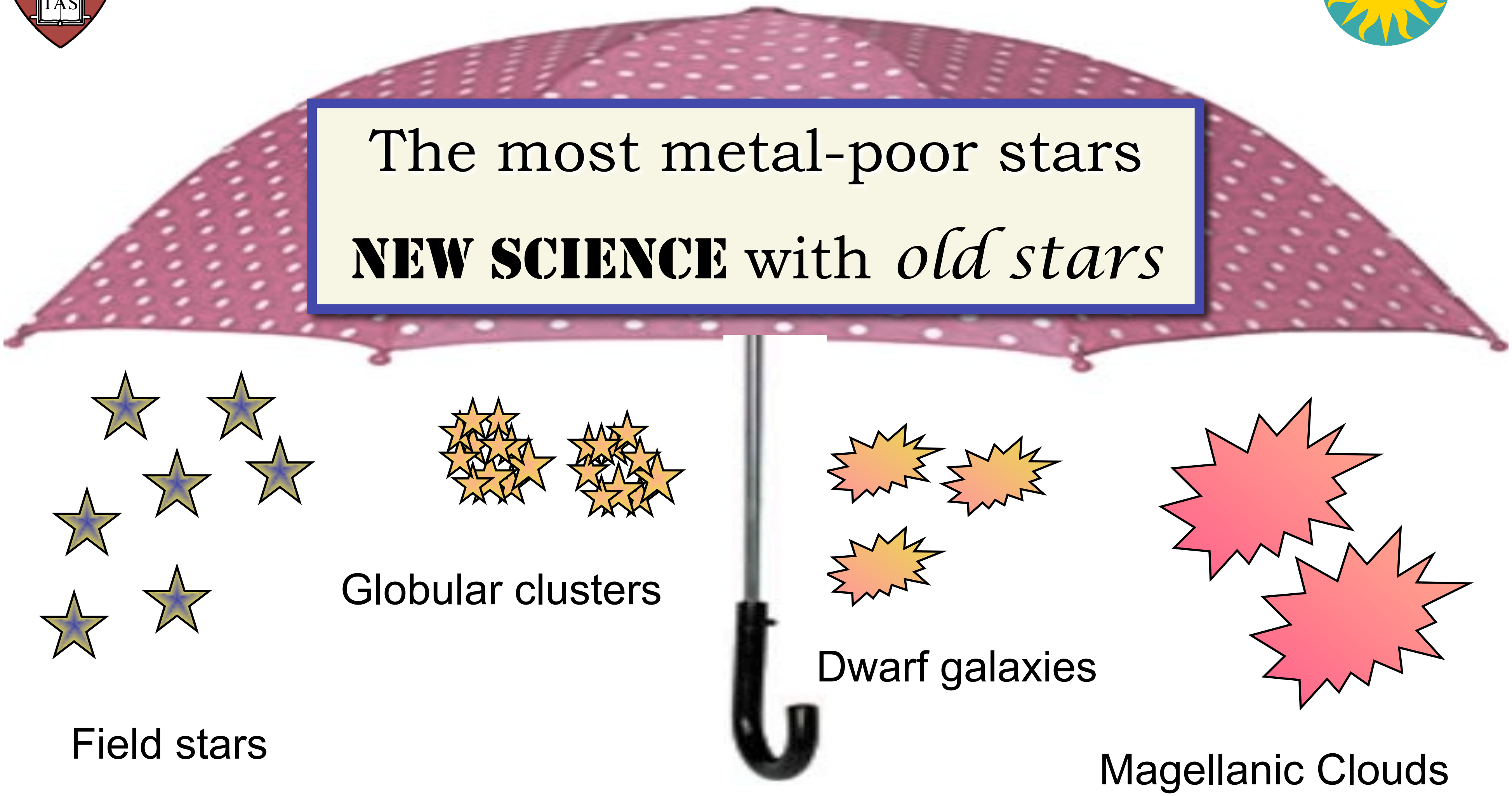
The most metal-poor stars

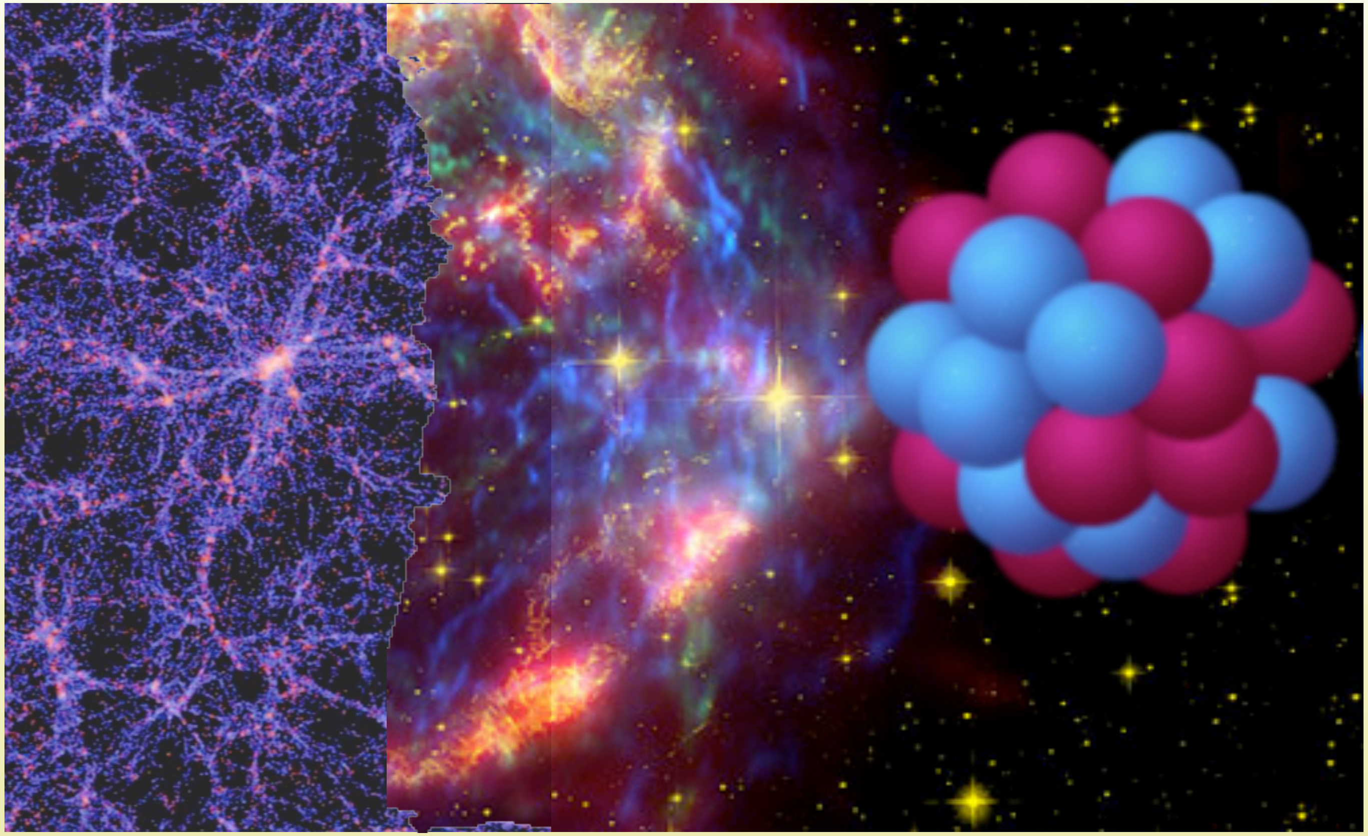
NEW SCIENCE with *old stars*



Anna Frebel

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

Why bother??



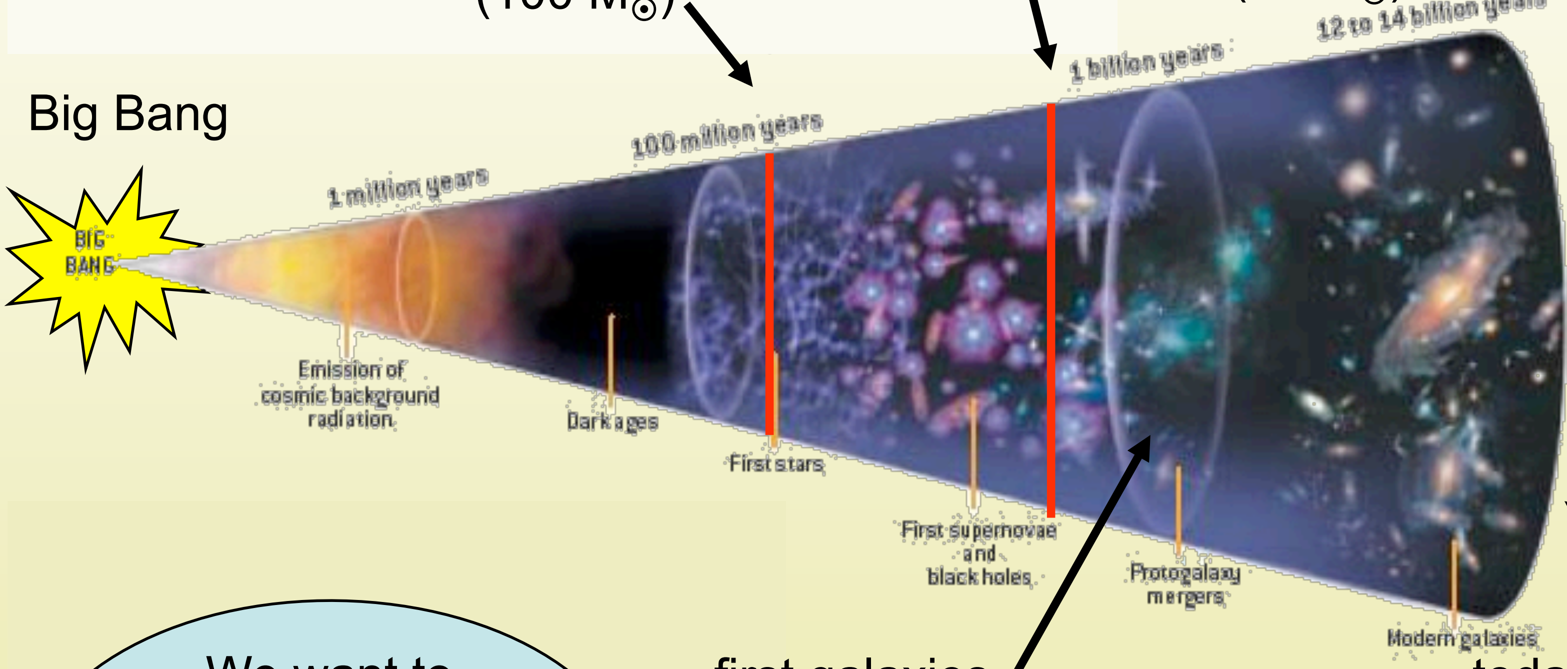
Cosmology | Stellar Astronomy | Nuclear Astrophysics

A LONG, LONG TIME AGO...

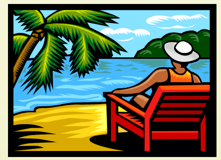
First stars
(100 $M_\odot$)

2nd and later generations
of stars (~1 $M_\odot$)

Big Bang



today



first galaxies

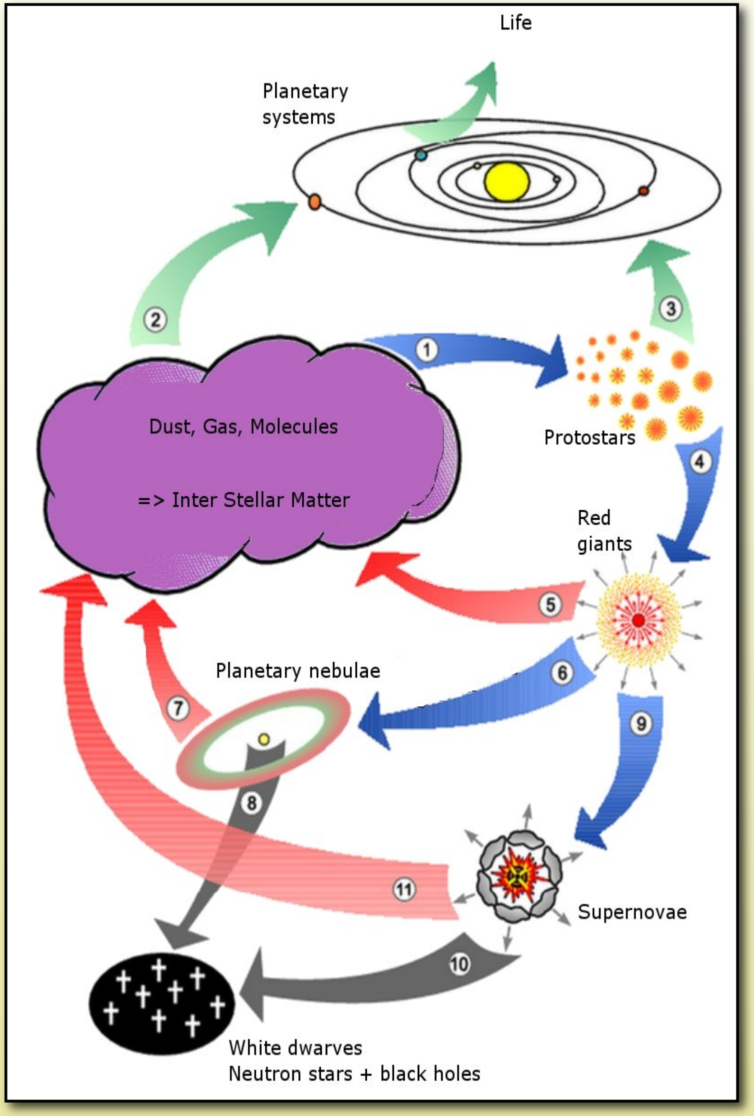
today's galaxies

SCIENTIFIC AMERICAN
Larson & Bromm 2001

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

Cosmic time (not to scale)

CHEMICAL EVOLUTION



Zentrum für Astronomie und Astrophysik, TU Berlin

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)!

Astronomer's periodic table

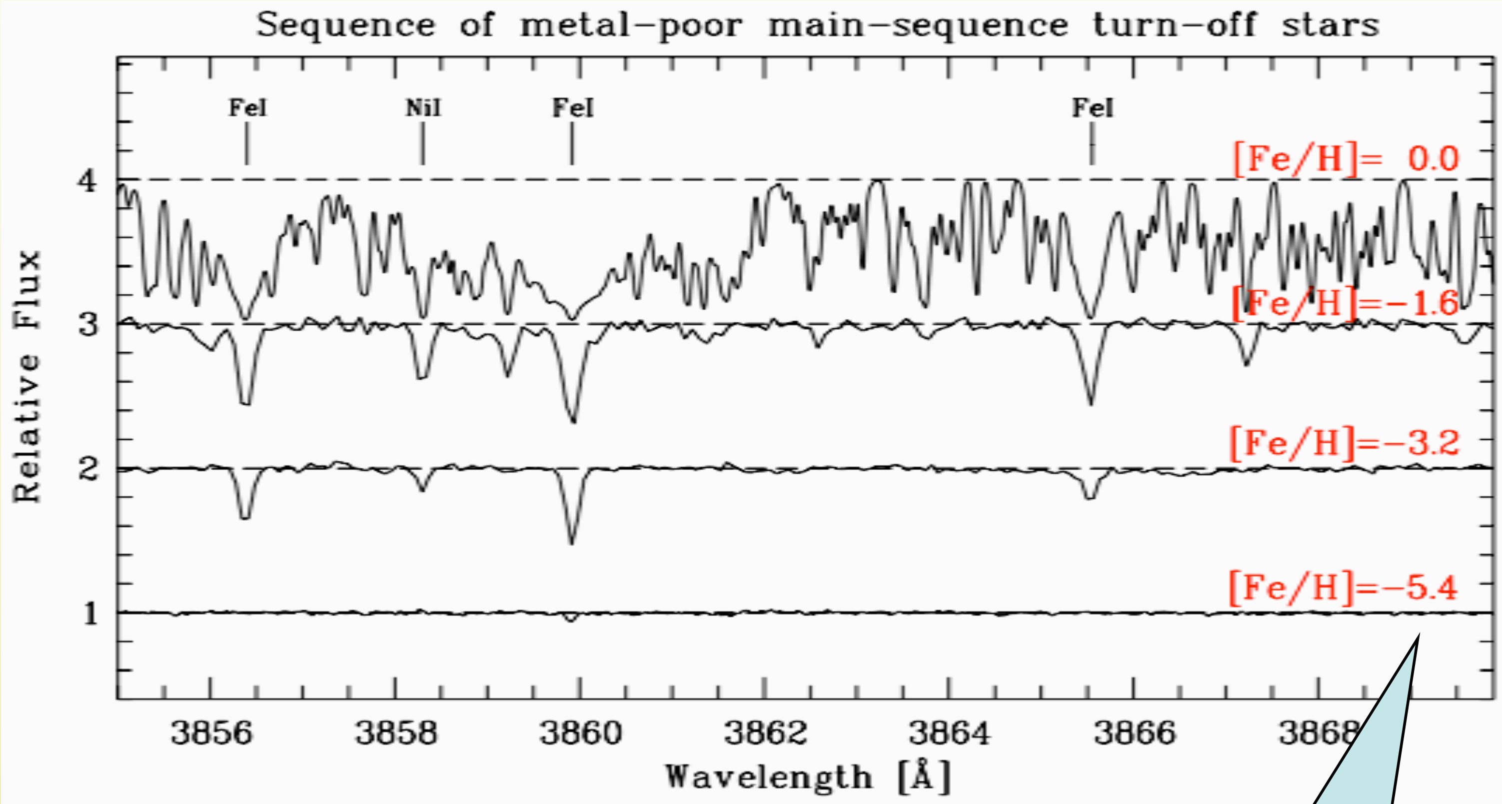
hydrogen	helium
1	2
H	He
1.0079	4.0026

Metals Z

[Fe often used to trace overall "metallicity" Z of a star]

Taking a spectroscopic look

"Look-back time"



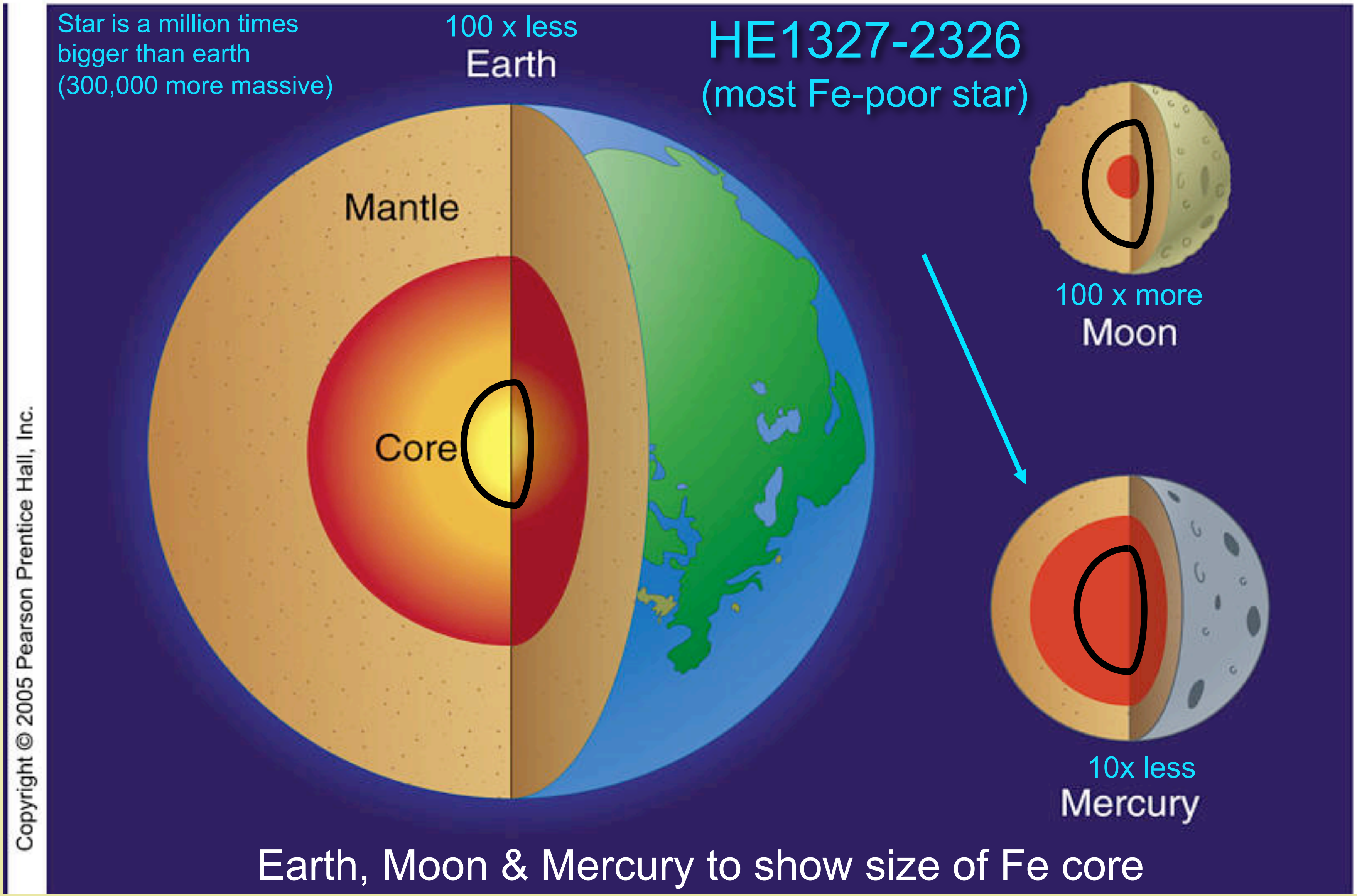
Galactic chemical evolution

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

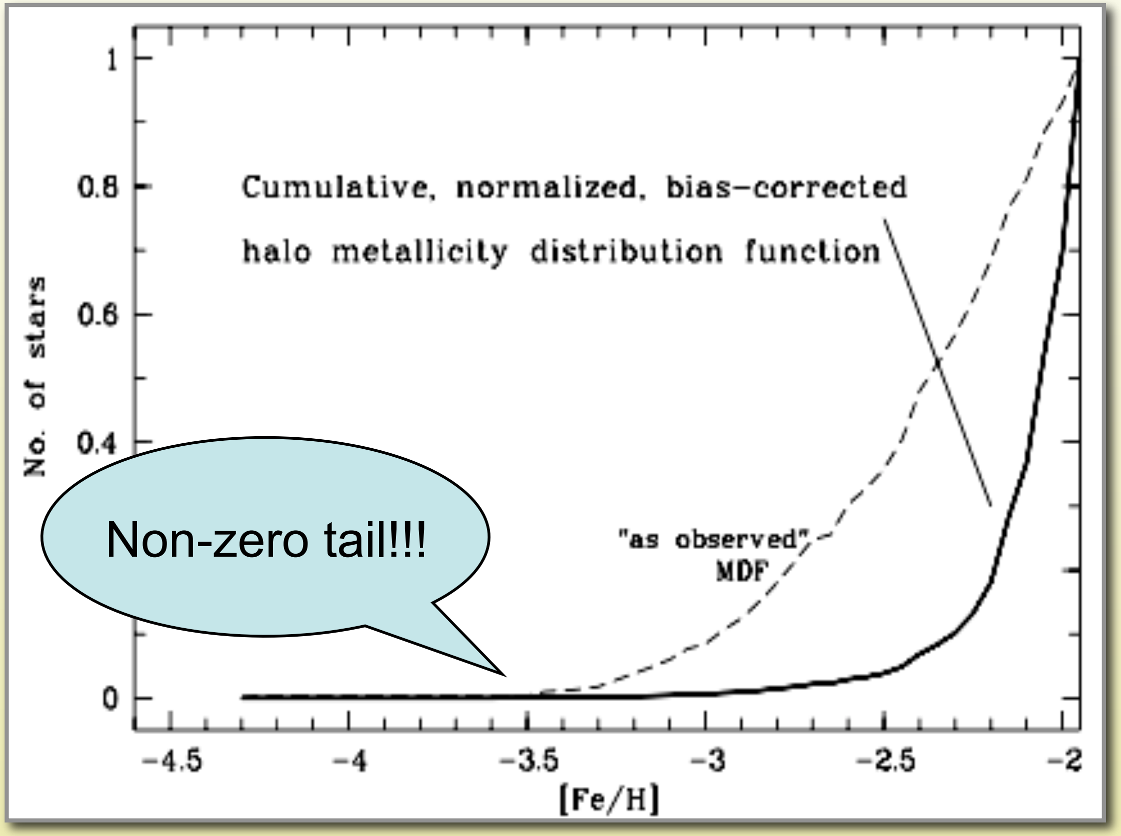
How much iron is in there?



Halo Metallicity distribution function (MDF)

What's in the non-zero tail?

- ~130 stars stud ied with high-resolution so far
- r-process stars (talks by Sneden/Ishimaru/others)
- r+s process stars (talks by Karakas/Cristallo/others)
- really C-rich stars
- other crazy abundance patterns
- stars with [Fe/H]<-5.0



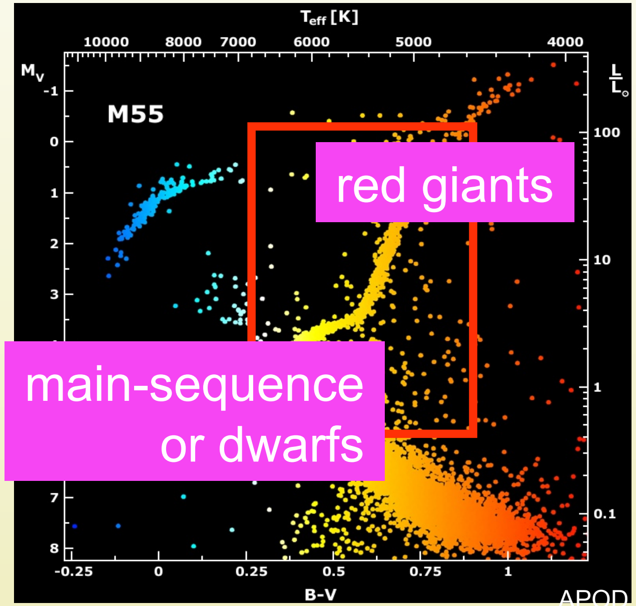
Schoerck et al. 2008

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

WHAT CAN WE LEARN FROM OLD HALO STARS?

Low-mass stars (M < 1 M☉)
⇒ 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

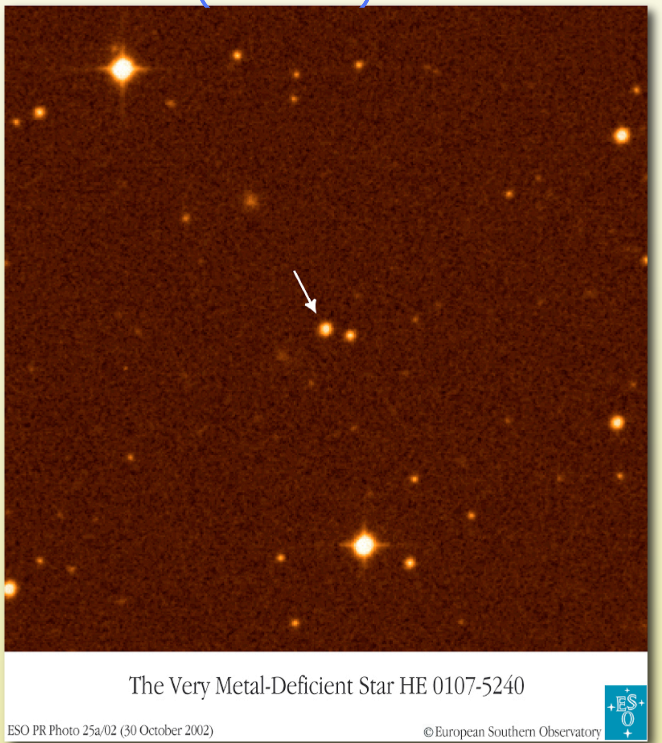
Galactic metal-poor stars are a great tool for near-field cosmology because they are the local equivalent to the high-redshift Universe!

THE MOST IRON-DEFICIENT STARS KNOWN

HE 0107-5240
Red giant
(5200K)

Masses: 0.6 - 0.8 $M_\odot$

HE 1327-2326
Subgiant
(6180K)



$[Fe/H]_{NLTE}$ = -5.2
Christlieb et al. (2002), Nature 419, 904
Christlieb et al. (2004), ApJ 603, 708
Bessell et al. (2004), ApJ 612, L61

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

Anna Frebel

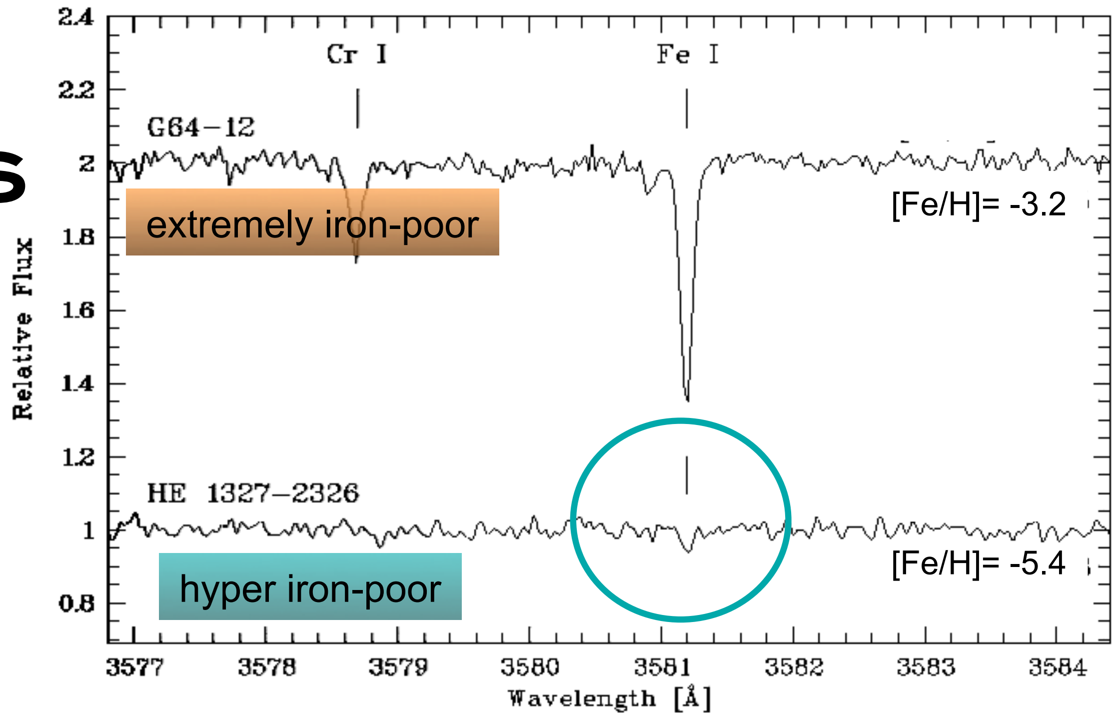
Metal-poor stars

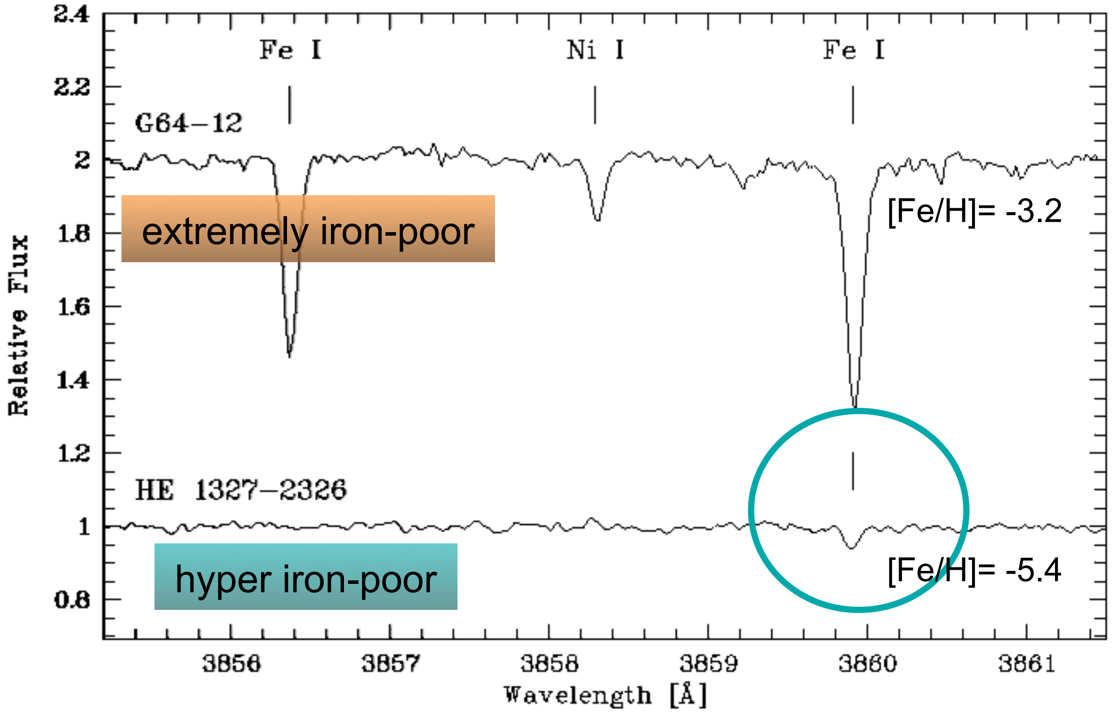
Tiny little Iron Wiggles

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

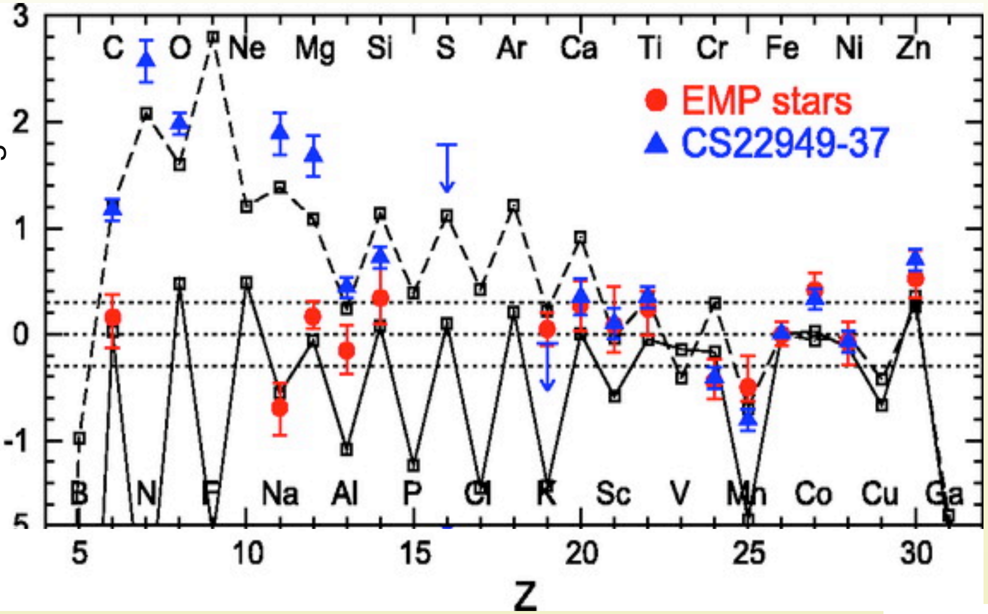
Record holder for the **lowest Fe abundance** observed in a star:
=> [Fe/H] = -5.4





More "normal" metal-poor stars

Tominaga et al.



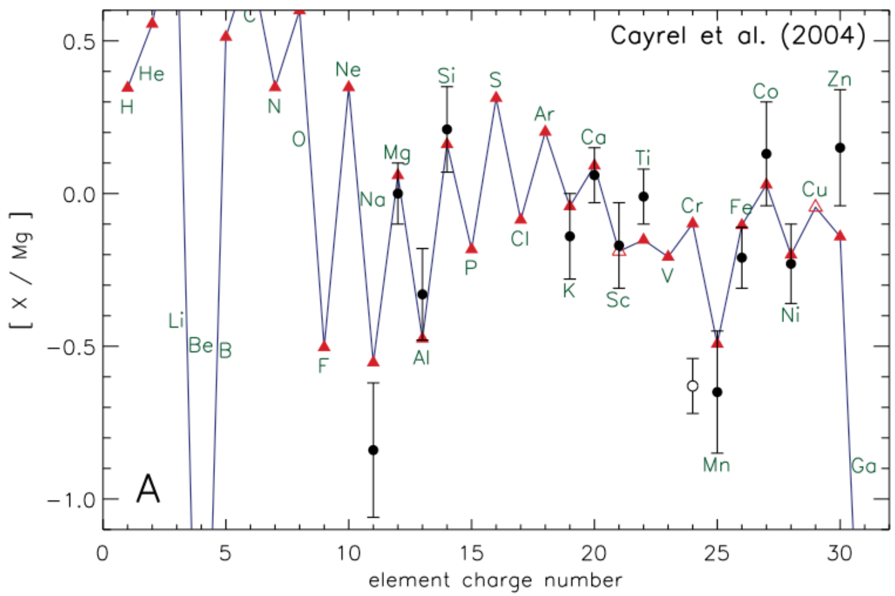
Typical metal-poor stars with [Fe/H]~-3.0 (may contain elements from several generations of SNe)

<u>Best fit models</u>:
-11$M_\odot$ PopIII SN with 0.6/1.2E51
- 10-100$M_\odot$ Salpeter MF, 0.9E51
(fitting of SN nucleosynthesis grid)

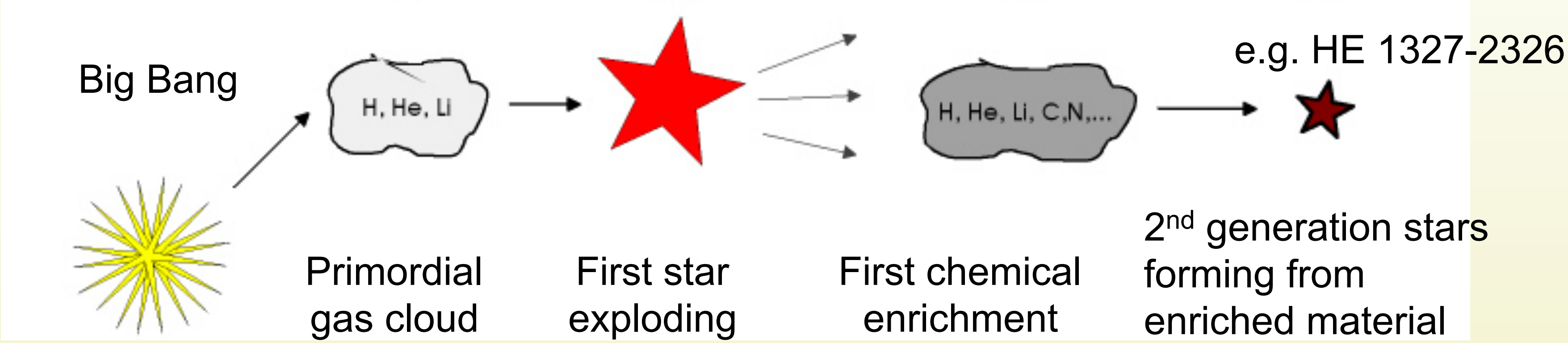
Normal EMP stars (red dots) and carbon-rich extremely metal-poor stars (blue triangles)

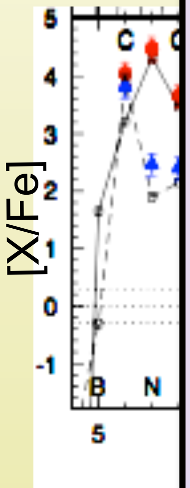
<u>Best fit models:</u>
with explosion energies of
- E51 = 3.0 (dashed line)
- E51 = 120 (solid line)

Heger & Woosley 2008



How and when did these early stars form?





The most metal-poor stars

They provide the only available diagnosis for
- zero-metallicity Pop III nucleosynthesis
- early SNe
- early chemical enrichment!

But, the results are heavily dependent on
- better understanding of SN explosion
- SN nucleosynthesis
- how the yields get dispersed (i.e. turbulence, mixing)

Heger & Woosley 2008

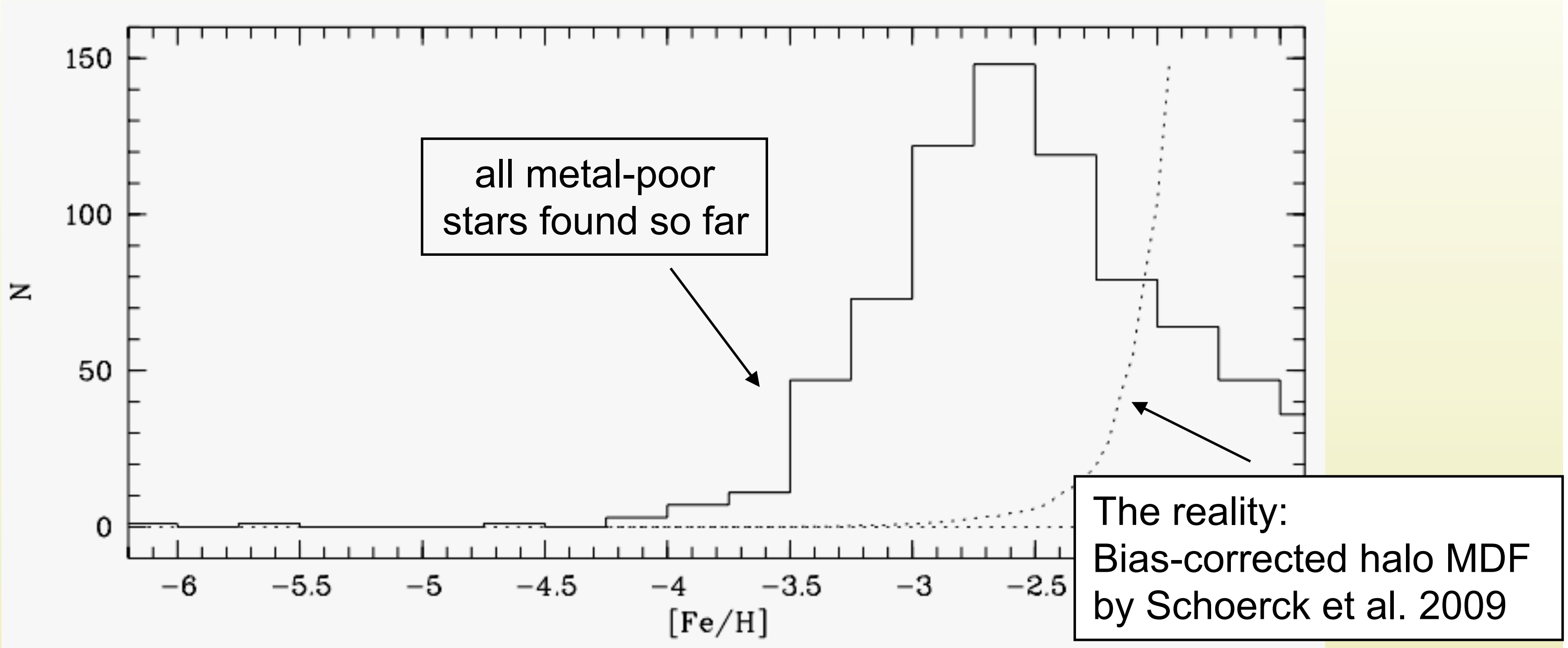
25M
mixi
(mas

(fitting of SN nucleosynthesis grid)

ANNA FREBEL

METAL-POOR STARS

METALLICITY DISTRIBUTION OF LITERATURE STARS W/ HIGH-RESOLUTION ABUNDANCES



<u>“Advertisement”:</u>

A compilation of abundances of ~800 metal-poor stars with [Fe/H]~<-2.0 can be found at

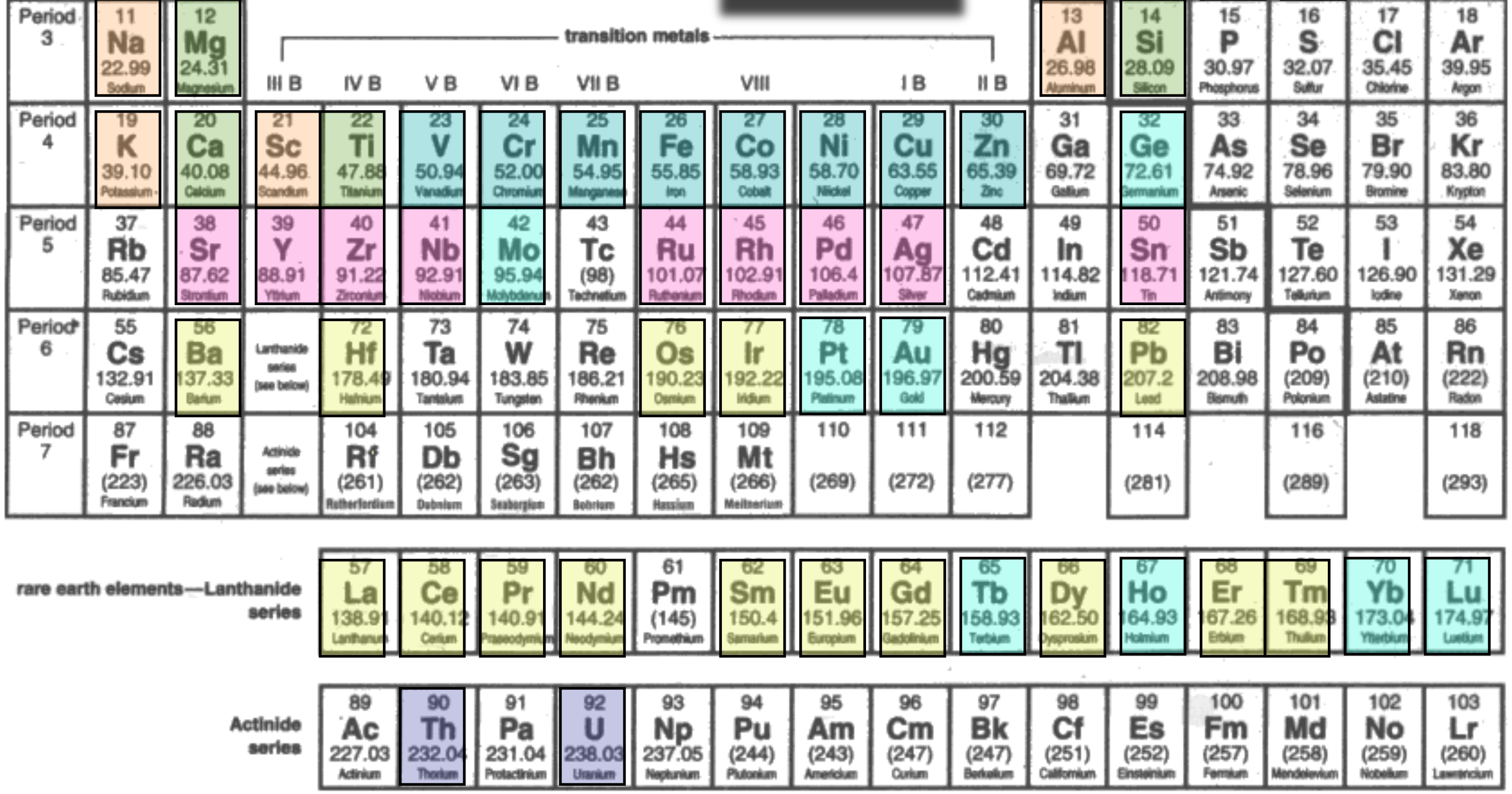
www.cfa.harvard.edu/~afrebel/abundances/abund.html

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

Cosmic Labs: r-process stars in the halo

HE 1523-0901
B = 12.1 mag
T_{eff} = 4630 ± 70K
log g = 1.0 (red giant)
[Fe/H] = −3.0

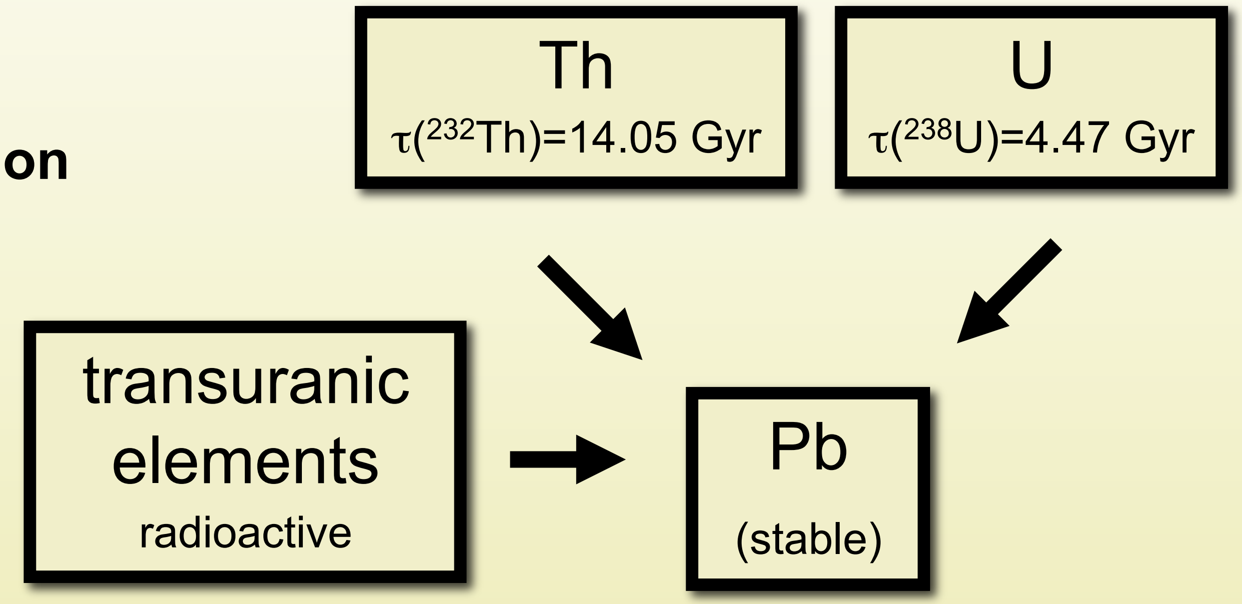
Frebel et al. 2007, ApJ 660, L117
Frebel et al. 2010, in prep.



At the end of everything: Lead (Pb)

In the r-process, and relevant for r-process metal-poor stars

Different Pb production channels



A comparison of Th, U, Pb stellar abundances
with r-process predictions
- constrains r-process models
- shows what the different production channels are!

LEAD ABUNDANCE PREDICTION FOR R-PROCESS STARS

first “U” star

total Pb from decay only: log ε(Pb) = –0.72

	t=0	t=13 Gyr	HE 1523-0901	CS31082-001
log(Th/U)	**0.26**	**0.84**	**0.86**	0.89
log(Th/Pb)	**-1.327**	**-1.316**	**-0.85**	-0.43
log(U/Pb)	**-2.208**	**-2.161**	**-1.71**	-1.32
log(Pb)	**-0.426**	**-0.346**	**~-0.35**	-0.55

Th-U-Pb in r-process metal-poor stars

“textbook” stars like HE1523 crucial for self-consistency tests of rapid nucleosynthesis via Th-U-Pb combo!

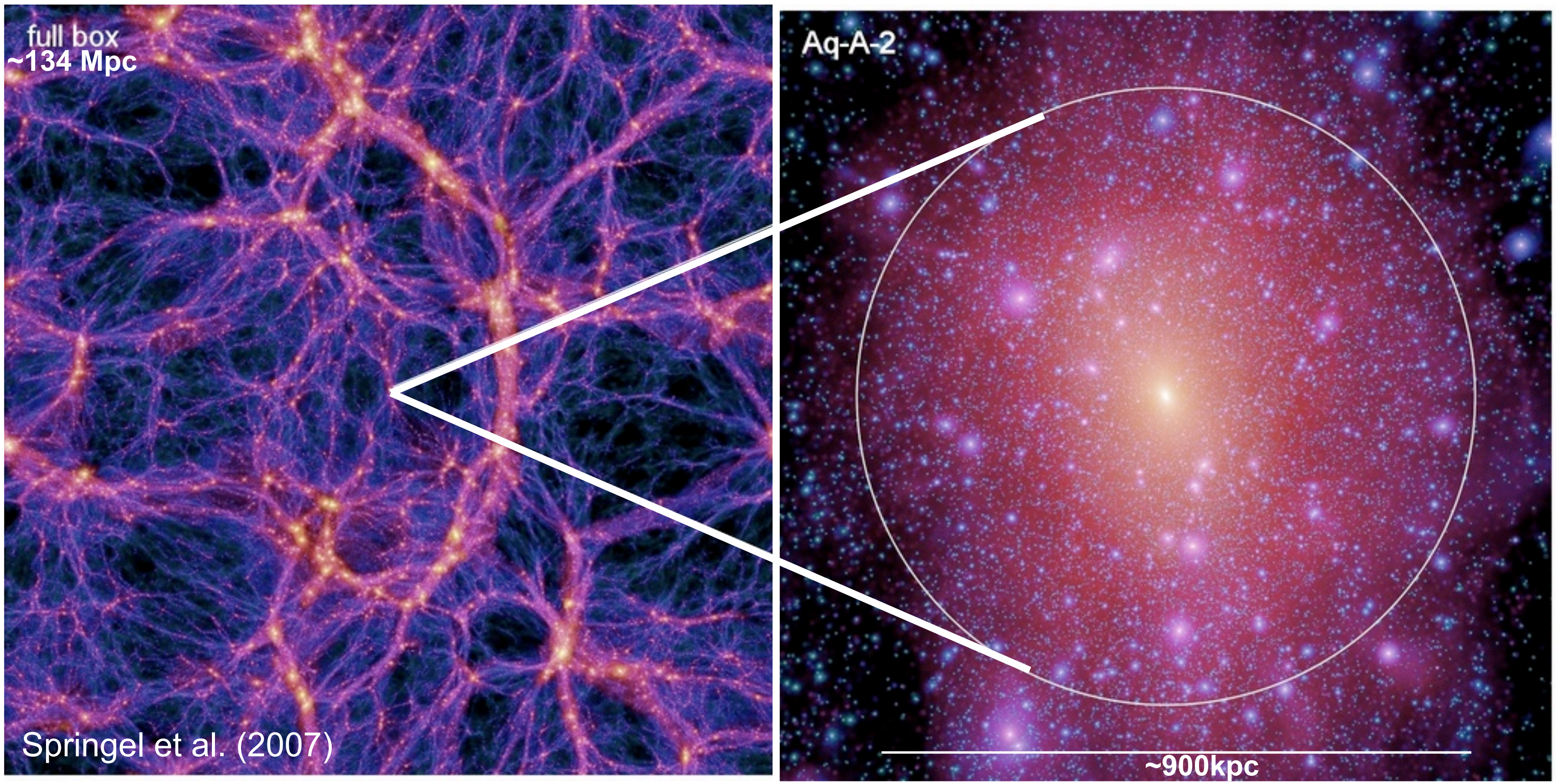
But, the results are depending on

- r-process model calculations!
- also one the data and “star” quality

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.



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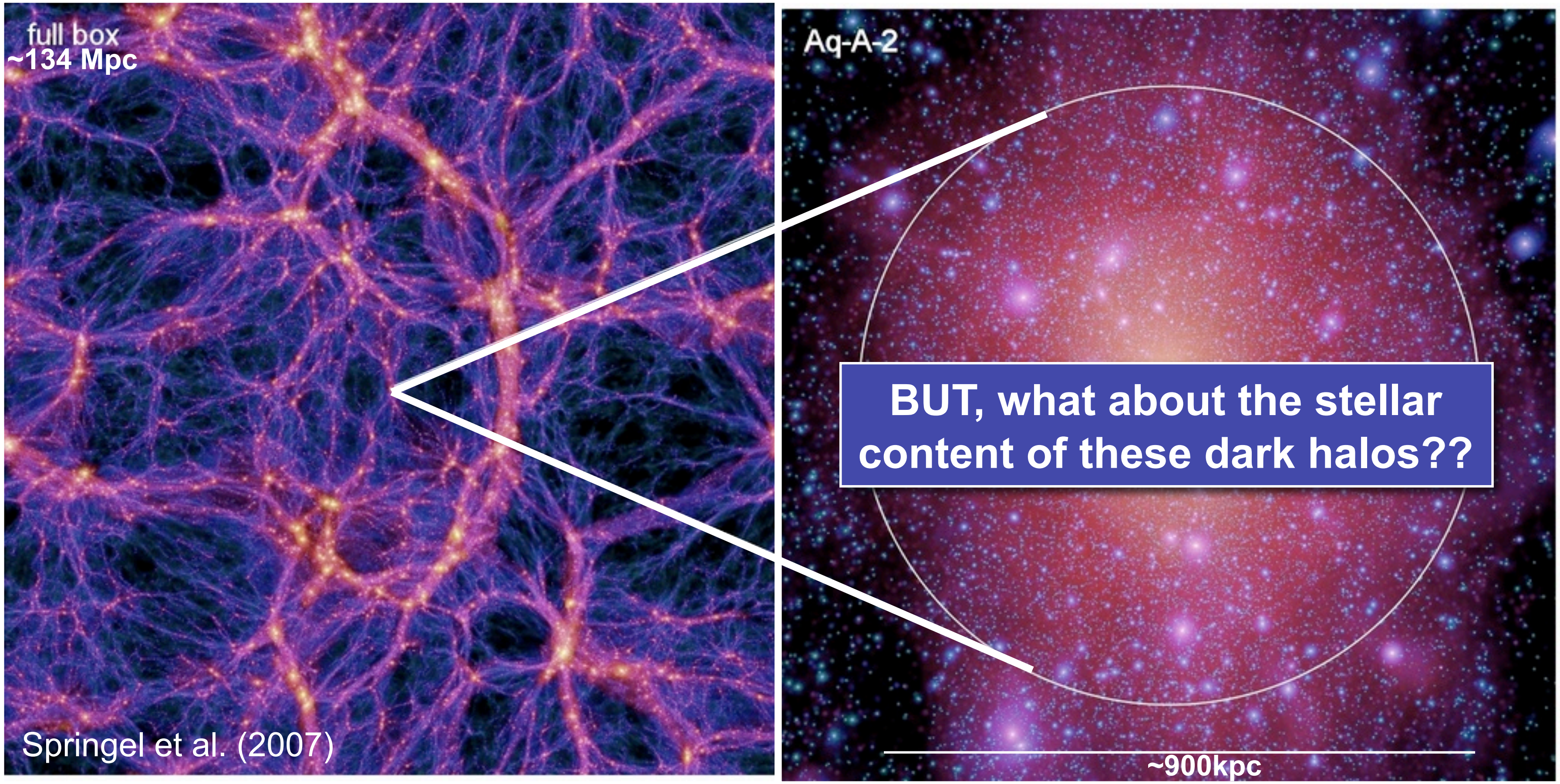
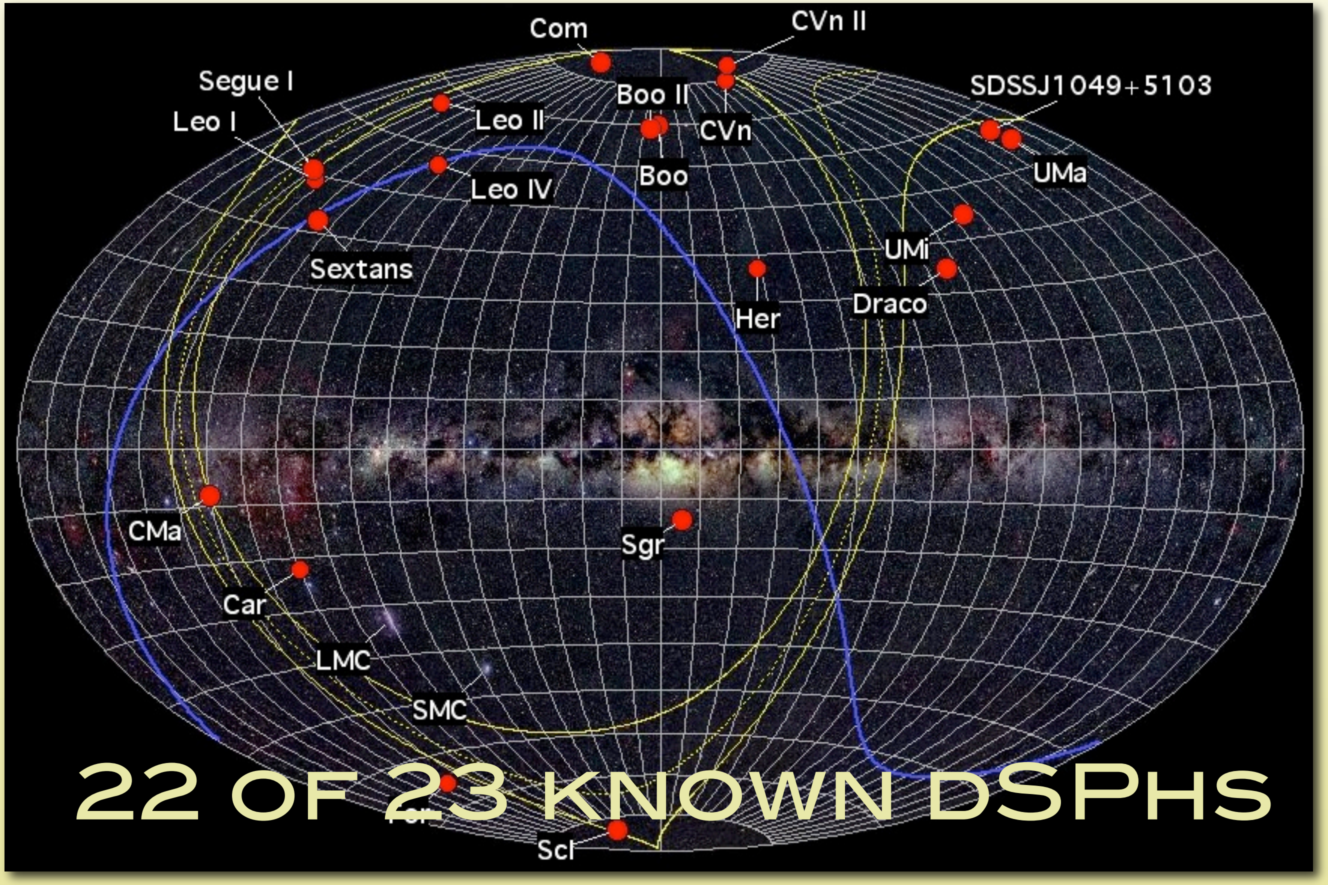


The Milky Way's satellites

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.

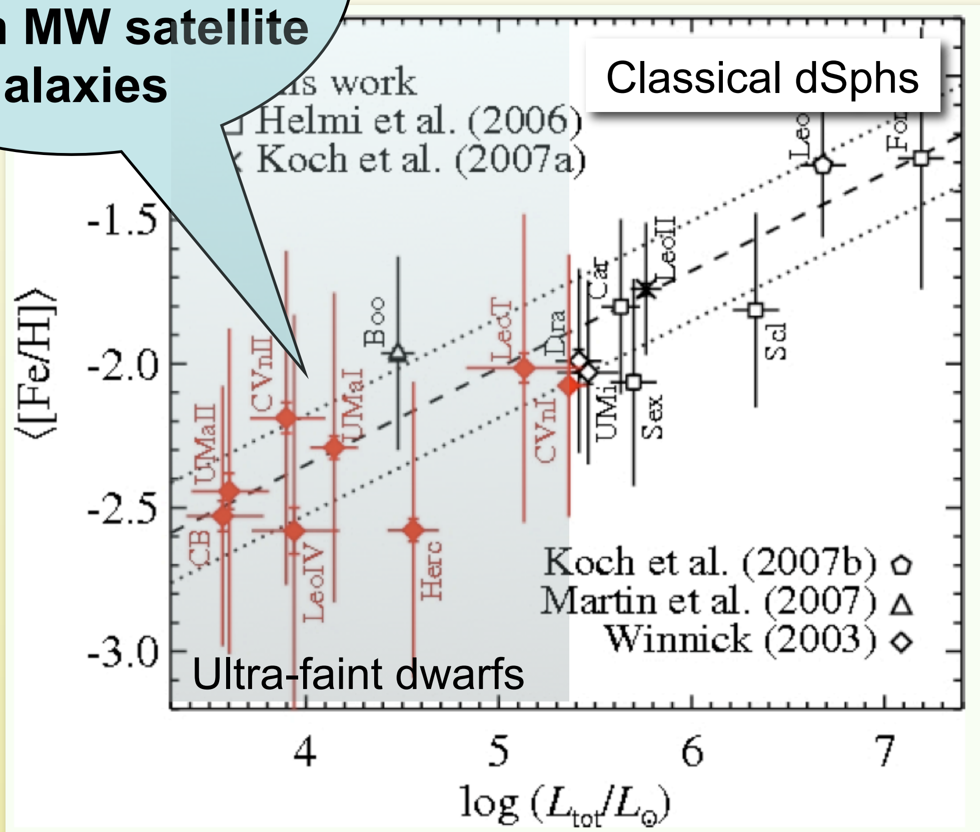


22 of 23 known dSPhs

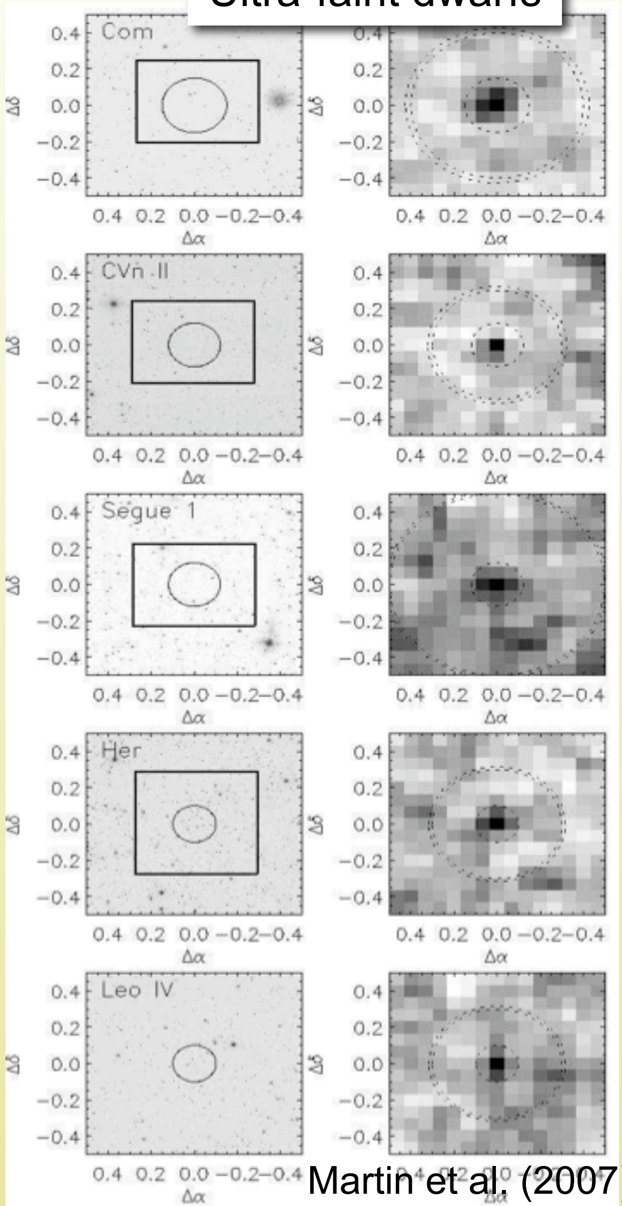
Metallicity-Luminosity Relation

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

Classical dSphs



Ultra-faint dwarfs



Martin et al. (2007)

What can we learn from the existing dwarf galaxies?

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

Stellar metallicities [Fe/H] & abundances [X/Fe] of metal-poor stars in dwarf galaxies **should agree** with those found in the MW halo

Reminder: dwarf galaxies are SIMPLE systems so we deal with less chemical evolution/less yield superposition => we can better trace individual SNe yields and other nucleosynthetic details!

ANNA FREBEL

ULTRA-FAINT DWARF GALAXY ABUNDANCES

Excellent agreement with the MW chemical evolution

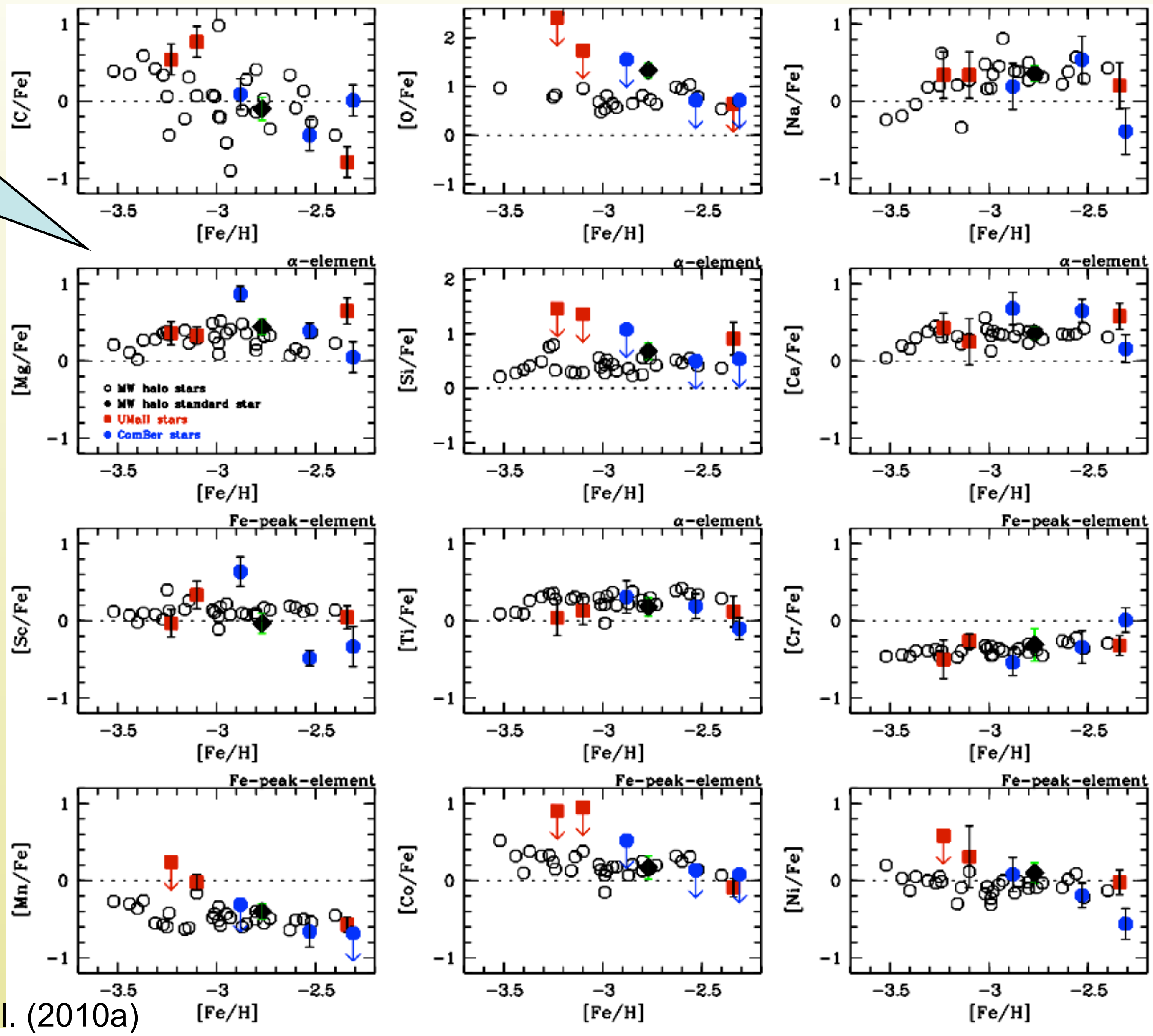
Cay... (black open circles)

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

red squares: Ursa Major II

blue dots: Coma Berenices

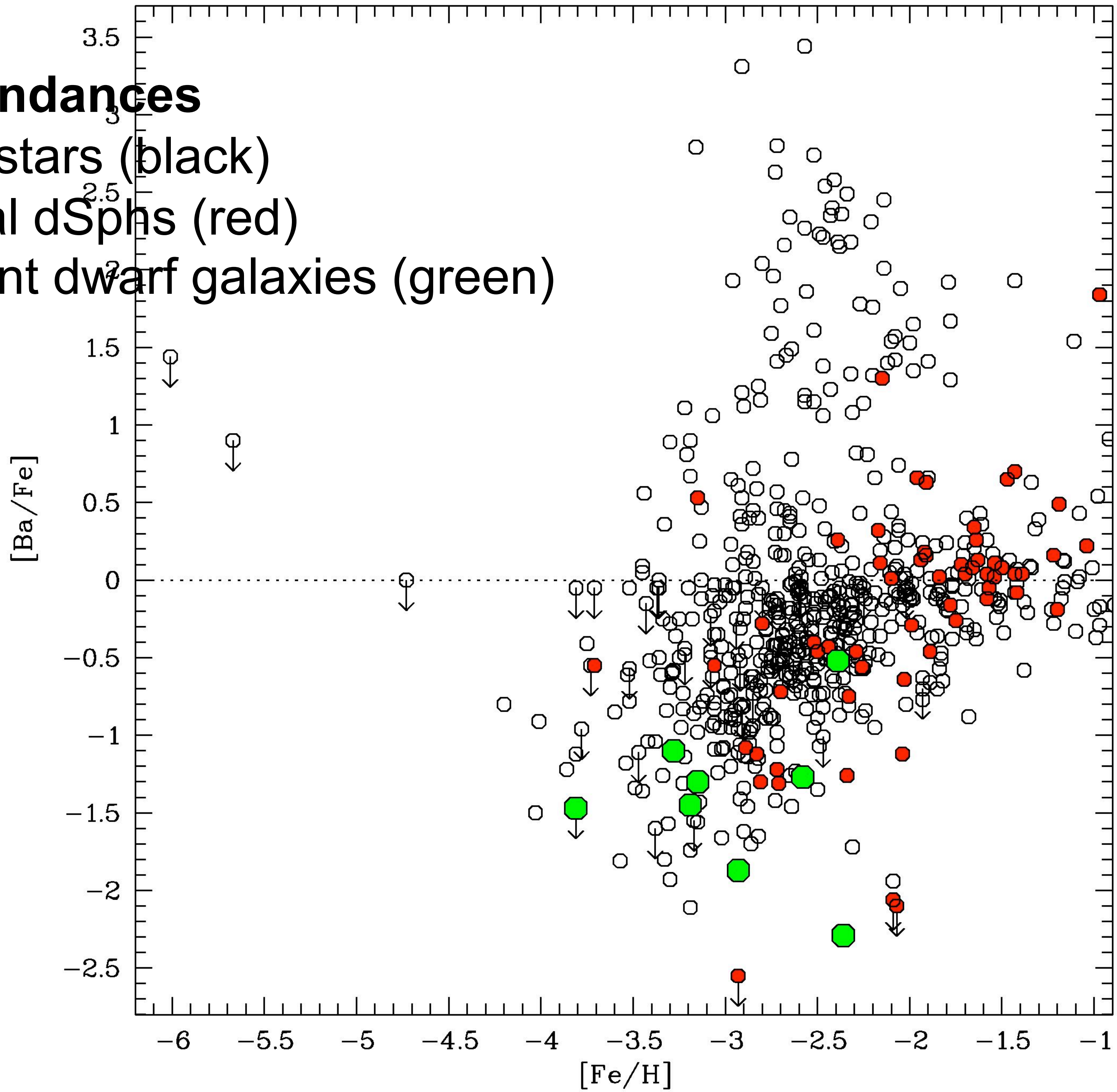
black diamond: MW halo giant



Frebel et al. (2010a)

METAL-POOR STARS

Ba abundances
of halo stars (black)
classical dSphs (red)
ultra-faint dwarf galaxies (green)



AN EXTREMELY METAL-POOR RED GIANT STAR IN SCULPTOR

Metal-poor stars in dwarf galaxies:

Stellar archaeology meets near-field cosmology

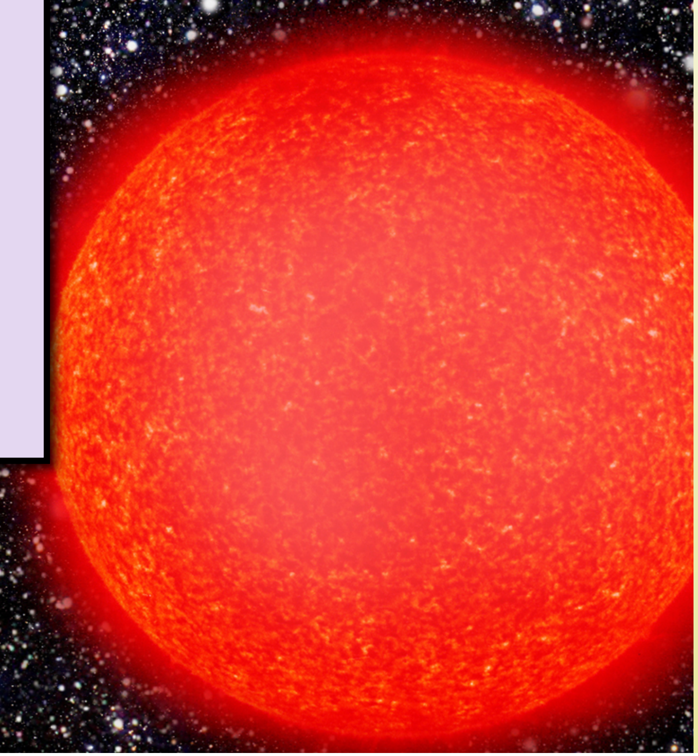
- early chemical evolution in early systems
- what are the building blocks of the Milky Way?

But, the results are heavily dependent on

- cosmological simulations of the first stars, first SN & first galaxies
- SN nucleosynthesis
- how the yields get dispersed (i.e. turbulence, mixing)

"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)

Little Diamonds in the sky...

"Metal-poor stars are a girl's best friend!"

Metal-poor stars are just like diamonds

- they are rare
- they last (almost) forever
- they are good for many occasions/applications
- they contain a lot of carbon
- they are difficult to come by
- they make you happy!

We have found many so just tell us what you need them for :)

PS. And even the carbon was once made it a red giant!