CARBON-ENHANCED METAL-POOR STARS
in the Milky Way and dwarf galaxies

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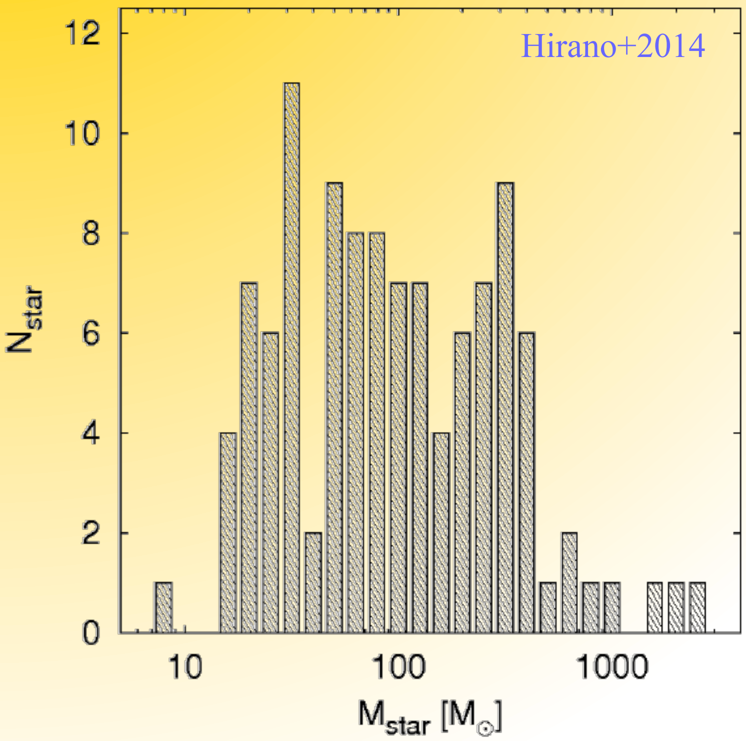
"Reconstructing the Milky Way history"

Bad Honnef, June 4, 2015

LIVING FOSSILS OF THE FIRST STARS

e.g. Omukai&Nishi98;Abel,Brian&Norman 02;Bromm+02;Omukai&Palla03;Bromm & Loeb04;Tan&McKee04;O'Shea&Norman06 McKee&Tan08;Ripamonti+02;Schleicher+09;Turk+09/11;Yoshida+06/08;Hosokawa+11/15;Clark+11;Greif+12;Hirano+14/15..

FIRST STARS



$M_* > 10\ M_\odot$

$\tau_* < 20 \times 10^6$ years

Exact mass range? IMF ?

The first stars are predicted to form at z ~ 20-30 in $M \approx 10^6\ M_\odot$ minihaloes $T_{vir} < 10^4$ K

The microphysics of H_2 sets the scale of the proto-stellar clouds $M_J \approx 700\ M_\odot$

Complications in the next accretion phase :

e.g. Radiative feedback Hosokawa+11/15; Hirano+14

Disk fragmentation Greif+12

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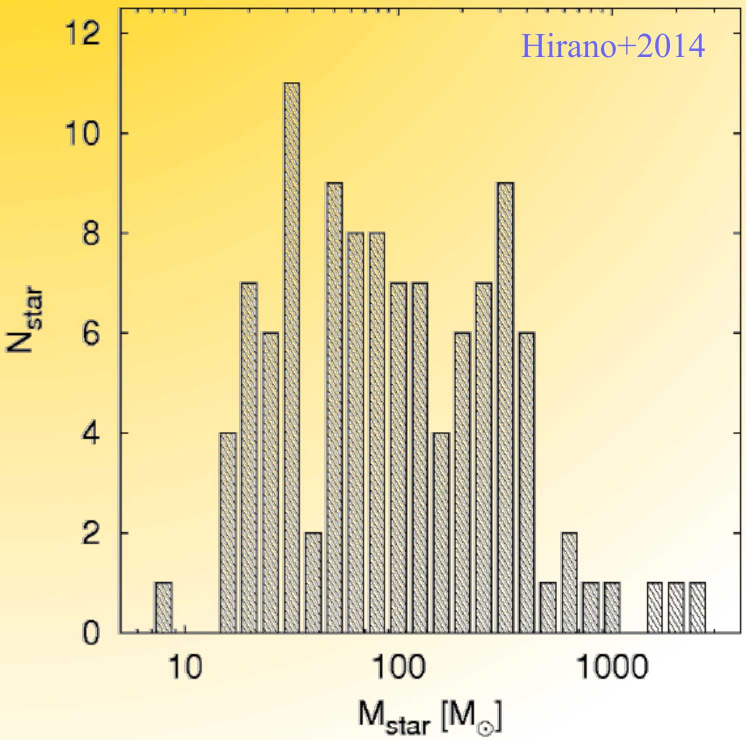


$M_* > 10\ M_\odot$

$\tau_* < 20 \times 10^6$ years

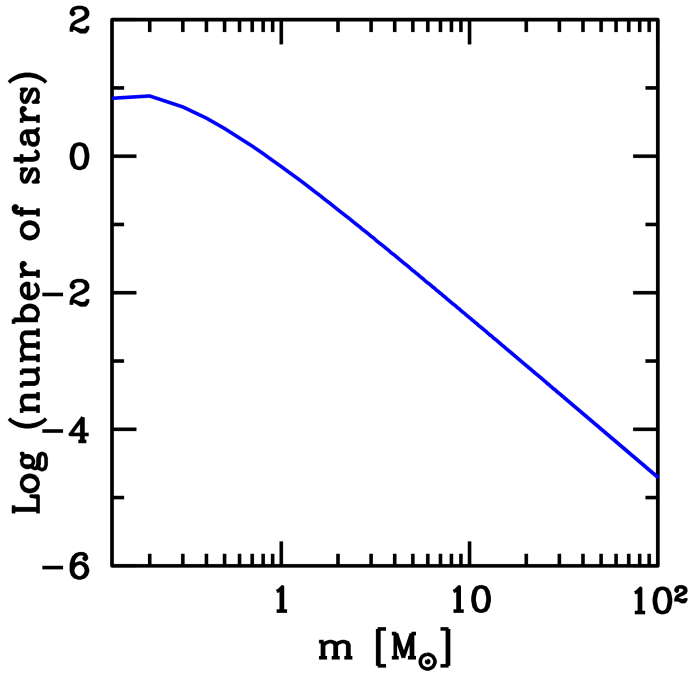
Exact mass range? IMF ?

$Z_{cr} = 10^{-5\pm1} Z_\odot$

e.g. Bromm+01;Omukai+01/05; Schneider+02/03/06/10

METALS & DUST

TODAY STARS



Salpeter-like IMF

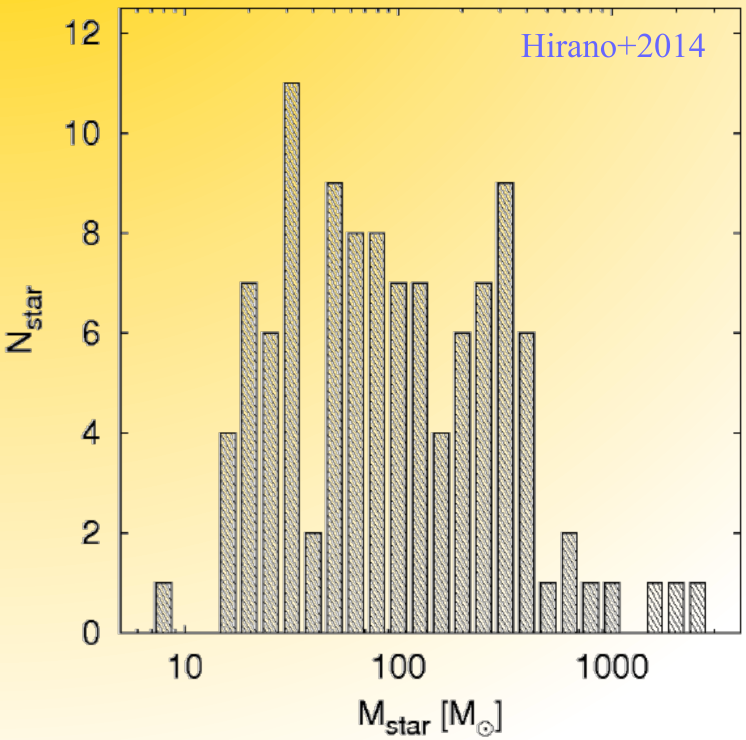
$M_* = (0.1\text{-}100)\ M_\odot$

$\tau_* > 14 \times 10^9$ years

LIVING FOSSILS OF THE FIRST STARS

e.g. Omukai&Nishi98;Abel,Brian&Norman 02;Bromm+02;Omukai&Palla03;Bromm & Loeb04;Tan&McKee04;O'Shea&Norman06 McKee&Tan08;Ripamonti+02;Schleicher+09;Turk+09/11;Yoshida+06/08;Hosokawa+11/15;Clark+11;Greif+12;Hirano+14/15..

FIRST STARS



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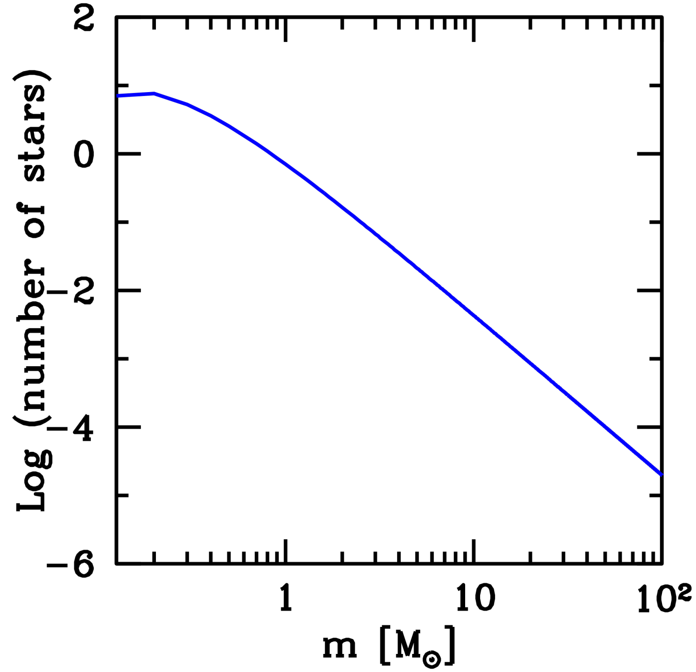
TODAY STARS



Salpeter-like IMF

$M_* = (0.1\text{-}100)\ M_\odot$

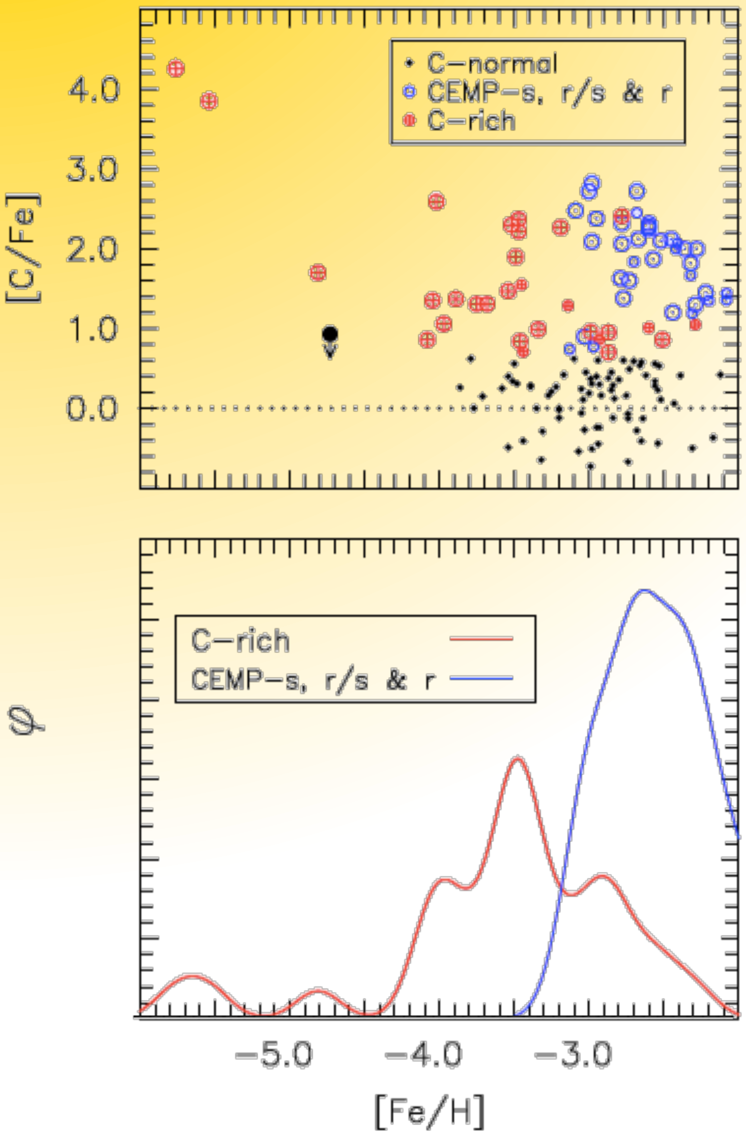
$\tau_* > 14 \times 10^9$ years

WE CAN OBSERVE THEM TODAY

CARBON-ENHANCED STARS IN THE GALACTIC HALO

e.g. Christlieb+02; Frebel+05; Caffau+11; Keller+14; Lucatello+05; Beers & Christlieb 05; Aoki+07; Lee+13; Bonifacio+15

Norris+2013



CEMP stars : [C/Fe] > 0.7

CEMP-s: enriched in s-process neutron capture elements (Ba)

CEMP-r: enriched in r-process neutron capture elements (Eu)

Mass accretion from an AGB companion
(> 80% in binary systems Lucatello+05; Starkenburg+14)

CEMP-no: no enhancement of Ba or Eu
No binary systems

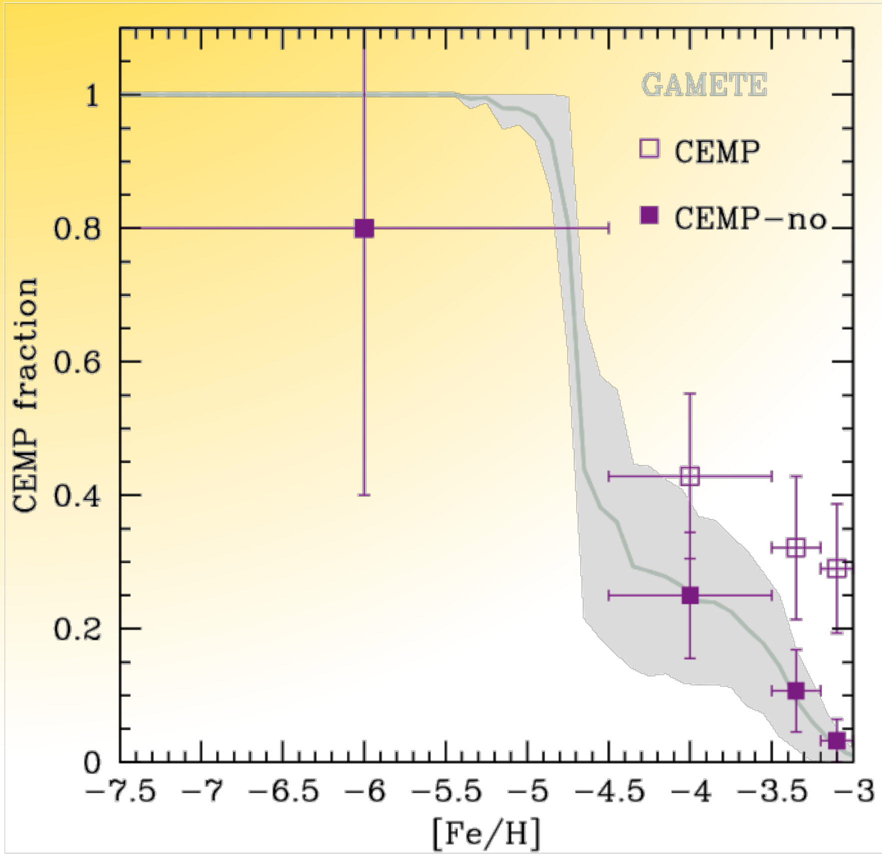
Imprint of *primordial Faint SN with mixing and fallback* Umeda & Nototo 03; Iwamoto+05; Joggerst+09; Marassi+14

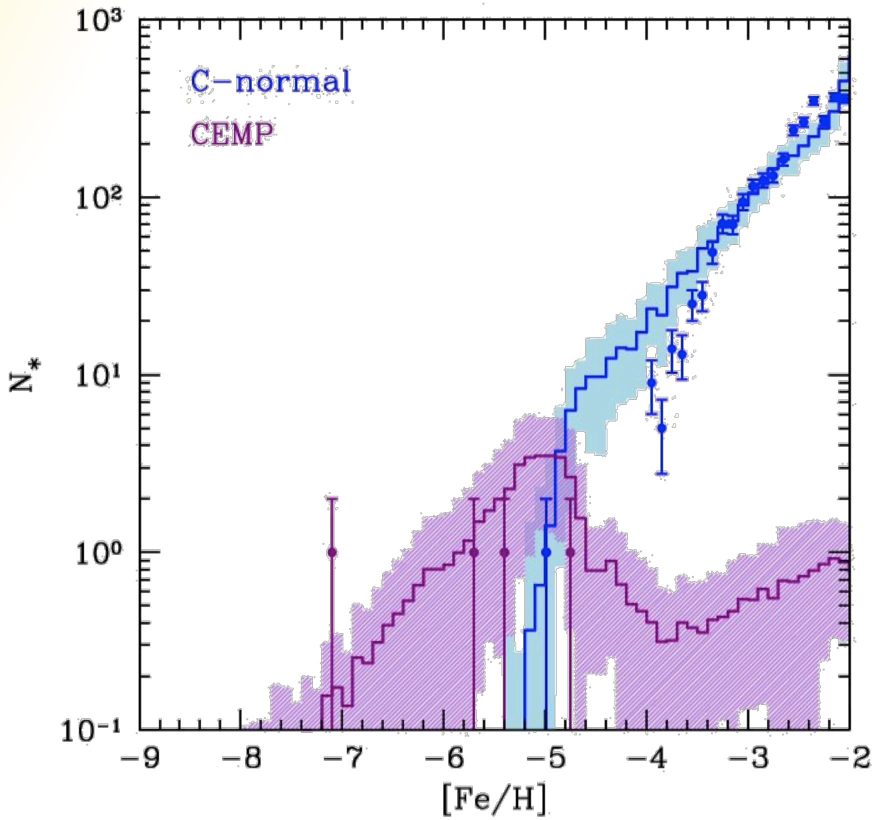
MERGER TREE MODEL FOR THE EARLY MILKY WAY FORMATION

GAlaxyMergerTree&Evolution (GAMETE): Salvadori+07/08; Salvadori+10/14; de Bennassuti+14

PopIII masses M = (10-100) $M_{\odot}$ and *faint SN explosions* if M = (10-40) $M_{\odot}$

de Bennassuti, Schneider, Valiante & SS 2014; de Bennassuti, SS + in prep



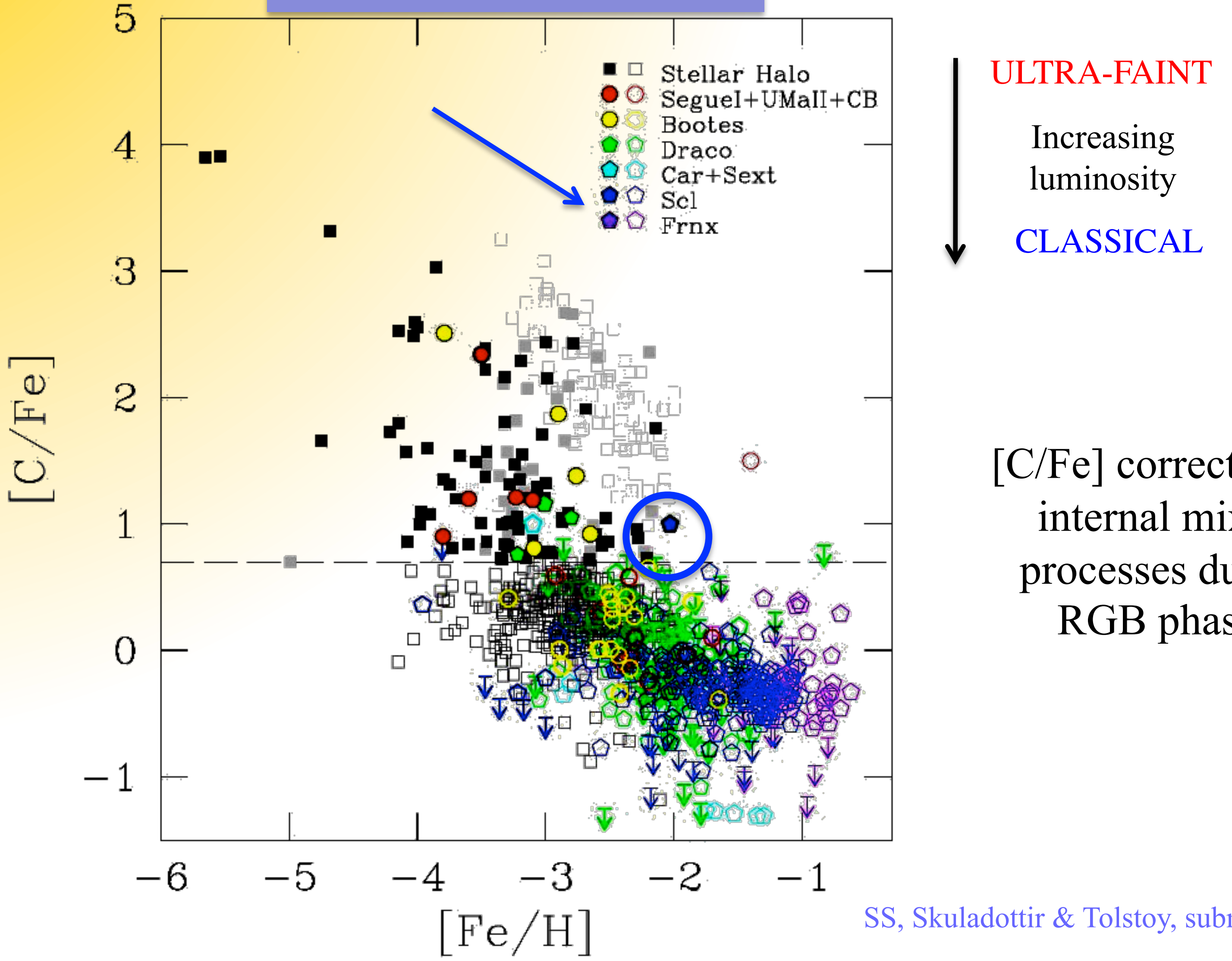


Primordial faint SN should dominate the early metal enrichment to explain the observed CEMP fraction in the Galactic halo (de Bennassuti+14; see also Cooke & Madau 14)

CARBON-ENHANCED METAL-POOR STARS

HALO: Placco+13; DWARFS: Norris+2010; Frebel+10/14; Lai+11; Cohen & Huang 2009; Shetrone+13; Kirby+15, Honda+11; Venn+12; Tafelmeyer+10; Starkenburg+13; Simon+14; Kirby+15; Skuladottir+15

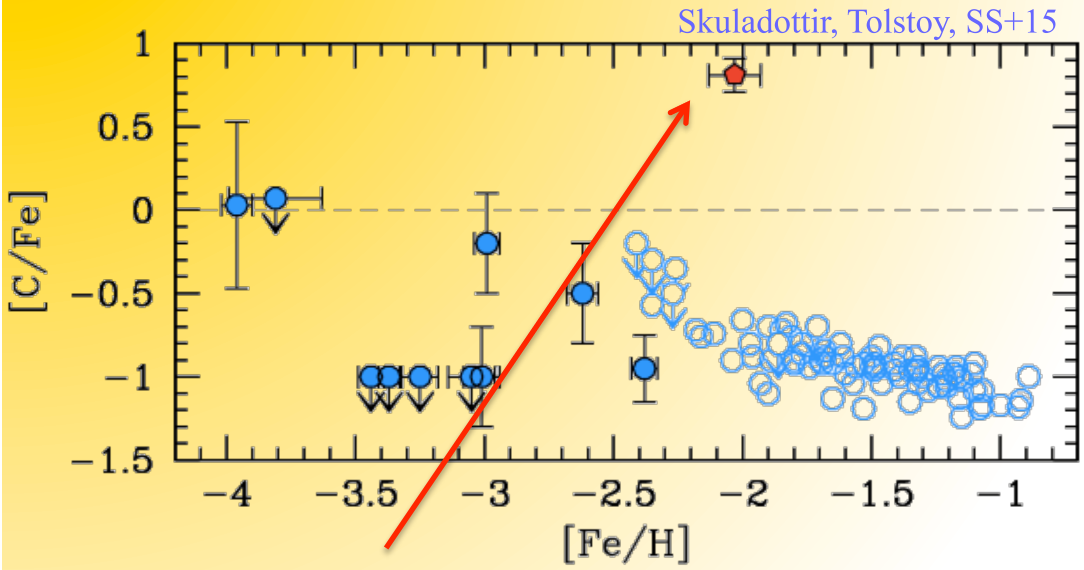
HALO vs DWARFS



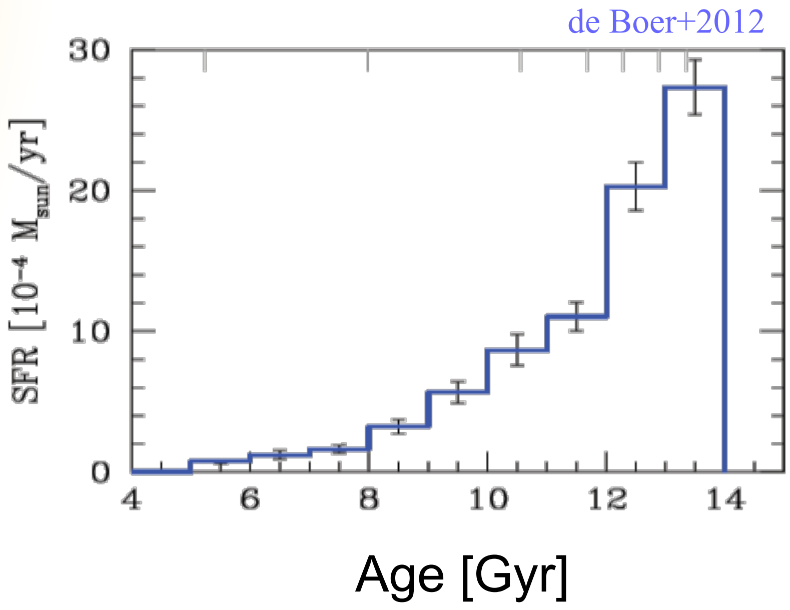
[C/Fe] corrected for internal mixing processes during RGB phases

SS, Skuladottir & Tolstoy, submitted

THE FIRST CARBON-ENHANCED STAR IN SCULPTOR



VLT/UVES HR spectrum:
the first CEMP-no star in Sculptor



1) Why the *only* CEMP-no star observed in Sculptor has *high [Fe/H]* ?

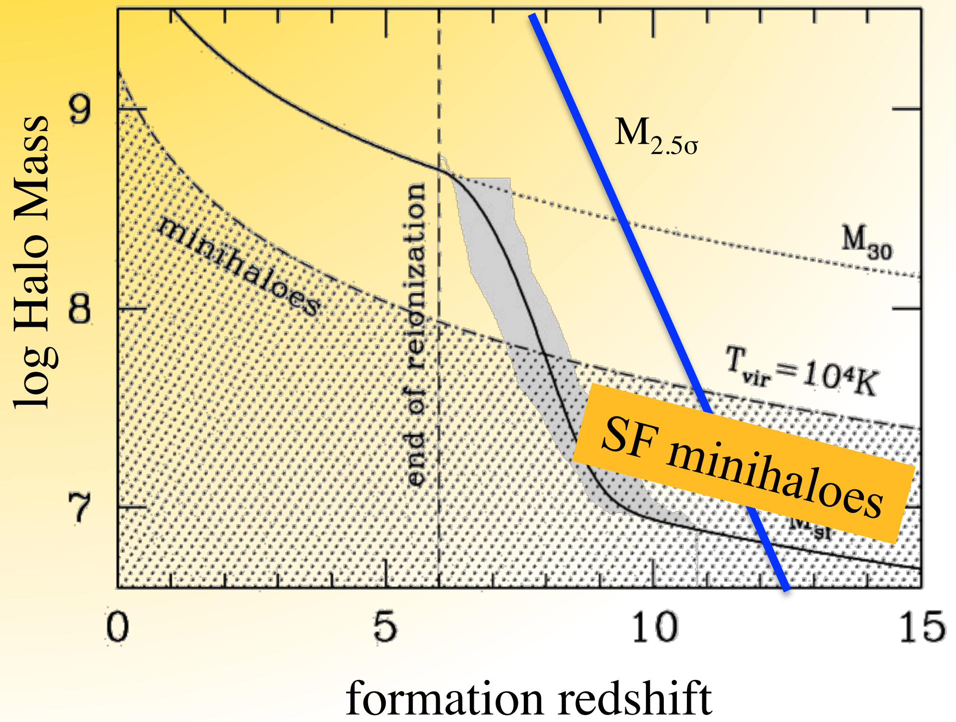
2) Does the frequency of Carbon-enhanced stars depend on *galaxy luminosity* ?

3) Are current observations of Carbon-enhanced stars in dwarf galaxies still consistent with the idea that these stars have been imprinted by *primordial faint SN* ?

DATA-CONSTRAINED MODEL FOR MW & DWARF GALAXIES

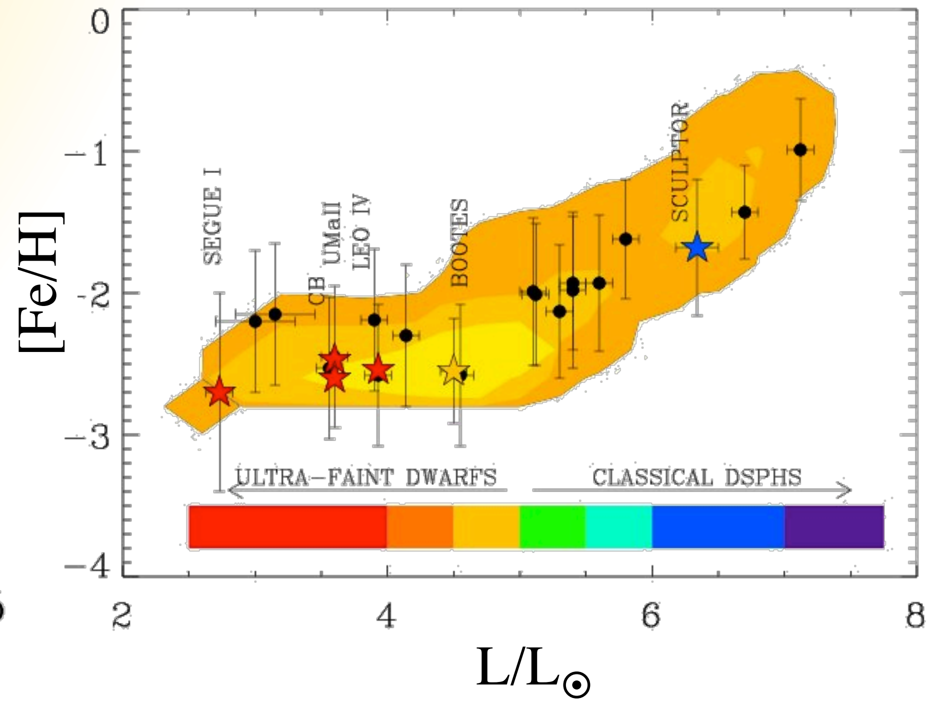
Salvadori+2008; Salvadori & Ferrara 09/12; Salvadori+2014

Star-forming progenitors/satellites



MW dwarf satellites

Salvadori & Ferrara 09/12; SS, Skuladottir & Tolstoy



Reionization and Metal enrichment
of the Milky Way environment

$$f_*^{H2} \propto f_* (T_{vir}/2x10^4\,K)^3$$

DATA-CONSTRAINED MODEL FOR MW & DWARF GALAXIES

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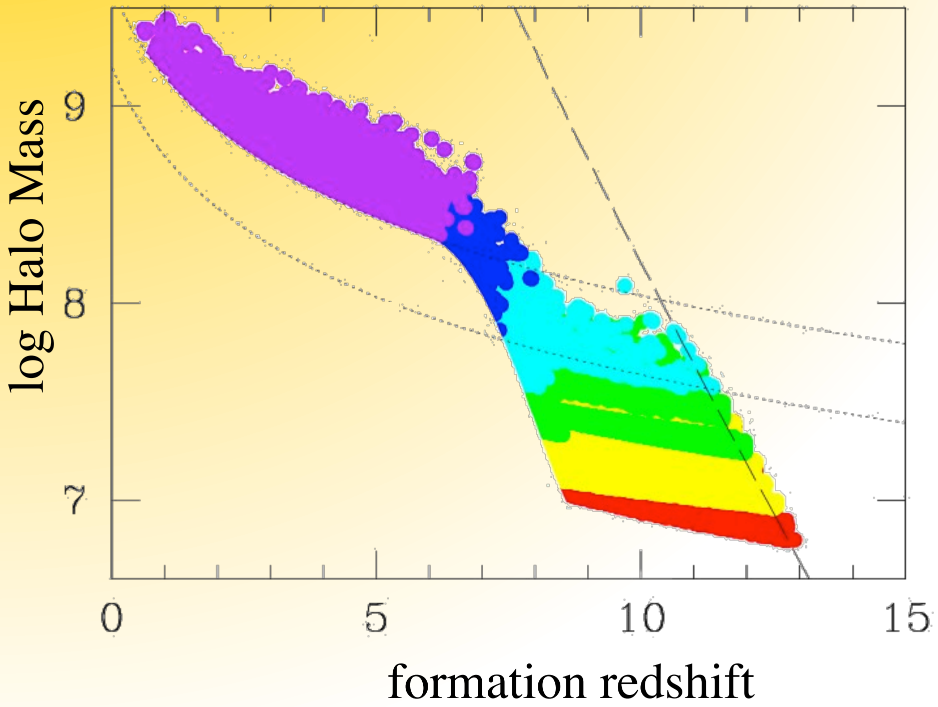

MW dwarf satellites

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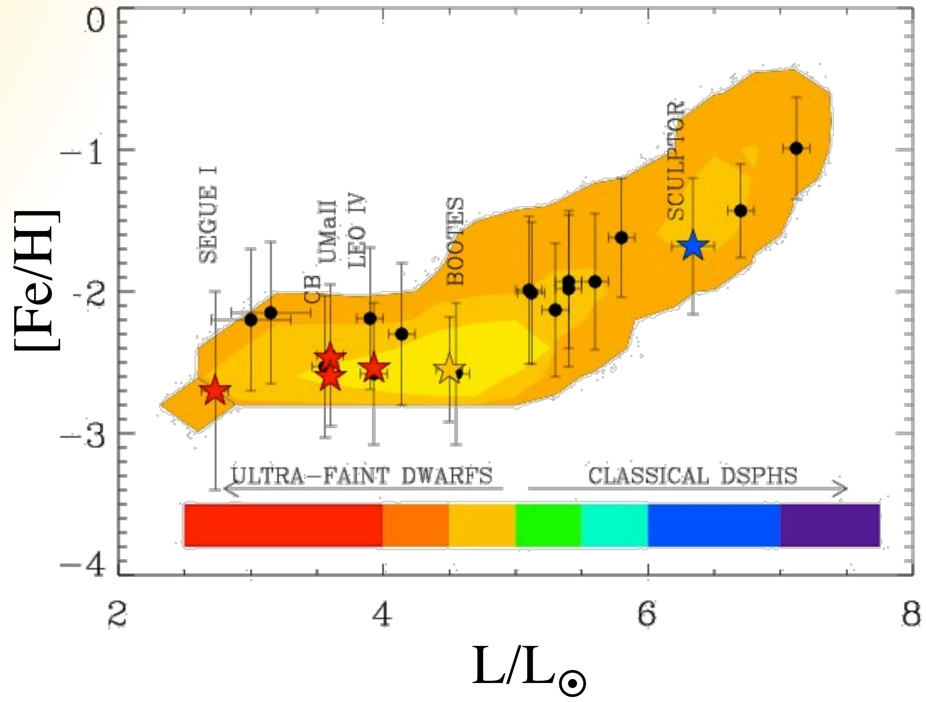
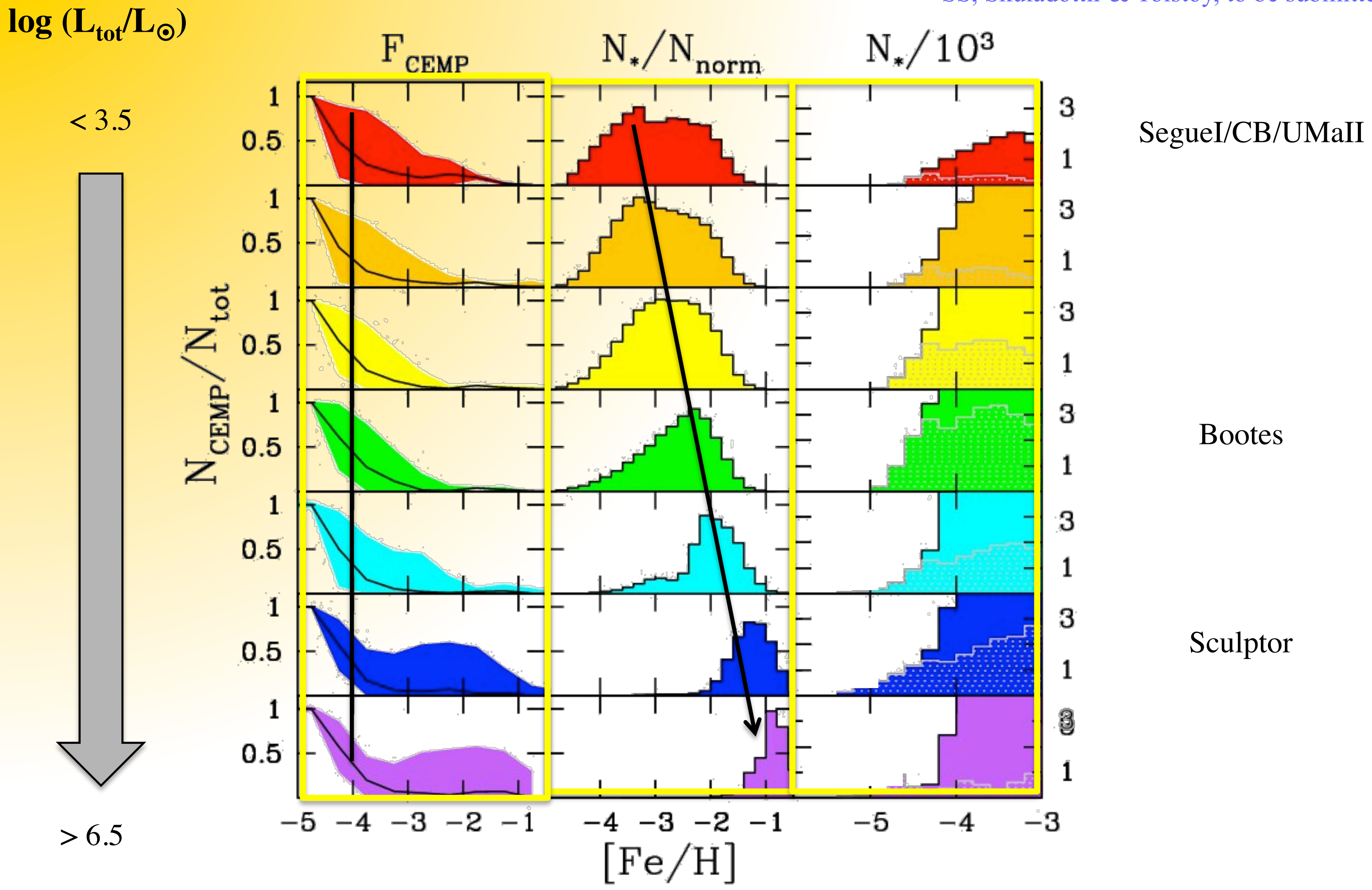


Ultra-faint dwarf galaxies are predicted to form prior the end of reionization in star-forming mini-haloes with $M < 10^{7.5}\ M_\odot$ (Salvadori & Ferrara 09/12, Bovill & Ricotti 09/11; Munoz+09)

→ Consistent with recently observations (e.g. Brown+14) and simulations (e.g. Bland-Hawthorn+15)

THE GLOBAL PICTURE

SS, Skuladottir & Tolstoy, to be submitted



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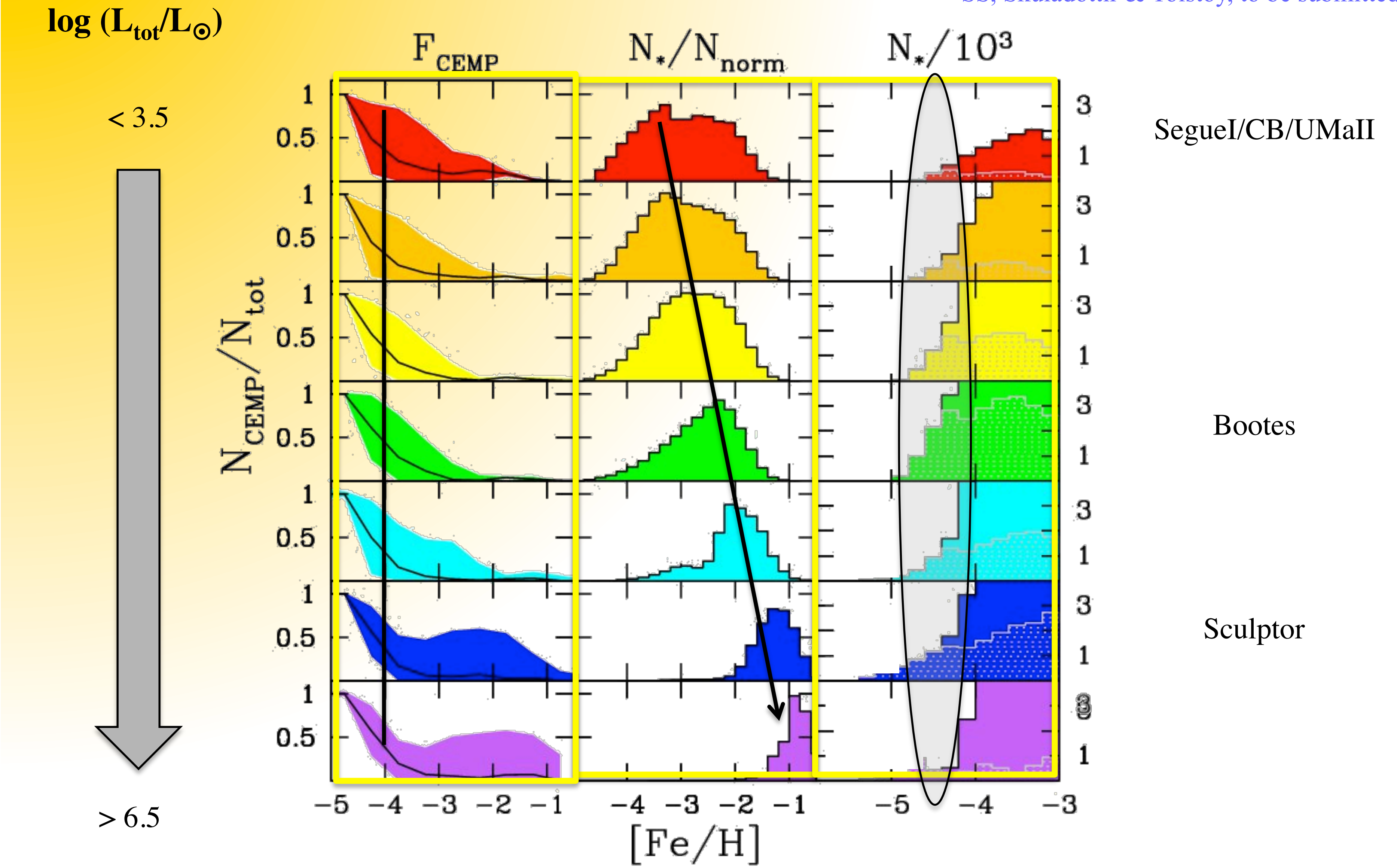

THE GLOBAL PICTURE

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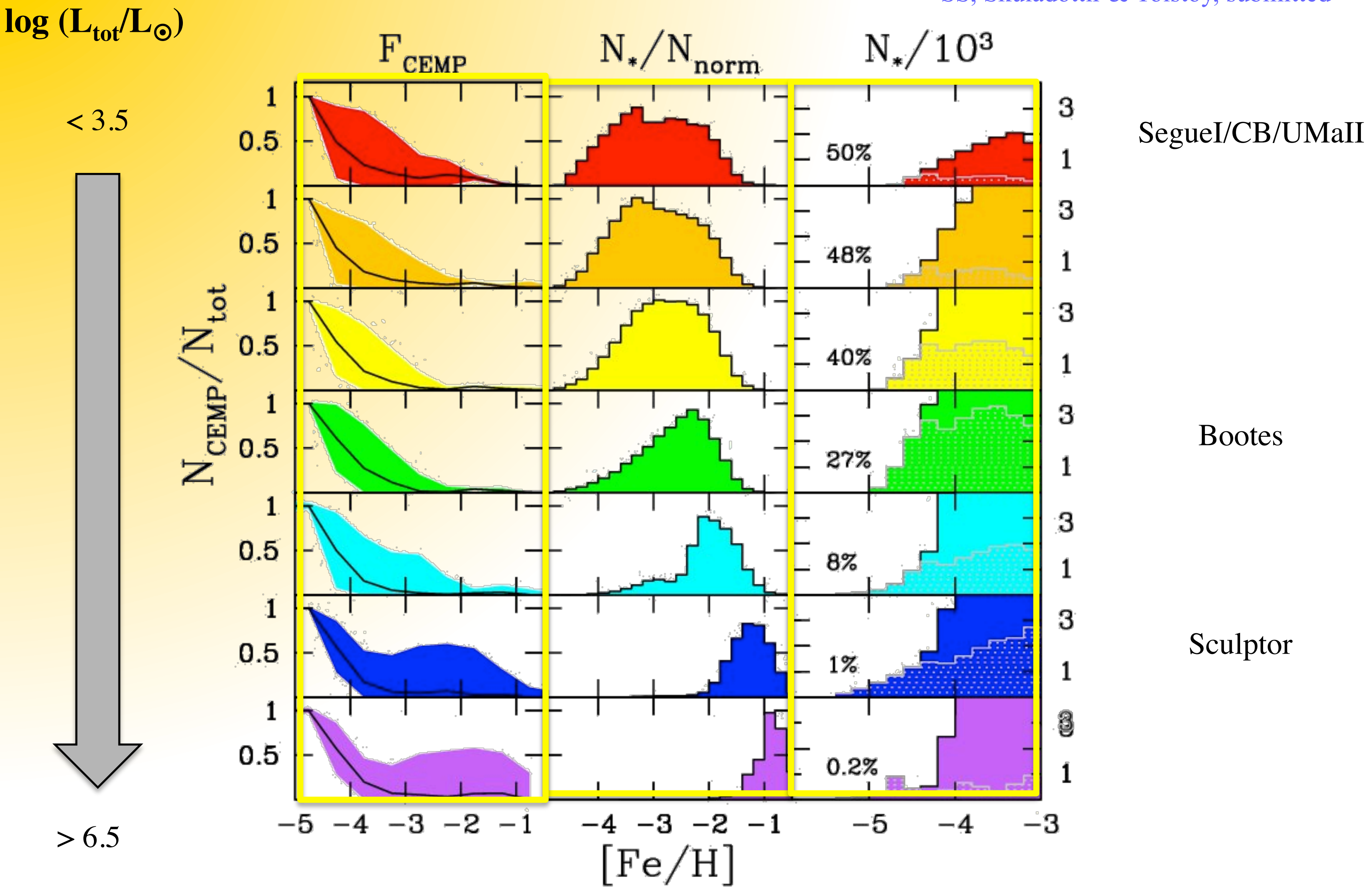
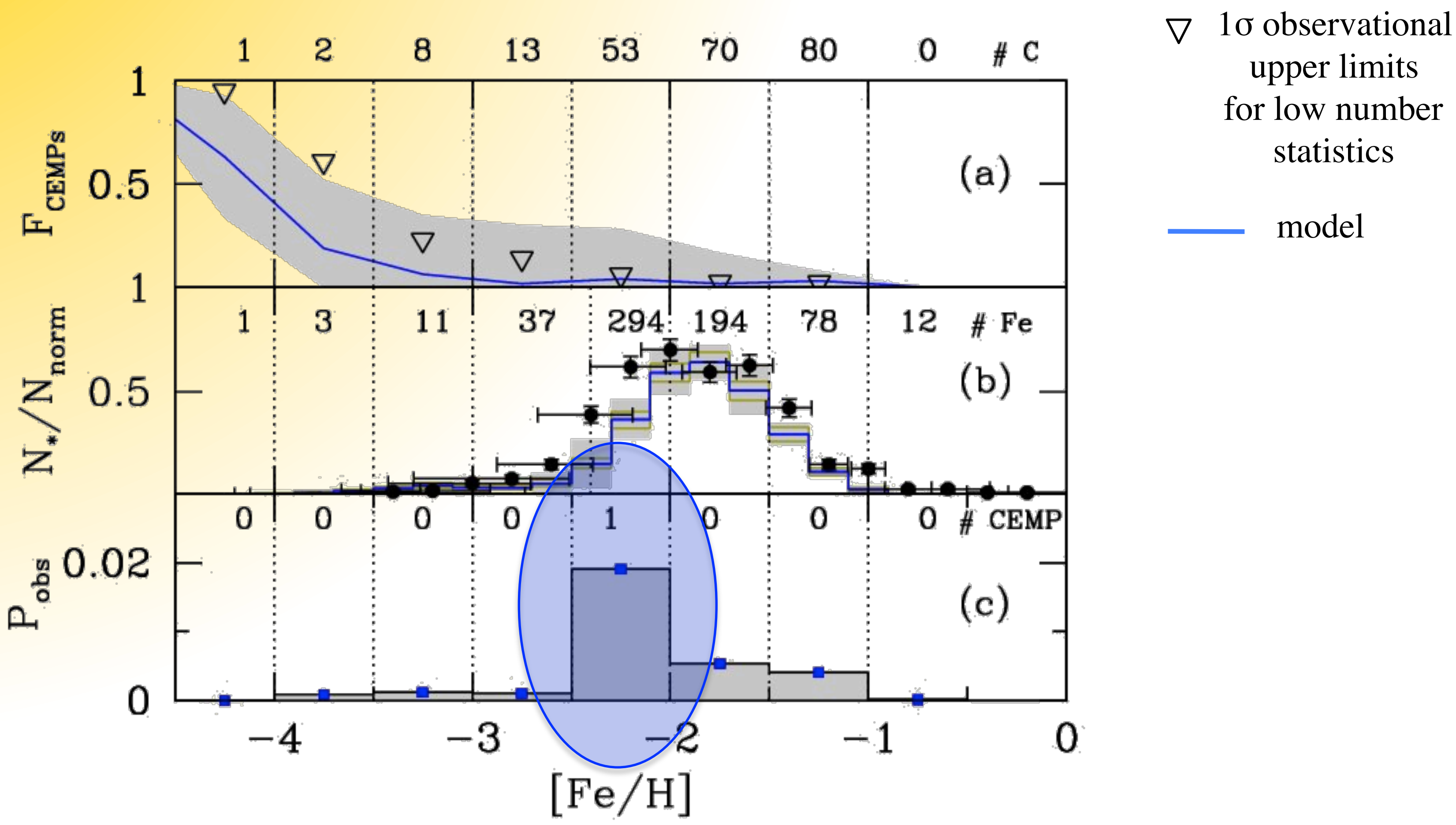


The fraction of stars with [Fe/H] < −3 strongly decreases with galaxy luminosity.

CARBON ENHANCED STARS IN SCULPTOR

SS, Skuladottir & Tolstoy, to be submitted

THE SCULPTOR DSPH GALAXY

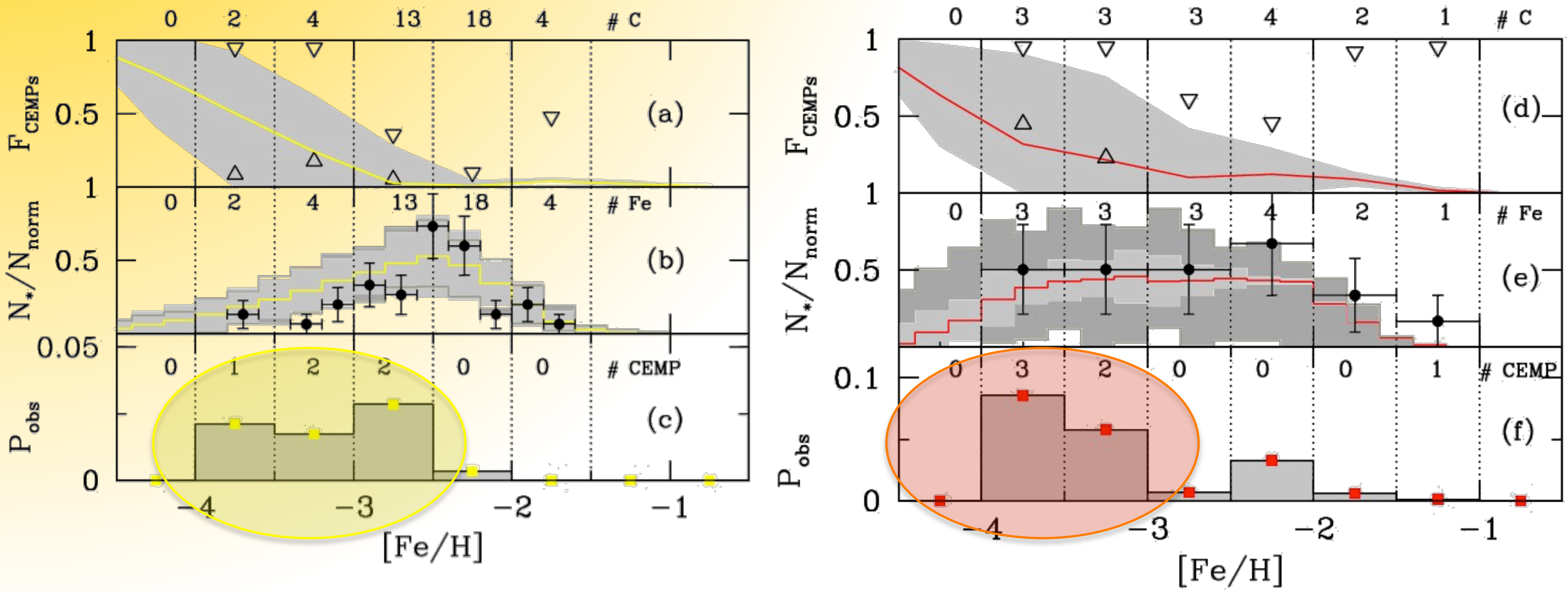


The probability to observe a star that is also Carbon-enhanced is maximal at [Fe/H] ≈ −2.

CARBON-ENHANCES STARS IN ULTRA-FAINT DWARFS

SS, Skuladottir & Tolstoy, to be submitted

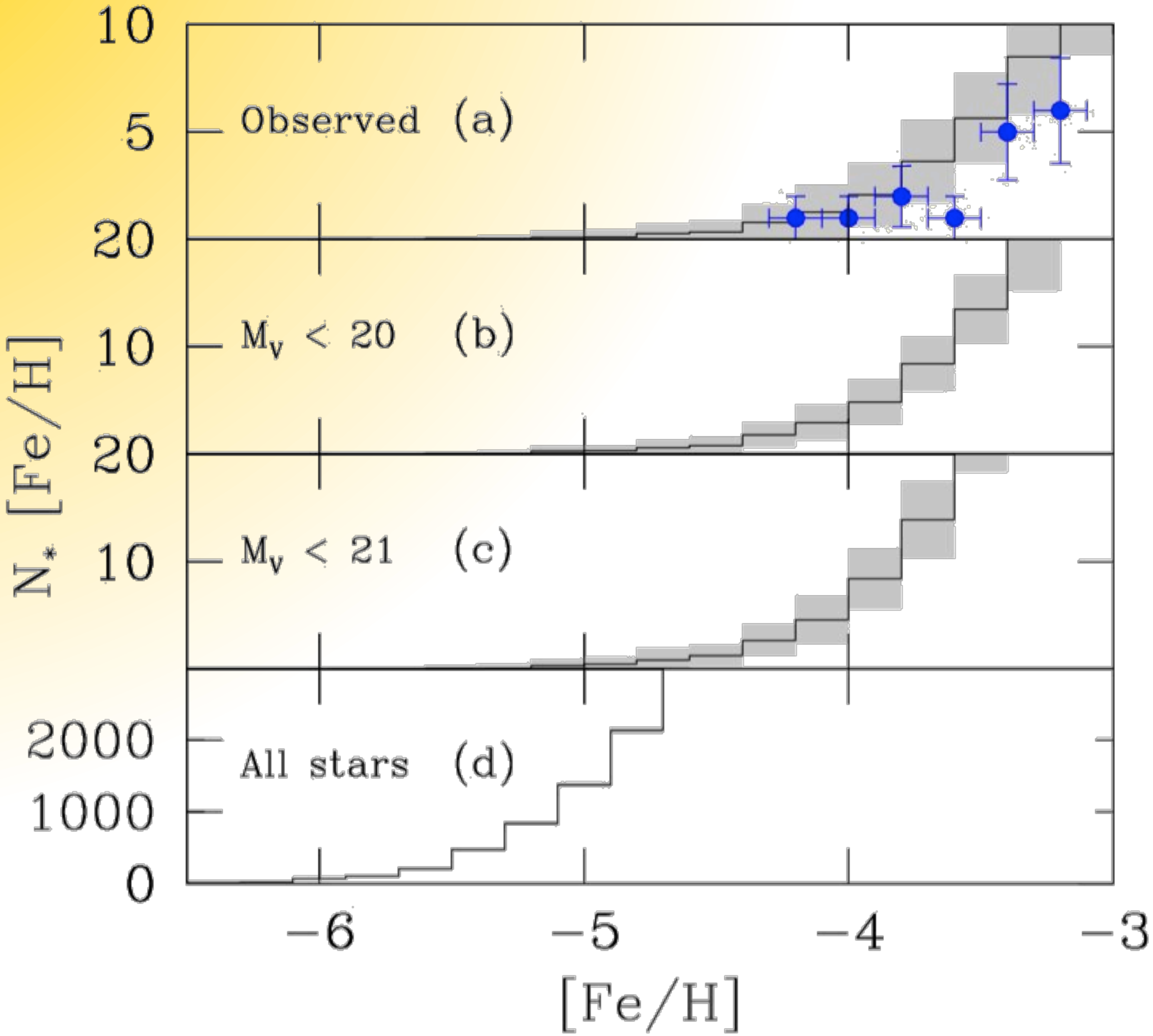
BOOTES $L_{tot} \sim 10^5 L_\odot$ FAINTEST UFDs $L_{tot} < 10^4 L_\odot$



In ultra-faint dwarf galaxies the probability to observe a star that is also Carbon-enhanced is higher and shifted towards lower [Fe/H]

PREDICTIONS FOR SCULPTOR

SS, Skuladottir & Tolstoy, submitted



≈ 700 stars

≈ 1600 stars

≈ 2600 stars

CONCLUSIONS

– *Galactic archaeology is a key tool to investigate the properties of the first stellar generations and the early cosmic star-formation processes*

– *With larger stellar samples we can find many second-generation stars, and possibly constrain the nature and mass spectrum of the first stars!*

→ *We are entering in a golden era for Near-Field Cosmology.*

– *Carbon-enhanced metal-poor (CEMP-no) stars are likely imprinted by primordial faint SNe.*

→ *If this is true – and LCDM is correct – then we should find more CEMP-no stars at [Fe/H]< −3.5 in Sculptor by increasing the stellar samples.*