First Stars in the Milky Way environment

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Galaxies, Etoiles, Physique et Instrumentation

The Milky Way and its environment

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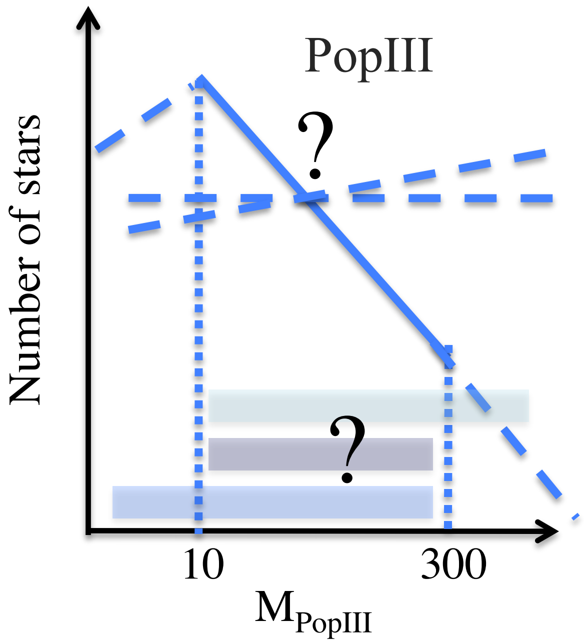
FIRST STARS – THEORY & OPEN QUESTIONS:

e.g. Omukai&Nishi98;Abel+02;Bromm+02;Omukai&Palla03;Bromm&Loeb04;Tan&McKee04/08;O'Shea&Norman06; Ripamonti+02; Schleicher+09;Turk+09/11;Yoshida+06/08;H osokawa+11/15; Clark+11; Greif+12; Hirano+14/15; Stacy+14/16

FIRST STARS



The first stars likely formed at z ~ 20-30 in $M \approx 10^{6\text{-}7} M_{\odot}$ minihaloes $T_{vir} < 10^4$ K

What was the typical mass of the first stars? Initial Mass Function?

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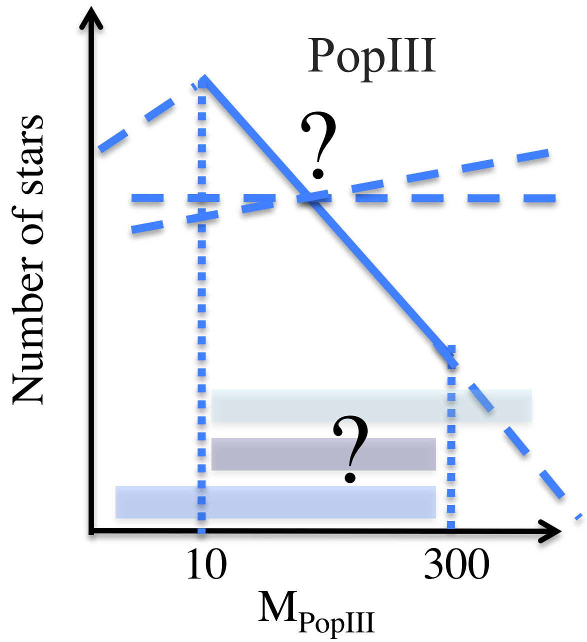


$M_* > 10\ M_\odot$

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

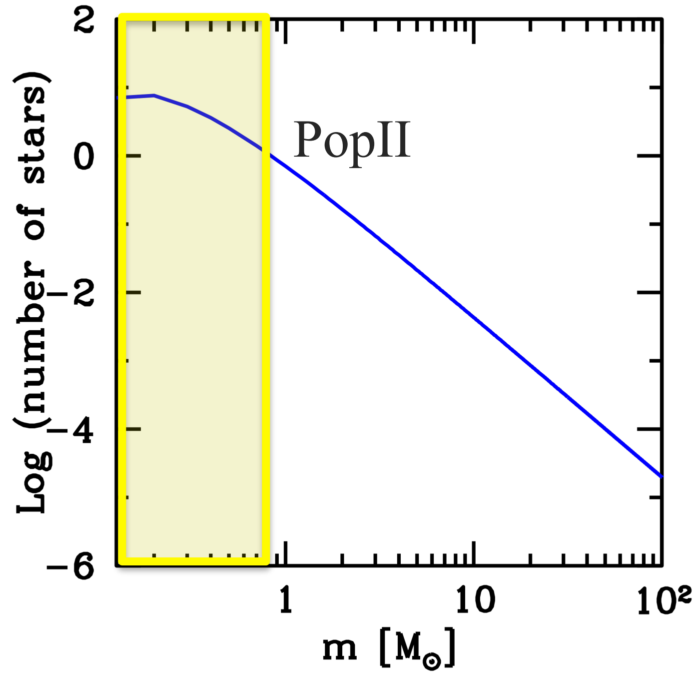
Exact mass range? IMF ?

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

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

METALS & DUST

TODAY STARS



Salpeter-like IMF

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

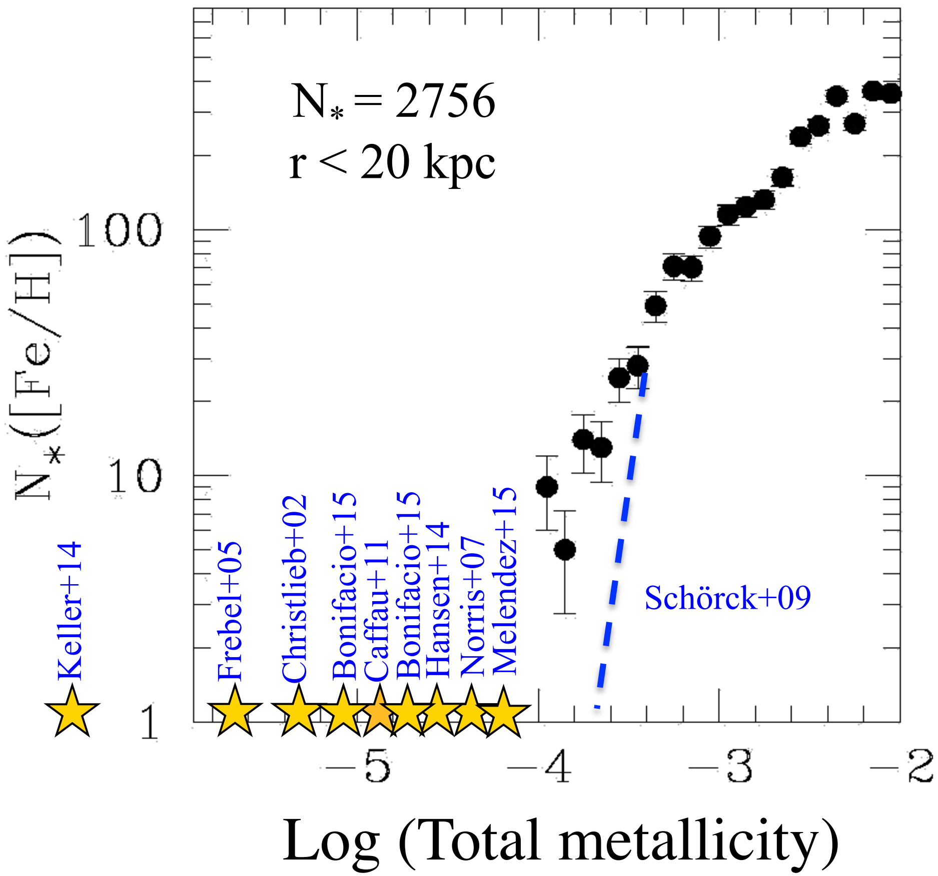
$\tau_* > 14 \times 10^9$ years

WE CAN OBSERVE THEM TODAY

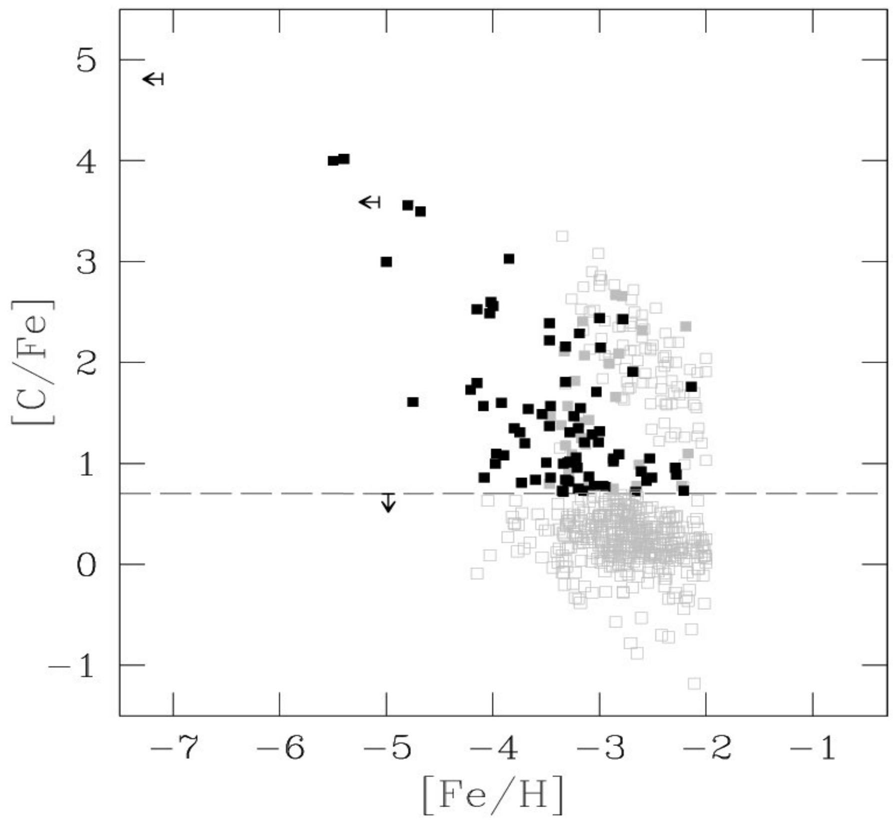
GALACTIC HALO STARS: OBSERVATIONS

e.g. Beers&Christlieb05; Christlieb+02/13; Frebel+05/15; Norris+07/10; Shoerck+09; Lee+13; Placco+13; Caffau+11/13; Yong +12/13; Placco+14/15; Keller+14; Spite+14; Hansen+15; Bonifacio+15

Metallicity Distribution Function



Carbon-Enhanced Metal-Poor stars



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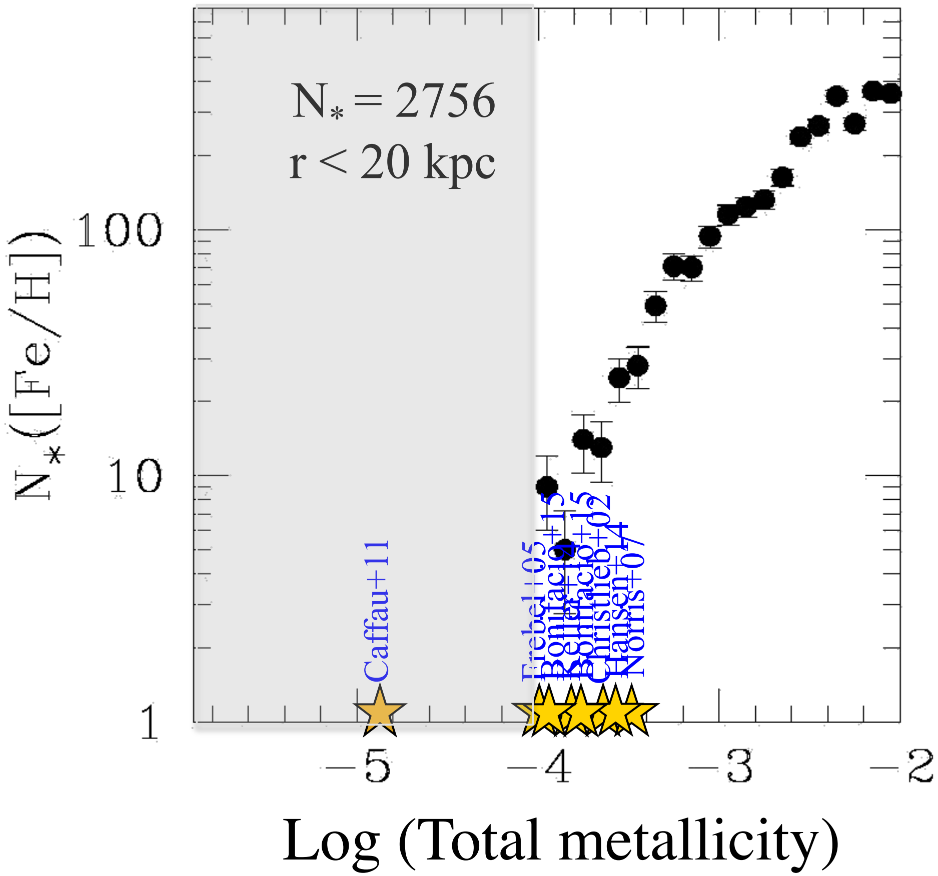

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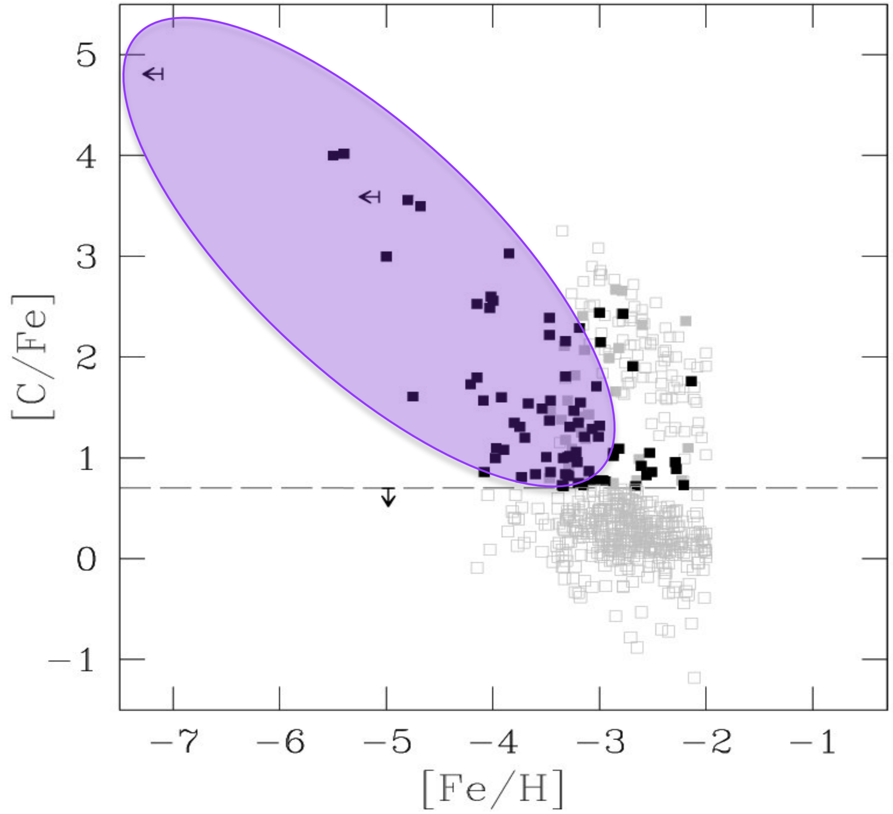


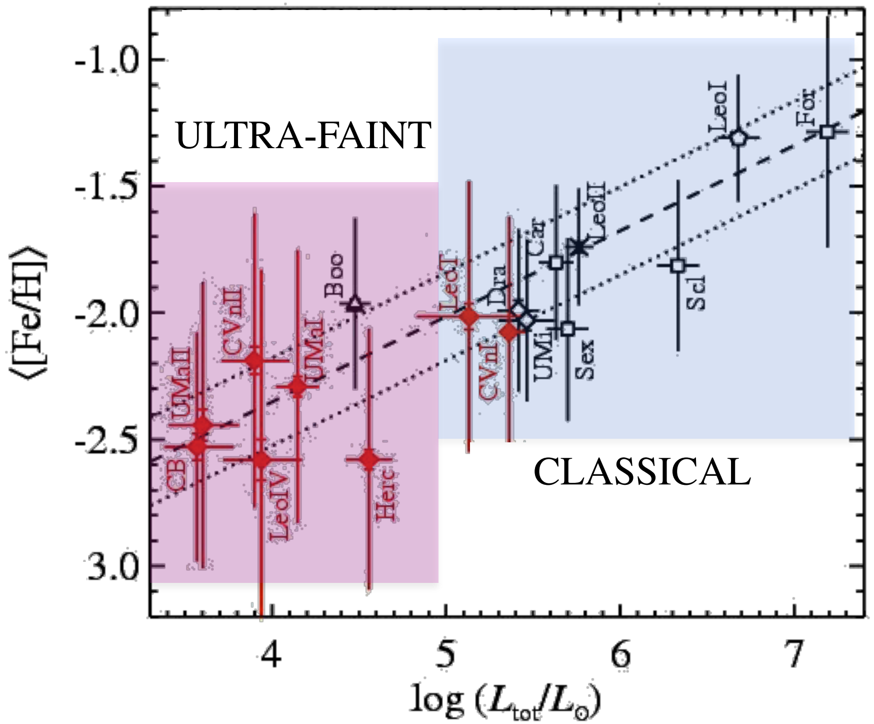
Are all Carbon-enhanced metal-poor stars descendants of the first stars?
Why C-enhanced and C-normal stars coexist at low [Fe/H]?

MILKY WAY DWARF GALAXIES

e.g. Battaglia+06; Helmi+06; Kirby+08/11/14; Starkenburg+10/13; Frebel+11/14; Ji+14; Lai+11/14; Cohen & Huang 09; Shetrone+13; Venn+12; Tafelmeyer+10; Simon+14; Skuladottir+15

The Iron-Luminosity Relation

Kirby+08/11



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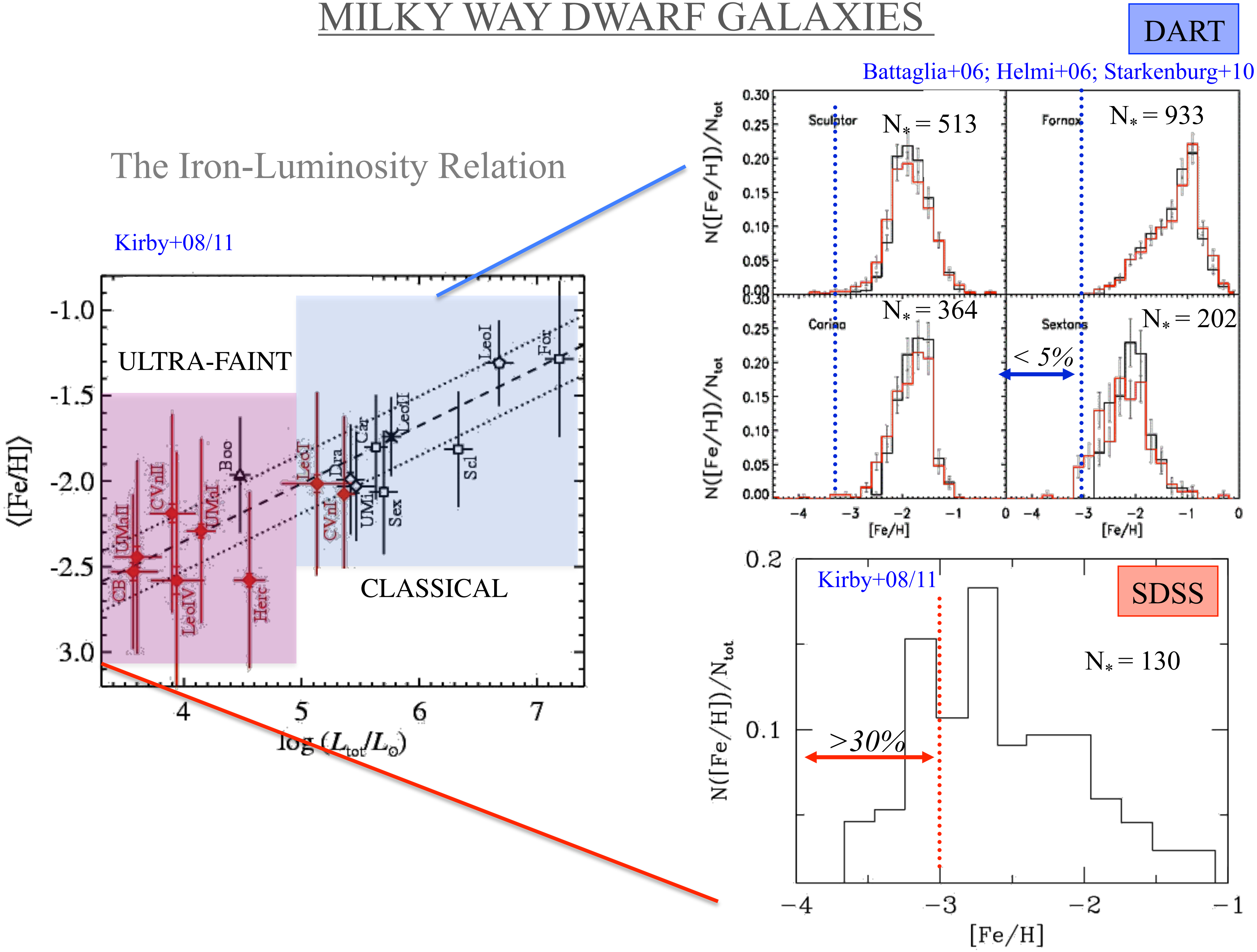
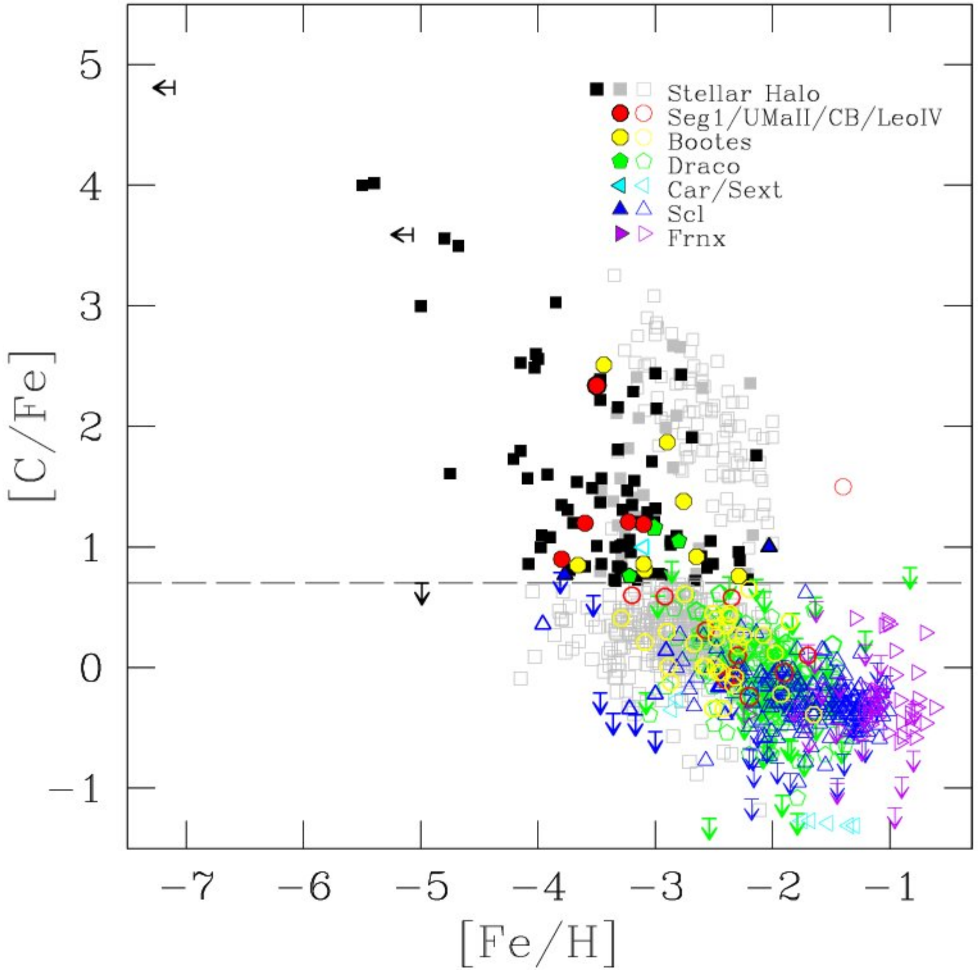


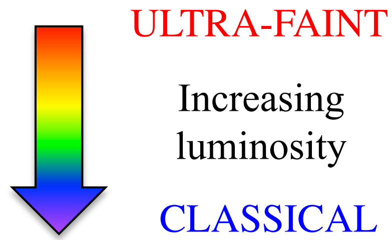
CARBON-ENHANCED METAL-POOR STARS

e.g. Placco+13/14/15; Christlieb+02/08; Caffau+11/13; Norris+10/12; Bonifacio+15; Frebel+05/10/14; Lai+11/14; Cohen & Huang 09; Shetrone+13; Kirby+15; Honda+11; Venn+12; Tafelmeyer+10; Starkenburg+13; Simon+14; Spite+14; Kirby+15; Skuladottir+15

HALO vs DWARFS



SS, Skuladottir & Tolstoy 15



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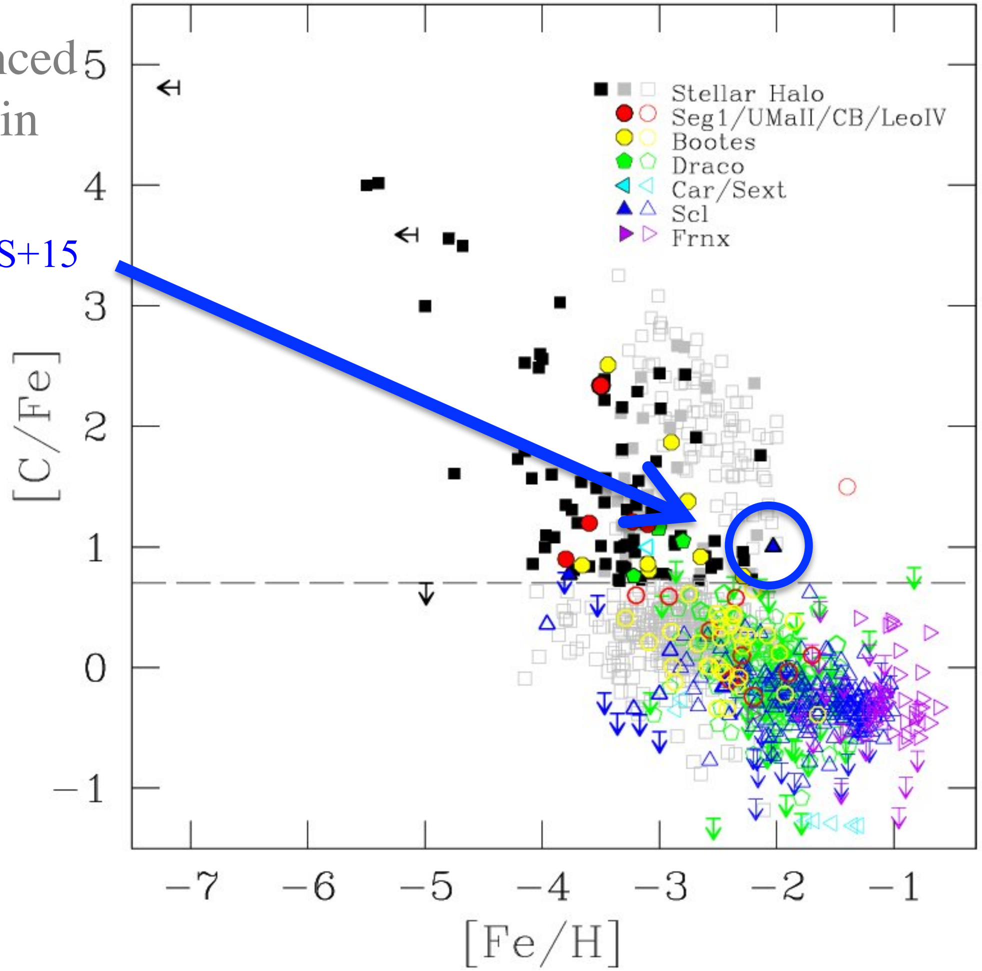
HALO vs DWARFS

The first C-enhanced metal-poor star in Sculptor

Skuladottir, Tolstoy, SS+15



SS, Skuladottir & Tolstoy 15

ULTRA-FAINT

Increasing luminosity

CLASSICAL

Does the incidence of C-enhanced stars depend on the environment of formation?

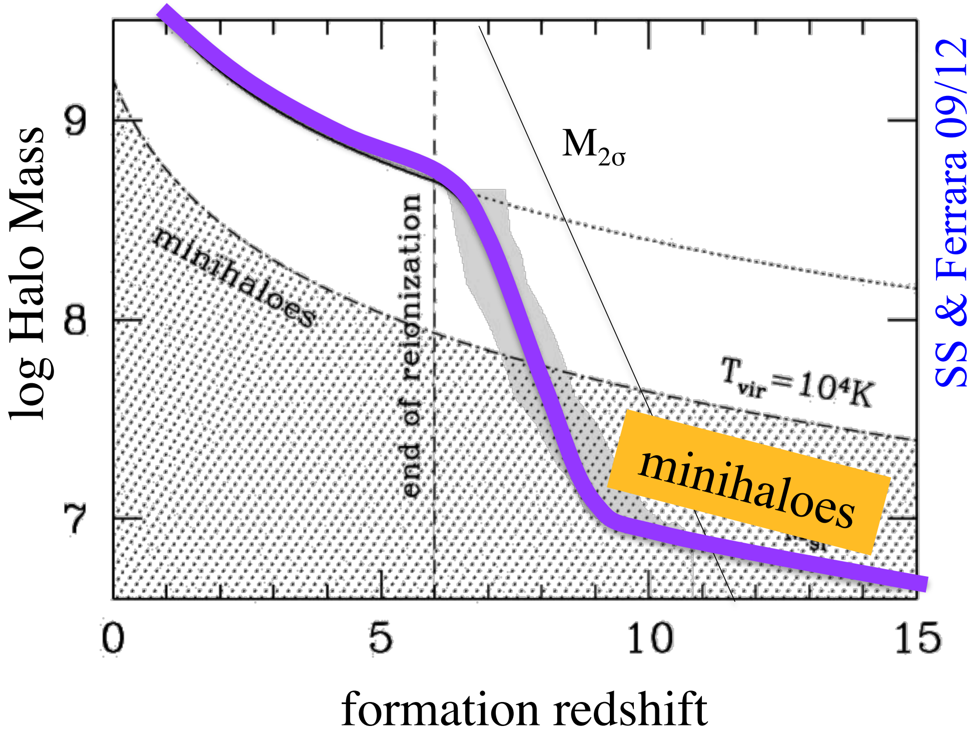
MODELING THE LOCAL GROUP FORMATION

e.g. Tumlinson 06; SS+07/08; Komiya+07/10/14; De Lucia & Helmi 08; SS&Ferrara09/12; Tumlinson 10; Li +11; Font+13; de Bennassuti+14; SS+14/15; Hartwig+15; Ishiyama+15; Crosby+15; Graziani+15; Griffen+15

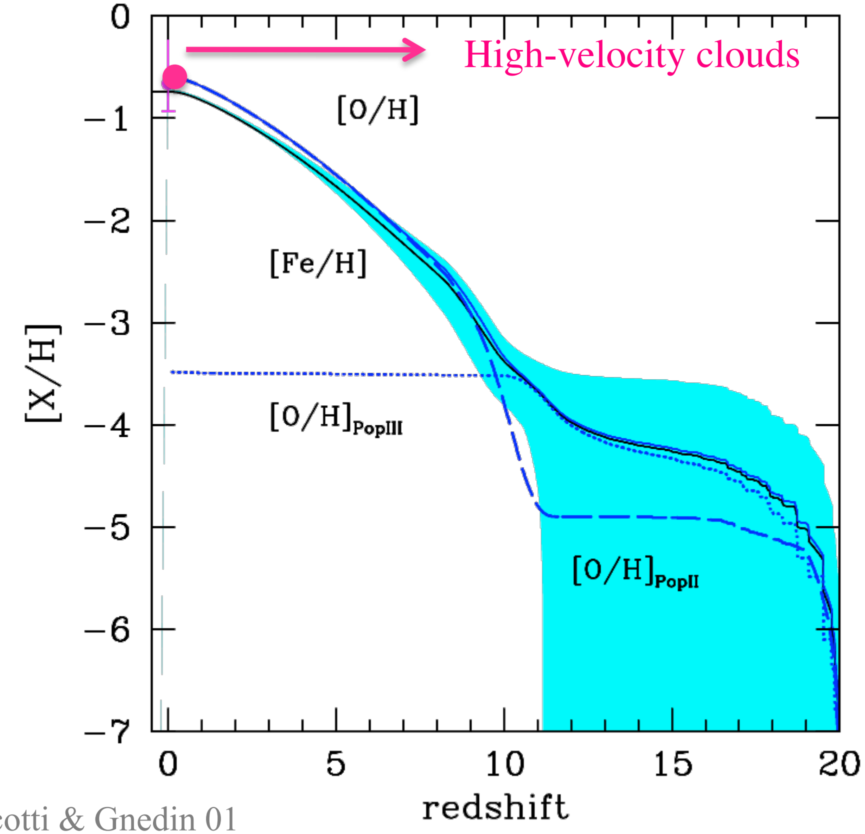
Data-calibrated merger tree models for the Local Group formation

Critical metallicity, minihaloes, and metal enrichment of the MW environment

Star-forming progenitors/satellites



The Milky Way environment

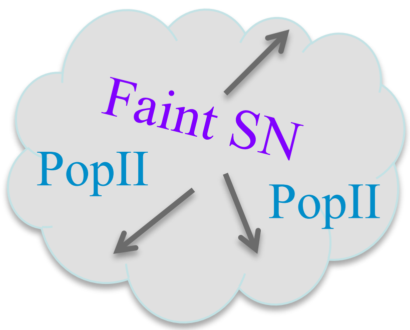


$f_*^{H2} \propto f_* (T_{vir}/10^4 K)^3$ e.g. Madau+01; Ricotti & Gnedin 01

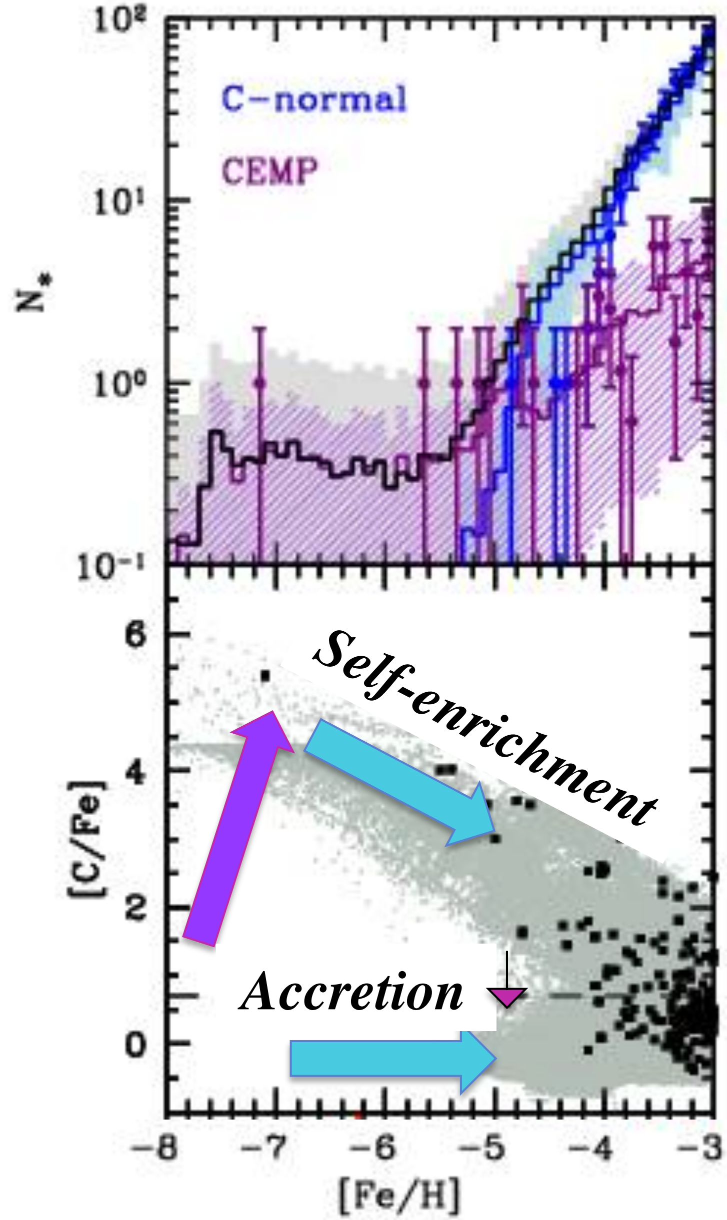
INTERPRETING THE GALACTIC HALO MDF

de Bennassuti, SS+ re-submitted to MNRAS after minor revision

$Z_{ISM} > Z_{cr}$

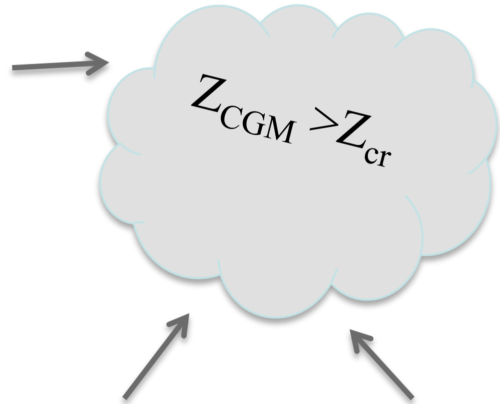


Pop III:
Faint SN



$m_{popIII} = (10\text{-}300)\ M_{\odot}$

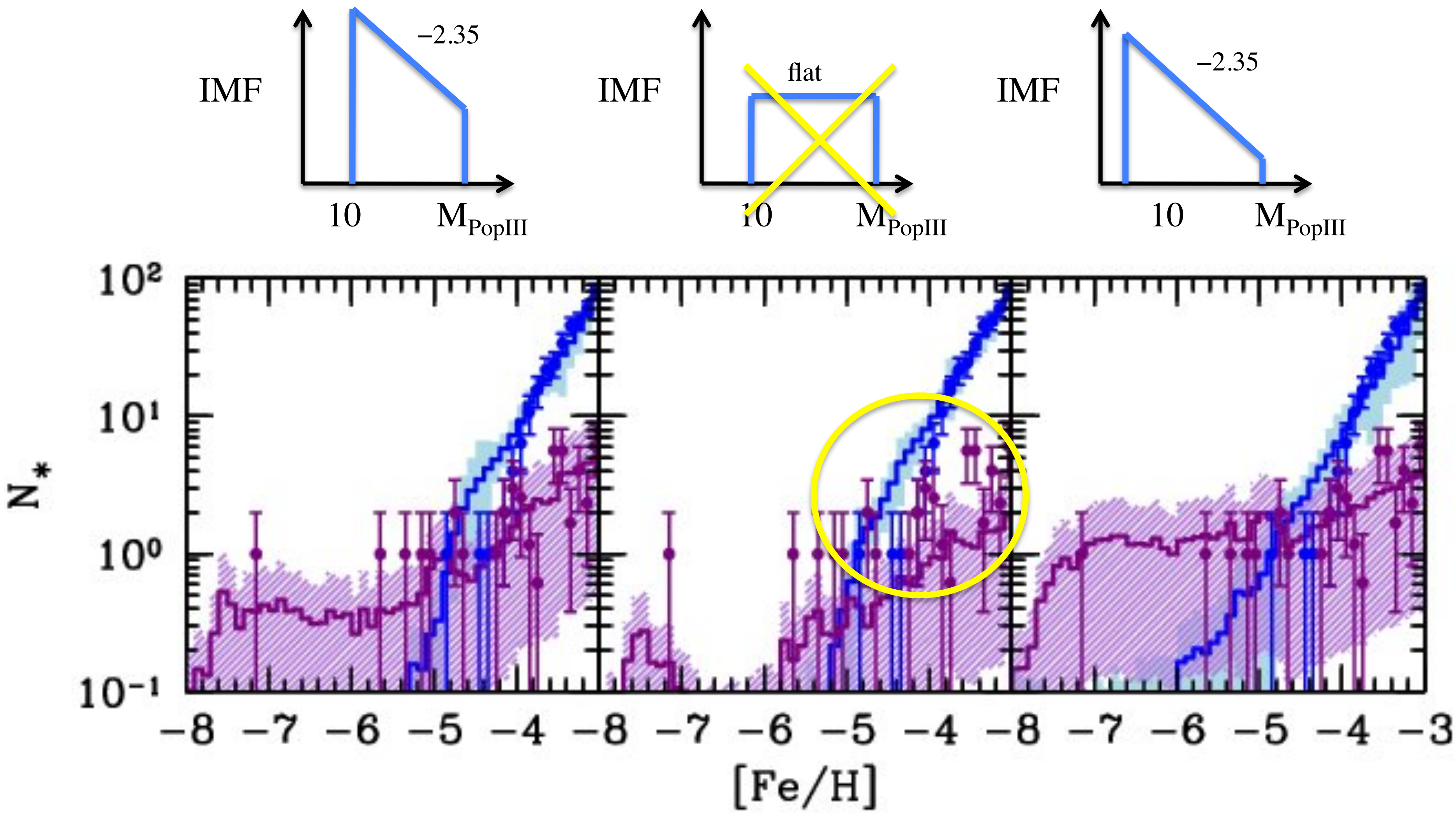
Salpeter-like slope
PopIII IMF sampling



PopII:
normal SNII

CAN WE FURTHER CONSTRAIN THE POPIII IMF?

de Bennassuti, SS+ re-submitted to MNRAS after minor revision

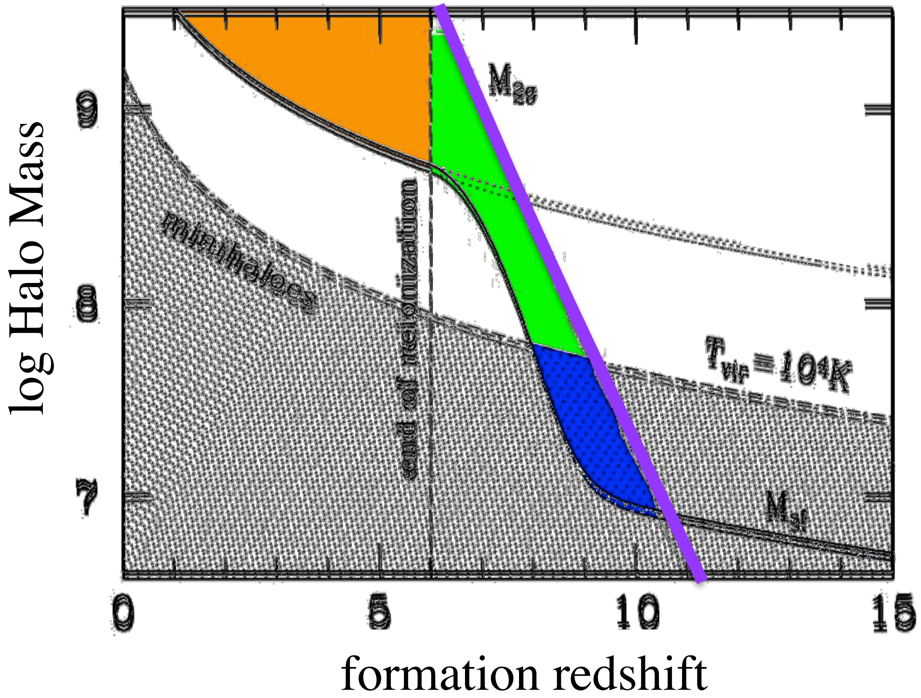


By increasing the sample of [Fe/H] < −3 CEMP stars we can make it!

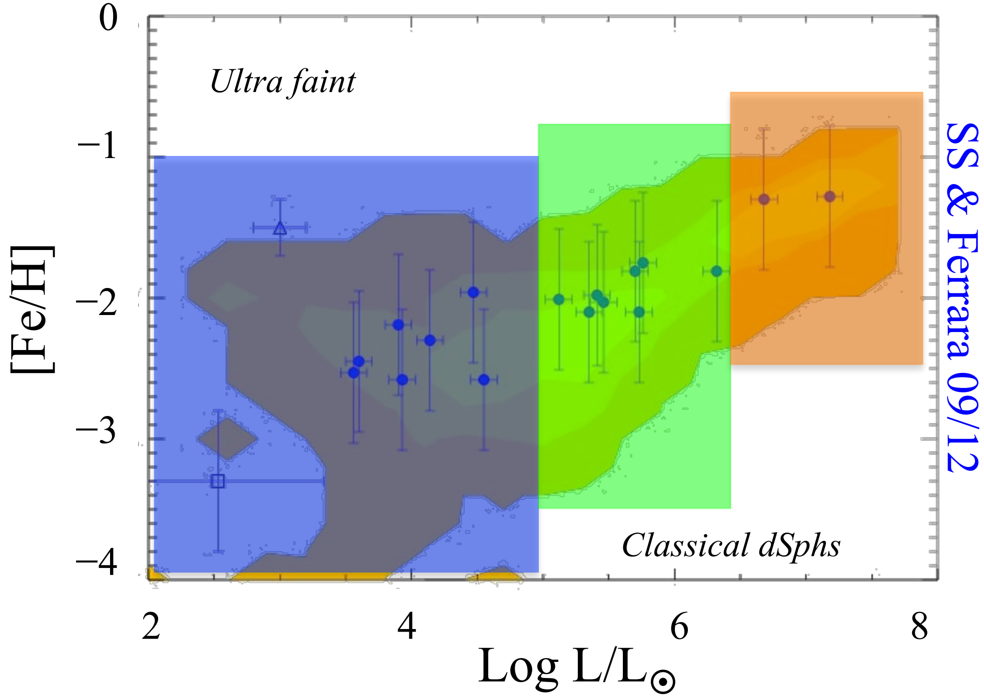
MODELING MW DWARF GALAXIES

e.g. Gnedin & Ricotti05; Bovill&Ricotti09/11; SS&Ferrara09/12; Munoz+09; Tumlinson10; Li+11/12; Font+; Starkenburg+13; Romano+; Fiorenzo+14; Hartwig+15; SS+14/15

Star-forming progenitors/satellites



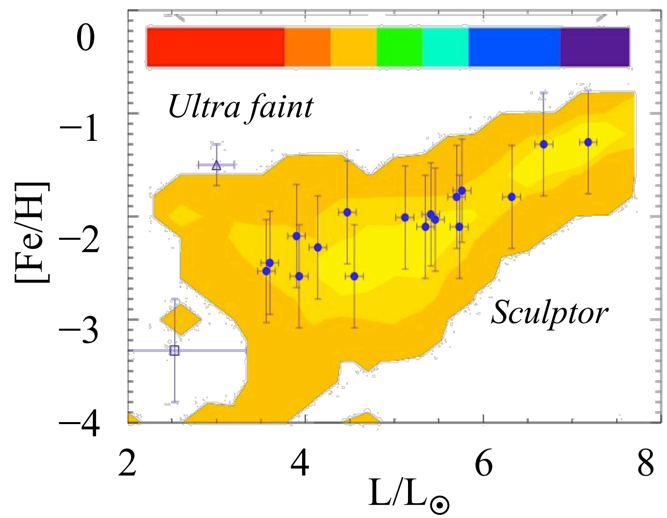
Milky Way dwarf galaxies



Ultra-faint dwarf galaxies are predicted to be mini-haloes that *inefficiently* formed stars during reionization $z > 7$ → e.g. Brown+14; Wise+14; Fiorenzo+14; Bland-Hawthorn+14

THE GLOBAL PICTURE

SS, Skuladottir & Tolstoy 15



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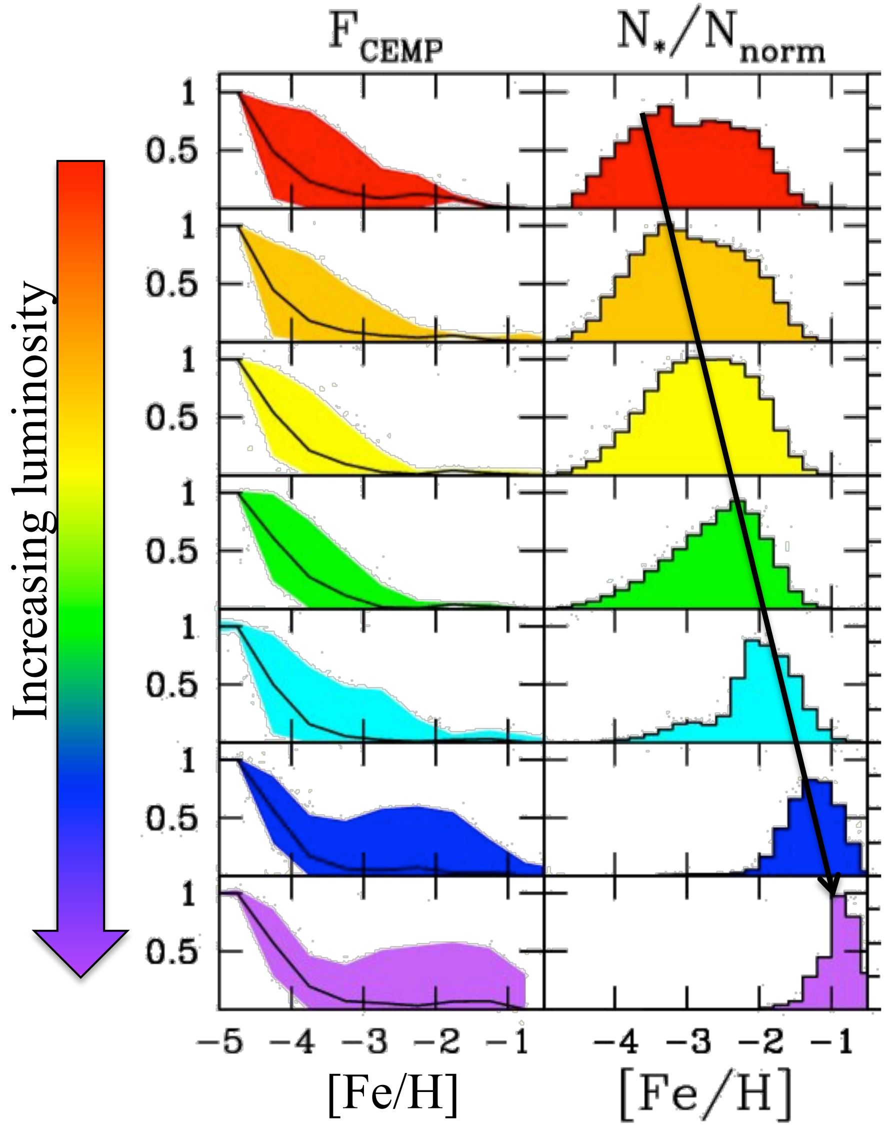

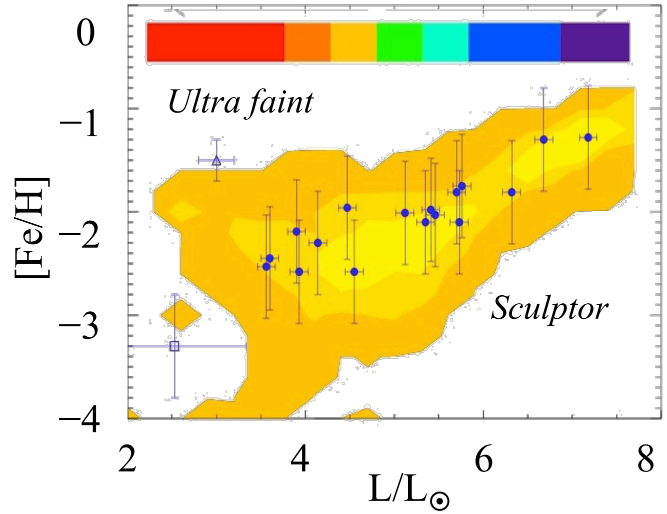

The fraction of stars with [Fe/H] < −3 strongly decreases with galaxy luminosity

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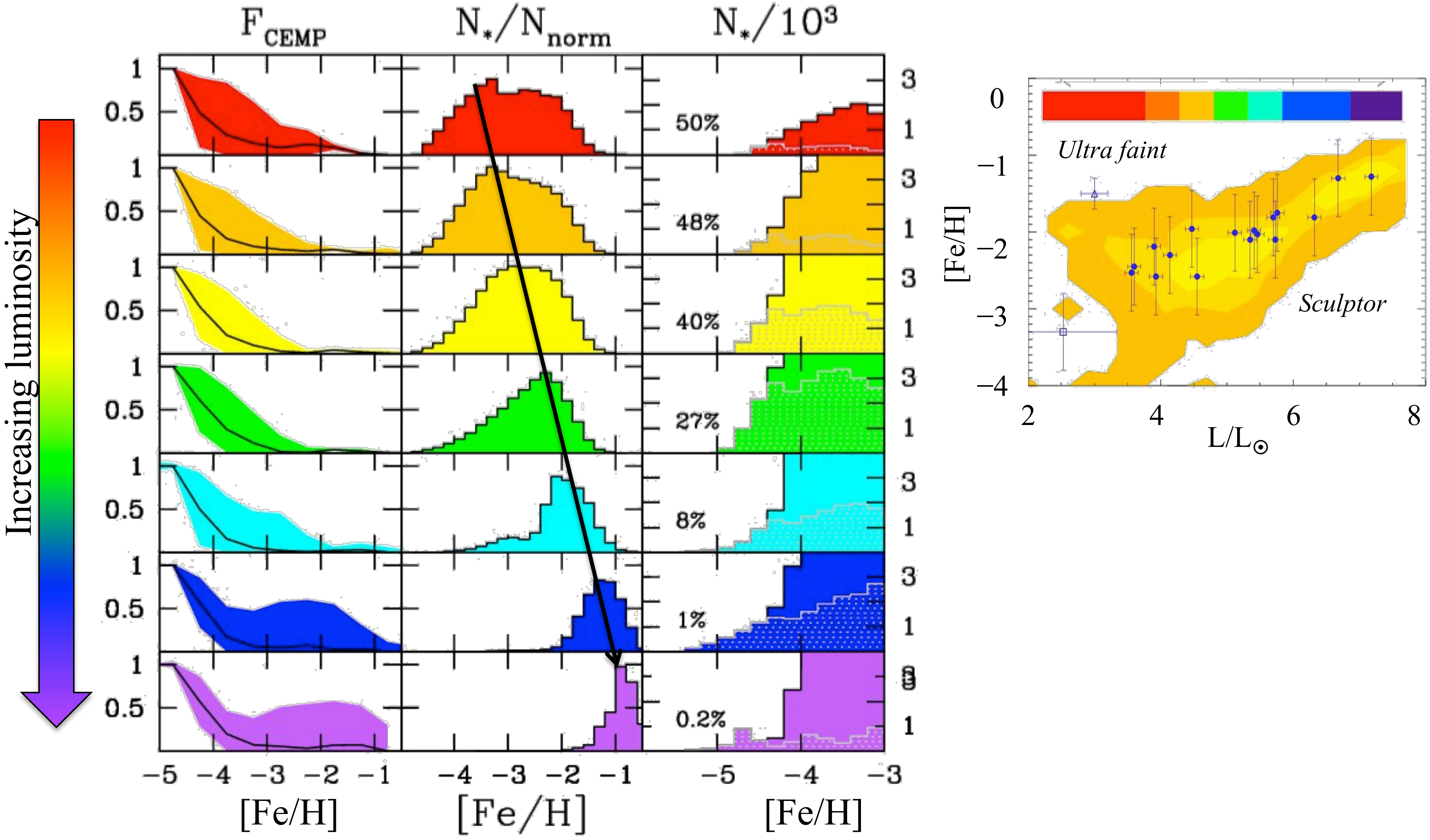

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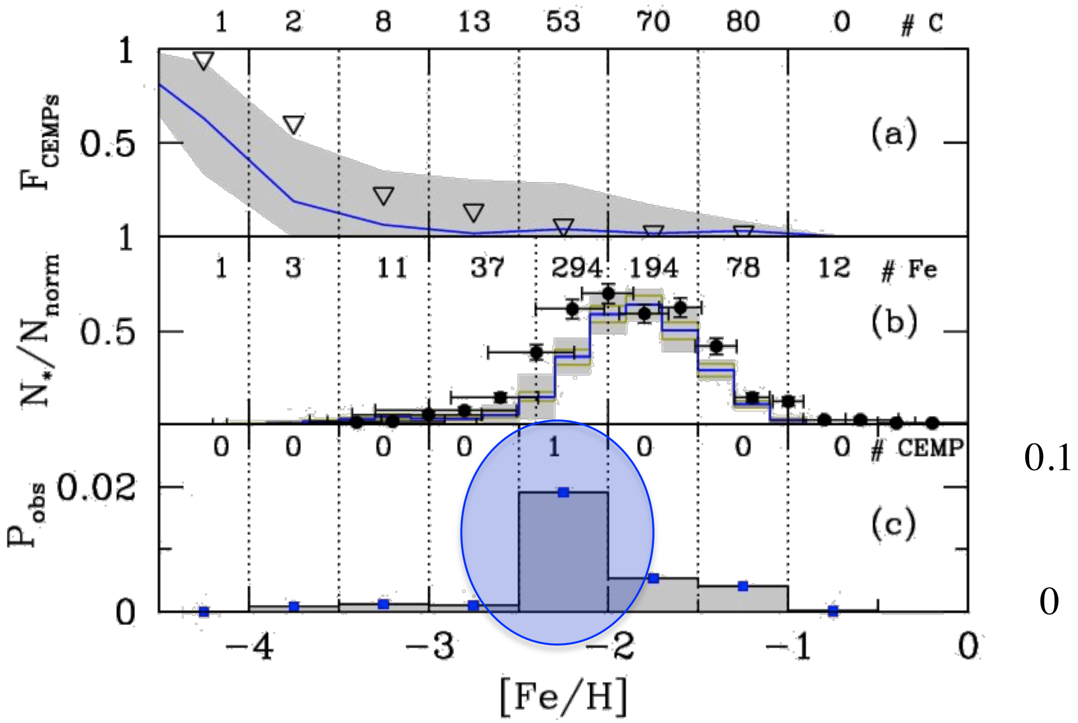
CARBON-ENHANCED STARS IN DWARF GALAXIES

SS, Skuladottir & Tolstoy 2015

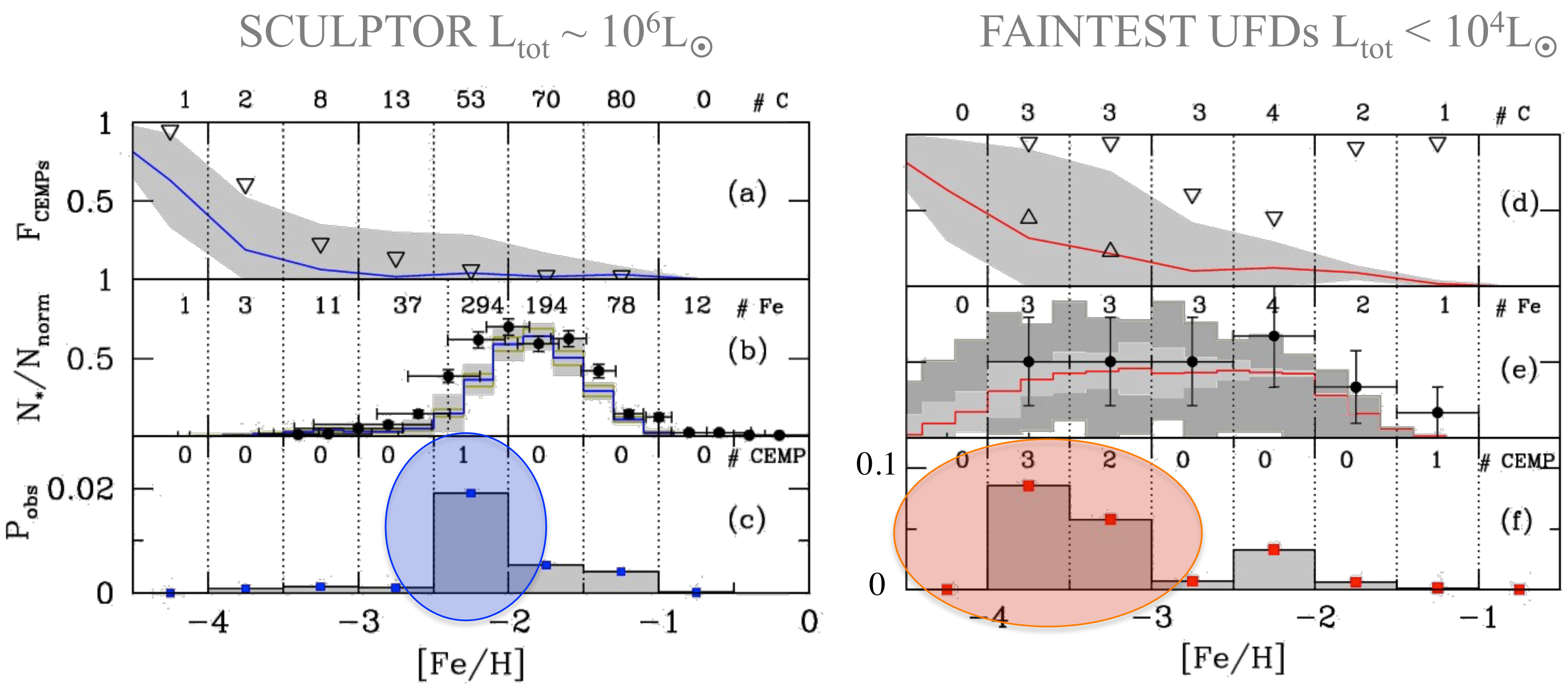
SCULPTOR $L_{tot} \sim 10^6 L_\odot$



In Sculptor, the probability to observe a C-enhanced star is maximal at [Fe/H] ≈ −2

CARBON-ENHANCED STARS IN DWARF GALAXIES

SS, Skuladottir & Tolstoy 2015



In UFDs the probability is higher and shifted at lower [Fe/H] → fossil galaxies!

CONCLUSIONS

The Milky Way and its environment is a powerful laboratory to study the properties of the first stars and the early galaxy formation processes.

- Carbon-enhanced metal-poor stars have been most likely enriched by the chemical products of zero-metallicity faint SN

→ With larger stellar samples we can find many of these second-generation stars and constrain the mass spectrum of the first stars – de Bennassuti, SS+16

- The observed properties of ultra-faint dwarfs are ALL consistent with the idea that they are the living fossils of star-forming mini-haloes formed at $z > 6$

→ We should find more Carbon-enhanced metal-poor stars in classical dwarf galaxies if the ΛCDM is correct: key predictions for future surveys – SS+15