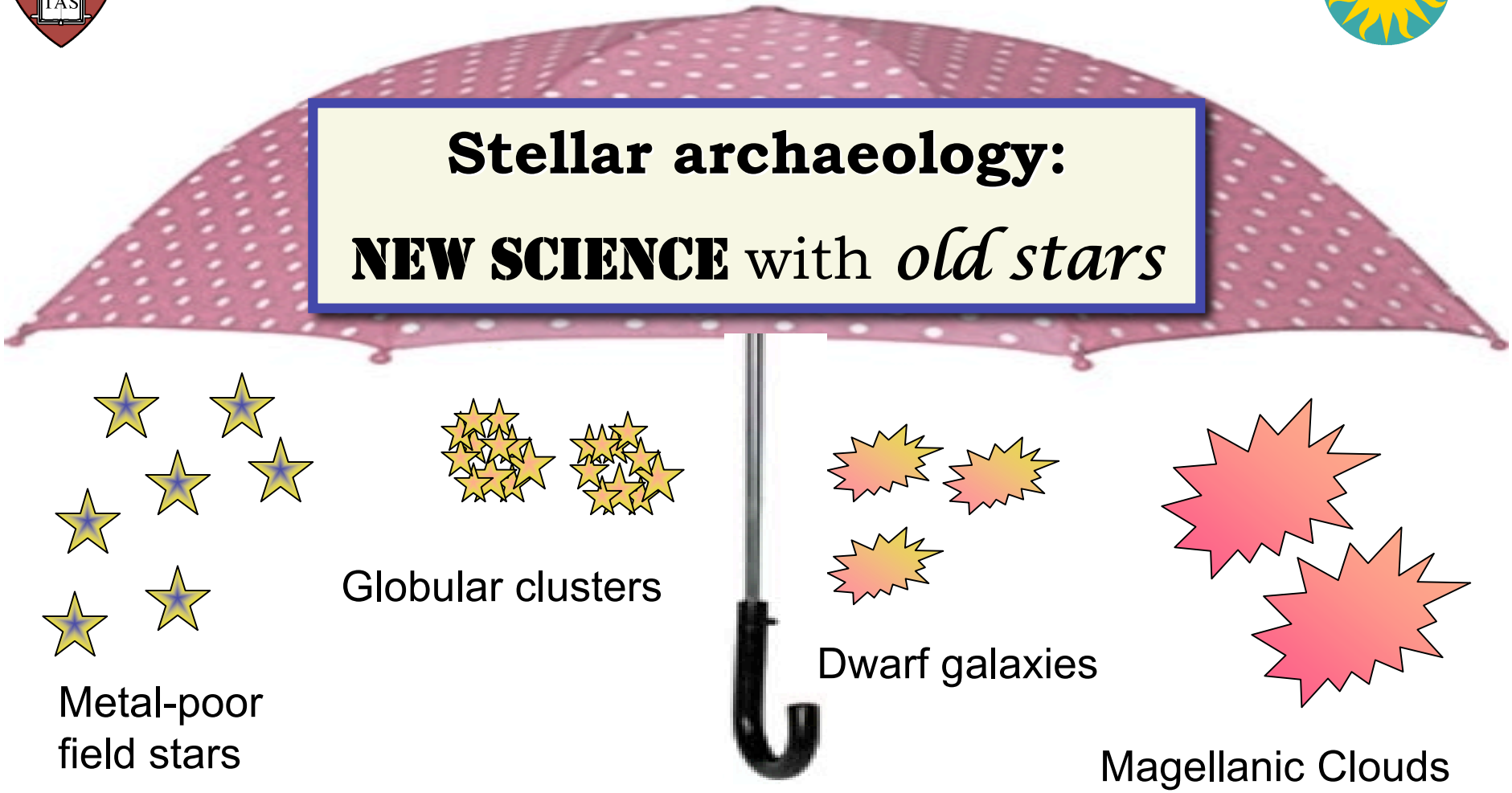


Anna Frebel

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?

- ✓ **Near-field cosmology: Formation of the galactic halo**
  Chemical history of dwarf galaxies & hierarchical galaxy growth

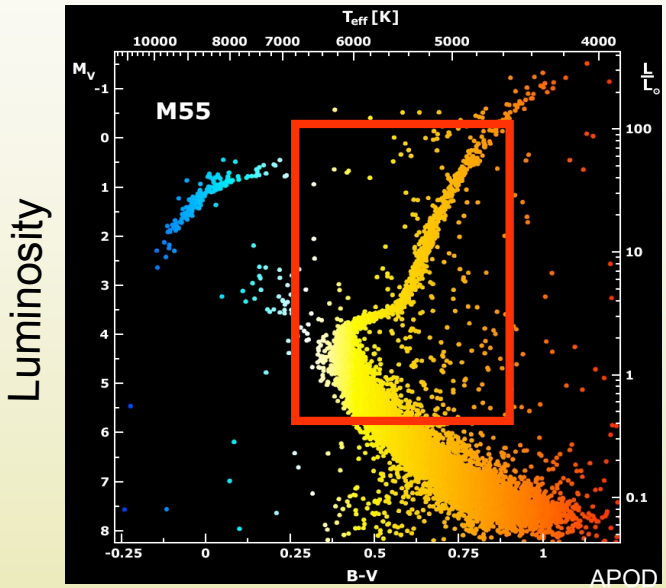
- ✓ **Advertisement: Abundances of ~800 literature stars**
  Do-it-yourself: Plotting abundance trends has never been easier

- ✓ **Giant Magellan Telescope needs JINA/you!!**
  Should the nuc-astro community support G-Clef? (of course..!)

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...

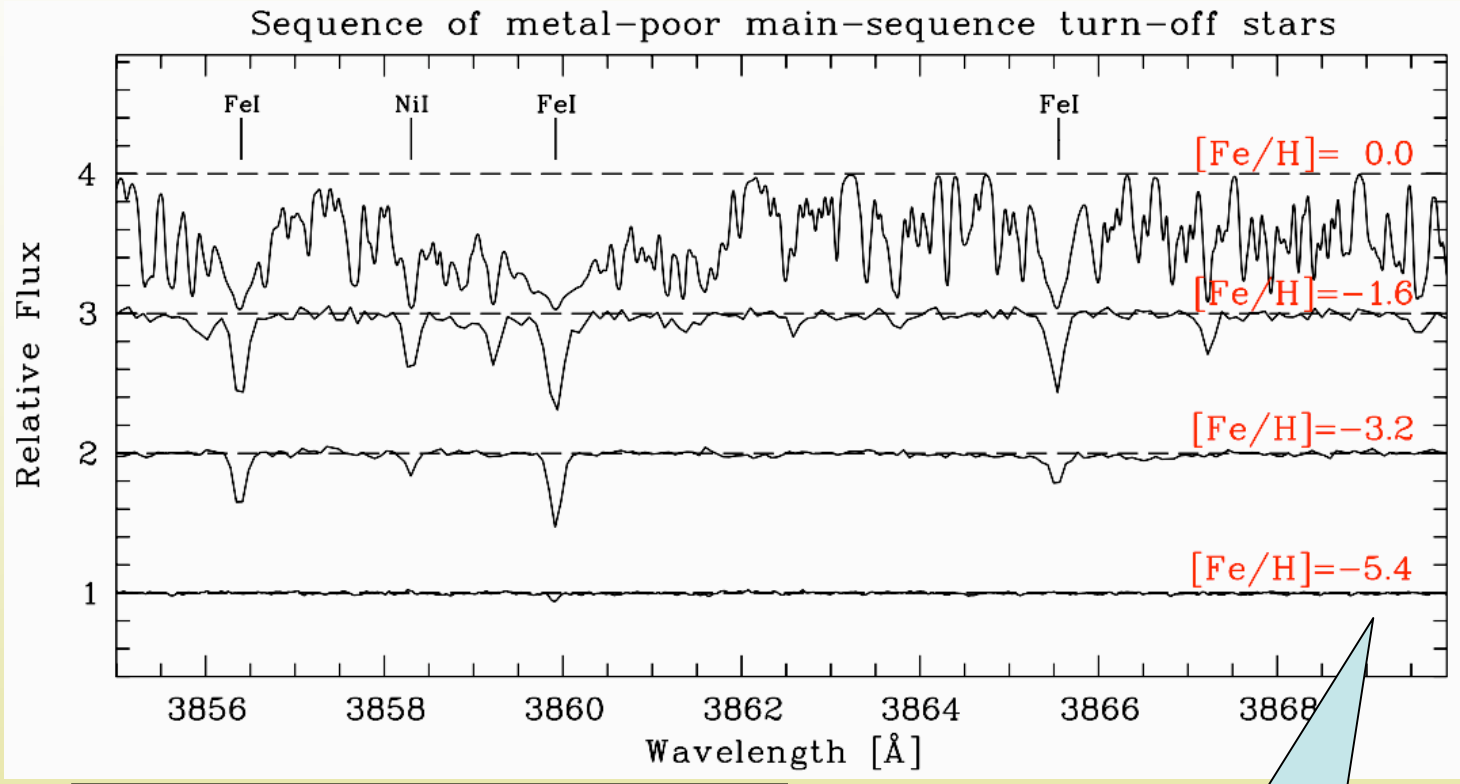
- ✓ Origin and evolution of chemical elements
- ✓ Relevant nucleosynthesis processes and sites
- ✓ Chemical and dynamical history of the Galaxy
- ✓ Lower limit to the age of the Universe

... 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 of the high-redshift Universe!

TAKING A SPECTROSCOPIC LOOK



"Look-back time"

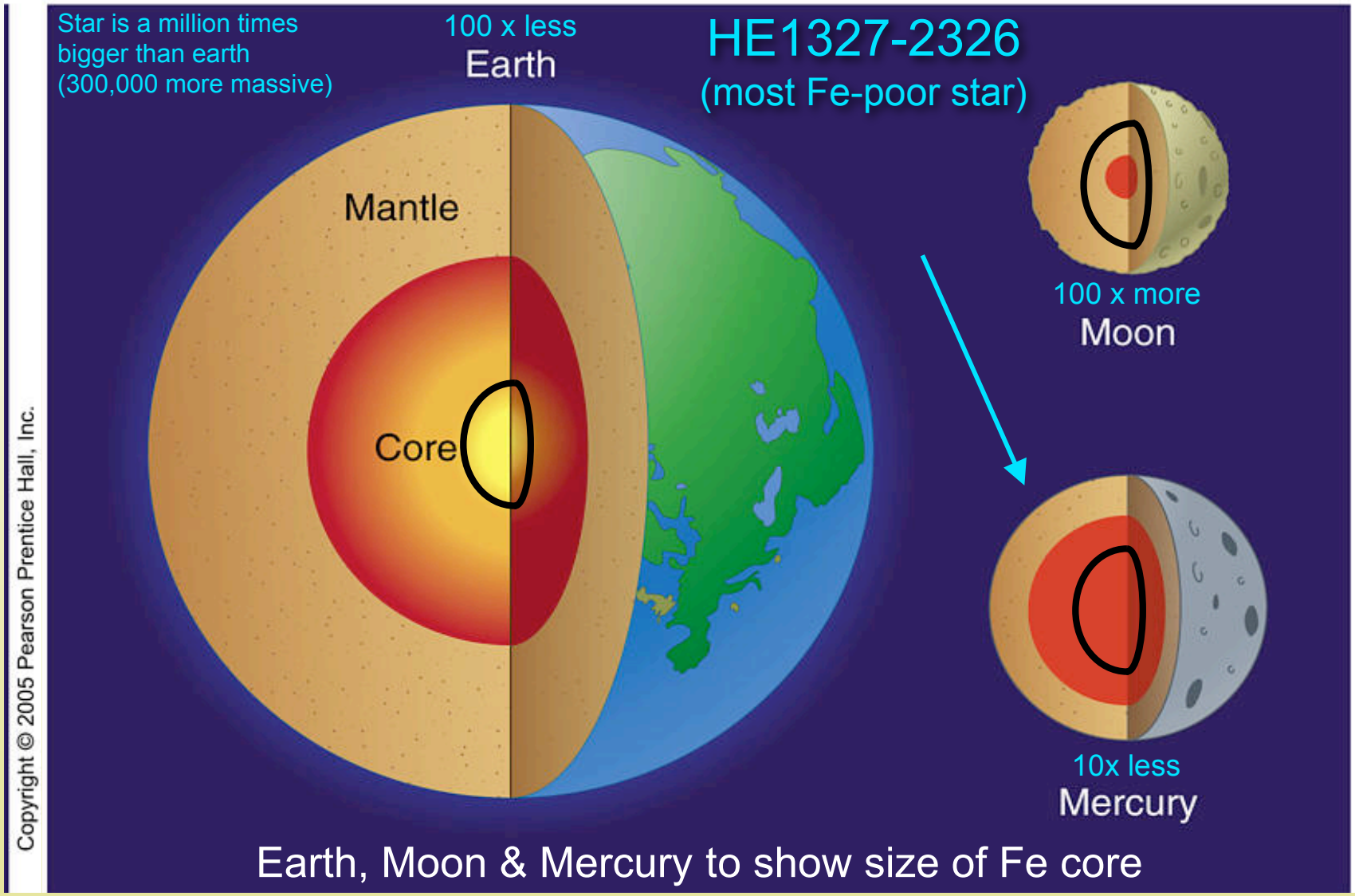
Galactic chemical evolution

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

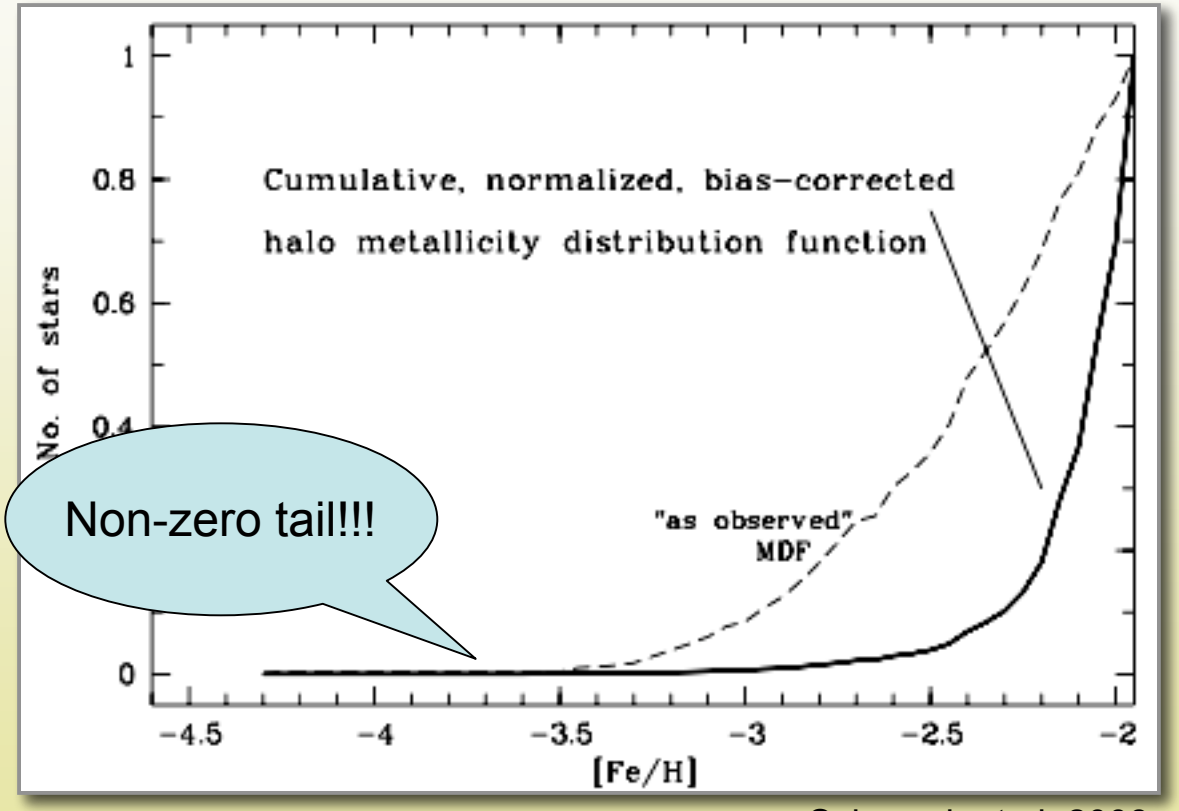
How much iron is in there?



HALO METALLICITY DISTRIBUTION FUNCTION (MDF)

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

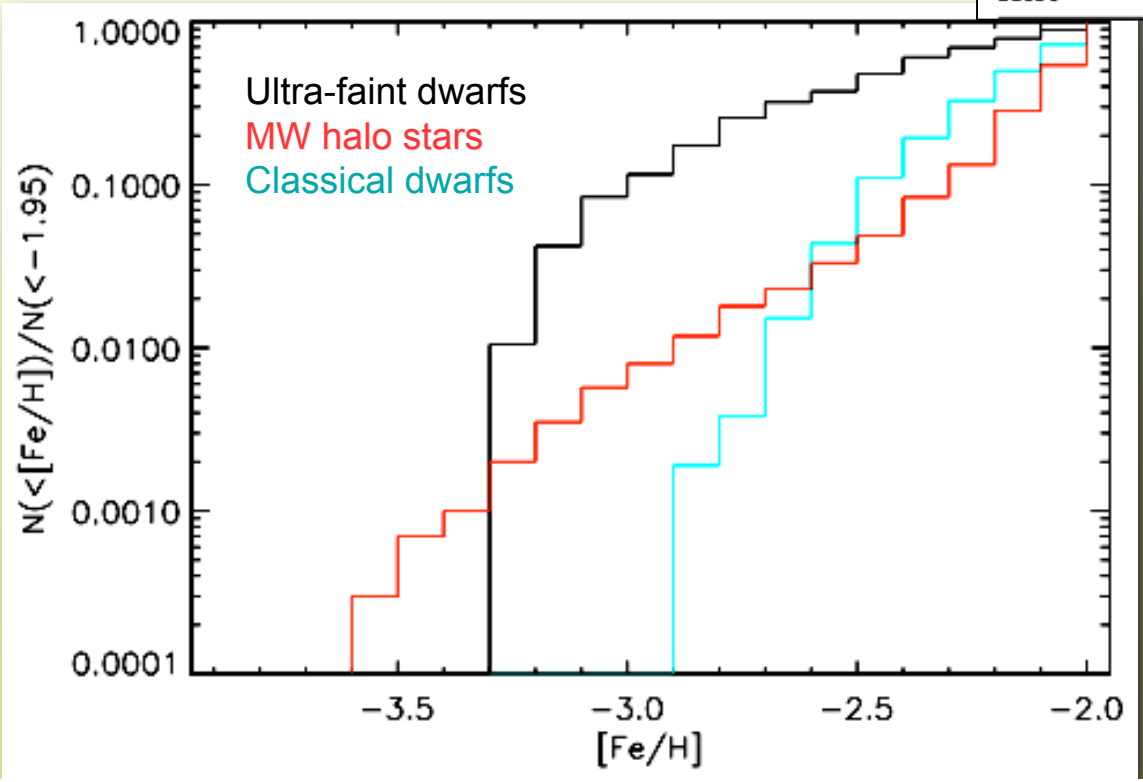
The most metal-poor stars are extremely rare but extremely important!

METALLICITY DISTRIBUTION FUNCTION OF DSPH GALAXIES

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

ULTRAFAINT dSph METALLICITIES

dSph	N^a	$\log (L/L_\odot)^b$	$\langle$[Fe/H]$\rangle$	$\sigma_{[Fe/H]}$
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)

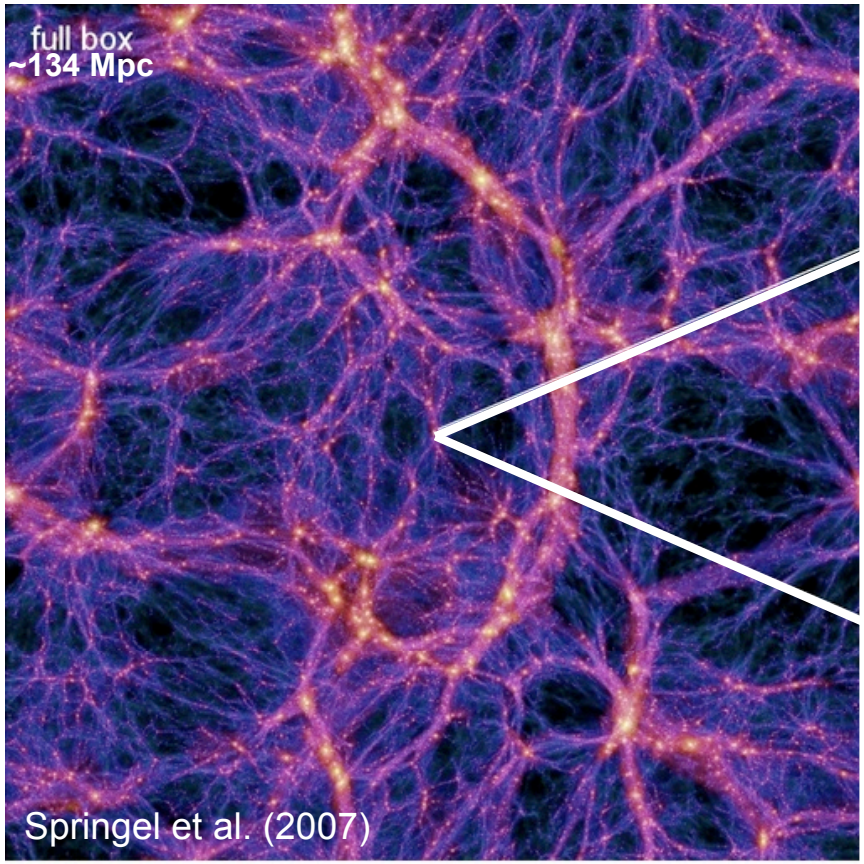
"classical" dSph have no extremely metal-poor stars?!? (Helmi et al. 2006)

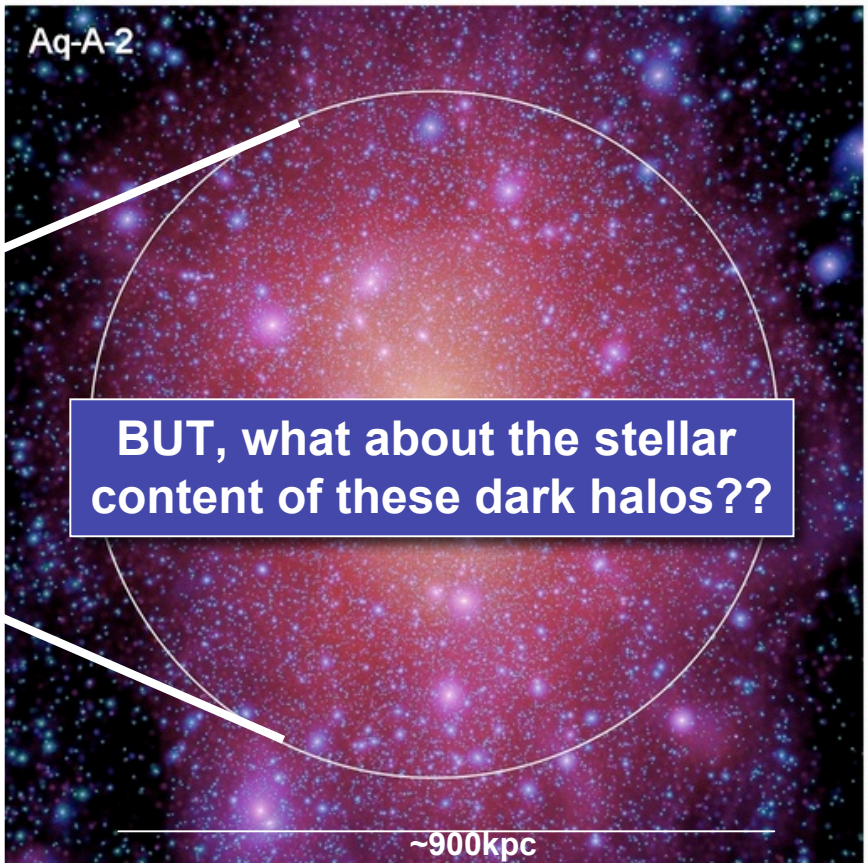
=> yes, they do!

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").

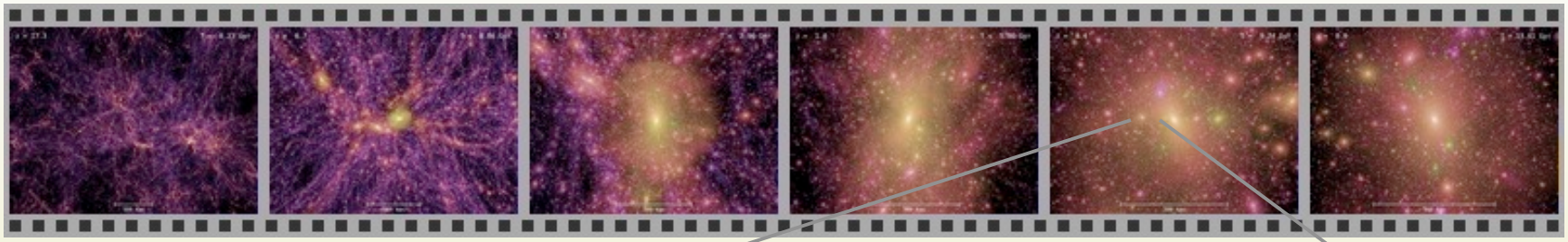
Many small halos survive this process and are predicted to be around today.





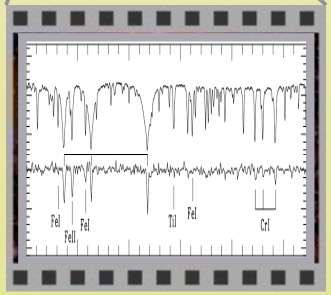
What does stellar archaeology have to do with galaxy formation?

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



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

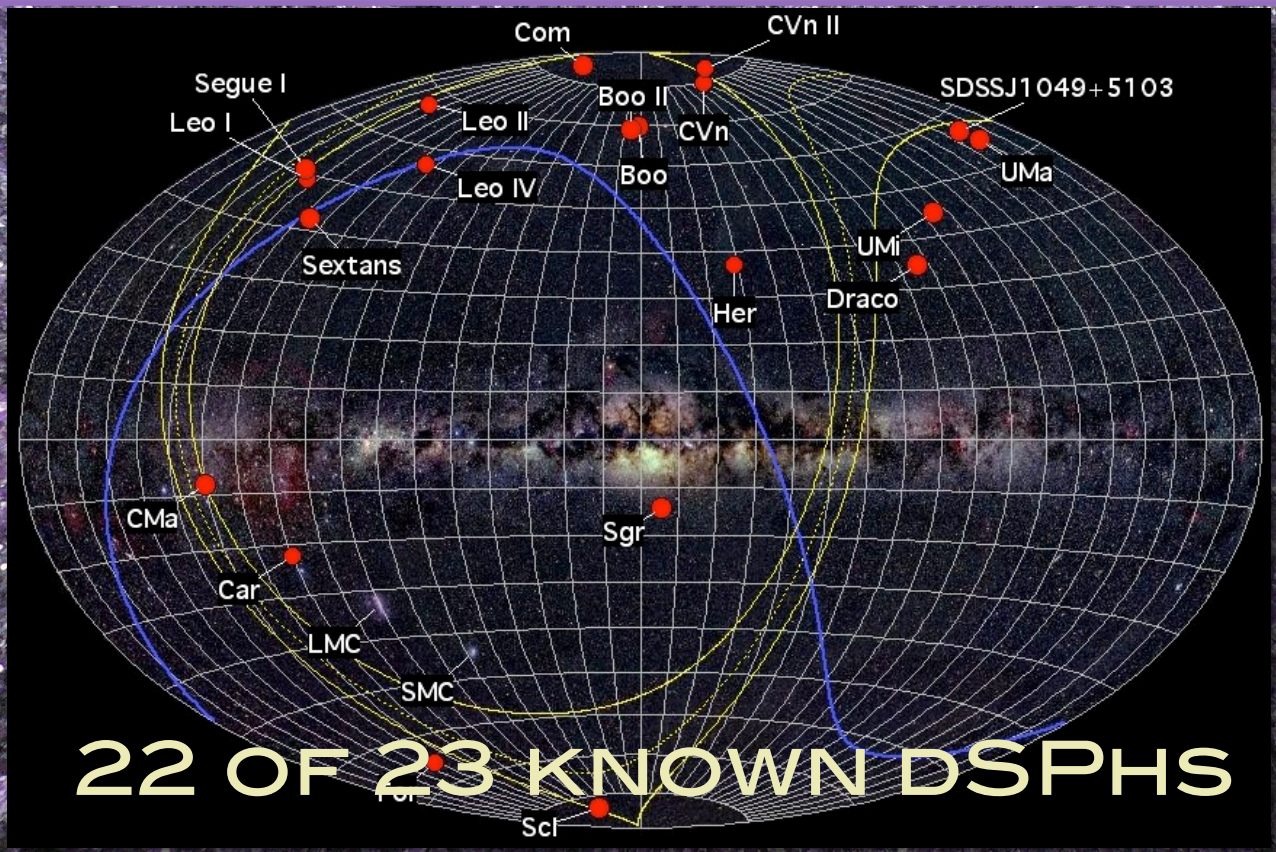
Spectroscopic observations of stellar populations and streams (=luminous matter)



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.



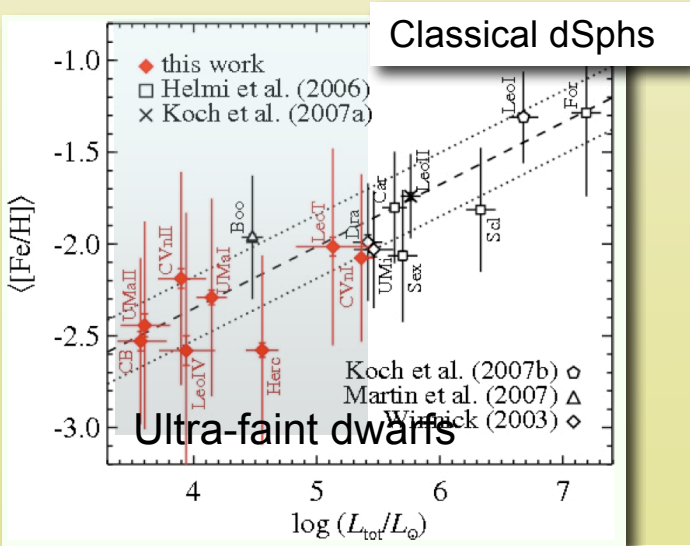
How do the observed dwarf galaxies relate to the MW halo?

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

Stellar metallicities [Fe/H] & abundance ratios [X/Fe] 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 more luminous classical dwarfs; higher metallicity stars show different abundances...

Ultra-faint dwarfs had not been studied before



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)**

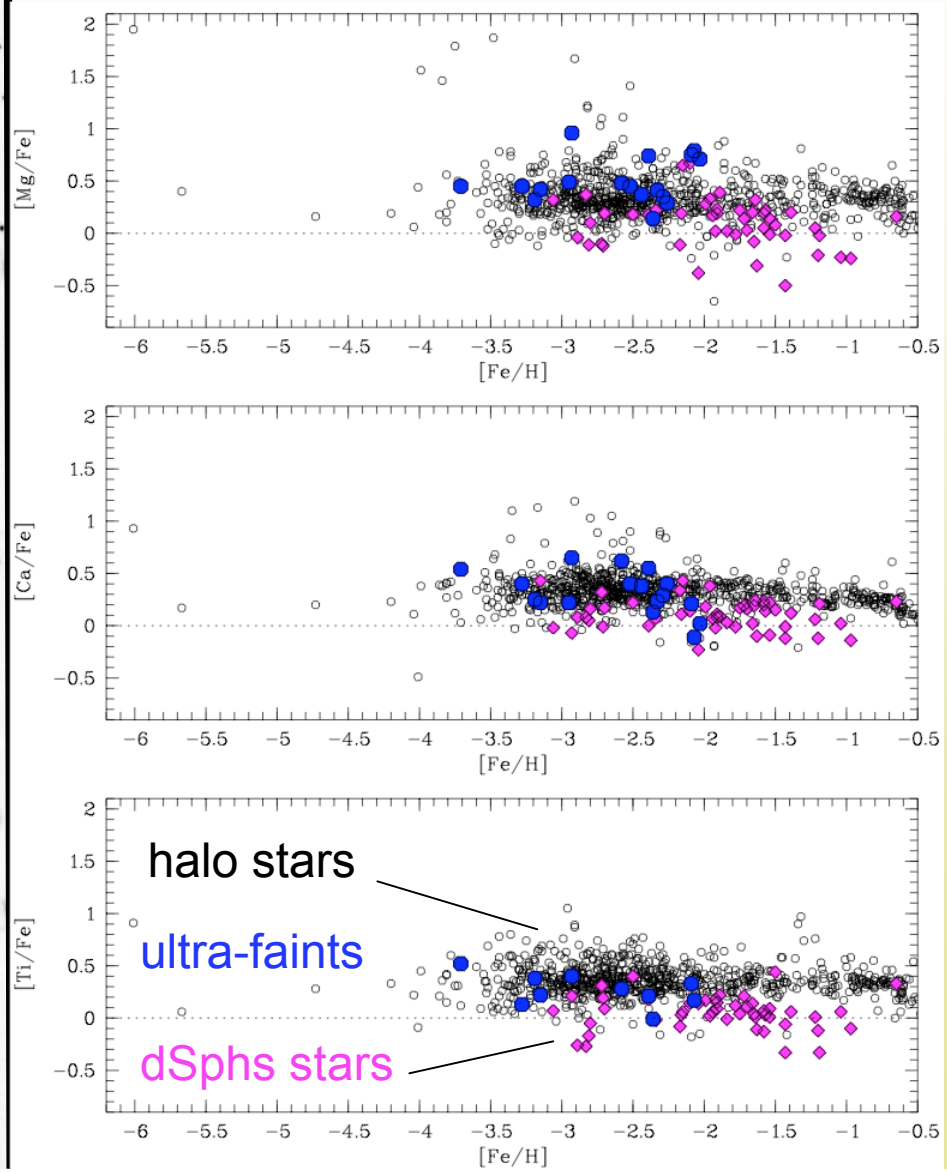
High-res. observations of fainter stars is very challenging...

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)**

We just collected more data (4 more stars!)

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**.

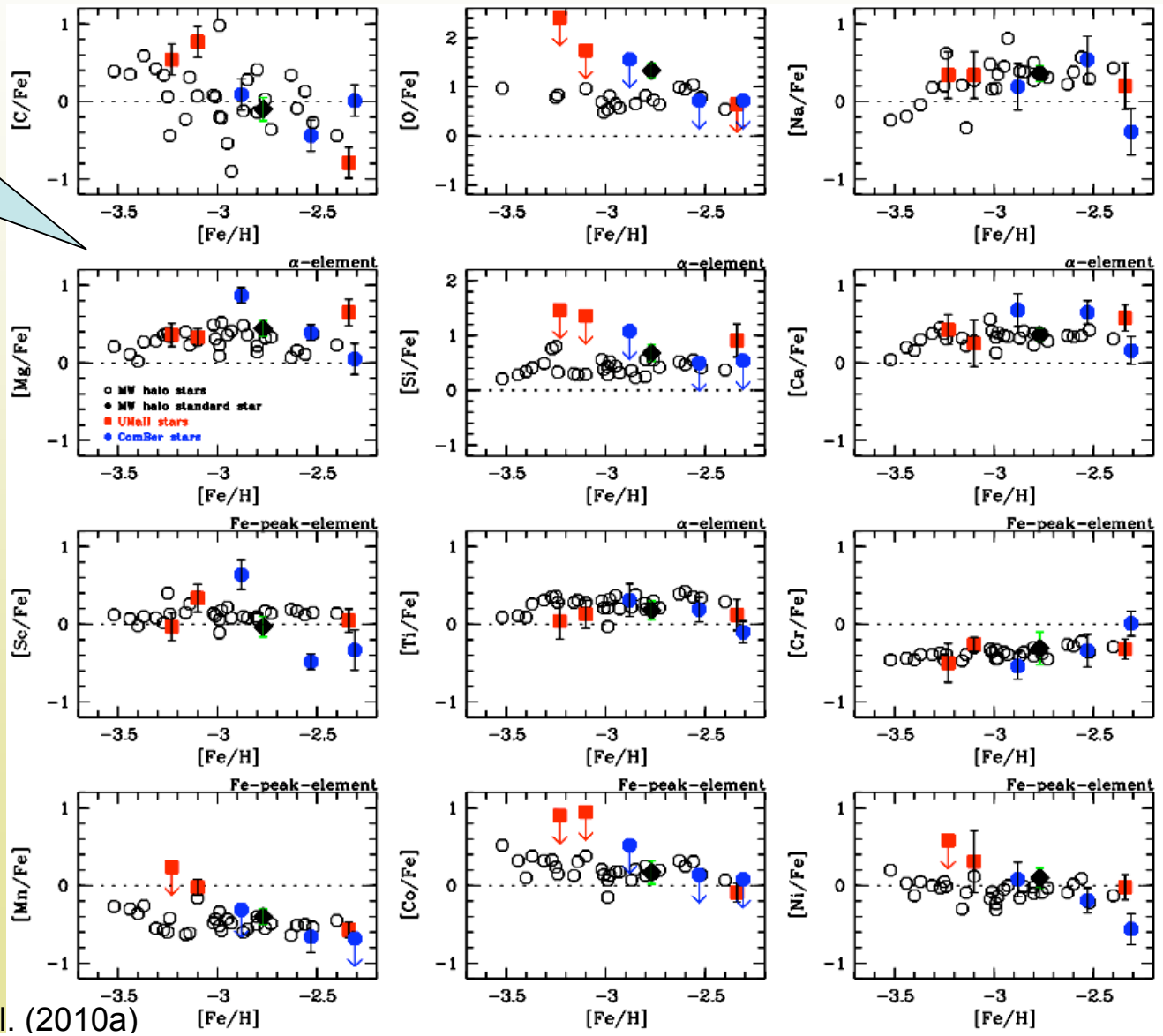
ULTRA-FAINT DWARF GALAXY ABUNDANCES

Excellent agreement with the MW chemical evolution

Cay… …
(black open circles)

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

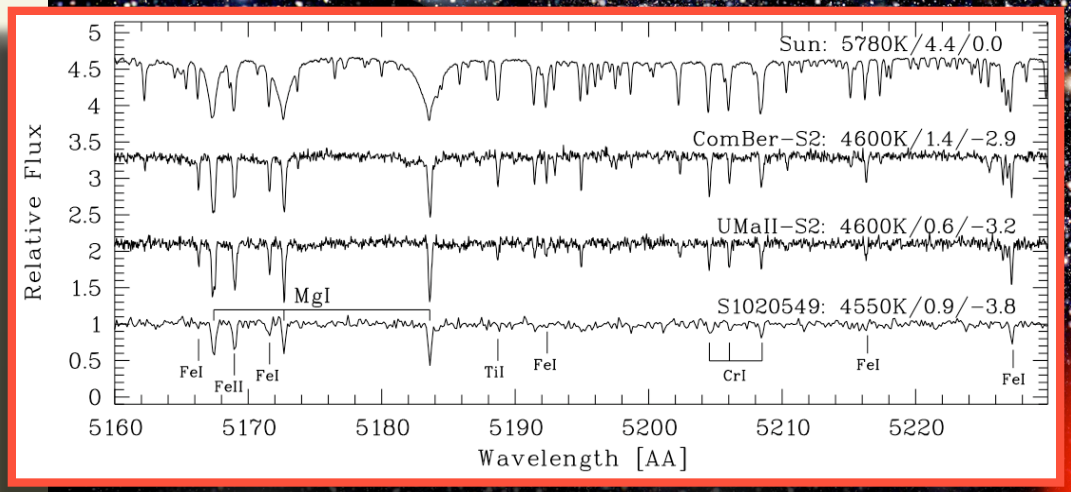
red squares:
Ursa Major II
blue dots:
Coma Berenices
black diamond:
MW halo giant



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

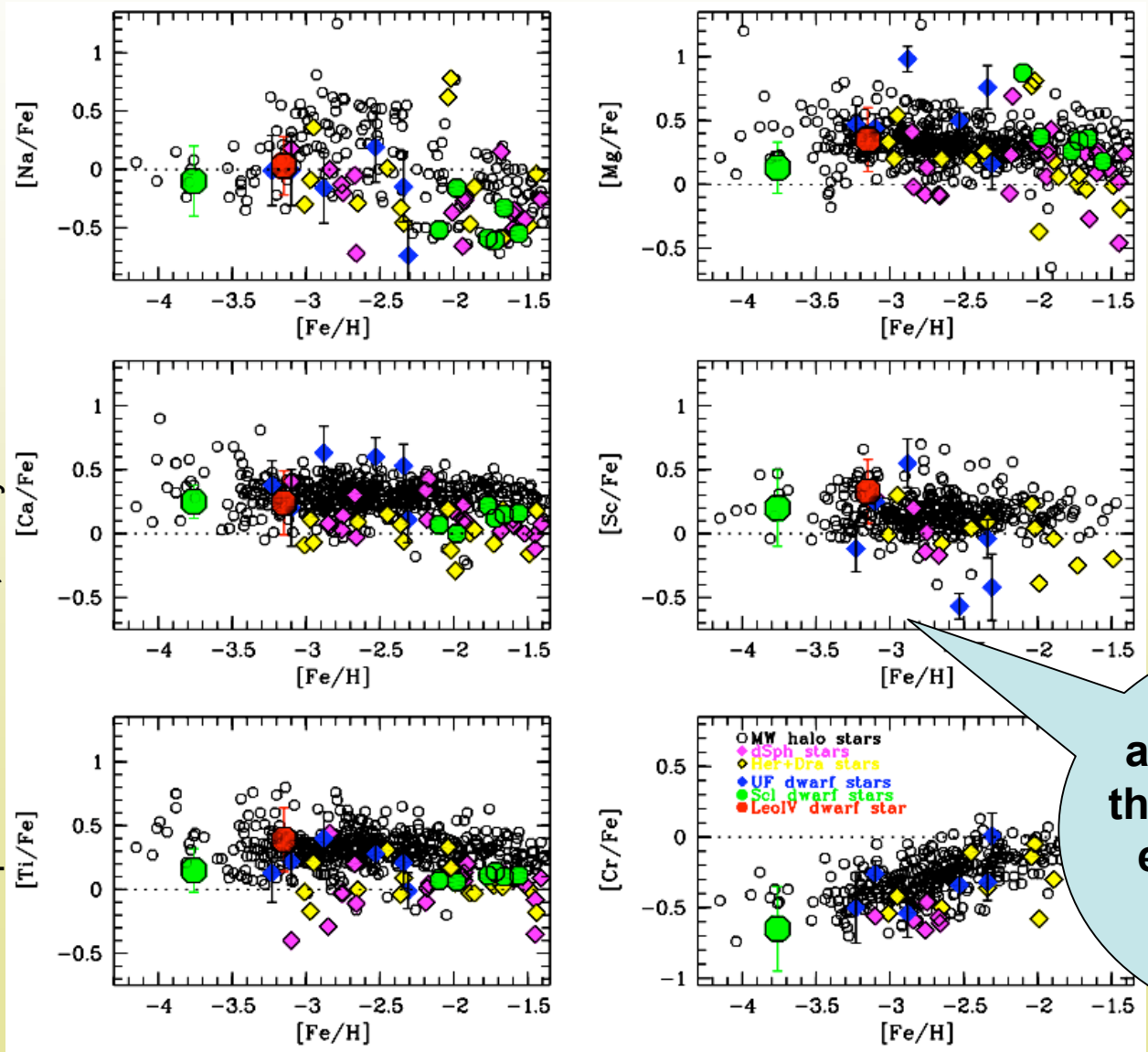
New [Fe/H] = -3.8 star in the classical dSph Sculptor (selected from Kirby et al. 2009)

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

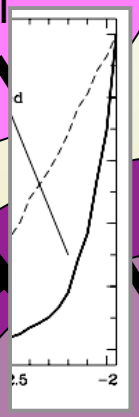
Excellent agreement with the MW chemical evolution; also for Scl and LeoIV!!

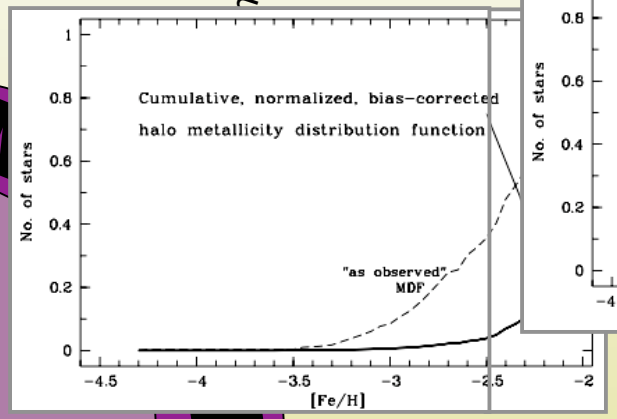
ASSEMBLY OF THE METAL-POOR TAIL OF THE HALO

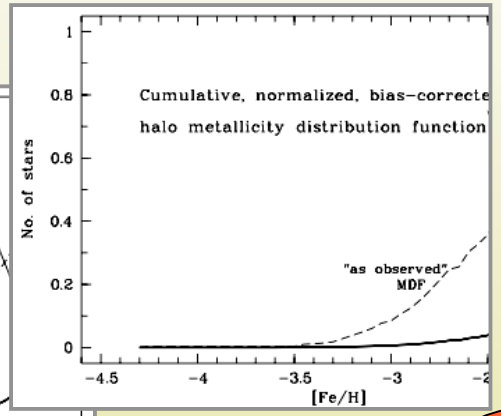
ANNA FREBEL

METAL-POOR STARS

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







metal-poor stars

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

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

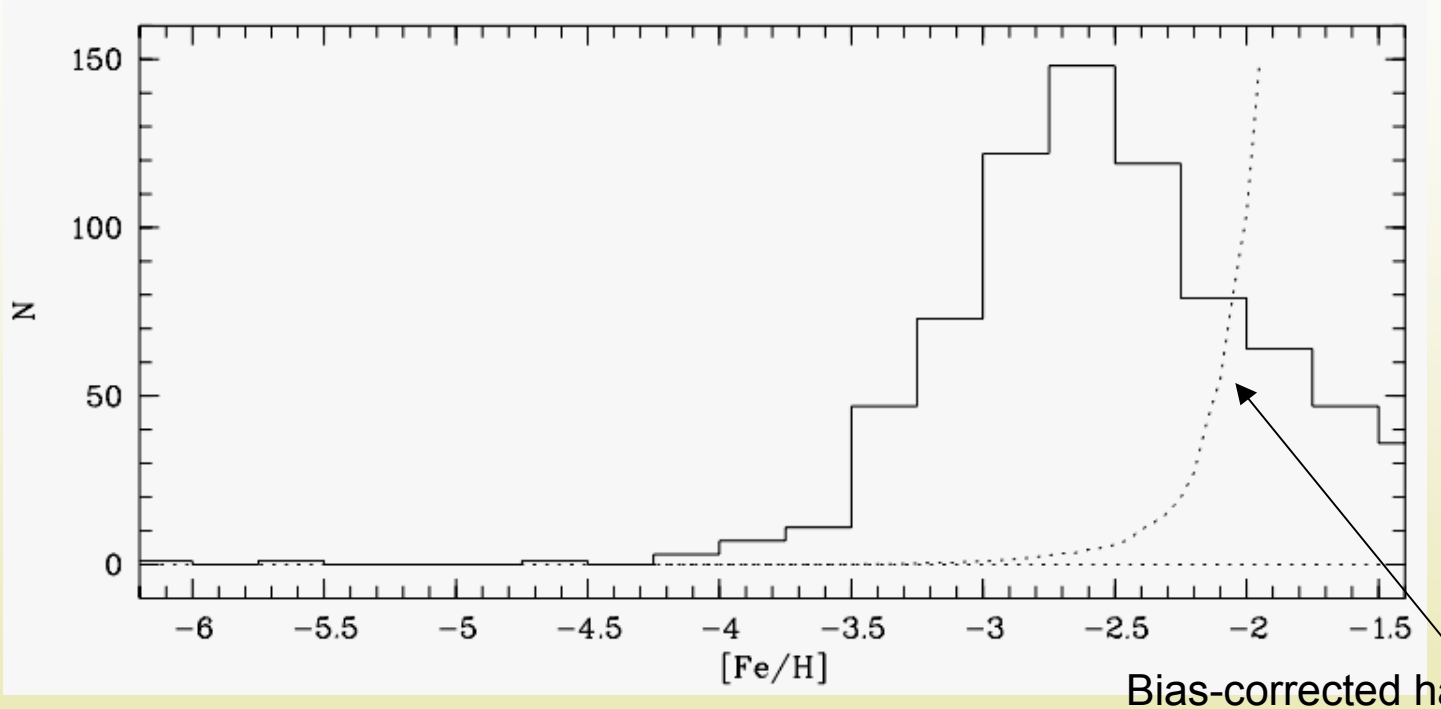
Additional metal-poor stars

"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!?!

...an *Ad* and a *Call for Help!*

METALLICITY DISTRIBUTION OF THE STARS IN THE ABUNDANCE TABLE



Bias-corrected halo MDF
by Schoerck et al. 2009

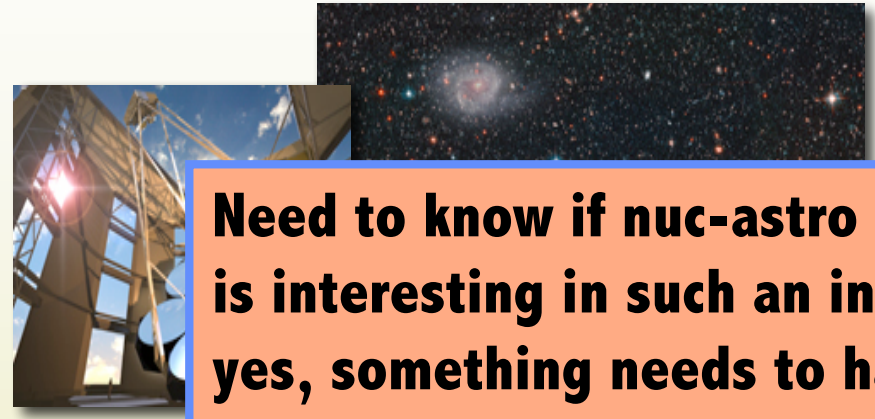
"Advertisement":

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

(to be published in Frebel 2010, AN, review paper)

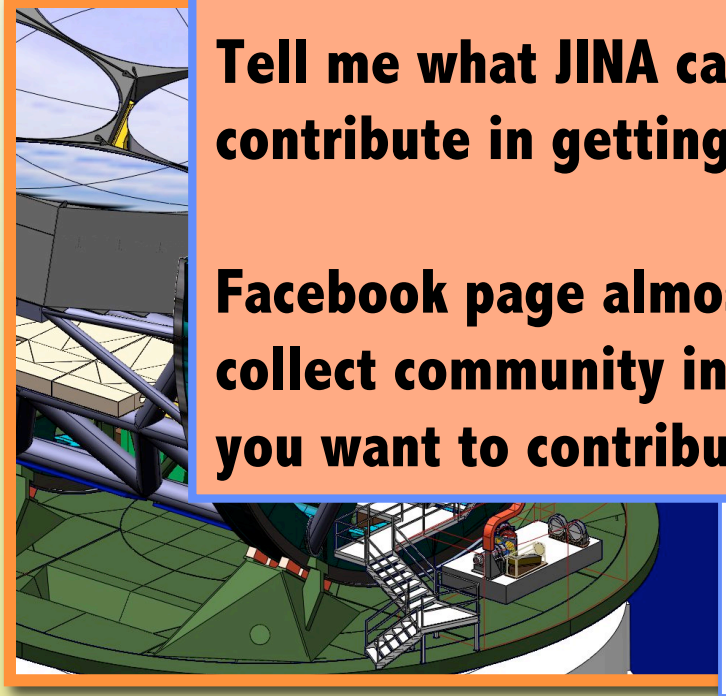
GMT NEEDS YOU..!!!



Need to know if nuc-astro community is interesting in such an instrument. If yes, something needs to happen NOW!

Tell me what JINA can/should contribute in getting G-Clef *selected*!!

Facebook page almost set up to collect community input -- email me if you want to contribute!



lution spectrograph

A; AF member of group

cept study; deadline

all optical stellar cl. U-stars etc.

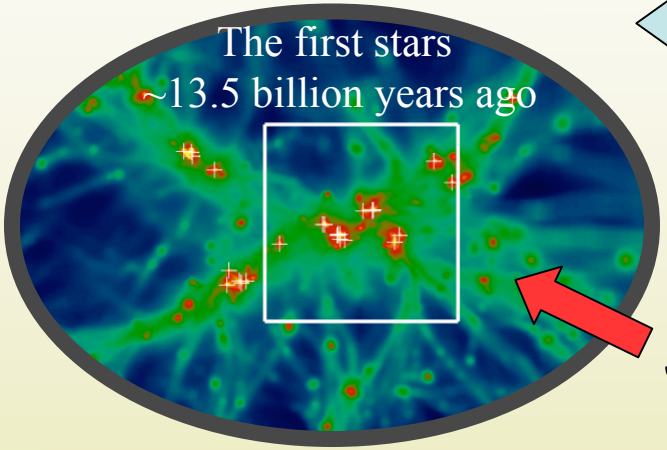
- if not selected, there will be NO high-res spectrograph on the next-gen telescopes in the US!

Take Home "Star Stuff"

Anna Frebel

Metal-poor stars

The first heavy elements
seed stars and galaxies



JINA

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

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