# Three case studies:

The behavior of C as f(luminosity) in GC stars

A detailed study of M15, with extremely large star-to-star abundance variations

The Mg isotopic ratio in halo field stars in an M71, the importance of the AGB and the halo timescale for formation

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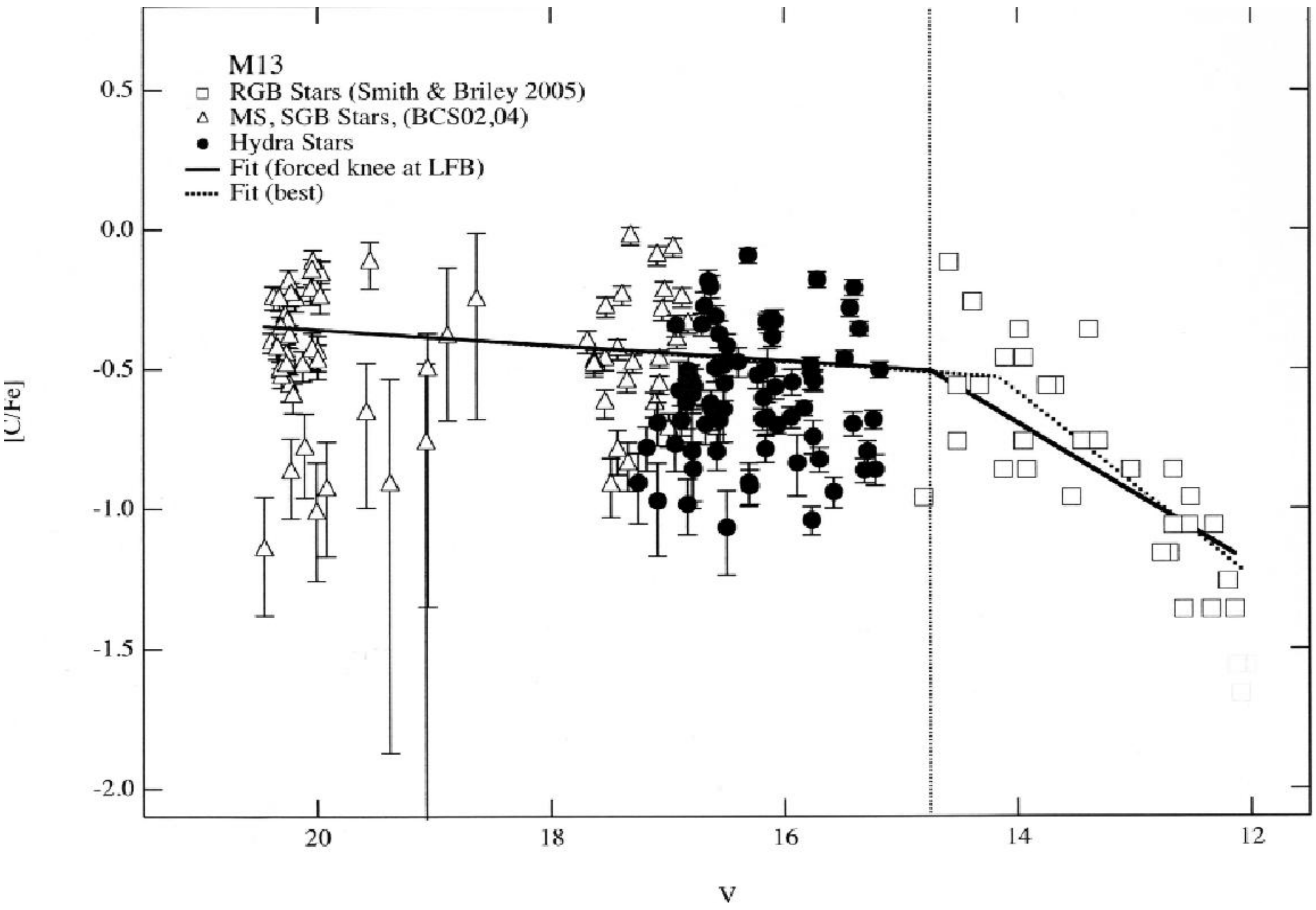
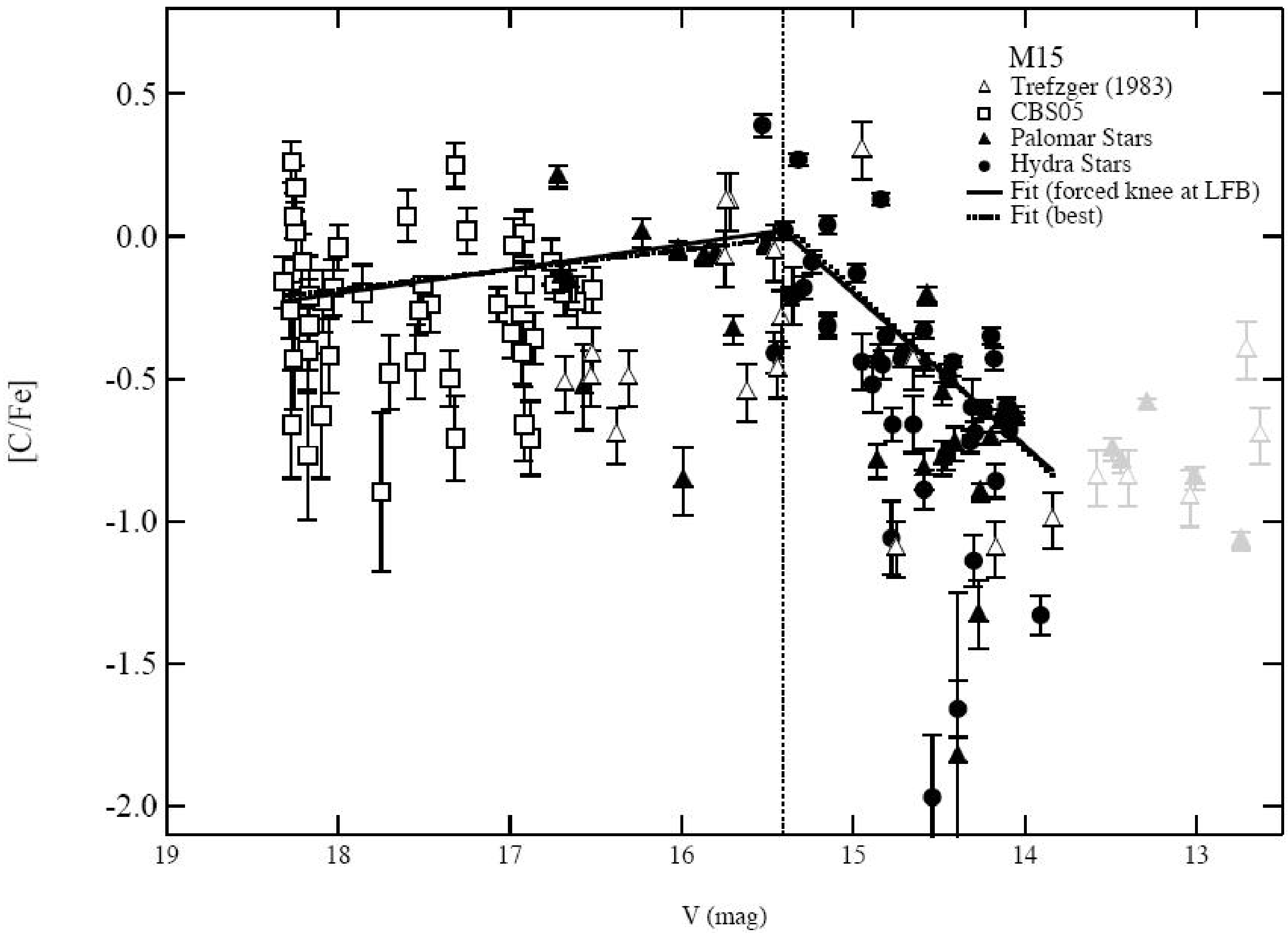
KITP Globular Cluster Meeting, Santa Barbara, Jan 2009

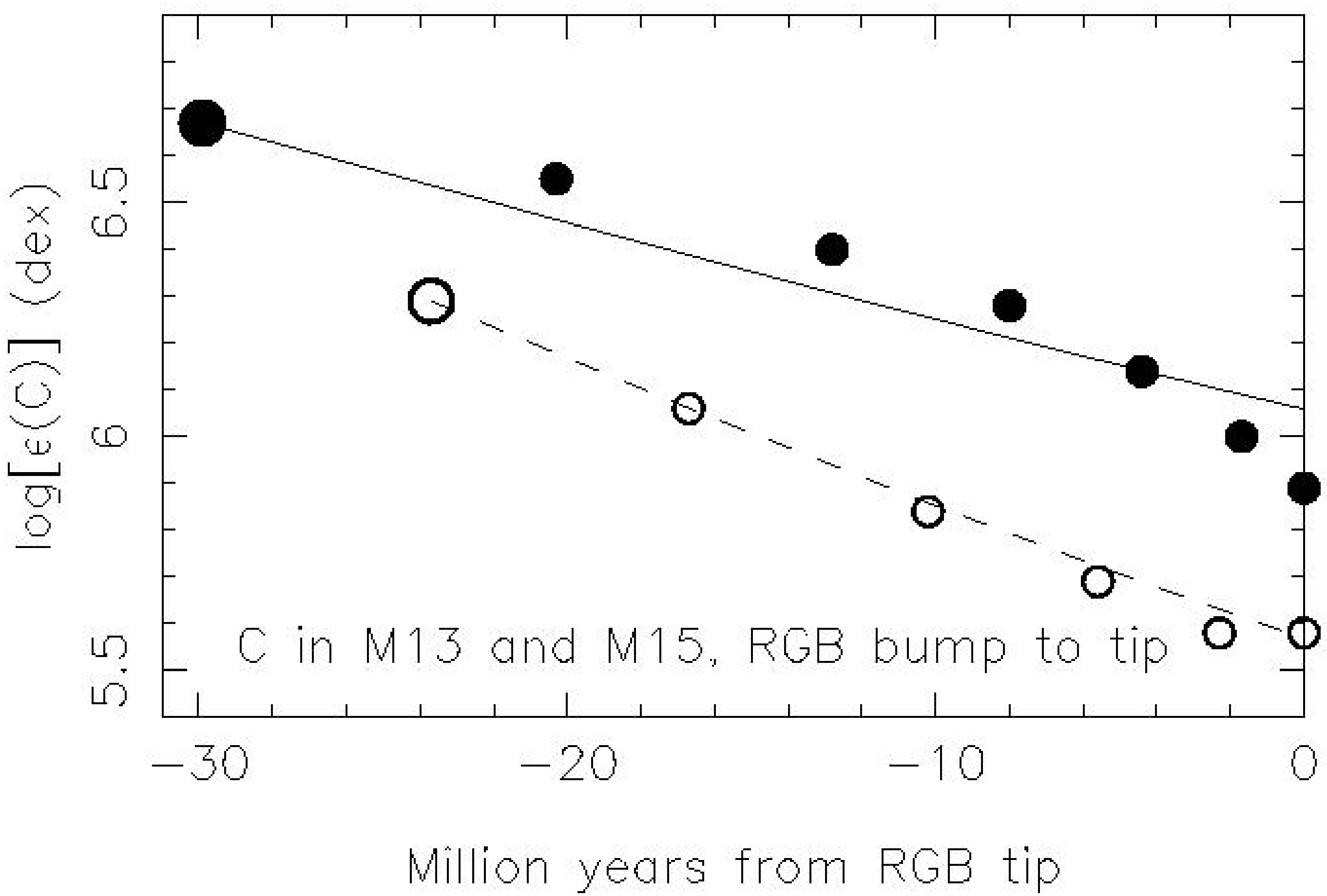
# M13 [C/Fe] vs V, RGB bump marked, double linear fit with knee + scatter at all evolutionary phases including below MSTO



# M15 [C/Fe] vs V from near MSTO to RGB tip, RGB bump marked, double linear fit with knee



Carbon depletion model, RGB bump to Tip, exp. decline, d[C/Fe]/dt -0.023 dex/Myr for M13, -0.035 dex/Myr for M15, 5 to 8% of convective envelope circulates into C burning region/Myr.



# M15, a GC with very strong star-to-star abundance variations

M15 is among the most metal-poor GCs known.

Very strong star-to-star variations in C and N, high amplitude correlations and anti-correlations among O, Na and Al.

No evidence of star-to-star variations for Ca to Ni

Very strong star-to-star variations among heavy elements, r-process, range of a factor of 5

Carbon star (C2 band seen) low on RGB, s process ?, may be remnant of a mass transfer binary and a former AGB star.

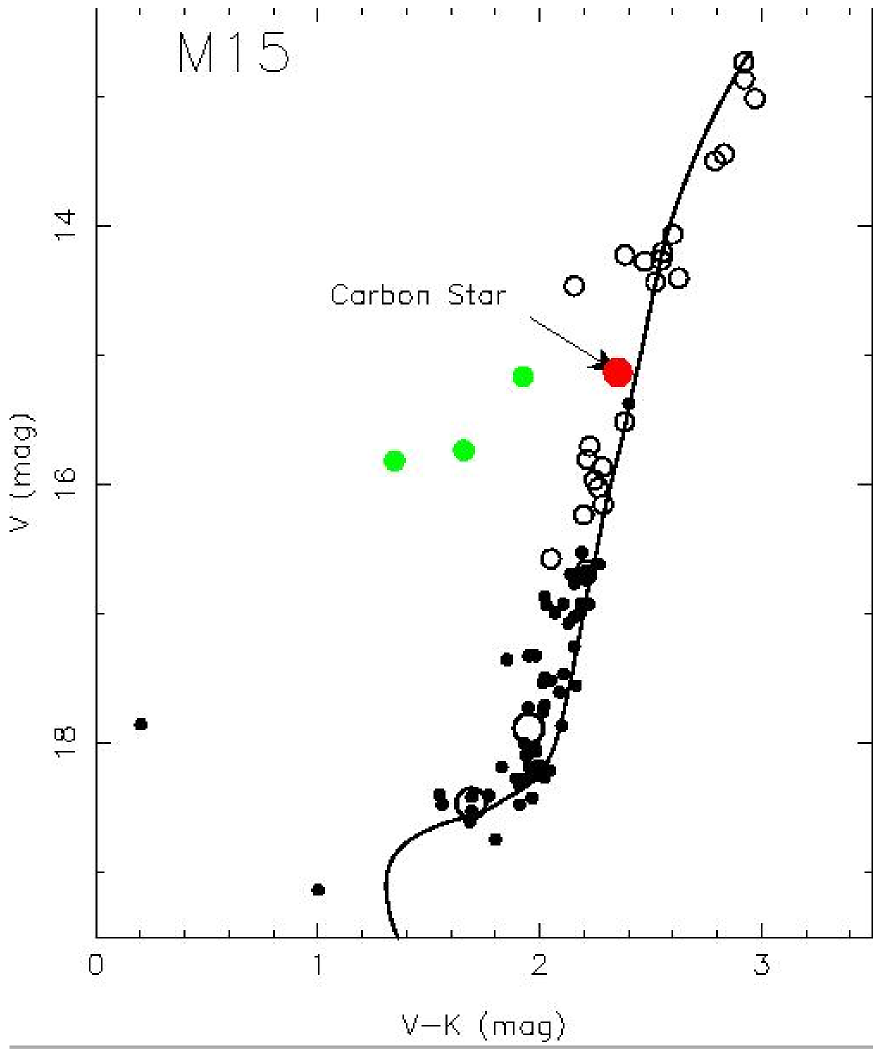
## Amplitude of light element corrections and of heavy element scatter

Expect range of star-to-star differences to be bigger in more massive GCs, easier to retain AGB ejecta

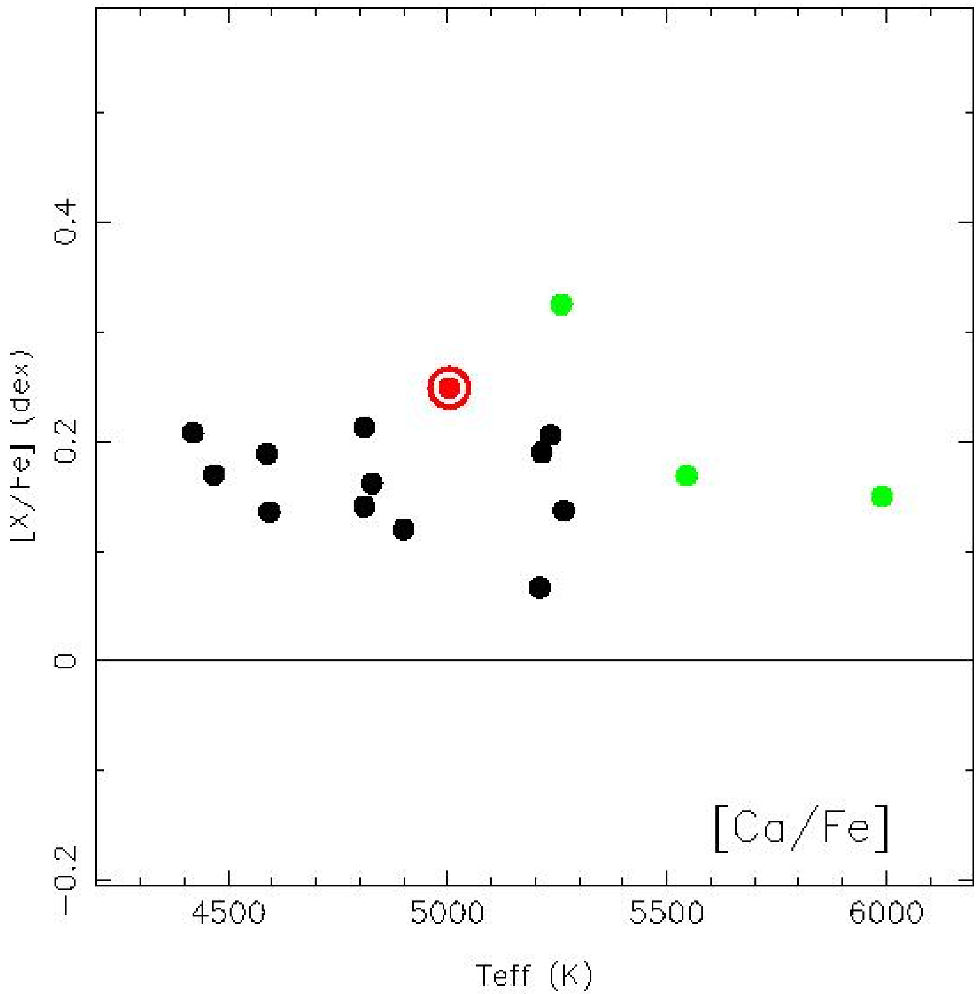
Expect range of star-to-star differences to be bigger in more metal-poor GCs, where adding a fixed amount of processed material produces bigger changes in abundance ratios.

M15 is both highly luminous (in top 10% of Galactic GCs) and very metal-poor.

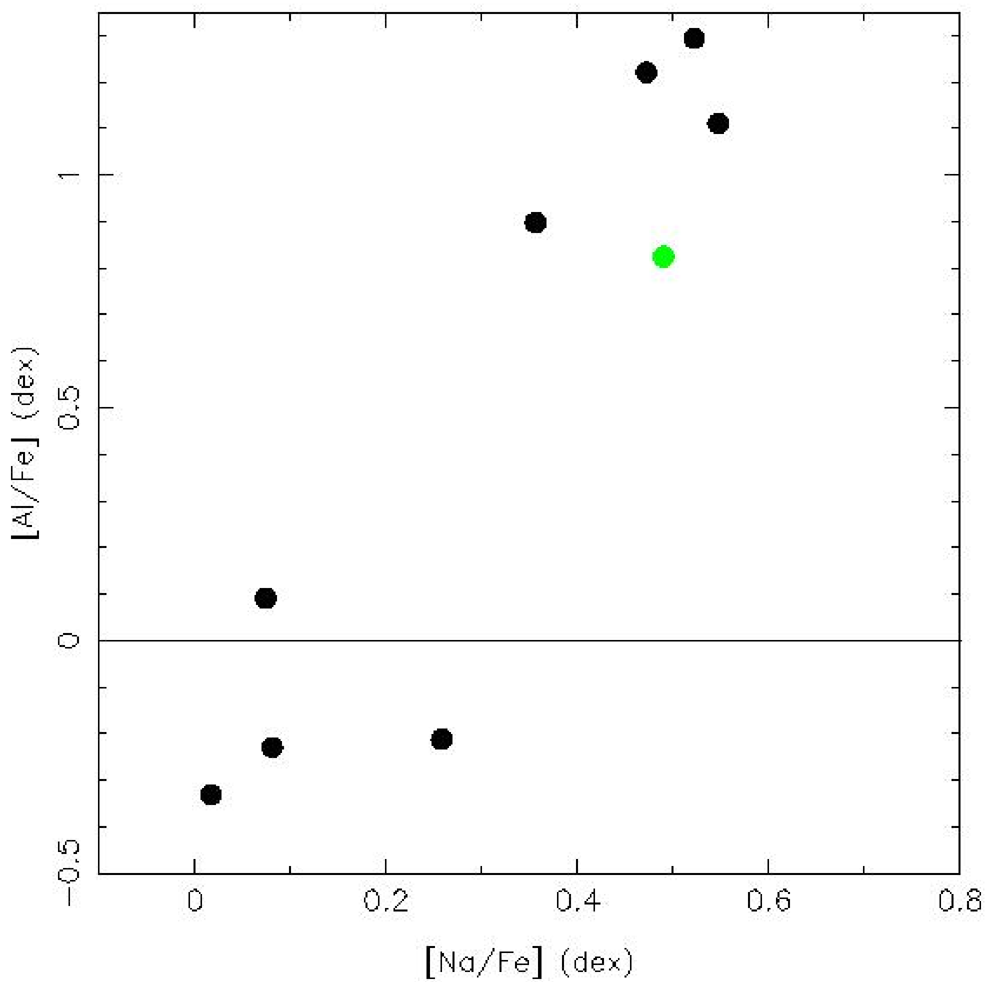
# M15 HIRES/Keck (abundance analysis, open circles) and LRIS/Keck Sample (CH and NH bands)



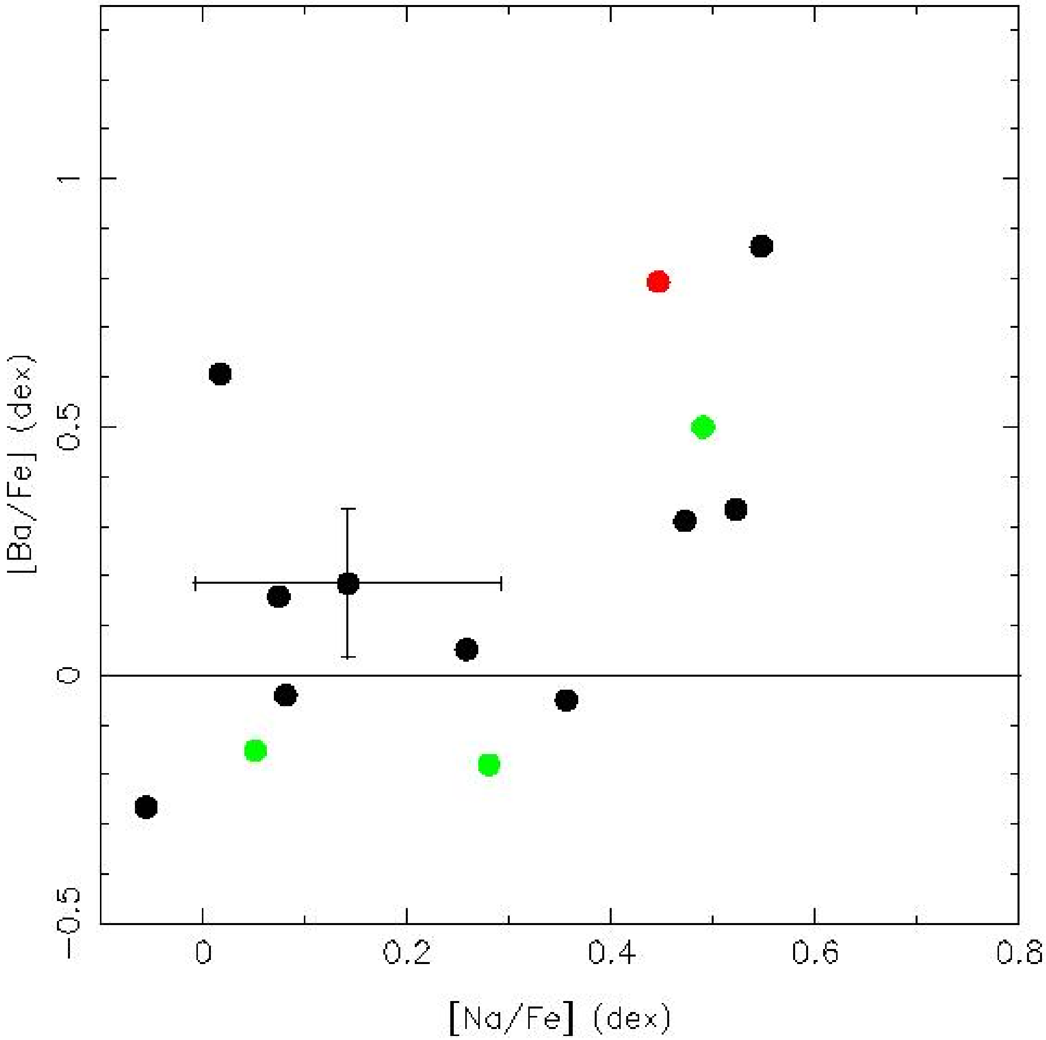
# M15 [Ca/Fe] vs Teff, very small scatter, constant abundance ratio, typical of elements Ca to Ni



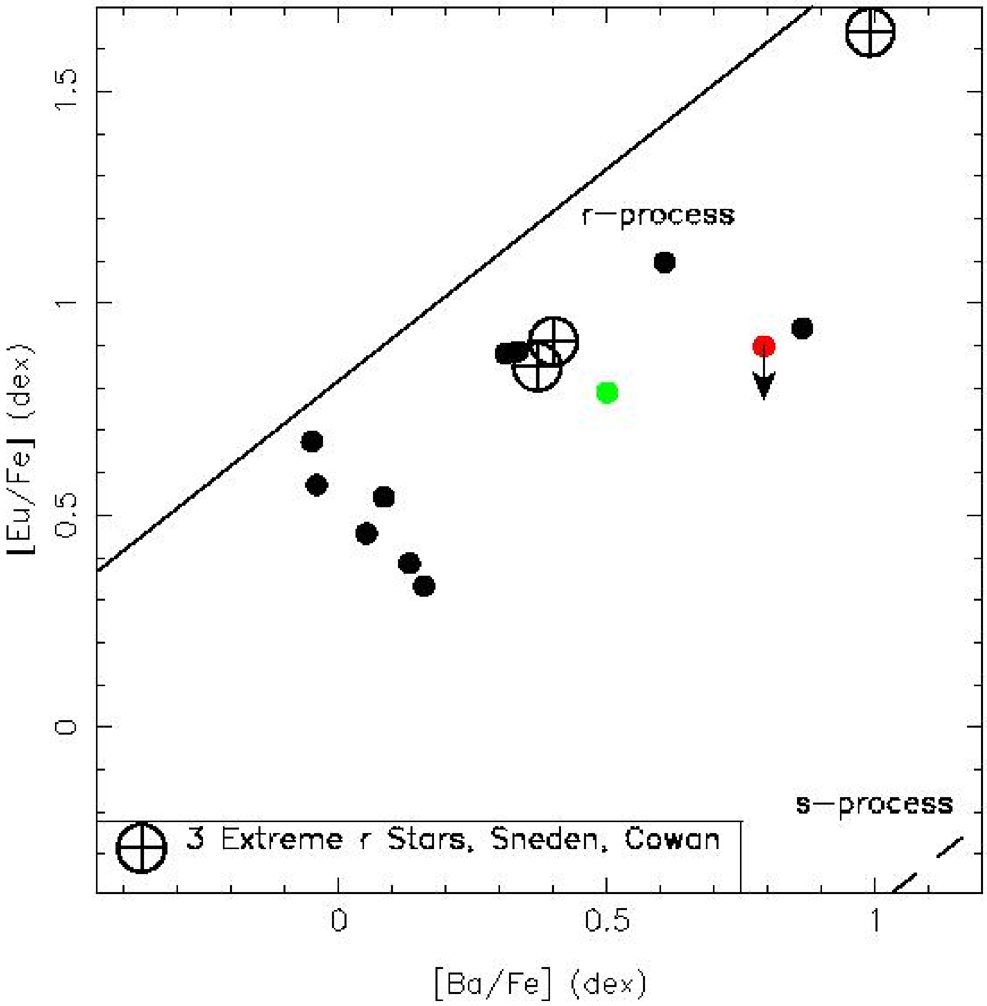
# M15 [Al/Fe vs [Na/Fe], normal group and both high group, Al abund varies by > factor of 20 from star to star in M15



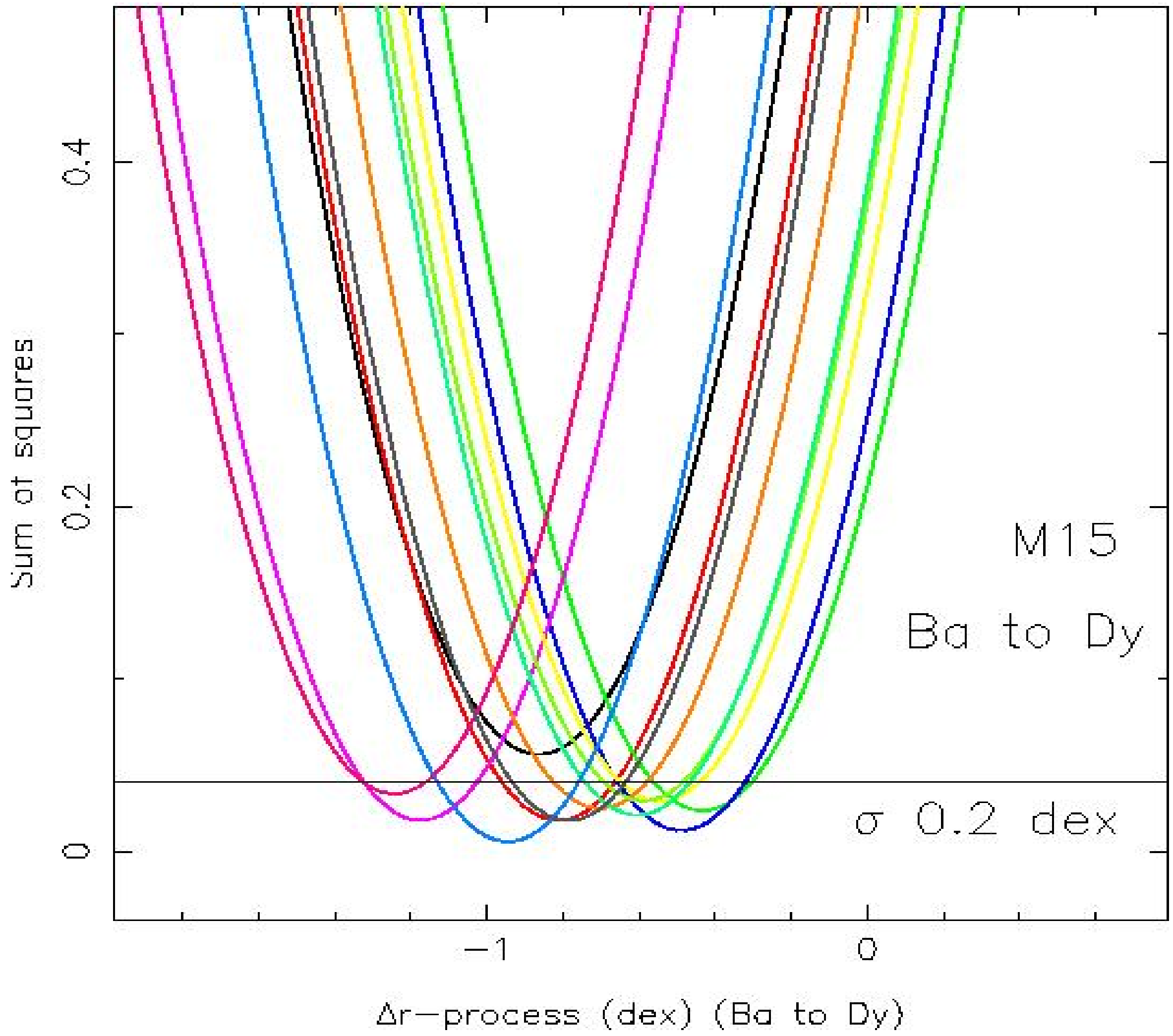
# M15: Probable correlation between enhanced Na and enhanced Ba, i.e. lightest and heaviest elements detected

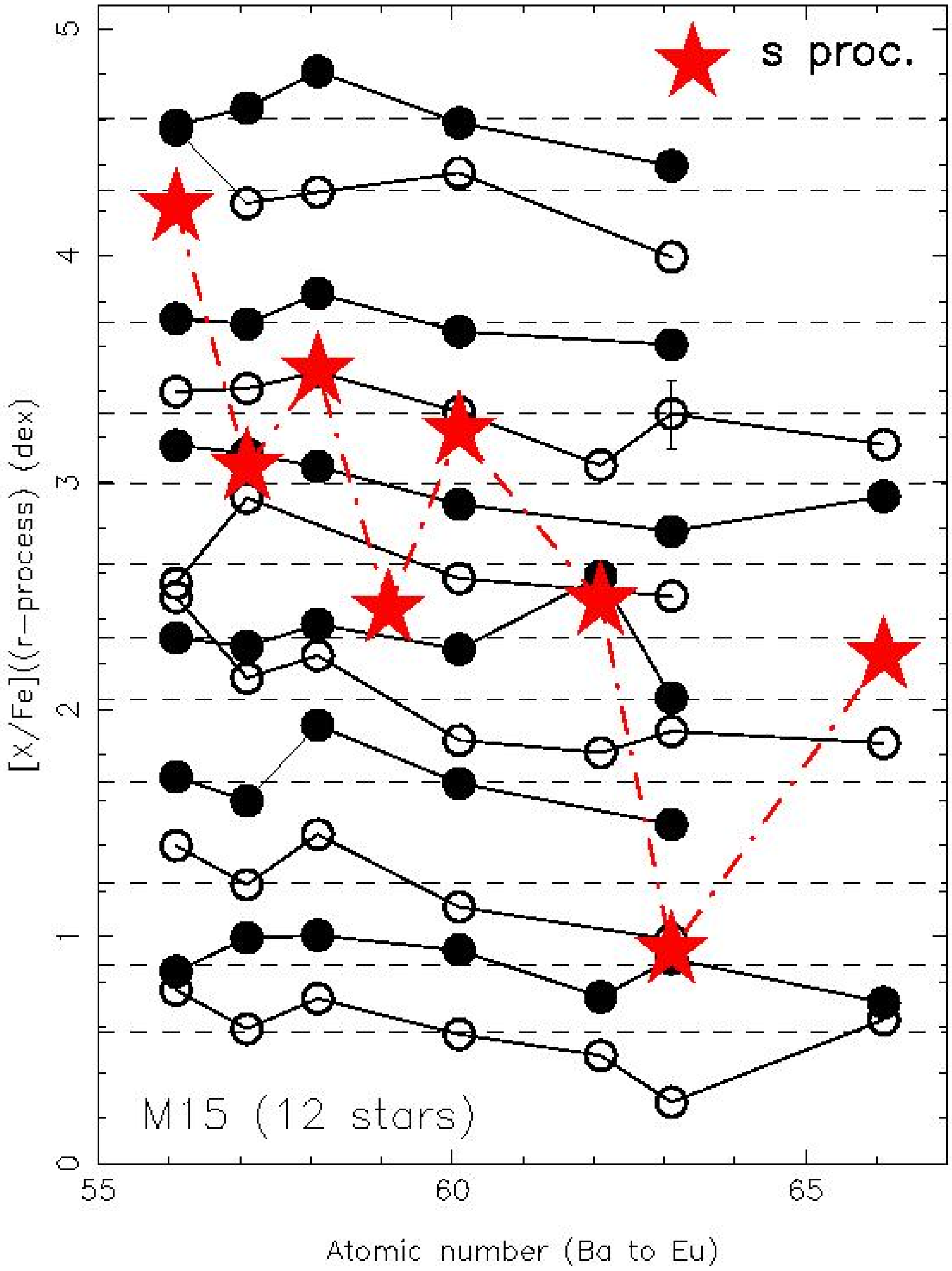


# M15: Ba/Eu ratio is that of the r-process, not the s-process, except perhaps for the C-star



rms deviation/r-elements Ba to Dy from scaled pure r-abundance ratios.  All but 1 star $\sigma$ < 0.2 dex. Range of 5 in [r-process/Fe]






Abundance ratios in 12 M15 stars from Ba to Dy. Horizontal line is pure r-process. Red stars = ratios for pure s-process in Sun.

1. M15 heavy elements shown here are r-process dominated

2. r-process contribution for fixed [Fe/H] varies by 0.7 dex (a factor of 5 !)

# Mg isotopic ratios from MgH band constrain halo formation timescale

- Mg 24 = 6 He atoms, so can be produced from zero metallicity, and is abundant in ejecta of SNII (core collapse of massive stars)

- Mg 25 and Mg 26 are secondary isotopes made in massive stars at a low rate and also produced in intermediate mass (3 to 6 Msun) AGB stars

- The Mg isotopic ratios (Mg25/Mg24 and Mg26/Mg24) increase when the AGB contributes. Thus measuring them we can detect the contribution, if any from the AGB. The Solar ratio is 79:10:11 for Mg24, 25, 26.

- We see NO contribution from the AGB in metal-poor halo dwarfs and in unmixed M71 giants.

- Thus the time scale for the collapse of the halo $<$ lifetime of int. mass AGB star, about 0.3 Gyr years based on nucleosynthesis & stellar evolution calculations.

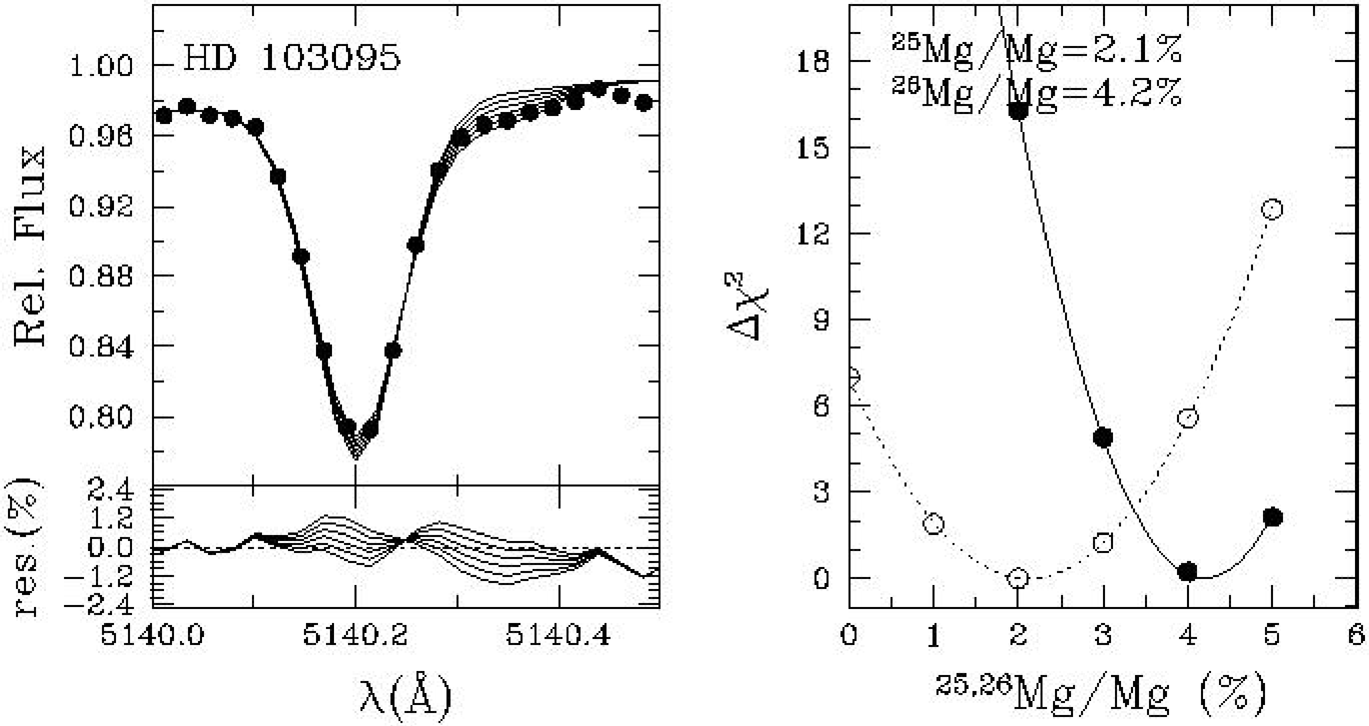
# Why is our result better than previous attempts, which claimed to see a substantial AGB contribution in halo dwarfs ?

- Very careful selection of genuine halo dwarfs, eliminated thick disk

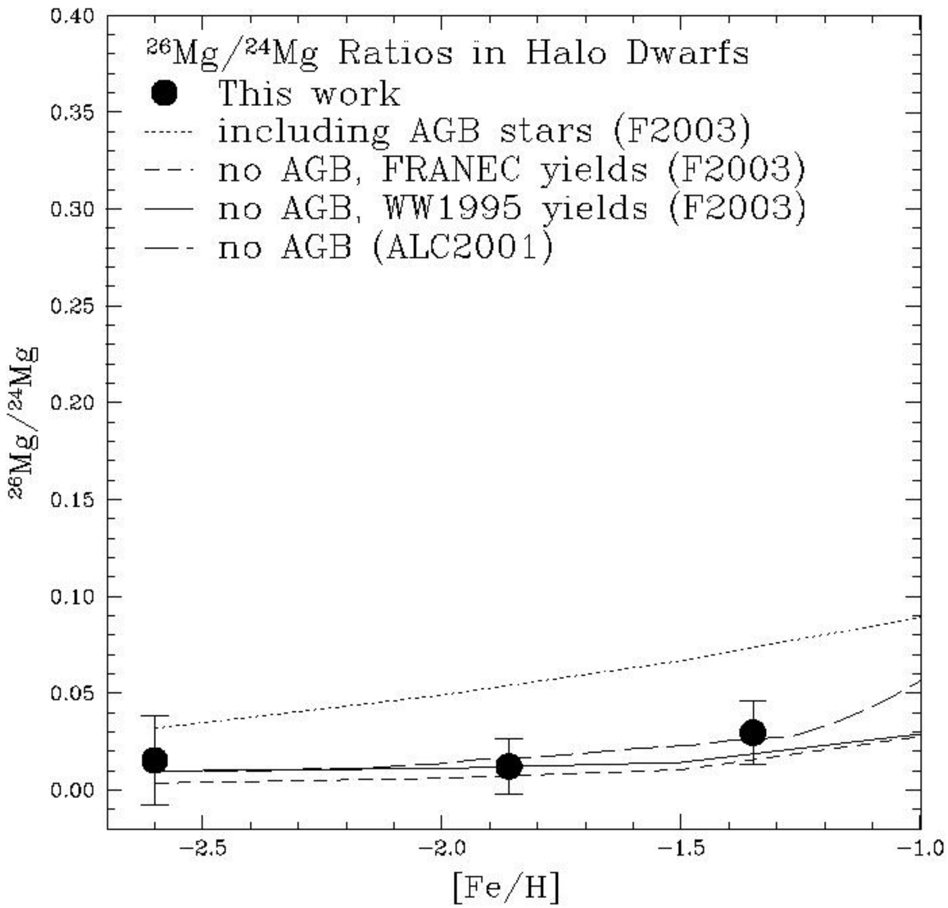
- Very extensive line list including C2 bands as well as MgH and atomic lines generated for spectral syntheses (Jorge Melendez did this part)

- Very high spectral resolution (using 0.4 arcsec slit with HIRES-R) and very high signal-to-noise ratio spectra obtained for specifically for this project

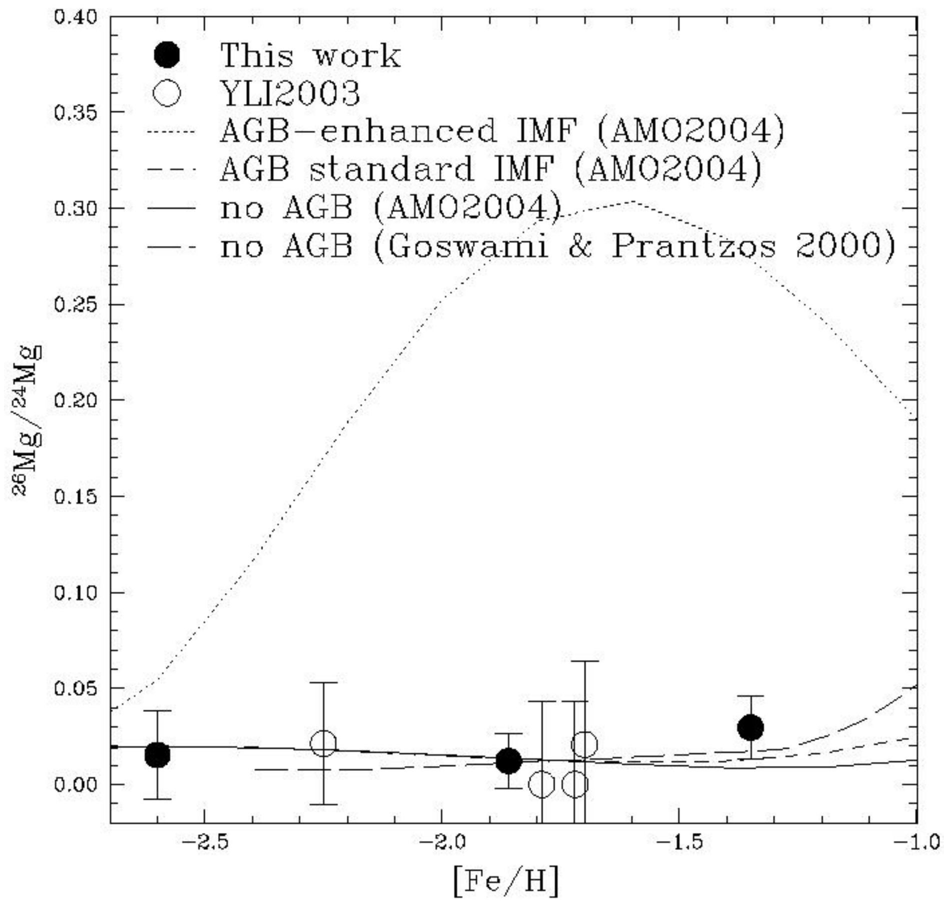
Difficult to do, MgH band 5150 A, isotopic separation small, need spec res ~ 100,000. Impossible until new HIRES detector was installed, need SNR > 100/pixel. Spec. syn. 0 to 5% Mg25,26/Mg.



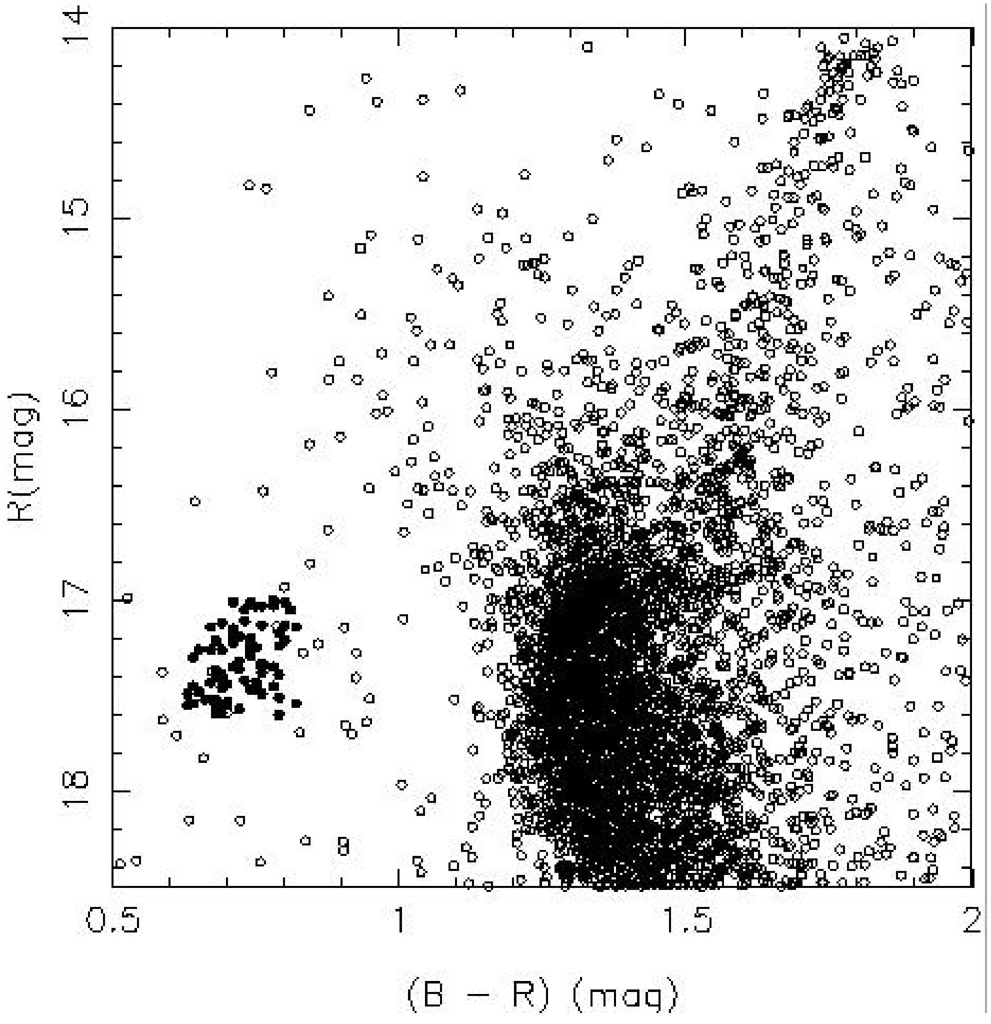
# Our Result for Mg 25,26/Mg24 Compared to Chemical Evolution Models for the Galactic Halo



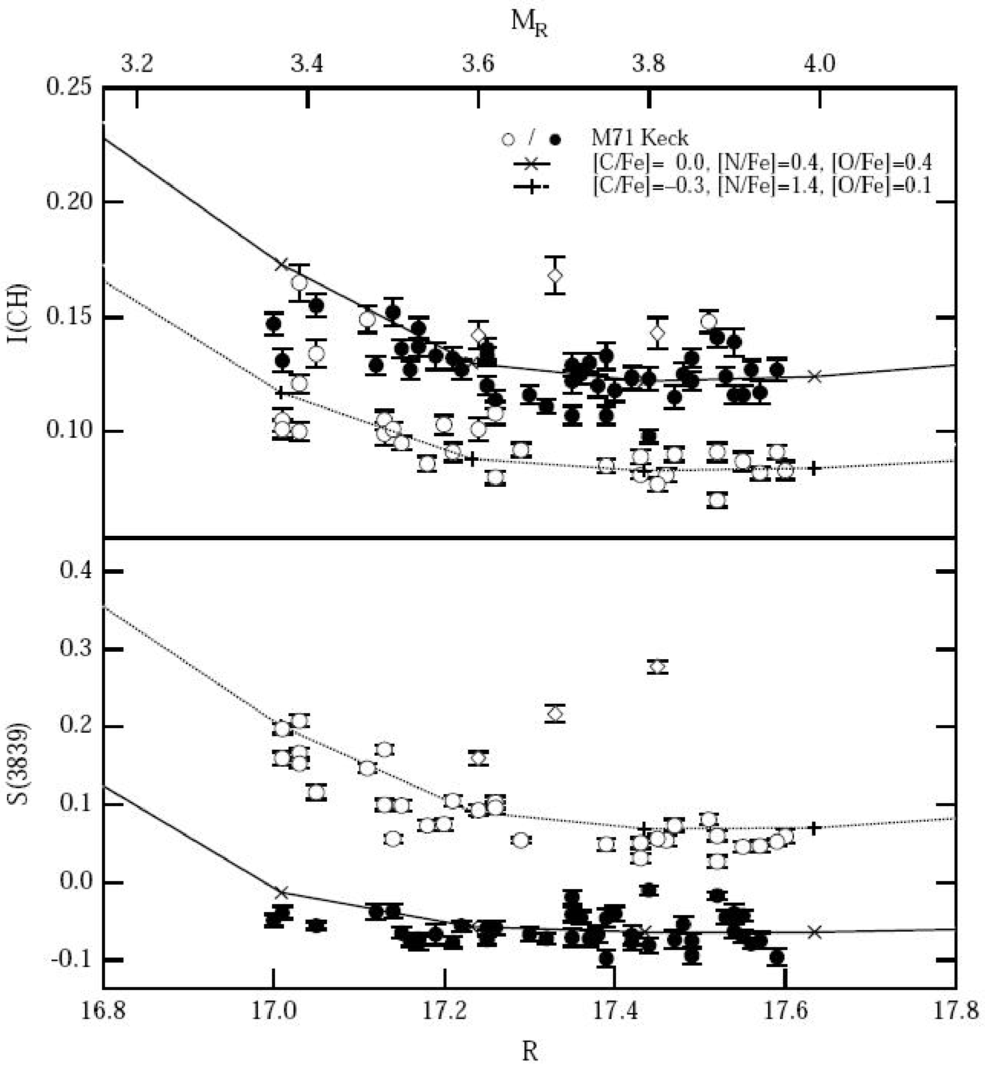
We add in those stars we believe to be genuine halo dwarfs from Yong et al (2003). No evidence for AGB nucleosynthesis. Halo formation timescale to -1.5 dex < 0.3 Gyr years



# Sample of M71 MSTO Stars for CH, CN with LRIS/Keck (Cohen & Briley, published)



# CH and CN Indices for MSTO M71 Stars; Curves From Spectral Synthesis Modeling



# New Keck Spectra of M71 Giants Near RGB Tip

Extremely high SNR HIRES spectra obtained for 8 stars in M71 near RGB tip, plus published spectrum of 1 M71 tip star from Yong et al

Spectral resolution 90,000

Very accurate abundance ratios

Measurement of Mg25/Mg and Mg26/Mg using spectral synthesis, line list includes several molecular features in addition to MgH band.

Following figures: Filled circle – CN rich, open circle, CN weak for M71 luminous giants

# Abundance Ratios (No Scatter Expected) vs Teff in M71 (Melendez & Cohen, 2009) Note σ([Fe/H]) 6%, σ([Ni/Fe]) 3.5%, σ([Si/Fe]) 5%

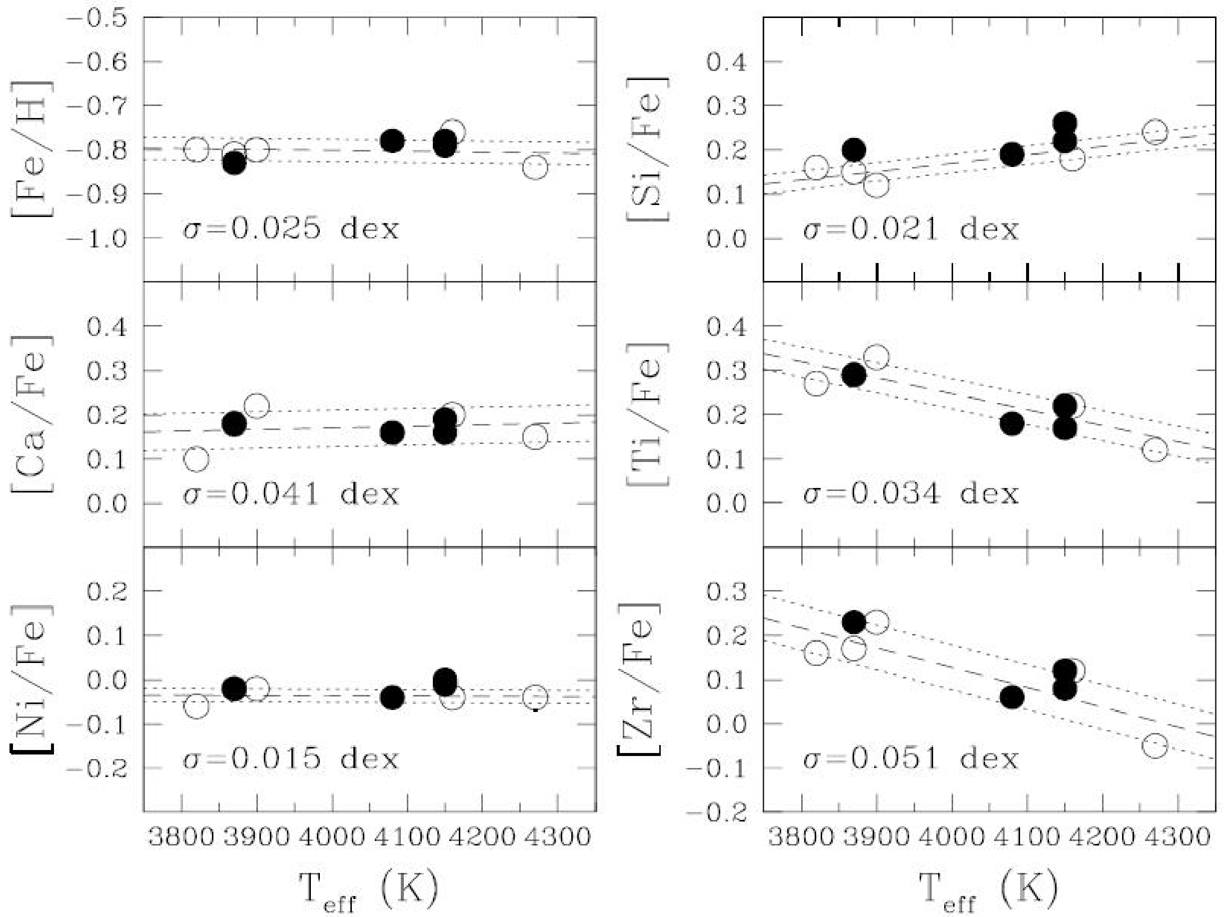



**Fig. 5.** [Fe/H] and [Si,Ca,Ti,Ni,Zr/Fe] abundance ratios (dex) as a function of $T_{eff}$. Open and filled circles represent CN-weak and CN-strong stars, respectively. The dashed line is a fit to the CN-weak stars, and the dotted lines shows the scatter ($\sigma$) around the fit.

# [X/Fe] vs Teff for M71 Giants Near RGB Tip (Melendez & Cohen, 2009, ApJ submitted), normal/CN-rich separation

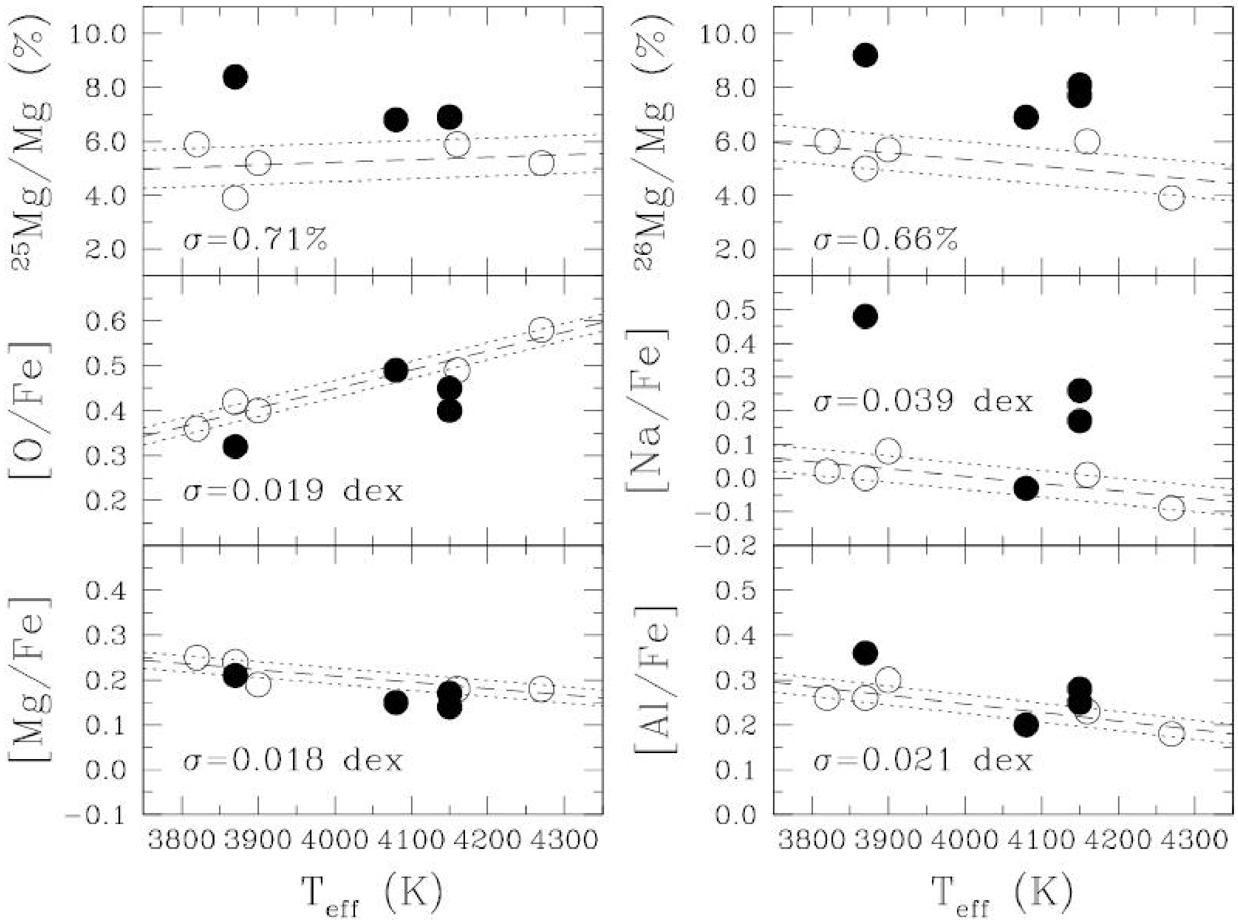



**Fig. 4.** $^{25,26}$Mg/Mg ratios and [O,Na,Mg,Al/Fe] abundance ratios (dex) as a function of $T_{eff}$. Open and filled circles represent CN-weak and CN-strong stars, respectively. The dashed line is a fit to the CN-weak stars, and the dotted lines shows the scatter ($\sigma$) around the fit.

# 26Mg/Total Mg vs [Na, O, Mg or Al/Fe], M71

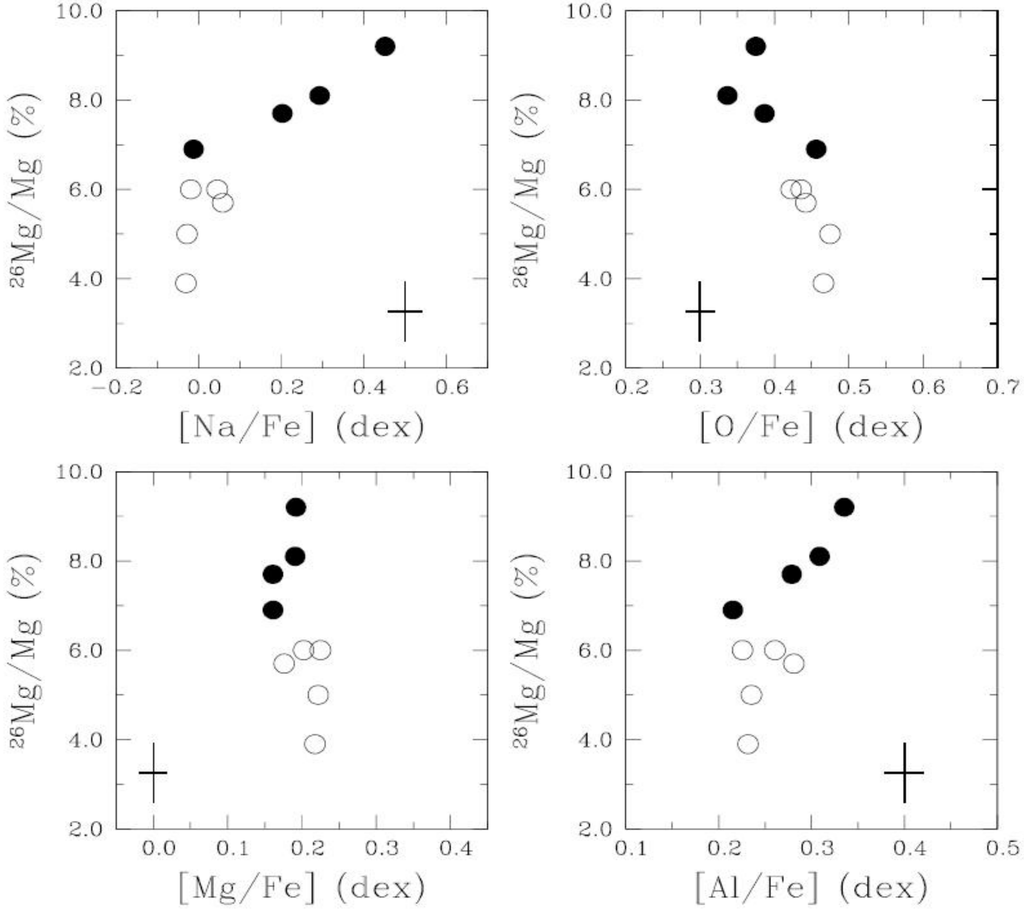



**Fig. 7.** $^{26}$Mg/Mg ratios as a function of [Na/Fe], [O/Fe], [Mg/Fe] and [Al/Fe]. Open and filled circles represent CN-weak and CN-strong stars, respectively. Trends with $T_{eff}$ have been corrected for the elemental [X/Fe] ratios (O, Na, Mg, Al).

# Correlations among O, Na, Mg, and Al in M71 Sample (Melendez & Cohen, 2009) O vs Na vs Al real, but << M15

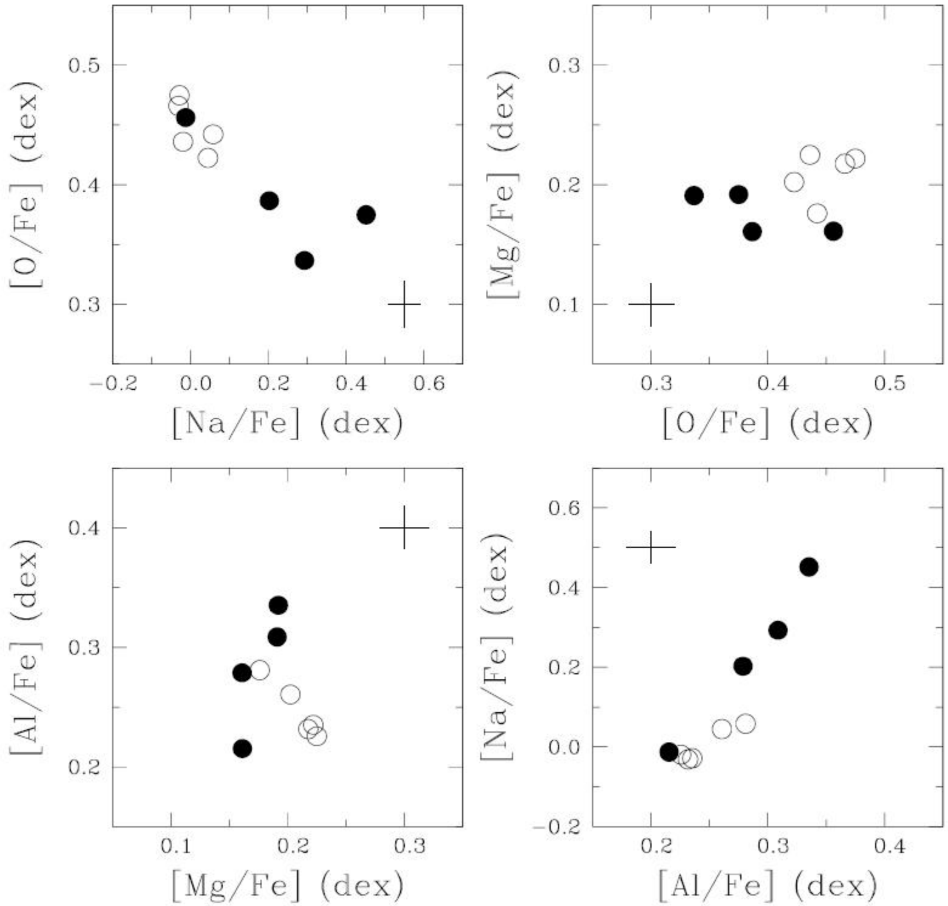



**Fig. 8.** Correlations between O, Na, Mg and Al. Open and filled circles represent CN-weak and CN-strong stars, respectively. The abundance ratios have been corrected for trends with $T_{eff}$. A clear anti-correlation is seen between O and Na, and a well-defined correlation is seen between Na and Al.

# Adding in M71 Data to Halo Mg Isotopic Evolution, unmixed M71 giants ([Fe/H] -0.8 dex) still no AGB contribution. Mixed giants YES AGB contrib.

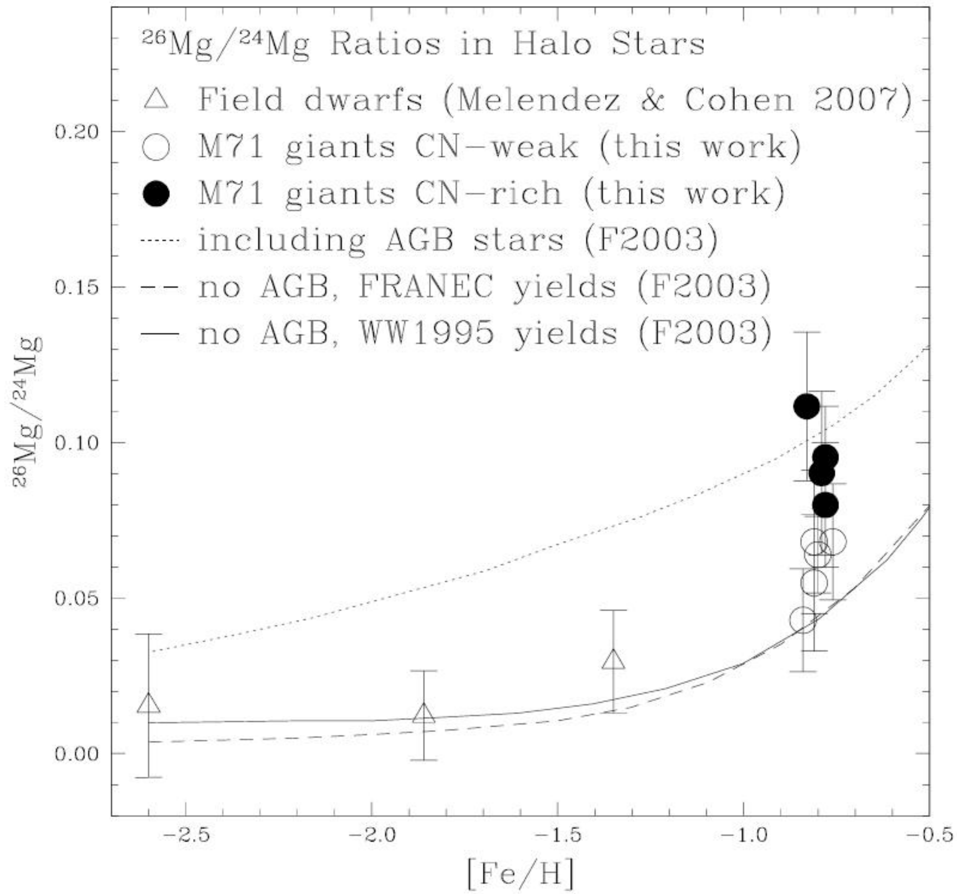



**Fig. 9.** Our $^{26}$Mg/$^{24}$Mg ratios in both field dwarfs (triangles; Melendez & Cohen 2007) and M71 giants (circles; this work) as a function of [Fe/H]. Chemical evolution models by Fenner et al. (2003) including (dotted line) and excluding (solid and dashed lines) AGB stars are shown. At the metallicity of M71 ([Fe/H] = -0.8) the isotopic ratios in the CN-weak stars (open circles) are explained by massive stars, but the CN-strong stars (filled circles) may have been polluted by IM AGB stars.

# Issues

- Why are CH and CN essentially bimodal in metal-rich GCs like M71, but scatter between high and low limits in M15 ?  Does this reflect uniformity of mixing throughout the young GC ?

- When does the AGB start to contribute in the halo ?  Did the halo reach its max. Fe-metallicity so rapidly that this did not happen or is there something wrong with the models, evol. tracks, etc

# Conclusions

- No sign yet of AGB contribution to pristine halo stars at [Fe/H] -0.8 dex. Intrinsic $\sigma$[Fe/H] < 6%, $\sigma$[Si/Fe] < 5%
- Mixed stars in M71 show signs of AGB contribution
- M15 light elements strong variations, Fe-peak no var.
- M15 heavy elements are r-process, with range of r/Fe of a factor of 5.  Appear correlated with Na abundance.
- M15 low luminosity C star with v high Ba, may be s-process