Extremely Metal Poor Stars

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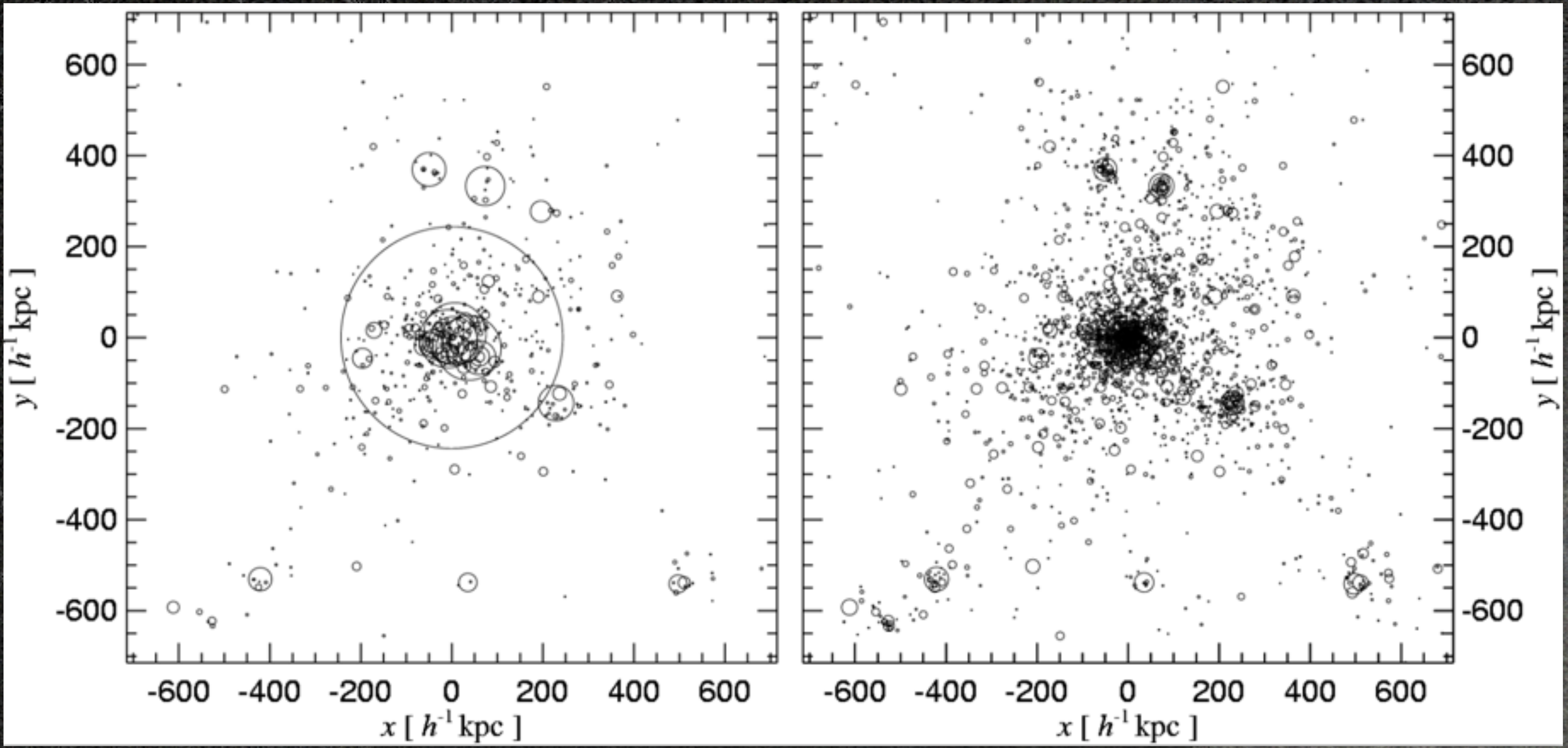
Pristine collaboration : Else Starkenburg, Nicolas Martin, + ~ 20 colleagues
StarNet collaboration : Sebastien Fabbro, KV + ~5 colleagues

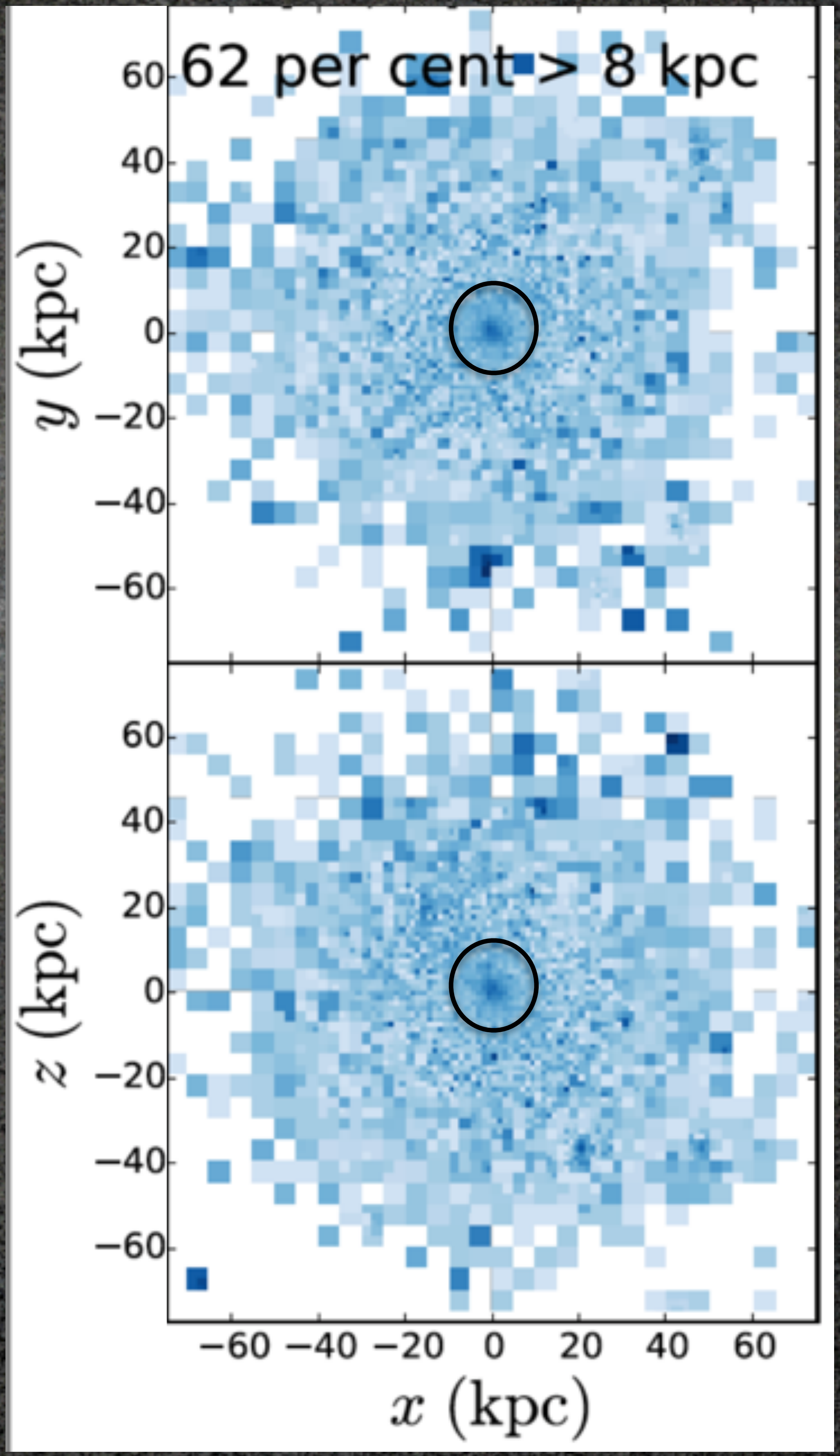
Springel & White 2000



1% "earliest" 1% "lowest metallicity"

Projections of the galaxy distribution in a cube of comoving side 1.4h^{-1} Mpc around a ``Milky Way" halo at z=0, from the parallel tree-code, Gadget (*Springel et al. 2001*), with semi-analytic galaxy formation recipes from *Kauffmann et al. (1999)*.

Starkenburg et al. 2017



Analysis of the APOSTLE (high resolution) simulations of Local Group galaxy pairs (*Sawala et al. 2016)*

shows the location & mass density of stars, and lots of substructures

Furthermore, many of the oldest stars (<0.8 Gyr after the Big Bang) are in the outer parts of the Galaxy (>8 kpc).

colour coded by % of old stars, with [Fe/H] < -2.5

If 0.8 $M_\odot$ stars formed at these early epochs, then they would exist on the MSTO today.

1. central bulges
2. halo & substructures
3. dwarf galaxies *

Difficult to determine the ages of the oldest MSTO stars $\longrightarrow$

assume an age-metallicity relationship

1. central bulges — [Fe/H] < -2
2. halo & substructures — [Fe/H] < -3
3. dwarf galaxies * — [Fe/H] < -3 * *later?*

Wise et al. 2012

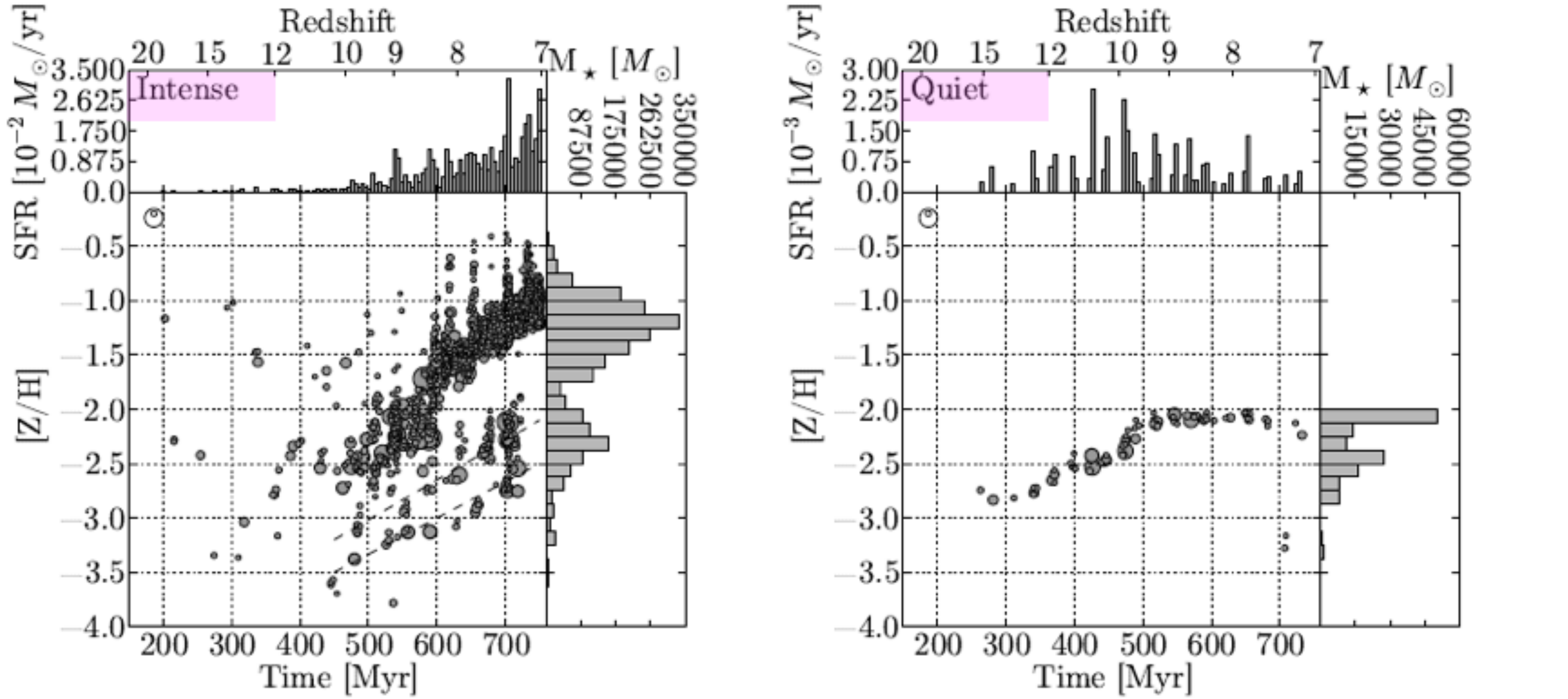


FIG. 6.— The scatter plots show the metal-enriched (Pop II) star formation history of the intense (left) and quiet (right) halos as a function of total metallicity, i.e. the sum of metal ejecta from both Pop II and Pop III SNe, at $z = 7$. Each circle represents a star cluster, whose area is proportional to its mass. The open circles in the upper right represent 10^3 and 10^4 $M_\odot$ star clusters. The upper histogram shows the SFR. The right histogram depicts the stellar metallicity distribution. The intense halo shows a large spread in metallicity at $z > 10$ because these stars formed in progenitor halos that were enriched by different SN explosions. At $z < 10$, the majority of stellar metallicities increase as the halo is self-enriched. The spikes in metallicity at $t = 620$, 650, and 700 Myr show induced star formation with enhanced metallicities in SN remnant shells. The dashed lines in the left panel guide the eye to two stellar populations that were formed in two satellite halos, merging at $z = 7.5$. The quiet halo evolves in relative isolation and steadily increases its metallicity to [Z/H] ~ -2 until there is an equilibrium between *in-situ* star formation and metal-poor inflows from filaments.

Benitez-Llambay et al. 2016

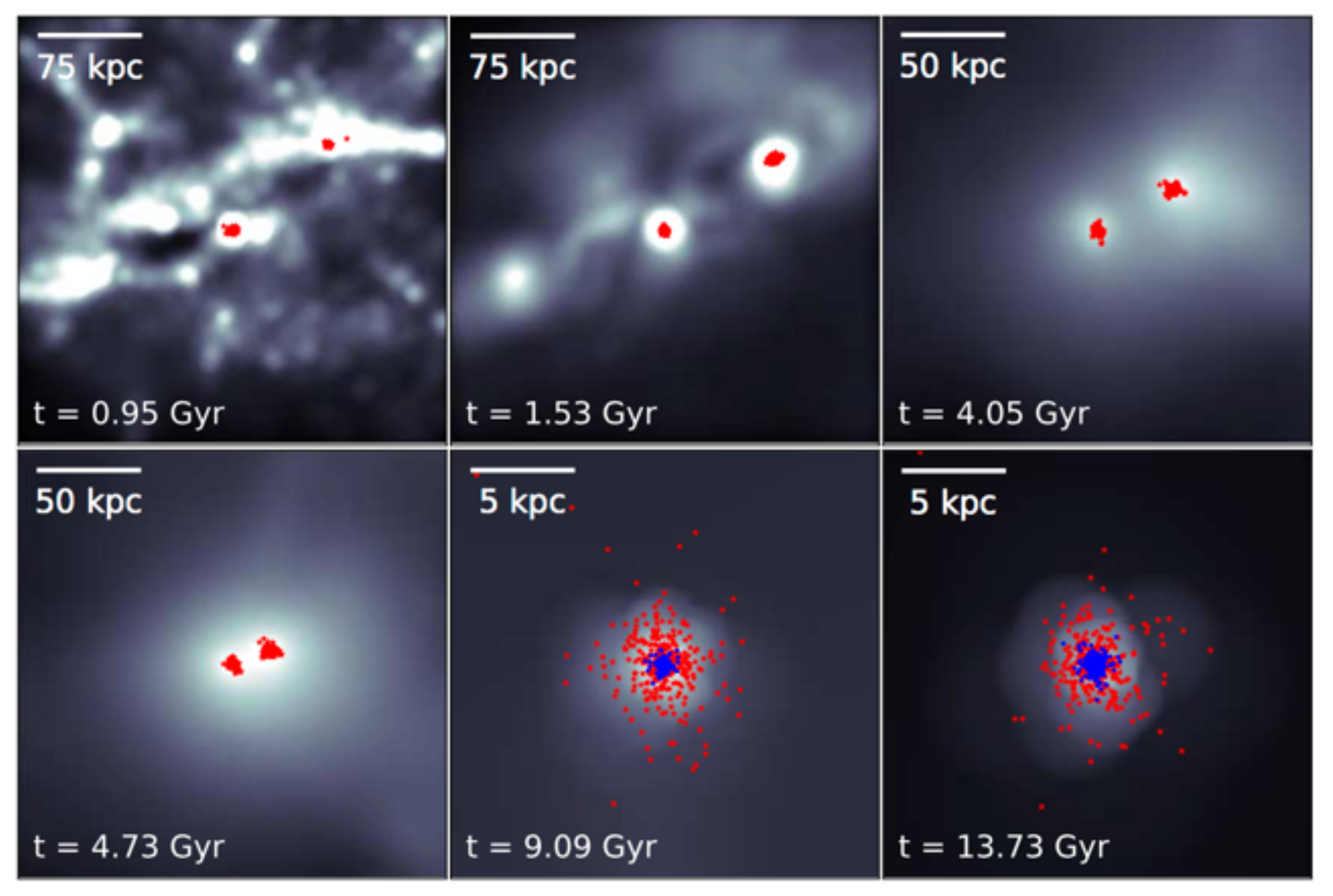
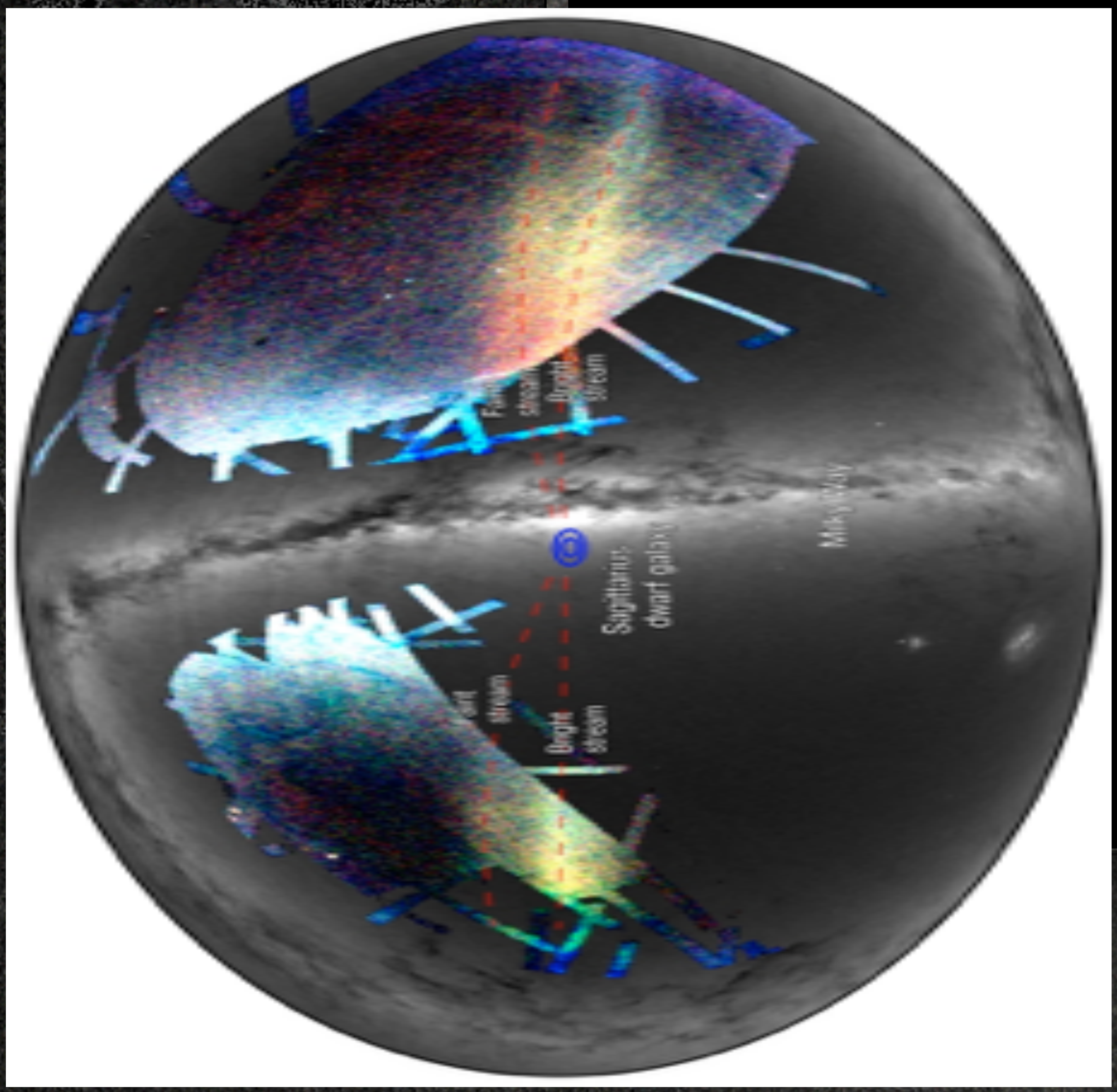


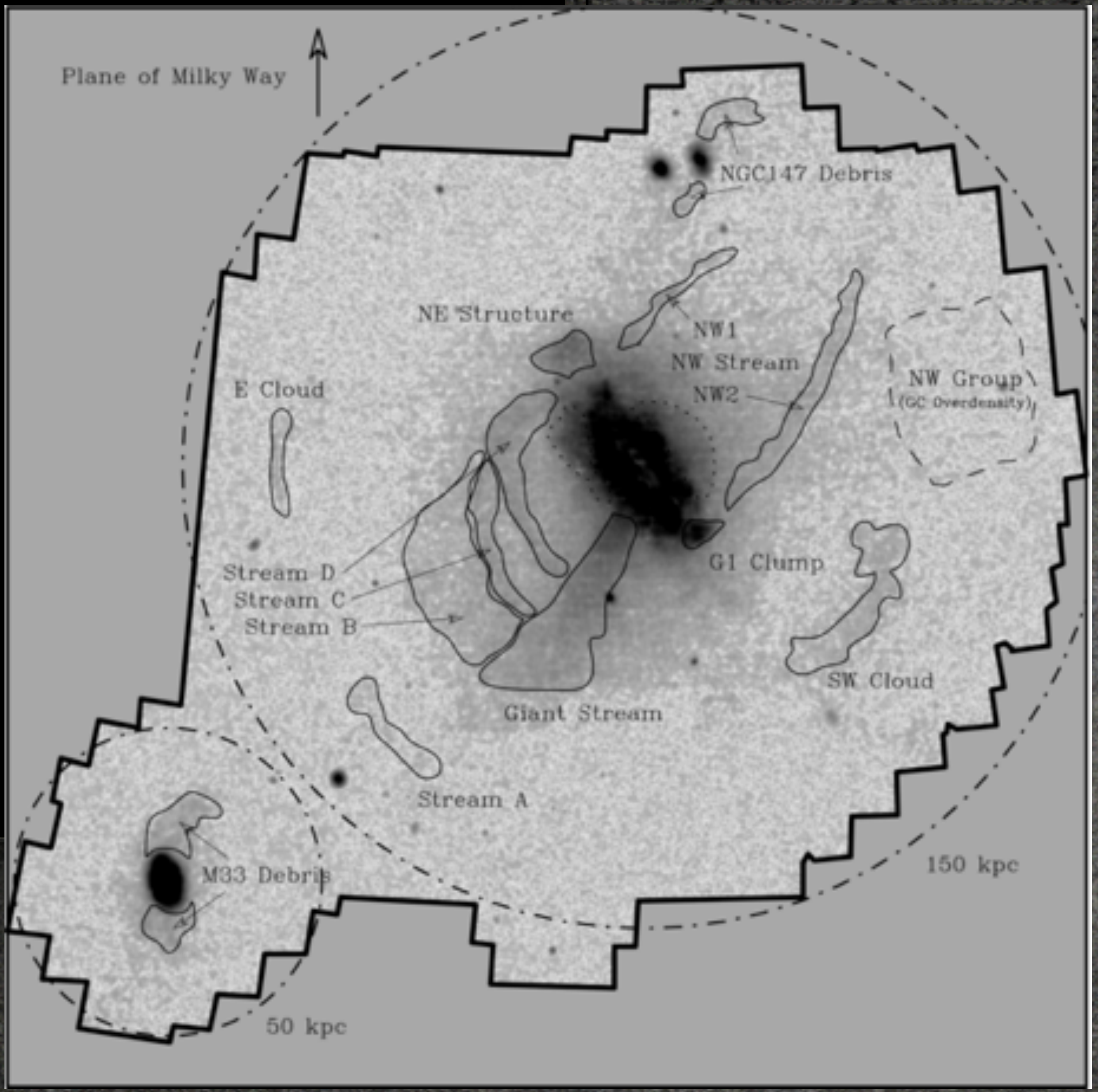
Figure 4. Projected gas and stellar distribution of the "D4" dwarf, shown as a function of time. Different shades of grey indicate gas density; red starred symbols denote stars that belong to the "old" stellar component at $z = 0$ (i.e., those with formation times $t_{\rm form} < 4.5$ Gyr). Blue dots indicate the same, but for "young" stars (i.e., $t_{\rm form} \geqslant 4.5$ Gyr, see Fig. 1). Note that the old stellar population is assembled through a sequence of mergers, which culminate in a rather major event at $t \sim 5$ Gyrs that prompts the in situ formation of the younger component.

Studies of the properties & distribution of the EMP stars relevant to,

- formation of bulges
- in situ and accretion history of halo
- star formation histories of hosts
- nucleosynthesis & supernova yields
- IMF of the first stars

We see streams in stellar densities, but have yet to precisely map the halo in metallicity



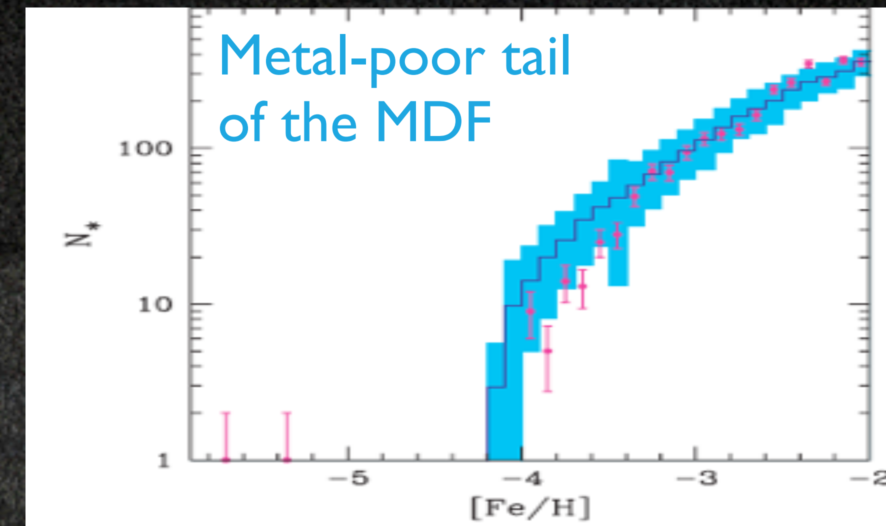


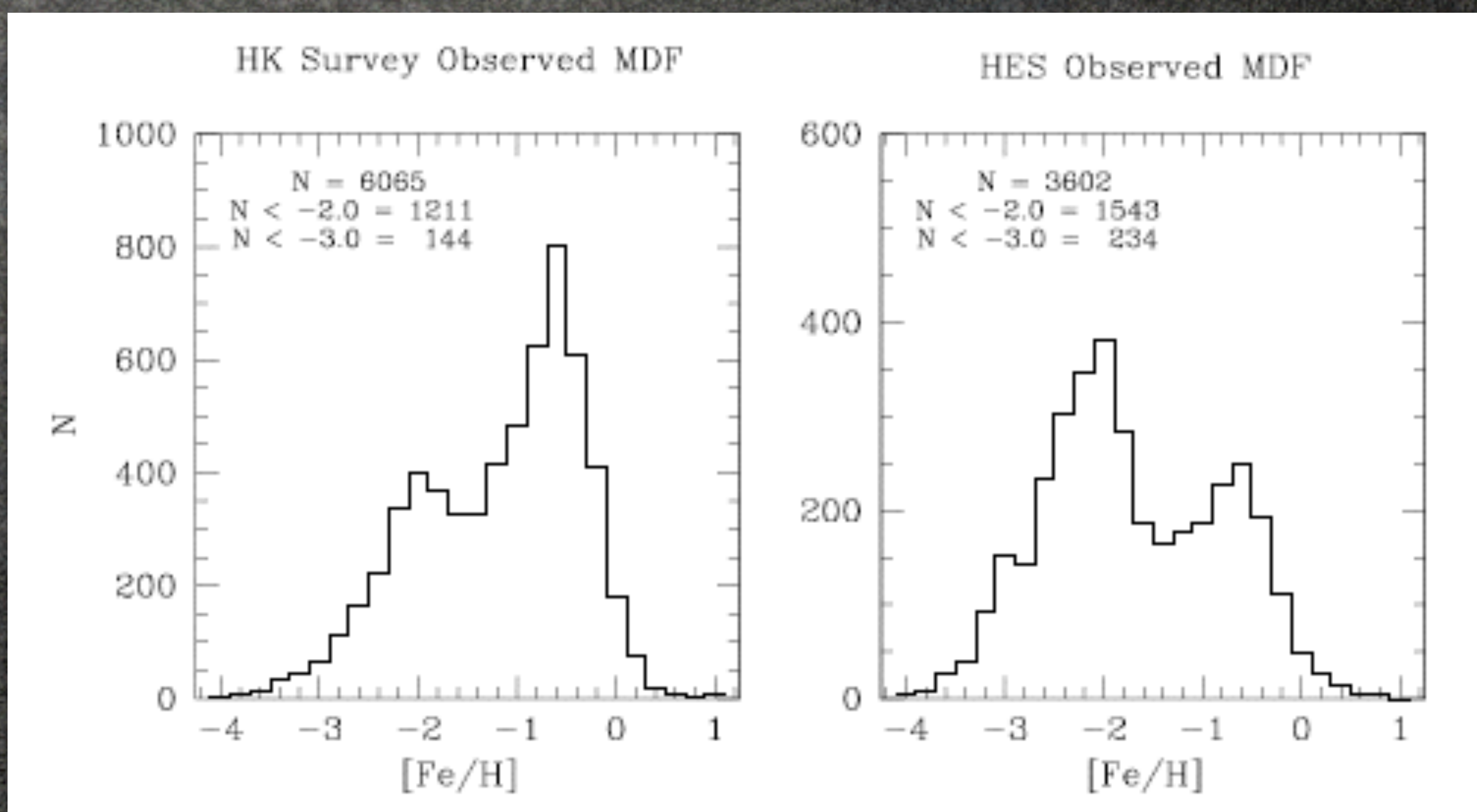
SDSS Galactic survey

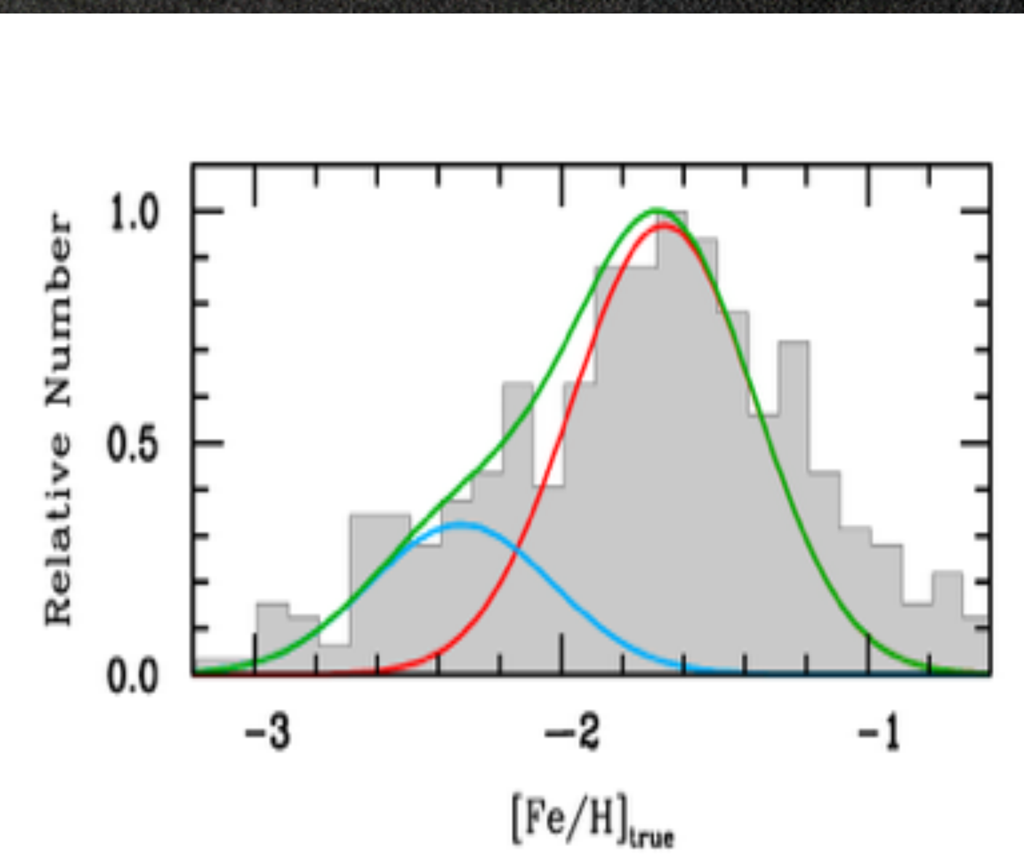
CFHT M31 survey

Beers et al. 2005, An et al. 2013

Searches for EMP stars have been focused on the Galactic halo.





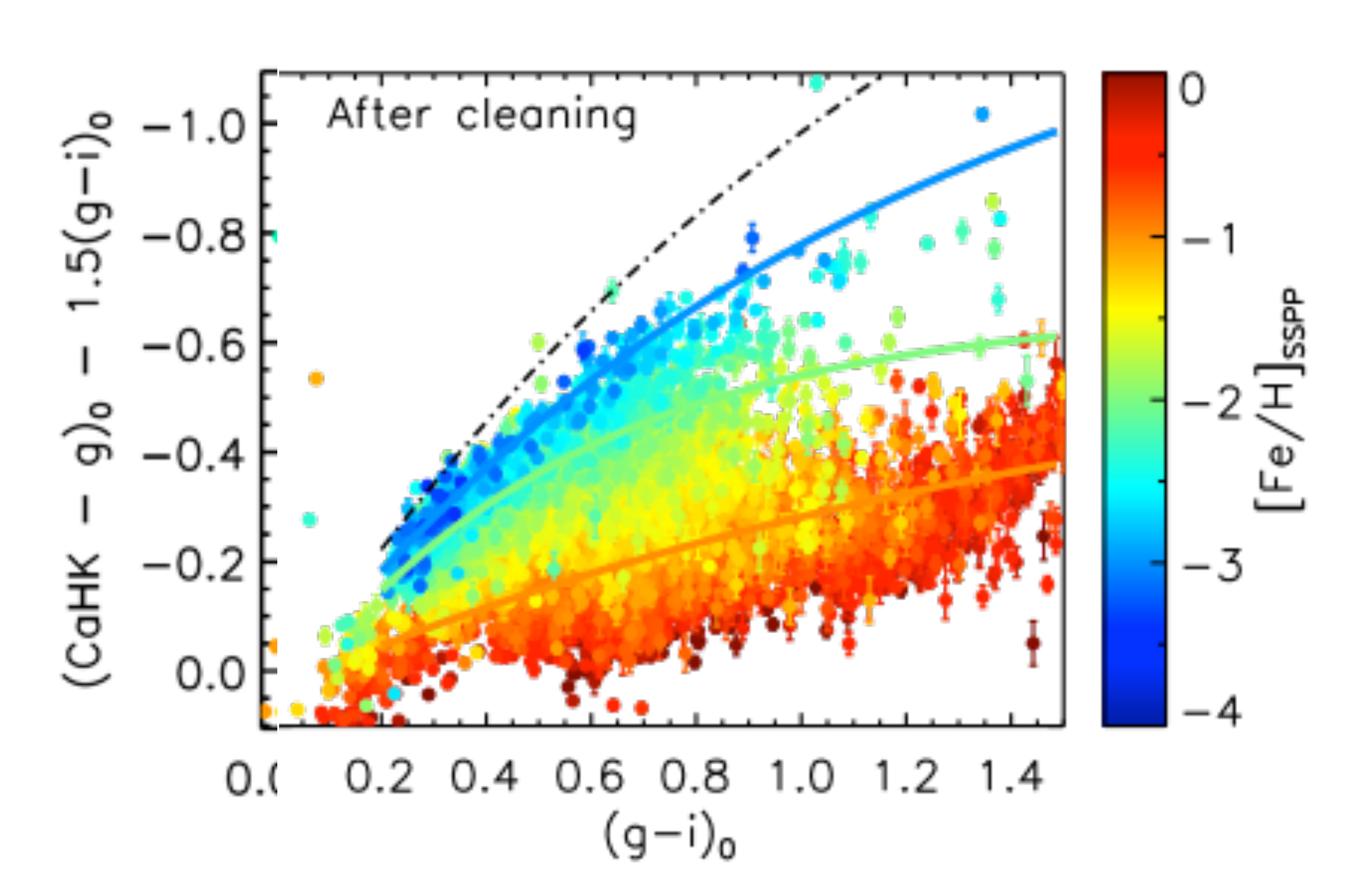


HK & HES objective prism surveys (HES goes 2 mag deeper), and SDSS Stripe 82 analysis

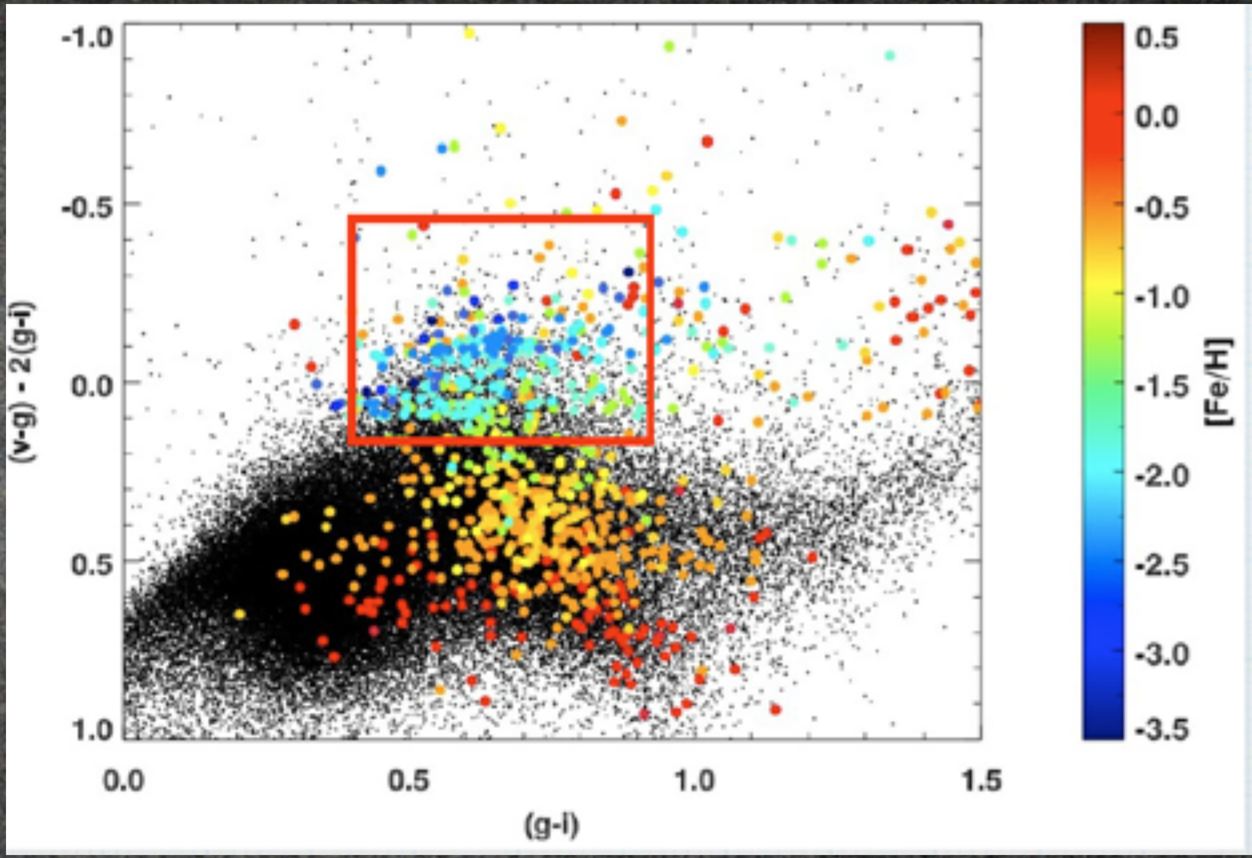
Starkenburg et al. 2017

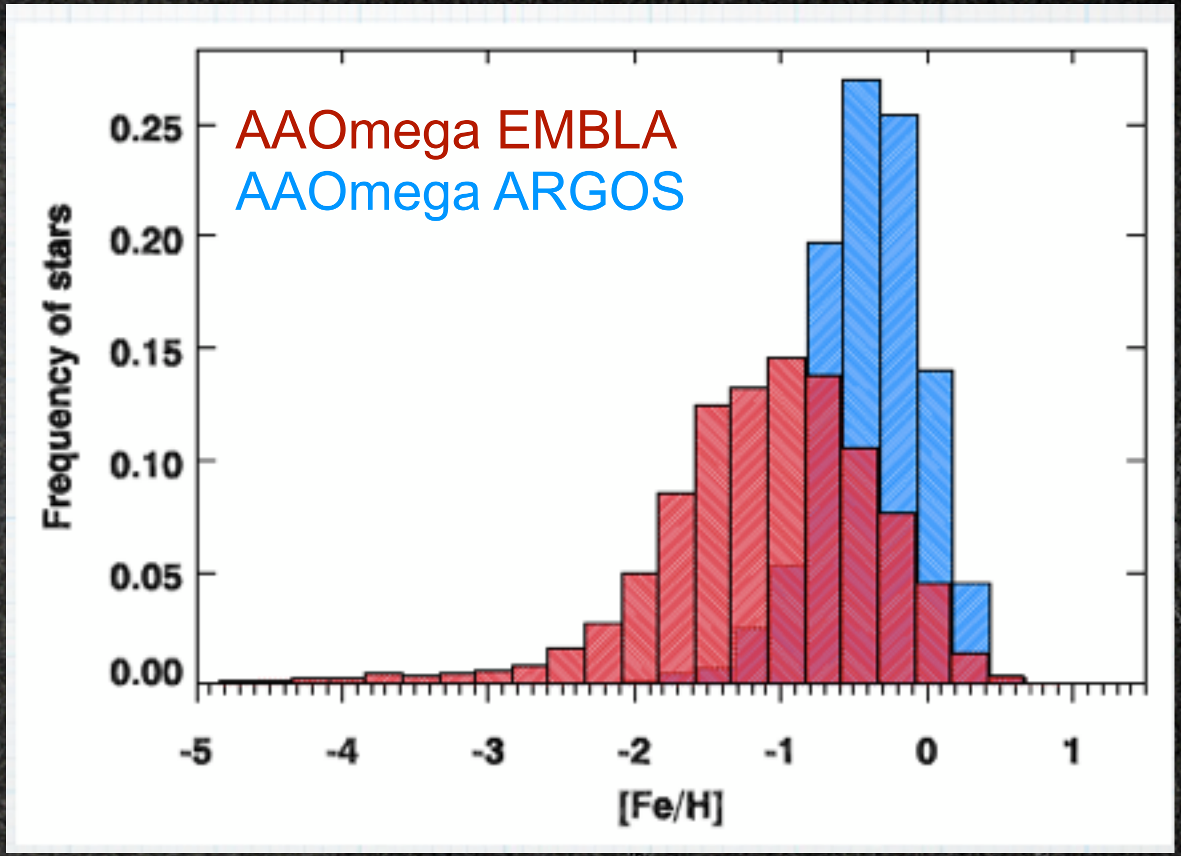
The Pristine Survey

see Else's talk on Wednesday!



Metal Poor Stars in the Bulge



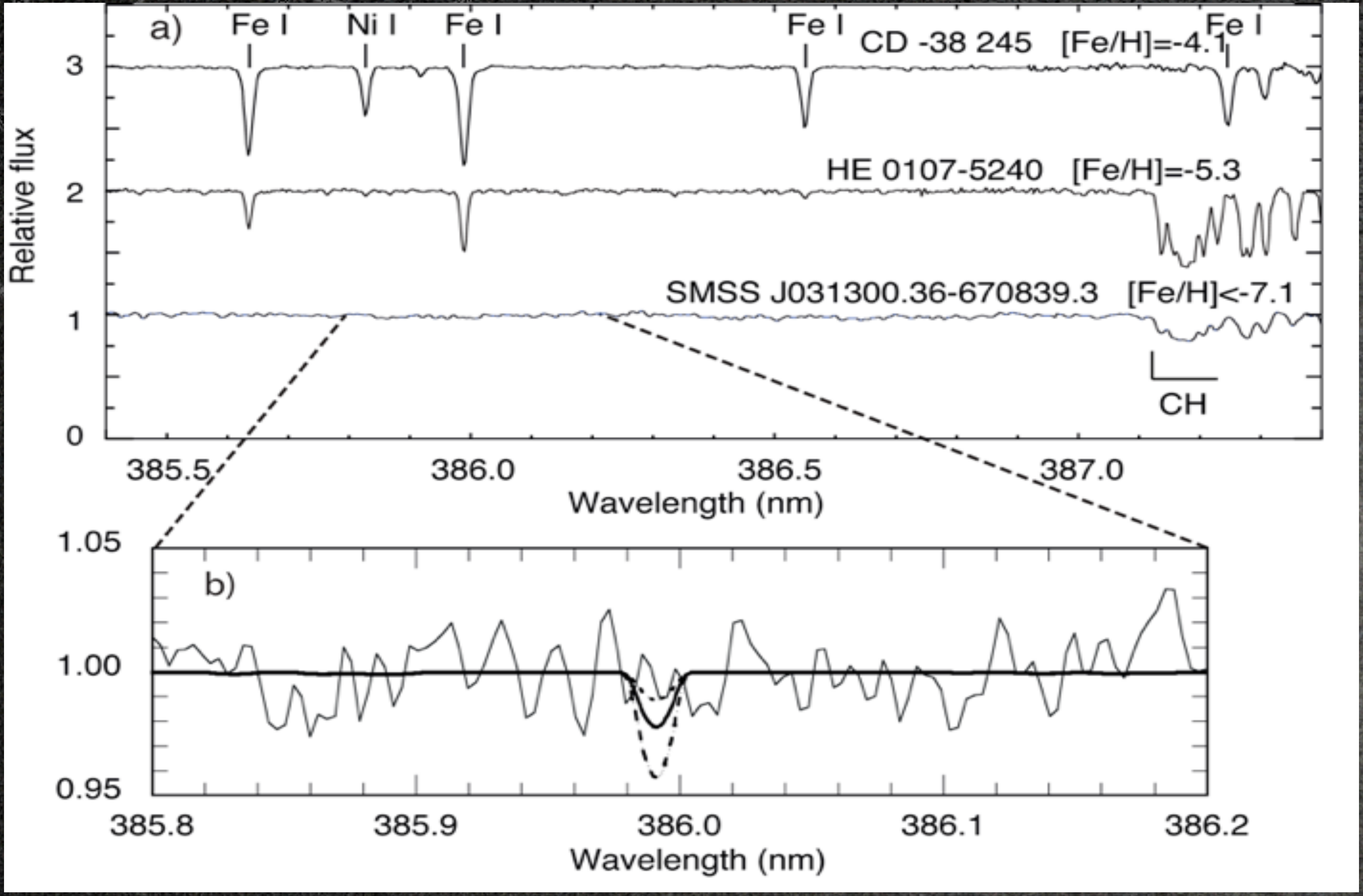


AAOmega **EMBLA** survey selected ~60 stars from SkyMapper with [Fe/H] < -2 !

VLT/UVES & Magellan/MIKE spectra, Halo like chemistries & orbits

AAOmega **ARGOS** (350 stars per 2h) selected from SkyMapper

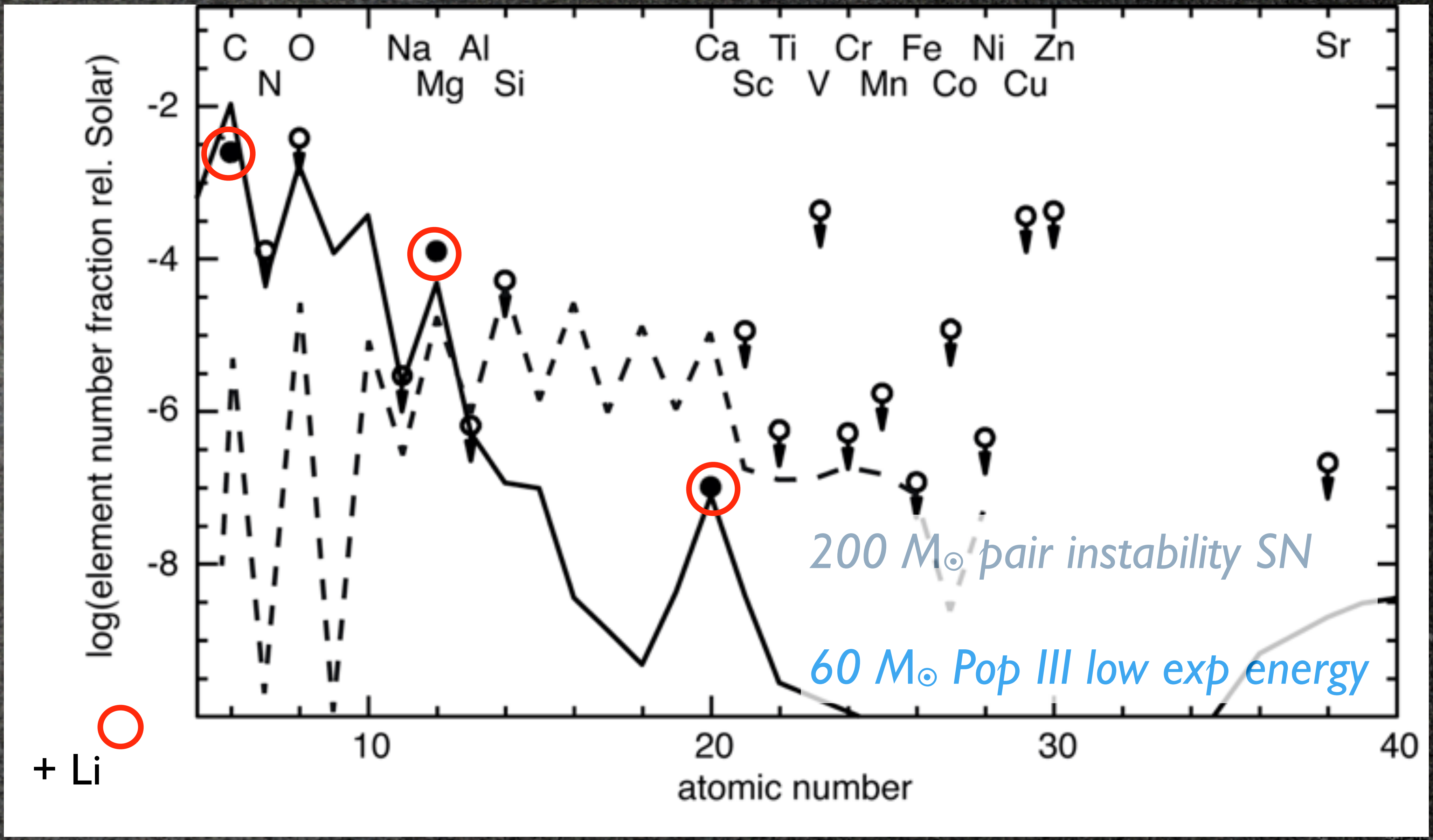
Keller et al. 2014



SMSS J031300.36-670839.3 (SMSS 0313-6708)

Abundance Profiling

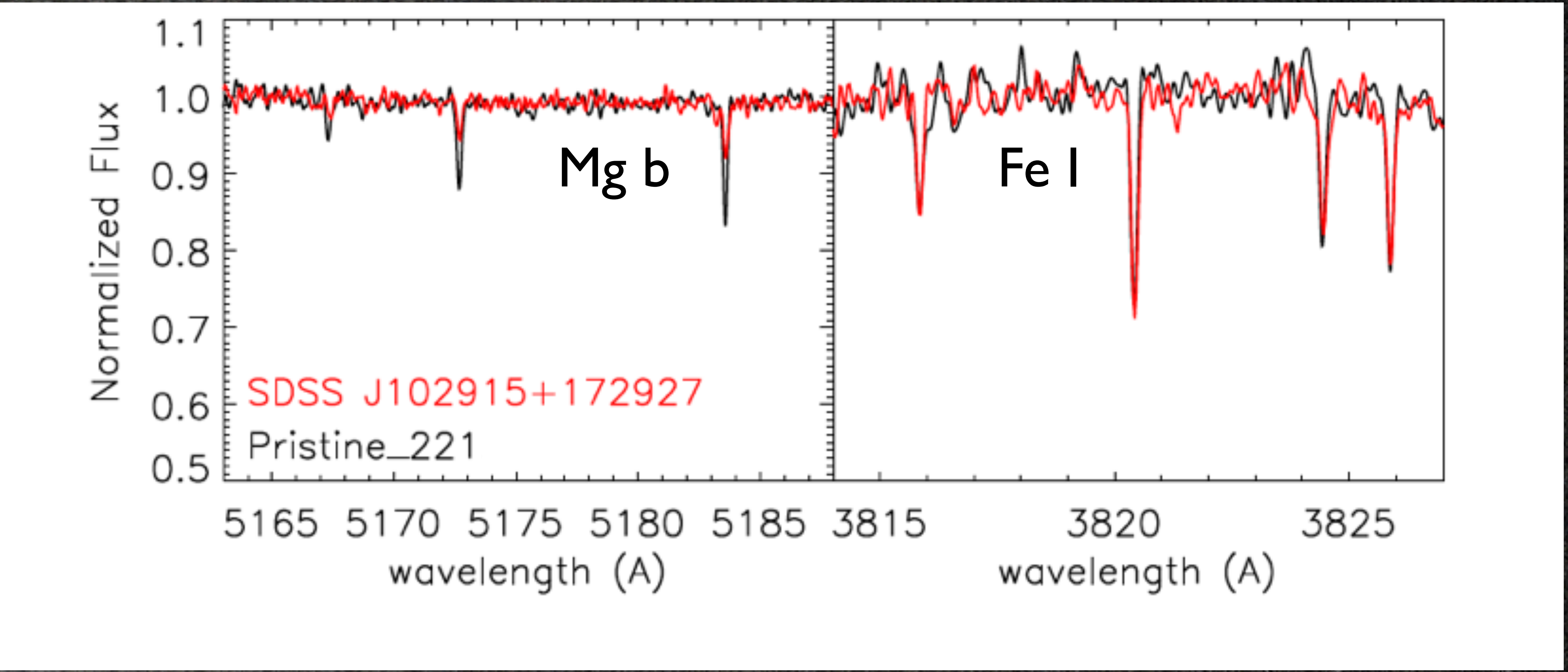
Keller et al. 2014



SMSS J031300.36-670839.3 (SMSS 0313-6708)

Clarkson et al. 2018

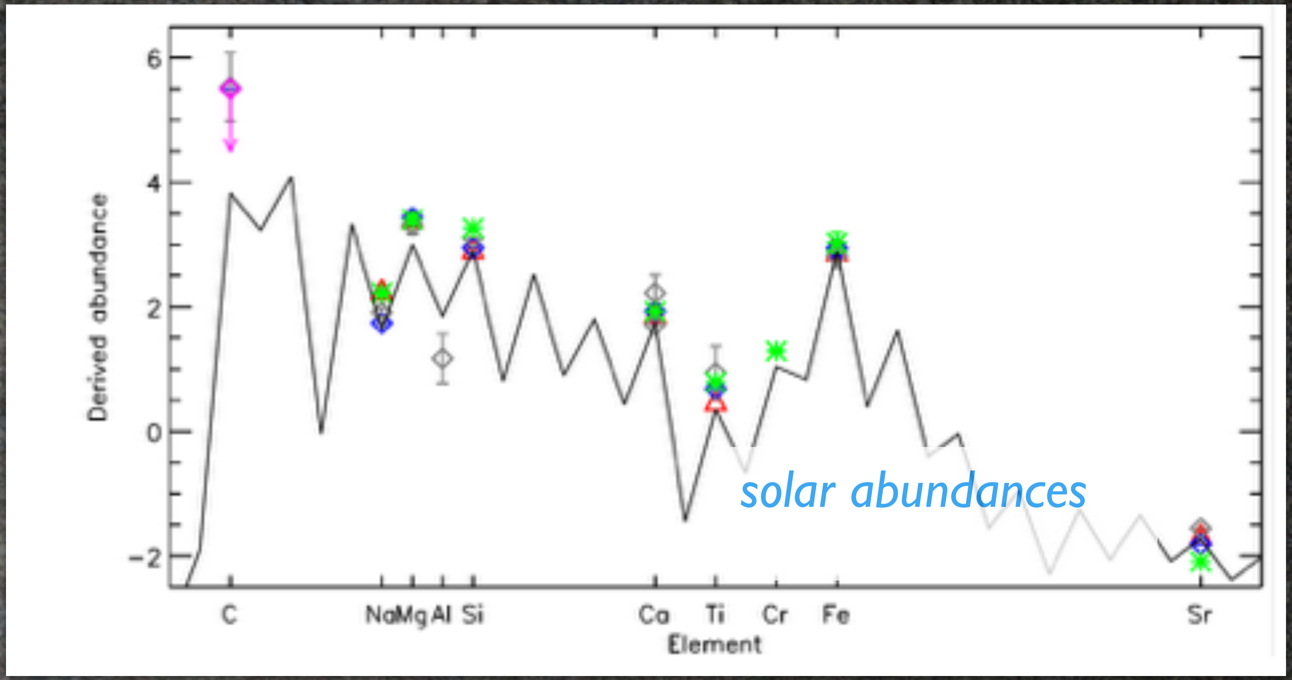
Starkenburg et al. 2018, Caffau et al. 2011



Both stars have [Fe] ~ -5, but unlike most EMP stars, they are not C-rich, where [C/Fe] < 1

Keller et al. 2014, Starkenburg et al. 2018

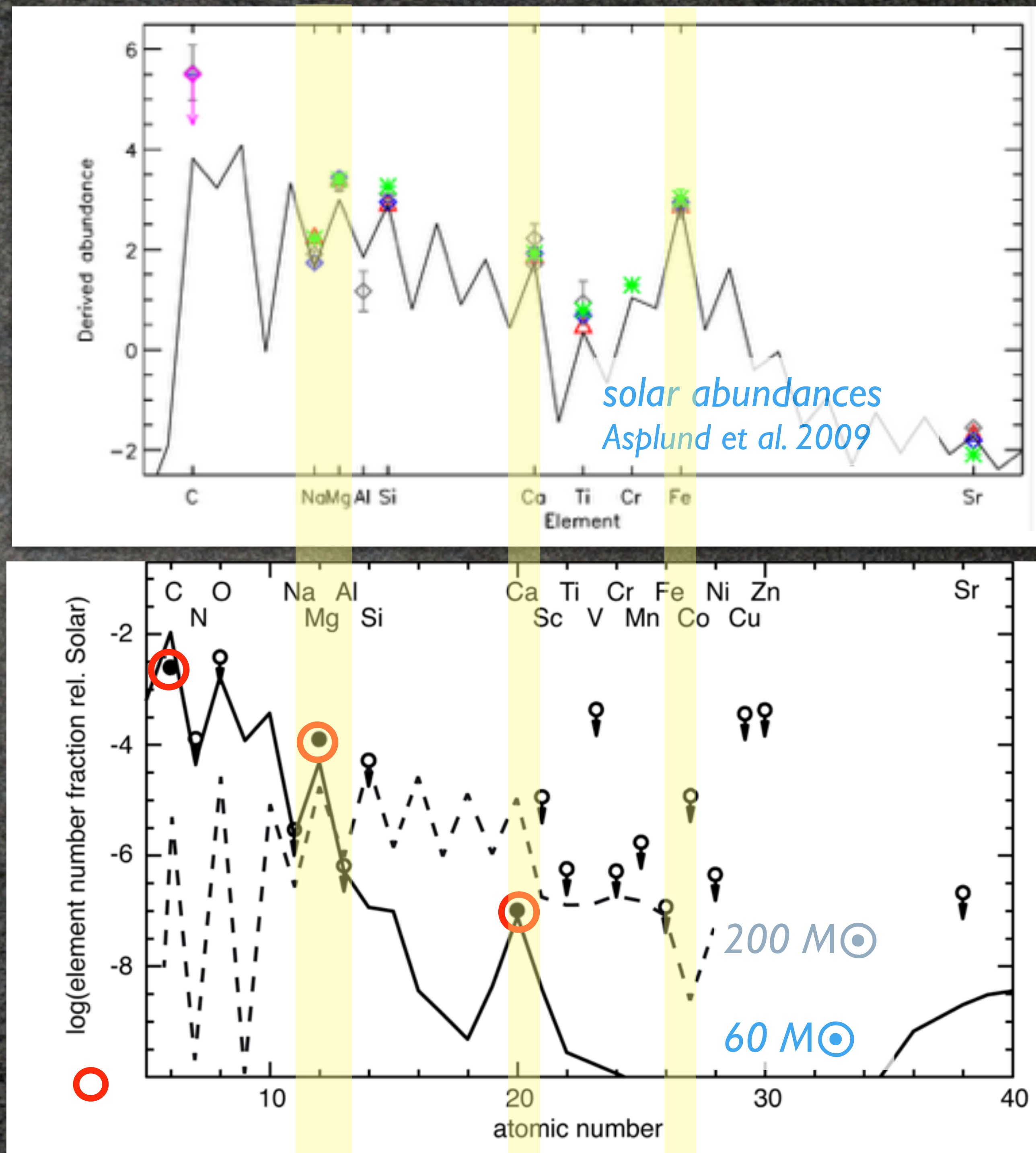
[Fe]



Keller et al. 2014, Starkenburg et al. 2018

[Fe]

[Fe]

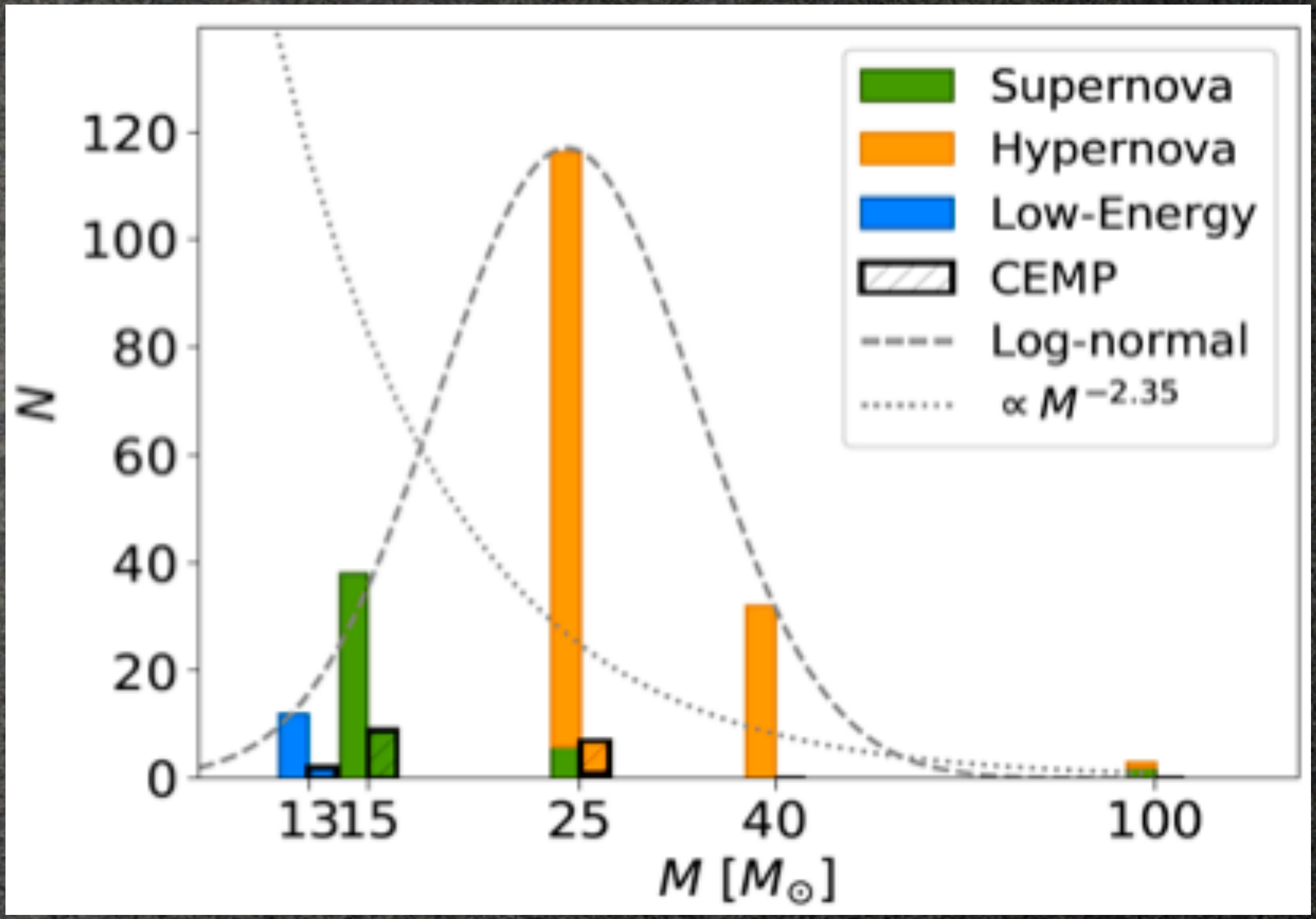


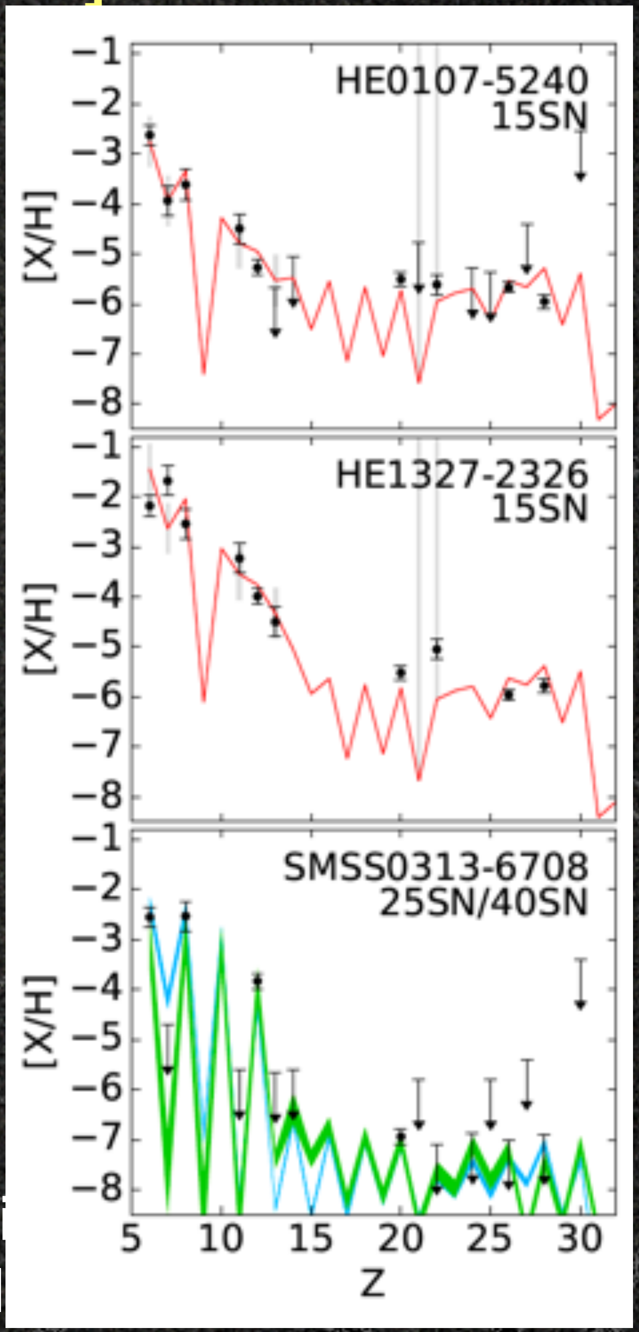
The abundance profiles of these [Fe] < -4 stars differ,

they do not have the same distribution of elements,

C, Mg, Ca, Fe

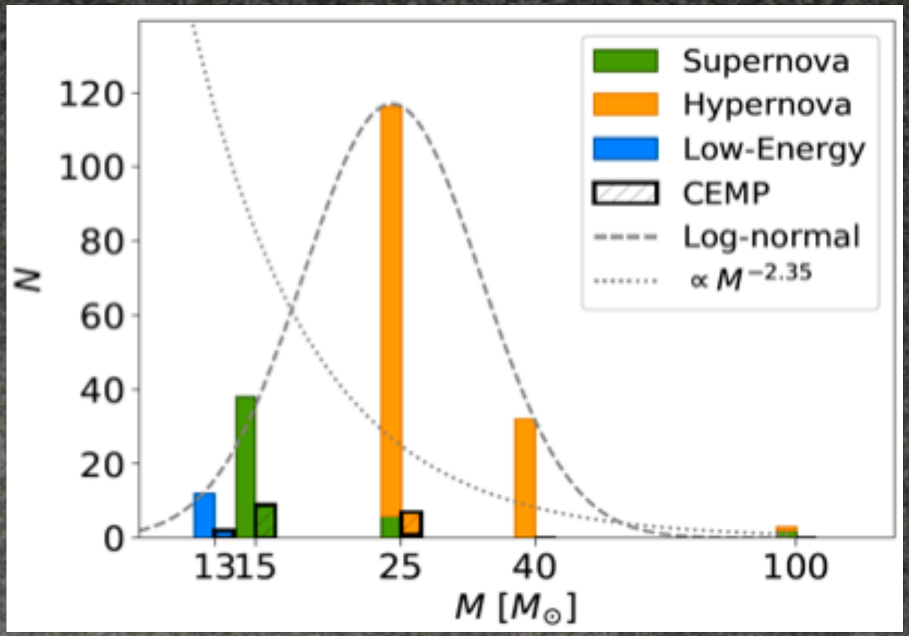
Abundance Profiling of ~200 stars with [Fe/H] < -3





- Element abundances from C to Zn were compared with supernova yi stars with masses from 13 to 100 $M_\odot$, and a variety of mixing and fal
- The gray dashed line shows the best-fit log-normal function to the histogram.
- Nearly all EMP stars can be fit with yields from SN/HN with ~normal masses.

Ishigaki et al. 2018, Tominaga et al. 2014



Nearly all EMP stars can be fit with yields from SN/HN with ~normal masses.

Implications for IMF of First Stars

- either higher mass first stars rare
- or higher mass first stars did not contribute metals (ext. fallback)
- or SN from higher mass first stars inhibit the formation of the lower mass stars that we study today

But just look at that *distribution*!

We need more EMP stars with detailed abundance results (& possibly over a wider range of locations, e.g., bulge too) to better constrain the first stars IMF.

Hartwig et al. 2018

C, Mg, Fe abundance differences from metal poor SN of various mass progenitors and explosion energies, and their combined effects on ISM metal abundances.

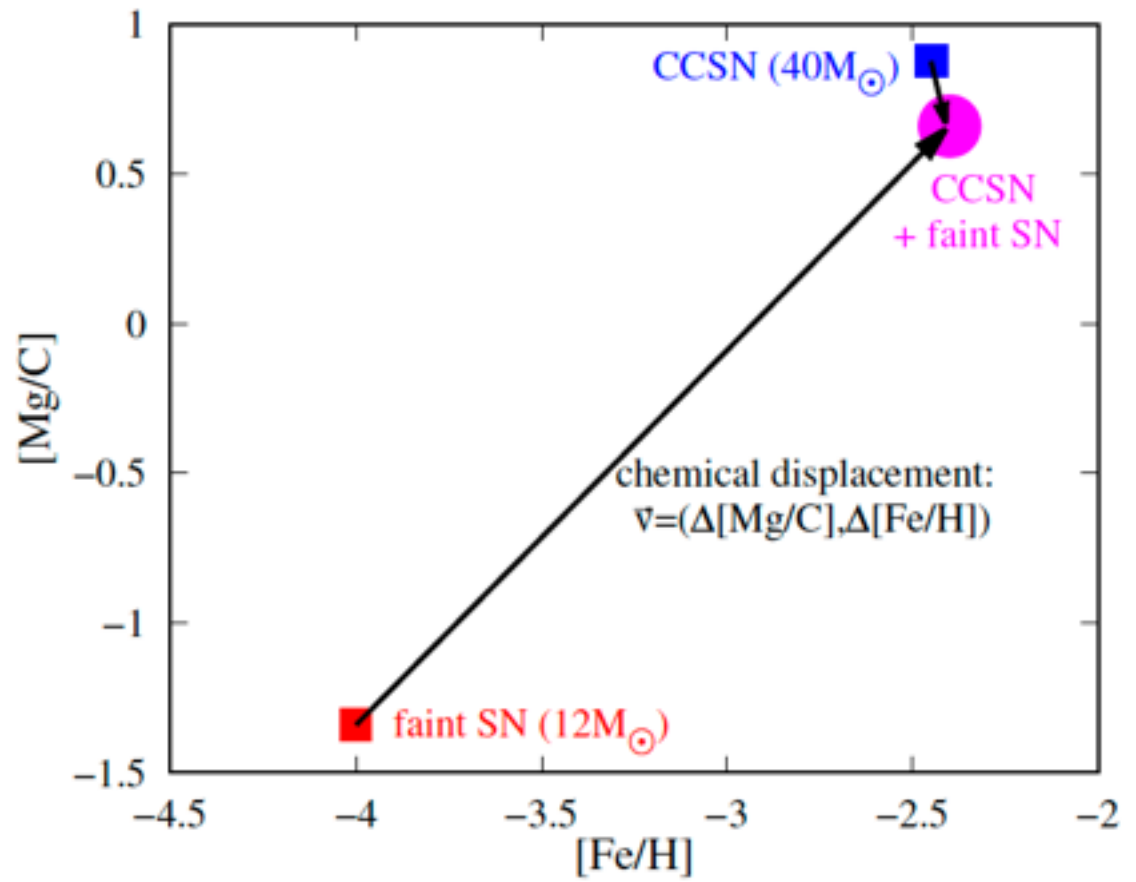
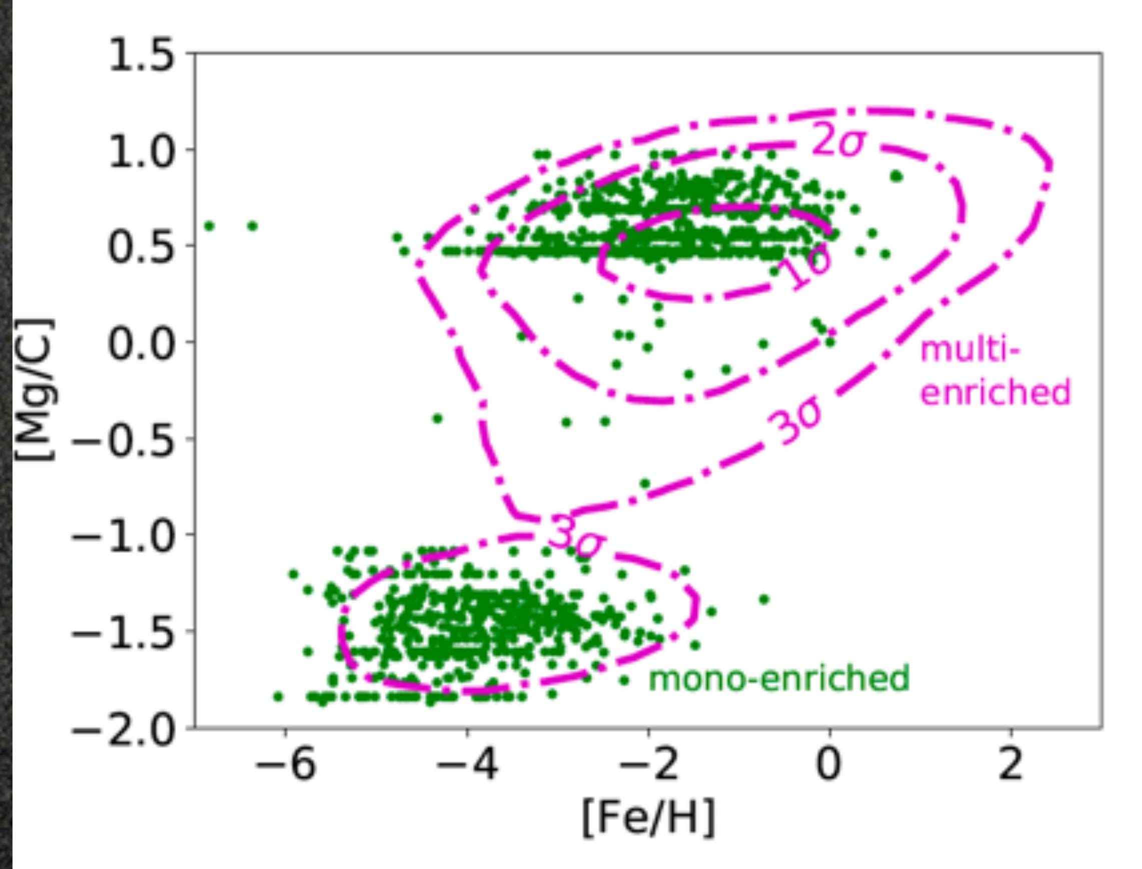
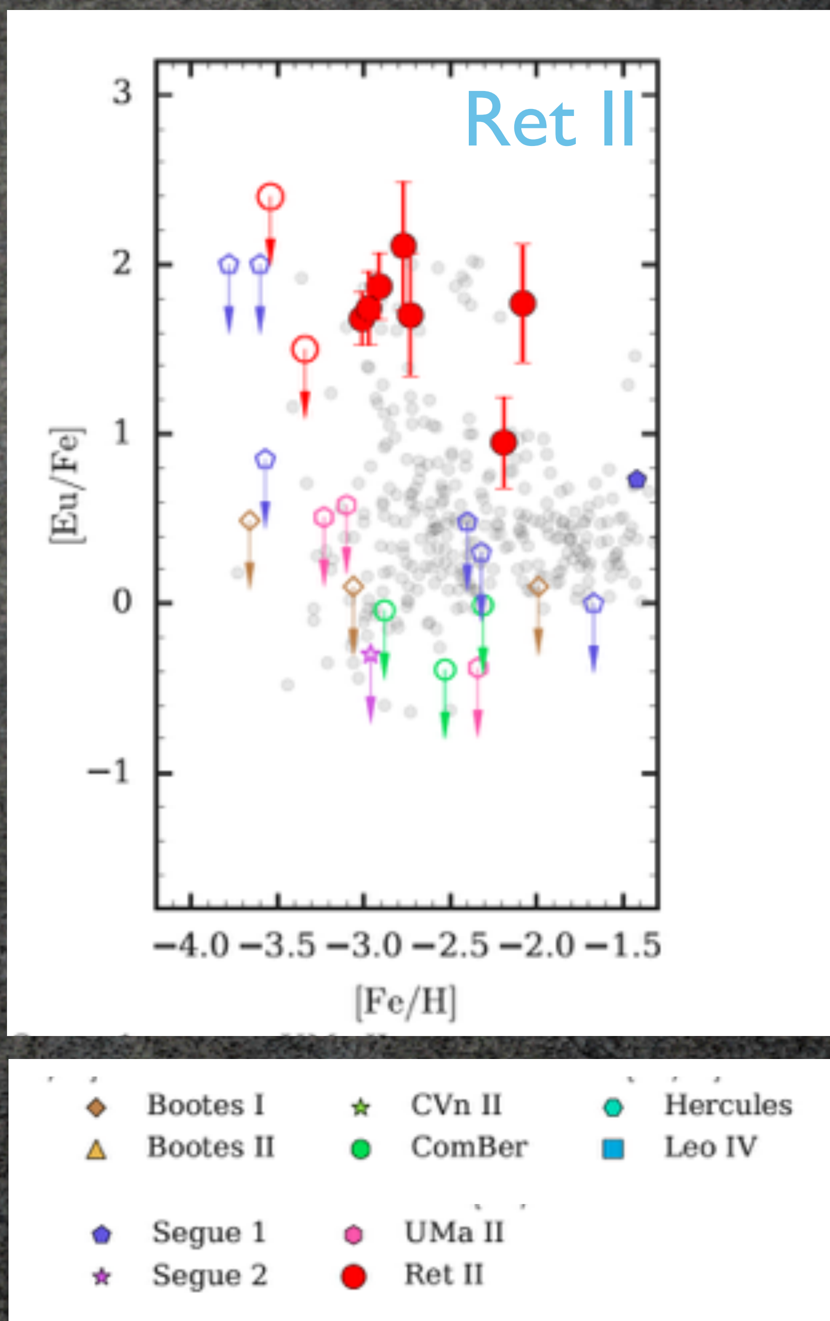


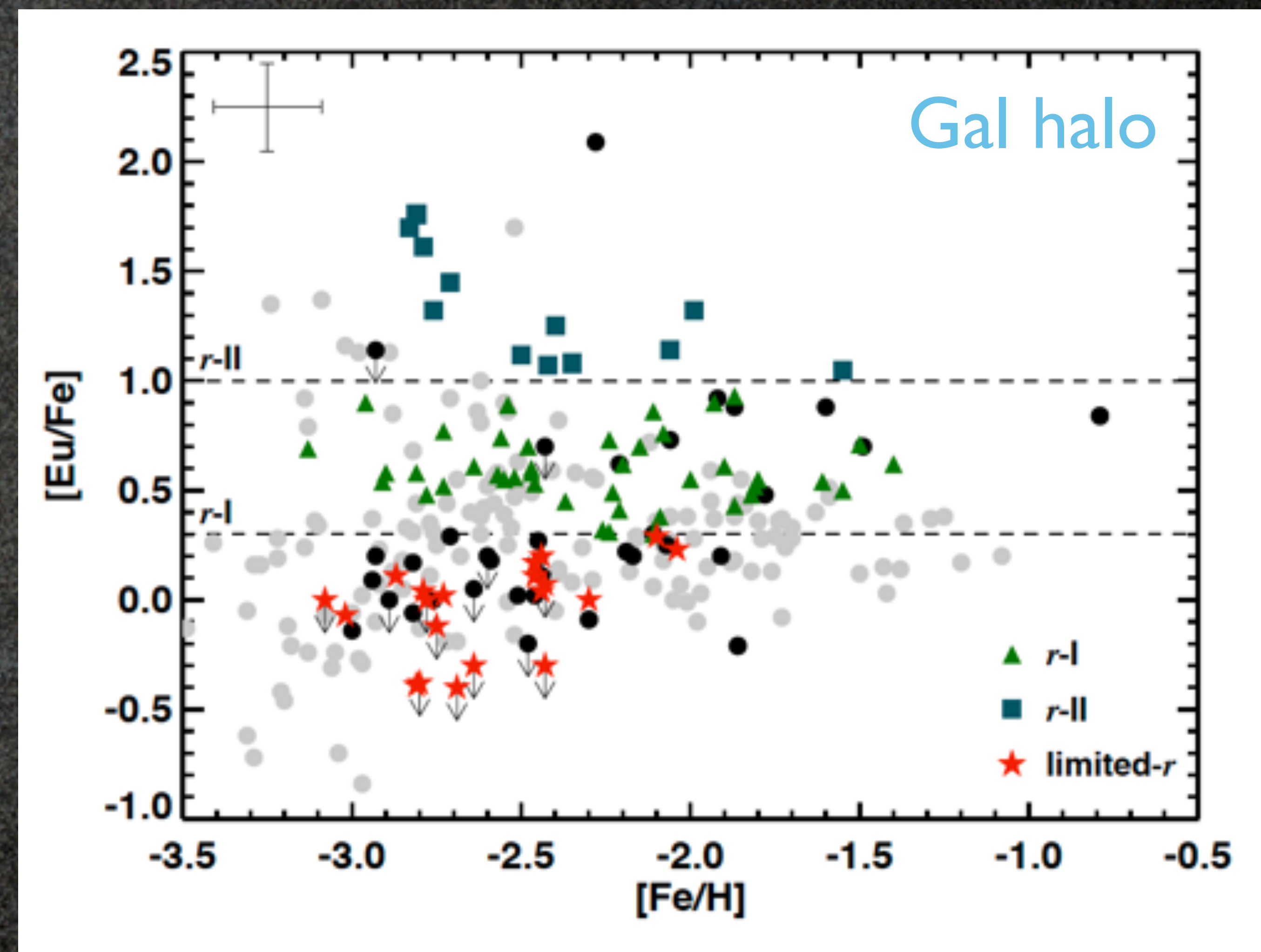
Figure 12. Illustration and definition of the chemical displacement for two example SNe. Combining the yields of two SNe with different progenitor masses results in an effective displacement of the ISM metal abundances. We define the chemical displacement as the resulting vector field of this operation.



Ji et al. 2016, Hansen et al. 2018, Sakari et al. 2018, Roederer 2014,2016

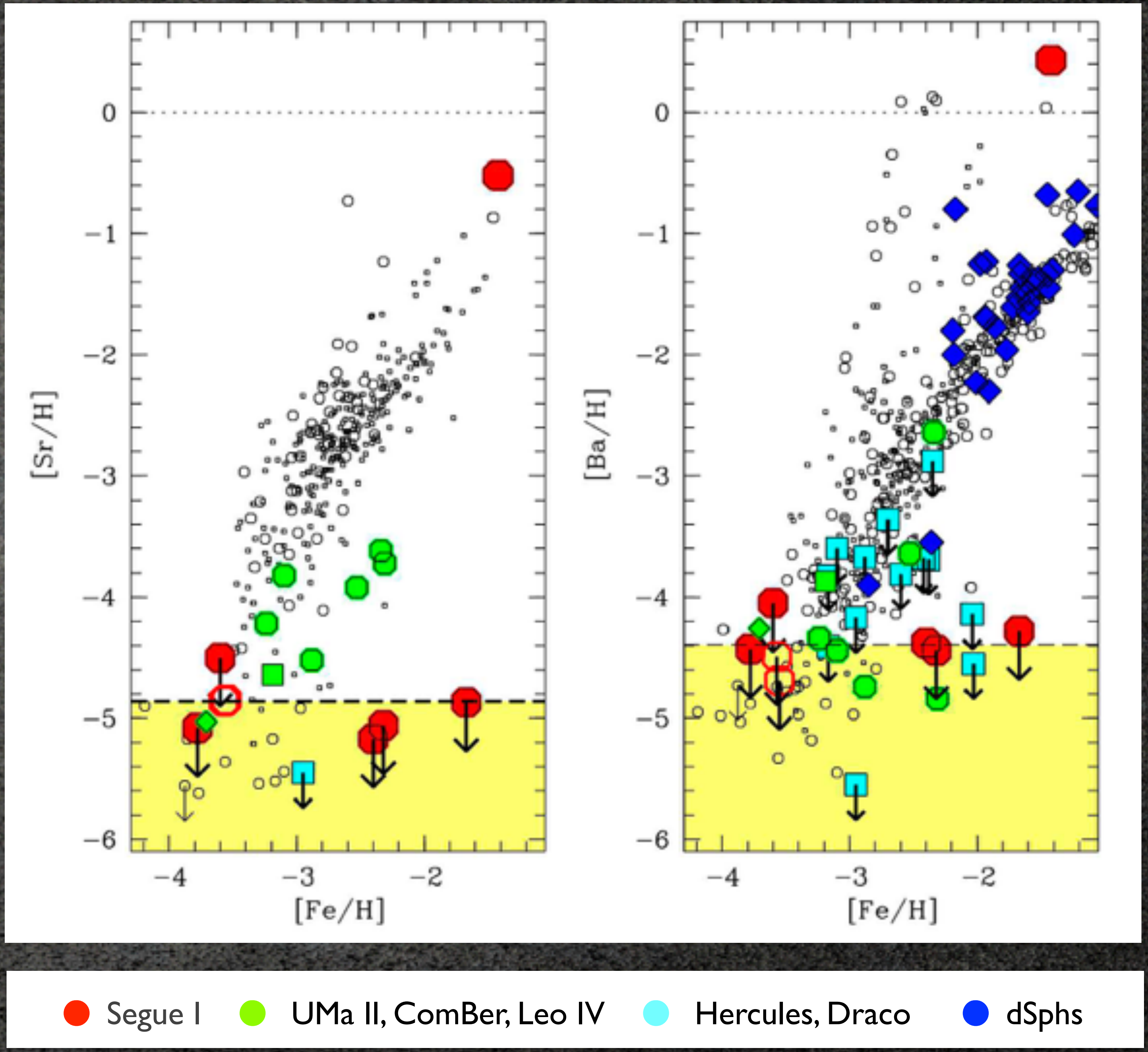
EMP stars excellent to study the cite(s) for the r-process & yields





The r-process alliance

Frebel et al. 2014



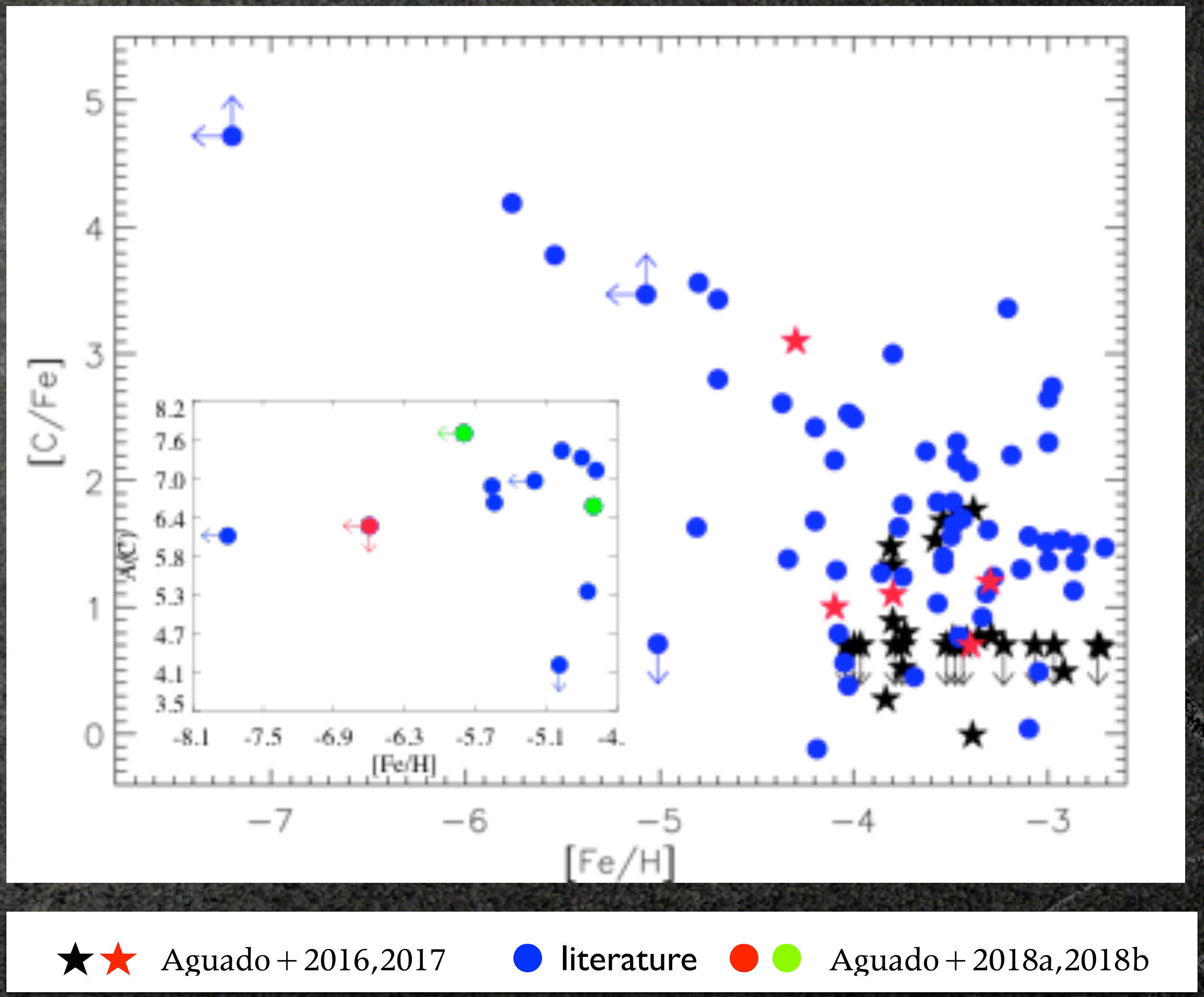
Ultra Faint Dwarf Galaxies

even stars in the UFD galaxies have Sr or Ba, from 1/few metal-poor SN

Thus, (main) r-process in binary neutron star mergers,

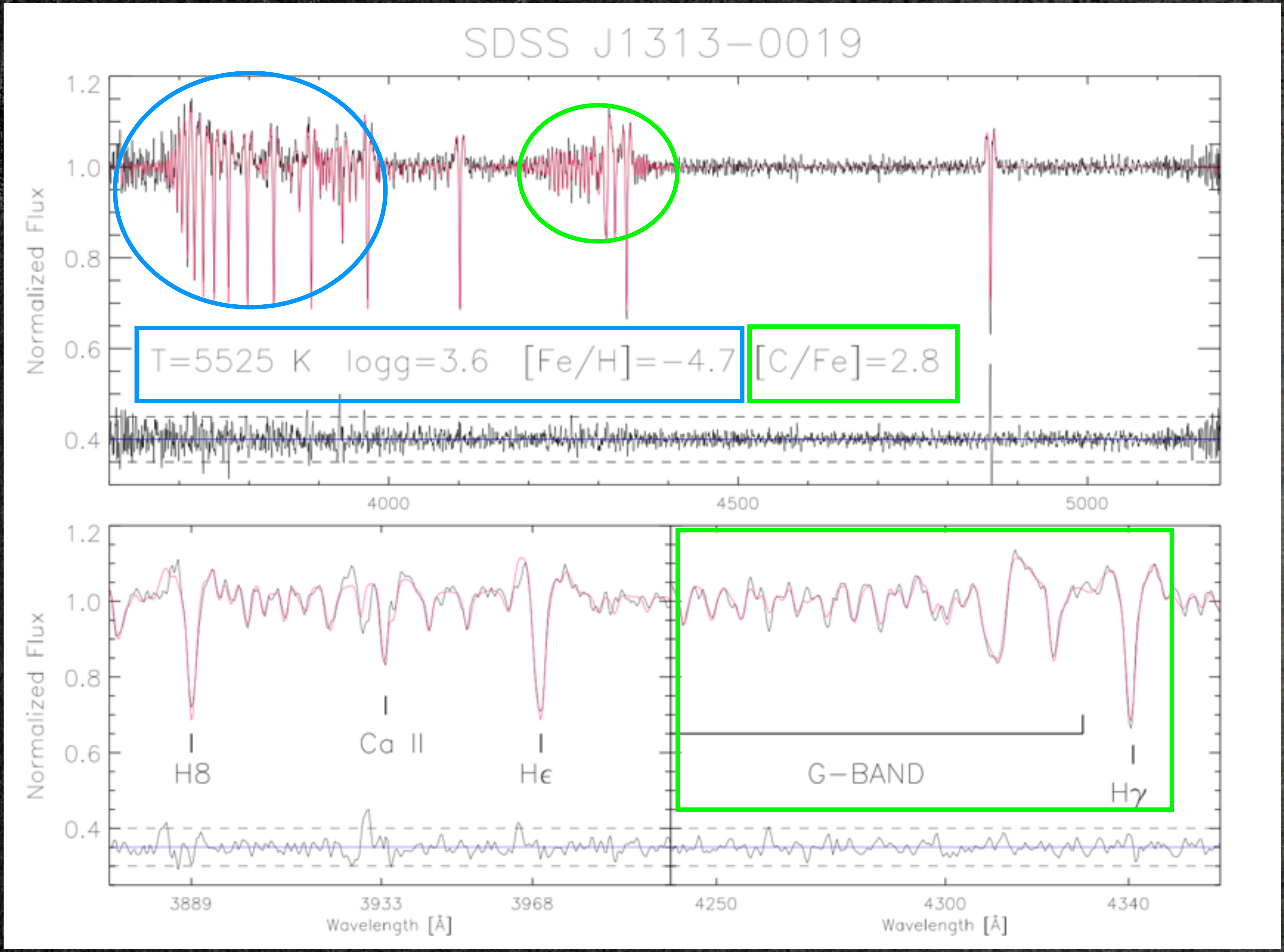
but also (weak) r-process in SN II, since UFDs simple systems, with a ~single episode of SF, ended by blow out of the gas.

new EMP stars from SDSS, BOSS, LAMOST: WHT/ISIS R=3500

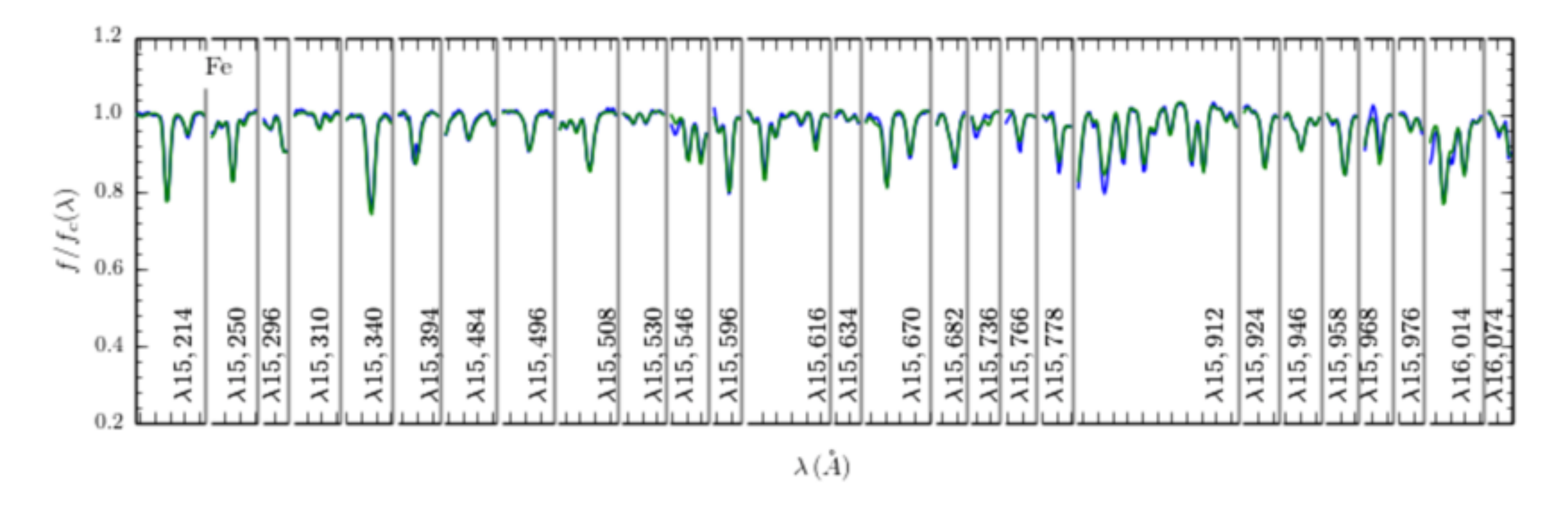


FERRE

Aguado et al. 2016

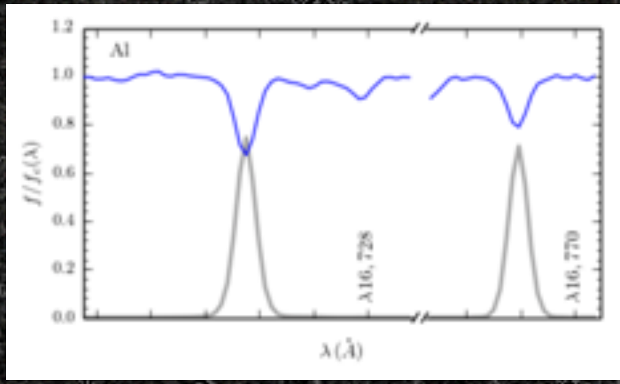


Jo Bovy at https://github.com/jobovy/apogee



FERRE is also the backbone for ASPCAP

- selected windows for elemental abundances
- weighting scheme from calibrations
- works! but can be slow



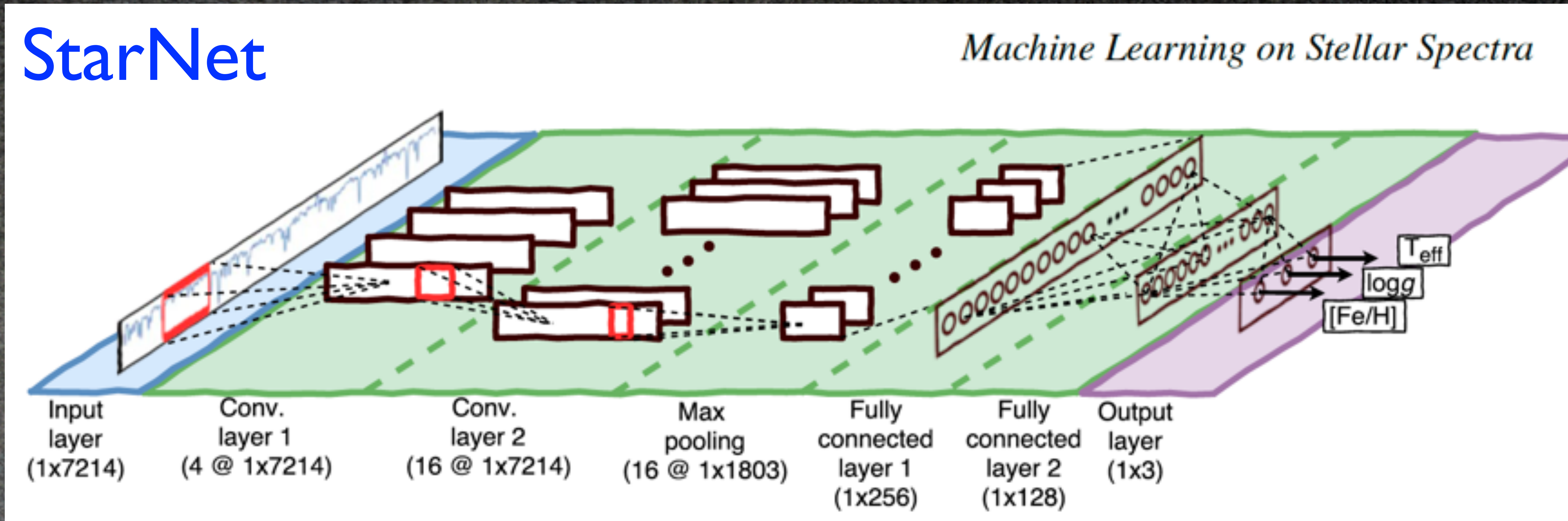
χ^2	FERRE	*Allende-Prieto et al. 2006*
χ^2	SME	*Piskunov & Valenti 2017*
data-driven	The Cannon	*Ness et al. 2015*
PCA	Matisse/Gauguin	*Recio-Blanco et al. 2006*
NN	The Payne	*Ting et al. 2018*
NN	StarNet	*Fabbro et al. 2018*

Machine Learning / Deep Learning / AI
Convolutional Neural Networks

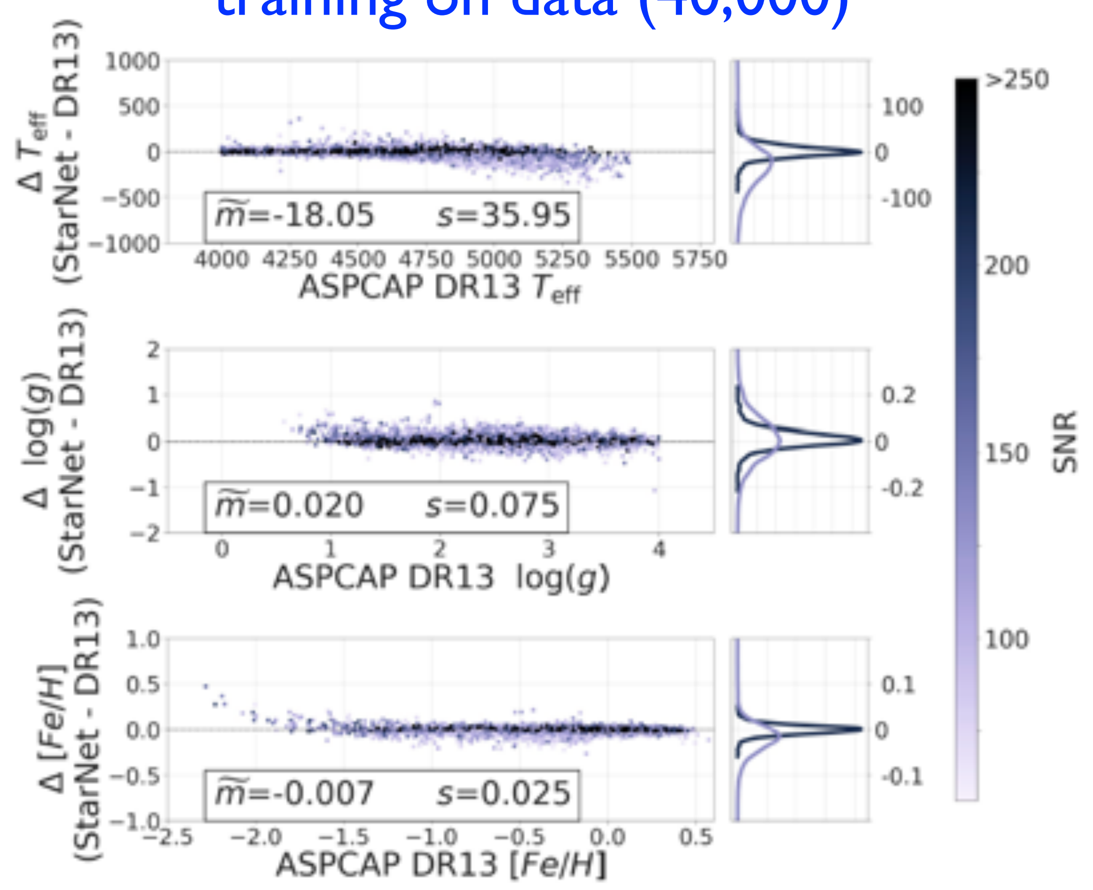
[Google Kepler planet search application]

Tensorflow, keras algorithms
adopted in StarNet

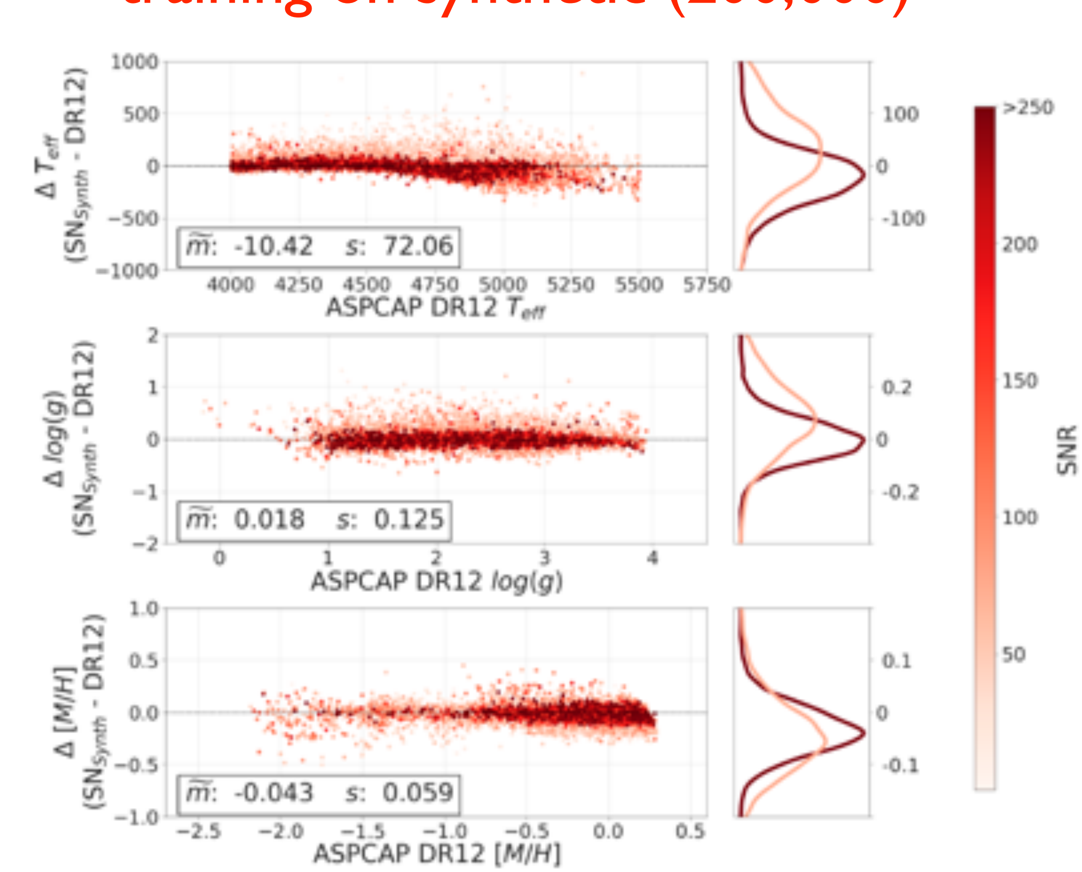
Fabbro et al. 2018



training on data (40,000)

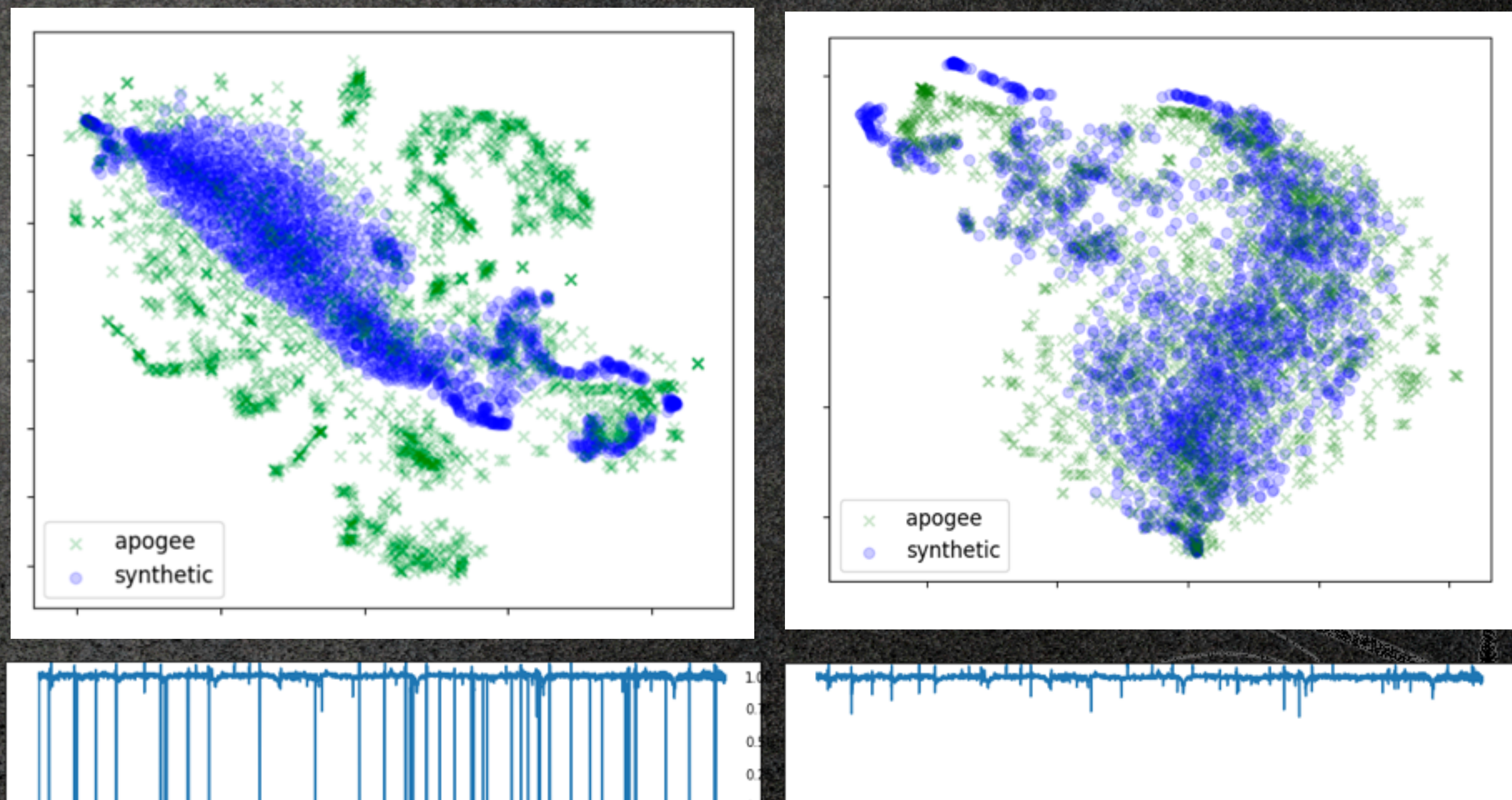


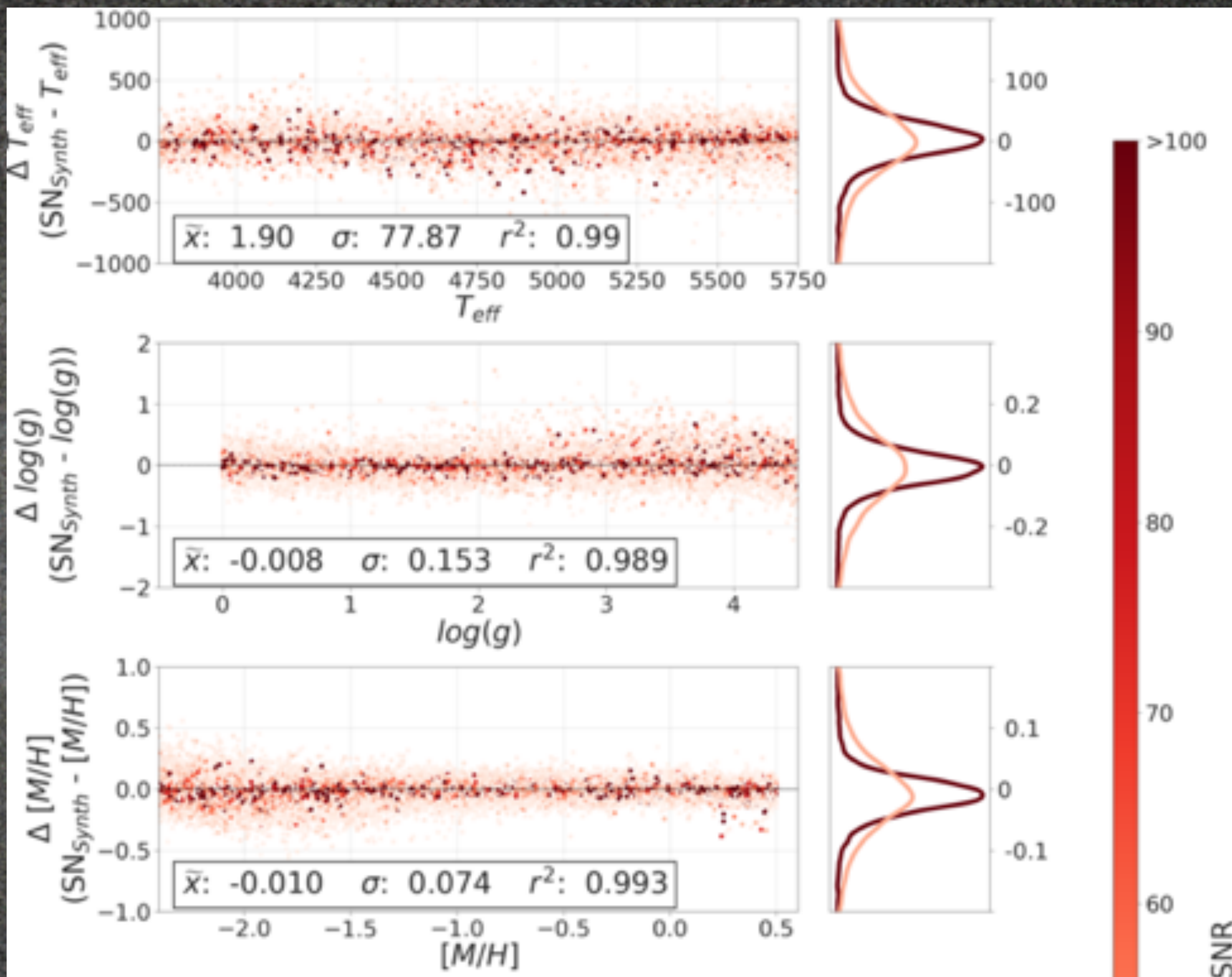
training on synthetic (200,000)

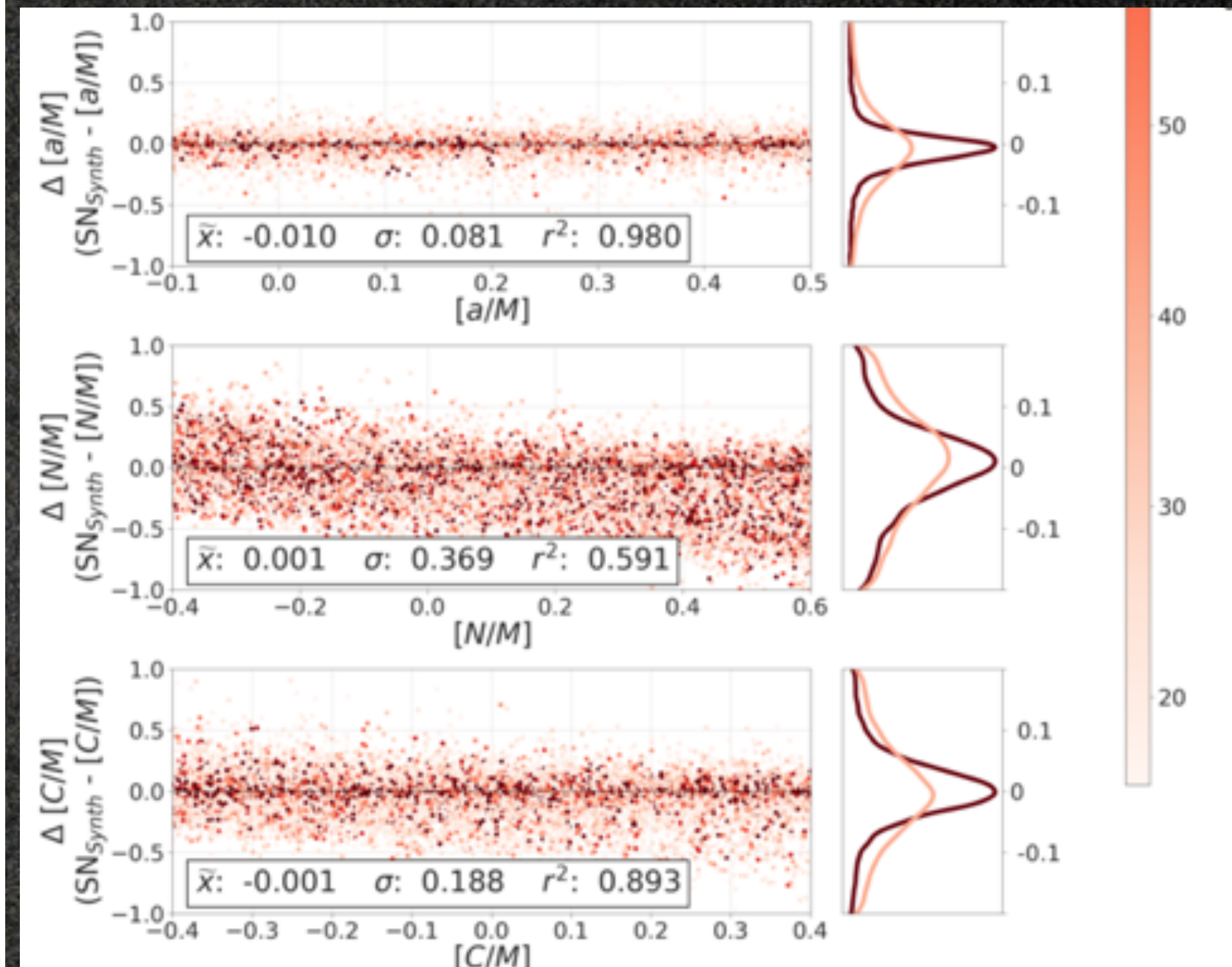


Fabbro et al. 2018

t-SNE test comparing parameters space of the observed APOGEE and synthetic spectra







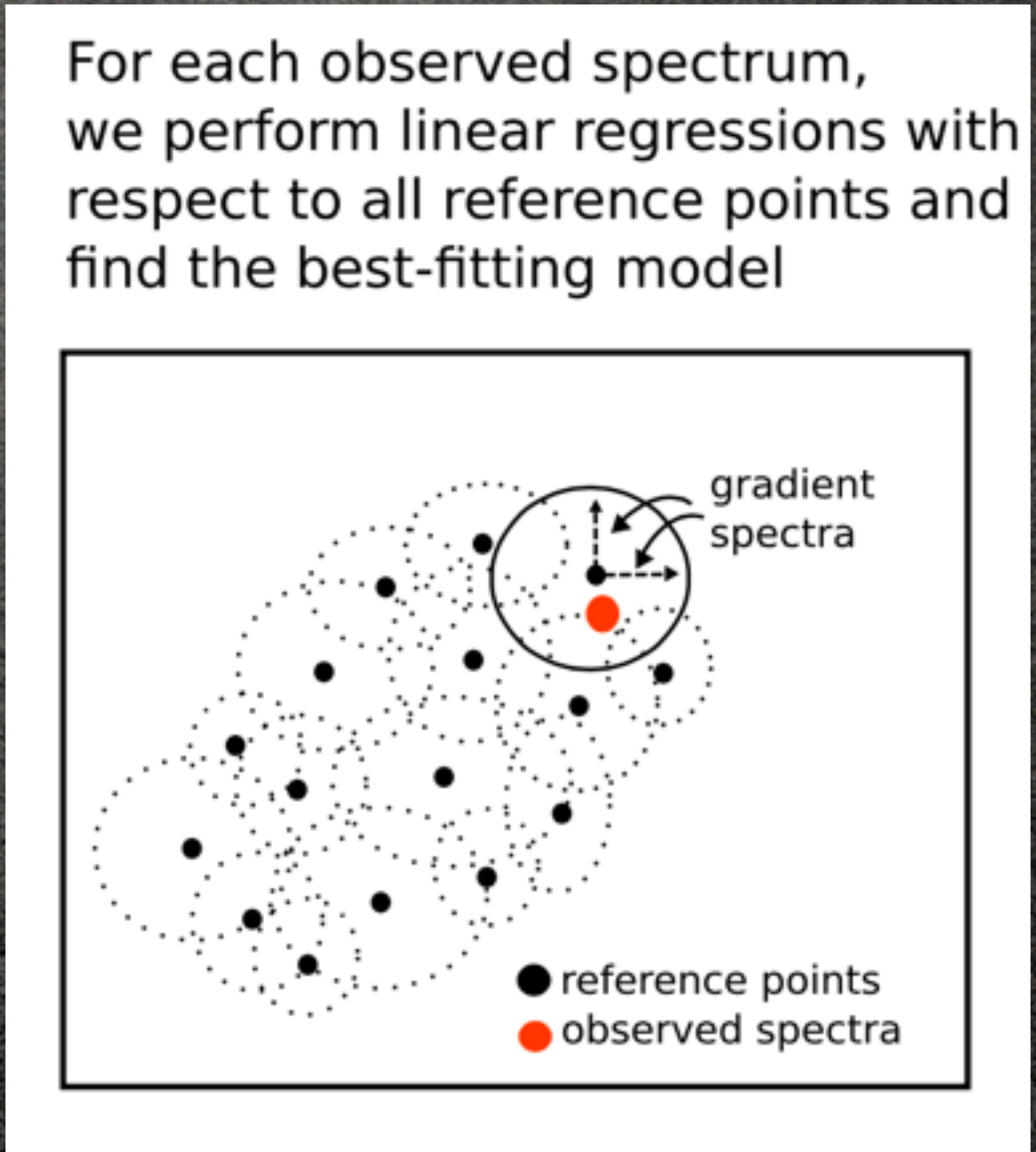
Testing C, N, and alpha's with synthetic spectra showed larger uncertainties.

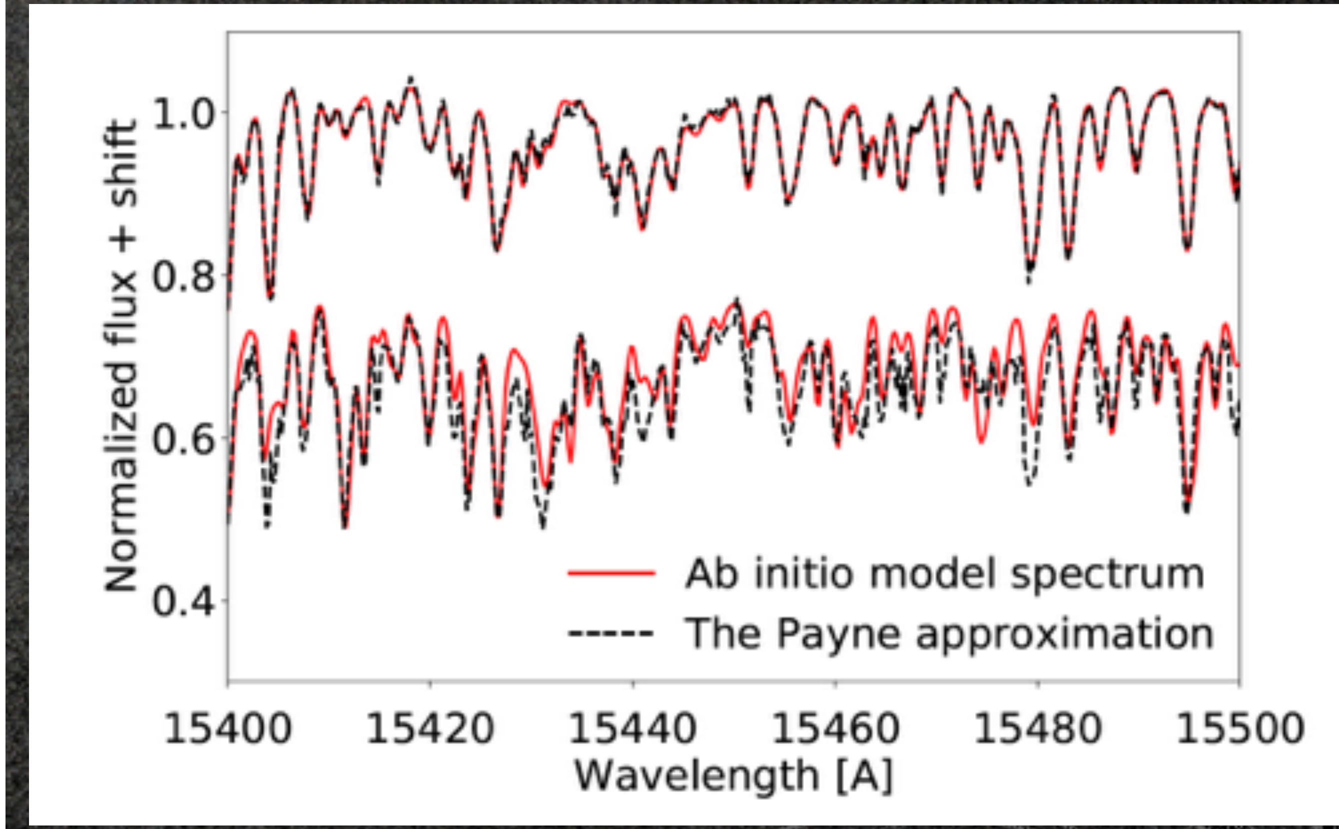
Currently studying ways to incorporate training errors with an observational error spectrum

Ting et al. 2016

Increasing the number of stellar labels (parameters) can really slow down the training (infeasible).

Ab initio models (2000), and then generating a subgrid (Taylor sphere)





Ting et al. 2018

Fast & homogeneous methodolgy for red giants & dwarfs (T, log g), over a range of metallicities (at least [Fe/H] > -1)

Extremely important in era of spectroscopic surveys!

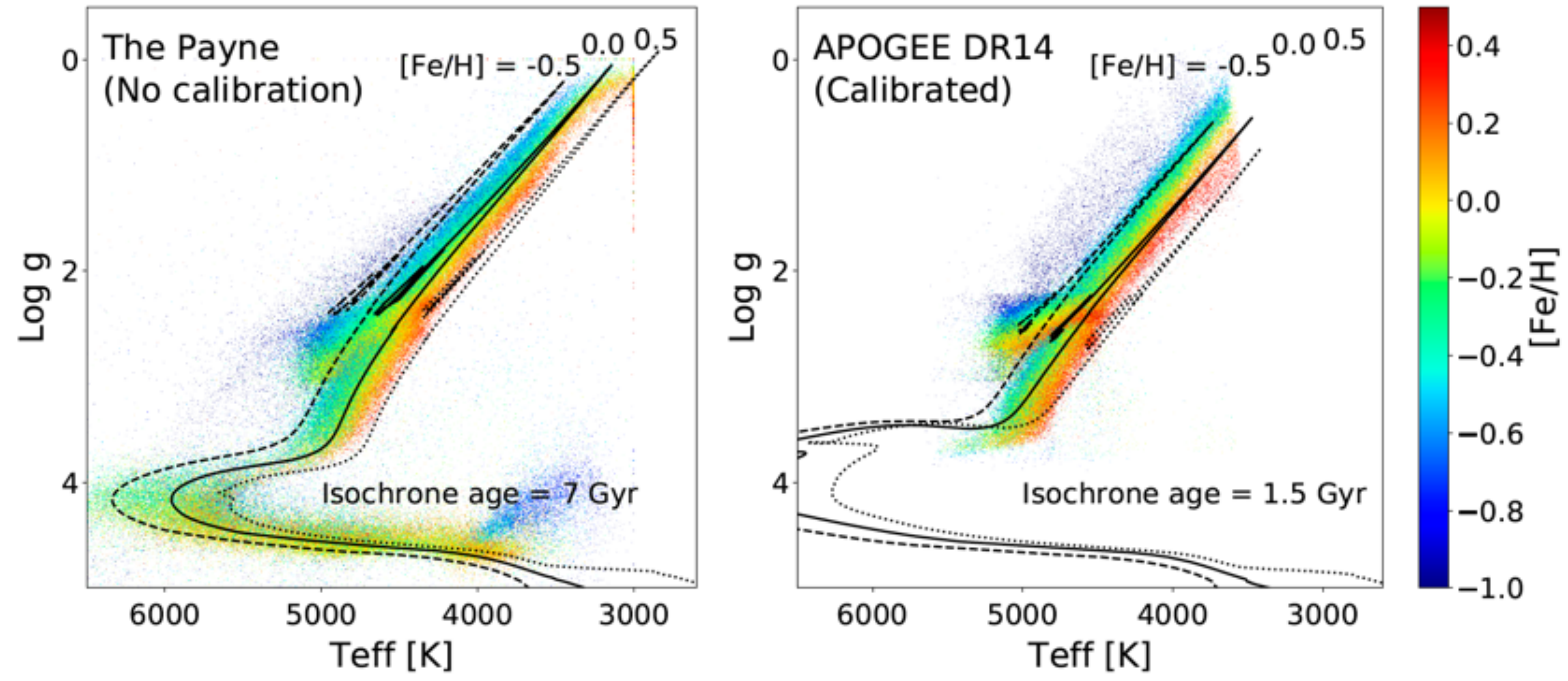
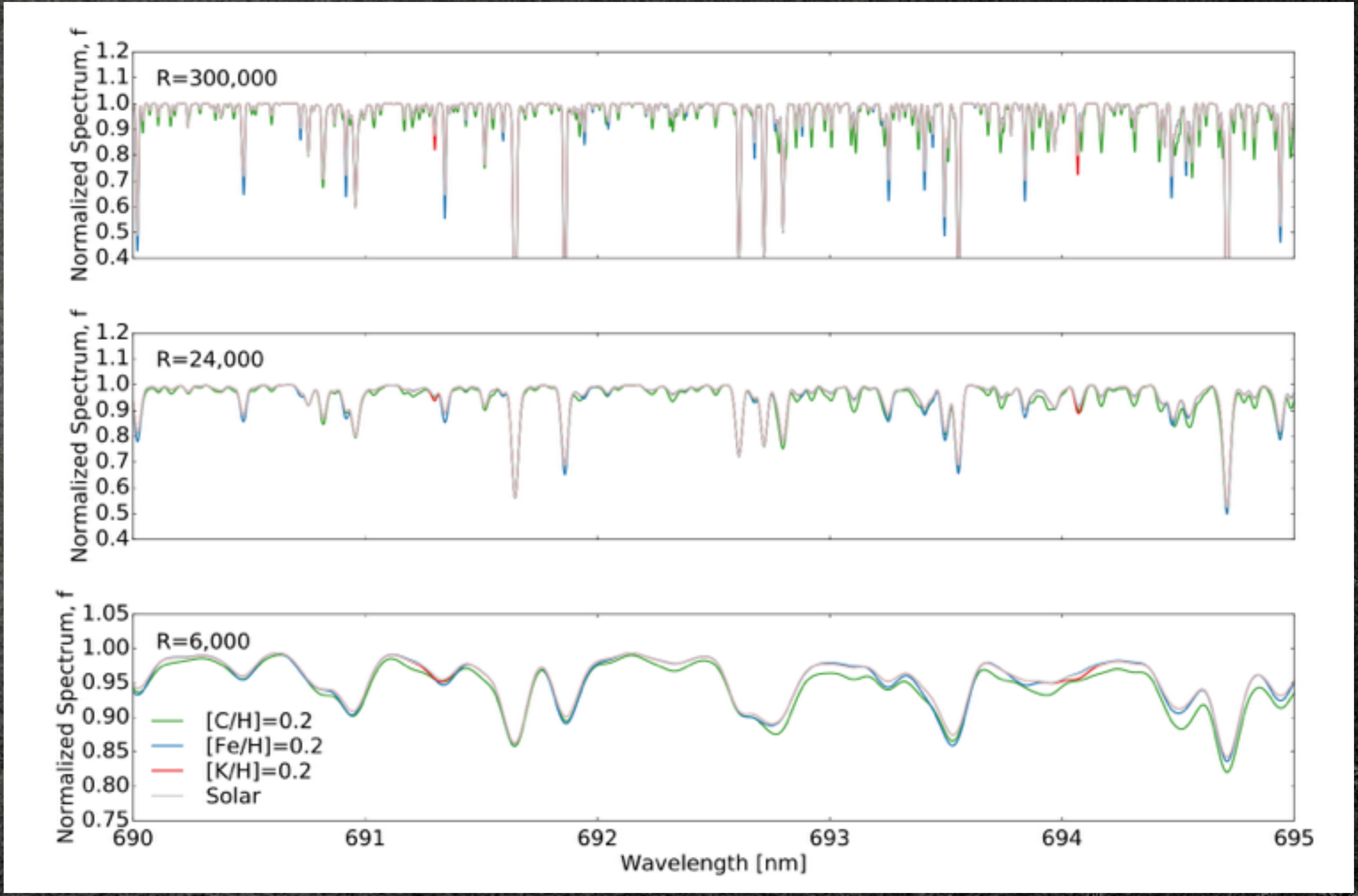


Figure 7. *The Payne* measures physically sensible $T_{\rm eff}$, $\log g$ and [Fe/H] for both giants and dwarfs simultaneously without requiring external calibration. On the left-hand side, we show *The Payne* $T_{\rm eff}$-$\log g$ Kiel diagram overplotted with MIST isochrones assuming a stellar age of 7 Gyr. On the right-hand side, we show the APOGEE DR14 *calibrated* counterparts and with MIST isochrones at 1.5 Gyr. *The Payne* derives stellar parameters that are consistent with stellar isochrones for both giants and dwarfs star with only a single *The Payne* model. For metal poor dwarfs with $T_{\rm eff} < 4000$ K, the results deviate strongly from the isochrones. This could be due to the Kurucz models 1D stellar atmosphere is a poor assumption in this regime or simply the line list is not well calibrated at this temperature and metallicity range.

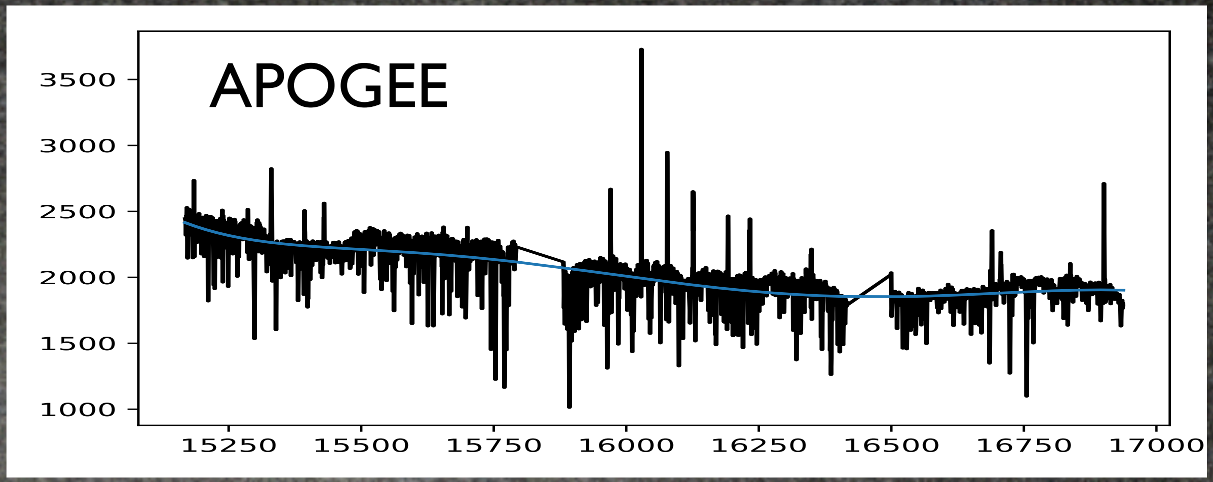
Ting et al. 2017

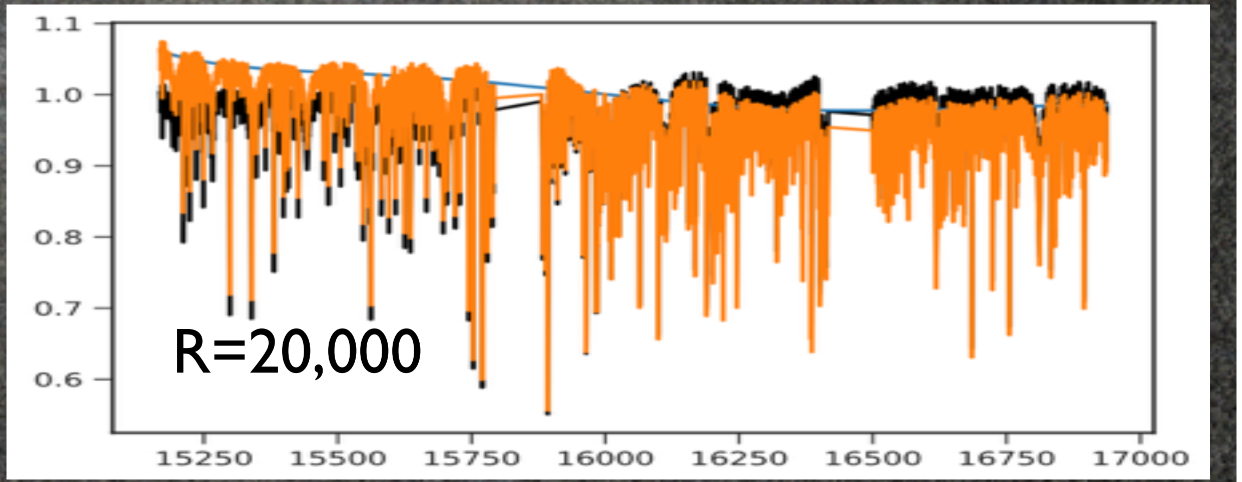
Preliminary studies of Wavelength Range, Resolution, and Continuum



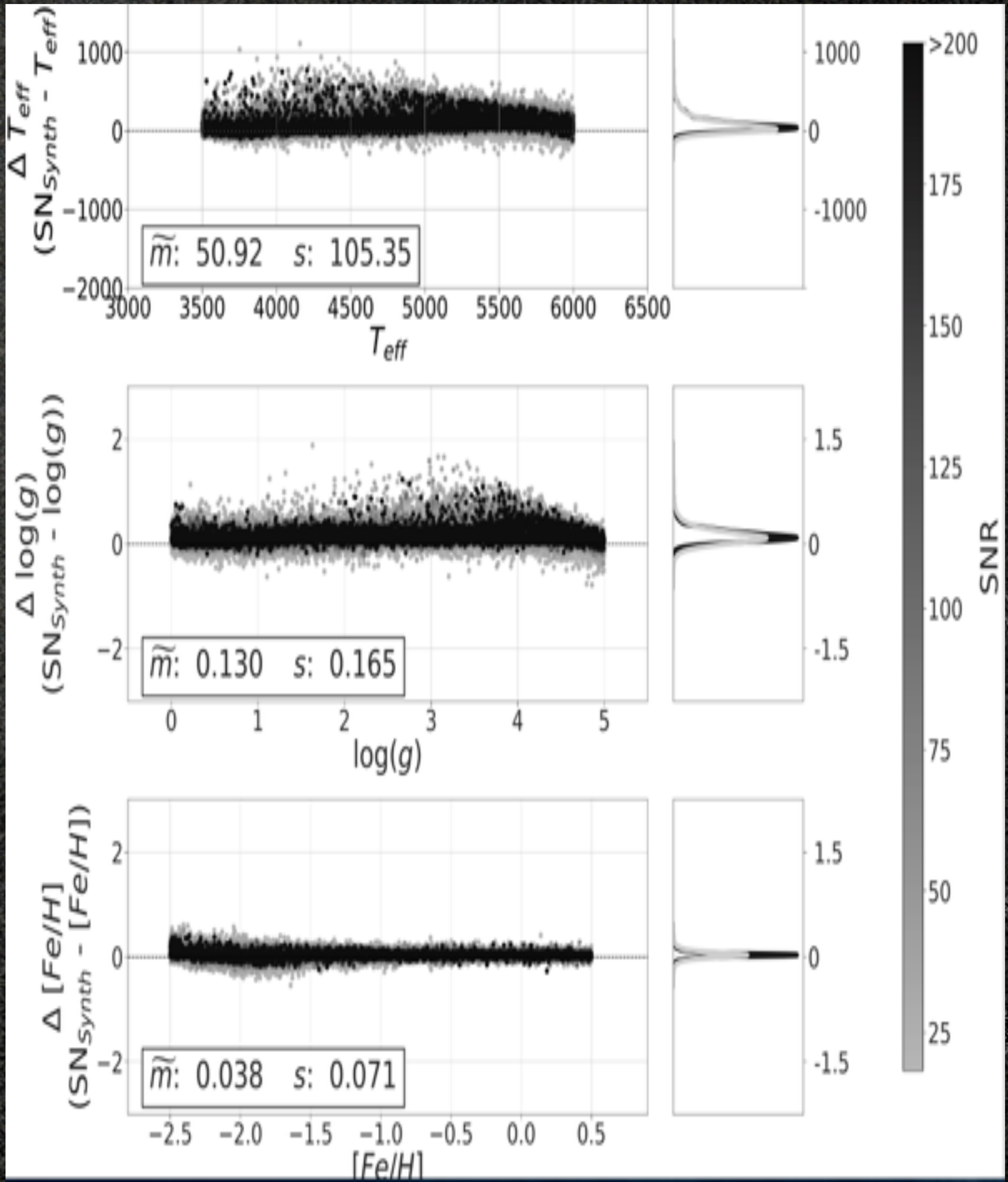
Kielty, Bialek, Venn, Fabbro, in prep

Preliminary studies of Wavelength Range, Resolution, and Continuum



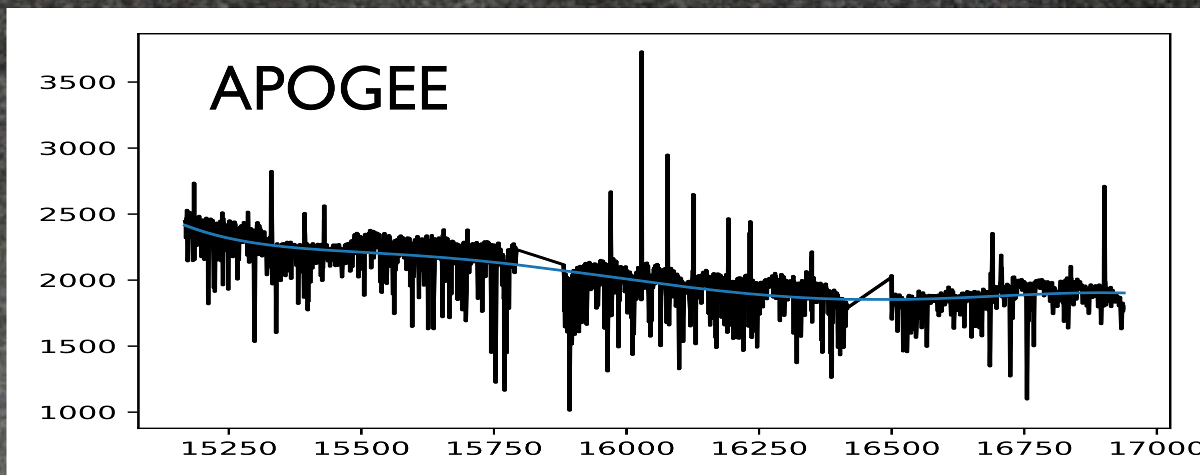


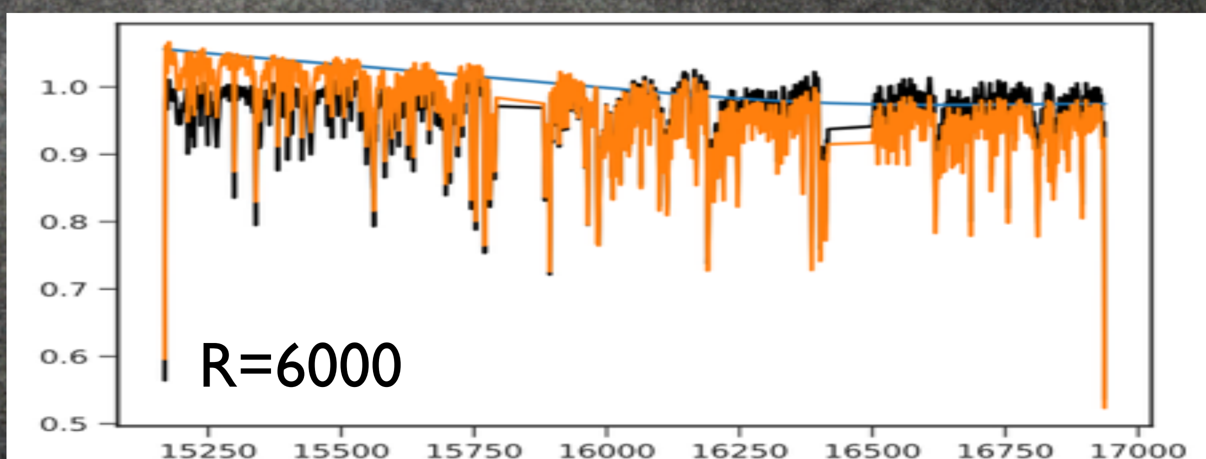
applying +1% (asymmetric)



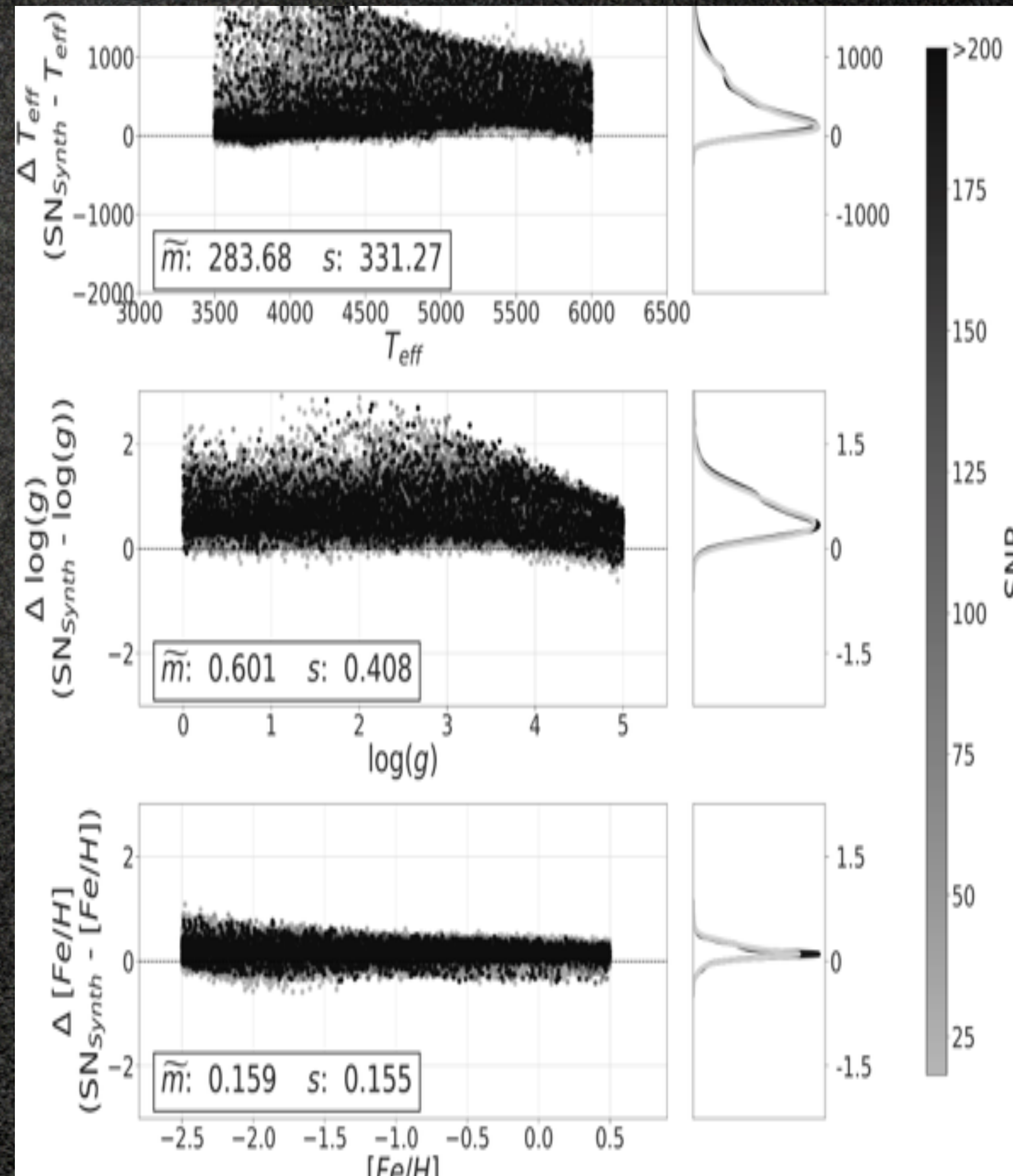
Kielty, Bialek, Venn, Fabbro, in prep

Preliminary studies of Wavelength Range, Resolution, and Continuum



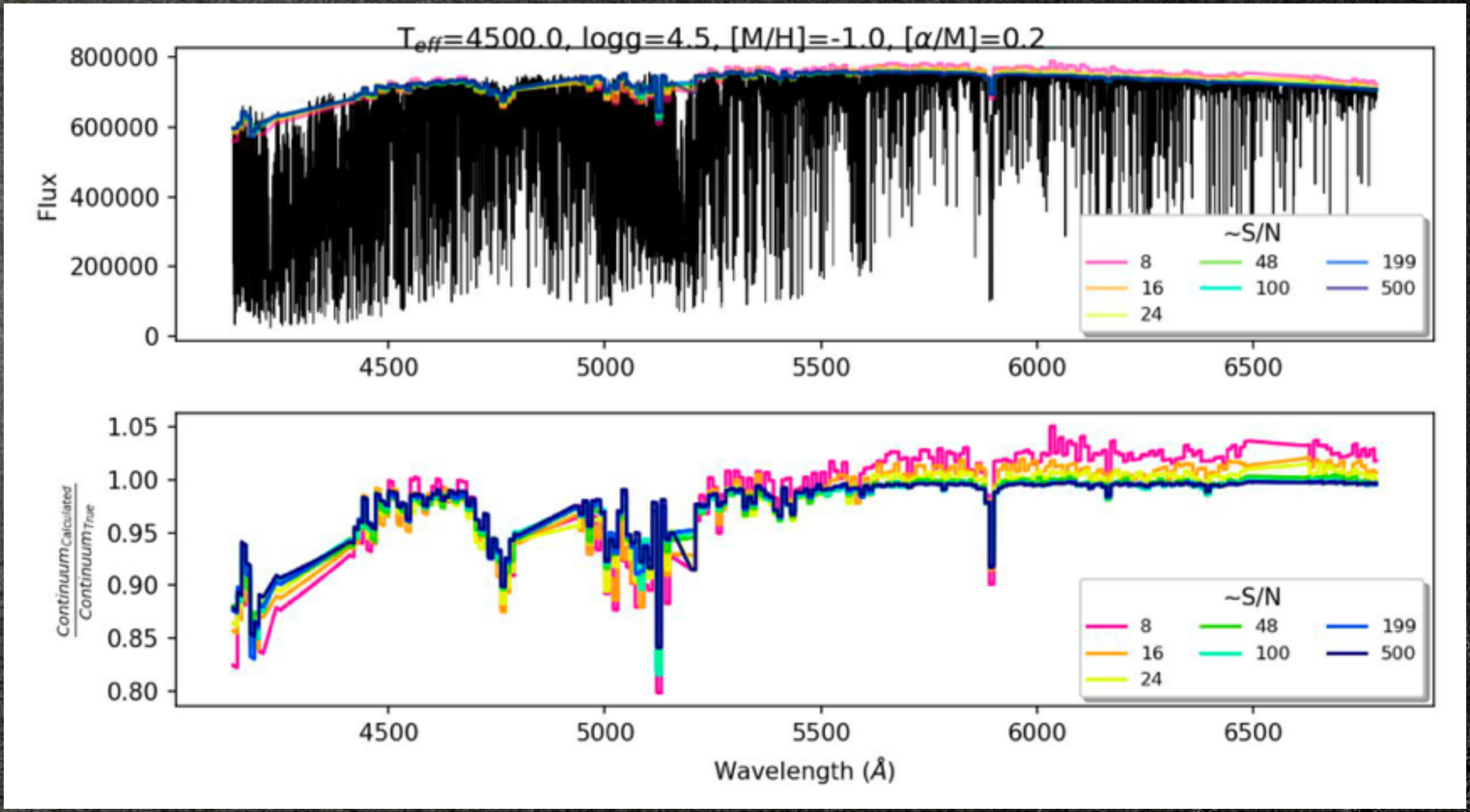


applying +4% (asymmetric)



Kielty, Bialek, Venn, Fabbro, in prep

Preliminary studies of Wavelength Range, Resolution, and Continuum



~4% (asymmetric)

Summary

EMP stars are rare but useful for

- testing galaxy halo & bulge formation
- testing dwarf galaxy star SFH

- constraining metal-poor supernova yields & r-process sites
- Abundance profiling of EMP stars to determine the first stars IMF

Fast & homogenous data analysis methodologies are being developed, necessary for the era of spectroscopic surveys

- LR: Gaia, LAMOST, DESI, BOSS, PFS
- HR: Gaia-ESO, GALAH, APOGEE+, WEAVE, 4MOST, MSE

Thanks to the Organizers!