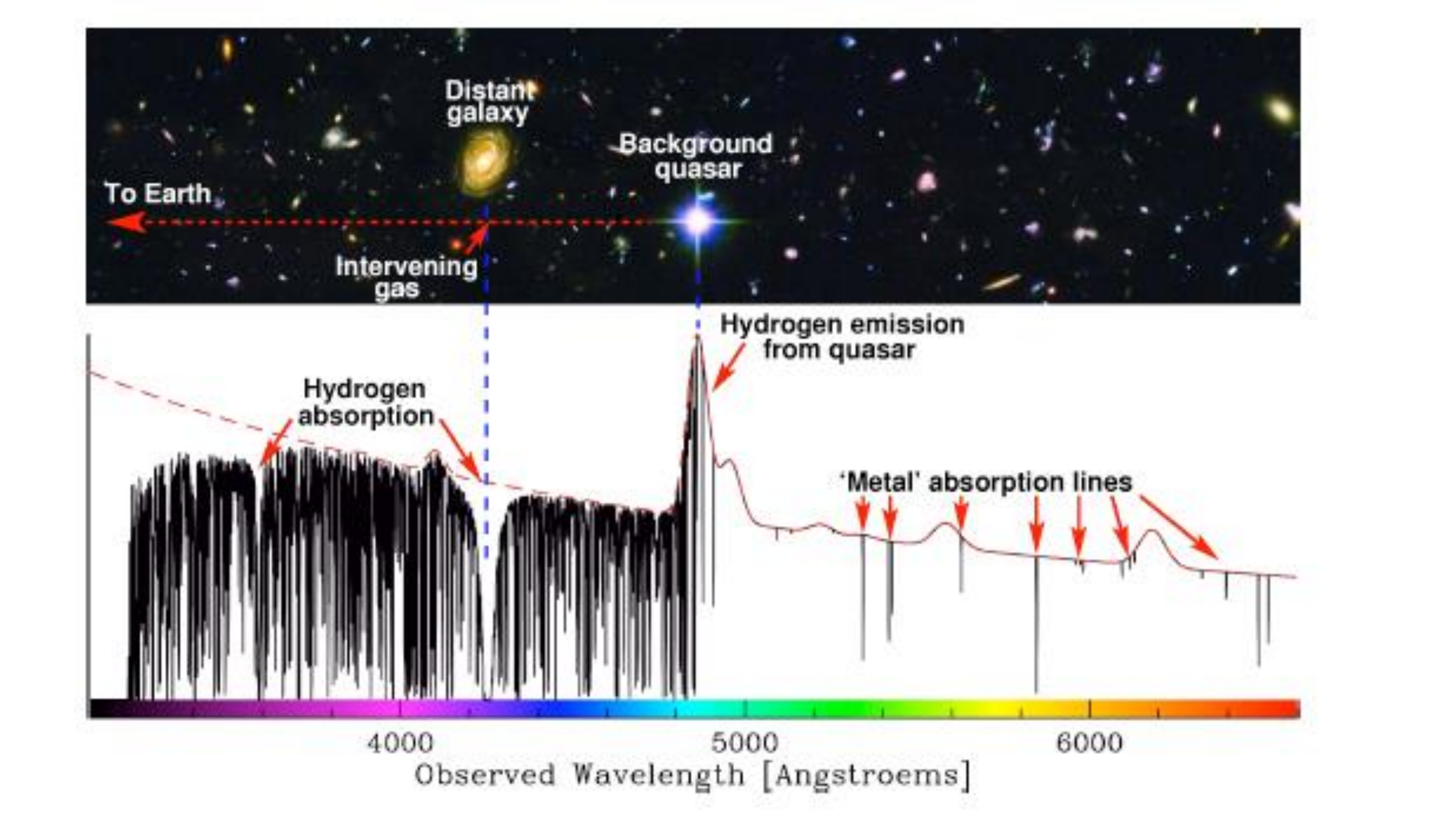


Yoon et al. (2016) – A(Na) and A(Mg) vs. A(C)



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

Connections with high-z DLA Systems



The Song Remains the Same

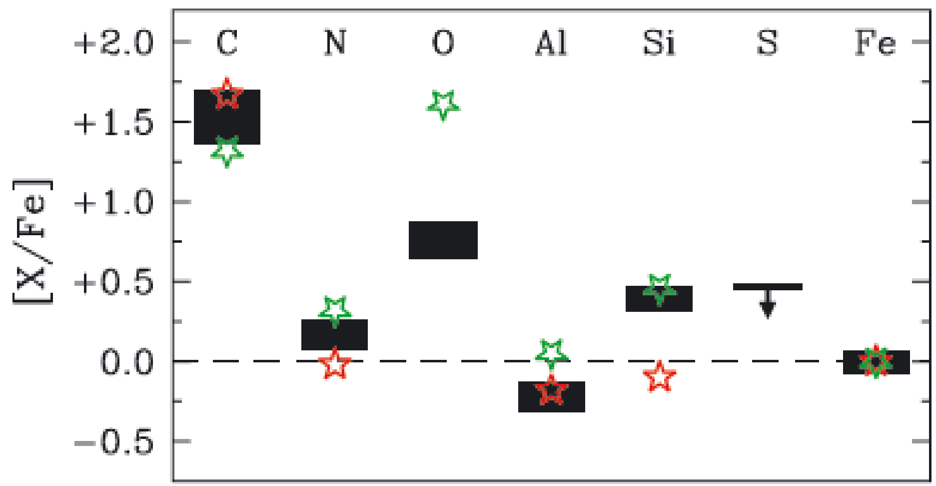


Figure 7. Comparison of element abundances in the $z_{abs} = 2.340\,0972$ DLA (filled black boxes) and in Galactic halo stars with an Fe abundance within a factor of 2 of the DLA (open magenta boxes). The numbers below the element labels indicate the number of stars that contributed to the determination of the 'typical' stellar abundances, and the heights of the magenta boxes reflect the dispersion of each set of measurements. Top panel: comparison with all CEMP stars that have $-3.34 \le$ [Fe/H] ≤ -2.74. Middle panel: comparison with CEMP-no stars that have $-3.34 \le$ [Fe/H] ≤ -2.74. For this case, the oxygen abundance of a single CEMP-no star is shown by the open circle. Lower panel: comparing the DLA abundance pattern with the stellar abundance patterns of HE 0143−0441 (red symbols; a CEMP-s star with [Fe/H] = −2.21, [Ba/Fe] = +0.62 from Cohen et al. 2004) and BD+44°493 (green symbols; a CEMP-no star with [Fe/H] = −3.73, [Ba/Fe] = −0.55 from Ito et al. 2009). Note that in this last panel, we have plotted [X/Fe] as opposed to [X/H]. In all panels the dashed line represents the solar abundance.

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

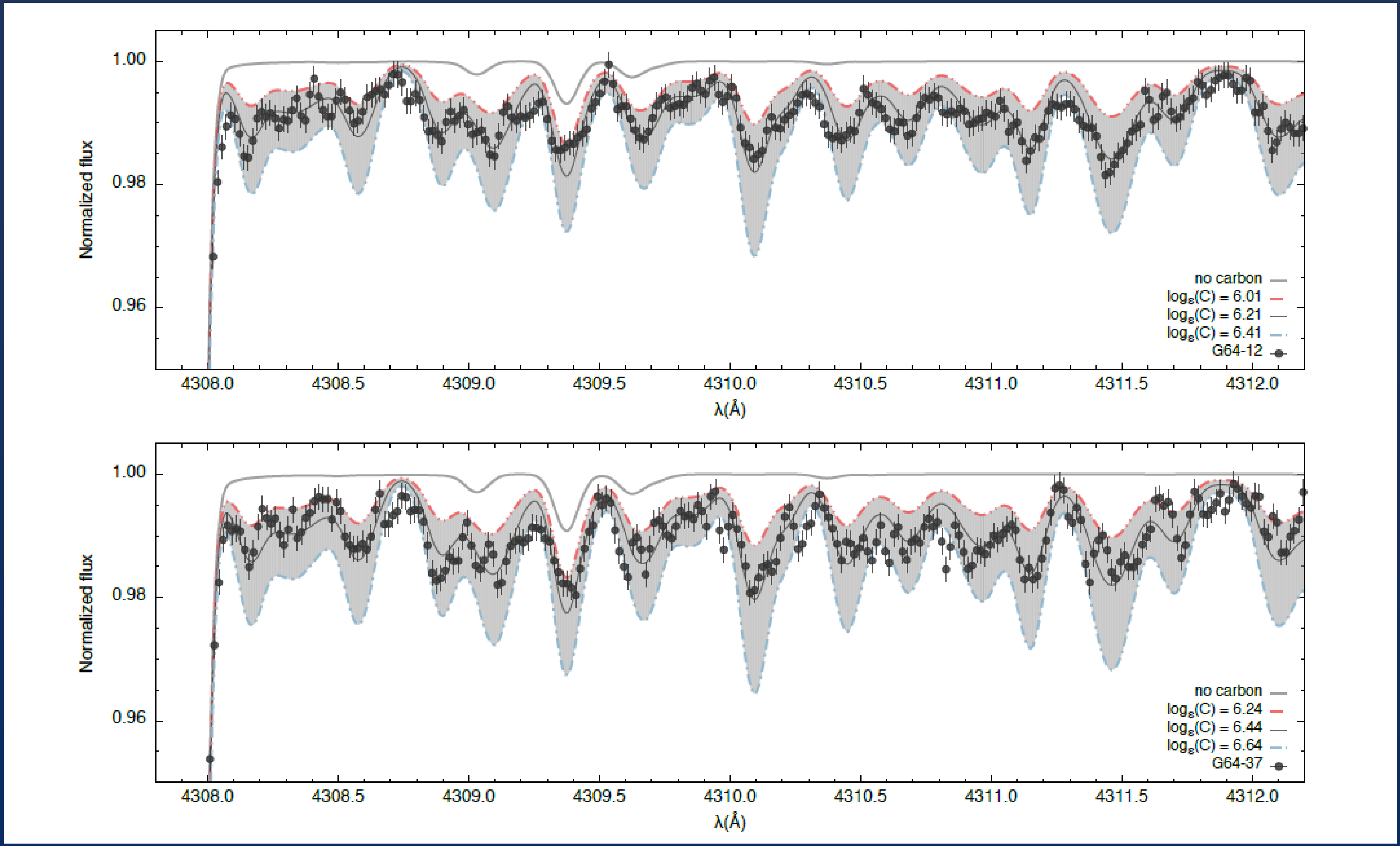
ABSTRACT

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 $\sim$ 2-3, and explosion energies by factors of $\sim$ 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)

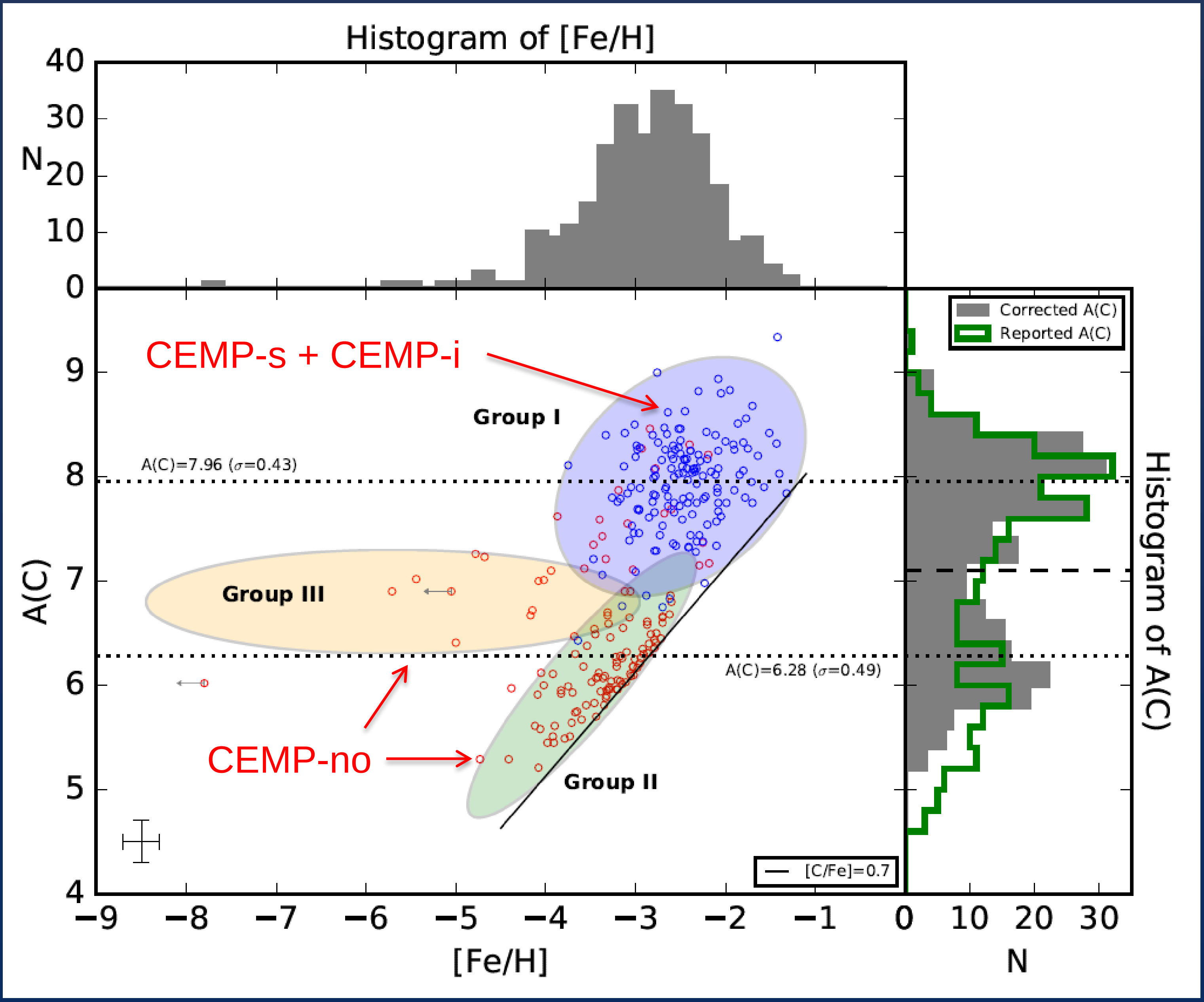
Placco et al. (2016)

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]



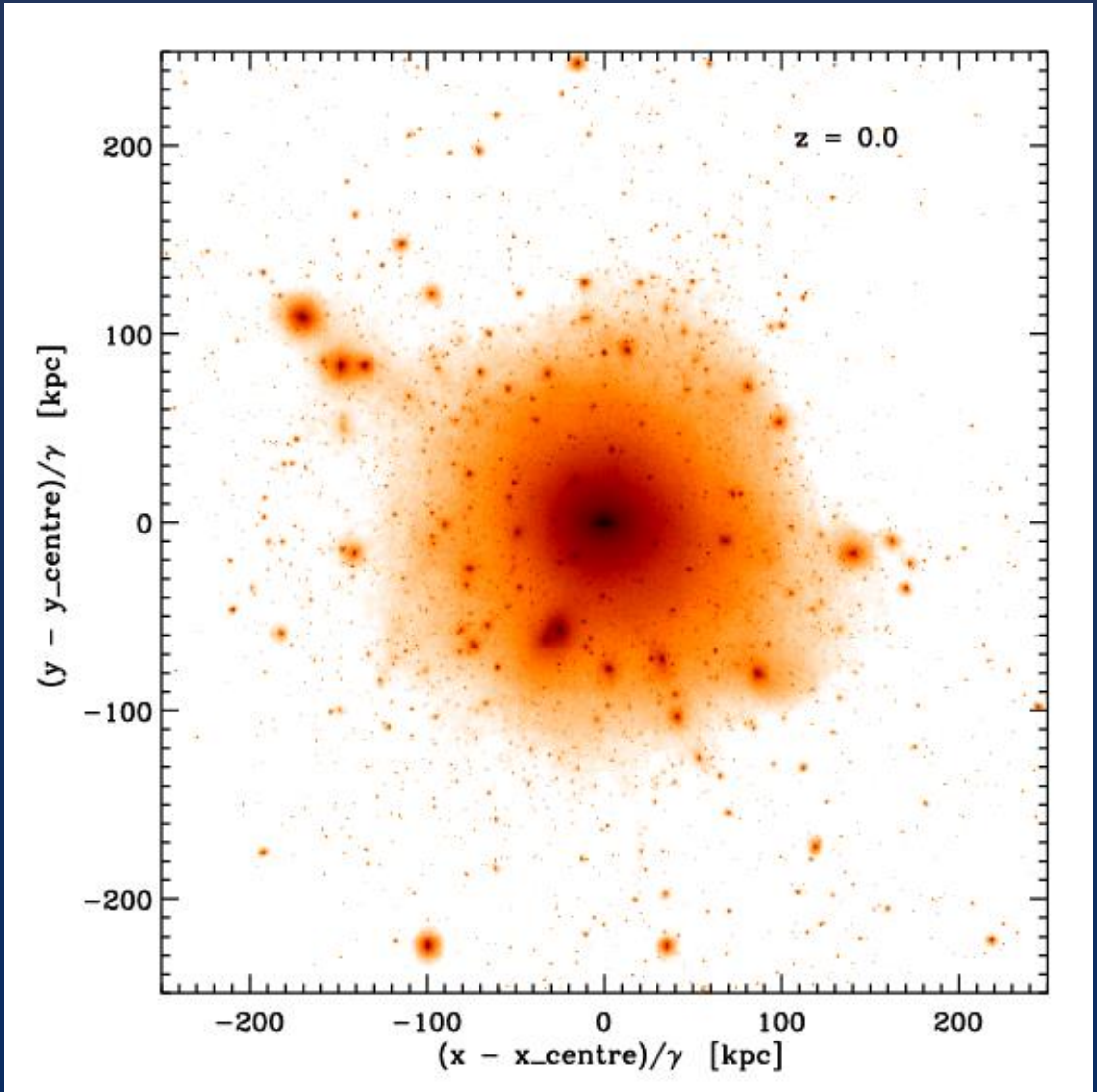
Known MP Stars – Pre and Post SDSS/SEGUE-1/SEGUE-2

Name	Metallicity		Pre	Post
Metal-Poor	MP	[Fe/H] < -1.0	15,000	150,000+
Very Metal-Poor	VMP	[Fe/H] < -2.0	3,000	30,000+
Extremely Metal-Poor	EMP	[Fe/H] < -3.0	400	1000+
Ultra Metal-Poor	UMP	[Fe/H] < -4.0	6	25
Hyper Metal-Poor	HMP	[Fe/H] < -5.0	2	5
Mega Metal-Poor	MMP	[Fe/H] < -6.0	1	1
Septa Metal-Poor	SMP	[Fe/H] < -7.0	1	1
Octa Metal-Poor	OMP	[Fe/H] < -8.0	0	0
Giga Metal-Poor	GMP	[Fe/H] < -9.0	0	0

Why have UMP and lower stars proven so difficult to find ?

Assembly History of the Milky Way

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

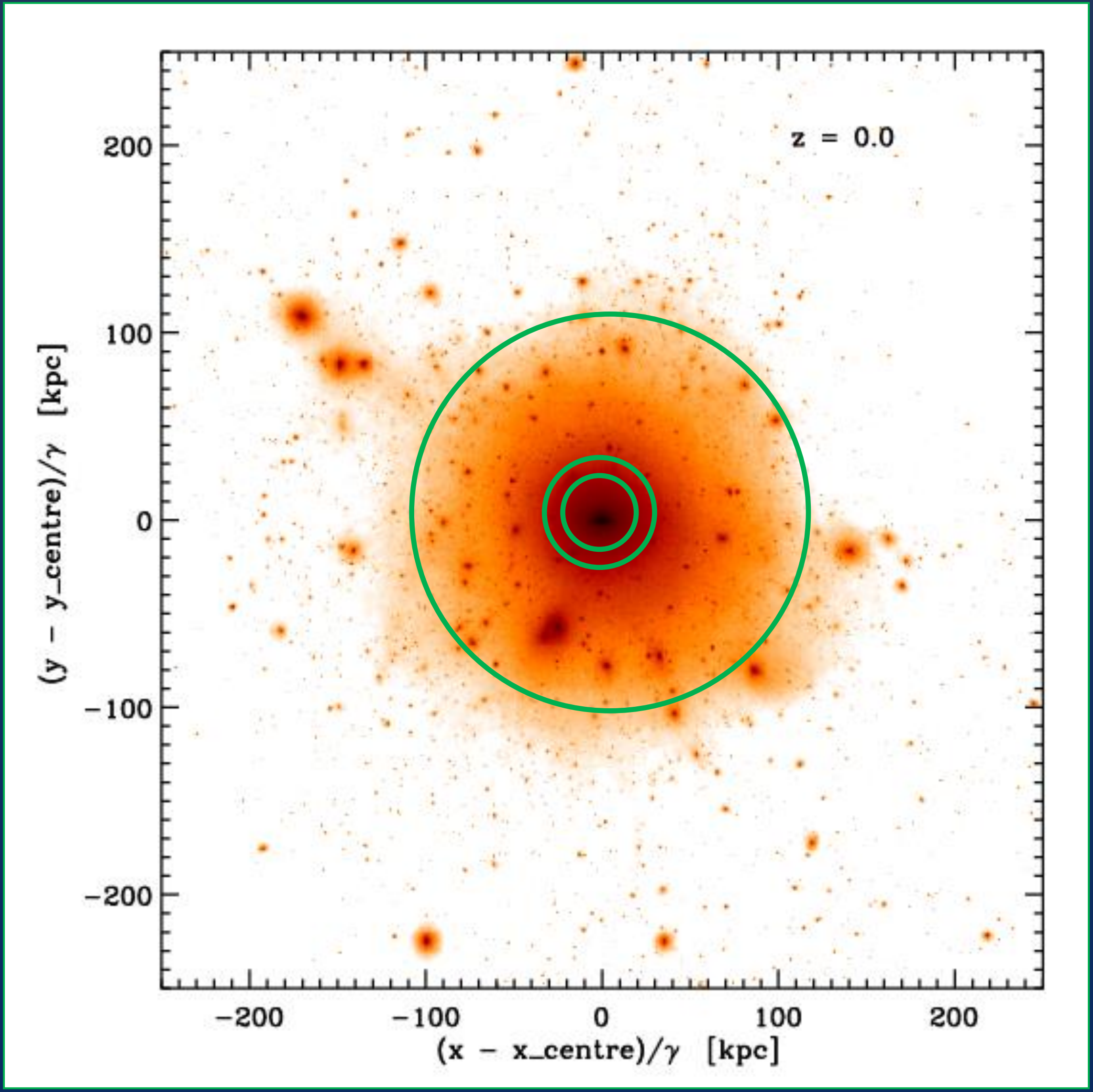


Spectroscopic Surveys of the Halo

- HK Survey
  B_{lim} ~ 15.5
  Reach for giants
~ 15-20 kpc

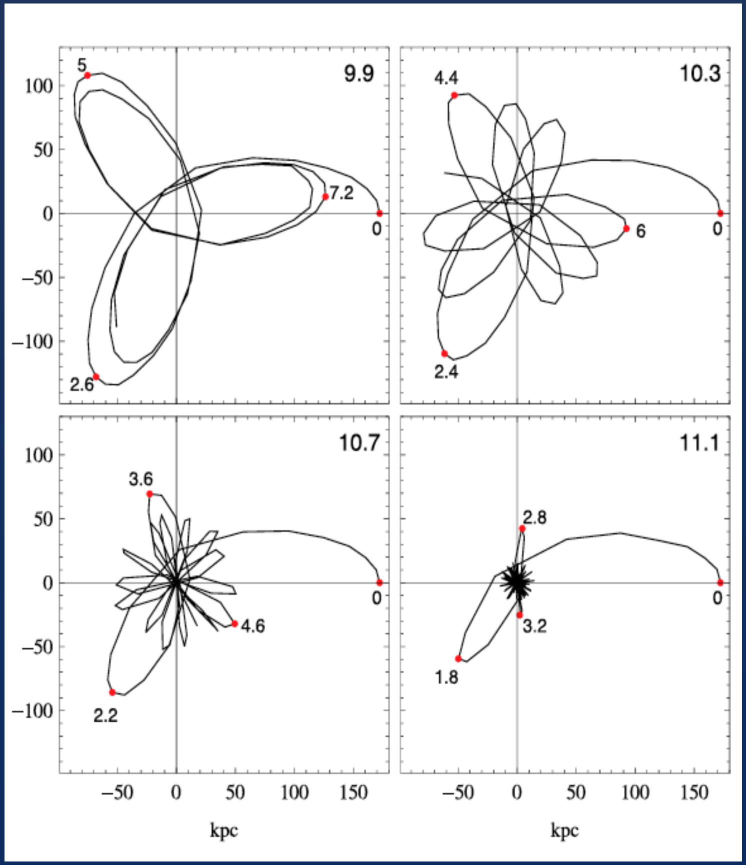
- Hamburg/ESO
  B_{lim} ~ 17
  Reach for giants
~ 25-30 kpc

- SDSS/SEGUE
  B_{lim} ~ 20-22
  Reach for giants
~ 100-150 kpc

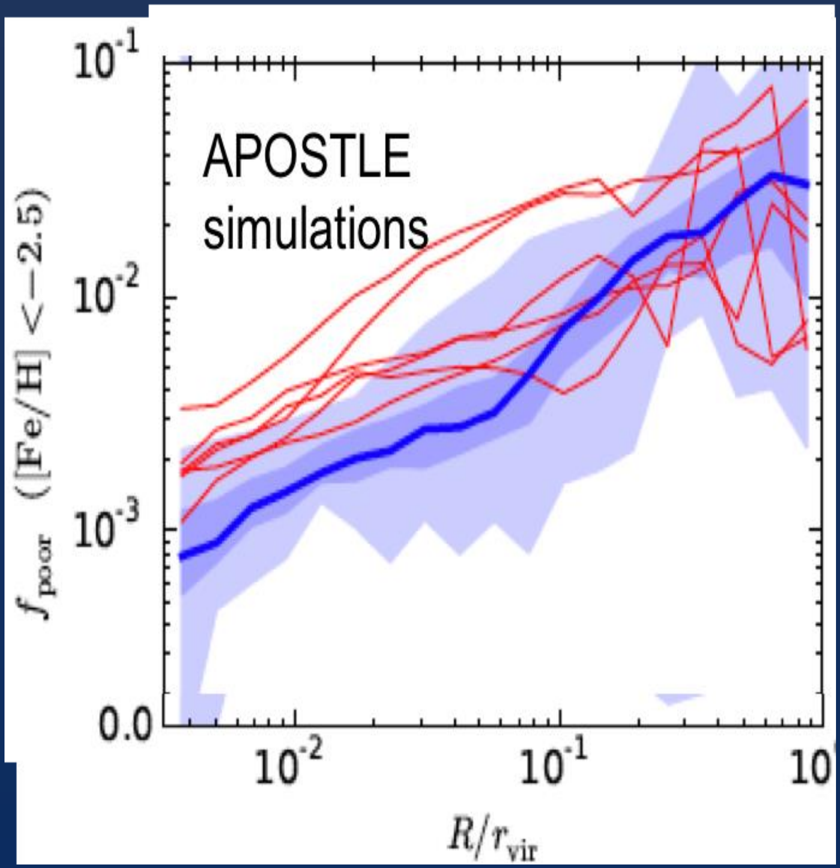


Where are the UMP Stars Hiding?

Amorisco+2016

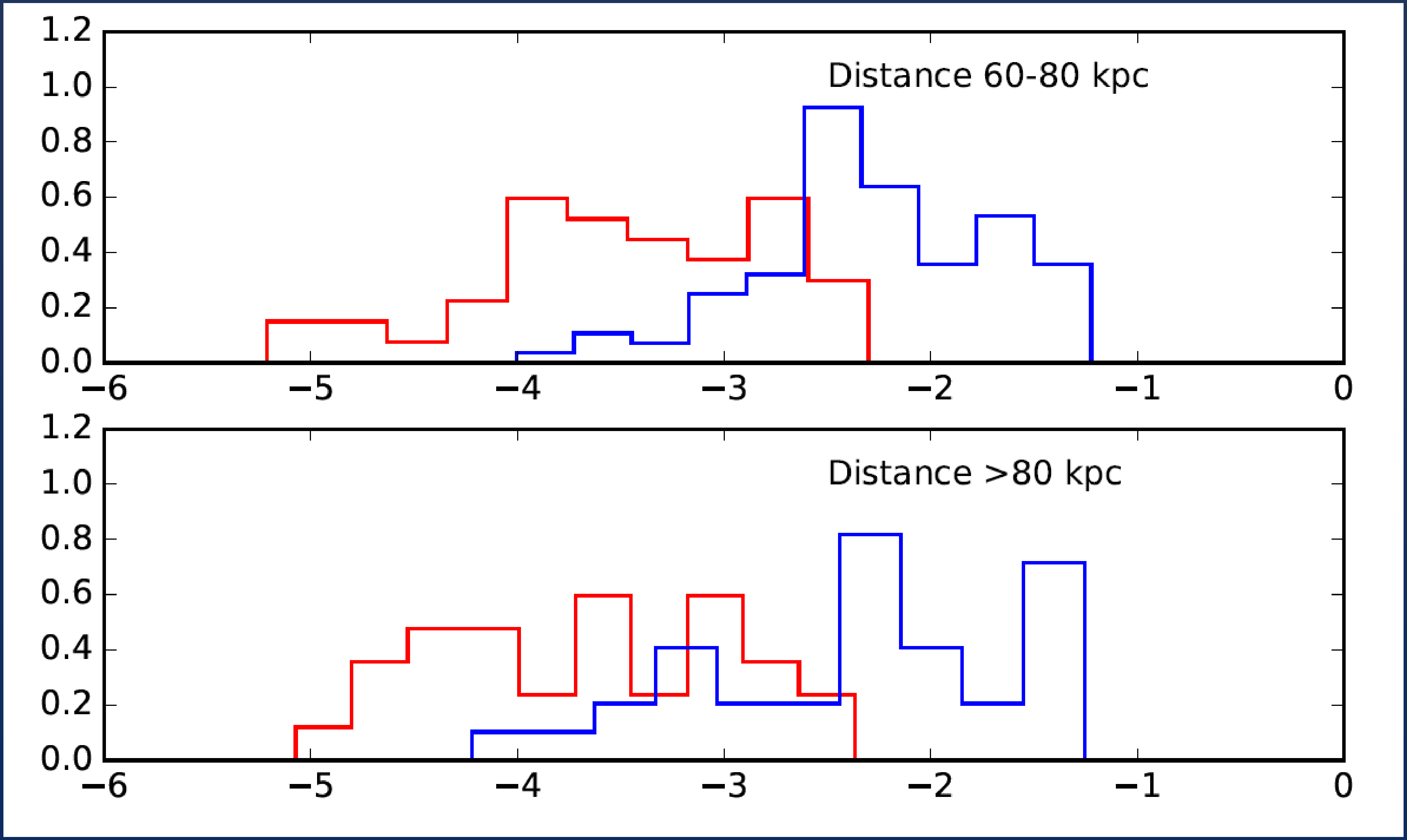


Starkenburg+2016



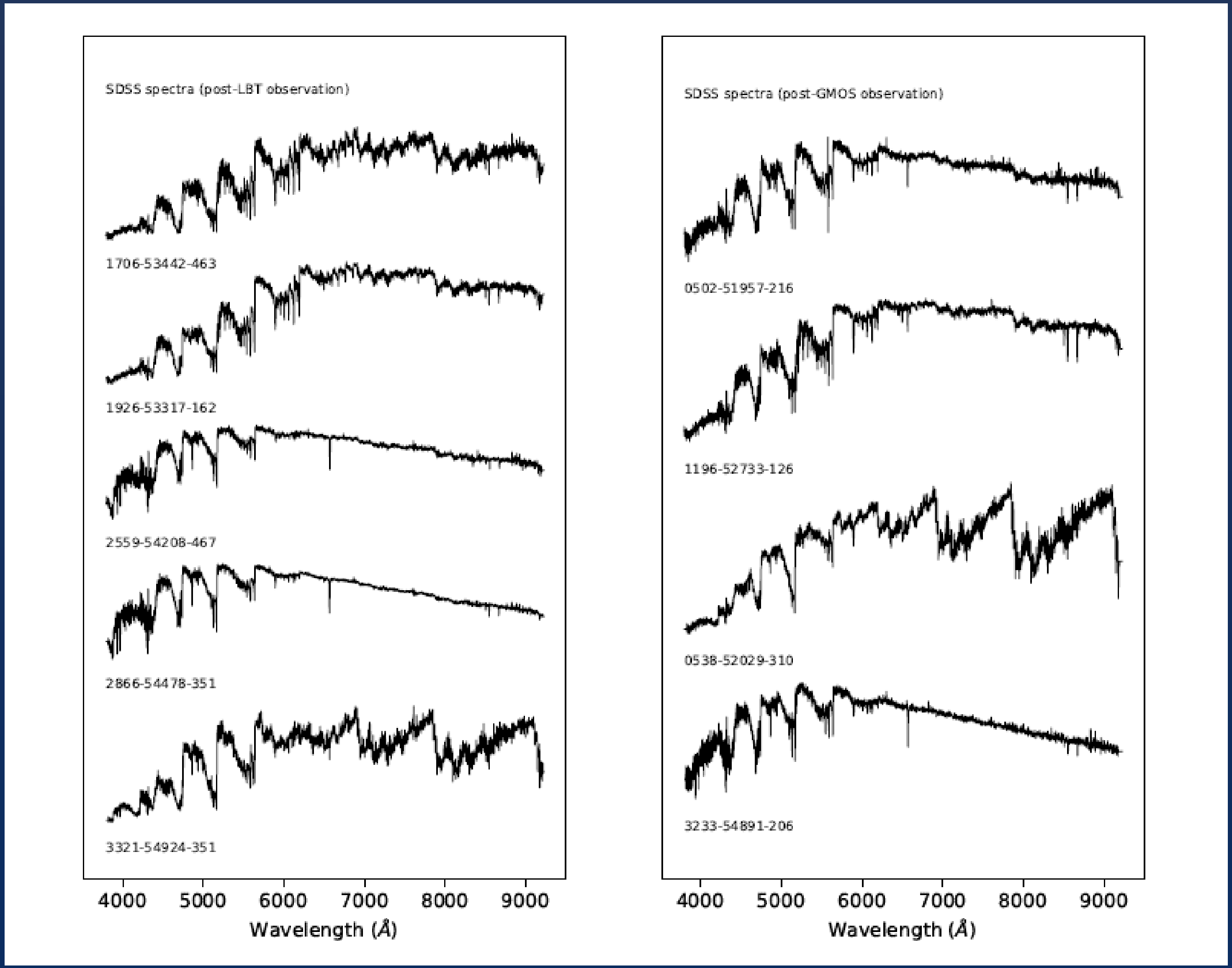
Low-mass mini-halos never penetrate to deep inside the halo

Where are the UMP Stars Hiding?



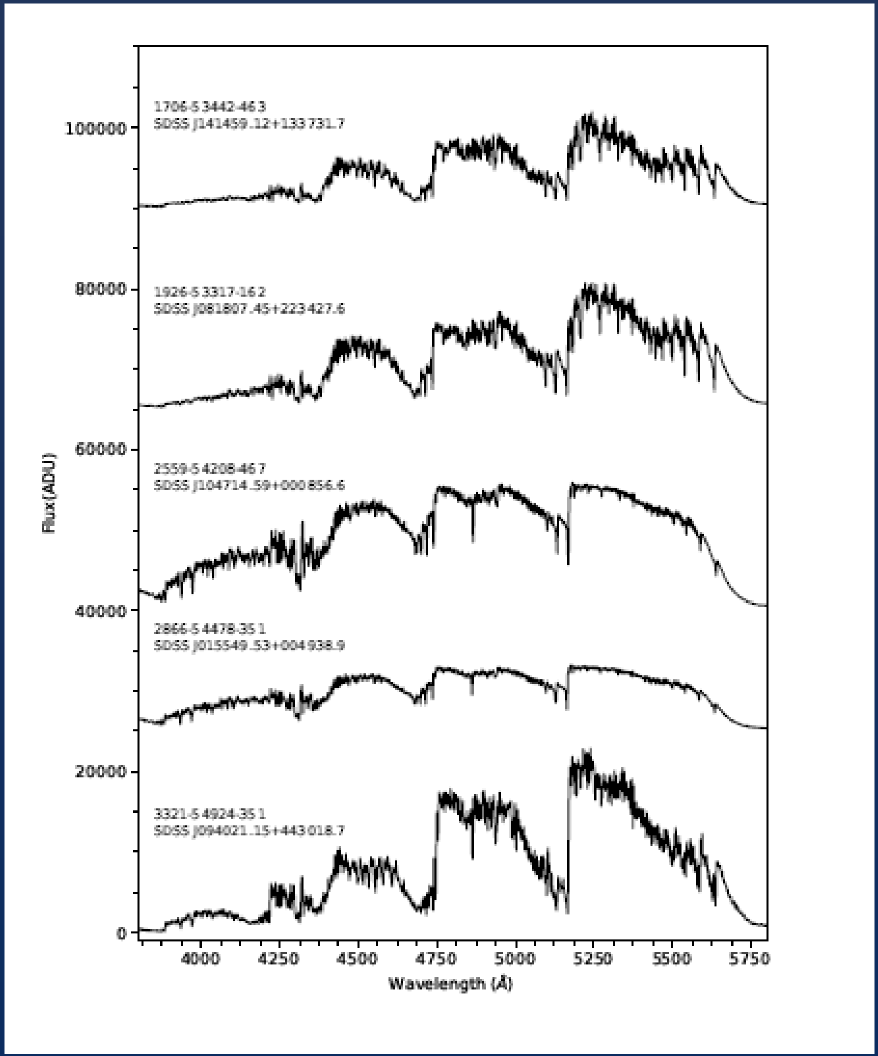
Apparent gradients in [Fe/H] for carbon-normal / CEMP stars

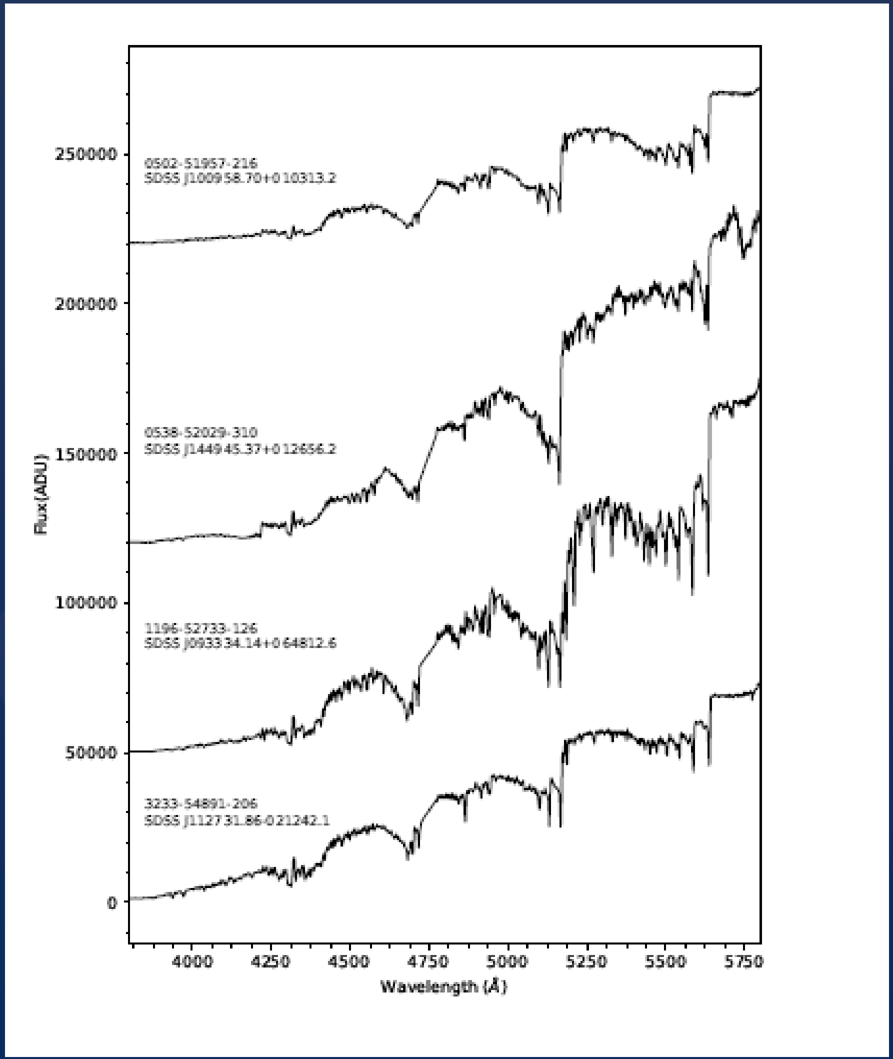
CEMP Stars at the Edge of the Milky Way



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

CEMP Stars at the Edge of the Milky Way

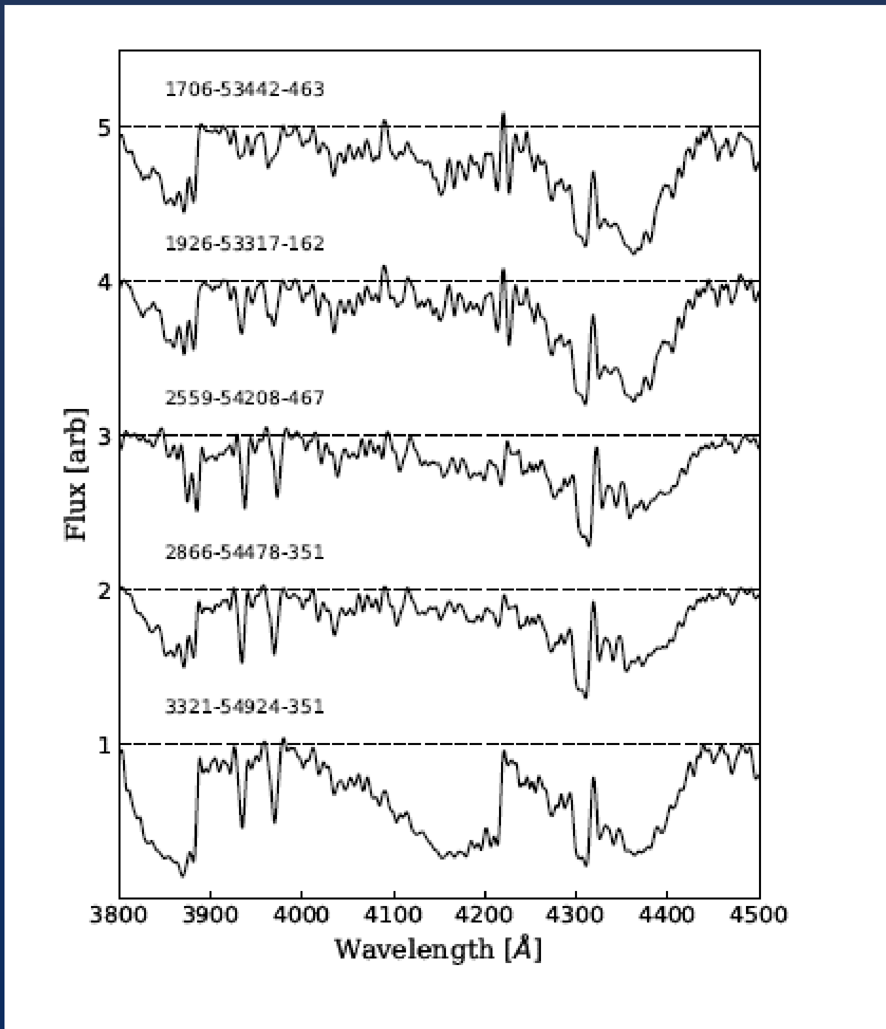




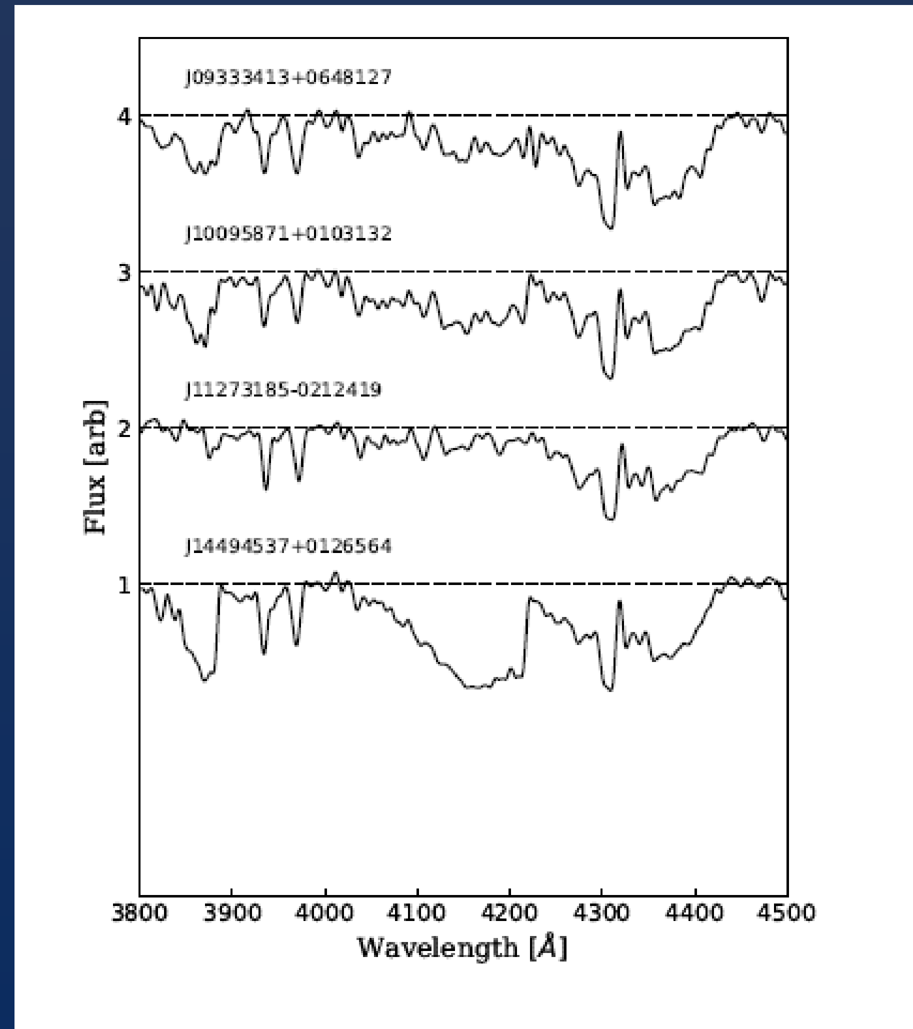
LBT/MODS Spectra

Gemini/GMOS Spectra

CEMP Stars at the Edge of the Milky Way



LBT/MODS Spectra



Gemini/GMOS Spectra

CEMP Stars at the Edge of the Milky Way

Table 2. Derived stellar parameters

Name	S/N		T_{eff}	log g	[Fe/H]	[C/Fe]	[N/Fe]	A(C)	$A(C)_{ec}$[a]	Subclass[b]	Distance[c]
	Ca H	CH band	(K)	(cgs)							(kpc)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
0502-51957-216			4870	1.50	-3.63	3.31		8.11			
0538-52029-310			4086	0.00	-3.48	2.32		7.27			
1196-52733-126			4450	0.63	-4.14	2.98		7.27			
1706-53442-463	46	88	3872	-0.33	-4.40	3.70					
1926-53317-162	59	109	3755	-0.50	-4.45	4.40*					
2559-54208-467	121	166	4836	1.43	-4.12	3.41		7.72			
2866-54478-351	87	119	4984	1.76	-3.92	3.90		8.41			
3233-54891-206			4880	1.52	-4.00	3.242		7.67			
3321-54924-351	82	130	4128	0.06	-3.67	3.50		8.26			

Present best estimates of stellar parameters – stay tuned