Chemical tagging and CEMPs in ultrafaint dwarfs

J. Bland-Hawthorn
University of Sydney

THE UNIVERSITY OF SYDNEY

Collaborators:
David Webster
Ralph Sutherland
Anna Frebel
Josh Simon
David Yong

Near Field Cosmology:
The domain of resolved stellar populations

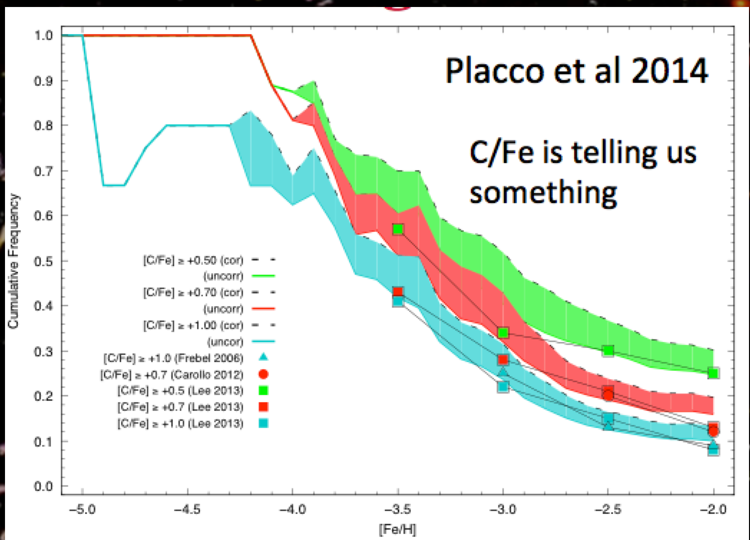
To understand the dominant physical processes in the early Universe ($z>1$) from the local stellar record

Most activity took place before $z\sim1$
but half of all stars are older than 8 Gyr

GA is the ultimate cold case

The Local Group is the size of the HUDF at z ~ 3.

GA probes intrinsically lower mass objects today.



We may be seeing imprint of reionization (z~8) locally.

We may be seeing first stars with CEMPs.

We may be seeing imprint of core/cusp destruction at z ~ 1-5.

Can we see cosmic SFH imprinted on the Galactic populations ? (rise & fall of NSM, HN, KN, MN, ...)

Is the thick disk a consequence of early onset turbulence ?

Are we probing WDM with dwarfs ?

Are we probing DM substructure in halo ?

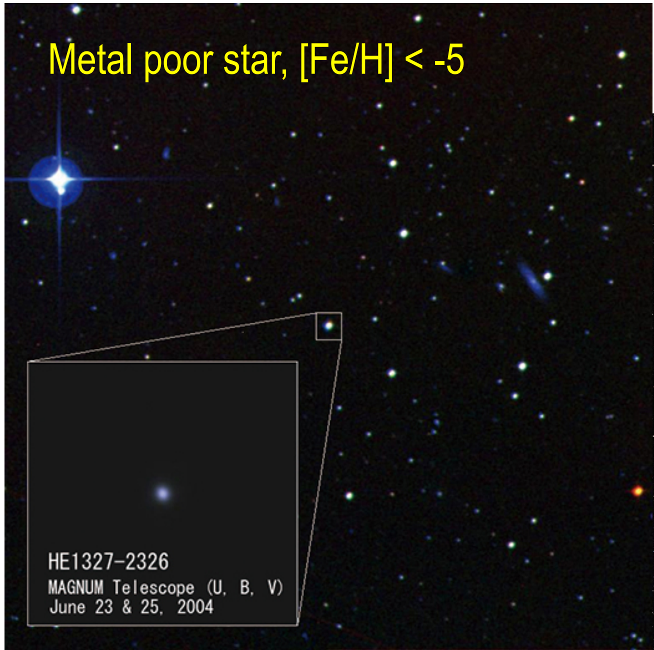
Can we detect specific signatures of the first stellar generations today?

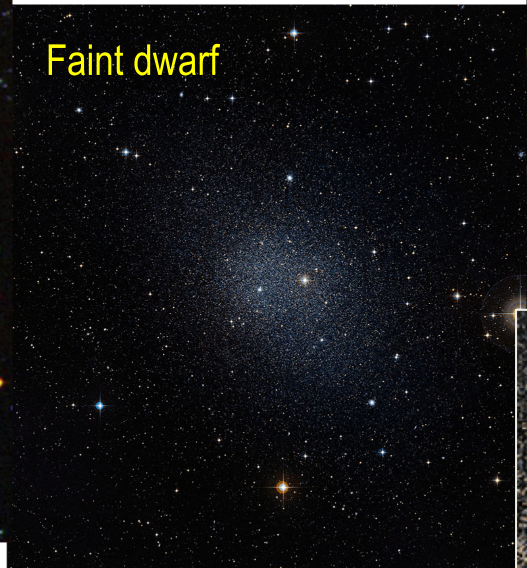
Beers & Christleib 2005, ARAA
Bromm & Yoshida 2011, ARAA
Karlsson, Bromm & JBH 2013, RMP
Frebel & Norris 2015, ARAA

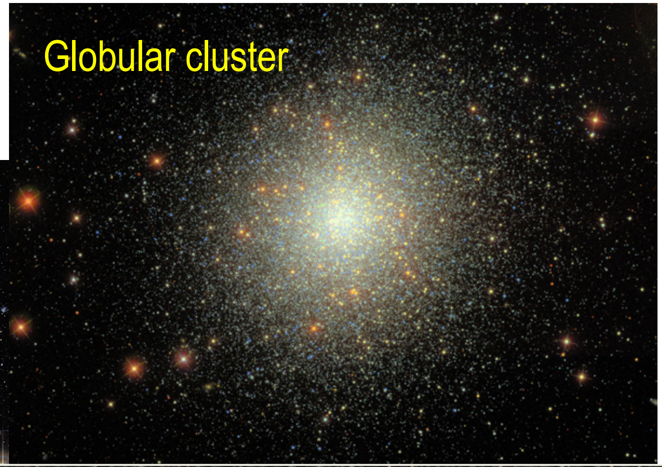
The lowest mass galaxies have very few star forming events and are the most affected by **reionization**. They may preserve the clearest signal of what happened in the early universe.

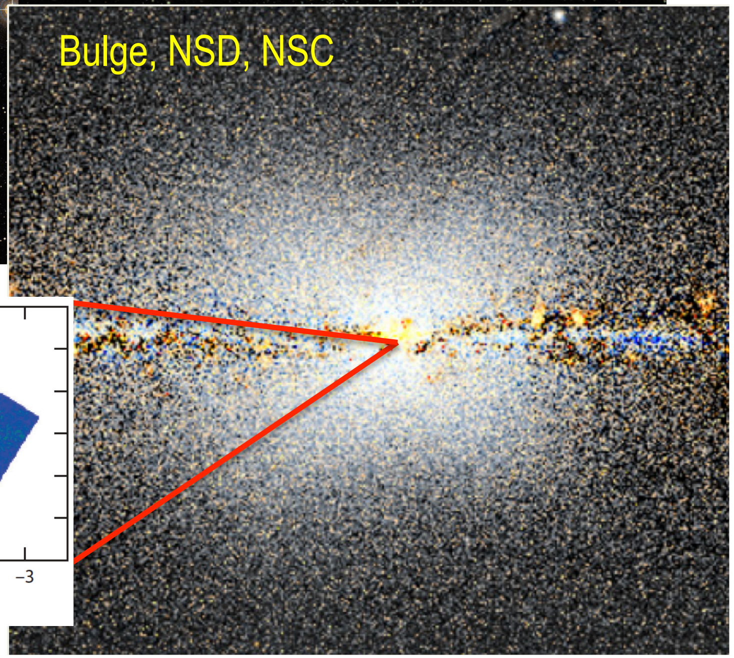
Where to look for signatures of first stellar generations ?

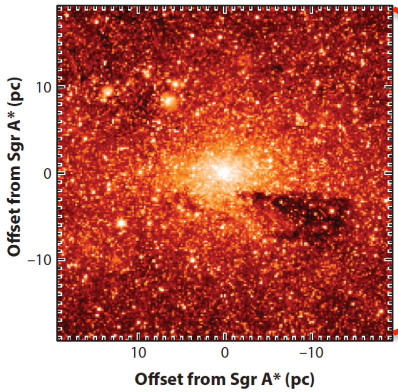
Our “**first star” models** produce abundance signatures that we can’t easily relate to the most metal poor stars (in our Galaxy) or to the most metal poor clouds at the highest redshifts**. Are we looking in the wrong place ?**

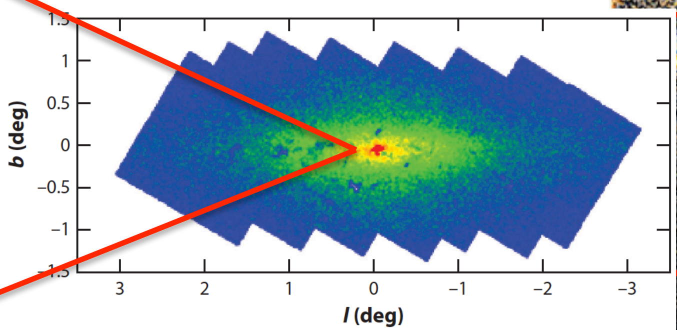












Are we seeing the signature of reionization in ultrafaint dwarfs?

Brown+ 2014
Weisz+ 2014a,b
Frebel, Simon & Kirby 2014
Webster+ 2014, 2015a,b
JBH, Sutherland & Webster 2015
Ritter+ 2015
Sluder+ 2015
Simon+ 2015
Ji, Frebel & Bromm 2015, 2016
Webster, Frebel & JBH 2016

The lowest mass galaxies have very few star forming events and are the most affected by **reionization**.

We search for chemical **enrichment** without chemical **evolution**.

THE ASTROPHYSICAL JOURNAL

The Astrophysical Journal > Volume 796 > Number 2

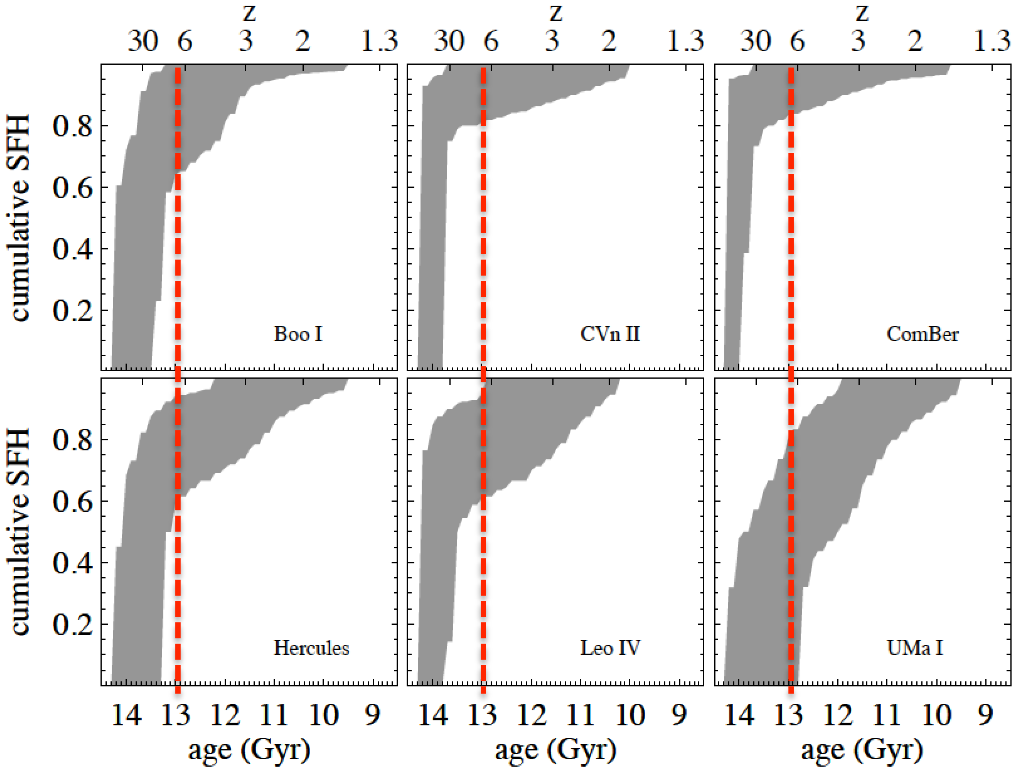
Thomas M. Brown *et al.* 2014 *ApJ* **796** 91 doi:10.1088/0004-637X/796/2/91

THE QUENCHING OF THE ULTRA-FAINT DWARF GALAXIES IN THE REIONIZATION ERA*

Thomas M. Brown[1], Jason Tumlinson[1], Marla Geha[2], Joshua D. Simon[3], Luis C. Vargas[2], Don A. VandenBerg[4], Evan N. Kirby[5], Jason S. Kalirai[1,6], Roberto J. Avila[1], Mario Gennaro[1], Henry C. Ferguson[1], Ricardo R. Muñoz[7], Puragra Guhathakurta[8], and Alvio Renzini[9]

Planck XVII (2016), **Z_{reion} ~ 8.3 ± 0.5**

Up to 90% of stars formed before Z_{reion} in lowest mass dwarfs $\leq 10^5 L_\odot$



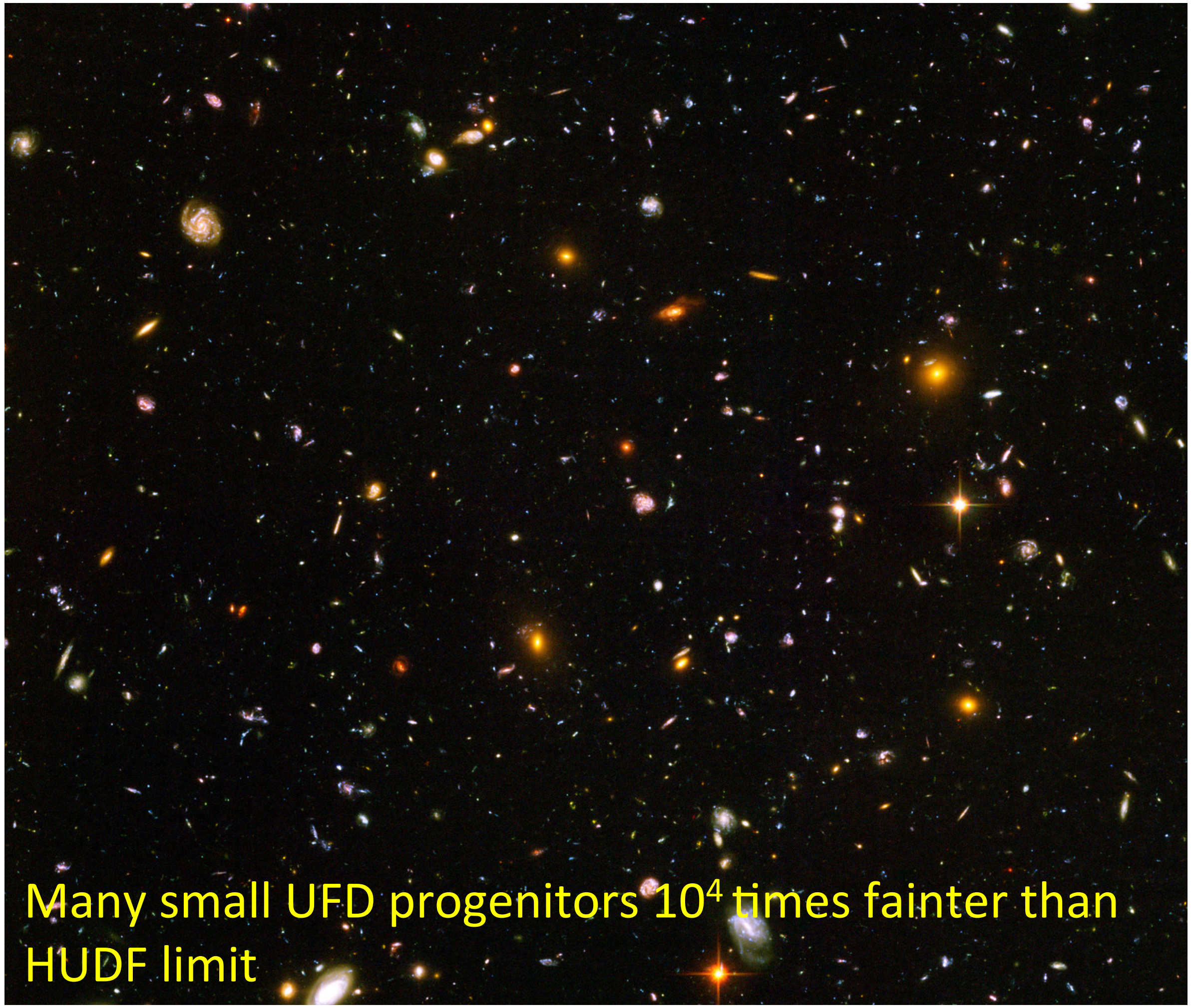
ACS/HST, DEIMOS/Keck

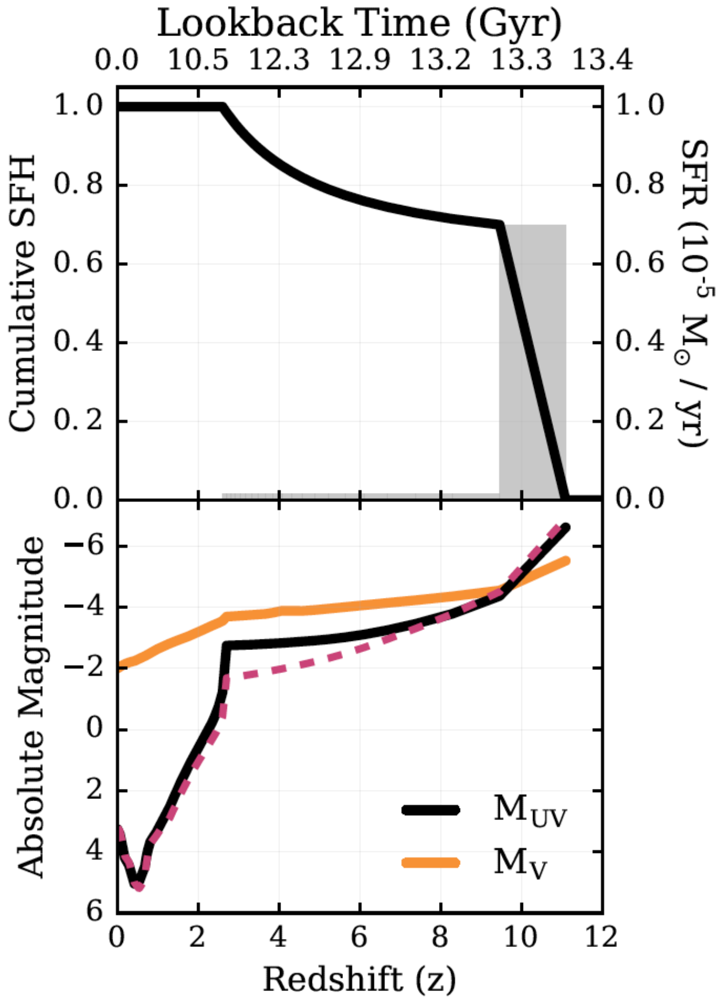
Victoria-Regina isochrones

Local Group Ultra-Faint Dwarf Galaxies in the Reionization Era

2017

Daniel R. Weisz[1], Michael Boylan-Kolchin[2]
[1]*Department of Astronomy, University of California Berkeley, Berkeley, CA 94720, USA; dan.weisz@berkeley.edu*
[2]*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712-1205, USA*





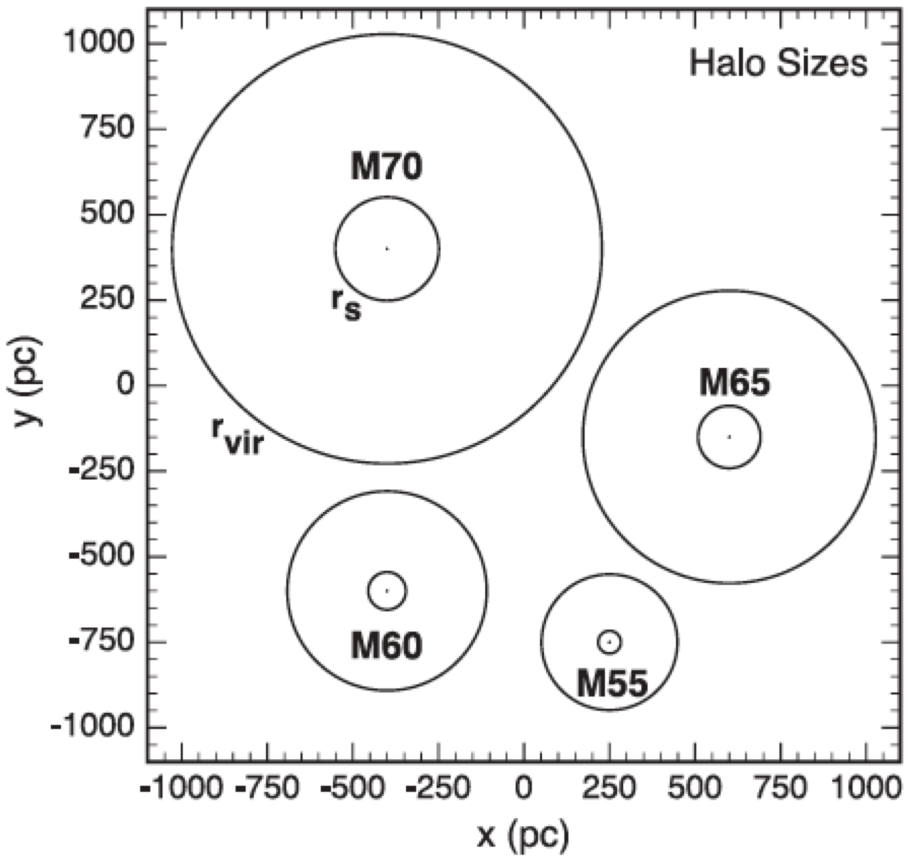
THE ASTROPHYSICAL JOURNAL

ULTRAFAINT DWARF GALAXIES—THE LOWEST-MASS RELICS FROM BEFORE REIONIZATION

Joss Bland-Hawthorn[1], Ralph Sutherland[2], and David Webster[3] 2015

Published 2015 July 9 • • The Astrophysical Journal, Volume 807, Number 2

Gas in halos $M_{vir} \sim 10^7\ M_\odot$ can survive pre-ionization & SN explosion of 25 $M_\odot$ star



How:

1. off-centred star
2. fractal medium initially in equilibrium with hot halo
3. **time dep. pre-ionization**
4. resolved SN shock front
5. clustered SF through **init. cluster mass function**

Results used in chemical tagging papers coming up…

We've also done extended SF, Type Ia, with no Type II and therefore **no** pre-ionization

THE ASTROPHYSICAL JOURNAL

ULTRAFAINT DWARF GALAXIES—THE LOWEST-MASS RELICS FROM BEFORE REIONIZATION

Joss Bland-Hawthorn[1], Ralph Sutherland[2], and David Webster[3]

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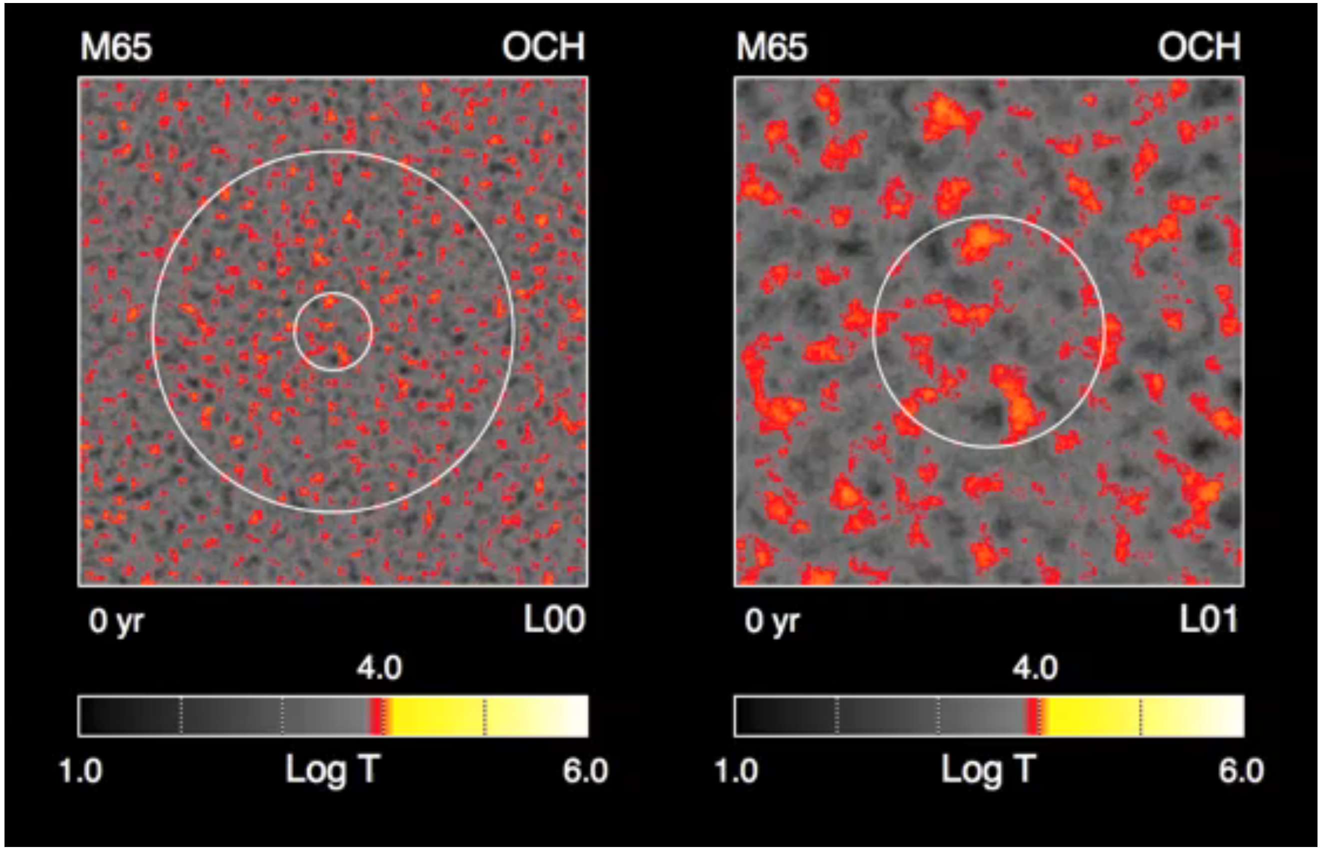
Gas in halos $M_{vir} \sim 10^7\ M_\odot$ can survive pre-ionization & SN explosion of 25 $M_\odot$ star

Movies: miocene.anu.edu.au/smallgalaxy/



How:

1. off-centred star
2. fractal medium initially in equilibrium with hot halo
3. **time dep. pre-ionization**
4. resolved SN shock front
5. clustered SF through **init. cluster mass function**

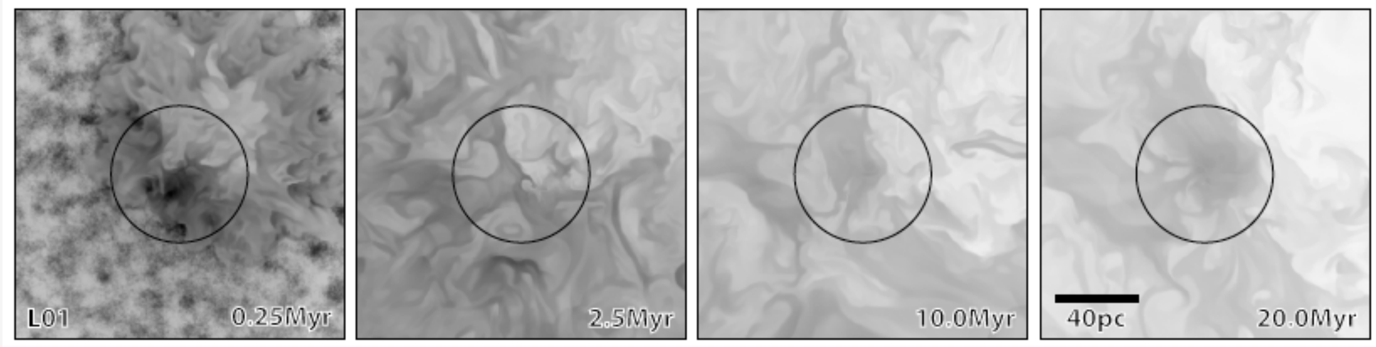
Results used in papers Webster+ 2014, 15a,b, 16

"Minimum mass galaxy" retains cold gas after one SN event

Bland-Hawthorn, Sutherland & Webster 2015

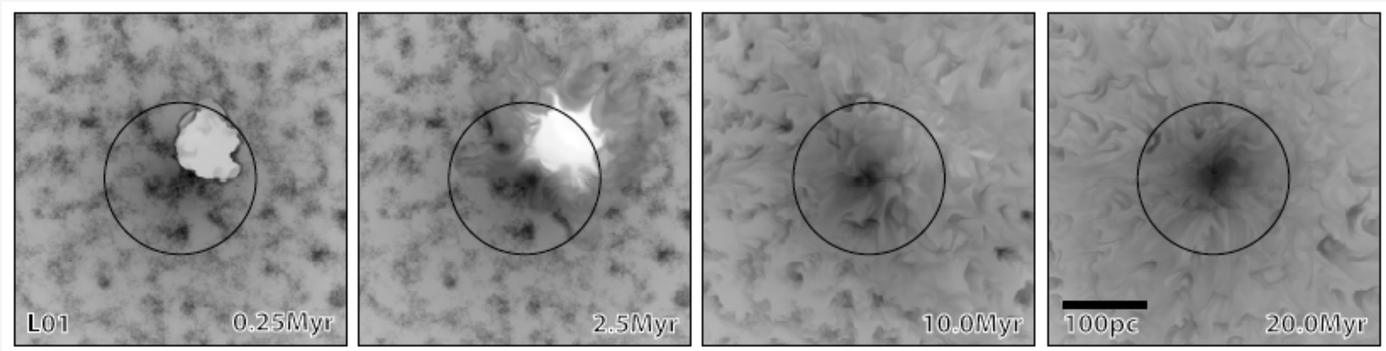
M_{vir} = 3x10^5 $M_\odot$

***no** gas retained in core*



M_{vir} = 3x10^6 $M_\odot$

cold gas retained



*1. The **minimum mass** of a galaxy can be **10x** less massive than previously thought (e.g. Mac Low & Ferrara)*

*2. The models share properties with **UFDs** (baryon mass, scale, kinematics, metals) and can explain very metal poor **DLAs** (Cooke et al 2011).*

New method:

identify ancient star clusters in UFDs
through chemical tagging

JBH+ 2010a,b
Karlsson+ 2012
Karlsson, Bromm & JBH 2013
Webster, Sutherland & JBH 2014
Webster, Frebel & JBH 2016

Chemical tagging in the lowest mass dwarf galaxies will allow us to associate stars that were born together.

The importance of ancient star clusters

- **First galaxies** can in principle have total masses ~10^7 $M_\odot$ -- strong statistical fluctuations in chemical signatures should exist
- The **cluster mass function** is a direct probe of the formation process (reionization, pressure, etc.)
- CLusters can be **age-dated** more accurately than individual stars
- The summed stellar signature is the most reliable gauge of the **progenitor cloud** (indep. of binarity, mass transfer, mixing)
- These **building blocks** help to reconstruct the SFH more accurately; event driven rather than continuous distribution
- We predict that a **reconstructed star cluster** will provide the first definitive statement on first star signatures; we can trace clusters to very low [Fe/H]
- Can we find **clumped CEMP signatures** in ultrafaint dwarfs? Can we unravel how this event took place?

How massive a uniform star cluster?

JBH et al (2010a)

Cloud dynamical time (Tan+ 06)

$$t_{\rm cr} = \frac{0.95}{\sqrt{\alpha_{\rm vir} G}} \left(\frac{M}{\Sigma^3}\right)^{1/4}$$

M = cloud gas mass ~ 10^6 M_o
Σ = cloud col. density ~ 0.3 g cm^{-2}

The cloud's virial ratio $\alpha_{\rm vir} \approx 1-2$ is the ratio of kinetic to gravitational energy. So if t_{form} = 4 t_{cr} then

$$t_{\rm form} \approx 3.0 \left(\frac{\epsilon}{0.2}\right)^{-1/4} \left(\frac{M_*}{10^4\, M_\odot}\right)^{1/4} \,{\rm Myr}$$

$$\epsilon = M_*/M = 0.2$$

i.e. fraction of cloud ➔ stars

We conclude that <u>all</u> open clusters up to 10^5 M_o are uniform since t_{SN} > 3 Myr for most SNe in these clusters. For globular densities, the upper mass limit is 10^7 M_o !!

nature International weekly journal of science

NATURE | LETTER

日本語要約

Early turbulent mixing as the origin of chemical homogeneity in open star clusters

Yi Feng & Mark R. Krumholz

Affiliations | Contributions | Corresponding author

Nature **513**, 523–525 (25 September 2014) | doi:10.1038/nature13662
Received 28 February 2014 | Accepted 01 July 2014 | Published online 31 August 2014

The abundances of elements in stars are critical clues to stars' origins. Observed star-to-star variations in logarithmic abundance within an open star cluster—a gravitationally bound ensemble of stars in the Galactic plane—are typically only about 0.01 to 0.05 over many elements[1, 2, 3, 4, 5, 6, 7, 8, 9], which is noticeably smaller than the variation of about 0.06 to 0.3 seen in the interstellar medium from which the stars form[10, 11, 12, 13, 14]. It is unknown why star clusters are so homogenous, and whether homogeneity should also prevail in regions of lower star formation efficiency that do not produce bound clusters. Here we report simulations that trace the mixing of chemical elements as star-forming clouds assemble and collapse. We show that turbulent mixing during cloud assembly naturally produces a stellar abundance scatter at least five times smaller than that in the gas, which is sufficient to explain the observed chemical homogeneity of stars. Moreover, mixing

star cluster?

JBH et al (2010)

cloud gas mass ~ 10^6 M_o

cloud col. density ~ 0.3 g cm^{-2}

io of kinetic to gravitational

$$)^{1/4} \text{ Myr}$$

$$= M_*/M = 0.2$$

e. fraction of cloud ➔ stars

M_o are uniform since

r globular densities,

The Astrophysical Journal, 721:582–596, 2010 September 20 doi:10.1088/0004-637X/721/1/582

2010b

THE CHEMICAL SIGNATURES OF THE FIRST STAR CLUSTERS IN THE UNIVERSE

Joss Bland-Hawthorn[1,4], Torgny Karlsson[1,5], Sanjib Sharma[1], Mark Krumholz[2], and Joe Silk[3]
[1] Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia; jbh@physics.usyd.edu.au
[2] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95060, USA
[3] Physics Department, University of Oxford, OX1 3RH, UK
Received 2010 March 19; accepted 2010 July 15; published 2010 August 30

ABSTRACT

The chemical abundance patterns of the oldest stars in the Galaxy are expected to contain residual signatures of the first stars in the early universe. Numerous studies attempt to explain the intrinsic abundance scatter observed in some metal-poor populations in terms of chemical inhomogeneities dispersed throughout the early Galactic medium due to discrete enrichment events. Just how the complex data and models are to be interpreted with respect to "progenitor yields" remains an open question. Here we show that stochastic chemical evolution models to date have overlooked a crucial fact. Essentially, all stars today are born in highly homogeneous star clusters and it is likely that this was also true at early times. When this ingredient is included, the overall scatter in the abundance plane [Fe/H] versus [X/Fe] ($\mathcal{C}$-space), where X is a nucleosynthetic element, can be much less than derived from earlier models. Moreover, for moderately flat cluster mass functions ($\gamma \lesssim 2$), and/or for mass functions with a high mass cutoff ($M_{\rm max} \gtrsim 10^5\ M_\odot$), stars exhibit a high degree of clumping in $\mathcal{C}$-space that can be identified even in relatively small data samples. Since stellar abundances can be modified by mass transfer in close binaries, clustered signatures are essential for deriving the yields of the first supernovae. We present a statistical test to determine whether a given set of observations exhibit such behavior. Our initial work focuses on two dimensions in $\mathcal{C}$-space, but we show that the clustering signal can be greatly enhanced by additional abundance axes. The proposed experiment will be challenging on existing 8–10 m telescopes, but relatively straightforward for a multi-object echelle spectrograph mounted on a 25–40 m telescope.

Key words: galaxies: dwarf – Galaxy: abundances – Galaxy: evolution – Galaxy: formation – galaxies: star clusters: general

Online-only material: color figures

2D abundance space

Simulated galaxy on 8m (top) and on GMT (bottom):

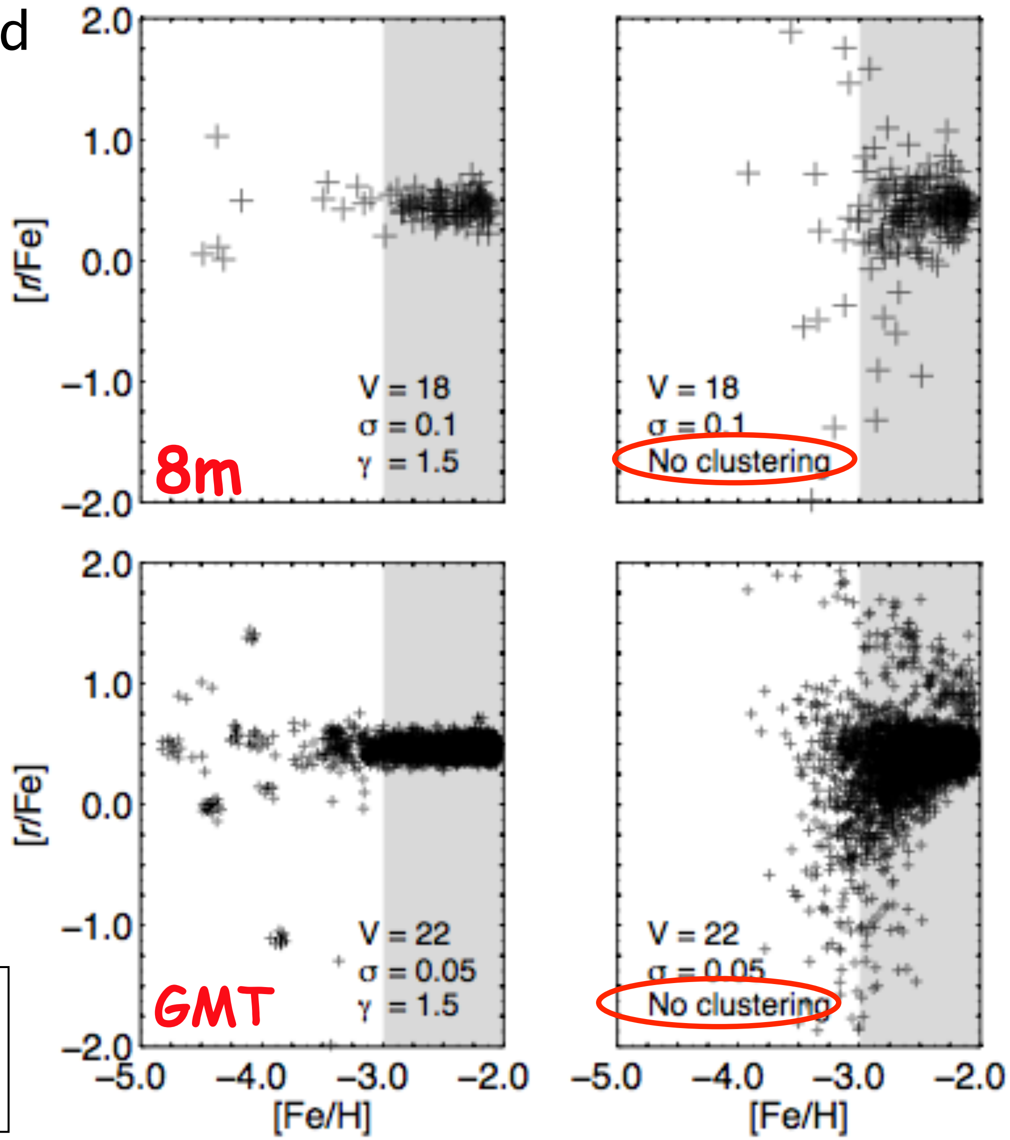
N ~ $1x10^6$ stars

M ~ $3x10^5$ M_o

L ~ $1x10^5$ L_o

D ~ 30 kpc

i.e. 10 stars with [Fe/H] < −3

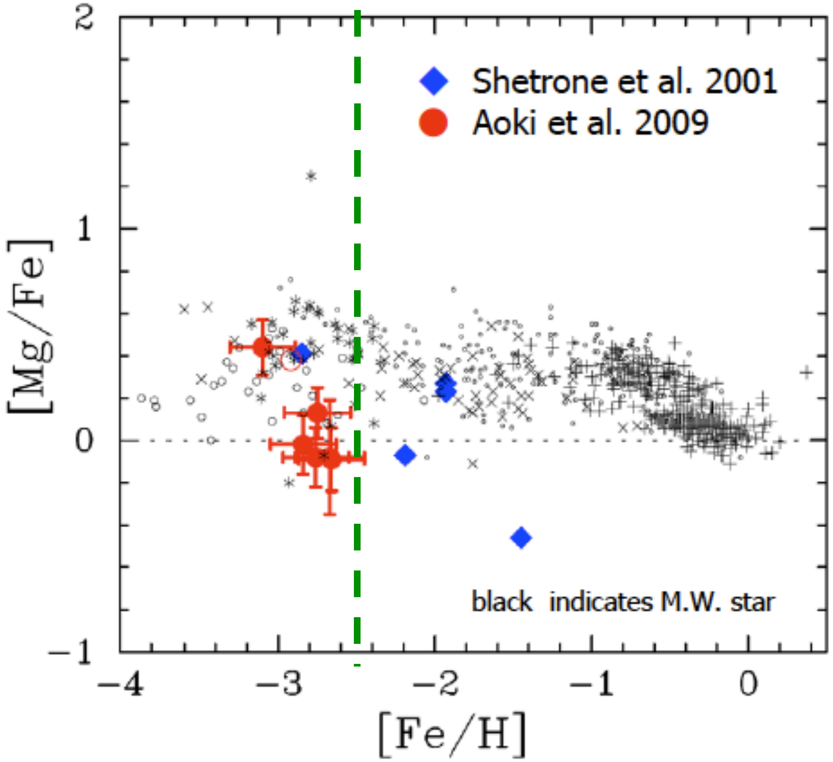


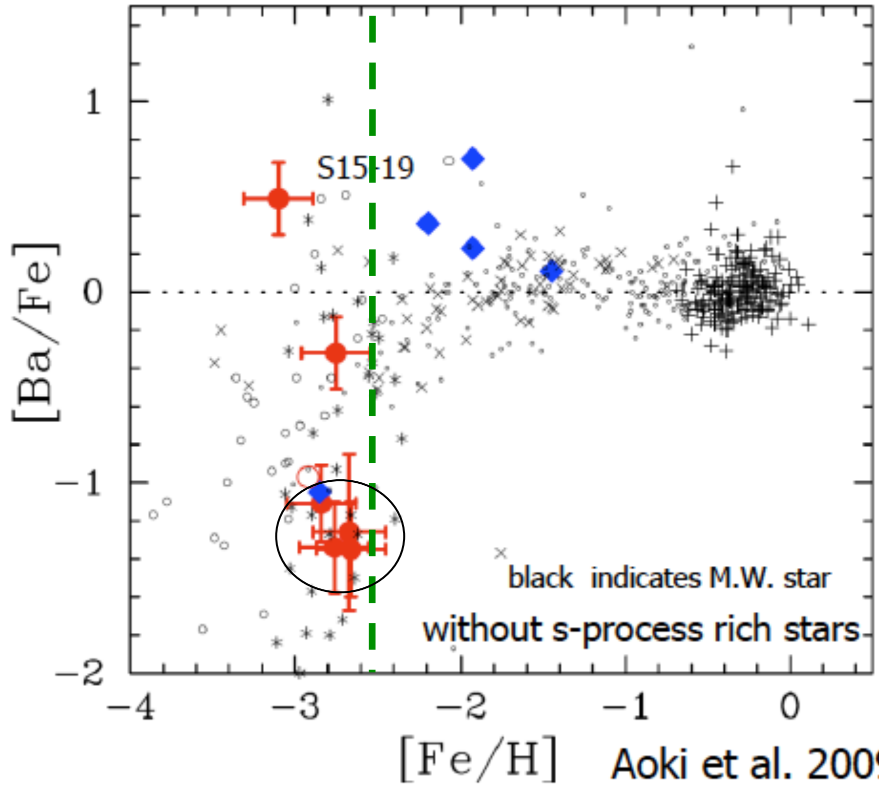
2D clustering will be seen by 8m

Expect stronger signal in 3D, 4D…

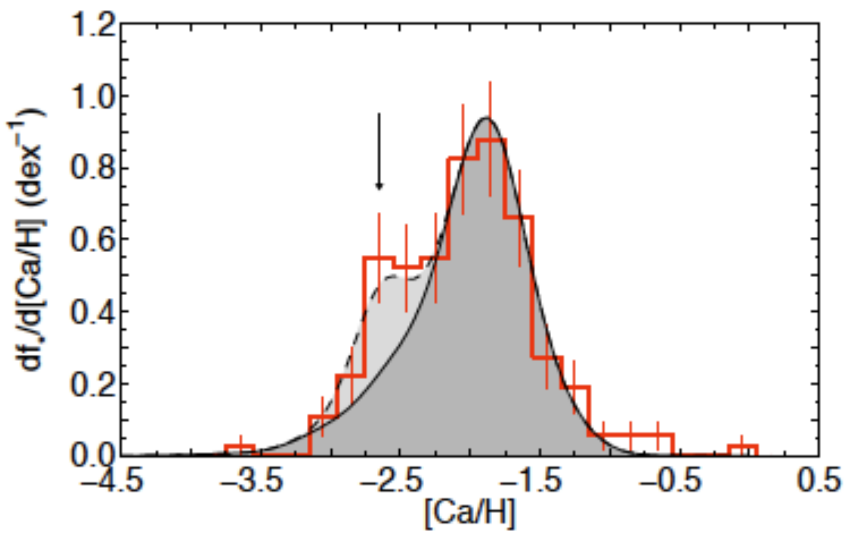
Sextans: relic star cluster?

If confirmed, this would be the most metal poor star cluster to date (Karlsson+ 2012)





Aoki et al. 2009



The stellar "cluster" seems to clump in other abundances

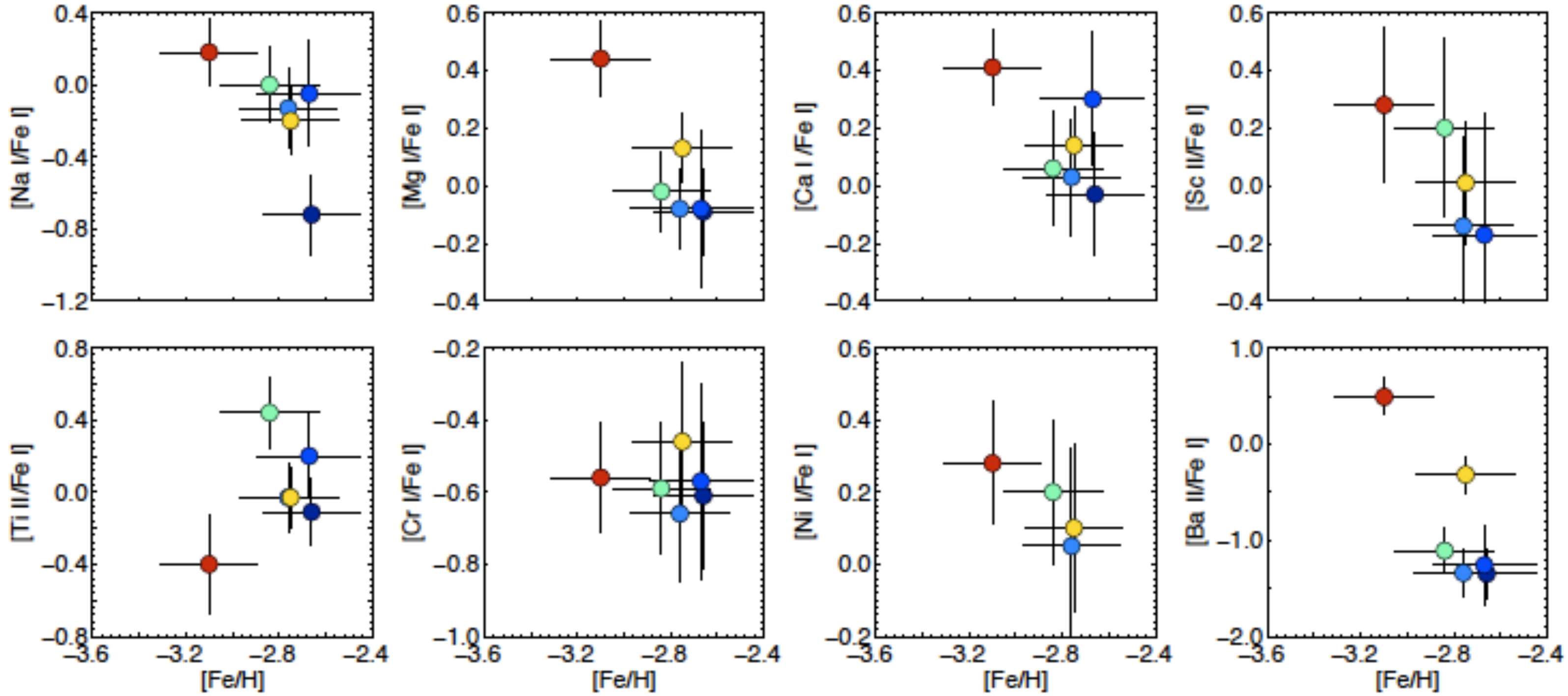


FIG. 1.— Chemical abundance ratios of six very metal-poor stars in the Sextans dSph. Abundance data are taken from Aoki et al. (2009). Stars are color coded according to their [Mg/Fe] ratio. The three stars with nearly identical [Mg/Fe] (colored in blue) also have very similar [Fe/H]. These stars all clump together in Ti, Cr, and Ba, as well. One of the "blue" stars, S 10 − 14, is substantially deficient in Na. The scandium abundance could not be measured in S 10 − 14, while Nickel could not be measured in S 10 − 14 and S 14 − 98.

If confirmed, this would be the most metal poor star cluster to date (Karlsson+ 2012)

SEGUE 1: AN UNEVOLVED FOSSIL GALAXY FROM THE EARLY UNIVERSE*

Anna Frebel[1], Joshua D. Simon[2], and Evan N. Kirby[3,4]
[1] Kavli Institute for Astrophysics and Space Research and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2] Observatories of the Carnegie Institution of Washington, Pasadena, CA 91101, USA
[3] Center for Galaxy Evolution, Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
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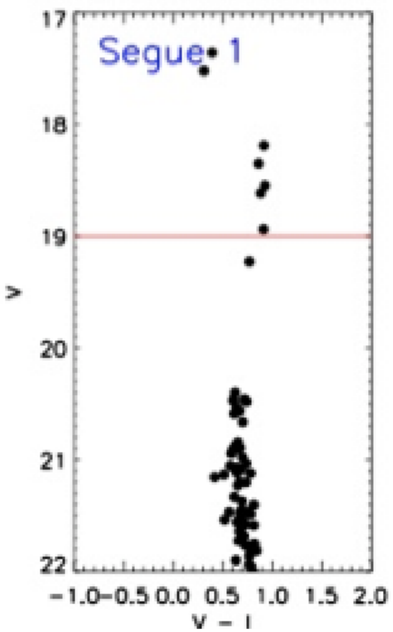
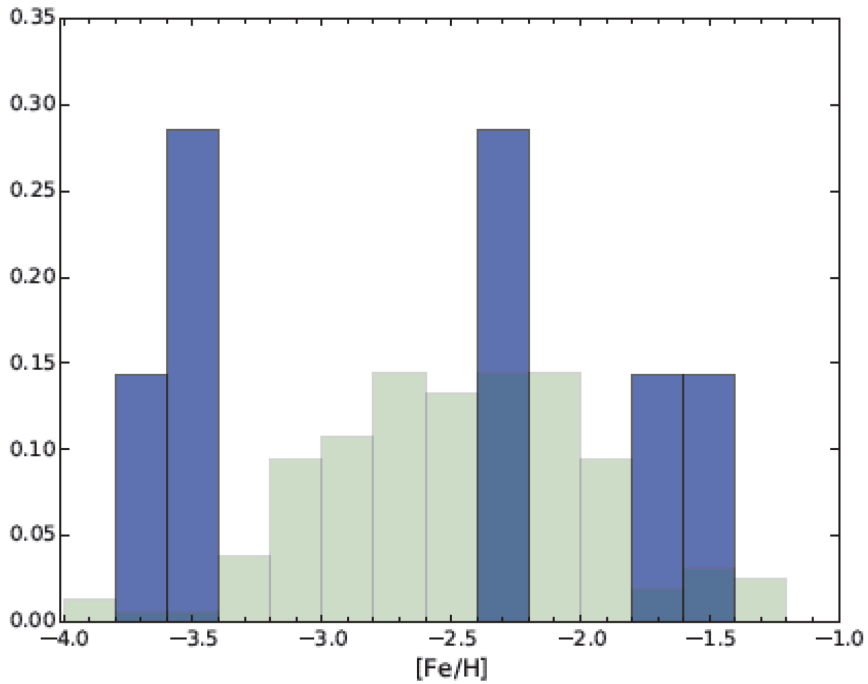
2014



[α/Fe] = 0.5

[Sr/H], [Ba/H] suppressed

T_{SF} < 30-50 Myr



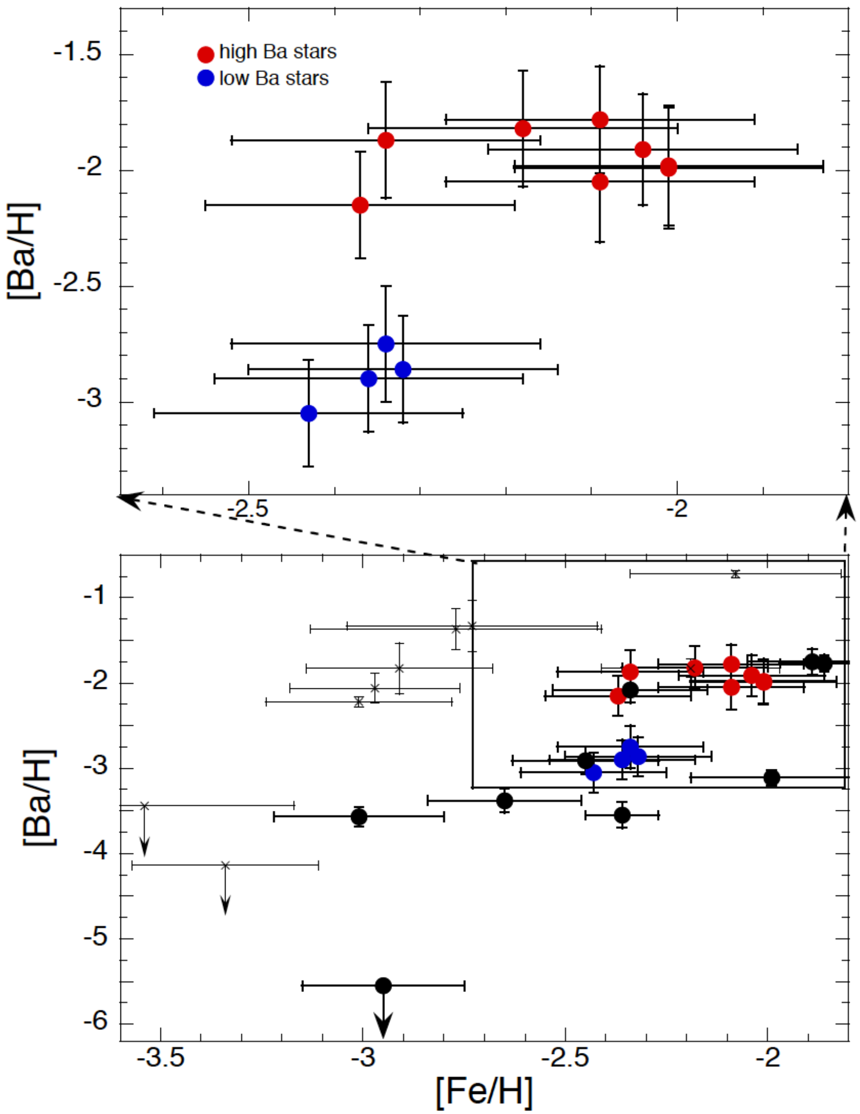
The clumping is statistically significant (Webster, Frebel & JBH 2016)

Hoping for more results from Jan 2017
Keck time: JBH, Frebel, Simon, Yong

ENRICHMENT IN R-PROCESS ELEMENTS FROM MULTIPLE DISTINCT EVENTS IN THE EARLY DRACO DWARF SPHEROIDAL GALAXY*

2017

Takuji Tsujimoto[1,2], Tadafumi Matsuno[2], Wako Aoki[1,2], Miho N. Ishigaki[3], and Toshikazu Shigeyama[4]
[1]National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan; taku.tsujimoto@nao.ac.jp
[2]Department of Astronomical Science, School of Physical Sciences, SOKENDAI (The Graduate University for Advanced Studies), Mitaka, Tokyo 181-8588, Japan
[3]Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, Chiba 277-8583, Japan



CrossMark

COMPLETE ELEMENT ABUNDANCES OF NINE STARS IN THE *r*-PROCESS GALAXY RETICULUM II*

2016

Alexander P. Ji[1,2], Anna Frebel[1,2], Joshua D. Simon[3], and Anirudh Chiti[1]
[1] Department of Physics and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; alexji@mit.edu
[2] Joint Institute for Nuclear Astrophysics—Center for Evolution of the Elements, East Lansing, MI:48824, USA
[3] Observatories of the Carnegie Institution of Washington, 813 Santa Barbara St., Pasadena, CA 91101, USA
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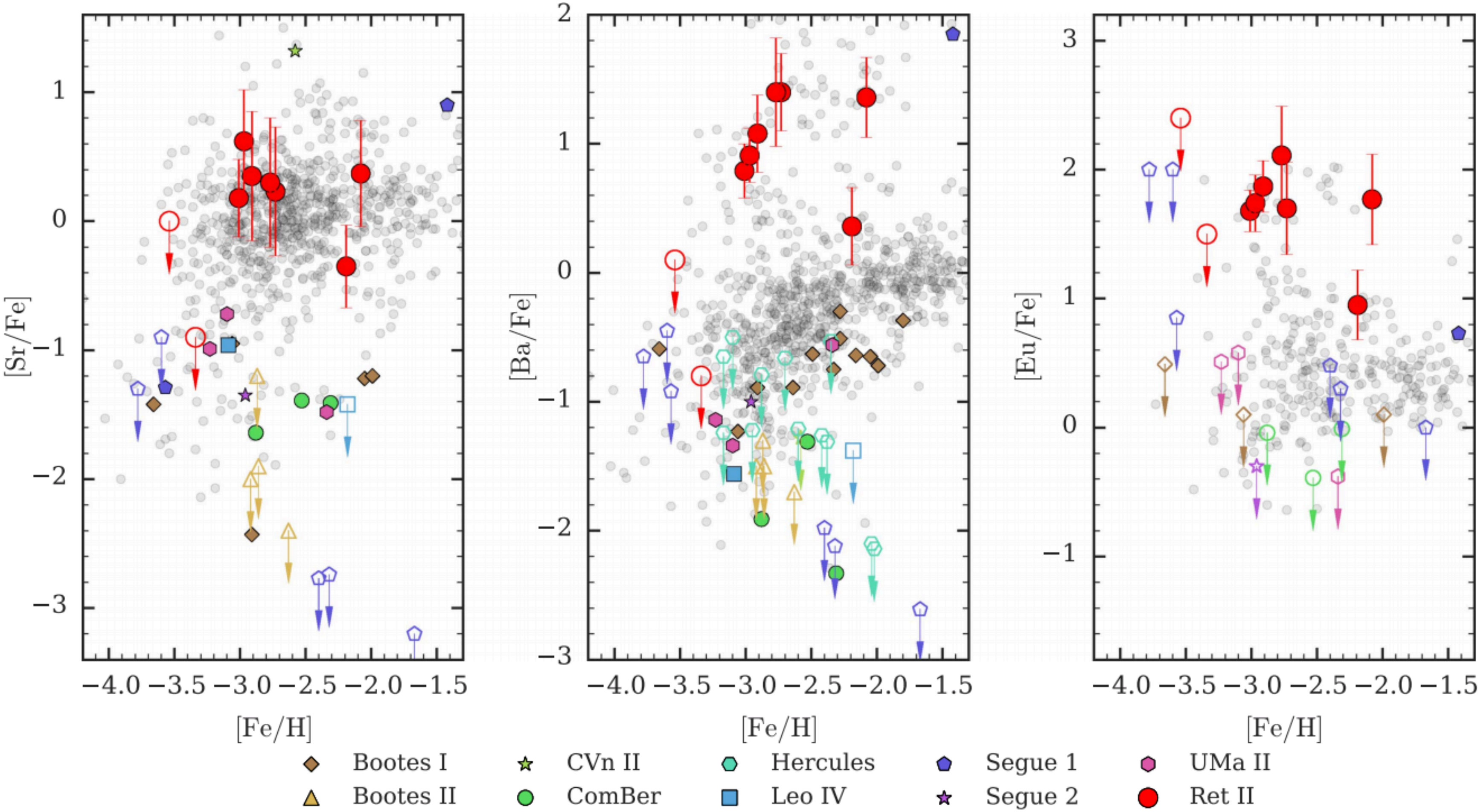


Figure 3. Neutron-capture element abundances for Sr, Ba, and Eu. Symbols are the same as in Figure 2. DES J033531−540148 and DES J033556−540316 have only upper limits that are consistent with other UFD stars. Note that DES J033531−540148 has a [Sr/Fe] = −1.73 detection (Roederer et al. 2016b). The other seven stars have extremely enhanced neutron-capture abundances, although DES J033548−540349 is less enhanced. CVn II has a star with very high [Sr/Fe] but no detectable Ba (François et al. 2016). The star in Segue 1 with high neutron-capture abundances has experienced binary mass transfer (Frebel et al. 2014).

What is the statistical significance of "clustering" in abundance space?

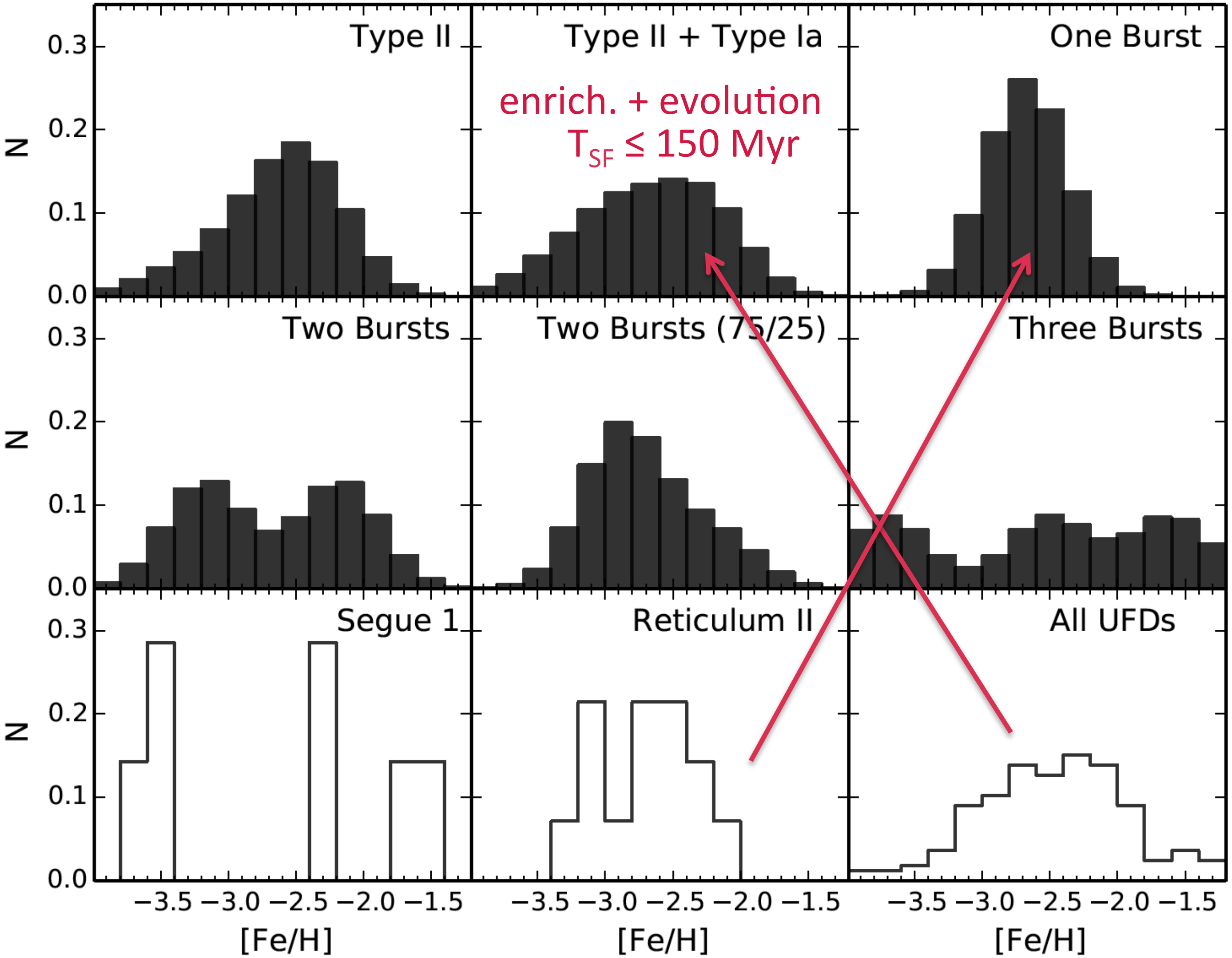
What can we learn?

Method: 1. build models of UFD formation and evolution; 2. insert cluster formation; 3. test for clustering signatures; 4. attempt to unravel the sequence of events.

What do these [Fe/H] distributions look like for clustered SF?

Note: this is only using a <u>single</u> dimension of *C*-space

$T_{SF} \leq 50$ Myr



Webster et al 2015

STATISTICS OF CLUSTERED OVER RANDOM EVENTS

Webster, Frebel & JBH (2015)

Beale pseudo F-statistic (1969)

$$F^* = \frac{J_1^2 - J_2^2}{J_2^2} \frac{(N - c_2)c_2^{-2/p}}{(N-1) - (N - c_2)c_2^{-2/p}}$$

number of abundance data points

number of abundance dimensions

number of clusters

models with more parameters are penalized

$$J_1^2 = \Sigma_i (x_i - \mu)^2$$ unclustered simulation

$$J_2^2 = \Sigma_k \Sigma_{k_i} (x_{k_i} - \mu_k)^2$$ clustered simulation

compare RMS differences between models (*k* peaks)

TABLE 1

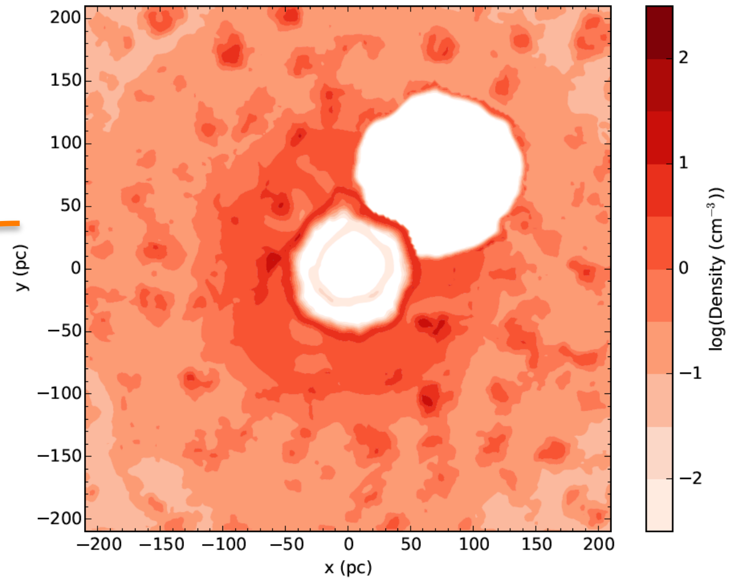
PROBABILITY OF SEVEN STARS FORMING THREE OR MORE DISTINCT (SEPARATED BY 0.3 OR 0.55 DEX IN [FE/H]) GROUPS OF STARS.

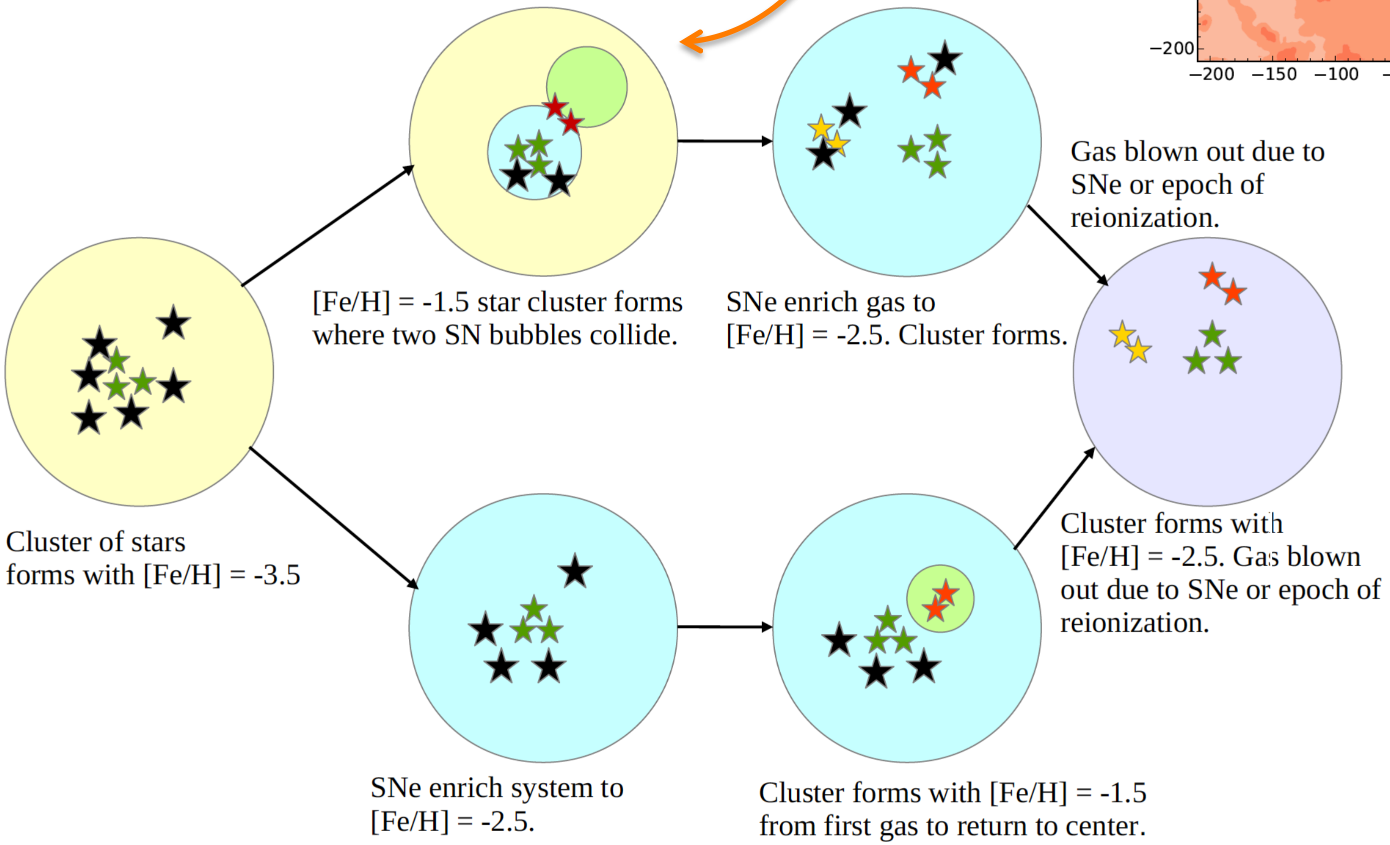
Model	0.3 dex Unclustered	0.3 dex Clustered	0.55 dex Unclustered	0.55 dex Clustered
Gaussian	0.6%	3.7%	<0.01%	0.1%
Type II & Ia	5.1%	8.7%	0.2%	2.0%
Type II	3.4%	7.0%	0.1%	1.4%
Two bursts	6.7%	9.7%	0.3%	2.5%
Two bursts 75/25	3.2%	6.1%	0.1%	0.9%
Three bursts	5.6%	14.7%	2.7%	7.6%

Can we unravel a SF event sequence?

Not with the limited abundance space [Fe/H], [a/Fe], [C/Fe] presently available.

But we can limit the options.





[Fe/H]=-1.5 is really difficult without overlapping bubbles.

Lower path requires inhomogeneity.

Upper path requires v. special conditions.

Webster, Frebel & JBH (2016)

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Connecting the First Galaxies with Ultrafaint Dwarfs in the Local Group: Chemical Signatures of Population III Stars

Myoungwon Jeon[1,2], Gurtina Besla[1], and Volker Bromm[3]
[1] Department of Astronomy, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA; myjeon@email.arizona.edu
[2] Center for Global Converging Humanities, Kyung Hee University, Korea
[3] Department of Astronomy, University of Texas, TX 78712, USA
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Abstract

We investigate the star formation history (SFH) and chemical evolution of isolated analogs of Local Group (LG) ultrafaint dwarf galaxies (UFDs; stellar mass range of $10^2\ M_\odot < M_* < 10^5\ M_\odot$) and gas-rich, low-mass dwarfs (Leo P analogs; stellar mass range of $10^5\ M_\odot < M_* < 10^6\ M_\odot$). We perform a suite of cosmological hydrodynamic zoom-in simulations to follow their evolution from the era of the first generation of stars down to $z = 0$. We confirm that reionization, combined with supernova (SN) feedback, is primarily responsible for the truncated star formation in UFDs. Specifically, halos with a virial mass of $M_{\rm vir} \lesssim 2 \times 10^9\ M_\odot$ form $\gtrsim$90% of stars prior to reionization. Our work further demonstrates the importance of Population III stars, with their intrinsically high [C/Fe] yields and the associated external metal enrichment, in producing low-metallicity stars ([Fe/H] $\lesssim -4$) and carbon-enhanced metal-poor (CEMP) stars. We find that UFDs are composite systems, assembled from multiple progenitor halos, some of which hosted only Population II stars formed in environments externally enriched by SNe in neighboring halos, naturally producing extremely low metallicity Population II stars. We illustrate how the simulated chemical enrichment may be used to constrain the SFHs of true observed UFDs. We find that Leo P analogs can form in halos with $M_{\rm vir} \sim 4 \times 10^9\ M_\odot$ ($z = 0$). Such systems are less affected by reionization and continue to form stars until $z = 0$, causing higher-metallicity tails. Finally, we predict the existence of extremely low metallicity stars in LG UFD galaxies that preserve the pure chemical signatures of Population III nucleosynthesis.

This is an elegant use of targetted simulations to bring together first stars, first galaxies, reionization, UFD, CEMP & First Star signatures today…

NEAR FIELD COSMOLOGY

Where next ?

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THE CHEMICAL SIGNATURES OF THE FIRST STAR CLUSTERS IN THE UNIVERSE

Joss Bland-Hawthorn[1,4], Torgny Karlsson[1,5],
[1] Sydney Institute for Astronomy, School of Physics, Univer
[2] Department of Astronomy and Astrophysics, U
[3] Physics Department, Unive
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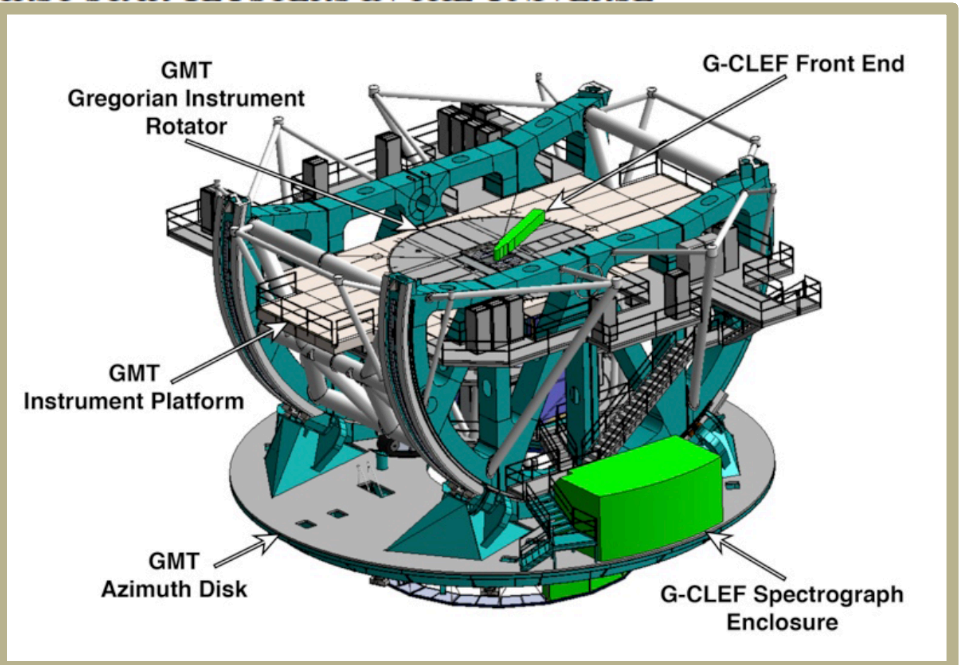


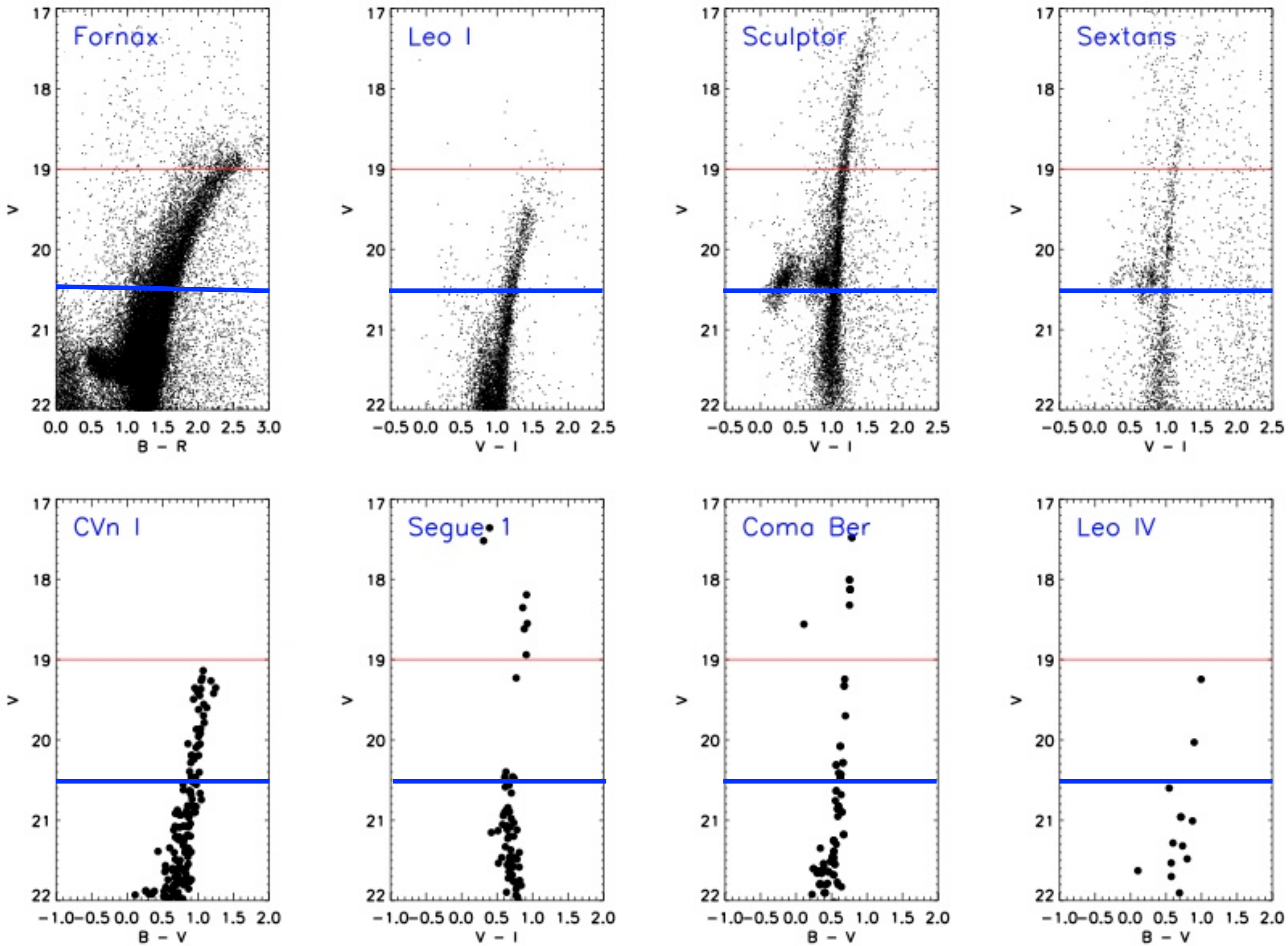
ABS

The chemical abundance patterns of the oldest stars in th
first stars in the early universe. Numerous studies attempt
metal-poor populations in terms of chemical inhomogen
to discrete enrichment events. Just how the complex data
yields" remains an open question. Here we show that stoc
crucial fact. Essentially, all stars today are born in highly
true at early times. When this ingredient is included, the c
($\mathcal{C}$-space), where X is a nucleosynthetic element, can be
moderately flat cluster mass functions ($\gamma \lesssim 2$), and/or fo
stars exhibit a high degree of clumping in $\mathcal{C}$-space that ca
stellar abundances can be modified by mass transfer in c
the yields of the first supernovae. We present a statistical test to determine whether a given set of observations exhibit
such behavior. Our initial work focuses on two dimensions in $\mathcal{C}$-space, but we show that the clustering signal can be
greatly enhanced by additional abundance axes. The proposed experiment will be challenging on existing 8–10 m
telescopes, but relatively straightforward for a multi-object echelle spectrograph mounted on a 25–40 m telescope.

Key words: galaxies: dwarf – Galaxy: abundances – Galaxy: evolution – Galaxy: formation – galaxies: star clusters: general

Online-only material: color figures

GMT + Manifest + G-Clef was entirely the motivation for this paper.
We really need this to feed ~10 fibres over the full 20' field.



8m limit @ R=20K, V ~ 19, SNR ~ 30, 15 hours, **OPTICAL** (Frebel):
observe C, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Co, Ni, Zn, Ba, Sr

GMT/G-Clef (~10 objects in 20' field) limit @ R=20K should get us to V ~ 20.5

Happy Birthday, Tim !

But don’t rest on your laurels ; there’s so much more to do.