Abundance Gradients in the Milky Way Disk: APOGEE Results from Open Clusters Survey

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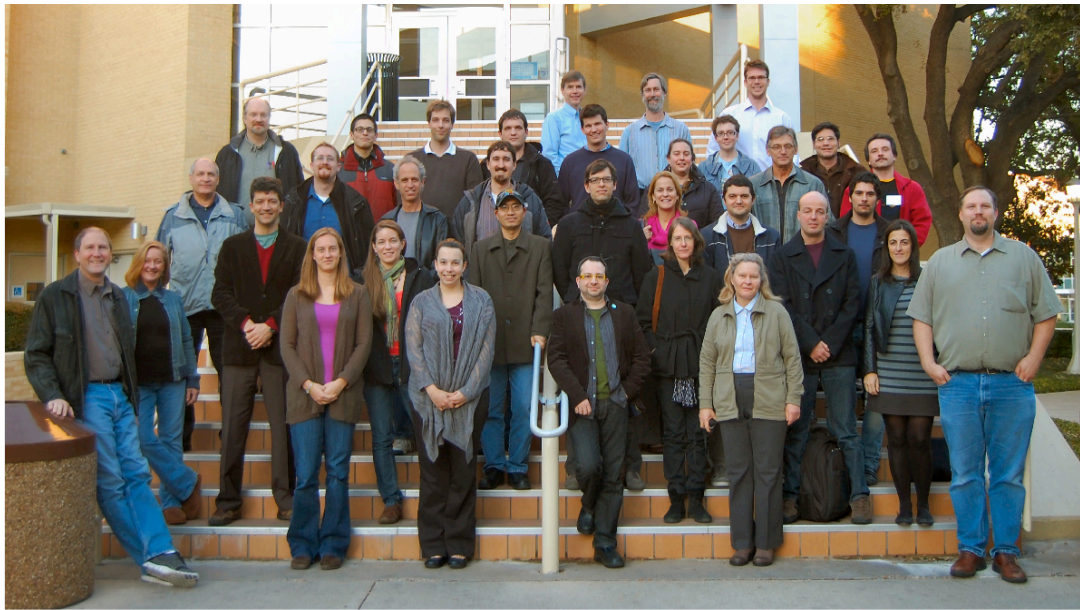
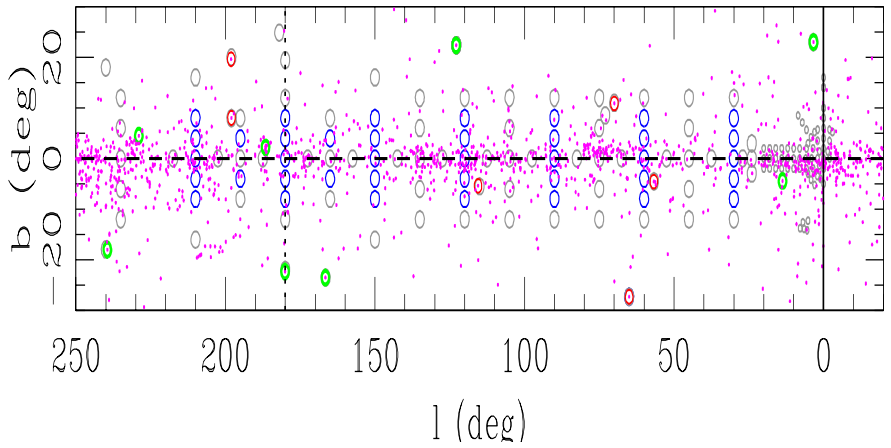
Steve Majewski; Verne Smith; Jennifer Johnson; John Holtzman; Gail Zasowski; Szabolcz Meszaros; Diogo Souto & The APOGEE team …. The many people who contributed to the APOGEE targeting, observing, data reduction, model atmospheres calculations, line list construction etc… (Most of them in this picture…)



The APOGEE Open Cluster Chemical Analysis and Mapping (OCCAM) Survey

~150 star cluster candidates in APOGEE1 fields



Advantage: Homogeneous & uniform APOGEE sample to explore Galactic gradients from Open Clusters.

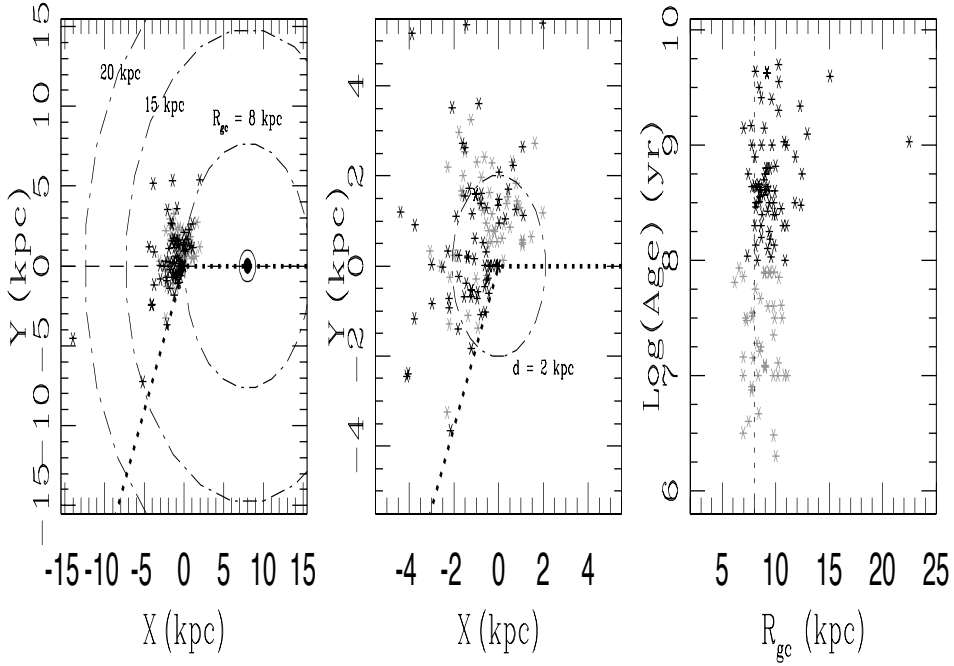
Open cluster members including:

- Cluster age, distance & reddening (Frinchaboy et al. 2015)

+

SDSS3/APOGEE data (**DR12**) providing:

- ~150 m/s precision radial velocities
- Stellar parameters: Teff, log g, [m/H]
- Detailed Abundances of 16 elements (≤ 0.1 dex internal accuracy)
  C, N, O, Na, Mg, Al, Si, S, K, Ca, Ti, V, Mn, Fe, Co, Ni > derived automatically



Automatic Abundance Pipeline ASPCAP

1-D LTE abundances obtained automatically from matches of APOGEE spectra to Synthetic Libraries

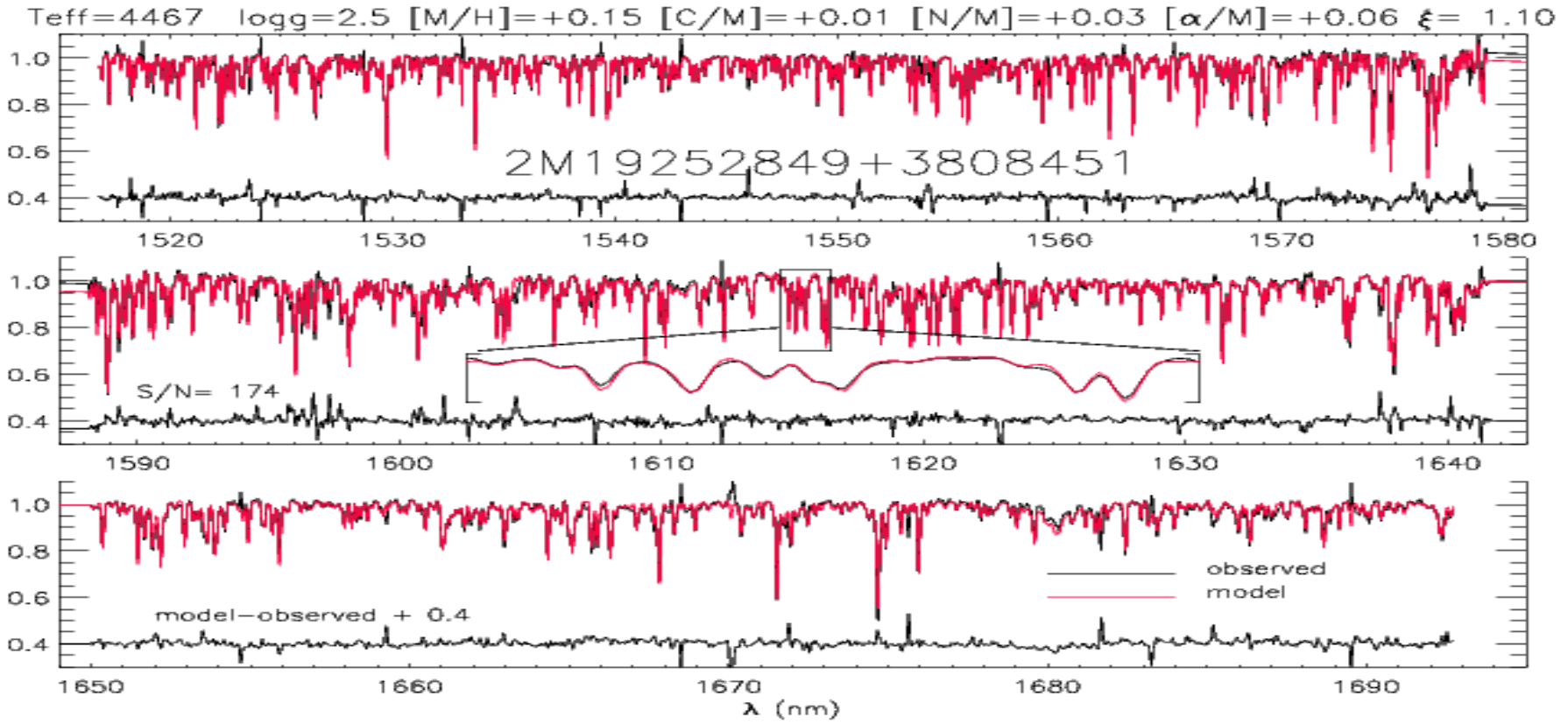
Criterion: chi-square; Search optimization: Nelder-Mead algorithm

Parameters: Teff, logg, ξ, and chemical composition

Method: 1) Fit 7 main parameters simultaneously then 2) Derive individual abundances

Step 1: Simultaneous 7(6)-D optimization of: Teff, log g, [Fe/H], [C-N-alpha/Fe],(ξ)

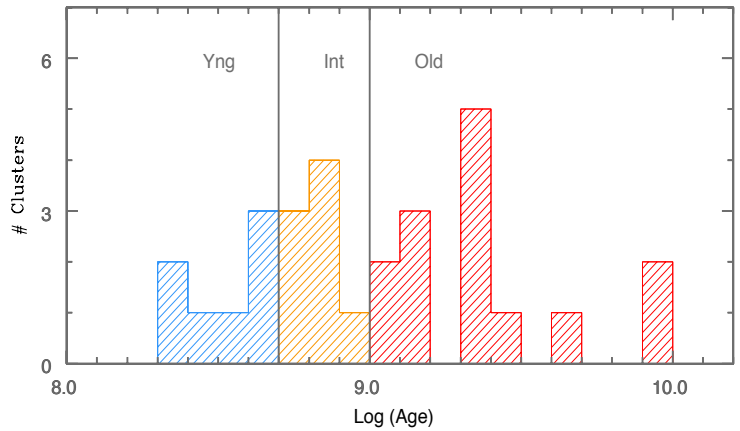
Step 2: Best fitting syntheses to small spectral windows around lines from each species

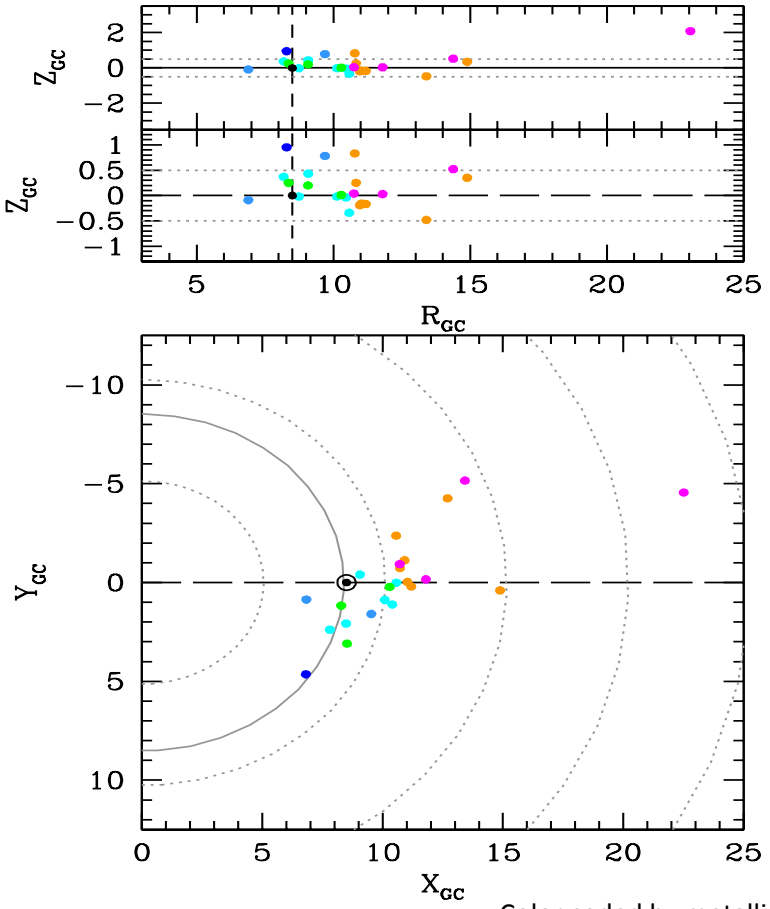


APOGEE Open Cluster Chemical Analysis and Mapping (OCCAM) Survey

- 304 red-giants members
- Total of 29 Open clusters;
- 7 being calibration clusters which cover a range in metallicities
- Rg from: roughly 7 – 23 Kpc; Mostly concentrated between 8 -15 Kpc with only one cluster beyond ~15 Kpc
- Mostly on the plane with Z < 0.5 Kpc; although with exceptions like Berkeley 29

- Covering a range in ages 200 Myr – 10 Gyr



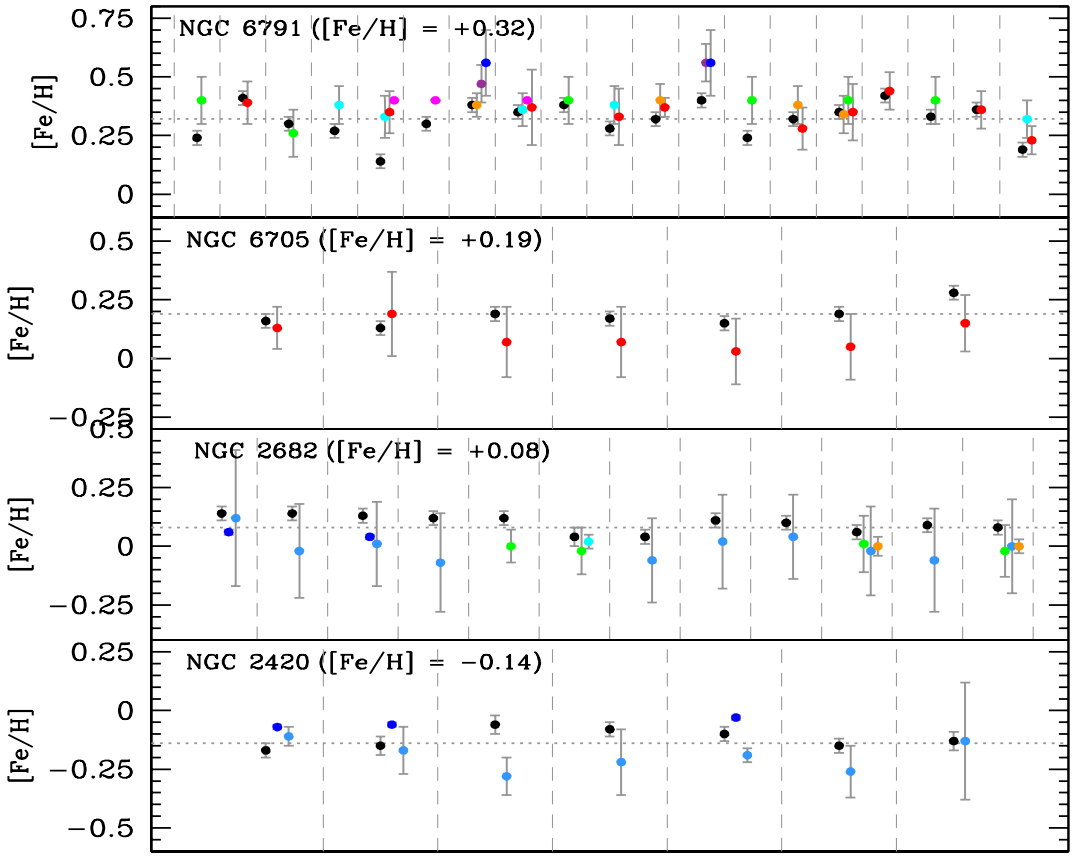


Color coded by metallicity
Blue: [Fe/H] > 0.25
Ltblue: 0.15 < [Fe/H] < 0.25
Cyan: 0.05 < [Fe/H] < 0.15
Green: -0.05 < [Fe/H] < 0.05
Orange: -0.15 < [Fe/H] < -0.05
Red: -0.25 < [Fe/H] < -0.15
Magenta: [Fe/H] < -0.25

ASPCAP DR12 Metallicities

- 4 clusters from our sample covering a range in [Fe/H]
- **Star-by-star comparison**: Individual results for stars in common in different studies, mostly optical (by no means complete)
- Overall there is not an obvious systematic trend and results ~agree within ~0.15 dex or less; some discrepant points

ASPCAP metallicities:
Below @ super-solar Fe;
manual analysis of NGC 6791
Slight above than GAIA-ESO



APOGEE : Black circles

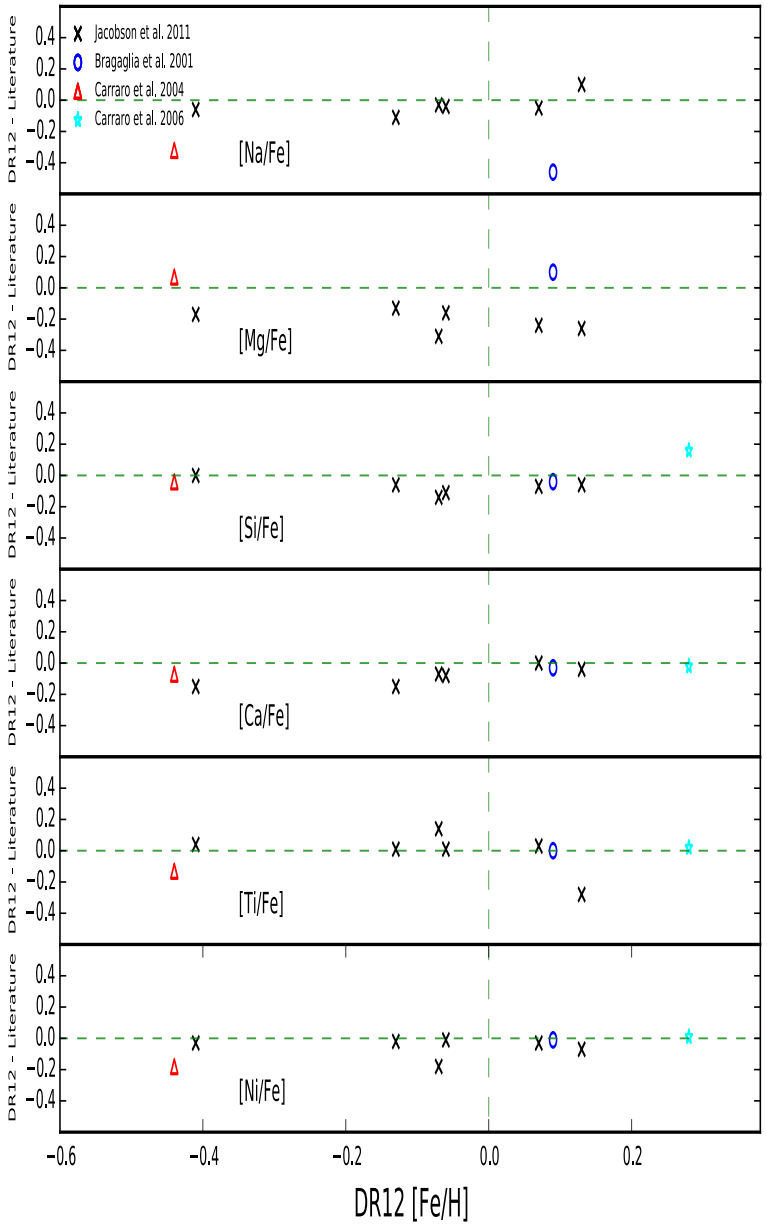
NGC 6791: (20 stars)
Red: Cunha et al. (2015)
Blue: Carretta et al. (2007)
Green: Bragaglia et al. (2014)
Cyan: Origlia et al. (2006)
Magenta: Cenarro et al. (2006)
Orange: Carraro et al. (2006)
Purple: Gratton et al. (2006)

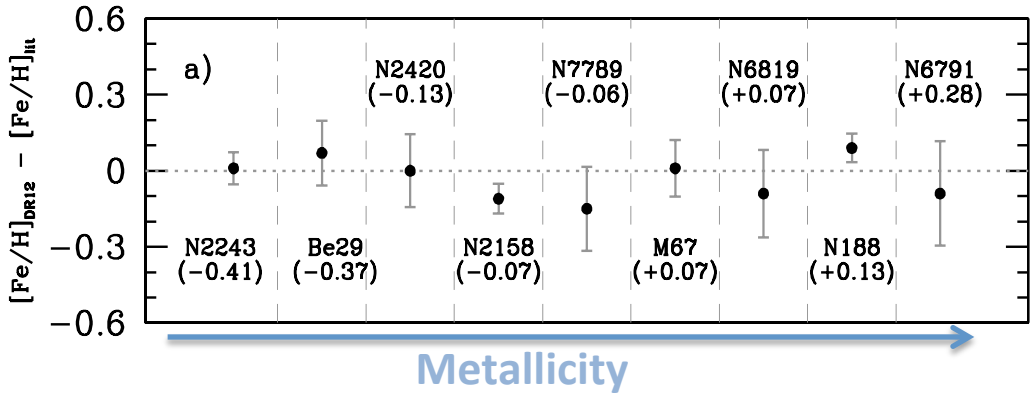
NGC 6705: (7 stars)
Red: Gaia-ESO (2014)

NGC 2682 (12 stars)
Dark Blue: Pancino et al. (2010)
Light Blue: Jacobson et al. (2011)
Green: Tautvaisiene et al. (2000)
Cyan: Randich et al. (2006)
Orange: Reddy et al. (2013)

NGC 2420: (7 stars)
Dark Blue: Pancino et al.(2010)
Light Blue: Jacobson et al. (2011)

DR12 Average Abundances vs Literature





9 APOGEE1 Calibration Open Clusters

NGC 6819 Bragaglia et al.; **Berkeley 29; NGC 6791** Carraro et al.; **NGC 2243**; **NGC 2420**; **NGC 2158**; **NGC 7789**; **NGC 2682**; **NGC 188** Jacobson et al.

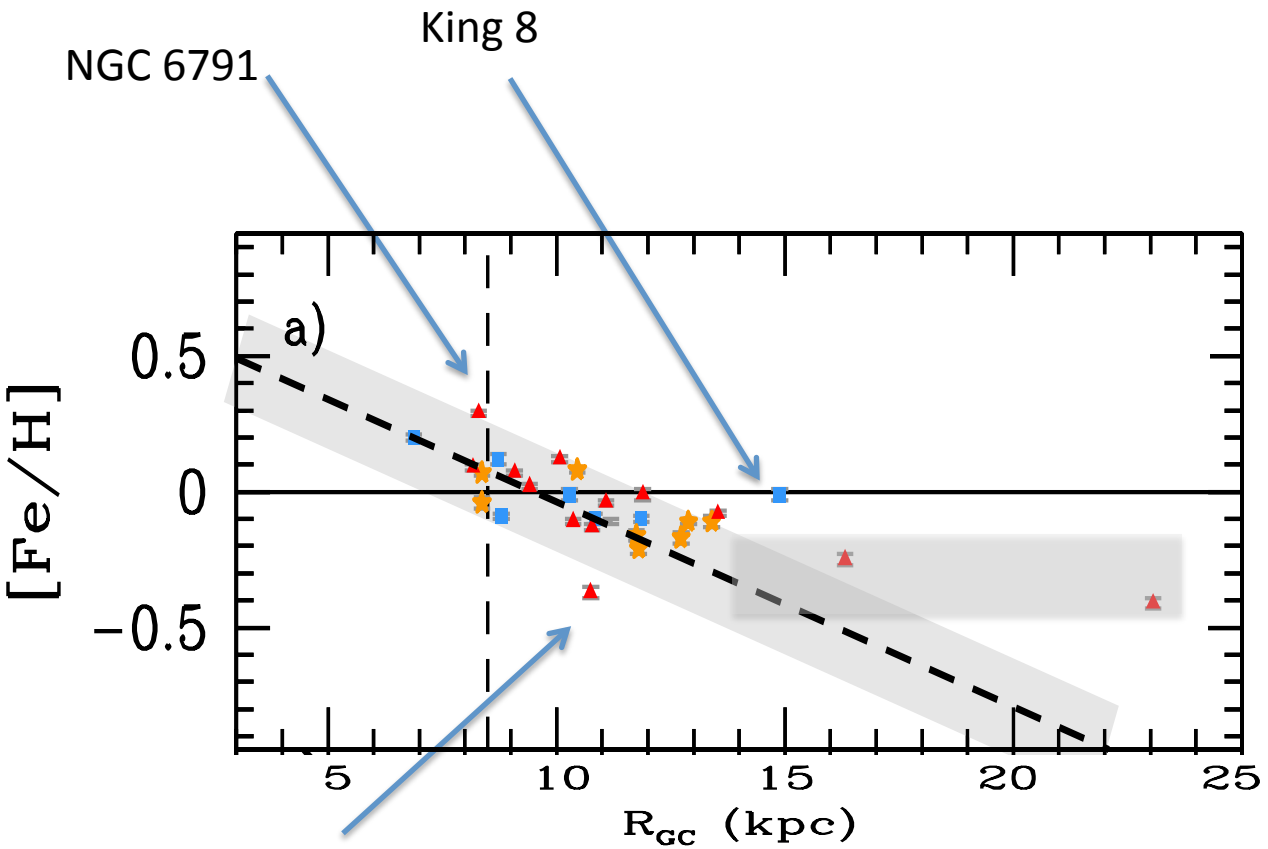
- Average cluster metallicities overall agree at the ~0.1 - 0.15 dex level
- There are some systematic differences at the level of 0.1-0.2 dex in the averages
- Larger systematics for Mg (lower than Jacobson et al.) and Na (Bragaglia et al. and Carraro et al.)
- Ti more scatter
- But differences also between the studies

Metallicity Gradients

29 Open Clusters from the Apogee OCCAM Survey

- Much steeper slope @ inner than ~12 Kpc & flat @ outer region;
- Not inconsistent with a change of slope at ~12 - 13 Kpc
- Slope for Rg < 12 Kpc : -0.076 dex/ Kpc

- Mostly scatter within the grey shaded line
- Some scatter beyond +/-0.2 dex; some outliers
- Some of this scatter is real? The abundances are reliable?



Trumpler 5

Clusters color-coded by age:
Young < 0.5 Gyr
Intermediate: 0.5 Gyr – 1 Gyr
Old: log (age) > 1 Gyr

- NGC6791: Independent analysis of sample spanning the RGB and RC (Cunha et al. 2015)

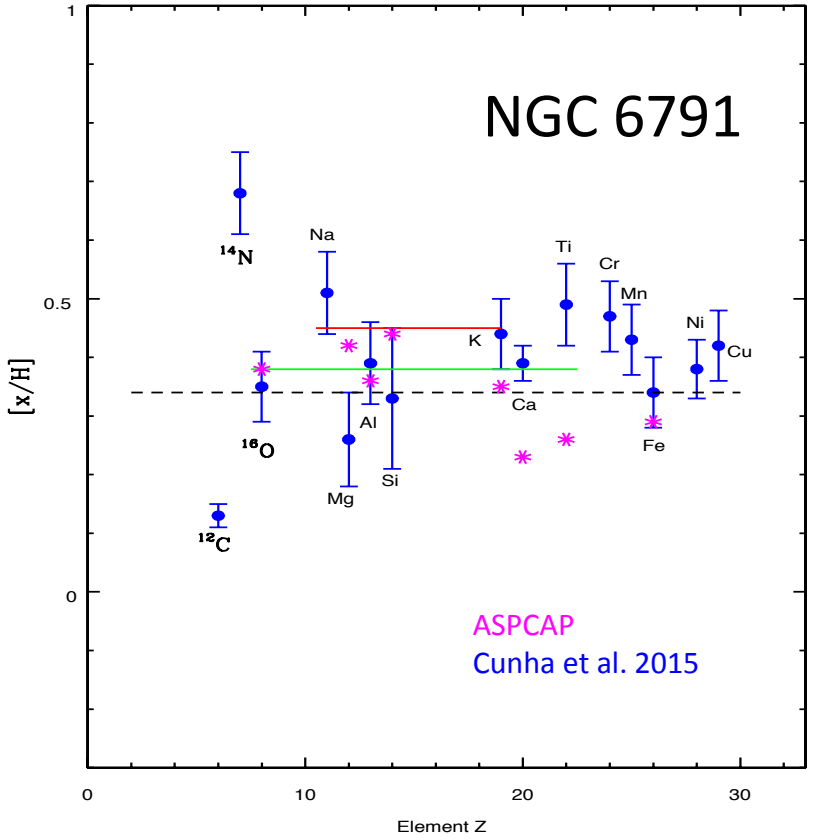
This very old (8 Gyr) and massive OC is:

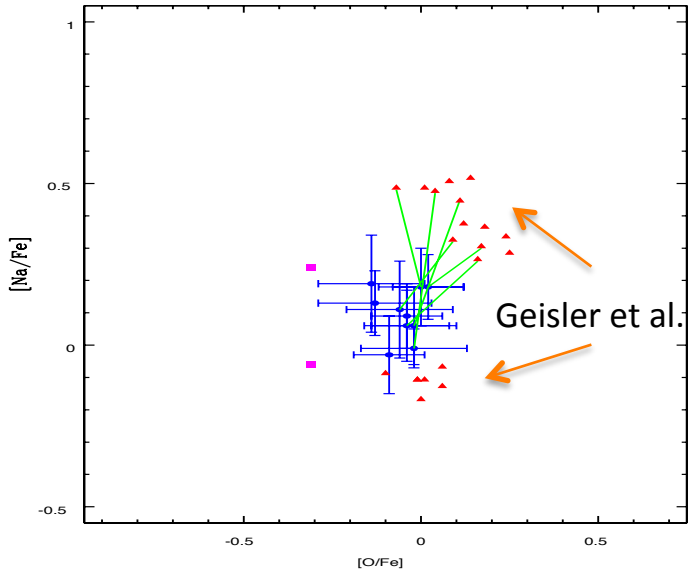
- Chemically **homogenous** to the level ~0.06 dex (star-to-star scatter)
- Very metal-rich: [Fe/H]=+0.34 +/- 0.06 (black dashed line)

Bragaglia et al. (2014): A(Fe)=0.37+-0.06;
+ Boesgaard et al. (2015)

- We do not confirm the two Na populations found in Geisler et al. (2012) ; find single population

NGC6791 could be a captured system? Or migration from the inner galaxy ??





NGC6791 19210112

Mg I λ15740.716

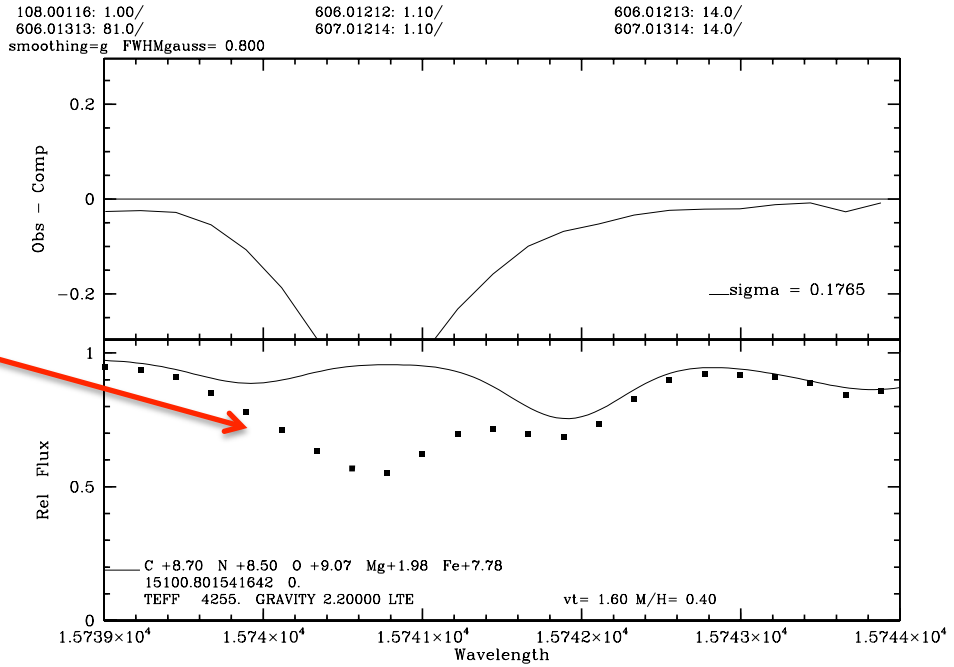
No Mg

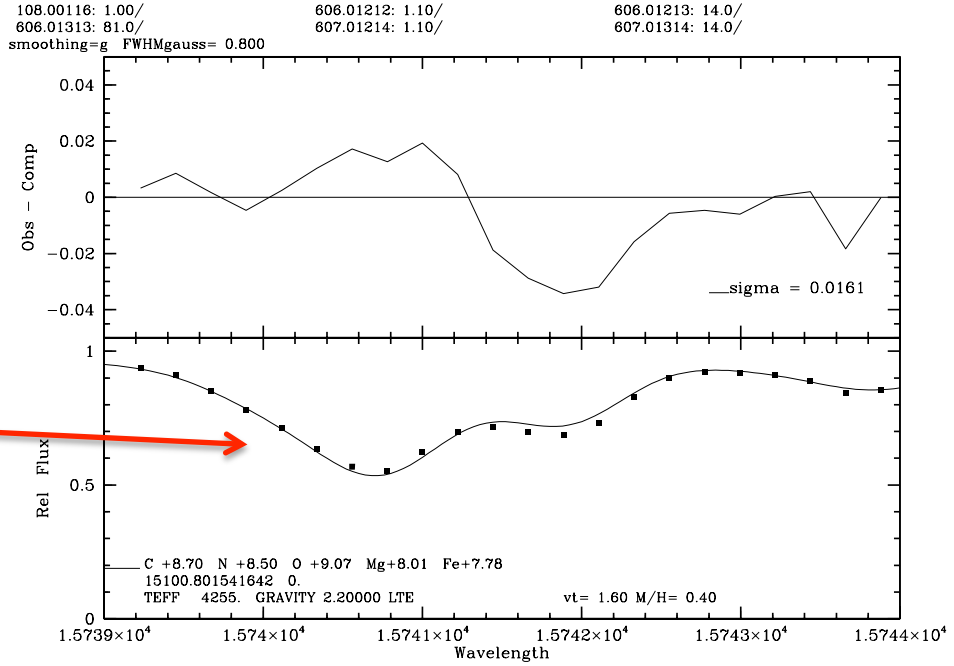
Example of fitting one element

Define the window with the pixel Information

Minimize the residuals

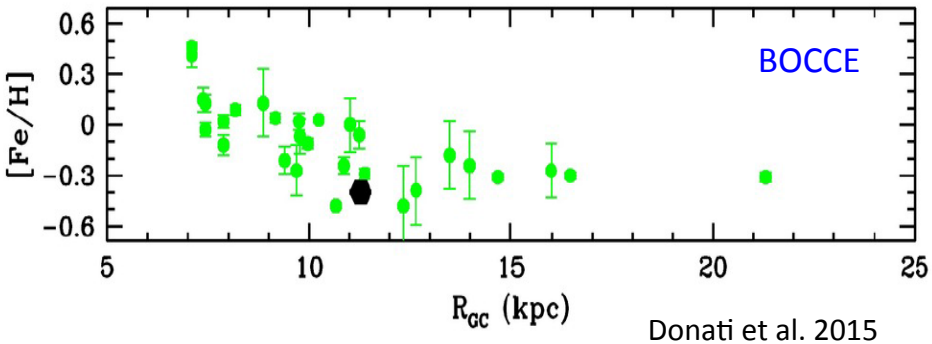
A(Mg)= 8.01



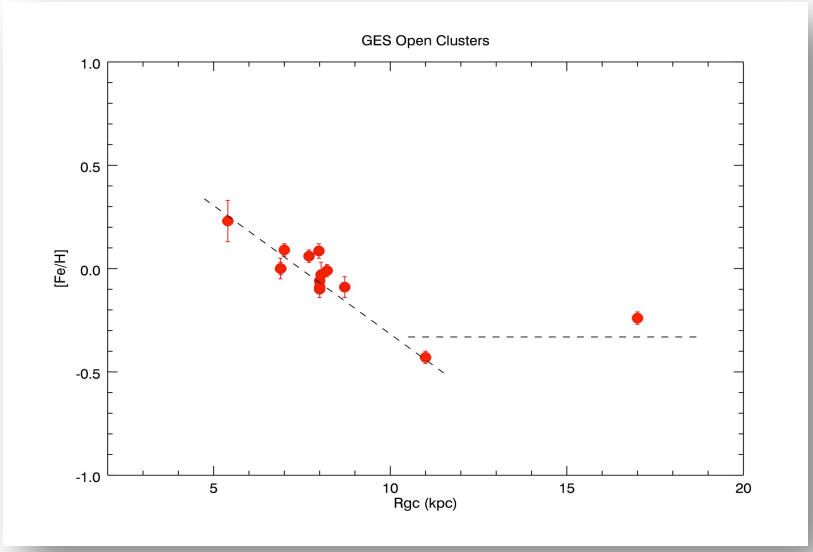


Comparisons with other results from the Literature

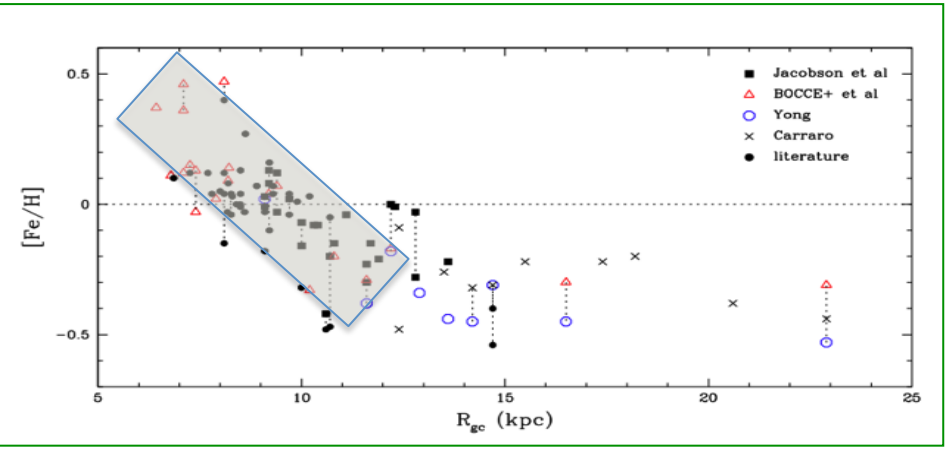
- Decreasing metallicity to ~ 12 Kpc + Plateau [Fe/H] ~ -0.4 dex all the way out
- Some dispersion @ any Rg



Donati et al. 2015



(Magrini; Sexto 2015)



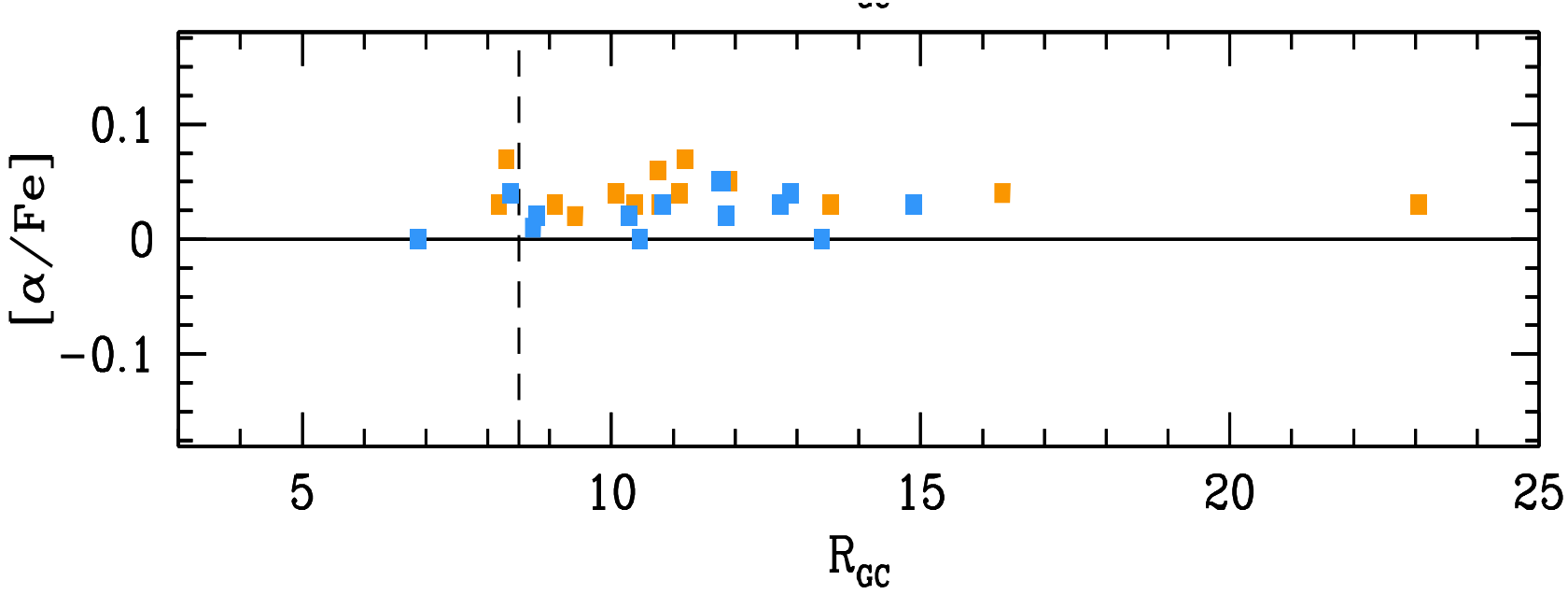
Compilation by Friel of high-res results from ~ 70 clusters: Sestito et al 2008; Magrini et al 2009; Jacobson et al 2011; Pancino et al 2011; Yong et al 2012; BOCCE (Bragaglia et al.; Carreta et al. Gratton et al.)

GAIA- ESO SURVEY (GES)

- Still small number of clusters (13 clusters)
- Better coverage @ the inner disk
- Small abundance dispersion at a given Rg
- Steep gradient @ inner region ~-0.13 dex/ Kpc
- Some evidence for a break @ ~10 Kpc

CAUTION: This mixes different ages and there is radial migration; more complicated

ASPCAP [Alpha/Fe] Gradient

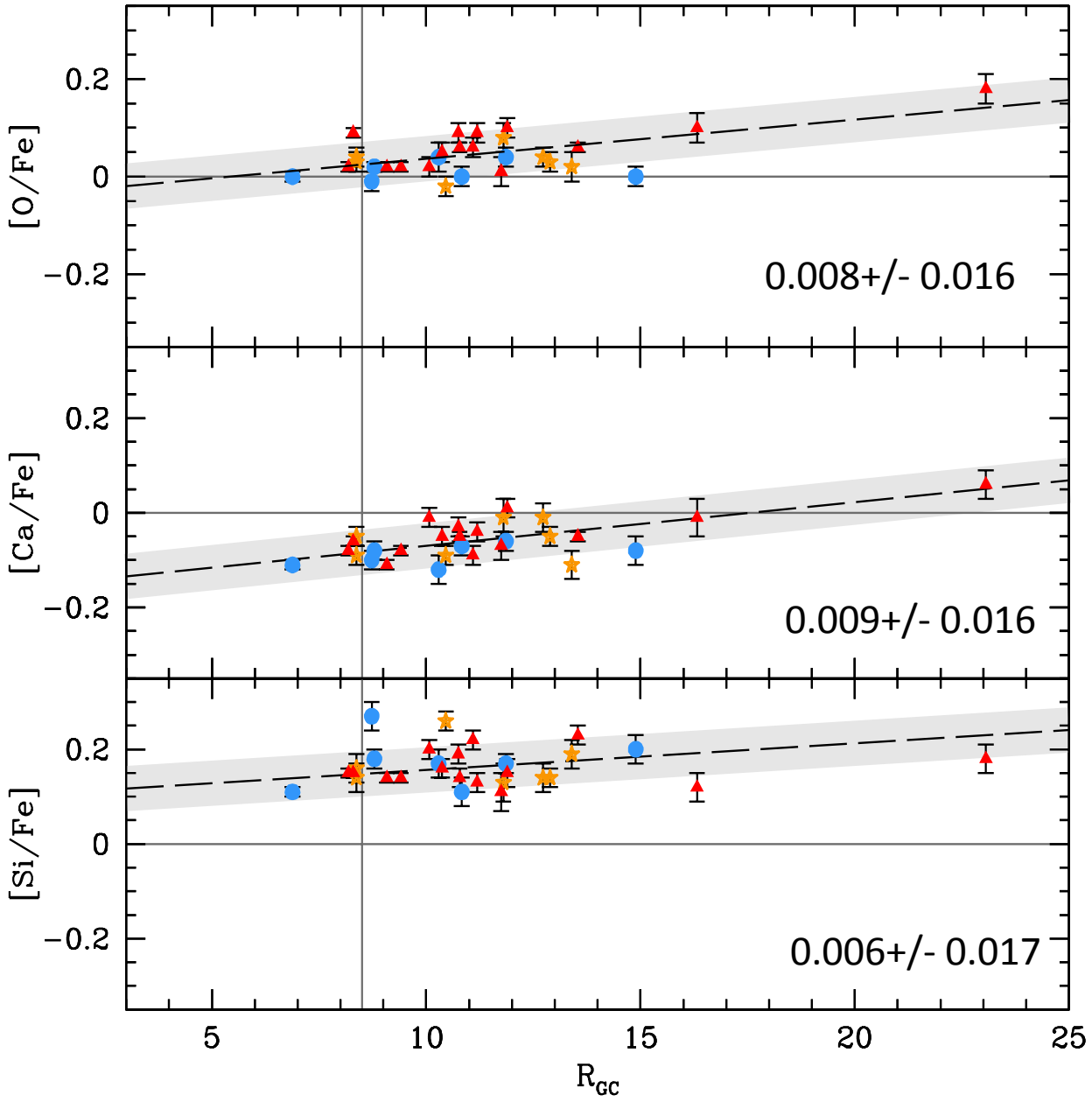


- Alpha element abundances from overall fits to the spectra with ASPCAP
- No clear evidence for bimodality
- Less scatter
- Single Slope; ~ Flat gradient
- Offset from the solar value

Young: log (age) < 9.0

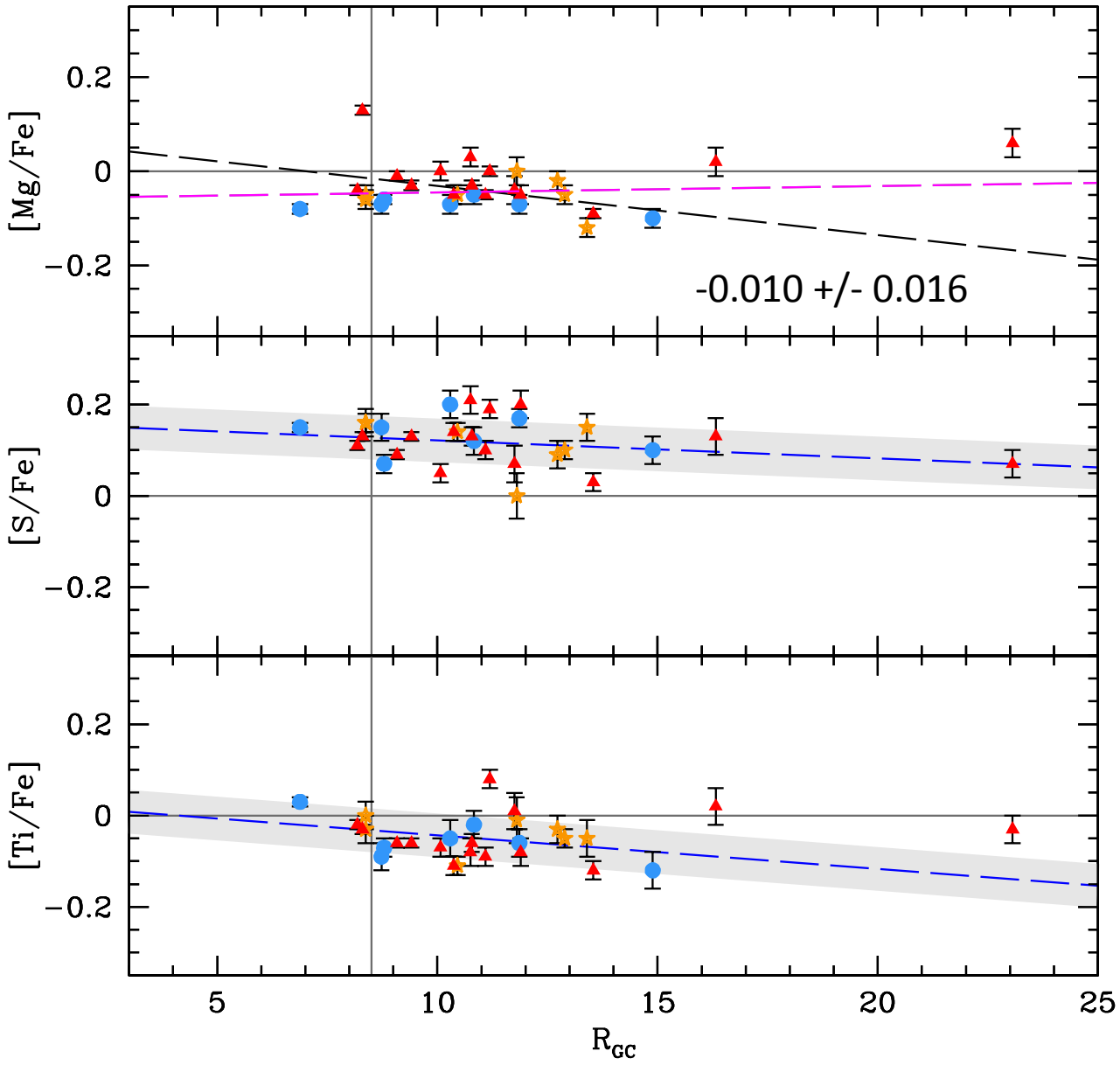
Old: log (age) > 9.0

Alpha/Fe Gradients



Basically FLAT!

- A very small positive gradient
- All 3 alpha-elements have very shallow slopes; consistent behavior with Rg
- ~ Consistent with zero slope
- Some hints that alpha/Fe may be higher in the outer disk but mostly Be29
- Offsets relative to solar value: Si has a positive systematic offset and Ca has some below but not as large
- Silicon's offset puts the ASPCAP alphas above solar



Removing NGC6791

- Mg is basically Flat

Slope: +0.001+- 0.016 dex/Kpc

Not clear offset

Sulfur & Titanium

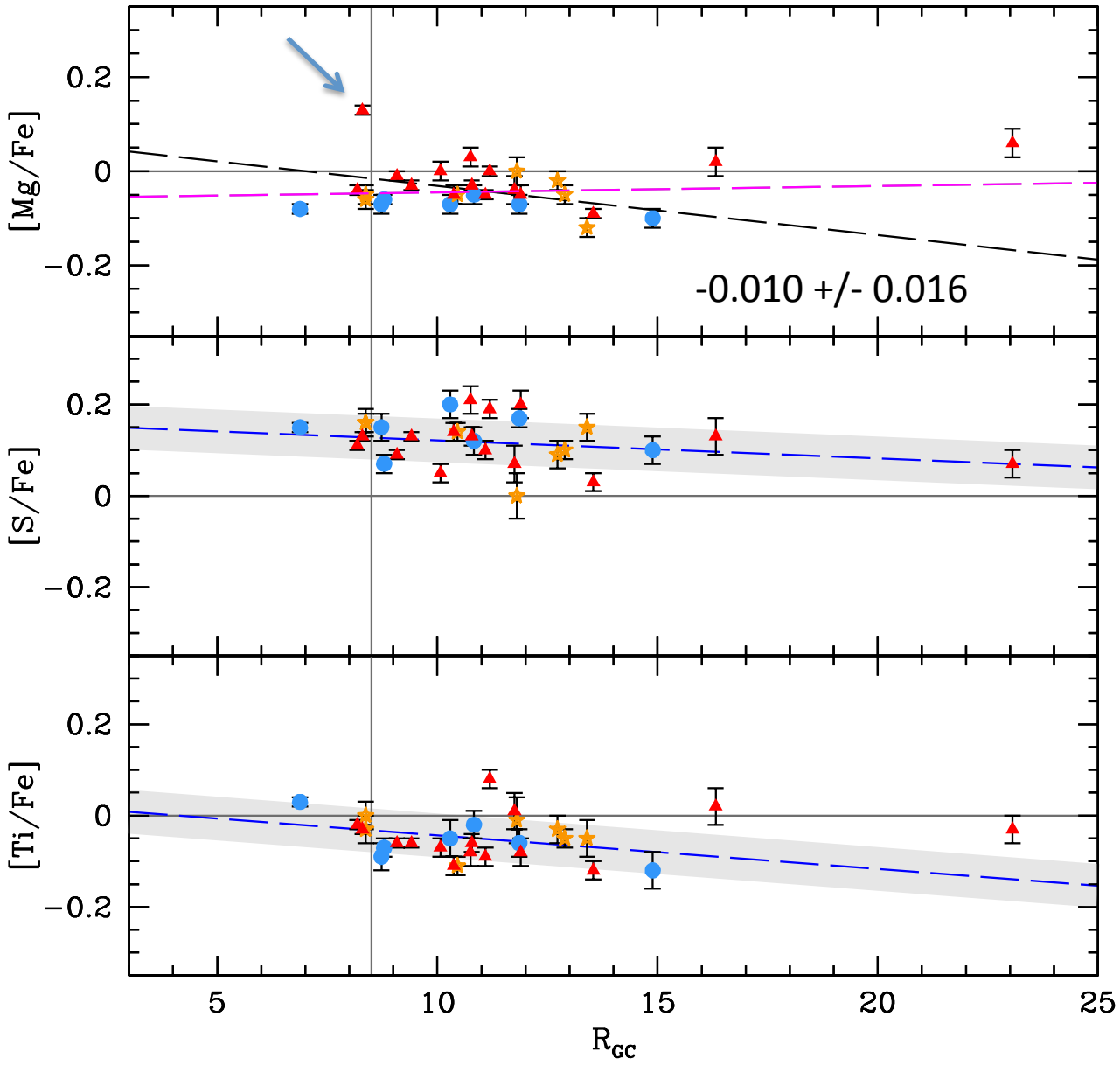
Not considering at this point.

Titanium has issues…

Behavior of [Ti/Fe] vs [Fe/H] does not make sense

Work in Progress!

Magnesium



High Mg/Fe not confirmed by manual analysis in Cunha et al. (2015)

Removing NGC6791

- Mg gradient is basically Flat

Slope: +0.001+- 0.016 dex/ Kpc

Sulfur & Titanium

Not considering at this point.

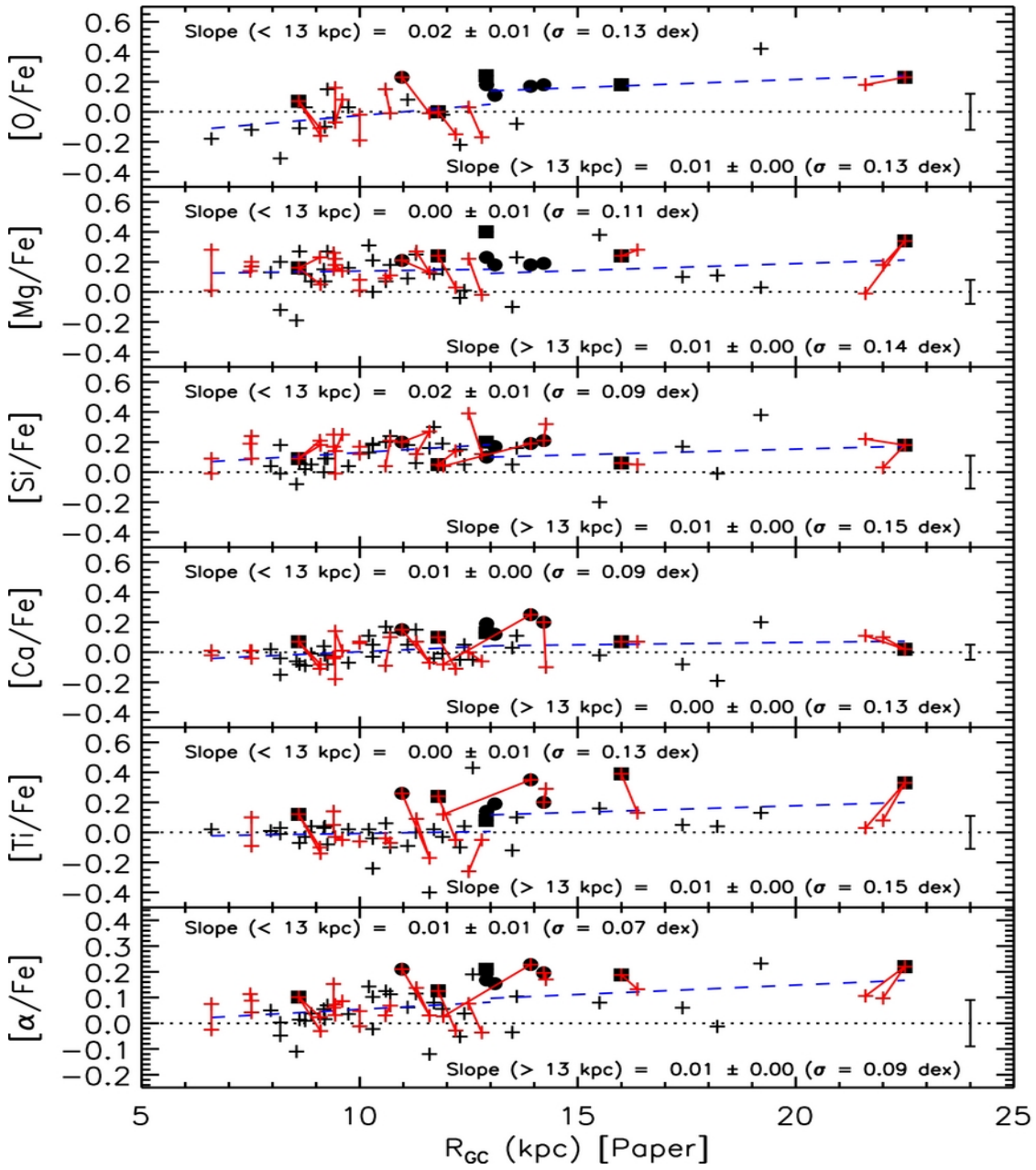
Titanium has issues…

Behavior of [Ti/Fe] vs [Fe/H] does not make sense

Work in Progress!

Comparisons with other results from the Literature

Literature compilation from Yong et al. (2012)



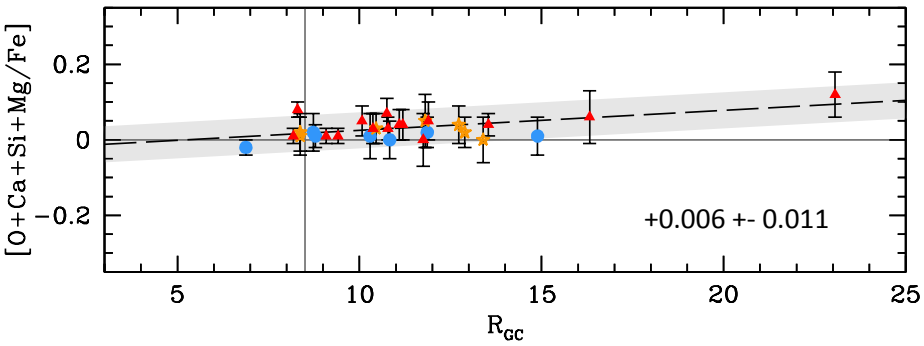
Yong et al. (2012):

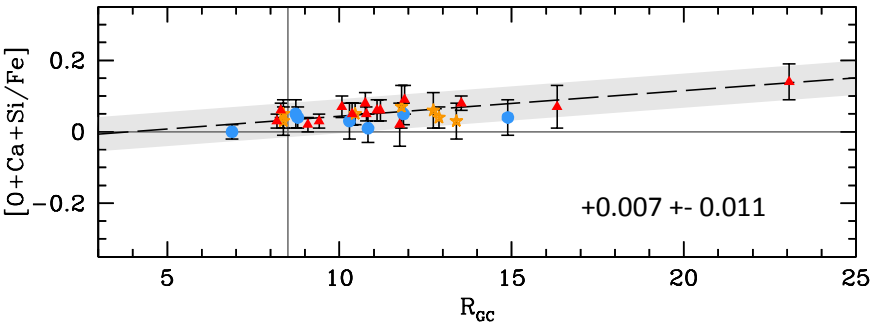
- Linear fits to the data with RGC < 13 kpc and RGC > 13 kpc.
- Connected red symbols > multiple measurements of the same cluster

- Compares well with APOGEE OCCAM results
- Basically a single very flat slope of 0.01 +/- 0.01 dex/Kpc can fit all alphas
- There are also some offsets for Si, as well as Mg

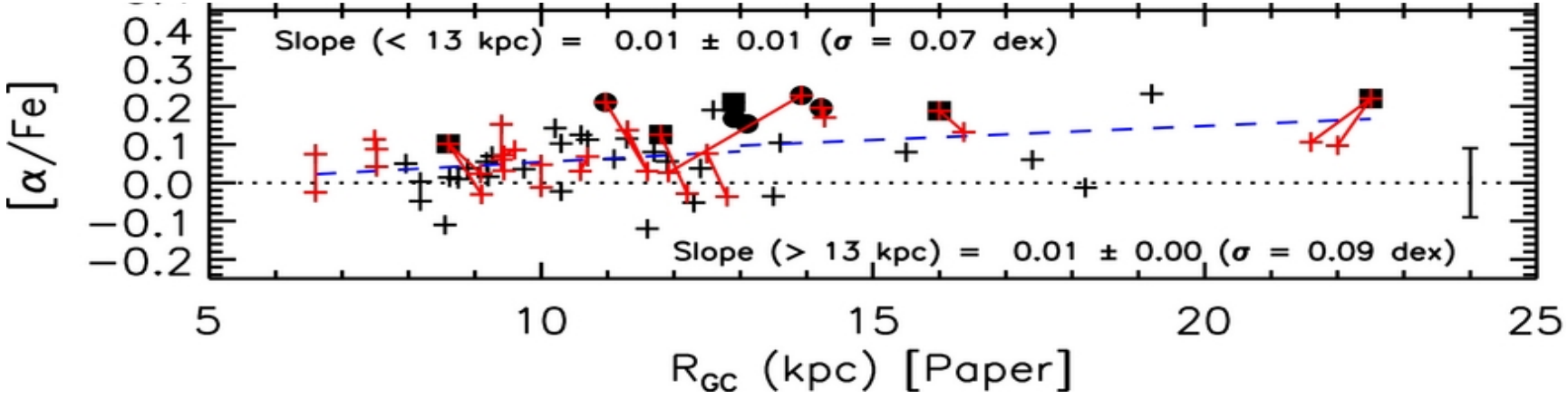
Comparisons with other results from the Literature

OCCAM





Yong et al. (2012)



Time Evolution of Gradients

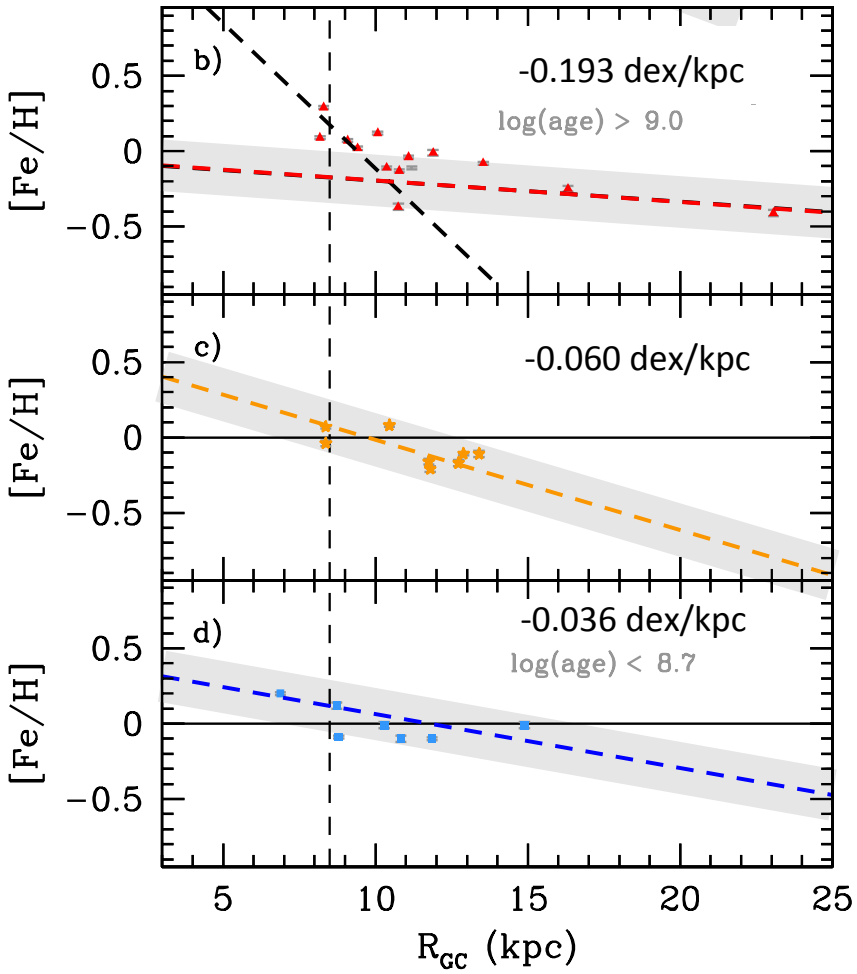
Gradients Flattening with time?

Slopes calculated for samples of OC within somewhat arbitrary age bins

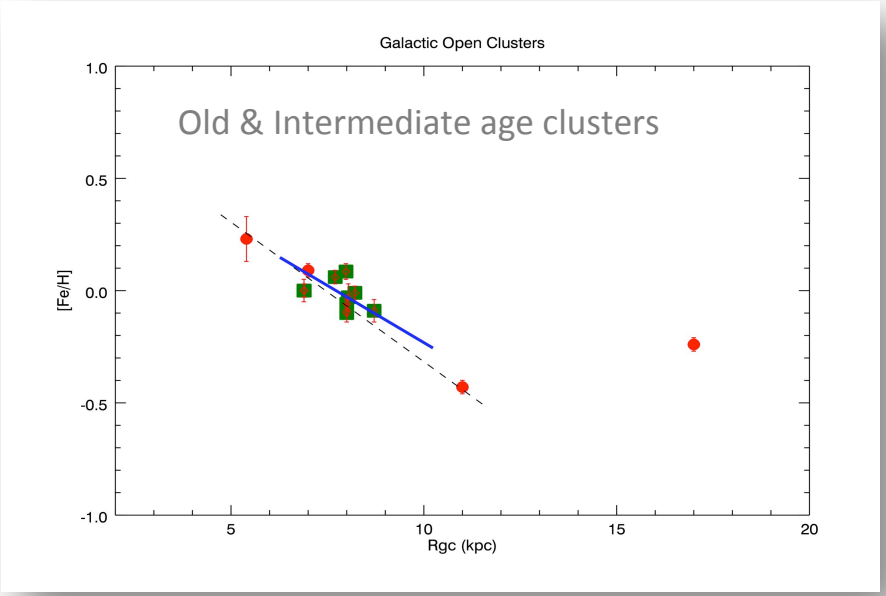
Some evidence for a break in slope for old cluster sample….

Rg coverage not uniform in all 3 samples: only old clusters sample has coverage beyond ~ 15 Kpc

For ~8 – 15 Kpc:
Some indication that gradients get flatter as the Galaxy evolves…
Oldest OCs: -0.19 dex/ Kpc
Young: ~ -0.036 dex/ Kpc



Initial Results from GES



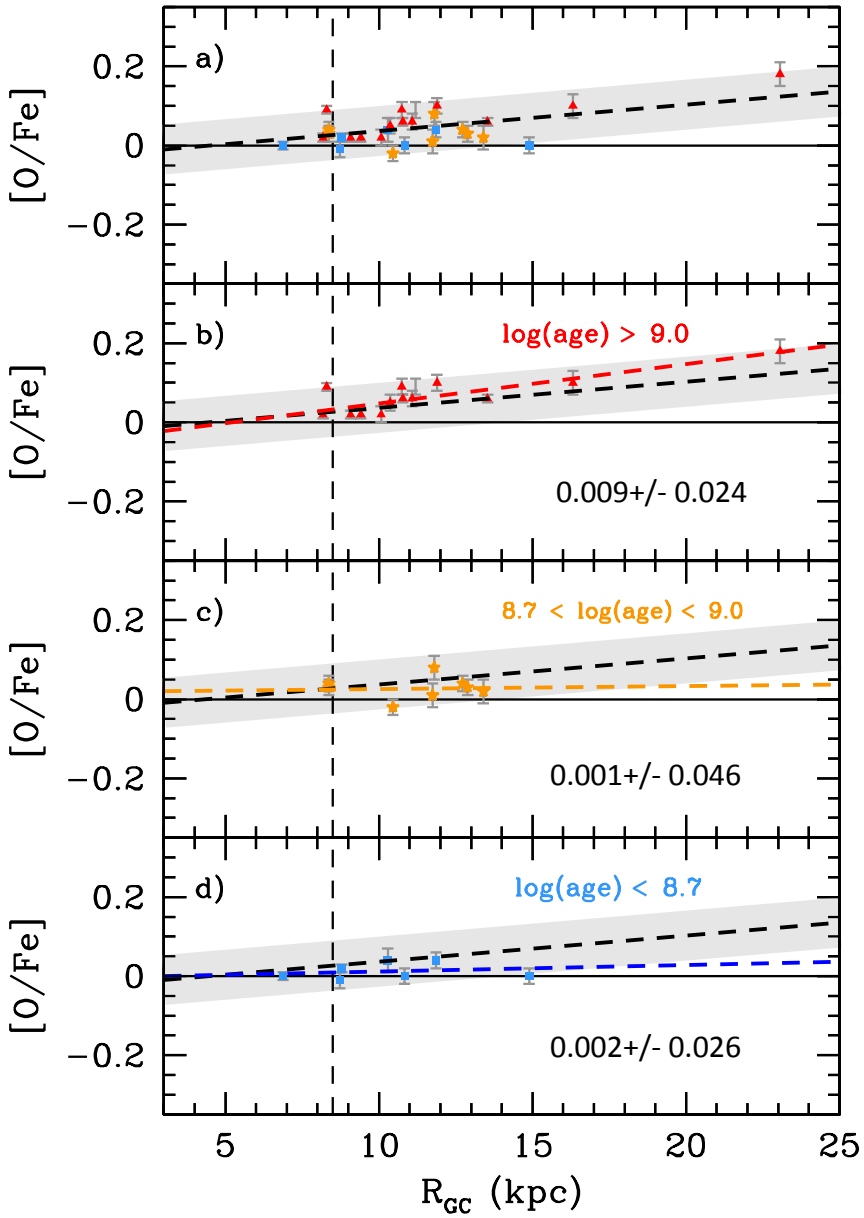
Magrini (Sexto 2015)

Evidence for a flattening with time?

- Perhaps some initial indication of flatening of gradients for younger clusters
- But not yet conclusive

Evolution of [O/Fe]

- Not a significant difference between the gradients
- All pretty flat within 0.00 – 0.01 dex/ Kpc
- The higher alpha abundances in the old clusters beyond 15 Kpc are responsible for some of the possible small differences in the slope
- Gradients seem to flatten very little (or nothing) for the younger clusters



A Few Conclusions

- We are entering a new era in the study of metallicity gradients from Open Clusters

- Homogenous and self-consistent analyses of chemical abundances in surveys (like Gaia ESO and APOGEE) will represent an important step forward

- The Apogee OCCAM survey will deliver a homogenous set of OC parameters like Reddening, Ages, Distances, RV's, as well as, stellar parameters, metallicities and detailed chemical abundances of up to 16 elements.

- Initial results for a sample of 29 Open clusters from APOGEE OCCAM indicate:

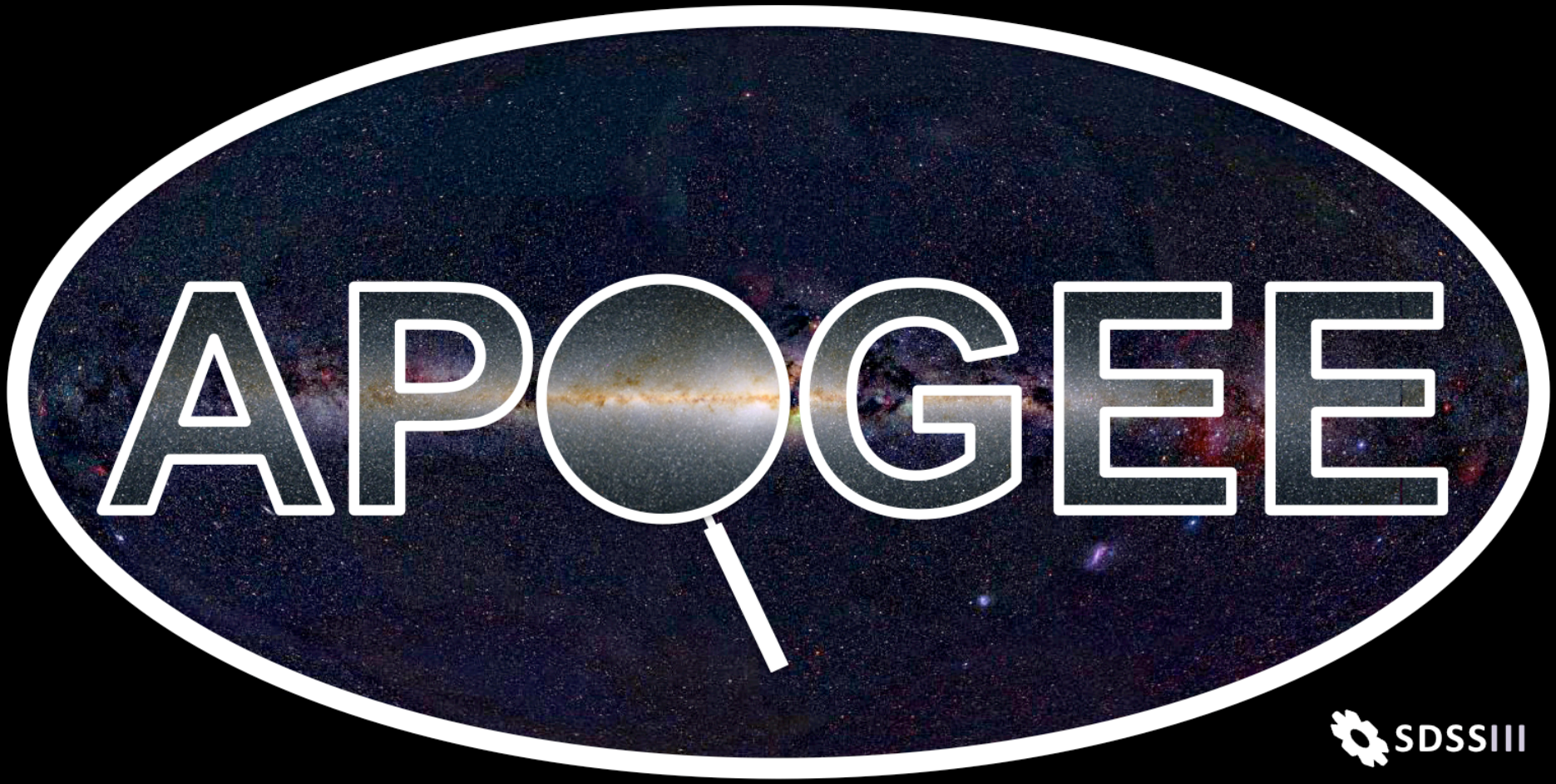
[Fe/H] gradients are steeper in inner disk and flatter towards the other disk

The [Alpha/Fe] gradients are flat all the way through the disk

There is some indication of flattening of gradients with time.

More clusters coming!

Thank you!



Logo by Gail Zasowski.