Carbon Enhanced Metal Poor (CEMP) Stars and the Halo System of the Milky Way

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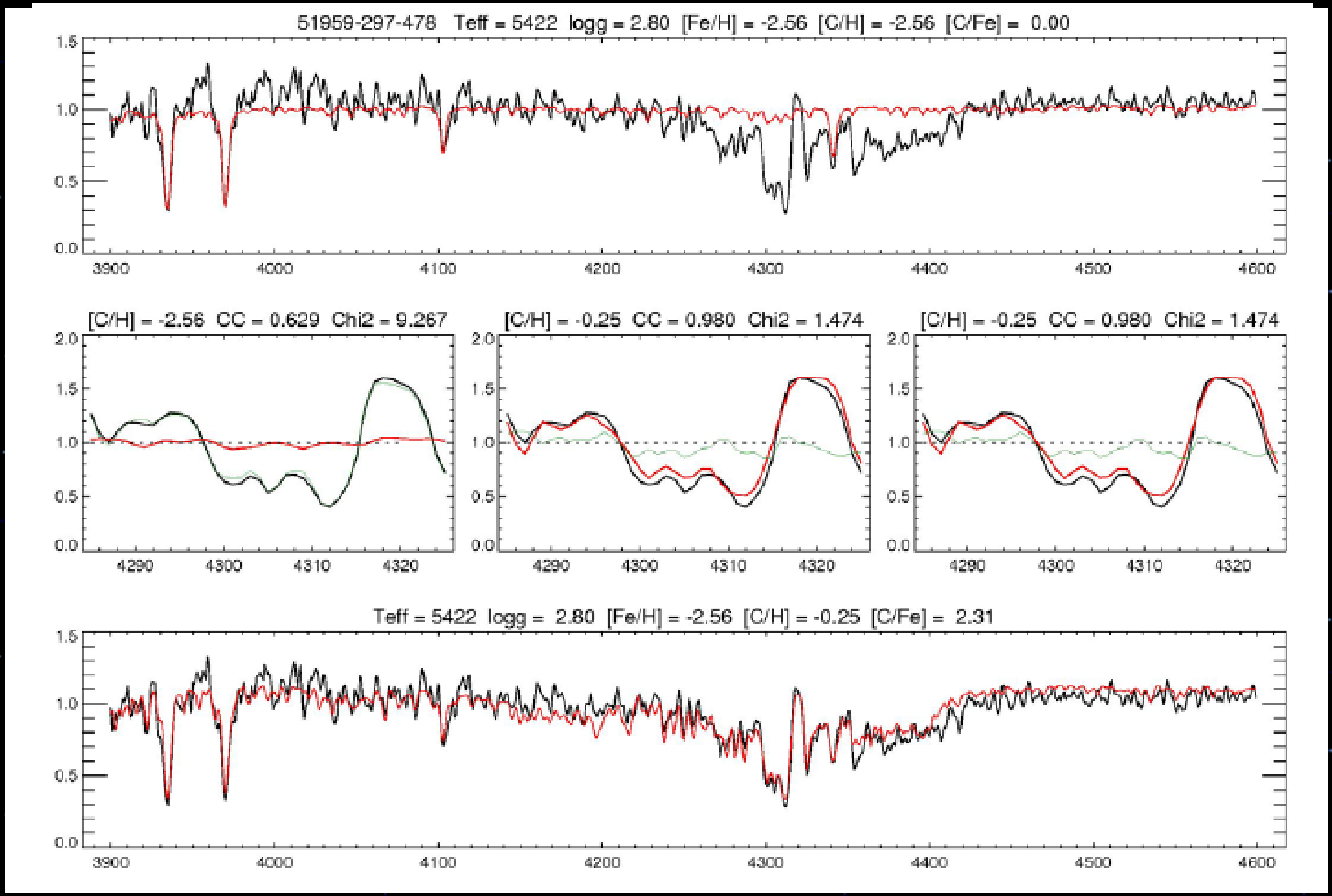
Carbon Enhanced Metal Poor Stars (CEMP)

CEMP = Carbon Enhanced Metal Poor Stars - Strong CH absorption bands



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 stars 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

- But Why ? – Carollo et al. (2012) suggest that it is population driven

CEMP stars contain useful information on the nature of nucleosynthesis in the early Galaxy.

Exploration of Nature's Laboratory for Neutron-Capture Processes

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

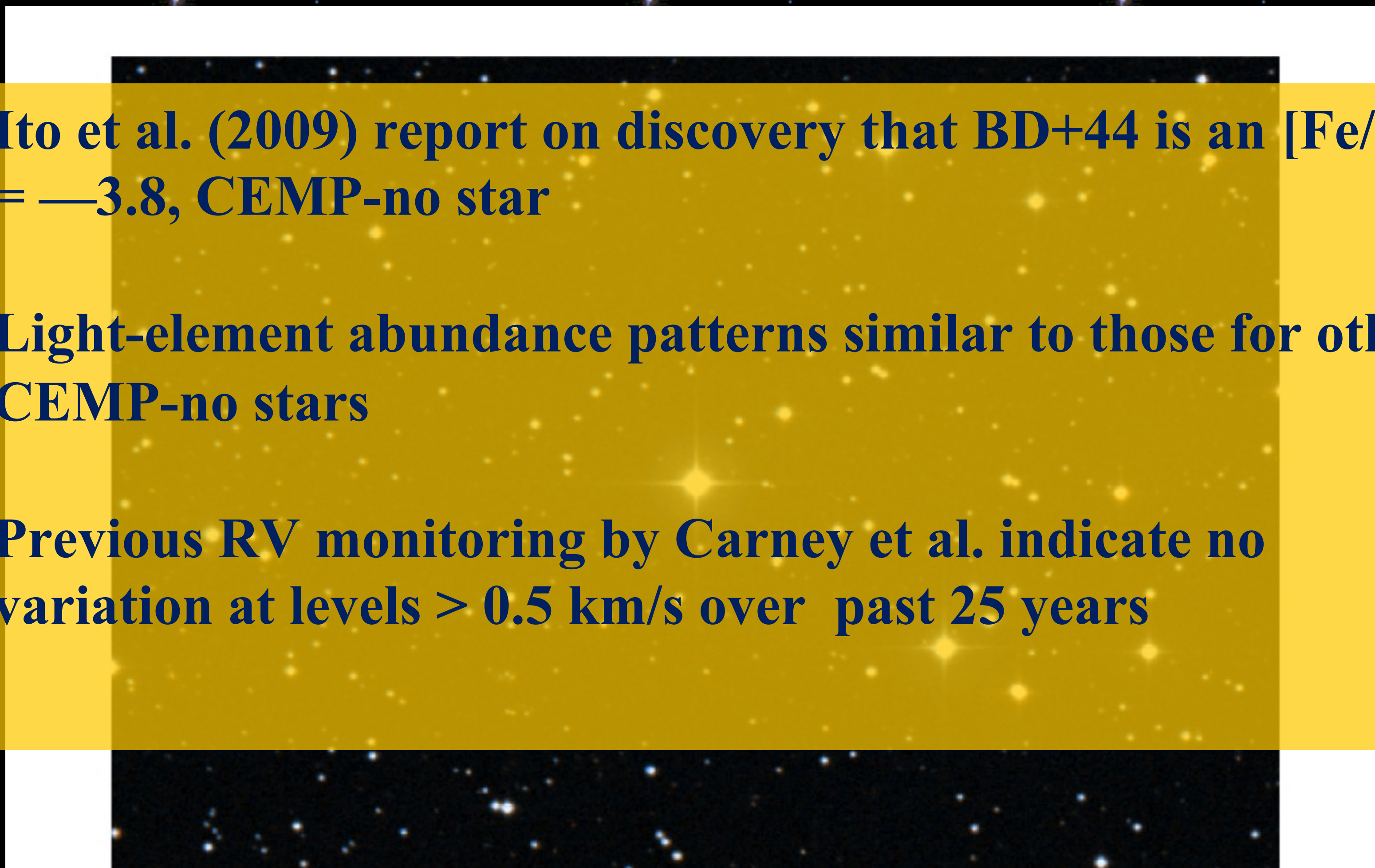
Beers & Christlieb ARAA (2005)

CEMP classes

CEMP-s: [C/Fe] > +1.0; [Ba/Fe] > +1.0; [Ba/Eu] > +0.5
Progenitor: Intermediate mass stars during AGB phase in a binary system

CEMP-no: [C/Fe] > +1.0 and [Ba/Fe] < 0
Progenitors:
•Faint Supernova Models (Umeda & Nomoto, 2003; Iwamoto et al. 2005)
•Nucleosynthesis in Rotating Massive Stars (Meynet 2006, and references therein)

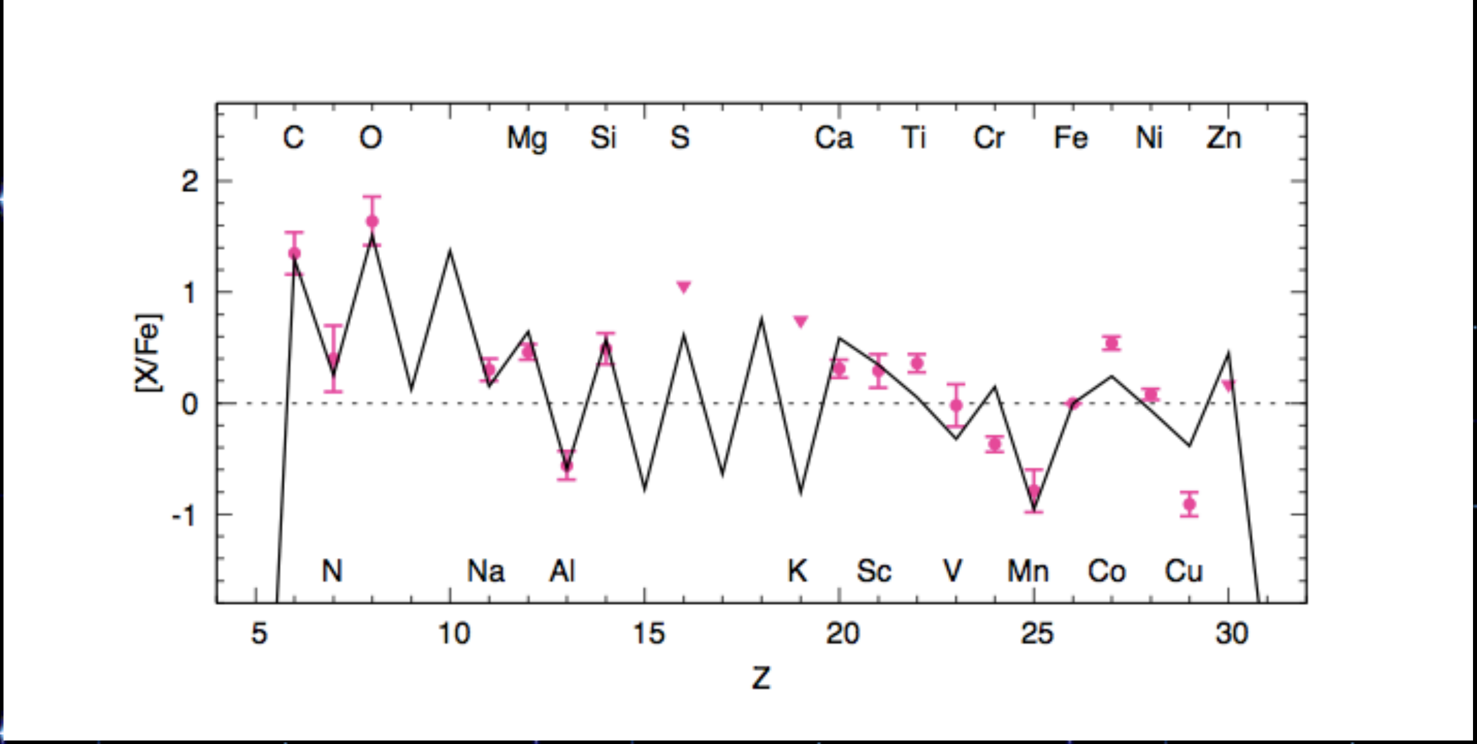
BD+44:493 – A 9th Magnitude Messenger from the Early Universe



- Ito et al. (2009) report on discovery that BD+44 is an [Fe/H] = —3.8, CEMP-no star
- 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

An Object of COSMOLOGICAL Significance with Diffraction Spikes

Abundance Pattern Compared to 25 M_o Faint Supernova Model



Not in a binary system: RV rms variation over 25 years is 0.73 km/s

Ito et al. (2013) : CEMP-no → Carbon excess probably form faint supenova

The Halo System of the Milky Way: The CEMP stars connection

Chemistry of the Halo System: The CEMP stars connection

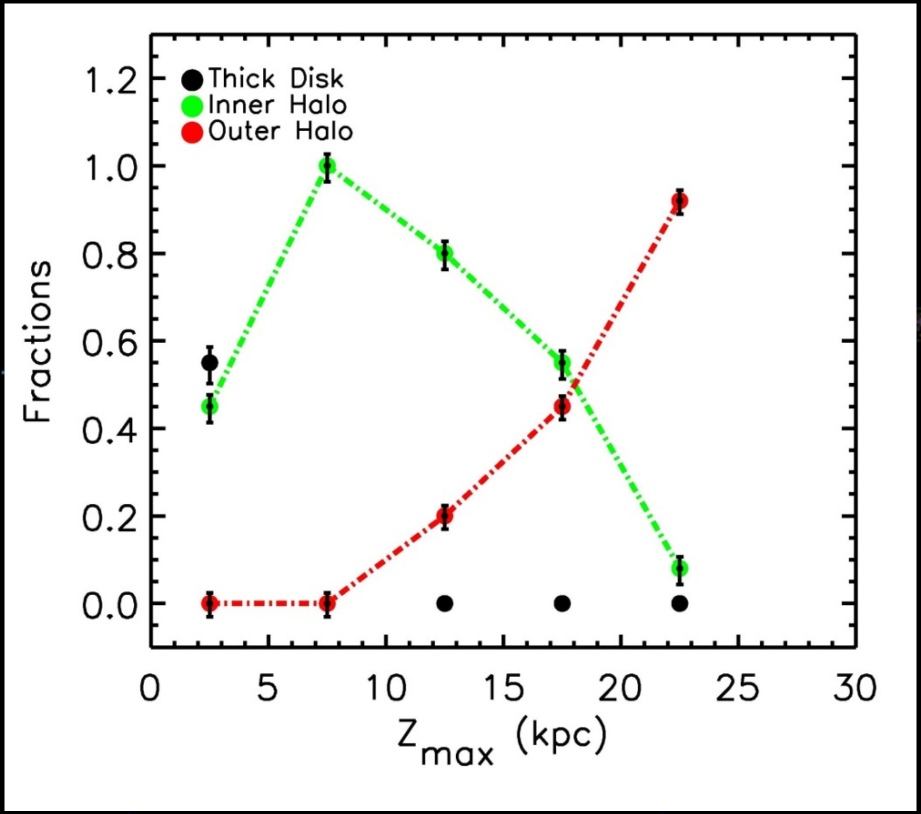
Carollo D. et al., Nature 2007, Vol. 450, 1020-1025
(See also Carollo D. et al. 2010 and Beers et al. 2012)

Halo → Halos

- **Inner Halo:**
  - Dominant at R < 10-15 kpc
  - Highly eccentric orbits
  - Slightly Prograde
  - Metallicity peak at [Fe/H] = -1.6
- **Outer Halo:**
  - Dominant at R > 15-20 kpc
  - More uniform distribution of eccentricity
  - Highly retrograde orbits
  - Metallicity peak around [Fe/H] = -2.2

Fractions of Inner and Outer Halo

(Carollo et al. 2010, ApJ, 712, 692)



Stellar Fractions, F_{IN} and F_{OUT}, as a function of Z_{max}

The value Z_{max} ~ 15-20 kpc is the inversion point!

Inner halo stars have rapo < 15 kpc
Outer Halo stars have rapo > 15 kpc

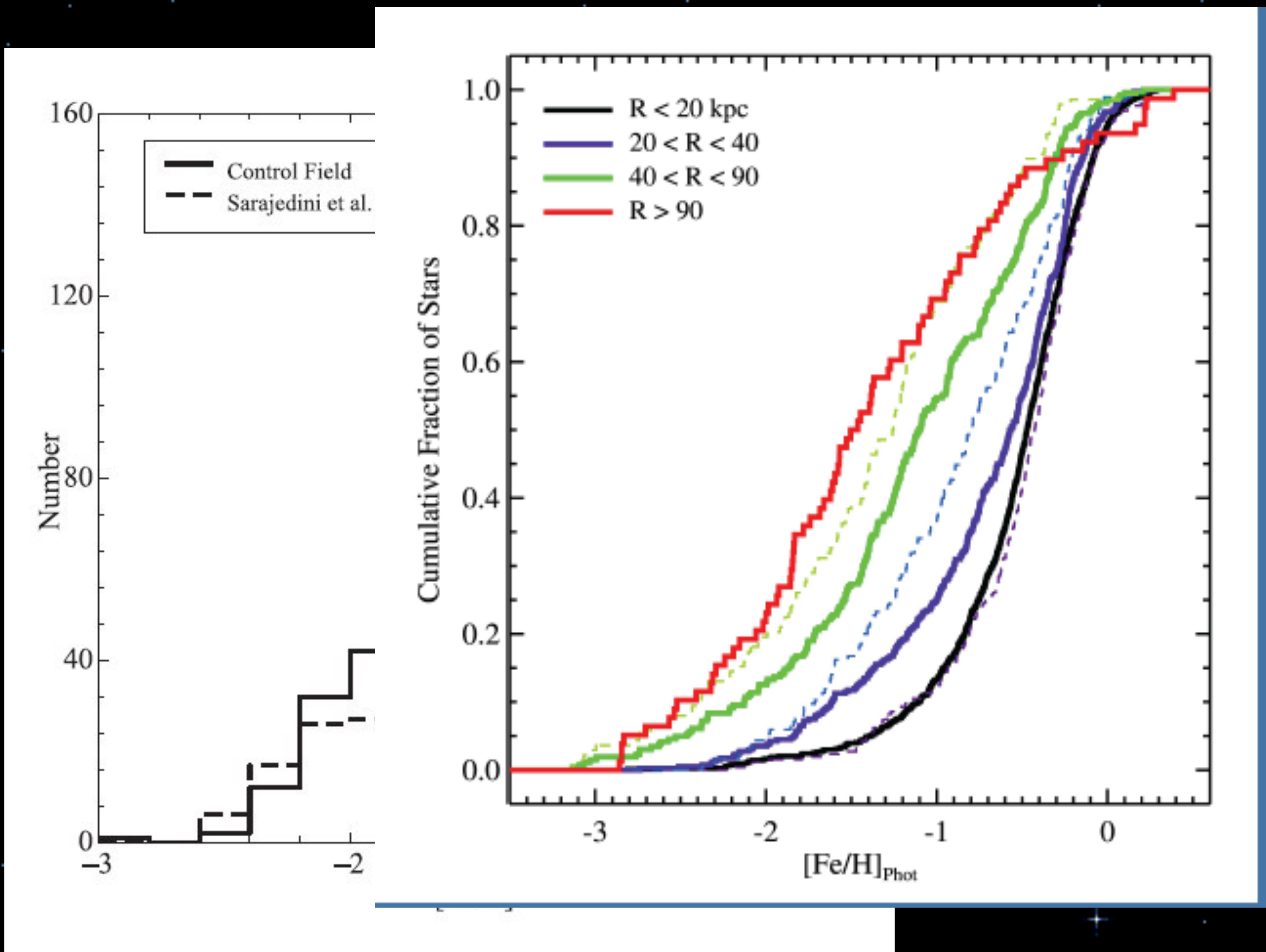
The dual halo: observational evidences from other surveys

- ✓ Nissen & Schuster (2010): Solar Neighbourhood Sample
- ✓ de Jong et al. (2010) : Segue Vertical Photometry Stripes
- ✓ Kinman et al. (2012): BHB and RR-Lyrae
- ✓ An et al. 2013: Equatorial Stripe 82
- ✓ Hattori et al. 2013: BHB stars in SDSS/SEGUE

M31: Two Metallicity Peaks in RR-Lyrae

Sarajedini et al. 2012

Gilbert et al. 2013



allicity distribution
t [Fe/H] ~ -1.3 and

: in situ stellar

eak: accreted

t with the findings
al. (2007, 2010).

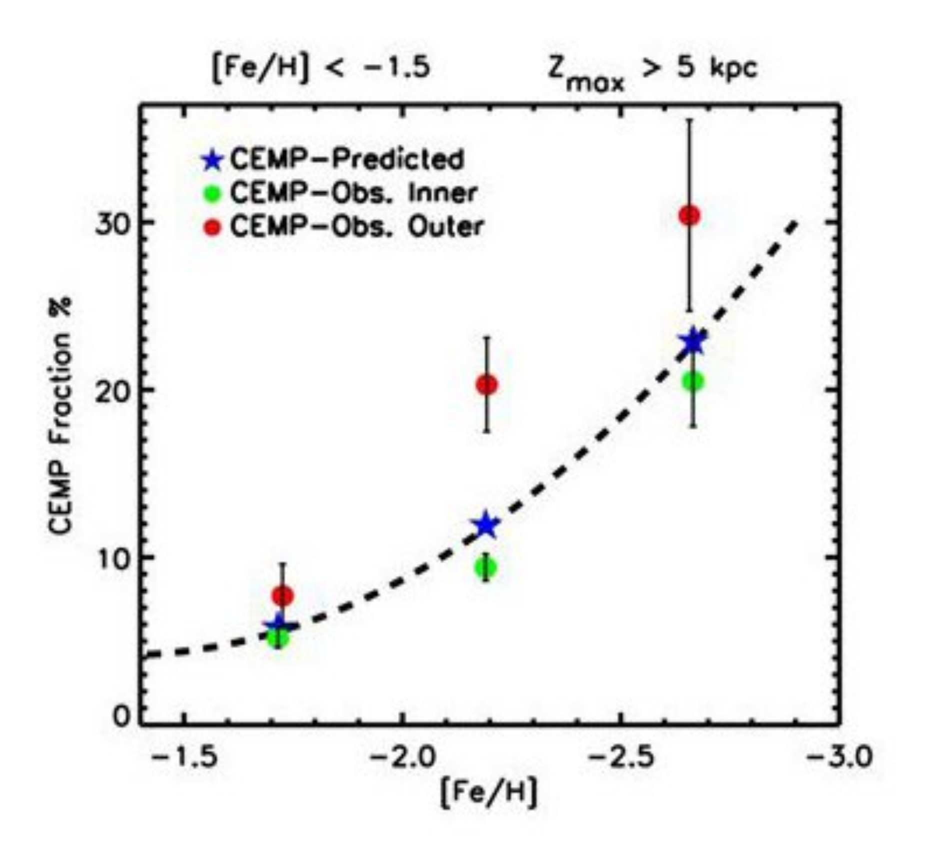
The Dual Halo in the High Resolution Simulations

Different chemo-cosmological codes are in agreement

Simulated stellar halos are formed by a combination of in-situ and debris stars from accreted satellites (Zolotov et al. 2009, Font et al. 2011, McCarthy et al. 2012, Tissera et al. 2012,2013)

→ Simulated stellar halo exhibit a shift in metallicity as a function of the galactic radius
→ Simulated stellar halo shows a shear in the mean rotational velocity between in situ and accreted halo components

CEMP Stars in the Inner and Outer Halo
(Carollo D. et al. 2012 ApJ, 744, 195)



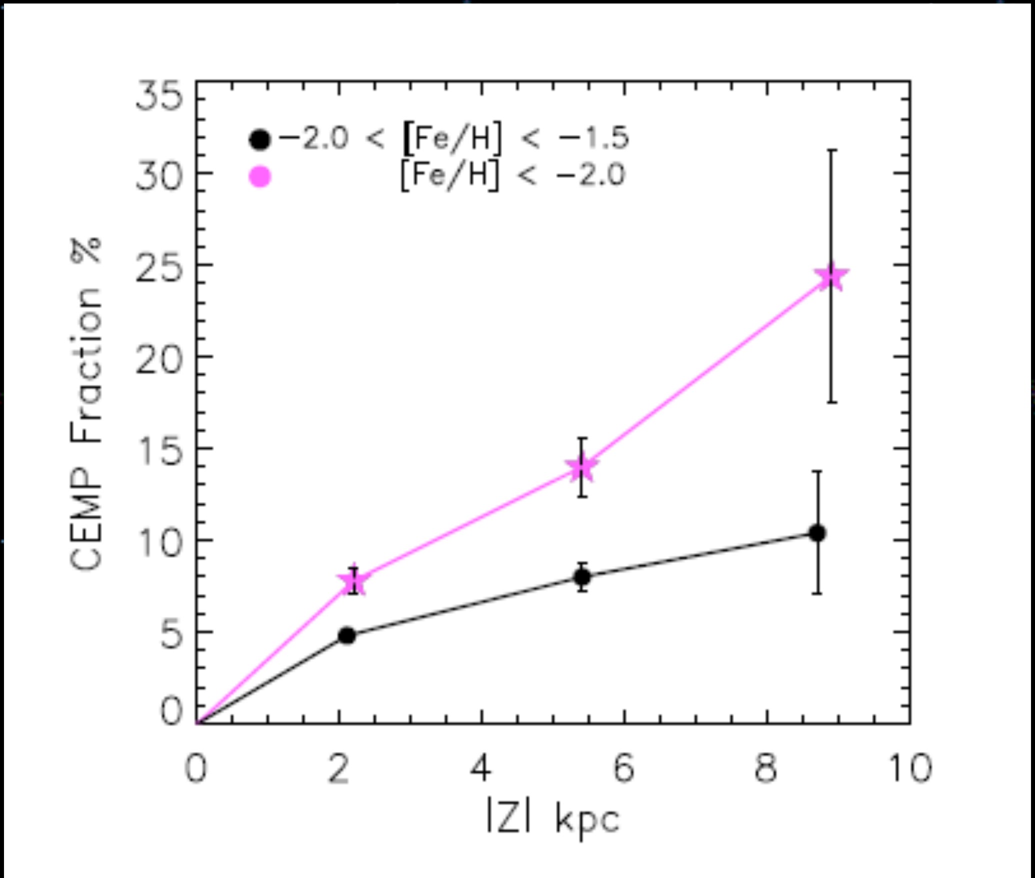
Observed increases of CEMP stars as [Fe/H] decreases

At -2.5 < [Fe/H] < -2.0:

$$\mathrm{CEMP}_{Outer-Halo} \approx 2 \times \mathrm{CEMP}_{Inner-Halo}$$

The higher fraction of CEMP stars is driven by the outer-halo population.

Global CEMP Fraction vs. |Z|



Clear increase of *f* (CEMP) with |Z|

(not expected for single halo)

Fractions of CEMP-no and CEMP-s in the inner-outer halo

Carollo D., Freeman, K. et al., 2013, ApJ, submitted

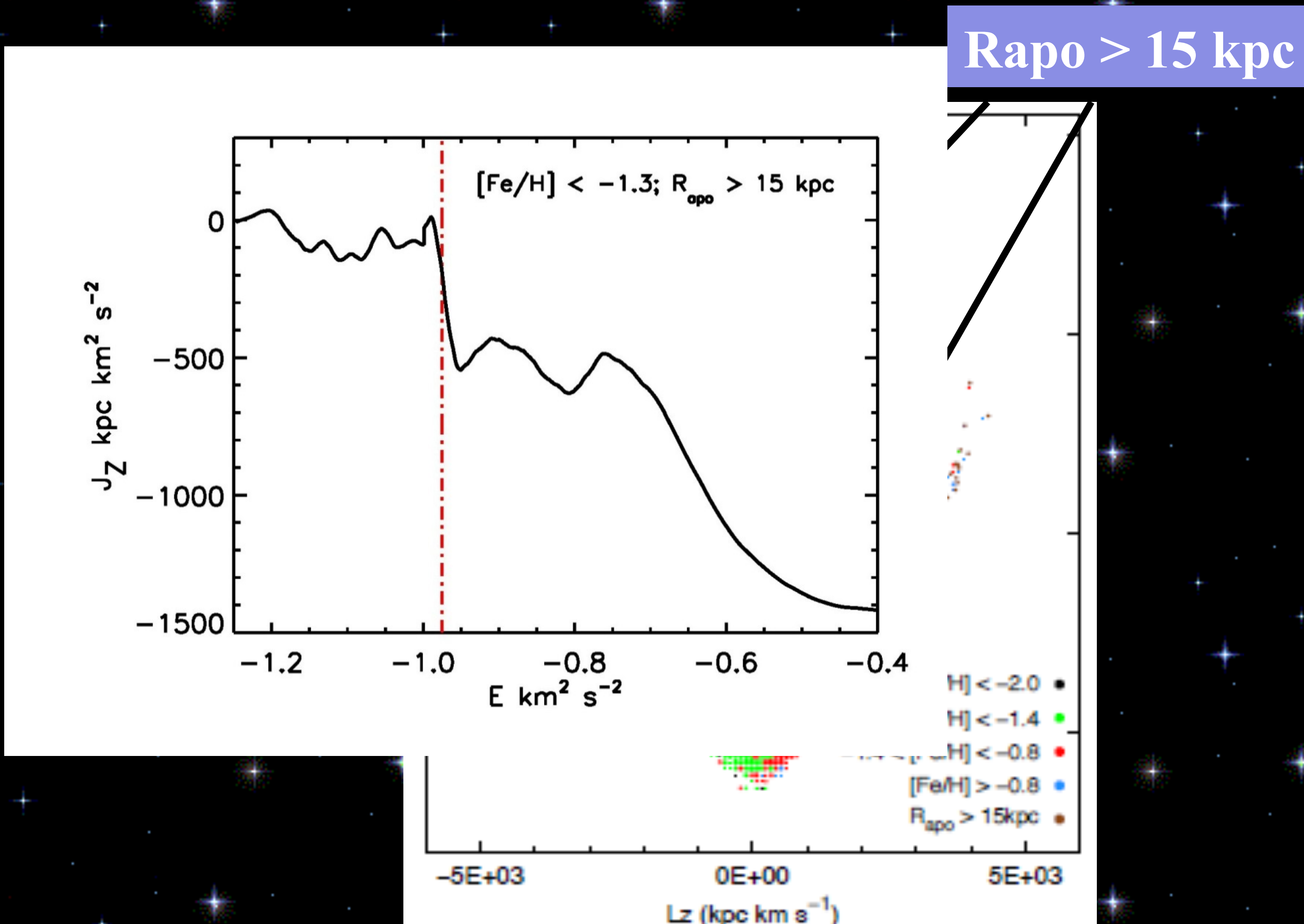
- Sample of 300 stars with high resolution spectroscopy obtained with Subaru and other sources (Aoki et al. 2013, Norris et al. 2013 and references therein).

- High res. suitable to get the Barium signature
  → CEMP-s/CEMP-no

- Inner/Outer Halo Membership assigned by using integrals of motion and orbital parameters (apo-galactic distance)

IHP-OHP Memberships by using Integrals of Motion

Carollo D., Freeman, K. et al., 2013, ApJ, submitted



IHP-OHP memberships by using Integrals of Motion

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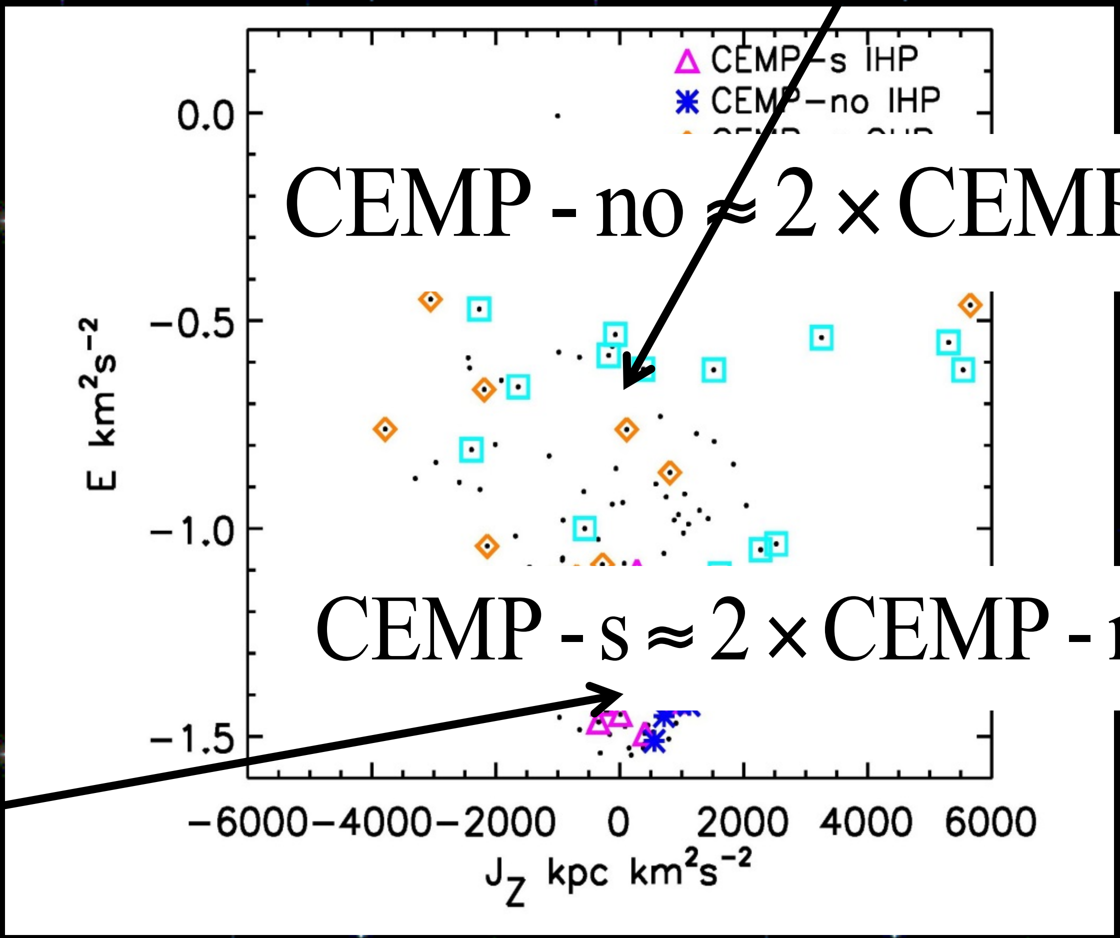
OHP



$$\text{CEMP - no} \approx 2 \times \text{CEMP - s}$$

$$\text{CEMP - s} \approx 2 \times \text{CEMP - no}$$

IHP

Implication for the Formation of the Halo System

Different Spatial Distributions
Different Kinematics
Different Chemical Composition (MDFs)

→ Distinct Astrophysical Origin
→ Crucial to Understand the Formation and Subsequent Evolution of the Milky Way

Inner Halo: Dissipative merger of few massive sub-Galactic fragments formed at early stage, mainly in situ stars

Outer Halo: Dissipationless chaotic merging of small sub-systems within a pre-existing Dark Matter Halo, mainly accreted stars

Implication for the formation of the Halo System

- ✓ CEMP-s: formed in binary systems with an intermediate mass star M = 1.5-6$M_{()}$ (significant production of neutron-capture elements)

- ✓ CEMP-no: origin much less clear!

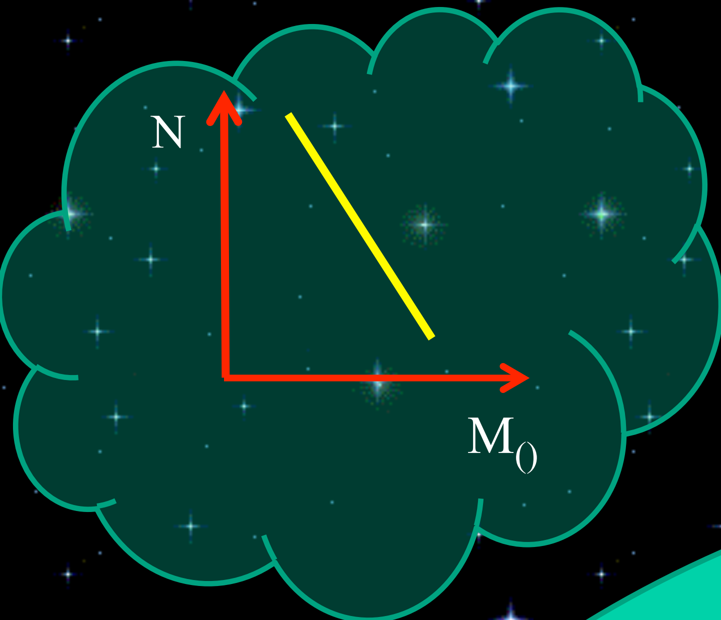
Possible scenarios: Faint supernova or massive fast rotating stars

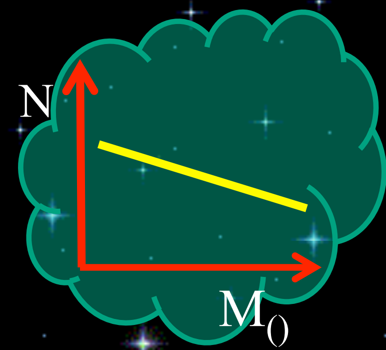
- ✓ Lets consider the mass transfer scenario for the CEMP-s and the Faint-SNe for the CEMP-no → the former predominate in the inner-halo population, the latter are more numerous in the outer-halo population

- ✓ CEMP-s and CEMP-no phenomena vary with the mass of the stars that produced the Carbon → link with the IMF

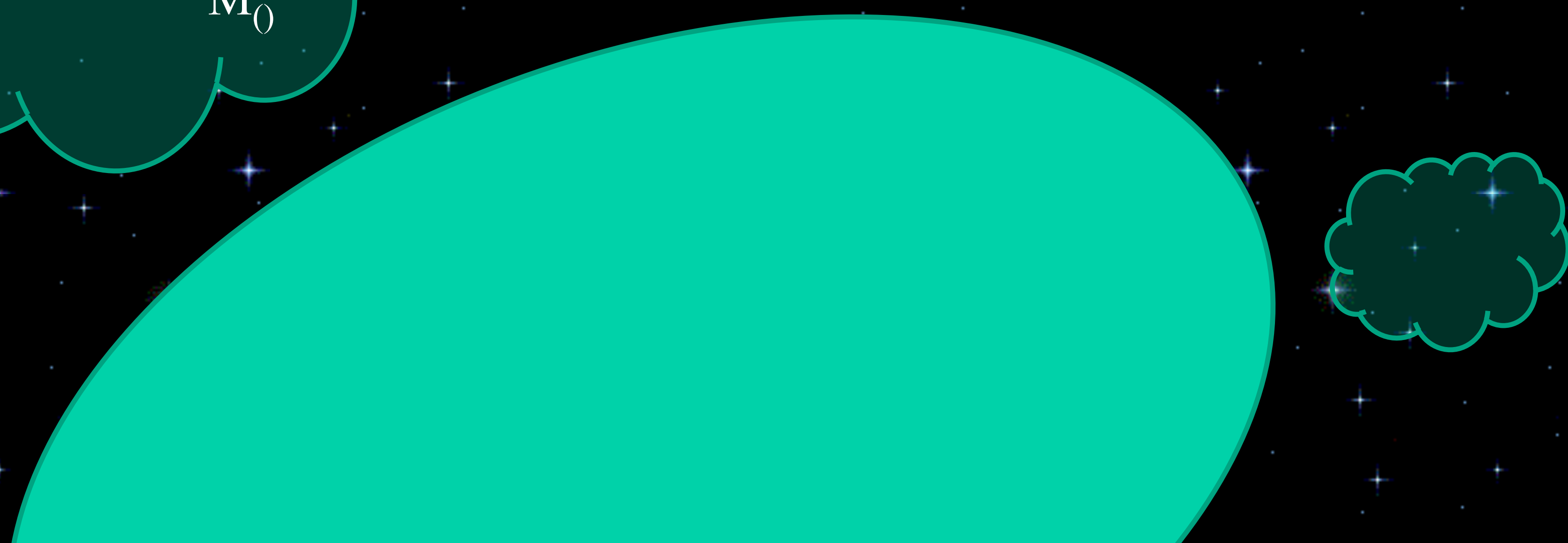
Salpeter IMF: slope changes from α = -2.35 to α = -1.5

Inner-Halo progenitors:
IMF Steeper





Outer-Halo progenitors:
IMF Flatter



Implication for the formation of the Halo System

- ✓ Higher mass progenitors had steeper IMF and higher frequency of CEMP-s stars
- ✓ Lower mass progenitors had flatter IMF and higher frequency of CEMP-no stars
- ✓ Trend confirmed in HST studies of the IMF in the SMG and two UFDs satellites of the Milky Way (Kalirai et al. 2013, Brown et al. 2012 Geha et al. 2013)
- ✓ More observations and theoretical works needed to confirm this scenario

CEMP-no stars in the Outer Halo:

Do they have the chemical imprint of the first generations of stars?

What about galaxies at high redshift?

Connections with high-z DLA Systems

Carbon enhancement in Damped Lyman Alpha system with [Fe/H] ~ -3, [C/Fe] ~ 1.5, observed at z ~ 2.3 (Cooke et al. 2011b)

→ Suggests possible connections between these high redshift galaxies and the early building blocks of the Milky Way –like galaxies

→ Initial chemical composition of the gas from which CEMP stars subsequently formed

The Milky Way from Death Valley