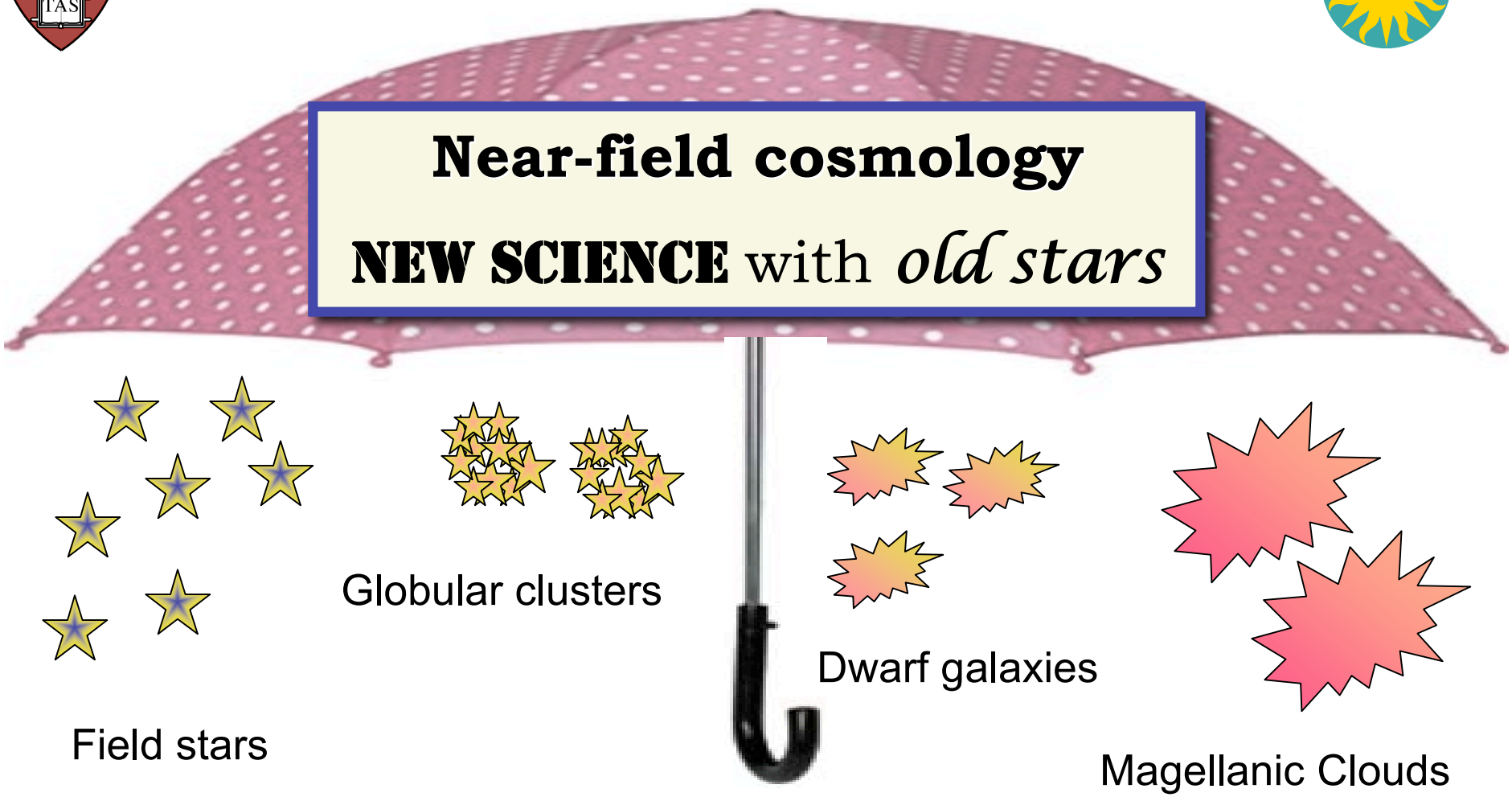
Near-field cosmology

NEW SCIENCE with *old stars*



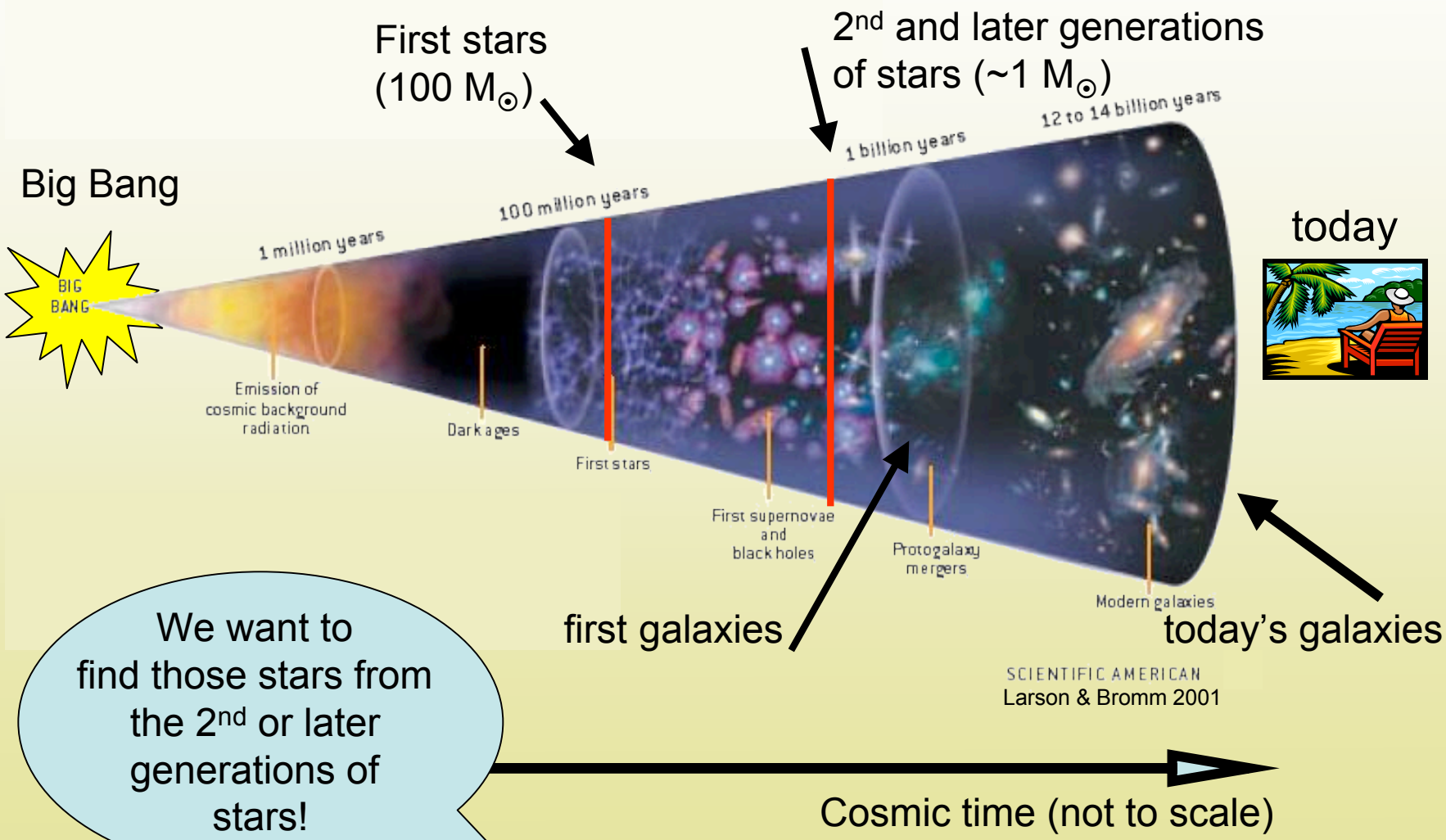
Anna Frebel

Clay Fellow (OIR & ITC)
Harvard-Smithsonian Center for Astrophysics

Outline

- ✓ **Introducing metal-poor stars**
  Why are we interested and what is their role in the early Universe?
- ✓ **Stellar archaeology: Fossils of the earliest times**
  The most iron-poor stars with [Fe/H]<–5.0
- ✓ **Near-field cosmology: Formation of the galactic halo**
  Chemical history of dwarf galaxies & hierarchical galaxy growth
- ✓ **Outlook & Conclusions**

A long, long time ago...

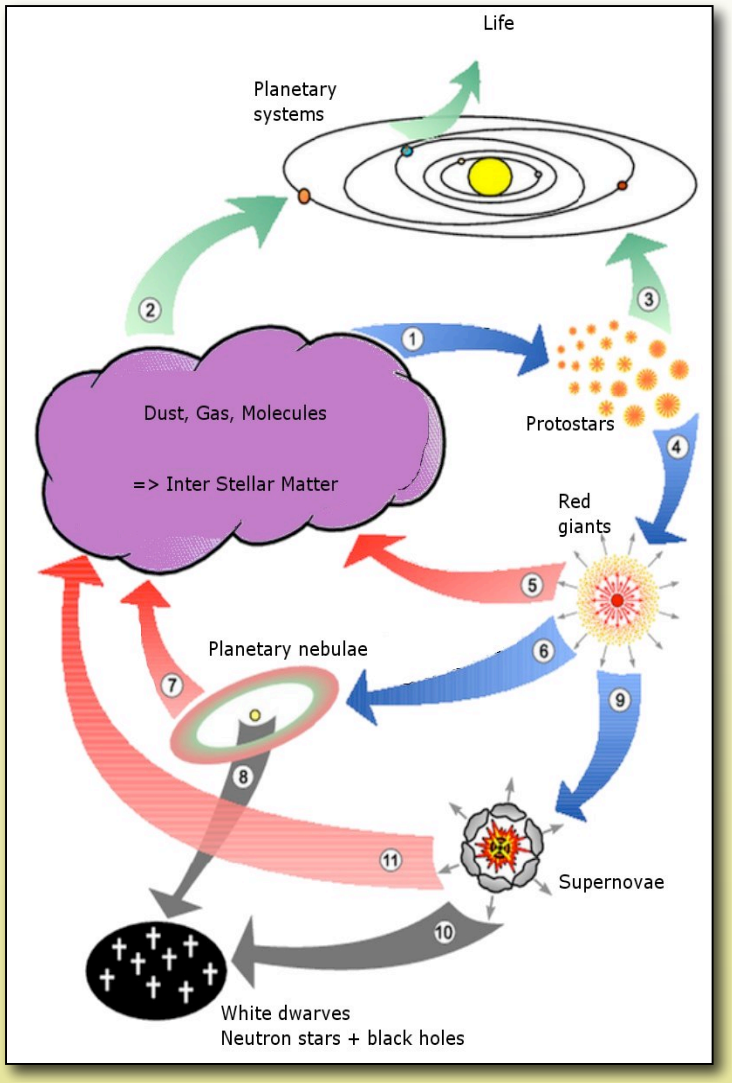


We want to find those stars from the 2nd or later generations of stars!

Finding the needle in the Haystack

Old stars from the early Universe are extremely rare!

Chemical Evolution



All the atoms (except H, He & Li) were created in stars!

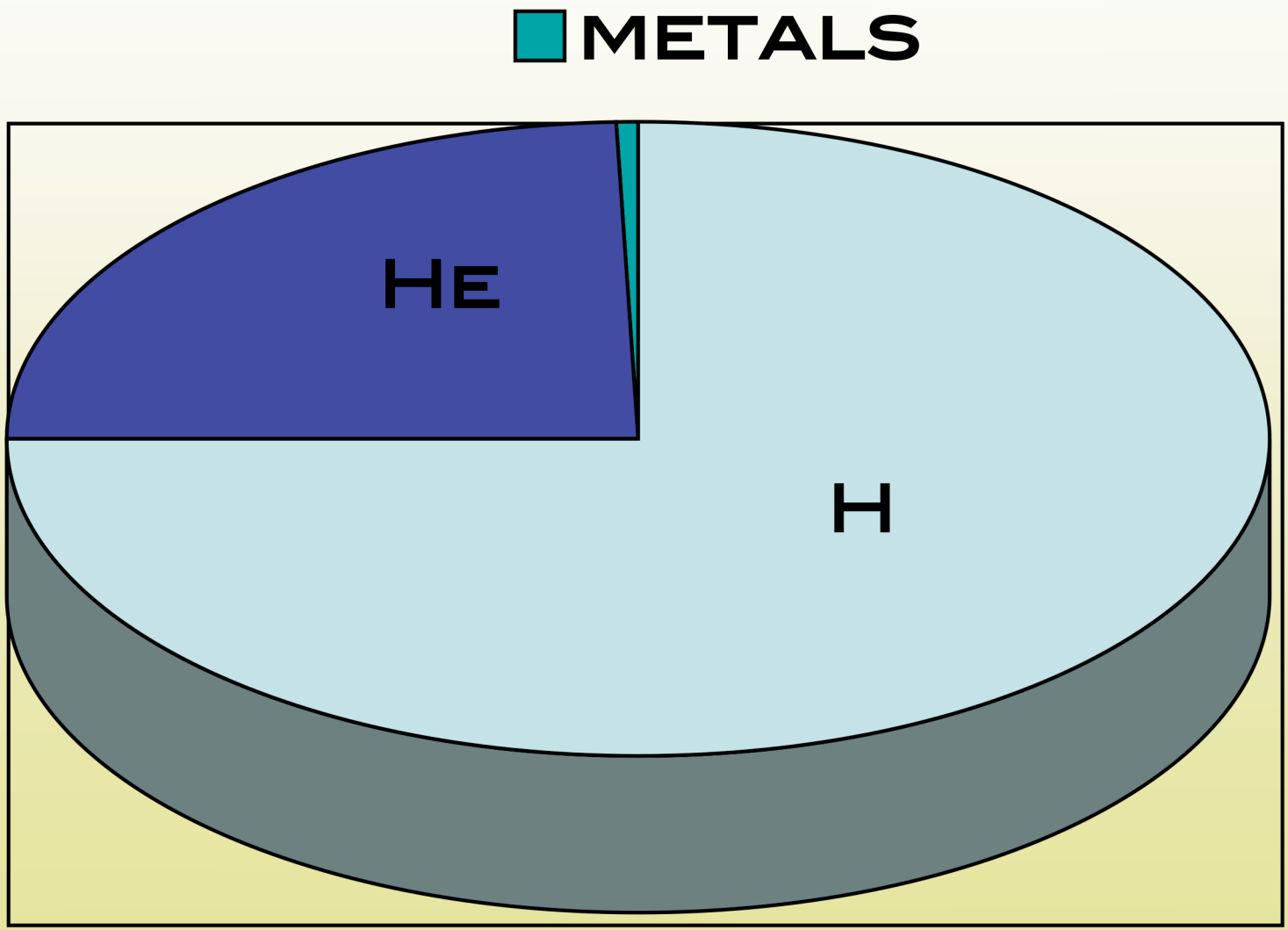
Pop III: zero-metallicity stars
Pop II: old halo stars
Pop I: young disk stars

We are made of stardust!

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

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

About a star...



Astronomer's Periodic Table

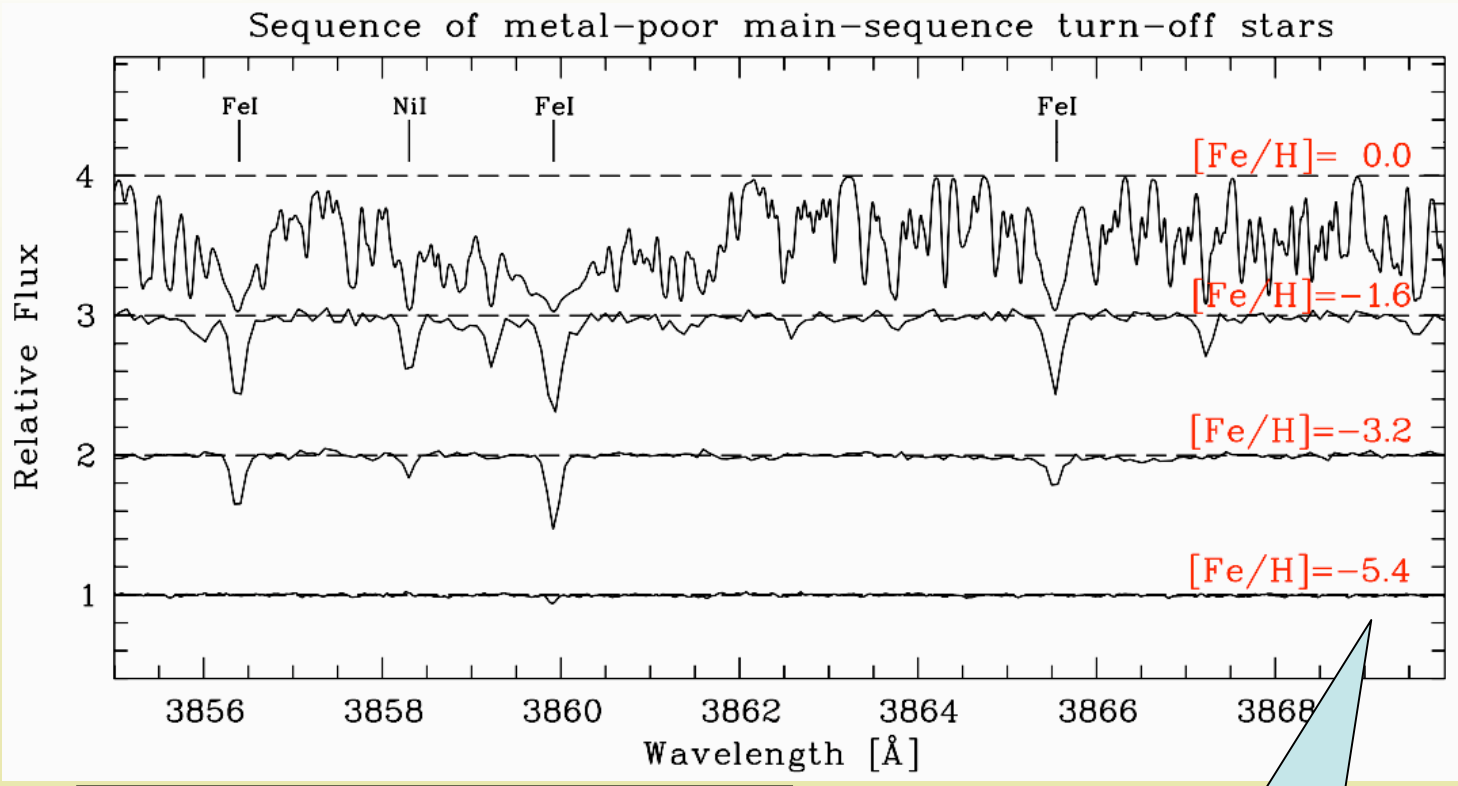
hydrogen 1 **H** 1.0079	helium 2 **He** 4.0026

Metals Z

[Fe often used to trace metallicity Z]

Taking a spectroscopic look

"Look-back time"



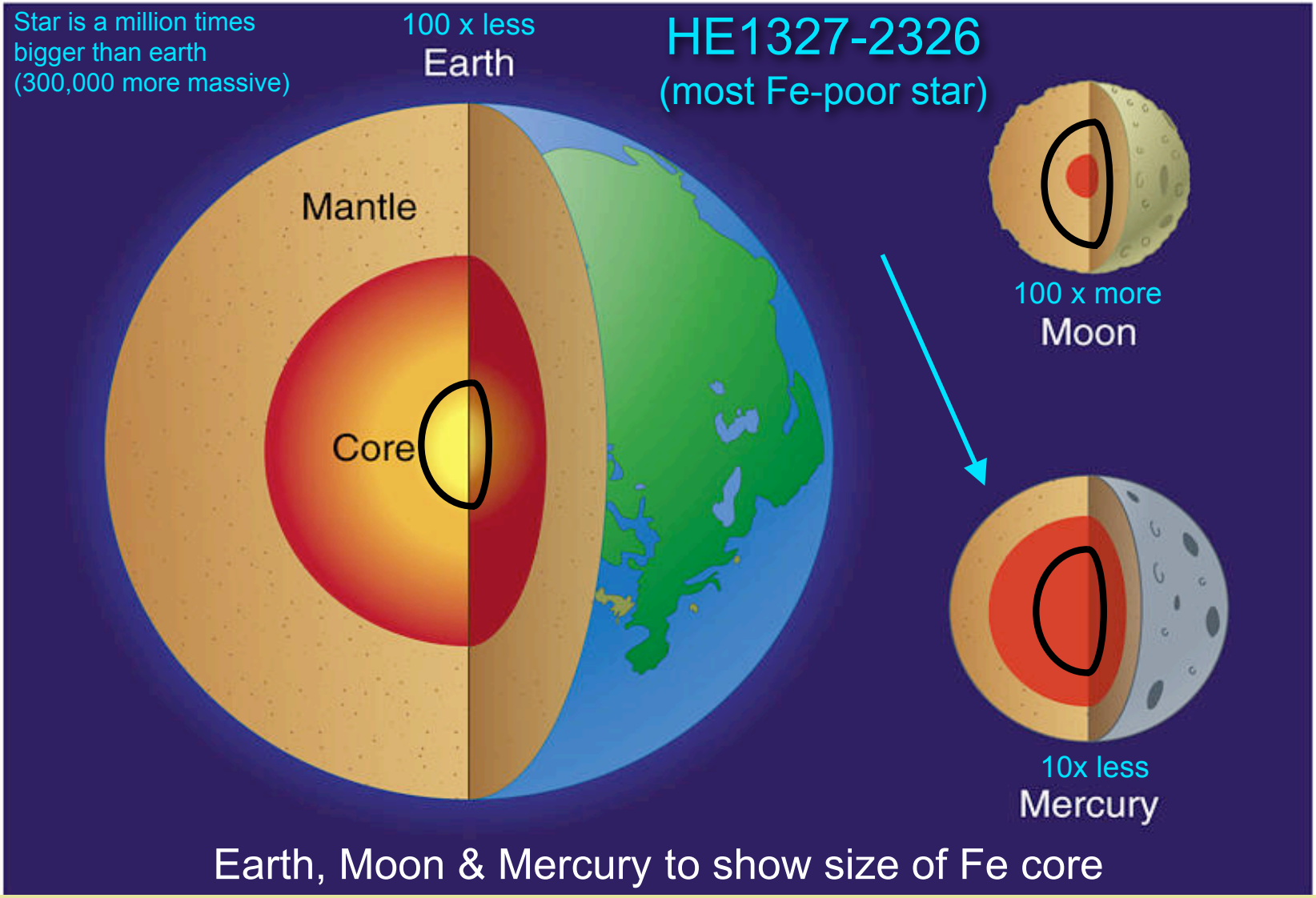
Galactic chemical evolution

Abundances are derived from integrated absorption line strengths

$$[Fe/H] = \log(N_{Fe}/N_H)_* - \log(N_{Fe}/N_H)_\odot$$

equals 1/250,000th of the solar Fe abundance

How much iron is in there?

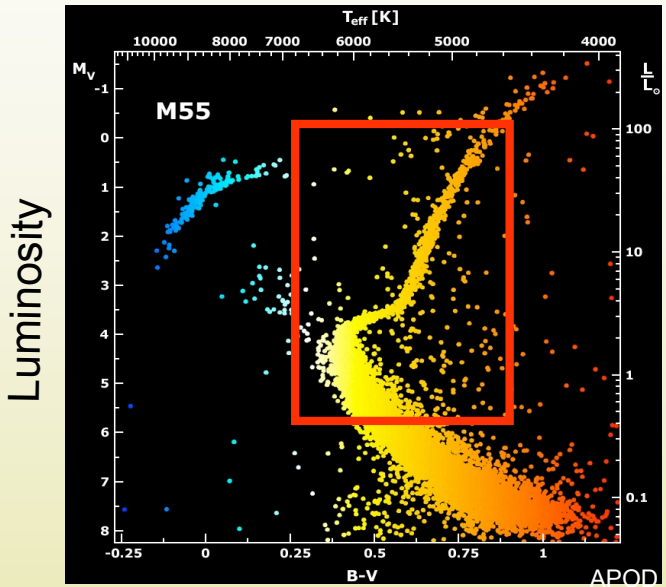


Copyright © 2005 Pearson Prentice Hall, Inc.

What can we learn from old halo stars?

Low-mass stars (M < 1 $M_\odot$)
⇒ lifetimes > 10 billion years
⇒ unevolved stars are still around!

Hertzsprung-Russell-diagram



Luminosity

Temperature

Using "fossil" metal-poor stars to reconstruct...

- ✓ Origin and evolution of chemical elements
- ✓ Relevant nucleosynthesis processes and sites
- ✓ Chemical and dynamical history of the Galaxy
- ✓ Lower limit to the age of the Universe

... and to provide constraints

- ✓ Nature of the first stars & initial mass function
- ✓ Nucleosynthesis & chemical yields of first/early SNe
- ✓ Early star & early galaxy formation processes
- ✓ Hierarchical merging of galaxies (observed abundances are 'end product' that have to be reproduced by any comprehensive galaxy formation model)
- ✓ Formation of the galactic halo by detailed understanding of its stellar content

Galactic metal-poor stars are a great tool for near-field cosmology because they are the local equivalent to the high-redshift Universe!

CLASSIFICATION SCHEME

Range	Term	Acronym	#
[Fe/H] ≥ +0.5	Super metal-rich	SMR	some
[Fe/H] = 0.0	Solar	—	a lot!
[Fe/H] ≤ –1.0	Metal-poor	MP	very many
[Fe/H] ≤ –2.0	Very metal-poor	VMP	many
[Fe/H] ≤ –3.0	Extremely metal-poor	EMP	~100
[Fe/H] ≤ –4.0	Ultra metal-poor	UMP	1
[Fe/H] ≤ –5.0	Hyper metal-poor	HMP	2
[Fe/H] ≤ –6.0	Mega metal-poor	MMP	--

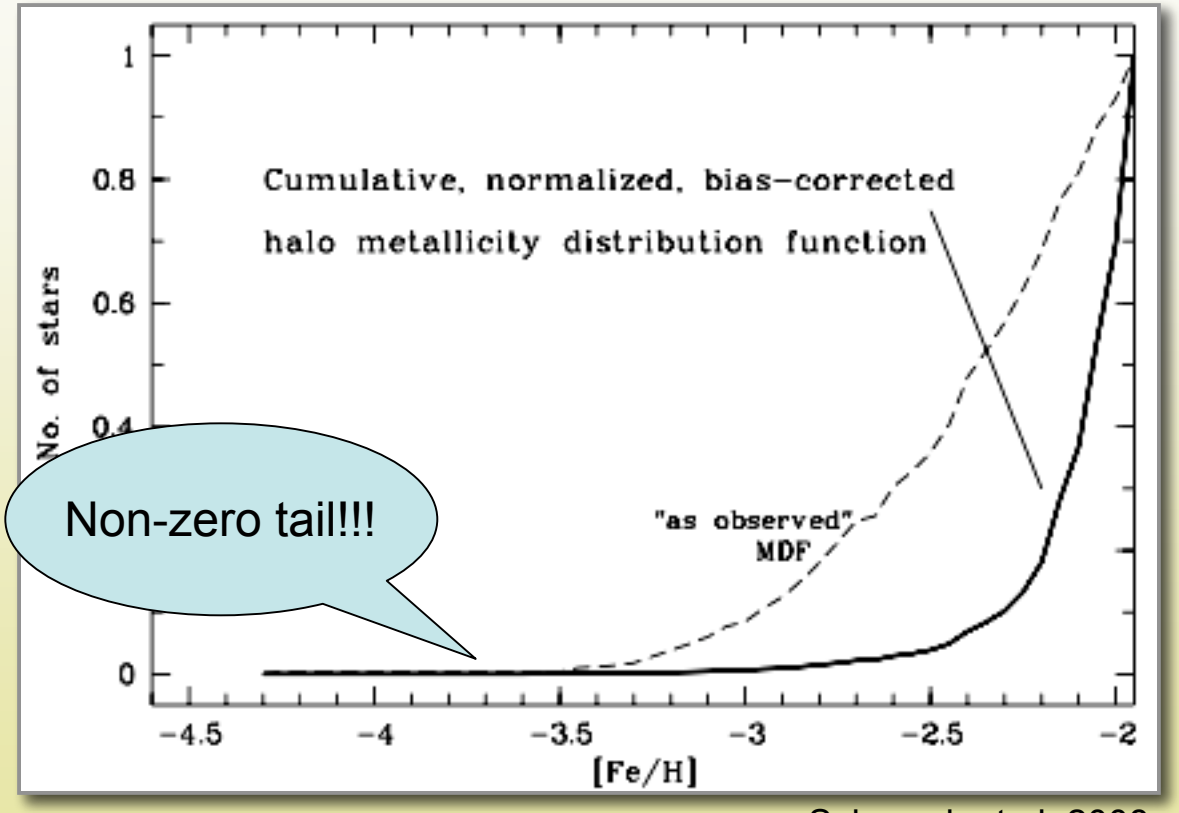
Extreme Pop II stars!

as suggested by Beers & Christlieb 2005

Halo Metallicity distribution function (MDF)

Previous 'as observed', raw MDF is **not** a realistic presentation!

(but shows that we have been doing a good job in finding these stars..)



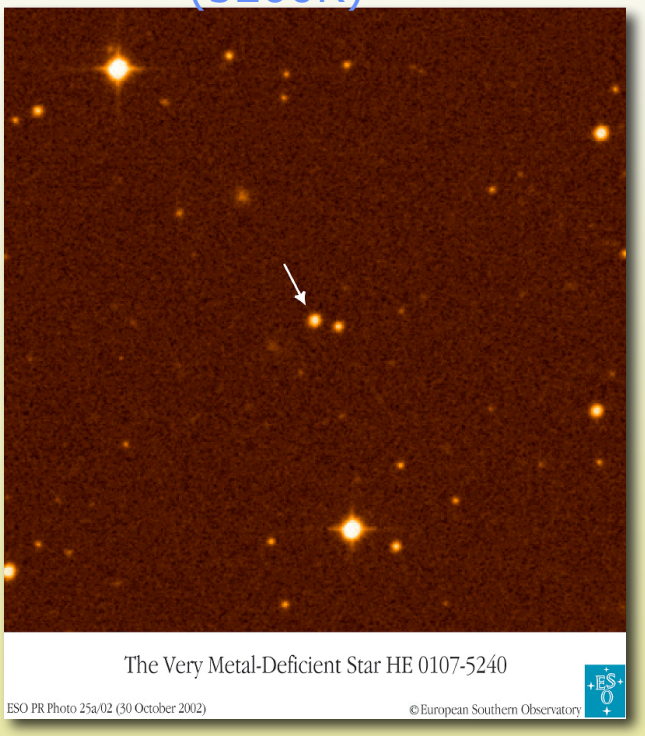
Schoerck et al. 2008

The most metal-poor stars are extremely rare but extremely important!

The most iron-deficient stars known

HE 0107–5240

Red giant
(5200K)



$[Fe/H]_{NLTE} = -5.2$

Christlieb et al. (2002), Nature 419, 904
Christlieb et al. (2004), ApJ 603, 708
Bessell et al. (2004), ApJ 612, L61

Masses: 0.6 - 0.8 $M_\odot$

HE 1327–2326

Subgiant
(6180K)

$[Fe/H]_{NLTE} = -5.4$

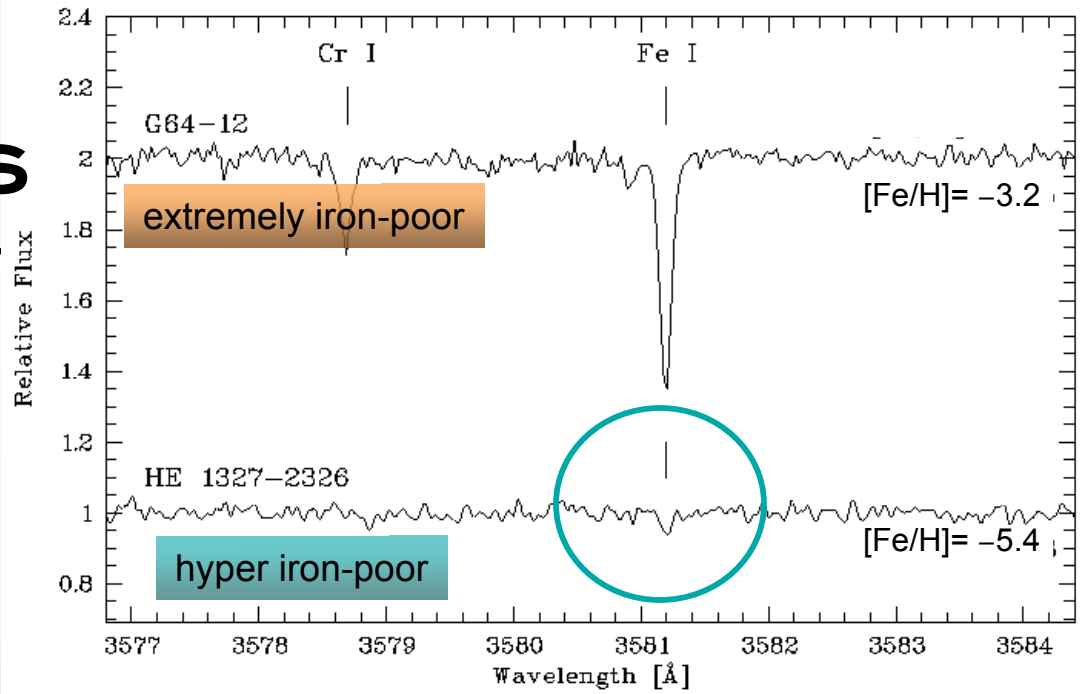
Frebel et al. 2005, Nature 434, 871
Frebel et al. 2006, ApJ 638, L17
Aoki, Frebel et al. 2006, ApJ 639, 897
Frebel et al. 2008, ApJ 684, 588

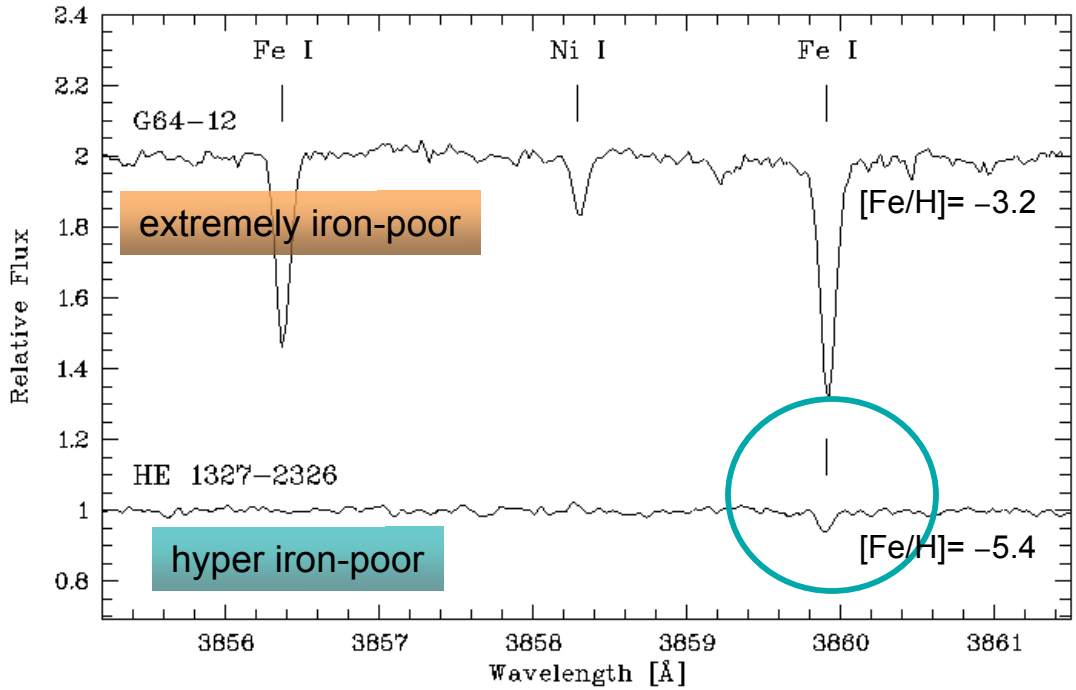
Tiny little Iron Wiggles

High-resolution (R~60,000) Subaru/HDS spectrum (7h exposure time; taken by W. Aoki)

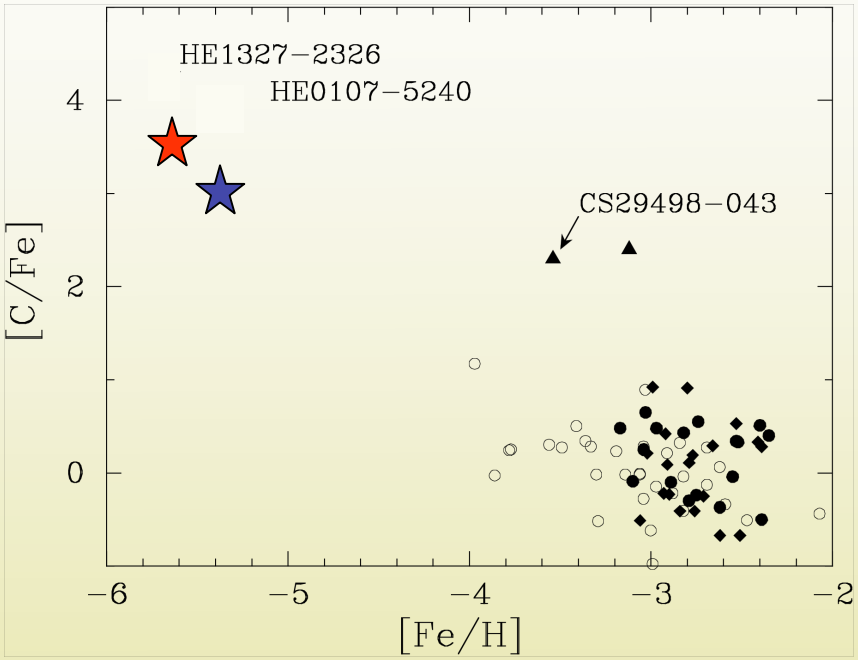
Extremely weak iron absorption lines detected
⇒ "Hyper iron-poor" star

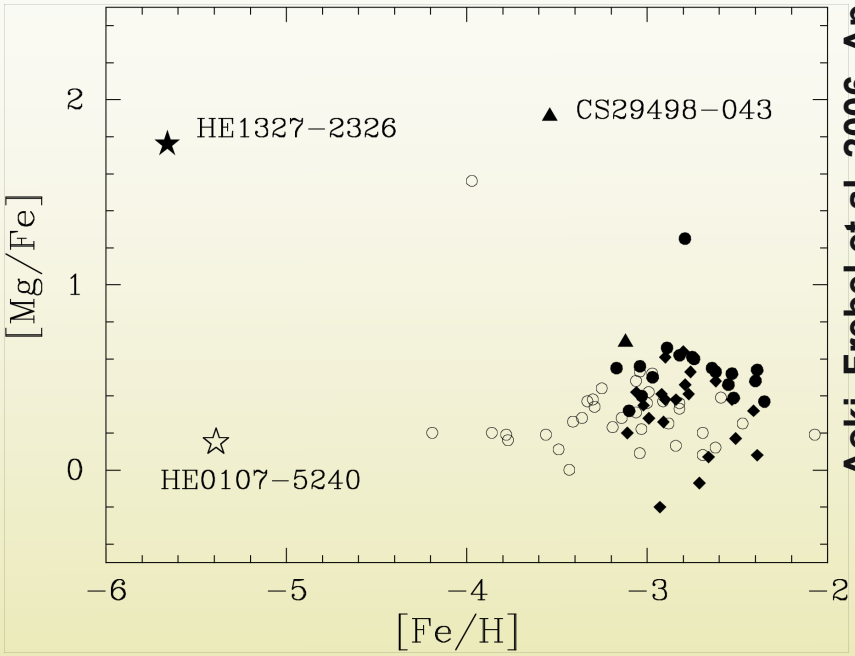
Record holder for the **lowest Fe abundance** observed in a star:
=> [Fe/H] = -5.4





What is so special about the most Fe-poor stars?





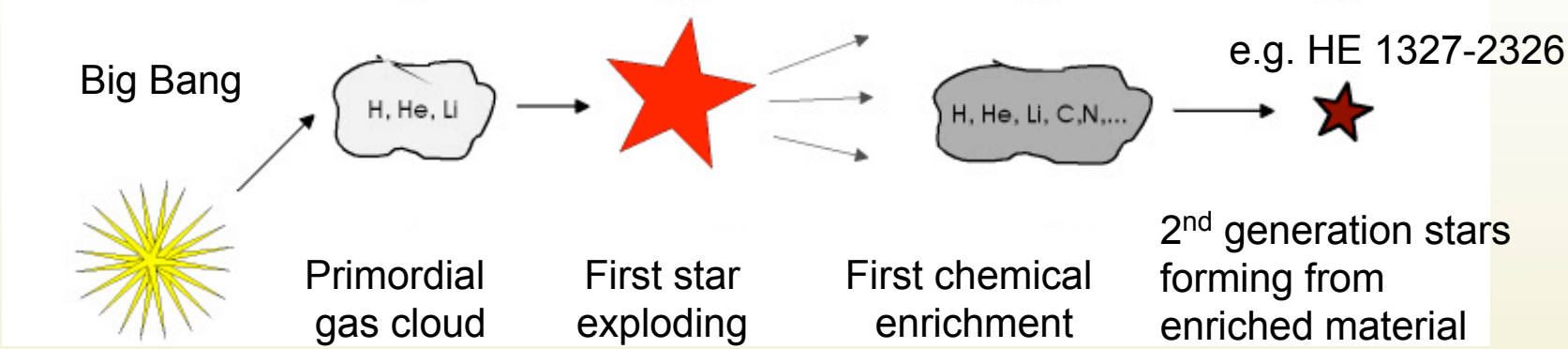
Aoki, Frebel et al. 2006, ApJ

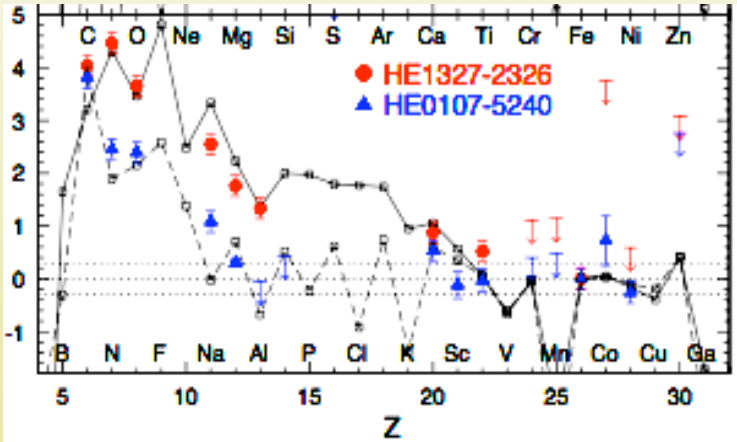
hyper Fe-poor	ultra Fe-poor	extremely Fe-poor	very Fe-poor

hyper Fe-poor	ultra Fe-poor	extremely Fe-poor	very Fe-poor

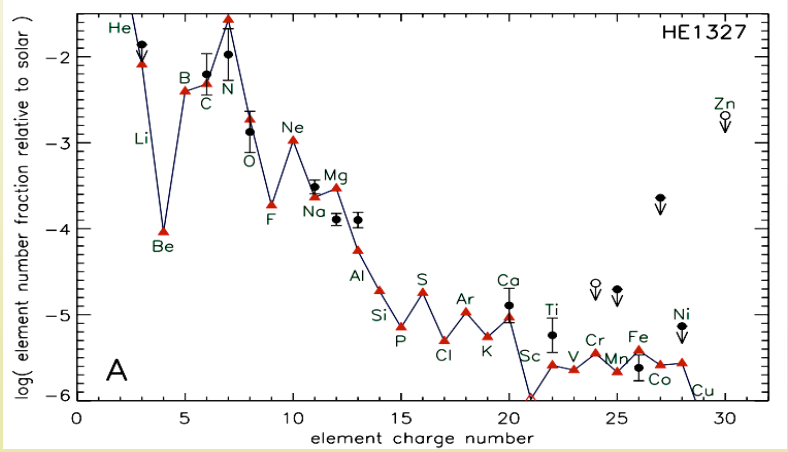
The very different chemical signature of the hyper iron-poor stars is crucial for understanding the formation of the elements!

How and when did these early stars form?





Tominaga et al. 2007



Heger & Woosley 2008

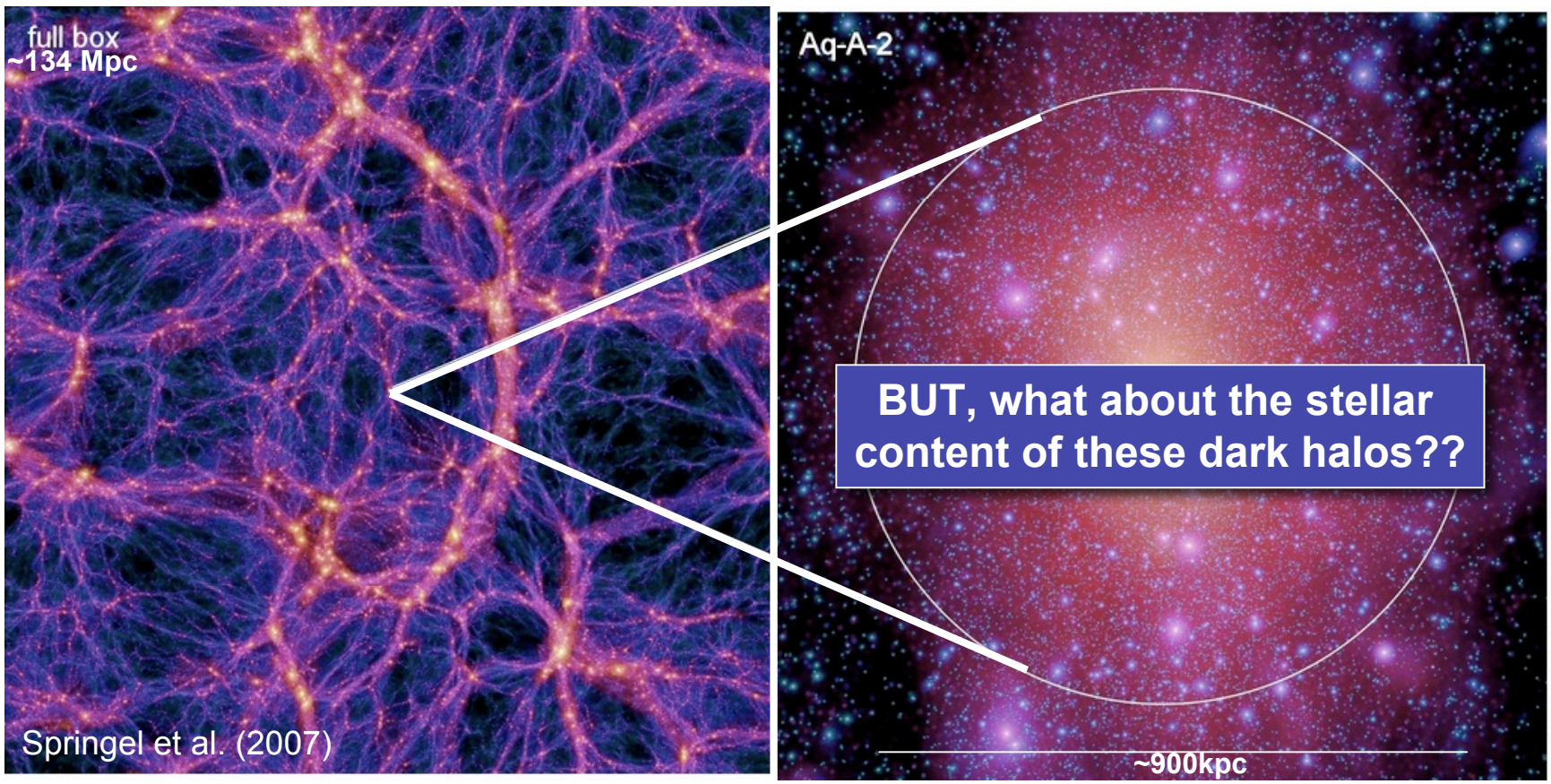
Why important?

Metal-poor stars provide the only available diagnosis for zero-metallicity Pop III nucleosynthesis/early SNe and early chemical enrichment

The ΛCDM universe

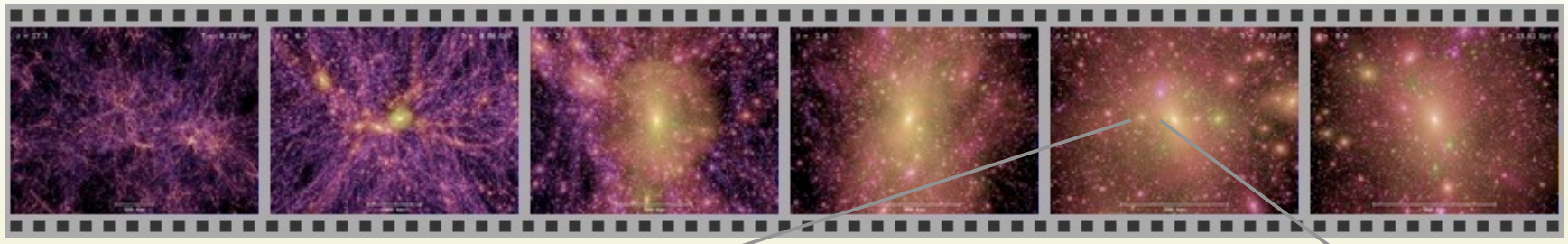
CDM simulations of galaxy assembly show that **very few larger halos** plus **many smaller halos** merged to form the Galactic halo ("hierarchical growth").

Many small halos survive this process and are predicted to be around today.



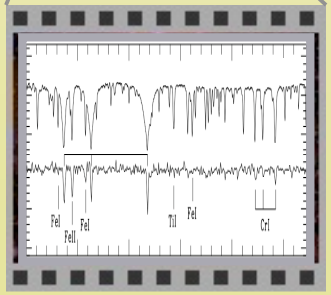
What does stellar archaeology have to do with galaxy formation?

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



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

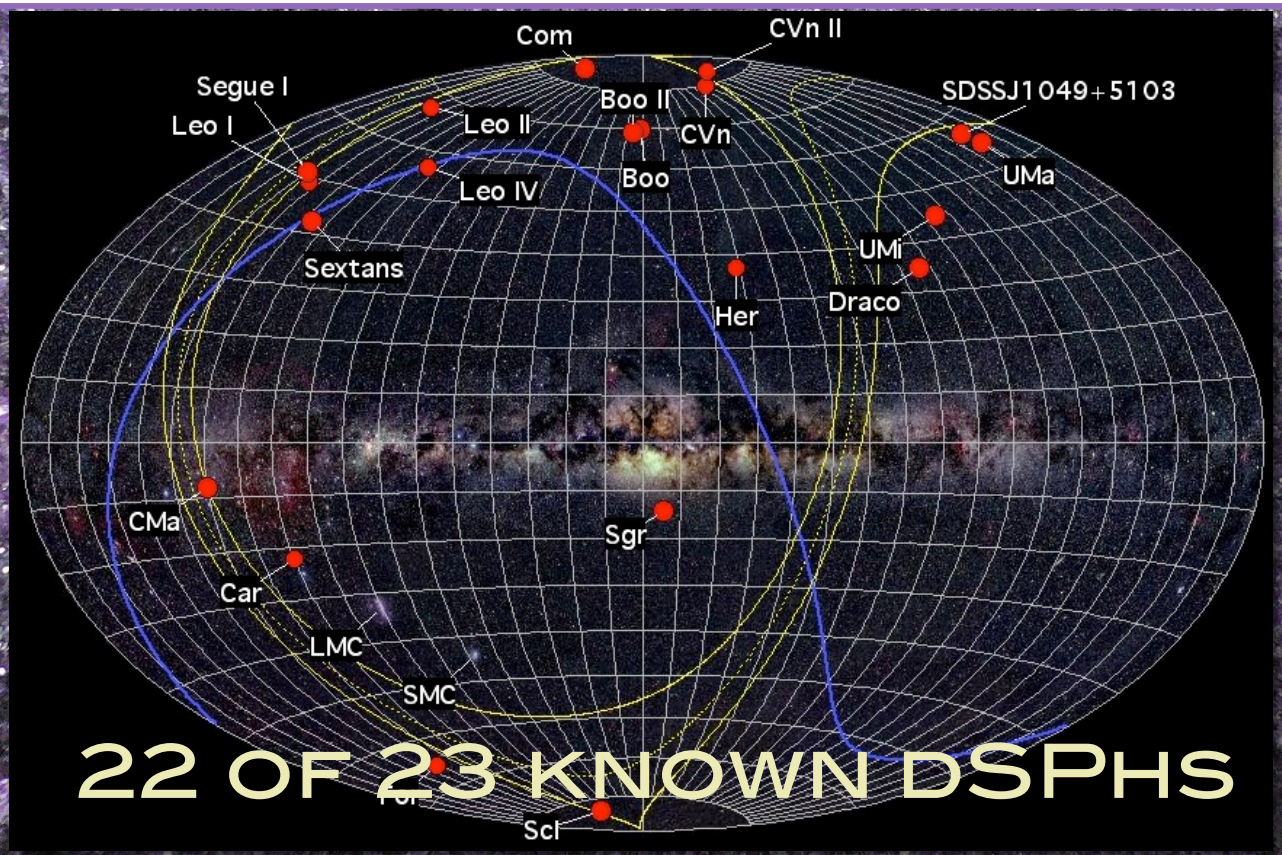
Spectroscopic observations of stellar populations and streams (=luminous matter)



The Milky Way's satellites

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

dSph = gas poor dwarf gal. dIrr = gas rich dwarf gal.



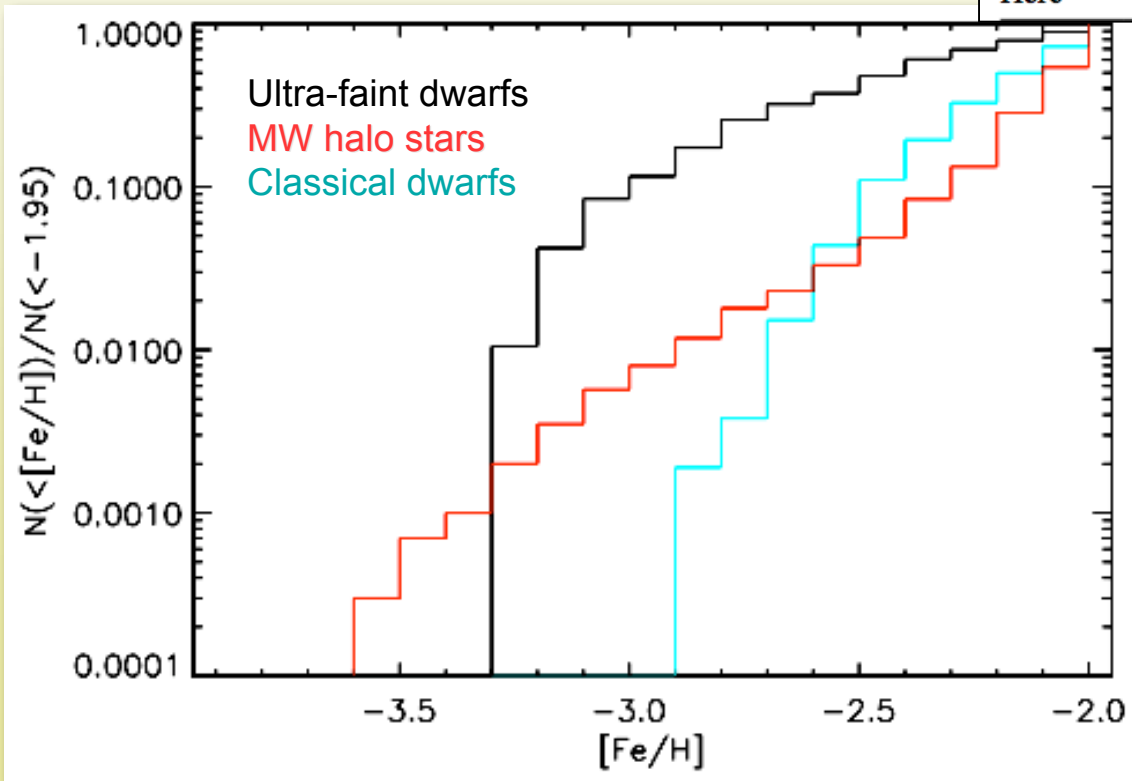
22 of 23 known dSphs

Metallicity distribution function of dSph galaxies

More metal-poor stars in the ultra-faints than in halo!?!

Ultrafaint dSph Metallicities

dSph	N^a	$\log (L/L_\odot)^b$	⟨[Fe/H]⟩	$\sigma_{[Fe/H]}$
UMa II	12	3.6 ± 0.2	−2.44 ± 0.06	0.57
Leo T	19	5.1 ± 0.3	−2.02 ± 0.05	0.54
UMa I	28	4.1 ± 0.1	−2.29 ± 0.04	0.54
Leo IV	12	3.9 ± 0.2	−2.58 ± 0.08	0.75
Com	24	3.6 ± 0.2	−2.53 ± 0.05	0.45
CVn II	16	3.9 ± 0.2	−2.19 ± 0.05	0.58
CVn I	165	5.4 ± 0.1	−2.08 ± 0.02	0.46
Herc	22	4.6 ± 0.1	−2.58 ± 0.04	0.51



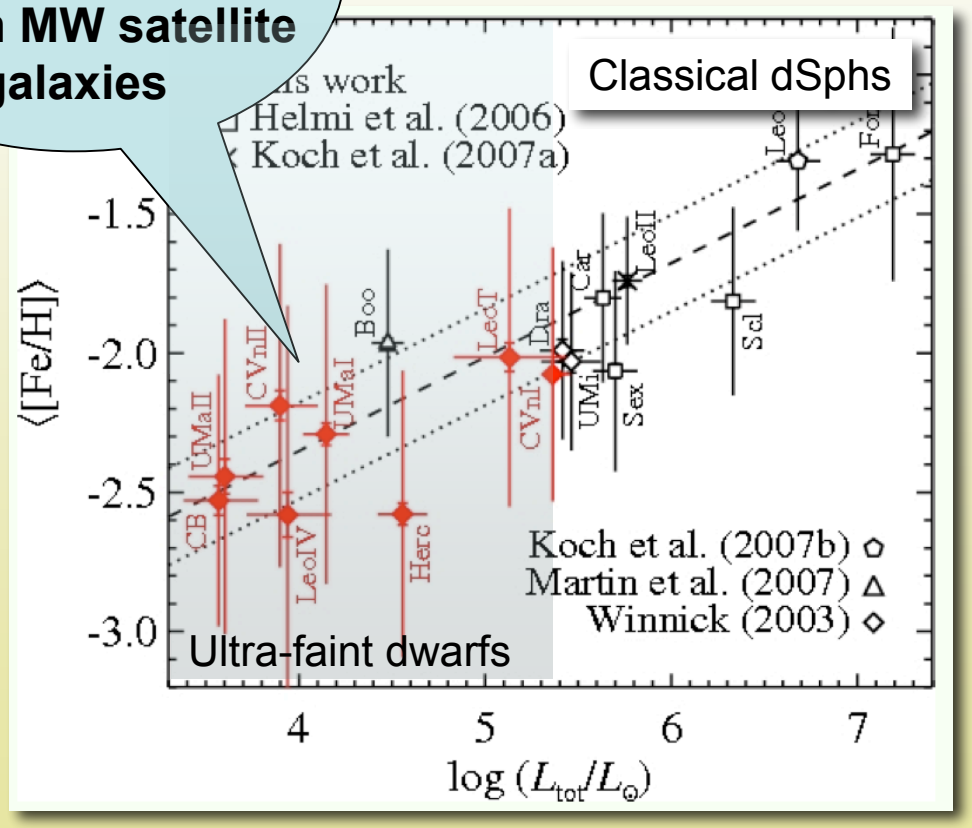
Kirby et al. (2008)
(targets selected from Simon & Geha 2007)

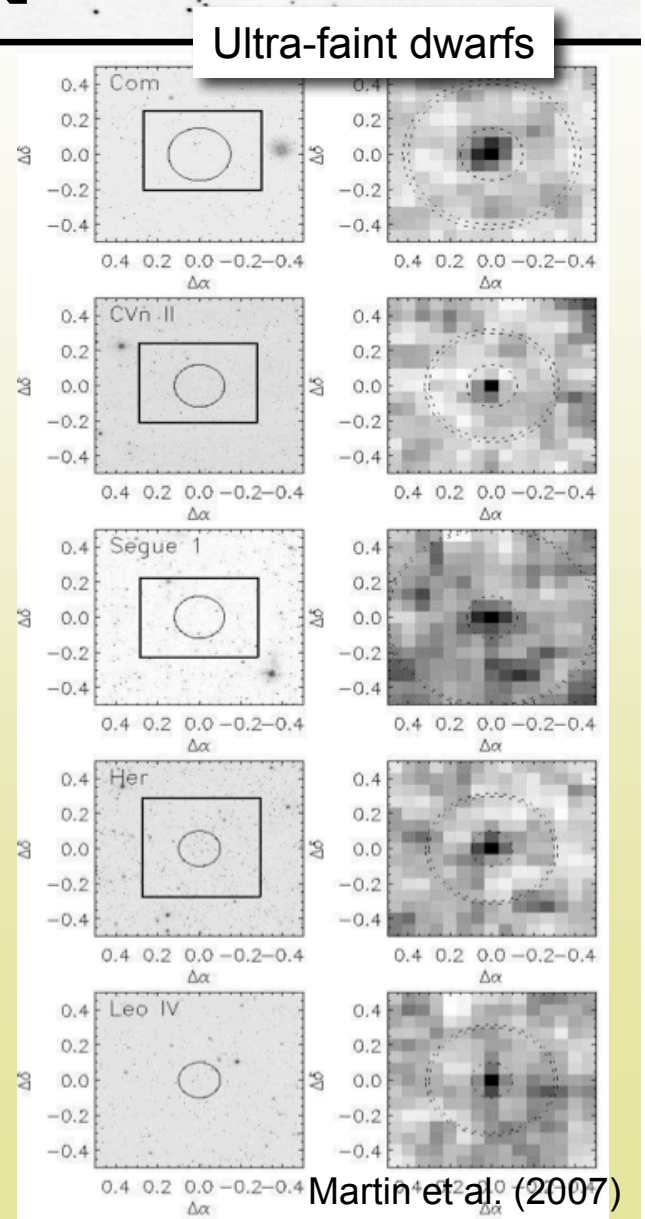
"classical" dSph have no extremely metal-poor stars?!? (Helmi et al. 2006)

=> yes, they do!

METALLICITY-LUMINOSITY RELATION

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





Martin et al. (2007)

What can we learn from the existing dwarf galaxies?

Stellar archaeology: examine the chemical history in search for their **oldest population** to learn about

- early chemical evolution *in small systems*
- chemical signatures that *relate dwarf galaxies to MW*

If surviving dwarfs are *analogs* of early MW building blocks then we should find chemical evidence of it!

Stellar metallicities & abundances of metal-poor stars in dwarf galaxies **should agree** with those found in the MW halo

And previous studies failed to find extremely metal-poor stars in the classical dwarfs; higher metallicity stars show different abundances...

High-res. observations of stars in dwarf galaxies

- **Ultra-faint dwarf galaxies**

✓ Keck/HIRES, Feb 2008, R=34k *(Frebel et al. '10, ApJ)*
✓ Six brightest (16.8<V<18.2) stars in **Ursa Major II & Coma Berenices**
✓ **Two stars have *[Fe/H] < –3.0*** **(t_{exp} = up to 5.3h per star)**

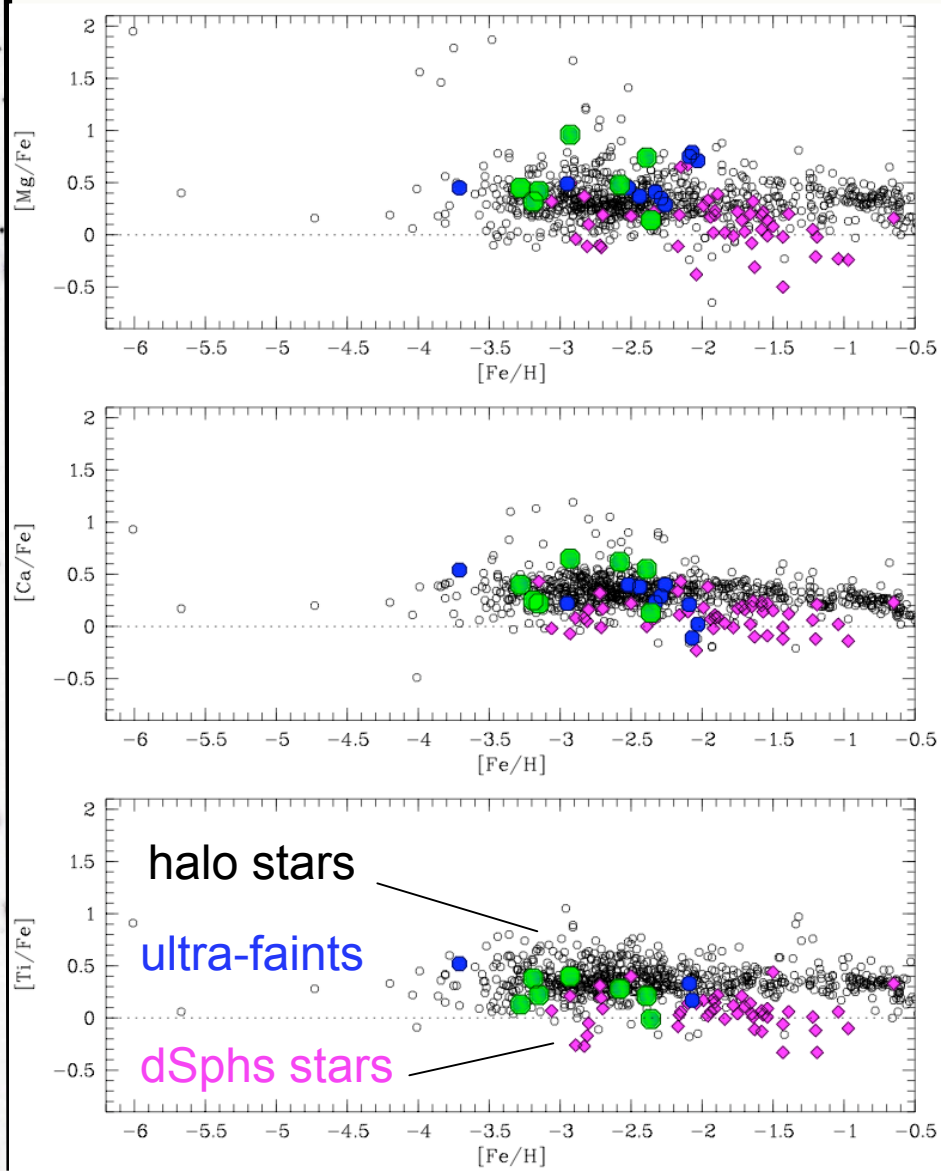
✓ Magellan/MIKE, Mar 2009, R=19k *(Simon, Frebel et al '10,ApJLsubm)*
✓ *The brightest* star (V=19.2 !!) in **Leo IV (at 154 kpc in the outer halo)**
✓ ***[Fe/H] = –3.1*** **(t_{exp} = 9h)**

High-res. observations of fainter stars is very challenging...

- **Classical dwarf spheroidal galaxies**

✓ Magellan/MIKE, Jul 2009, R=36k *(Frebel, Kirby & Simon 2010,Nature)*
✓ Star (V=18.2) in **Sculptor** (selected from Kirby et al. 09)
✓ ***[Fe/H] = –3.8*** **(t_{exp} = 7.5h)**

Mg, Ca, Ti (α-elements)



No discrepancy of ultra-faint dwarf galaxy stars with those of MW halo (at low metallicities)!

- Stars in ultra-faint dwarfs studied by AF and colleagues (Ursa MajorII, Coma Berenices, LeoIV) (Frebel+2010, Simon+2010)
- Stars in ultra-faint dwarfs studied by others (Hercules, Bootes) (Koch+2008, Norris+2009)
- Stars in classical dSphs (Sculptor, Carinae, Draco, Sextans, Ursa Minor, Fornax, Leo) (Shetrone+2001,2003, Venn+2004, Sadakane+04, Aoki+2009)
- Halo stars (e.g. Cayrel+2004, Barklem+2005, Aoki+2005, Lai+2008 plus many others!) **See Frebel (2010) review for a complete list of abundances and references**.

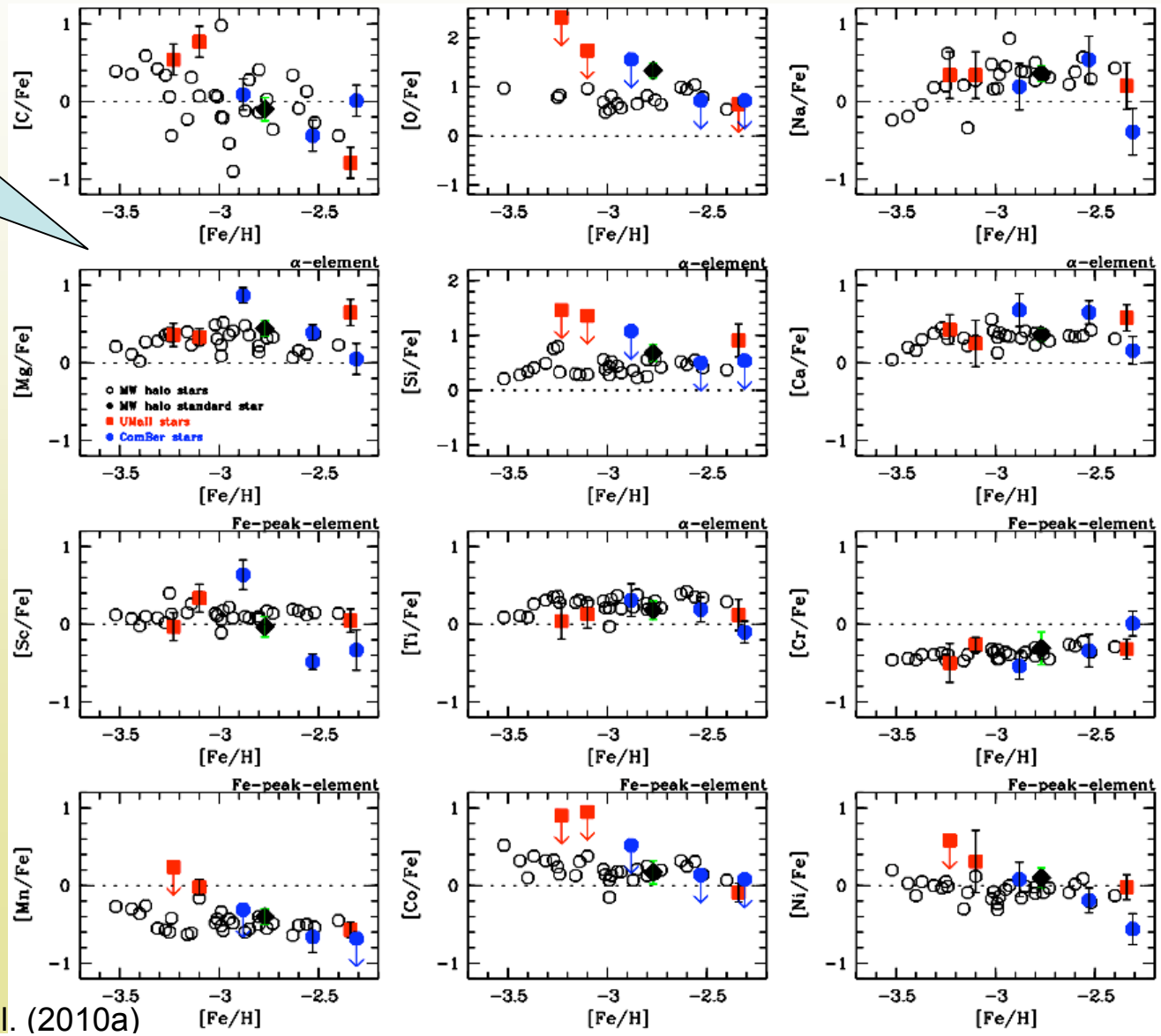
ULTRA-FAINT DWARF GALAXY ABUNDANCES

Excellent agreement with the MW chemical evolution

Cay
(black open circles)

Spread in some elements (C, n-capture elements)

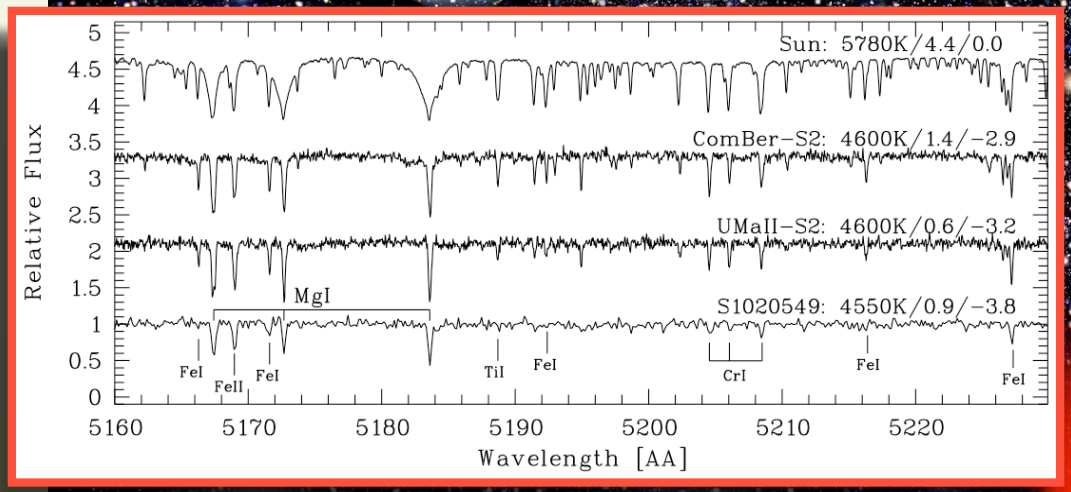
red squares:
Ursa Major II
blue dots:
Coma Berenices
black diamond:
MW halo giant



Frebel et al. (2010a)

An Extremely metal-poor red giant star in Sculptor

Previous studies claimed that the classical dwarfs do not host any stars with [Fe/H] <-3.0... (Helmi et al. 2006)!



"Linking dwarf galaxies to halo building blocks with the most metal-poor star in Sculptor"

Frebel, Kirby+Simon 2010b, Nature

New [Fe/H] = -3.8 star in the classical dSph Sculptor

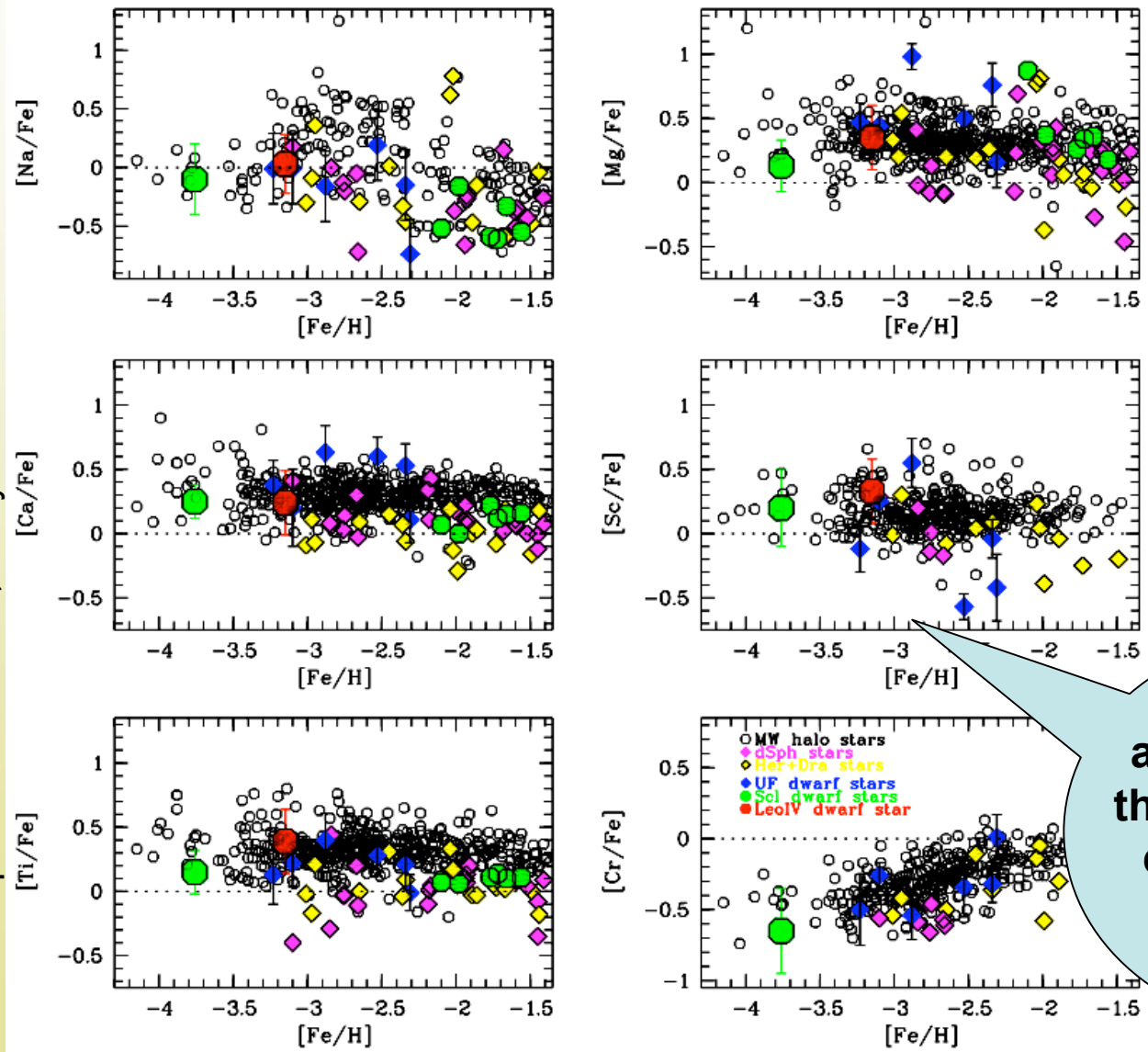
(selected from Kirby et al. 2009)

EMP stars in Sculptor and LeoIV

Anna Frebel

Metal-poor stars

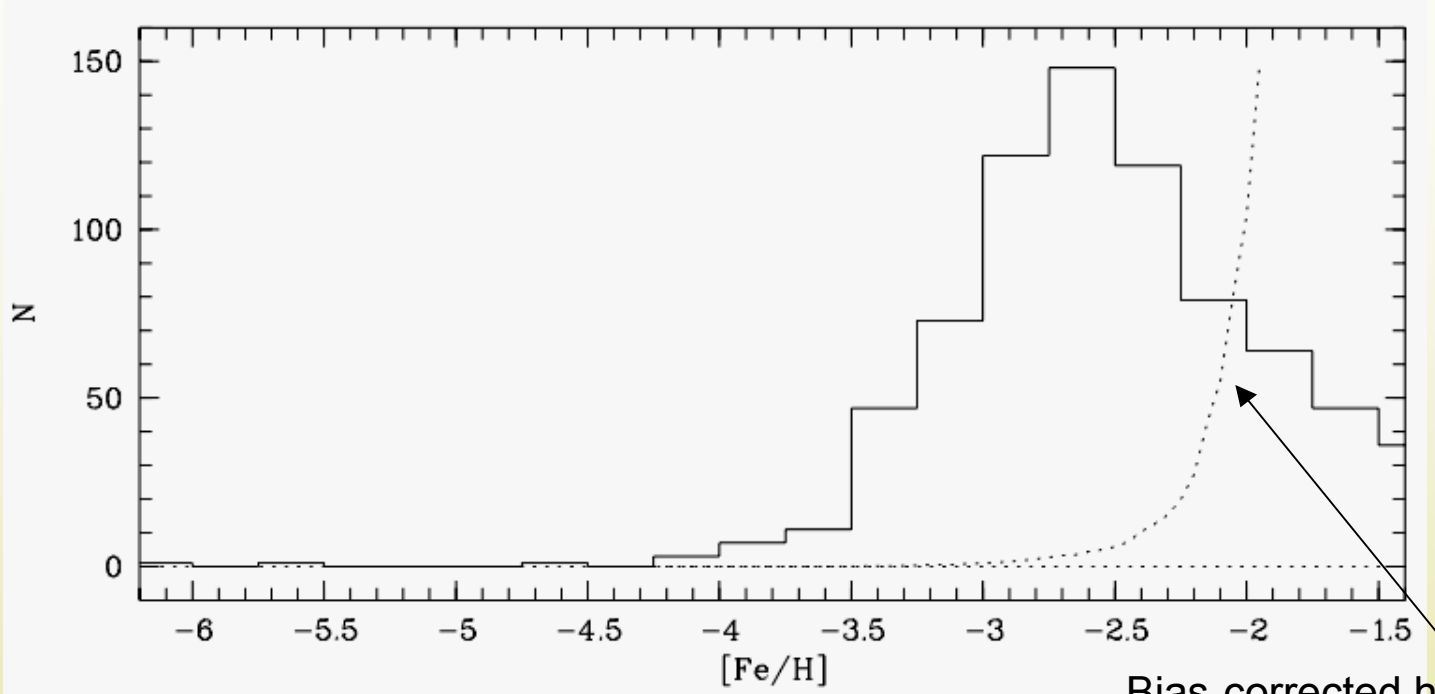
adapted from Frebel, Kirby & Simon (2010b) Nature



- **Scl targets** (Frebel+10b)
- **LeoIV target** (Simon+10)
- UMaII/ComBer (Frebel+10a)
- Her + Draco (Koch+09, Cohen+09)
- classical dSph (compiled by Venn+04)
- MW halo stars

Excellent agreement with the MW chemical evolution; also for Scl and LeoIV!!

Metallicity distribution of literature stars w/ high-resolution abundances



Bias-corrected halo MDF by Schoerck et al. 2009

"Advertisement":

A compilation of abundances of ~800 metal-poor stars with [Fe/H]~<-2.0 can be found at www.cfa.harvard.edu/~afrebel/abundances/abund.html

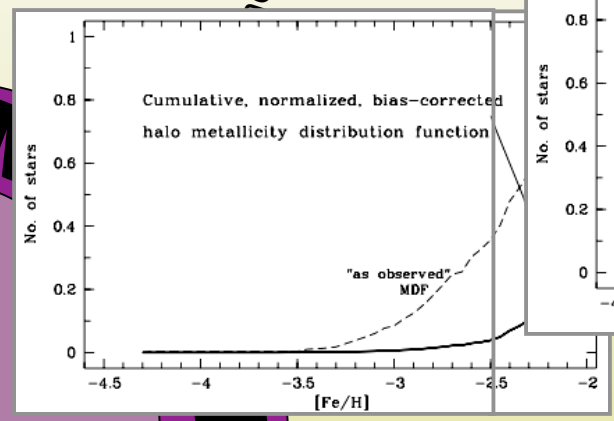
(*published in Frebel 2010, AN, review paper on metal-poor stars*)

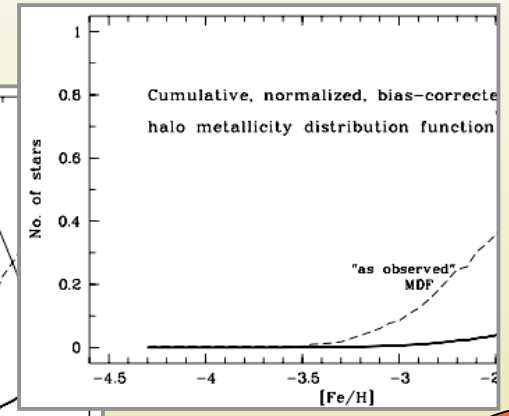
ASSEMBLY OF THE METAL-POOR TAIL OF THE HALO

ANNA FREBEL

METAL-POOR STARS

More massive, Magellanic Cloud-sized objects contribute **mass**
[Fe/H]~-1





Inner Halo
$[Fe/H]_{average}$ ~ -1.2

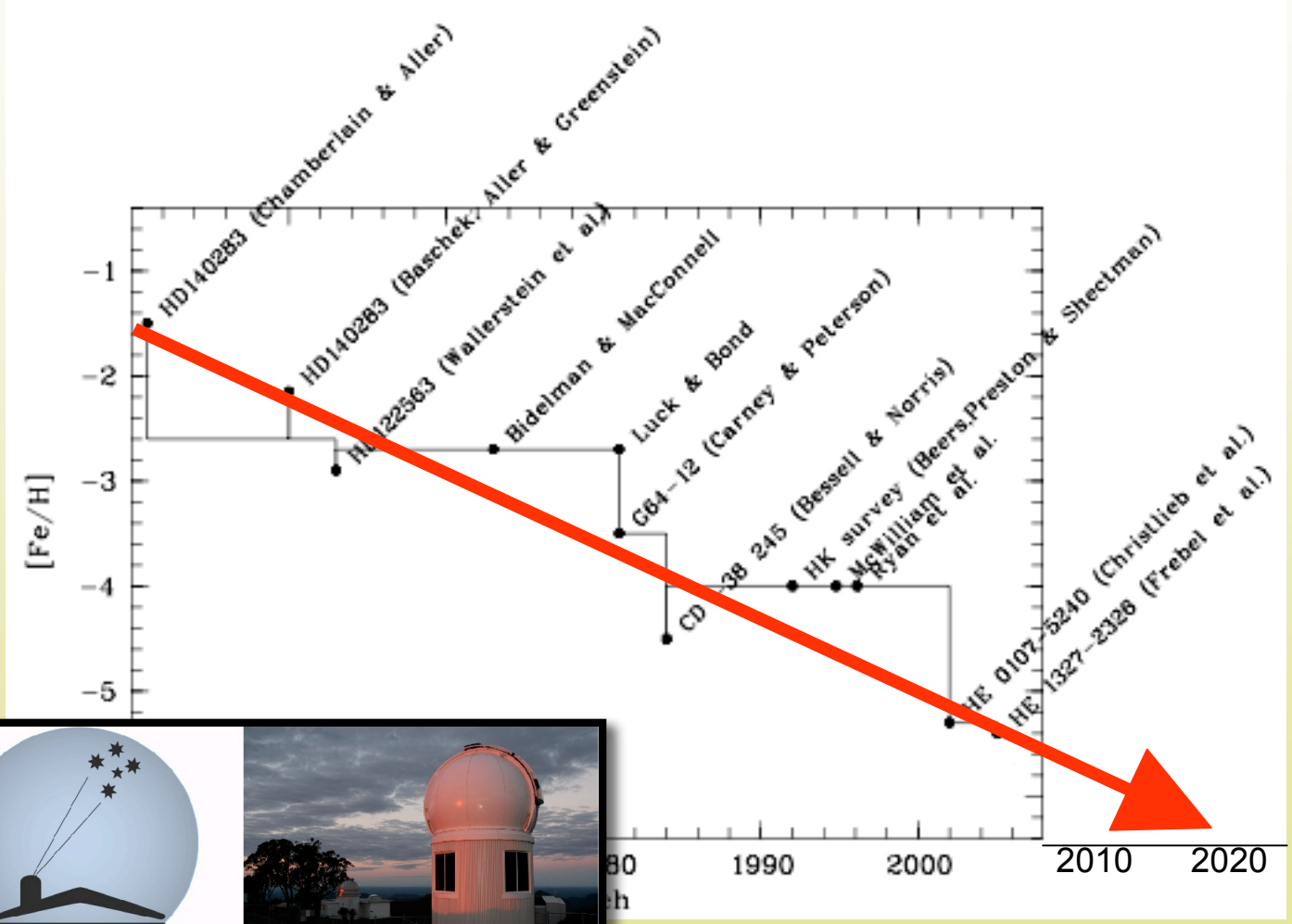
Additional metal-poor stars

Ultra-faint dwarfs
$L \sim 10^4 L_\odot$
$[Fe/H]_{min}$~–3.5 (Norris+: med-res data)

"classical" dSphs
$L \sim 10^6 L_\odot$
$[Fe/H]_{min}$ = –3.8 (NEW!)

Maybe all of the most metal-poor "halo" stars have been deposited by dwarf galaxies!?!

What I expect from the extremely large telescopes



The Lowest observable metallicity in the Galaxy

- Assuming a top-heavy IMF (~100 $M_\odot$);

crit. metallicity for low-mass SF: $[C/H]_{min} = -3.5$ (Bromm & Loeb 03)

- Max. [C/Fe] in any metal-poor star: $[C/Fe]_{max} = 3.8$ (HE1327-2326; Frebel+ 08)

$\Rightarrow$ $[Fe/H]_{min} = [Fe/C]_{min} - [C/H]_{min} = -7.3$

- Max. [Mg/Fe] in any metal-poor star: $[C/Mg]_{min} = 2.5$ (HE0107-5240; Collet+ 06)

$\Rightarrow$ $[Mg/H]_{min} = -6.0$

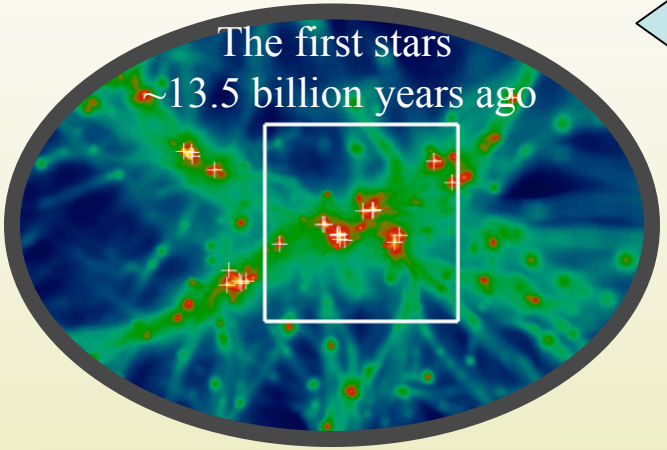
And it is technically feasible to measure Fe and Mg abundances this low!

This is an important prediction for what may be discovered with the next generation of optical 20-40m telescopes!

(Frebel, Johnson & Bromm 2009)

Take home "star stuff"

The first heavy elements seed stars and galaxies



The chemical fingerprint of the early Universe is found in the oldest stars

Chemical evolution proceeds; big stars explode soon, small stars live long