Galactic Archaeology to its limits: Understanding the most pristine stars

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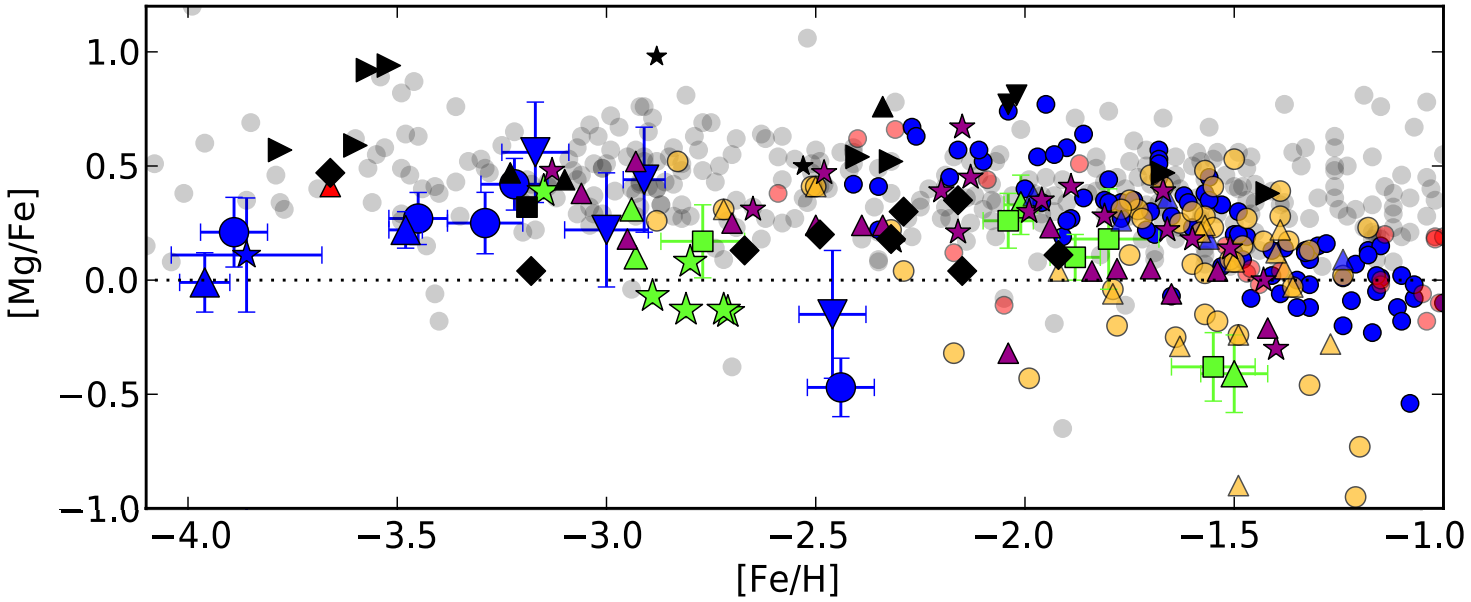
The most pristine stars in the dwarfs

Looking into the α-elements, the more metal-poor components look more like the Milky Way.

Are the early phases of star formation universal?



Sculptor, Tolstoy, Hill, Tosi, 2009; Tafelemeyer 2010; Frebel et al., 2010; Starkenburg et al. 2013;

Sextans, Shetrone et al. 2001; Aoki et al. 2009; Tafelemeyer 2010

Fornax, Tafelmeyer et al 2010 Letarte et al. 2010

Carina, Shetrone et al. 2013; Koch et al. 2008; Venn et al. 2014; Lemasle et al. 2012

Leo IV Hercules UMa II Segue I Comber I Boötes Koch et al 2008; Aden et al. 2011 Norris et al. 2010; Simon et al. 2010 Frebel et al. 2014

Draco & UMi Shetrone et al. 2001; Fulbright et al. 2004; Cohen & Huang 2009;2010; Sadakane et al. 2004;

MW Honda et al. 2004; Cayrel et al. 2004; Spite et al. 2005; Aoki et al. 2005; Cohen et al. 2013, 2006, 2004; Spite et al. 2006; Aoki et al. 2007; Lai et al. 2008; Yong et al. 2013; Ishigaki et al. 2013

Figure courtesy: Pascale Jablonka

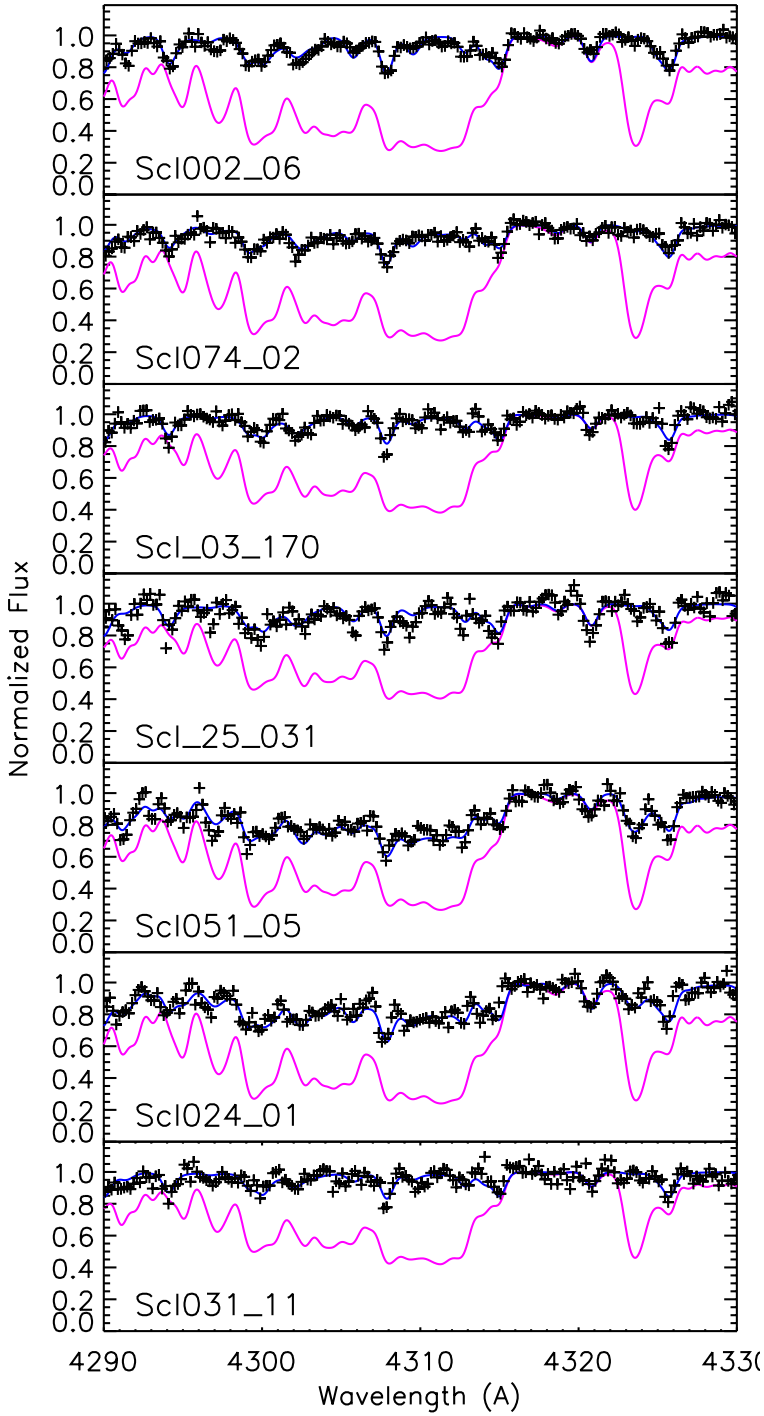
Different in Carbon?

Starkenburg et al., 2013a.

None are Carbon-rich

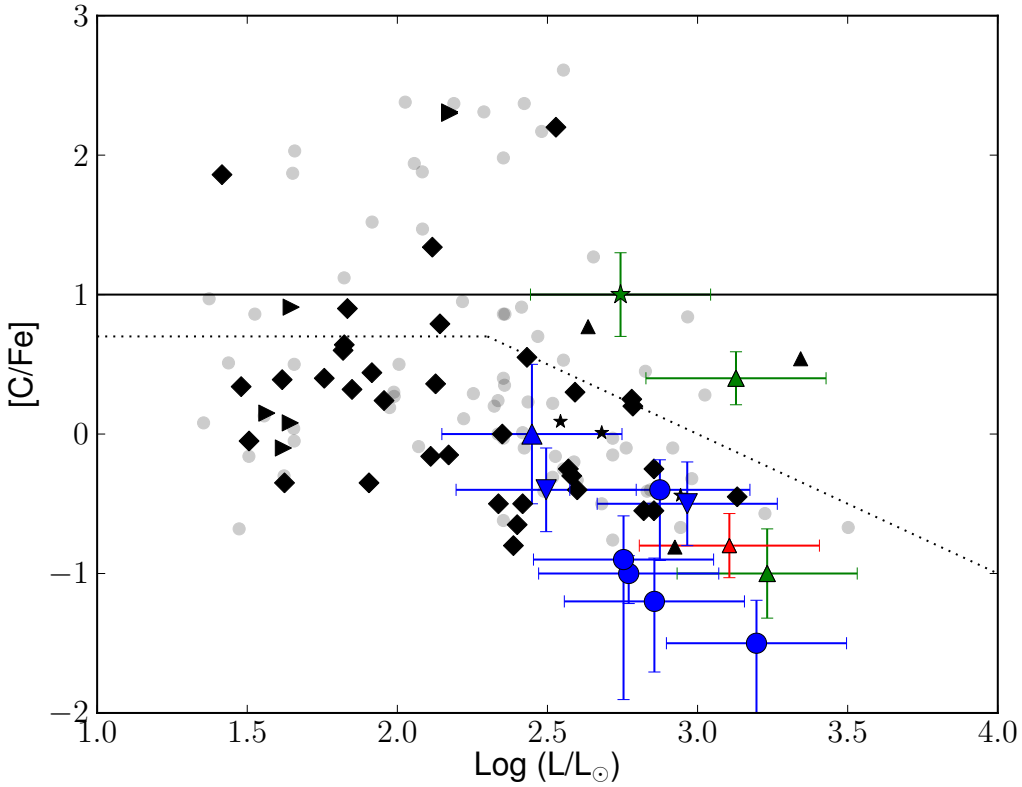
- But C-rich stars in MW
- 20-32% (Yong et al., 2013, Placcio et al., 2014)
- Chance? 2-13%

- We need bigger samples!



Different in Carbon?

- C-measurements not made for most dwarf spheroidal studies



- Few C-rich stars are found in smaller systems (mostly ultra-faint dwarfs)

Sculptor, Tolstoy, Hill, Tosi, 2009; Tafelmeyer 2010; Frebel et al., 2010; Starkenburg et al. 2013;

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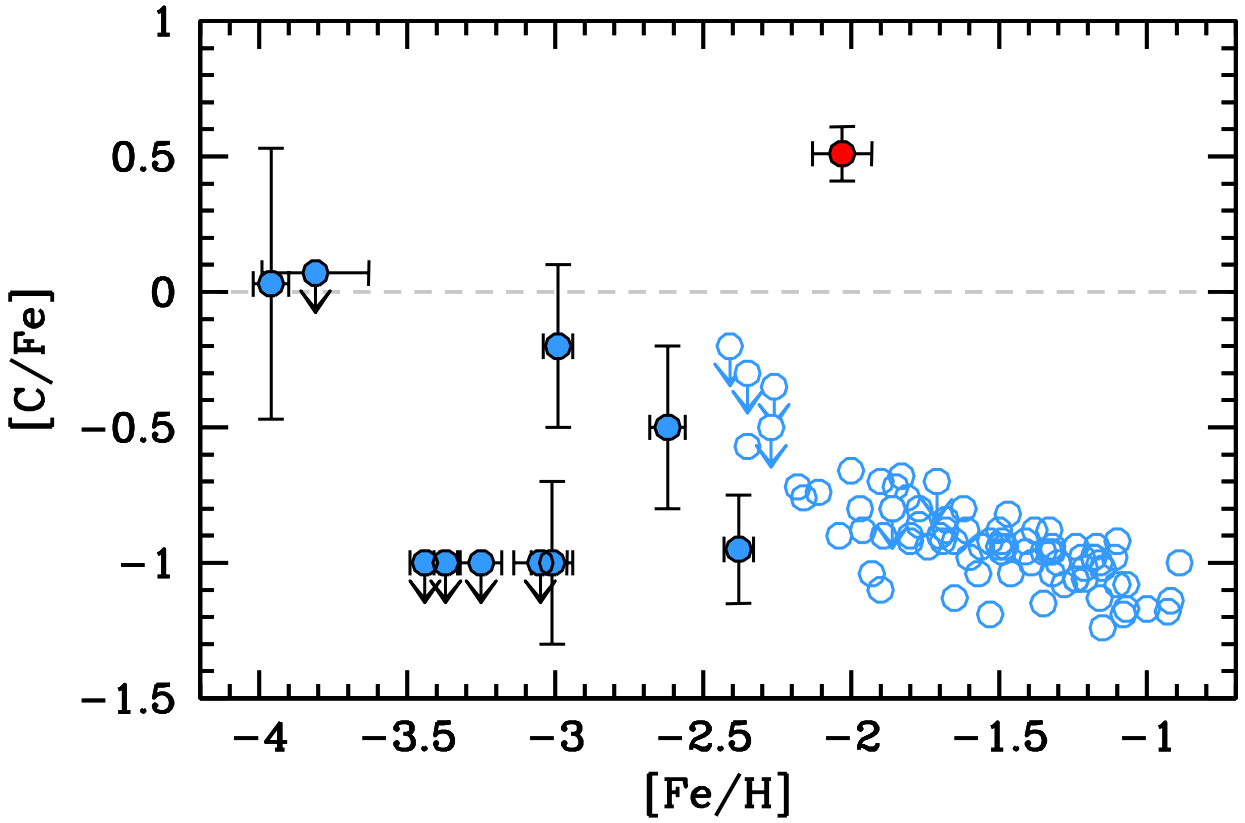
Figure courtesy: Pascale Jablonka

A Carbon-enhanced star in Sculptor

A. Skúladóttir, E. Tolstoy, S. Salvadori, V. Hill, M. Pettini, M. D. Shetrone, and E. Starkenburg - submitted

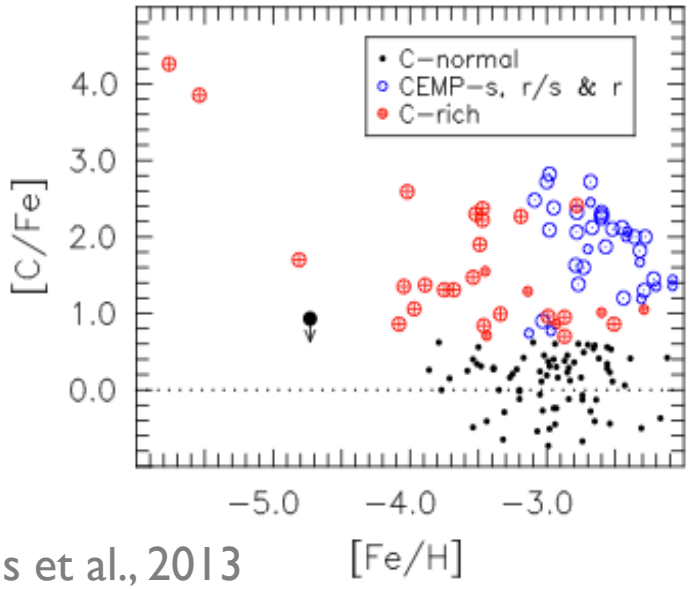
- Found in larger multi-object spectroscopy setting
  - The only candidate that stands out



What does this tell us about the dwarf environment?

- Why do metal-poor stars show an overabundance in Carbon?

- Two main "types" of Carbon-enhanced metal-poor stars
  - CEMP-s [Ba/Fe] > 1.0
  - CEMP-no [Ba/Fe] < 0.0



Norris et al., 2013

Why are they C-rich?

- Explanation 1: A binary companion dumped it

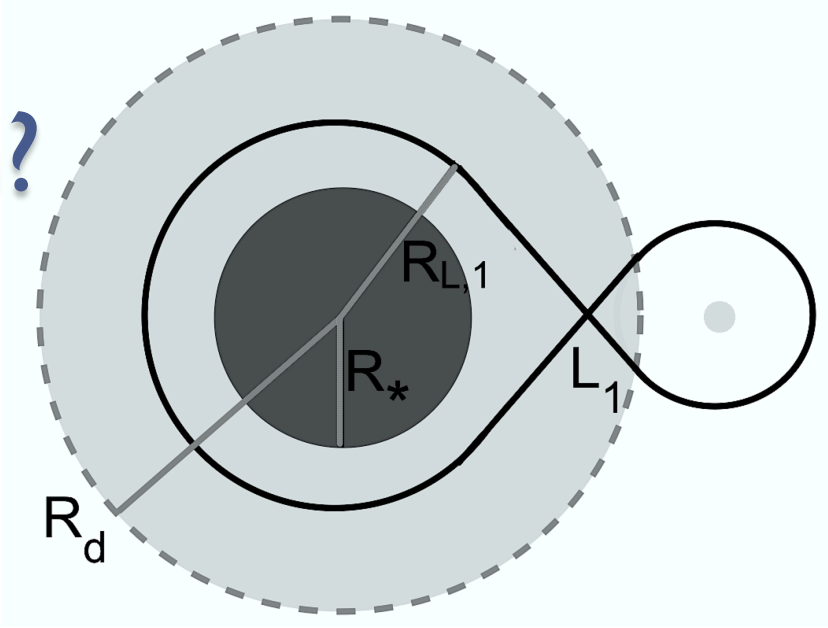


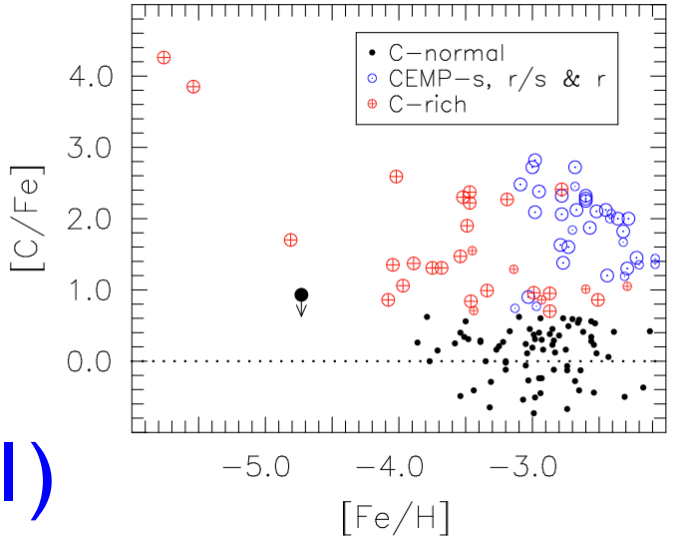
Figure from Abate et al., 2013

  - AGB stars make lots of Carbon, can be transported to companion
    - AGB stars also make s-process (Ba)
    - BUT some models predict that not all AGB stars will make s-process (Herwig et al., 2004, Siess et al., 2004)

    - Binarity can be checked by radial velocity monitoring!

Why are they C-rich?

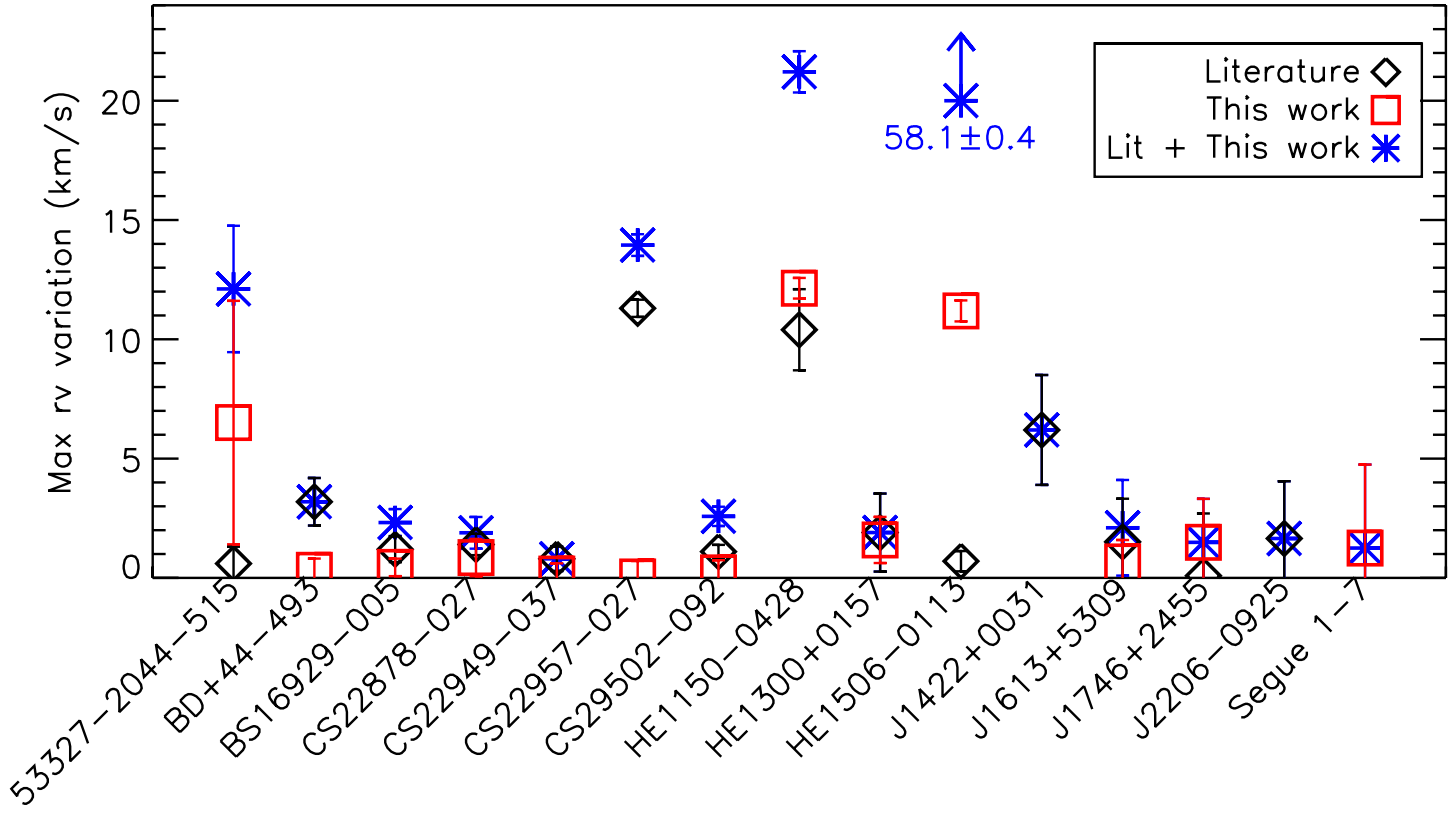
Results from radial velocity monitoring



- CEMP-s (+s-process, [Ba/Fe]>1)
  - Radial velocity monitoring: Consistent with all being in binary systems (Lucatello et al., 2005 and refs therein)
    - C-enrichment from pollution due to AGB companion
- CEMP-no (no s-process, [Ba/Fe]<0)
  - Radial velocity monitoring ongoing
    - (Hansen et al., 2012, Norris et al., 2013, Cohen et al., 2013, Andersen et al., in prep, Starkenburg et al., 2014, Aoki et al., in prep)

Binaries?

- What about CEMP-no?
  - Some are in binaries!
  - ….but not all it seems



Starkenburg, Shetrone, McConnachie & Venn, 2014 and upcoming data from SALT and CFHT programs

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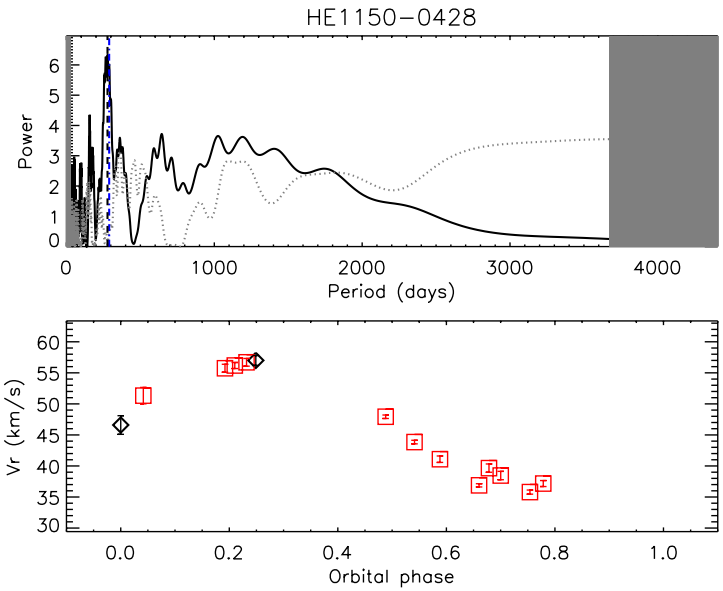
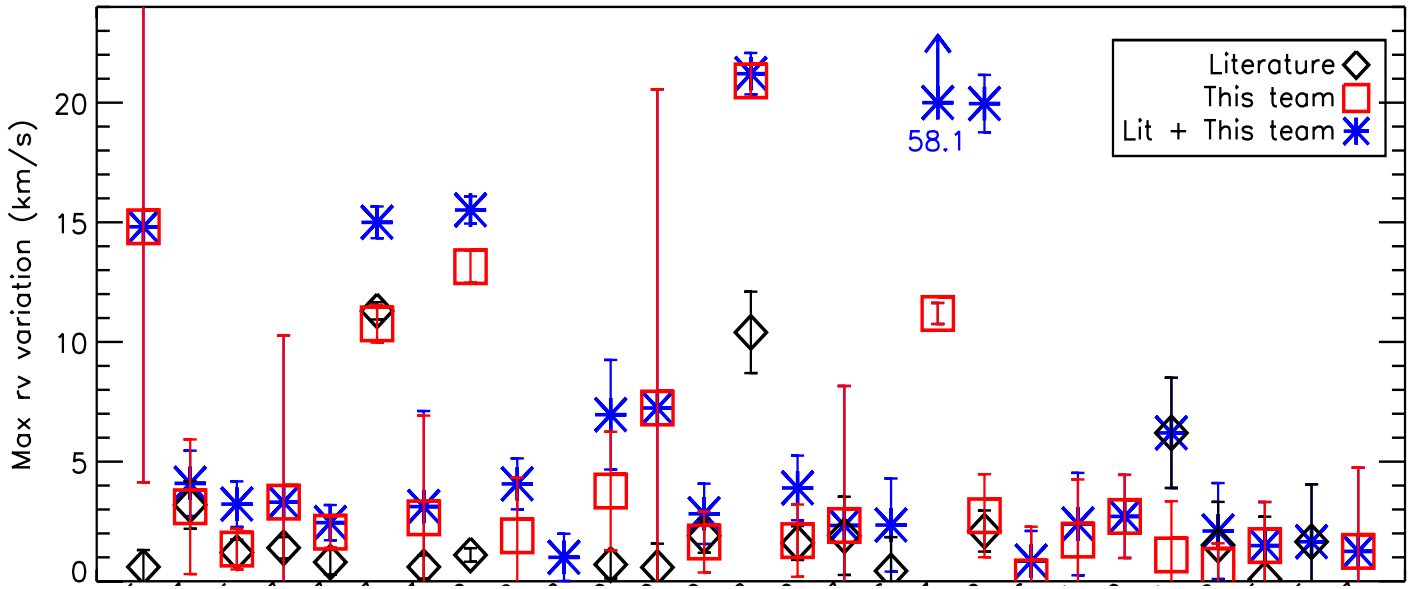


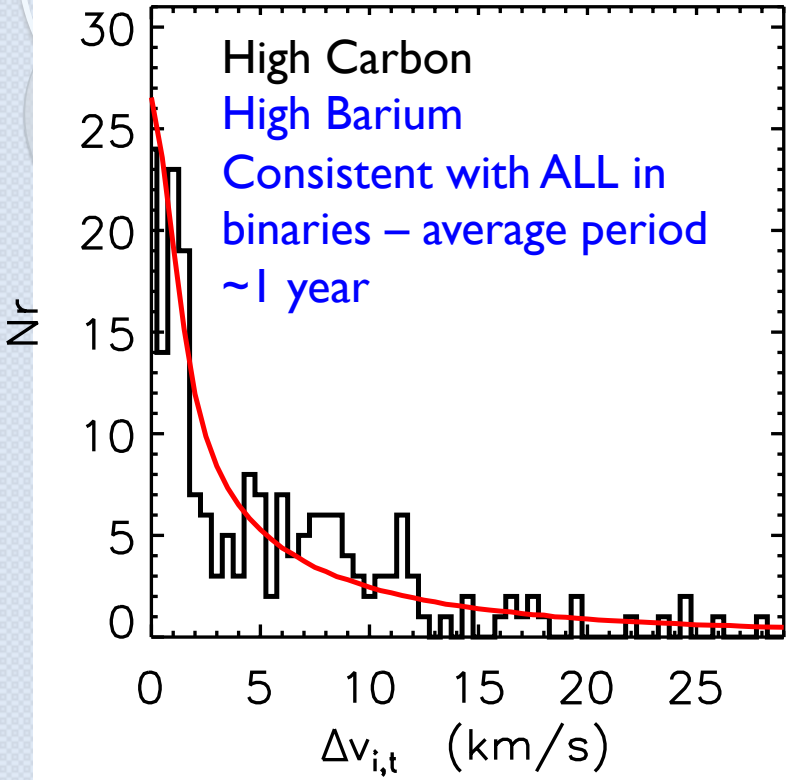


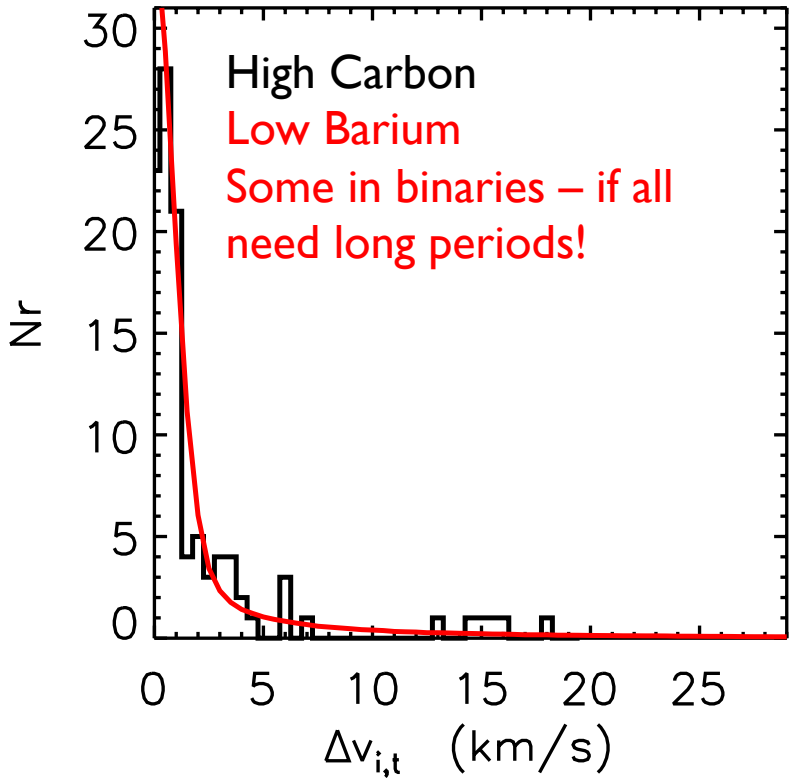
PRELIMINARY

Starkenburg, Shetrone, McConnachie & Venn, 2014 and upcoming data from SALT and CFHT programs

Binaries?

Starkenburg, Shetrone, McConnachie & Venn, 2014



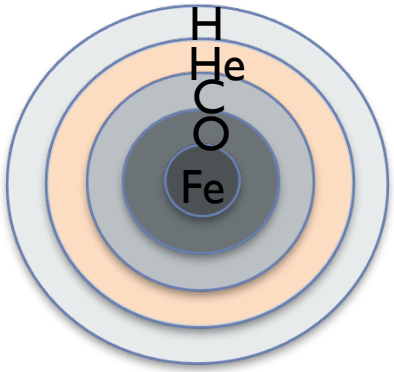


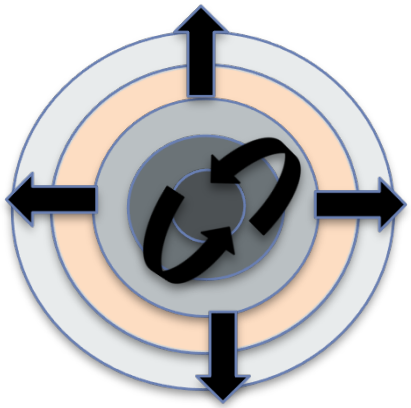
Different formation scenario

Data from HET + literature (Lucatello et al., 2005 for CEMP-s)

Why are they C-rich?

- Explanation II: They were born with it
  - Some models predict over-abundance Carbon in supernova feedback First Stars
    - Massive rotating stars; spinstars (Fryer, Woosley & Heger 2001; Meynet, Ekstrom & Maeder 2006; Chiappini et al. 2006; Karlsson 2006; Hirschi 2007; Meynet et al. 2010; Maeder & Meynet 2012; Cescutti et al. 2013, Chiappini et al., 2013)
    - Mixing & fall-back/faint supernovae (Umeda & Nomoto 2003; Limongi, Chieffi & Bonifacio 2003; Iwamoto et al. 2005; Umeda & Nomoto 2005; Tominaga, et al., 2007,2014)





Why are they C-rich?

- Explanation 11: They were born with it
  - Extra Carbon helps reach critical metallicity in surroundings

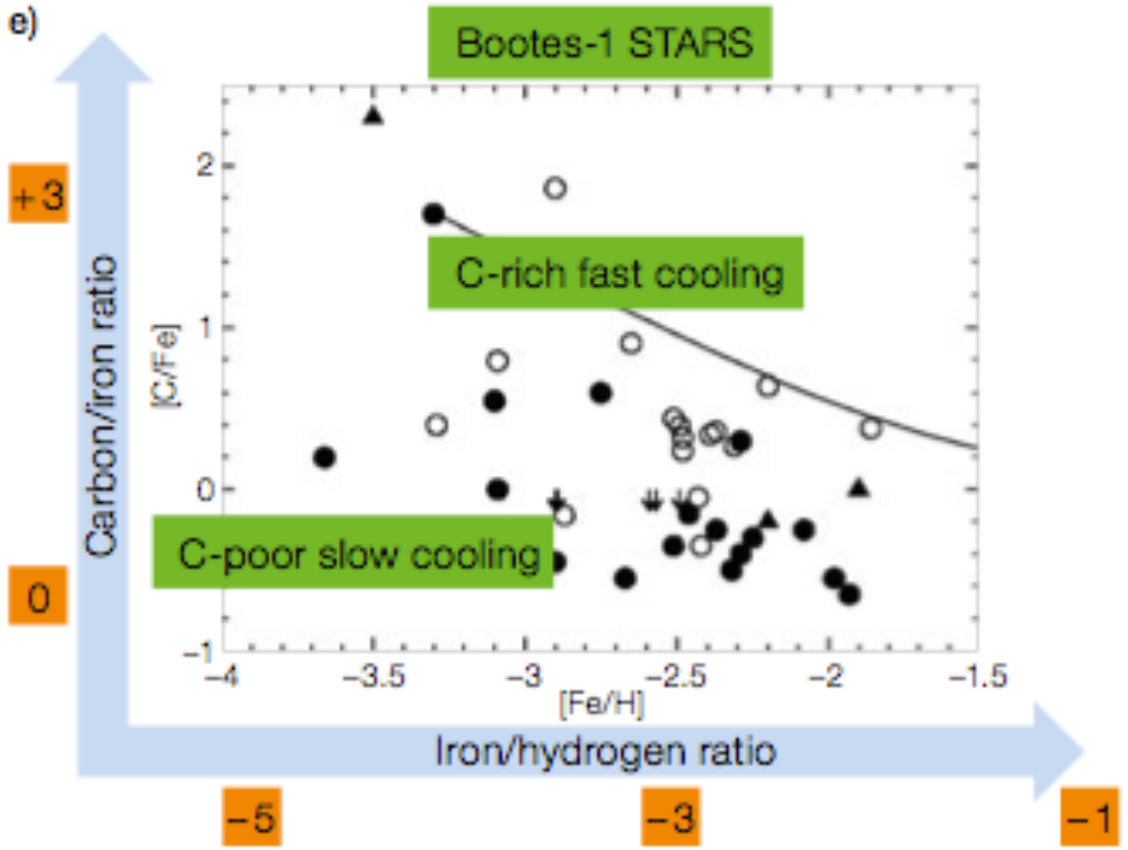
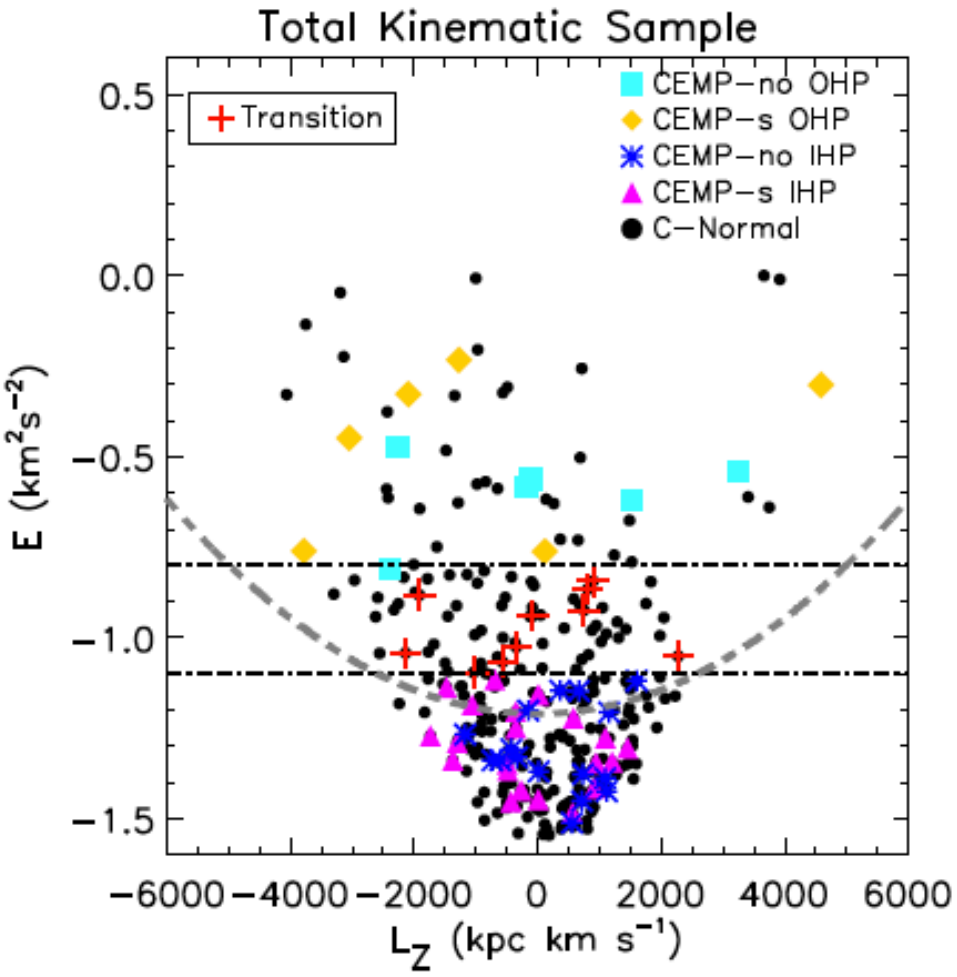


Figure from Gilmore et al., 2013

What about various environments?

- Disk & (dual) halo show different C-rich pops
- Relatively more CEMP-no outer halo
- Sign of
  - IMF variation? (Carollo 2012, Lee et al., 2013b, Carollo et al., 2014)
  - Binary properties?
- Dwarf C-rich stars mostly CEMP-no

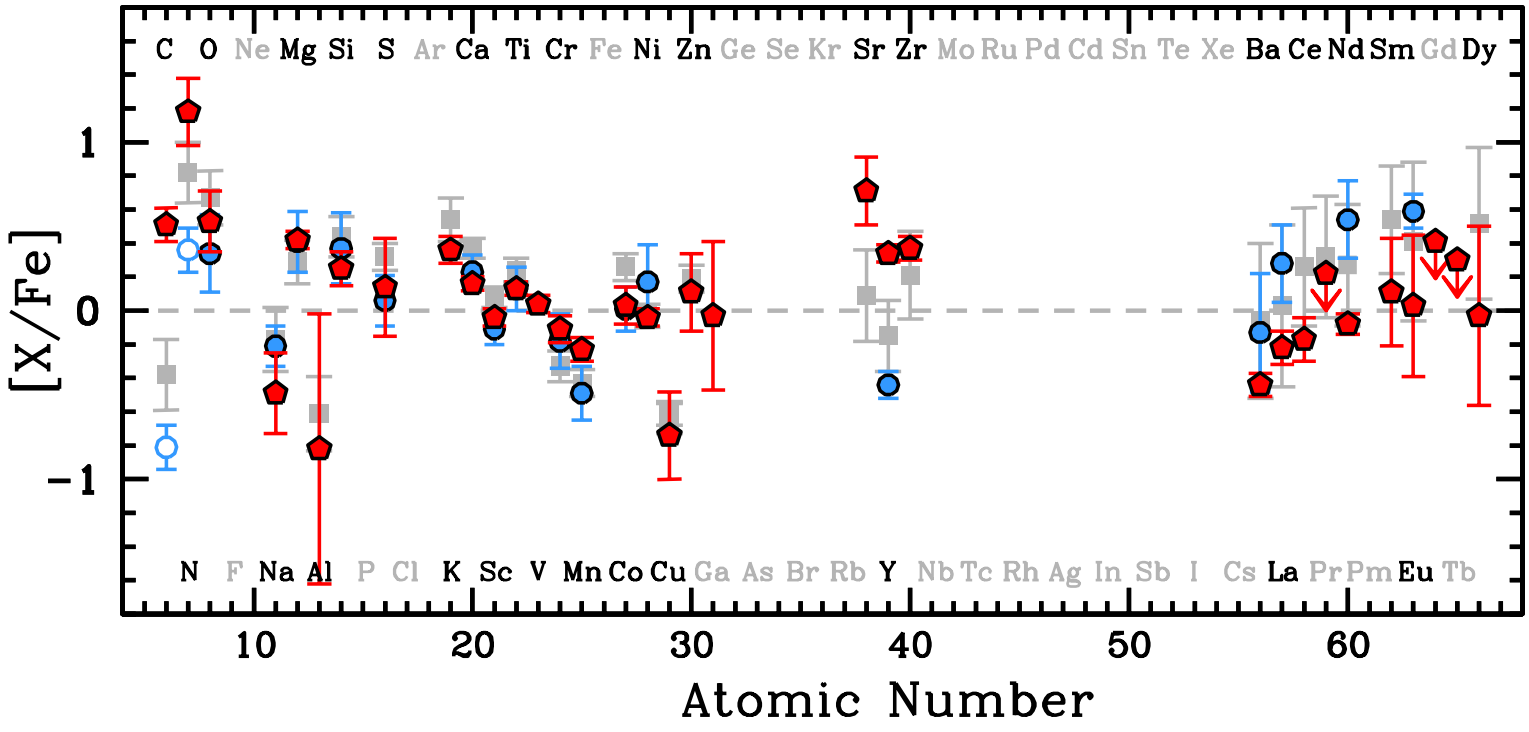


Carollo et al., 2014

A CEMP star in Sculptor

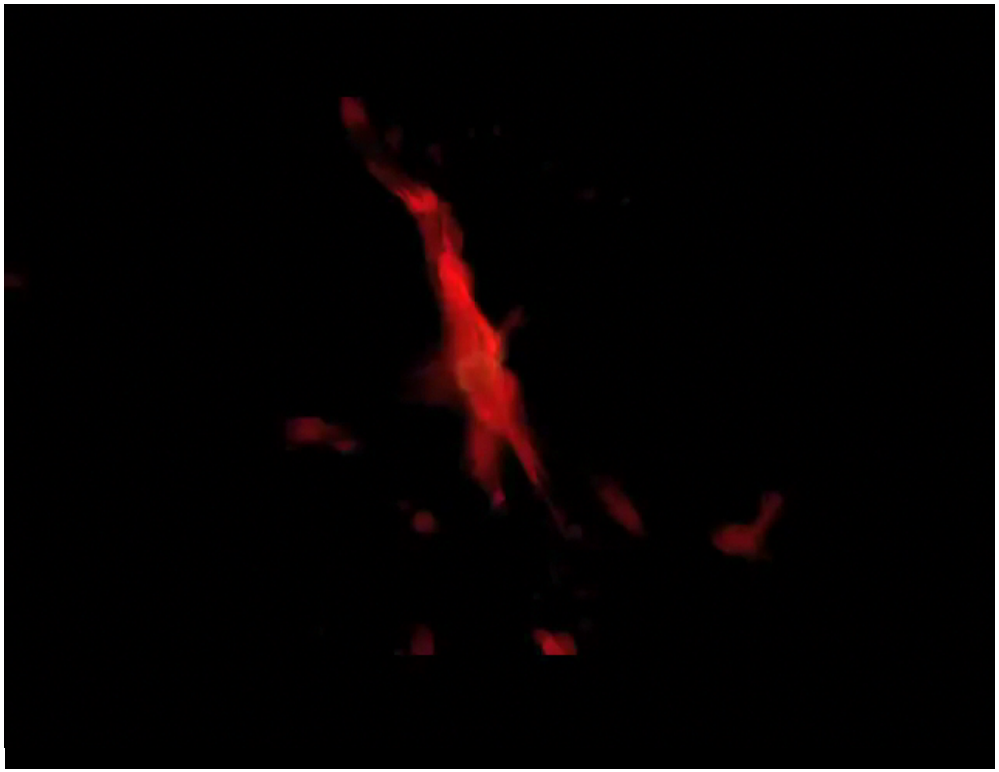
(A. Skúladóttir, E. Tolstoy, S. Salvadori, V. Hill, M. Pettini, M. D. Shetrone, and E. Starkenburg - submitted)

- CEMP-no star



Lessons learned from the most metal-poor stars

- Probing
  - Epoch of re-ionization
  - End of the cosmic dark ages
  - Chemical complexity & magnetic fields
- Uniquely studied in resolved stars

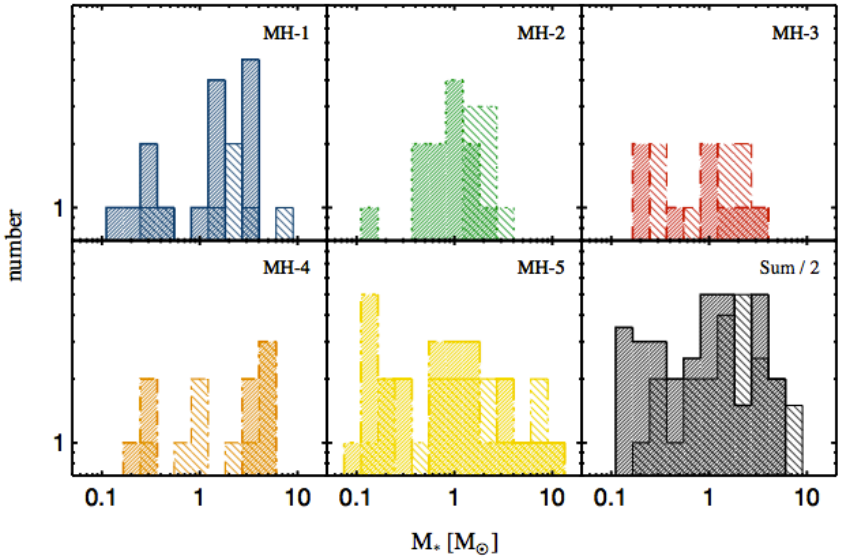


Movie "First Light", Wise, Abel, Kaehler, 2009

See reviews Bromm et al., 2012, Karlsson, Bromm & Bland-Hawthorn 2013, Nomoto 2014

Challenges

- Do also the first phases of star formation change with environment?
  - Need to get out of the (local) Milky Way
- How massive will First stars be?
  - Gas is hotter – inflow larger – accretion disk – Fragmentation??
  - "Metallicity floor": can a true First Star still be out there?
    - < 0.8 Msun
  - Need statistics



Protostellar mass function (not final masses)

Greif et al., 2011

Conclusions

- Despite a lot of data, still many elements & questions are *only* well studied within the Milky Way
- Pristine stars tell us stories about the earliest epochs of galaxy formation
  - Are there more Carbon-rich stars in the halo than in (some of) the dwarfs?
  - High Carbon, high Barium
    - Binaries with short periods – mass transfer
  - High Carbon, low Barium
    - Are different. Second generation?
- Future prospects:
  - Many different environments and
  - Gaining more statistics: Skymapper & other narrow band initiatives feeding to multi-object spectrographs (4MOST)