Homogeneous Chemical Abundances in Ultra-faint Dwarf Galaxies

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[X / H]

Nucleosynthesis

Nuclear physics
Stellar evolution
Supernovae
Stellar populations

[X / H]

Nucleosynthesis

Nuclear physics
Stellar evolution
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$$[X/H]$$

Hierarchical galaxy formation
Gas accretion and expulsion
Metal mixing
Star formation

Galaxy Formation

Nucleosynthesis

Nuclear physics
Stellar evolution
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Adding multiple nucleosynthetic sources assumes you know H

$$[X/H]$$

Hierarchical galaxy formation
Gas accretion and expulsion
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Galaxy Formation

Nucleosynthesis

Nuclear physics
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Supernovae
Stellar populations

$$[X/H]$$

Abundances

Atomic physics
Stellar atmospheres

Hierarchical galaxy formation
Gas accretion and expulsion
Metal mixing
Star formation

Galaxy Formation

Nucleosynthesis

Nuclear physics
Stellar evolution
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Stellar populations

"Connections":
The hope that
someone else
can help you
with your
impossible problem

$$[X/H]$$

Abundances

Atomic physics
Stellar atmospheres

Hierarchical galaxy formation
Gas accretion and expulsion
Metal mixing
Star formation

Galaxy Formation

Wouldn’t it be great if we could measure lots of small bursts of chemical enrichment?

Ultra-faint dwarf galaxies (UFDs)

- Milky Way satellite galaxies with resolved stars

  First one: Willman et al. 2005 (SDSS)

- Low luminosity (300 - 30,000 L_{sun})

  e.g., Bechtol et al. 2015

- Dark-matter-dominated (M/L > 100)

  Simon & Geha 2007

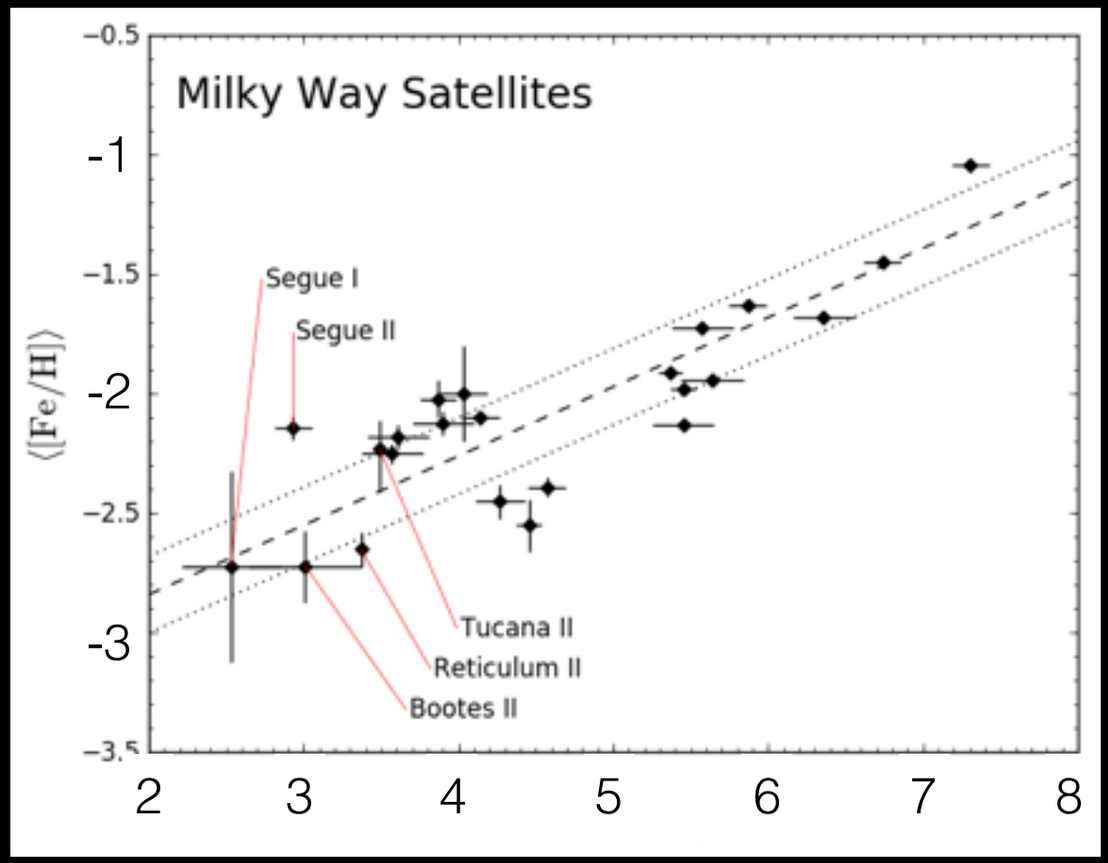
- Metal-poor (Mean [Fe/H] < -2)

  Kirby et al. 2008, Frebel et al. 2014

- Old (Mean stellar age 13.3 +/- 1 Gyr)

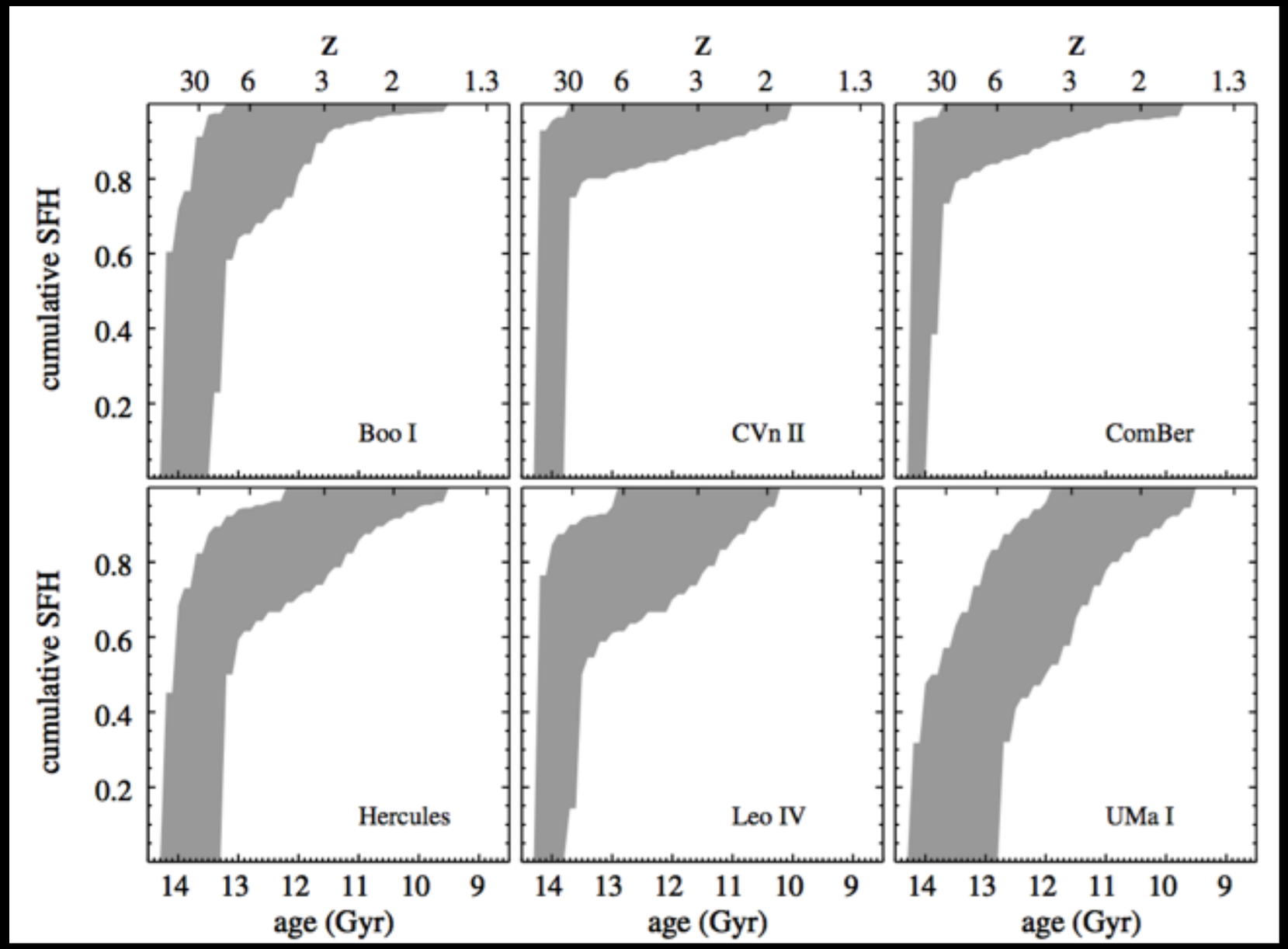
  Brown et al. 2014, Weisz et al. 2014

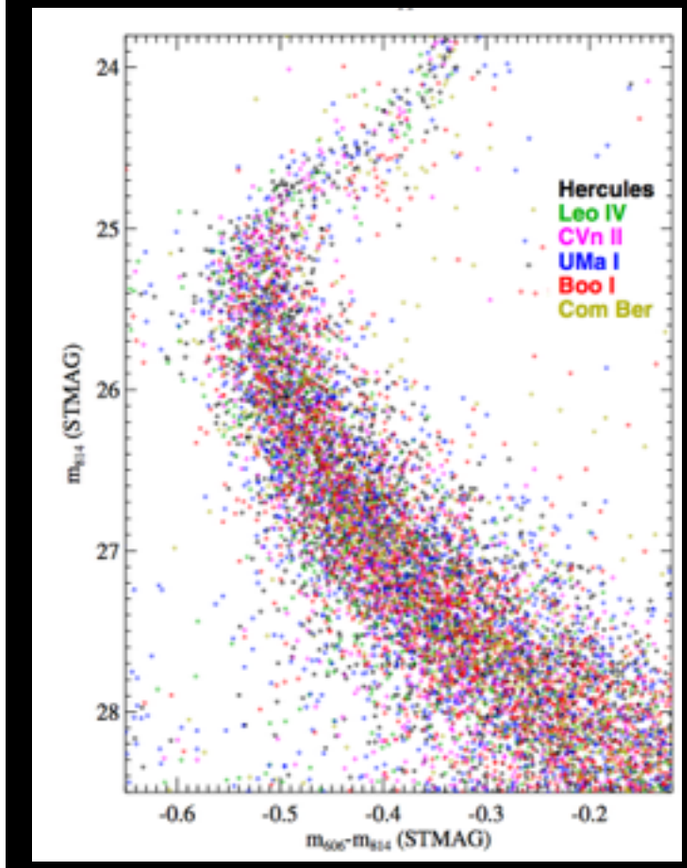
The stars in each UFD sample a short, independent burst of chemical enrichment.



McConnachie 2012, Kirby et al. 2013

UFDs: small AND form almost all stars before z ~ 6

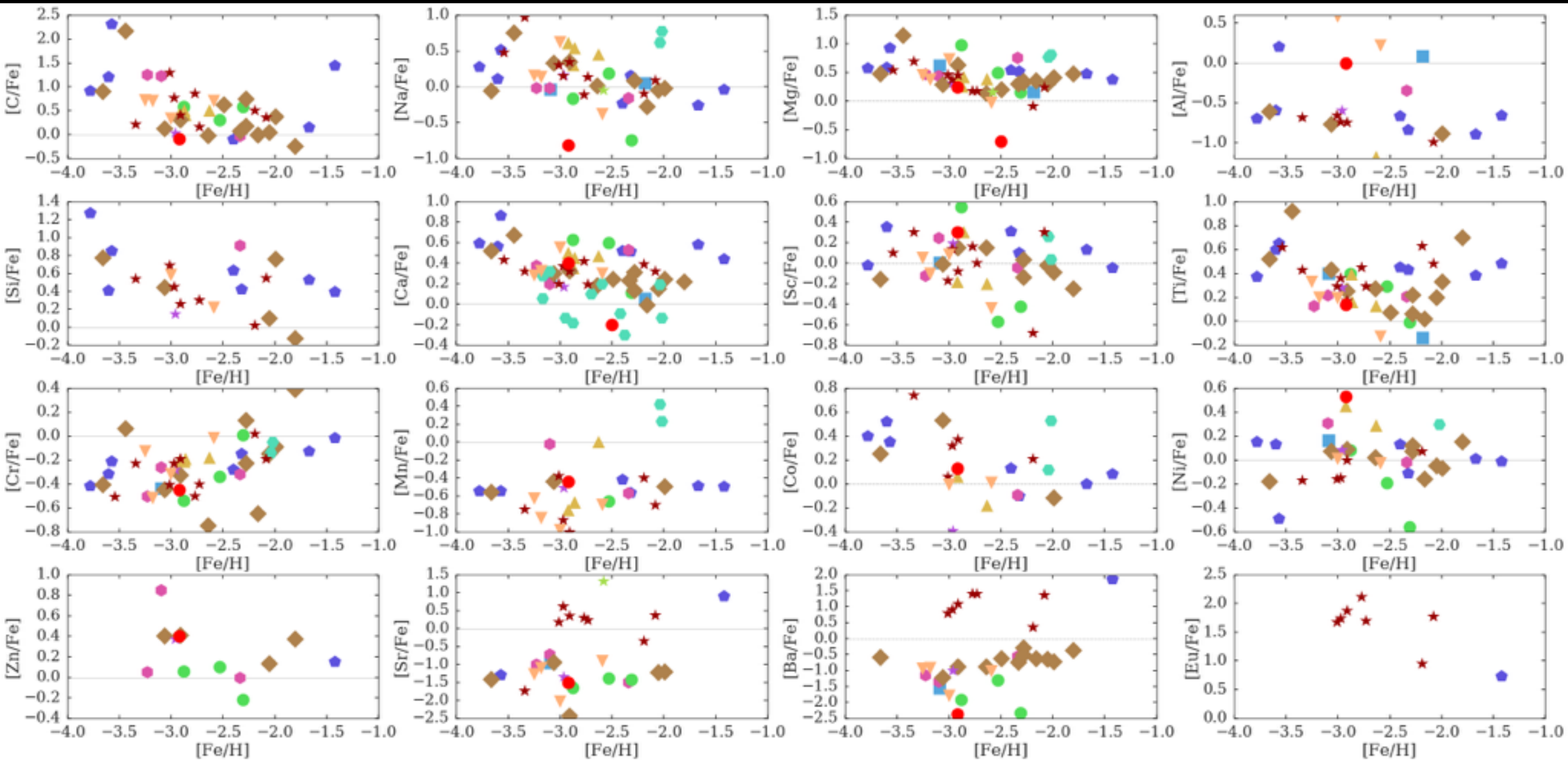




Brown et al. 2014

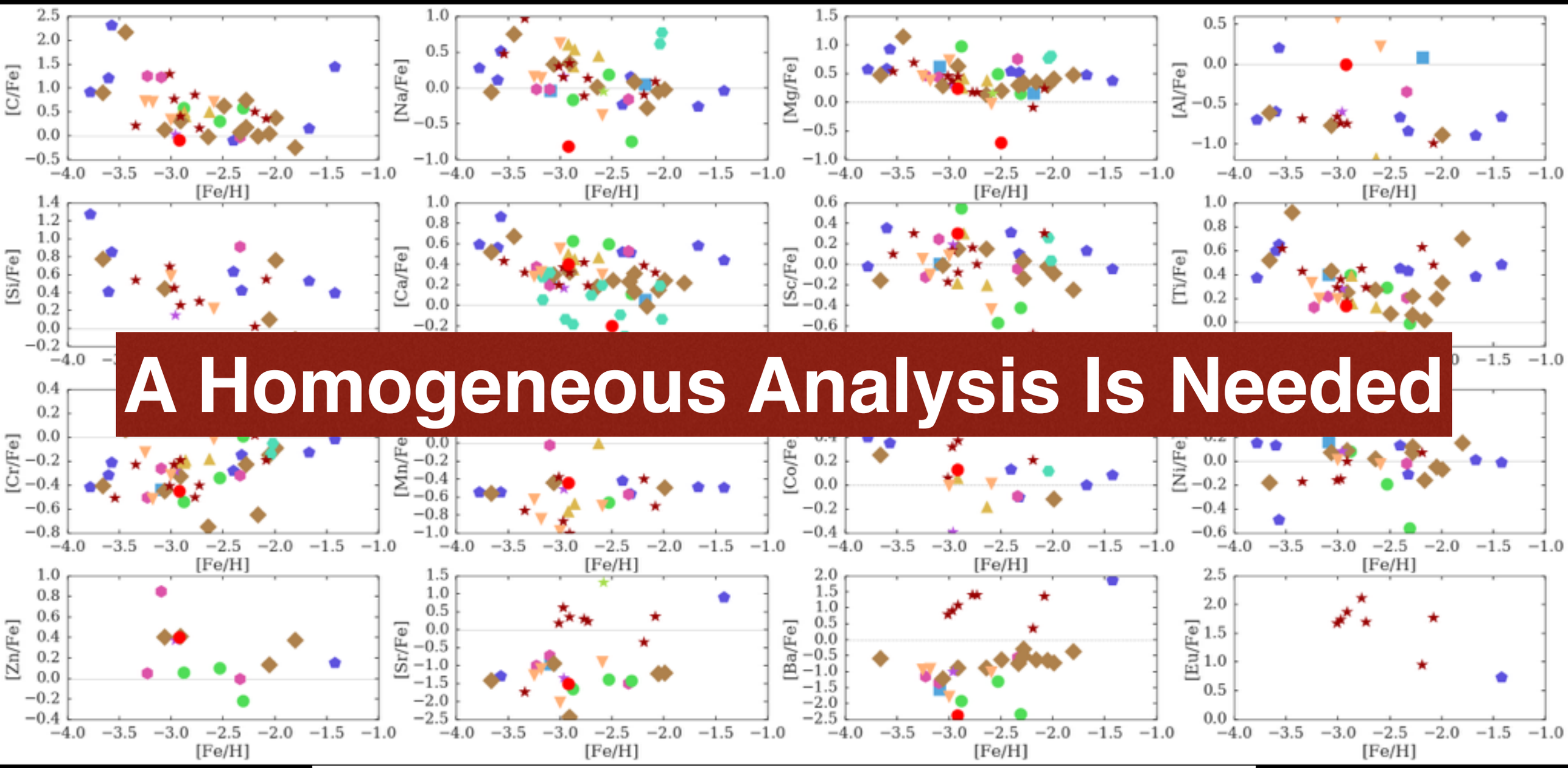
Accessible for *multiple* detailed galaxy formation simulations

Detailed Chemical Abundances in UFD stars



Feltzing+09, Norris+10, Simon+10, Frebel+10, Aden+11, Gilmore+13, Koch+13, Ishigaki+14, Frebel+14, Roederer+14, Frebel+16, Ji+16a-d, Francois+16, Roederer+16, Venn+17, Kirby+17, (Hansen+17)

Detailed Chemical Abundances in UFD stars



A Homogeneous Analysis Is Needed

Feltzing+09, Norris+10, Simon+10, Frebel+10, Aden+11, Gilmore+13, Koch+13, Ishigaki+14, Frebel+14, Roederer+14, Frebel+16, Ji+16a-d, Francois+16, Roederer+16, Venn+17, Kirby+17, (Hansen+17)

Simple Homogeneous Abundance Analysis

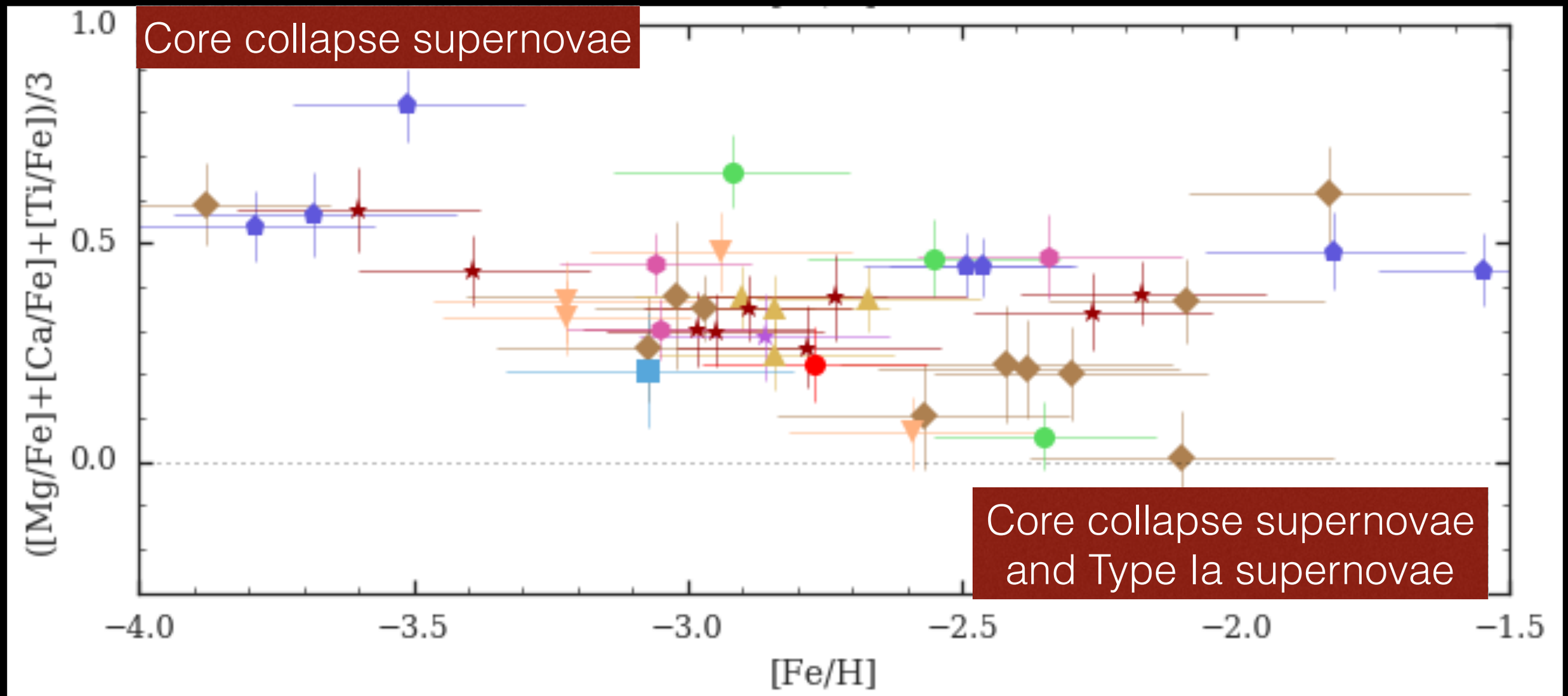
- Collect all published equivalent widths
  (Lose Tuc III, CVn II)

- Same atomic data for lines

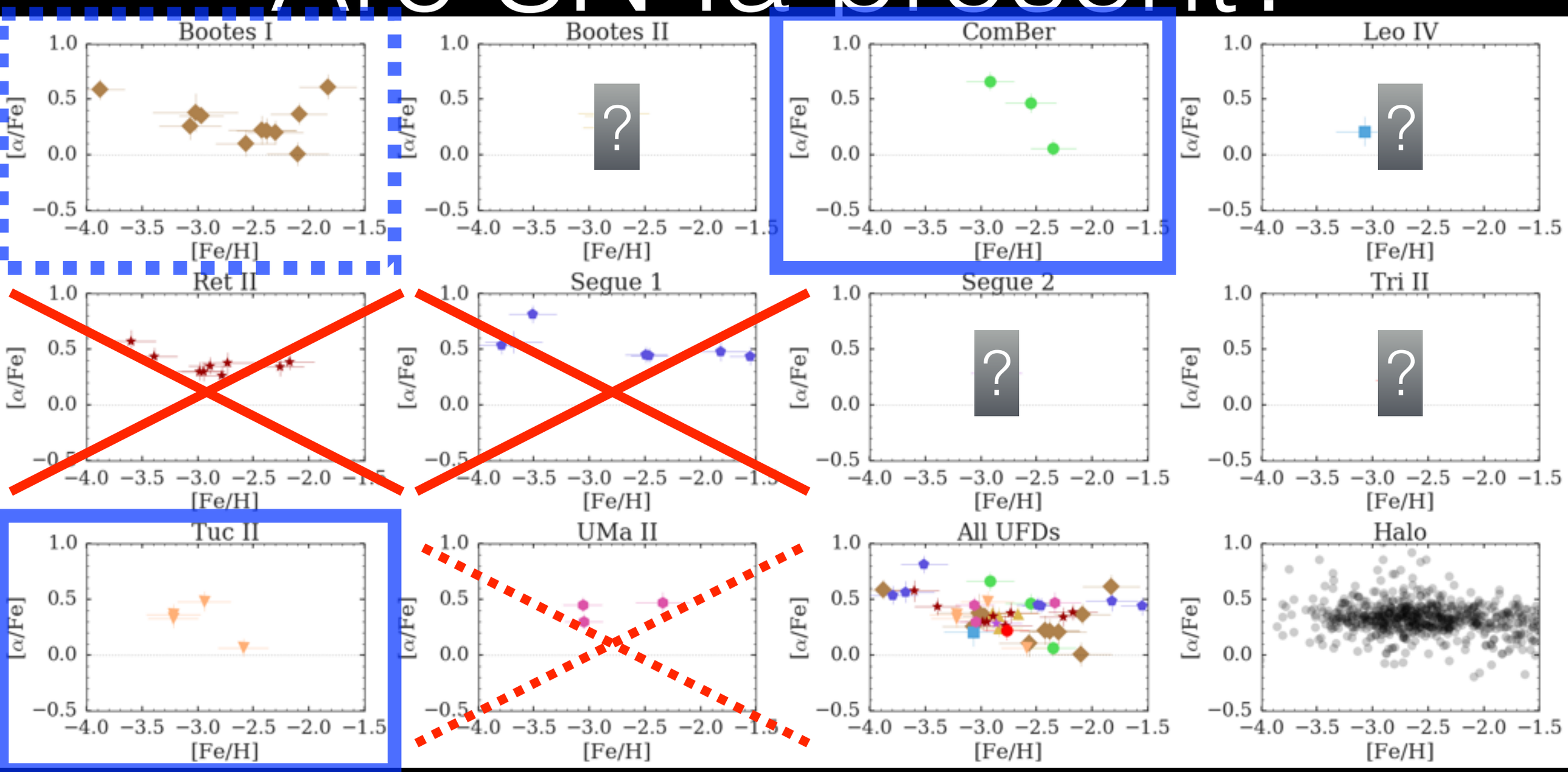
- Redetermine stellar parameters
  Fully spectroscopic: excitation, ionization, line strength balance
  1D LTE: MOOG 2014, Castelli-Kurucz atmospheres
  Empirical temperature correction (Frebel et al. 2013)
  (Lose Hercules: too few lines)

- Hope to add: multiple radiative transfer codes, stellar atmospheres, stellar parameter methods; NLTE; differential analysis; starting from raw spectra

[α/Fe] vs [Fe/H]

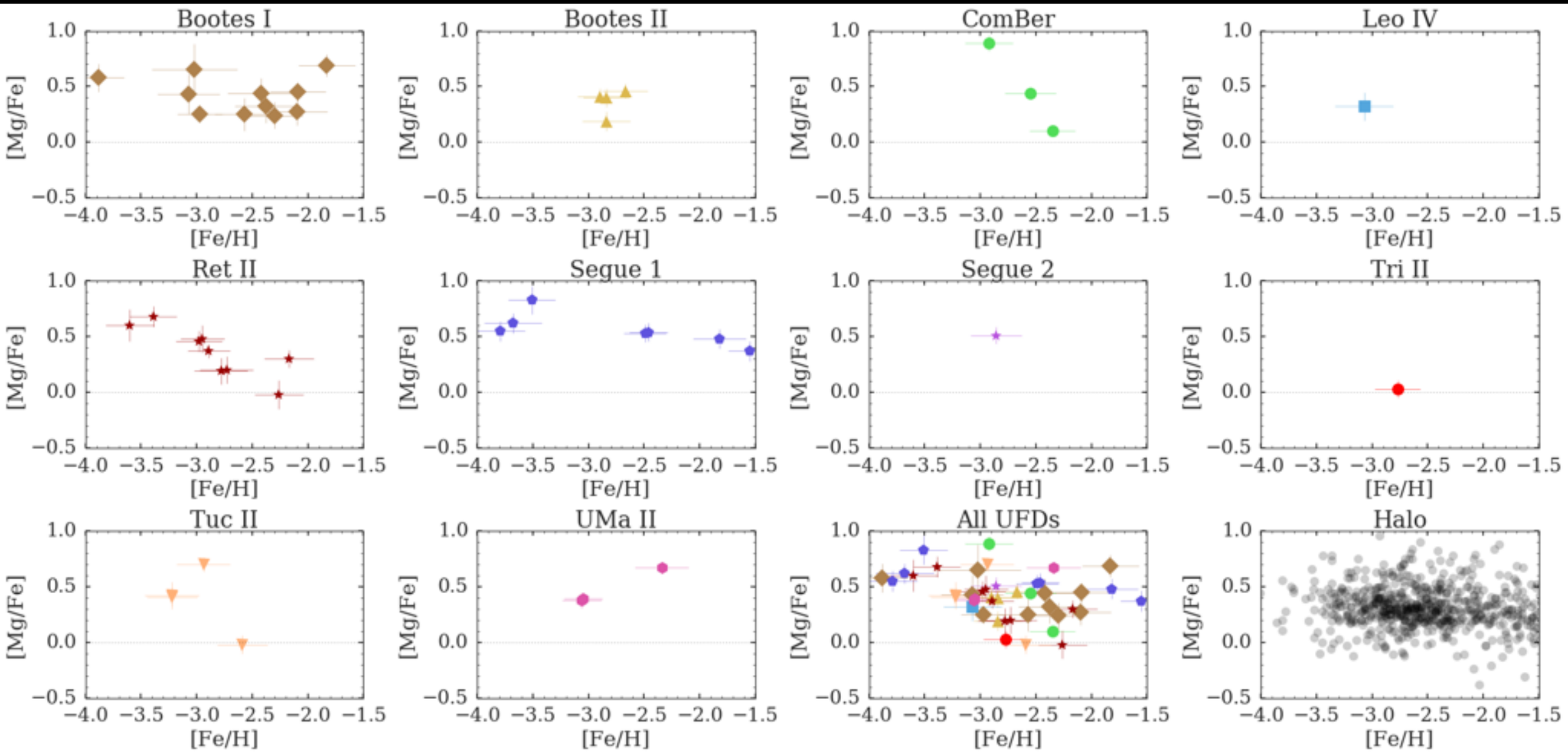

Core collapse supernovae
Core collapse supernovae
and Type Ia supernovae
([Mg/Fe]+[Ca/Fe]+[Ti/Fe])/3
[Fe/H]
1.0
0.5
0.0
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
Bootes I
Bootes II
ComBer
Hercules
Leo IV
Ret II
Segue 1
Segue 2
Tri II
Tuc II
UMa II

Are SN Ia present?



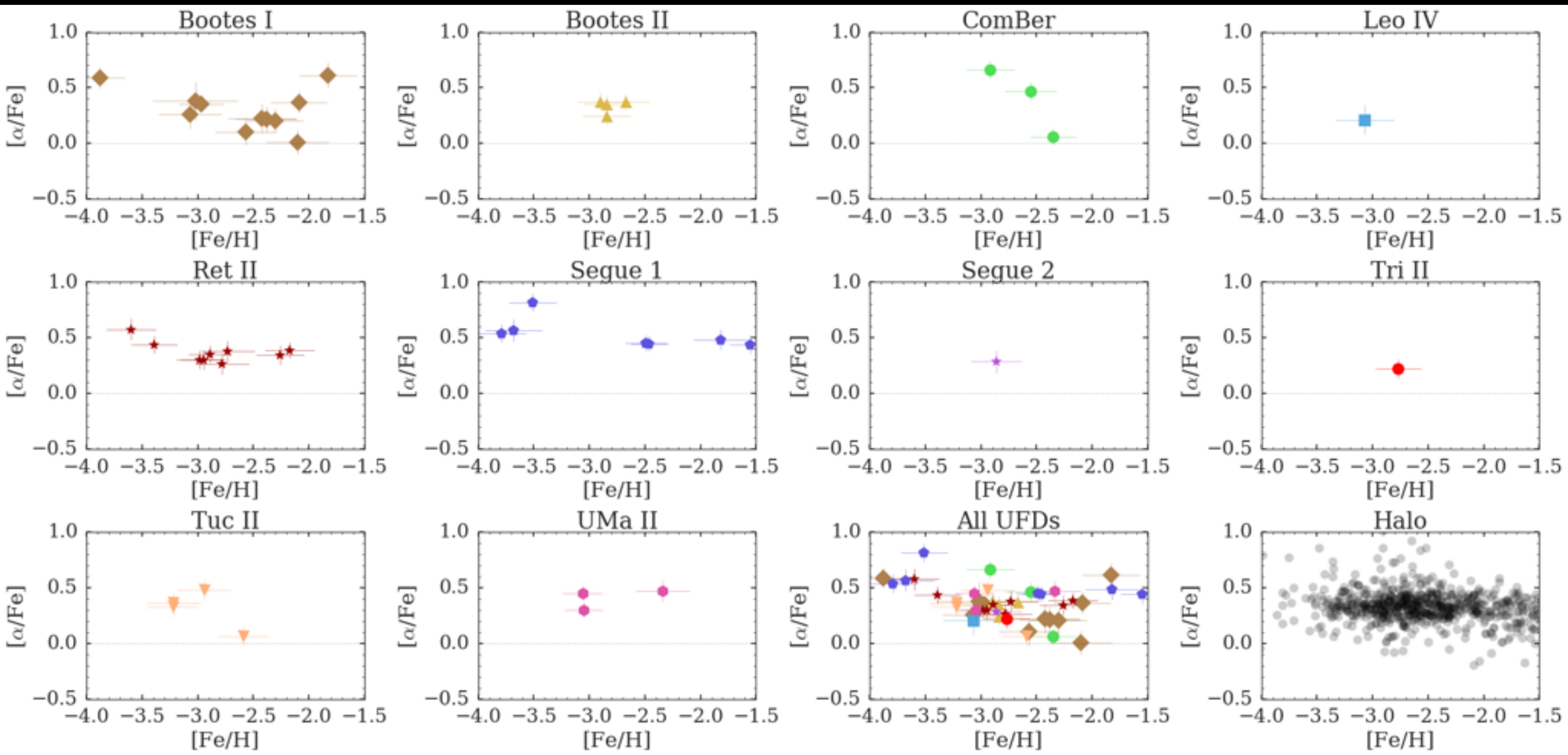
Average Mg, Ca, Ti

Mg ≠ α


Bootes I
Bootes II
ComBer
Leo IV
Ret II
Segue 1
Segue 2
Tri II
Tuc II
UMa II
All UFDs
Halo
[Mg/Fe]
[Fe/H]
1.0
0.5
0.0
−0.5
−4.0 −3.5 −3.0 −2.5 −2.0 −1.5

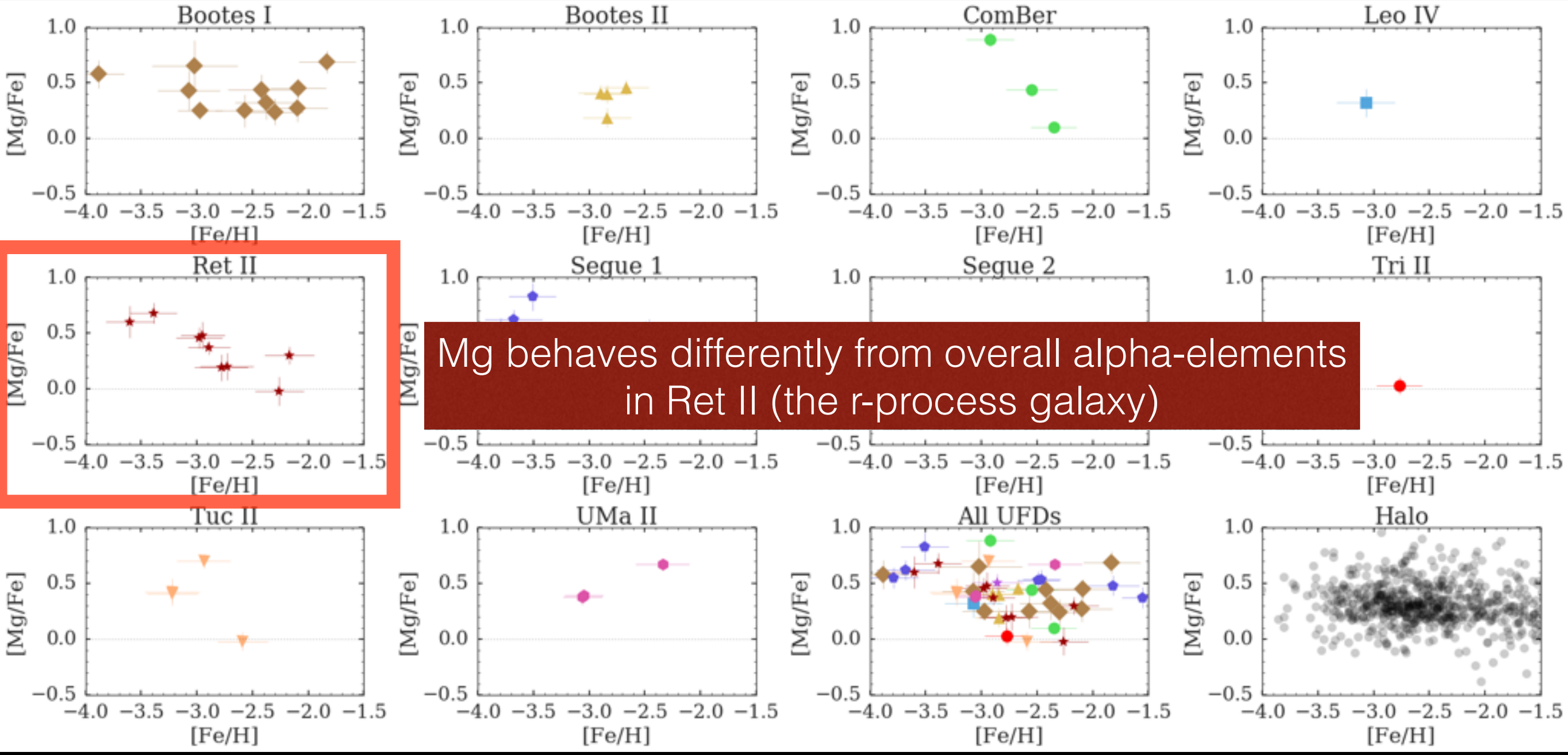
Mg only

Mg ≠ α



Average Mg, Ca, Ti

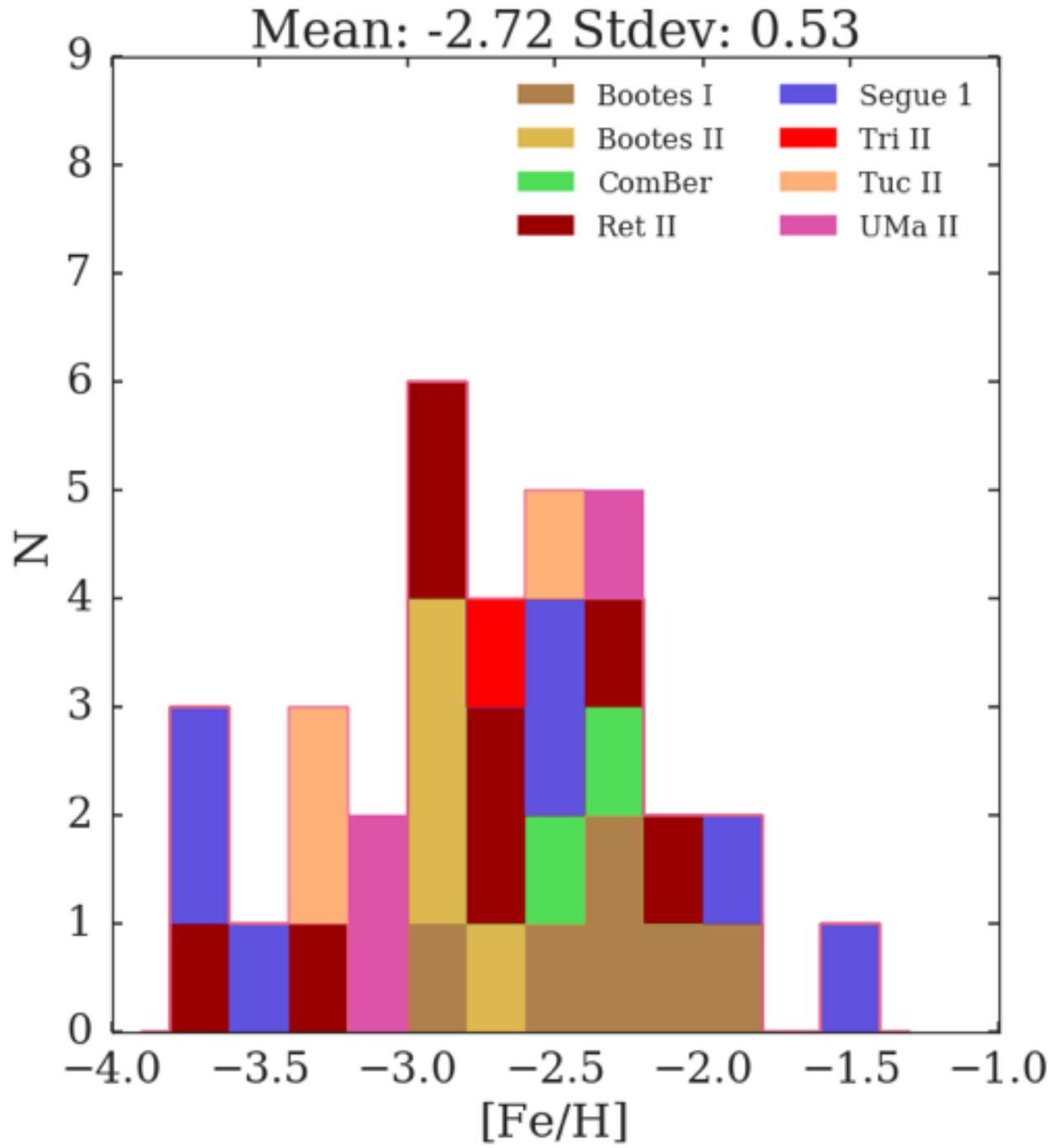
Mg ≠ α

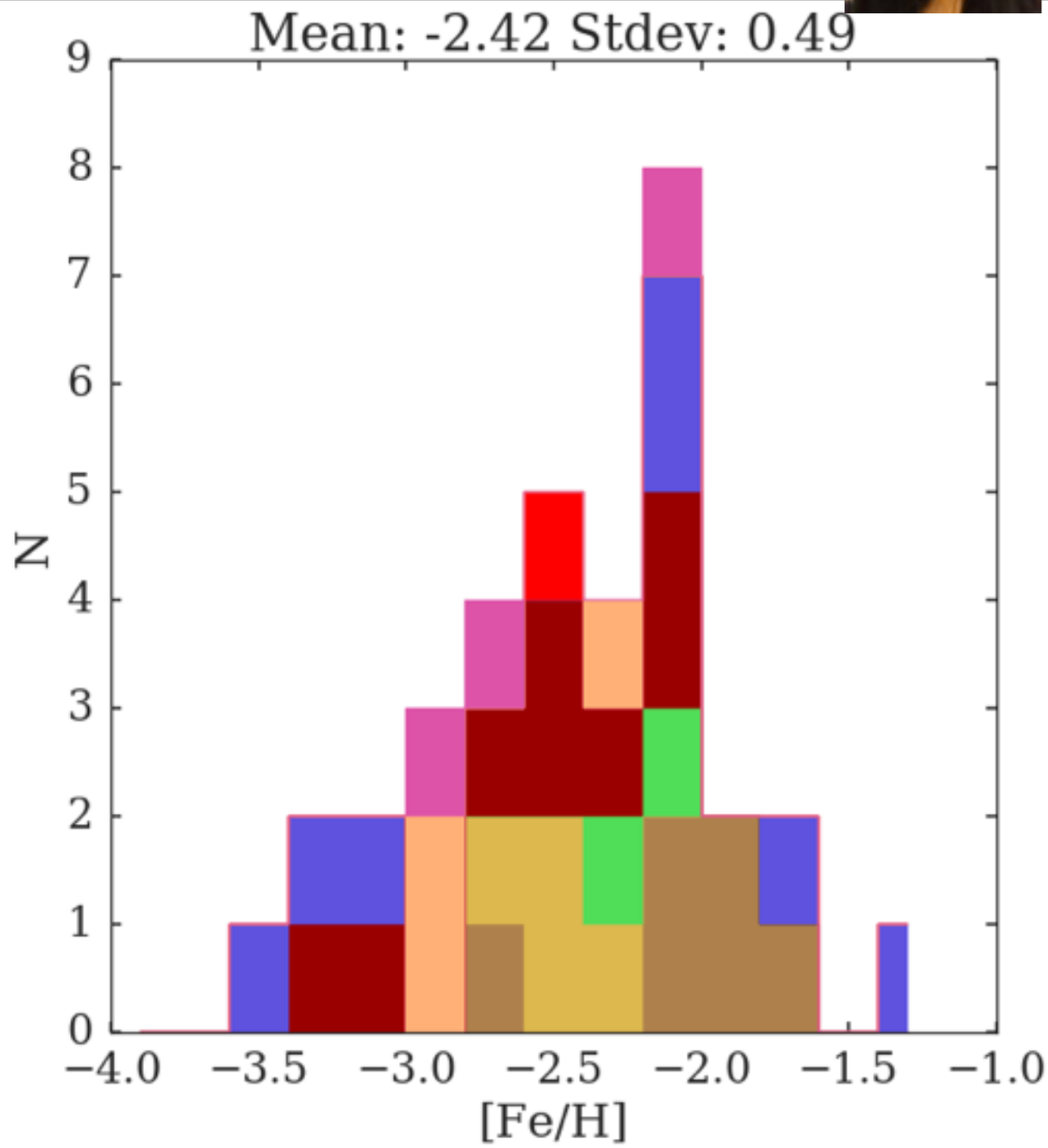


Mg behaves differently from overall alpha-elements in Ret II (the r-process galaxy)

Mg only

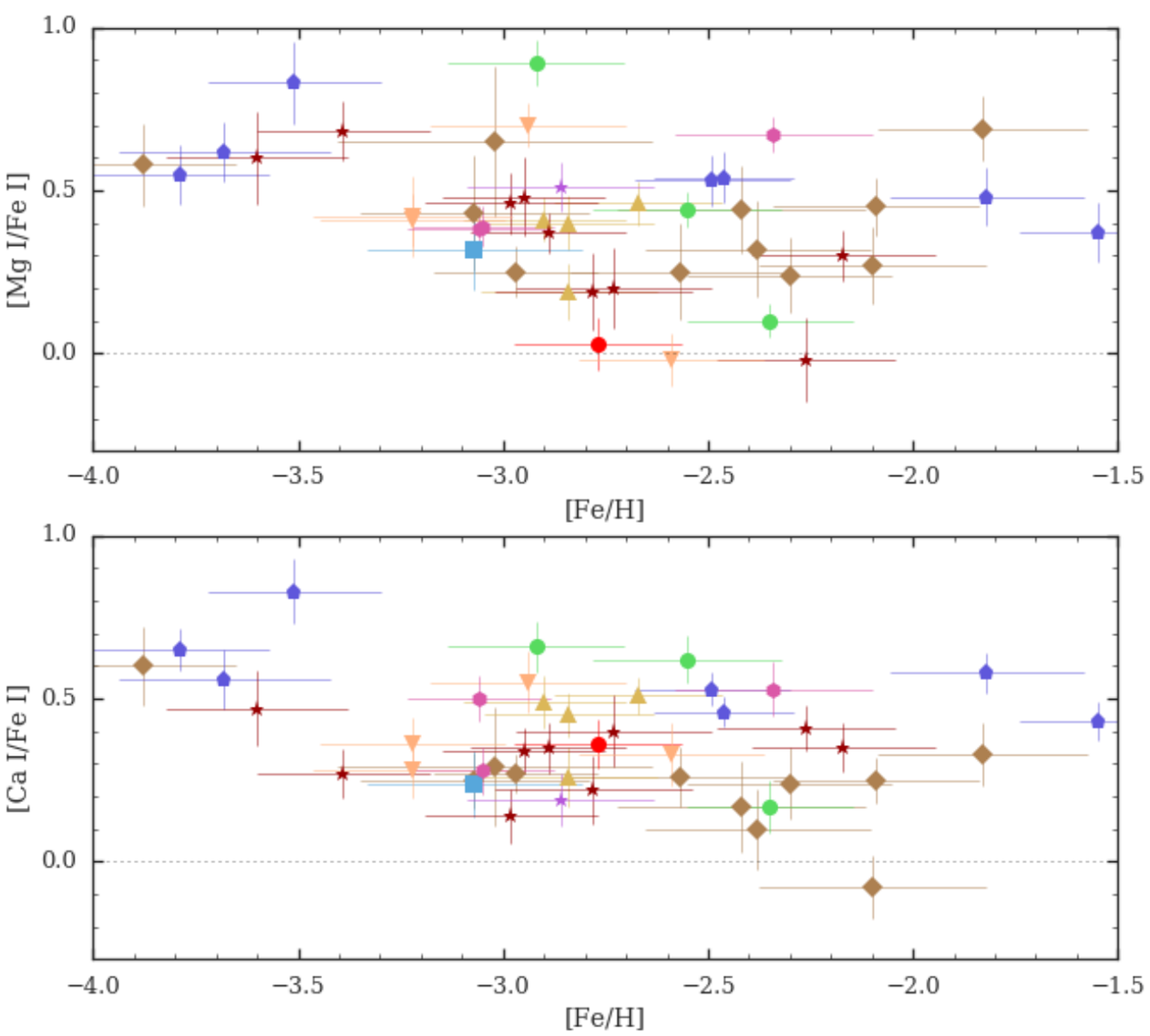
Non-LTE: in progress

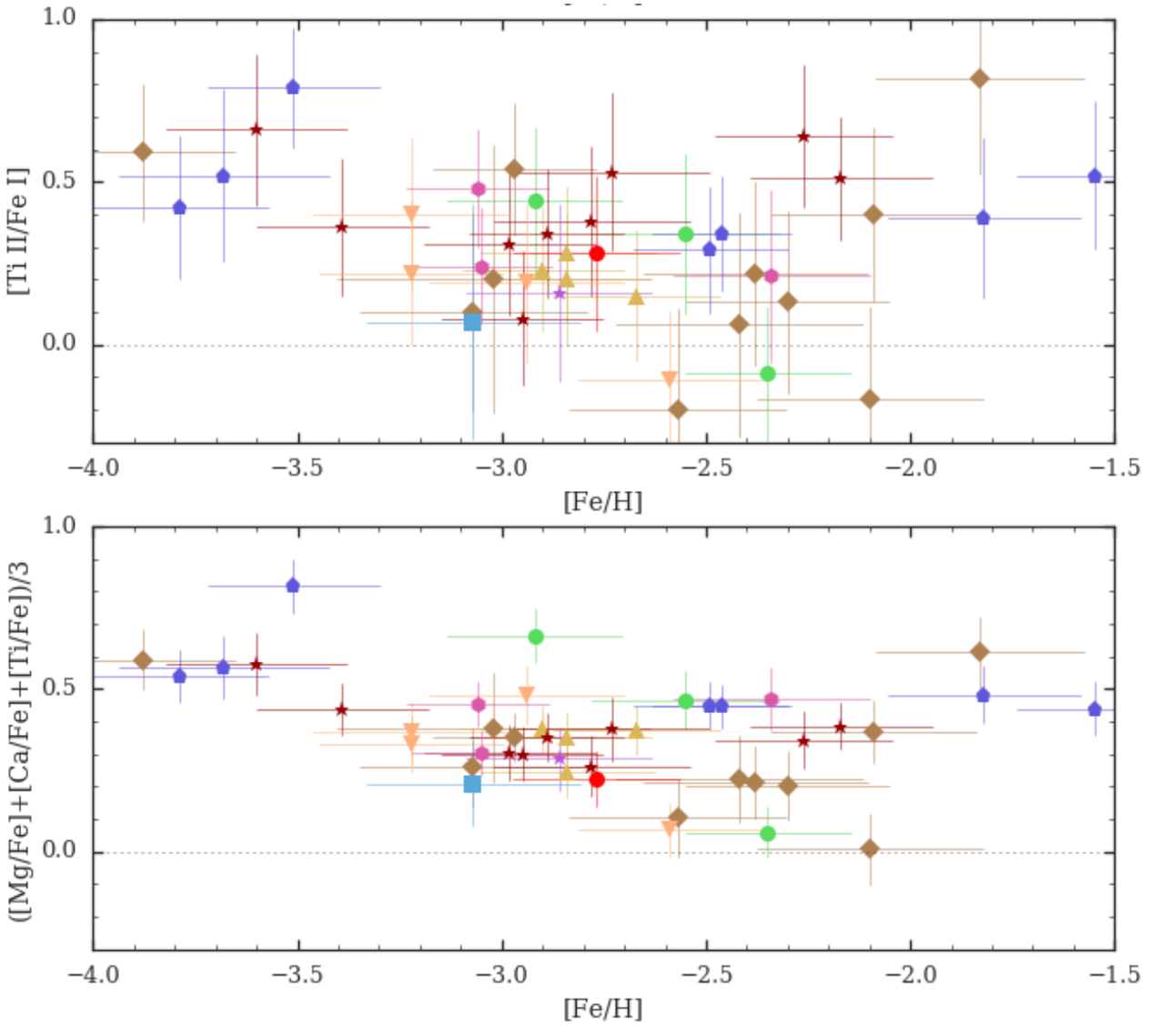




Summary

- UFDs sample many short, independent bursts of galaxy formation and chemical enrichment
- Homogeneous abundance analysis: allows comparisons between galaxies (Your advice appreciated!)
- Reticulum II (r-process galaxy) has [Mg/Fe] declining but other [alpha/Fe] ~constant


[Mg I/Fe I]
[Fe/H]


[Ti II/Fe I]
[Fe/H]

[Ca I/Fe I]
[Fe/H]

([Mg/Fe]+[Ca/Fe]+[Ti/Fe])/3
[Fe/H]

Bootes I
Bootes II
ComBer
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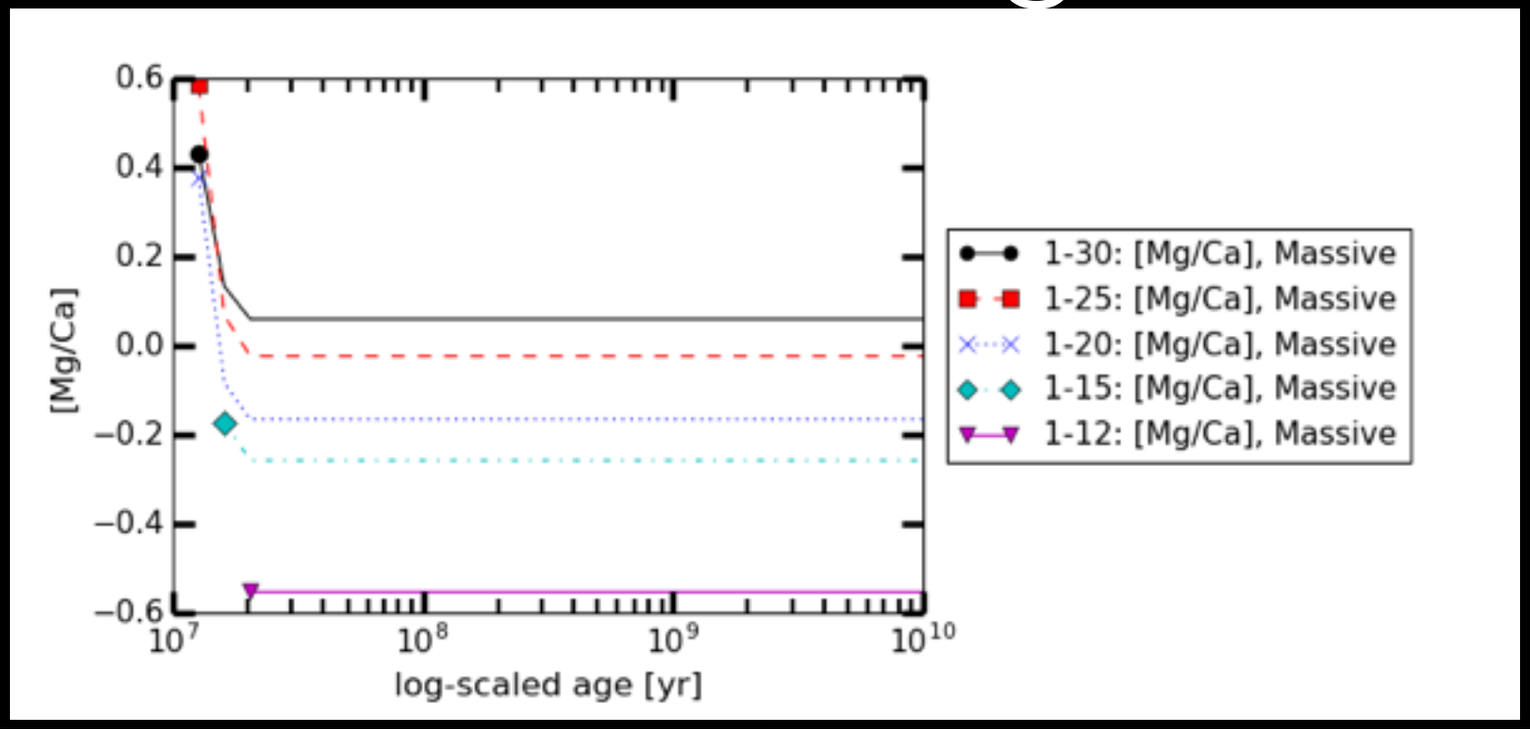
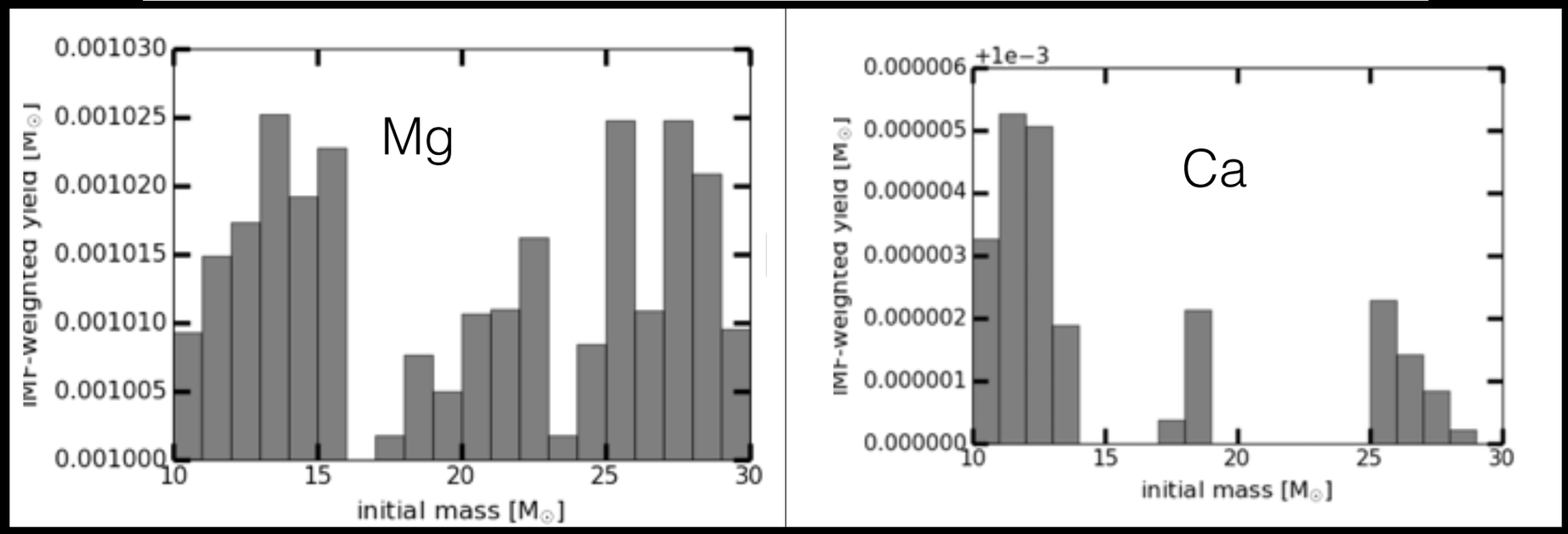
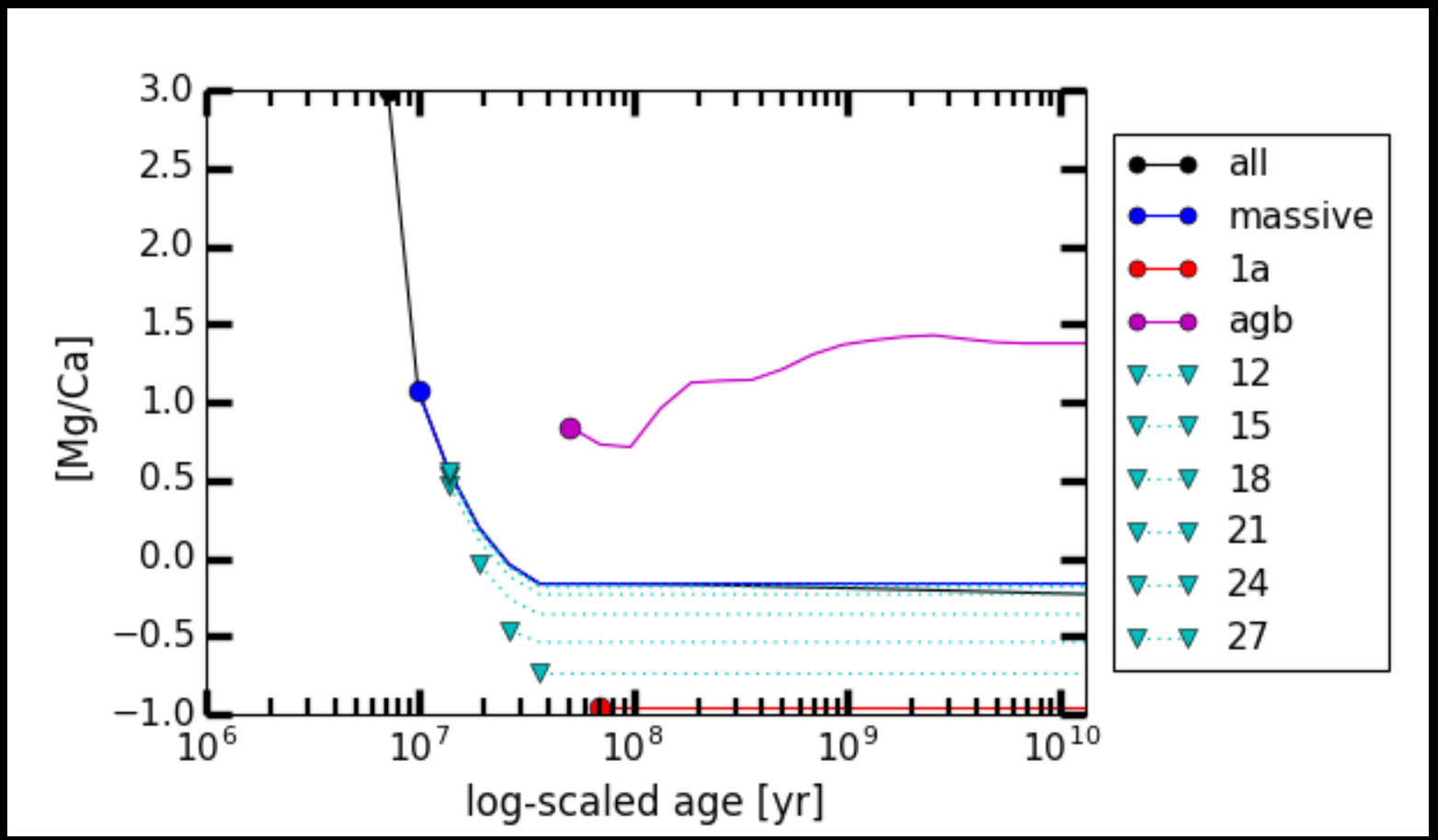
UMa II

Massive progenitor stars produce more Mg than Ca

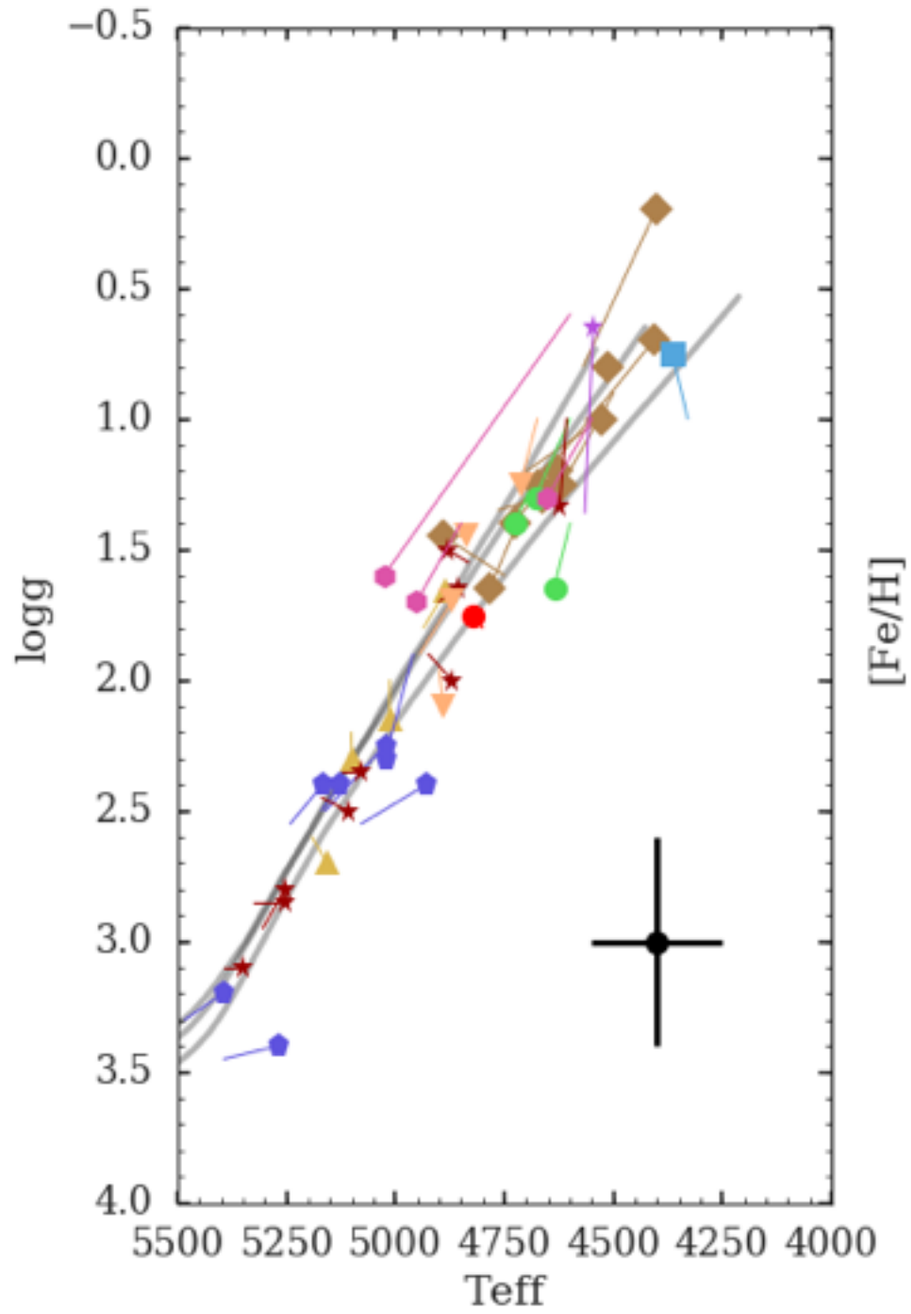


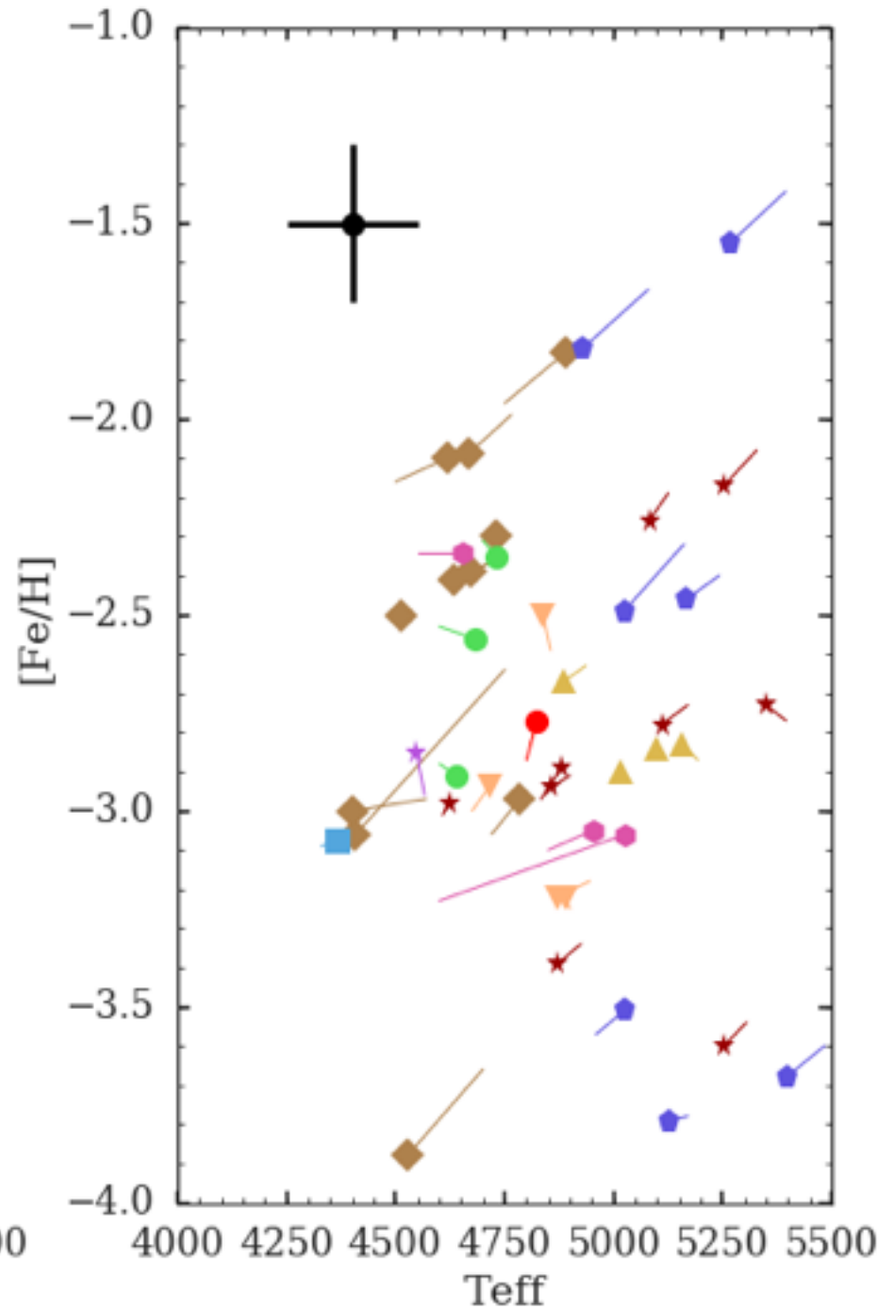


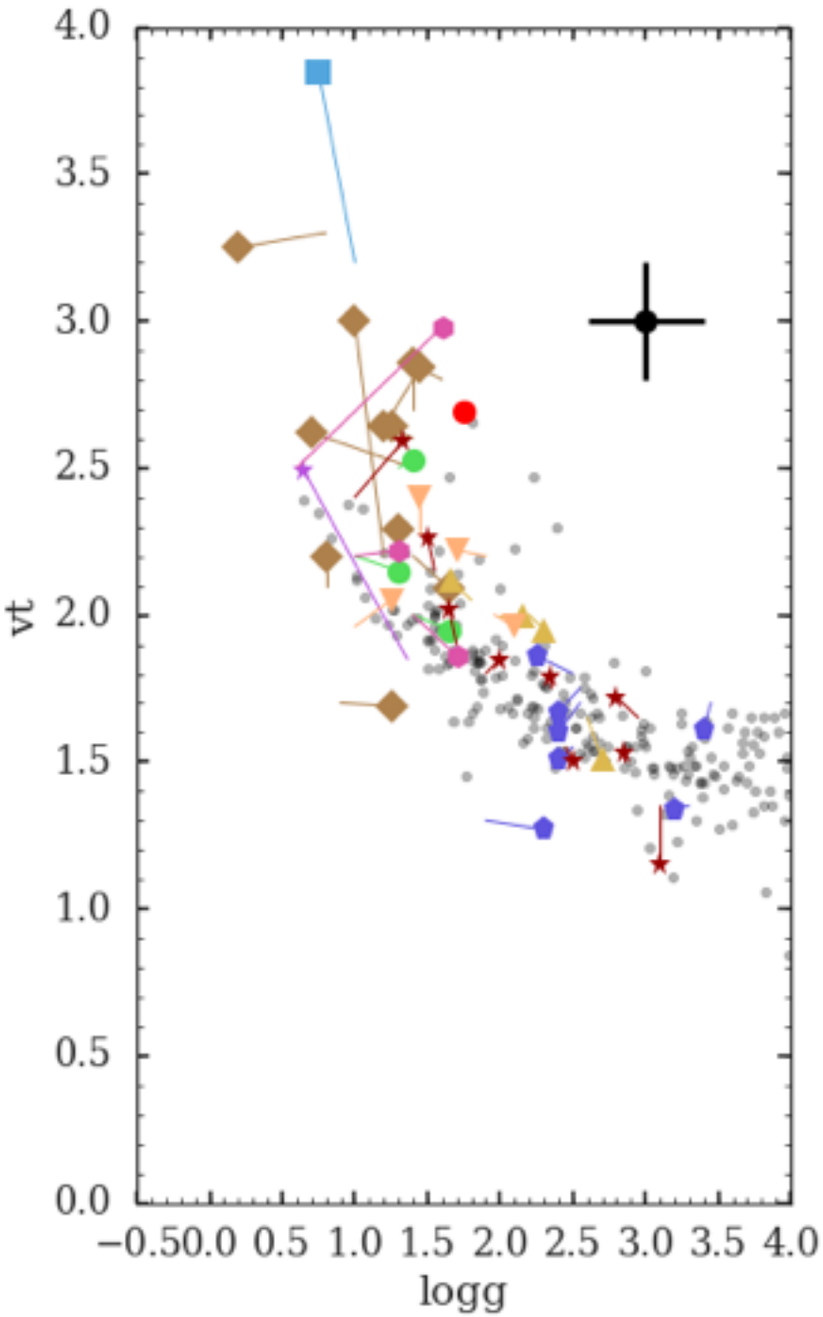
http://nugrid.github.io/NuPyCEE/


3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
[Mg/Ca]
10^6
10^7
10^8
10^9
10^{10}
log-scaled age [yr]
all
massive
1a
agb
12
15
18
21
24
27

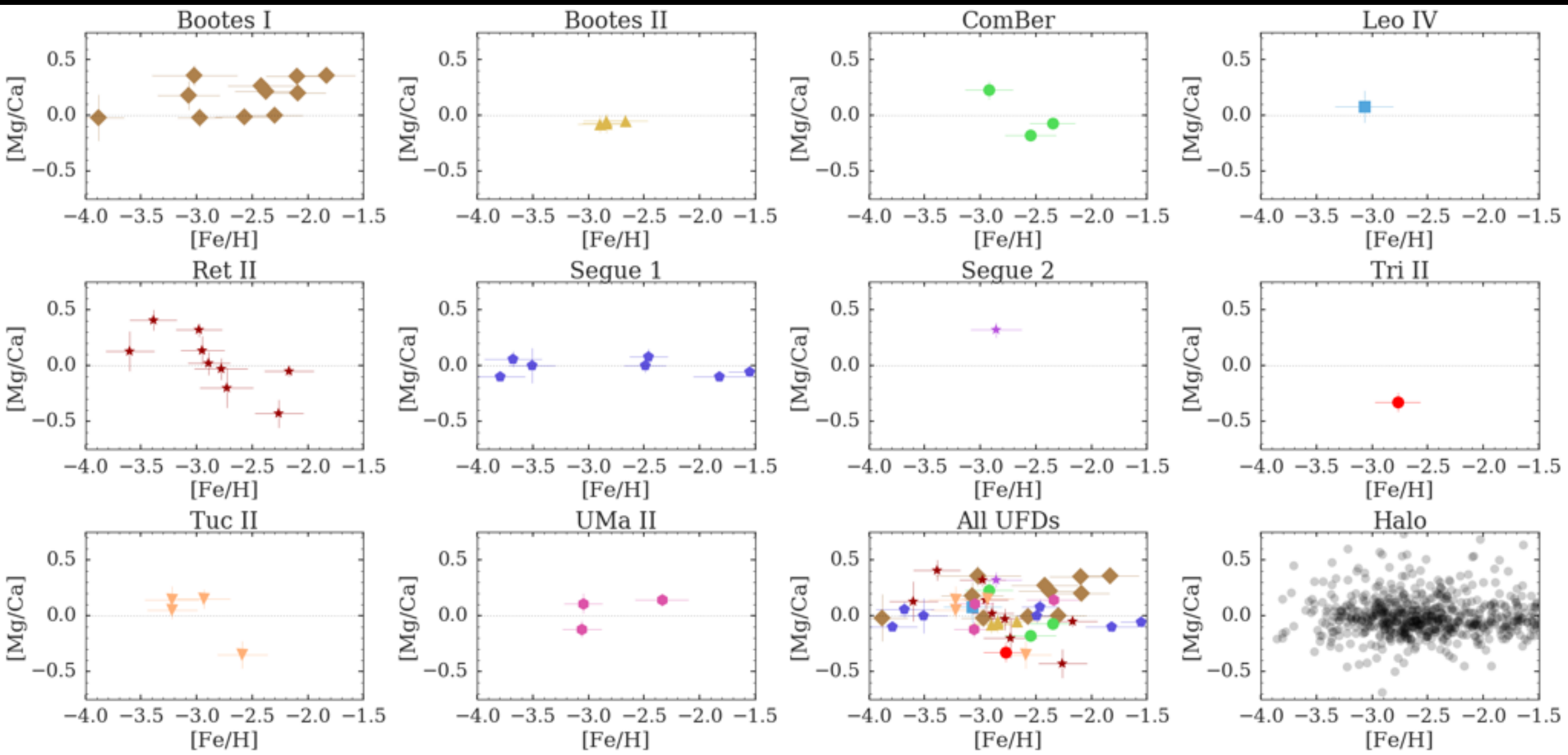
Stellar Parameters







Points = my homogeneous, line to literature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Segue 1
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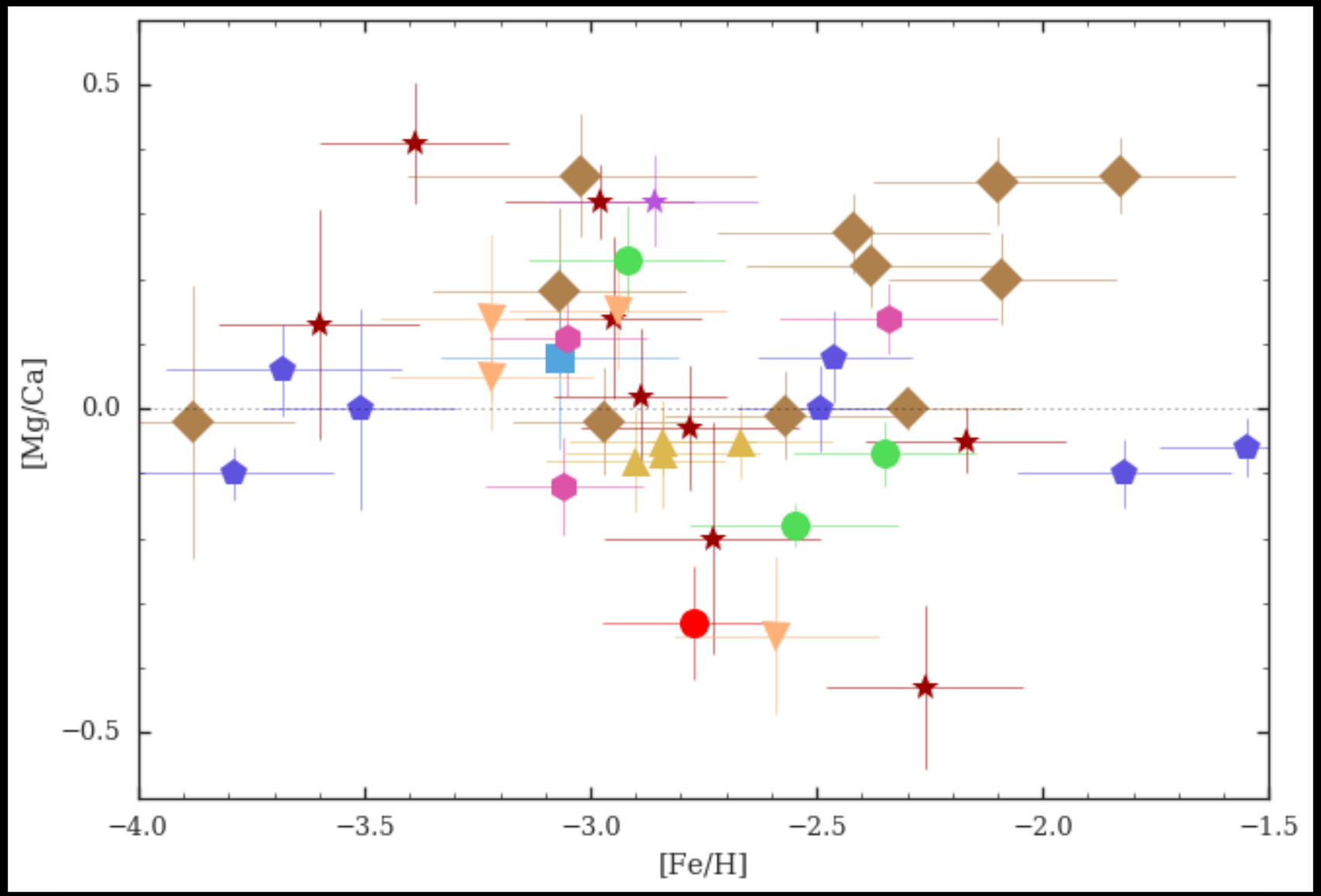
UMa II
All UFDs
Halo
[Mg/Ca]
[Fe/H]
0.5
0.0
−0.5
−4.0 −3.5 −3.0 −2.5 −2.0 −1.5

[Mg/Ca]



Bootes I
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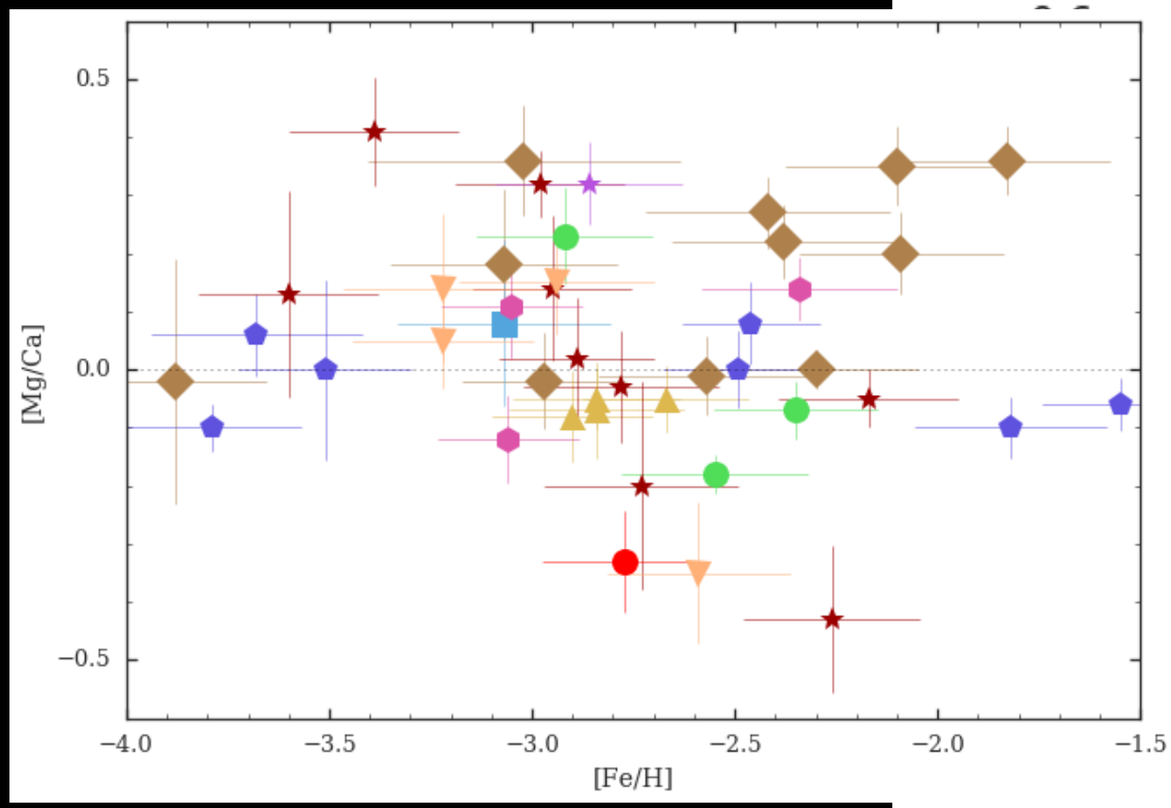

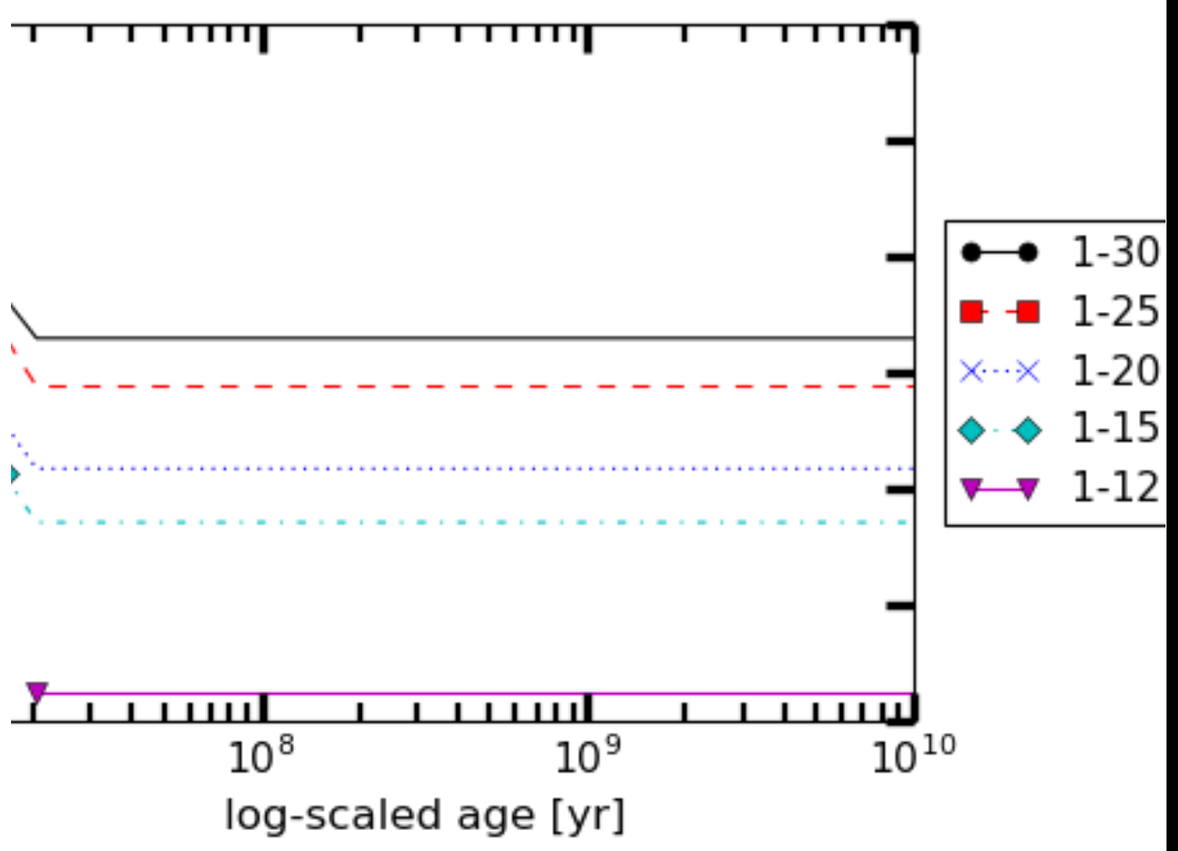

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Segue 1
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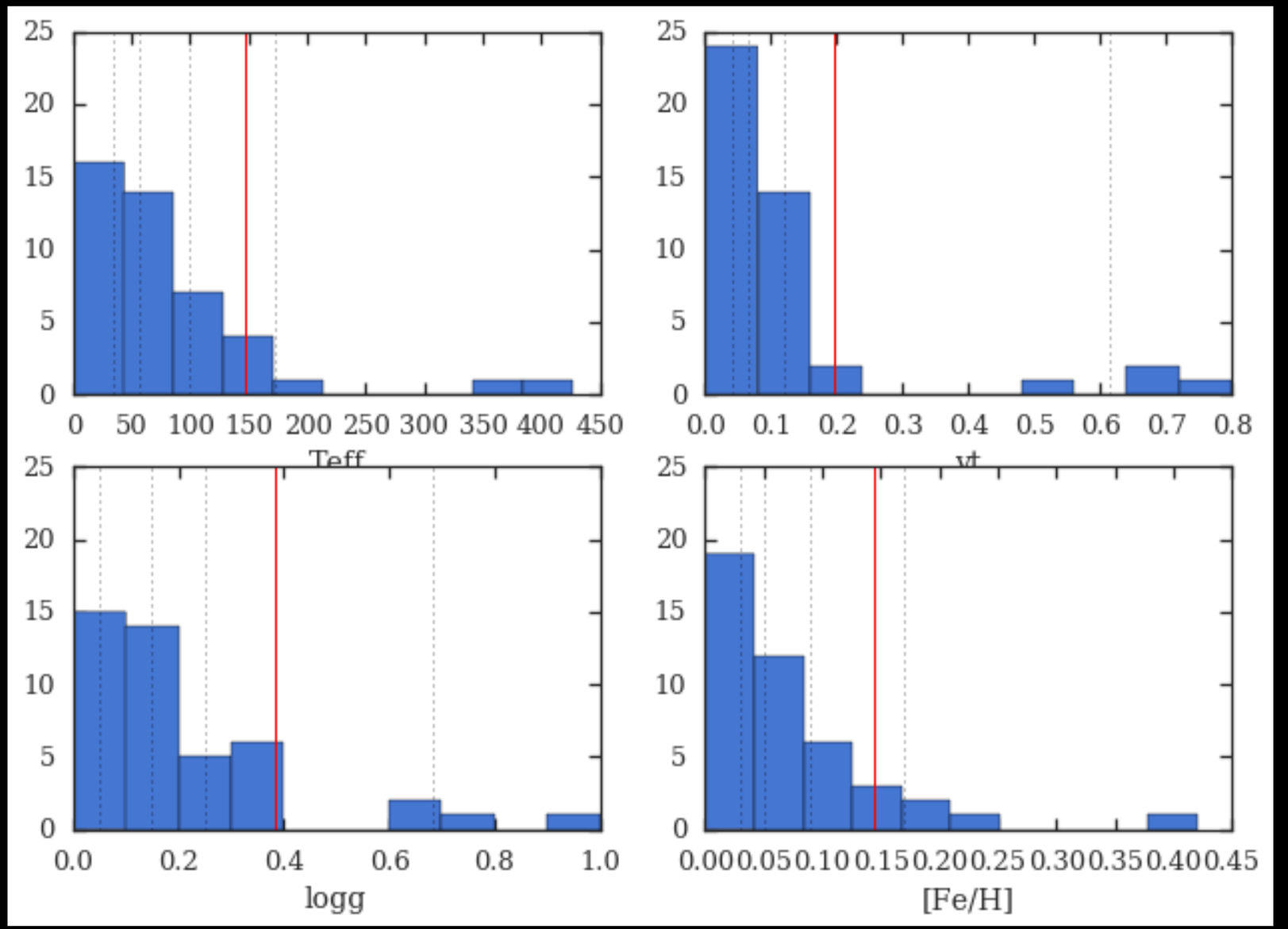
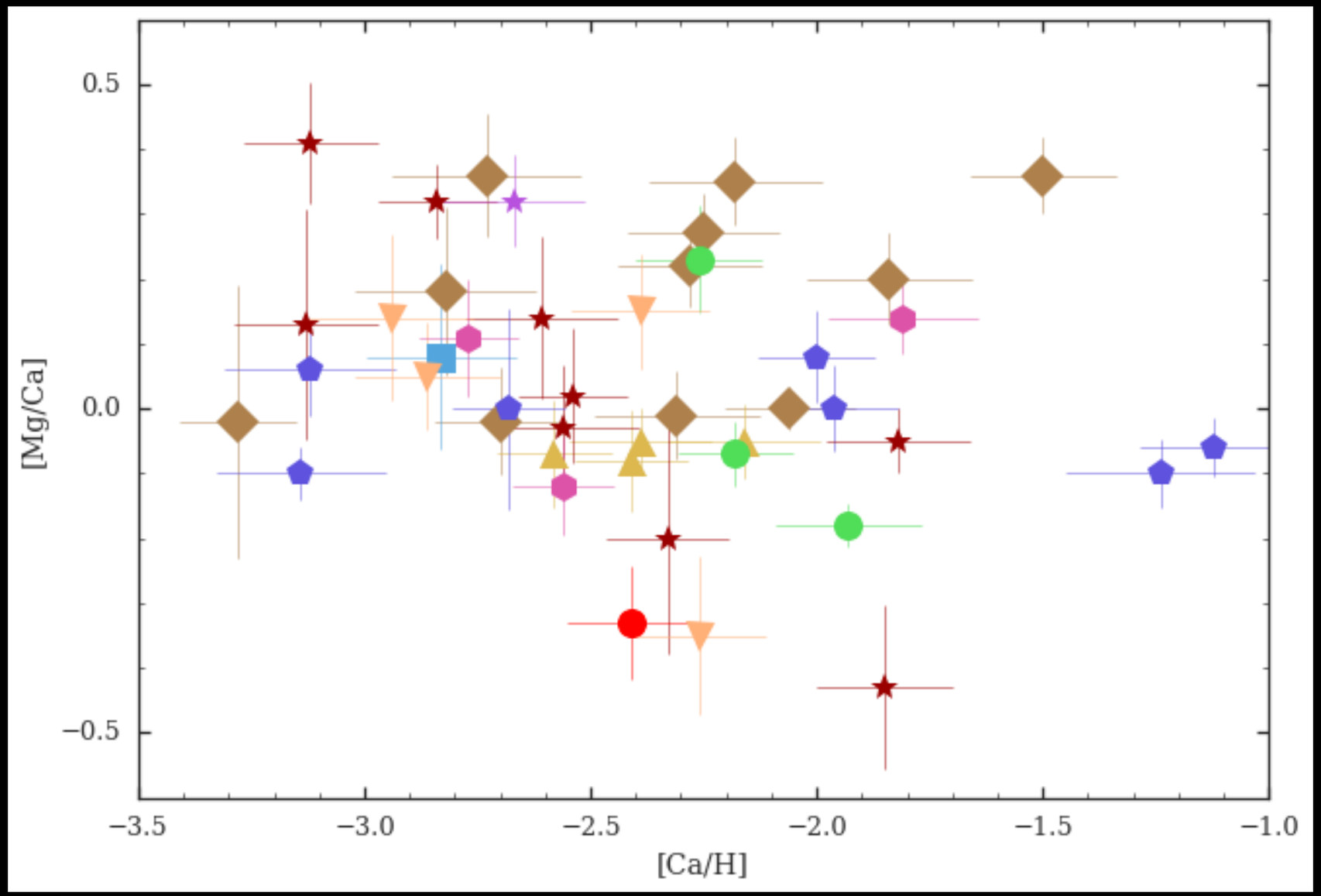

Teff
vt
logg
[Fe/H]


0.5
0.0
−0.5
[Mg/Ca]
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
[Ca/H]
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