

The Detailed Chemical Abundance Patterns of M3 I Globular Clusters

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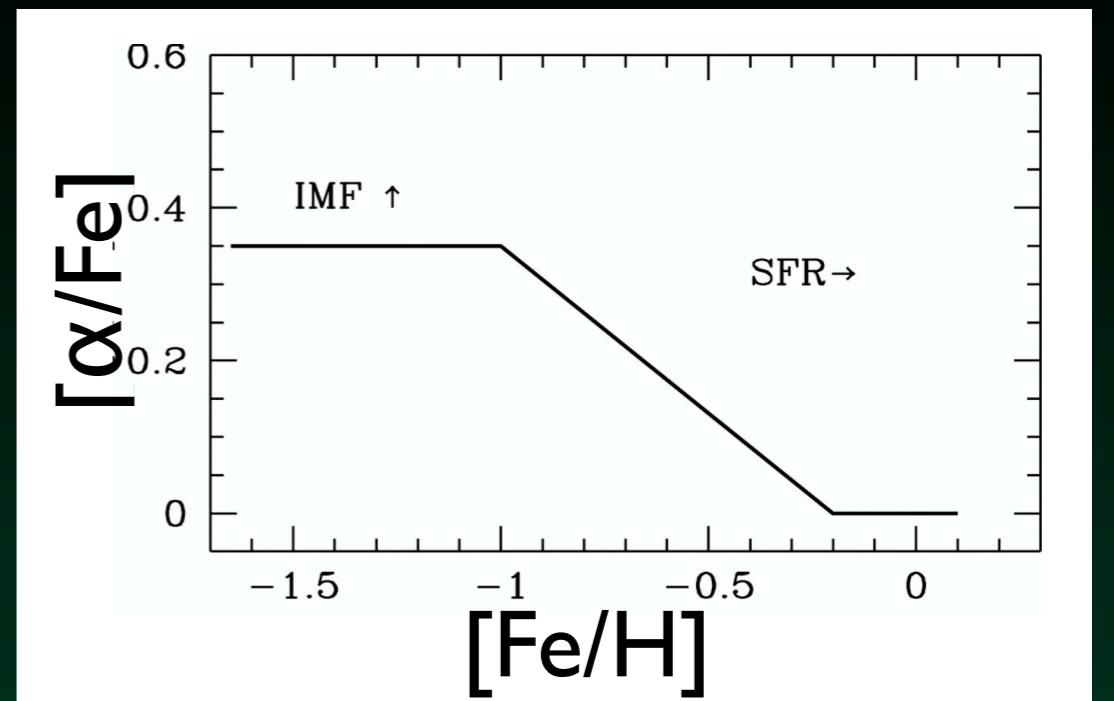
Motivation: Detailed Chemical Abundances

Stellar populations are key to studying galaxy formation

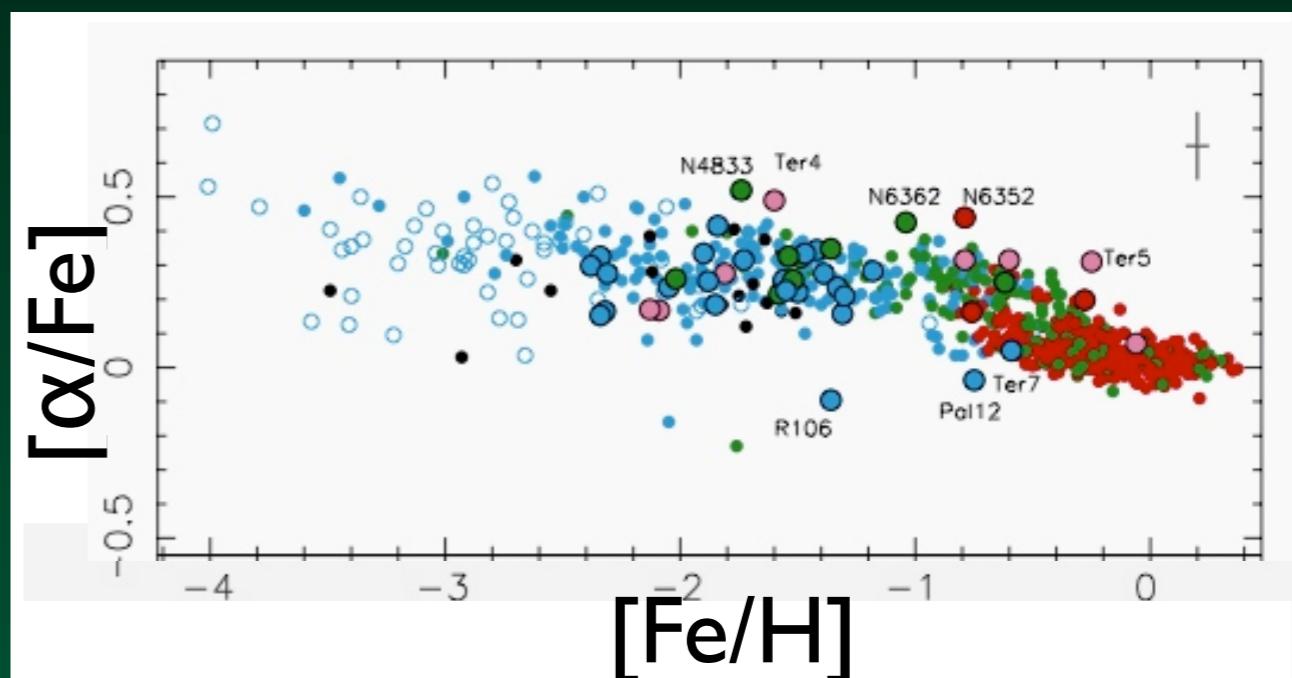
- ❖ Abundances of old stars trace galaxy formation histories
 - ❖ gas enrichment
 - ❖ star formation rates
 - ❖ supernovae rates/yields

But: The only large galaxy studied is the Milky Way

Individual stars are only accessible using high resolution spectra in nearby dwarf galaxies (i.e. within ~ 250 kpc)



McWilliam (1997)



Pritzl et al (2005)

α elements : O, Si, Ca, Ti, Mg

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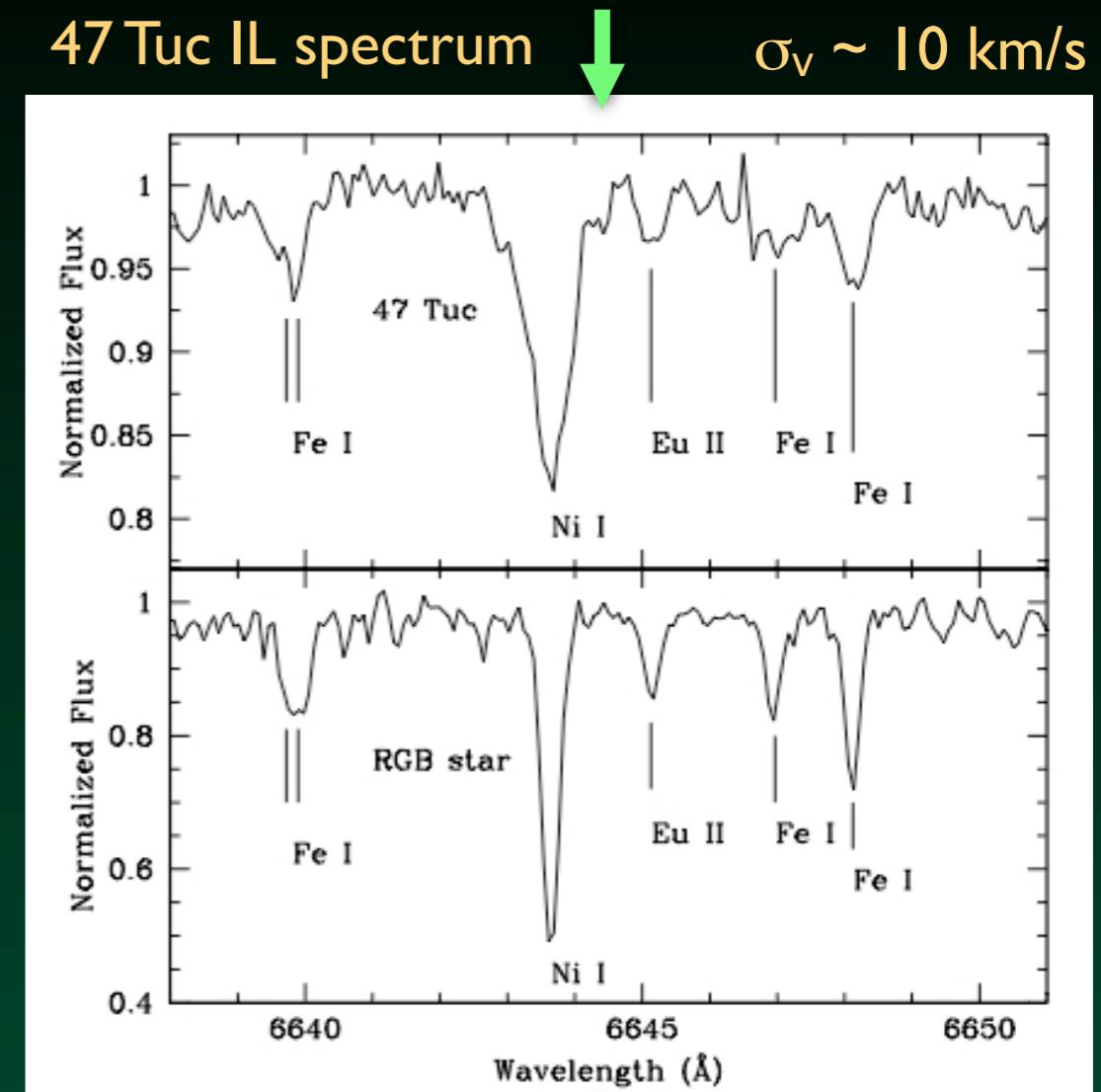
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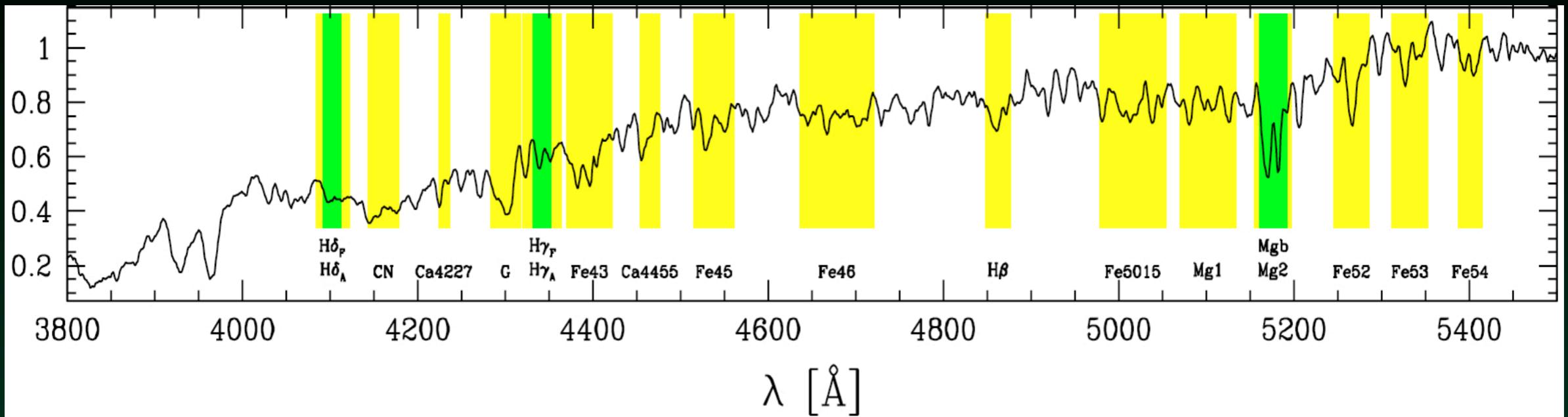
High resolution integrated light spectra (ILS) of GCs : accessible to ~ 4 Mpc today!



RGB star spectrum ↑

McWilliam & Bernstein (2008)

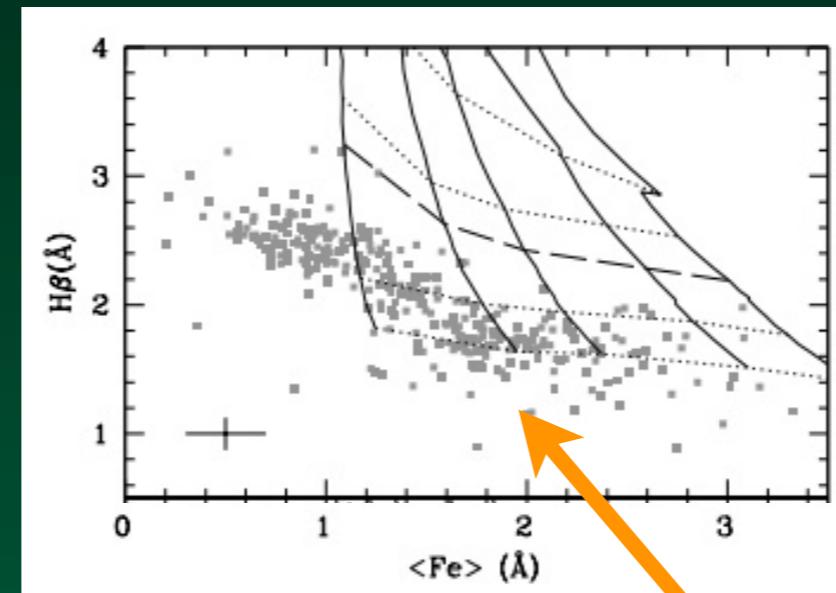
Why High Resolution Spectra of Globular Clusters?



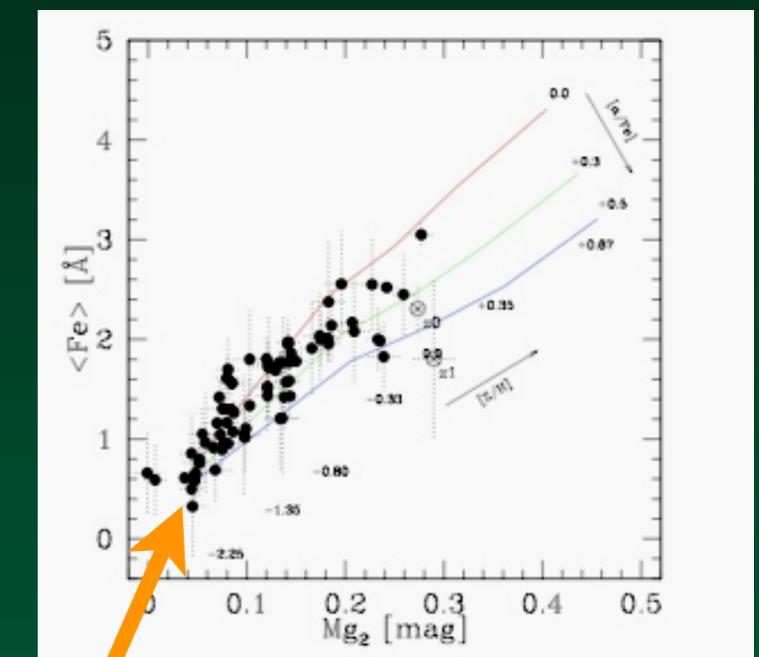
Puzia et al (2002)

Low resolution spectra and line index techniques are powerful but

- poor resolution in α and Fe at low [Fe/H]
- info on other [X/Fe] sparse
- relies on calibration to local stars



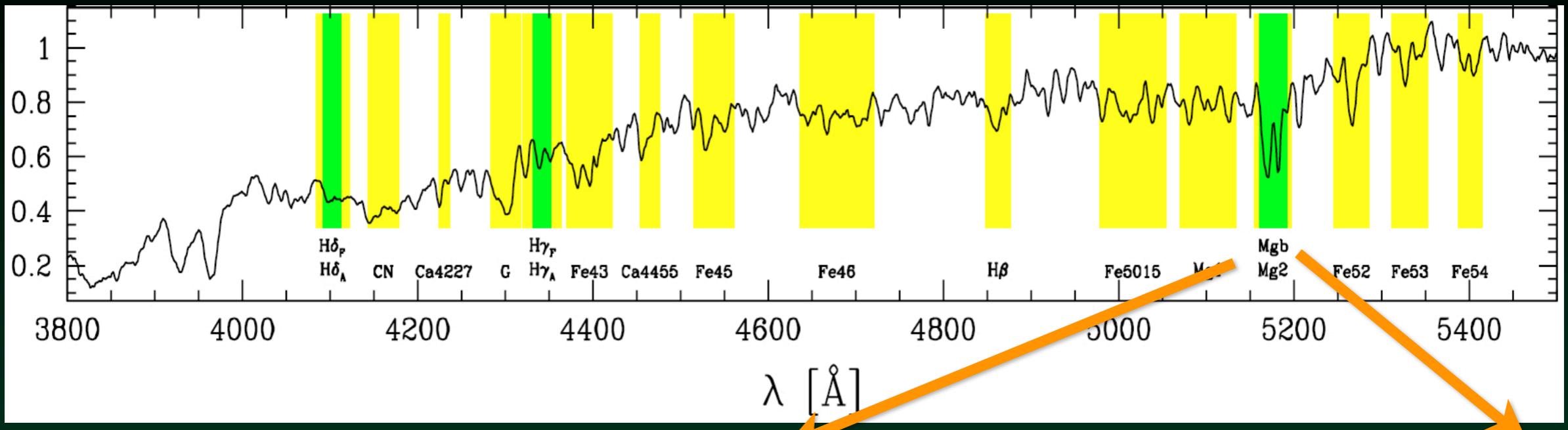
Caldwell et al (2011)



Puzia et al. (2005)

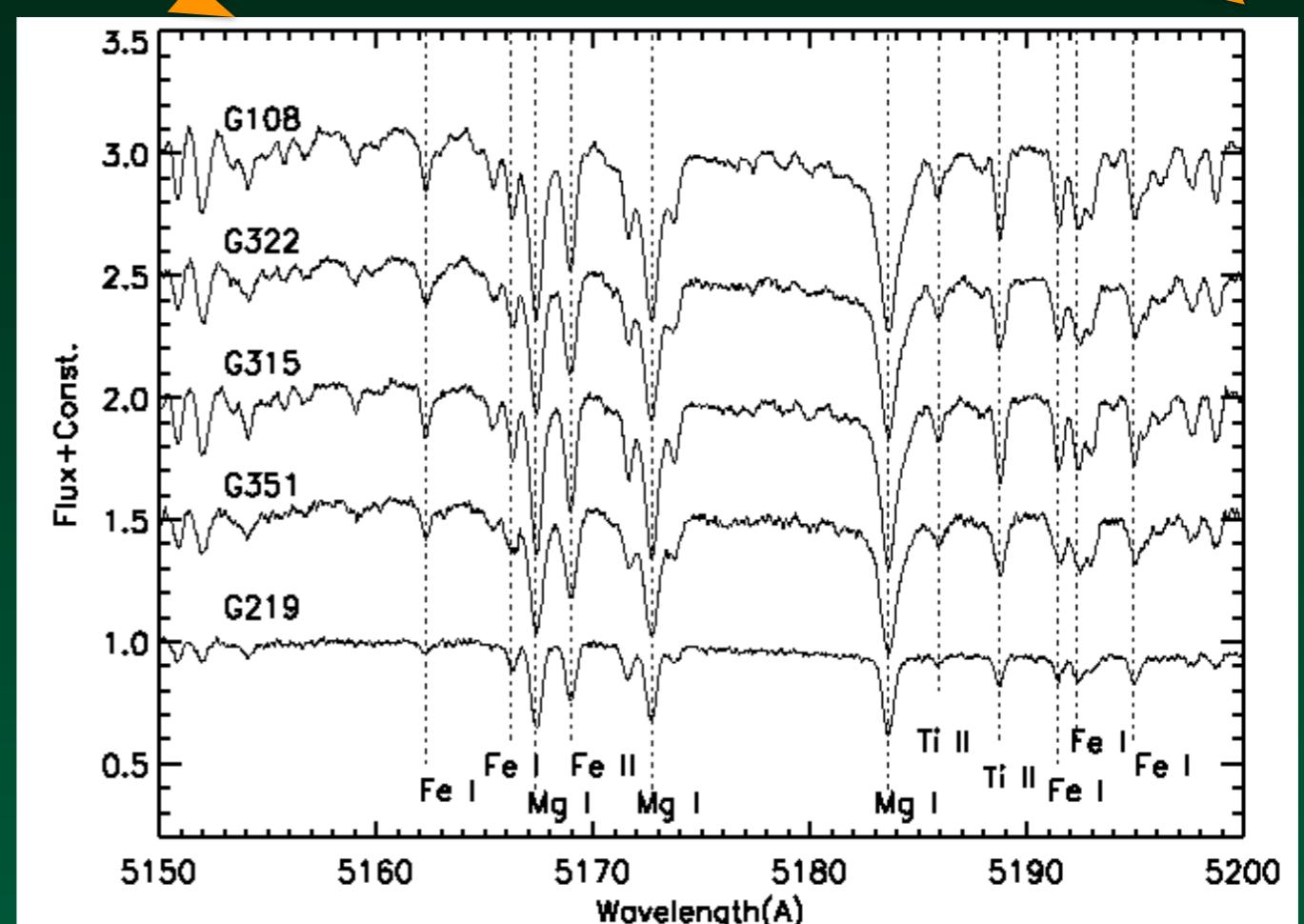
Clusters

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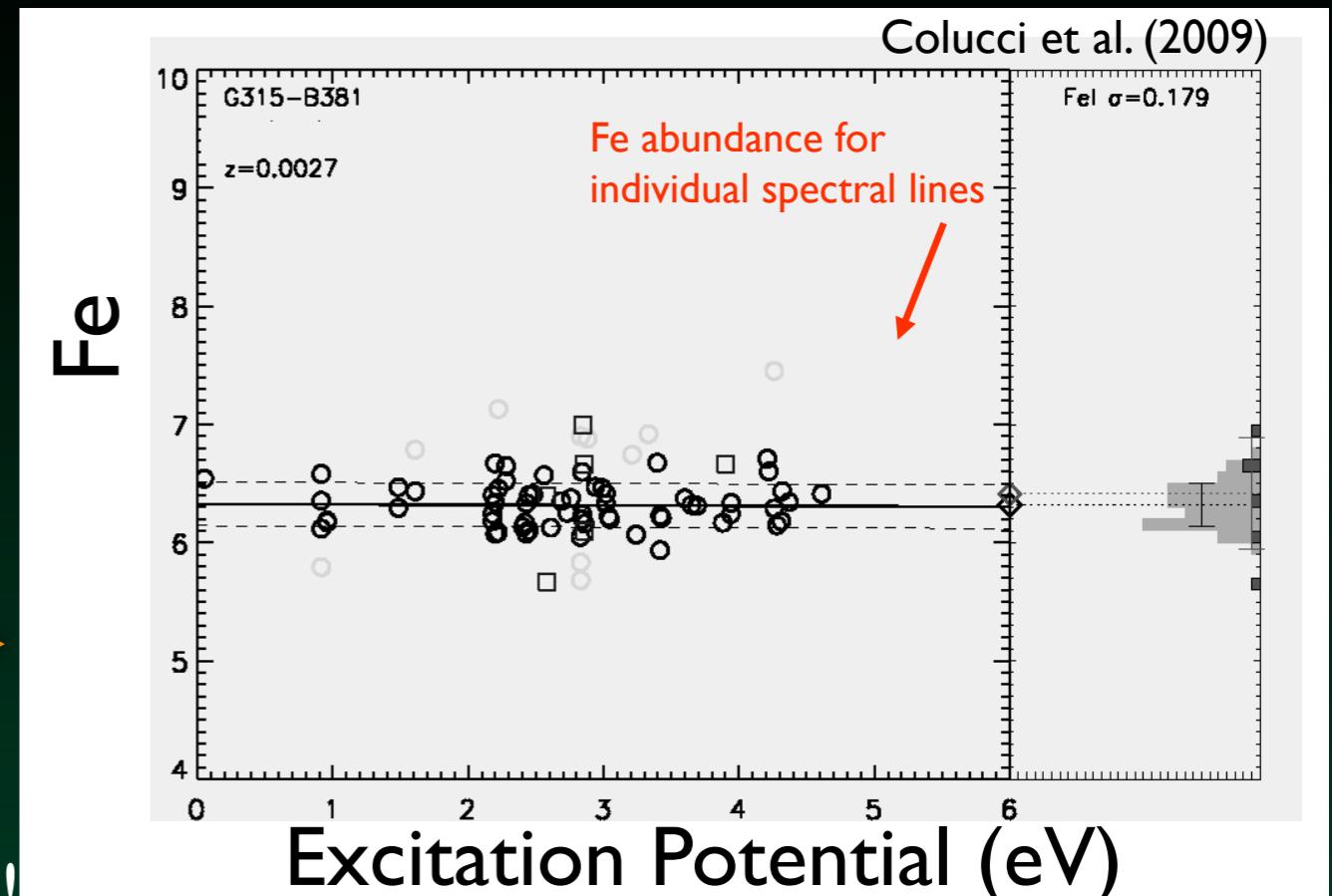
Our ILS Abundance Analysis Method

- ❖ Based on standard RGB star abundance analysis
- ❖ Use isochrones to represent entire cluster population
- ❖ Constrain Age and Z using EWs of 30 - 150 available Fe I lines 

- ❖ Also measure 20+ α , Fe-peak, neutron capture, and light elements!

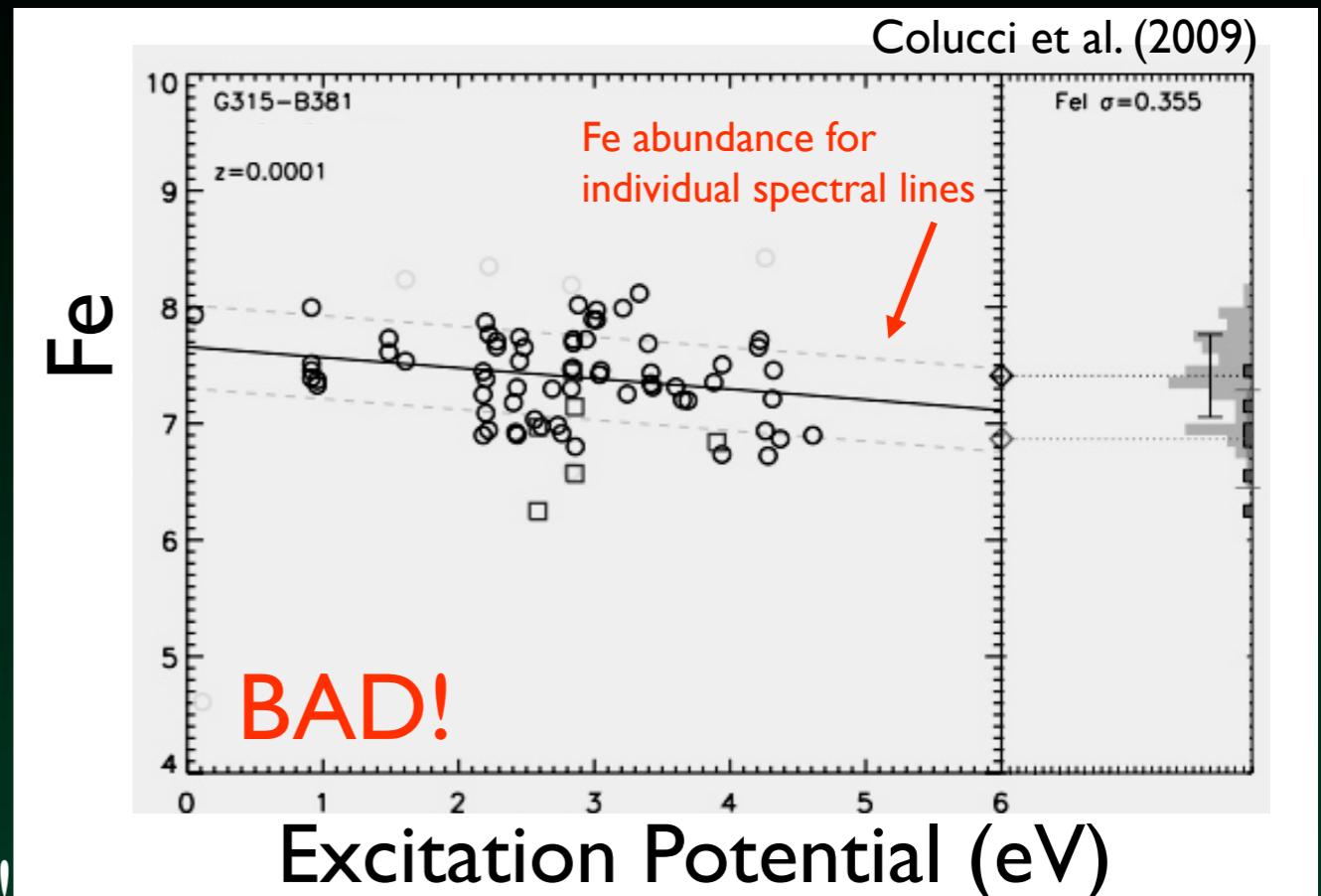
- ❖ Demonstrated accuracy of ± 0.1 dex in [Fe/H], [X/Fe]:
- ❖ Milky Way GCs with a range of [Fe/H], σv , Mv_{total} , HB morphology
(Bernstein & McWilliam 2002, 2005, McWilliam & Bernstein 2008, Cameron et al. 2010)
- ❖ Large Magellanic Cloud GCs with a range in age of 0.01 Gyr to > 10 Gyr
(Colucci et al. 2011, Colucci et al 2012, Colucci & Bernstein 2012)

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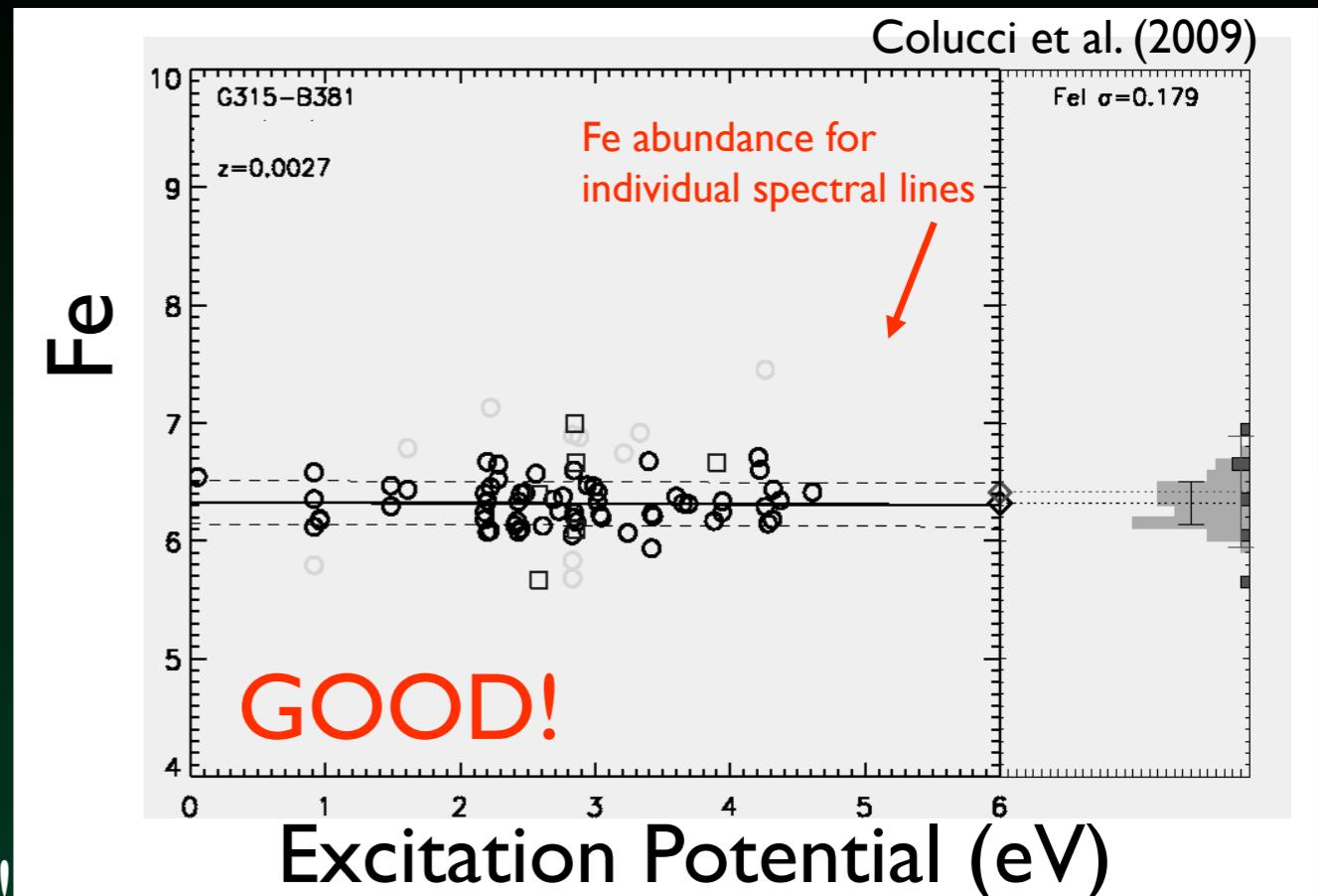


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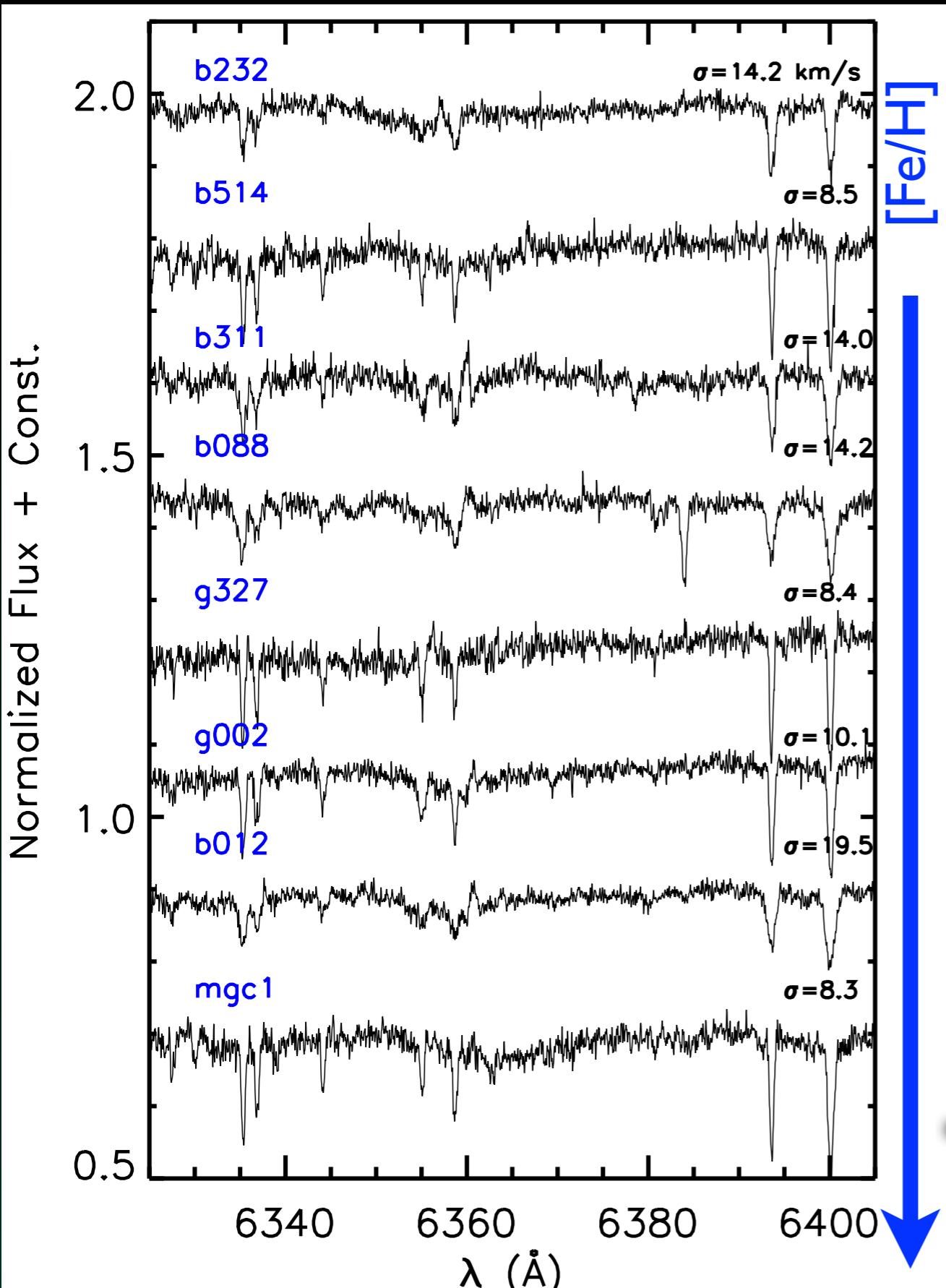
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M3 I Sample



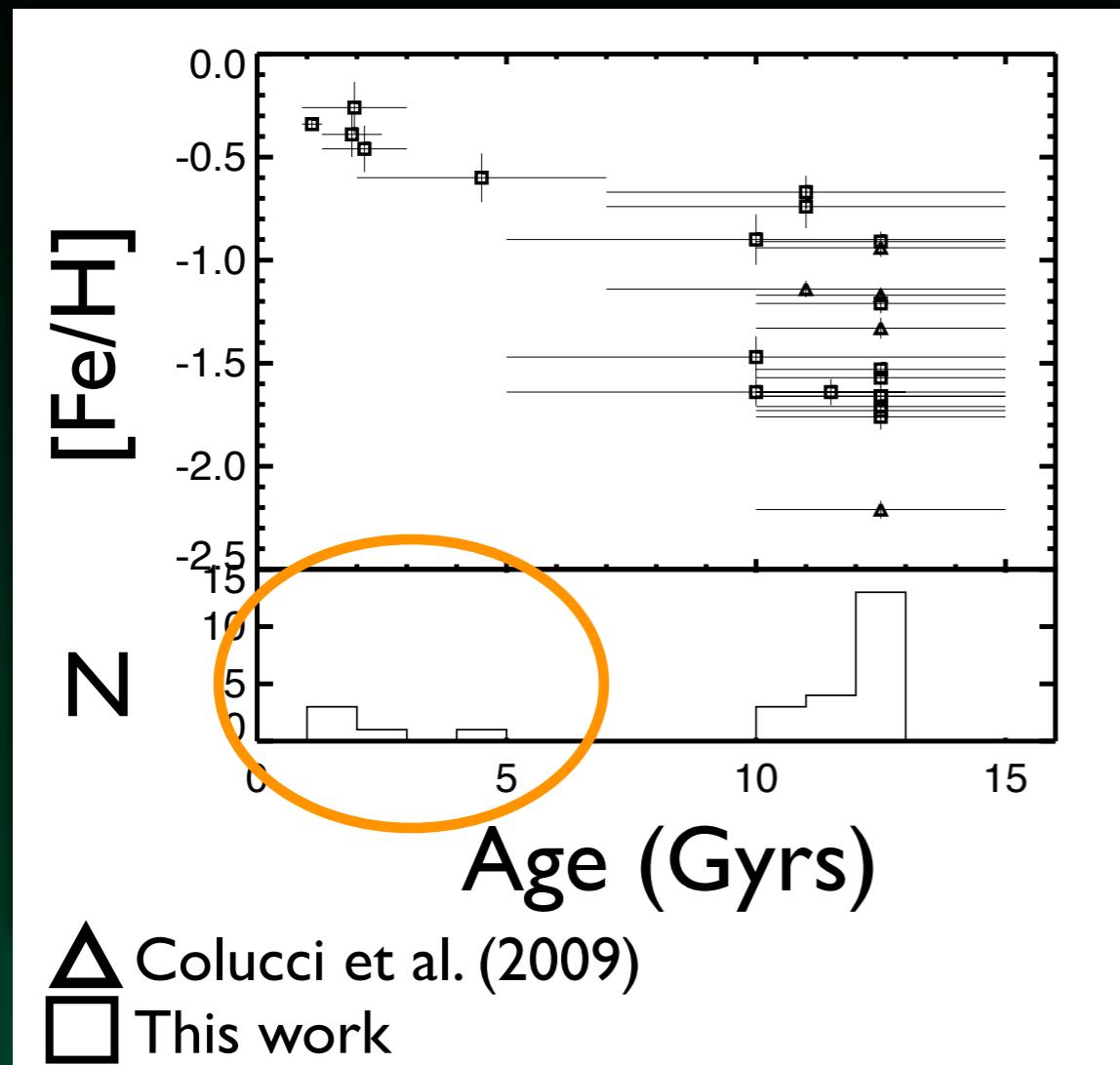
- Data from Keck/HIRES
- Resolution $\sim 24,000$
- 3500-8500 Å wavelength coverage
- SNR > 60

The Clusters:

- V Magnitudes of 14-17
- Galactocentric Radii of 2-117 kpc
- Metallicities of -2.2 to -0.1
- Velocity dispersions of 6 to 30 km/s

→ 27 GC spectra to date

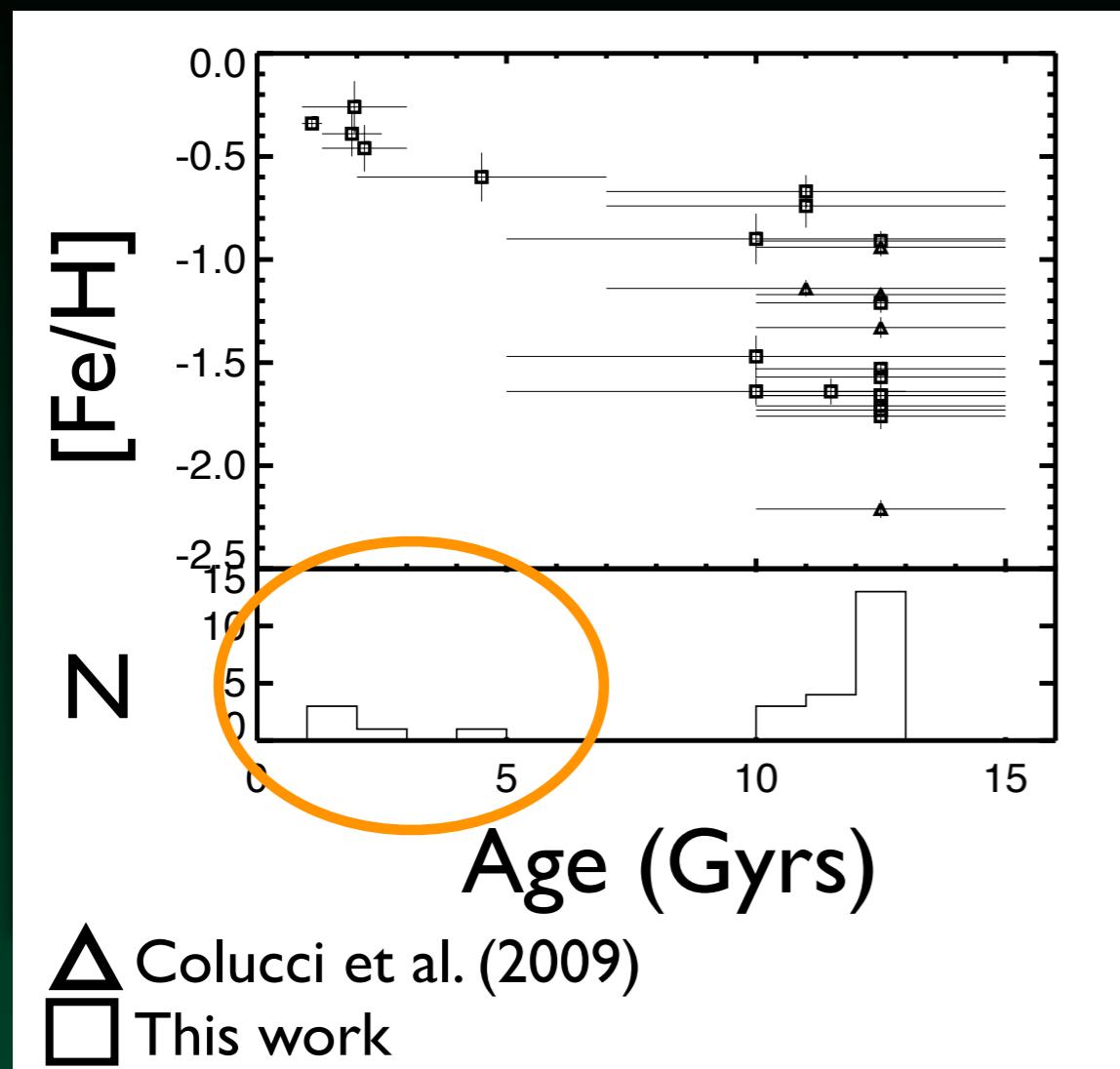
Initial Results: Fascinating if true!



- ❖ intermediate ages found at high $[Fe/H]$
- ❖ What about Blue Horizontal Branch stars?
- ❖ What else can we learn and how can we take advantage of our unique data?

Strong constraints required better tools!

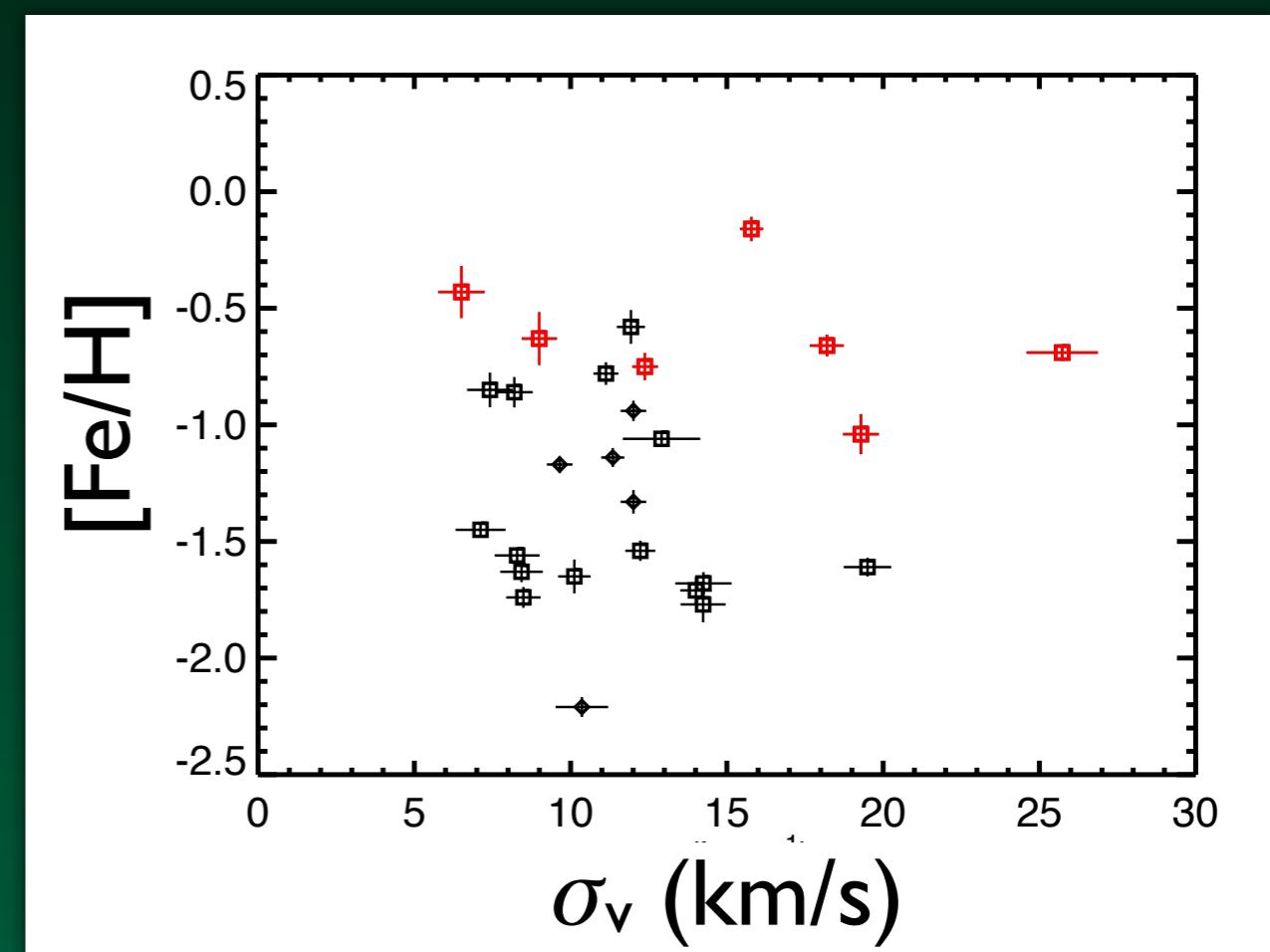
Developing Better Tools:



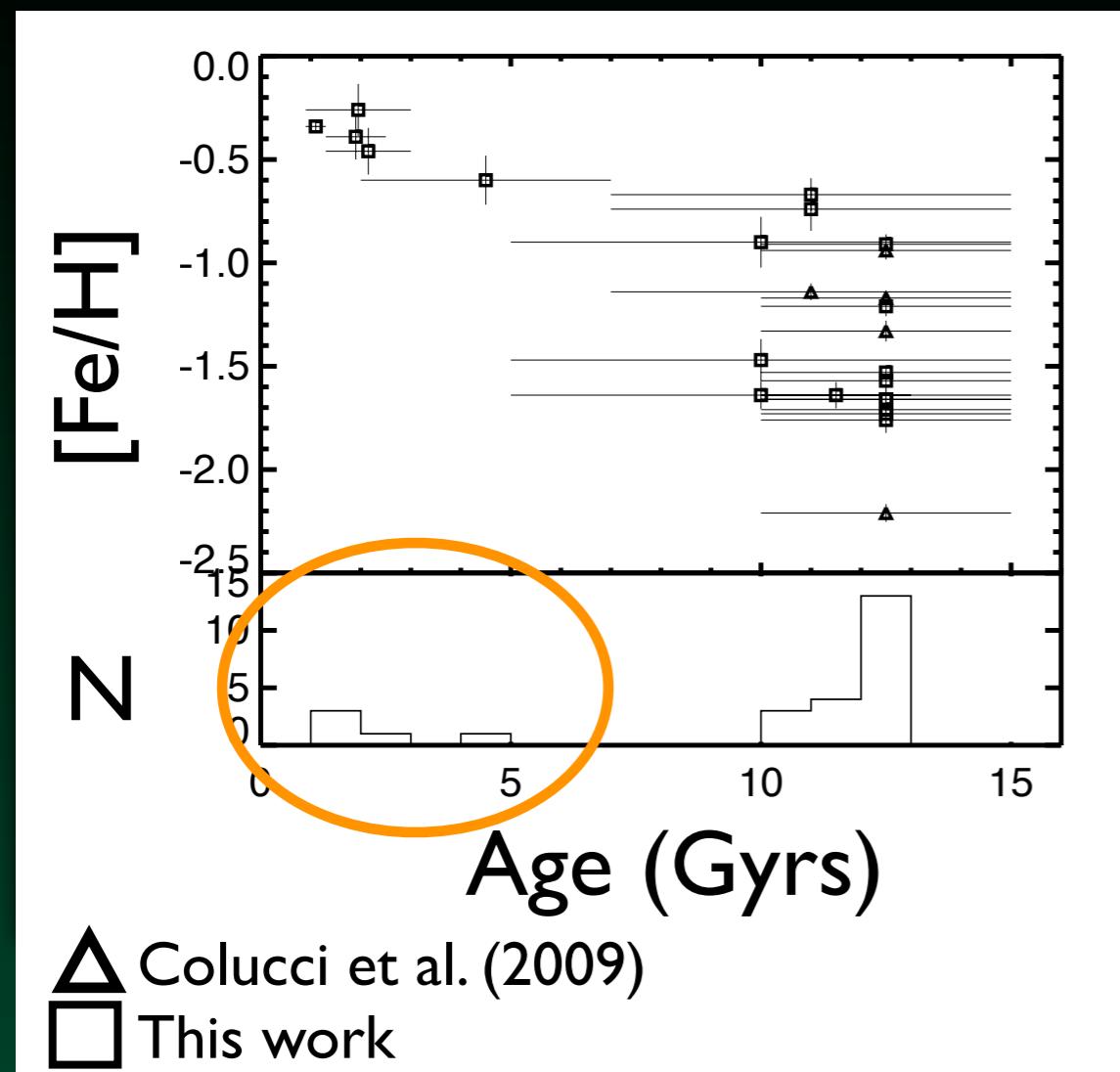
→ Synthesize all Fe Lines
for these GCs!

Two Subtleties Uncovered:

#1. Analysis of high [Fe/H] and high velocity dispersion GCs is really sensitive to line blending



Developing Better Tools:

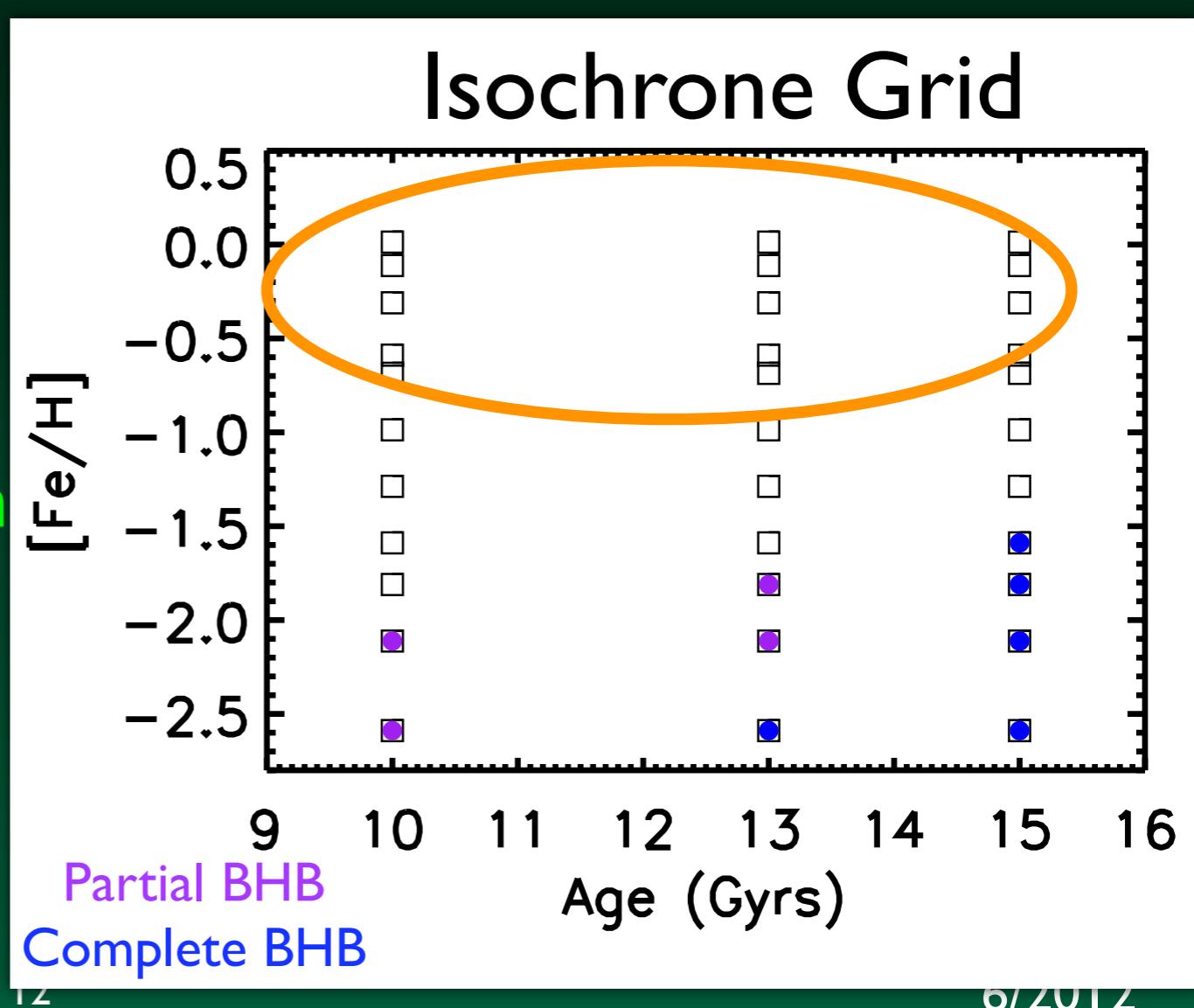


BHB stars are only present in a limited range in [Fe/H] and age in the isochrones

→ Put in BHB ad hoc!

Two Subtleties Uncovered:

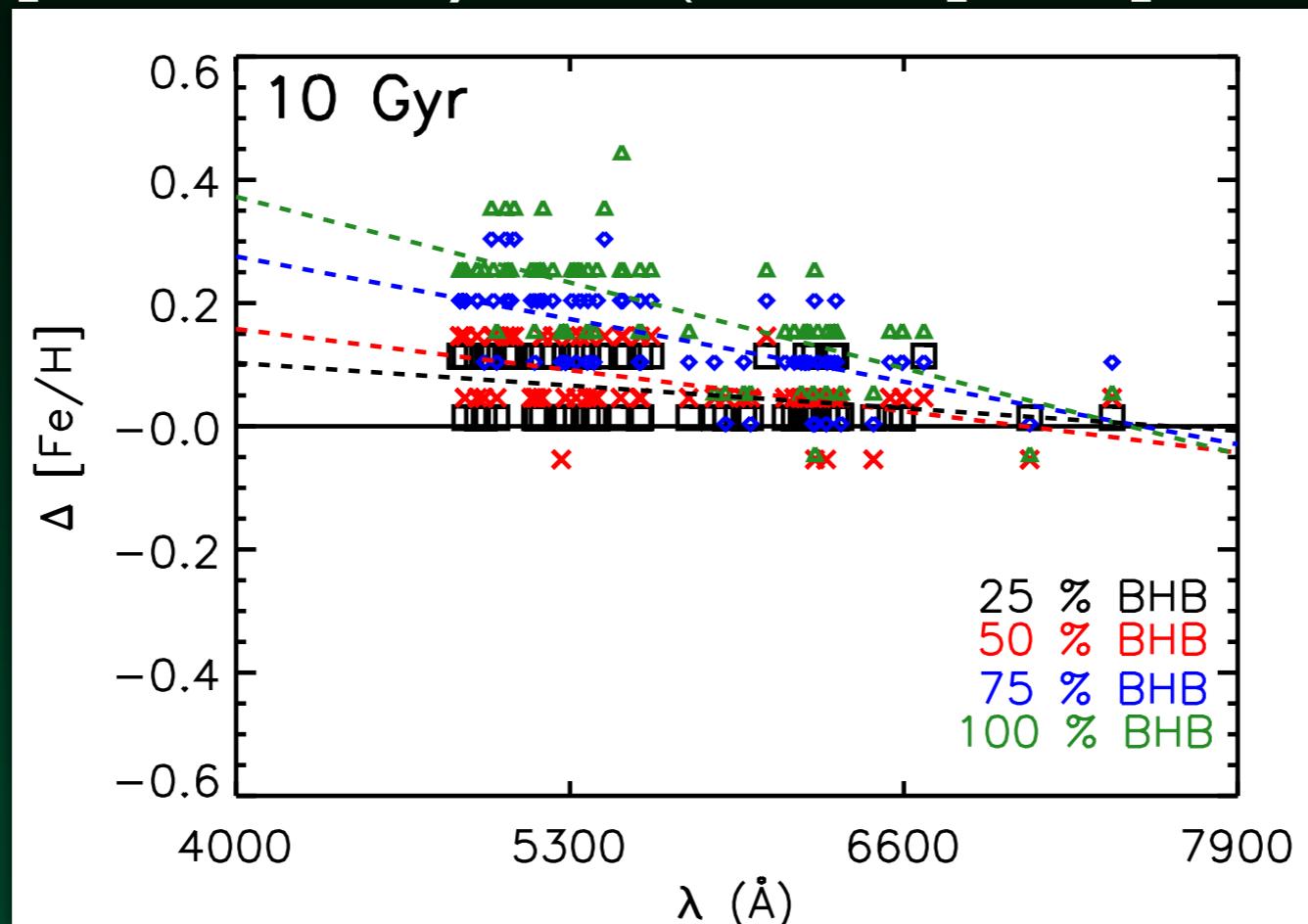
#2: high [Fe/H] and a blue horizontal branch (BHB) can affect age measurement



A simple method for evaluating (missing) blue flux

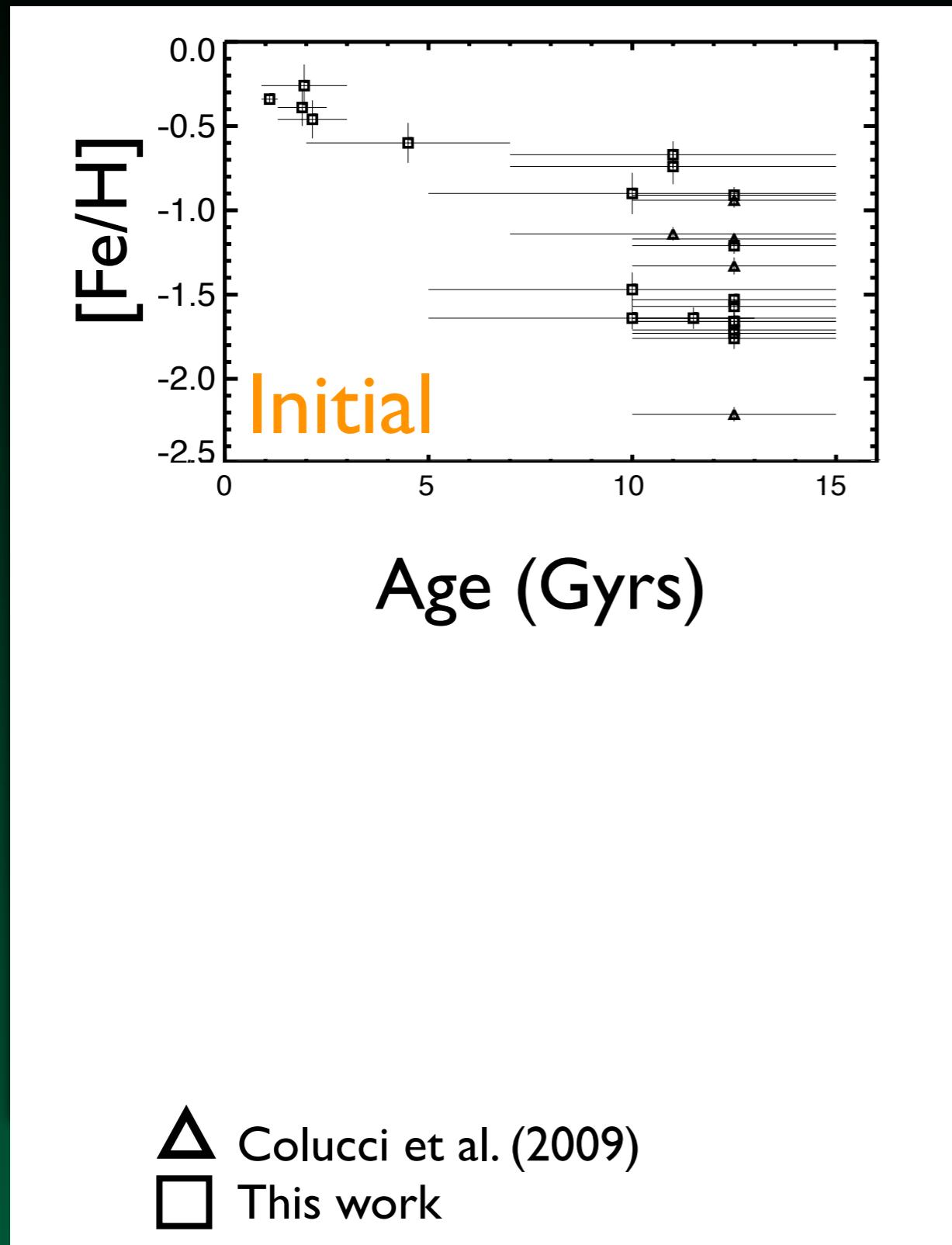
Example: Milky Way GC NGC 6752

- $[\text{Fe}/\text{H}] = -1.6$, 13 Gyrs (i.e low $[\text{Fe}/\text{H}]$ with BHB)



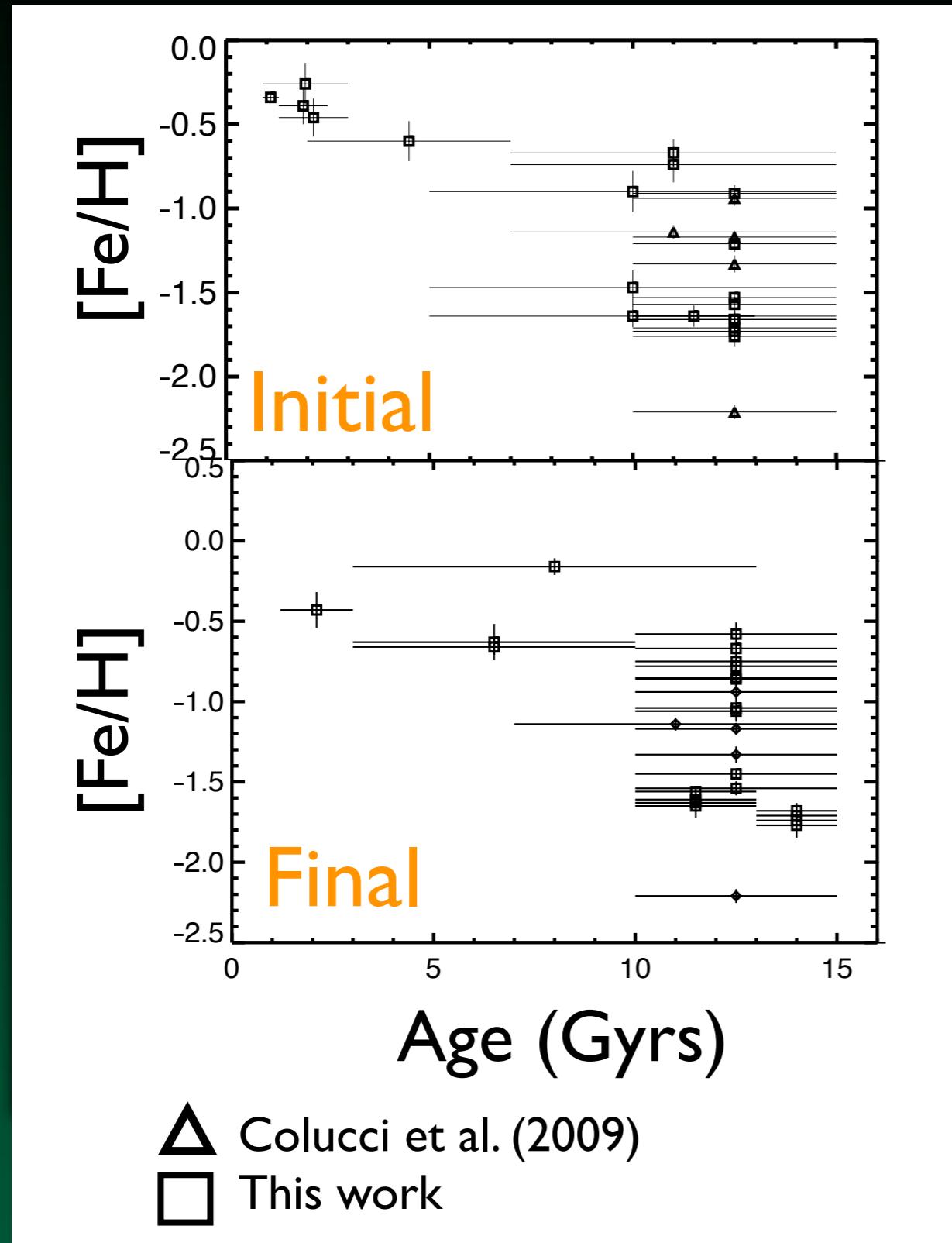
- Blue Lines most sensitive to BHB
- New result: Same age, better solution!
- In M31 high $[\text{Fe}/\text{H}]$ GCs ages can be more affected

M3 I Globular Cluster Fe and Age Results



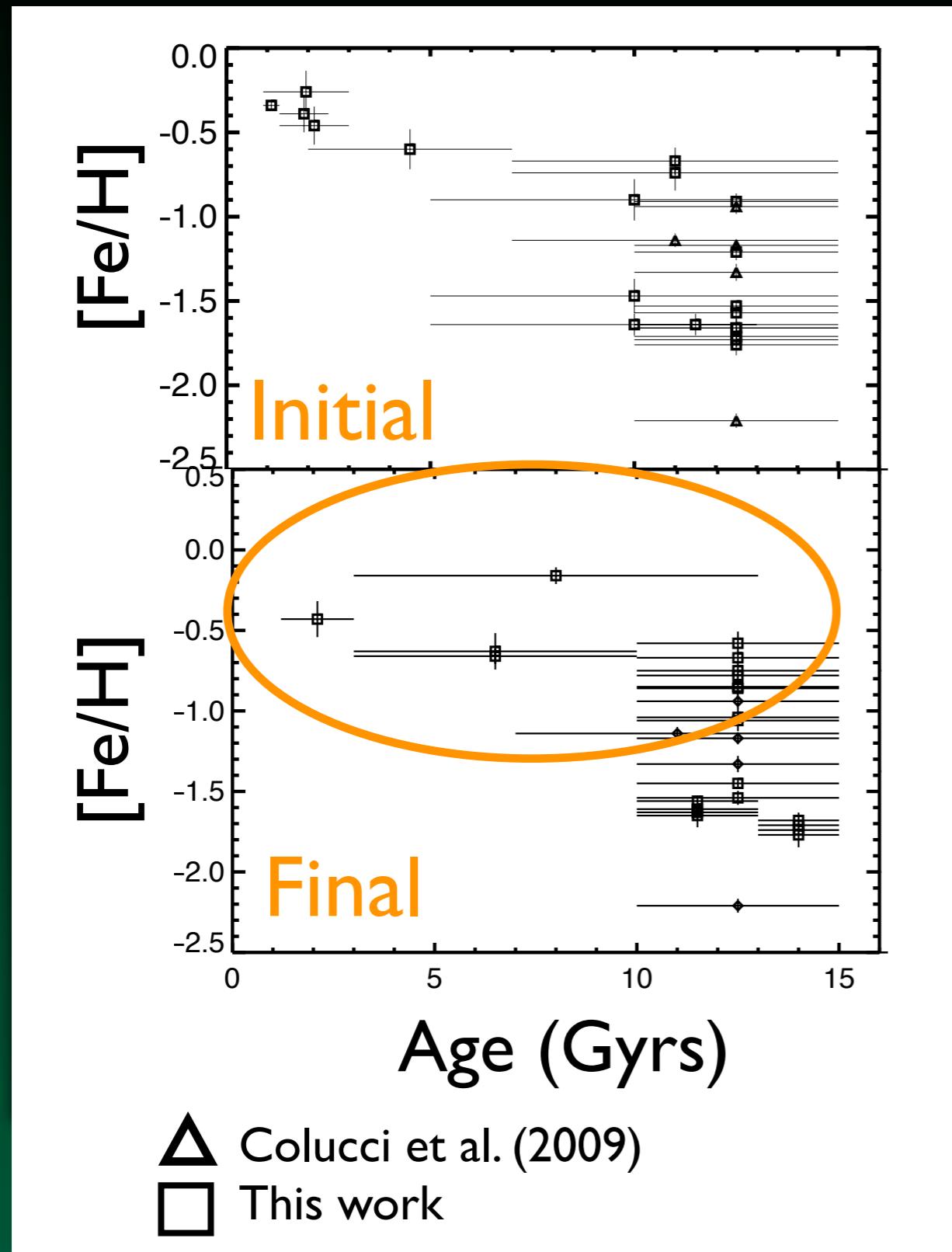
- $-2.2 < [\text{Fe}/\text{H}] < -0.1$

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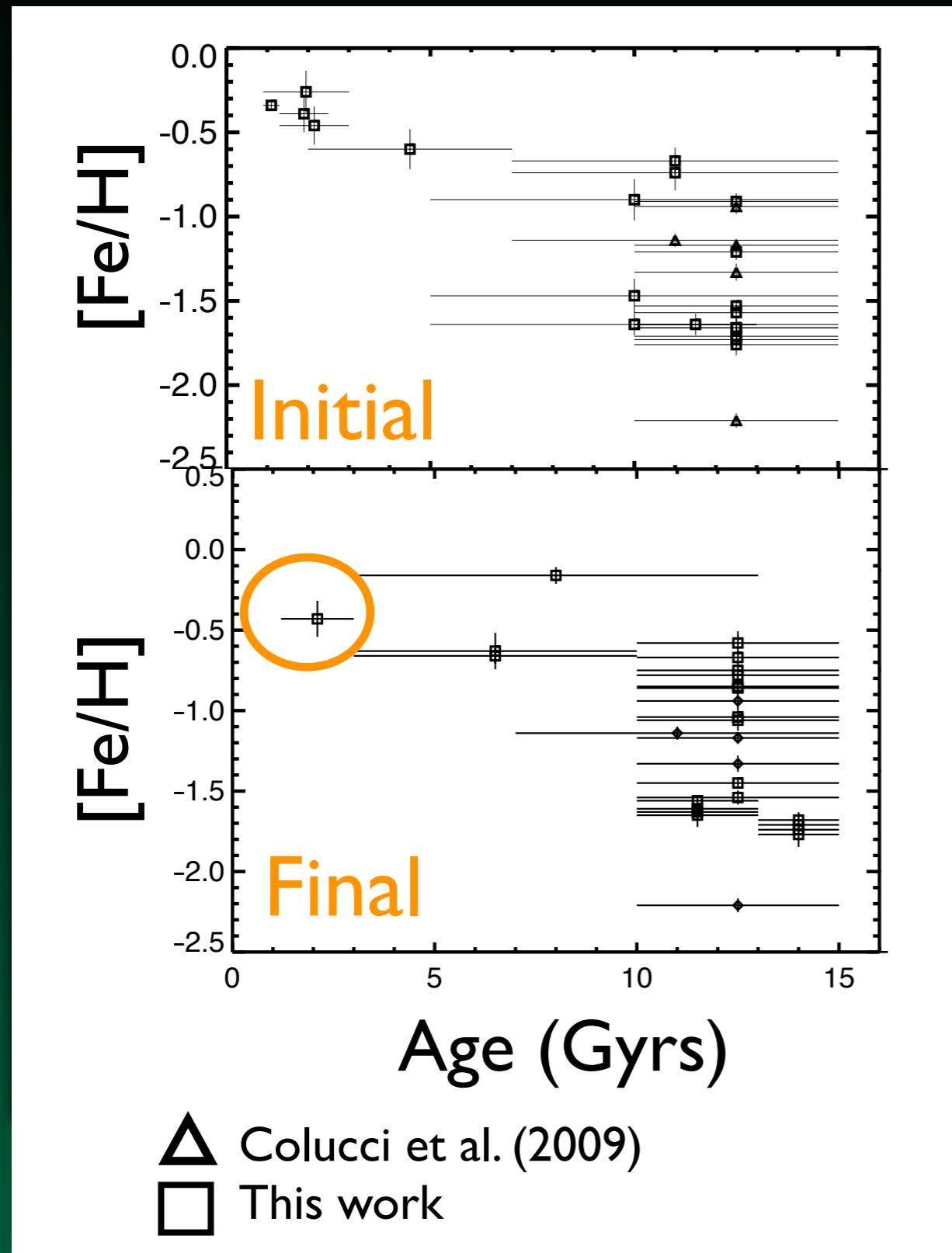
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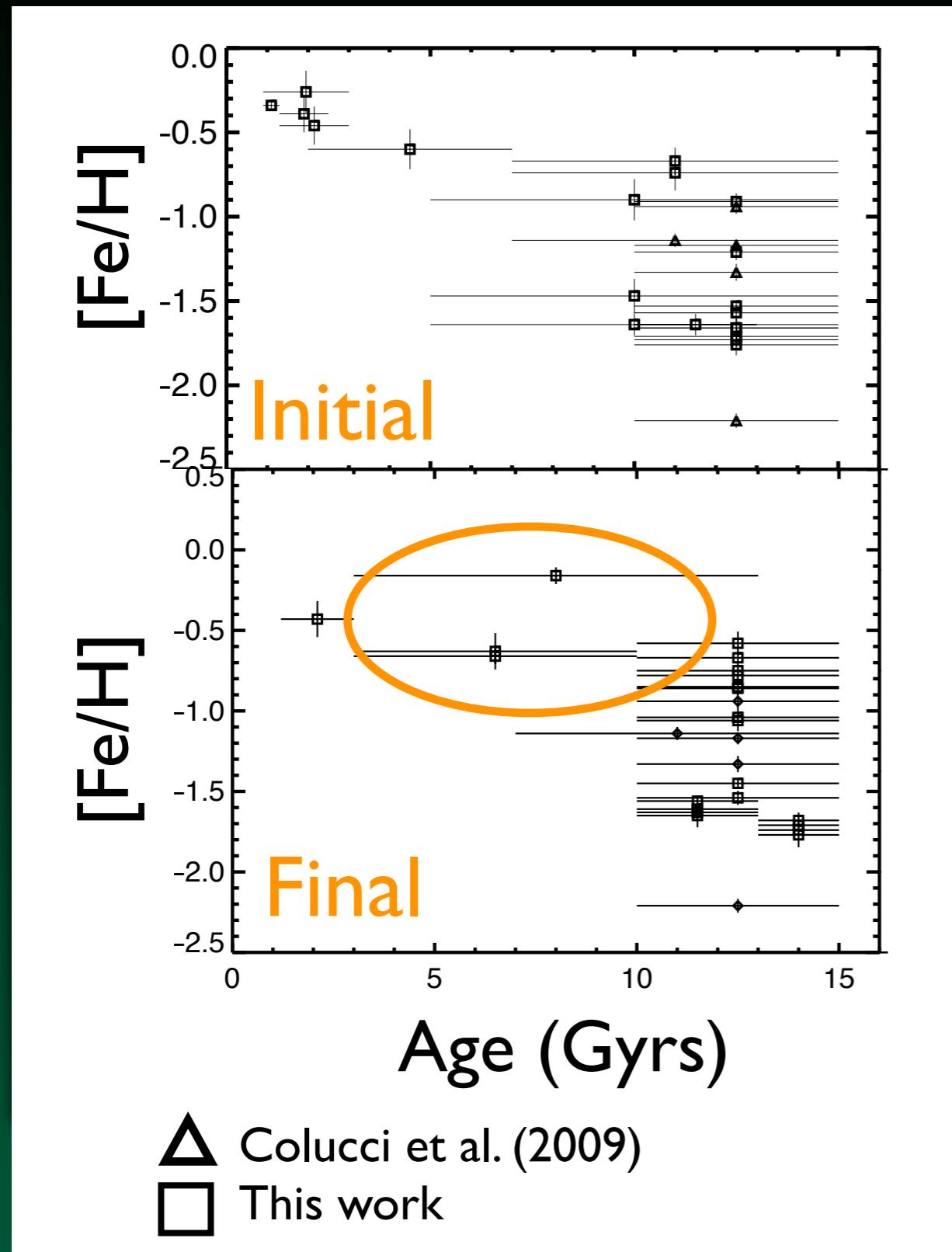
- $-2.2 < [\text{Fe}/\text{H}] < -0.1$
- A less extreme trend of decreasing age with increasing $[\text{Fe}/\text{H}]$... but several still present

M31 Globular Cluster Fe and Age Results



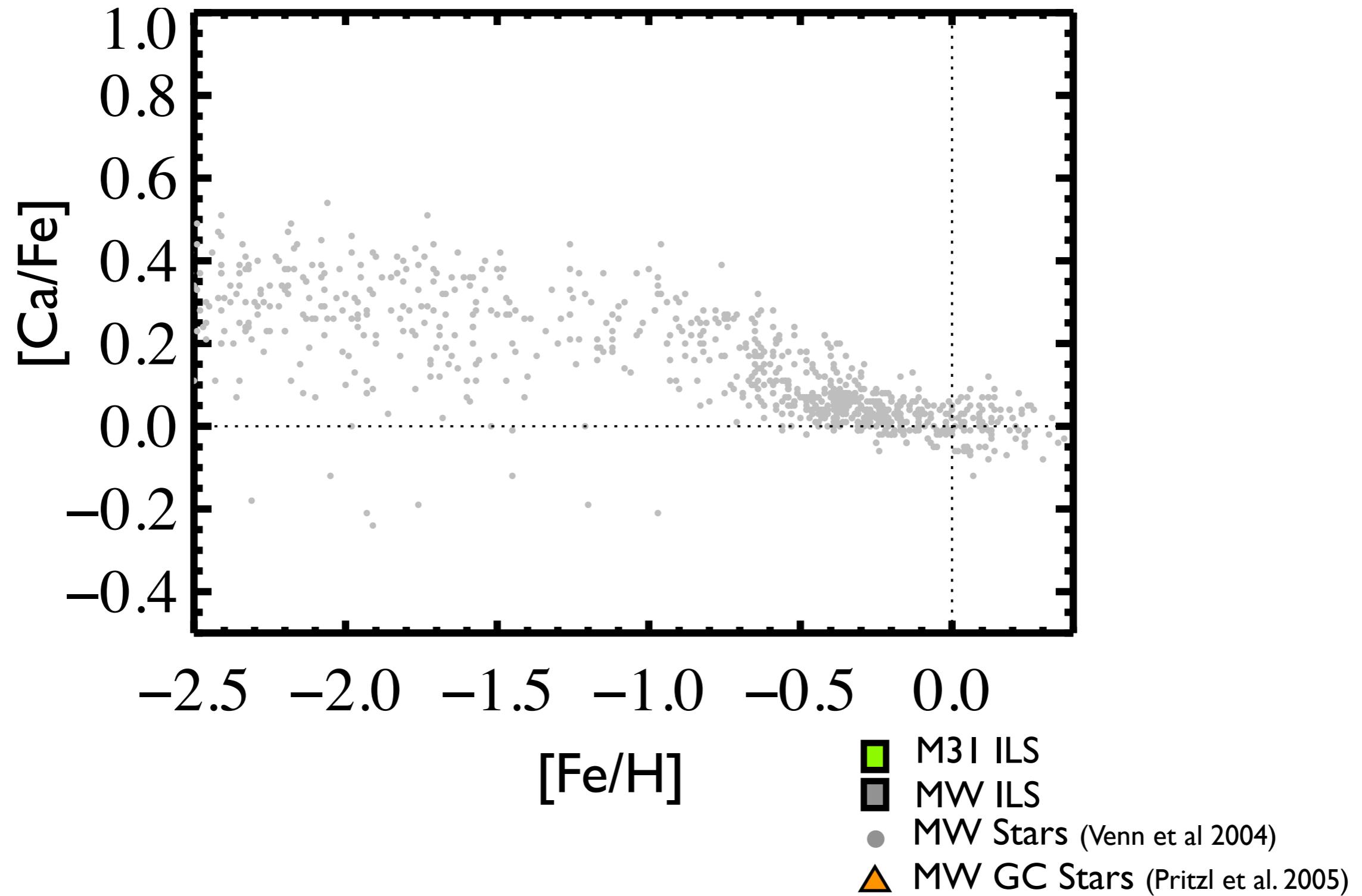
- $-2.2 < [\text{Fe}/\text{H}] < -0.1$
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- B029: A young metal-rich GC

M31 Globular Cluster Fe and Age Results

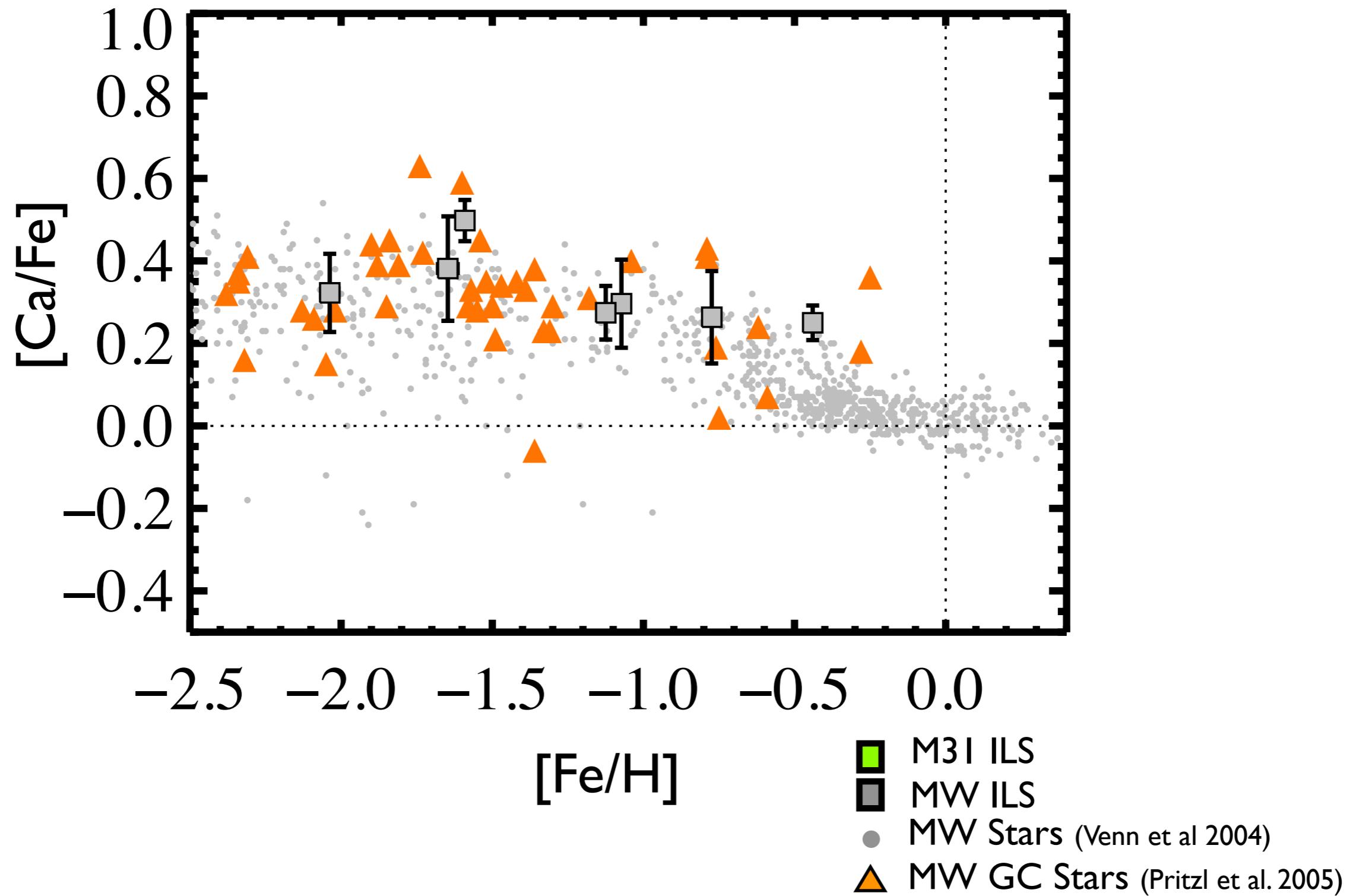


- $-2.2 < [\text{Fe}/\text{H}] < -0.1$
- A less extreme trend of decreasing age with increasing $[\text{Fe}/\text{H}]$... but several still present
- B029: A young metal-rich GC
- High $[\text{Fe}/\text{H}]$ GCs with BHGs!

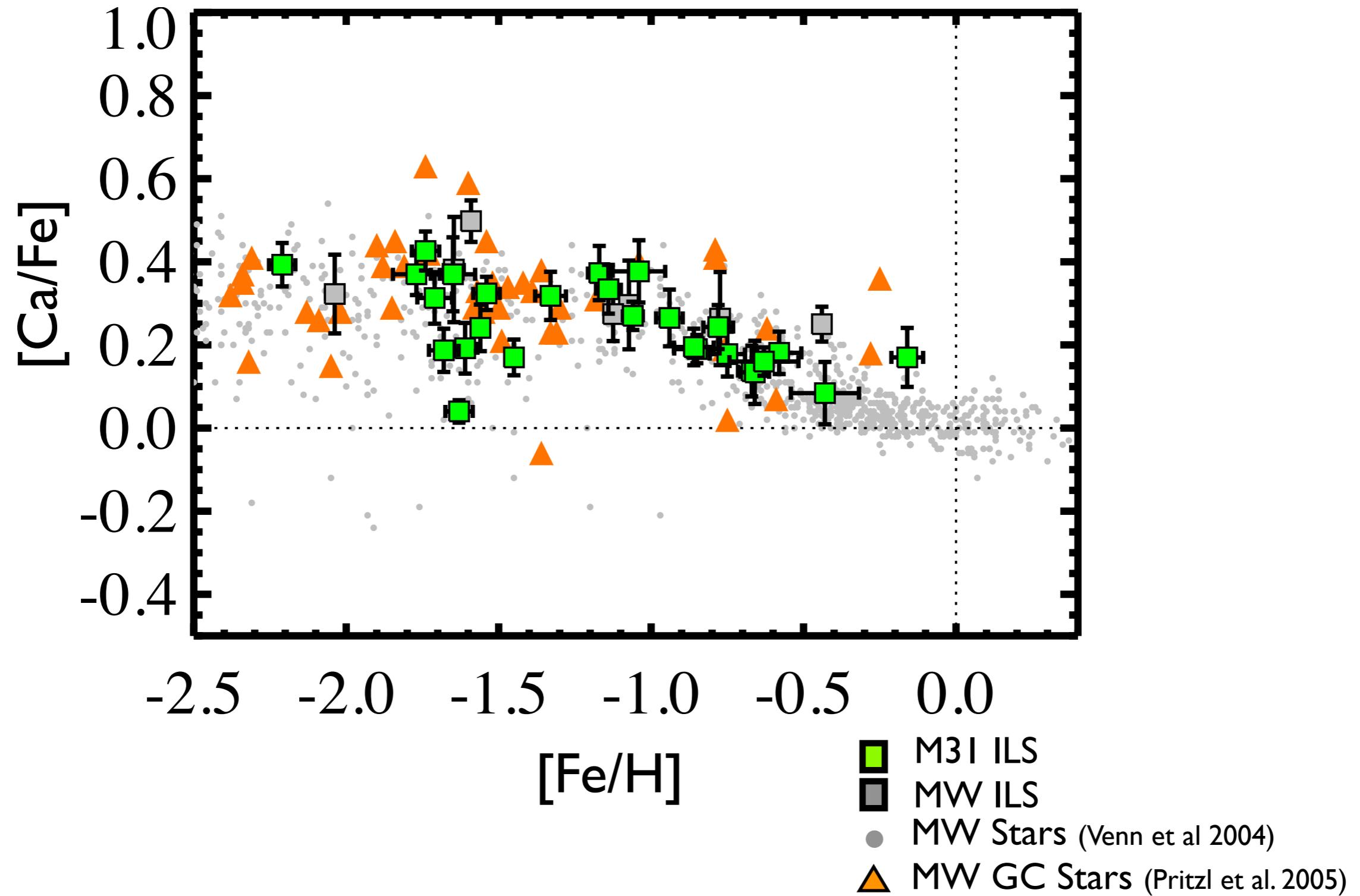
Results: First Individual Ca,Ti,Si measurements for M3I GCs



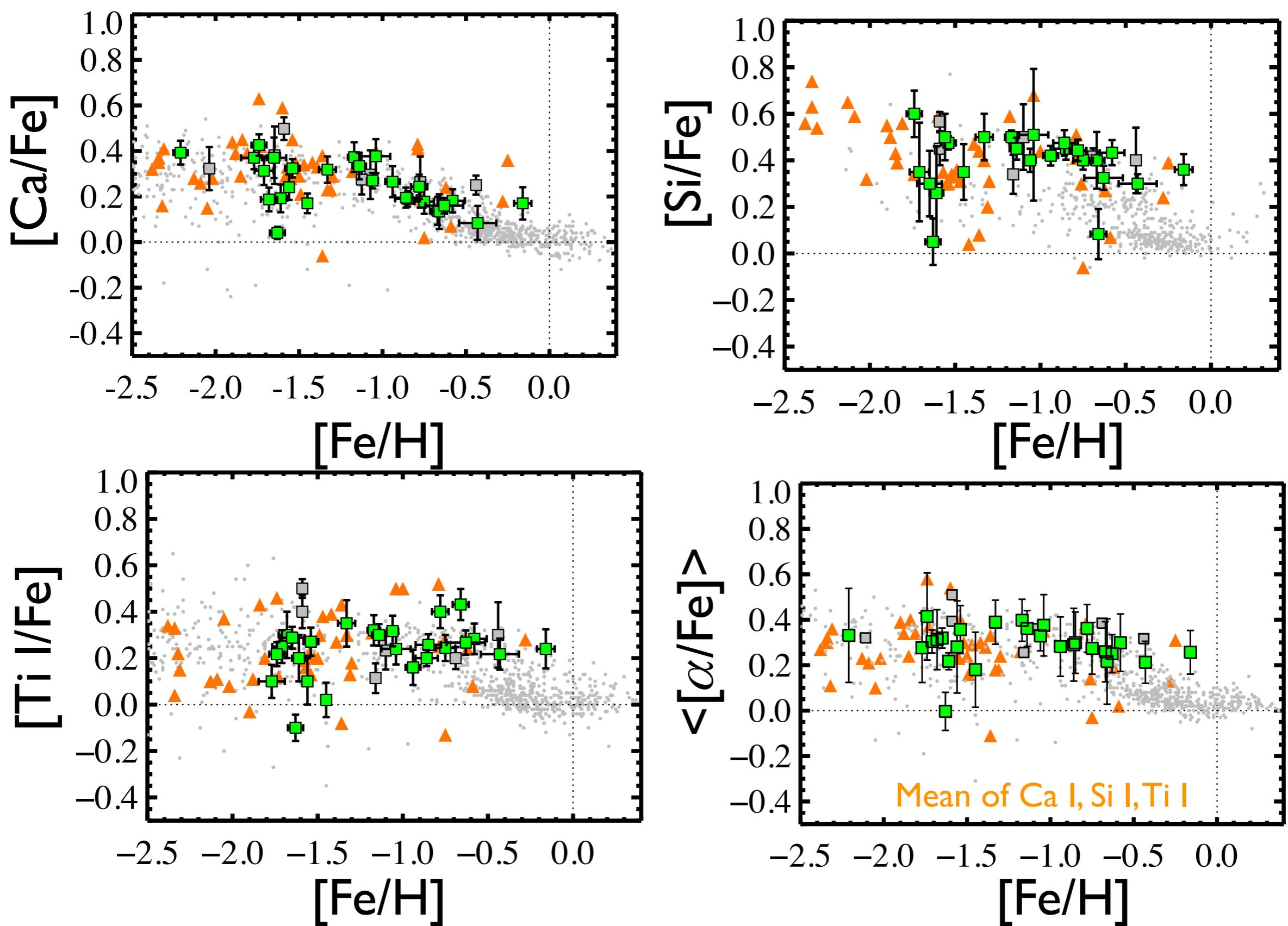
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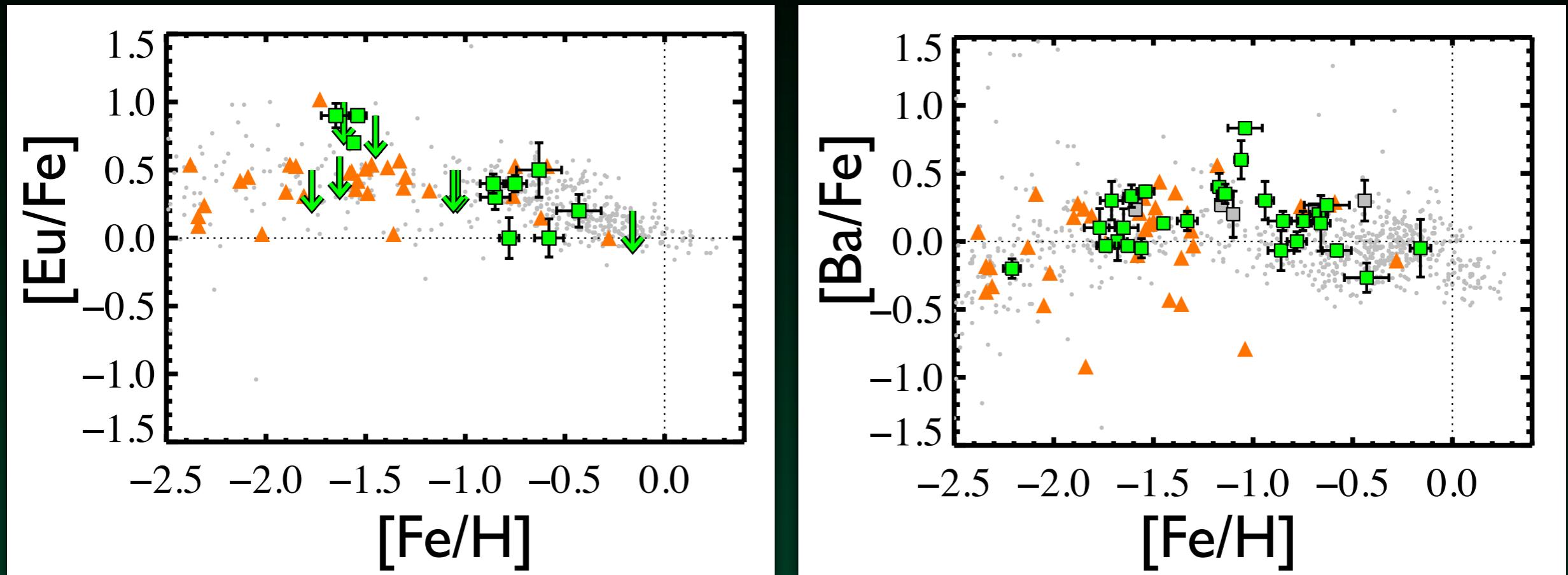
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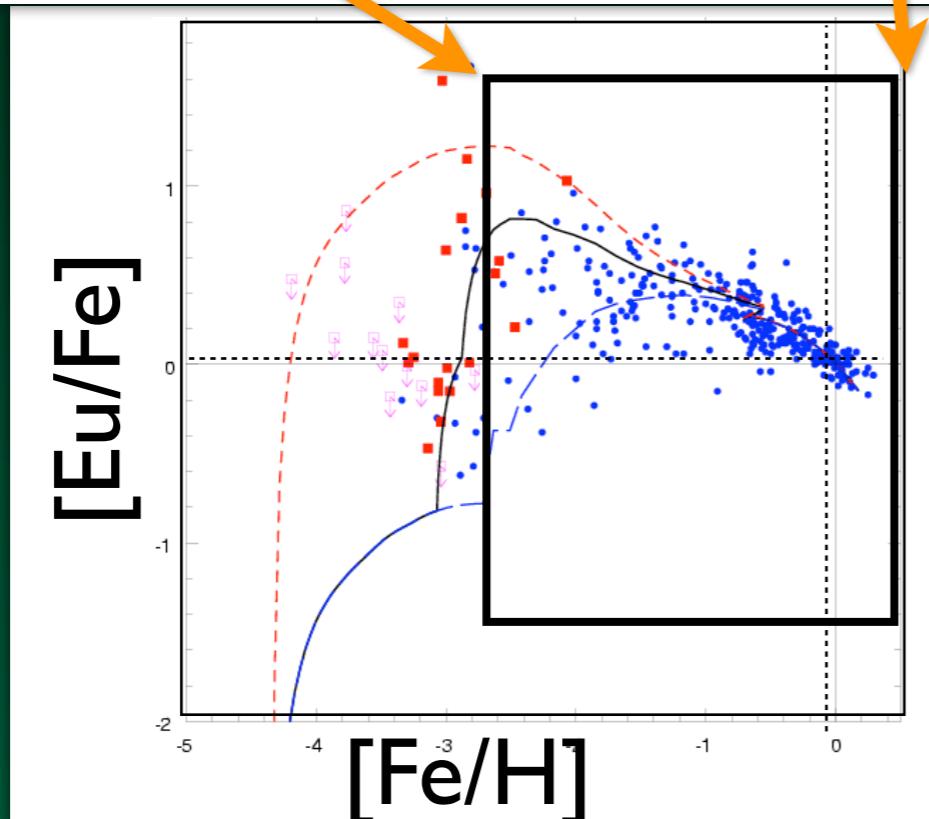
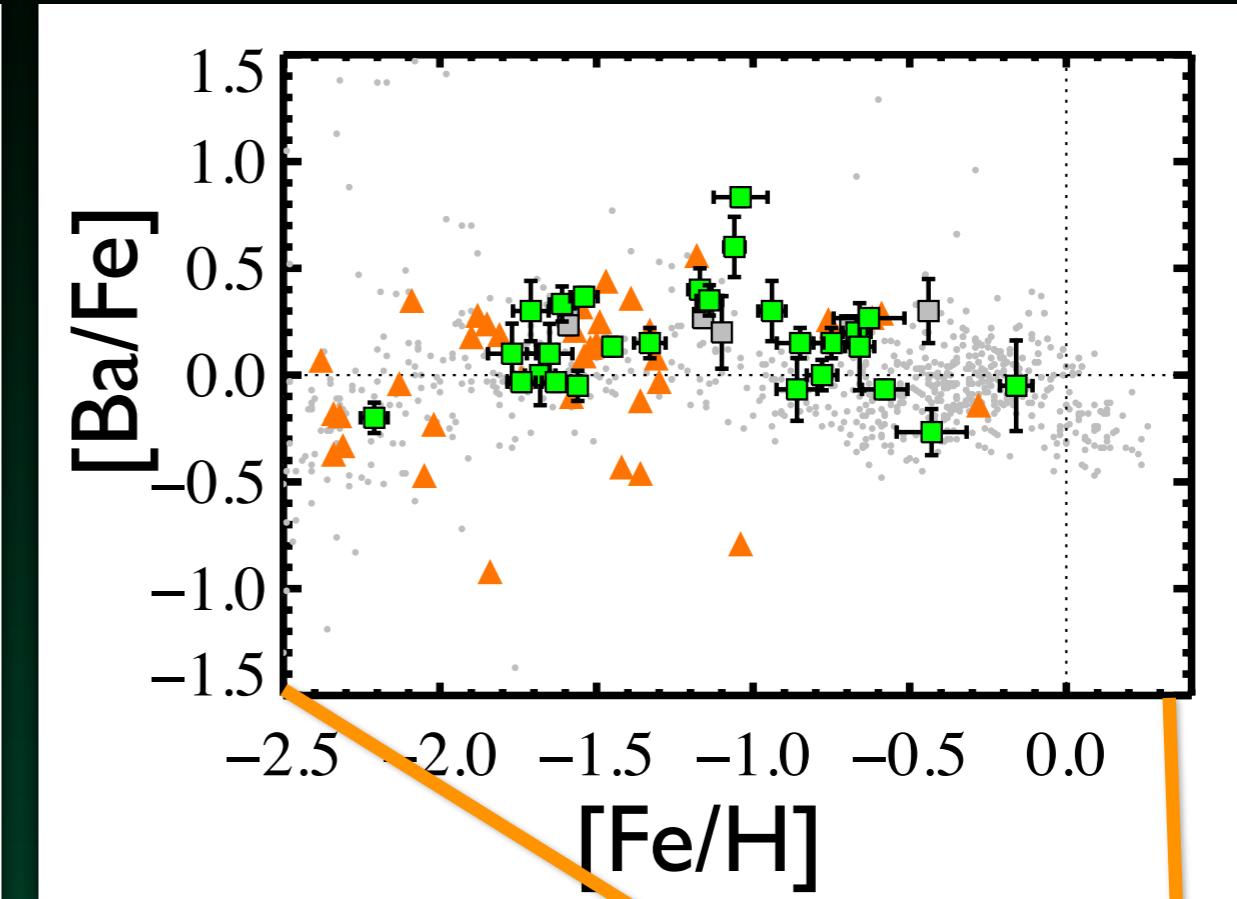
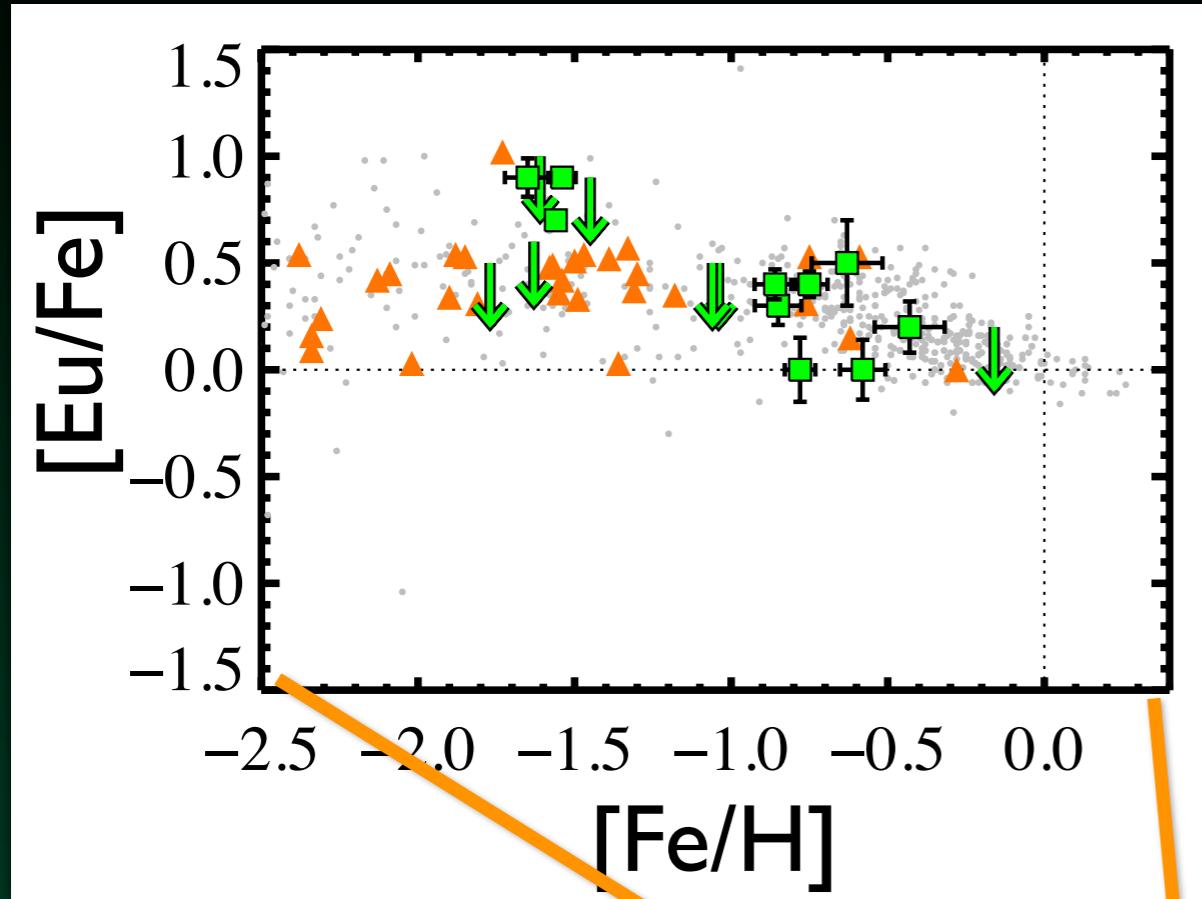
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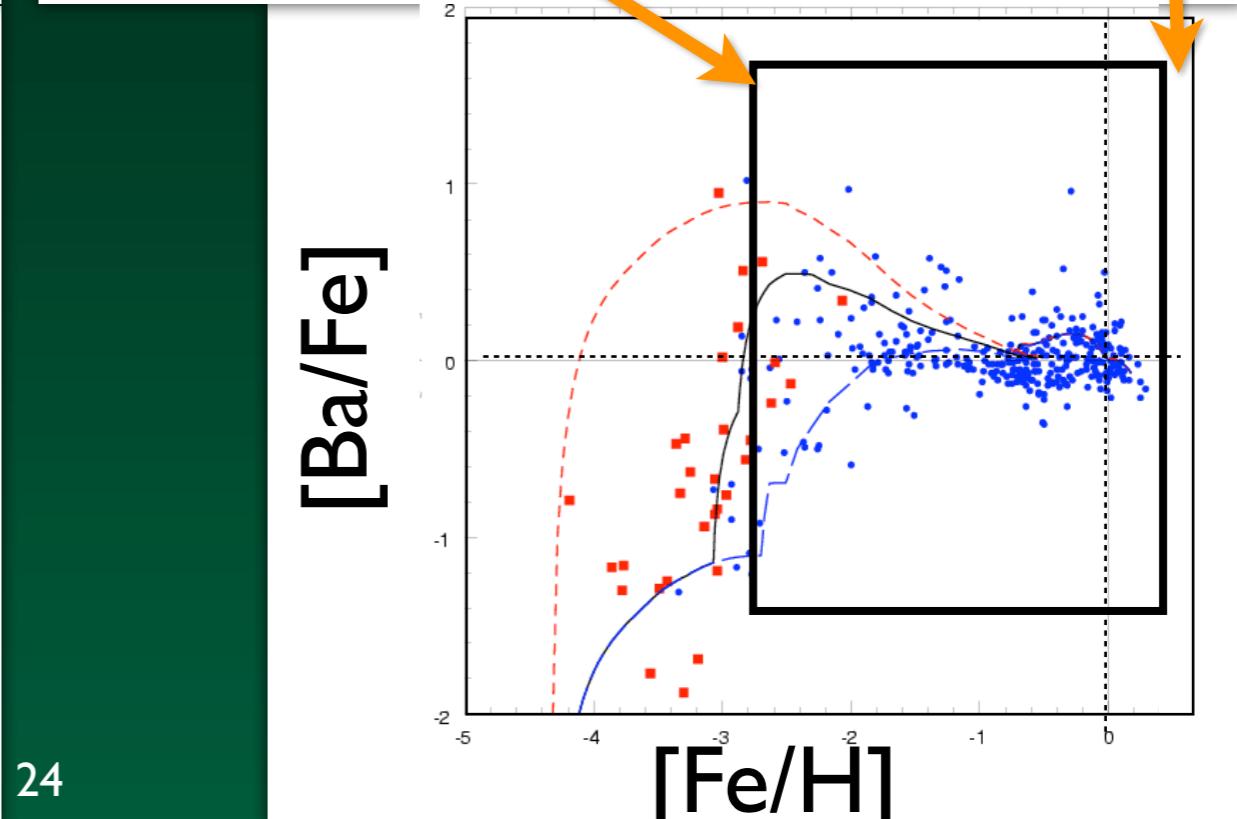
Beyond α -elements!

- ❖ 10 measurements of Eu, 7 upper limits
- ❖ knee in Eu, rising and flattening/declining Ba a signature of s-process enrichment by high metallicity AGB stars

Results: First Heavy Element measurements!



Cescutti et
al (2006)
MW
Models



Stay tuned for O, Na, Al, Mg, Ni, Sc, V,
Co, Mn, Cu, Cr, Y, Sr, La, Nd, Sm!

and more detailed horizontal branch
morphology constraints!

