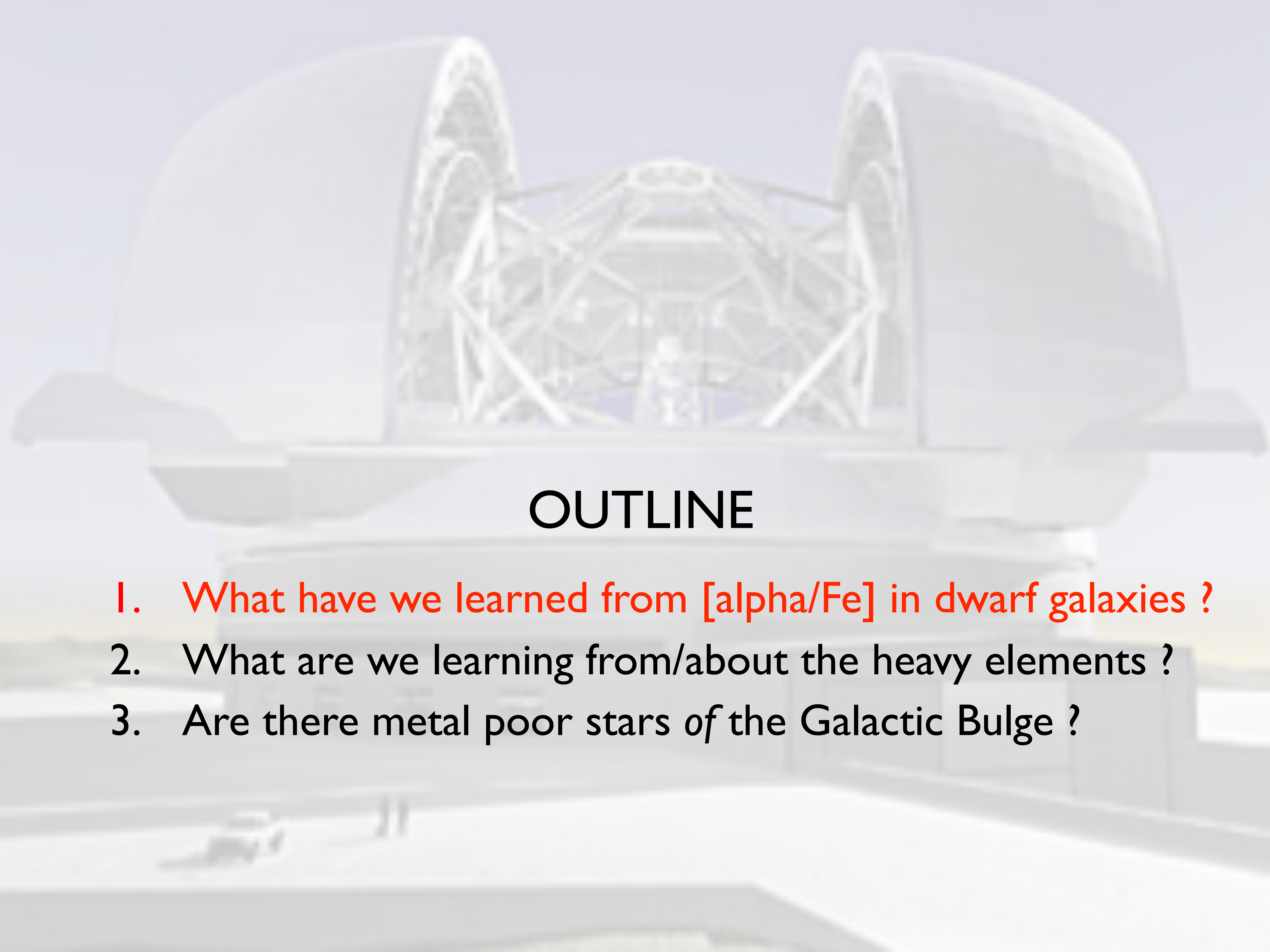
Stellar Abundances in Dwarf Galaxies, and Beyond

Kim Venn (UVic)

RASPUTIN : ESO
October 2014

OUTLINE

1. What have we learned from [alpha/Fe] in dwarf galaxies ?
2. What are we learning from/about the heavy elements ?
3. Are there metal poor stars *of* the Galactic Bulge ?



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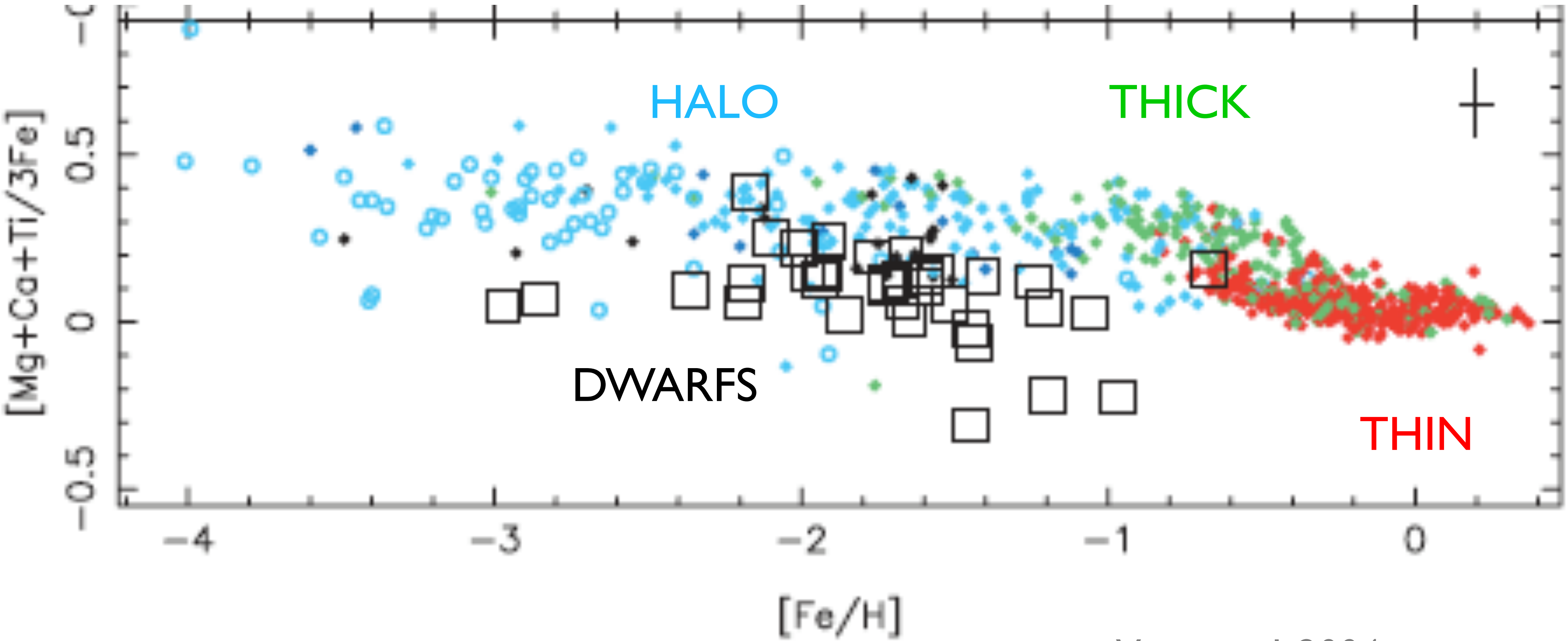
" .. The overwhelming majority of Milky Way stars, those in the Galactic thick disk and thin disk, seem to have nothing at all to do with dwarf galaxy origins."

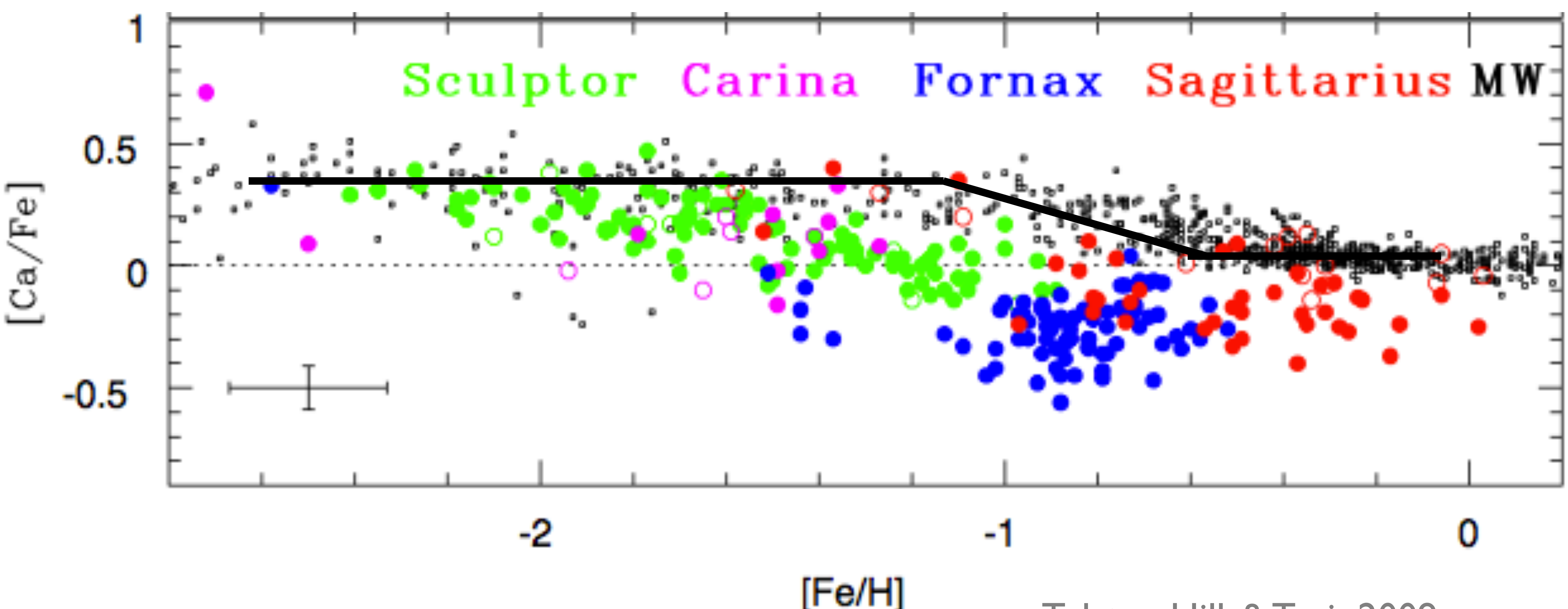
Gilmore (2013) in *Assembling the Puzzle of the Milky Way*, France.



Venn et al. 2004

Thanks to significant investments of telescope time by ESO, we now have the chemistries of many stars in individual dwarf galaxies.

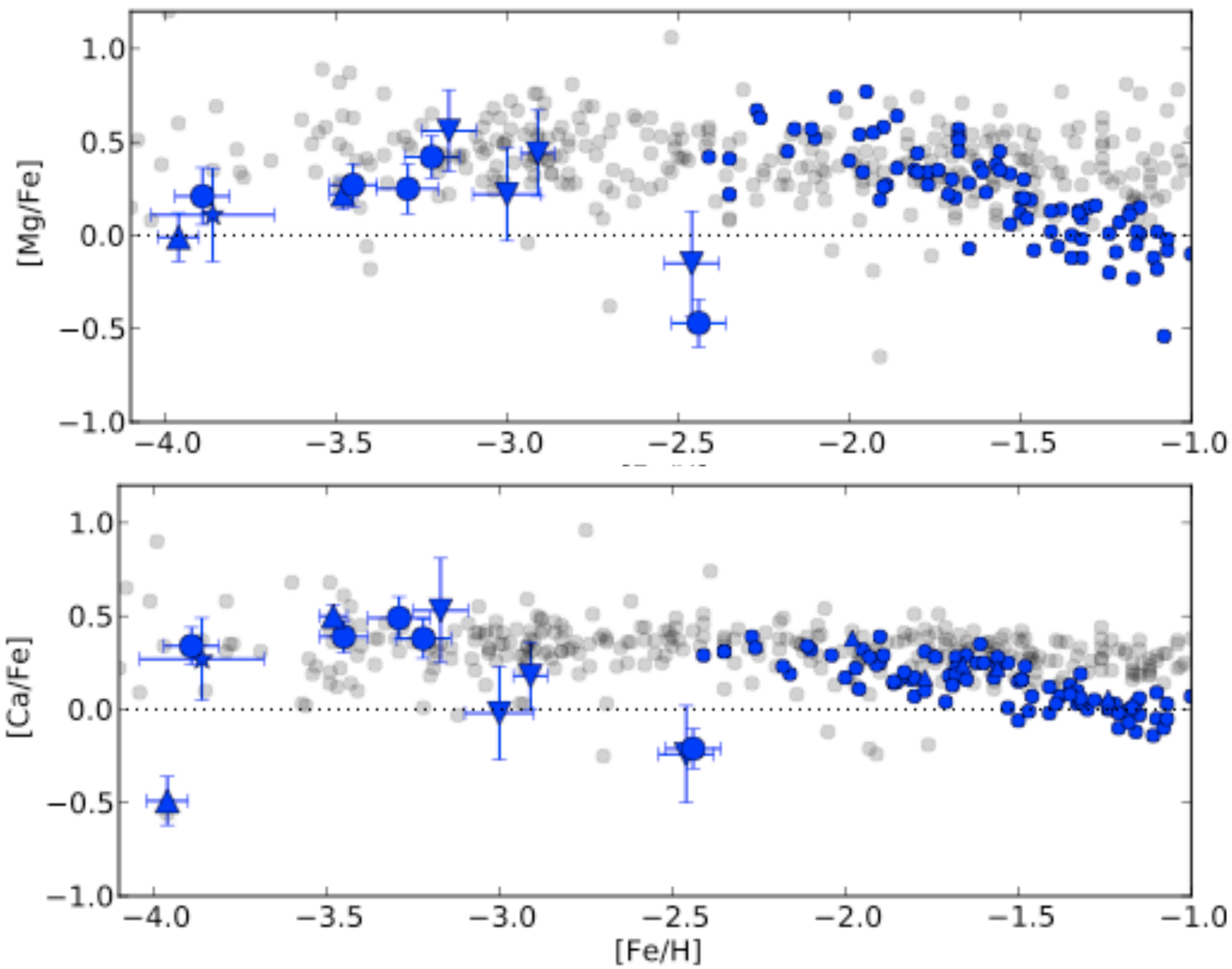
The patterns are attributed to the SFH, SFE, yields, ISM mixing, and IMF, and this dataset implies a possible correlation with dwarf galaxy mass.

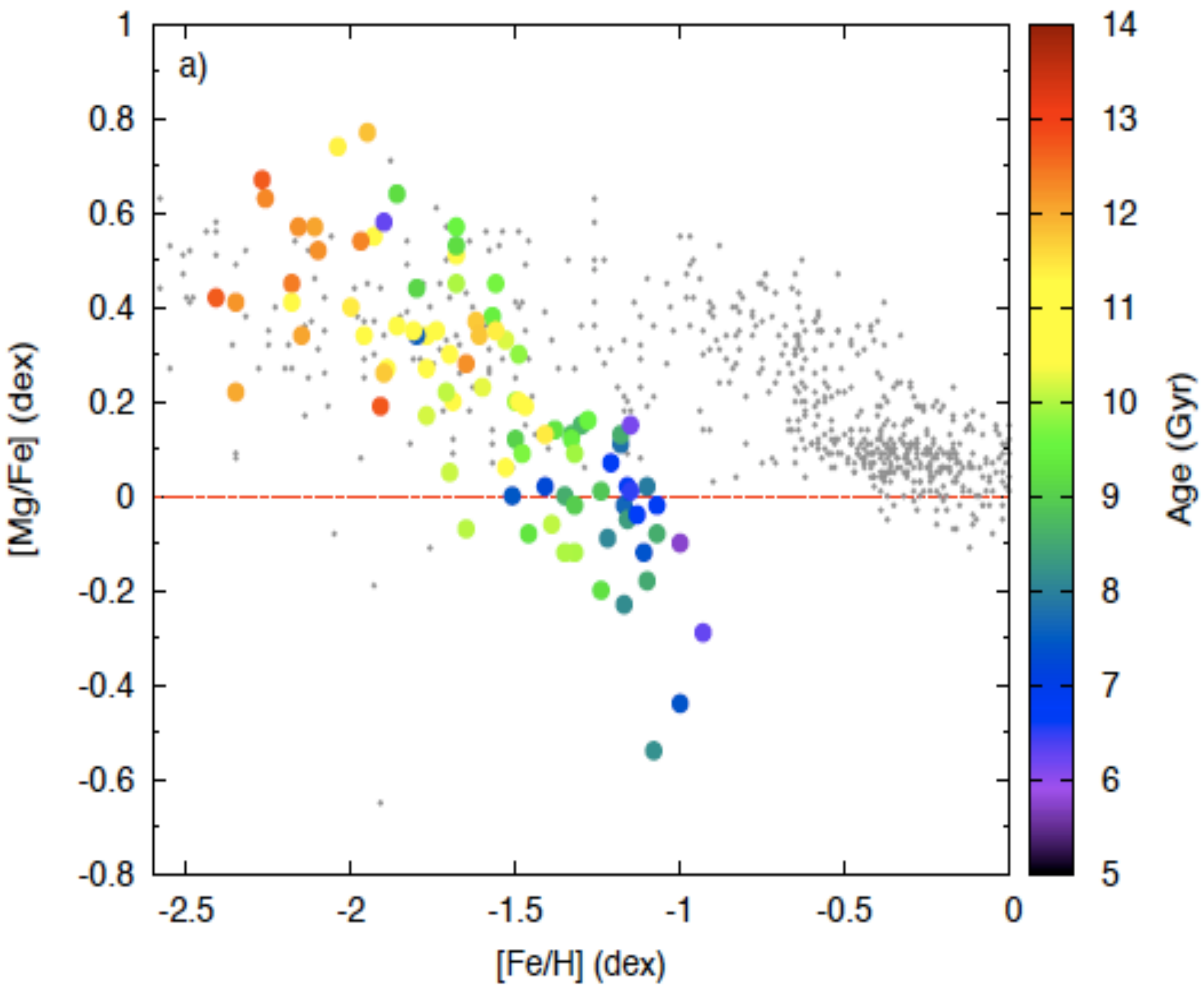


Tolstoy, Hill, & Tosi 2009

Sculptor

Most metal-poor stars with [Fe/H] < -2.0 are similar (with outliers).
Sculptor stars with [Fe/H] > -2.0 seem to have a clean age gradient.



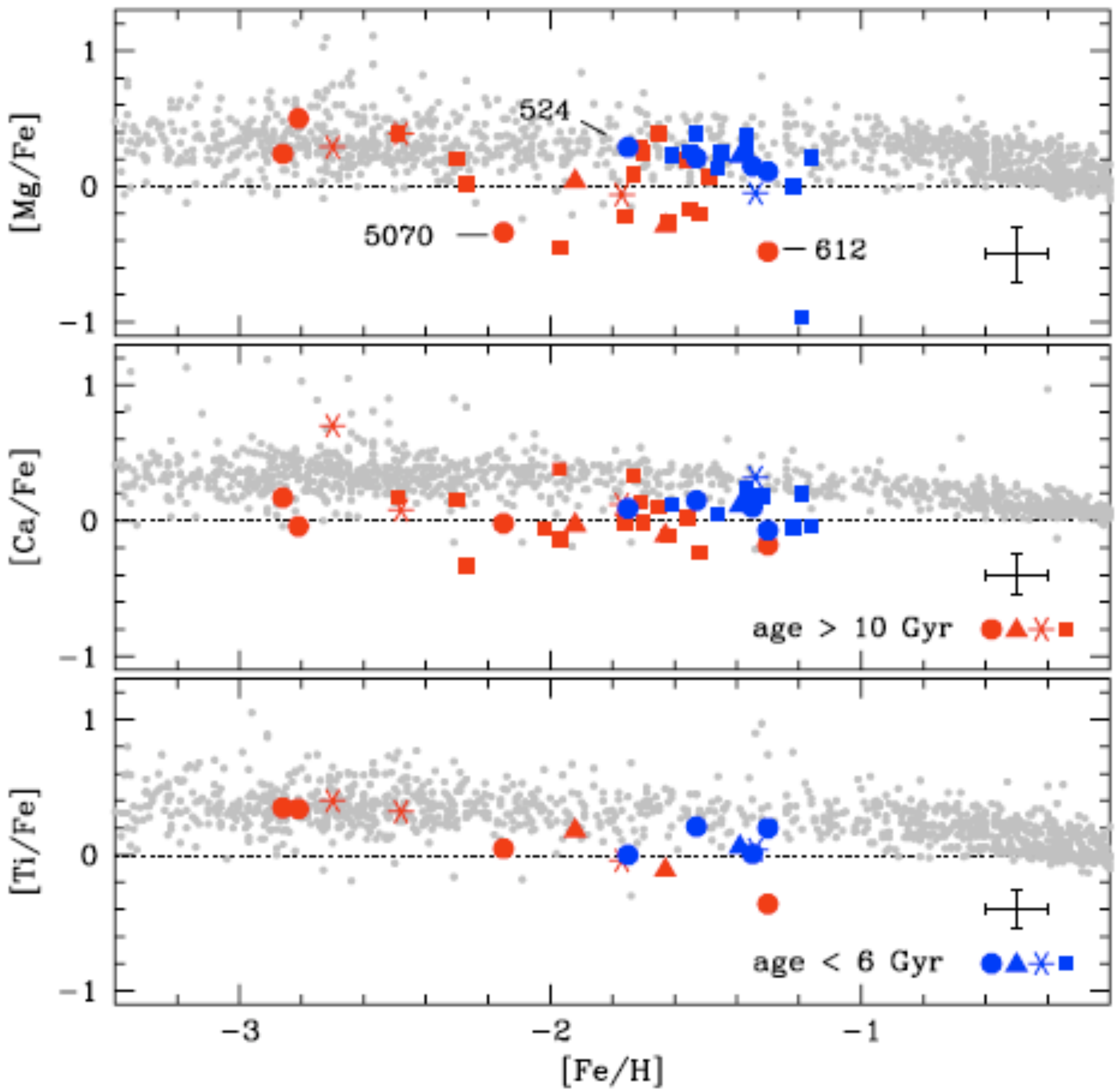


Jablonka et al. 2014
+ Starkenburg et al. 2013; Tafelmeyer et al. 2010
+ Frebel et al. 2010; Tolstoy, Hill, & Tosi 2009

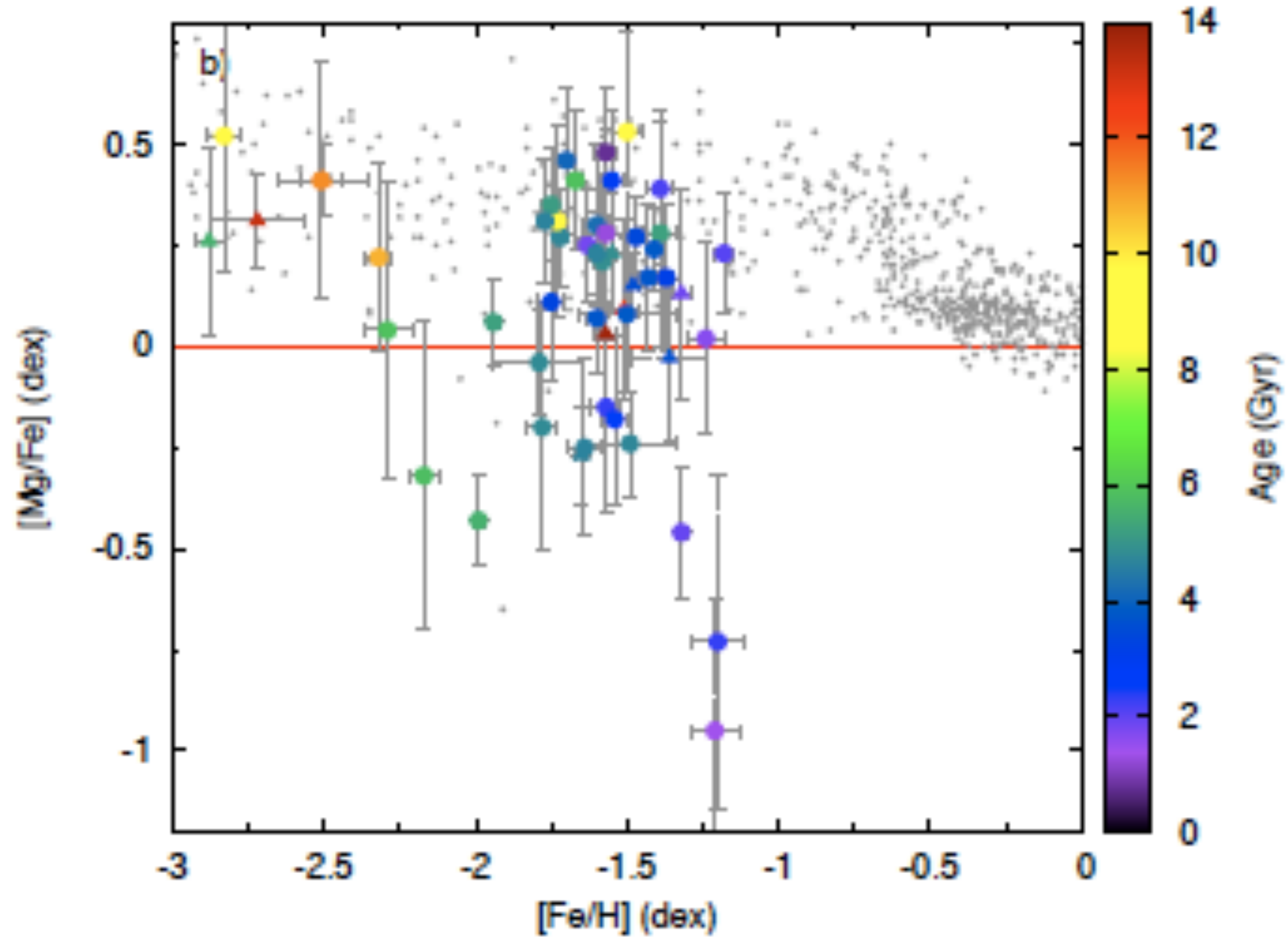
de Boer et al. 2012
+ Tolstoy et al. 2009
Ages from CMD and chemistry

Carina

Similarly high [alpha/Fe] ratios in metal-poor stars (with outliers).
Age-metallicity gradient is less clear, doubled?



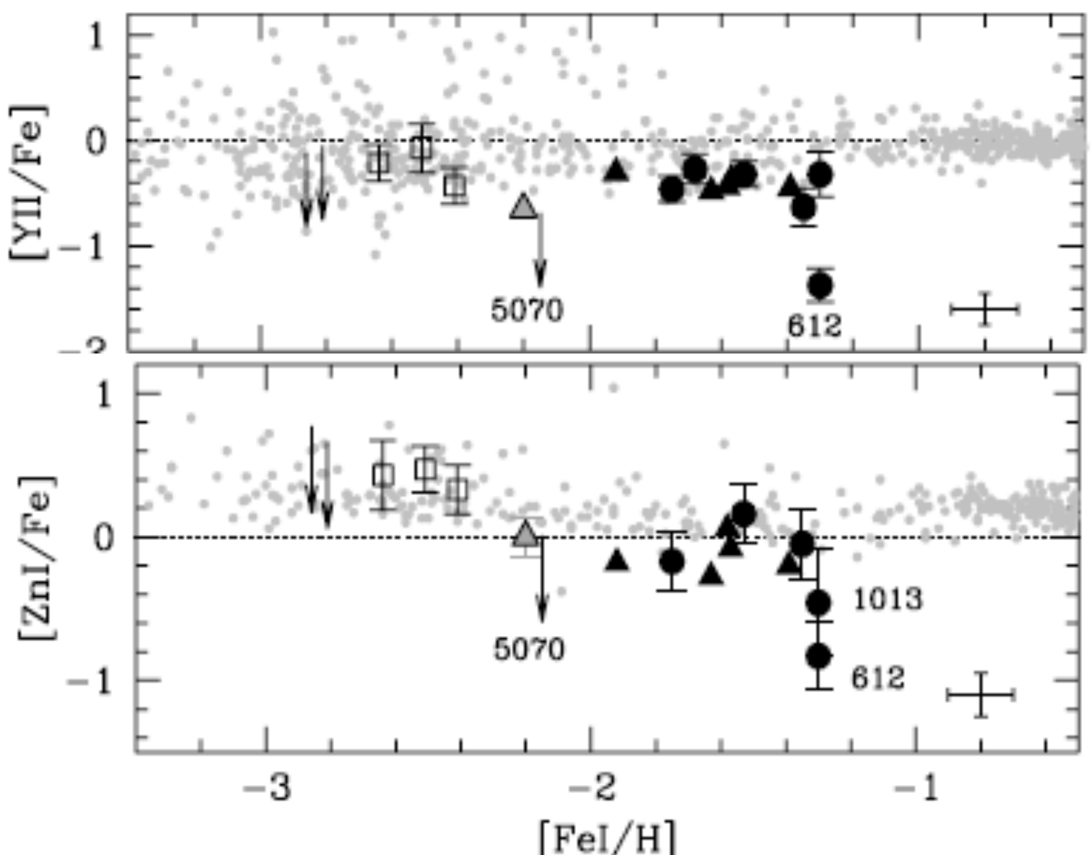
Venn et al. 2012, Lemasle et al. 2012
Fabrizio et al. TALK

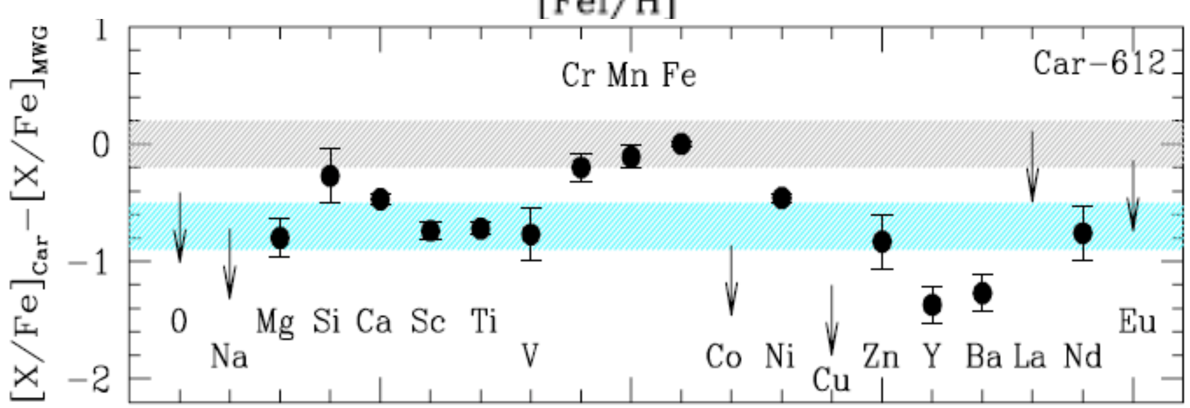


de Boer et al. 2014
+ Lemasle et al. 2012
+ Venn et al. 2012
+ Koch et al. 2008
+ Shetrone et al. 2003

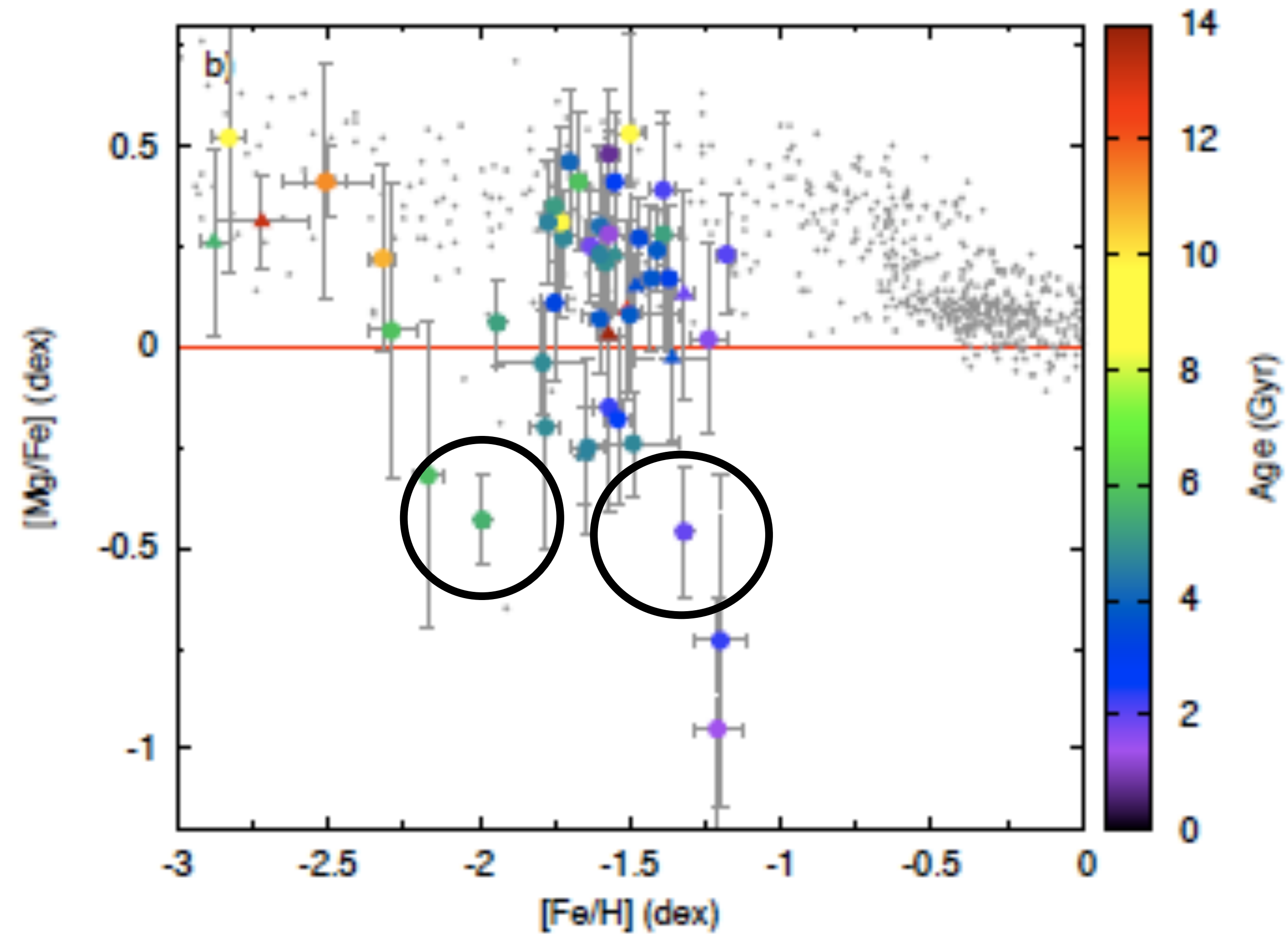
Carina

Outliers consistent with inhomogenenous mixing (iron pockets)
Age-metallicity relationship on the plateau is less clear.





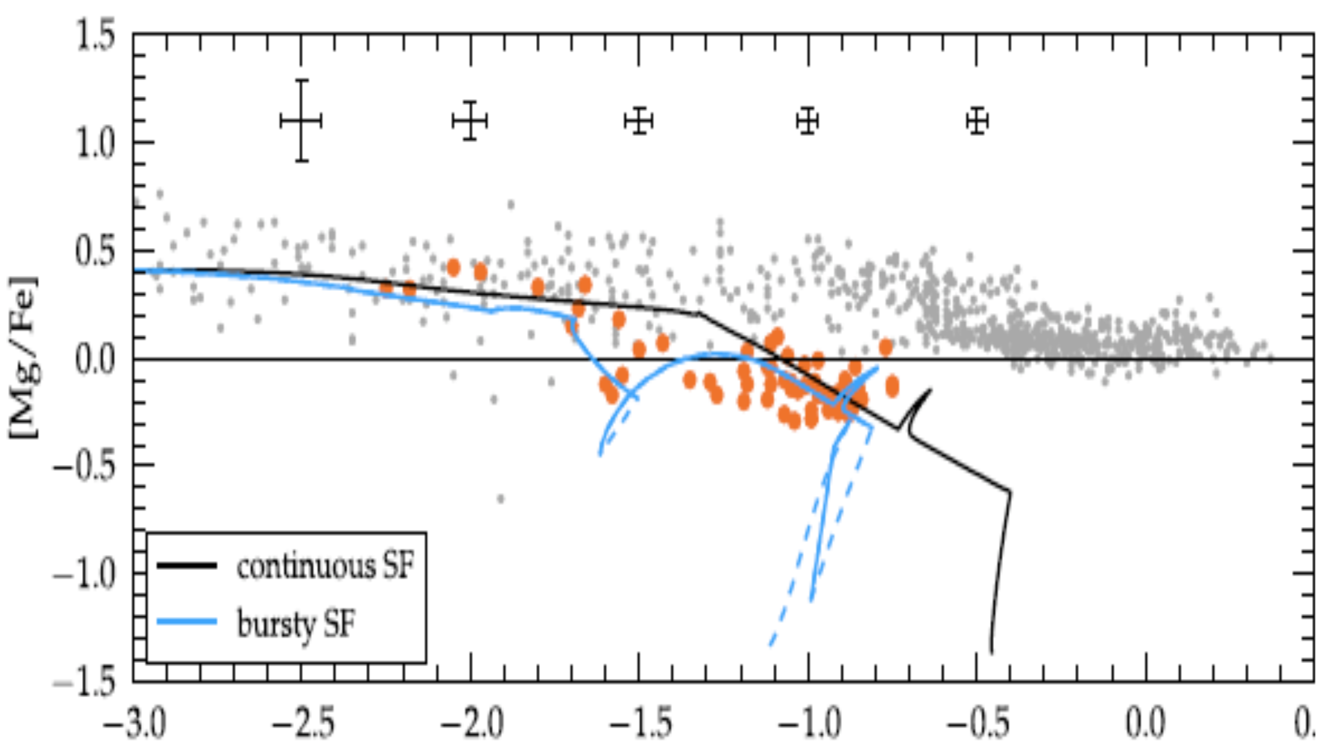
Venn et al. 2012



de Boer et al. 2014
+ Lemasle et al. 2012
+ Venn et al. 2012
+ Koch et al. 2008
+ Shetrone et al. 2003

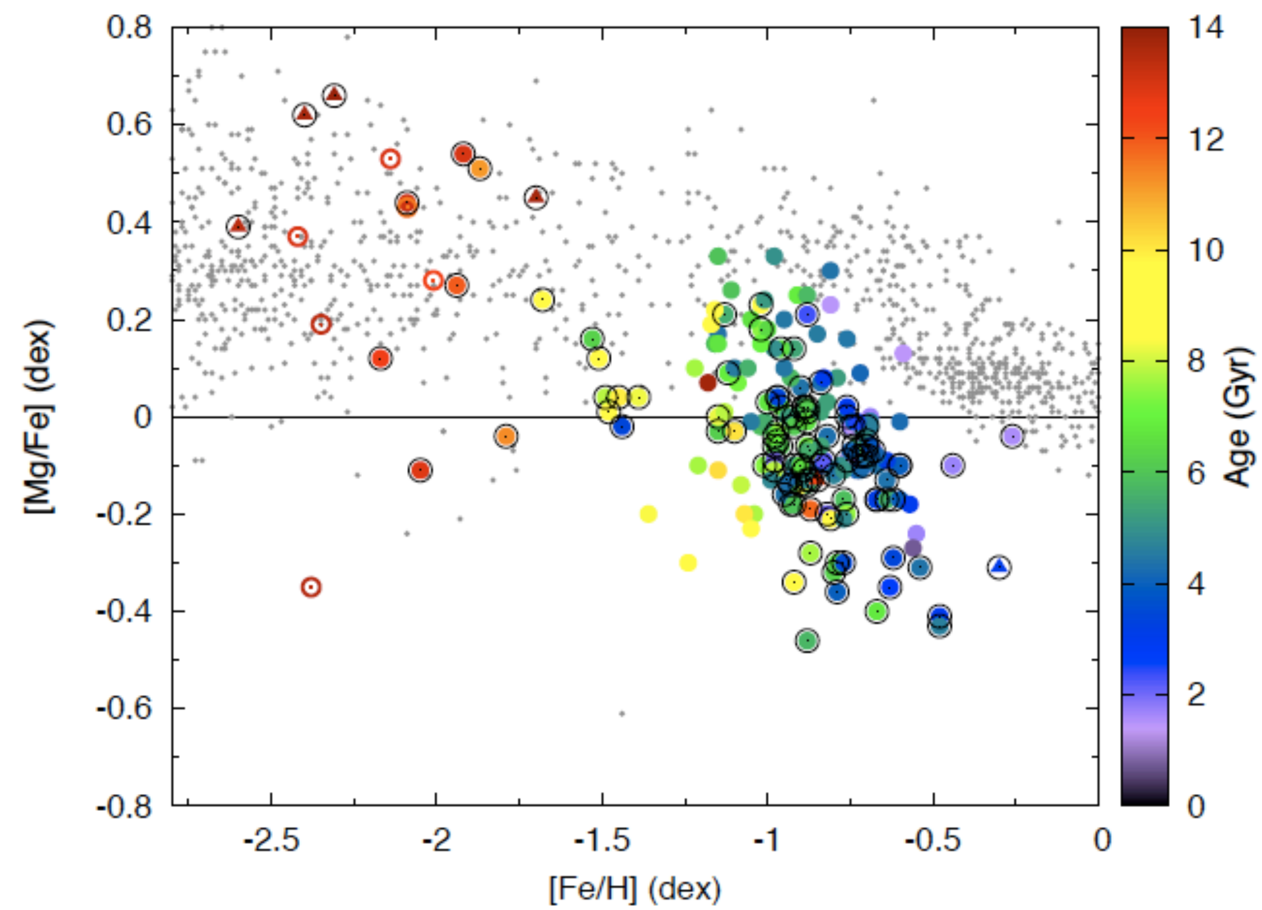
Fornax

Two independent studies show similar abundance patterns,
Identification of the plateau and knee is less clear with more data.



Hendricks et al. 2014

See Hendricks talk



Lemasle et al. 2014

+ Letarte et al. 2010, 2006

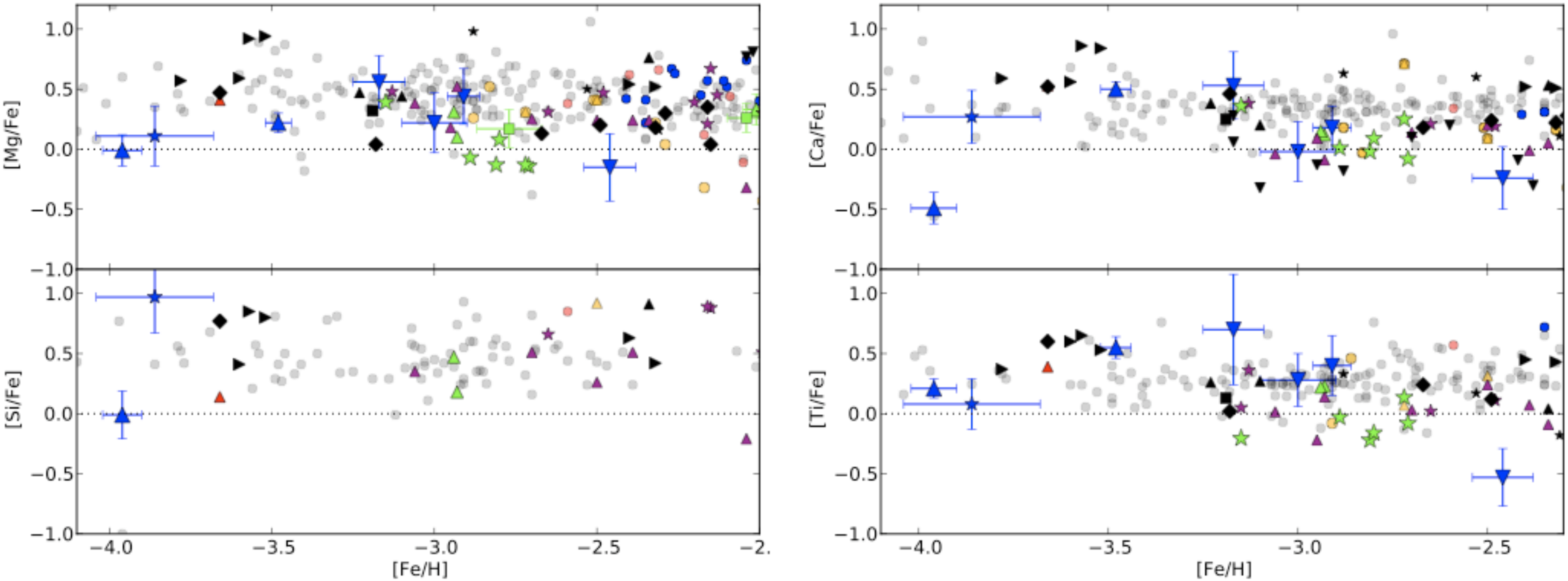
+ Tafelmeyer et al. 2010

+ Kirby et al. 2010

+ Larsen et al. 2012

All hosts

Plateau & dispersion in all dwarfs, [Fe/H] < -2.5 (*Jablonka et al. 2014*)



Sculptor, Tolstoy, Hill, Tosi, 2009; Tafelmeyer 2010; Frebel et al., 2010; Starkenburg et al. 2013;

Sextans, Shetrone et al. 2001; Aoki et al. 2009; Tafelmeyer 2010

Fornax, Tafelmeyer et al 2010 Letarte et al. 2010

Carina, Shetrone et al. 2013; Koch et al. 2008; Venn et al. 2012; Lemasle et al. 2012

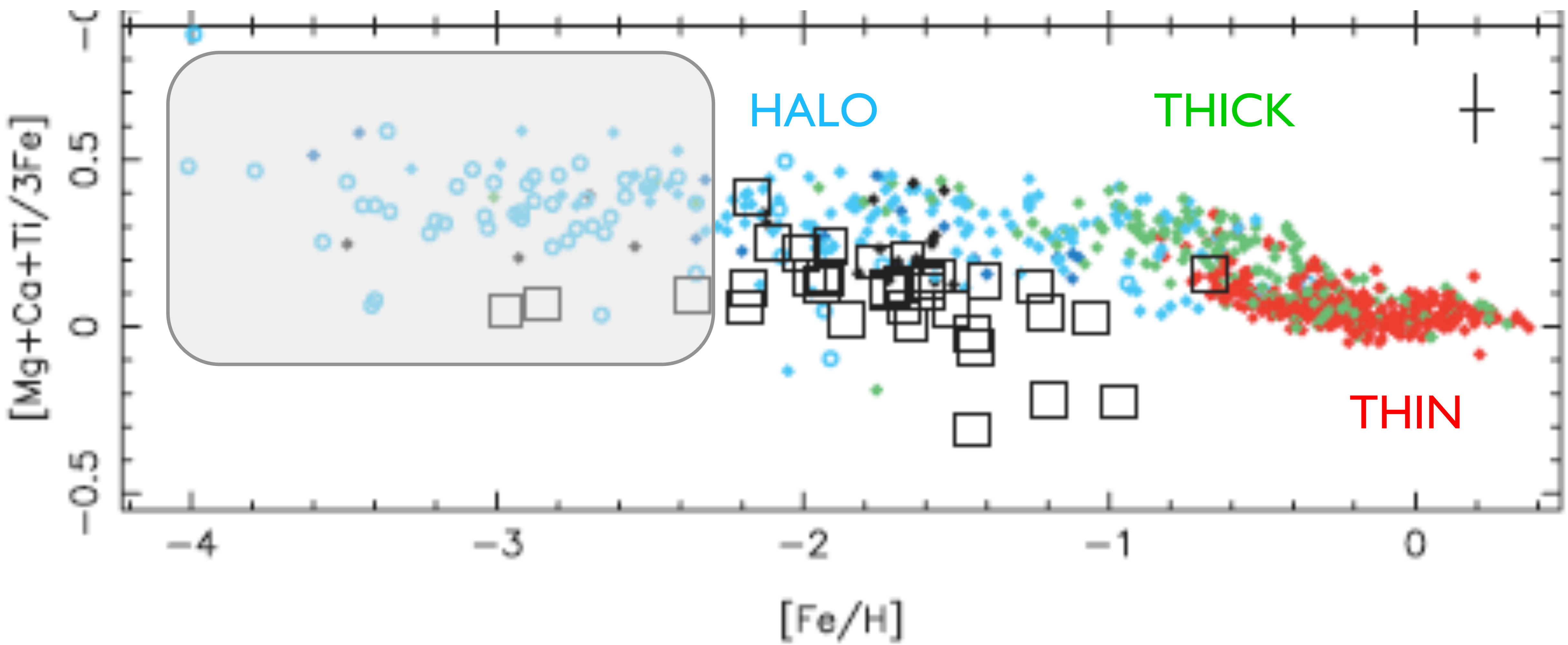
Leo IV Hercules UMa II Segue I Comber I Boötes Koch et al 2008; Aden et al. 2011 Norris et al. 2010; Simon et al. 2010 Frebel et al.2010, 2014

Draco & UMi Shetrone et al. 2001; Fulbright et al. 2004; Cohen & Huang 2009;2010; Sadakane et al. 2004;

MW Honda et al. 2004; Cayrel et al. 2004; Spite et al. 2005; Aoki et al. 2005; Cohen et al. 2013, 2006, 2004; Spite et al. 2006; Aoki et al. 2007; Lai et al. 2008; Yong et al. 2013; Ishigaki et al. 2013

Below [Fe/H] = -2.5, the plateau seems consistent in [alpha/Fe] though the dispersion is larger in dwarf galaxies than the MW,

inhomogeneous mixing in dwarfs, and
possibly a break down in age-metallicity at early times.



Note that Yong et al. 2013 and Aoki et al. 2013 show smaller dispersions for MW stars, too

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OUTLINE

1. What have we learned from [alpha/Fe] in dwarf galaxies ?
   - knee is a test of SFH, likely related to host mass
   - evidence for inhomogeneous mixing
   - breakdown(s) in age-metallicity relationship

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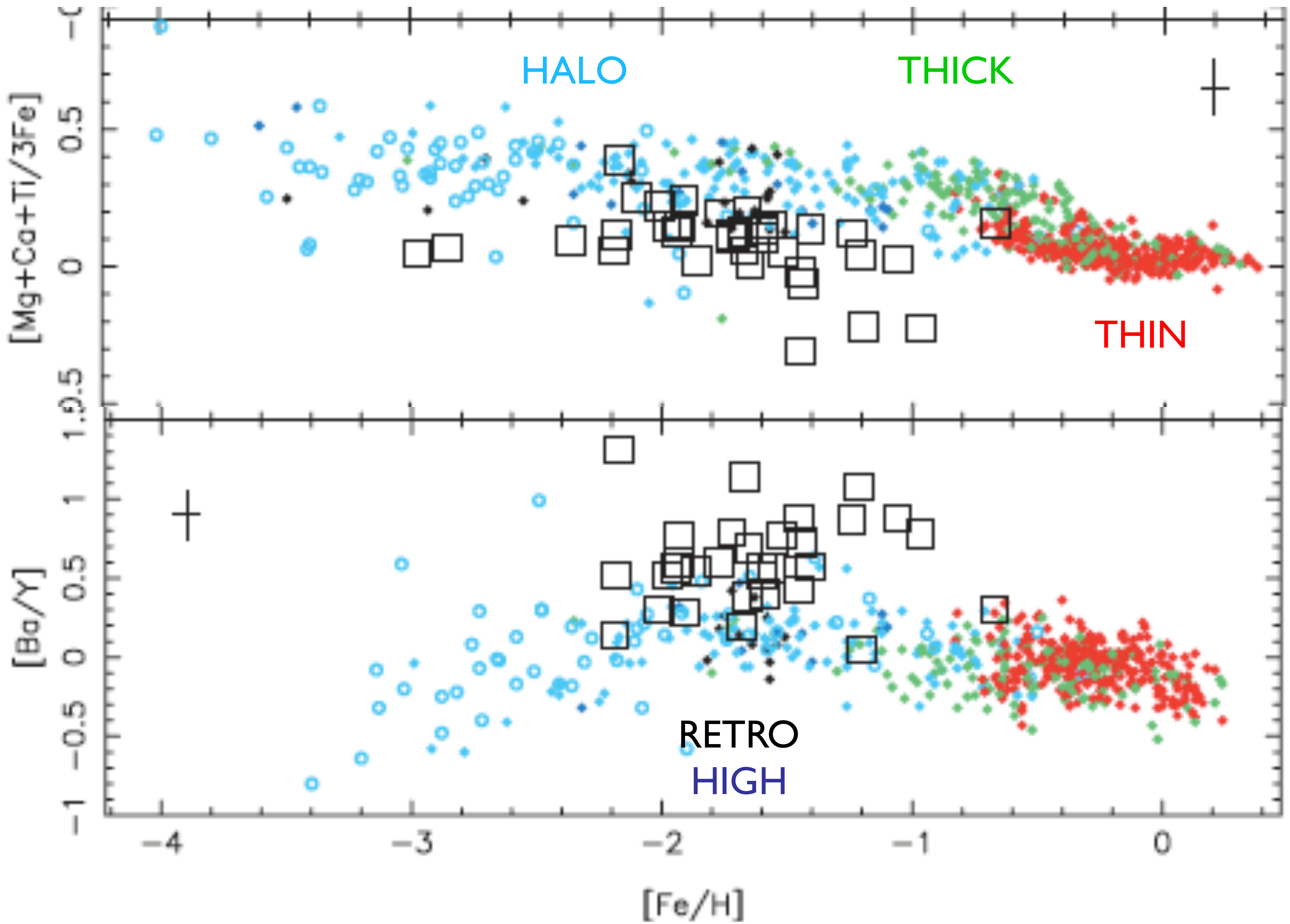
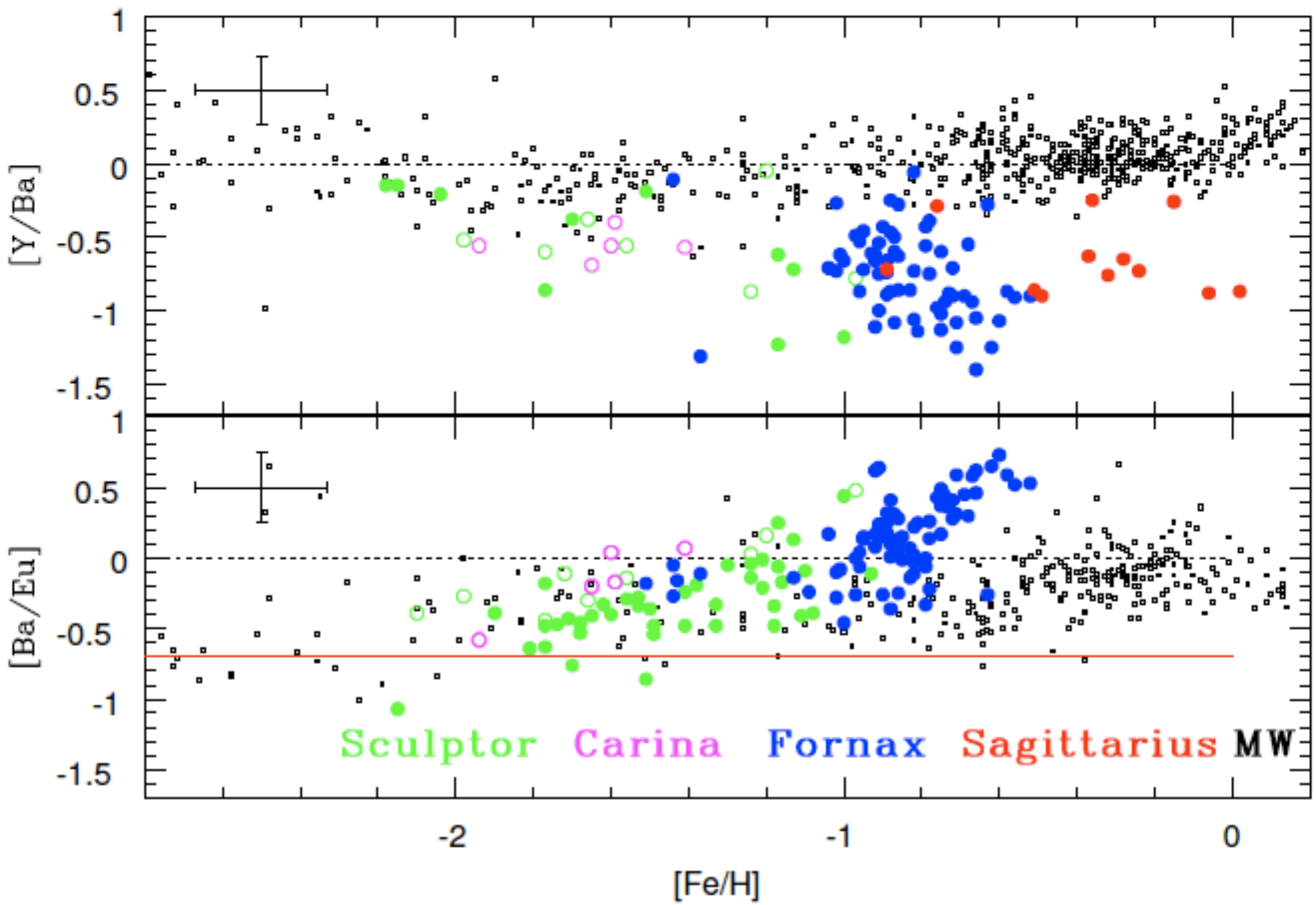


Venn et al. 2004

Higher-order elements above [Fe/H] ~ -2
also separate stars in dwarf galaxies from the MW

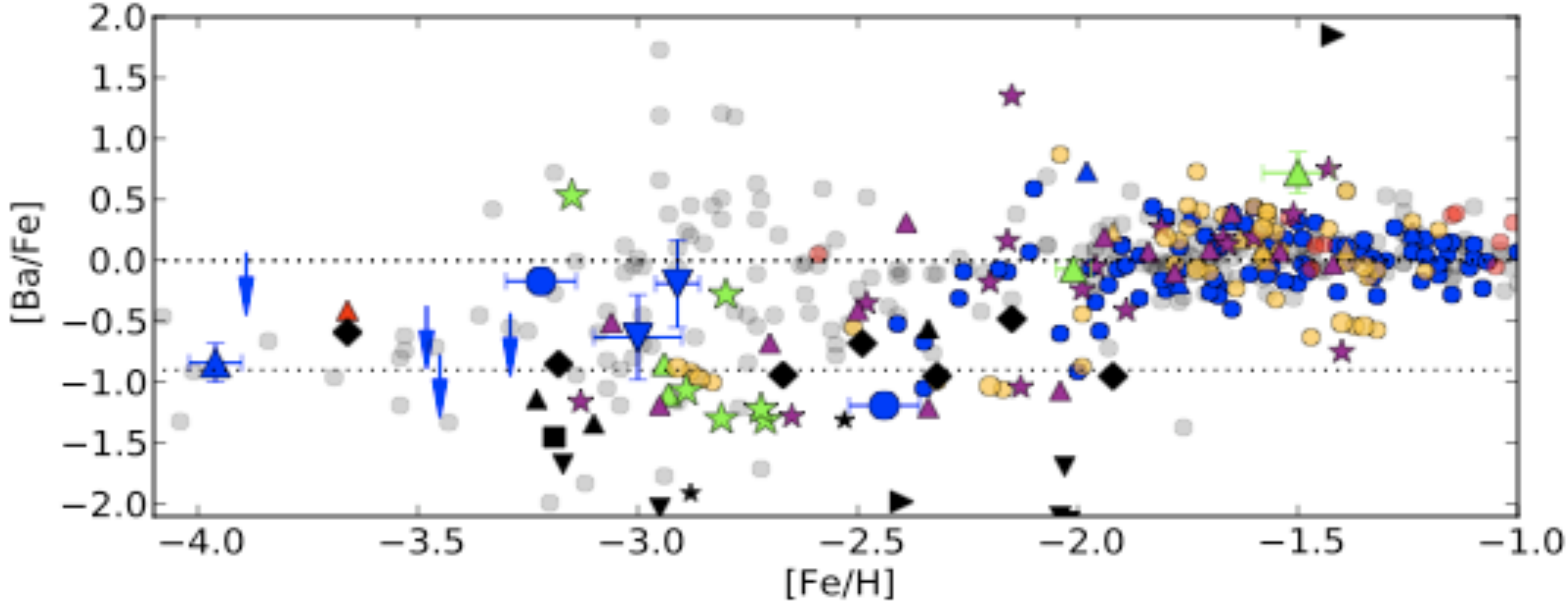


Tolstoy, Hill, & Tosi 2009

Heavy Elements

What about below [Fe/H] ~ -2 : see large dispersions in Ba

(*Jablonka et al. 2014*)



Sculptor, Tolstoy, Hill, Tosi, 2009; Tafelmeyer 2010; Frebel et al., 2010; Starkenburg et al. 2013;

Sextans, Shetrone et al. 2001; Aoki et al. 2009; Tafelmeyer 2010

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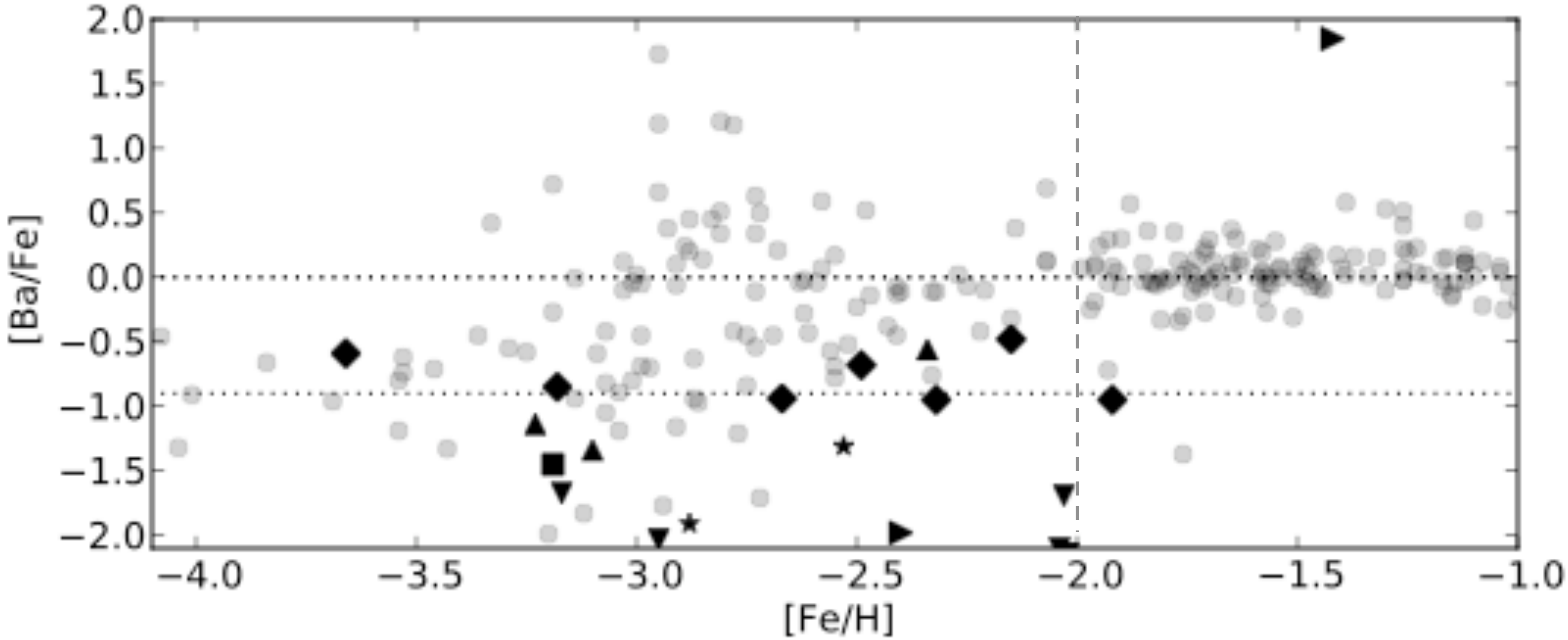
Heavy Elements

Except in the UFDs, which remain low

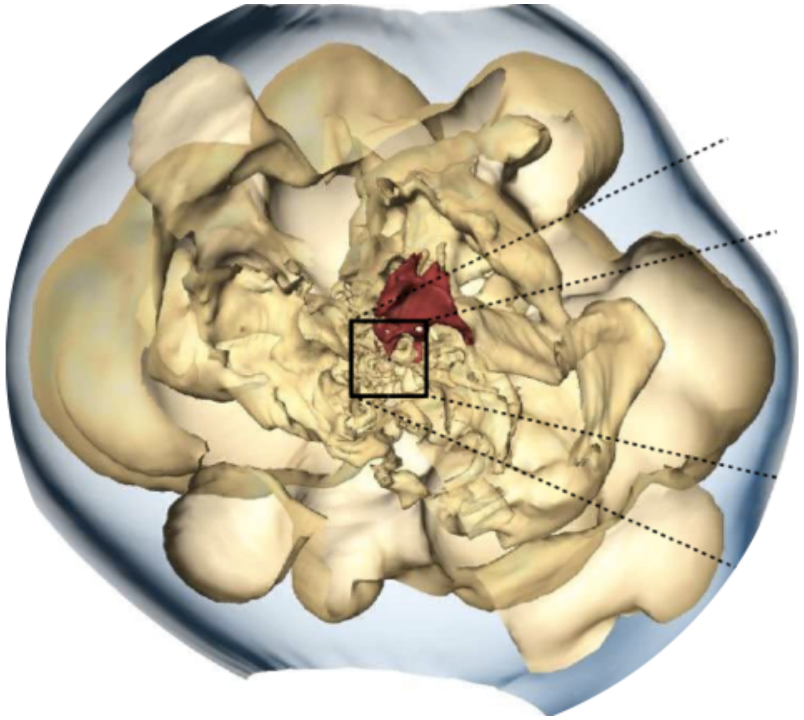


Stars in the UFD galaxies do not appear to have been enriched by a previous generation of AGB stars, *nor are r-process rich stars found.*

Do stars in UFD galaxies show any evidence for r-process enrichment?

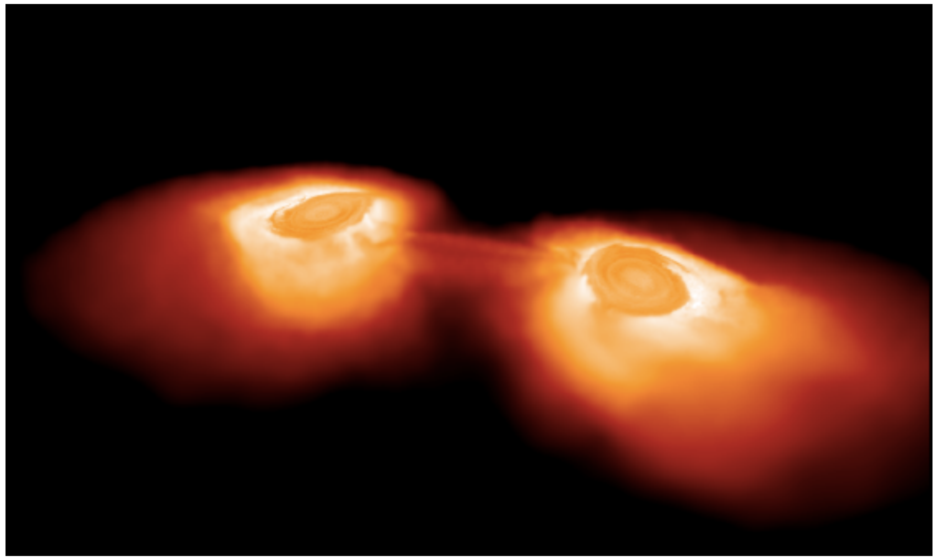
r-process sites

Core-collapse supernovae
(in particular proto-NS wind)



Woosley & Janka 2005; Martinez-Pinedo et al. 2012; Roberts et al. 2012; Fischer et al. 2012; Wanajo et al. 2011; Wanajo 2013

Compact binary mergers
(NS-NS and BH-NS mergers)

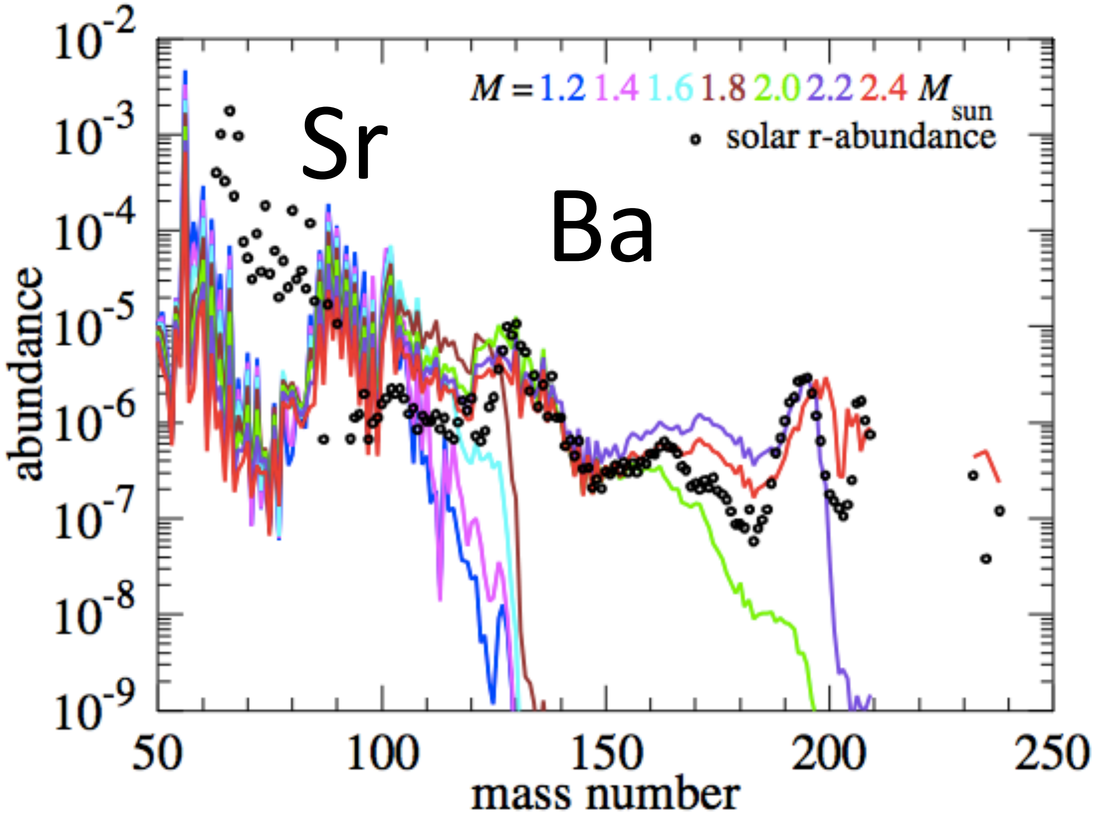


Lattimer & Schramm 1974; Symbalisty & Schramm 1982; Eichler et al. 1989; Meyer 1989; Freiburghaus et al. 1999 ; Rosswog et al. 2012; Bauswein et al. 2013; Korobkin et al. 2014

r-process sites

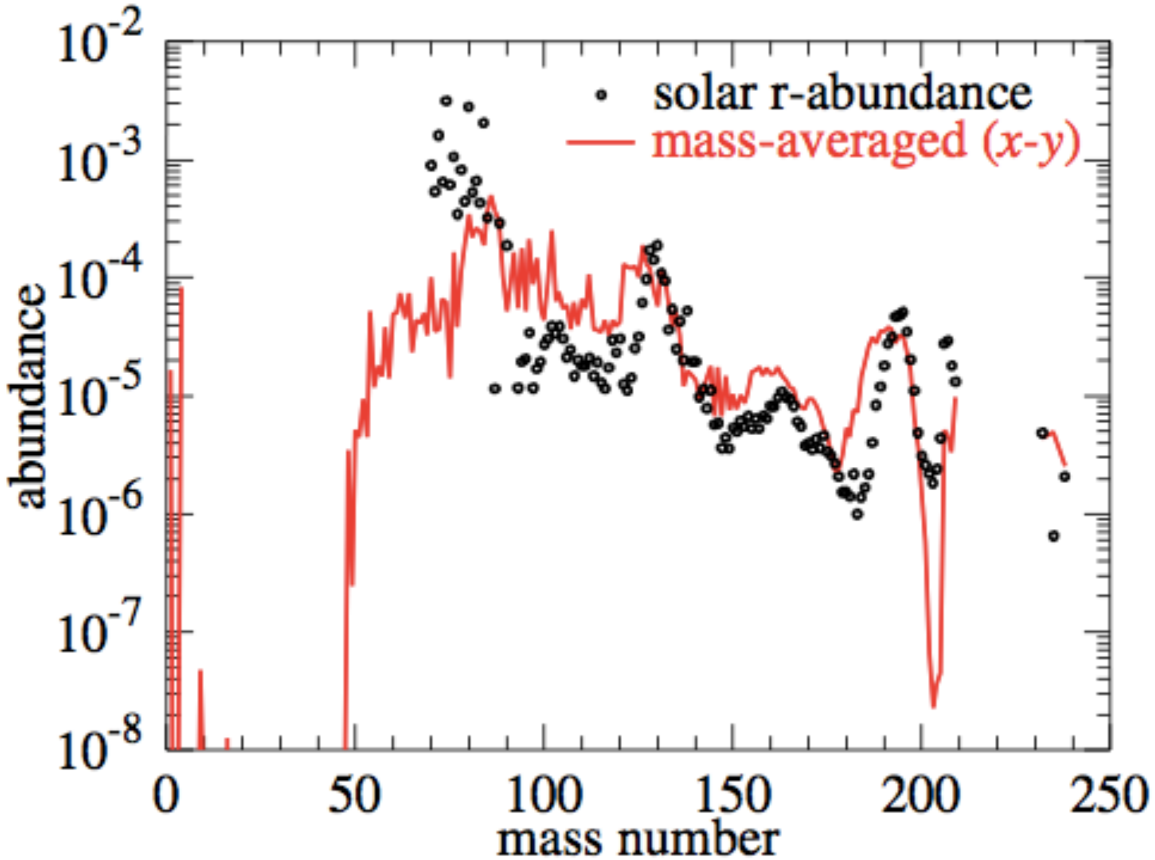
Both do a good job of the solar system heavy element distribution (if tuned carefully).

Core-collapse supernovae



Wanajo 2013

Compact binary mergers

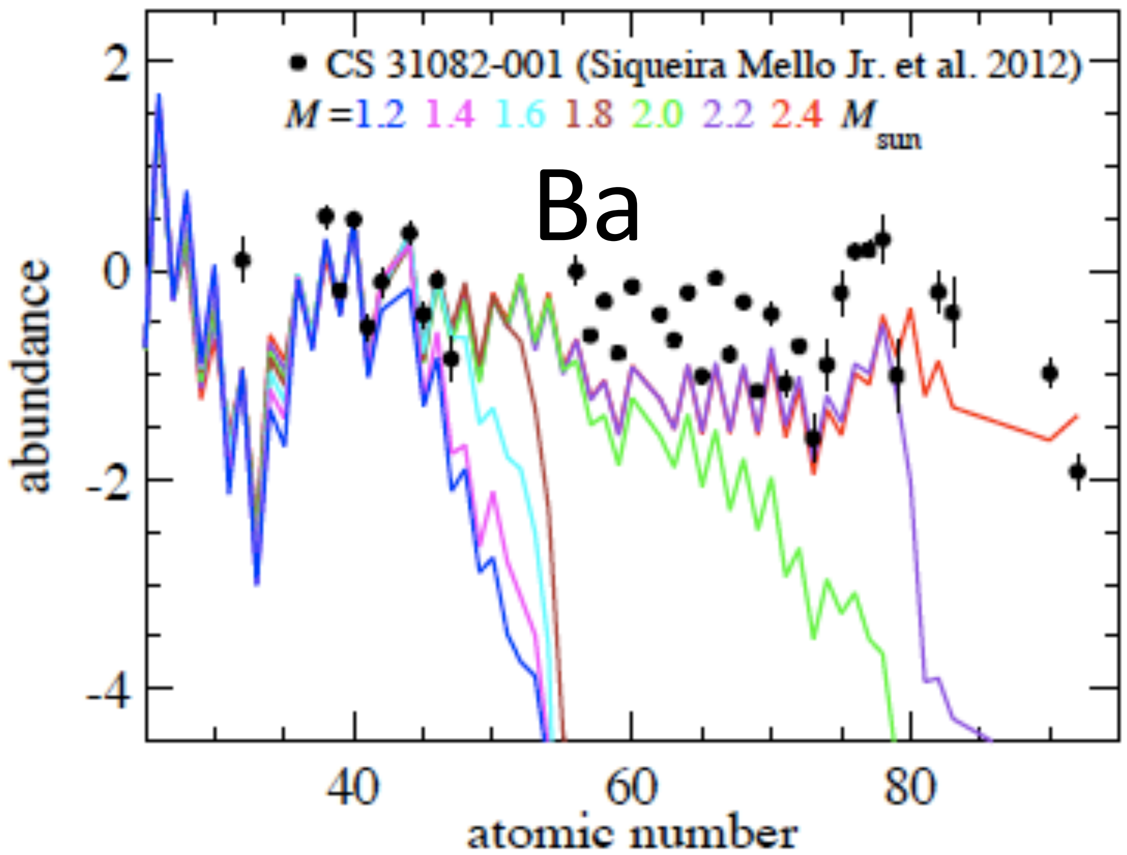


Wanajo et al. 2014

r-process sites

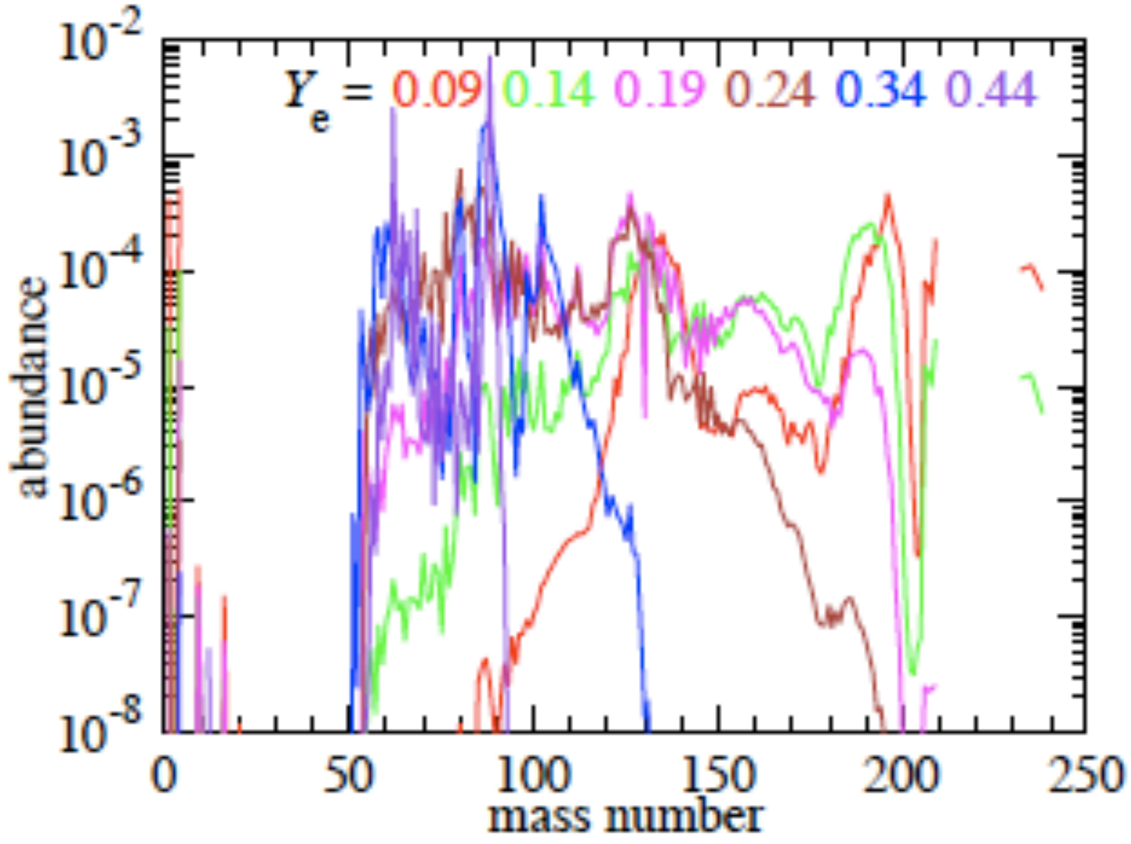
But heavy element distribution in some stars cannot be reproduced by core collapse SN II (above ~Ba)

Core-collapse supernovae



Wanajo 2013

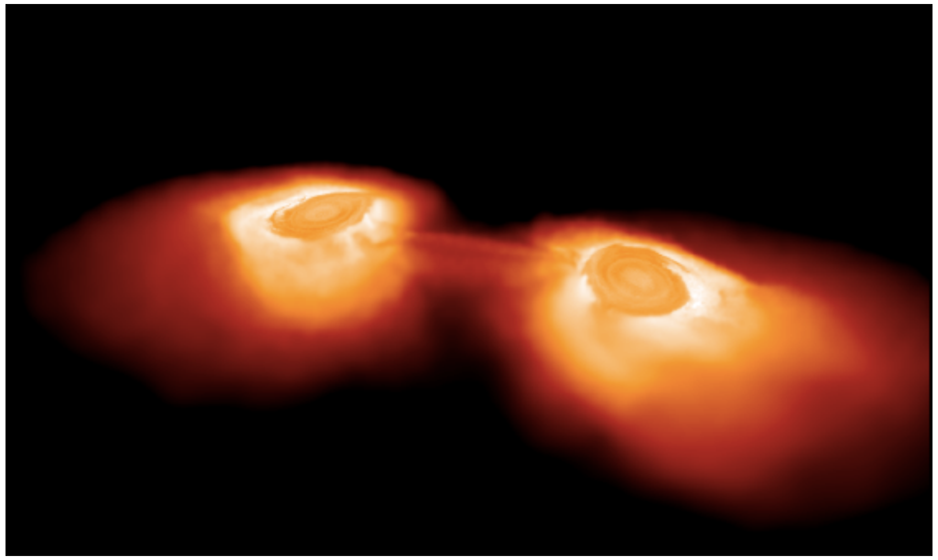
Compact binary mergers



Wanajo et al. 2014

Main r-process site !

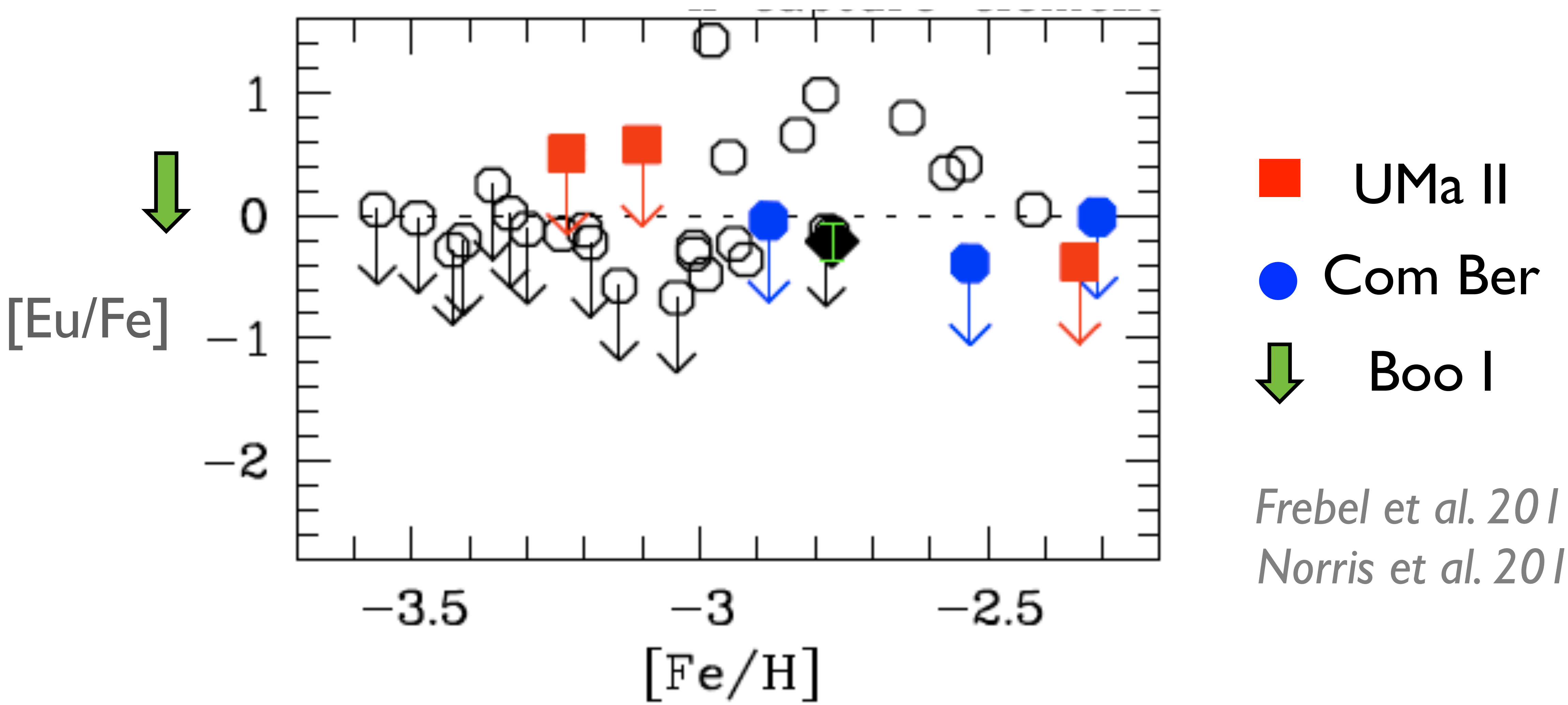
Compact binary mergers (CBM)



Problem is that CBM are rare:

- from observations of binary pulsars, Lorimer (2008) predicts only 4×10^{-15} events per year per solar mass.
- UFDs typically have 10^4 solar masses, thus expect << 0.1 events over lifetime, implying no CBM r-process enrichment (Tsujimoto & Shigeyama 2014)

No r-process in UFDs

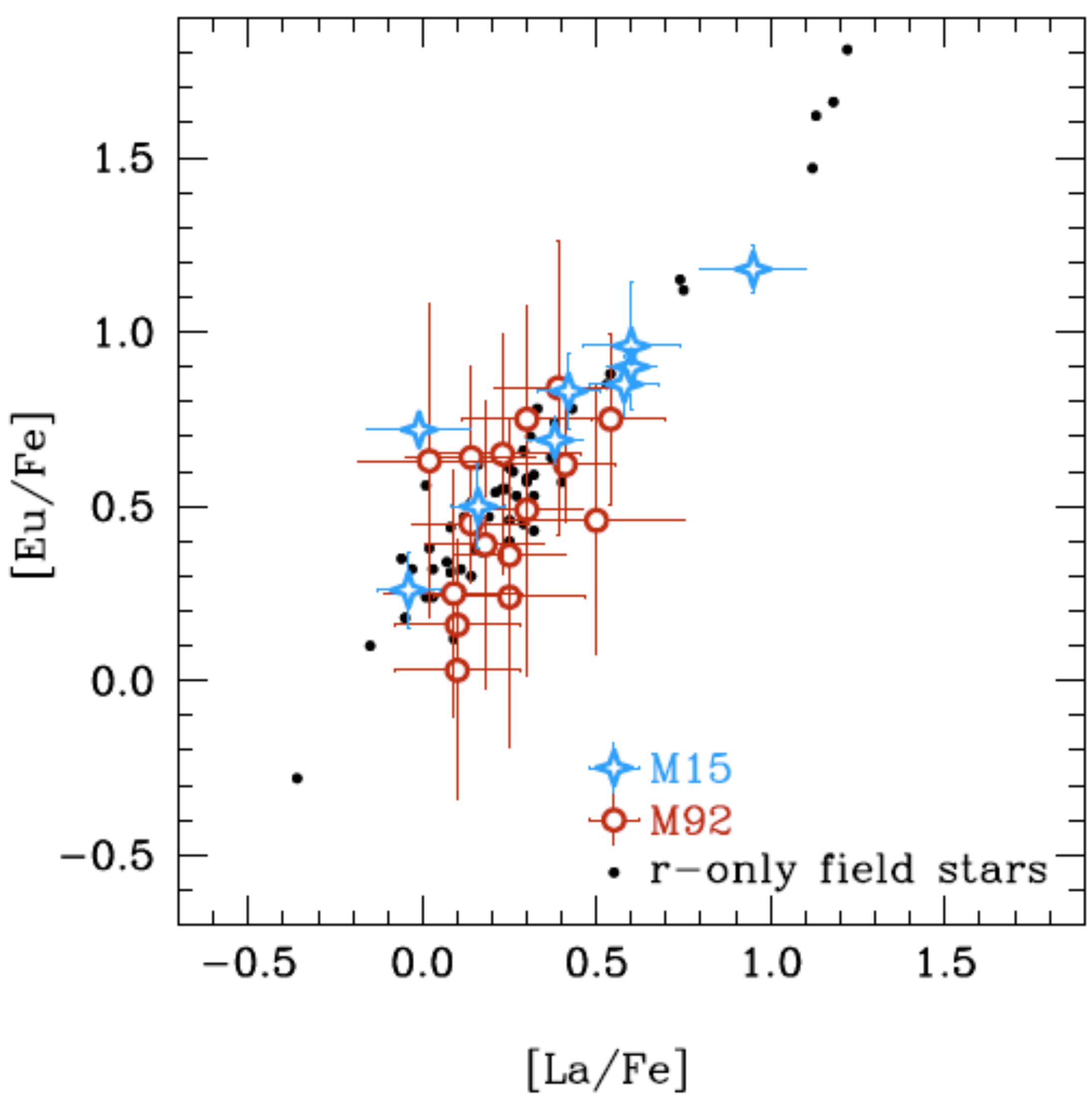


Frebel et al. 2010; Norris et al. 2010

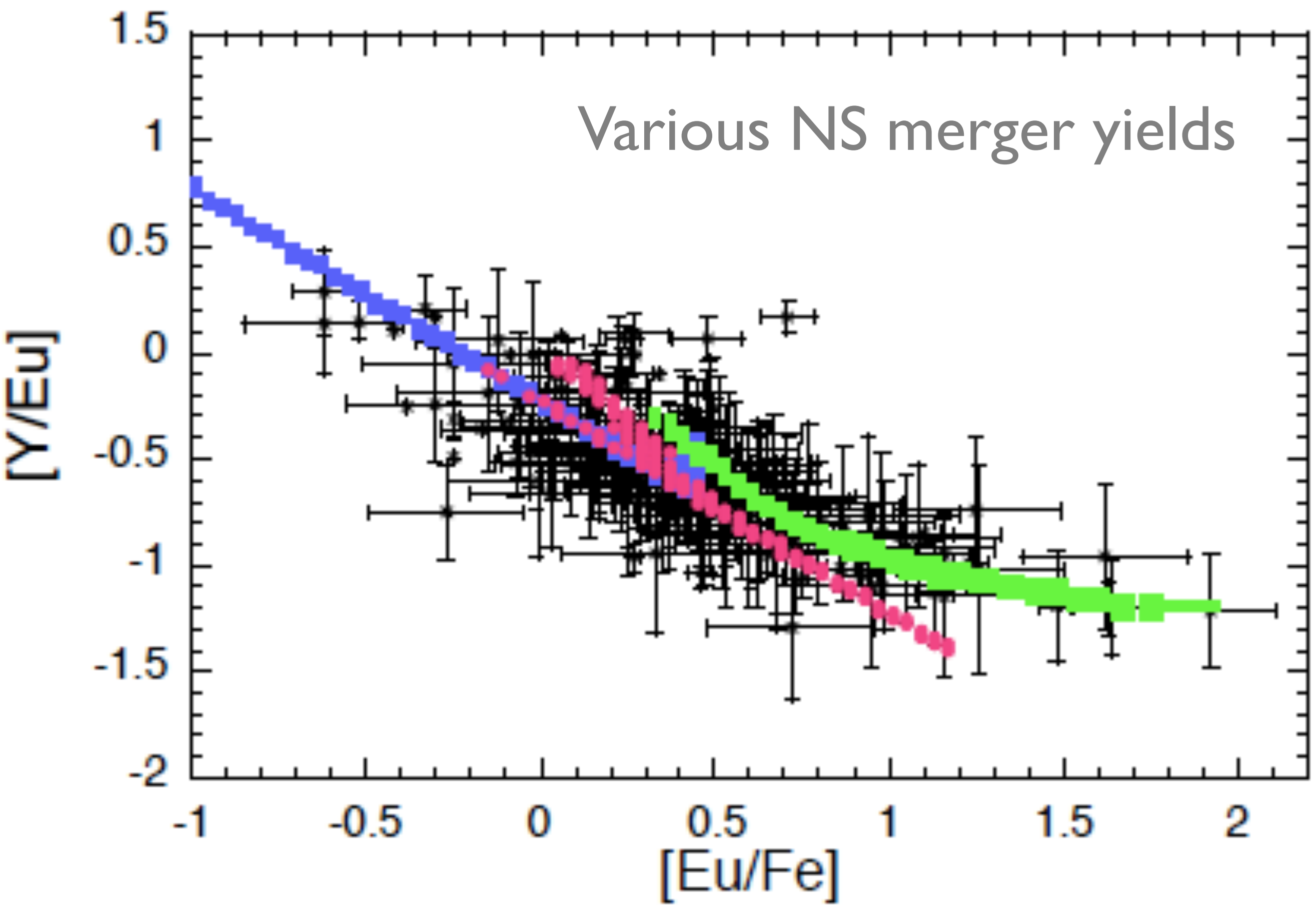
Along with the low [Ba/Fe] shown earlier, low [Eu/Fe] supports no CBM r-process enrichments in low mass UFD galaxies

r-process in some GCs

Compact binary mergers as the source of the r-process variations in M15 and M92 - to explain enrichments in La & Eu (without alpha, Fe, or Y!).



Roederer & Sneden 2011



Careful with axes, and no Y from NS mergers.

Tsujimoto & Shigeyama 2014

OUTLINE

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OUTLINE

2. What are we learning from/about the heavy elements ?

   Above [Fe/H]~ -2: chemically tag stars in/from dwarfs galaxies.

   Below [Fe/H]~ -2: stars in the UFD galaxies show no pure r-process enrichments

   Suggests NS mergers are the main site for heavy elements (>Ba).

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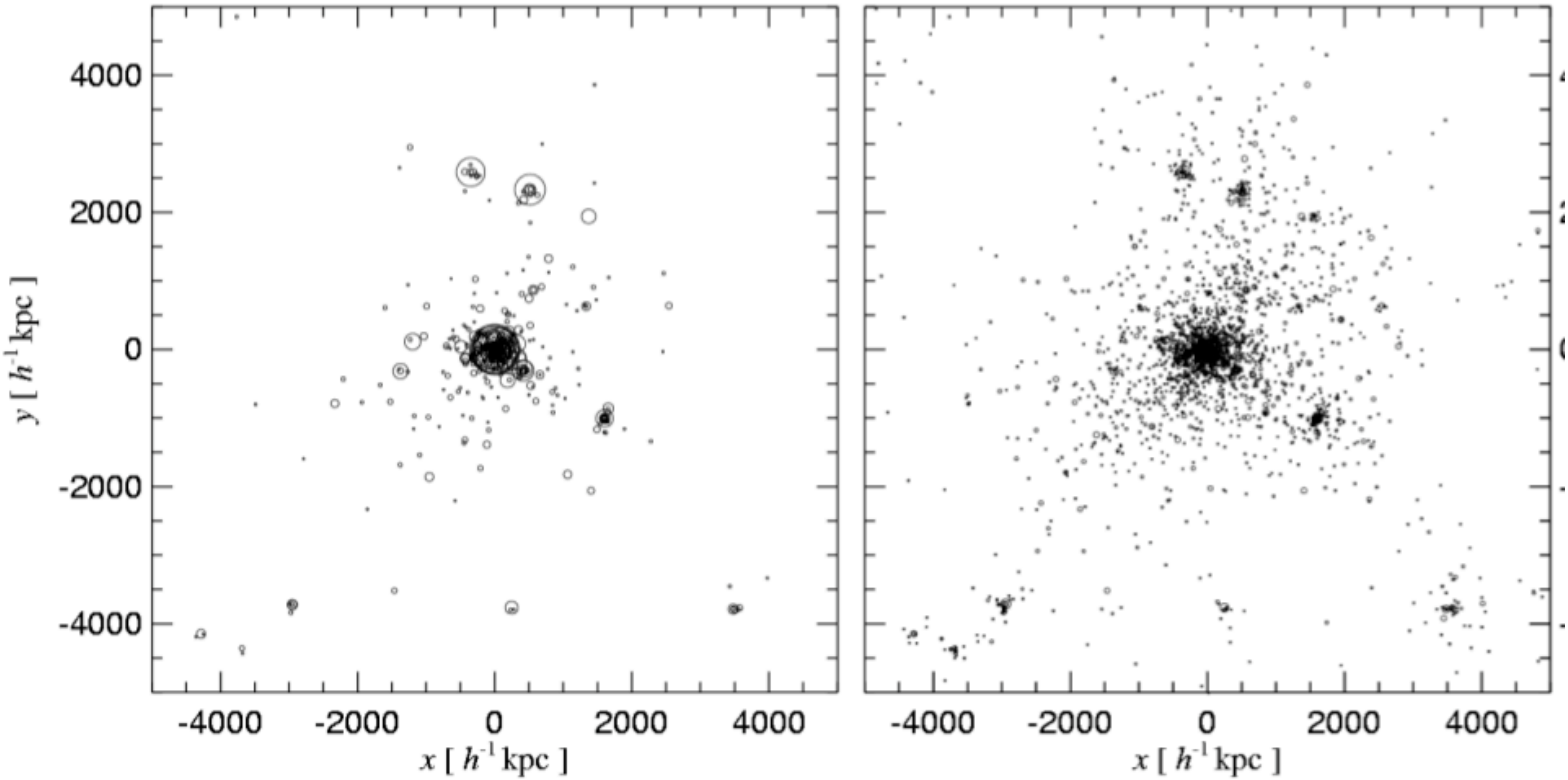
Initial conditions?

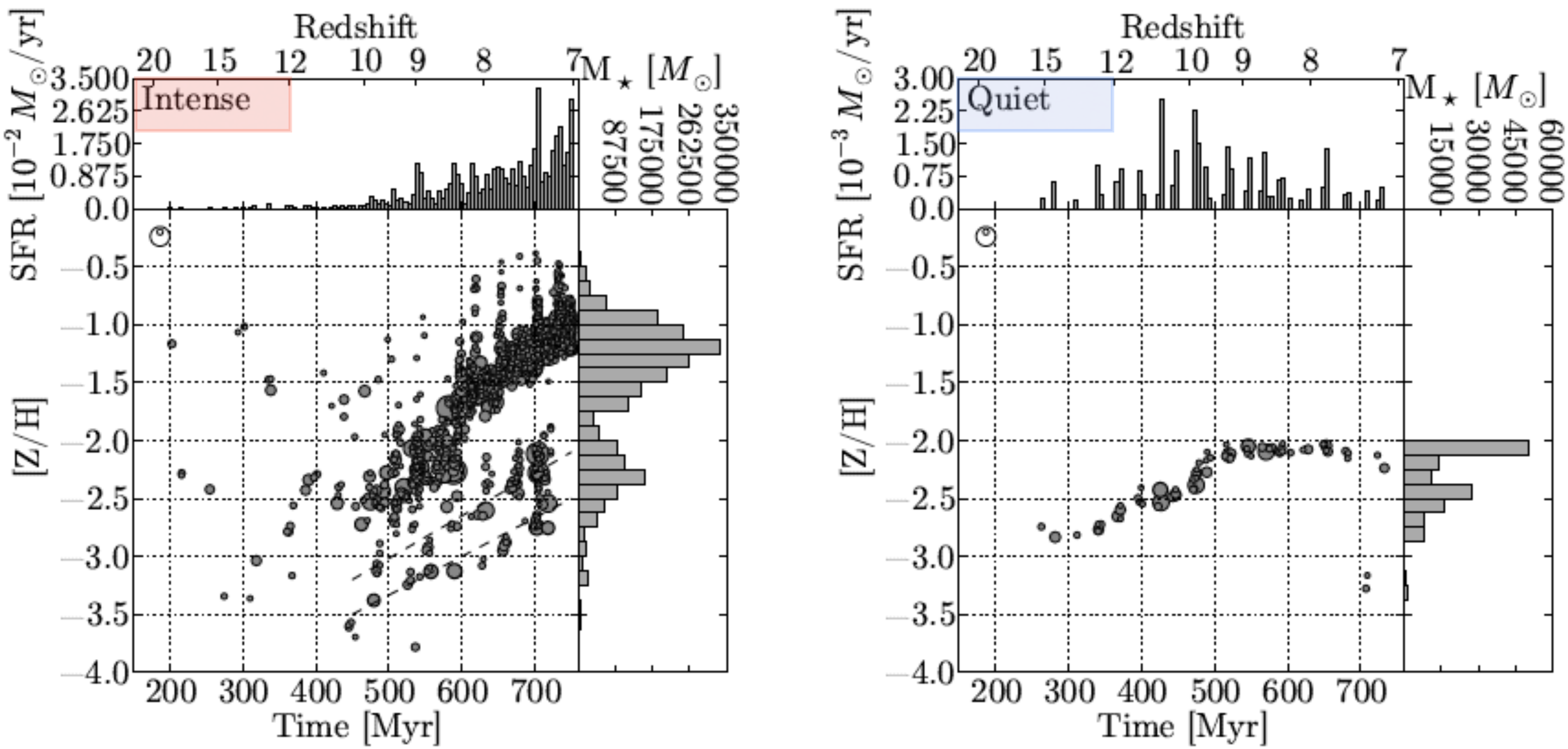
1% EARLIEST STARS — 1% MOST METAL POOR



WHITE & SPRINGEL 2000

Z=0

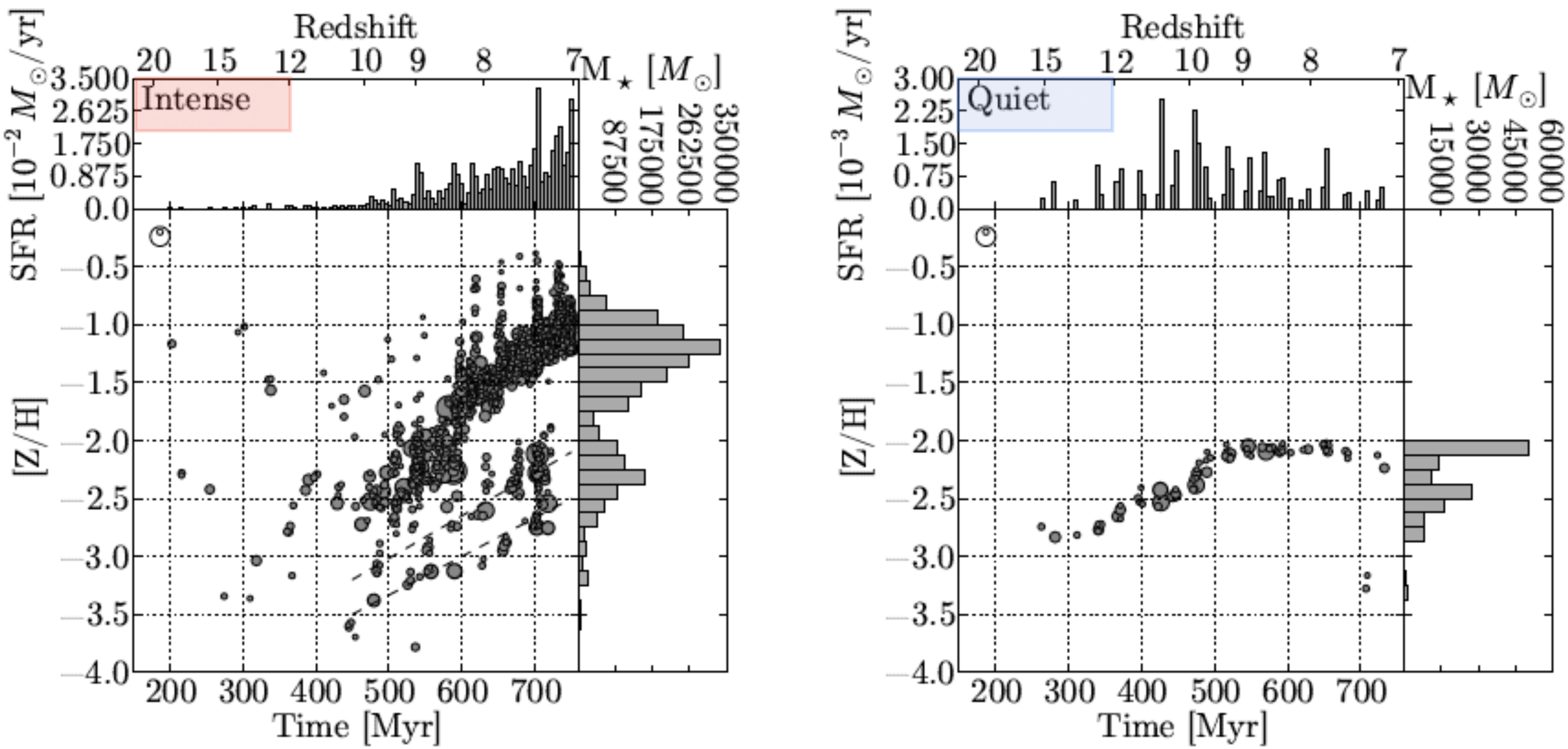
Initial conditions?



The OLDEST stars are not necessarily the most metal poor,
e.g., the Intense Model's oldest stars can have [Z/H] > -1.0 to -3.5.
e.g., the Quiet Model's most metal poor stars form later.

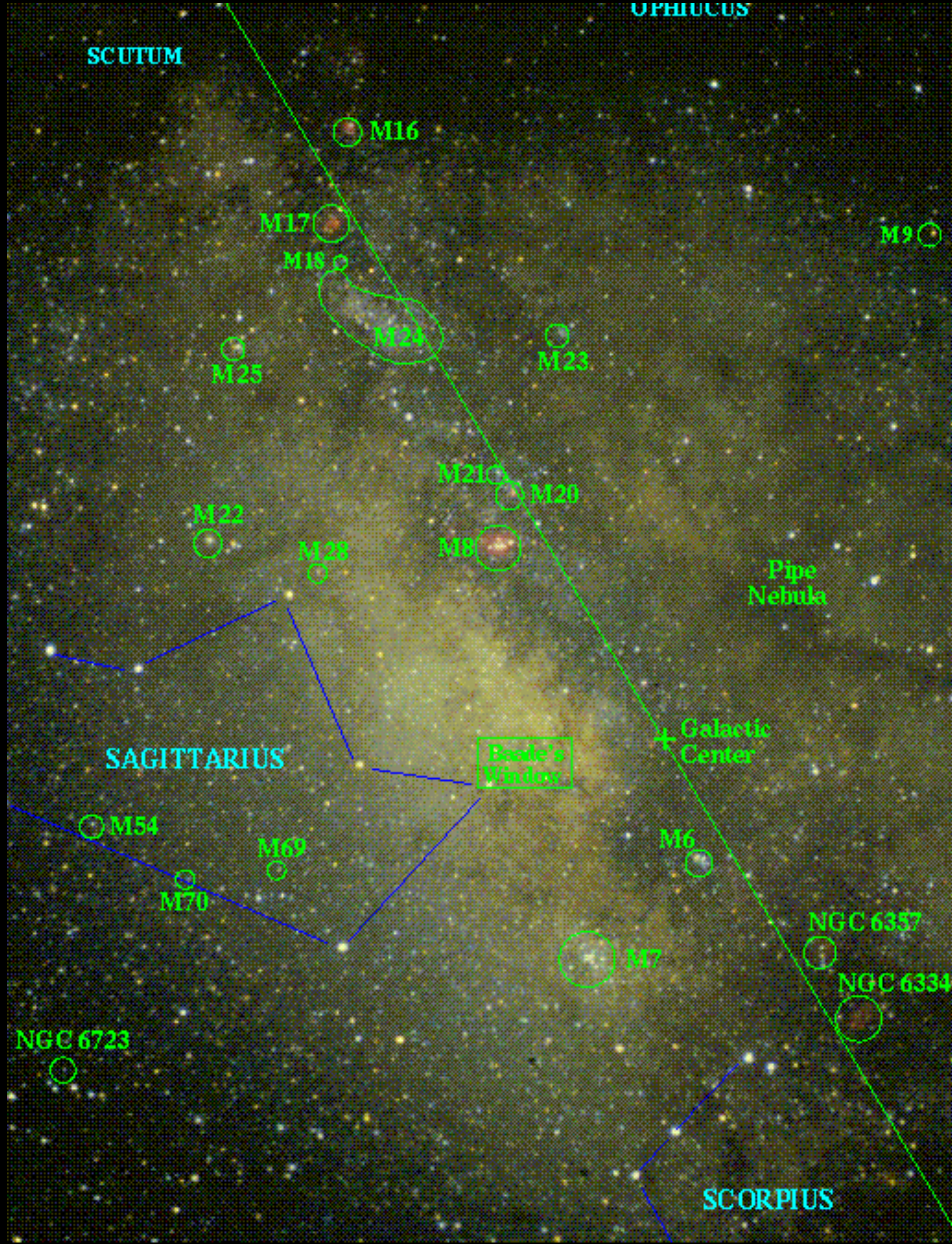
WISE ET AL. 2012

Initial conditions?



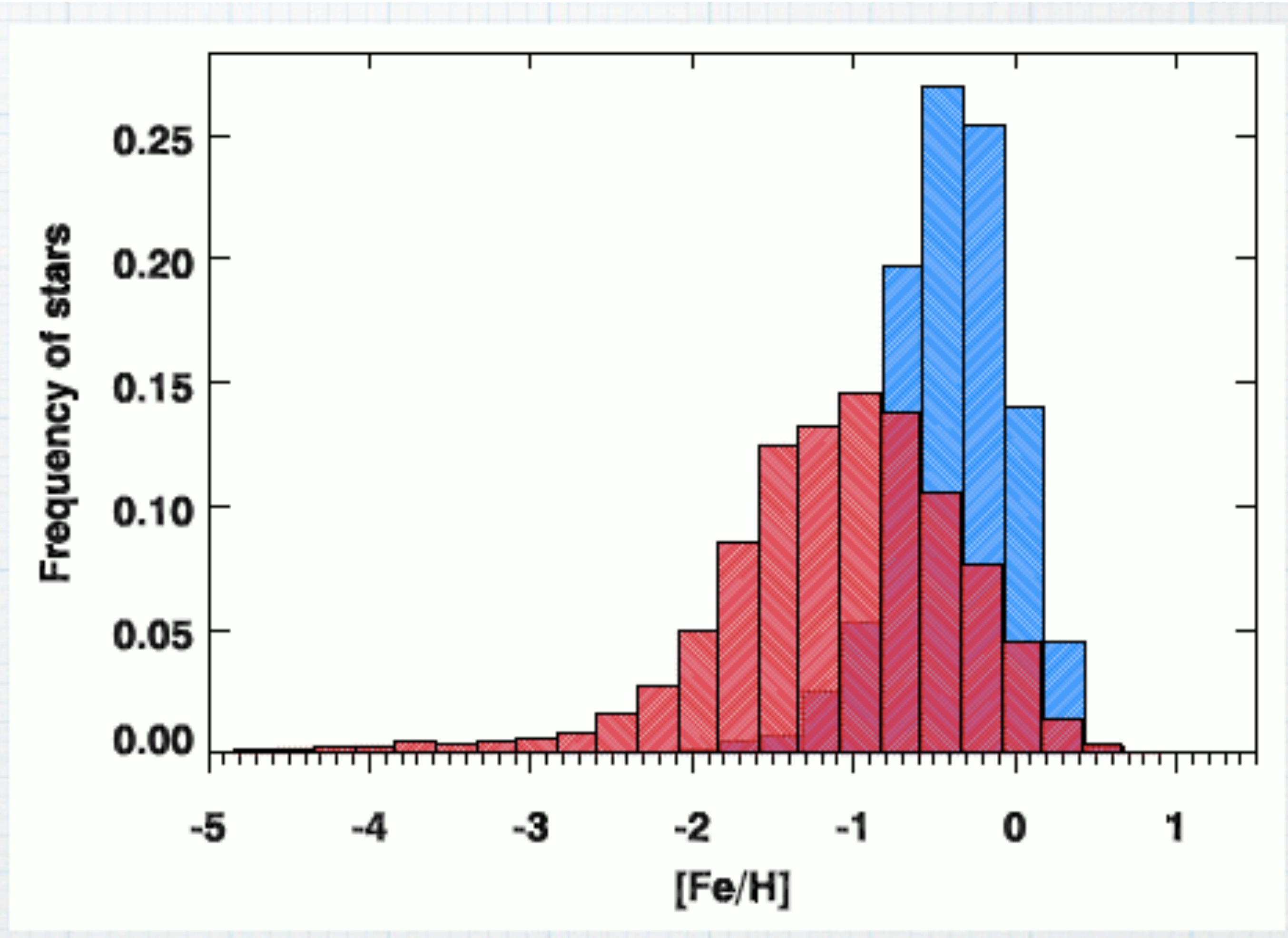
Thus, rather than focusing on most MP halo stars ([Fe/H] < -5) curious what MP stars in the Galactic Bulge may look like.

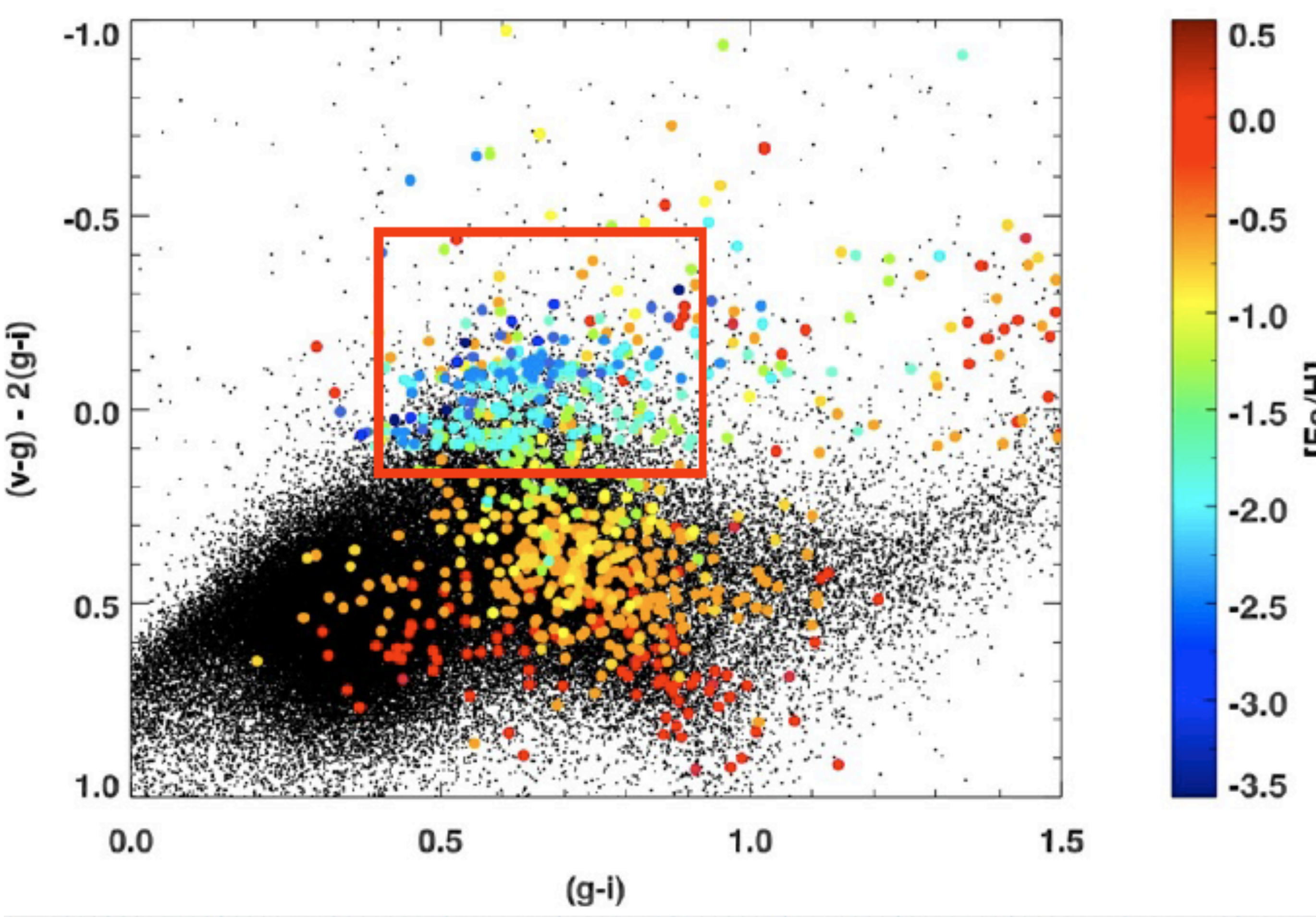
Wise et al. 2012


OPHIUCUS
SCUTUM
M16
M17
M9
M18
M24
M23
M25
M21
M20
M22
M28
M8
Pipe
Nebula
Galactic
Center
SAGITTARIUS
Baade's
Window
M54
M6
M69
M70
NGC 6357
M7
NGC 6334
NGC 6723
SCORPIUS

MP stars in the Bulge?

AAOmega EMBLA (Howes et al. 2014)
AAOmega ARGOS (Ness et al. 2013)

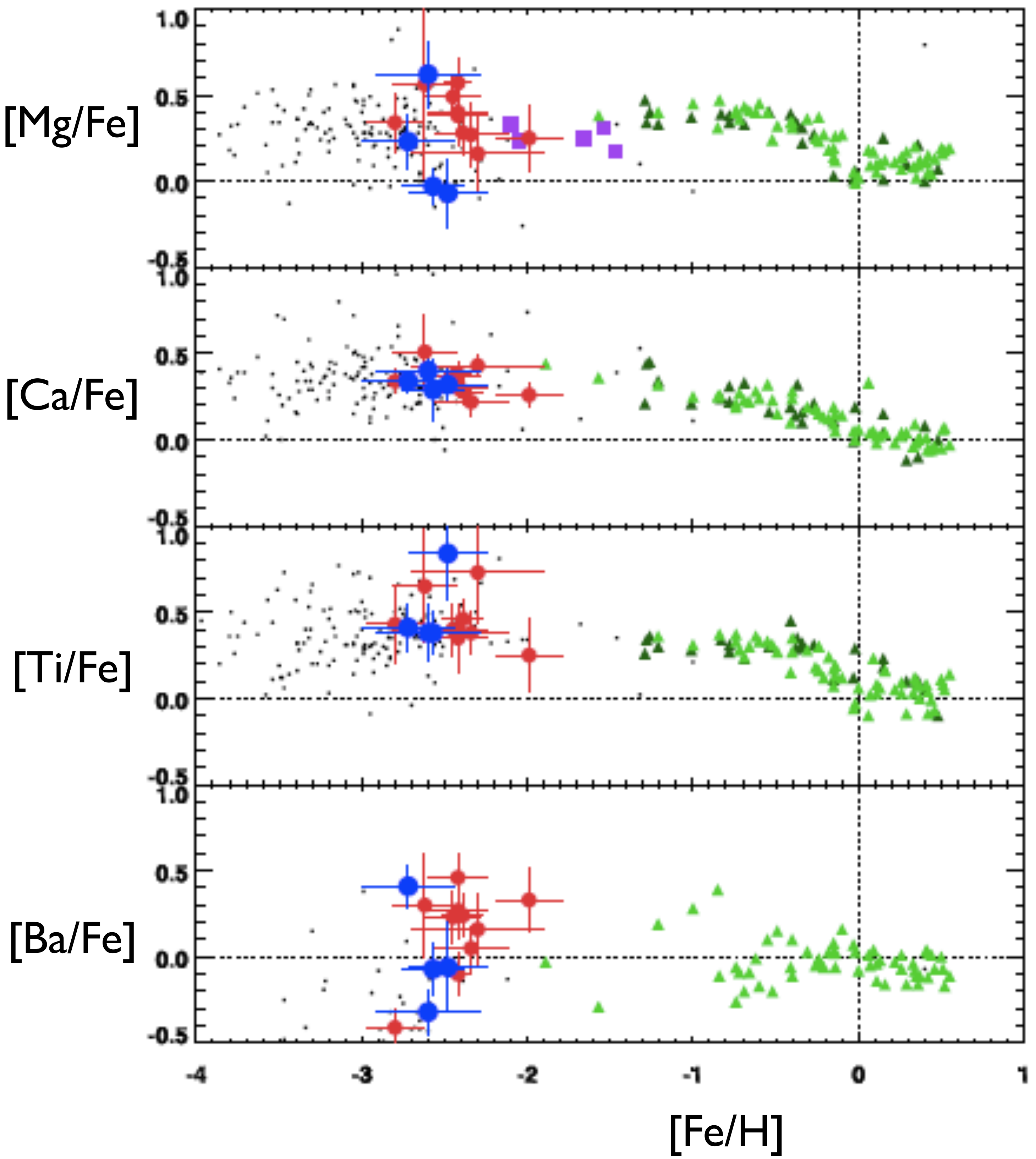




AAOmega (350 stars per 2h)
selected from SkyMapper
thus biased MDF

60 stars with [Fe/H] < -3 !
ESO/Gaia & Magellan/MIKE
follow-up spectroscopy

MP stars in the Bulge?



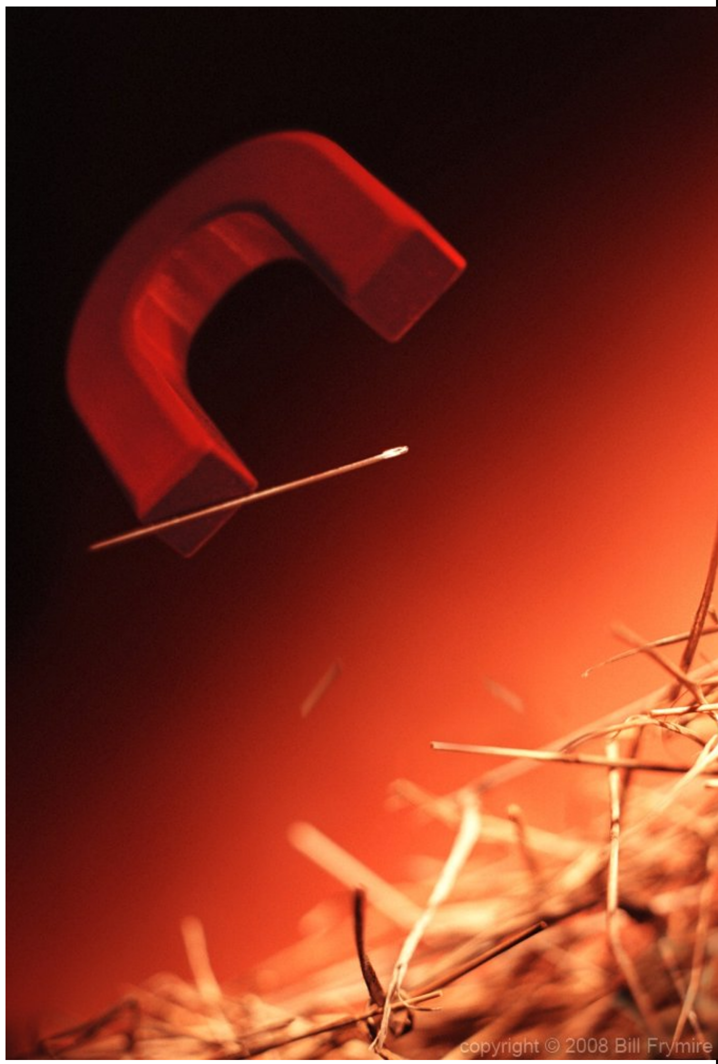
Howes et al. (2014)

- Bulge stars
- Halo comparisons

These stars look like normal halo stars, but they have more to come :

- More stars
- More elements

RAVEN (UVic + Subaru)



RAVEN
MOAO
+IRCS
Subaru

HST WFC3 Galactic Bulge Treasury

Brown et al. 2009, 2010

H ~ 16, reddening free indices where RGBs with [Fe/H] < -2

RAVEN is a Canadian-Japanese collaboration

Collaboration : UVic, NRC-HIA, NAOJ, & U.Tohoku

Timeline: CoDR March 2011

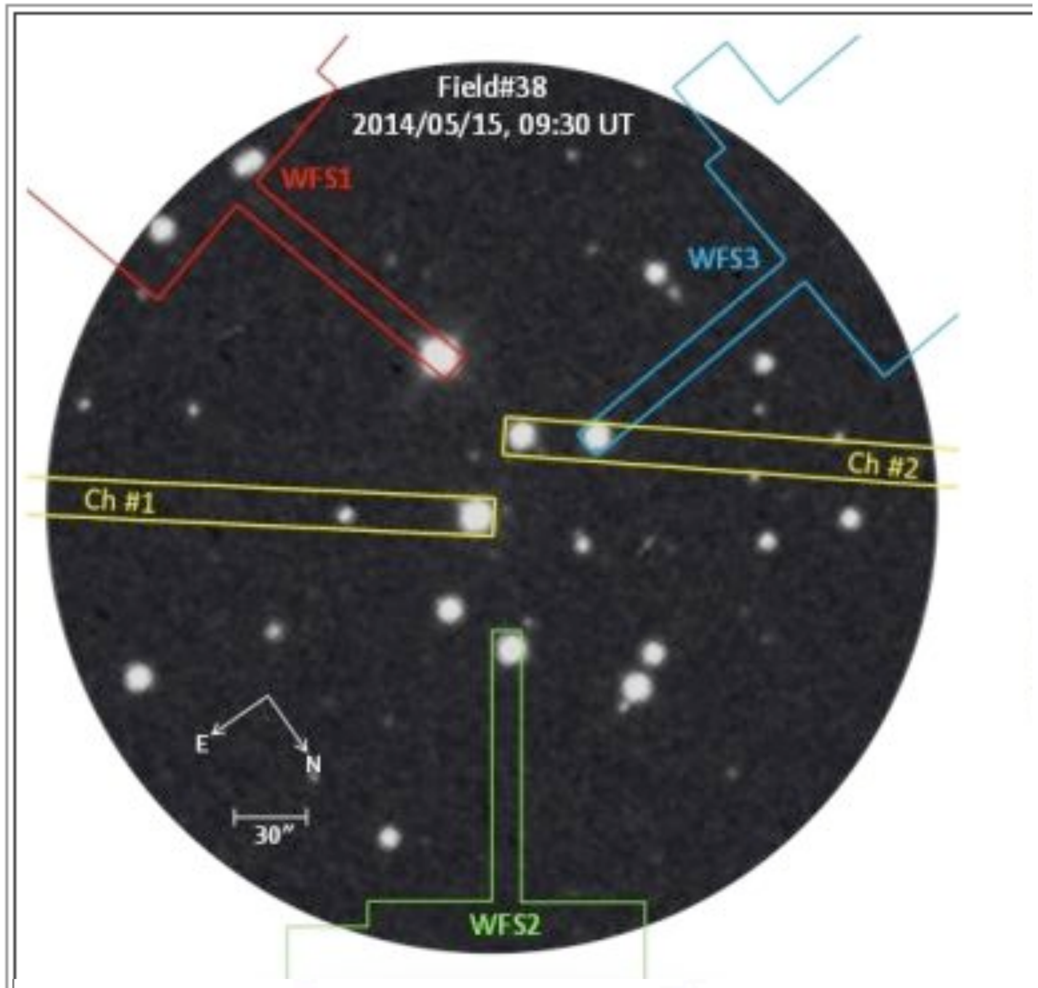
Shipped to Subaru Telescope, Dec 2013

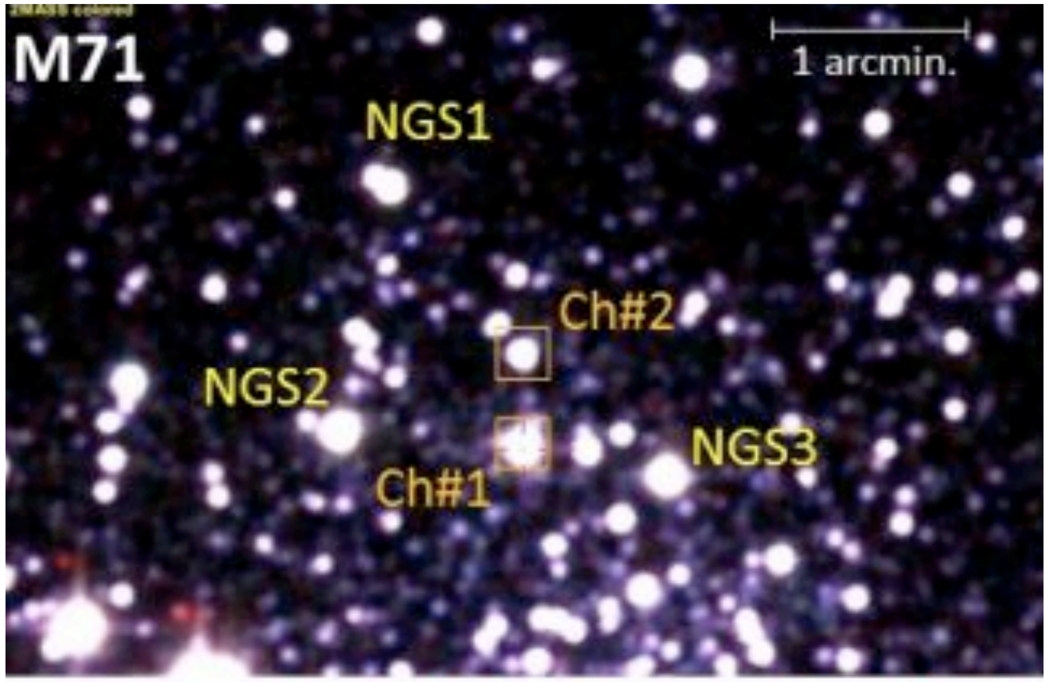
First light May 2014

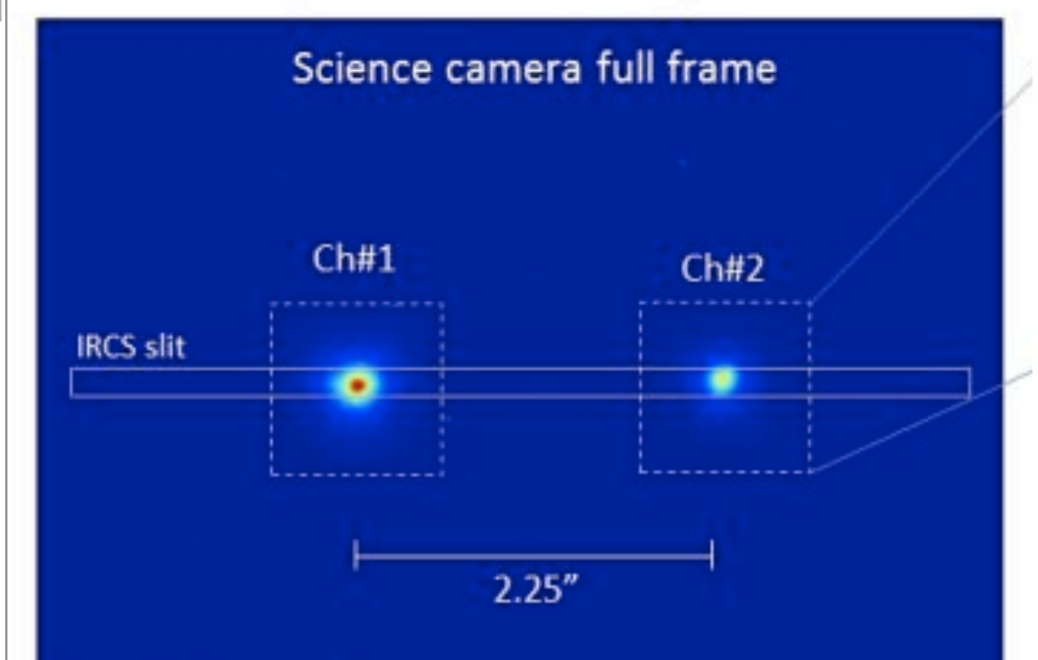
Engineering run Aug 2014

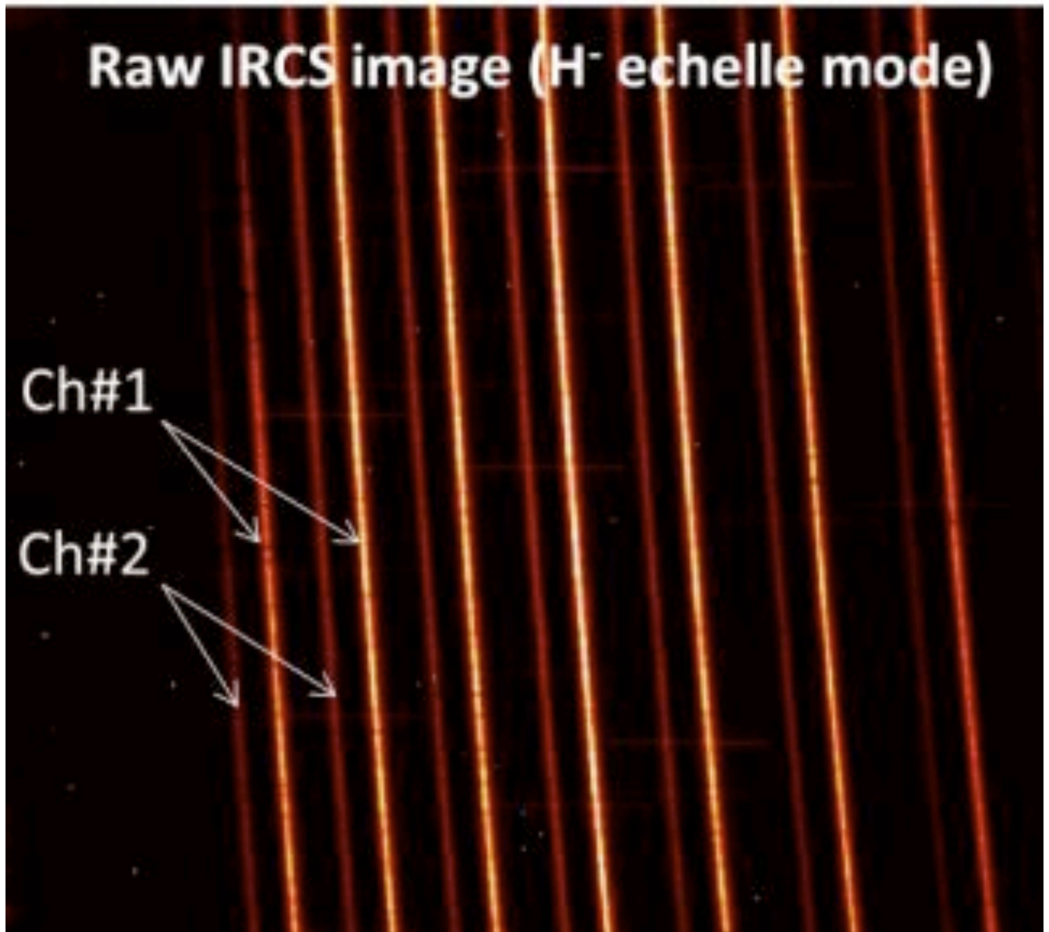
RAVEN First Light

http://web.uvic.ca/~lardiere/raven/releaseMay14/ravenFirstLight.html



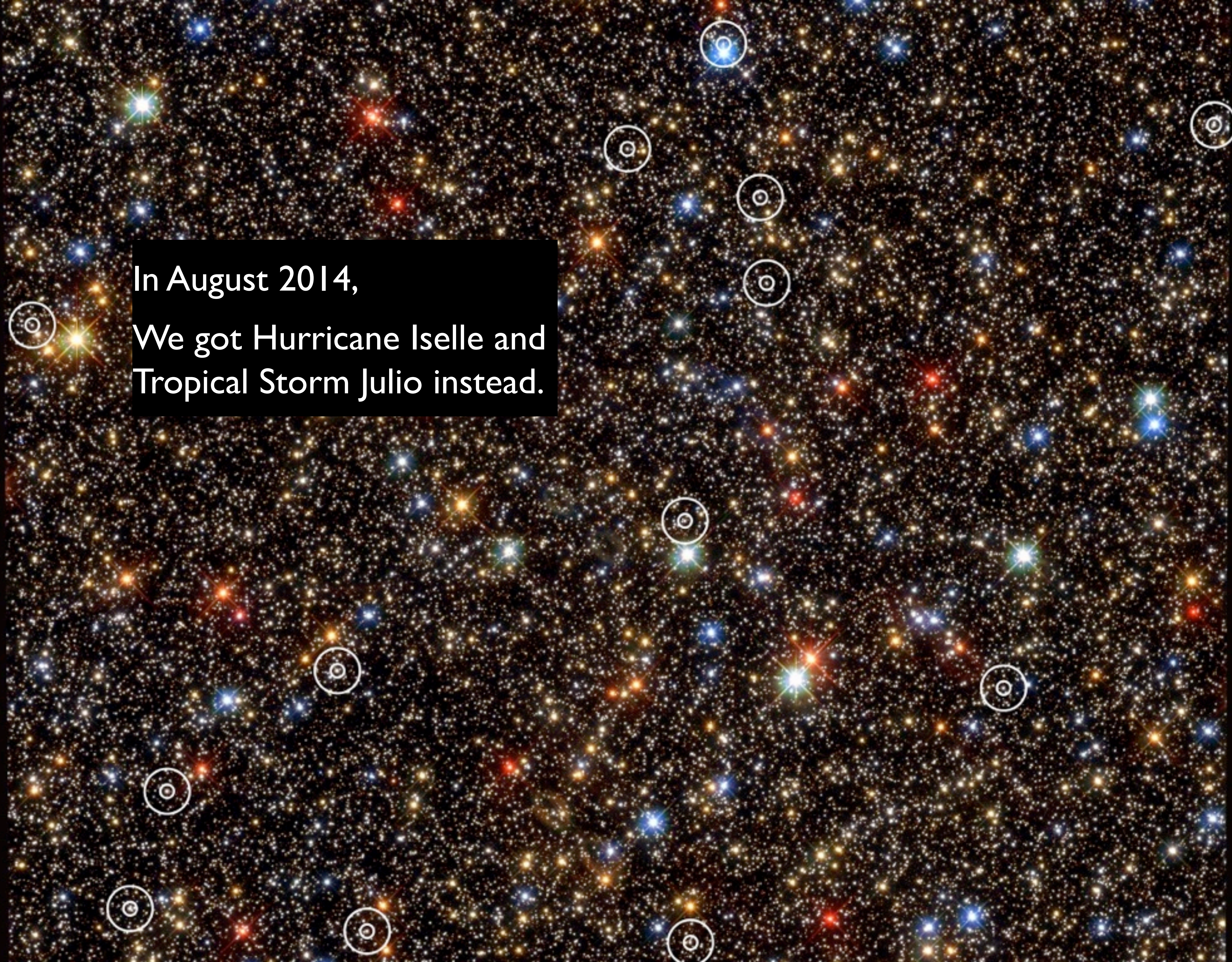






In August 2014,

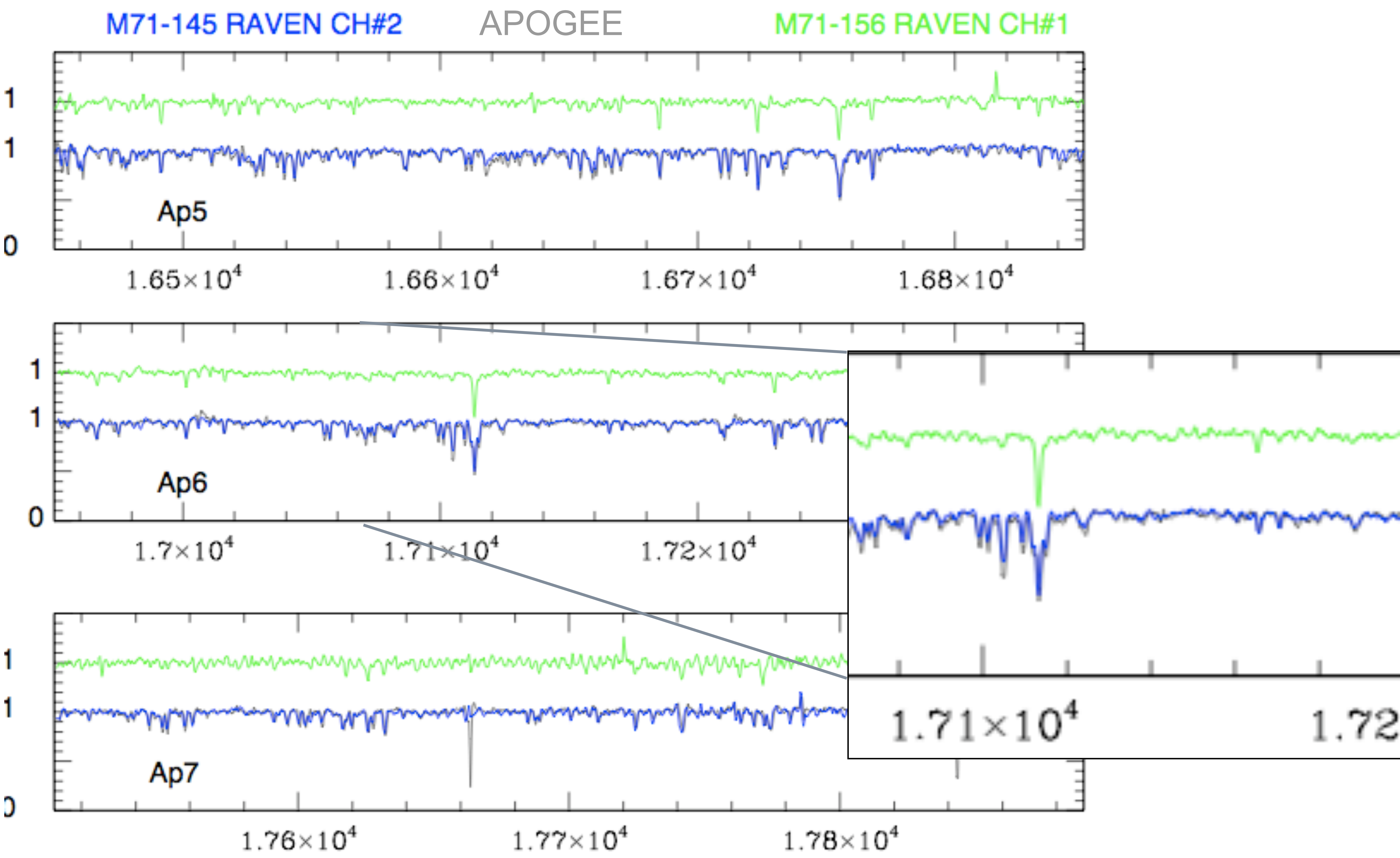
We hoped to gather IR spectra to chemically tag some Bulge stars !



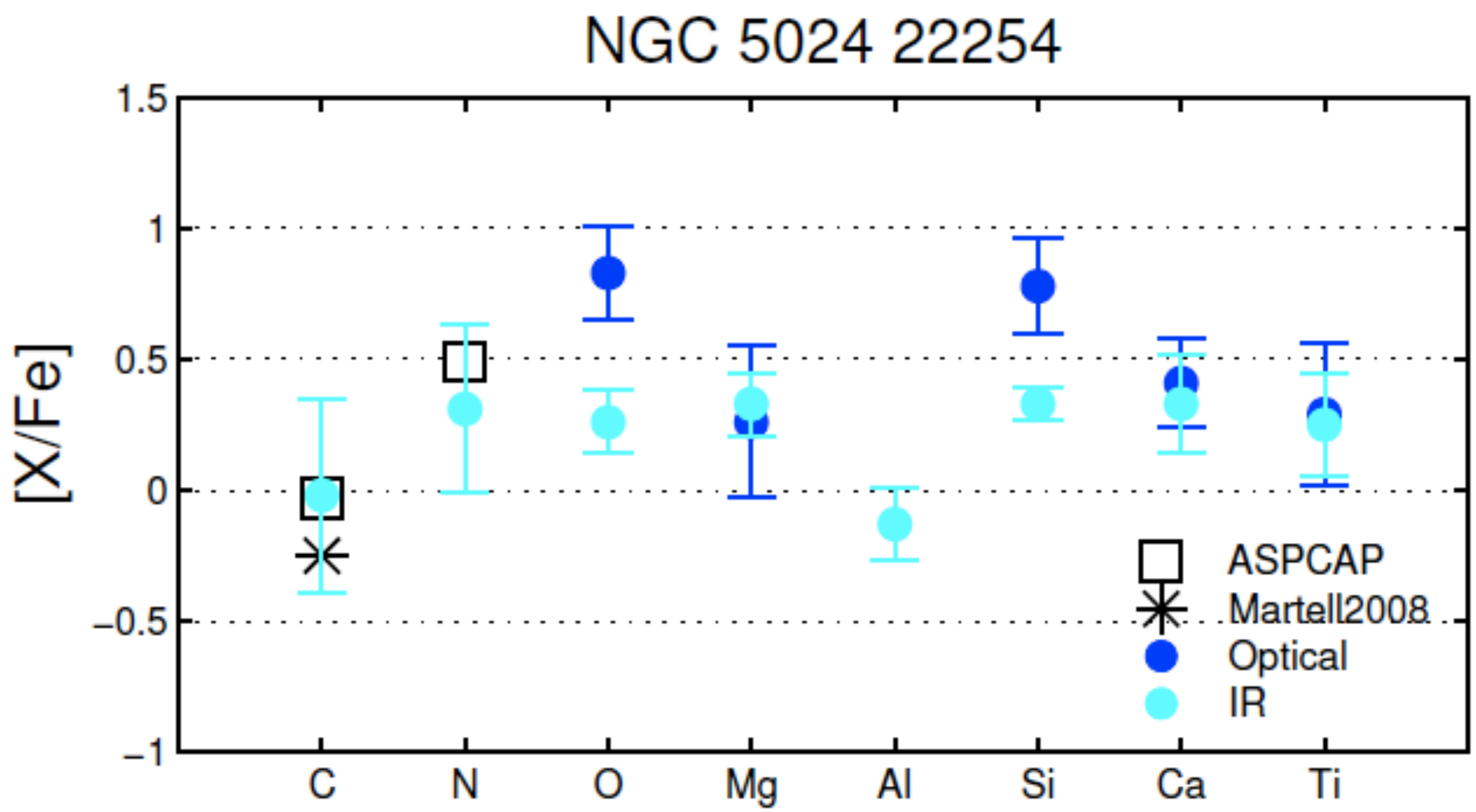
In August 2014,

We got Hurricane Iselle and Tropical Storm Julio instead.

First RAVEN spectra : M71



IR & Optical at [Fe/H] < -2



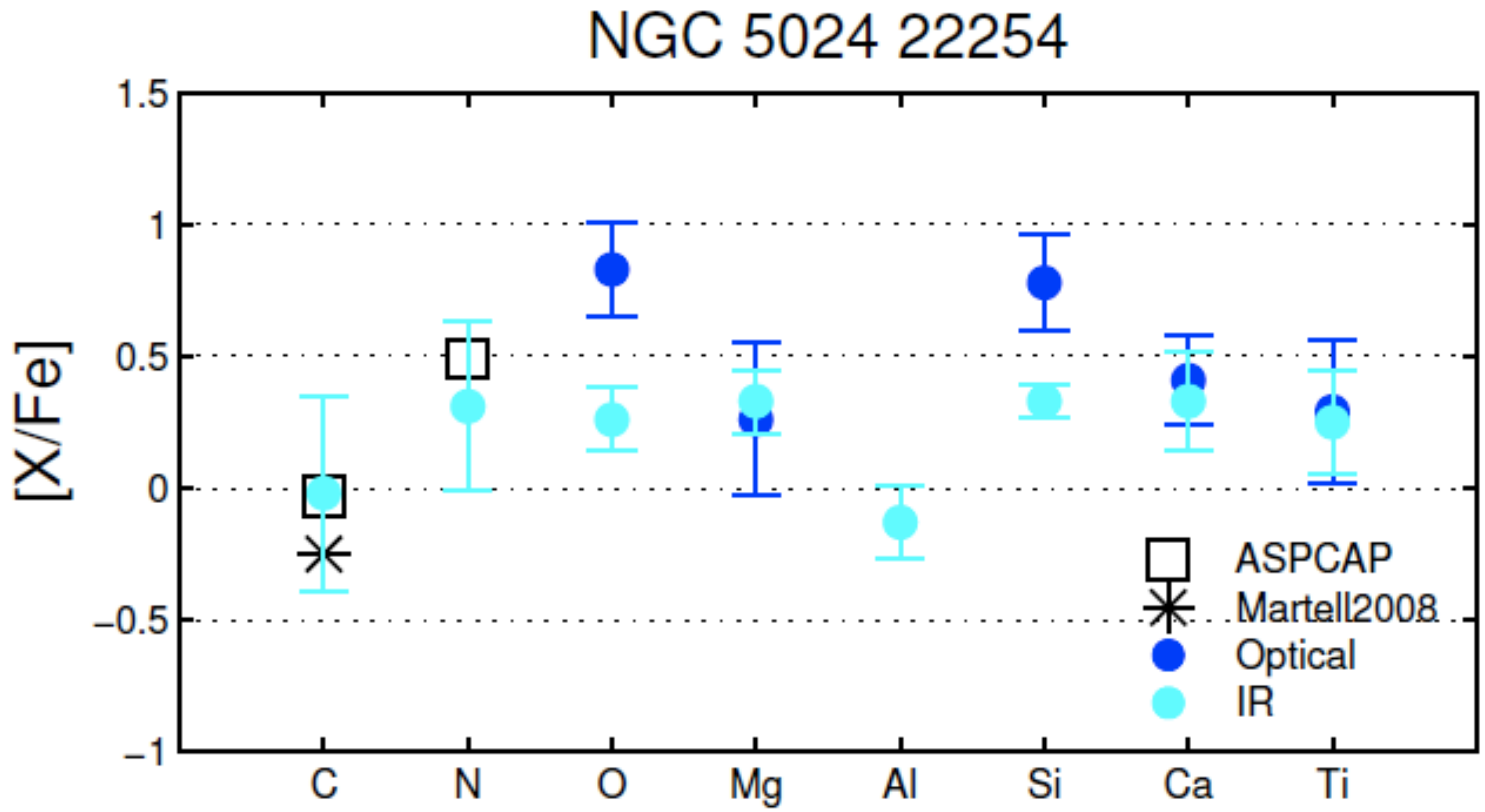
Lamb, Venn et al. 2014

[Fe/H] = -2.1

Optical: from HET spectrum, SNR~50

IR: from APOGEE spectrum, SNR~100

IR & Optical at [Fe/H] < -2



Lamb, Venn et al. 2014

Advantages:
reddening negligible
works with AO
CNO, Si, Al
independent Mg, Ti, Fe
Isochrone ages

Disadvantages:
stellar parameters trickier
[Fe/H] < -2.5 ?
heavy elements ?

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OUTLINE

3. Are there metal poor stars *of* the Galactic Bulge ?
    - Remains unclear, not chemically distinct ones yet.
    - Do dwarf galaxies inform us of the initial conditions of MW galaxy formation?

SUMMARY

Stellar abundances in dwarf galaxies are now plentiful, and used to study a broad spectrum of questions from stellar nucleosynthesis to stellar populations and galaxy evolution (but formation?).

Era of E-ELT will permit fainter stars to be examined (more distant hosts or less evolved stars), but may require AO to reach full potential

– crowded fields, high extinction regions

– thus IR spectroscopy worth developing now.

Neutron capture elements

- Core collapse supernovae do explode and are capable of producing light r-process elements anyway

- Neutron star mergers are rare events /stellar mass

less than 4×10^{-15} events per year per solar mass inferred from observations for binary pulsars (Lorimer 2008)

an ultra-faint dSph galaxy with a stellar mass of about 10^4 $M_\odot$ are expected to have undergone $\ll 0.1$ events in the past, implying no enrichment of r-process elements - as noticed by Tsujimoto & Shigeyama (2014)

Neutron capture elements

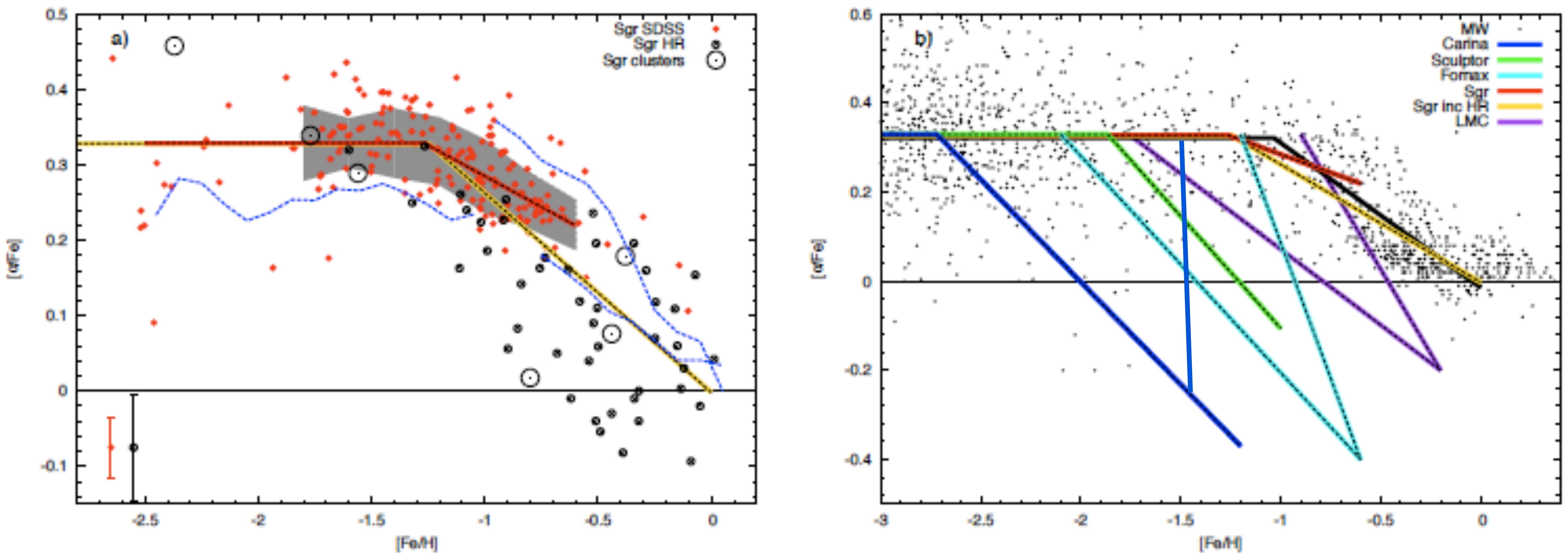
core-collapse supernovae
(CCSNe; in particular proto-NS wind)

Excluded as the major origin of heavy r-process elements. If not the main origin of the r-process elements beyond A ~ 110, they could be the sources of low-level abundances of Sr and Ba

compact binary mergers (CBMs) of double neutron star (NS–NS) and black hole–neutron star (BH–NS)

The bulk of the dynamical ejecta are appreciably shock-heated and neutrino processed, resulting in a wide range of Ye (≈0.09–0.45). The mass-averaged abundance distribution of calculated nucleosynthesis yields is in reasonable agreement with the full-mass range (A ≈ 90–240) of the solar r-process curve.

Sgr remnant

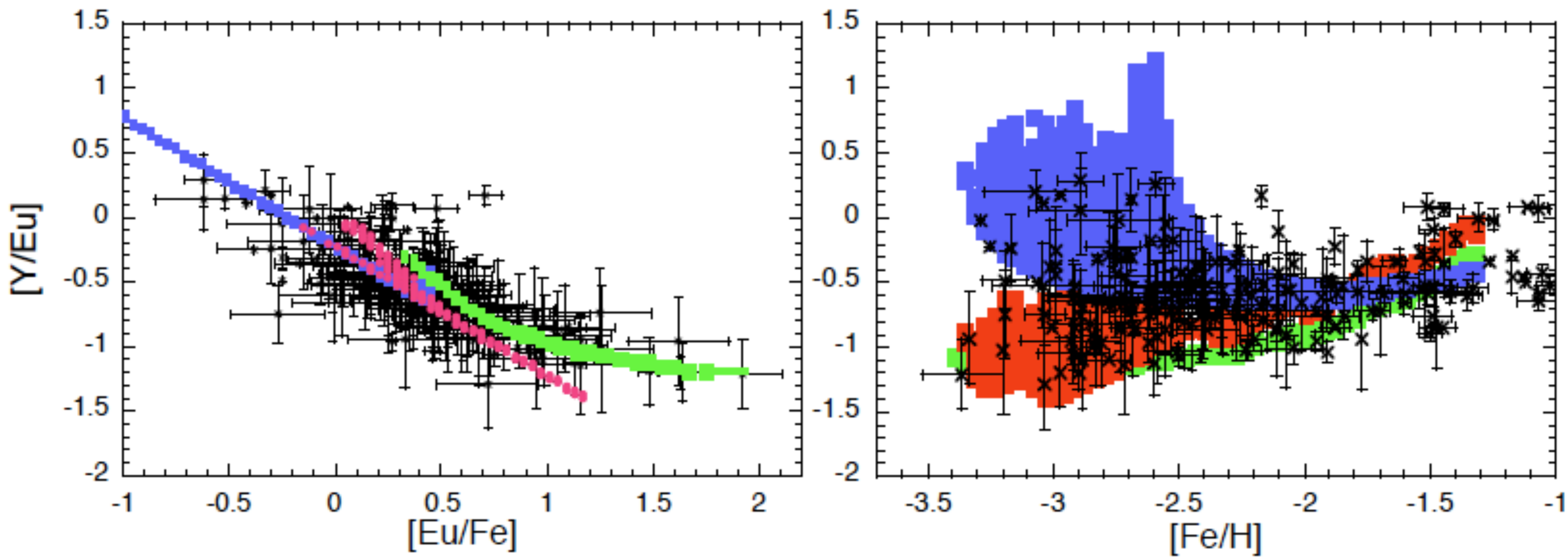


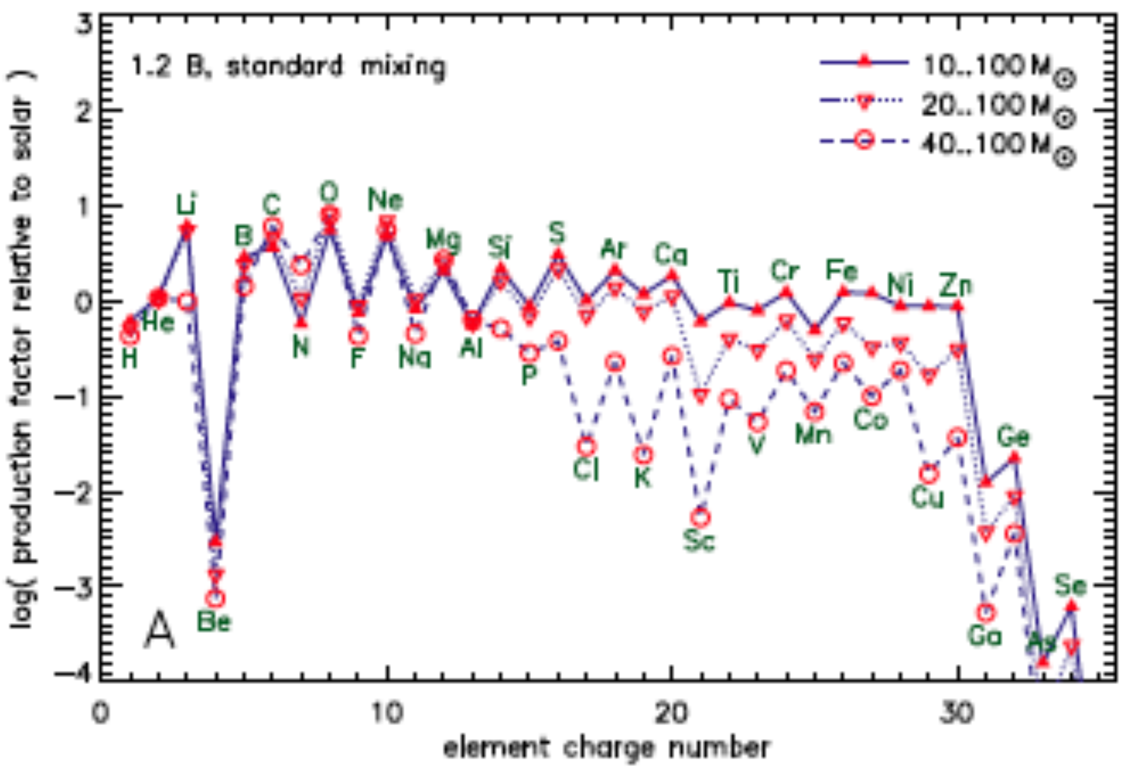
de Boer et al. 2014b : First time the [alpha/Fe] knee found for Sgr. SDSS R = 2000 spectra (Lee et al. pipeline)

After all of this data – we learn that only Sgr could contribute to the MW halo & disk(s) at later times, and the plateau does seem universal.

Heavy elements

Tsujimoto & Shigeyama 2014b further point out that what we have attributed to "shot noise" in metal poor stars
may have been lack of NS merger scenario
obscured by a poor choice of axes.



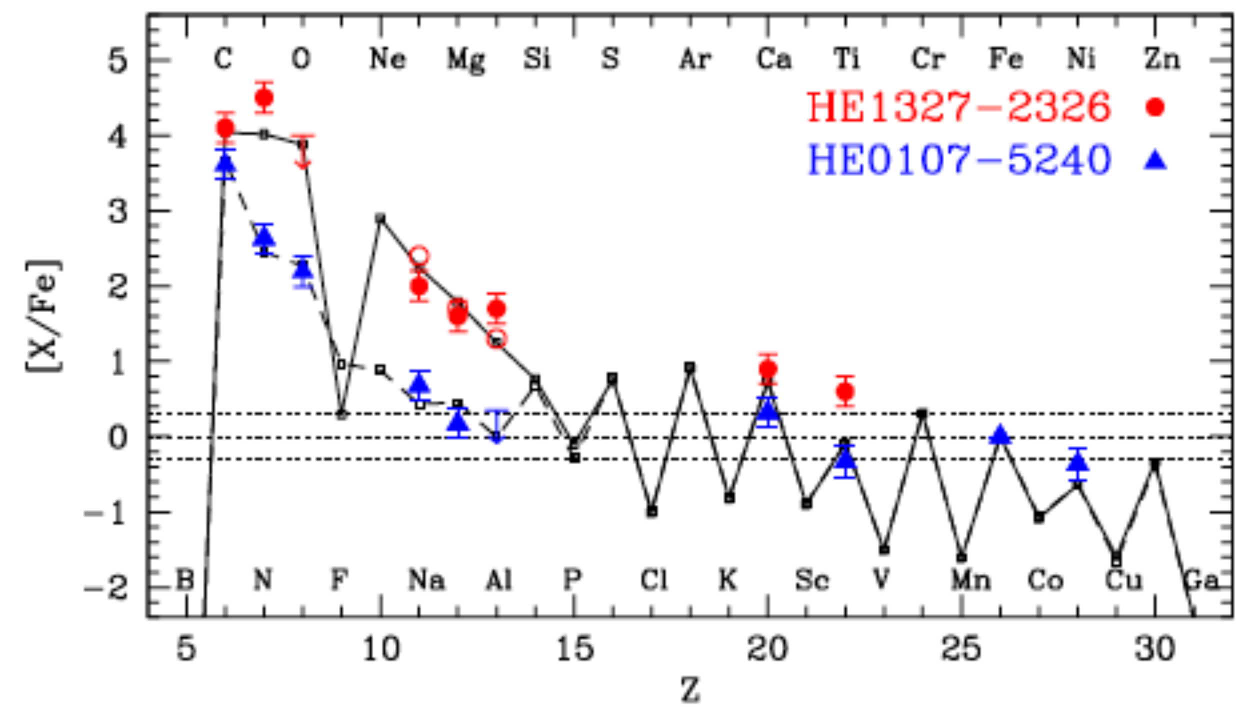


Heger & Woosley 2008

sample of models

little/no yields beyond Fe

similarly PISN (Heger & Woosley 2002)



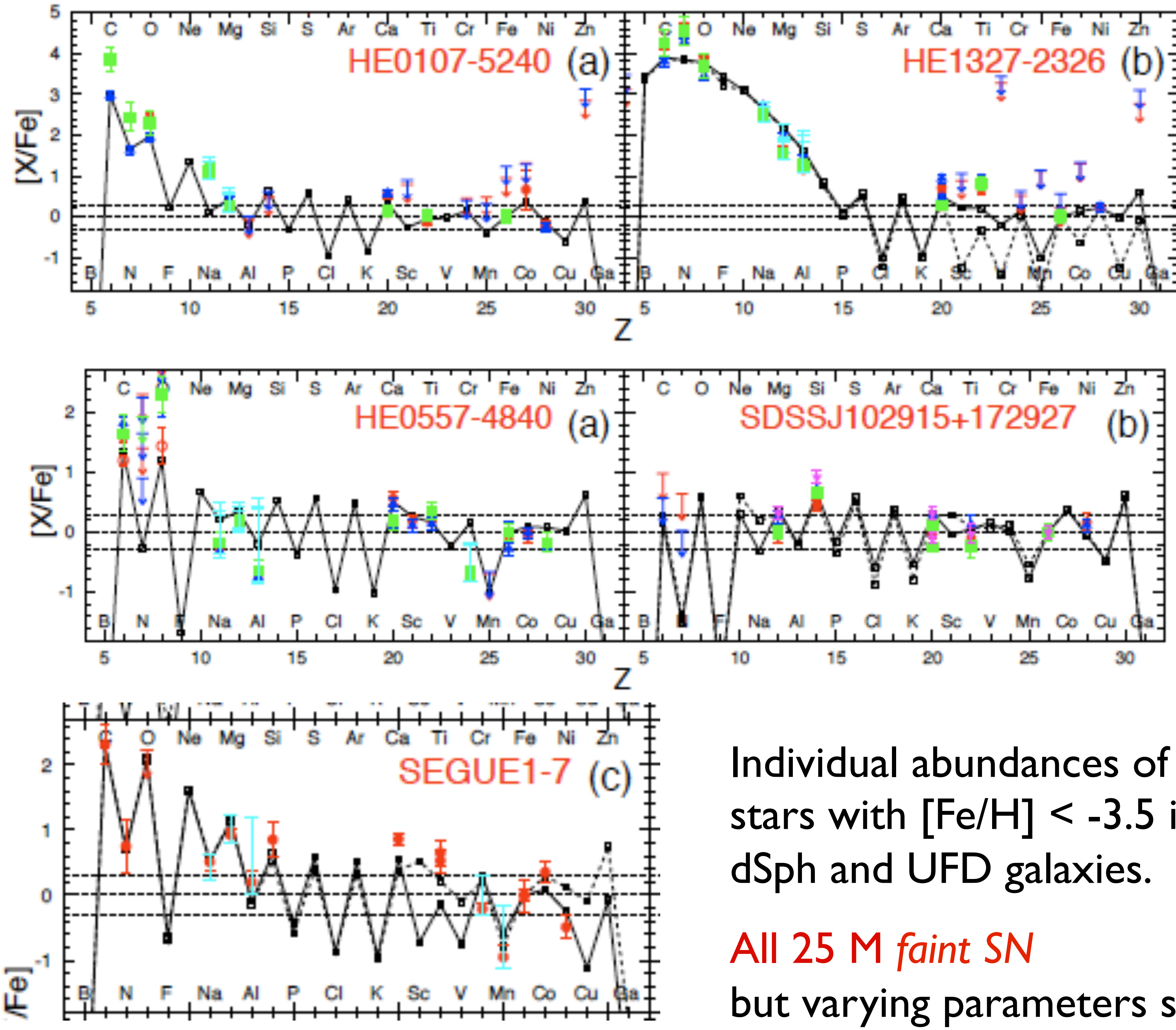
Iwamoto et al 2005

25 M Pop III "faint supernova"

(extensive mixing & fallback during the explosion)

"Faint SN"

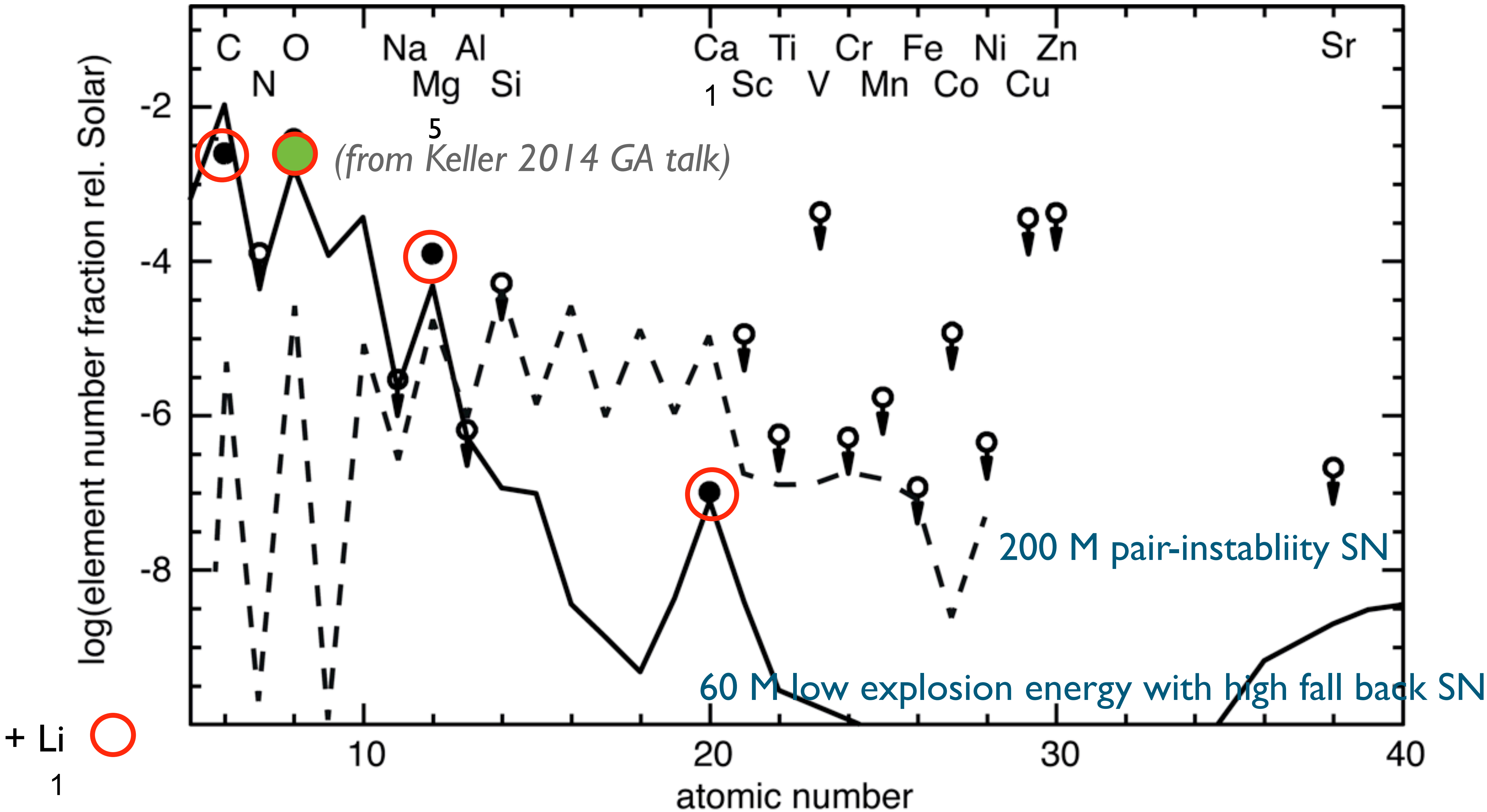
- is faint because Fe is synthesized from the 56Ni that powers the light curve.
- observed (e.g., SN1999br, SN 2008ha)
- satisfies many observational constraints (see list by Tominaga et al. 2014)



Individual abundances of 48 metal poor stars with [Fe/H] < -3.5 in the MW halo, dSph and UFD galaxies.

All 25 M *faint SN*
but varying parameters such as explosion energy, mass cuts, mixing efficiencies, etc.

Keller et al. 2014: 60 M low exp energy SN



The solid line shows the abundances predicted for a 60 M Population III star of relatively low explosion energy (1.8×10^{51} erg) and low levels of internal mixing (Joggerst, Woosley & Heger 2009). The dashed line shows the expected yield from a 200 M supernova (pair-instability mechanism).

Thus, are the metal poor stars in the MW halo and dwarfs actually representative of the First Stars?

Did 25 M faint SN contribute to

the ionizing photons at reionization?
the earliest stages of feedback?
significant stages of chemical evolution?