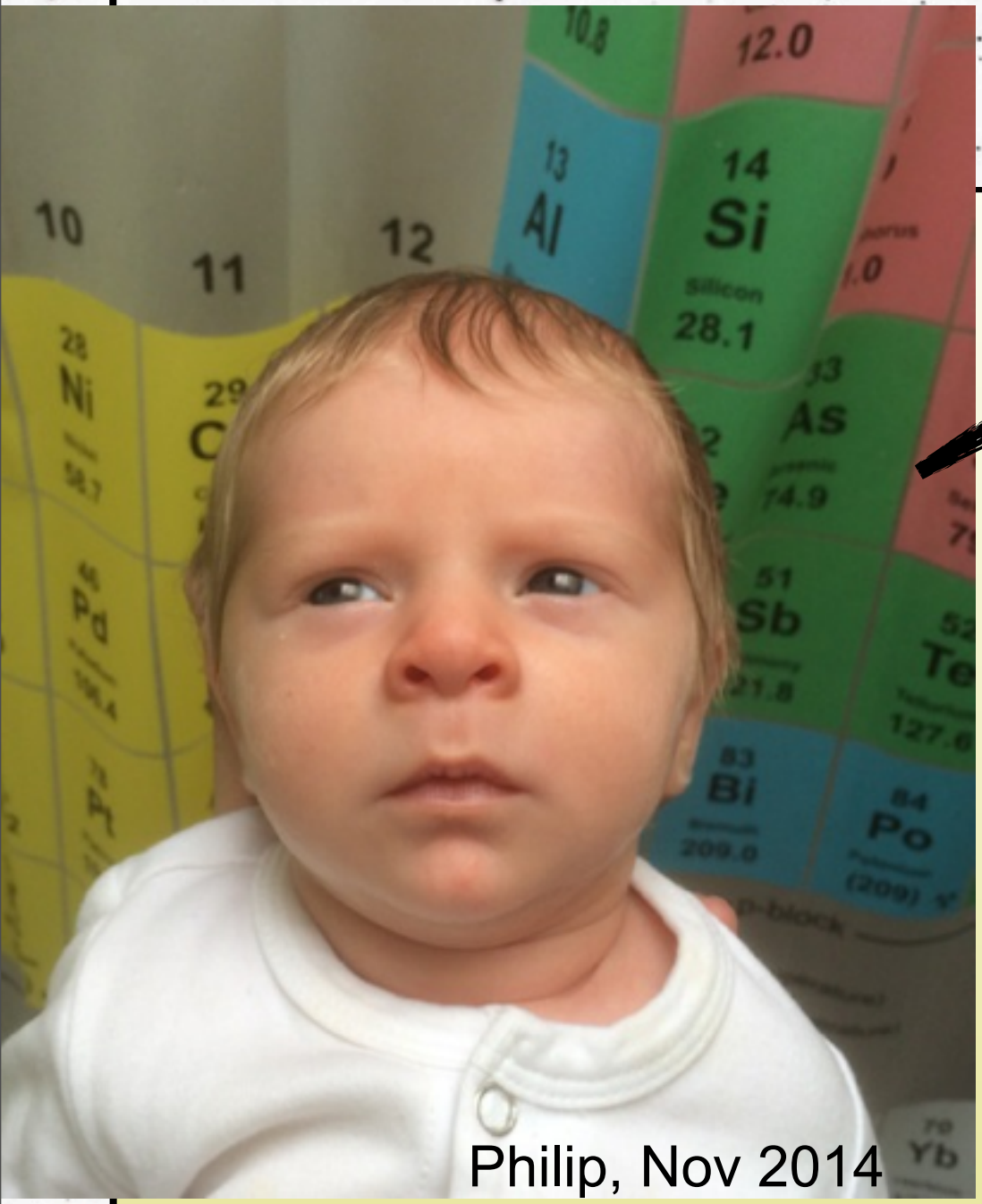
Hunting the first generations of stars and galaxies

Anna Frebel

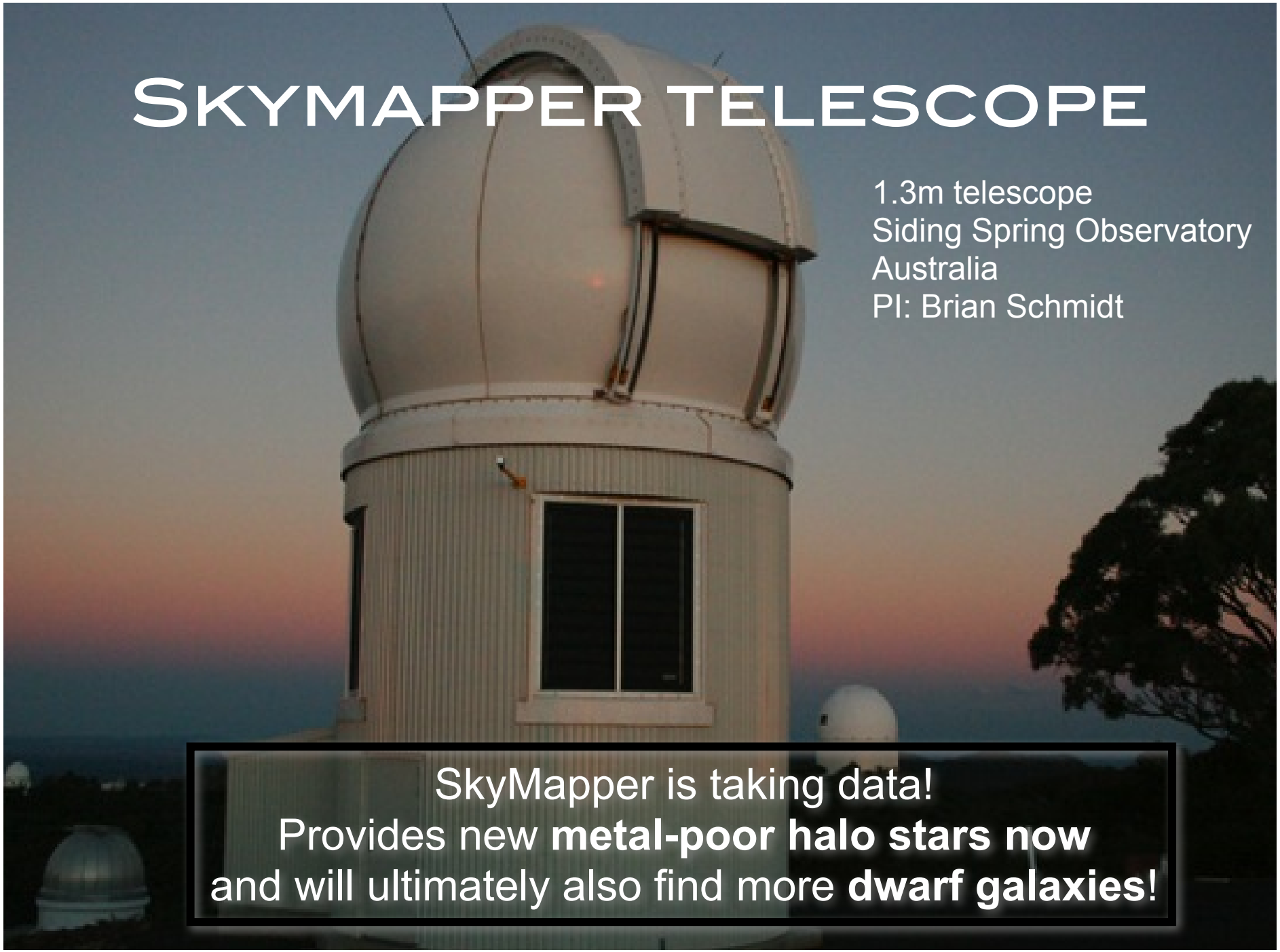
Massachusetts Institute of Technology



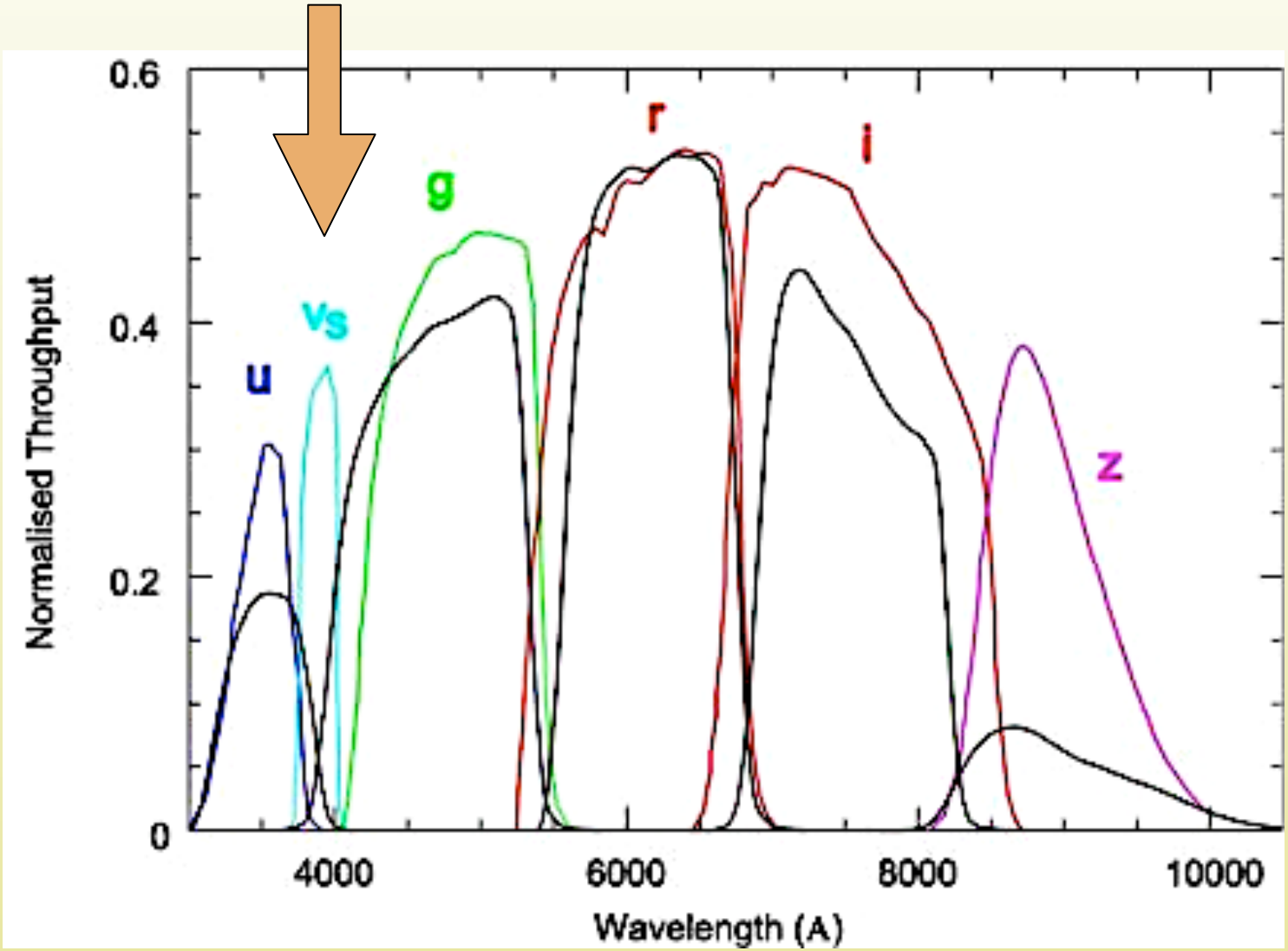
No, my dear -- but you can read about our recent progress here:

Near-Field Cosmology with Metal-Poor Stars

A. Frebel & J. E. Norris, 2015 ARA&A, in press


SKYMAPPER TELESCOPE
1.3m telescope
Siding Spring Observatory
Australia
PI: Brian Schmidt
SkyMapper is taking data!
Provides new **metal-poor halo stars now**
and will ultimately also find more **dwarf galaxies**!

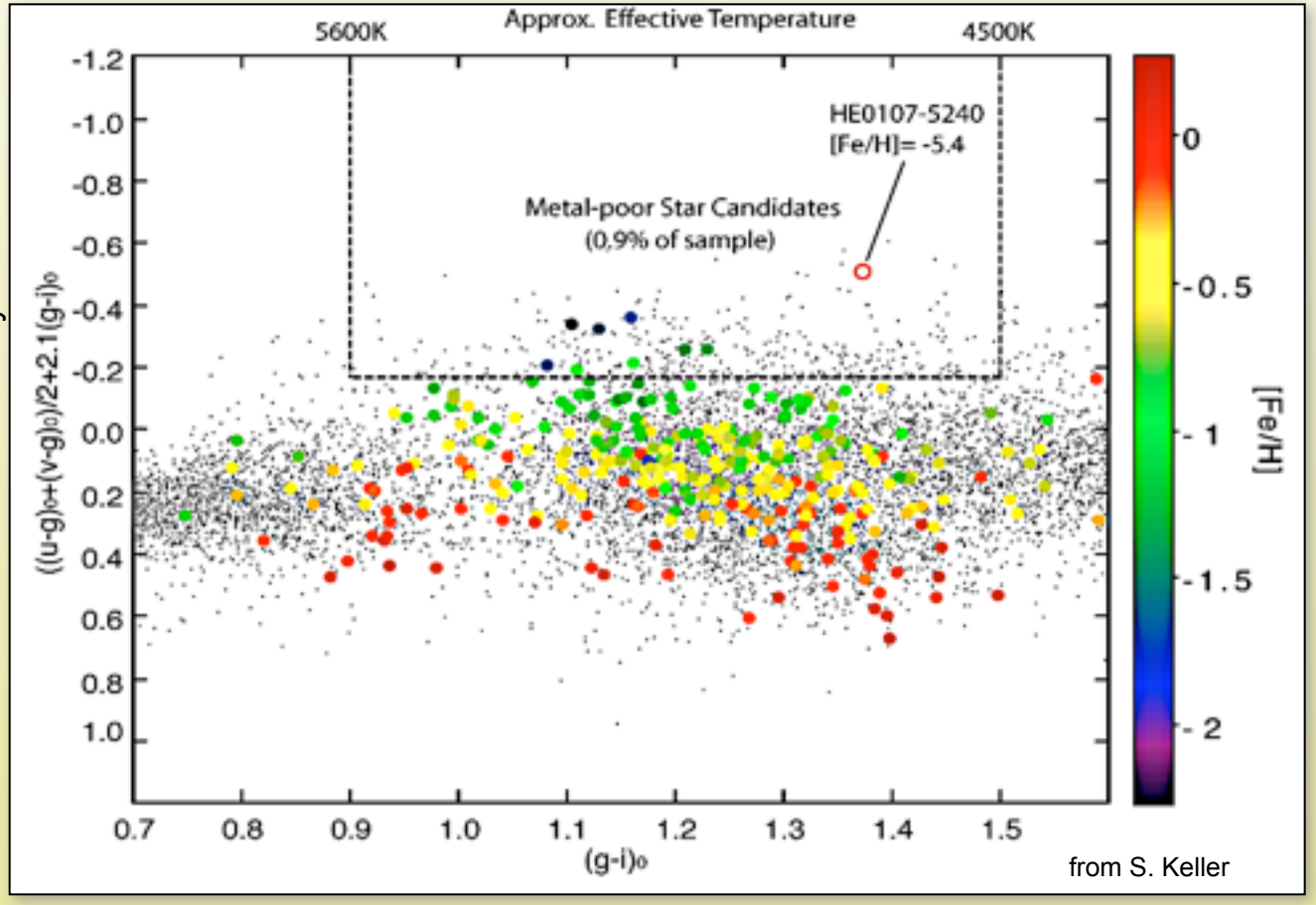
What does SkyMapper observe? The filter set



Keller et al. 2007, PASP

Mapping the Southern Sky

- New photometric technique to find metal-poor stars
- A survey of the South => **census of most metal-poor star**



Stefan Keller (ANU) has been leading this effort

Color code based on AAT/AEGIS follow-up med-res spectroscopy

Keller et al. 2015, in prep.

SkyMapper & Magellan: Match made in heaven

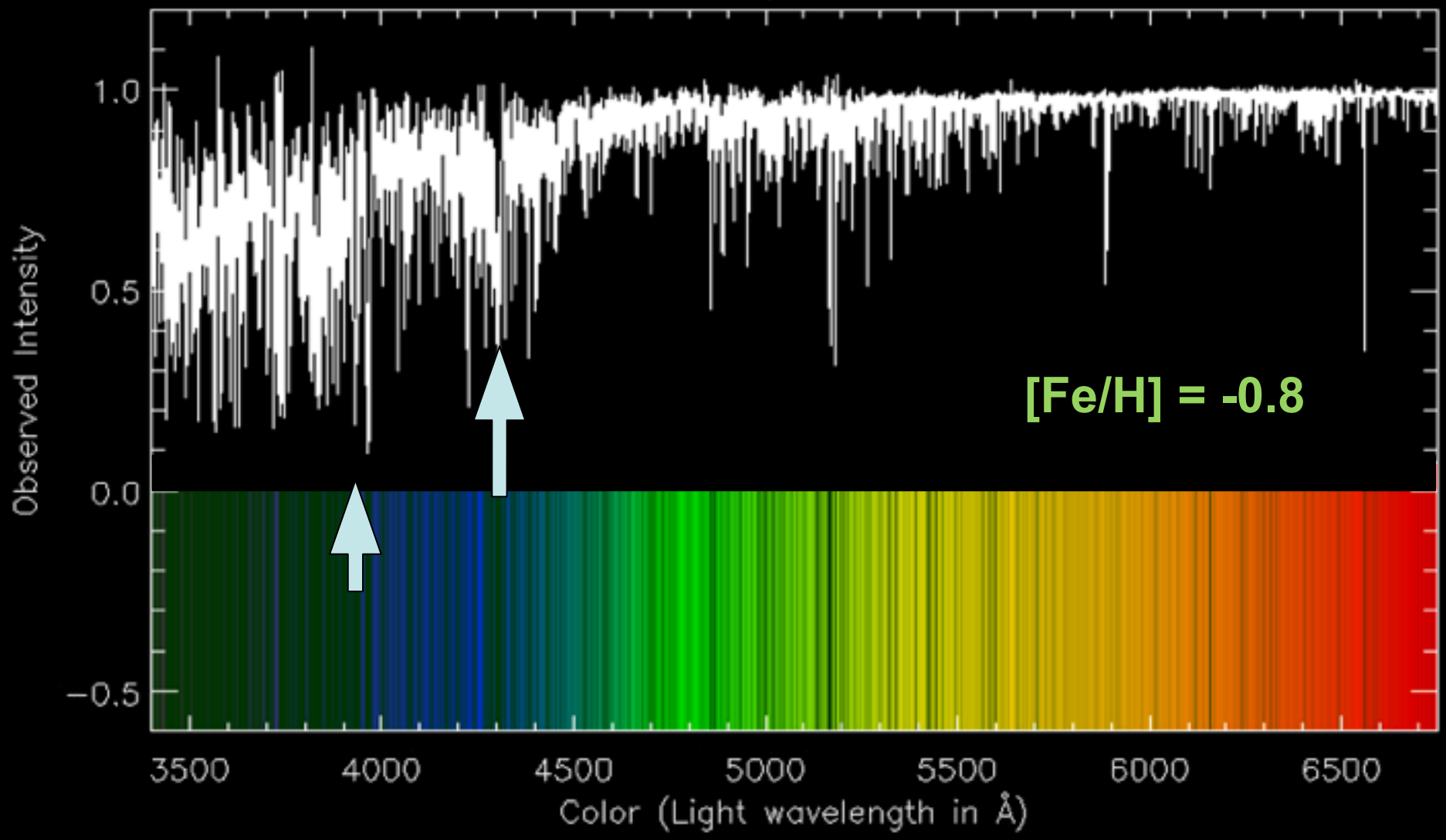
- SkyMapper can only provide **candidate** metal-poor stars
- High-resolution spectroscopy (R>20,000) is required to **confirm** metal-deficiency and to carry out chemical abundance analysis

Videos about observing with Magellan: youtube and annafrebel.com

Candidate metal-poor stars selected with high efficiency...

and observed w/ Clay 6.5m Magellan telescope (on left) at Las Campanas Observatory, Chile

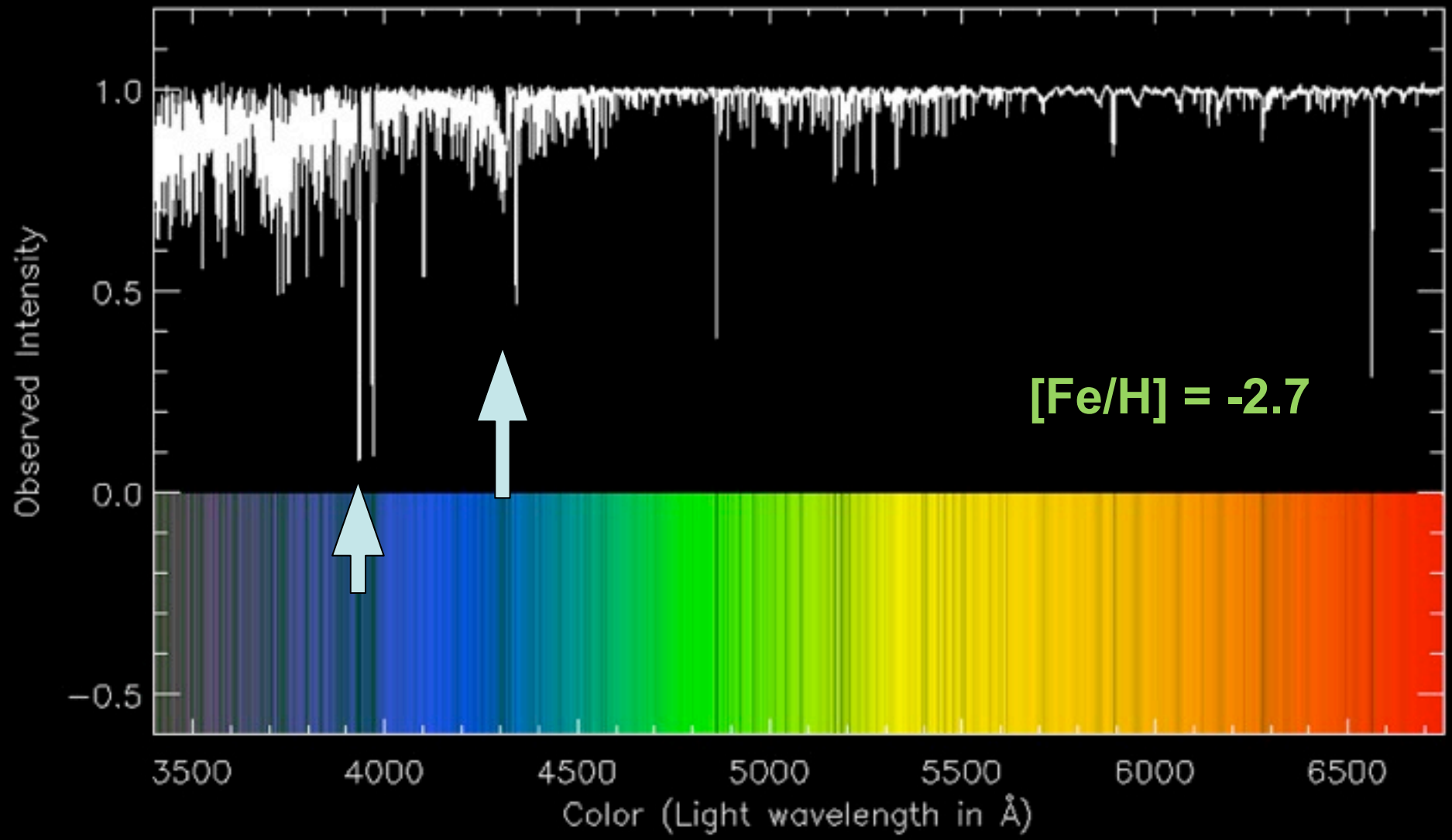
Existence of line ⇒ Element present in star



Line strength ⇒ Abundance of element

A. Frebel

Existence of line ⇒ Element present in star



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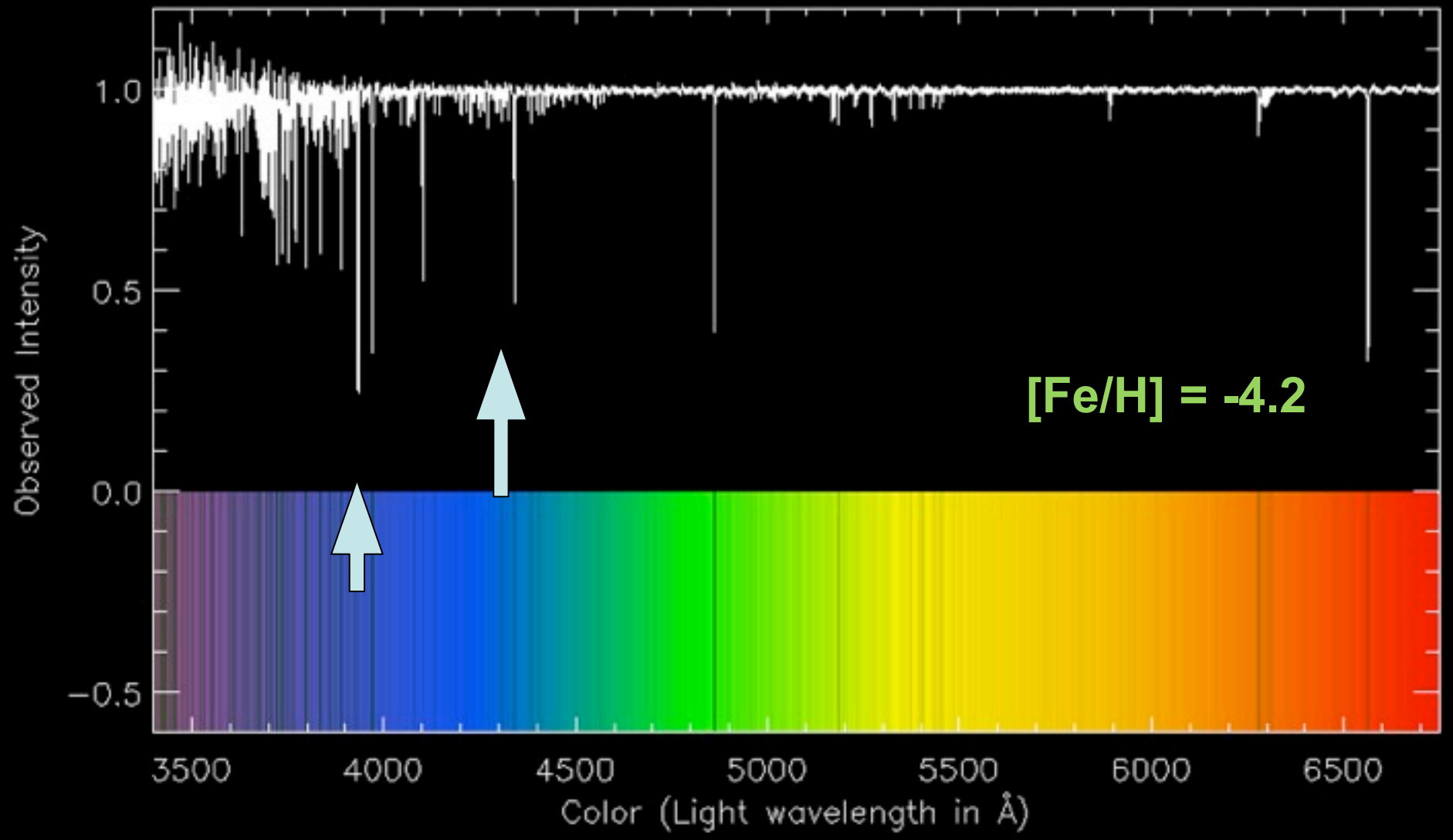
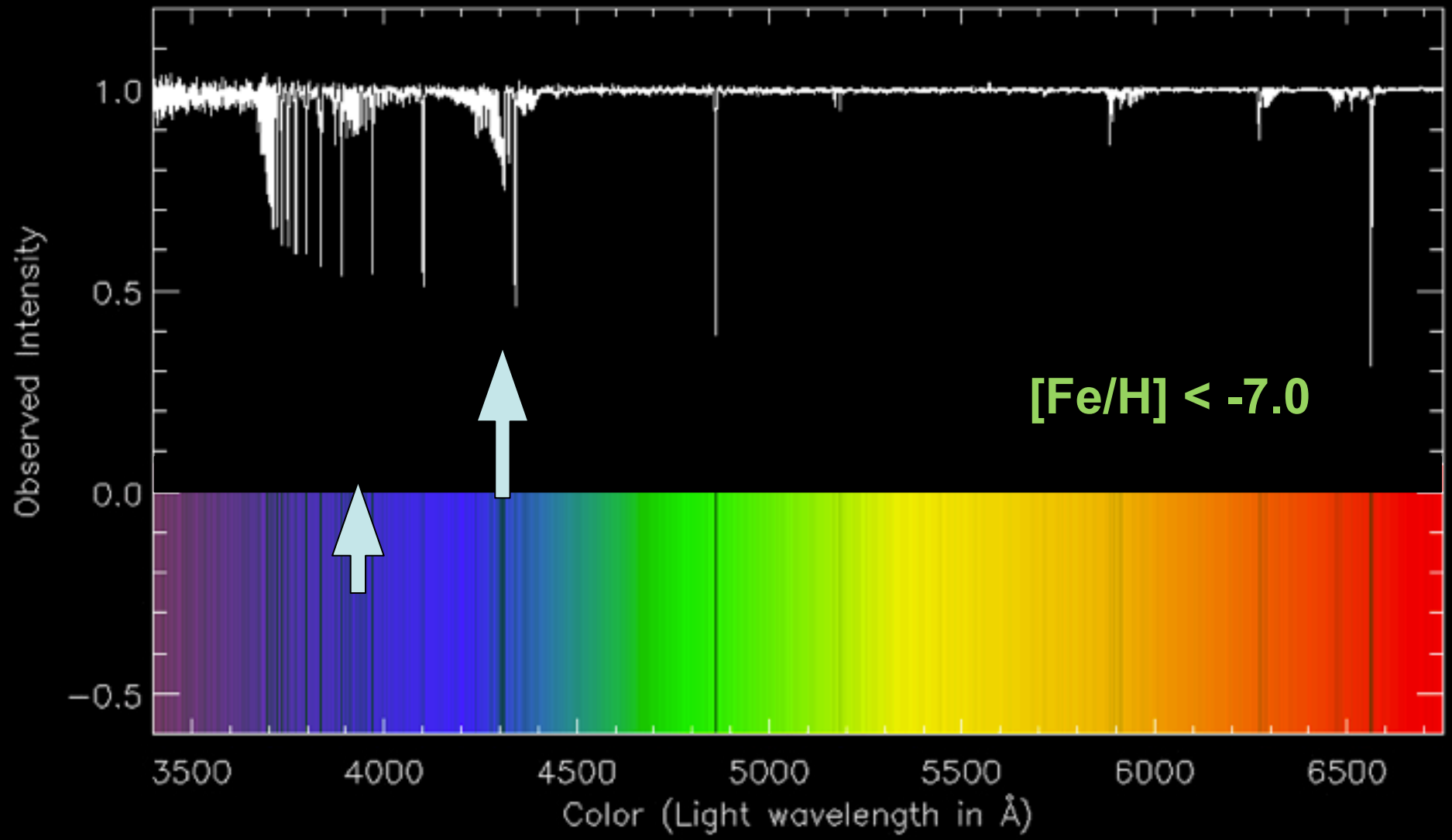


Line strength ⇒ Abundance of element

A. Frebel

Existence of line ⇒ Element present in star



Line strength ⇒ Abundance of element

A. Frebel

A true second-generation star

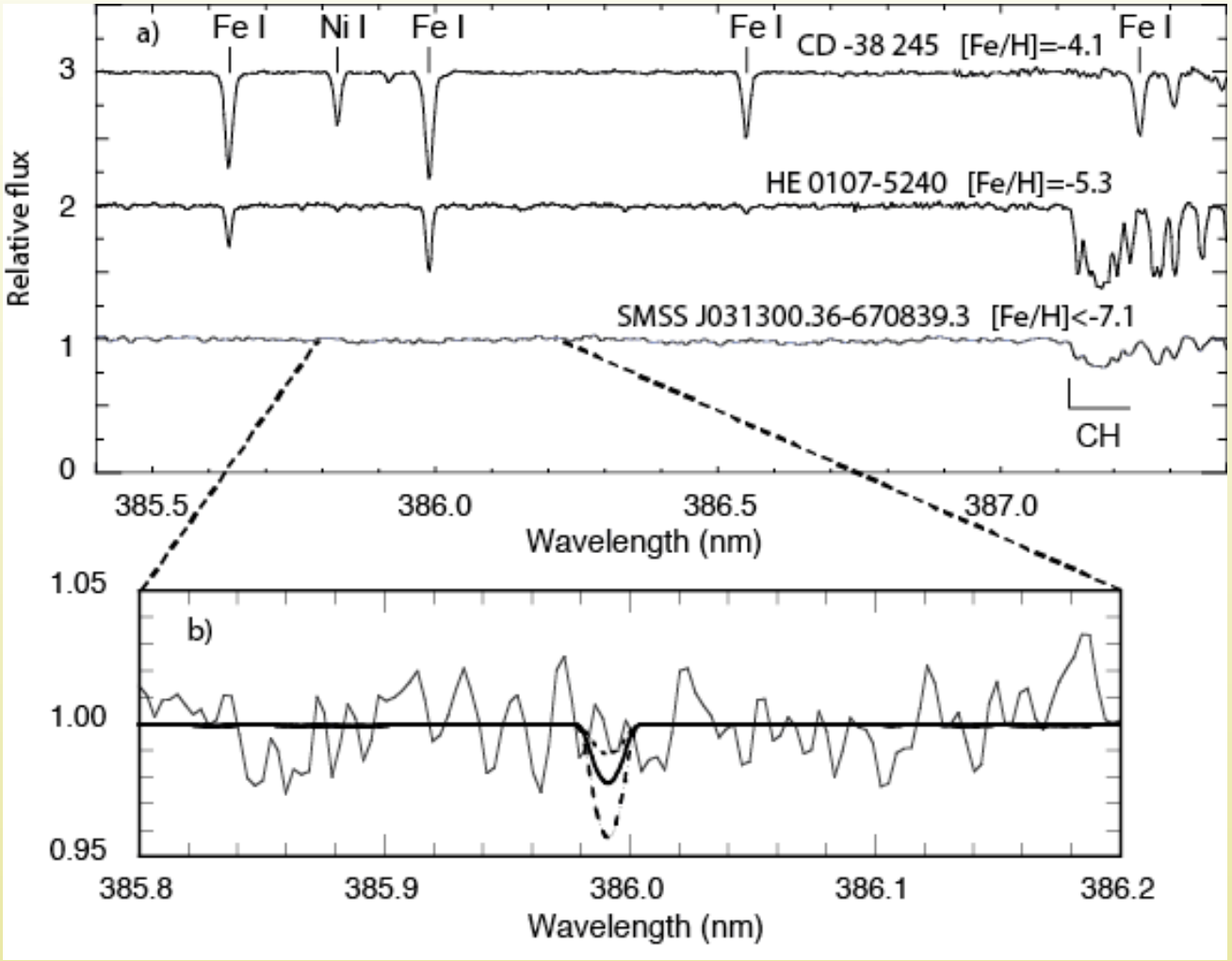
The actual title is
"A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.362670839.3"

S. C. Keller[1], M.S. Bessell[1], A. Frebel[2], A.R. Casey[1], M. Asplund[1], H. R. Jacobson[2], K. Lind[3], J. E. Norris[1], D. Yong[1], A. Heger[4], Z. Magic[1,5], G. S. Da Costa[1], B. P. Schmidt[1] & P. Tisserand[1]

2014, Nature, 506, 463

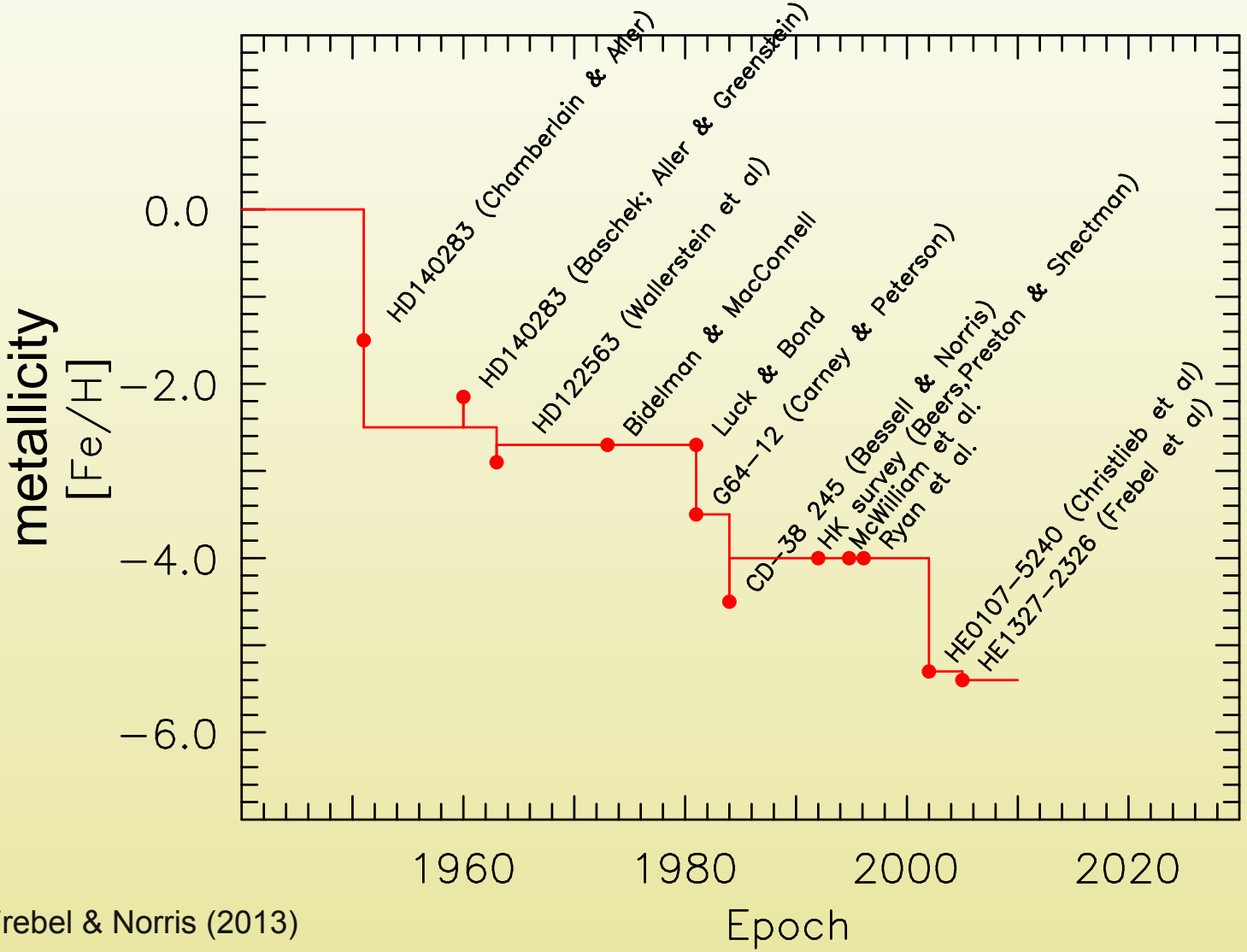
1: ANU, 2: MIT, 3: IoA Cambridge, 4: Monash Univ, 5: MPIA

No iron lines detected!



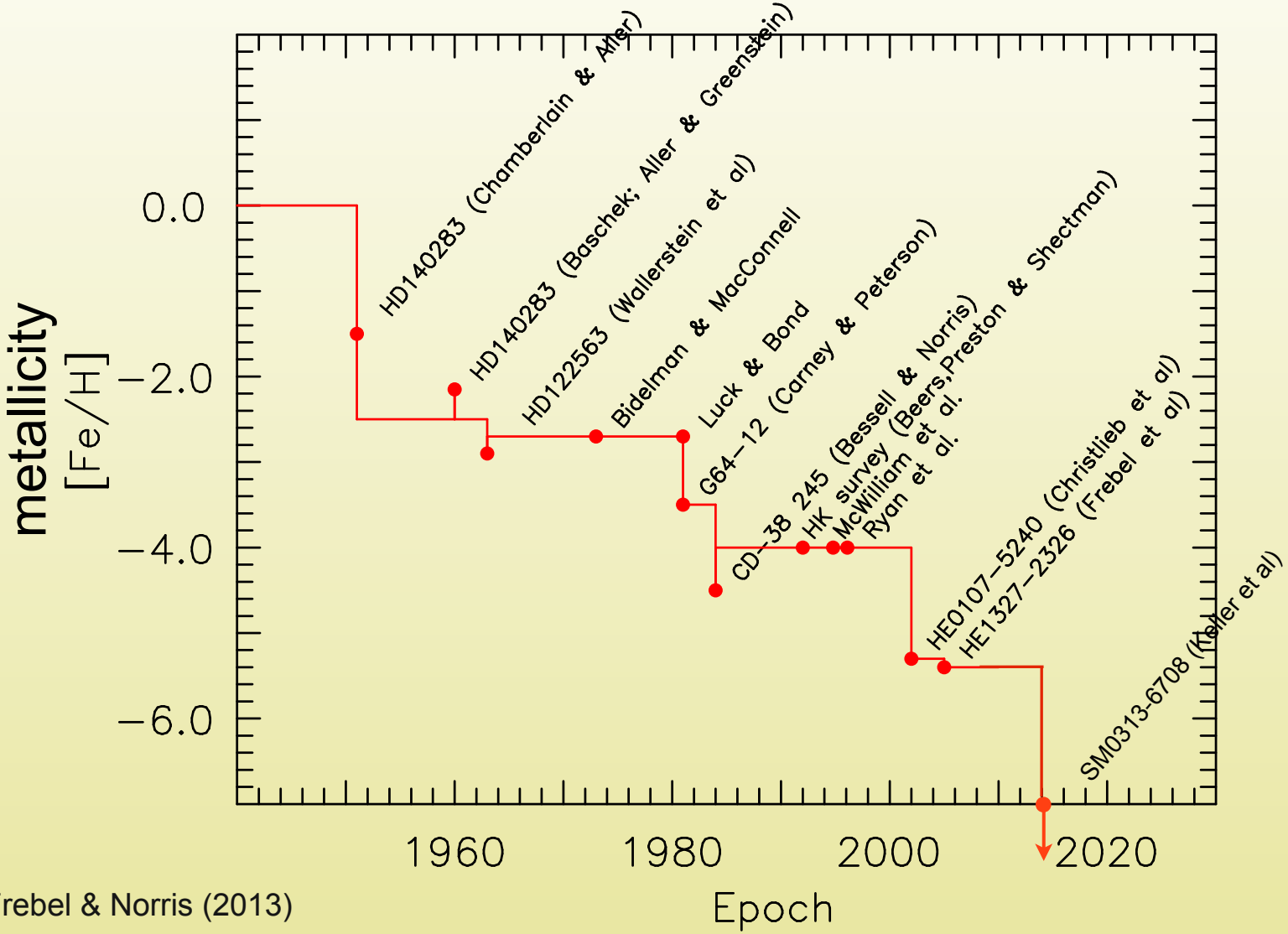
Keller et al. 2014, Nature

Discovering the most metal-poor stars



Frebel & Norris (2013)

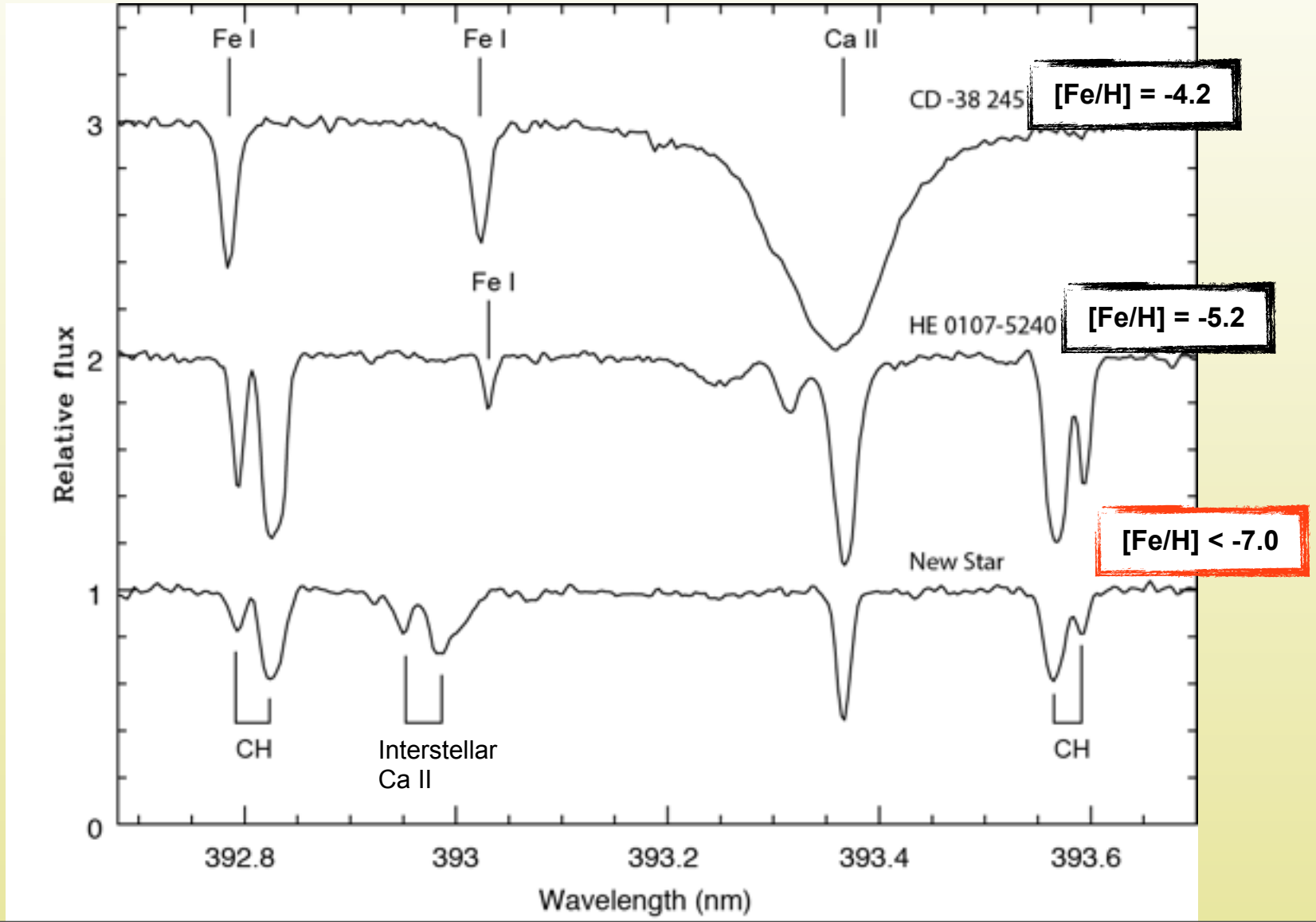
Discovering the most metal-poor stars



Frebel & Norris (2013)

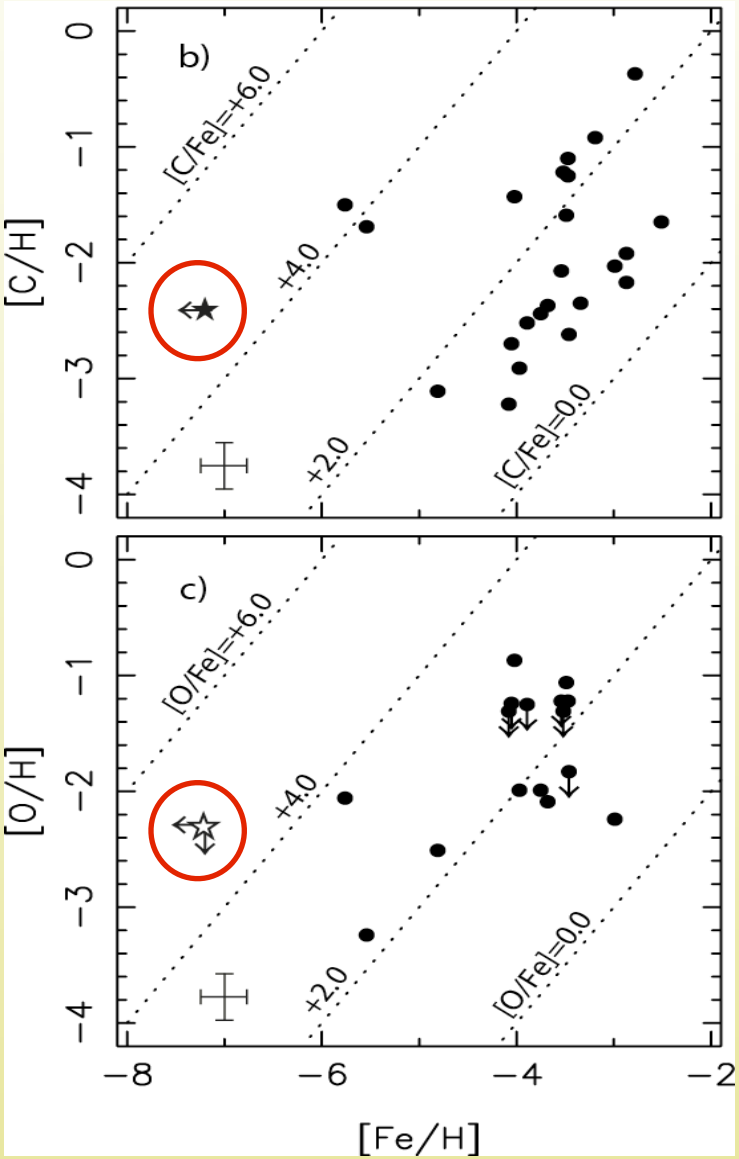
A TRUE SECOND-GENERATION STAR

Keller et al. 2014, Nature

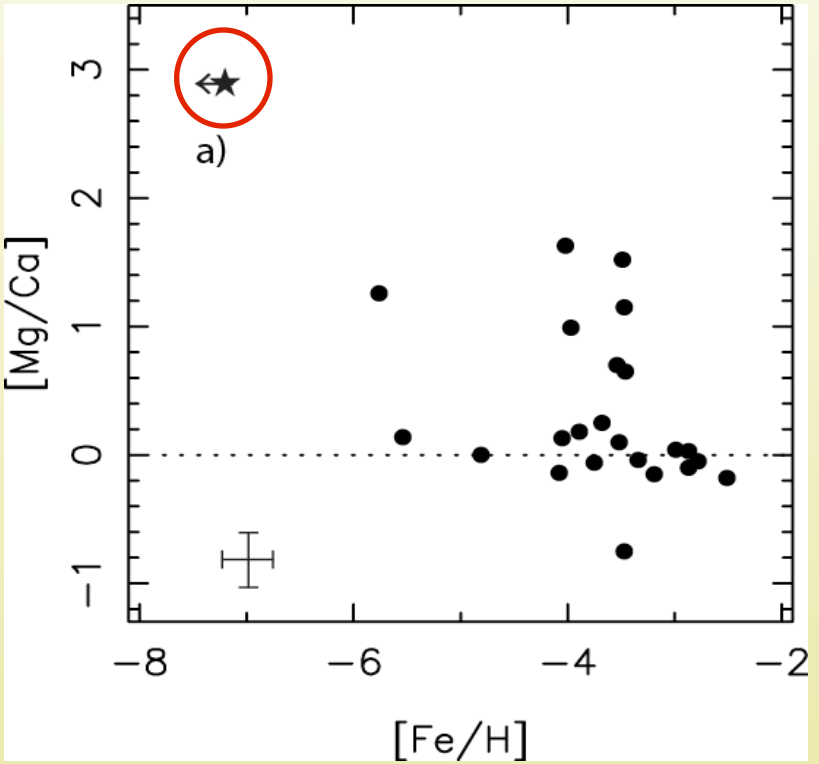


COMPARISON WITH OTHER STARS

Keller et al. 2014, Nature



[C/Fe]>4.8 (!)



[Mg/H] = - 4.3
[Ca/H] = - 7.2

Second/early generation stars

Stellar abundance signature: low Fe, some Ca, Mg, high C

Implications for the nature of the first stars

- ✓ Not ~100 Msun, but more like **50-60 Msun**
- ✓ Yields of first supernova must be low in Fe, high in C (also for [Fe/H] < -5 stars!) => **lower energy "faint" explosion** (e.g. Umeda & Nomoto 2003)
- ✓ High C could indicate rotation (new VLT data yields high O ab.) (Bessell et al. in prep)

Consequences: Pop III may not have reionized the Universe?

Great prospects for finding more metal-poor second-generation stars with SkyMapper for the ultimate diagnostic tool of the first stars. Stay tuned!

Segue 1: a surviving first galaxy?

”Segue 1: An Unevolved Fossil Galaxy from the Early Universe”

Anna Frebel, Josh Simon & Evan Kirby

2014 ApJ 786, 74

Recipe for identifying a first galaxy

The following needs to apply; based on chemical abundance measurements of all stars in an (ultra-faint) dwarf galaxy

1. Metallicity distribution function: **large spread (~3dex) and flat(ish)**
   => inhomogeneous mixing

2. Alpha-elements (Mg, Ca, Ti): **enhanced, like in halo stars**

3. Light elements (Na, Cr, Mn, Co, Ni): **like halo stars**
   => only core-collapse supernova enrichment (no SN Ia's !)

4. Heavy neutron-capture elements (Sr and Ba): **extremely low**
   => no AGB star enrichment

=> No clear evidence for star formation beyond two generations!

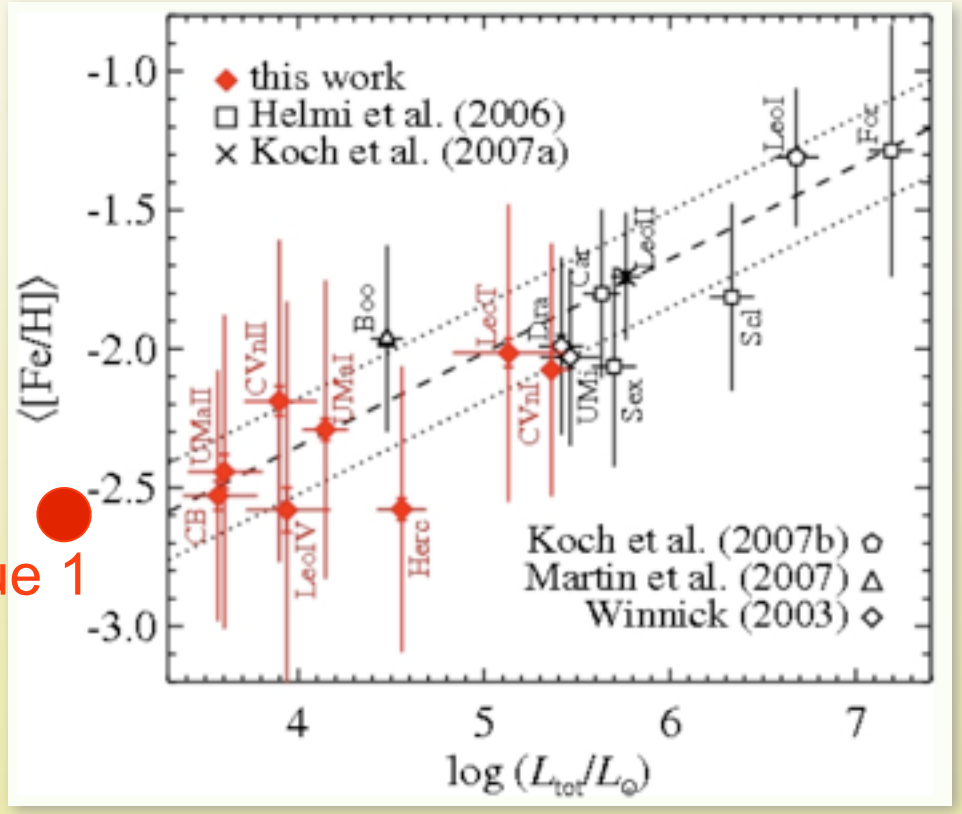
=> Best candidate for a surviving first galaxy!

Frebel & Bromm, 2012 ApJ

METALLICITY-LUMINOSITY RELATION

ANNA FREBEL

Kirby et al. 2008, ApJ



Segue 1

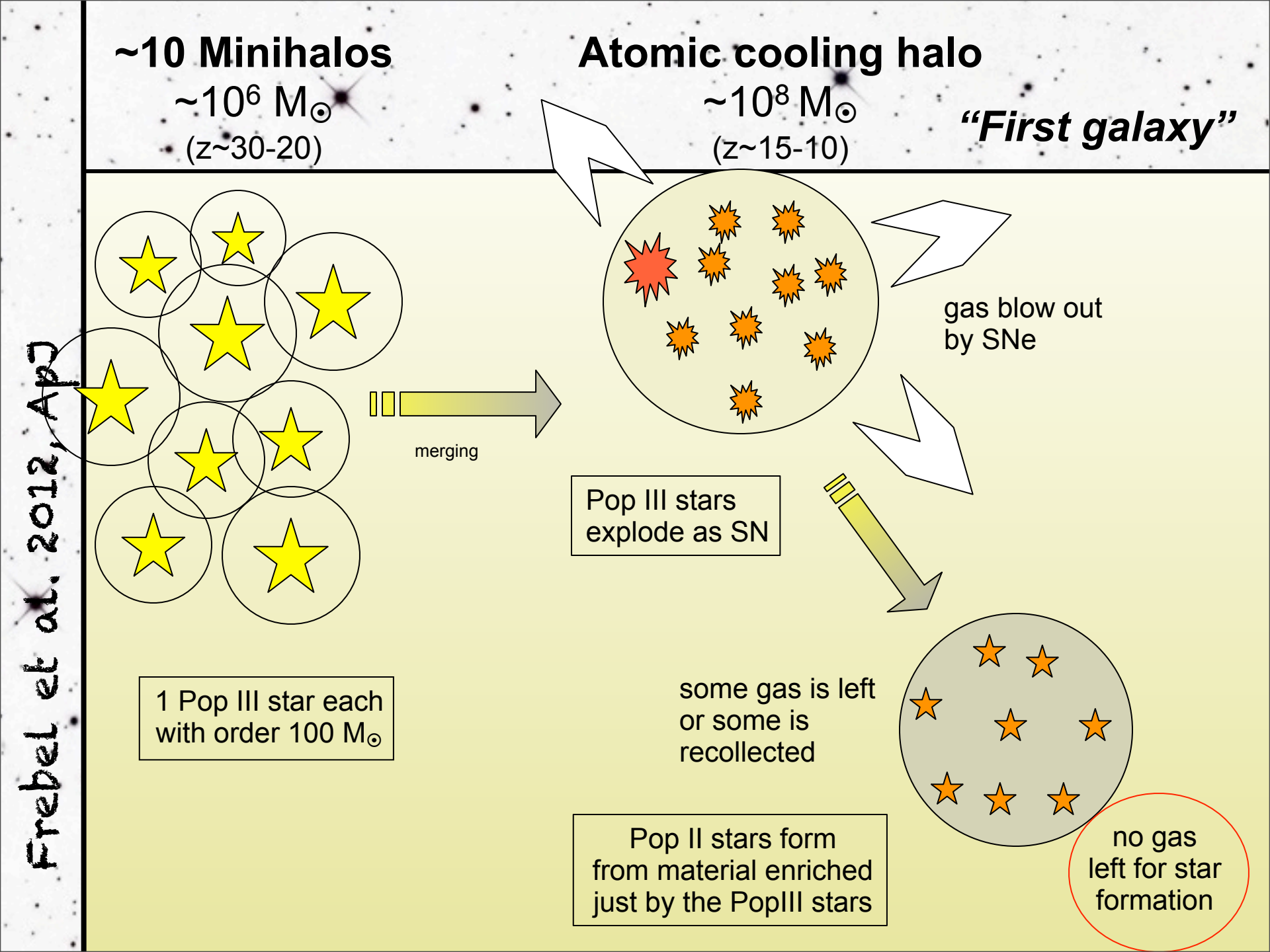
Ultra-faint dwarfs

Classical dSphs

Segue 1 properties:

M ~ 5.8 x 10^5 Msun
L ~ 10^3 Lsun
D ~ 23kpc
<[Fe/H]> ~-2.5

(e.g. Simon et al. 2011)


~10 Minihalos
~10^6 M⊙
(z~30-20)
Atomic cooling halo
~10^8 M⊙
(z~15-10)
"First galaxy"
merging
gas blow out
by SNe
Pop III stars
explode as SN
1 Pop III star each
with order 100 M⊙
some gas is left
or some is
recollected
Pop II stars form
from material enriched
just by the PopIII stars
no gas
left for star
formation
Frebel et al. 2012, ApJ

ENRICHMENT CHANNELS IN A FIRST GALAXY

Frebel et al. 2012, ApJ

first galaxy enriched by Pop III stars; **one burst of SF**

These enrichment events will not be sampled by later generations of stars in a such a first galaxy!

low-mass stars survive until today => we observe those!

No additional star formation due to lack of gas!

formation of the first galaxy from ~10 mini halos

second-gen. metal-poor stars, w/ some MF

higher-mass stars: AGB stars some: SN II

lower-mass stars: SN Ia

low-mass stars: survive!

Time

today

The abundance test!

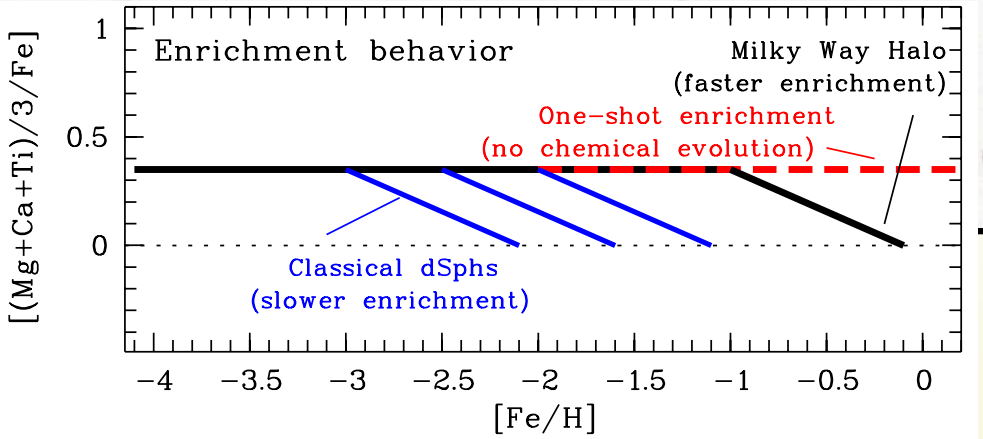
Frebel & Bromm, 2012 ApJ

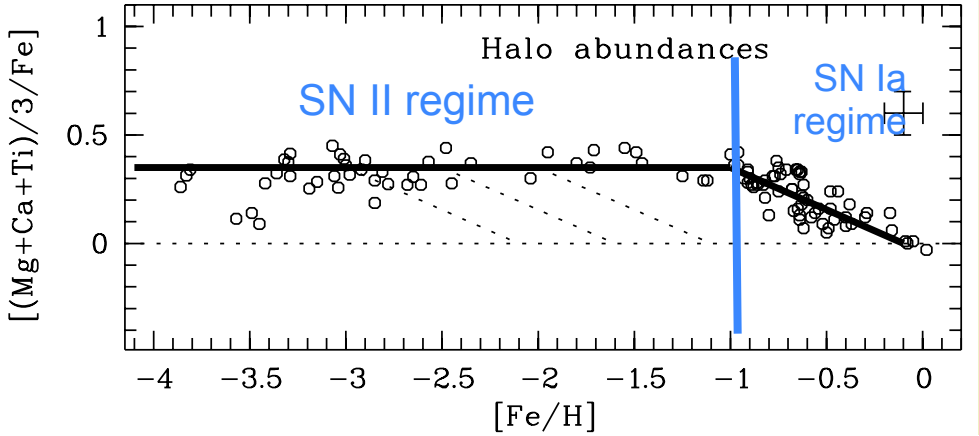
Prediction:

*In a first galaxy **no stars** should show abundance patterns that reflect either AGB or SN Ia enrichment!*

THE ABUNDANCE TEST!

Frebel & Bromm, 2012 ApJ





THE ABUNDANCE TEST!

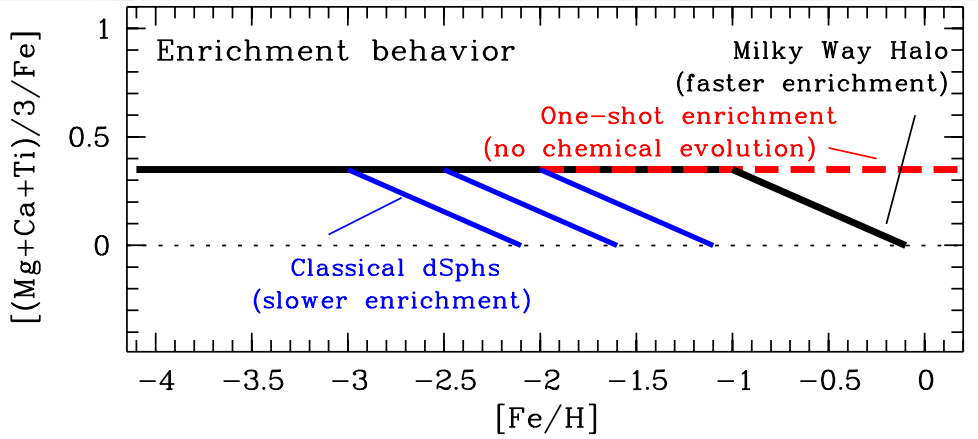
Criteria 1+2

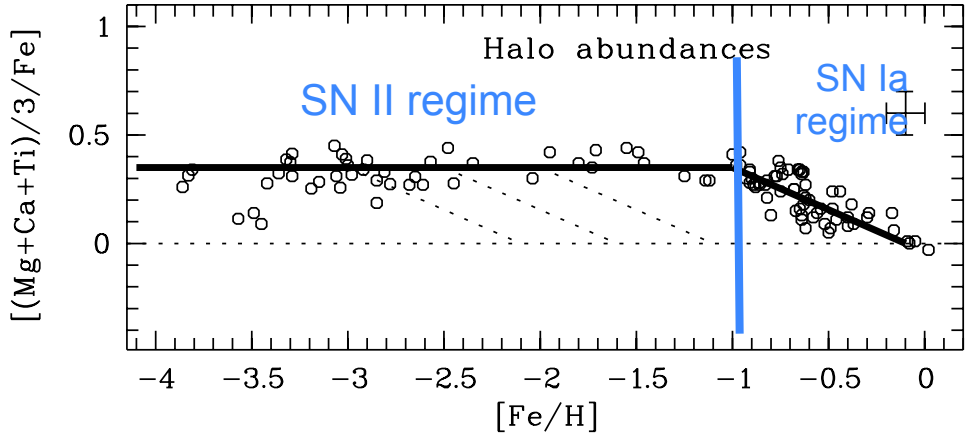
Fulfilled:

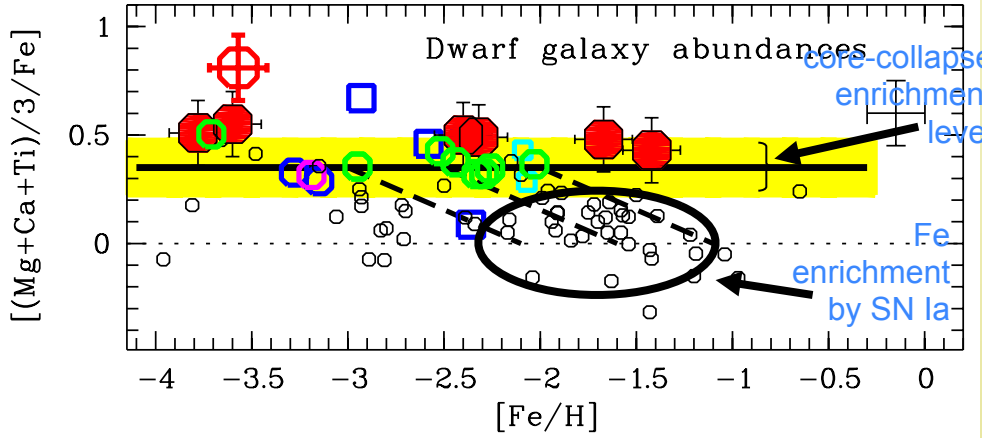
-MDF spread (2.5 dex)

-alpha-abundances enhanced

Frebel et al. 2014, ApJ





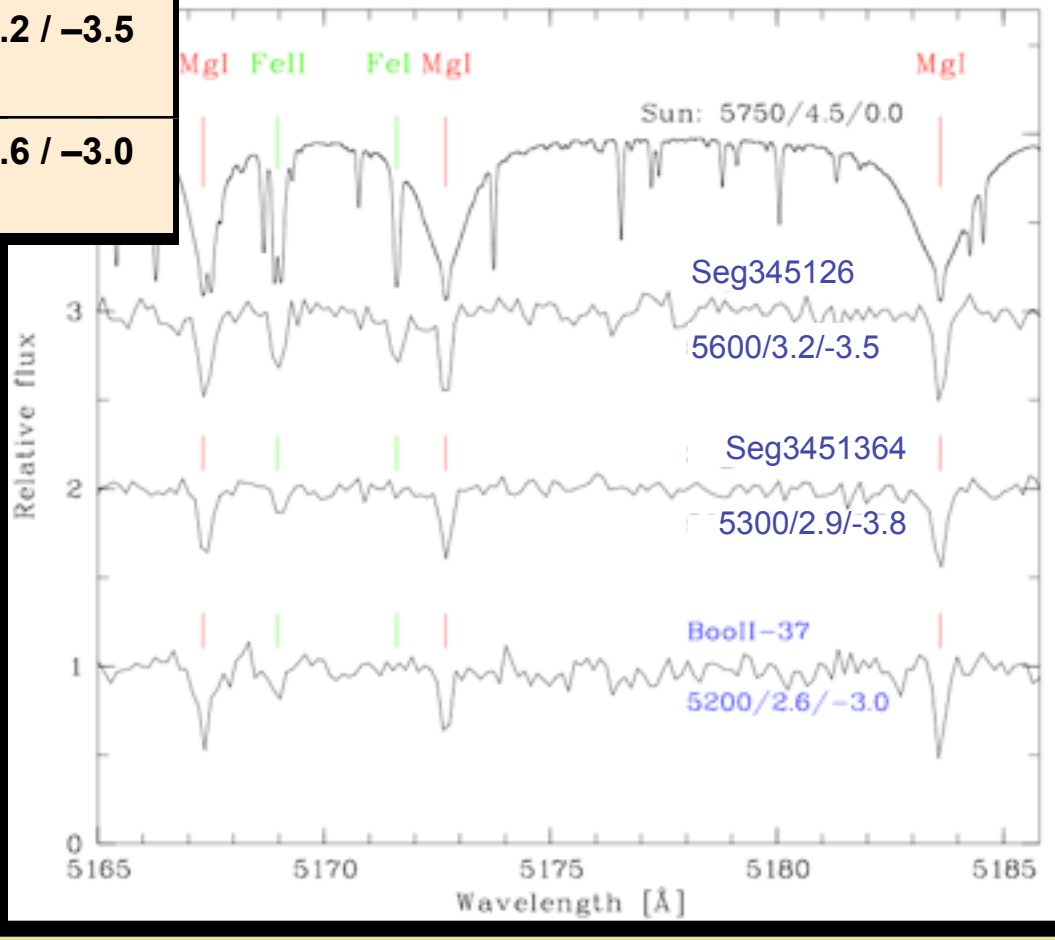


Frebel + Bromm 2012, ApJ; Frebel et al. 2014, ApJ
(data from Feltzing et al. 2009; Frebel et al. 2010b; Norris et al. 2010c; Simon et al. 2010;
Norris et al. 2010a; Aden et al. 2011; Cayrel et al. 2004; Francois et al. 2007; Venn et al. 2004)

MAGELLAN/MIKE SPECTRA

Star	g mag	t_{exp}	T_{eff} / log g / [Fe/H]
3451364 Segue 1	18.9	17 h	5300 / 2.9 / –3.8
3451326 Segue 1	19.4	7 h	5600 / 3.2 / –3.5
S37 Bootes II	19.5	14 h	5200 / 2.6 / –3.0

R~30,000



Star 3451364, with [Fe/H]=–3.8, is the most metal-poor star in any of the ultra-faint dwarf galaxies!

9h

17h

14h

Targets were selected from Kirby et al (*2008*) & Geha et al (*2009*)

Frebel et al. 2013, in prep.

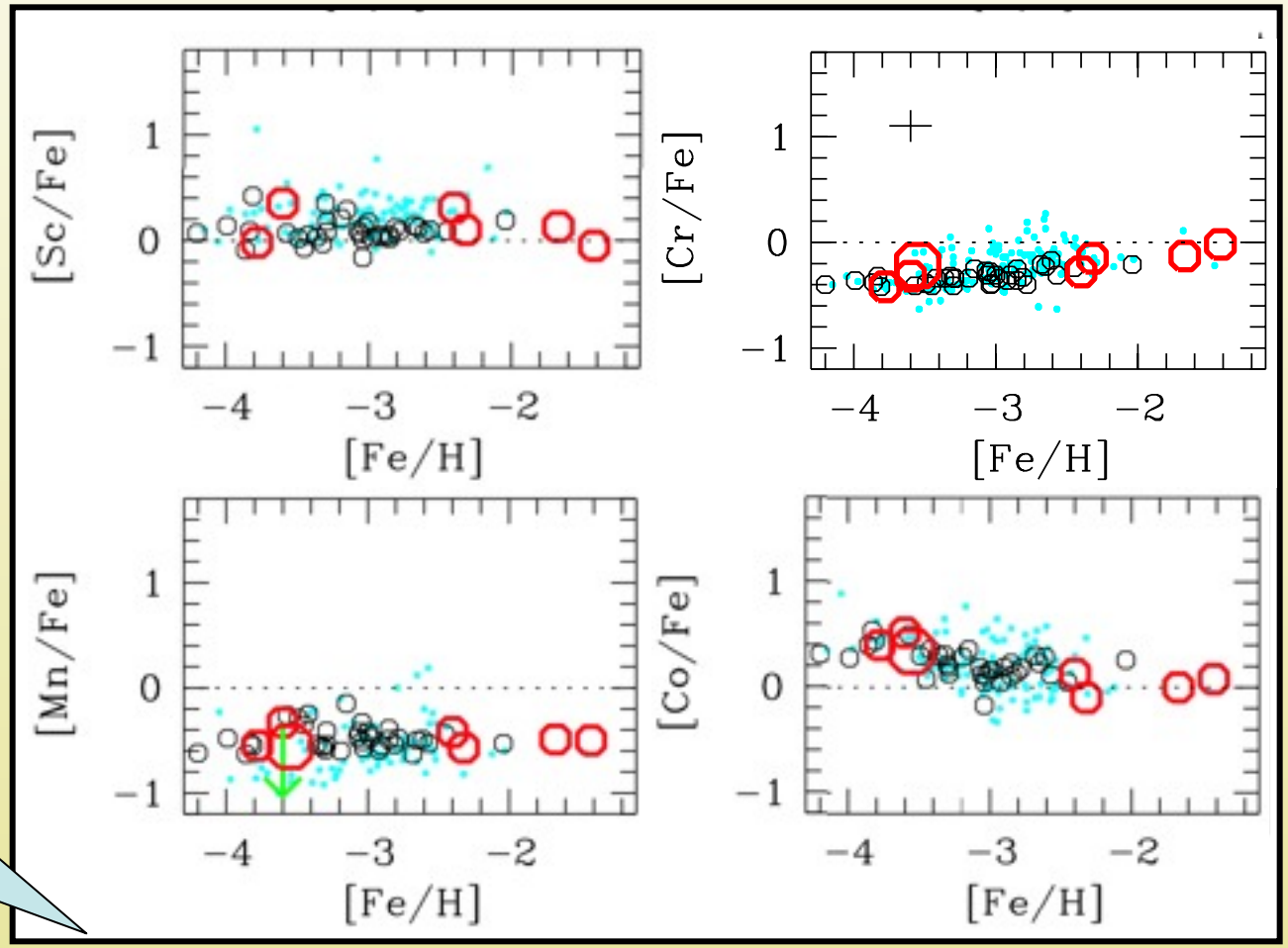
ULTRA-FAINT DWARF GALAXY STELLAR ABUNDANCE RATIOS

Criteria 3 Fulfilled: abundance agreements with halo stars

Frebel et al. 2014, ApJ.

Black and cyan open circles: Halo stars

Red circles: Segue 1 stars



Excellent agreement with the MW chemical evolution

HARDLY ANY NEUTRON-CAPTURE MATERIAL IN SEGUE 1 !

Criterion 4

Fulfilled:
lowest levels of neutron-capture elements

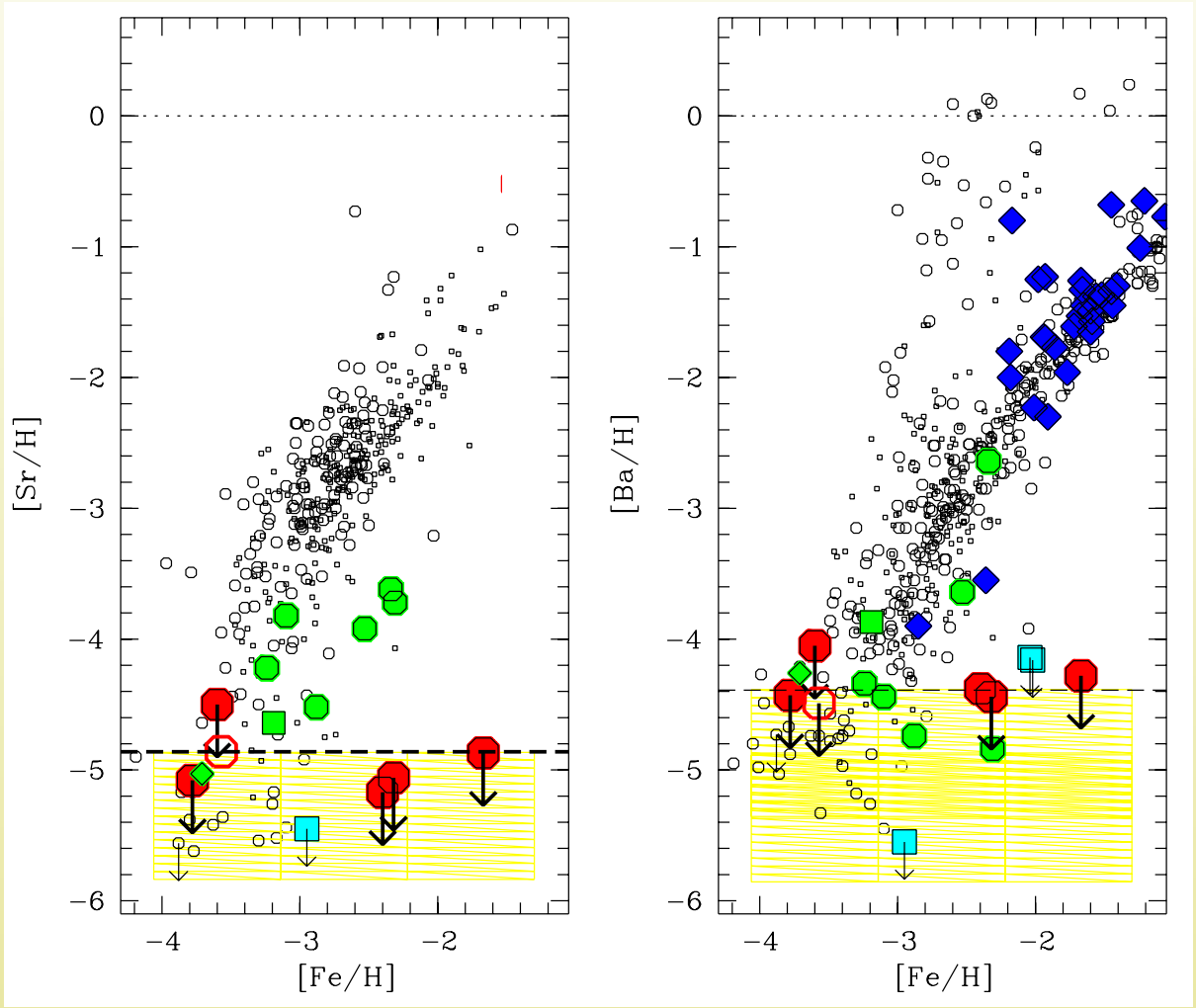
Black open circles: Halo stars

Blue diamonds: dSphs

Green circles: Com Ber, UMa II, Leo IV

Red circles: Segue 1 stars

Cyan: Draco, Hercules



First galaxy candidates

- Good candidates (!)
- **Segue 1** (~10^3 Lsun; 7 stars)

- Potential Candidates (?)
- Ursa Major II (~$5x10^3$ Lsun; 3 stars), Coma Berenices (~$5x10^3$ Lsun; 3 stars), Leo IV (~10^4 Lsun; 1 star)

- Probably not a candidate (??)
- **Bootes I** (5x10^4 Lsun; ~14 stars)

- Not a candidate (!)
  Hercules (~6x10^4Lsun; ~10 stars)

ANNA FREBEL

THE FIRST GALAXY SEGUE 1

THE PRIMEVAL POPULATIONS OF THE ULTRA-FAINT DWARF GALAXIES[1]

THOMAS M. BROWN[2], JASON TUMLINSON[3], MARLA GEHA[3], EVAN N. KIRBY[4], DON A. VANDENBERG[5], RICARDO R. MUÑOZ[7], JASON S. KALIRAI[2], JOSHUA D. SIMON[8], ROBERTO J. AVILA[2], PURAGRA GUHATHAKURTA[9], ALVIO RENZINI[10], AND HENRY C. FERGUSON[2]

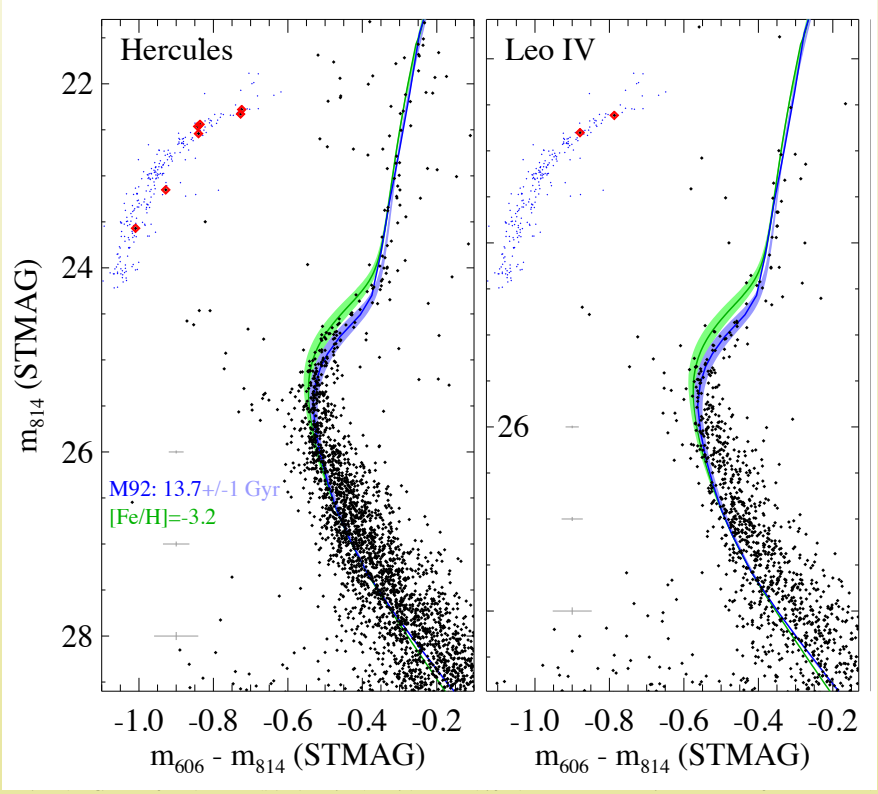
Accepted for publication in The Astrophysical Journal Letters

ABSTRACT

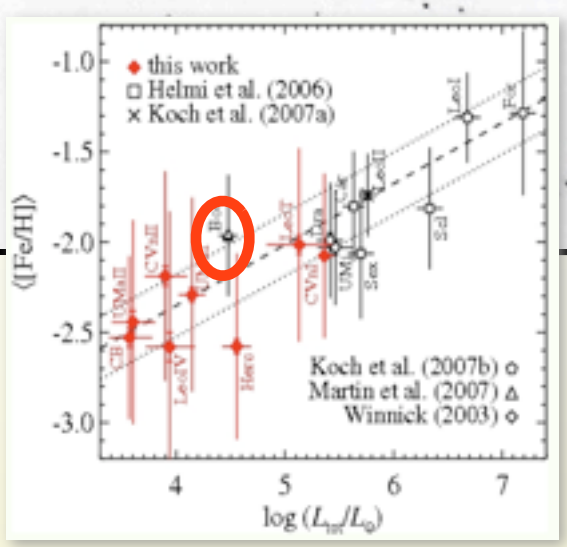
We present new constraints on the star formation histories of the ultra-faint dwarf (UFD) galaxies, using deep photometry obtained with the *Hubble Space Telescope (HST)*. A galaxy class recently discovered in the Sloan Digital Sky Survey, the UFDs appear to be an extension of the classical dwarf spheroidals to low luminosities, offering a new front in efforts to understand the missing satellite problem. They are the least luminous, most dark-matter dominated, and least chemically-evolved galaxies known. Our *HST* survey of six UFDs seeks to determine if these galaxies are true fossils from the early universe. We present here the preliminary analysis of three UFD galaxies: Hercules, Leo IV, and Ursa Major I. Classical dwarf spheroidals of the Local Group exhibit extended star formation histories, but these three Milky Way satellites are at least as old as the ancient globular cluster M92, with no evidence for intermediate-age populations. Their ages also appear to be synchronized to within ~1 Gyr of each other, as might be expected if their star formation was truncated by a global event, such as reionization.

Idea of surviving first/ earliest galaxies is not entirely crazy!

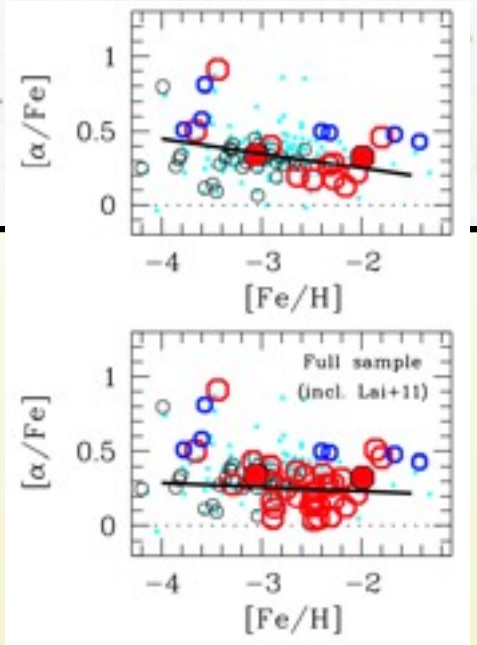
Many (most?) of the ultra-faint dwarfs show single-age populations that are as old the universe (roughly)



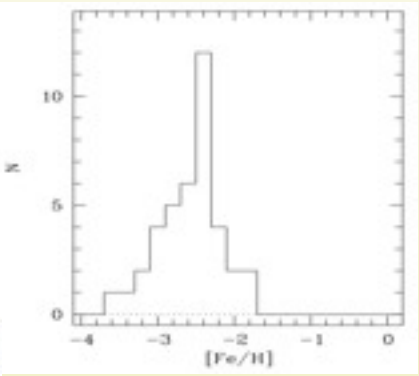
Bootes I

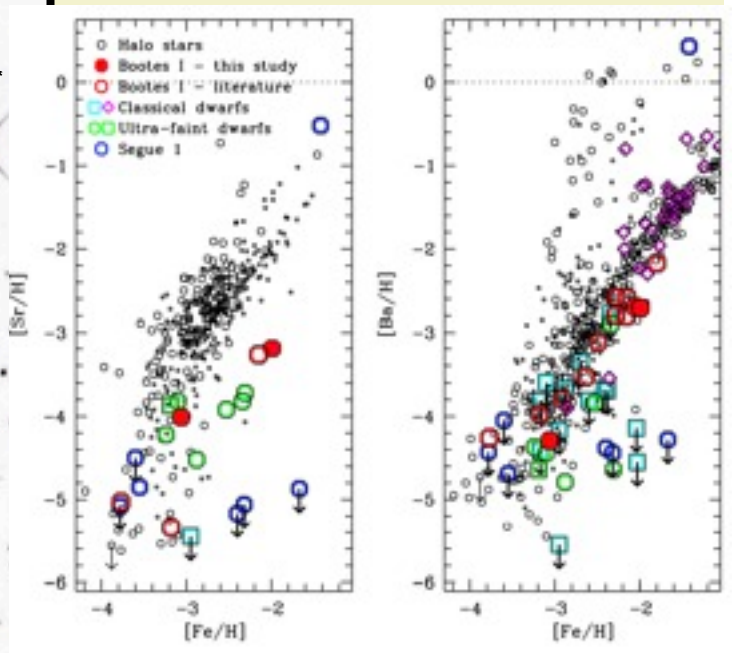


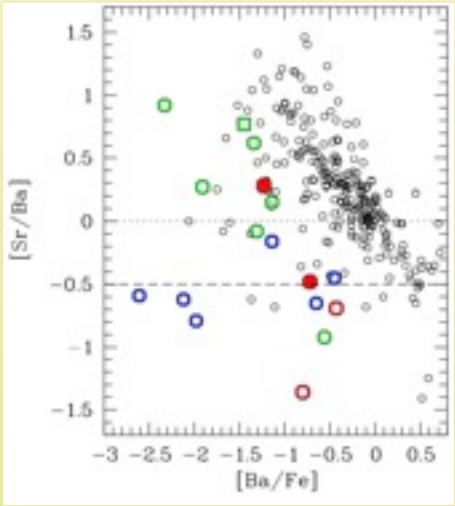
Not obvious what is going on...

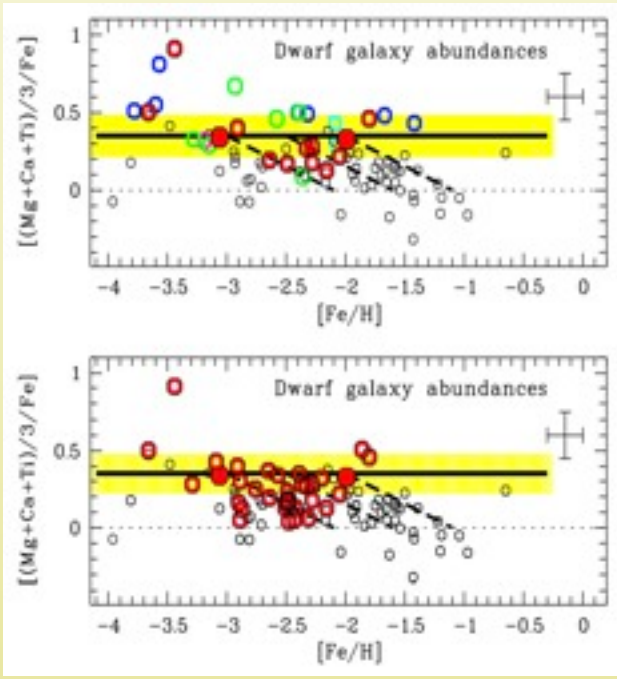


...half Segue-like, half dSphs-like





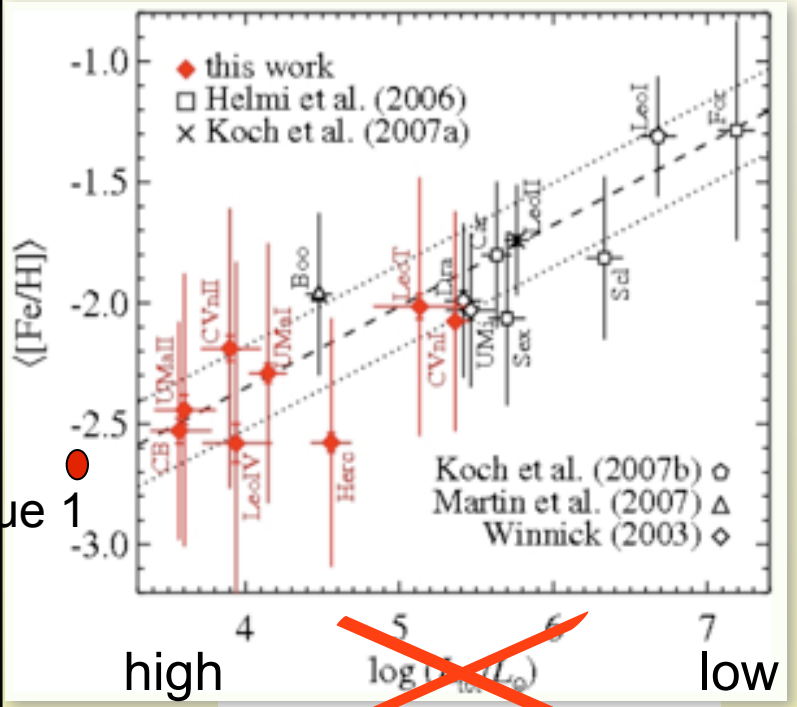




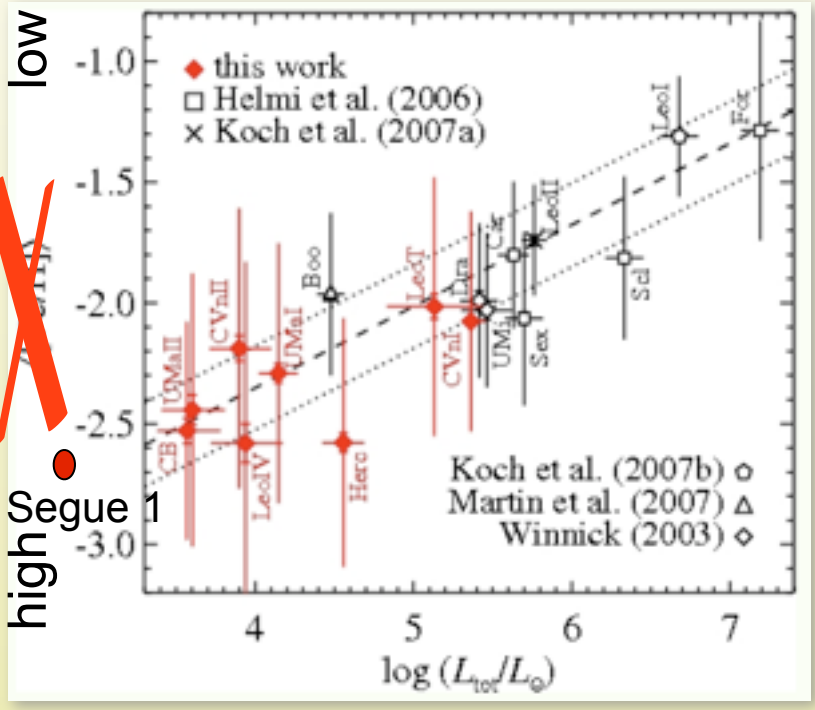
Frebel et al. 2015, to be subm.

A SPECULATION...

For spectroscopists



For dynamicists/theorists



Conclusion: We need more faint UFDs, pls!

Chemical signature of the first supernovae in Sculptor

Josh will talk about that - stay tuned!

Josh Simon, Heather Jacobson, Anna Frebel, et al.
2015 ApJ, in press, arxiv1412.5176

What is the whole story?

Through chemical abundance studies

What the first supernovae, first enrichment events, first galaxies, etc, were like

Big Bang

early gas cloud:
how the first low-mass stars formed (dust vs fine-struct. line cooling)

Dwarf galaxies:
information on building blocks;
13 Gyr survivors?

~13 billion years in between

As found eg with SkyMapper

Metal-poor stars today in the Milky Way

...Need Cosmological Simulations, b/c metal-poor stars aren't really going to help exploring those.