The quest for the most metal-poor stars in the universe

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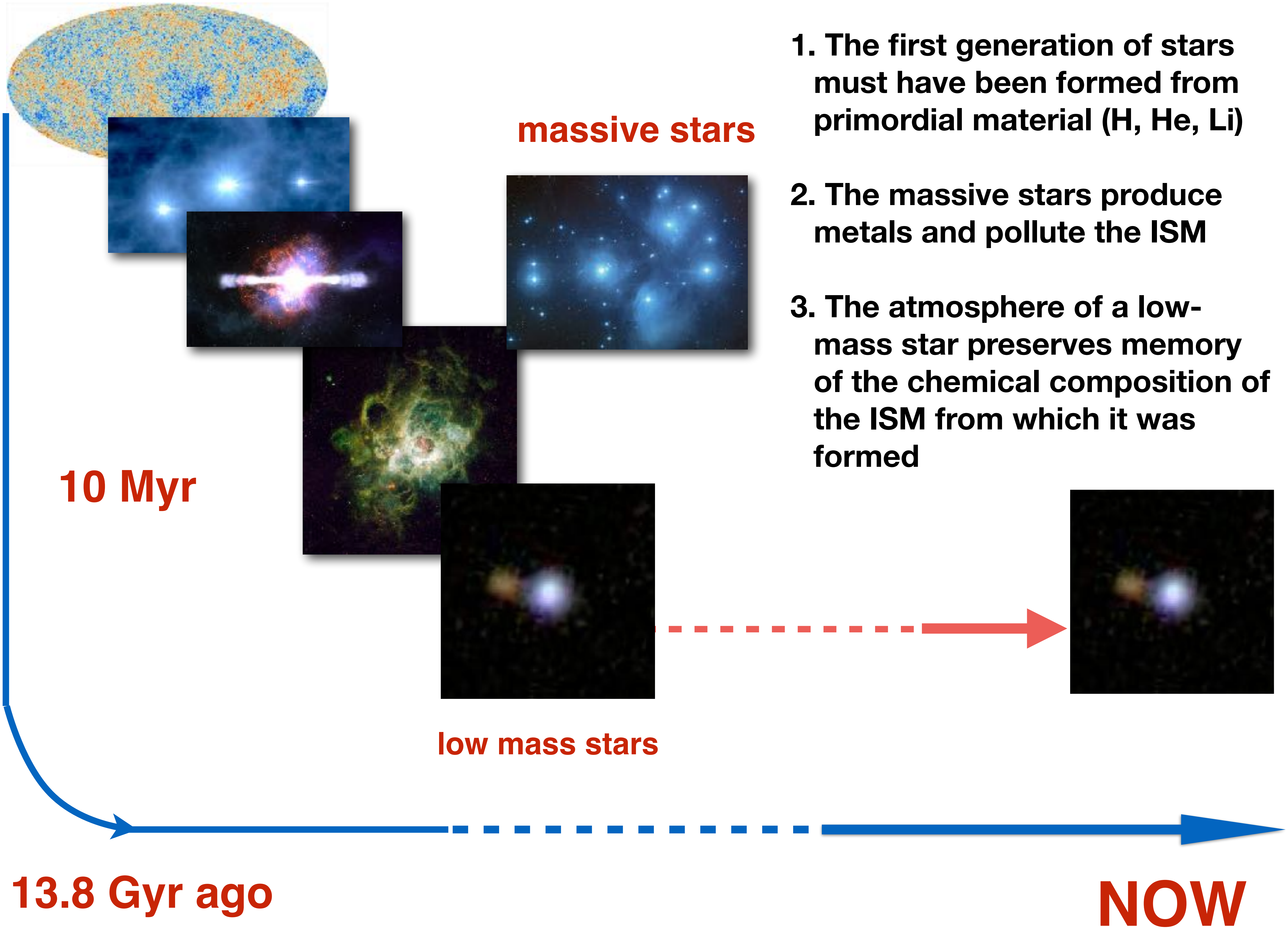

massive stars
1. The first generation of stars must have been formed from primordial material (H, He, Li)
2. The massive stars produce metals and pollute the ISM
3. The atmosphere of a low-mass star preserves memory of the chemical composition of the ISM from which it was formed
10 Myr
low mass stars
13.8 Gyr ago
NOW

The fact that no Pop III star could be found generated some frustration among workers in the field

WHERE IS POPULATION III?

HOWARD E. BOND
Department of Physics and Astronomy, Louisiana State University

Received 1980 December 1; accepted 1981 March 18

And if population III were population II?

R. Cayrel

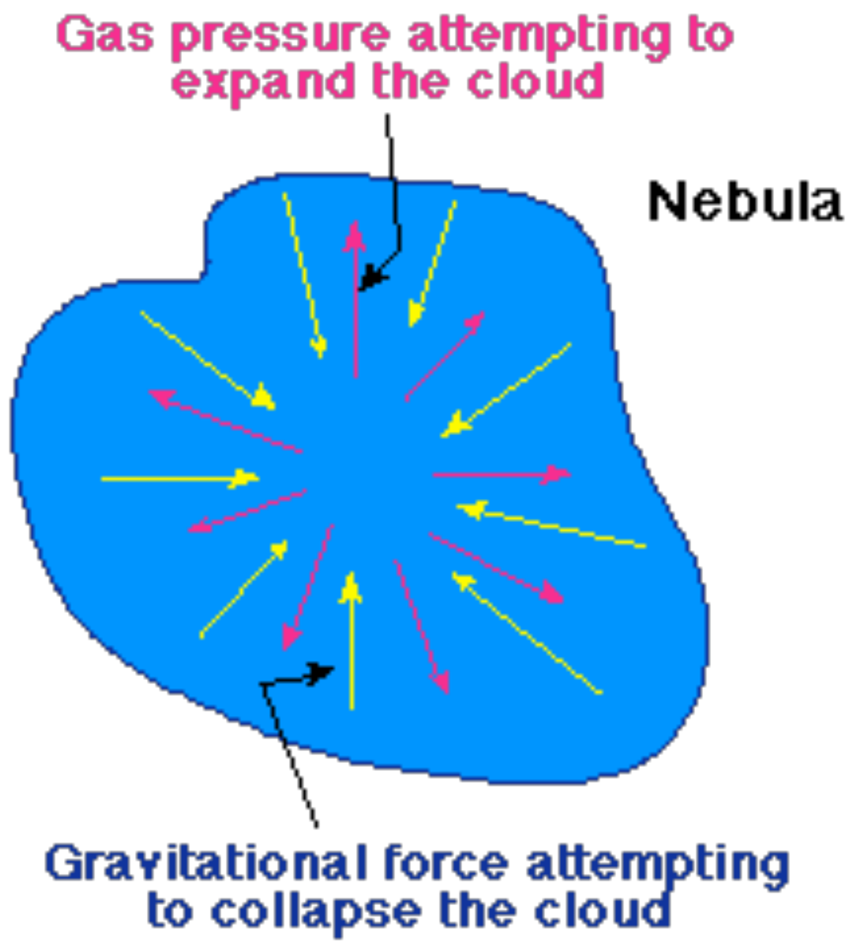
Received January 31, accepted May 5, 1986

What is the limit?

- Observationally:
  - 20 mÅ CaII K => [Ca/H]~ -9.4 (so ~ -10 for [Fe/H])
  - 20 mÅ FeII (3859Å) => [Fe/H] ~ -7.2

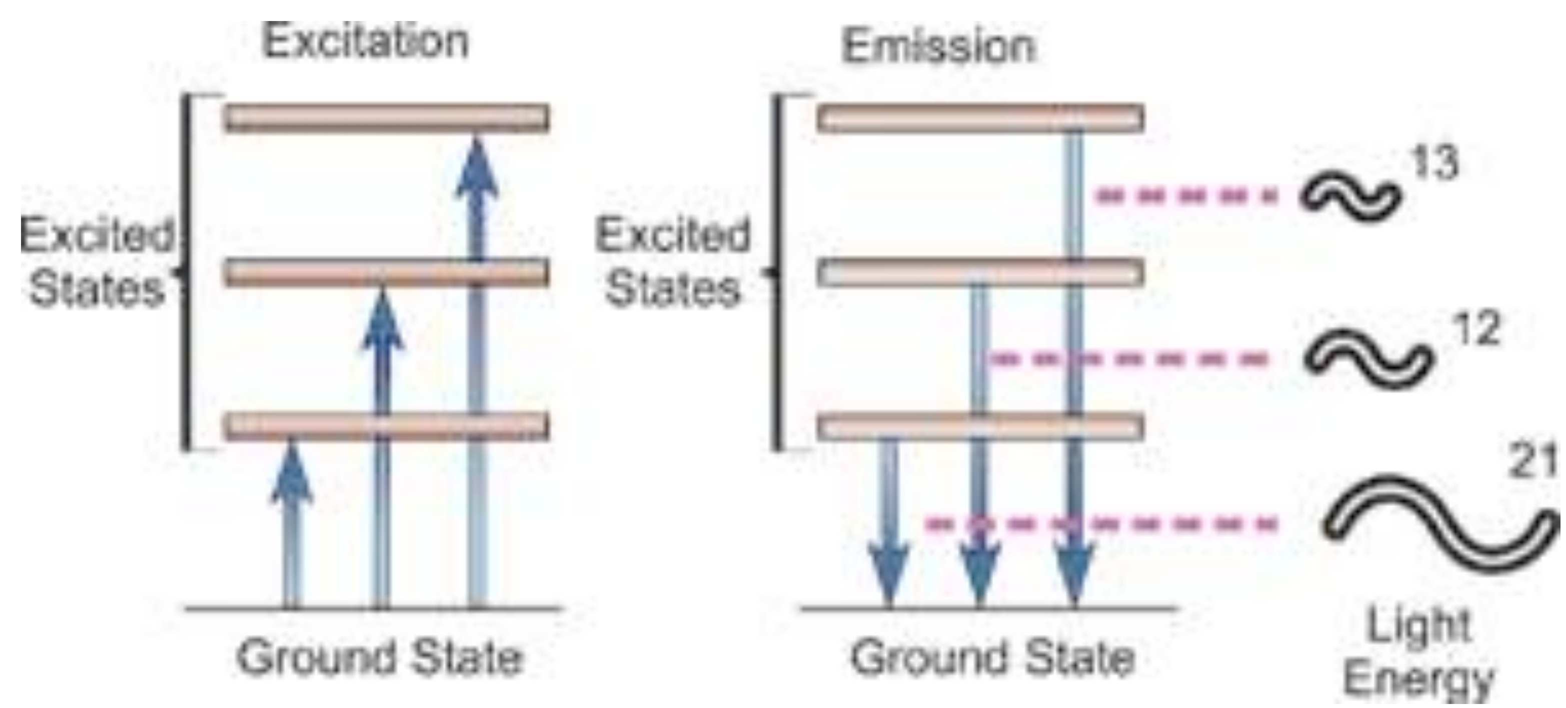
- But accretion by ISM => [Fe/H]~ -8.6 (starting from [Fe/H]~-10)
- Do they exist?

Frebel & Norris, 2011



In order to form a star you need to cool the gas during the collapse, to avoid the pressure to halt the collapse.

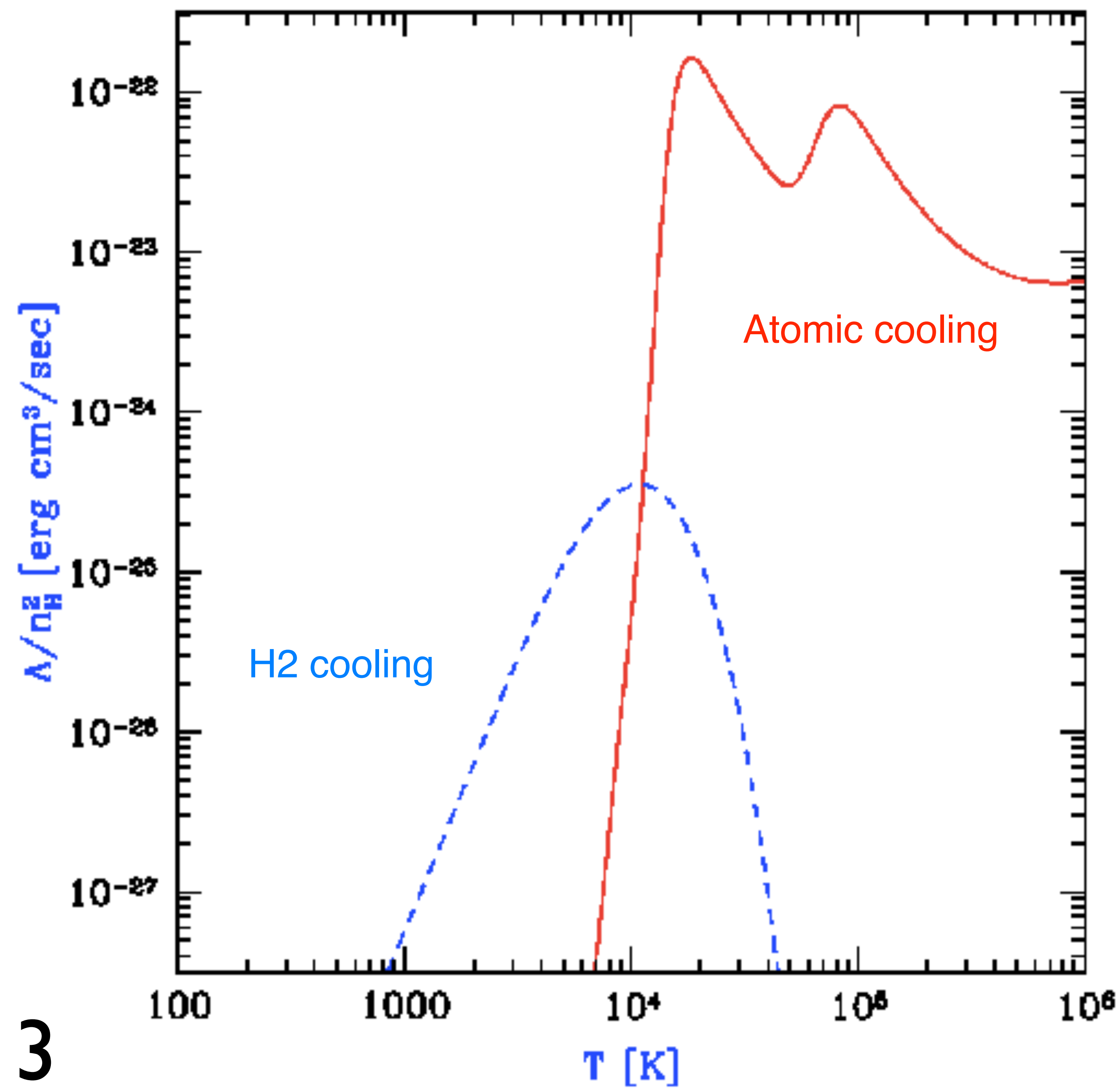
Collisional excitation and radiative recombination is a very effective mechanism to cool, but you need metals.



Formation of the First Stars

- The gas will heat up as a consequence of the collapse, either via adiabatic compression or due to shock heating.
- First Luminous Objects expected at z = 20-30 within halos of masses ~10^6 M_{sun} (mini-halos)
- H_2 cooling drives the temperature down again until the gas settles into a quasi hydrostatic state at T ~ 200 K and n ~ 10^4 cm^{-3}. Jeans mass: $M_J \sim 10^3$ M_{sun} (pre-stellar clump).
- A small hydrostatic proto-stellar core is formed first at the center of a Jeans-unstable cloud. This initial core subsequently grows through accretion.

$$T_{\rm vir} \simeq 2 \times 10^3 \ {\rm K} \left(\frac{M_h}{10^6 M_\odot}\right)^{2/3} \left(\frac{1+z}{20}\right)$$



Loeb 2010, Bromm 2012, 2013

Formation of the First Stars

$$\dot{M}_{\rm acc} \sim \frac{M_{\rm J}}{t_{\rm ff}} \propto \frac{T^{3/2}\rho^{-1/2}}{\rho^{-1/2}} \sim T^{3/2}$$

$$\text{Pop I: } T \sim 10\,\text{K} \Rightarrow \dot{M} \sim 10^{-5} M_\odot\,\text{yr}^{-1}$$

$$\text{Pop III: } T \sim 300\,\text{K} \Rightarrow \dot{M} \sim 10^{-3} M_\odot\,\text{yr}^{-1}$$

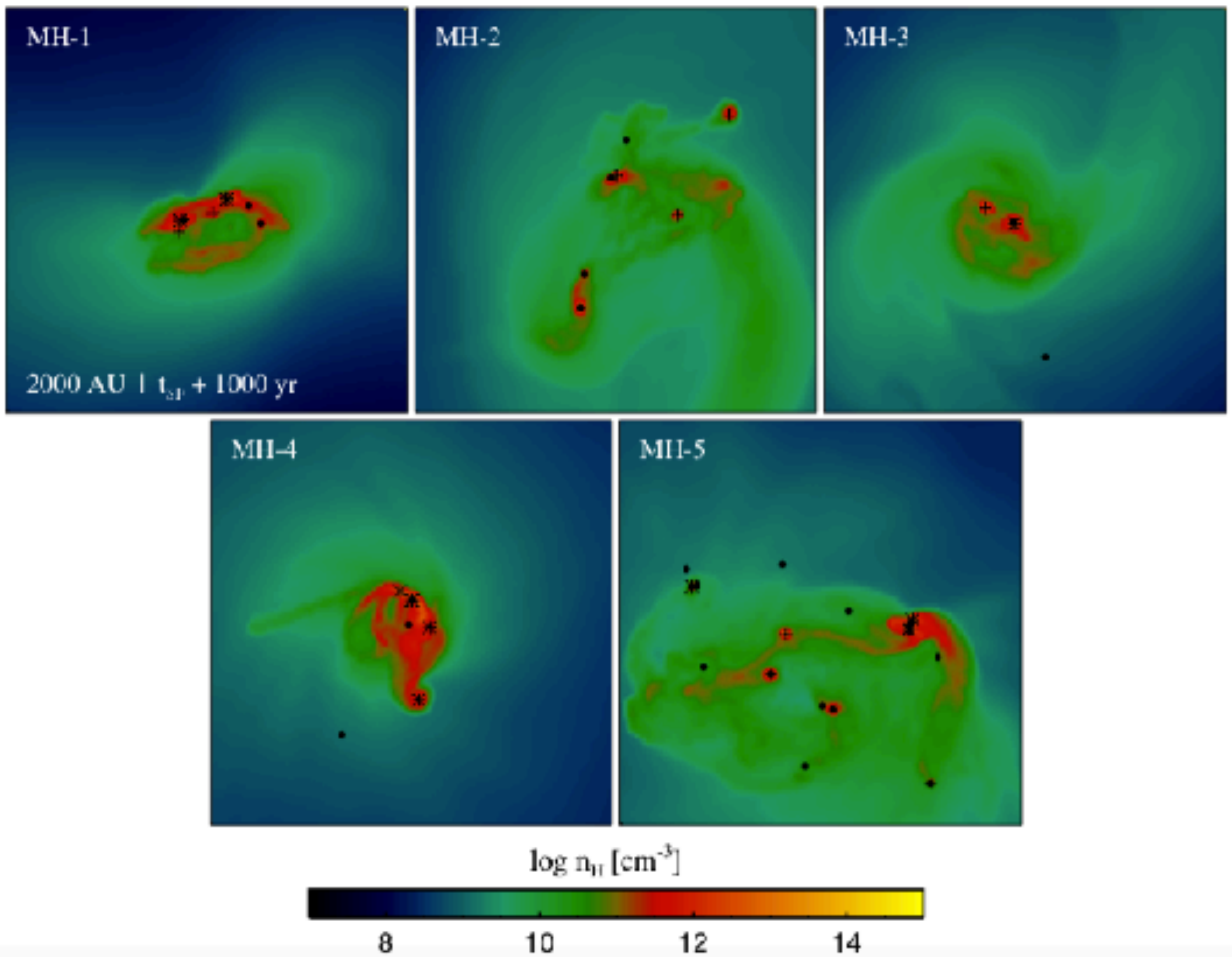
$$t_{\rm acc} \sim t_{\rm KH} \sim 10^5\,\text{yr}$$

$$M_* \sim \dot{M}_{\rm acc} t_{\rm acc} \sim 100 M_\odot$$

- Accretion onto a massive star proceeds for roughly the Kelvin Helmholtz timescale,
- t_{KH} is the time it takes a (massive) star to reach the hydrogen-burning main sequence.

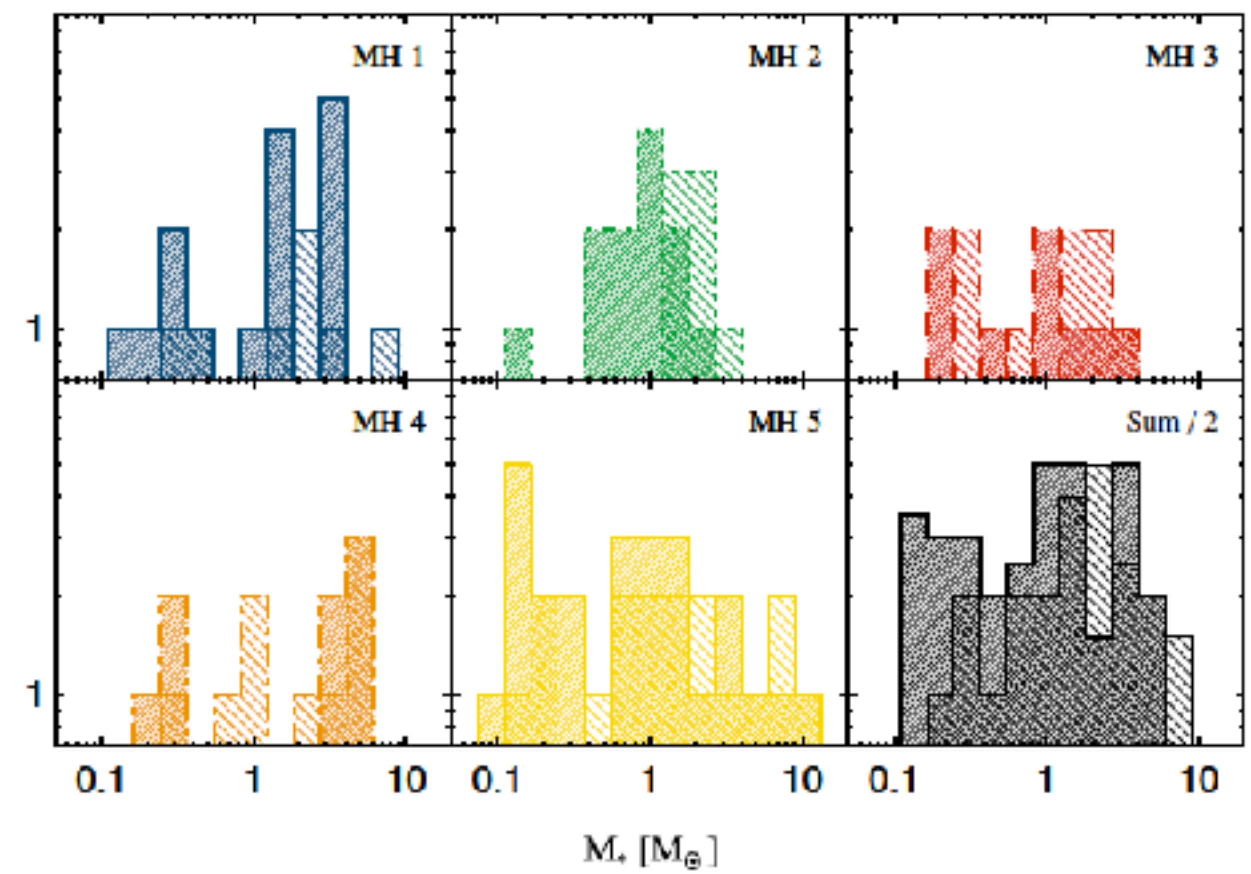
- Final masses will typically be smaller, since accretion may be terminated earlier on due to the negative radiative feedback from the growing protostar.

Formation of low mass stars



"[Clark et al. 2011] demonstrated that the accretion disks that build up around Population III stars are strongly susceptible to fragmentation and that the first stars should therefore form in clusters rather than in isolation. [...]

After an initial burst, gravitational instability recurs periodically, forming additional protostars with masses ranging from ~0.1 to 10 M⊙. "



- Central 2000 AU after 1000 yr of continued fragmentation and accretion. Dots are stars with M< 1 M⊙
- Flat distribution of masses between ~ 0.1 to 10 M⊙

Greif et al. 2011

Formation of low mass stars

- Zero metallicity ⇒ FRAGMENTATION (Clarke et al. 2011, Greif et al. 2011)

- Metallicity > Zcr⇒

    - CII & OI fine structure cooling (Bromm & Loeb 2003, e.g. **HE 1327-2326, HE 0107-5240**)

$$Z_{crit} \sim 10^{-3.5}\ Z_{\odot}$$

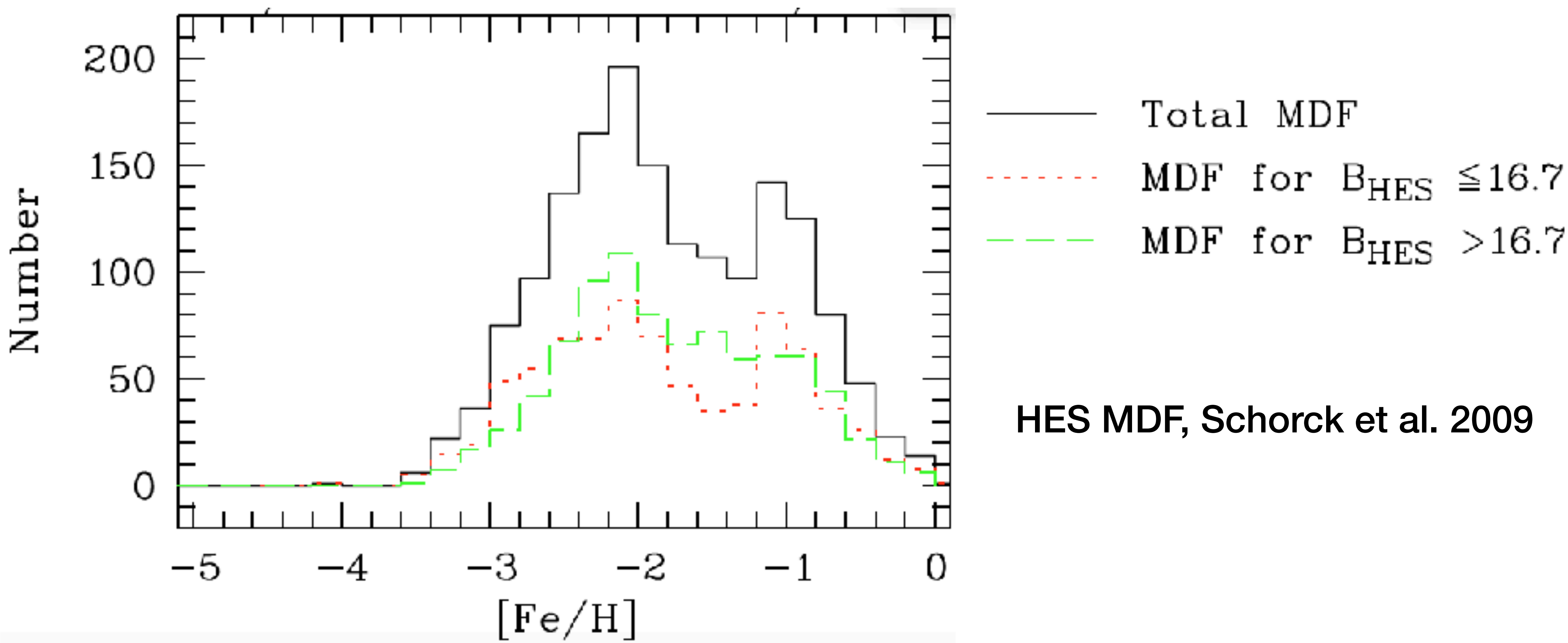
    - dust cooling + fragmentation (Schneider et al. 2012, e.g. **SDSS J102915+172927**)

$$Z_{crit} \sim 10^{-5}\ Z_{\odot}$$

Searches for extremely metal-poor stars

- Understand the formation of low mass stars in low metallicity gas
    - Do zero-metal low-mass stars exist?
    - What is the “critical metallicity” for low-mass star formation?
    - The chemical composition of the most metal-poor stars gives us information on the first massive stars
- Lithium and primordial nucleosynthesis predictions
    - Lithium abundance / destruction in EMP stars

EMP stars are exceedingly rare



HES MDF, Schorck et al. 2009

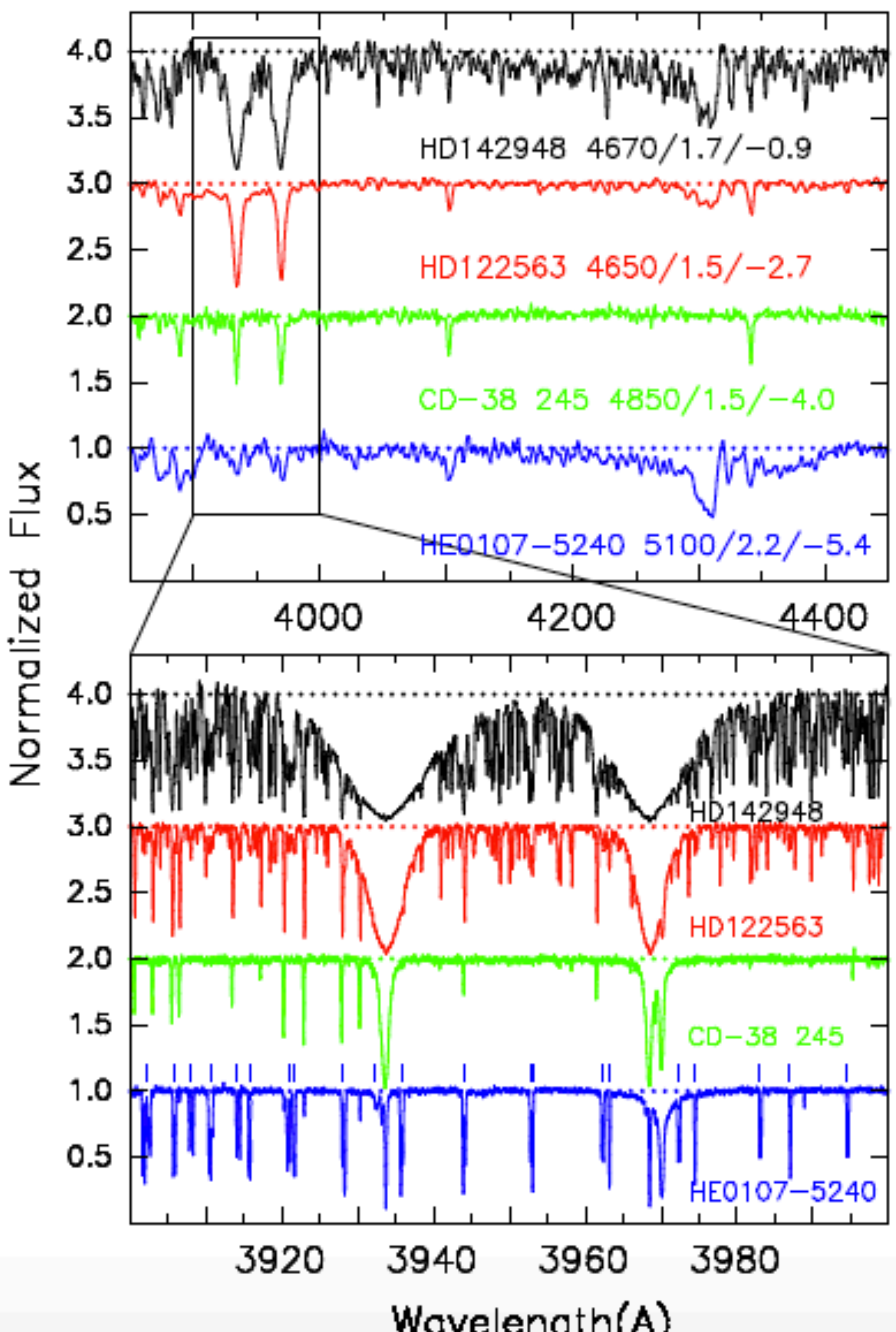
"[…] as a rule of thumb, the simple chemical enrichment model of the halo of Hartwick (1976) suggests that the number of stars should decrease by a factor of ten for each factor of ten decrease in abundance. […] In the solar neighbourhood one might expect to find ~ 1 in 200,000 stars with [Fe/H] < -3.5 dex."

Frebel & Norris 2011

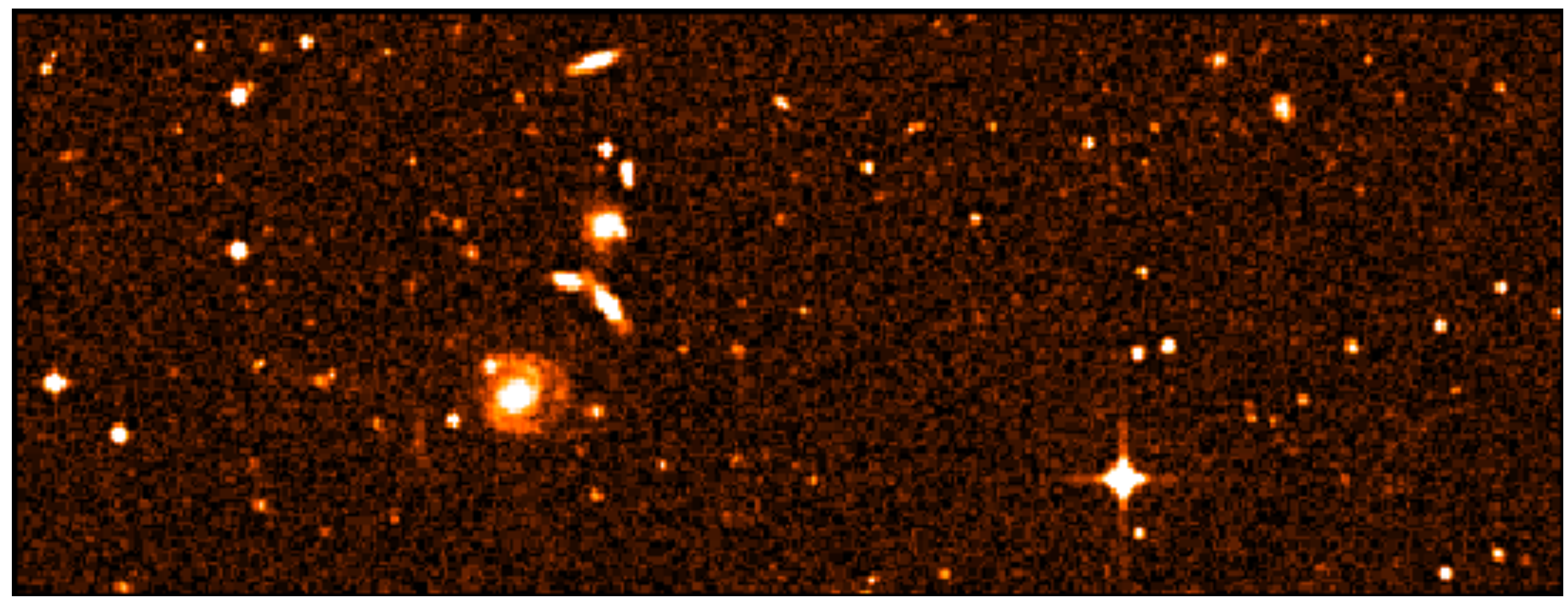
Prism objective surveys: HK & HES

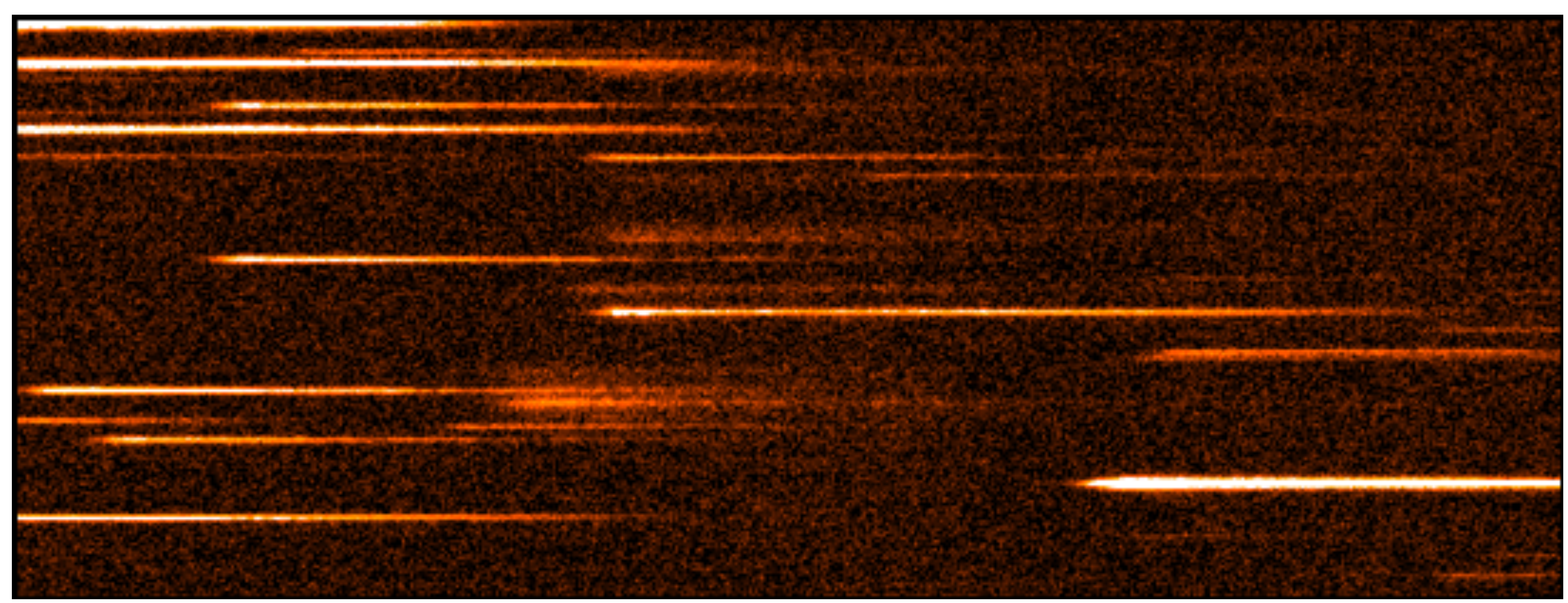
Prism objective (LR) plus Schmidt telescopes (wide field).

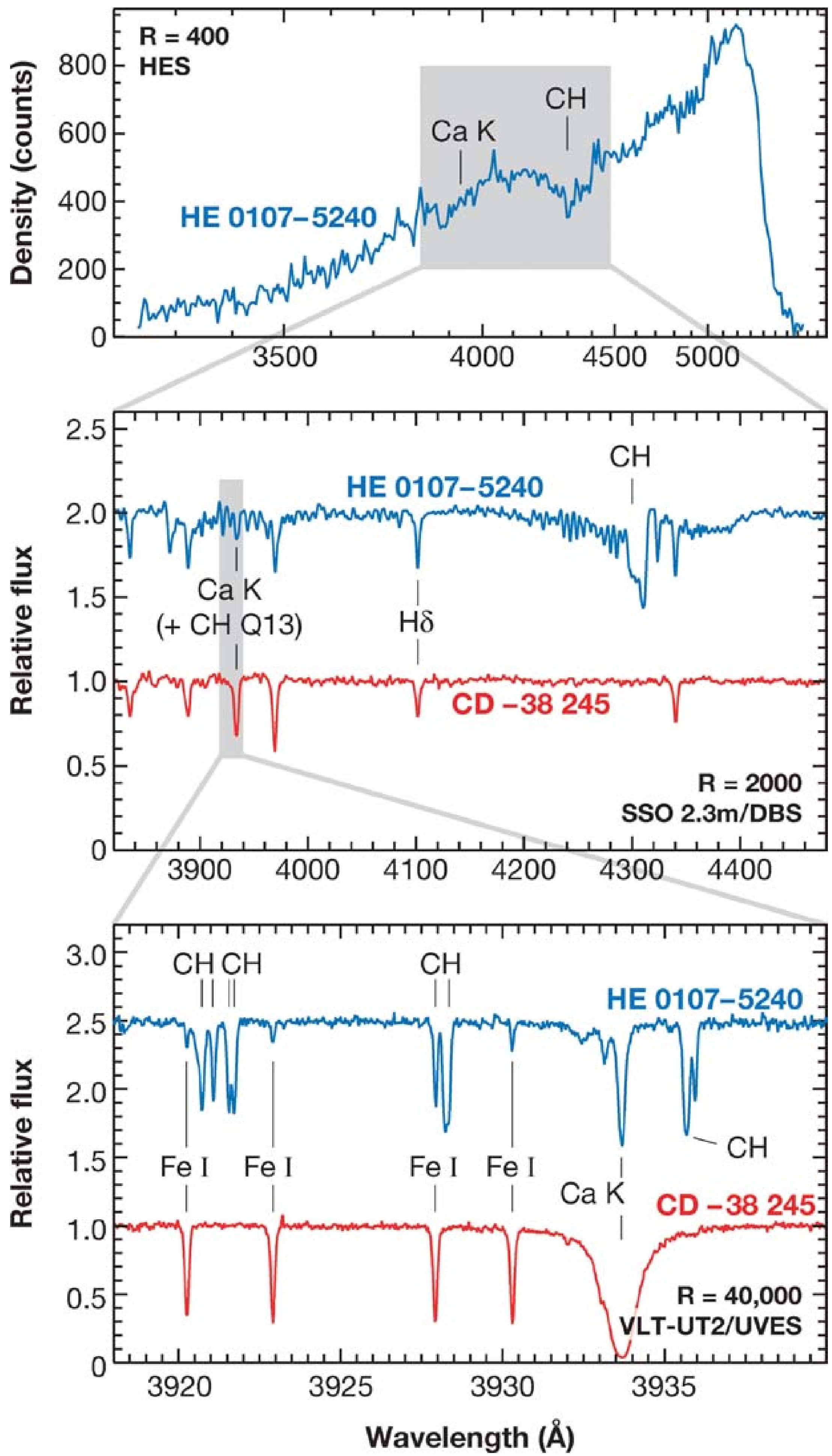
HK: short spectra inspected visually.
HES: long spectra, colors from the spectra.



About 10000 candidates each







From the objective prism candidates one had to collect medium resolution spectroscopy (R~2000) to confirm the metallicity and only after one could move to high resolution spectroscopy

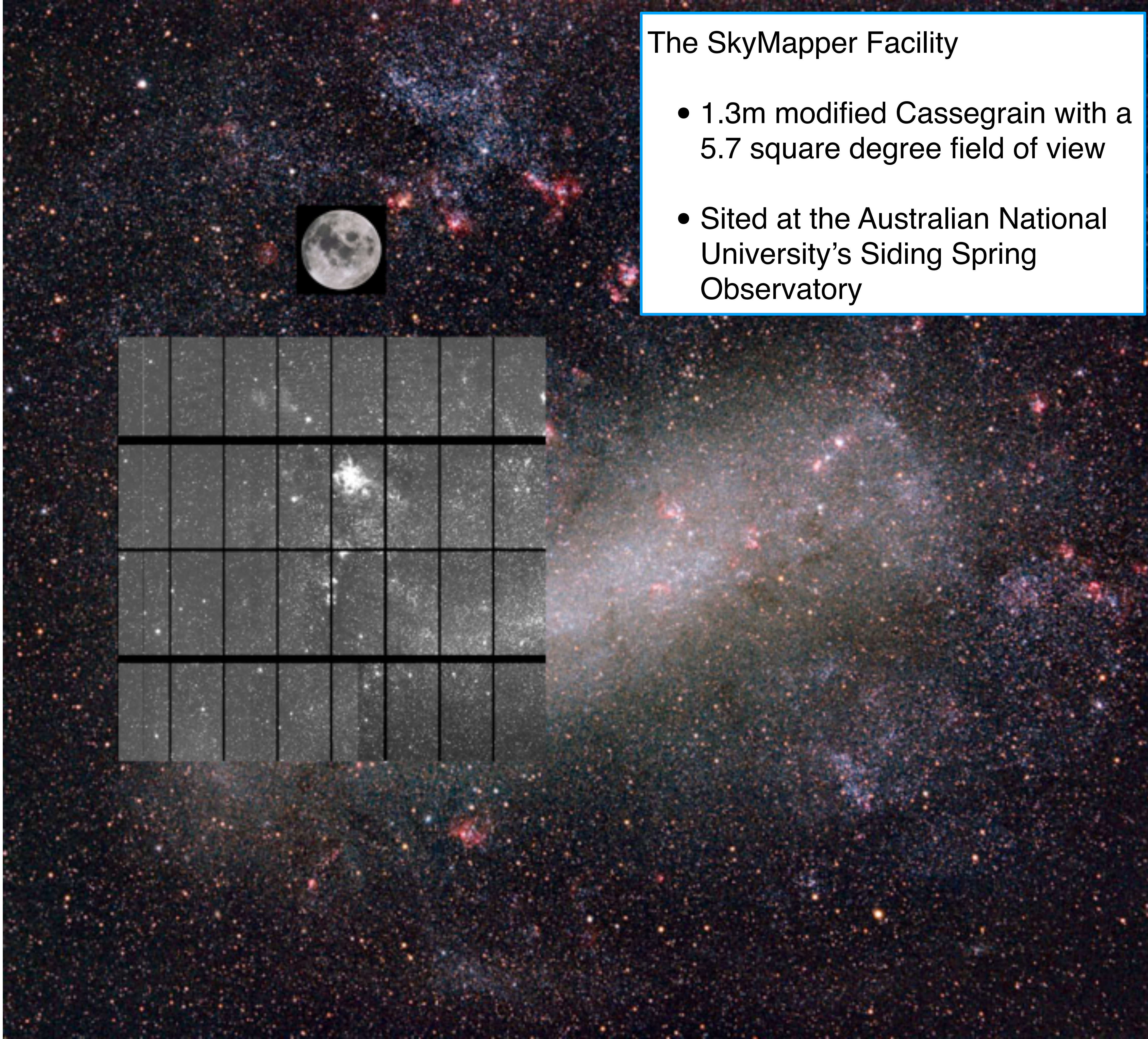
TABLE 3 "Effective yields" of metal-poor stars

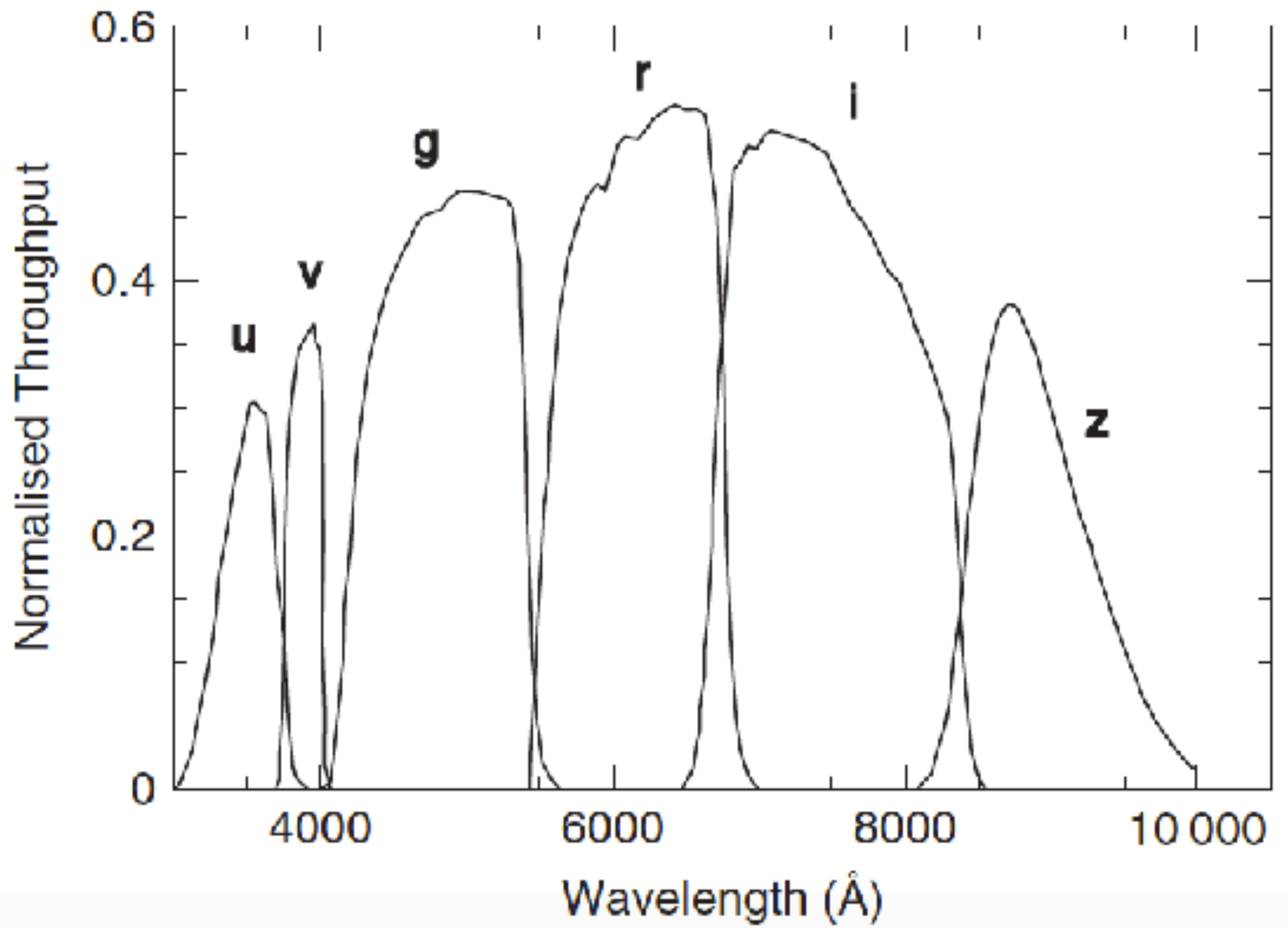
		[Fe/H]		
Survey	*N*	**<−2.0**	**<−2.5**	**<−3.0**
HK survey/no $B-V$	2614	11%	4%	1%
HK survey/with $B-V$	2140	32%	11%	3%
HES (faint turnoff stars)	571	59%	21%	6%
HES (faint giants)	643	50%	20%	6%

Beers & Christlieb 2005

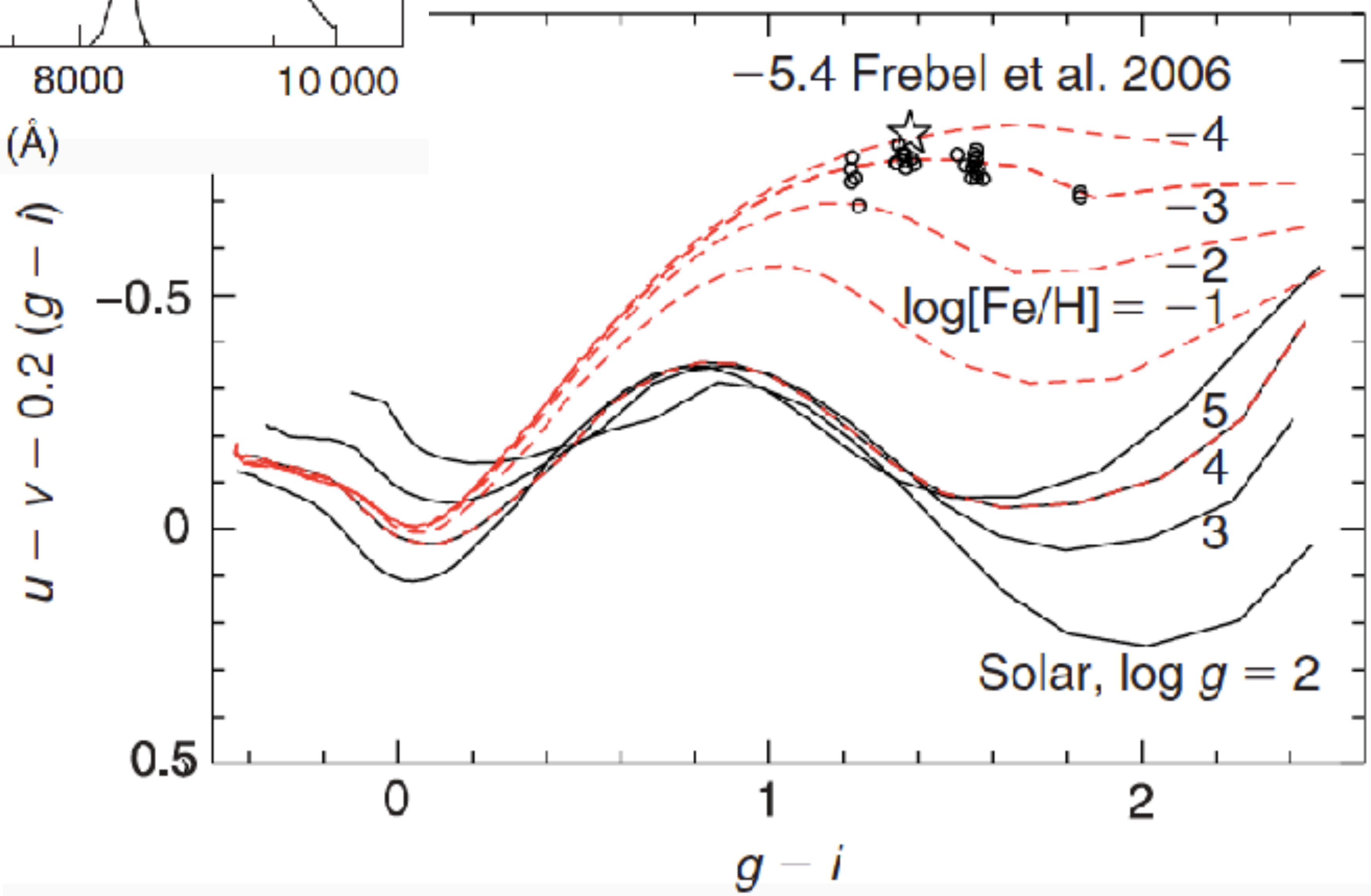
The SkyMapper Facility

- 1.3m modified Cassegrain with a 5.7 square degree field of view
- Sited at the Australian National University's Siding Spring Observatory



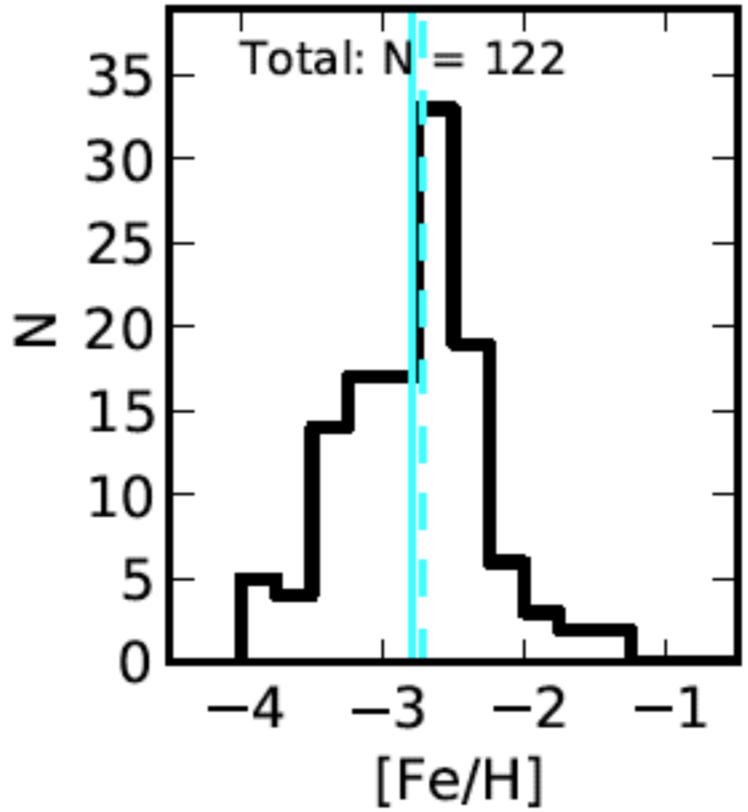


Skymapper filter set

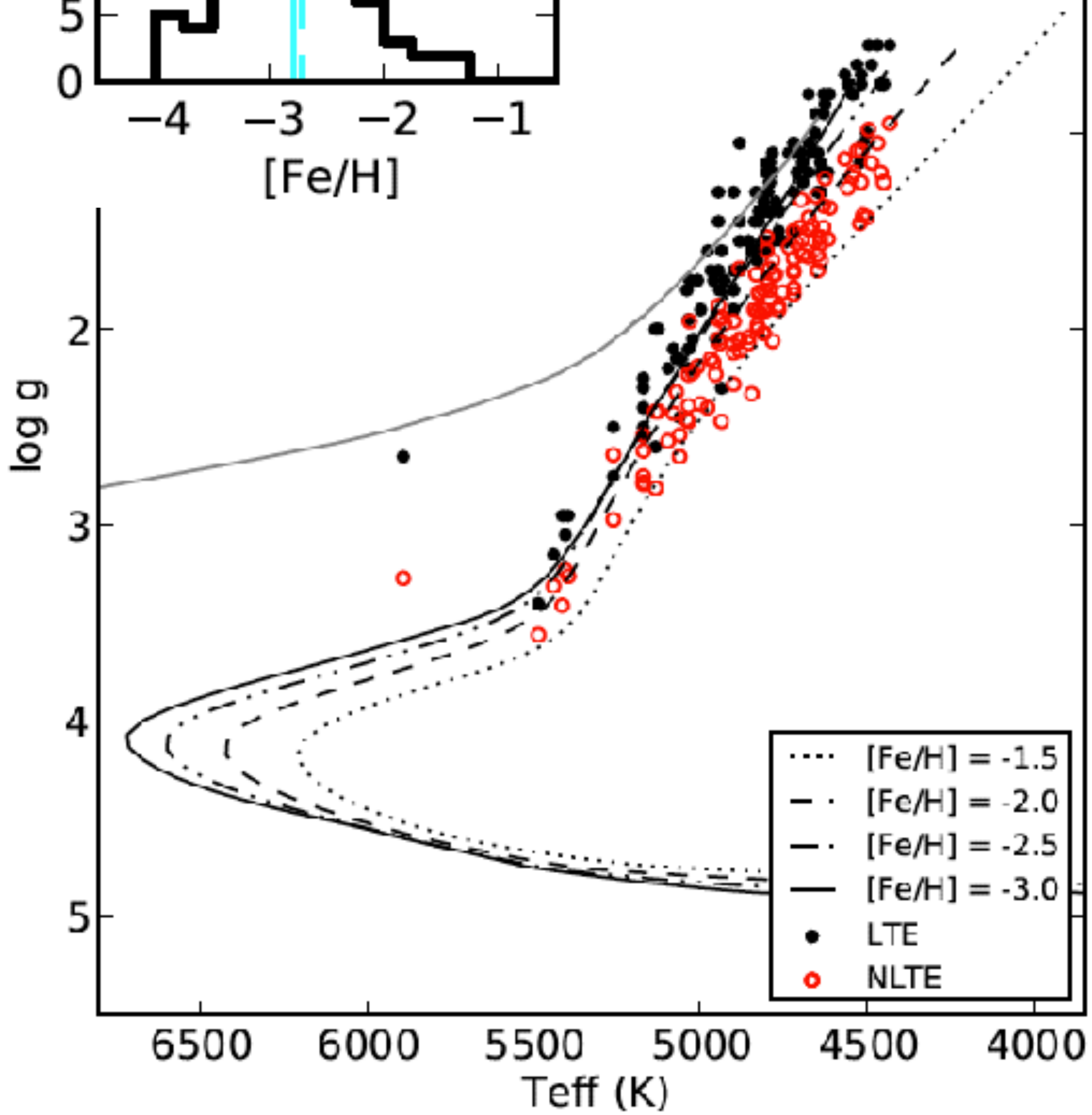


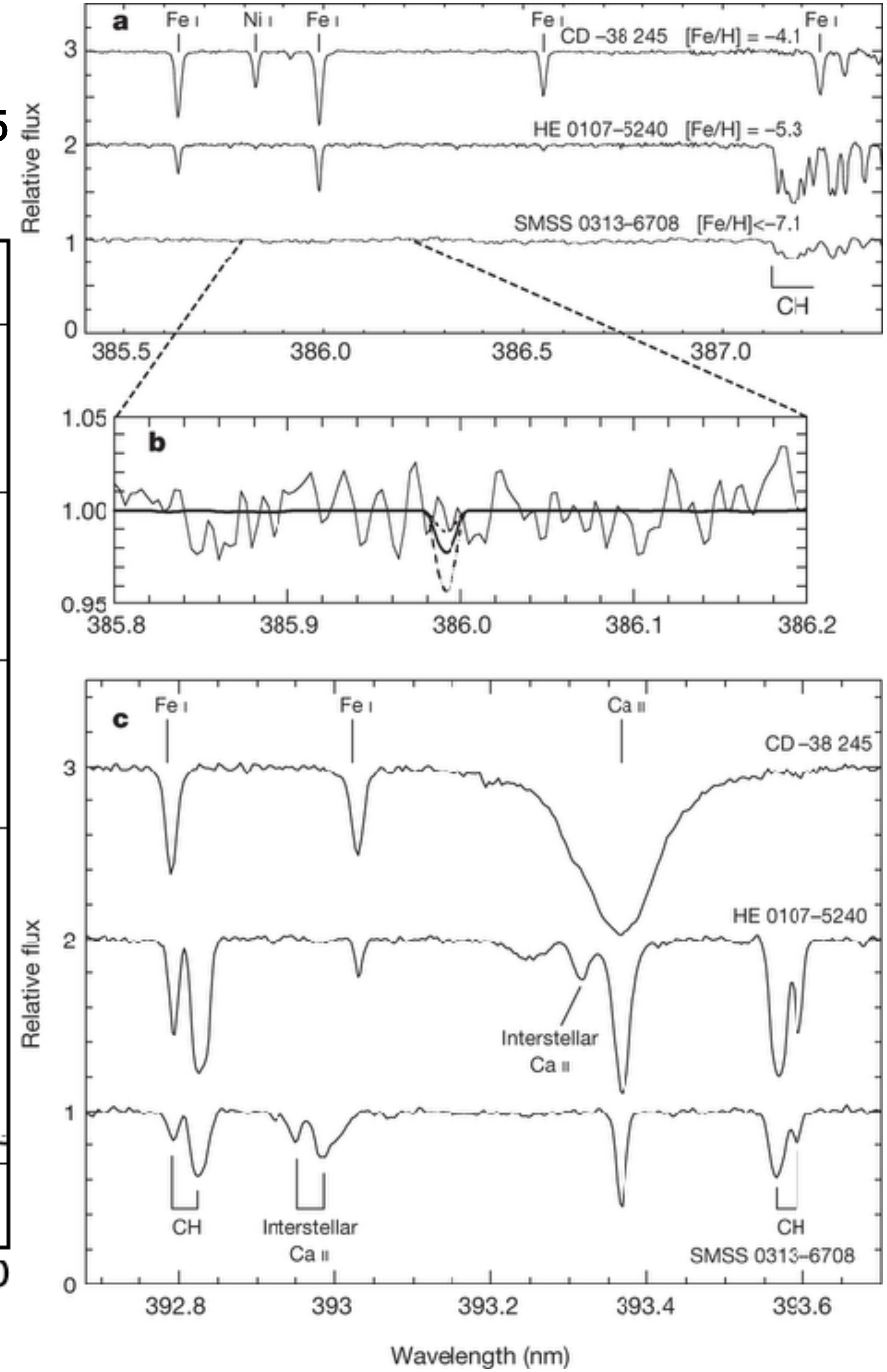
Metallicity calibration

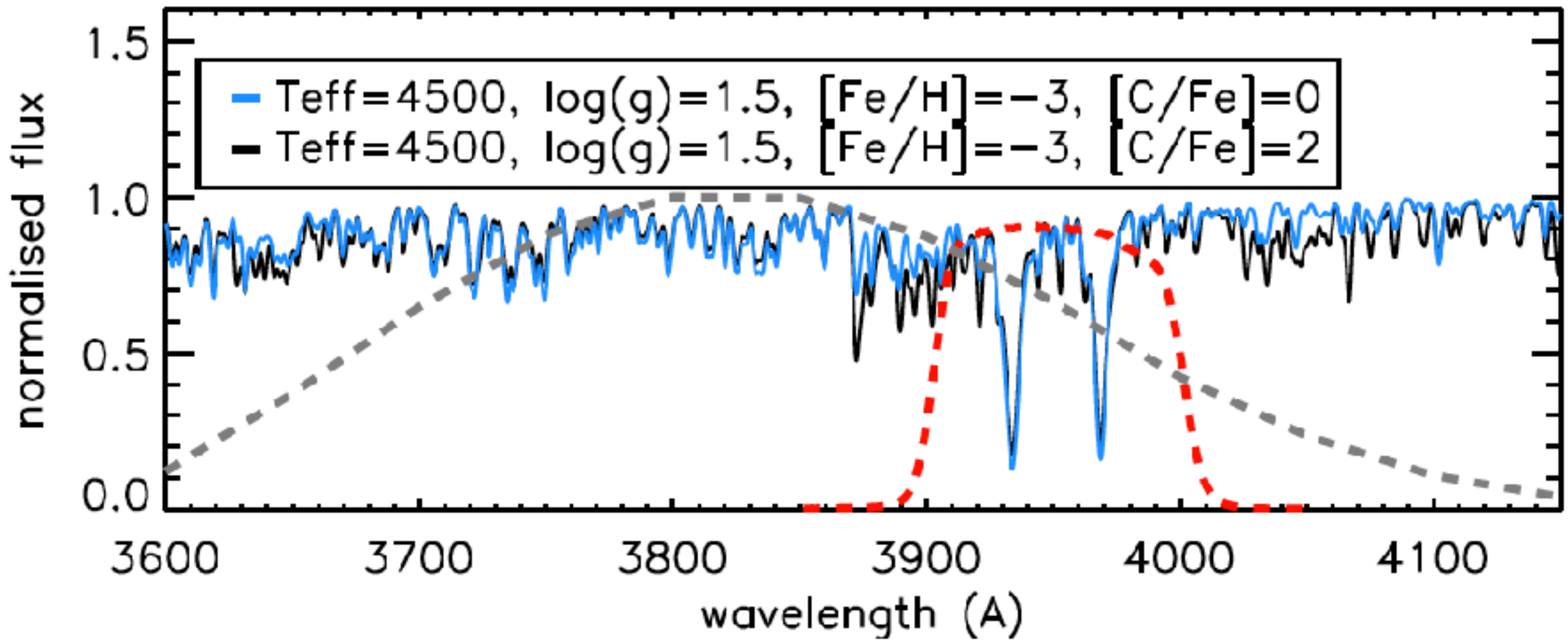
Keller et al. 2007

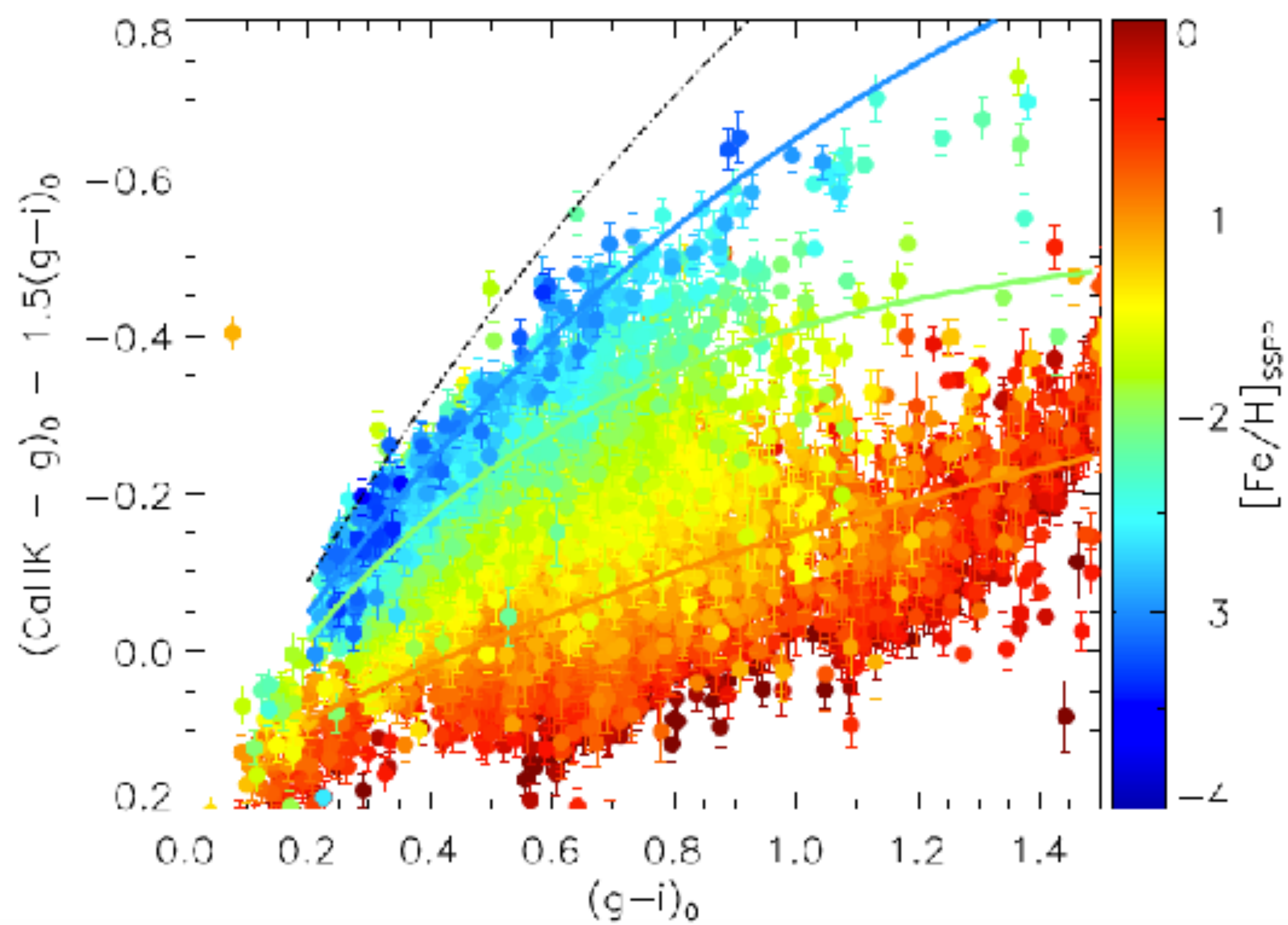


Keller et al. 2014
Jacobson et al. 2015









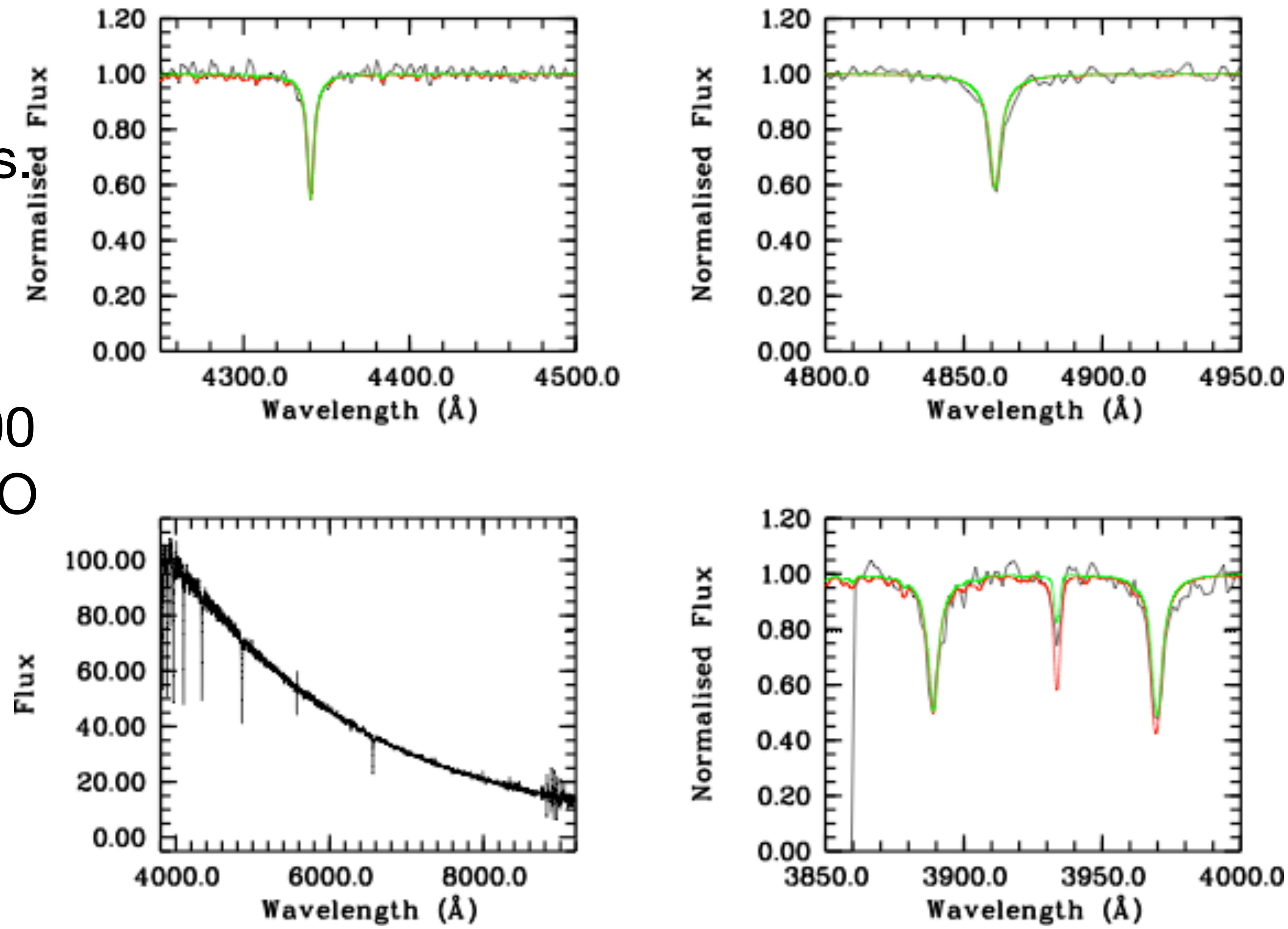
The pristine survey

- 3.6-meter Canada France Hawaii Telescope (CFHT);
- MegaCam, 1 deg^2 FoV
- 1000 deg2 covered as of Sept. 2016

Starkenburg et al. 2017

Turn Off Primordial Stars (TOPOS): Target Selection

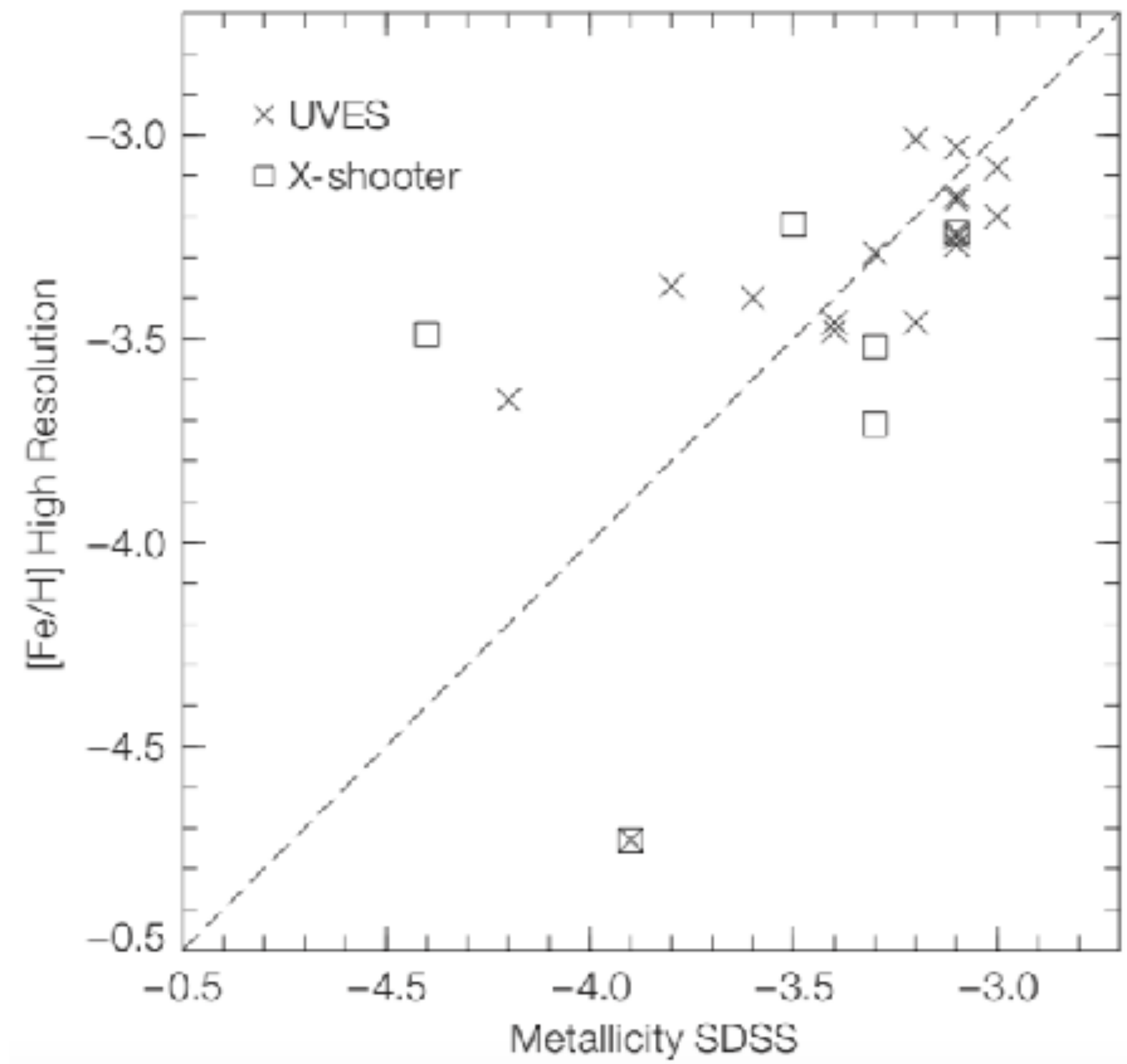
- DR12: 14,055 deg^2, photometry for 933 million unique objects. 852000 spectra of stars
- 180000 SDSS R=2000 spectra (potentially TO stars, photometry available) analyzed automatically
- Final selection by visual inspection



Observed spectrum and overimposed synthetic spectra [Fe/H]=-3.0 and [Fe/H]=-4.0

Turn Off Primordial Stars

TOPoS



Caffau et al. 2011

Observations:
- 150h @ VLT on LP (periods 89-92)
  - UVES proposals
  - X-Shooter proposals
  - Subaru proposals
  - FORS2 proposal

The TOPoS collaboration: Elisabetta Caffau, Piercarlo Bonifacio, Patrick Francois, Francois Spite, Monique Spite, Bertrand Plez, Roger Cayrel, Norbert Christlieb, Paul Clark, Simon Glover, Ralf Klessen, Andreas Koch, Hans-Gunter Ludwig, Lorenzo Monaco, Luca Sbordone, Matthias Steffen, Simone Zaggia

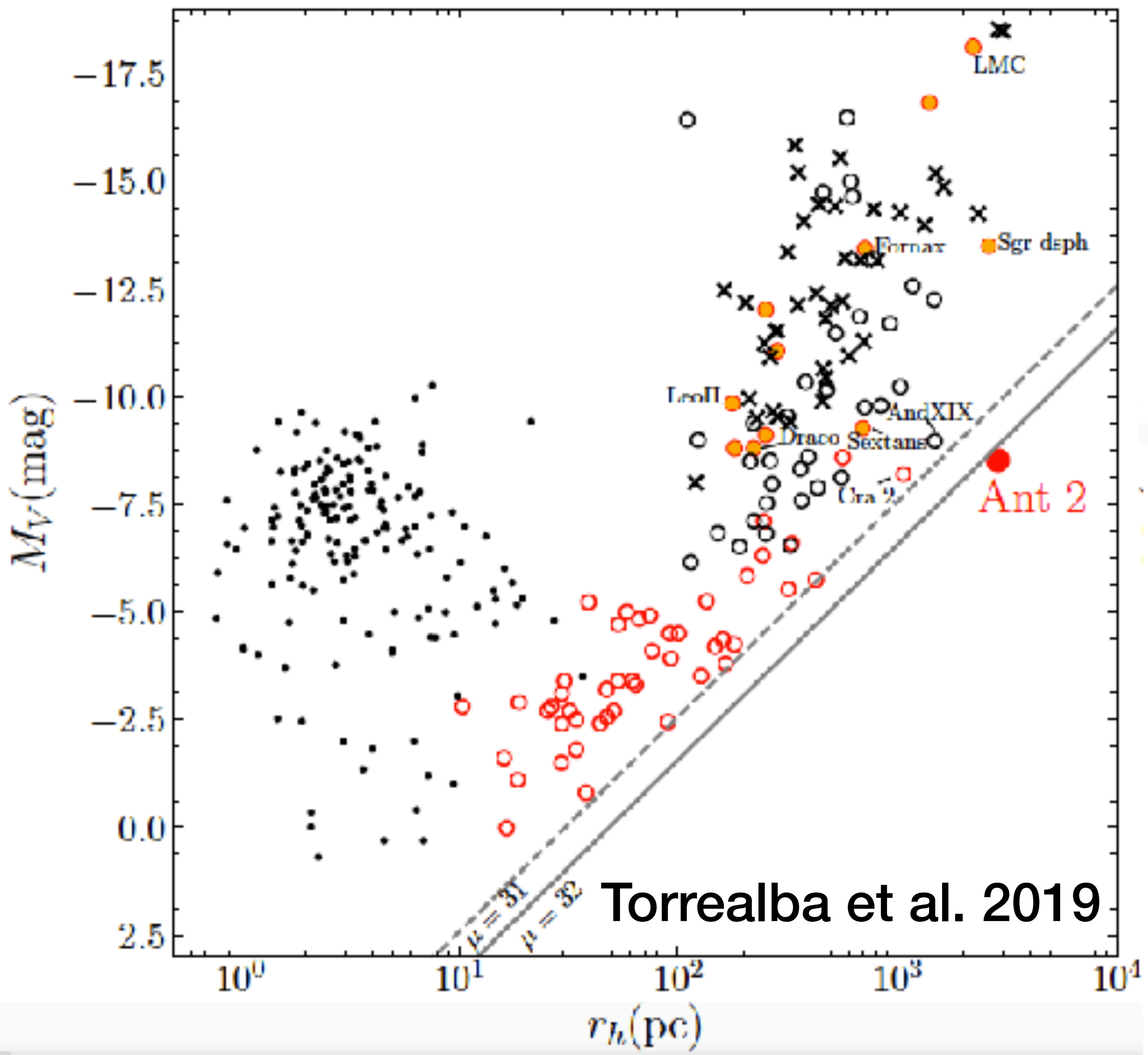
Other collaborators: Andy Gallagher, Stefania Salvadori, Alessando Chieffi, Marco Limongi, Paolo Molaro, Lyudmila Mashonkina, Fran¸cois Hammer, Vanessa Hill, Carlo Abate, David Aguado

- Extremely metal-poor stars are very rare objects
- The new discoveries are dominated by large surveys for pre-selection
- LAMOST
- SDSS + HR followups (e.g. Aguado et al. 2016, 2017)
- The AEGIS survey is a southern extension of SDSS/SEGUE using 2dF+AAO on the AAT (Yoon et al. 2018).
- The r-process alliance has selected stars from RAVE to search for r-enhanced stars at higher resolution as well as from Schlaufman & Casey (2017) for follow-up at low resolution (Placco et al. 2018)
- Kielty et al. (2018) were able to identify CEMP stars from IR APOGEE spectra, metallicity ~ -2.0
- The HERMES multi-object spectrograph on the AAT+2dF deploys ~ 400 fibers on the 2deg FoV. The GALAH survey (De Silva et al. 2015) aims at gathering spectra for ~1 million stars, down to V=14.

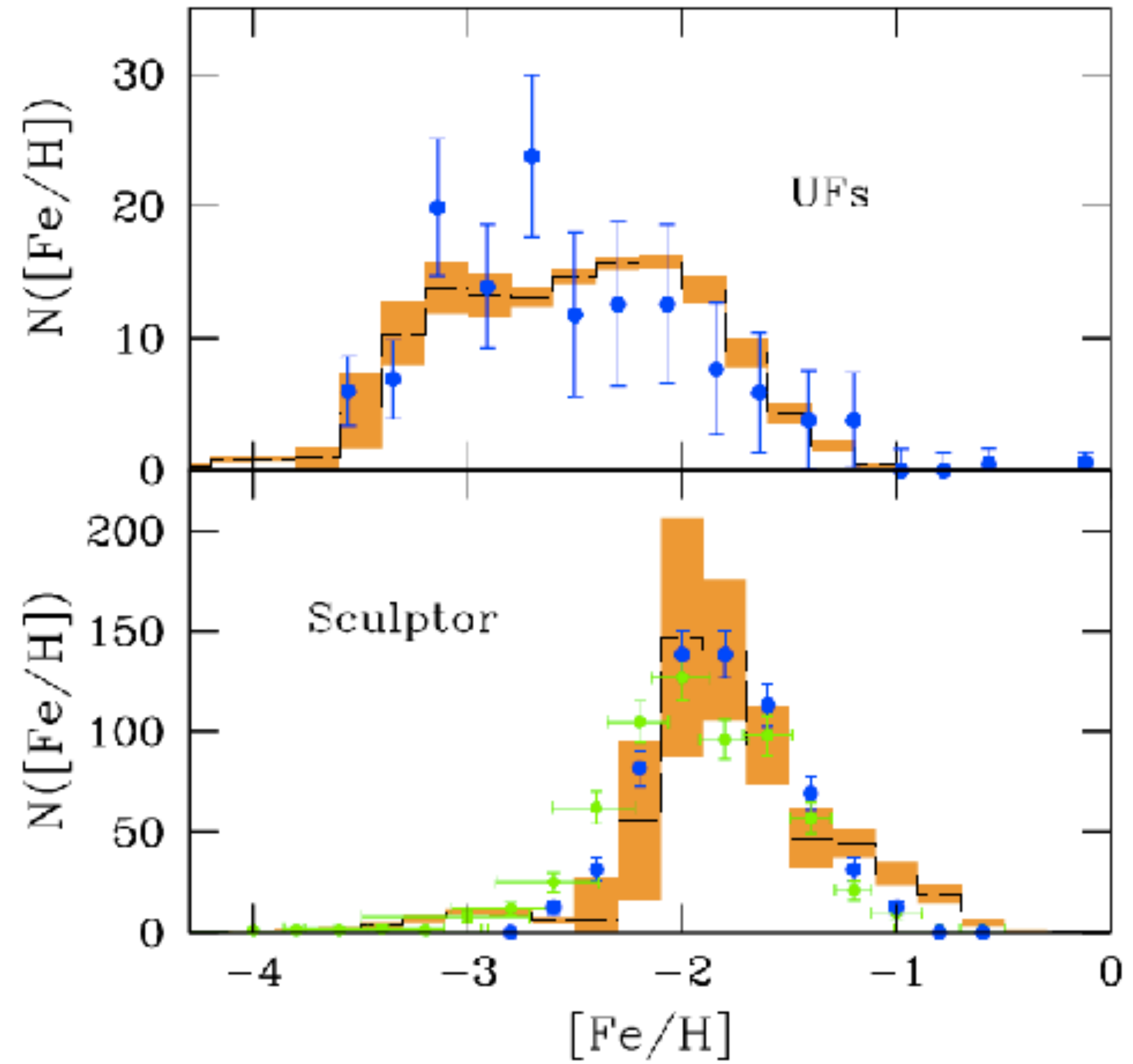
Ultra-faint dwarf galaxies MDF

"[…] In order to account for all of the ultra faint galaxies known within 30 kpc of the Galaxy […] this implies the existence of at least 1000 satellite galaxies within 300 kpc of the Milky Way."

Kelley et al. 2018, arXiv:1811.12413



Torrealba et al. 2019



Salvadori 2012

Ultra-faint dwarf galaxies are favorable environments to search for EMP stars

FORS2/VLT, M2FS/Magellan data for GrusII UFD

The TOPOS contribution

Table 1 The eight most Fe-poor stars

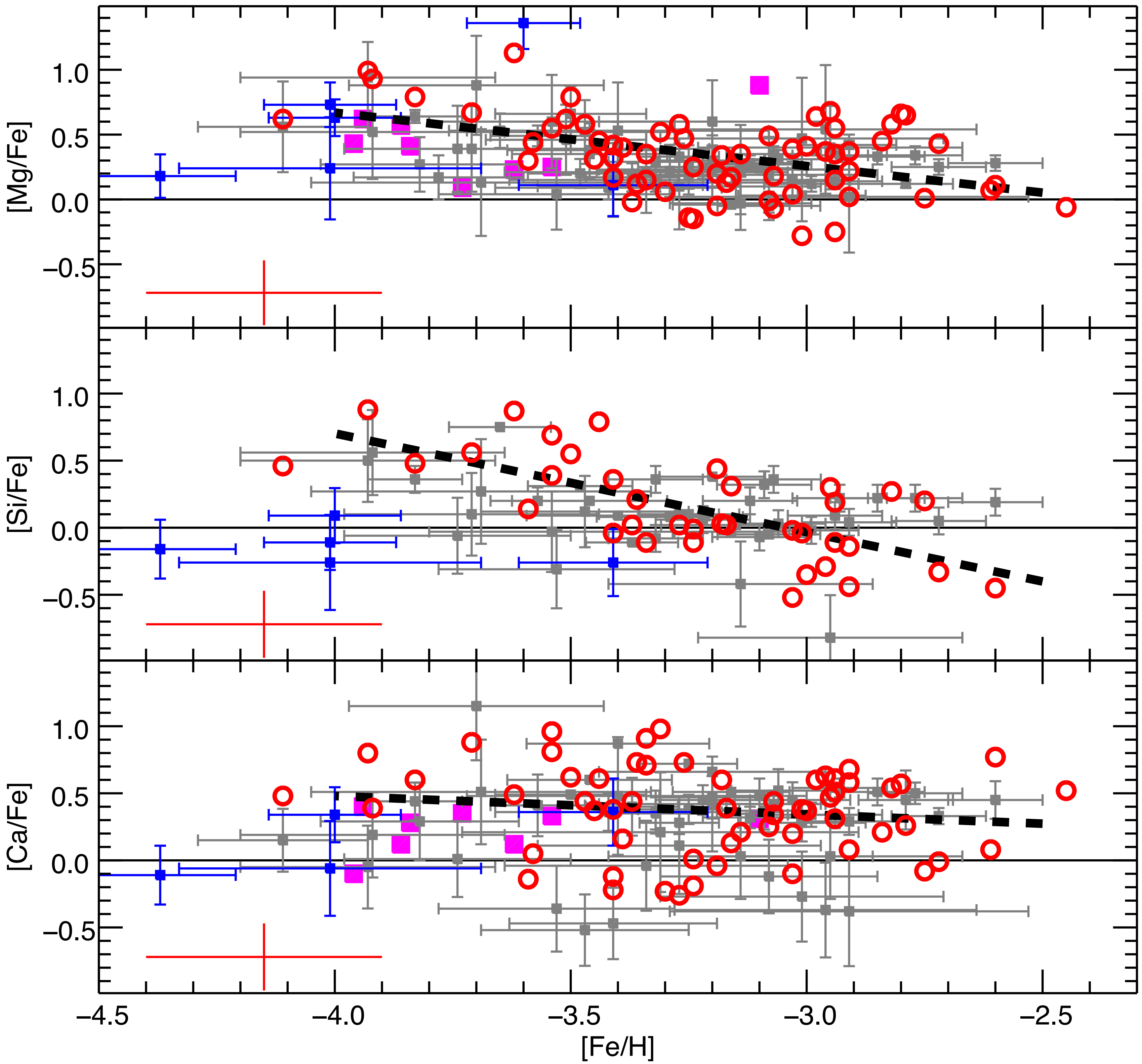
Frebel & Norris, 2015, ARAA, 53, 631

Object	RA (2000) Dec	T_{eff}	log g	[Fe/H]	[C/Fe]	V_r (km s^{-1})	References
SM 0313−6708[a]	03 13 00.4 −67 08 39.3	5,125	2.30	<−7.30	>+4.90	ND	Keller et al. (2014)
HE 1327−2326	13 30 06.0 −23 41 49.7	6,180	3.70	−5.66	+4.26	64	Frebel et al. (2005), Aoki et al. (2006)
HE 0107−5240	01 09 29.2 −52 24 34.2	5,100	2.20	−5.39	+3.70	44	Christlieb et al. (2002, 2004)
SD 1035+0641[a]	10 35 56.1 +06 41 44.0	6,262	1.5	<−5.1	>3.5	−70	Bonifacio et al. (2015)
HE 0557−4840	05 58 39.3 −48 39 56.8	4,900	2.20	−4.81	+1.65	212	Norris et al. (2007)
SD 1742+2531[a]	17 42 59.7 +25 31 35.9	6,345	1.5	−4.8	+3.6	−208	Bonifacio et al. (2015)
SD 1029+1729[a]	10 29 15.2 +17 29 28.0	5,811	4.00	−4.73	<+0.93	−34	Caffau et al. (2011a, 2012)
HE 0233−0343	02 36 29.7 −03 30 06.0	6,100	3.40	−4.68	+3.46	64	Hansen et al. (2014)

SDSS J092912.32+023817.0 [Fe/H]=-4.97; Caffau et al. 2016 (TOPOS III)

- SDSS J0023+0307: [Fe/H]< -6.6; Aguado et al. (2018), Francois et al. 2018, Frebel et al. 2018
- Pristine 221.8781+9.7844 (Starkenburg et al. 2018) [Fe/H]=-4.66, [C/Fe] ≤ 1.76
- SDSS J131326.89-001941.4, [Fe/H]=-4.3/-5.0 (Allende Prieto et al. 2015, Frebel et al. 2015)

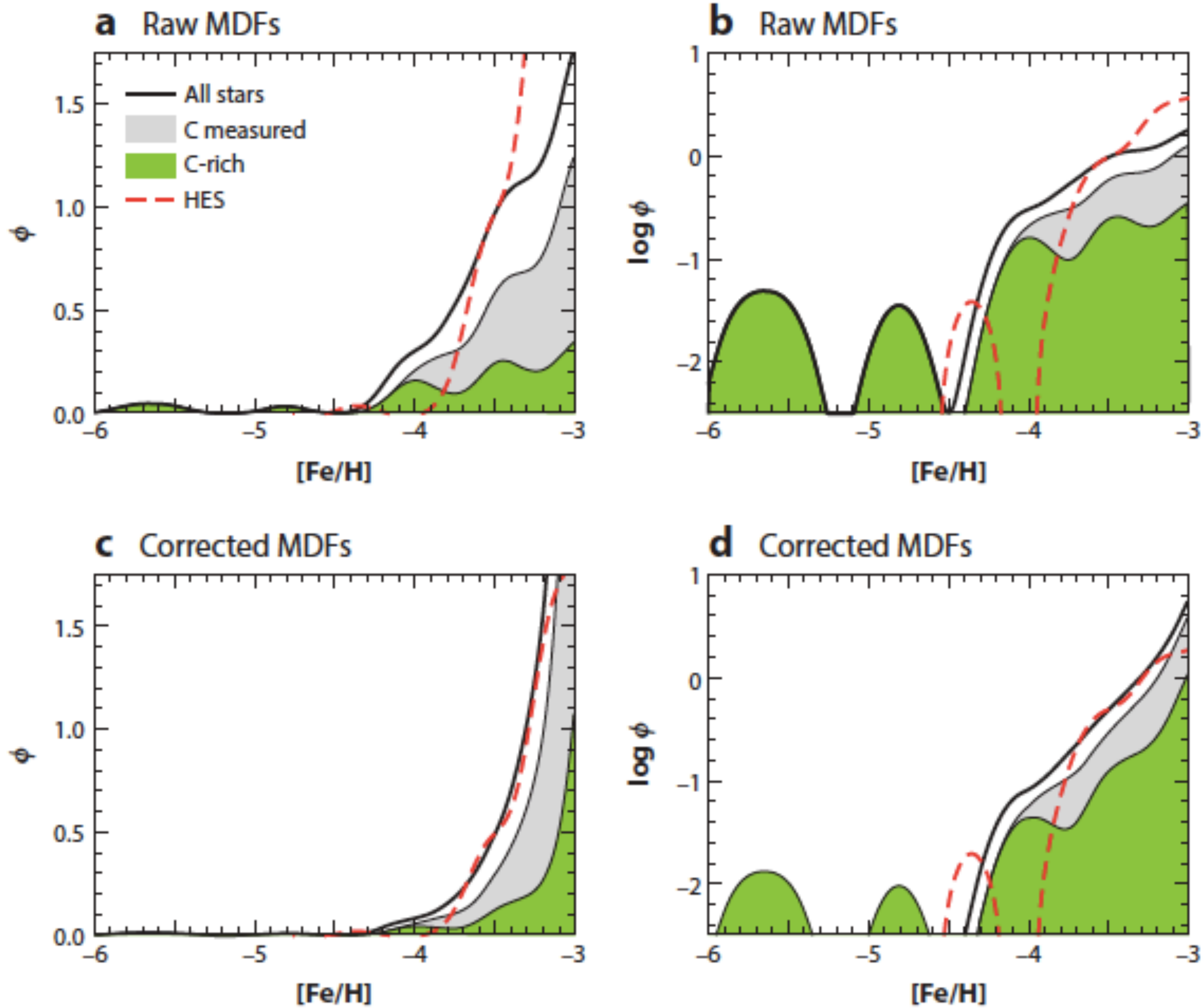
The TOPOS contribution



TOPoS project:

- **65 TO stars of which 49 with [Fe/H]≤ -3 (François et al. 2018, TOPoS V)**
- **6 TO stars with [Fe/H] ≤ -4 (Caffau et al. 2016, Bonifacio et al. 2018 - TOPoS III,IV)**

Note the low alpha/Fe stars



Frebel & Norris, 2015
(from Yong et al. 2013)

Figure 5

The Fe metallicity distribution function based on the high-resolution, high-S/N homogeneous abundance analysis by Yong et al. (2013a). The generalized histograms have been generated using a Gaussian kernel having $\sigma = 0.30$ dex, and these are presented on linear (*left*) and logarithmic (*right*) scales. Green and gray color coding is used to present the contribution of C-rich and C-normal stars, respectively, for which measurement was possible. Panels *a* and *b* refer to the raw data, and panels *c* and *d* show the same data corrected for completeness for the range $-4.0 < [Fe/H] < -3.0$, as described by Yong et al. (2013b). The dashed line shows the metallicity distribution function (MDF), which was based on Hamburg/ESO survey data by Schörck et al. (2009). Reproduced with permission of D. Yong, private communication.

Beers & Christlieb (2005)

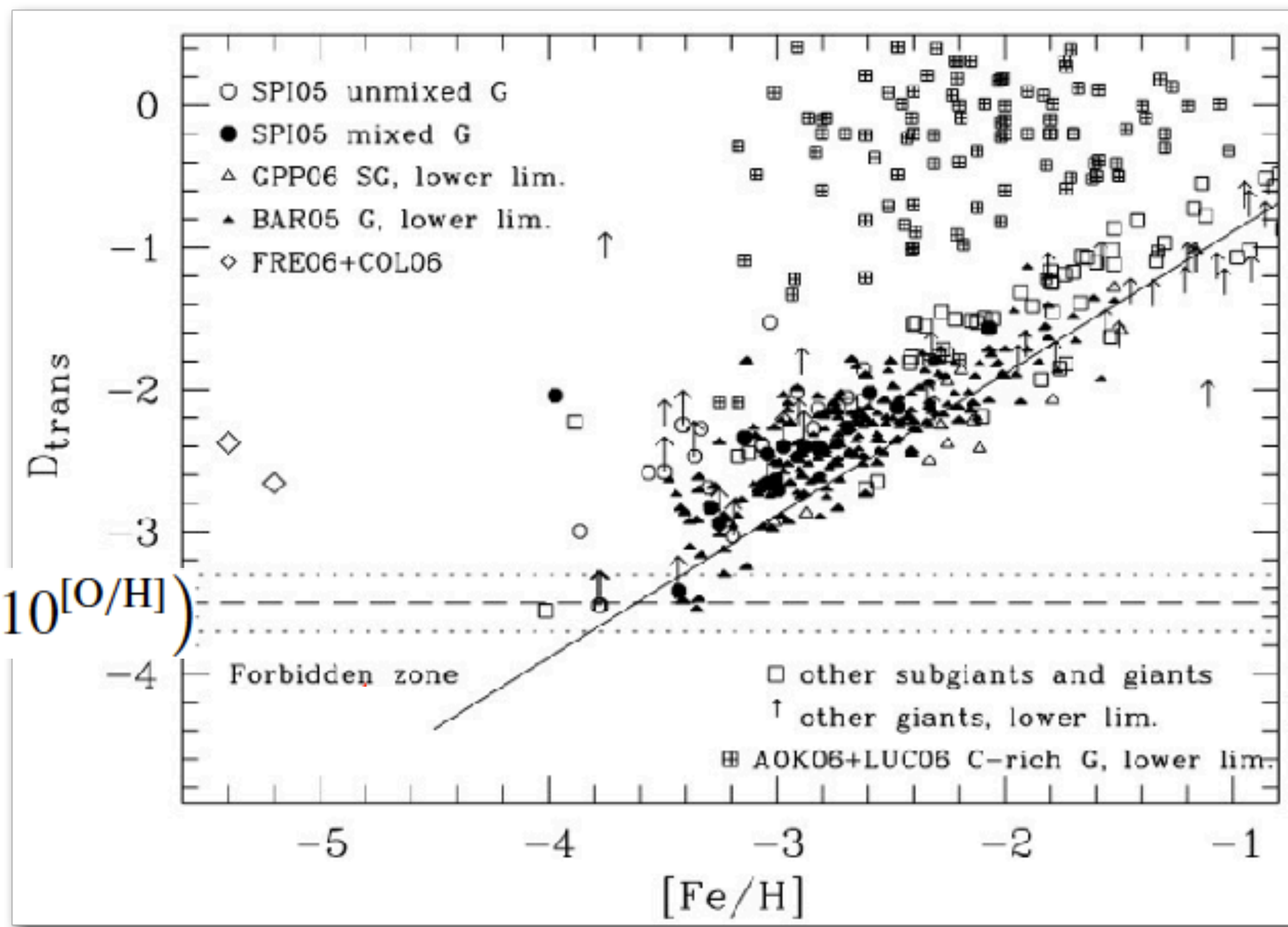
Carbon-enhanced metal-poor stars

CEMP	[C/Fe] > +1.0
CEMP-r	[C/Fe] > +1.0 and [Eu/Fe] > +1.0
CEMP-s	[C/Fe] > +1.0, [Ba/Fe] > +1.0, and [Ba/Eu] > +0.5
CEMP-r/s	[C/Fe] > +1.0 and 0.0 < [Ba/Eu] < +0.5
CEMP-no	[C/Fe] > +1.0 and [Ba/Fe] < 0

According to the theory of Bromm & Loeb (2003) a minimal quantity of C and O is necessary to form low mass stars

Transition discriminant

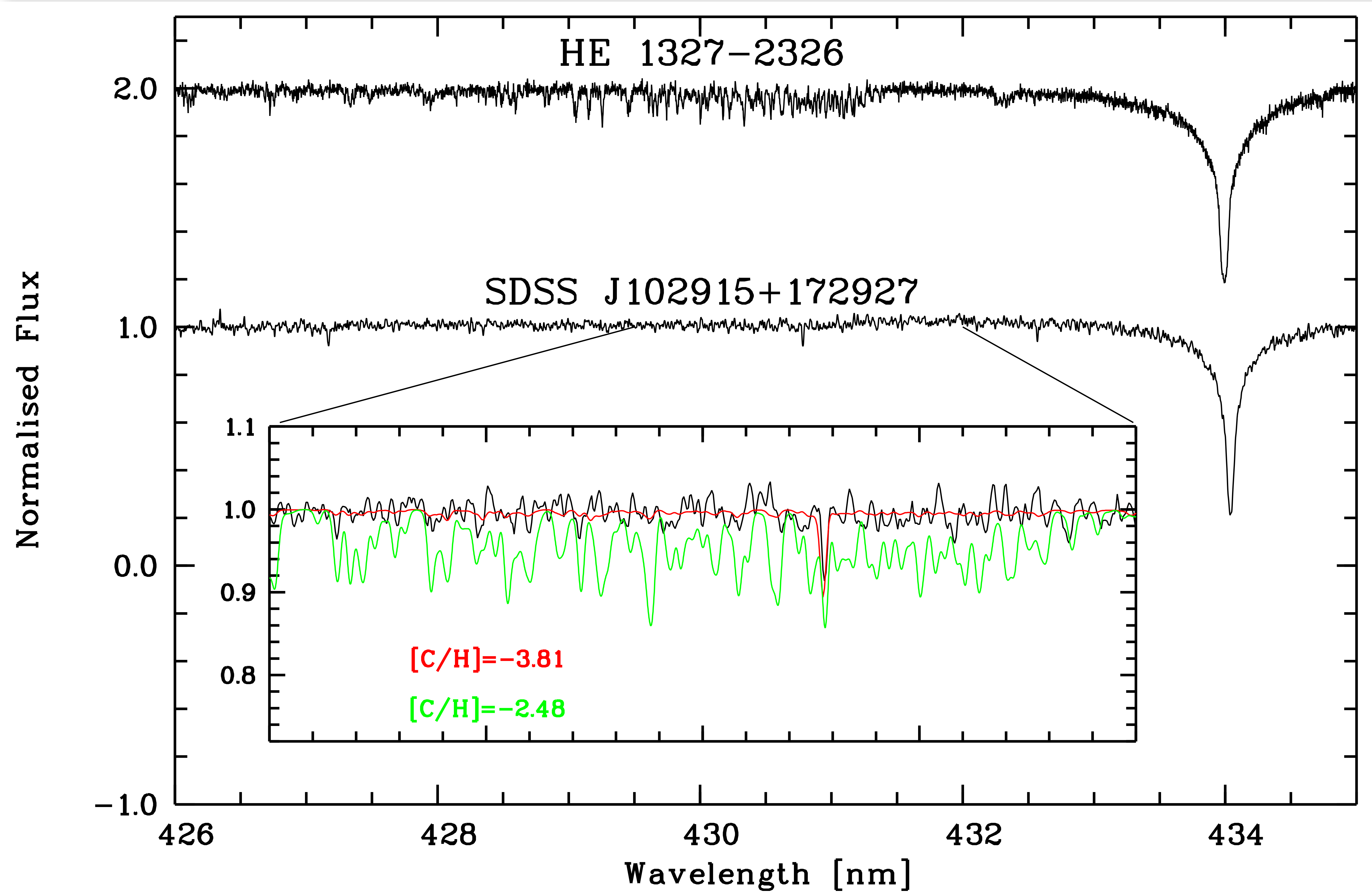
$$D_{\rm trans} \equiv \log_{10}\left(10^{[{\rm C/H}]} + 0.3 \times 10^{[{\rm O/H}]}\right)$$



Frebel et al. 2007

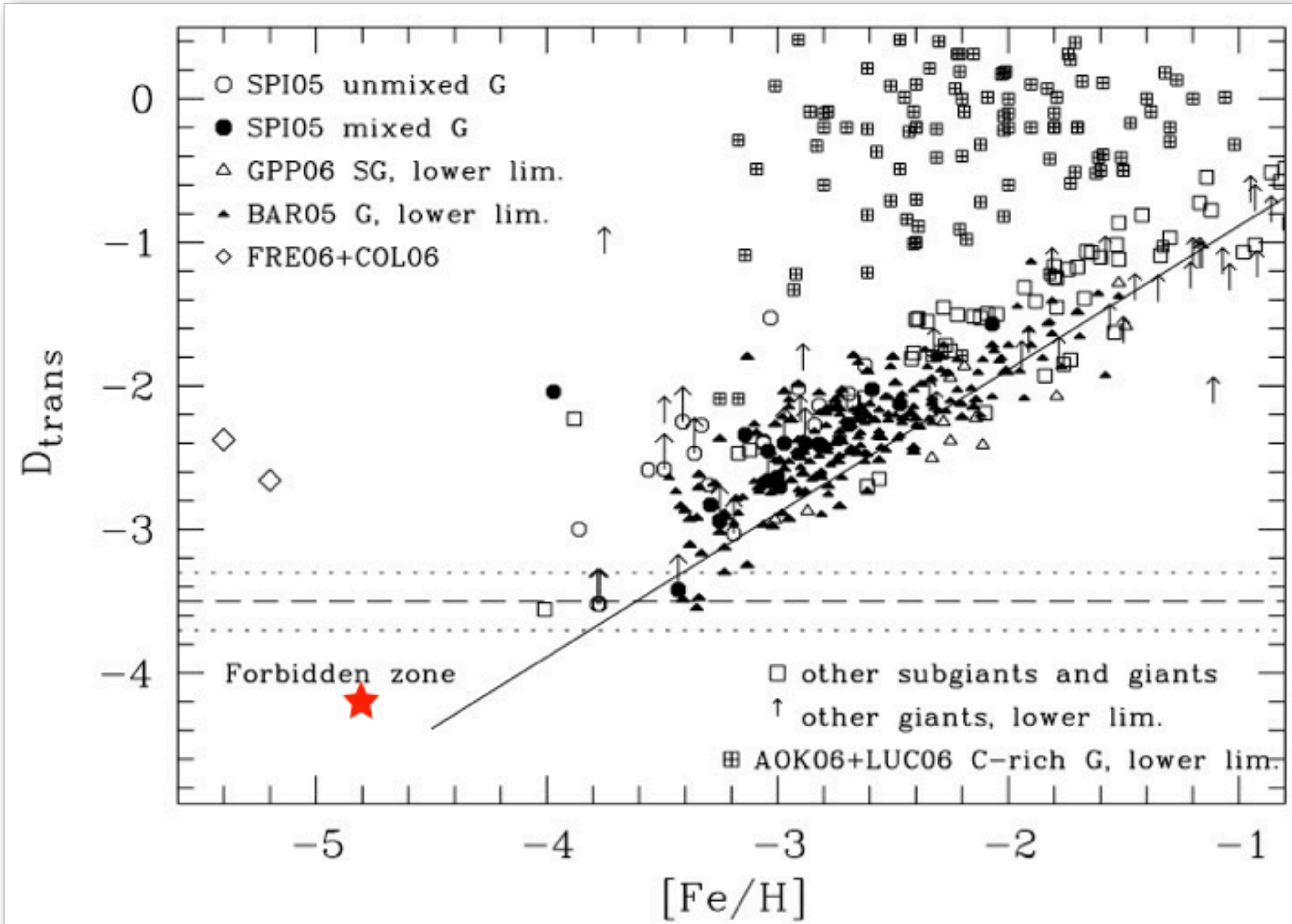
At last, no carbon...

Caffau et al., 2011, 2012



SDSS J102915+172927: the Caffau star

$$D_{\rm trans} \equiv \log_{10}\left(10^{[{\rm C/H}]} + 0.3 \times 10^{[{\rm O/H}]}\right)$$



According to the theory of Bromm & Loeb (2003) a minimal quantity of C and O is necessary to form low mass stars

But we have found a star in the forbidden zone

See also Starkenburg et al. 2018 (Pristine IV)

Frebel et al. 2007

Caffau et al. 2011, Nature, 477, 67

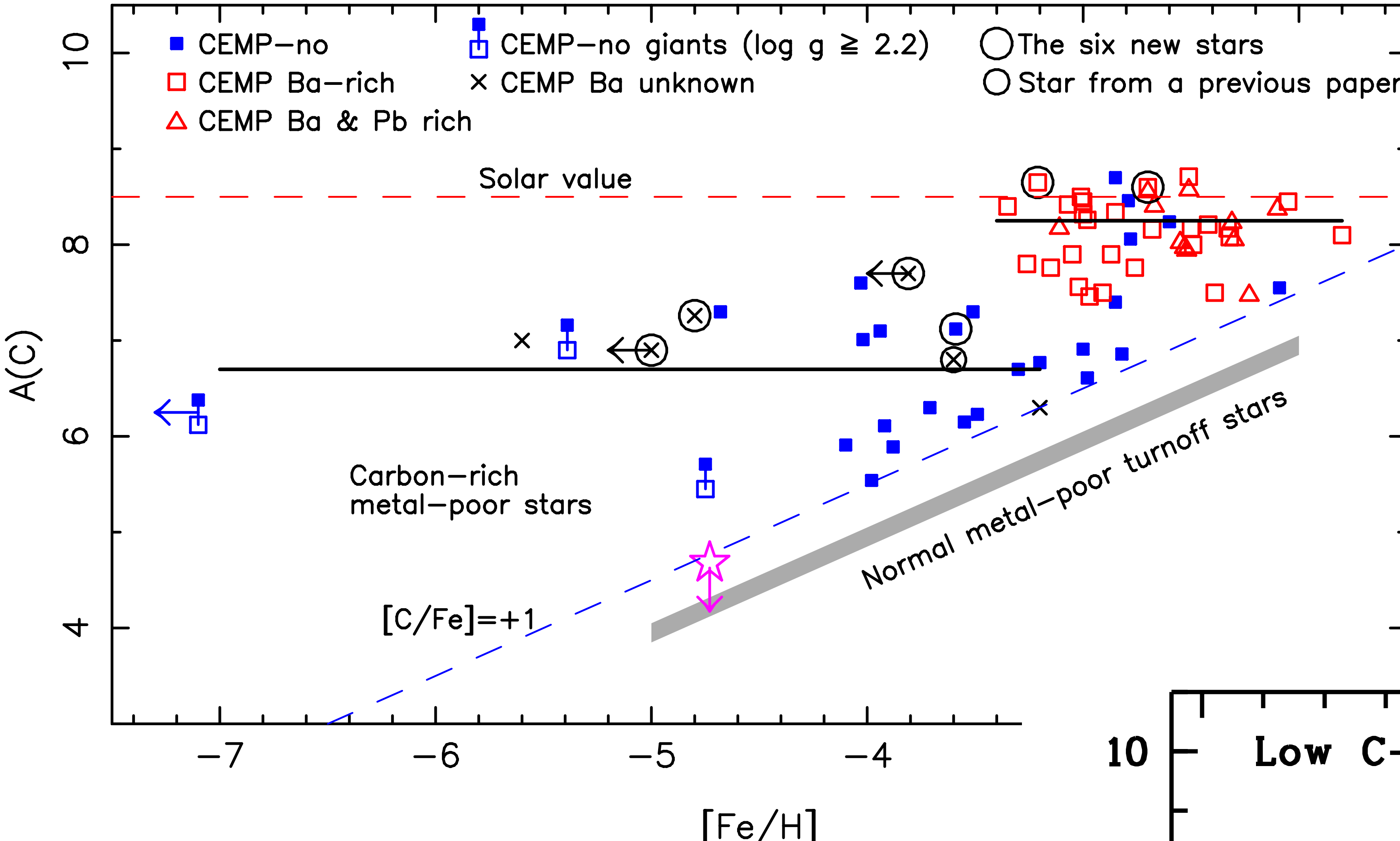
- There are various definitions of carbon-enhanced stars, and they refer to physically very different objects:

  - evolved stars in which C has been synthesized by nuclear reactions in the star itself (AGB “carbon-stars”)

  - binary system in which the more massive star transfers material processed by nuclear reactions (C-rich) to the companion. In this class are the so-called “CH stars” and some of the CEMP stars.

  - stars formed from gas in which the ratio C/Fe is several order of magnitudes higher than the solar ratio. Some of the CEMP stars (?)

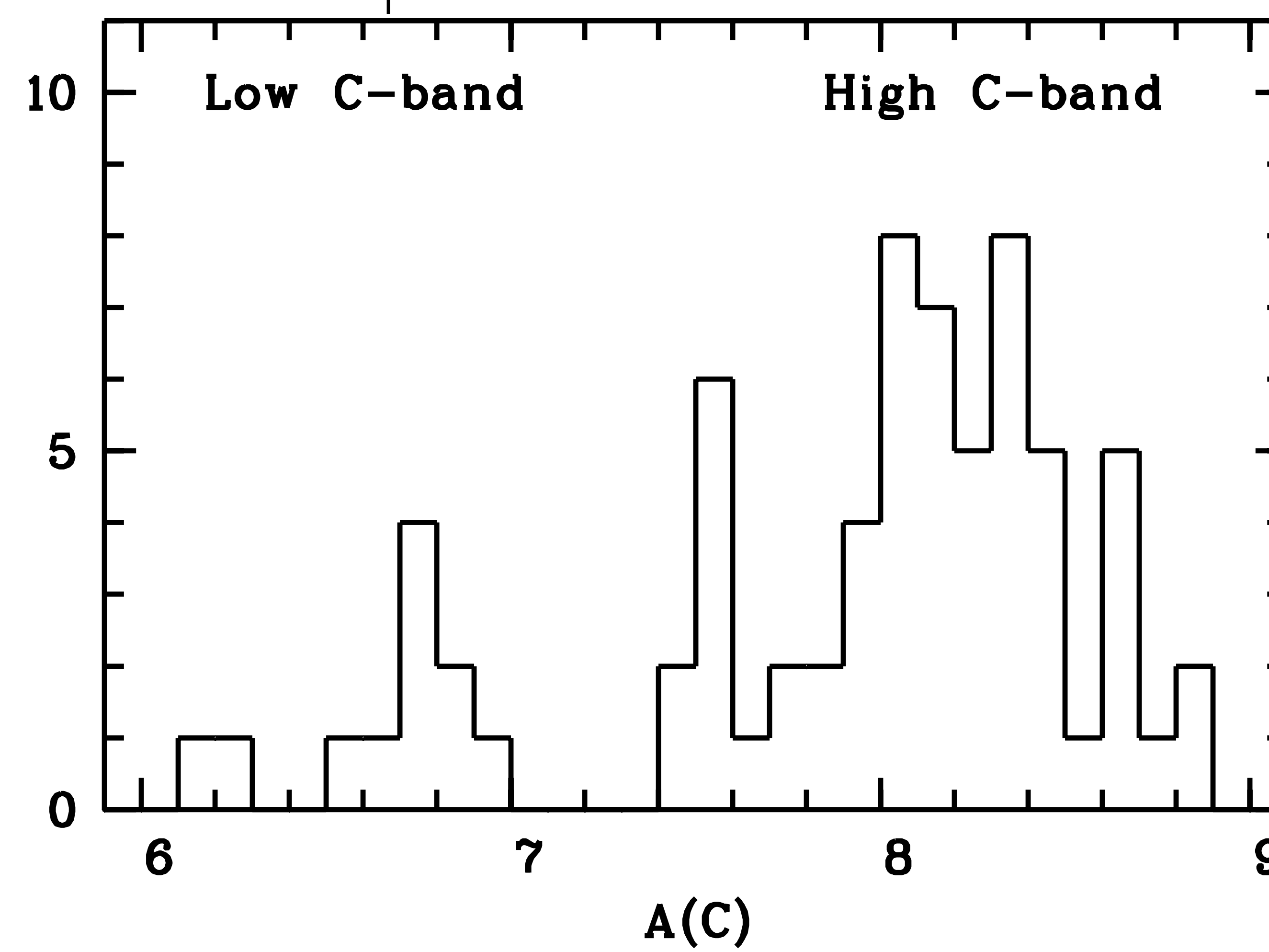
Two carbon bands



In a A(C) vs [Fe/H] plot (Spite et al. 2013), CEMP stars concentrate in two bands. Bonifacio et al. (2015, TOPoS II): a fairly clear separation between the bands and, most importantly, ALL low C-band stars are CEMP-no.

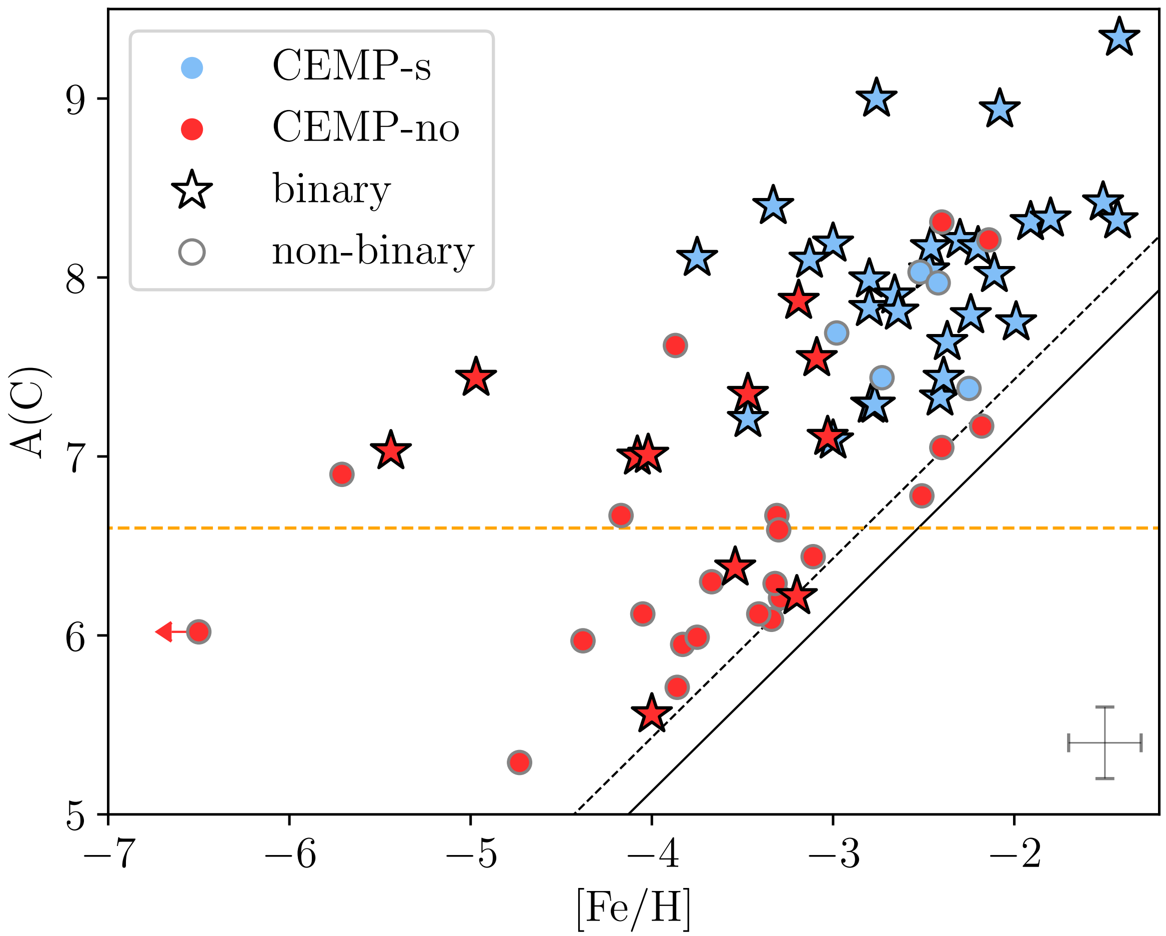
The high C-band is dominantly populated by CEMP-s stars, that are thought to be composed by binary systems (Lucatello et al. 2005, Starkenburg et al. 2014, Hansen et al. 2016b), claimed percentages vary from 82% to 100%.

On the other hand CEMP-no stars seem to have a fraction of binaries compatible with that in carbon-normal stars (Hansen et al. 2016a)

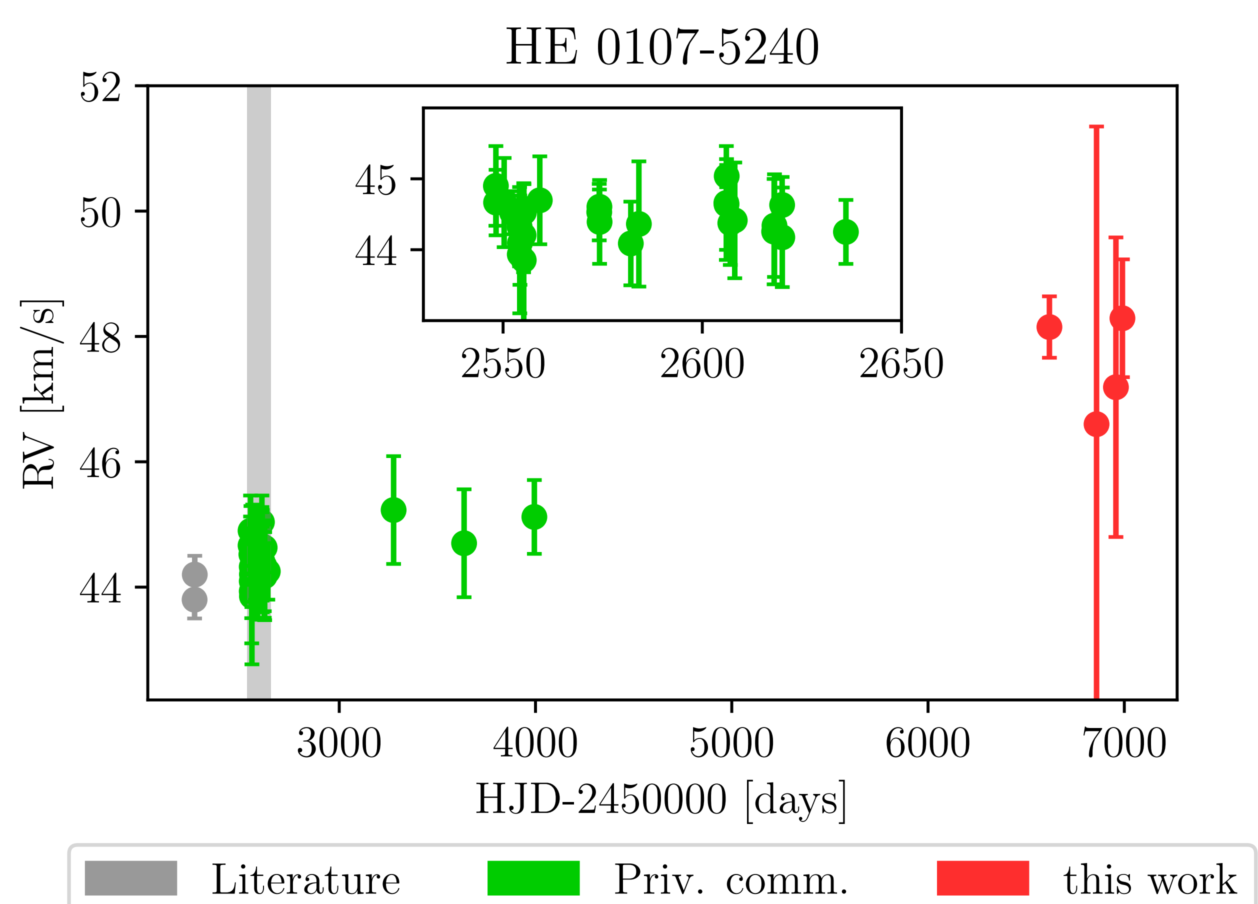


So: High-C —> mass transfer and
Low-C —> formed in C-rich cloud ?

Binarity among CEMP-no stars



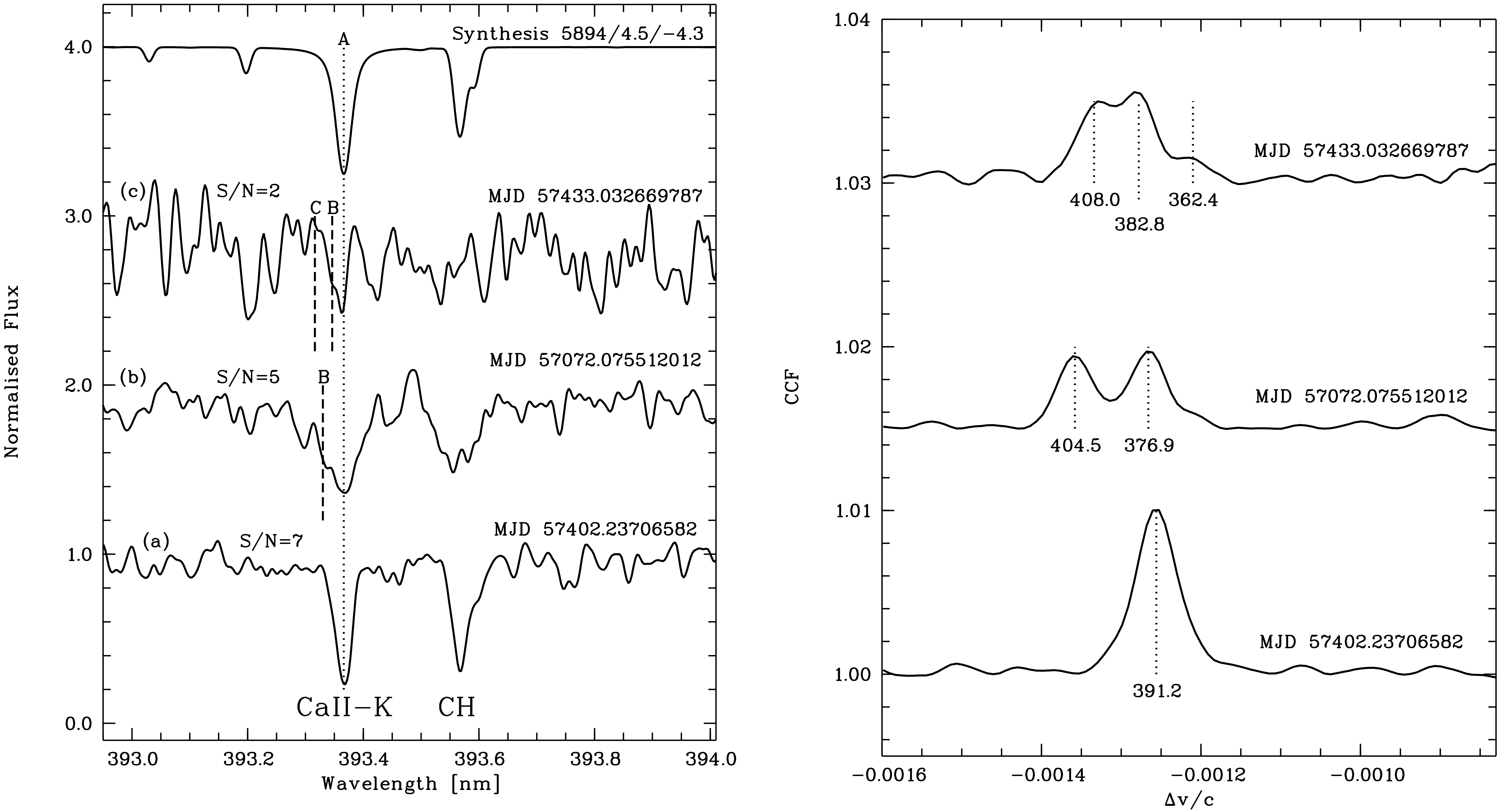
Arentsen et al. (2018) find a binary fraction among CEMP-no stars (32%) lower than among CEMP-s but higher than what found by Hansen et al. (2016a, 16%)



Strikingly HE 0107-5240 is found to be a binary and Arentsen et al. claim its abundance pattern can be explained by mass transfer from a (low-mass) AGB companion

Binarity

- **SDSS J092912.32+023817.0 ([Fe/H]=-4.97) is a multiple system (2 or 3 peaks in the CCF), CEMP star, unclear if CEMP-no.**



Caffau et al. 2016, TOPoS III

What have we learnt ?

The hypothesis that stars found in the lower C-band are always CEMP-no has so-far not been contradicted

Origin of the C-enhancement

No universally accepted hypothesis currently exists to explain the origins of the C-rich stars with [Fe/H] < −3.0 (which are almost exclusively CEMP-no stars). Different models.

Mixing and fallback

Owing to a low explosion energy (faint SN, $<10^{51}$erg), only the outer layers of the exploding star containing principally lighter elements, made in the earlier phases of stellar evolution, are ultimately ejected.

The innermost layers containing iron-peak elements, and especially iron from the last burning stage, remain close to the core and fall back onto the newly created black hole.

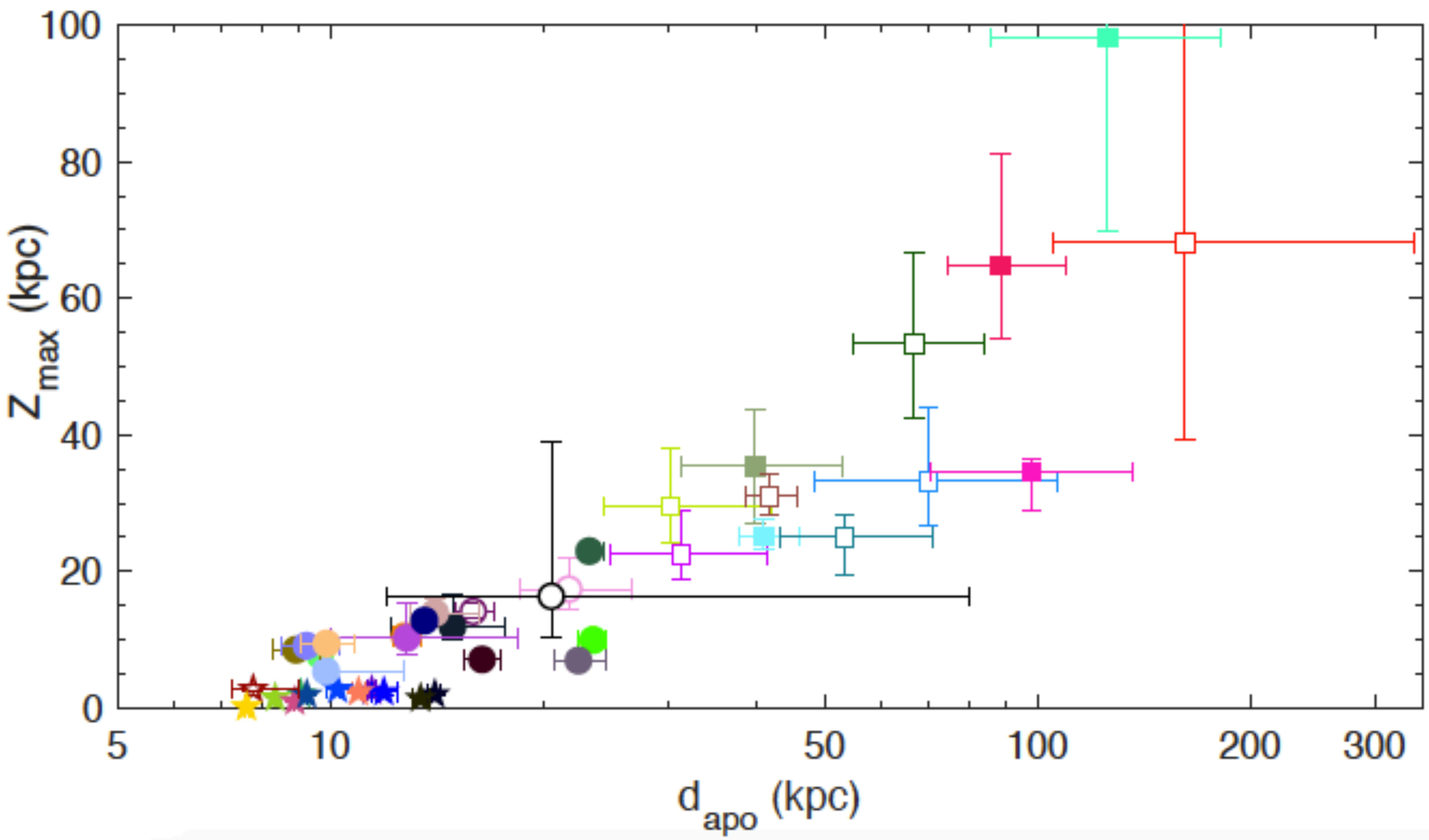
Only a small fraction is then ejected, resulting in little or even no enrichment in these elements.

Generally good fits can be obtained with the yields of mixing and fallback core collapse supernovae.

Ratio	Level (dex)	Population III properties	References
[C/Fe]	>1.0	Mixing and fallback, $Z = 0$, supernovae[a] Rotating, $Z \sim 0$, massive stars	Umeda & Nomoto (2003) Meynet et al. (2006)
[C/N]	<0.0	Rotating, $Z \sim 0$, massive stars	Meynet et al. (2006)
[Na, Mg, Al/Fe]	>1.0	Mixing and fallback, $Z = 0$, supernovae[a] Rotating, $Z \sim 0$, massive stars	Umeda & Nomoto (2003) Meynet et al. (2006)
[α/Fe]	~0.4	Supernovae[a]	Woosley & Weaver (1995)
[Ca/Fe]	>1.0	PISNe signature	Heger & Woosley (2002)
[Zn/Fe]	>0.5	High explosion energy supernovae[a]	Umeda & Nomoto (2002)

Frebel & Norris 2015

Orbits



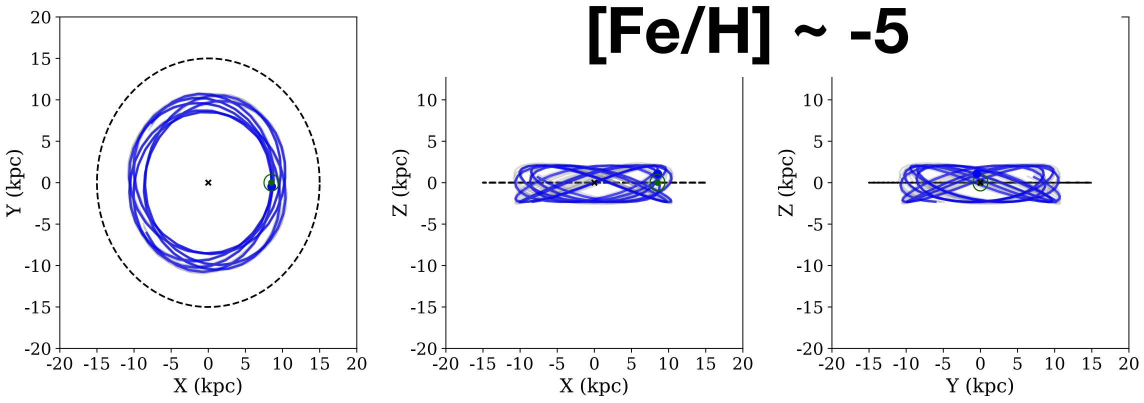
29% of all known UMP stars ([Fe/H]<-4 on prograde orbits confined within 3 kpc of the Milky Way plane.

Sestito et al. 2019

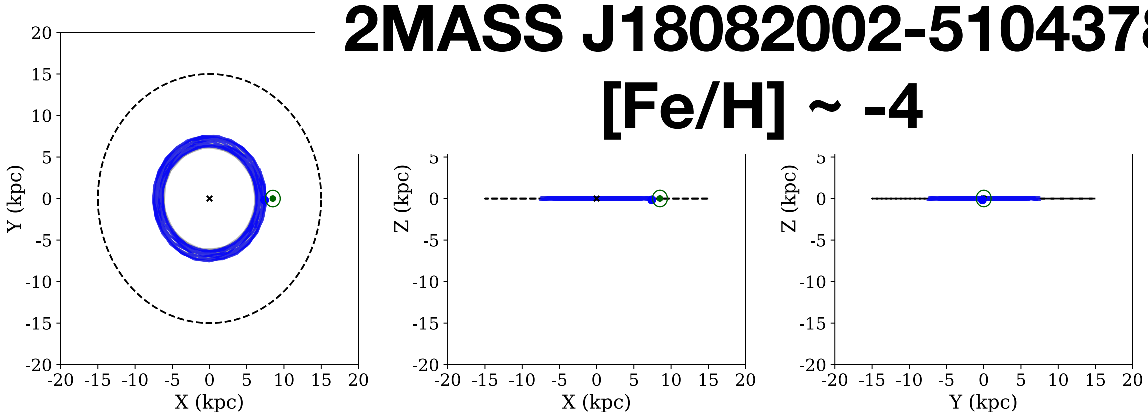
- "One intriguing interpretation is that these stars belonged to the massive building block(s) of the proto-Milky Way that formed the backbone of the Milky Way disc."

- "Alternatively, they may have been brought into the MilkyWay by one or more accretion events whose orbit was dragged into the plane by dynamical friction before disruption."

SDSS J102915+172927
[Fe/H] ~ -5

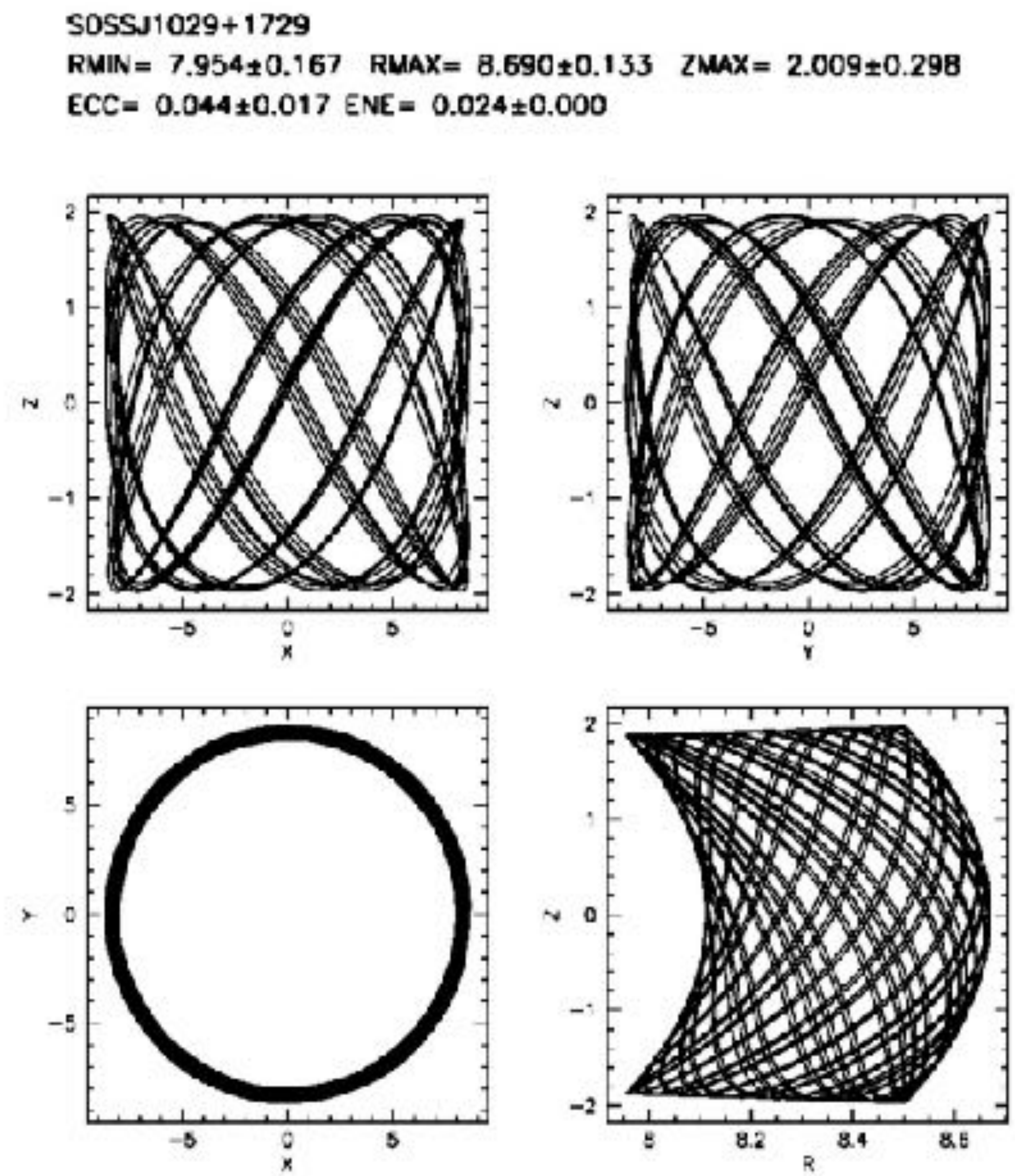


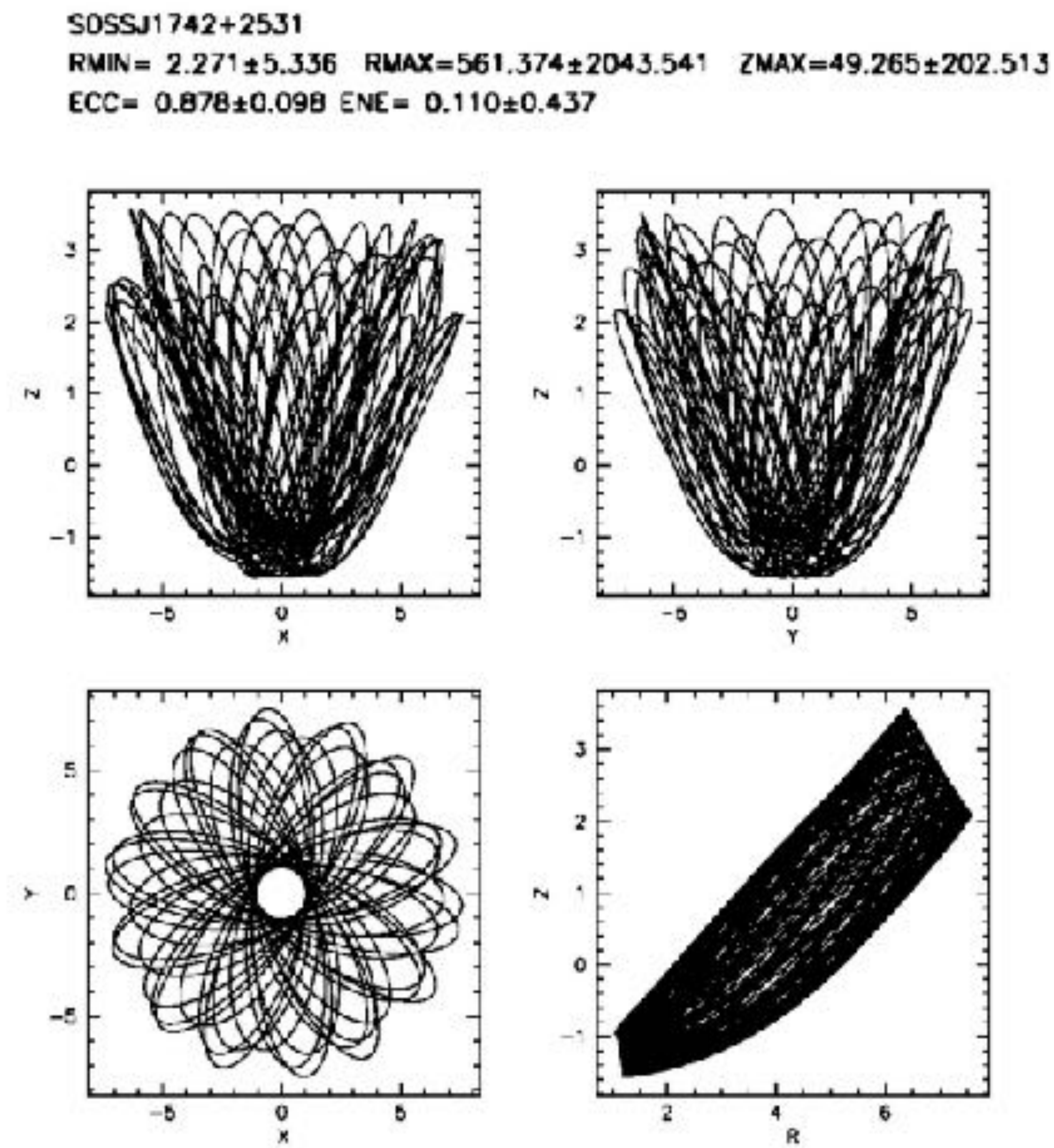
2MASS J18082002-5104378
[Fe/H] ~ -4



TOPoS VI: Kinematics - TBD

Andreas Koch and Simone Zaggia

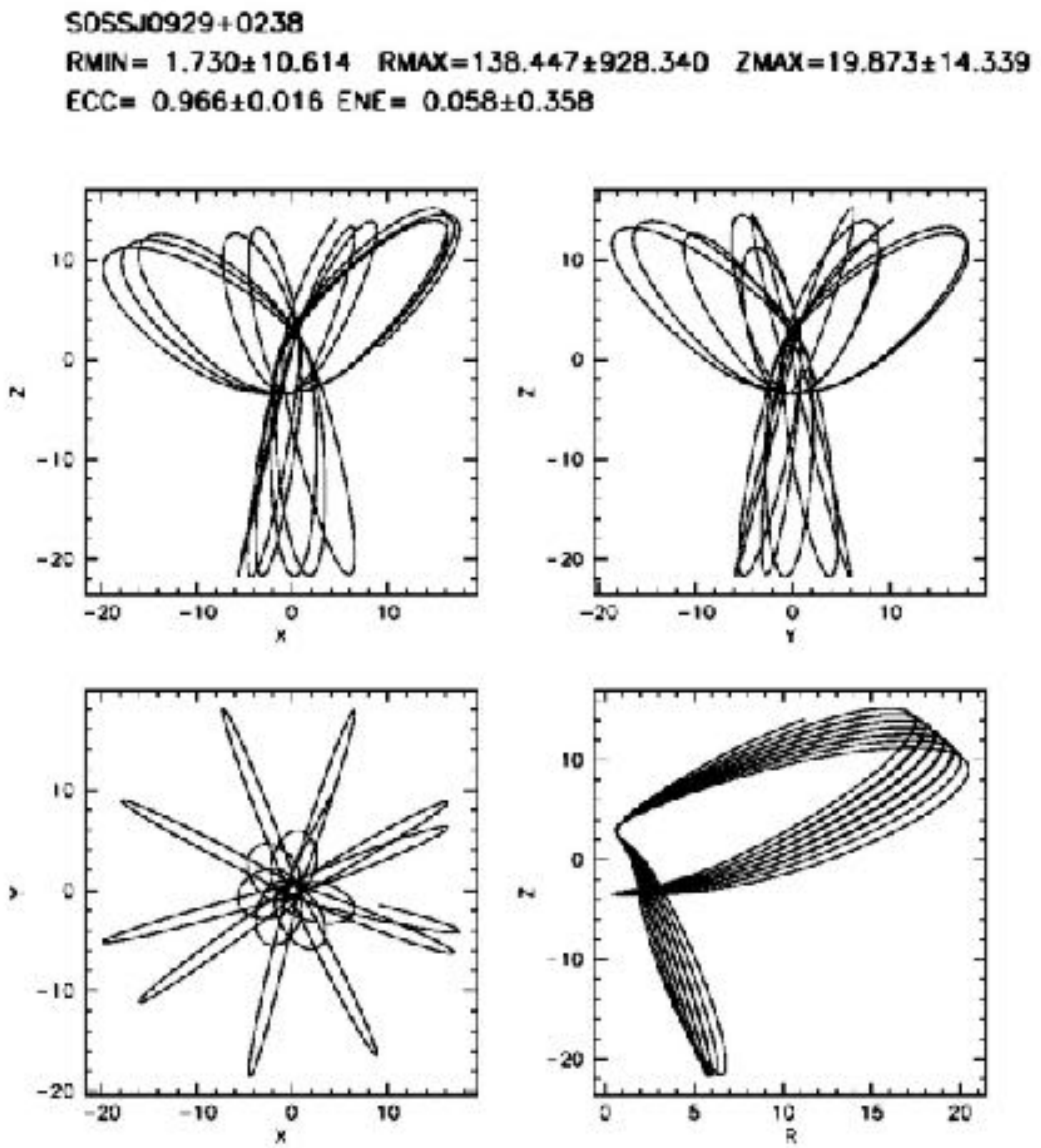


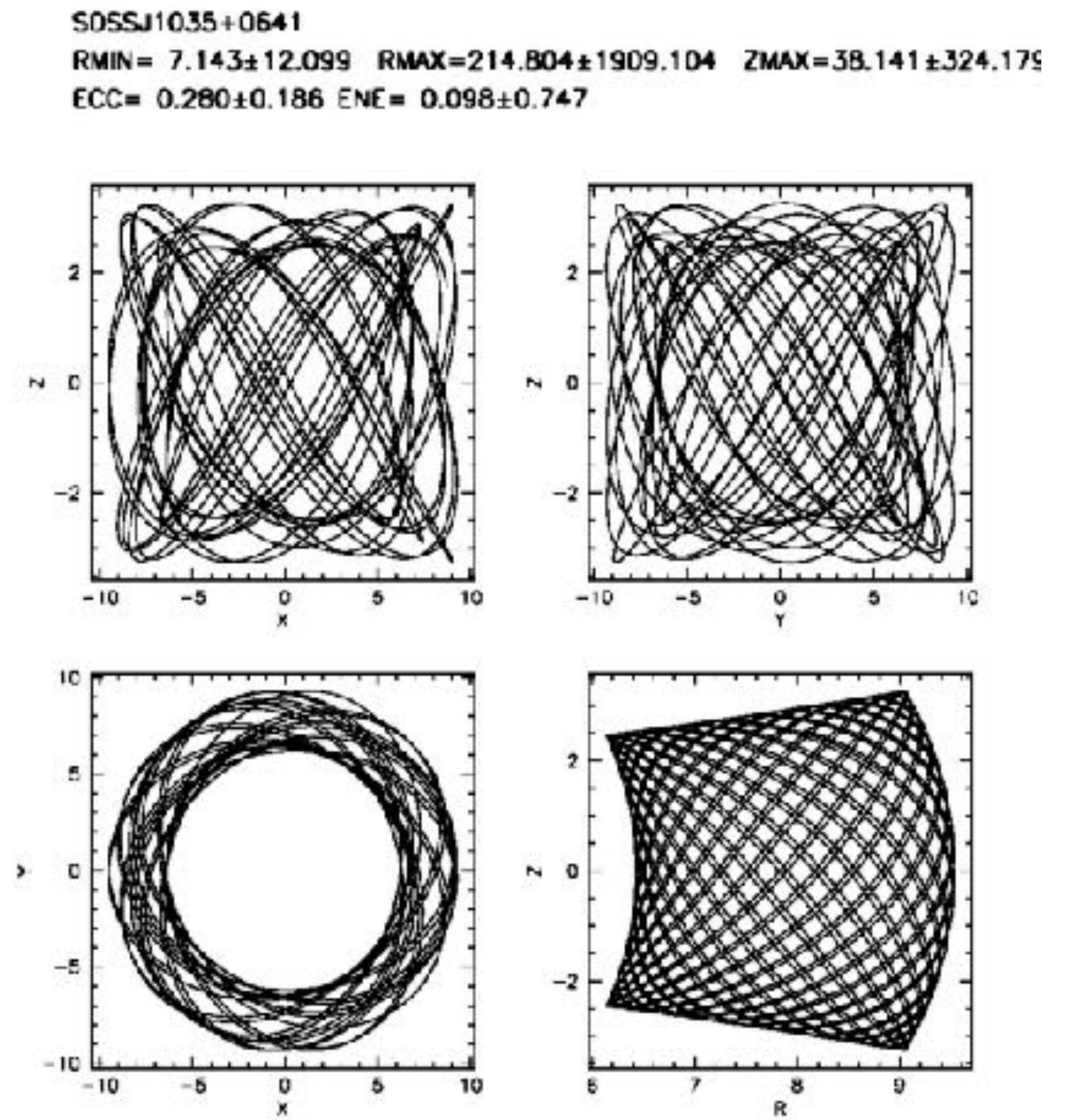


Leo - Hercules

TOPoS VI: Kinematics - TBD

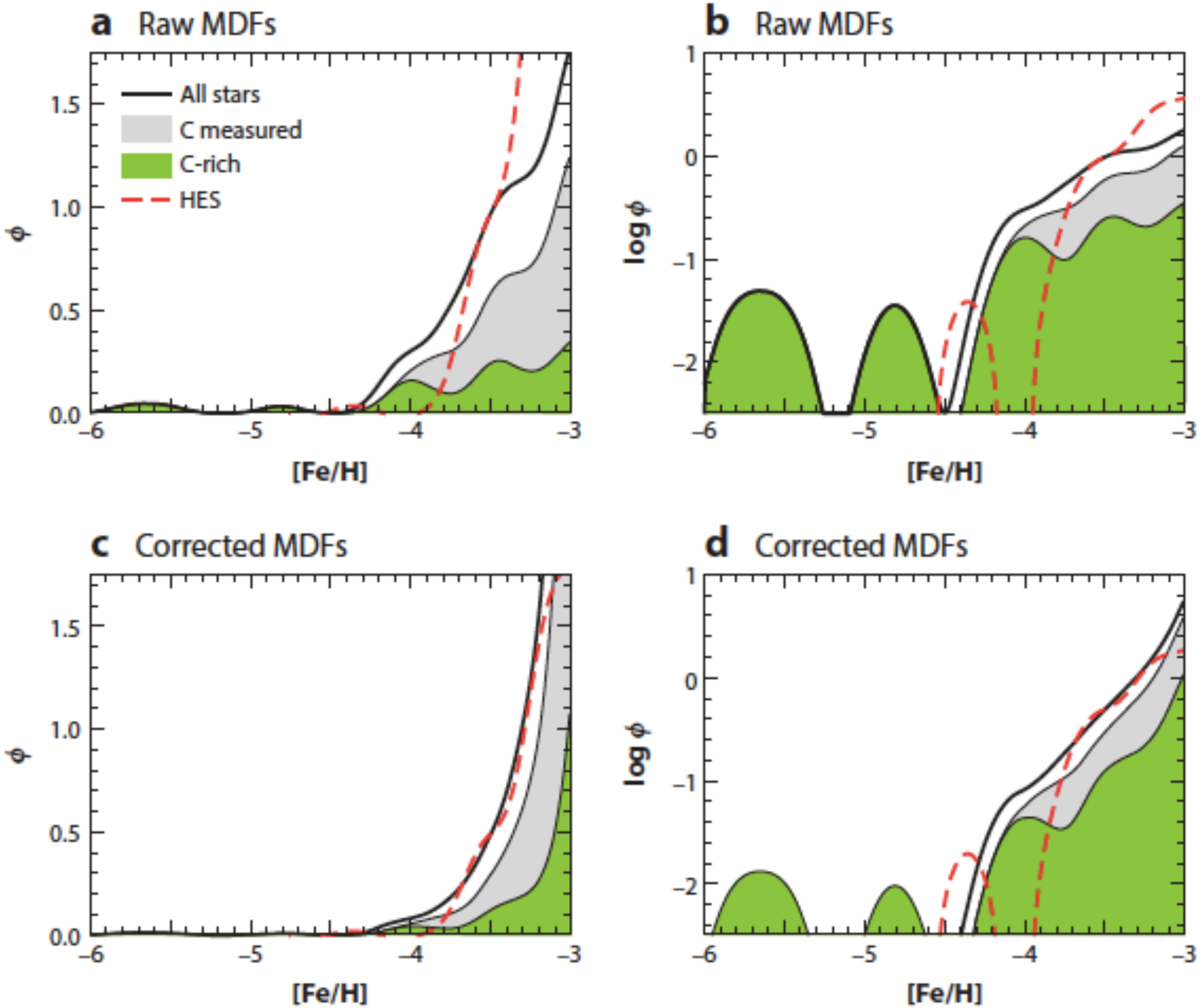
Andreas Koch and Simone Zaggia





Hydra - PataLeo

Metallicity distribution function



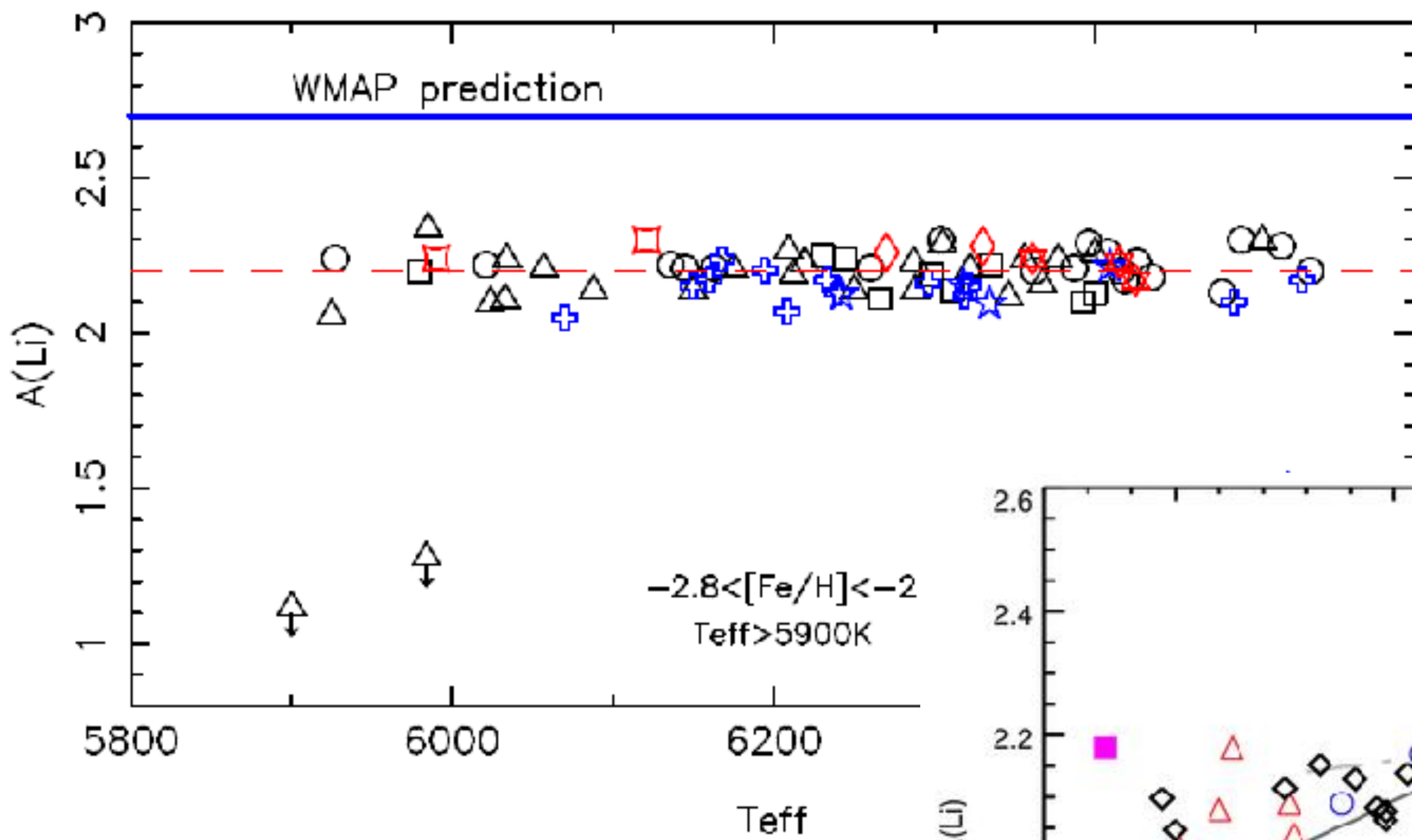
“After accounting for the completeness function, the “corrected” MDF does not exhibit the sudden drop at [Fe/ H]=– 3.6 that was found in recent samples of dwarfs and giants from the Hamburg/ ESO survey.”

Figure 5

The Fe metallicity distribution function based on the high-resolution, high-S/N homogeneous abundance analysis by Yong et al. (2013a). The generalized histograms have been generated using a Gaussian kernel having $\sigma = 0.30$ dex, and these are presented on linear (*left*) and logarithmic (*right*) scales. Green and gray color coding is used to present the contribution of C-rich and C-normal stars, respectively, for which measurement was possible. Panels *a* and *b* refer to the raw data, and panels *c* and *d* show the same data corrected for completeness for the range $-4.0 < [Fe/H] < -3.0$, as described by Yong et al. (2013b). The dashed line shows the metallicity distribution function (MDF), which was based on Hamburg/ESO survey data by Schörck et al. (2009). Reproduced with permission of D. Yong, private communication.

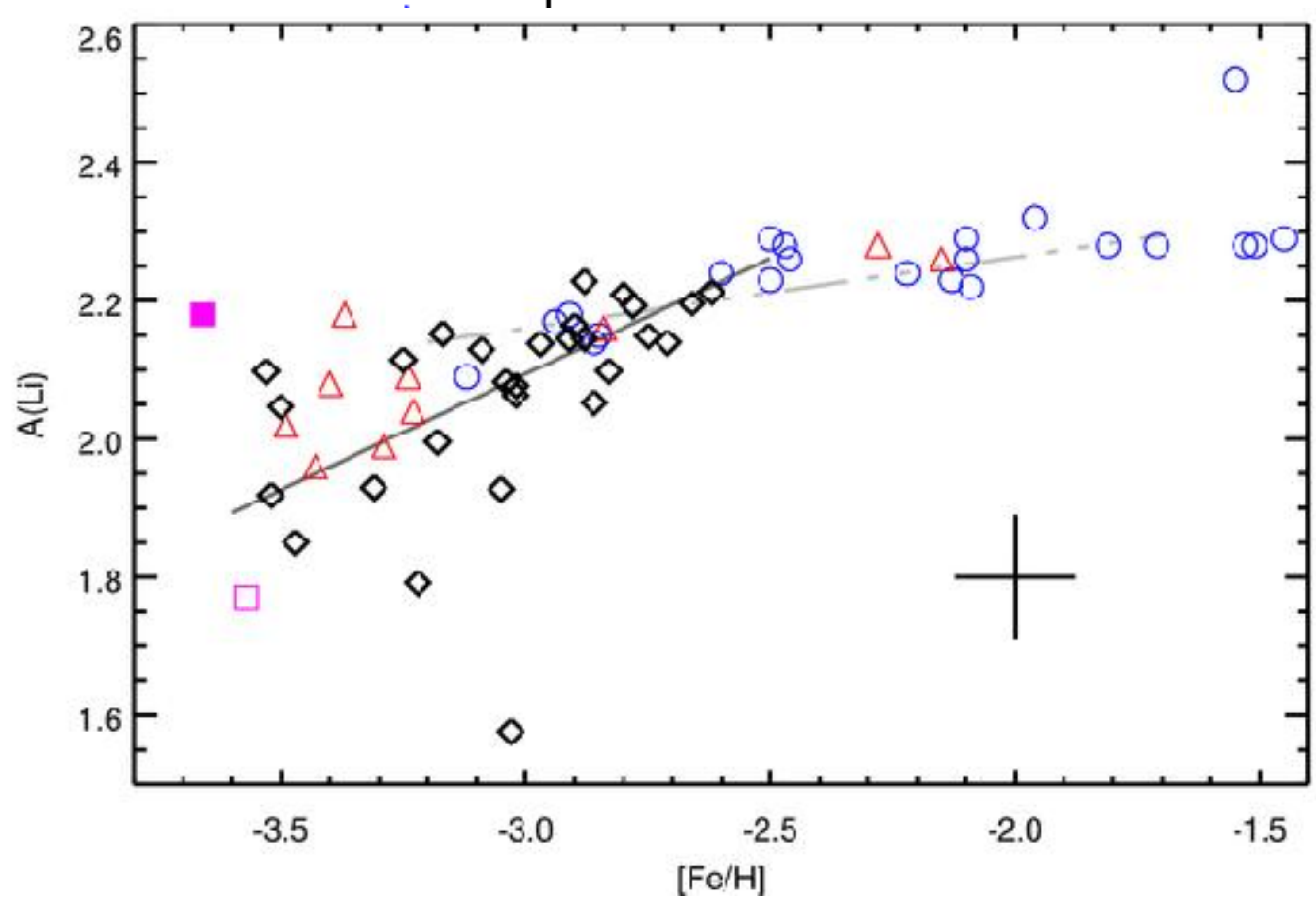
Yong et al. 2013, Frebel & Norris, 2015

The lithium content of metal-poor stars



The "cosmological Lithium problem"

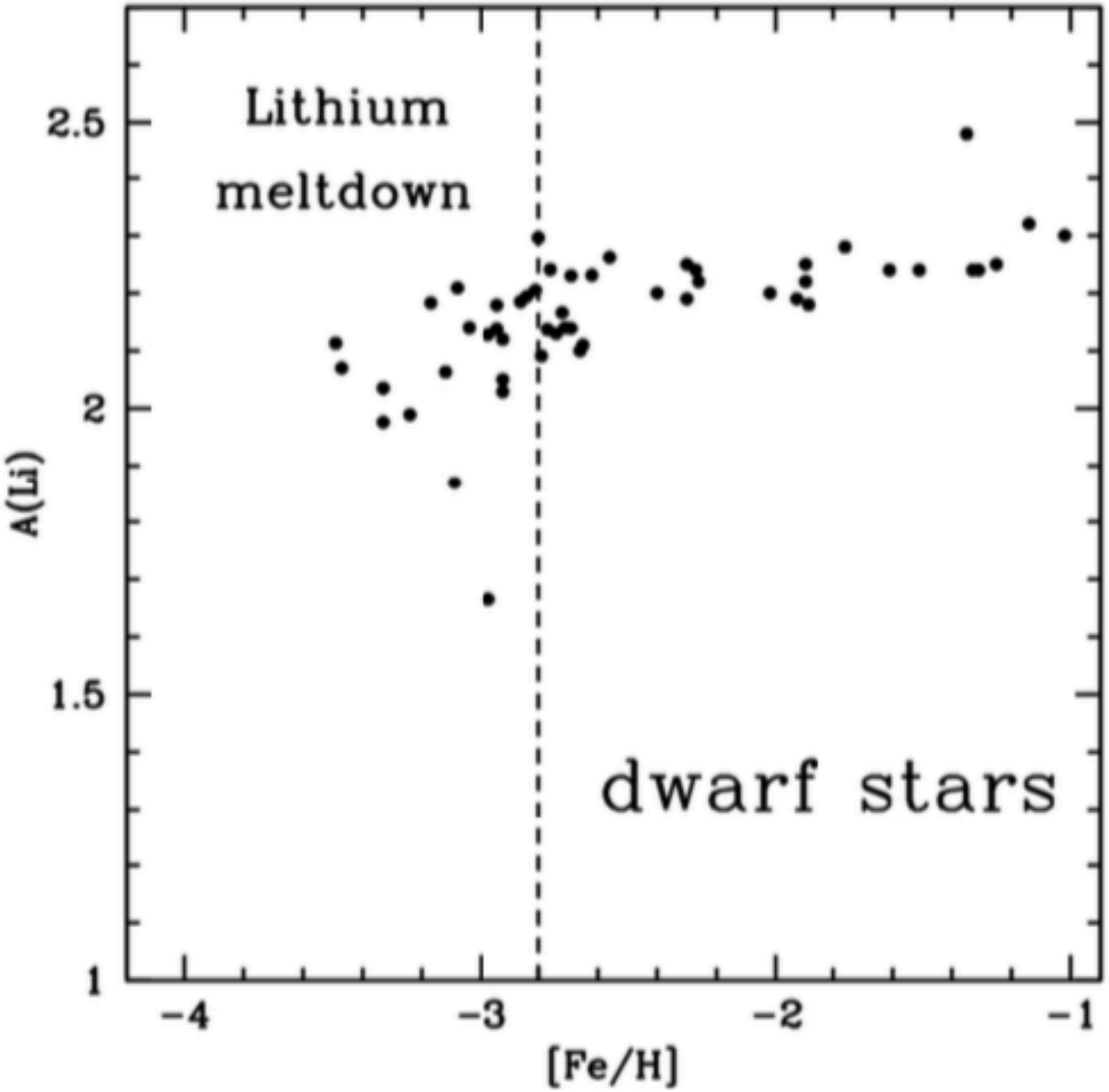
Spite et al. 2012

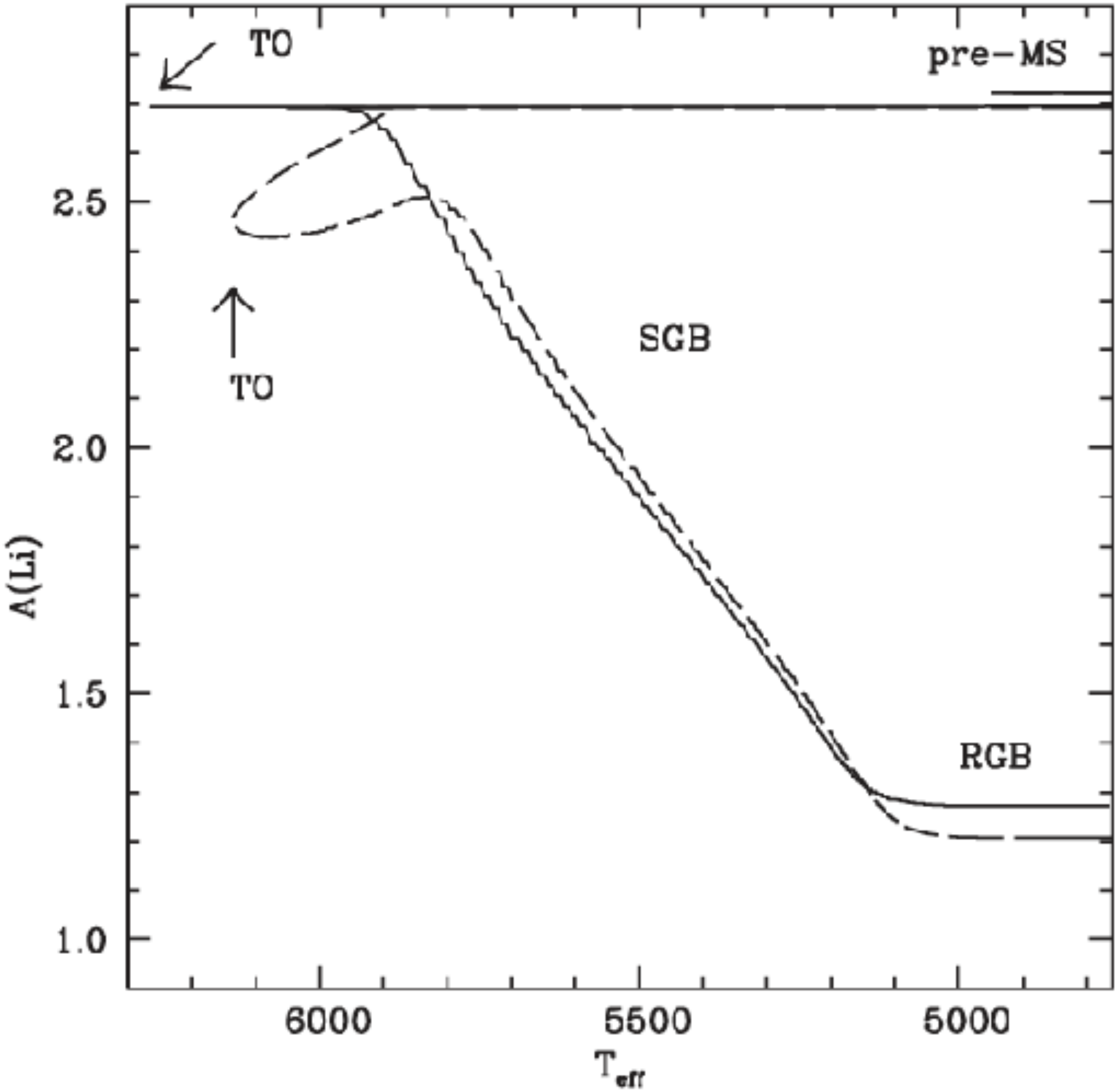


The "meltdown" of the Spite plateau

Sbordone et al. 2010
Aoki et al. 2009

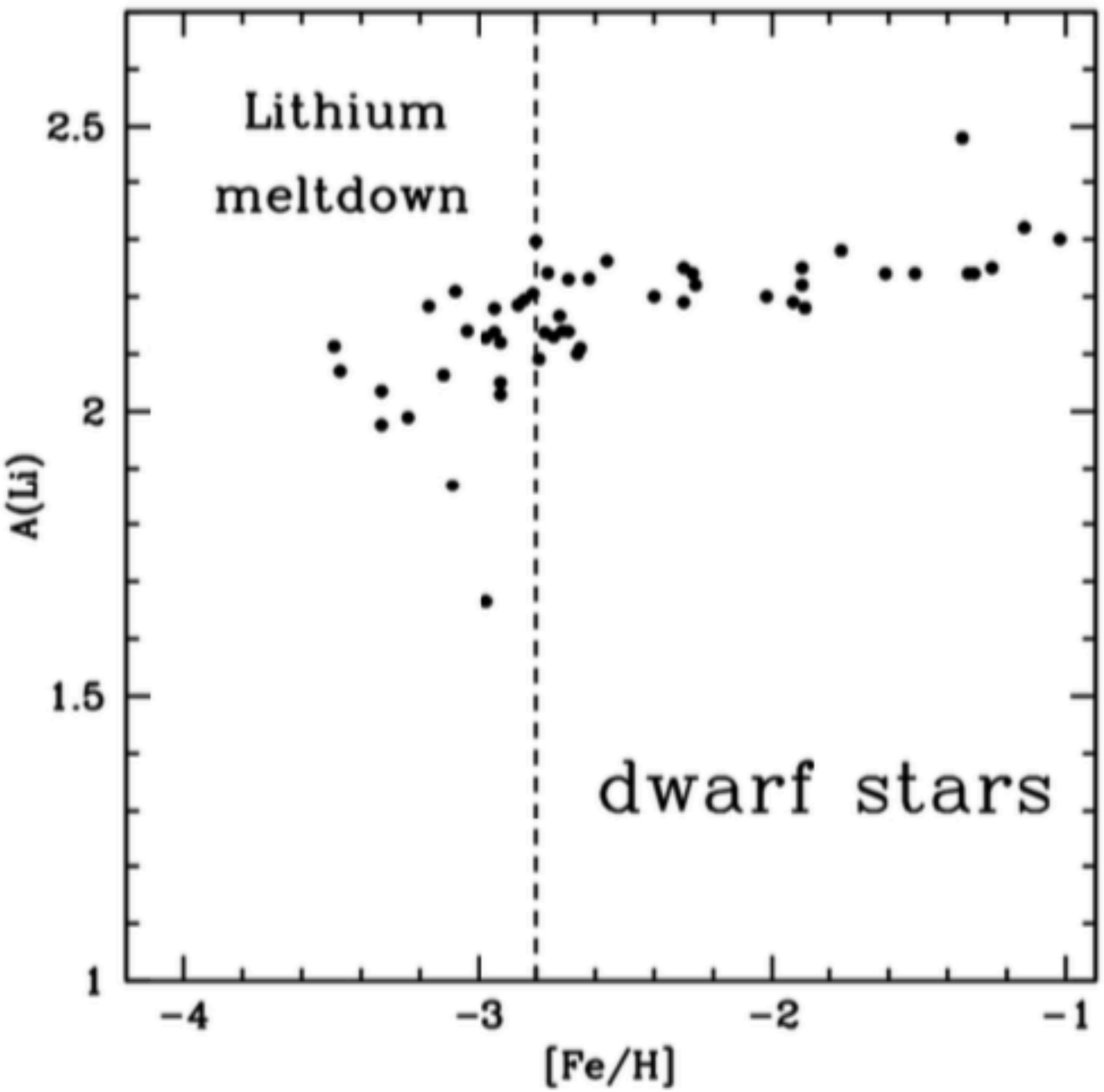
The lithium content of metal-poor stars

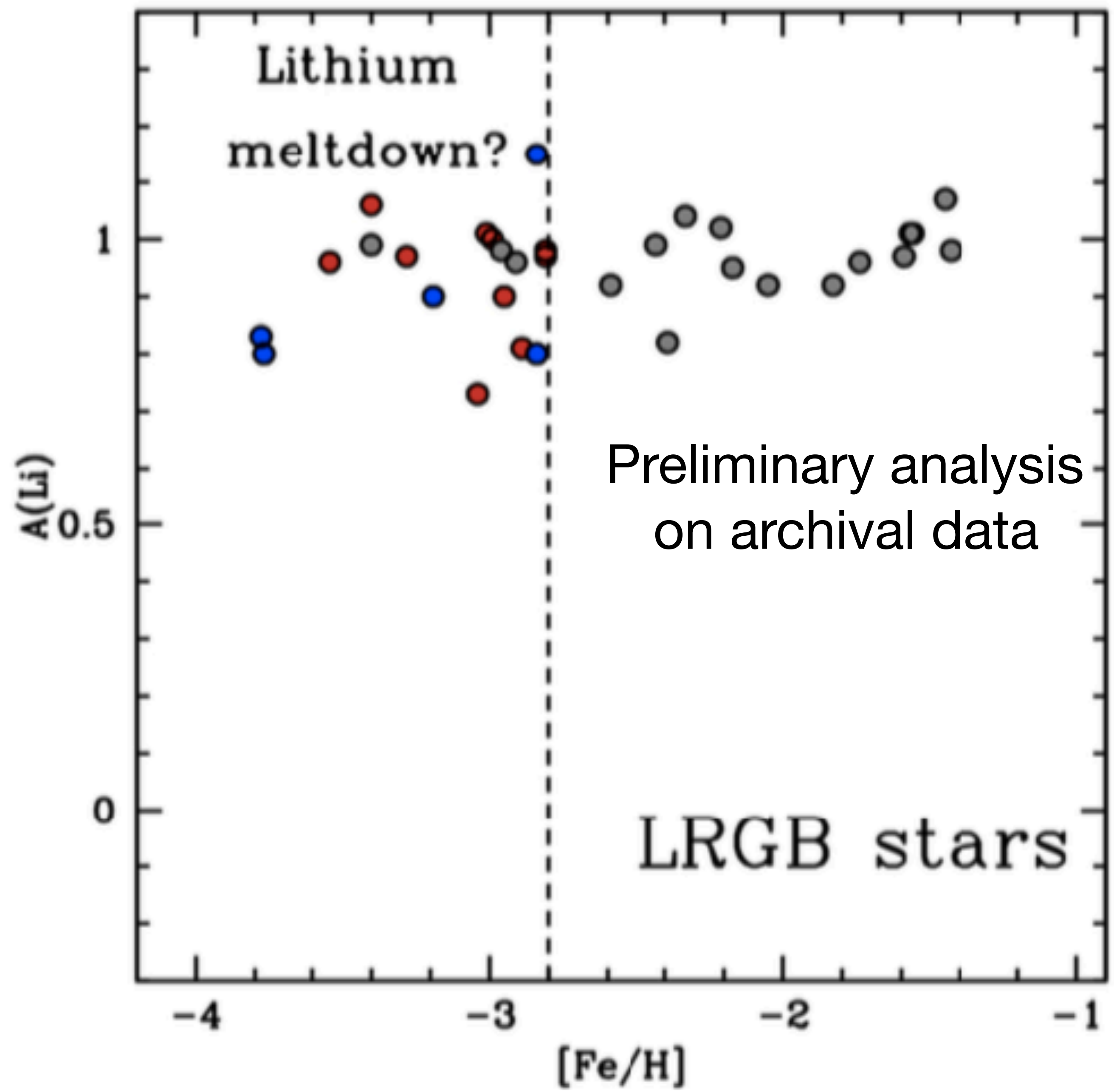




Mucciarelli et al. 2012

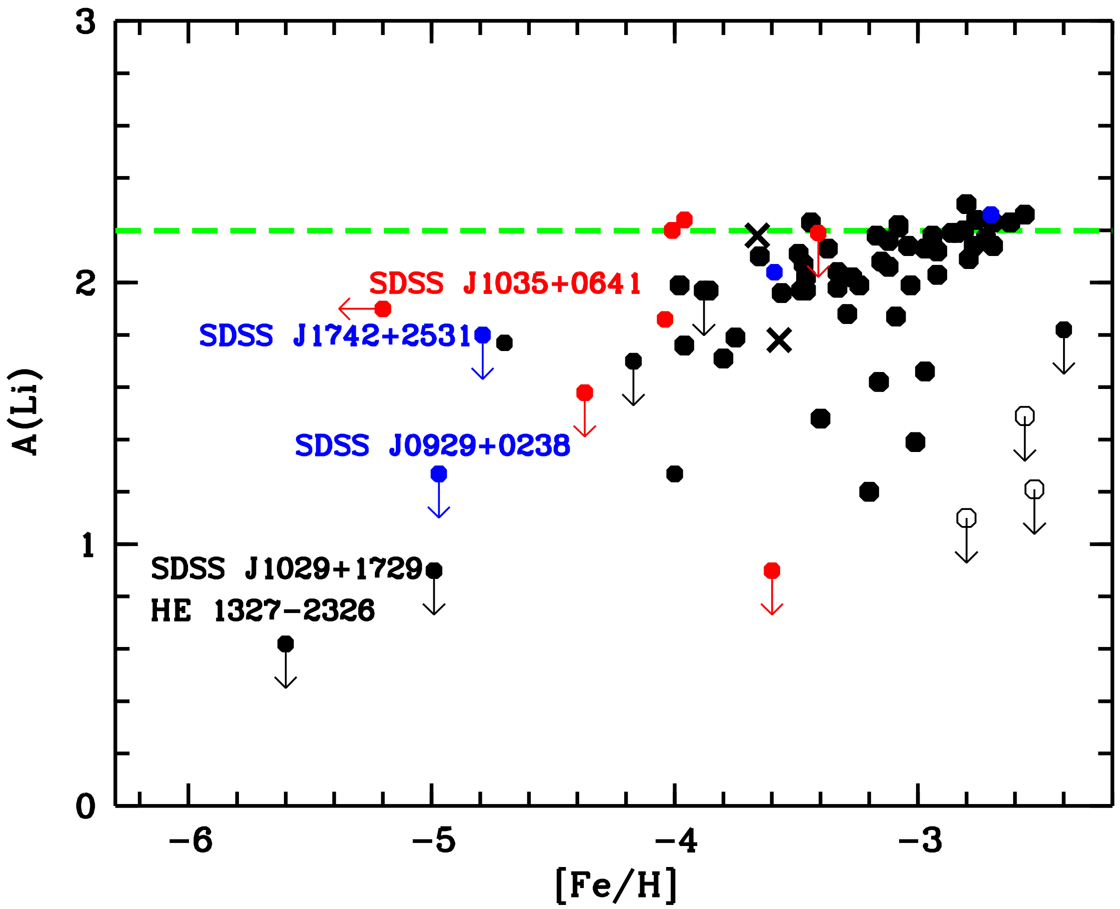
The lithium content of metal-poor stars

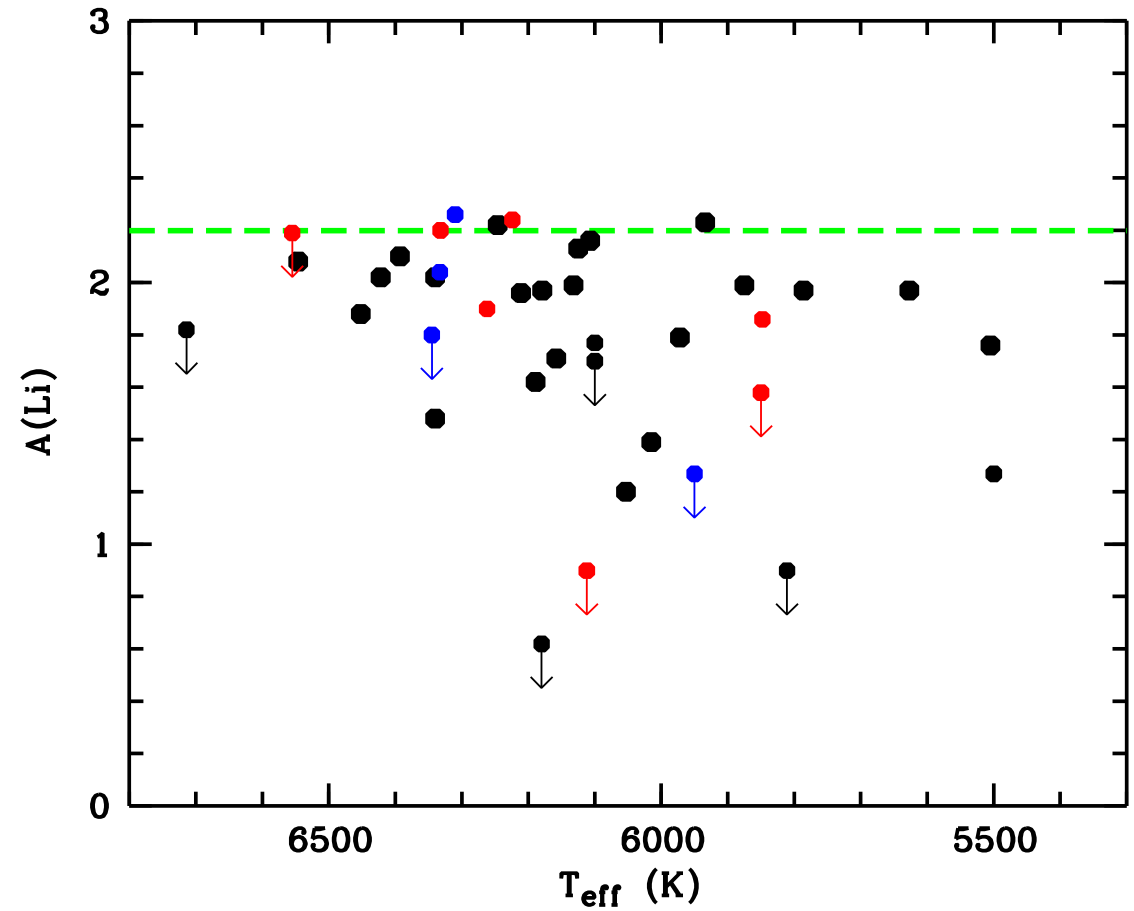




UVES/VLT + Mike/LCO, observations acquired

New Li measurements in EMP stars





- There are stars on the Spite plateau at least down to [Fe/H]=-4.0
- Even at [Fe/H]<-5.2 Li is measurable
- Below [Fe/H]=-3.5 stars at Teff< 6000K are Li -depleted
- The Teff for which lithium destruction in the stellar atmospheres becomes important increases as metallicity decreases (?)

Bonifacio et al. 2018, TOPoS IV

Searches for extremely metal-poor stars

- Understand the formation of low mass stars in low metallicity gas
  - Do zero-metal low-mass stars exist?
  - What is the “critical metallicity” for low-mass star formation?
  - The chemical composition of the most metal-poor stars gives us information on the first massive stars
- Lithium and primordial nucleosynthesis predictions
  - Lithium abundance / destruction in EMP stars

Thank you