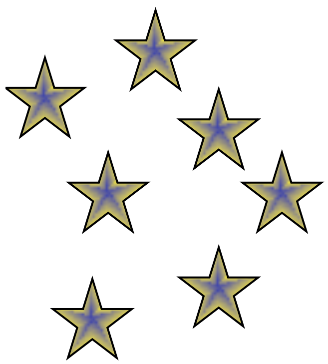
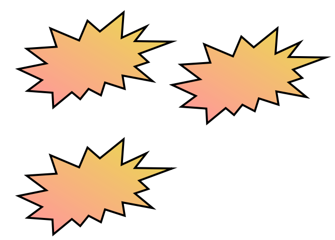
Chemical Abundances of Metal-Poor Stars & their Connection to the Pop III IMF





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WHAT TO DO WITH METAL-POOR STARS

Stellar archaeology cookbook: NEW SCIENCE with *old stars*

- ✓ **Stellar archaeology: Finding fossils of the earliest times**
  The most iron-poor stars with [Fe/H]<–5.0
  25-60M$_\odot$ (plus rotation)

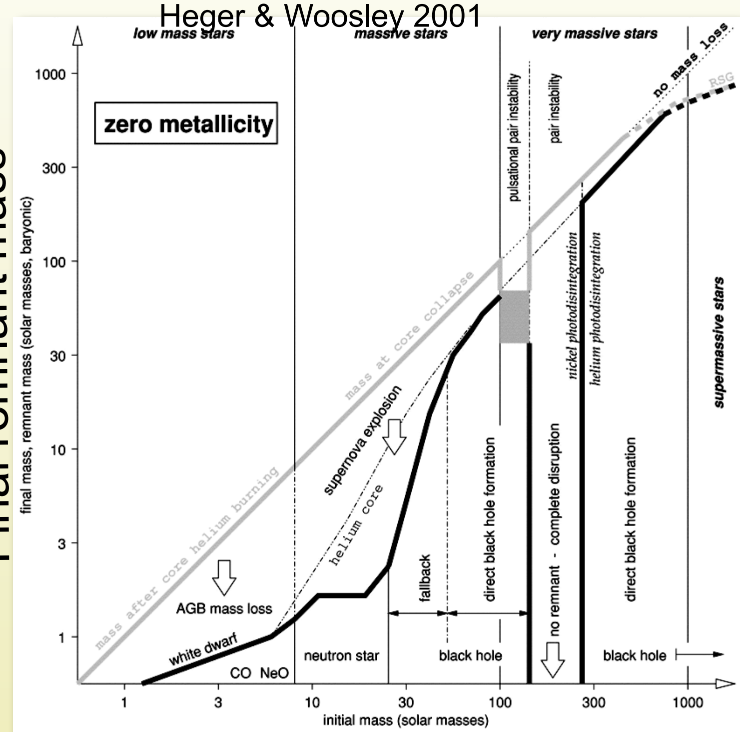
- ✓ **Nuclear astrophysics: Dating the oldest stars**
  Detecting r-process elements in metal-poor stars **~8-10M$_\odot$**

- ✓ **Near-field cosmology: Formation of the galactic halo**
  Chemical history of dwarf galaxies
  massive first stars?

- ✓ **Theoretical predictions for first & early stars**
  Test them with metal-poor stars
  did low-mass PopIII stars exist?

Heger & Woosley 2001

Final remnant mass



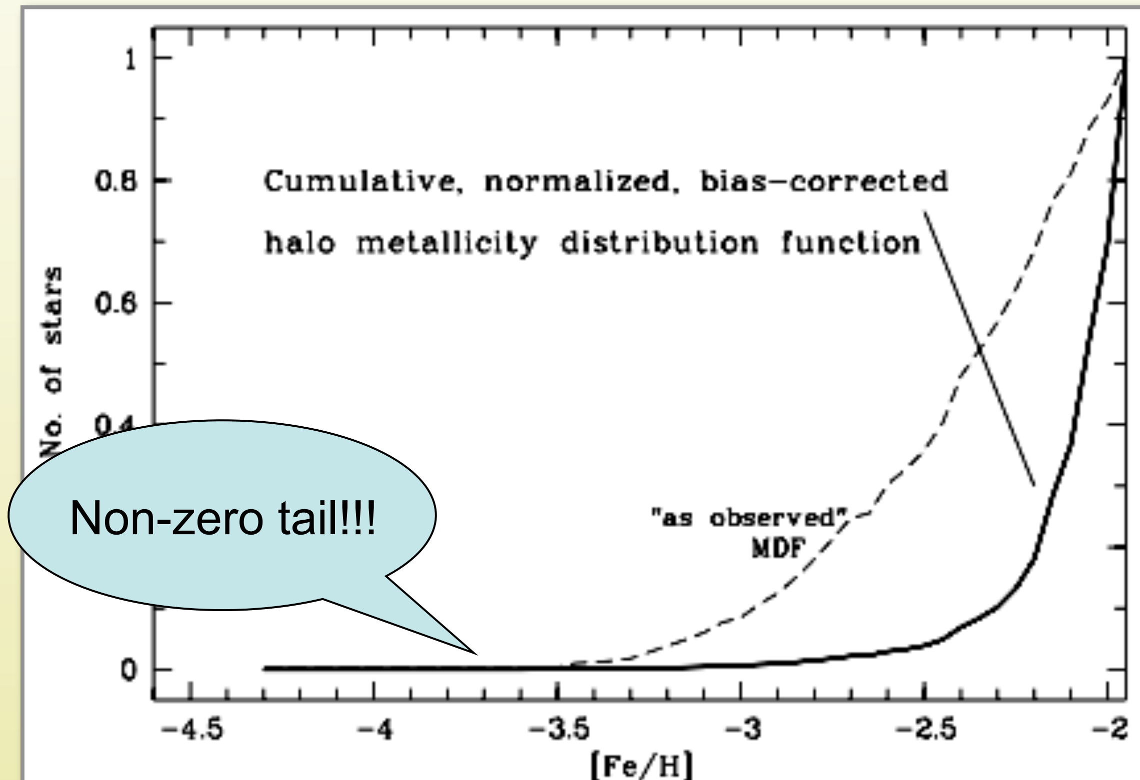
Initial mass

~10-140M$_\odot$ >260M$_\odot$

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..)

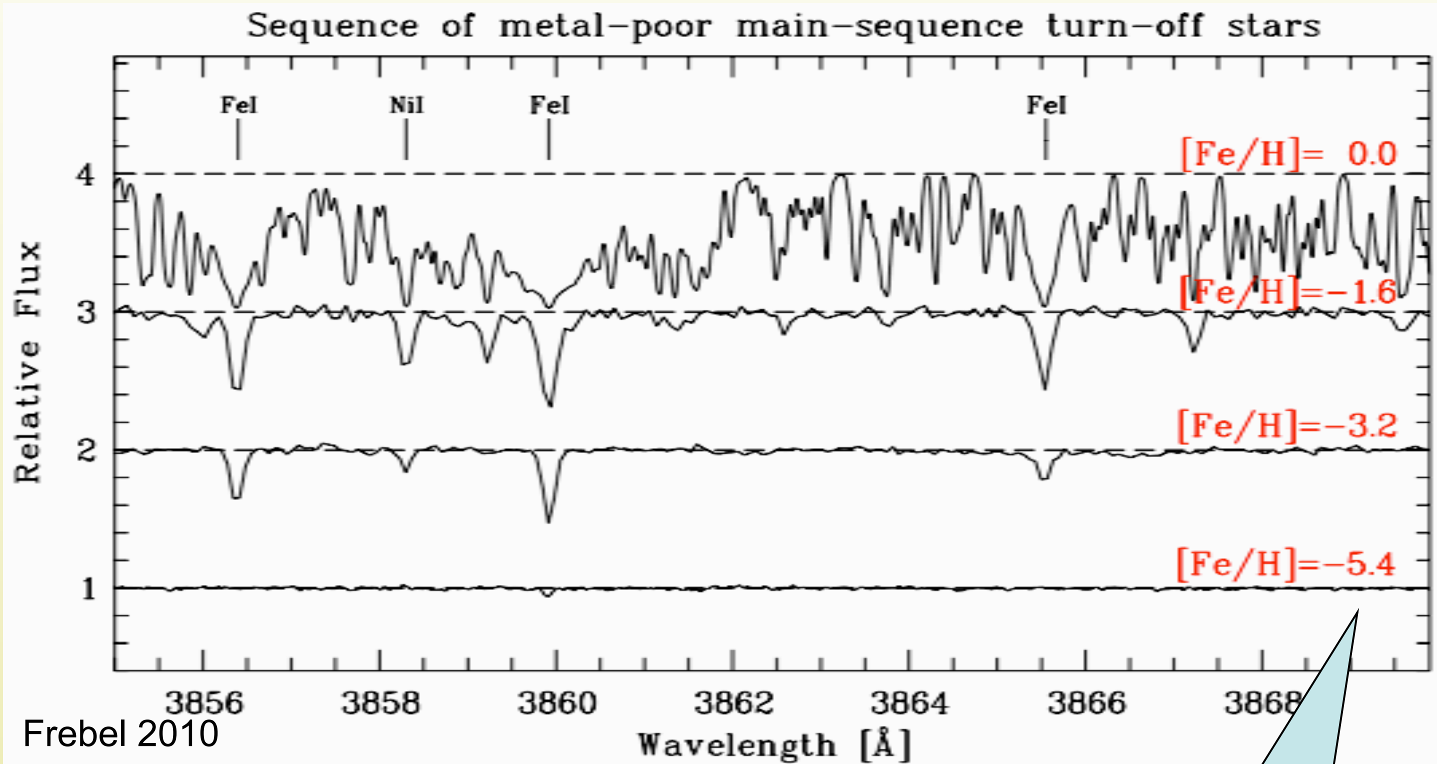


Schoerck et al. 2008

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

Taking a spectroscopic look

“Look-back time”



Frebel 2010

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

Cookbook -- part 1
Stellar archaeology

- Types of metal-poor stars:

The most iron-poor stars with [Fe/H]<–5.0
⇒ ~25Msun faint mixing and fallback PopIII SNe (low energy E51)
⇒ rotating massive PopIII 60Msun stars?

"Normal" scaled-solar metal-poor stars with -4.0<[Fe/H]<-2.5
⇒ more energetic hypernovae (E52)

Carbon-rich/s-rich metal-poor stars (in binary system)
=> Intermediate mass companion (<8Msun) to provide AGB nuc. products

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

The most iron-deficient stars known

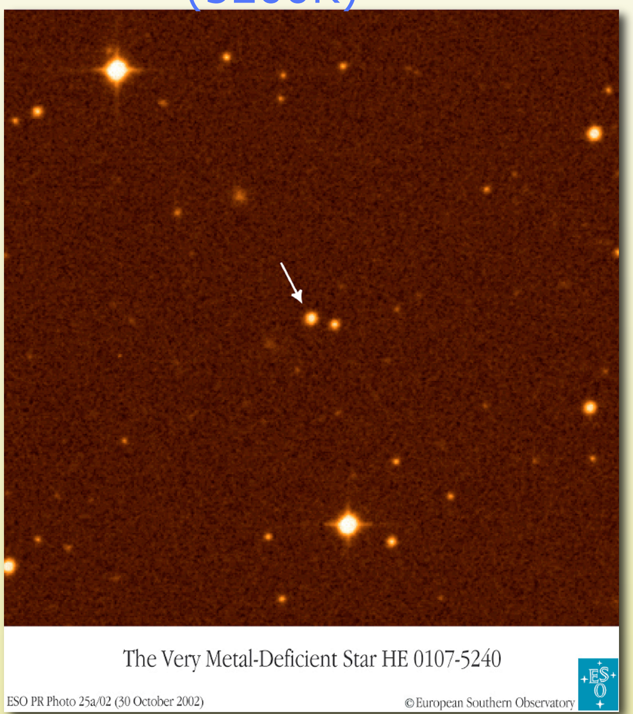
HE 0107-5240

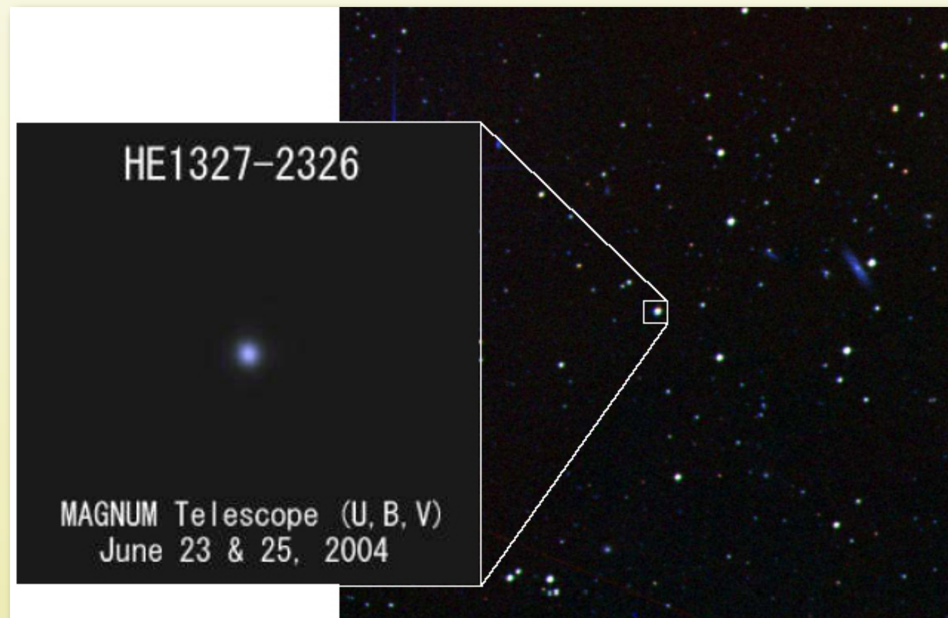
Red giant
(5200K)

Masses: 0.6 - 0.8 $M_\odot$

HE 1327-2326

Subgiant
(6180K)





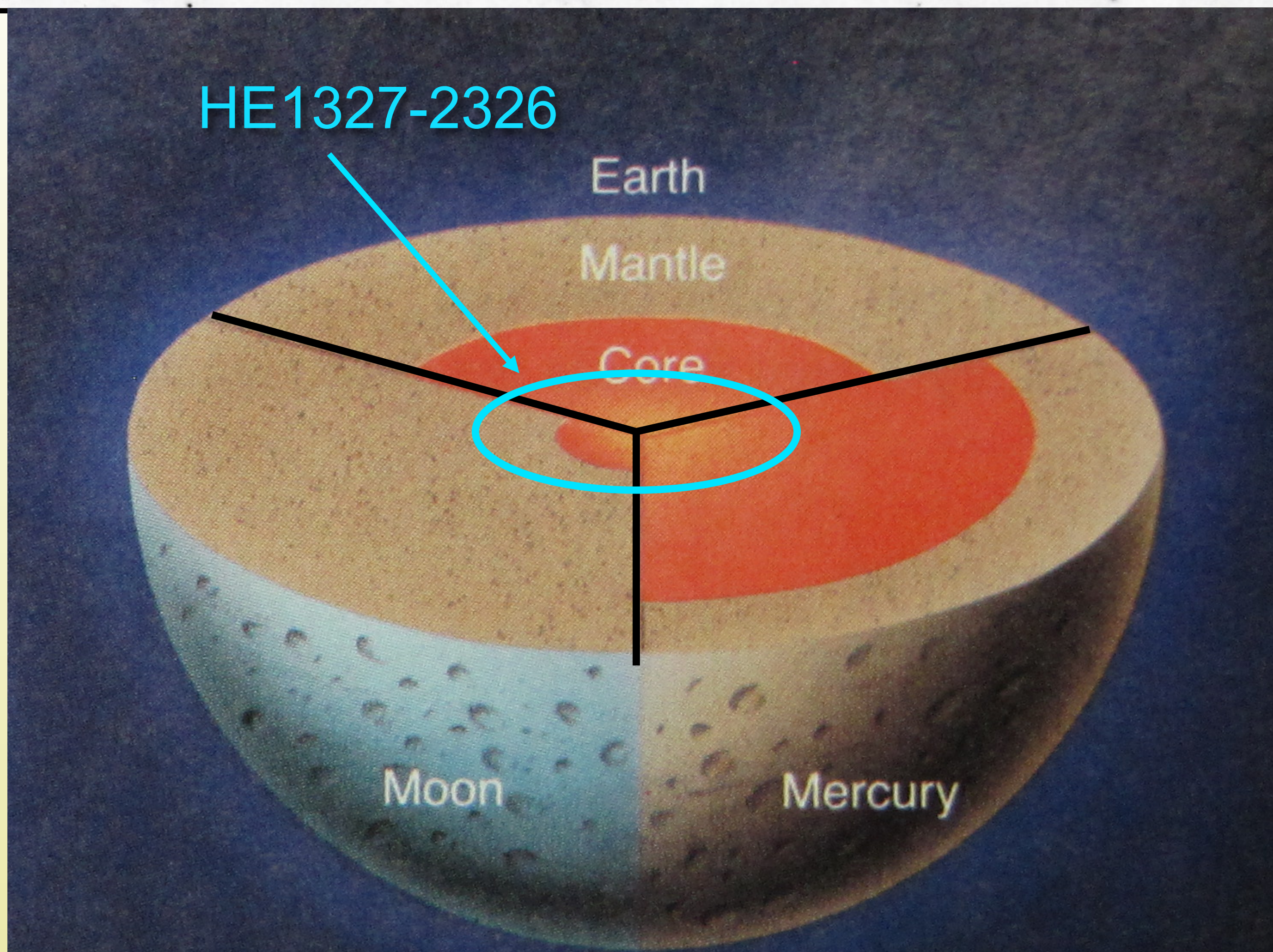
$[Fe/H]_{NLTE}$ = -5.2

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, 588i

How much iron is in there?



Relative scales of Earth, Moon & Mercury
to show size of Fe core

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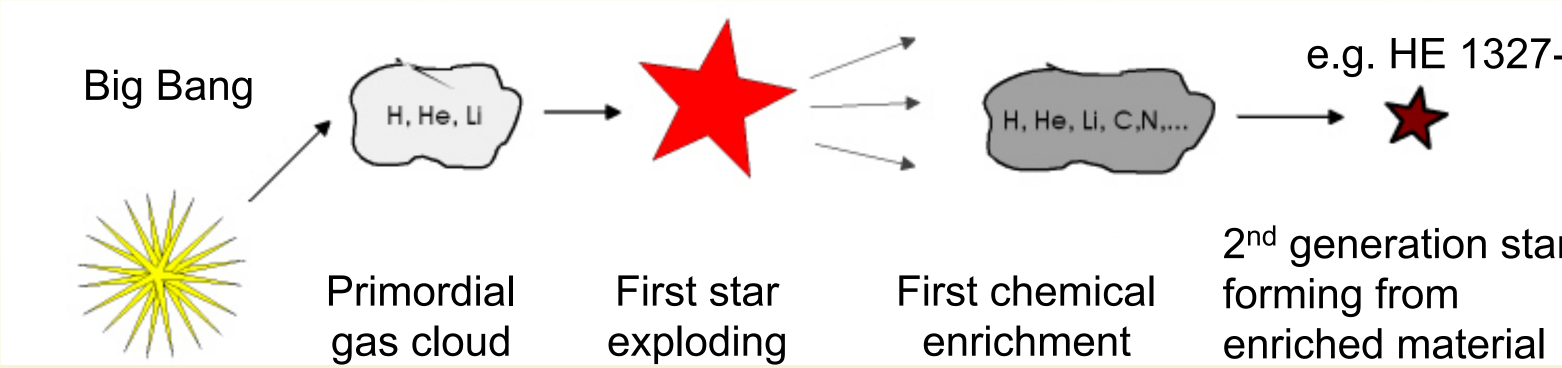
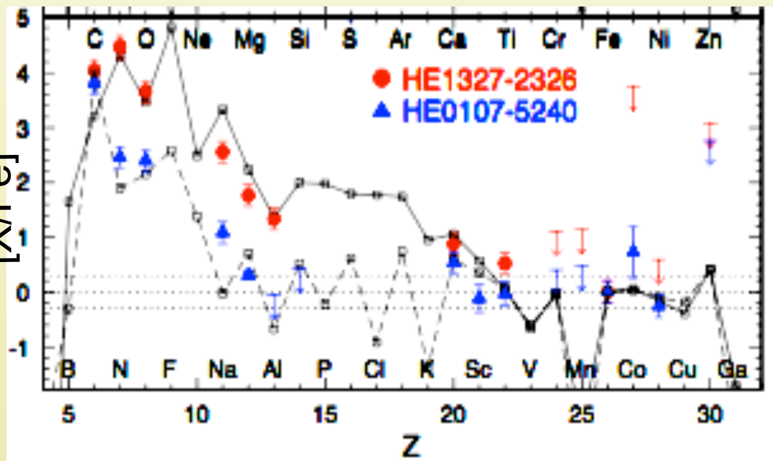
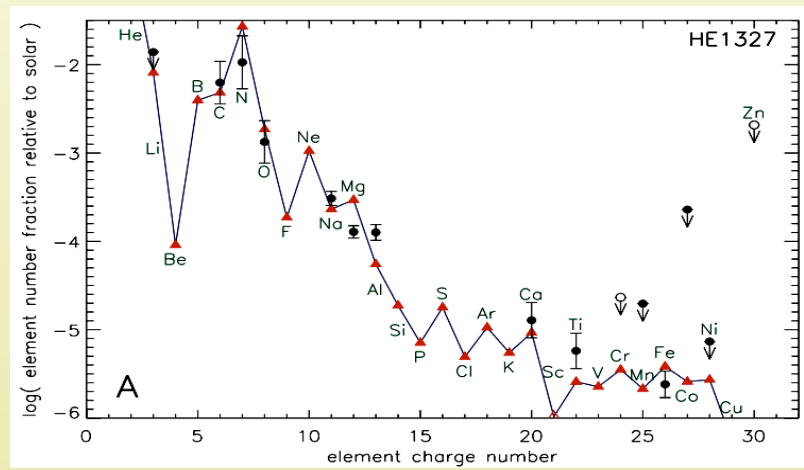
What to do with metal-poor stars

How and when did these early stars form?





Tominaga et al. 2007



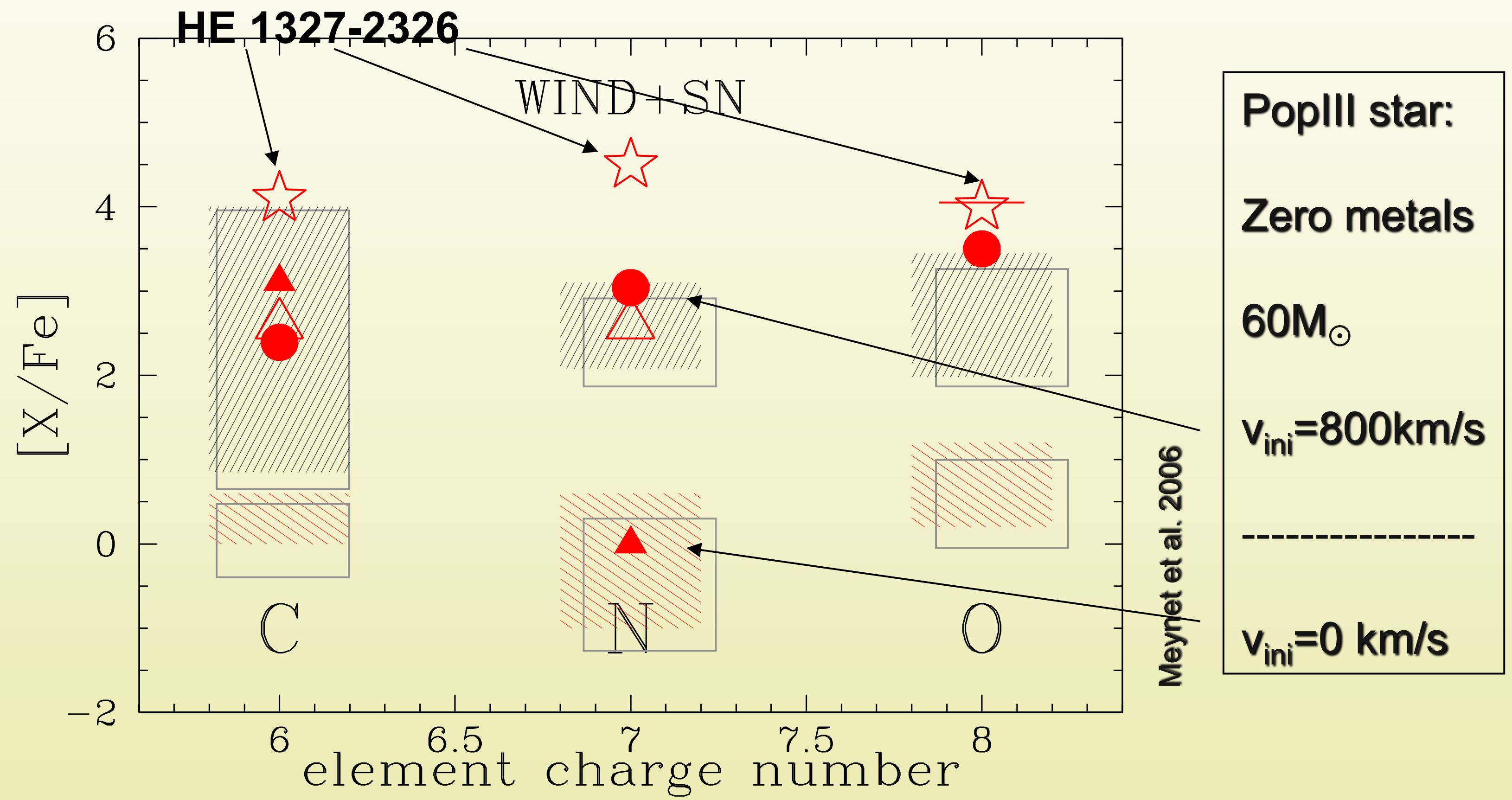
Heger & Woosley 2008

25Msun faint
mixing and fallback SN
(mass, expl. energy, mass cut)

best fit models:
- 20Msun PopIII SN with 0.3E51
- 15-40Msun Salpeter MF, 0.3E51
(fitting of SN nucleosynthesis grid)

Massive rotating PopIII stars

(Meynet/Maeder/Hirschi et al.)



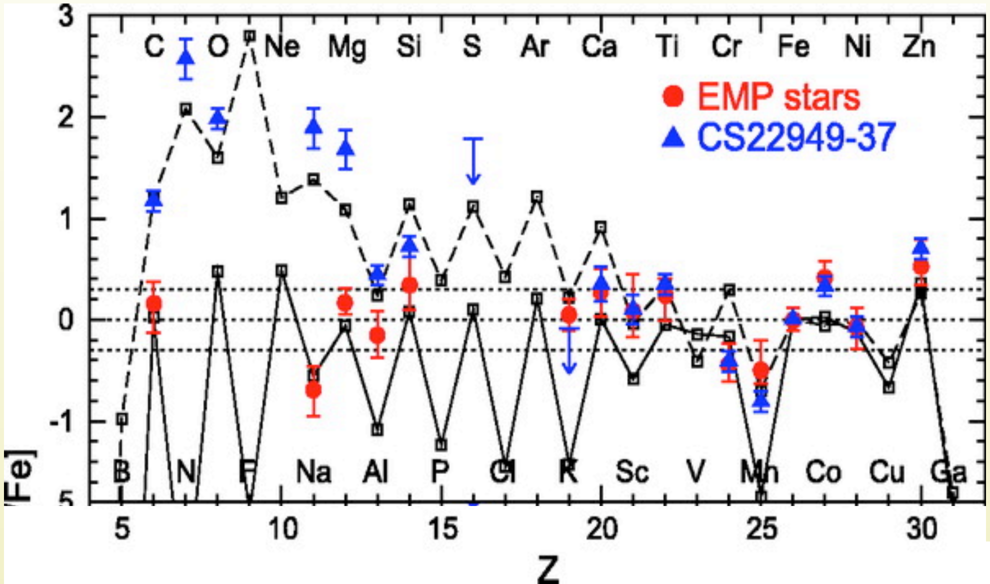
Solid circles: [Fe/H]=-6.6 with rotation

Solid triangles: [Fe/H]=-6.6 without rotation

stars: HE 1327-2326

empty triangles: G77-61

More "normal" metal-poor stars



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

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

Best fit models:

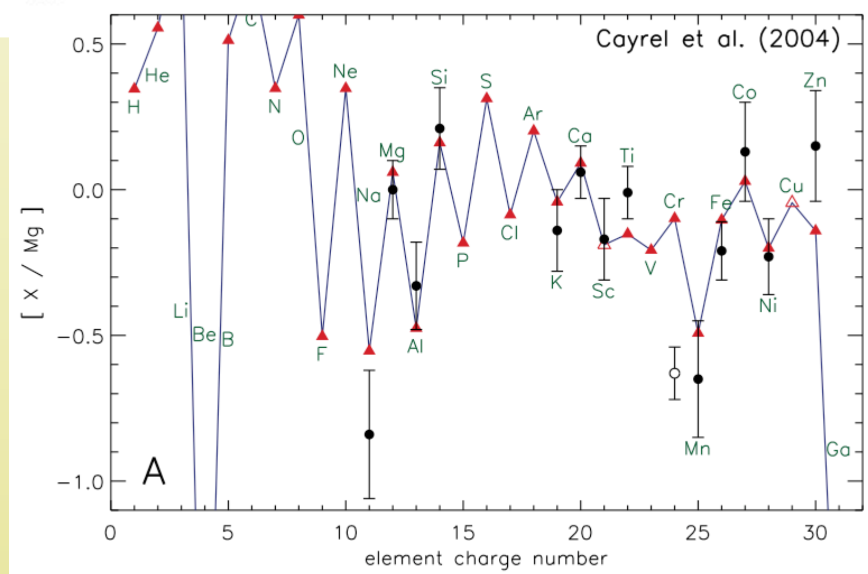
- E51 = 3.0 (dashed line)
- E51 = 120 (solid line)

Best fit models:

-11$M_\odot$ PopIII SN with 0.61.2E^{51}

- 10-100$M_\odot$ Salpeter MF, 0.9E^{51}

(fitting of SN nucleosynthesis grid)



Cookbook -- part 2
Nuclear astrophysics

- Types of metal-poor stars

r-process elements in metal-poor stars

⇒ main r-process (strongly r-process enhanced stars) ~8-10Msun progenitors (Qian+Wasserburg 03, Wanajo et al. 06a)

⇒ weak r-process signature: massive >20Msun progenitors (PopIII) (e.g. Ishimaru et al 05)

Question: Why do all of the strongly enhanced r-process stars have [Fe/H]~-3.0?

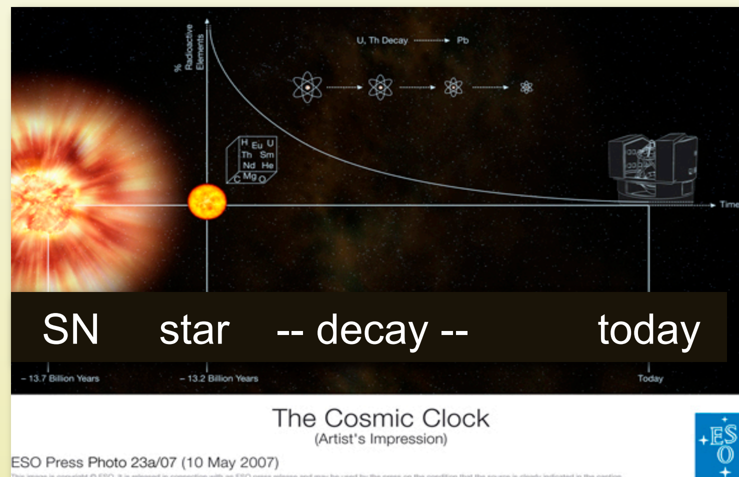
Why important?
r-process metal-poor stars provide the only available diagnosis for rapid nucleosynthesis and the search for its astrophysical sites and initial conditions

r-Process Enhanced Stars

(rapid neutron-capture process)

- Responsible for the production of the heaviest elements
- Most likely production site: SNe II => pre-enrichment
- Chemical “fingerprint” of previous nucleosynthesis event (only “visible” in the oldest stars because of low metallicity)

- ~5% of metal-poor stars with [Fe/H] < - 2.5 (Barklem et al. 05)
  ⇒ Only 15-20 stars known so far with [Eu/Fe] > 1.0



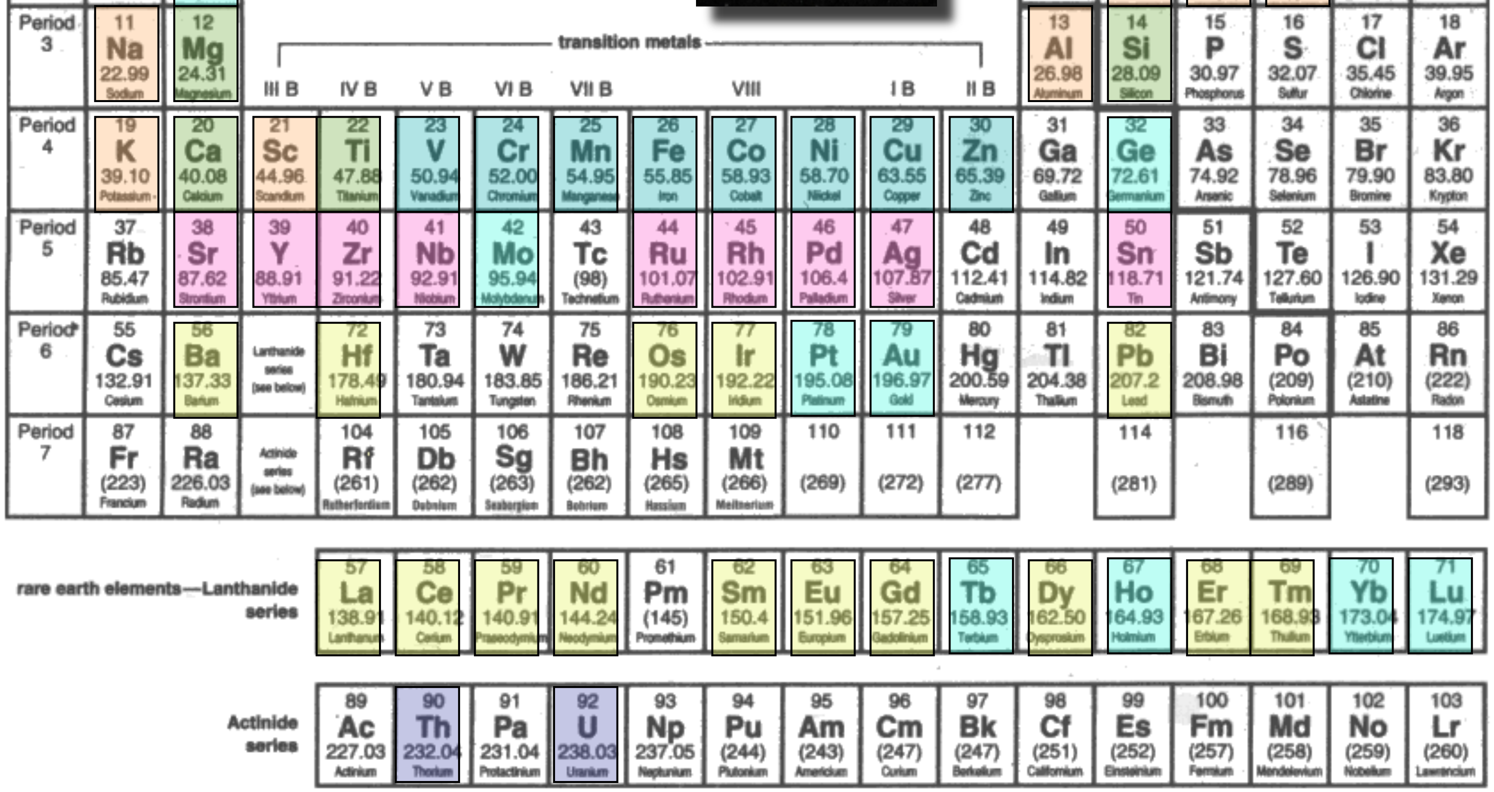
Nucleo-chronometry: obtain stellar ages from decaying Th, U and stable r-process elements (e.g. Eu, Os)

[Th and U can also be measured in the Sun, but the chemical evolution has progressed too far; required are old, metal-poor stars from times when only very few SNe had exploded in the universe]

COSMIC LABS: R-PROCESS ENRICHEDSTARS

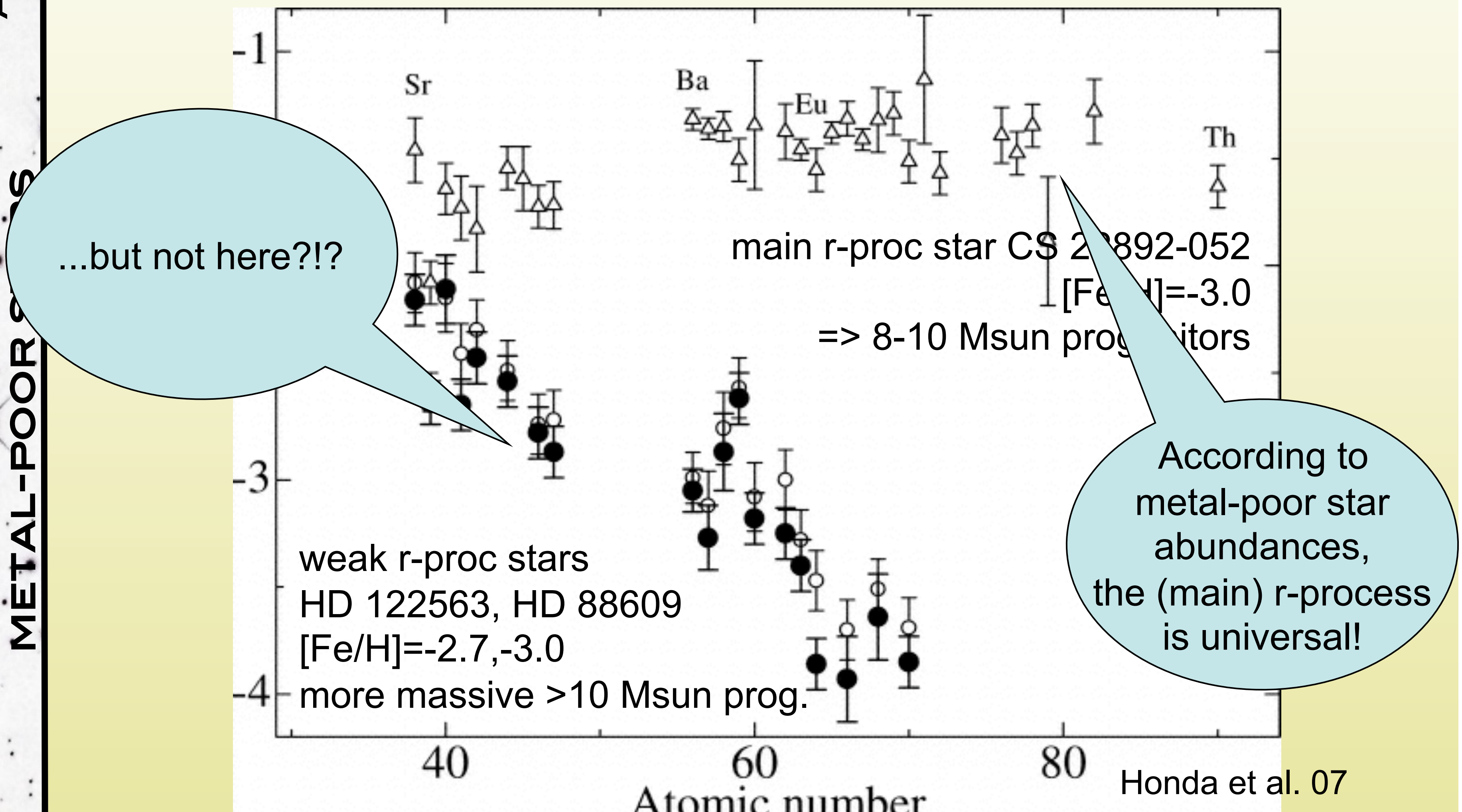
HE 1523-0901
B = 12.1 mag
T_{eff} = 4630 ± 70K
log g = 1.0 (red giant)
[Fe/H] = −3.0

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



Relative difference between "main" and "weak" r-process

Relative difference between "main" and "weak" r-process



Honda et al. 07

Cookbook part 3 -- Near-field cosmology

- Types of metal-poor stars:

*All metal-poor stars -- preferably in the *least* luminous systems*

⇒ Chemical patterns with "outliers" abundances **may show individual** (intrinsic) massive first star signatures

⇒ But generally, chemical evolution is **universal** at low metallicity!

⇒ The Galactic building blocks were likely **not very different** from the surviving dwarf galaxies orbiting the Milky Way now

Why important?

The least luminous dwarf galaxies may be closely related to the very first galaxies. Their metal-poor stars provide a new opportunity to study early star/galaxy formation AND the formation of the halo

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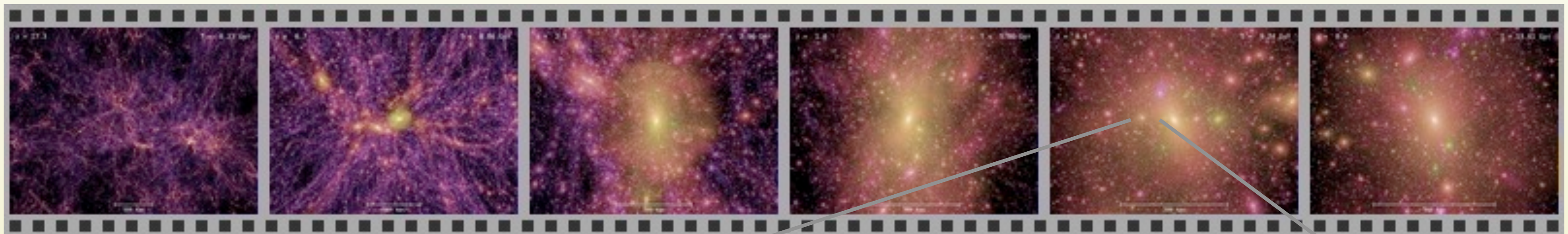
What to do with metal-poor stars

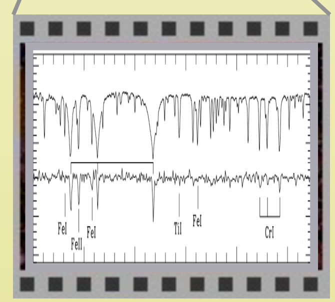
What does stellar archaeology have to do with galaxy formation?

In the ‘dark matter’ world: λCDM hierarchical structure formation model



In the ‘luminous’ world: Comprehensive understanding of galaxy formation

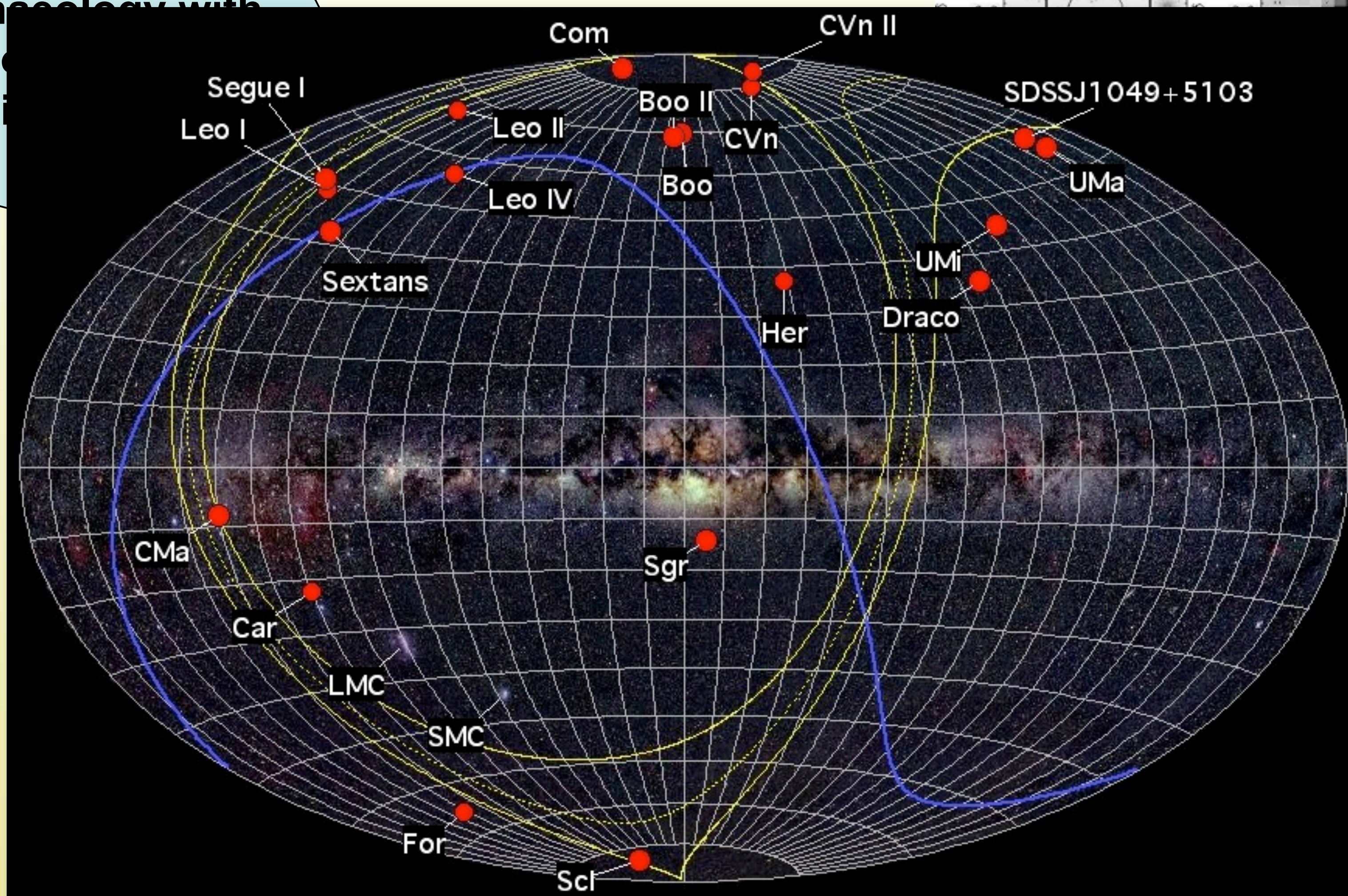
Spectroscopic observations of stellar populations and streams (=luminous matter)



Metallicity-Luminosity Relation

Stellar arch... the m... stars i...

Ultra-faint dwarfs



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*
- Dwarf galaxies may be closest relatives to first galaxies

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...

ANNA FREBEL

WHAT TO DO WITH METAL-POOR STARS

ULTRA-FAINT DWARF GALAXY *STELLAR* ABUNDANCES

Comparison with Cayrel+ 04 halo data (**black open circles**)

h… MW halo

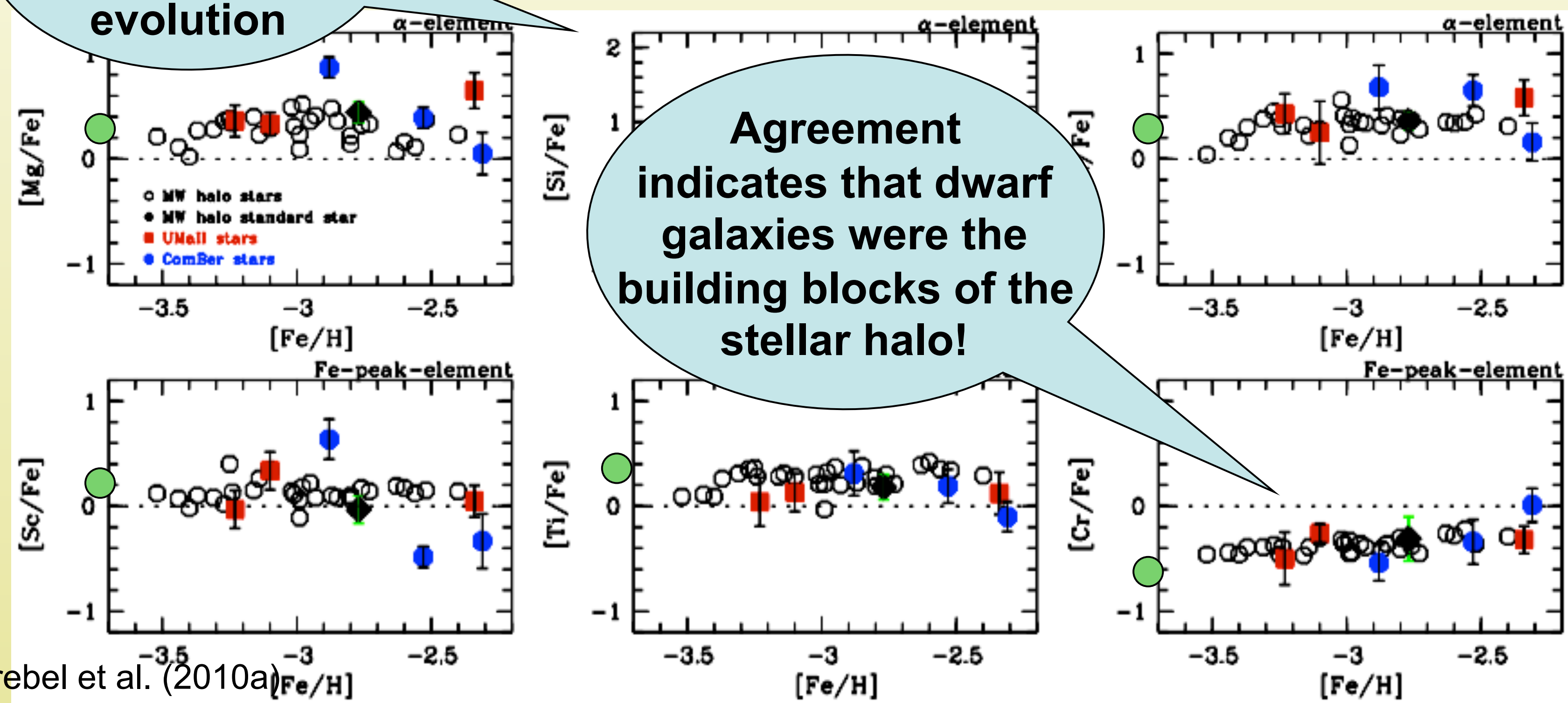
red squares: Ursa Major II

blue dots: Coma Berenices

Scl target (Frebel+10b)

Excellent agreement with the MW chemical evolution

Agreement indicates that dwarf galaxies were the building blocks of the stellar halo!

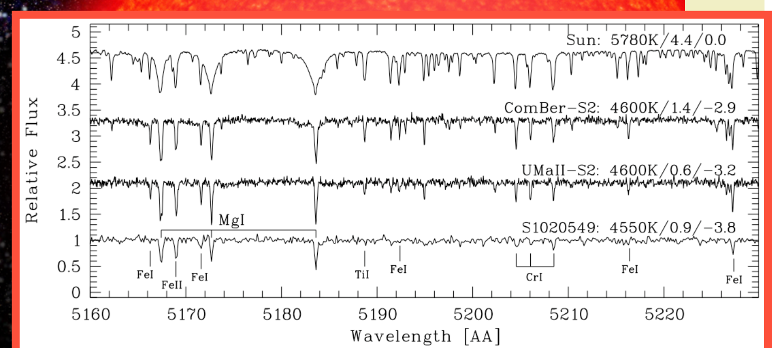


Frebel et al. (2010a)

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)!

New [Fe/H] = -3.8 star in the classical dSph Sculptor
(selected from Kirby et al. 2009)



Frebel, Kirby+Simon 2010b, Nature
(published last Thursday!!)

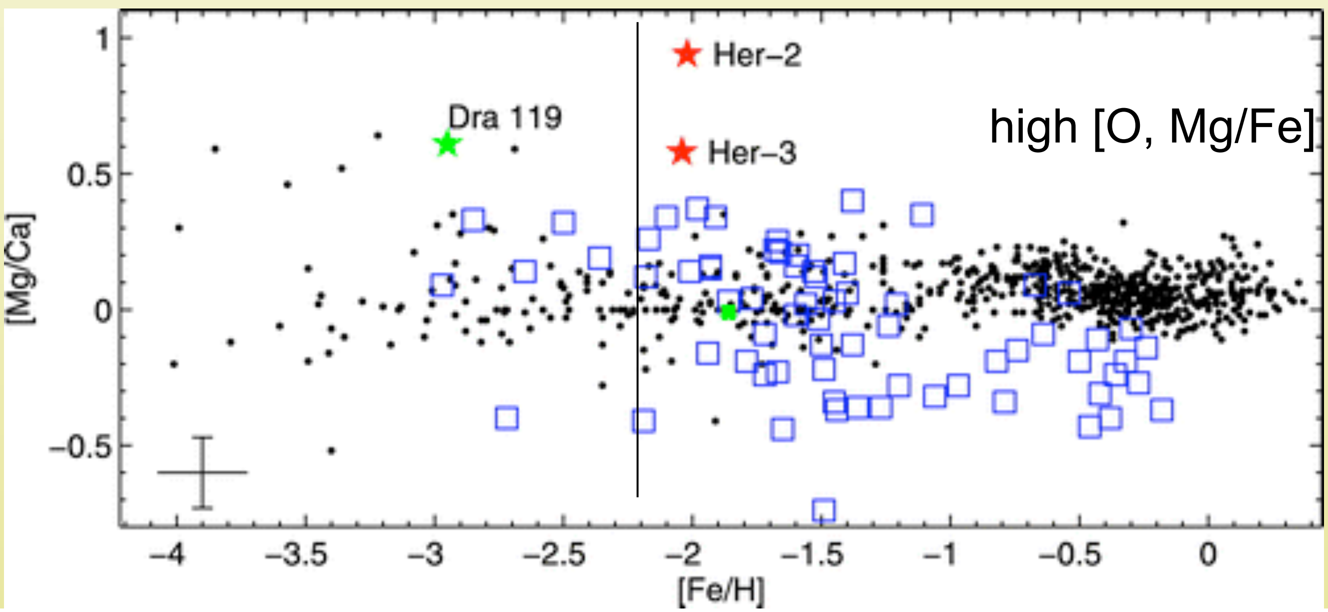
Individual supernova signatures?

Hercules dwarf galaxy (Koch et al. 08): stochastic evolution?

- "This suggests that either our stars are composed mainly of the **ejecta from the first, massive, Population III stars** (but at moderately high [Fe/H]), or that SN ejecta [..] were **diluted with ~30 times less hydrogen** than typical for extreme metal-poor stars."

Bootes I dwarf galaxy (Norris et al. 09):

- "Boo–1137 likely originated in a star-forming region where the abundances reflect either **poor mixing of SN ejecta**, or **poor sampling of the SN progenitor mass range**, or both."



high [O, Mg/Fe] ratios

Cook book part 4 -- Theoretical predictions

- Types of metal-poor stars:

The most iron- and carbon-poor stars

⇒ Top heavy IMF

⇒ Is there a “natural” critical metallicity?

Outer halo stars with kinematic properties

⇒ Are there PopIII low-mass stars? Have they been polluted to appear as PopII metal-poor stars?

What is the lowest observable metallicity?

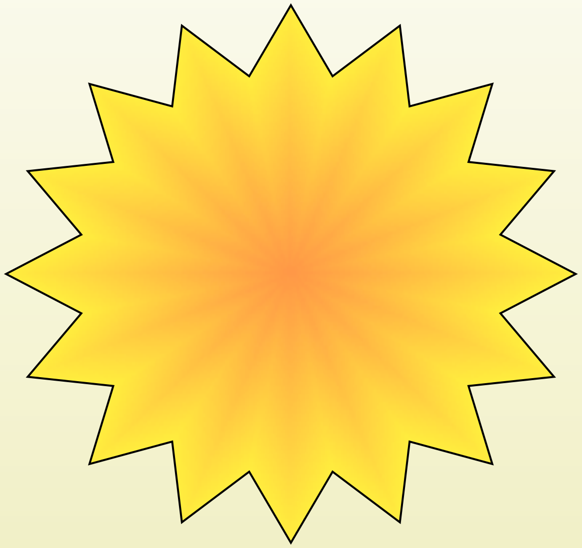
=> It depends on the IMF -- kinematic information crucial for searches

Why important?

Metal-poor stars are the **local versions of high redshift objects** and thus provide a unique opportunity to put early Universe theories to the test!

STAR FORMATION IN THE EARLY UNIVERSE

***BIG QUESTION*:**
What governs the transition between these two mass ranges?



First Stars: ~100 $M_\odot$
(e.g. Bromm+ '99, '01; Abel+ '00, '02
Tan & McKee 04, Yoshida et al. 08)

?

Working group III

Observable metal-poor stars: ~0.6 - 0.8 $M_\odot$

Need a cooling mechanism to facilitate fragmentation to small enough masses

- Bromm & Loeb 2003: "critical metallicity" of ISM
- Schneider et al. 2003: dust cooling

=>*Observational tests needed to confirm/refute such theories!*

Stellar archaeology: Testing early star formation theories

Bromm & Loeb 2003 → Frebel, Johnson & Bromm 2007

Bromm & Loeb 2003

Condition for formation of **low mass stars** in the early Universe:

Cooling of ISM by **C II and O I fine-structure lines**

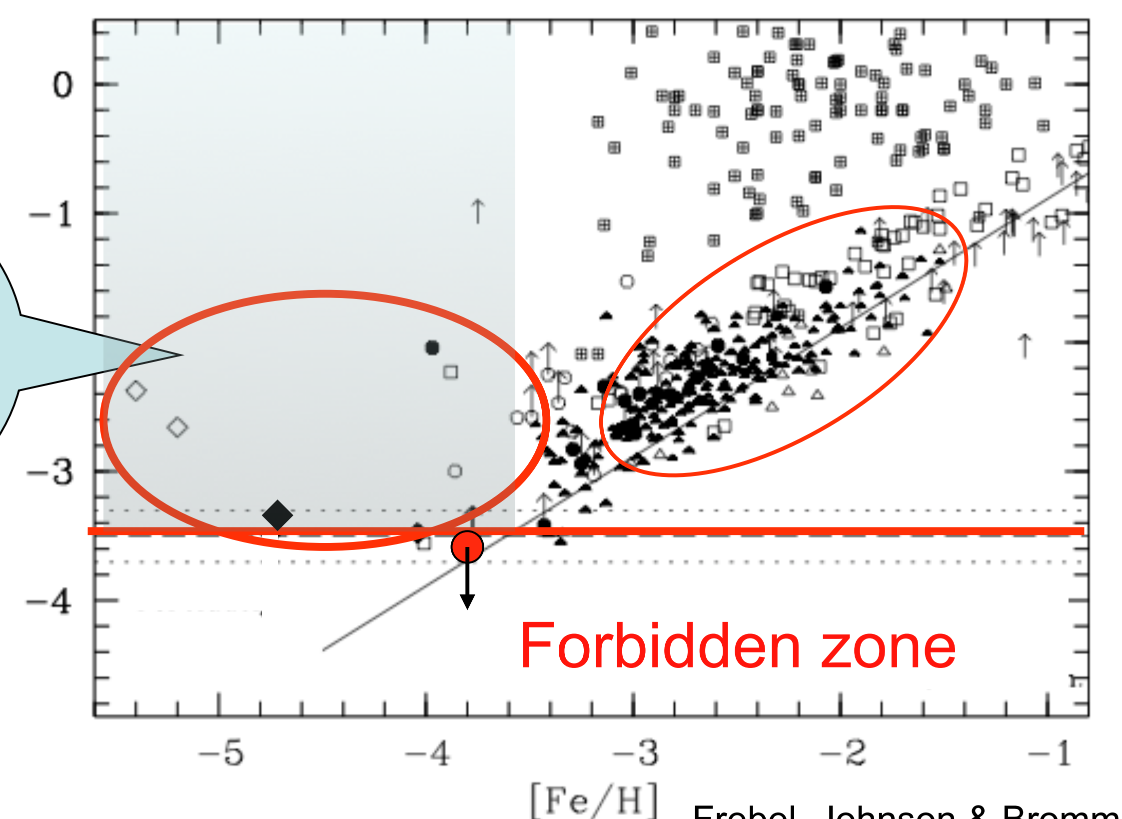
Frebel, Johnson & Bromm 2007

Observationally testable criterion:

$D_{trans} = \log_{10}(10^{[C/H]} + 0.3 \times 10^{[O/H]}) > -3.5$

Prediction:
Stars with [Fe/H]<-4.0 should posses large C and O excesses!

“Dust crit. metallicity"



Frebel, Johnson & Bromm 2007

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)

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

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

⇒ $[Mg/H]_{min} = -6.0$

(Frebel, Johnson & Bromm 2009)

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

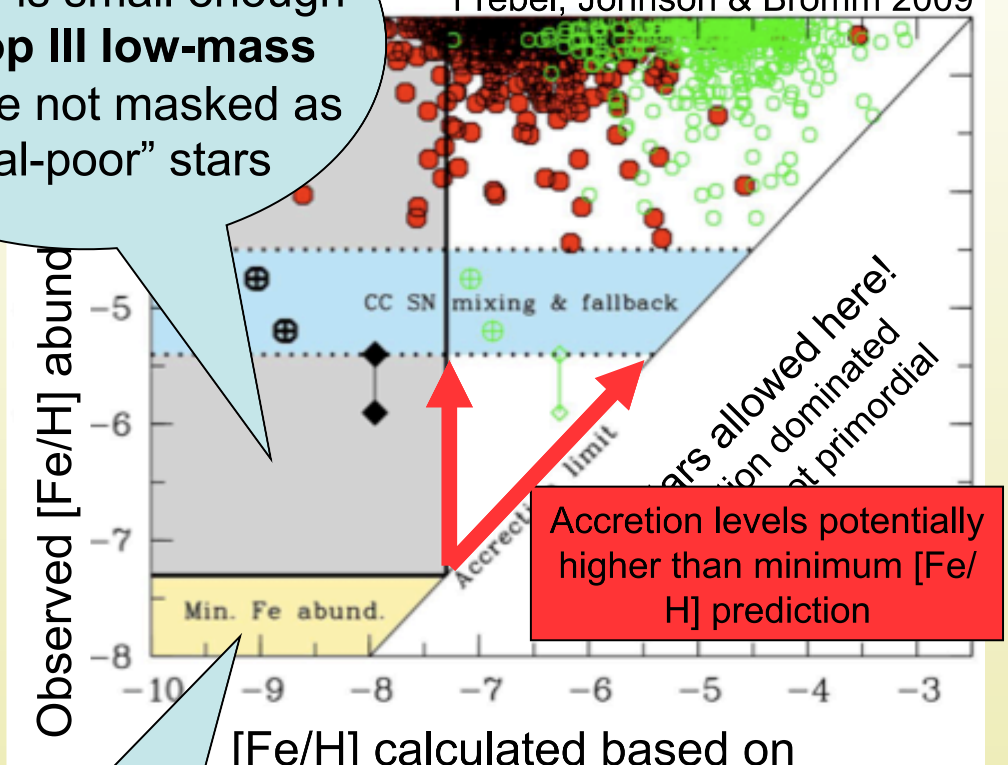
This is an important prediction for what may be discovered with the next generation of optical 20-40m telescopes!

BUT, is it physically possibly to find such low-Fe stars?
Or are there even lower-metallicity stars than that?

ACCRETION DOES NOT PREVENT US ROM FINDING SUCH STARS!

Stars in this region: pollution is small enough that **Pop III low-mass stars** are not masked as “metal-poor” stars

Frebel, Johnson & Bromm 2009



[Fe/H] calculated based on ISM accretion over 10 Gyr

Outer halo with extreme kinematics signatures are best candidates!

Data -- 400 SDSS metal-poor stars

Worst accretion case

[Fe/H] yield prediction by faint core-collapse SN

“IMF-sensitive” region (negligible accretion-pollution!)

Implications

Stars in the gray regime: We can then test the IMF!

Stars ABOVE $[Fe/H]_{min}$: top-heavy IMF likely

Stars BELOW $[Fe/H]_{min}$: low-mass PopIII stars exist

(=Salpeter-like IMF)

WHAT TO DO WITH METAL-POOR STARS

Advertisement:

A compilation of abundances of ~1200 metal-poor stars with [Fe/H]~<-2.0 can soon be found at http://www.cfa.harvard.edu/~afrebel/abundances

(to be published as online-only table in Frebel 2010, AN)