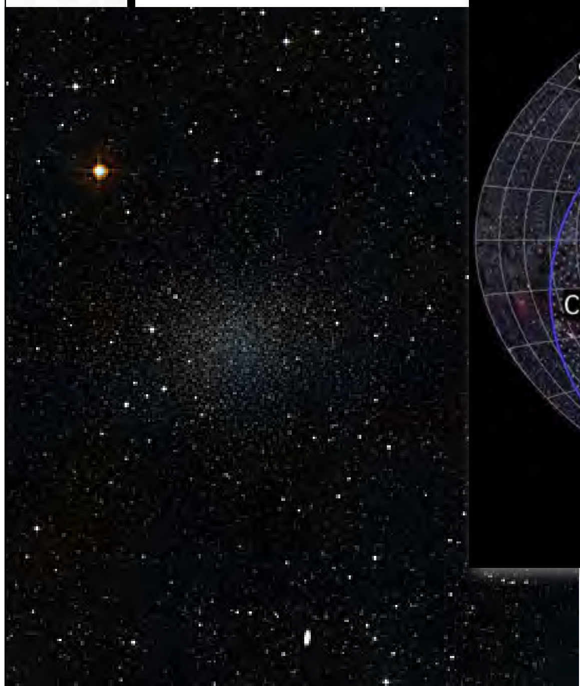
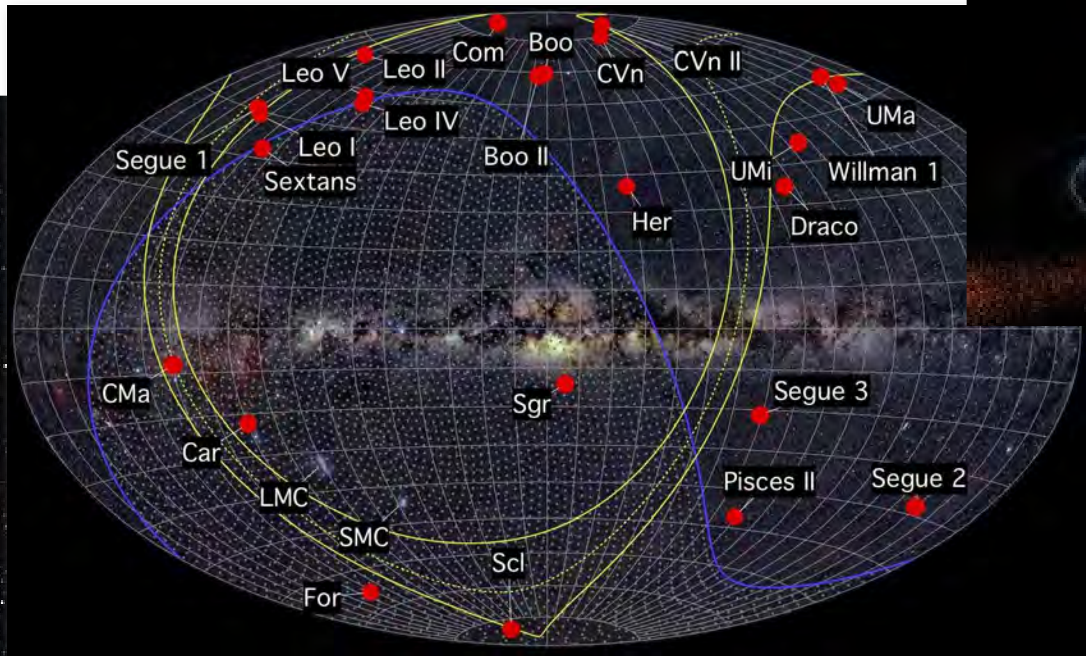
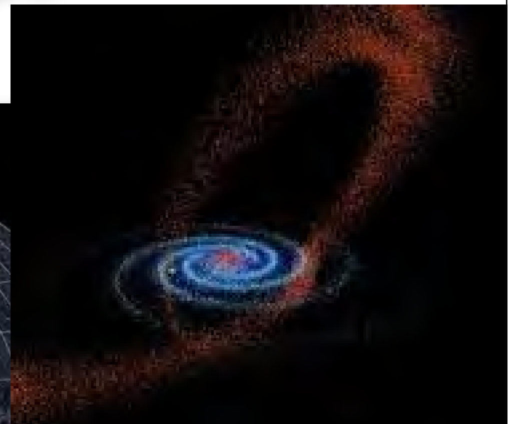
Are the ultra-faint dwarfs surviving first galaxies?







Anna Frebel

afrebel@mit.edu

Massachusetts Institute of Technology

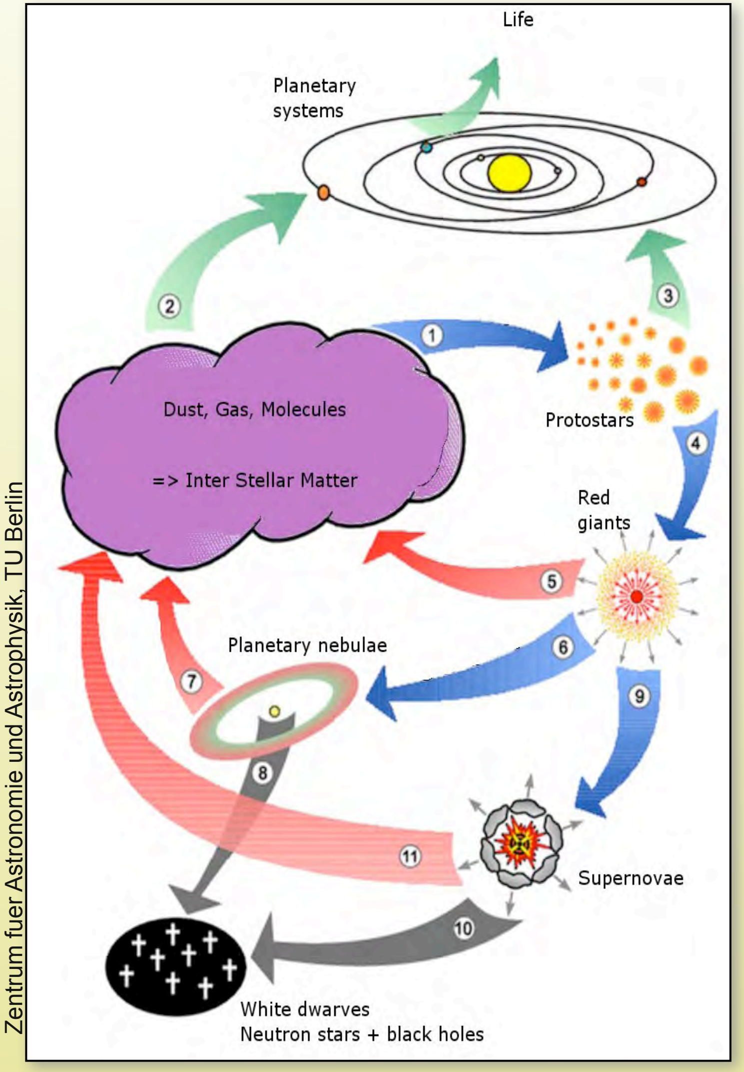
Main collaborators:

Josh Simon (Carnegie), Evan Kirby (CalTech), Volker Bromm (UTexas), Alex Ji (MIT)

Summary & Conclusions

- About a dozen stars in the ultra-faint dwarf galaxies have been observed with high-resolution spectroscopy **=> detailed chem. abundances available; same signatures as halo stars => potential Galactic building blocks**
- Segue 1 contains three extremely metal-poor stars => **all are carbon-enhanced**; other stars indicate only **massive star enrichment**
- Segue 1 chemical signature **consistent with that of a first galaxy** (=> inhomogeneous metal mixing, single SF event); also ultra-faint dwarfs **~13 billion years old** (Brown+12)
- First low-mass stars formed from **either dust or C,O fine-structure line cooled gas** (Segue 1: f.s.l. cooled gas likely)
- Survival rate of the the first systems **depends on reionization,** but perhaps Segue 1 is an actual example of survival
-

Introduction: Chemical Evolution



Zentrum fuer Astronomie und Astrophysik, TU Berlin

Old stars contain fewer elements (e.g., iron) than younger stars

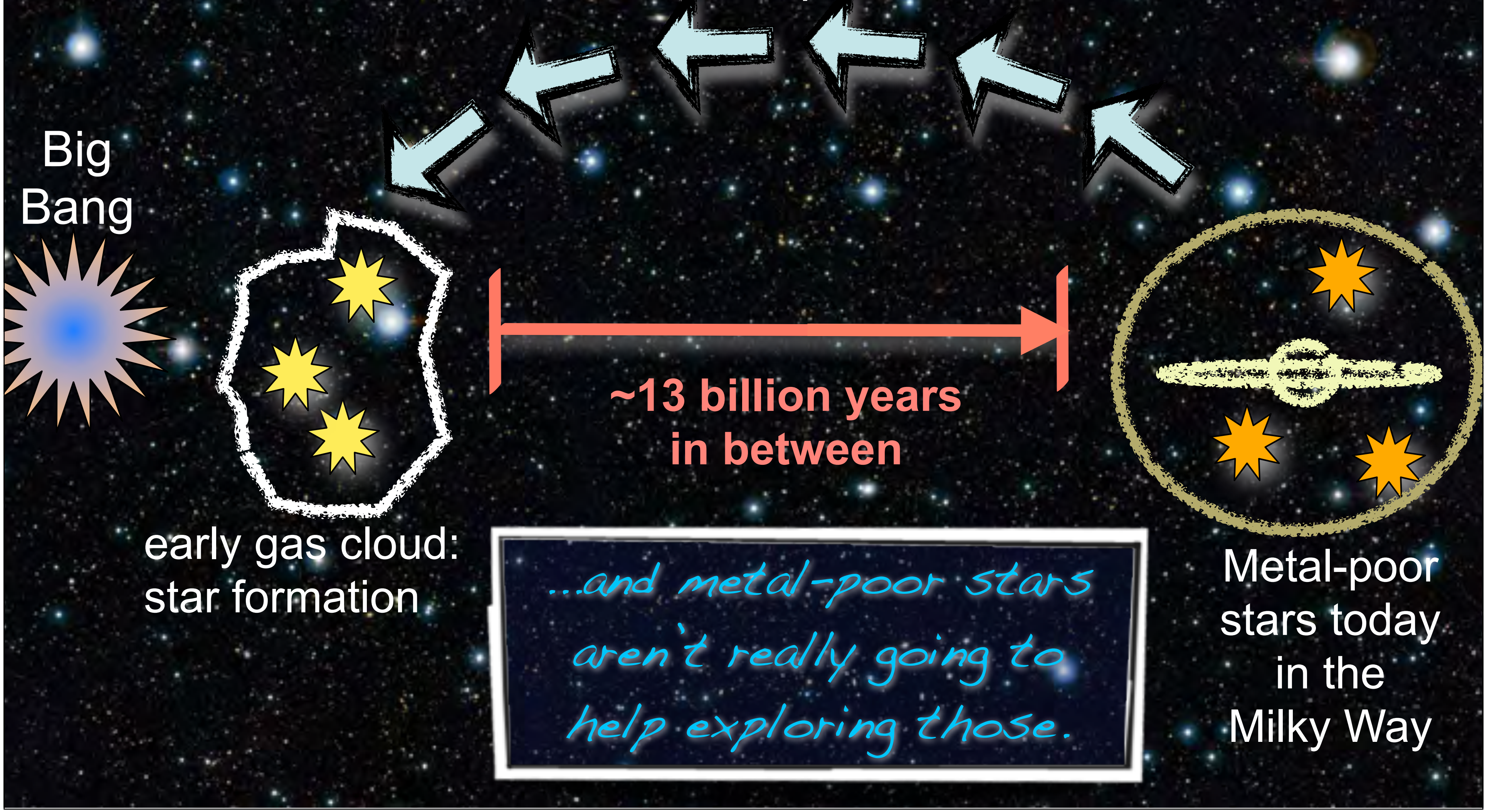
Pop III: zero-metallicity stars
Pop II: old halo stars
Pop I: young disk stars

We look for the stars with the **least amounts** of elements heavier than H and He (= extreme Pop II stars)!

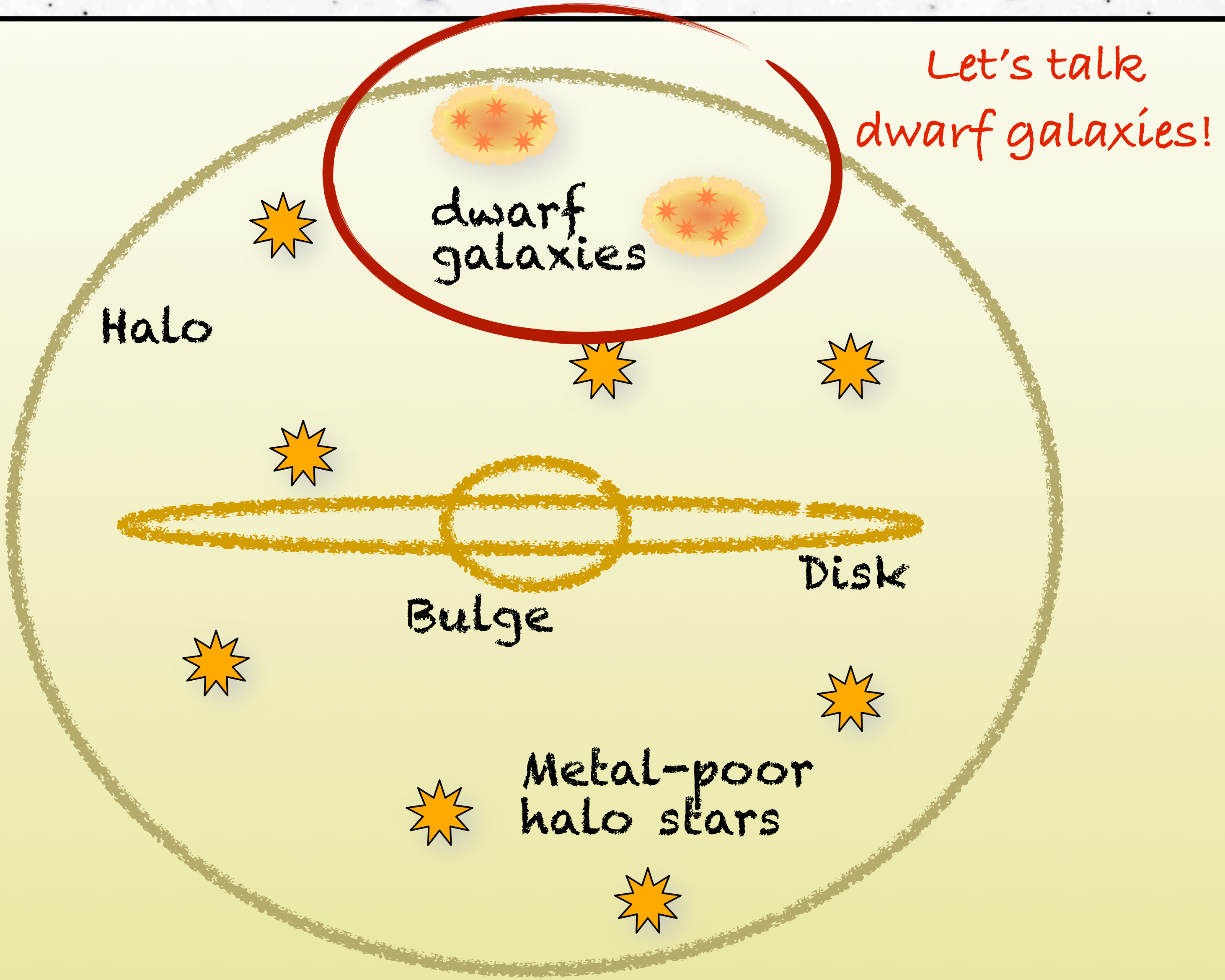
The most metal-poor stars are extremely rare

Introduction: Stellar archaeology

Through chemical abundance studies
of old metal-poor stars:



The Milky Way

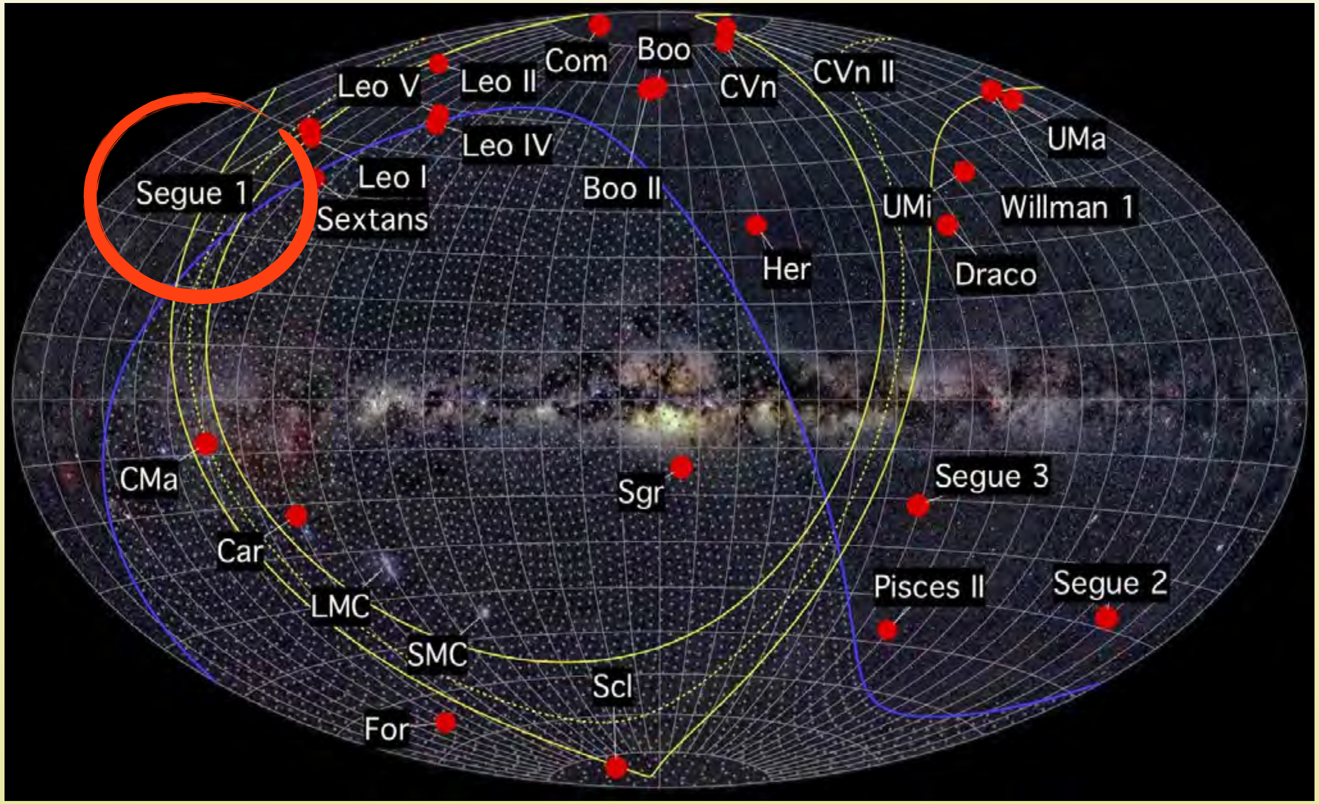


Anna Frebel

The Milky Way's satellites

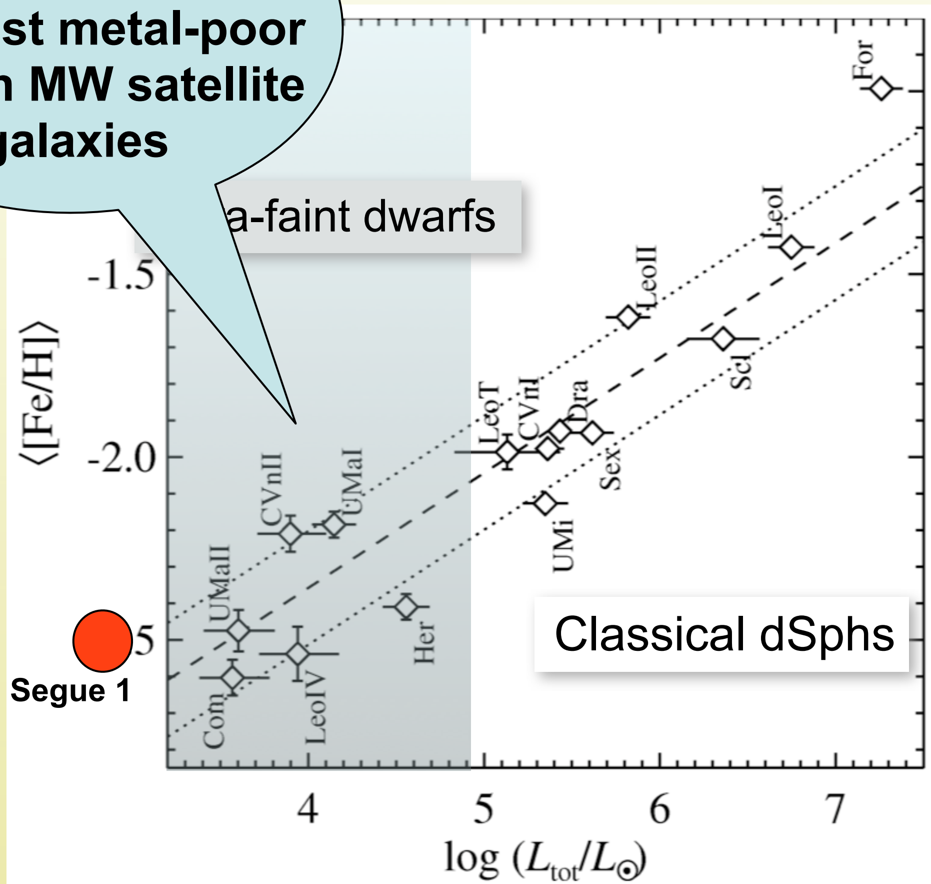
Dwarf galaxies are useful tools to study star formation and chemical evolution, early galaxy formation and the build-up of the Milky Way

dSph = gas poor dwarf galaxies dIrr = gas rich dwarf galaxies



Metallicity-Luminosity Relation

Stellar archaeology with the most metal-poor stars in MW satellite galaxies



updated from Kirby et al. 2008

All of the ultra-faints have huge abundance spreads!

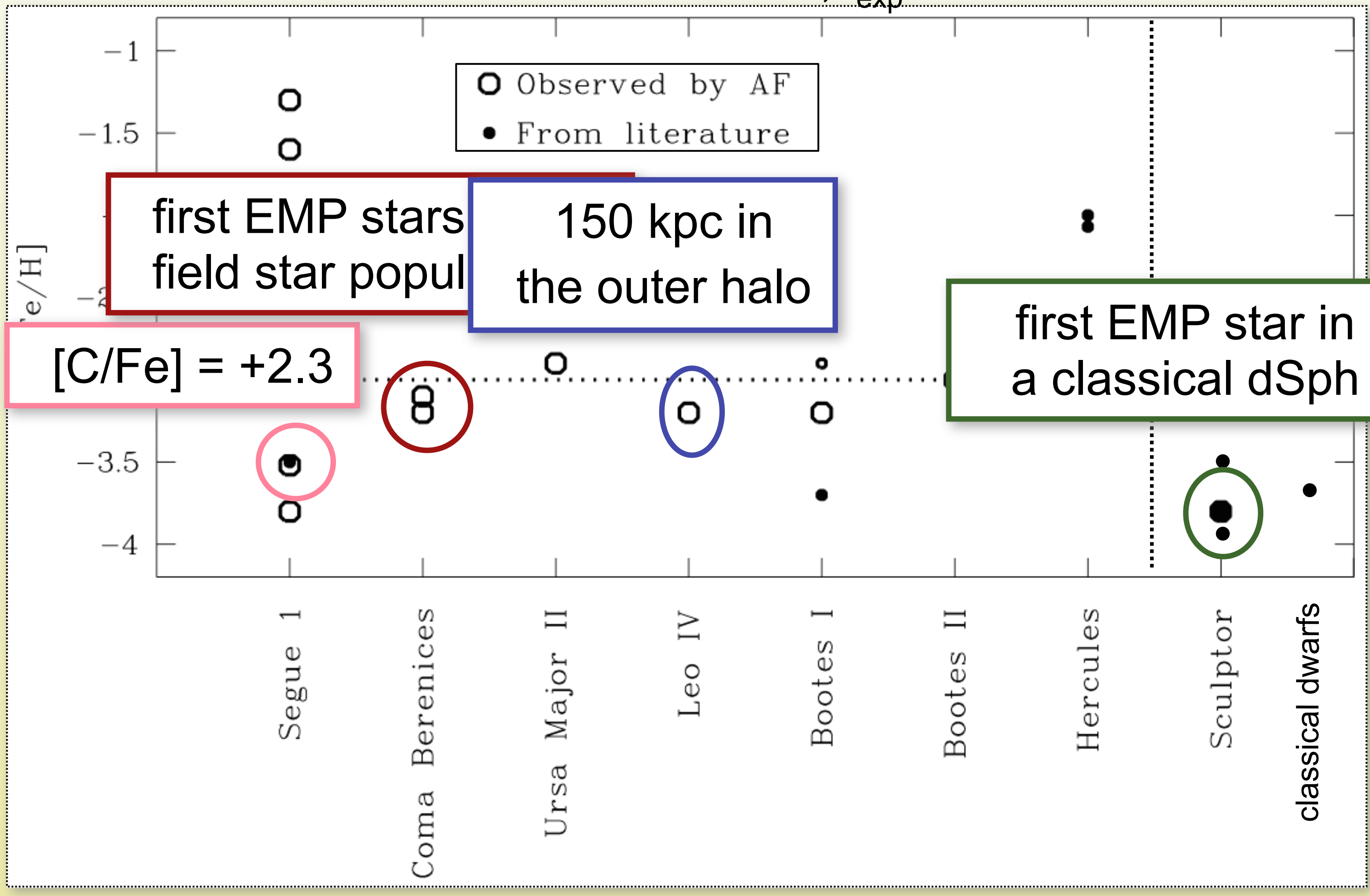
At least 2 dex and some up to ~3 dex:

-3.8 < [Fe/H] < -1.0

Status of high-resolution (R~30K) Spectroscopy of ultra-faint dwarf galaxy stars

Frebel et al. 2013, in prep.

faint stars: down to V=19.3, t_{exp} = 4 to 17 hours



Frebel et al 2010
Simon, Frebel et al 2010
Frebel, Kirby & Simon 2010, Nature
Norris et al. 2010a+b
Frebel et al 2013a+b in prep.

Anna Frebel

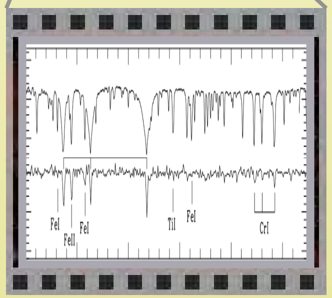
Using dwarf galaxies to study the nature of small halos

In the 'dark matter' world: CDM hierarchical structure formation model

Aquarius

In the 'luminous' world: Comprehensive understanding of galaxy formation

Spectroscopic observations
of stars and streams
(= luminous matter)



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

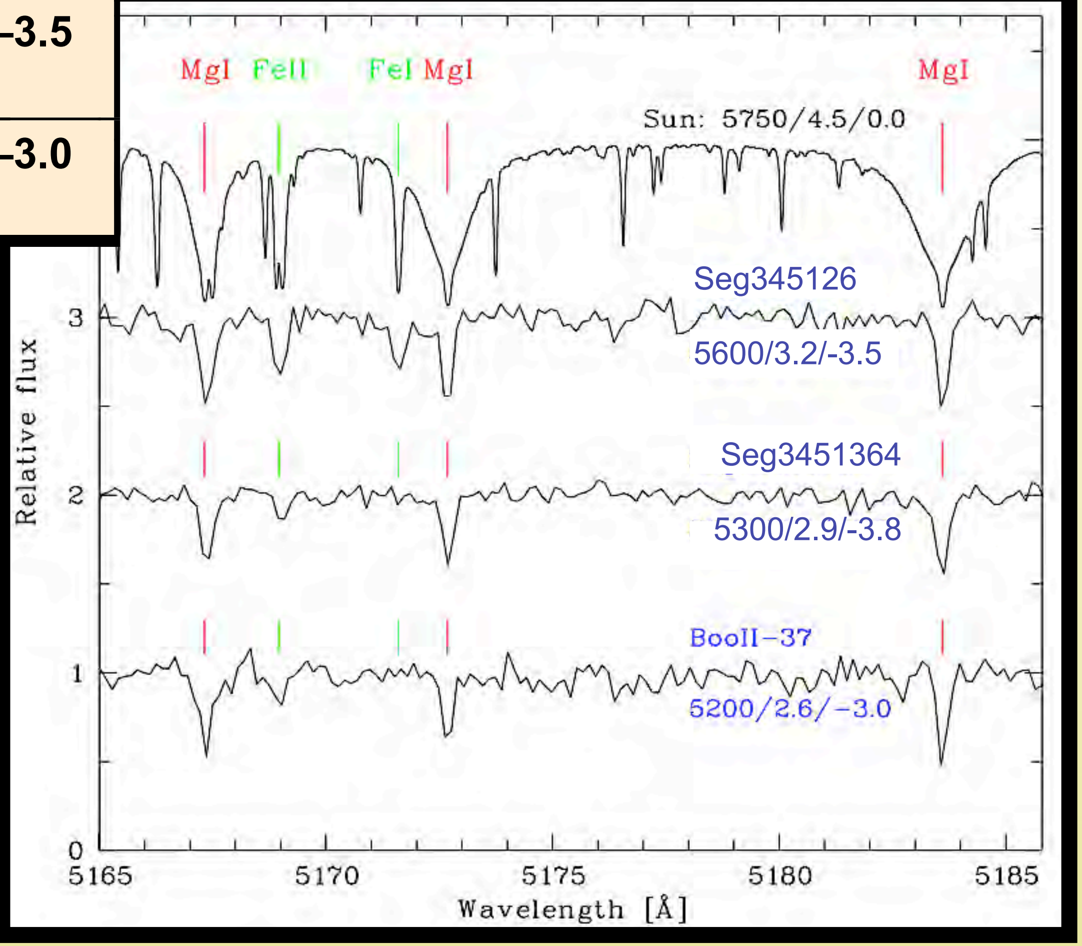
R~30,000

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

9h

17h

14h



Frebel et al. 201

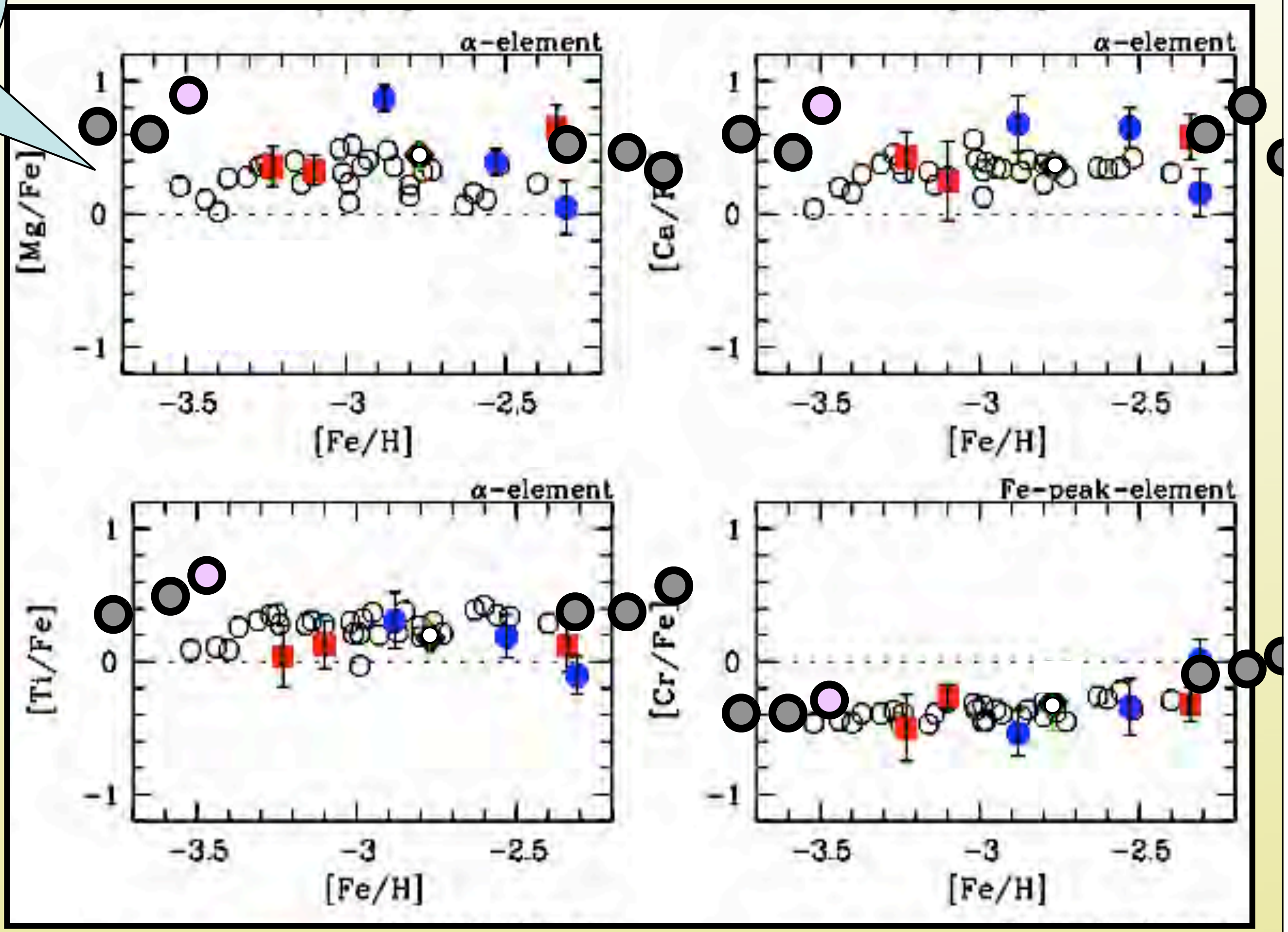
Targets were selected from Kirby et al (2008) & Geha et al (2009)

ULTRA-FAINT DWARF GALAXY STELLAR ABUNDANCE RATIOS

Anna Frebel

Frebel et al. 2010, ApJ

Excellent agreement with the MW chemical evolution



Black open circles:

Halo stars

Red squares:

Ursa Major II

Blue dots:

Coma Berenices

Some interesting numbers...

- Total number of stars below [Fe/H] = -3.8 in Milky Way: **12**
- Total number of stars below [Fe/H] = -3.8 in dwarfs: **4**

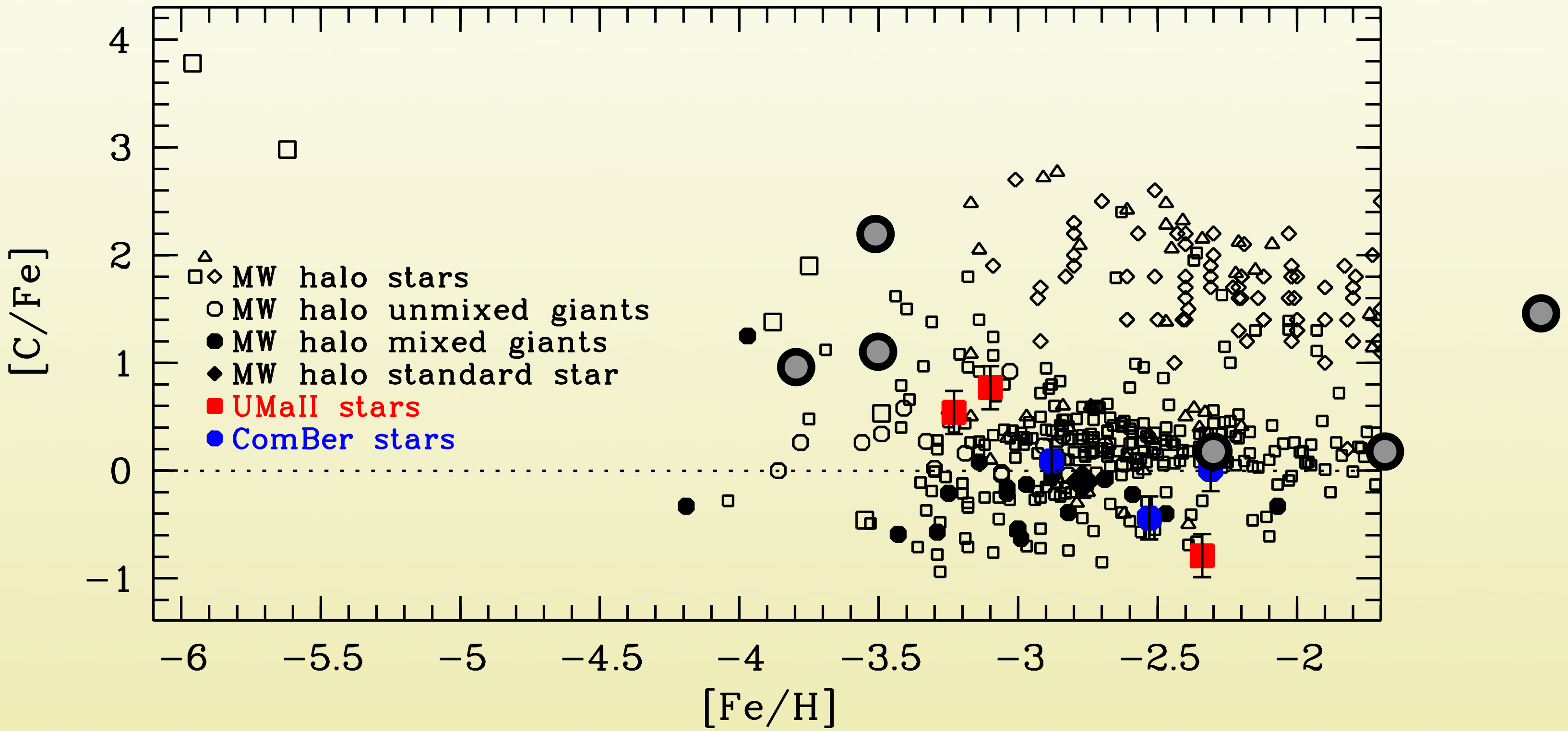
- Total number of stars below [Fe/H] = -3.5 in Milky Way: **30**
- Total number of stars below [Fe/H] = -3.5 in dwarfs: **8**

Years to search for EMP stars:
Halo **~30 years**
Dwarfs **~5 years**

~30% of the most metal-poor stars known are in dwarfs!!

Segue 1 has 10% of all known stars below [Fe/H] = -3.5!
(it only has 7 stars bright enough for high-resolution spectr.)

Carbon-rich extremely metal-poor stars: Segue 1



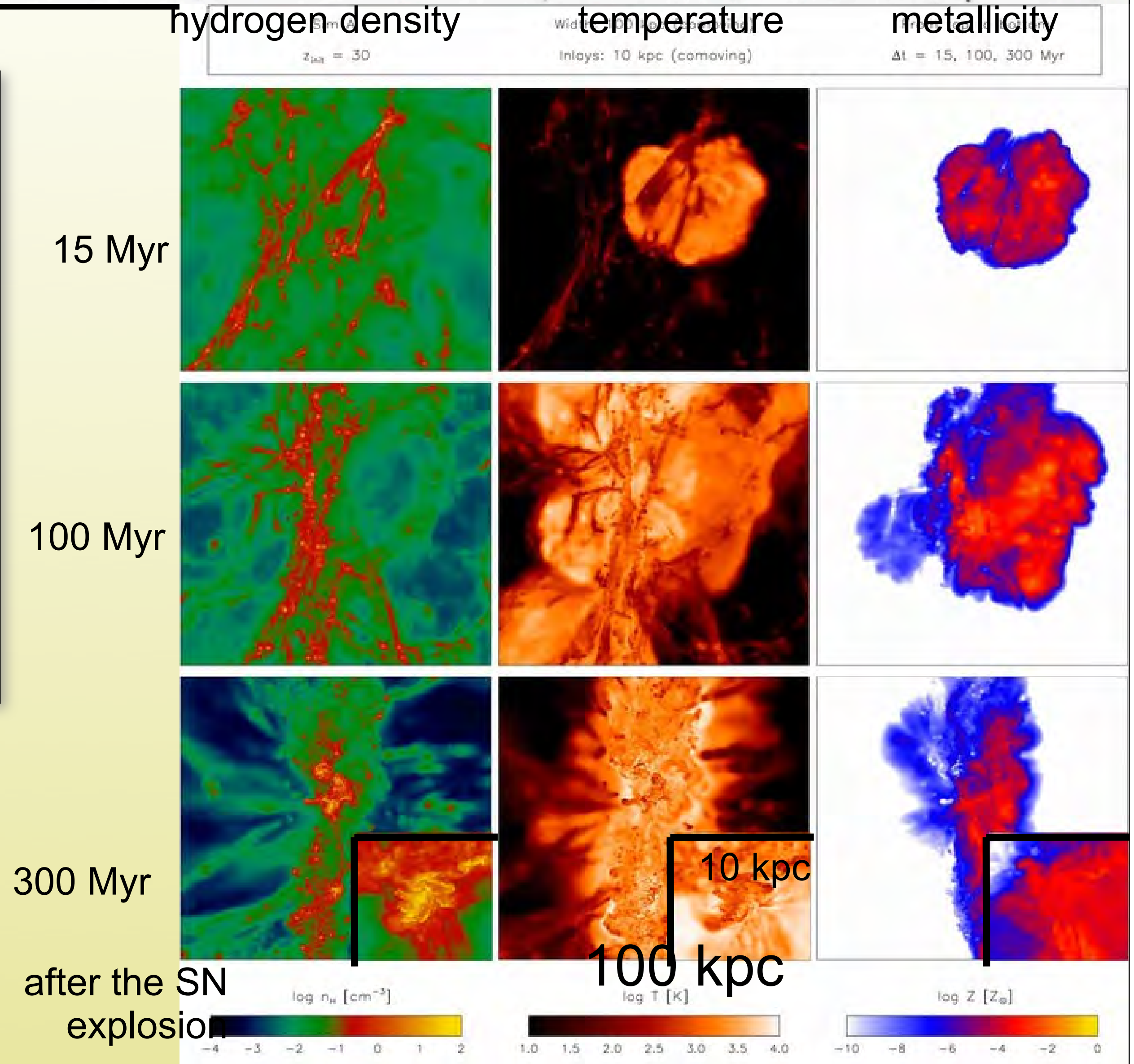
Massive rotating Pop III stars produce a lot of carbon... could provide material to cool gas within a first galaxy

The chemical signature of the first galaxy

Motivation

Study the beginning of star and galaxy formation based on detailed ab-initio hydro simulations of the first stars and the assembly of the first galaxy

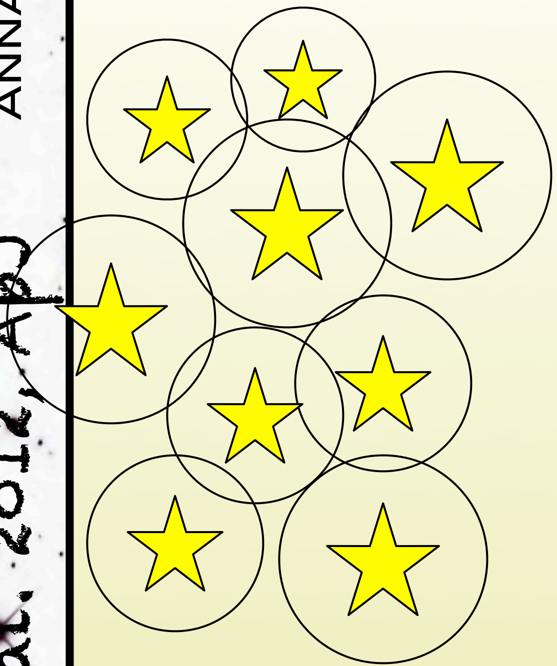
(e.g., Greif+10,11)



~10 Minihalos

~10^6 $M_\odot$

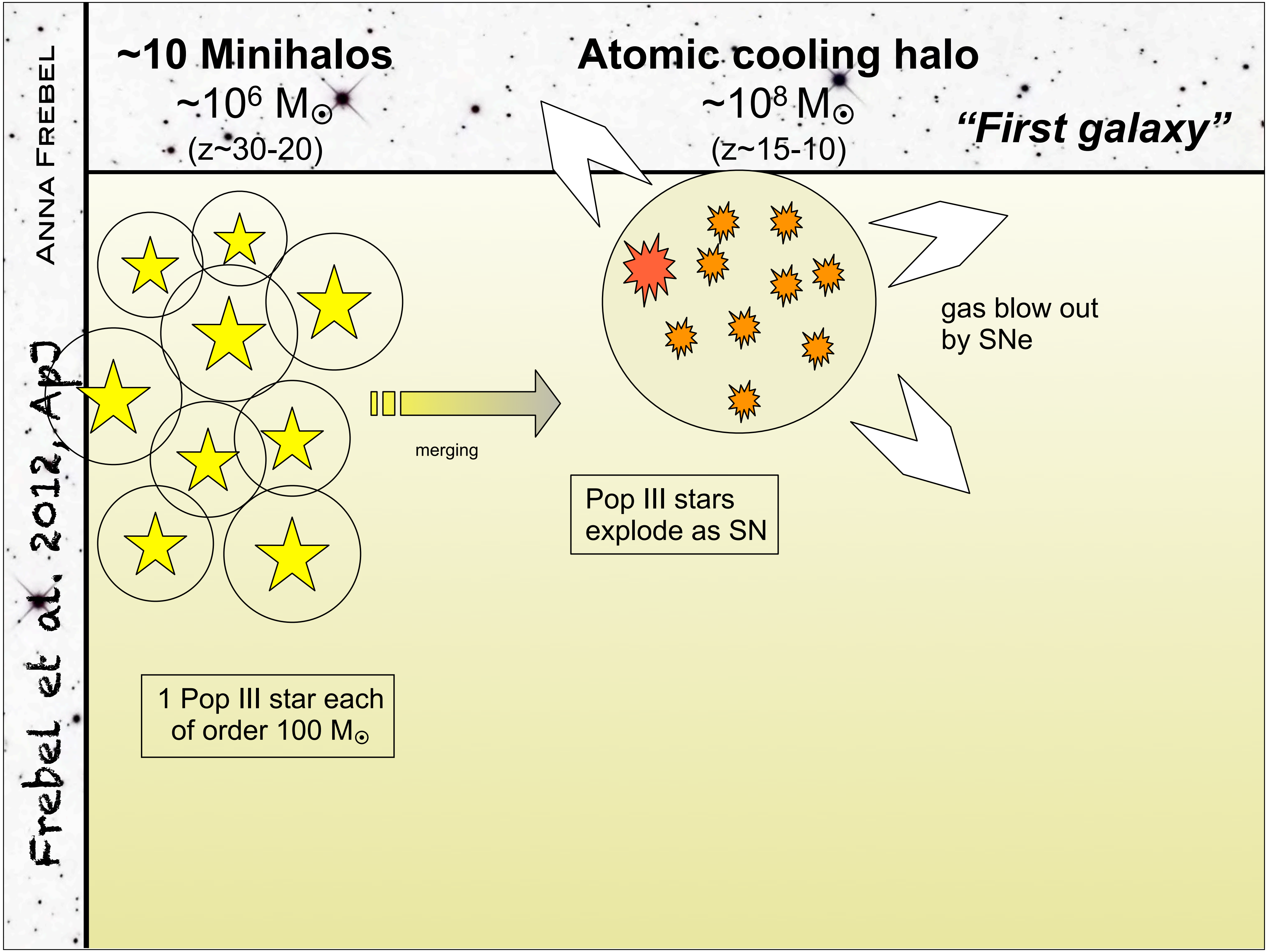
(z~30-20)

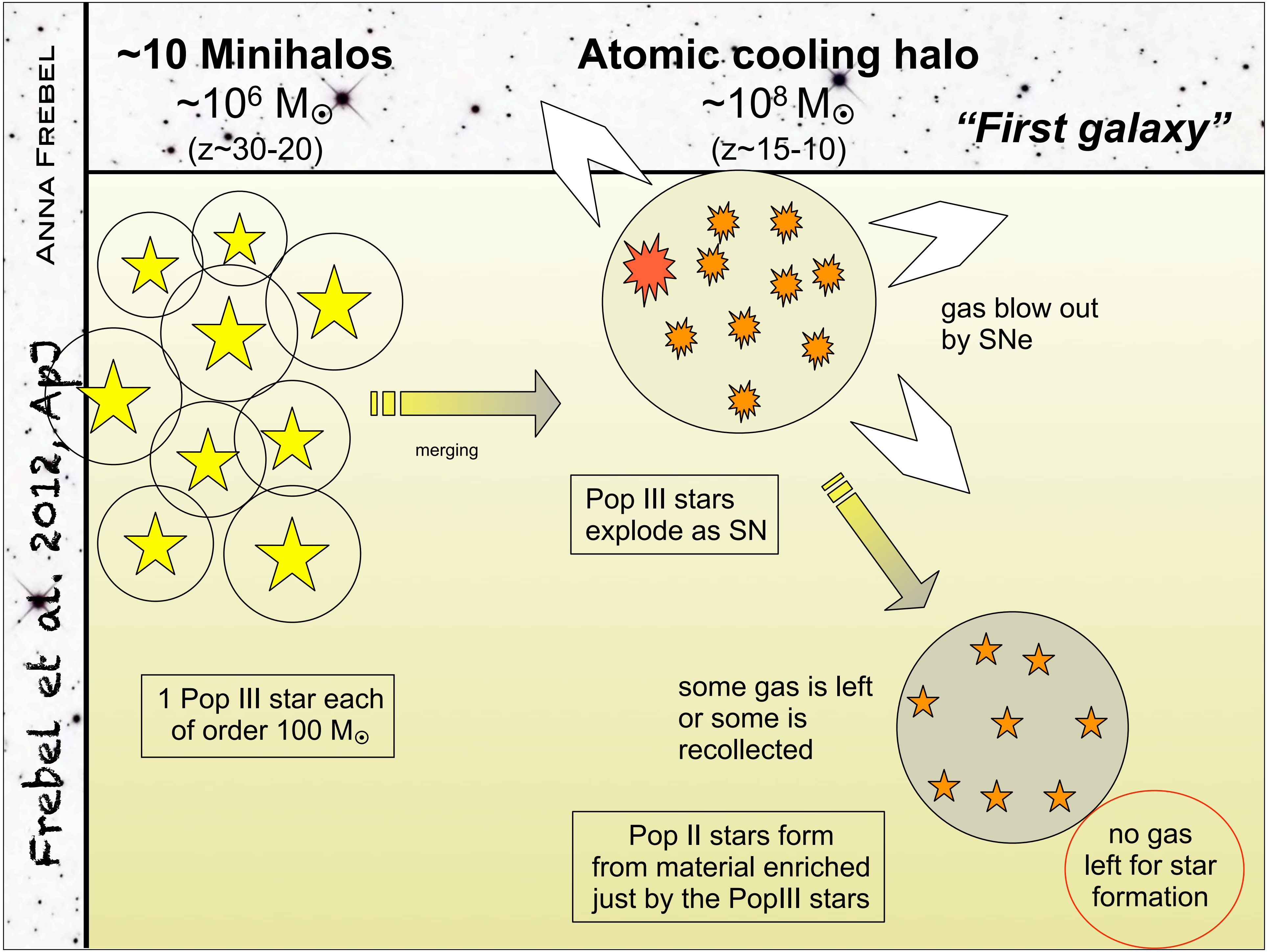


1 Pop III star each of order 100 $M_\odot$

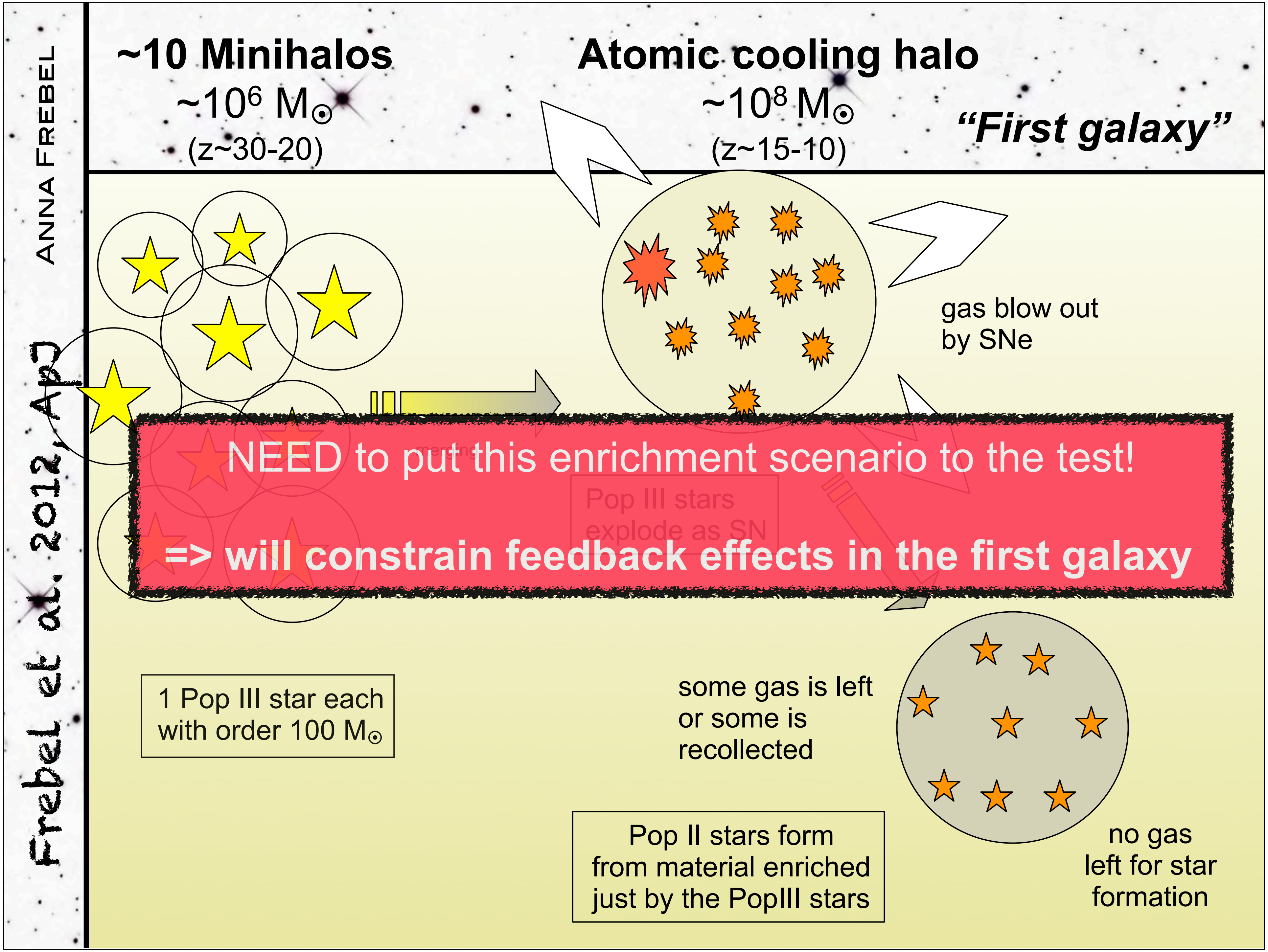
Anna Frebel

Frebel et al. 2012, ApJ


~10 Minihalos
~10^6 M⊙
(z~30-20)
Atomic cooling halo
~10^8 M⊙
(z~15-10)
"First galaxy"
gas blow out by SNe
merging
Pop III stars explode as SN
1 Pop III star each of order 100 M⊙
ANNA FREBEL
Frebel et al. 2012, ApJ



Anna Frebel
Frebel et al. 2012, ApJ
~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
of 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



ANNA FREBEL
Frebel et al. 2012, ApJ
~10 Minihalos
~10^6 M$_\odot$
(z~30-20)
Atomic cooling halo
~10^8 M$_\odot$
(z~15-10)
"First galaxy"
gas blow out
by SNe
Pop III stars
explode as SN
NEED to put this enrichment scenario to the test!
=> will constrain feedback effects in the first galaxy
1 Pop III star each
with order 100 M$_\odot$
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

Anna Frebel

Enrichment channels in a first galaxy

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

formation of the first galaxy from ~10 mini halos

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

Time

today

Frebel et al. 2012, ApJ

ENRICHMENT CHANNELS IN A FIRST GALAXY

ANNA FREBEL

Frebel et al. 2012, ApJ

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

formation of the first galaxy from ~10 mini halos

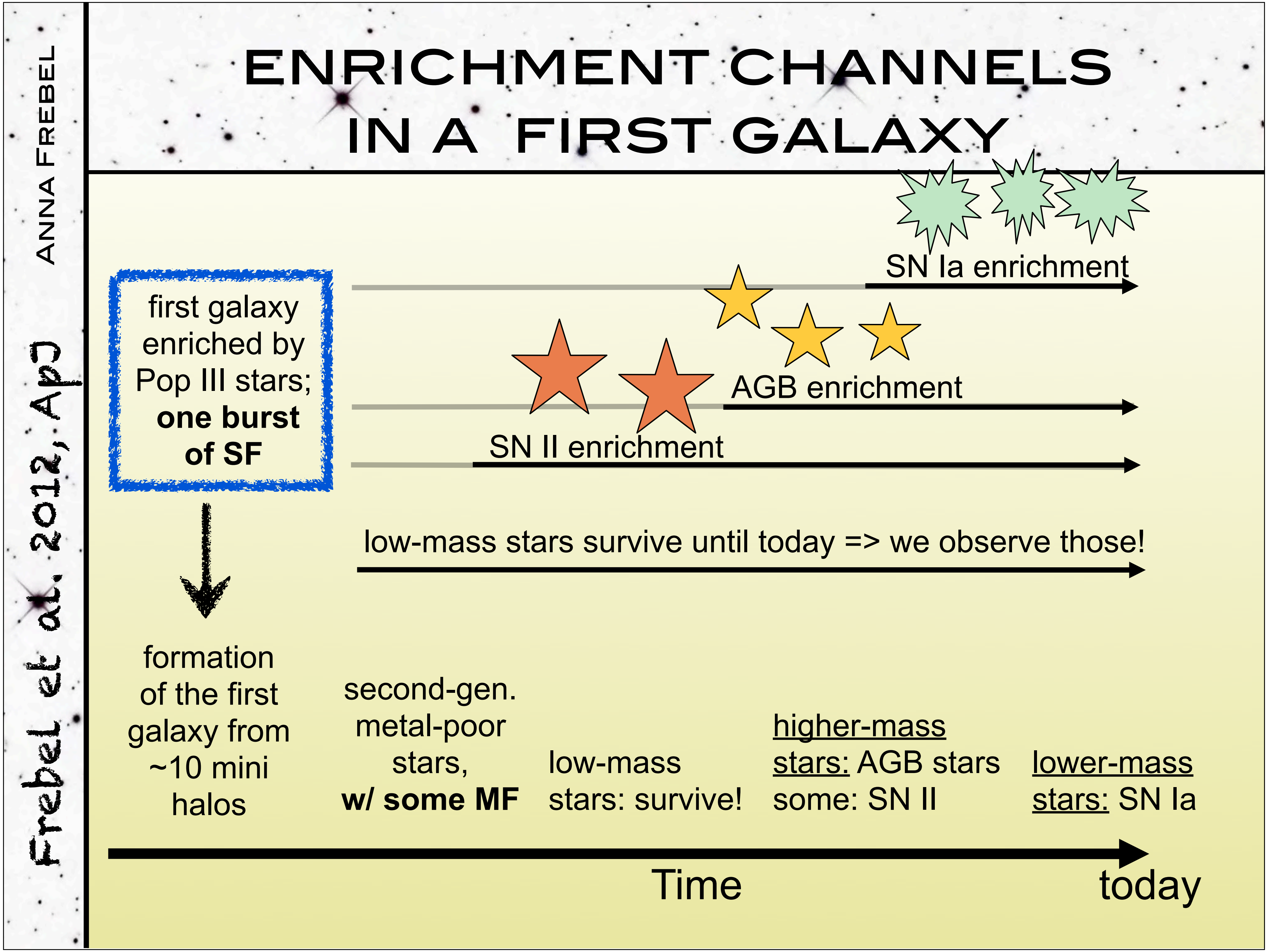
low-mass stars survive until today => we observe those!

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

low-mass stars: survive!

Time

today


ENRICHMENT CHANNELS
IN A FIRST GALAXY
Anna Frebel
Frebel et al. 2012, ApJ
first galaxy enriched by Pop III stars; **one burst of SF**
SN Ia enrichment
AGB enrichment
SN II enrichment
low-mass stars survive until today => we observe those!
formation of the first galaxy from ~10 mini halos
second-gen. metal-poor stars, **w/ some MF**
low-mass stars: survive!
higher-mass stars: AGB stars some: SN II
lower-mass stars: SN Ia
Time
today

Anna Frebel

Enrichment channels in a first galaxy

No additional star formation due to lack of gas!

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!

formation of the first galaxy from ~10 mini halos

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

low-mass stars: survive!

<u>higher-mass stars:</u> AGB stars some: SN II

<u>lower-mass stars:</u> SN Ia

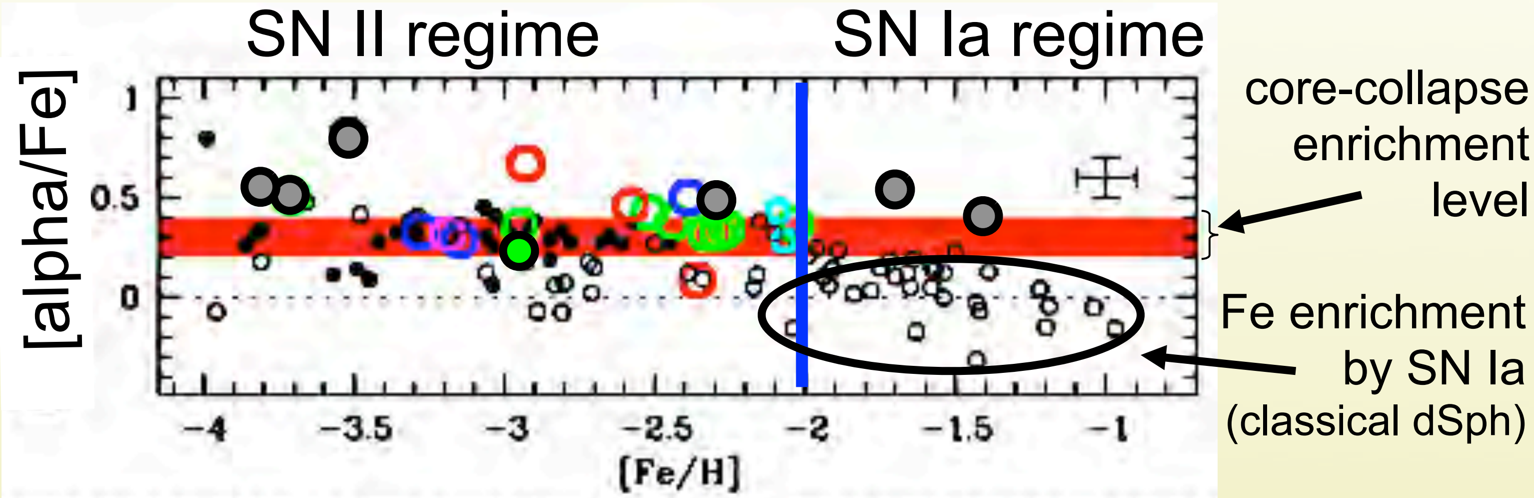
Time

today

Frebel et al. 2012, ApJ

Frebel et al. 2012, ApJ

The abundance test!
Testing for SN Ia enrichment



Frebel + Bromm ApJ 2012

(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)

Prediction:

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

AGB enrichment: can be tested with other elements

First galaxy candidates:

Ursa Major II, **Segue 1** & **Bootes I**, but also Coma Berenices, Leo IV (Hercules not! $L \sim 6 \times 10^4 L_{sun}$)

ANNA FREBEL

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

THOMAS M. BROWN[2], JASON TUMLINSON[2], MARLA GEHA[3], EVAN N. KIRBY[4,5], DON A. VANDENBERG[6], 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]

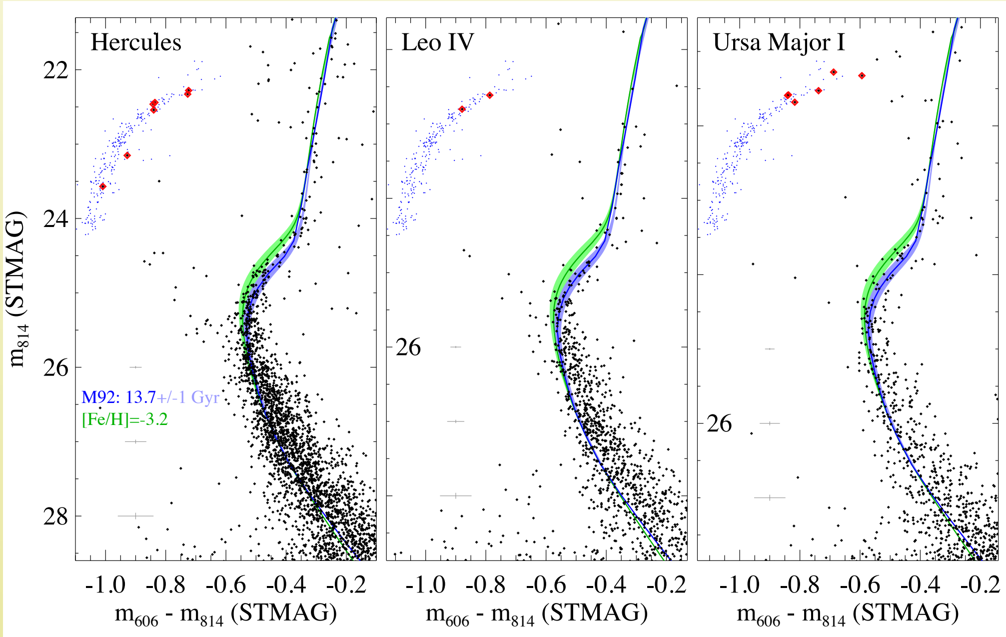
Accepted for publication in The Astrophysical Journal Letters

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.

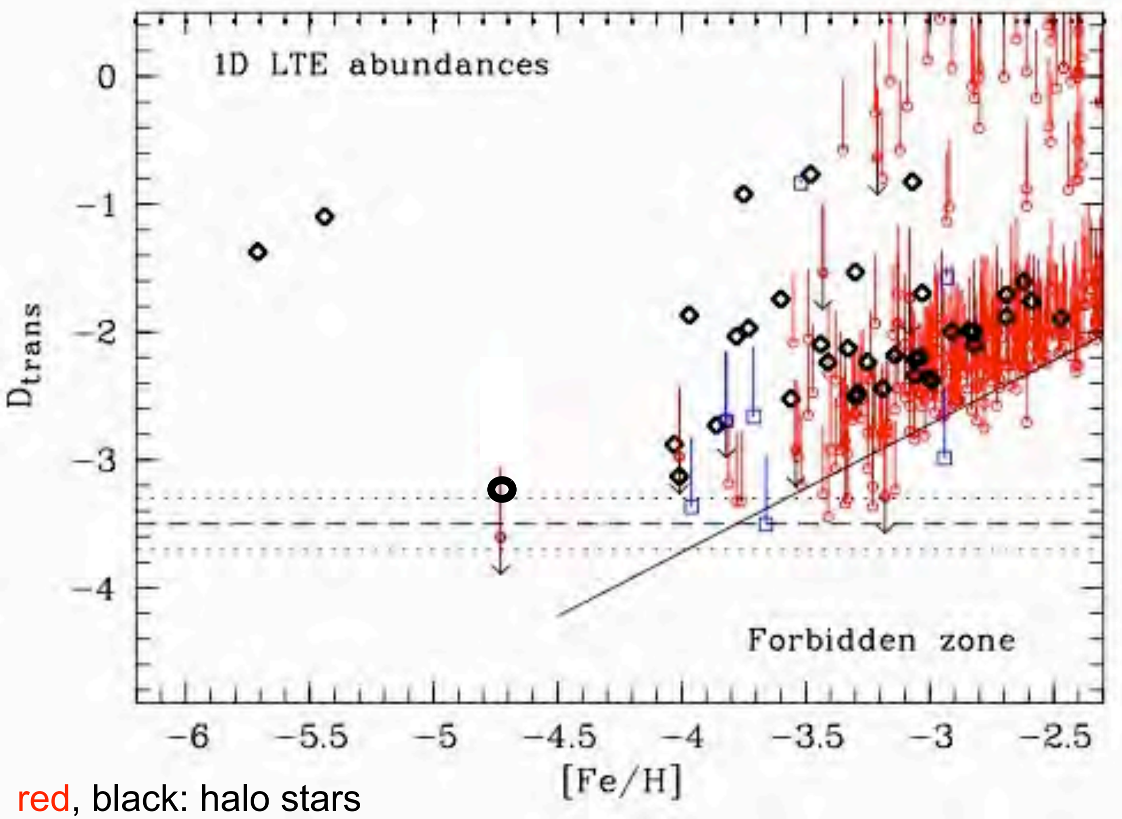
Herc, Leo IV & UMa I

- 13 Gyr old
- no intermed. age popul.
- >1Gyr age difference between them
- star formation truncated by global event such as reionization



FIRST LOW-MASS STAR FORMATION
DUST VS FINE-STRUCTURE COOLING

Frebel, Johnson & Bromm 07, MNRAS



red, black: halo stars
blue: dwarf galaxy stars

All except one of the most metal-poor stars likely formed from C,O fine-structure line cooled gas because they satisfy the D_{trans}>-3.5 criterion

Calculated w/ **updated** oxygen cooling rates:

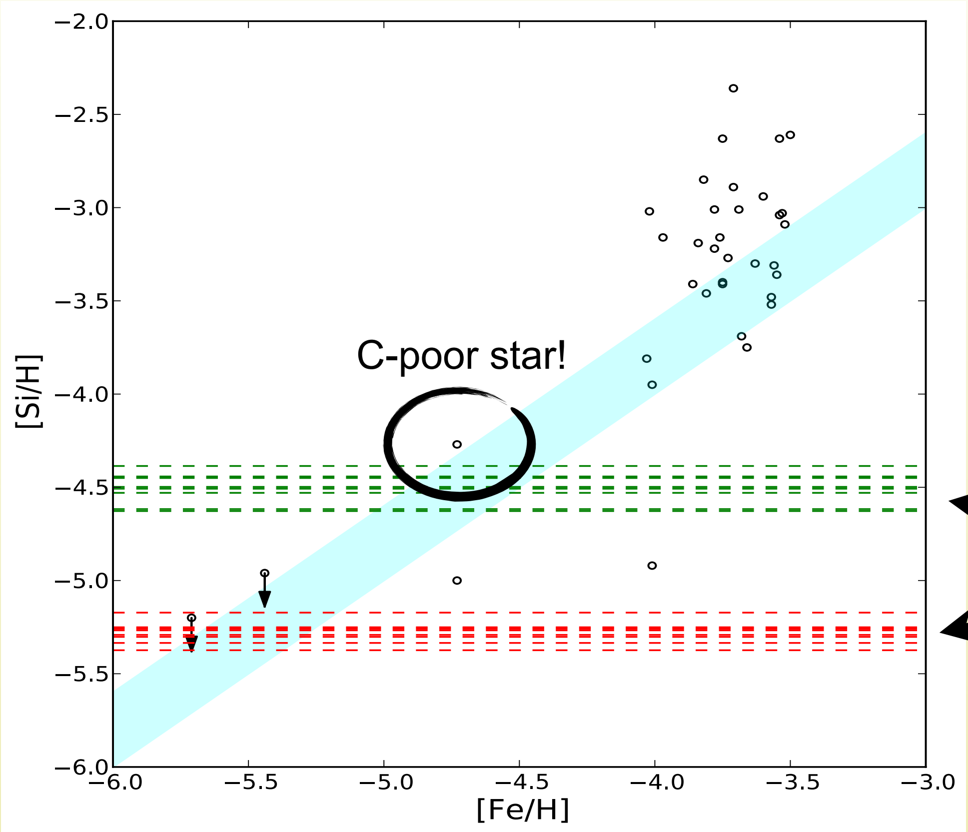
$$D_{trans} = \log_{10}(10^{[C/H]} + 0.9\times10^{[O/H]}) > -3.5$$

(see Frebel & Norris 2013)

But what about dust?

FIRST LOW-MASS STAR FORMATION
DUST VS FINE-STRUCTURE COOLING

Ji, Frebel & Bromm 2013, astroph



different dust models
(MW grain size distribution, grain size distr in SN shockwave)

Only carbon-poor metal-poor star is Si-rich: likely formed from dust-cooled gas

Current data suggests: Bimodal first/early low-mass star formation triggered by **either** dust **or** fine-structure line cooling

Something related to reionization...

More of a plea, really.

Dear theorists,

We need more realistic models for reionization to realistically simulate the effects of EoR on small halos/dwarf galaxies within the hierarchical assembly of galaxies like the Milky way.

Lunnan et al. say that the population of the faintest/smallest halos is affected in number by patchy vs instantaneous reionization models. This is important for our understanding of, like, everything!

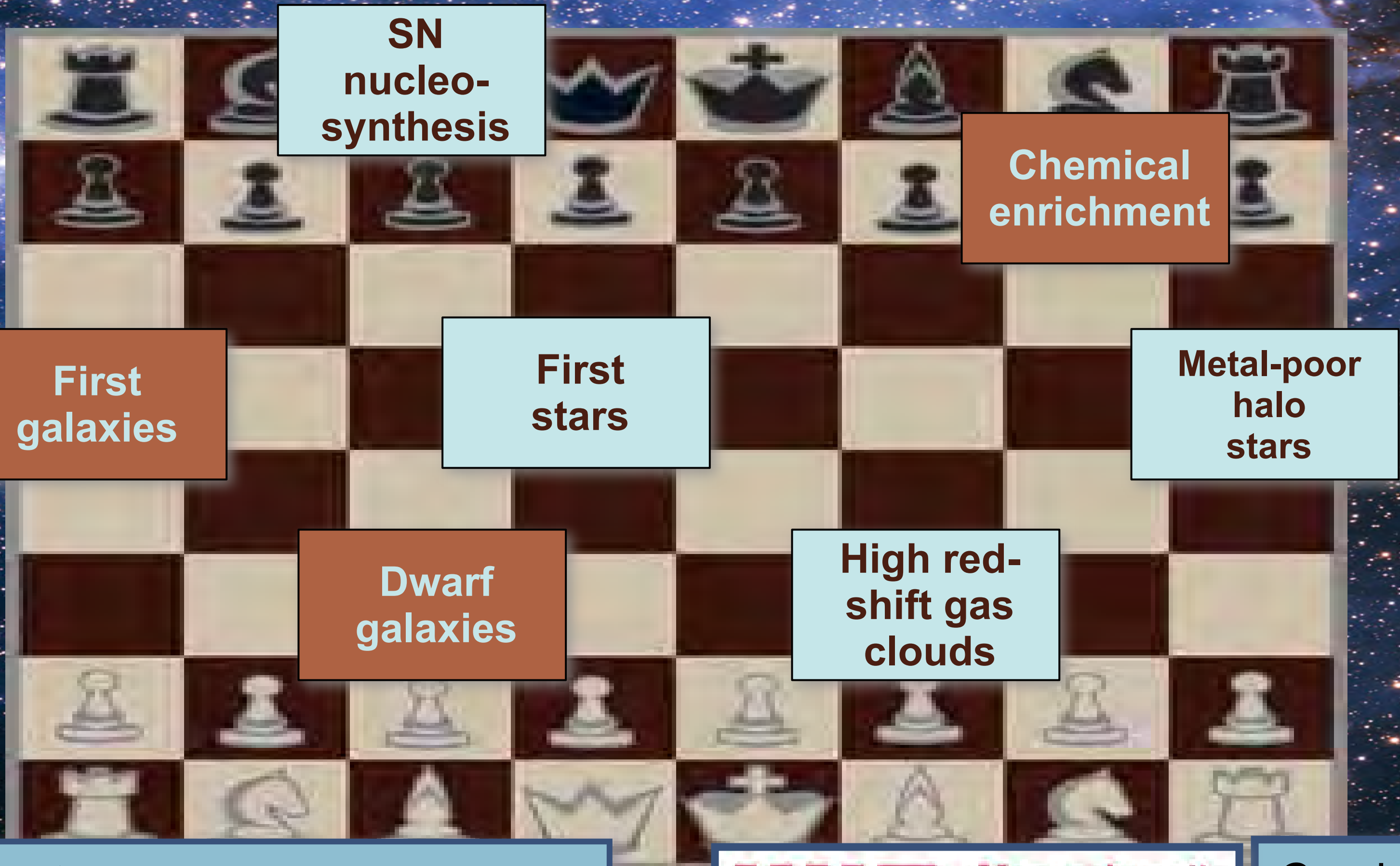
Thanks a bunch for working very hard on this!

The observers.

Summer 2014

The Origin of the Elements

When, where, and how did they form?



Contact:
Anna Frebel & Rob Simcoe, MIT

Massachusetts Institute of Technology

Cambridge, MA, USA

Summary & Conclusions

- About a dozen stars in the ultra-faint dwarf galaxies have been observed with high-resolution spectroscopy **=> detailed chem. abundances available; same signatures as halo stars => potential Galactic building blocks**
- Segue 1 contains three extremely metal-poor stars => **all are carbon-enhanced**; other stars indicate only **massive star enrichment**
- Segue 1 chemical signature **consistent with that of a first galaxy** (=> inhomogeneous metal mixing, single SF event); also ultra-faint dwarfs ~**13 billion years old** (Brown+12)
- First low-mass stars formed from **either dust or C,O fine-structure line cooled gas** (Segue 1: f.s.l. cooled gas likely)
- Survival rate of the the first systems **depends on reionization,** but perhaps Segue 1 is an actual example of survival
-