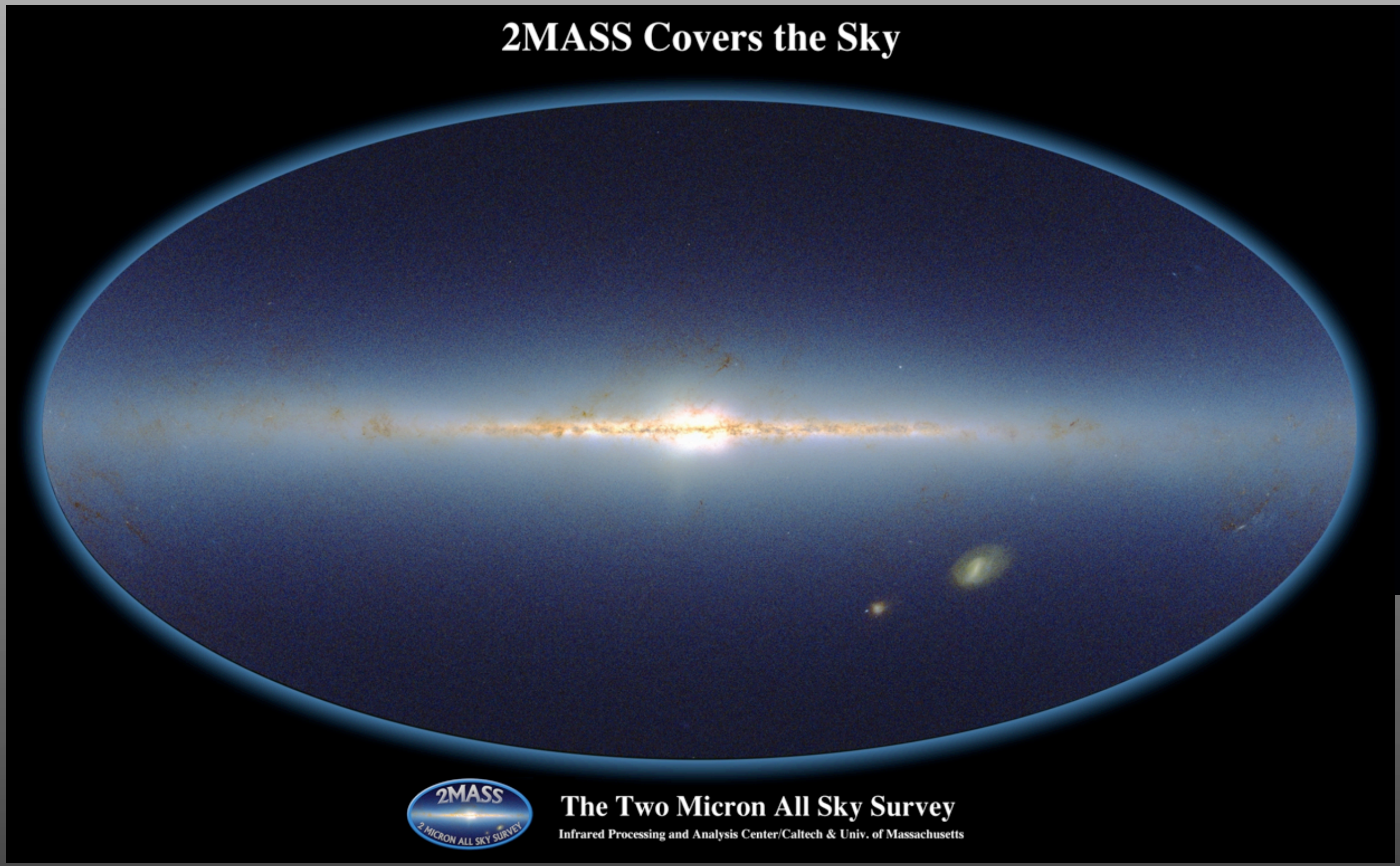
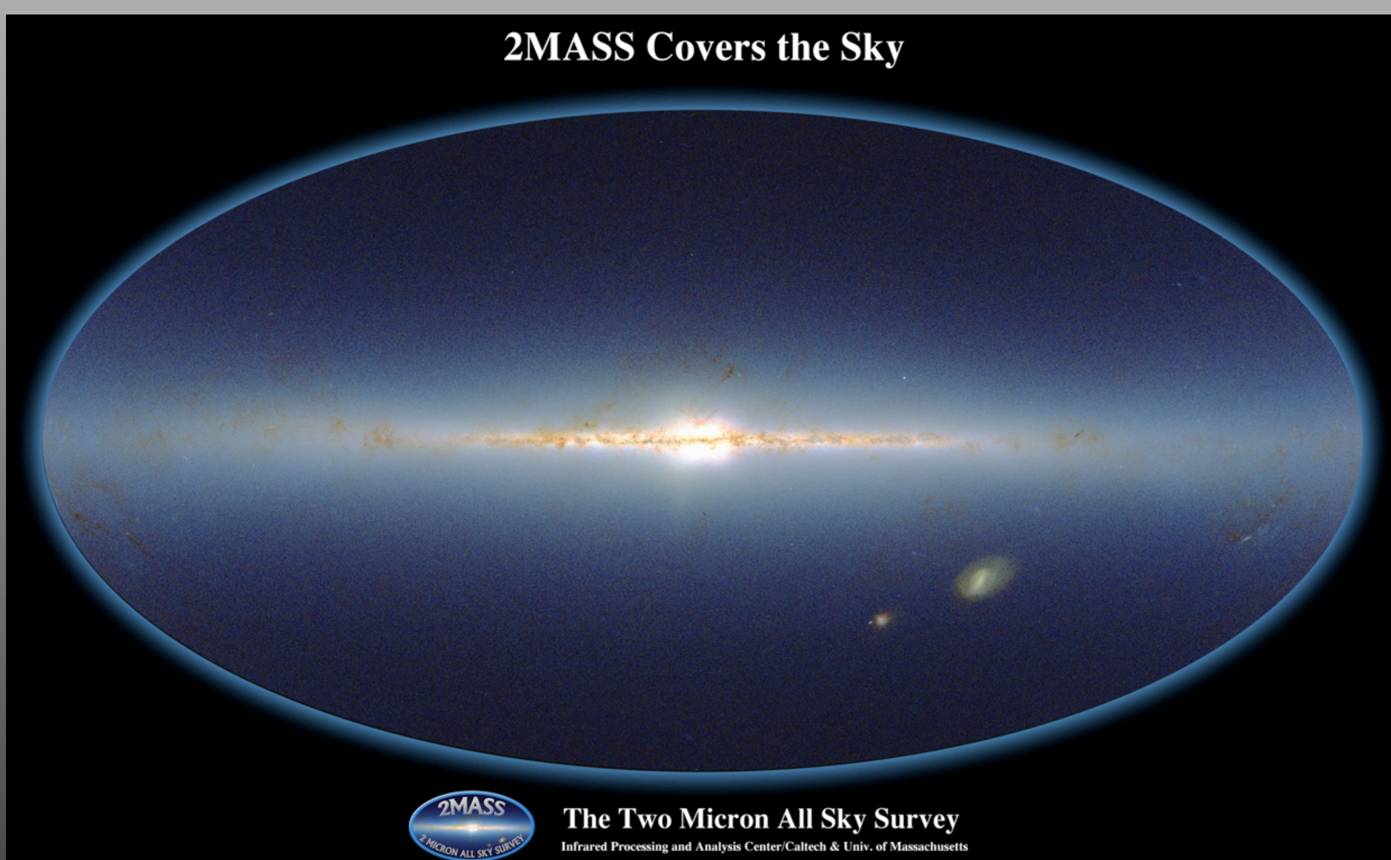
Element abundance ratios in stars of the outer Galactic disk

Bruce Carney (University of North Carolina)
Eileen Friel (Indiana University)



Outline

- **Introduction**
- New observations and interpretation
- Future directions



Why study the outer disk?

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Origin and evolution of galaxies

The Milky Way is the best example to study and the disk is the dominant stellar population

The composition of gas throughout the galaxy is controlled by the processes of star formation, evolution and death

Abundance gradients can be readily(?) measured and provide strong constraints on galaxy formation mechanisms

XIII CANARY ISLANDS
WINTER SCHOOL OF ASTROPHYSICS

Puerto de la Cruz, Tenerife

19-30 / XI / 2001

"Cosmochemistry:
the melting pot of elements"

"Models of Chemical Evolution of Galaxies and Intracluster Medium"
The Life Cycle of Stars
FRANCESCA MATTEUCCI
(University of Trieste, Italy)

Why use open clusters?

Why use open clusters?

Numerous
Ages (accuracy and a large range)
Distances (accuracy and a large range)
Radial velocities and chemical compositions
==>
Structure, kinematics and chemistry of the disk, and ideally the time variation of these quantities

The existing data (~1995)

Annu. Rev. Astron. Astrophys. 1995. 33:381–414

THE OLD OPEN CLUSTERS OF THE MILKY WAY

E. D. Friel

Maria Mitchell Observatory, 3 Vestal Street, Nantucket, Massac

KEY WORDS: Galactic structure, galaxy formation, Galactic disk, stellar a dances, stellar kinematics

ABSTRACT

The Galactic open clusters, in particular the oldest members, serve as excellent probes of the structure and evolution of the Galactic disk. Individual clusters provide excellent tests of stellar and dynamical evolution. Cluster spatial and age distributions provide insight into the processes of cluster formation and destruction that have allowed substantial numbers of old open clusters to survive. Spectroscopic and photometric data for the old clusters yield kinematic, abundance, and age information that clarifies the relationship between the old open cluster population and other Galactic populations. New samples of old open clusters, which span a large range in distance and age, are used to define disk abundance gradients and the cluster age-metallicity relationship, and they point to a complex history of chemical enrichment and mixing in the disk.

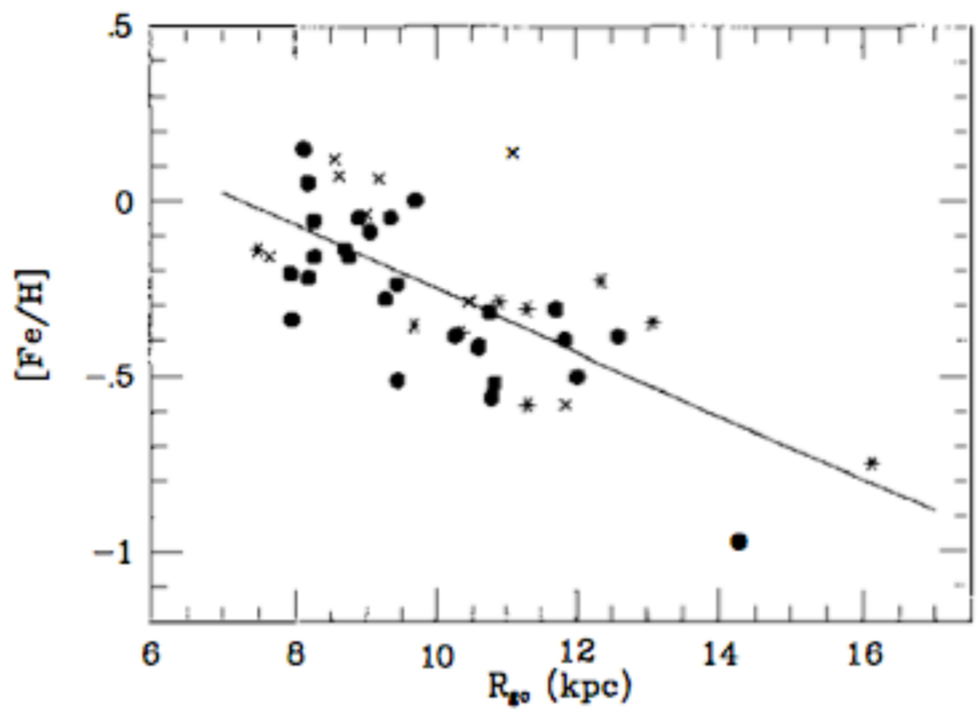

Figure 7 Radial abundance gradient for the old open clusters, with metallicities from Table 1. Filled circles are points from Friel & Janes (1993) or Thogersen et al (1994). Starred symbols are preliminary metallicities from Friel et al (1995). Crosses are data taken from Lynga (1987). The solid line is a least-squares fit to the data that yields an abundance gradient of $\Delta[Fe/H]/R_{gc} = -0.091 \pm 0.014$.

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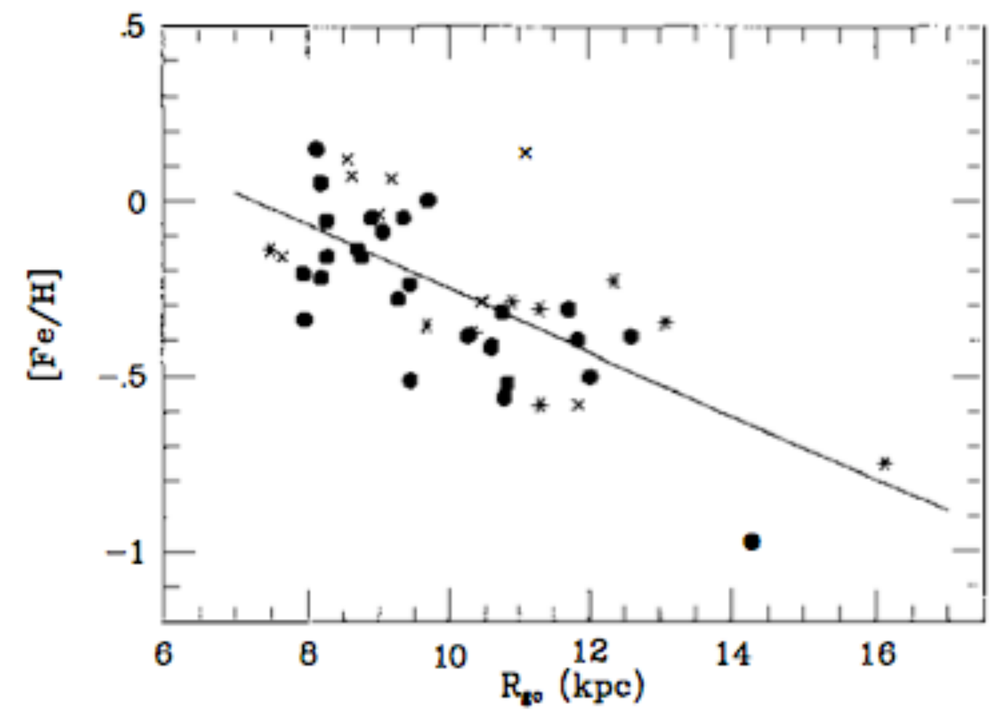

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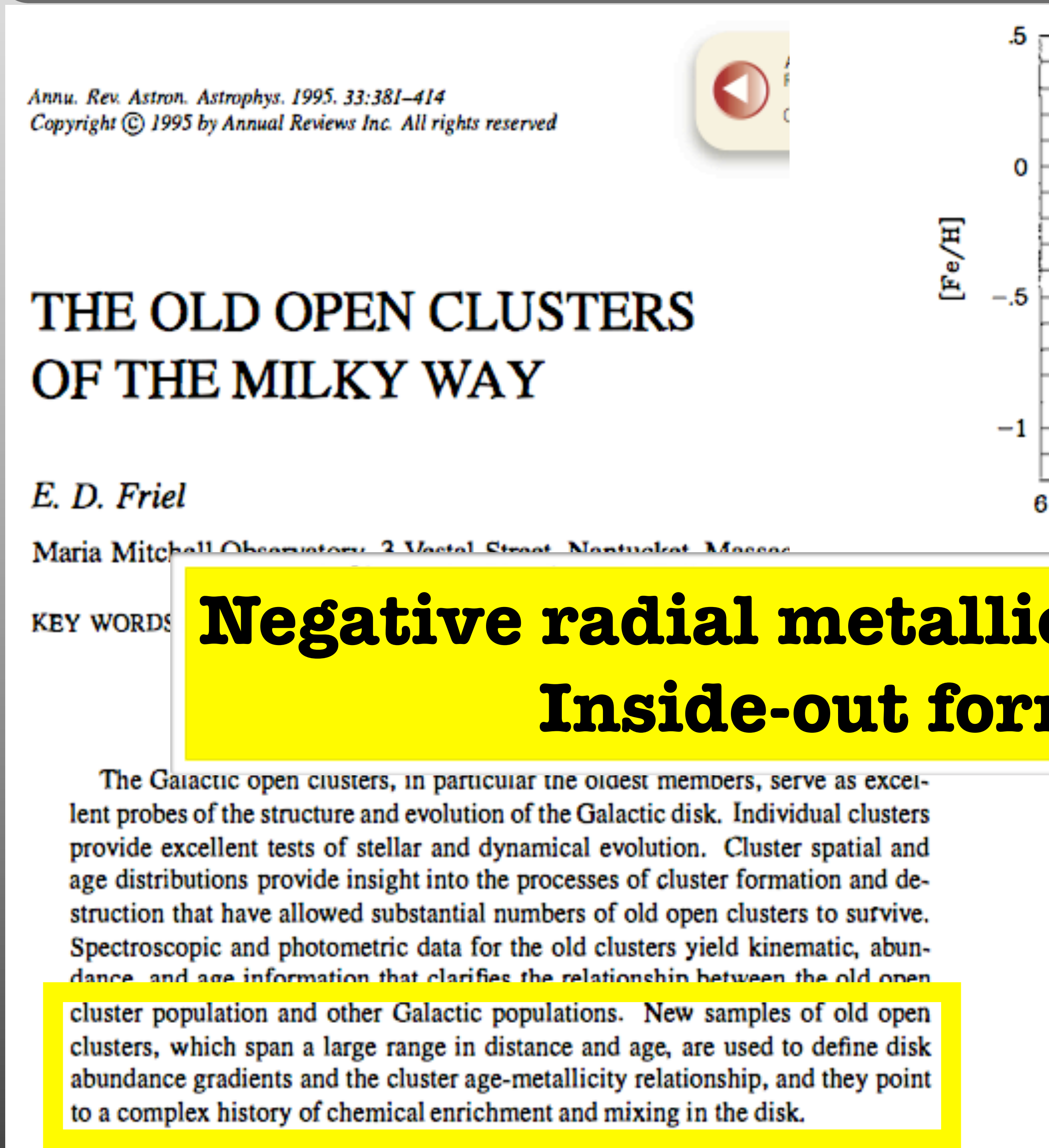

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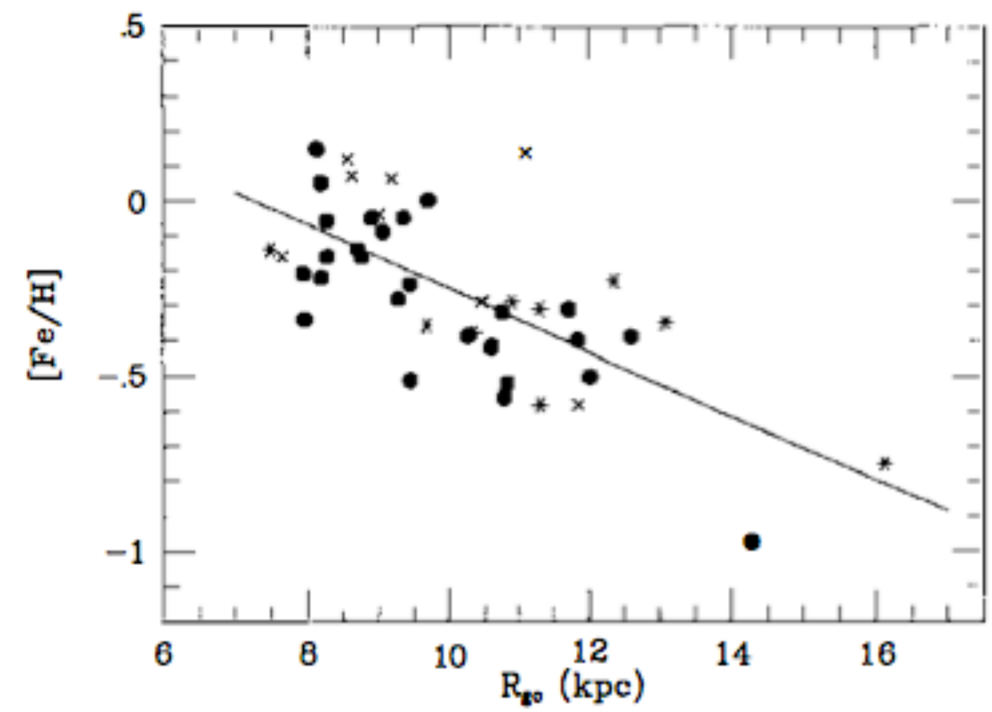
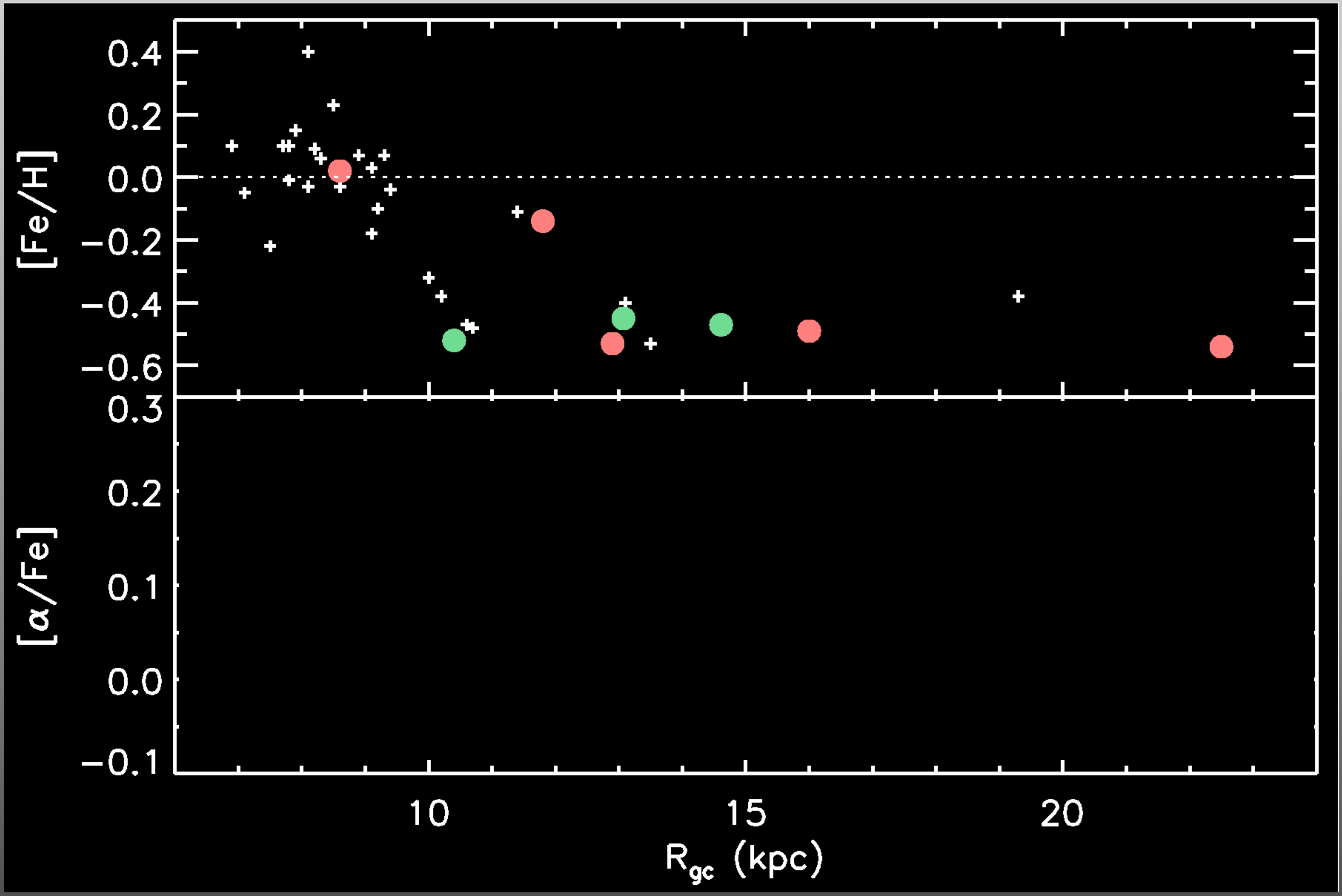


...om Table 1. ...ed symbols ...nga (1987). ...e/H]/R_{gc} =

Negative radial metallicity gradient ==>
Inside-out formation

The existing data (~2005)

Primarily old (>1Gyr) open clusters



The existing data (~2005)

Chiappini, Matteucci & Romano (2001)

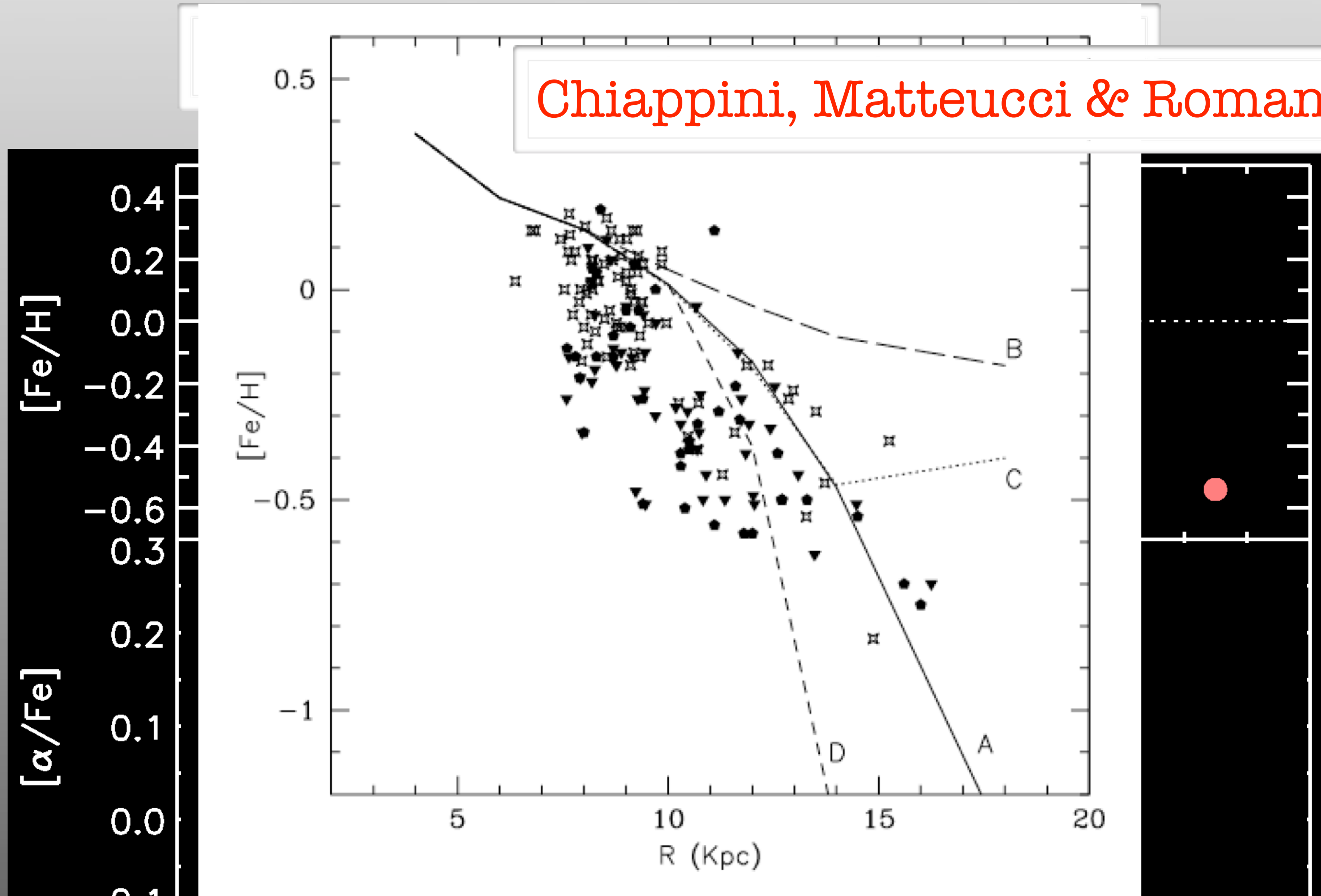
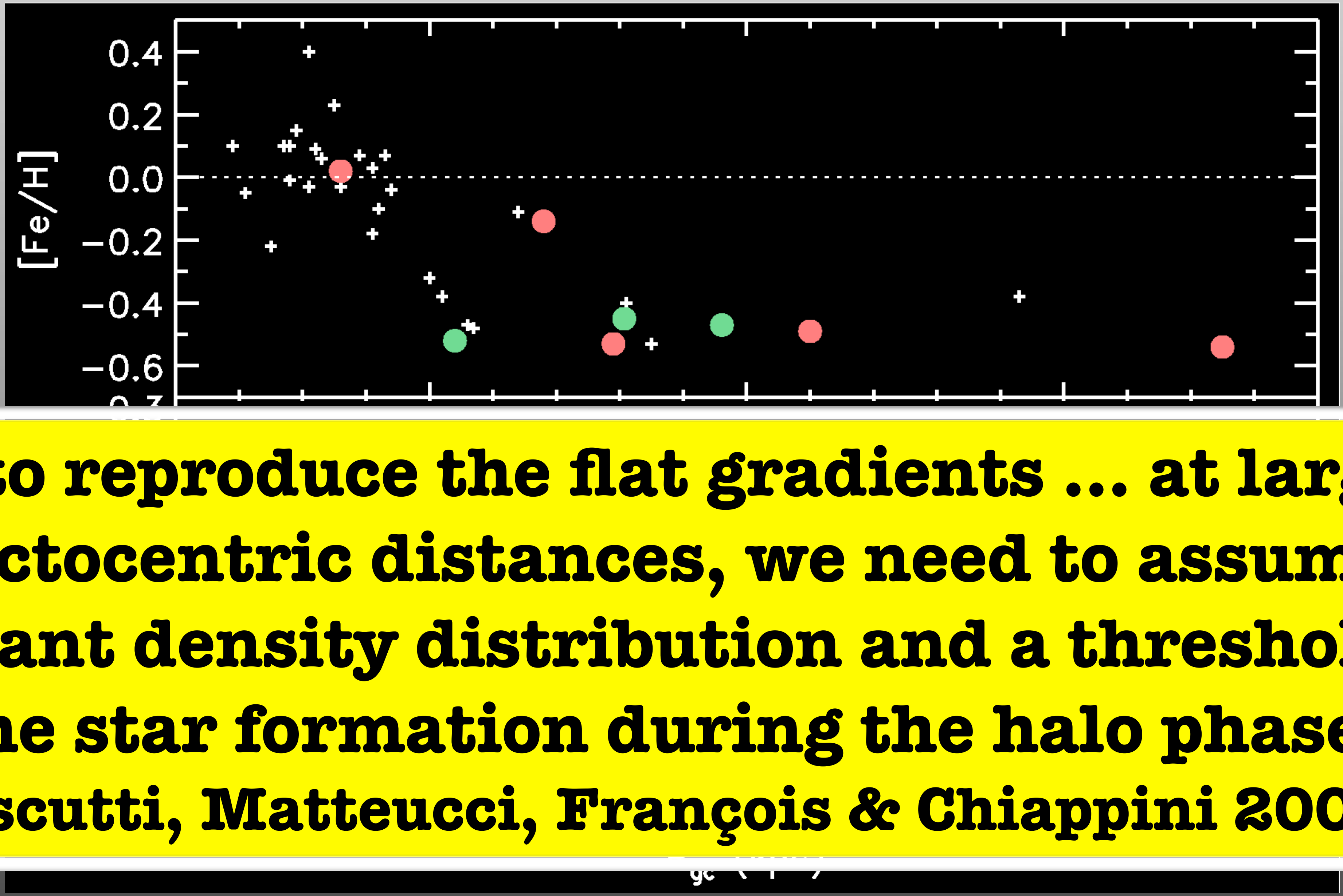


FIG. 10.—Predicted radial iron gradient at $t = t = t_{Gal} = 14$ Gyr from model A (*continuous line*), model B (*long-dashed line*), model C (*dotted line*), and model D (*short-dashed line*) compared to observational data: Twarog et al. 1997 (*stars*); Carraro et al. 1998 (*filled pentagons*); Friel 1999 (*filled triangles*).

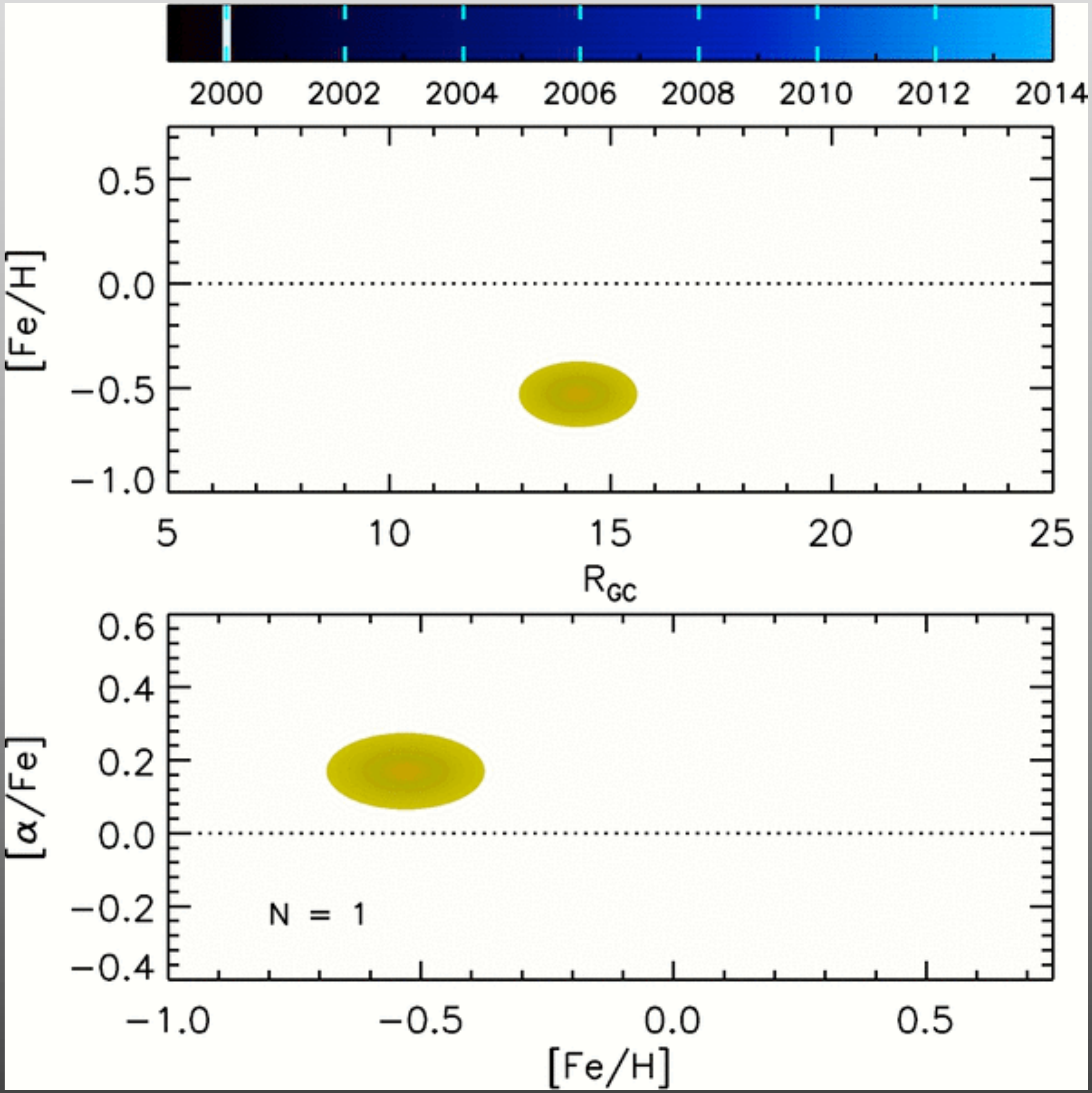
The existing data (~2005)

Primarily old (>1Gyr) open clusters



... to reproduce the flat gradients ... at large galactocentric distances, we need to assume a constant density distribution and a threshold in the star formation during the halo phase (Cescutti, Matteucci, François & Chiappini 2007)

The story so far ...



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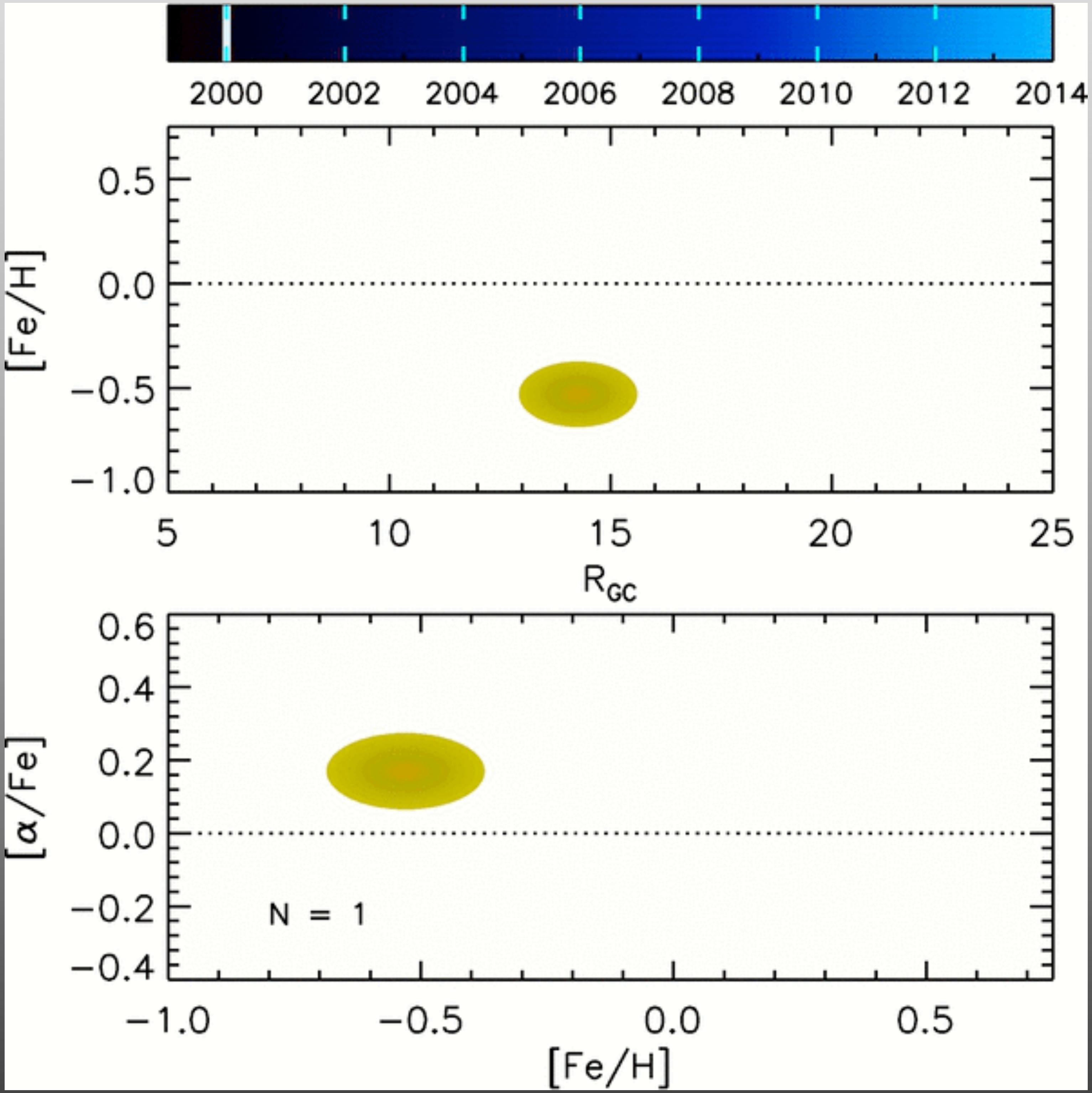
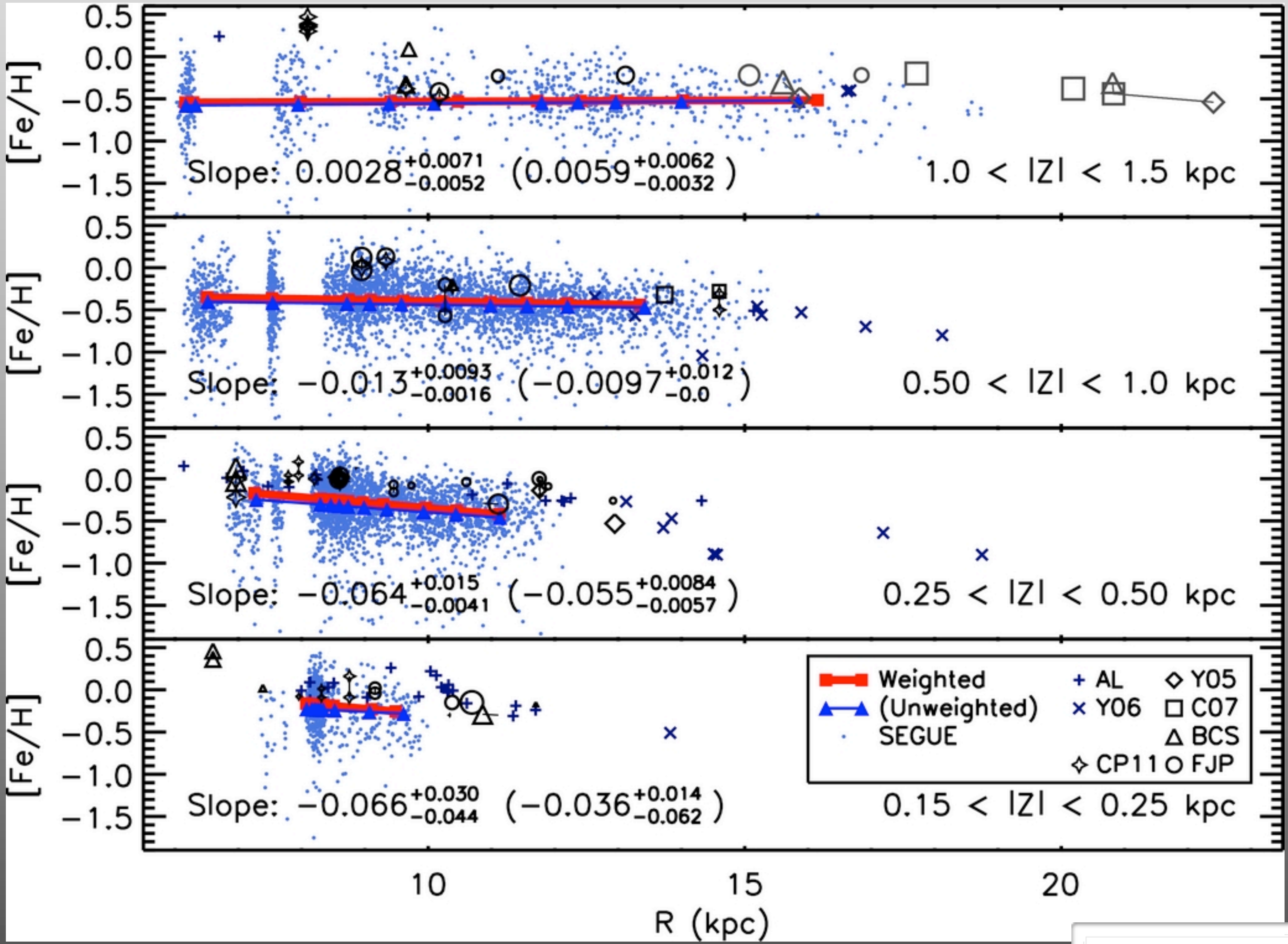


Open cluster literature data including …

Bragaglia
Carraro
Carrera
Carretta
de Silva
Friel
Hill
Jacobson
Pancino
Paulson
Sestito
Tautvaišienė
Villanova

The SDSS view



Cheng et al. (2012)

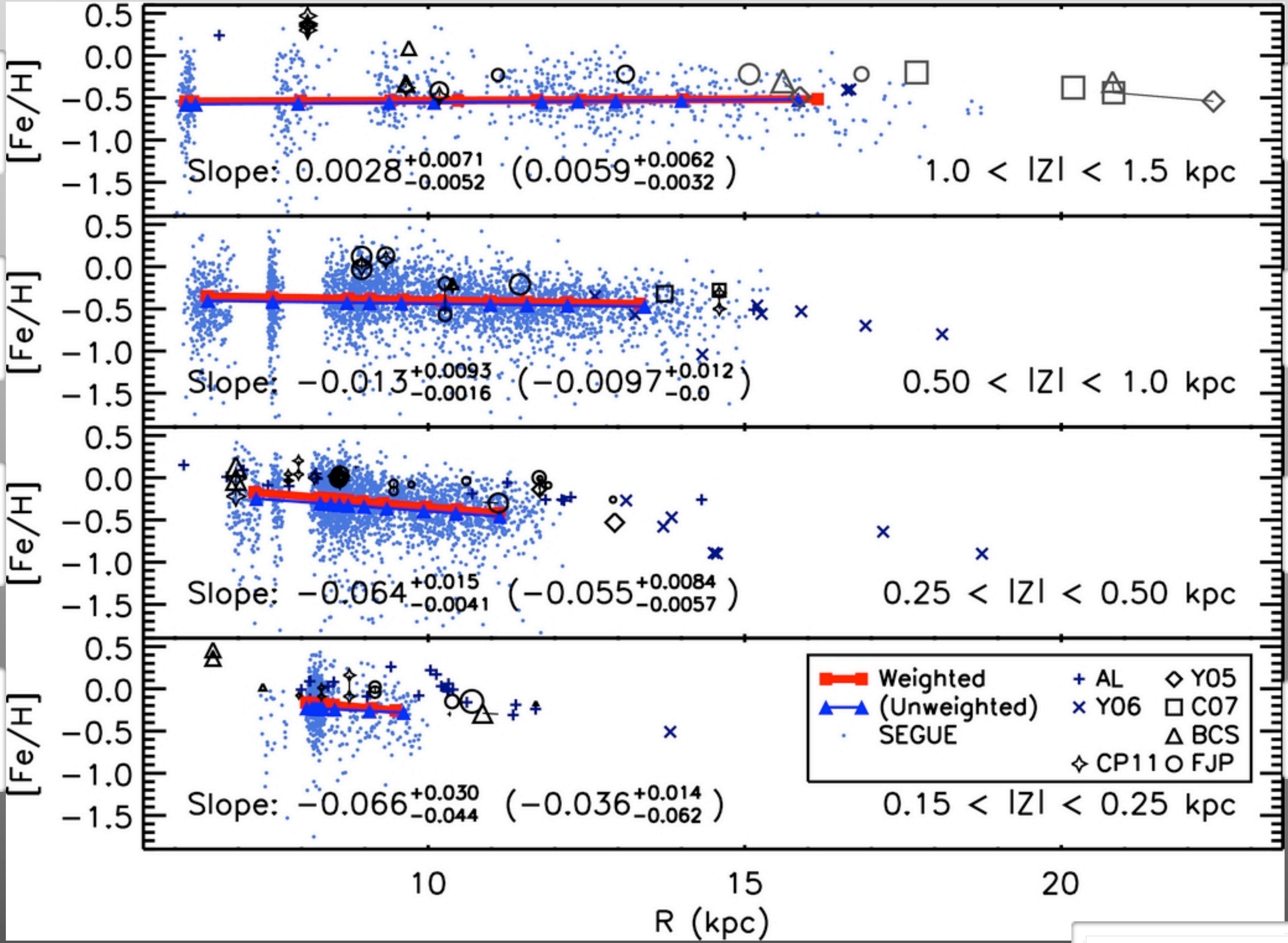
The SDSS view

Fe

Fe

Fe

Fe



1.0 < Z < 1.5

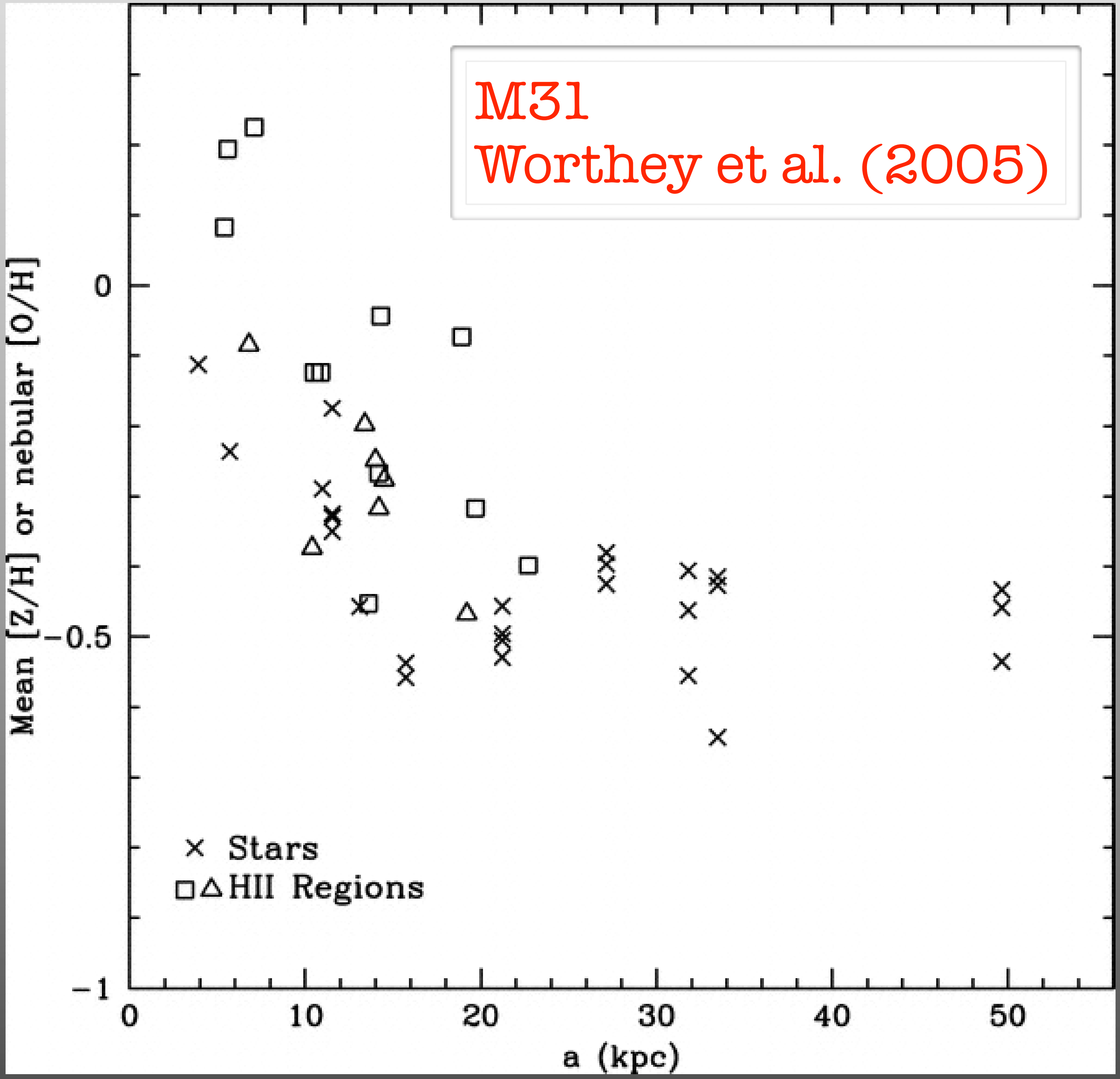
0.50 < Z < 1.0

0.25 < Z < 0.5

0.15 < Z < 0.25

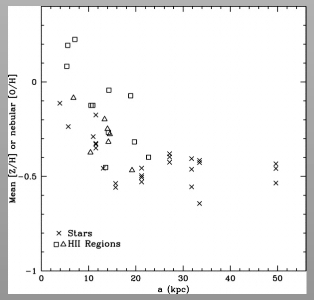
Cheng et al. (2012)

External galaxies



External galaxies

M31
Worthey et al. (2005)



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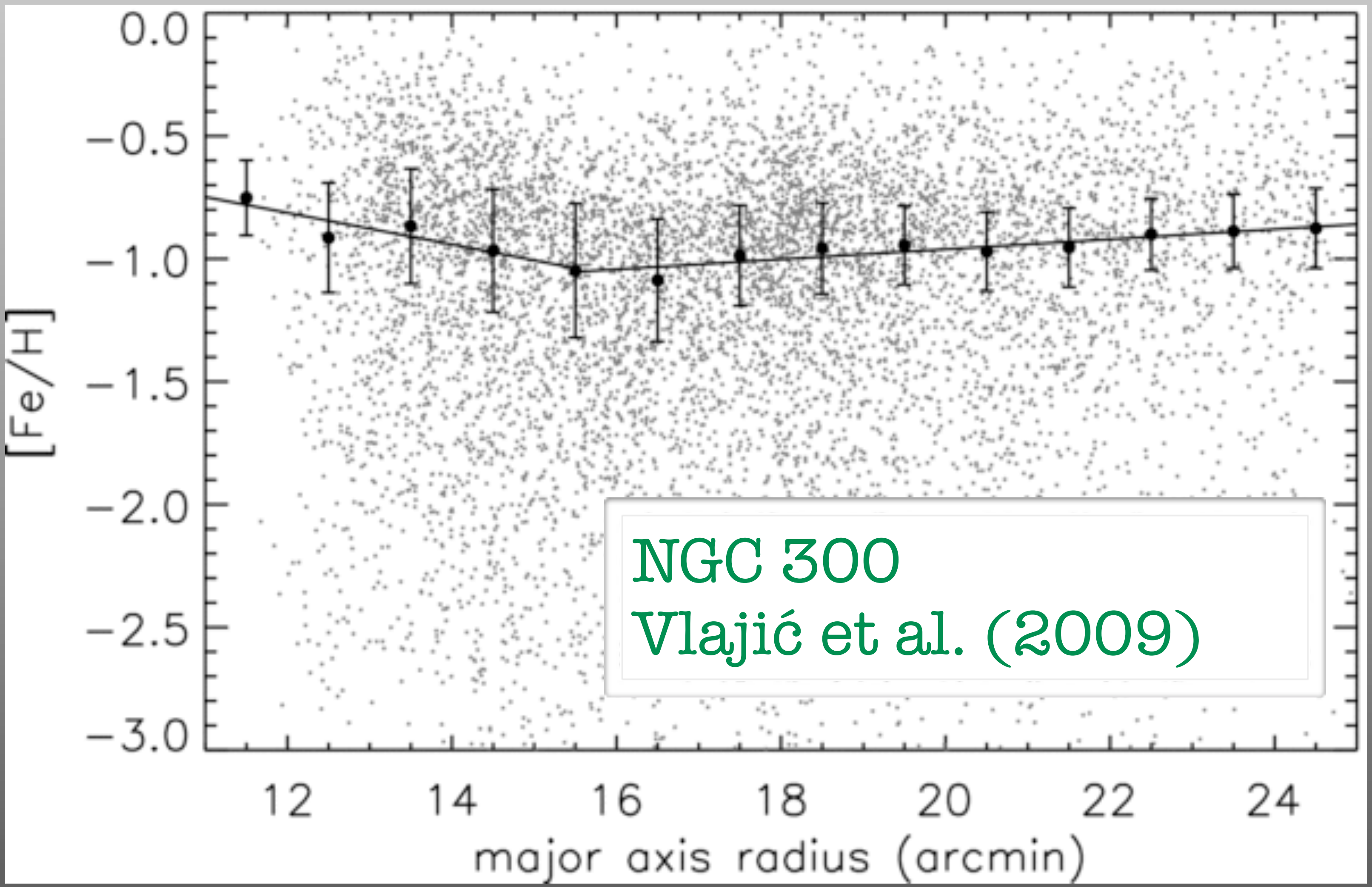

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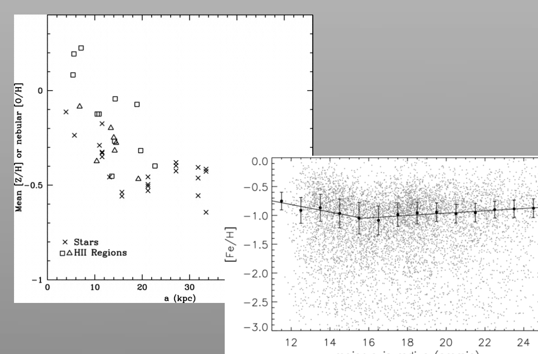
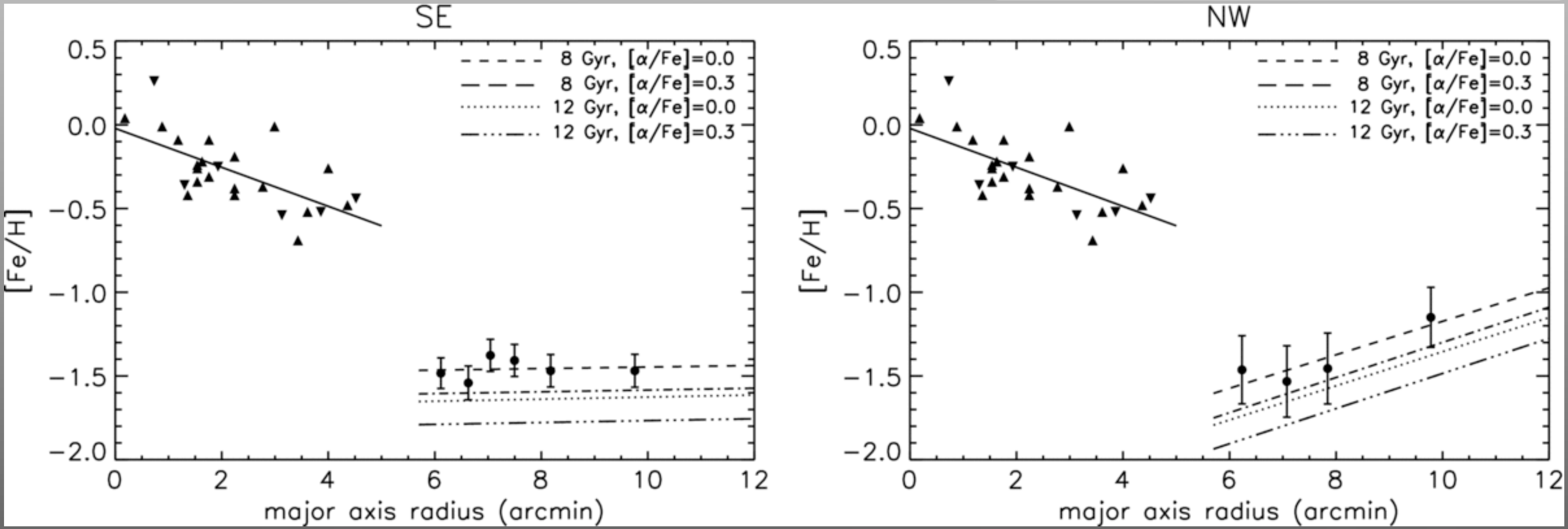


NGC 300
Vlajić et al. (2009)

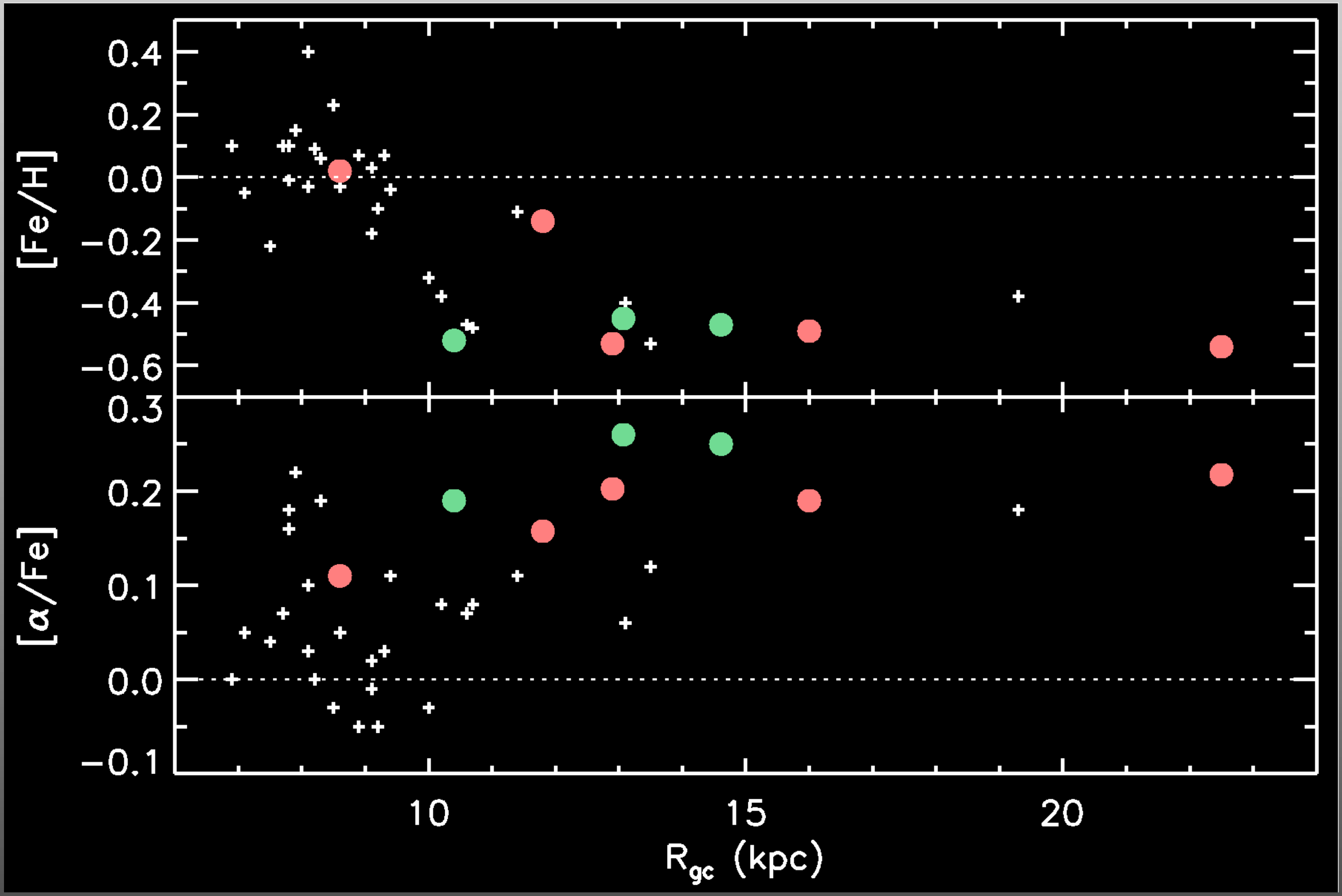
External galaxies

M31
Worthey et al. (2005)

NGC 7798
Vlajić et al. (2011)



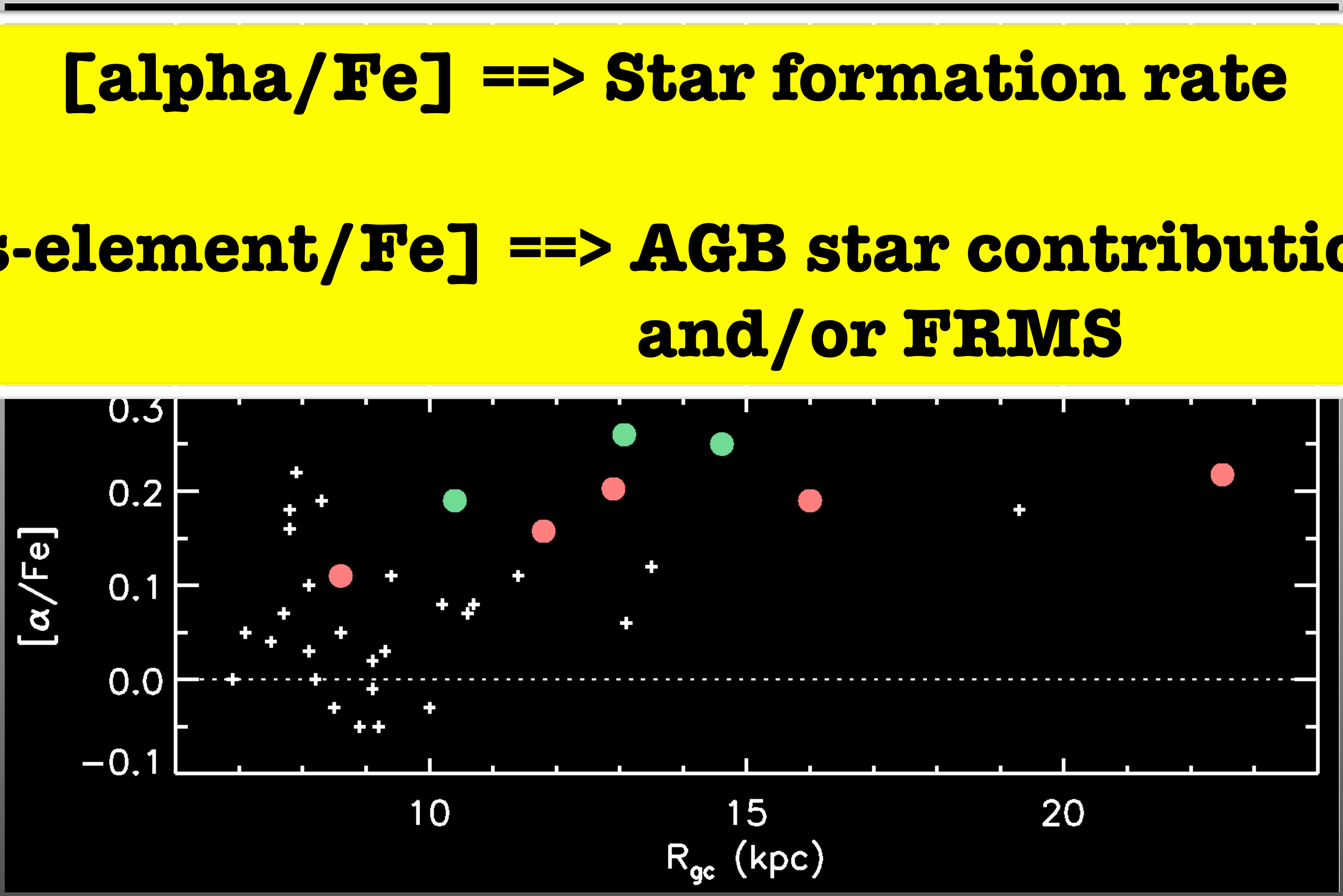
Beyond just [Fe/H]



Beyond just [Fe/H]

[alpha/Fe] ==> Star formation rate

[s-element/Fe] ==> AGB star contribution and/or FRMS



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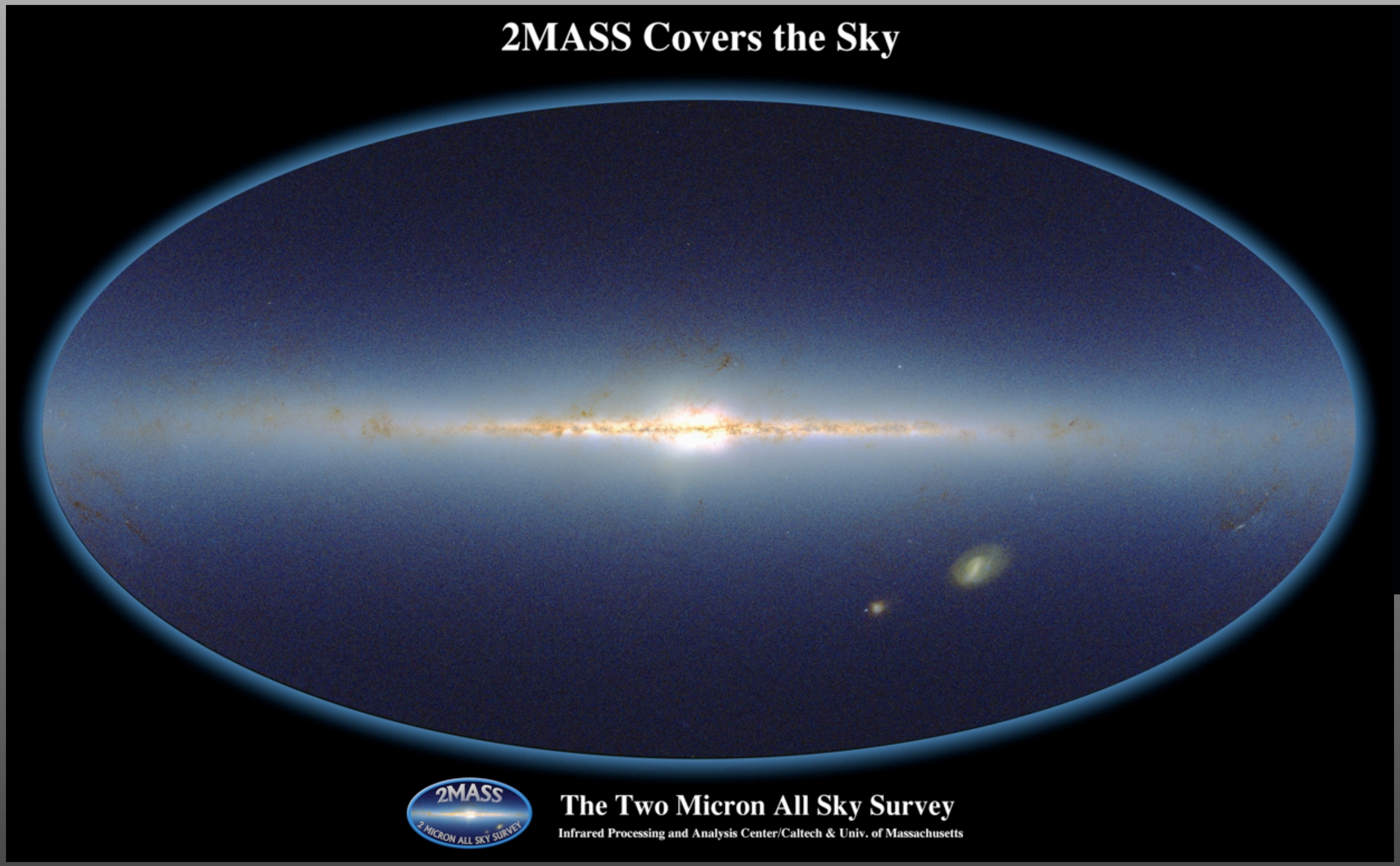
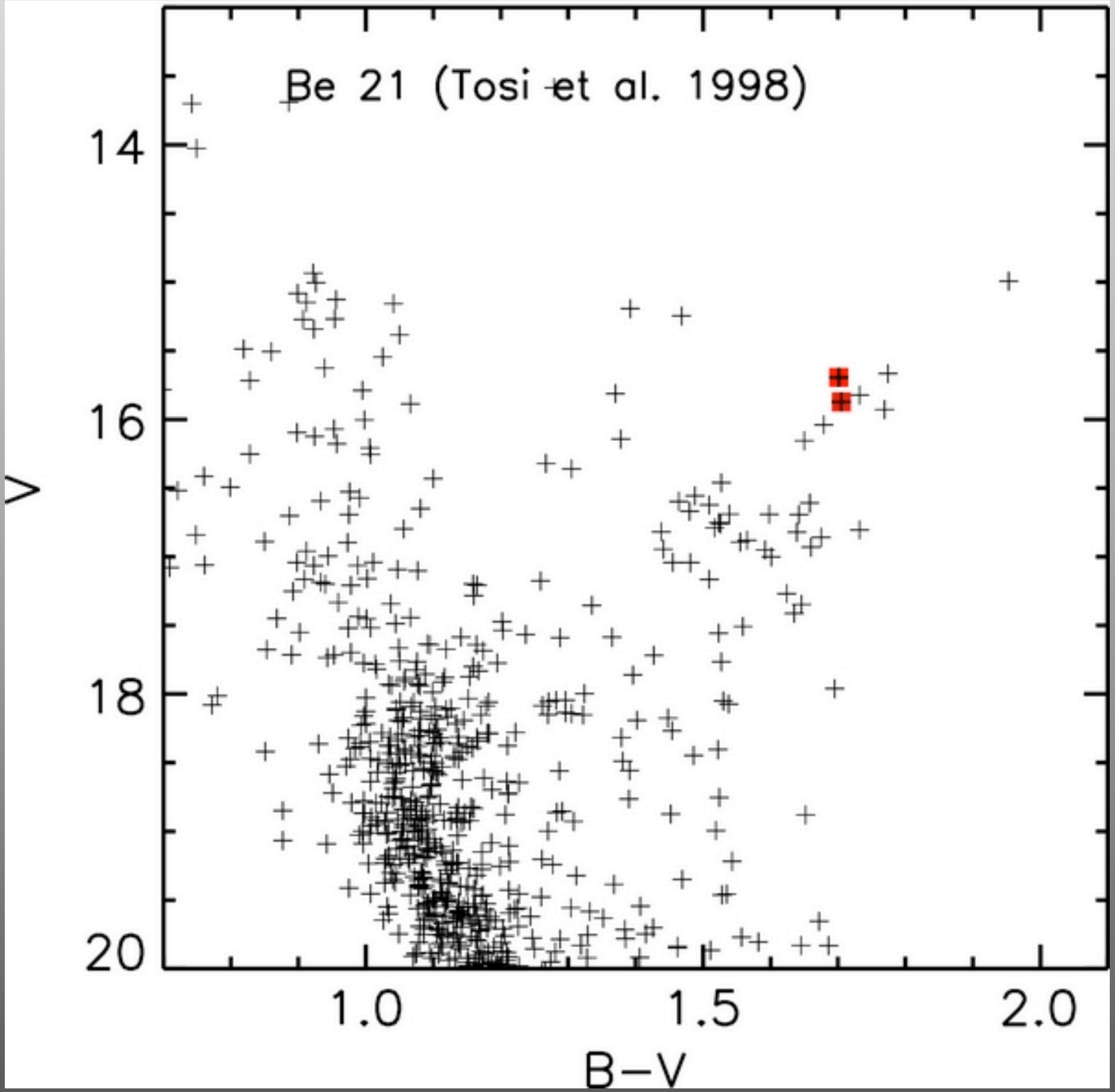


Australian National University

Target selection

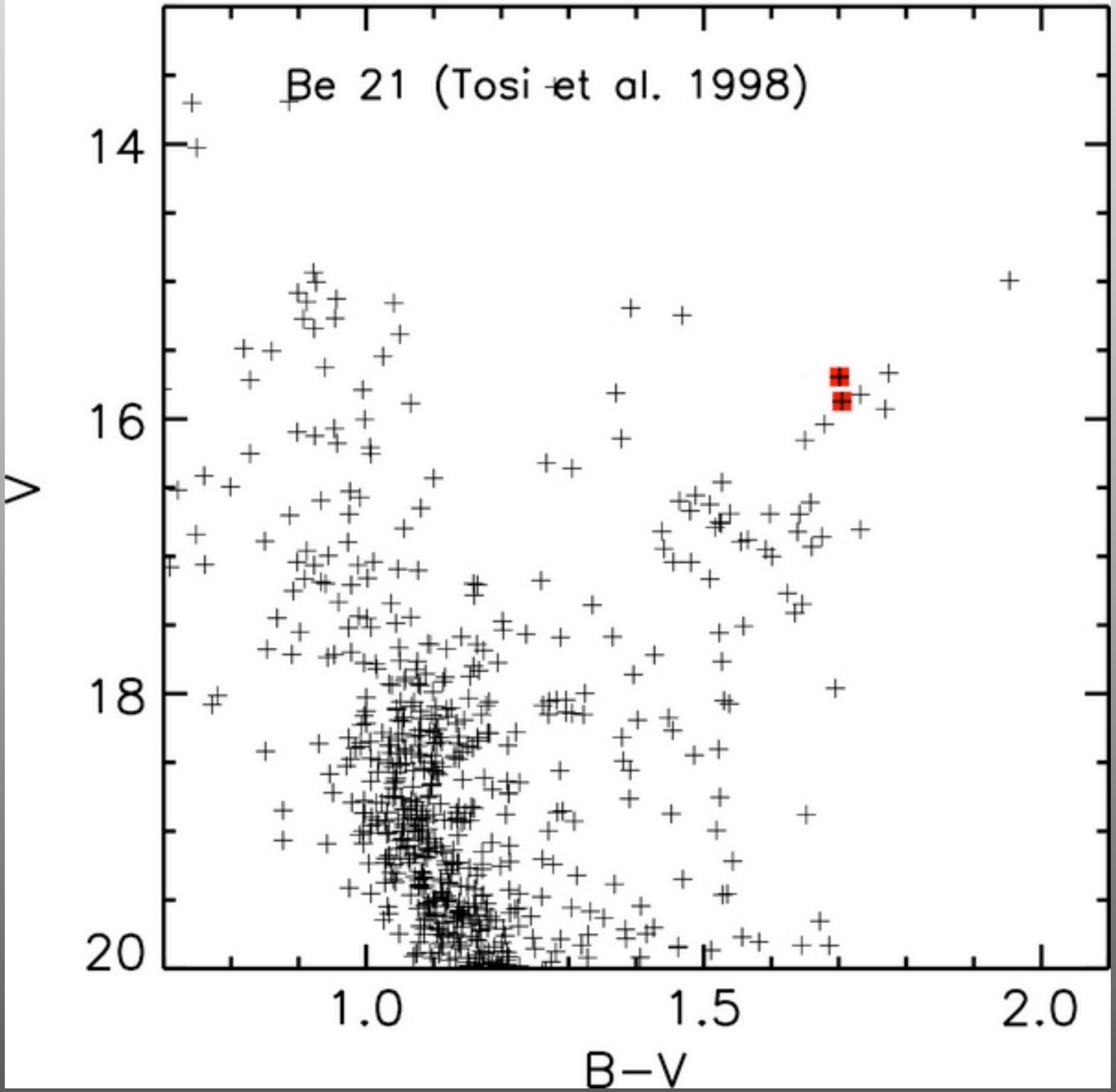


Target selection

Find **old** (> 2 Gyr), **distant** (RGC > 10 kpc) open clusters ==> Be18, Be21, Be22, Be32 and PWM4

Plausible locations in the optical and infrared CMDs

Use HIRES@Keck to obtain shorter exposures (**RVs**) and longer exposures (**chemical abundances**)



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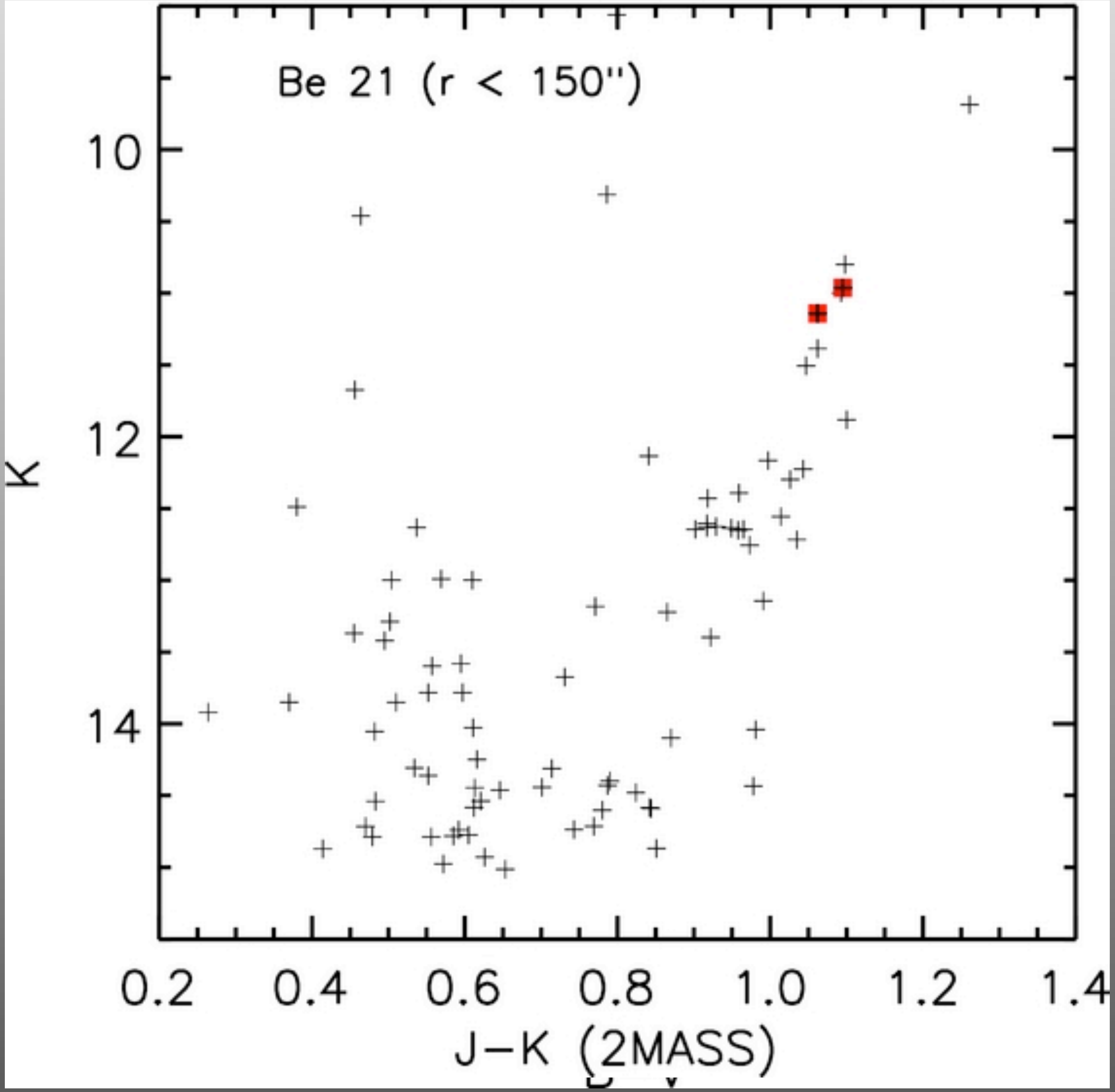
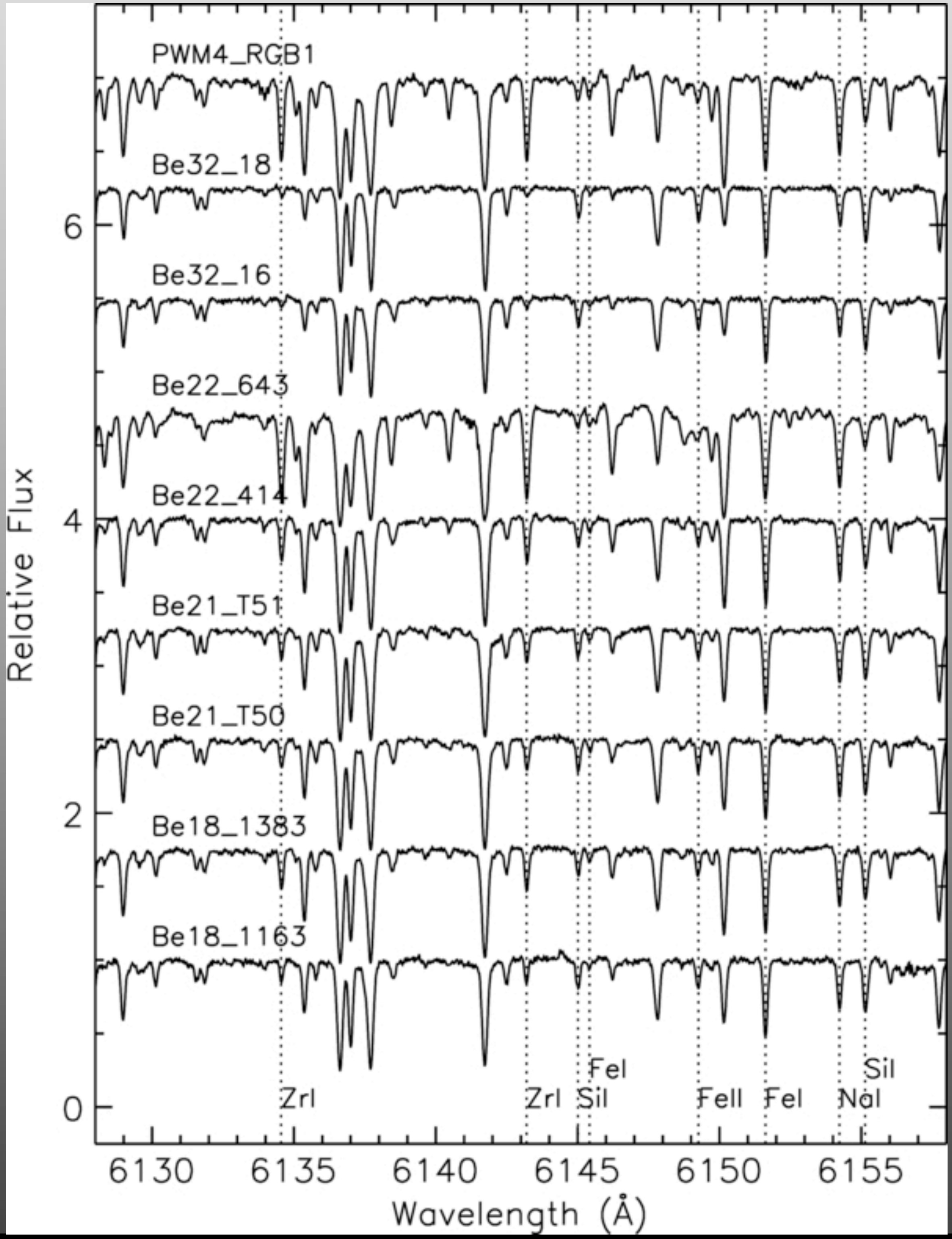


Observational material



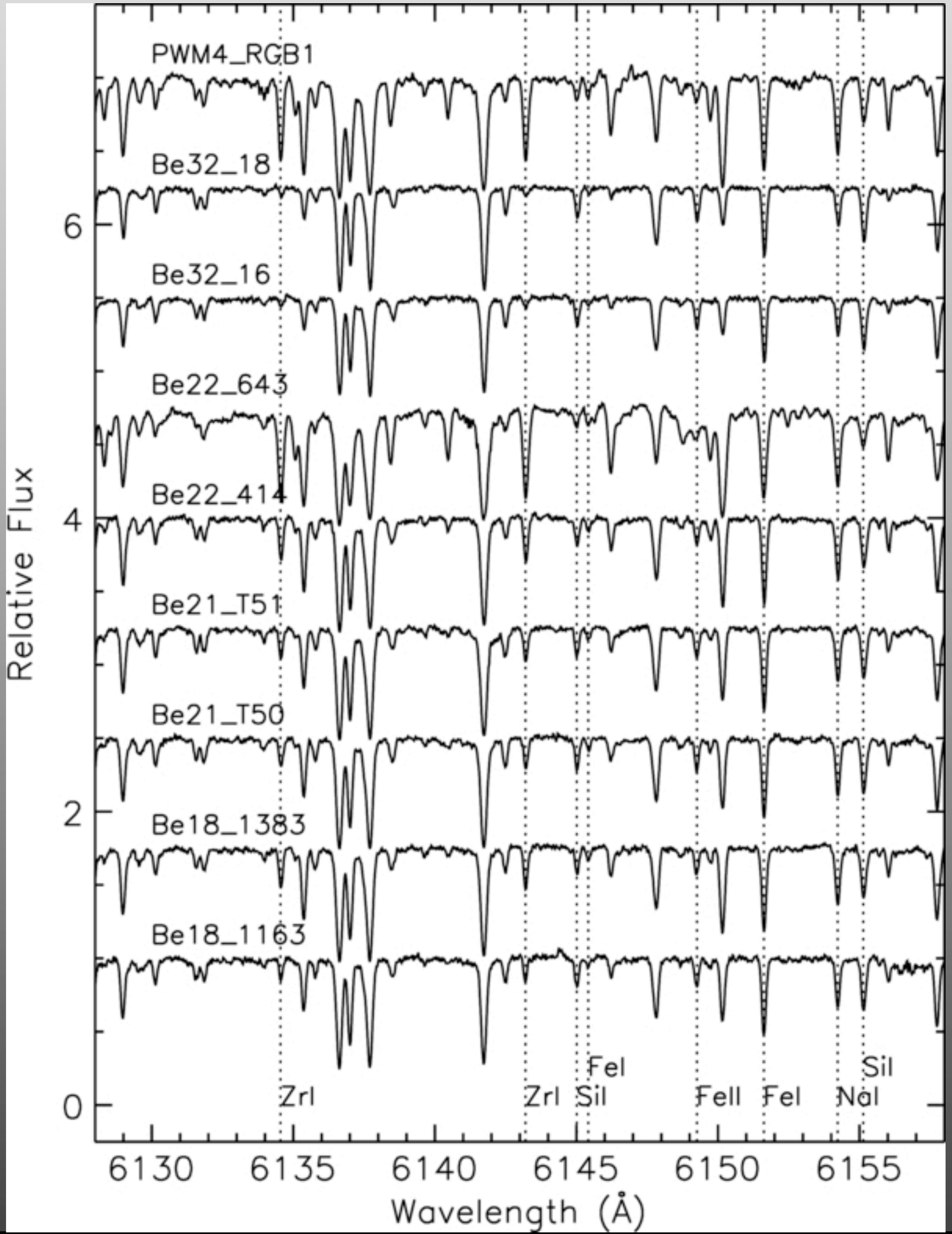
Observational material

High spectral resolution:
R=45,000

High signal-to-noise ratios:
S/N=100 per pixel

Large wavelength coverage:
4000-8000A

Standard 1D LTE analysis:
chemical abundances via spectrum synthesis and equivalent widths



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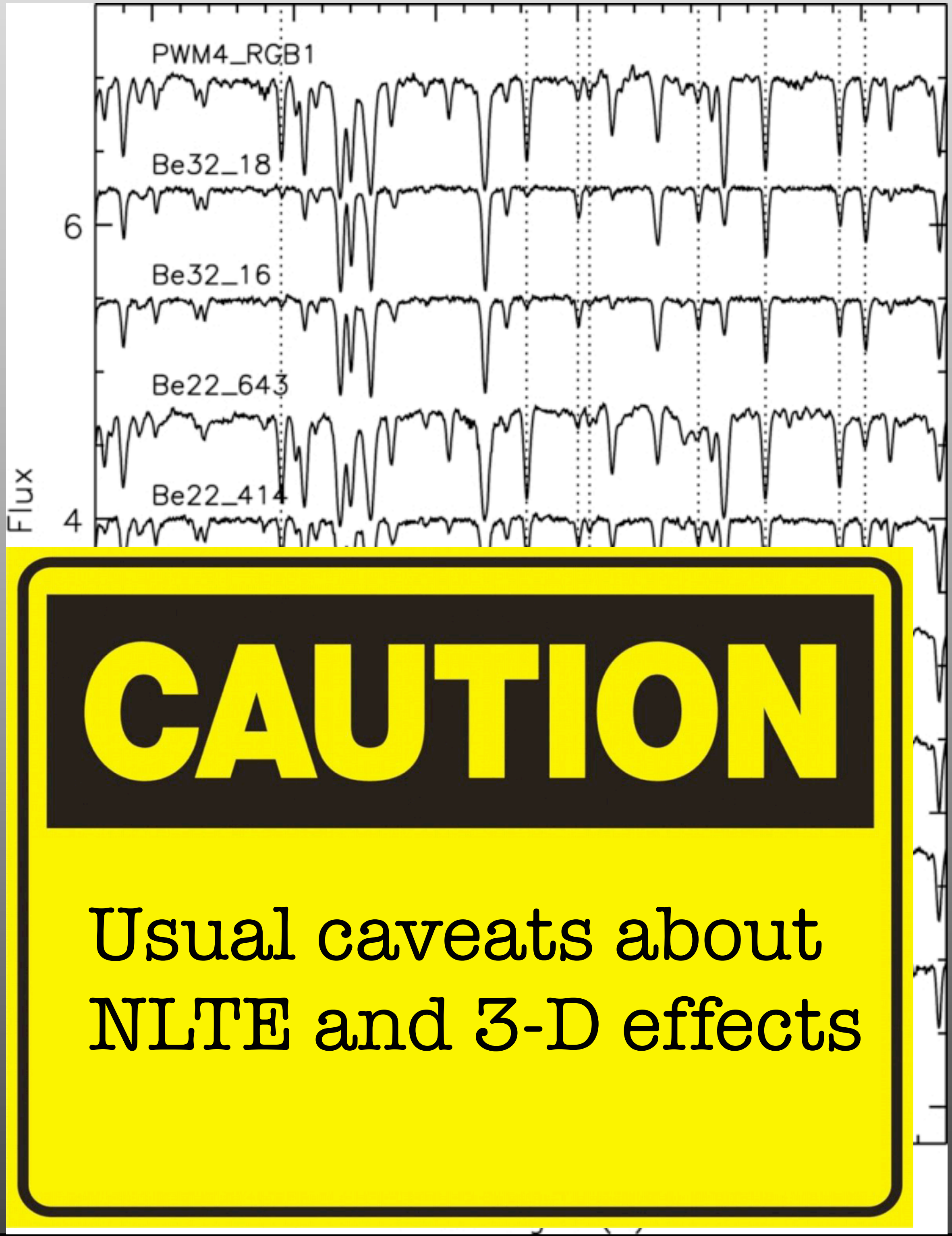

Reminder

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ORIGIN AND EVOLUTION OF GALAXIES

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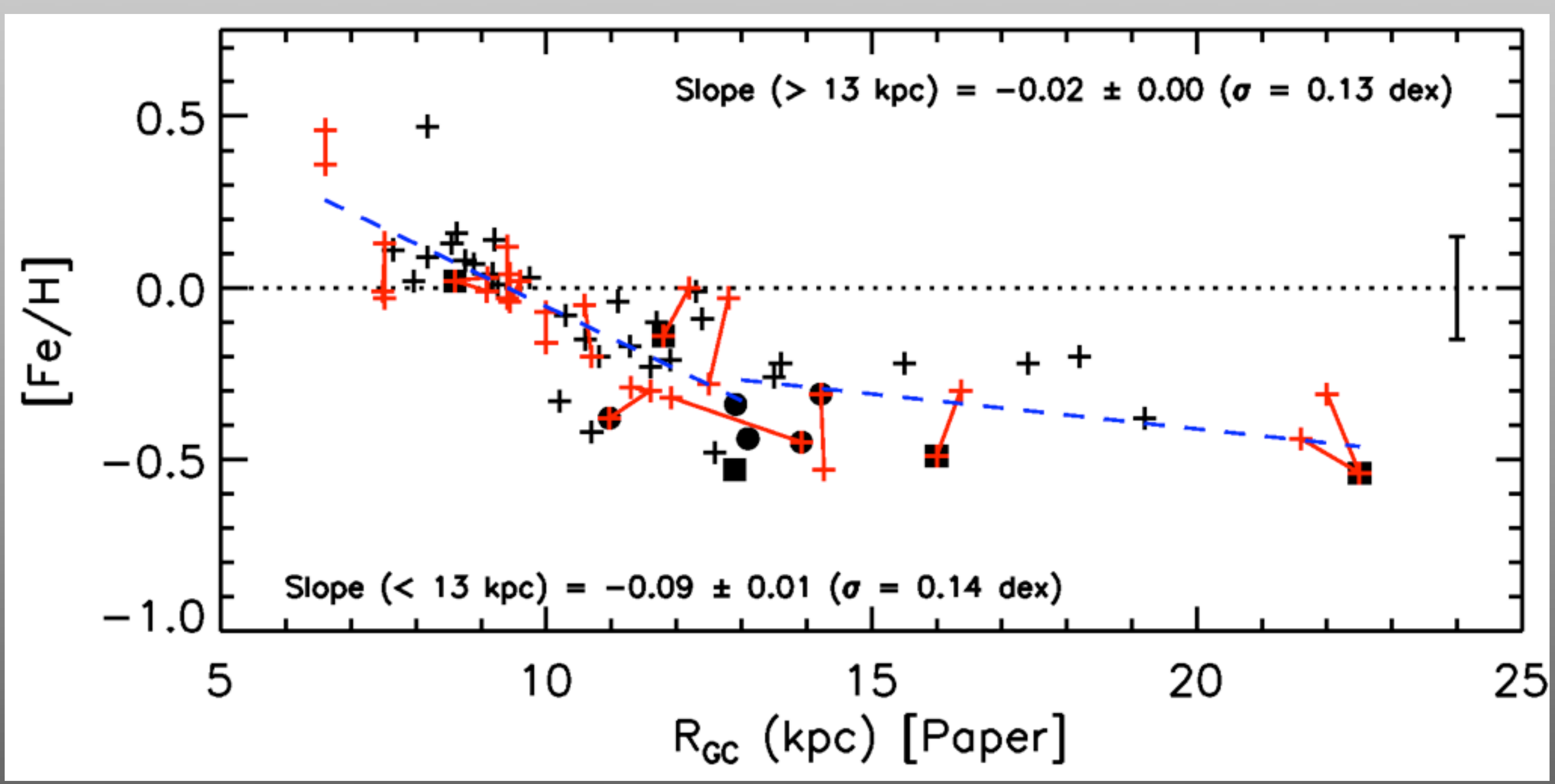
The composition of gas throughout the galaxy is controlled by the processes of star formation, evolution and death

Abundance gradients can be readily(?) measured and **provide strong constraints on galaxy formation mechanisms**

Structure, kinematics and **chemistry of the disk**, **and ideally the time variation** of these quantities

[Fe/H] vs. distance



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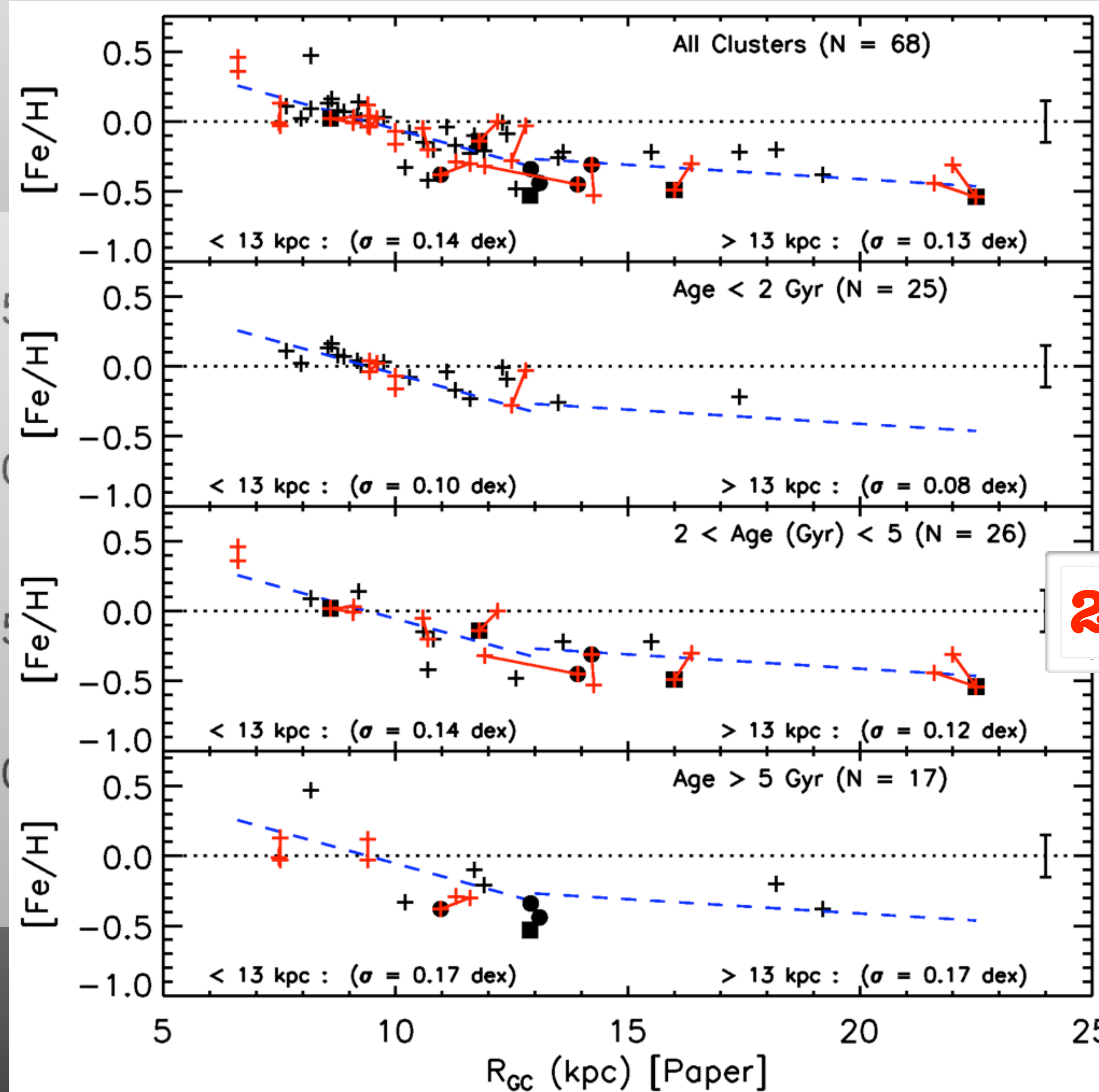
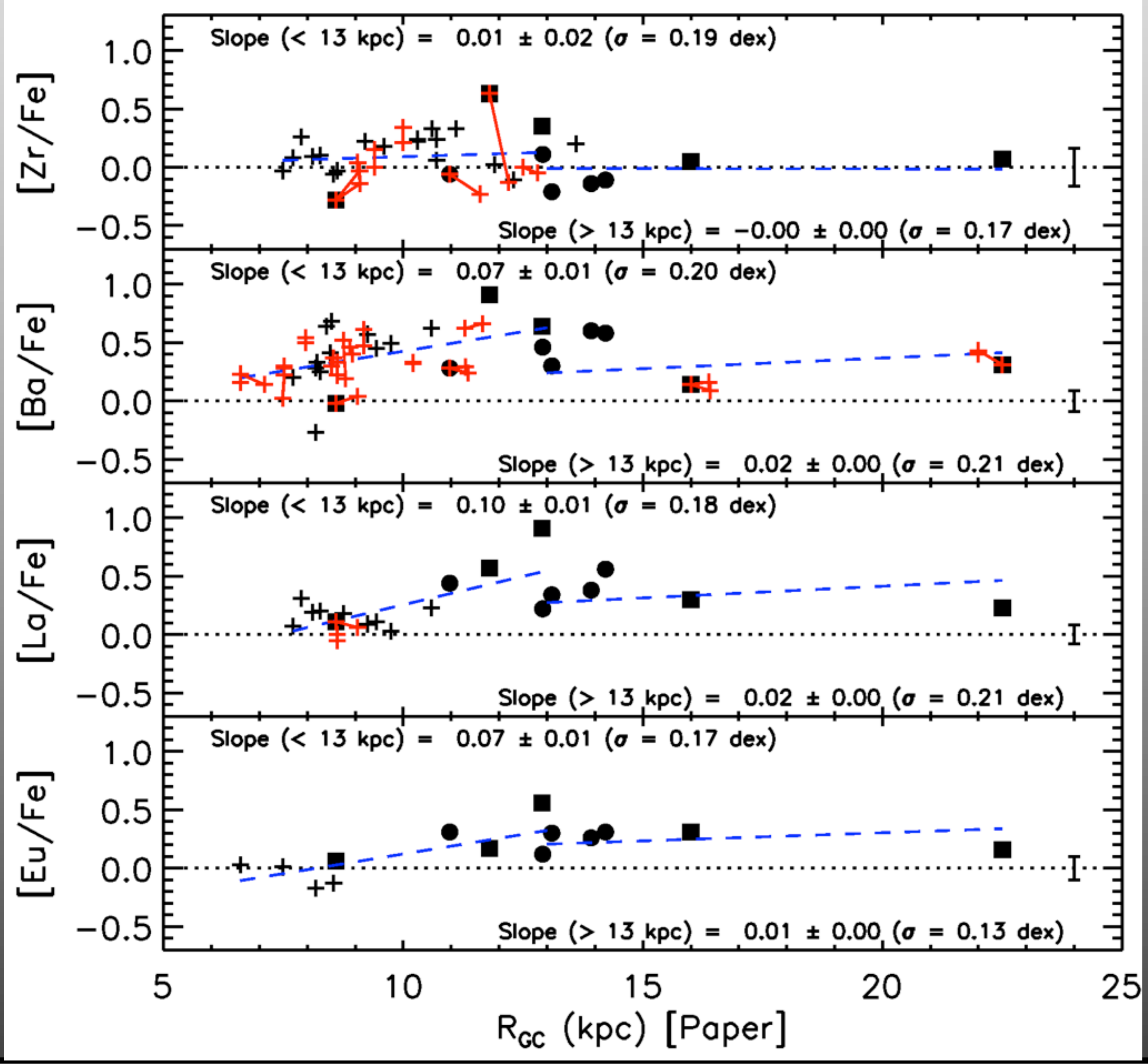


< 2 Gyr

2 < Age < 5 Gyr

> 5 Gyr

Neutron-cap vs. distance



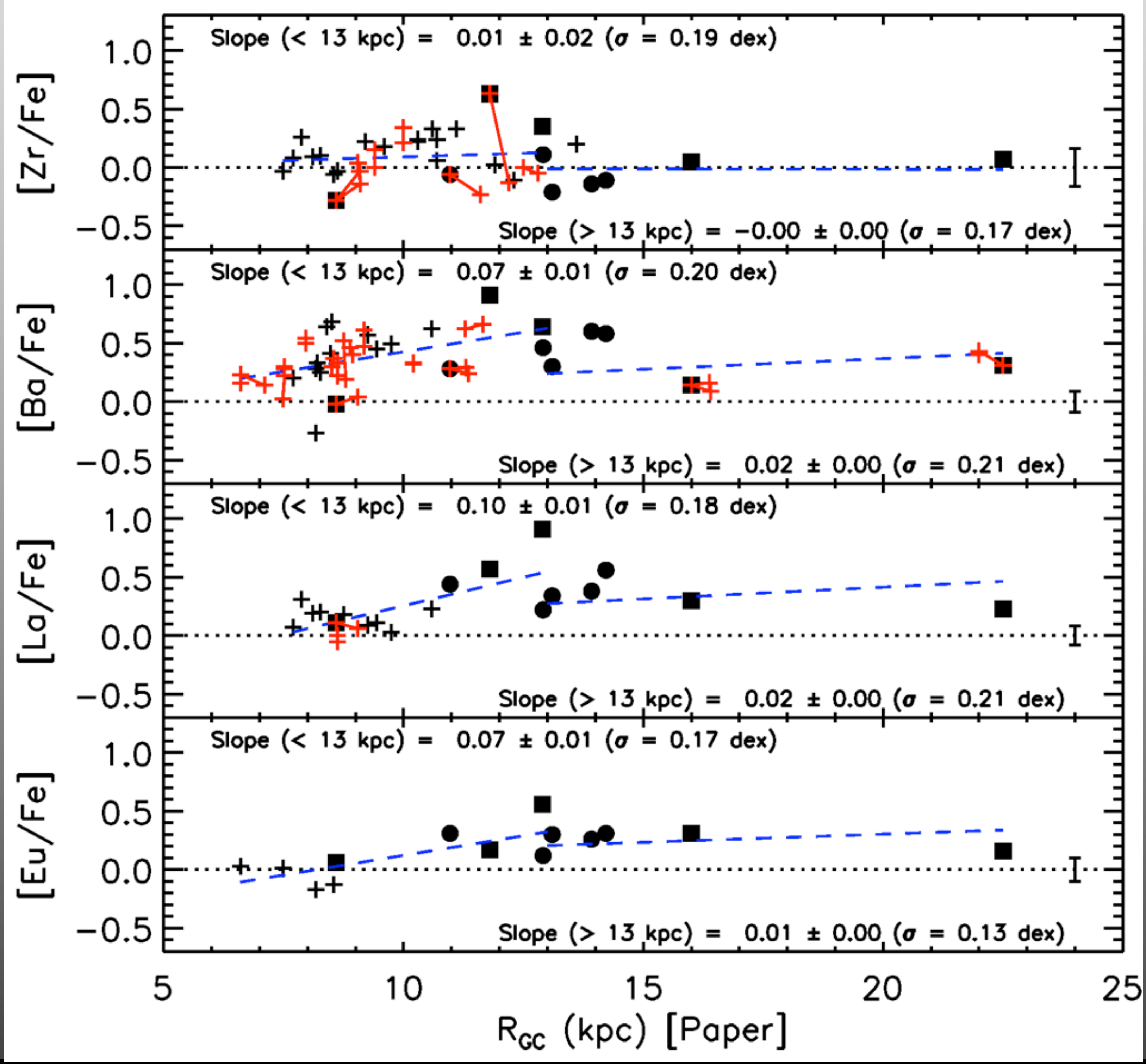
Neutron-cap vs. distance

Zr

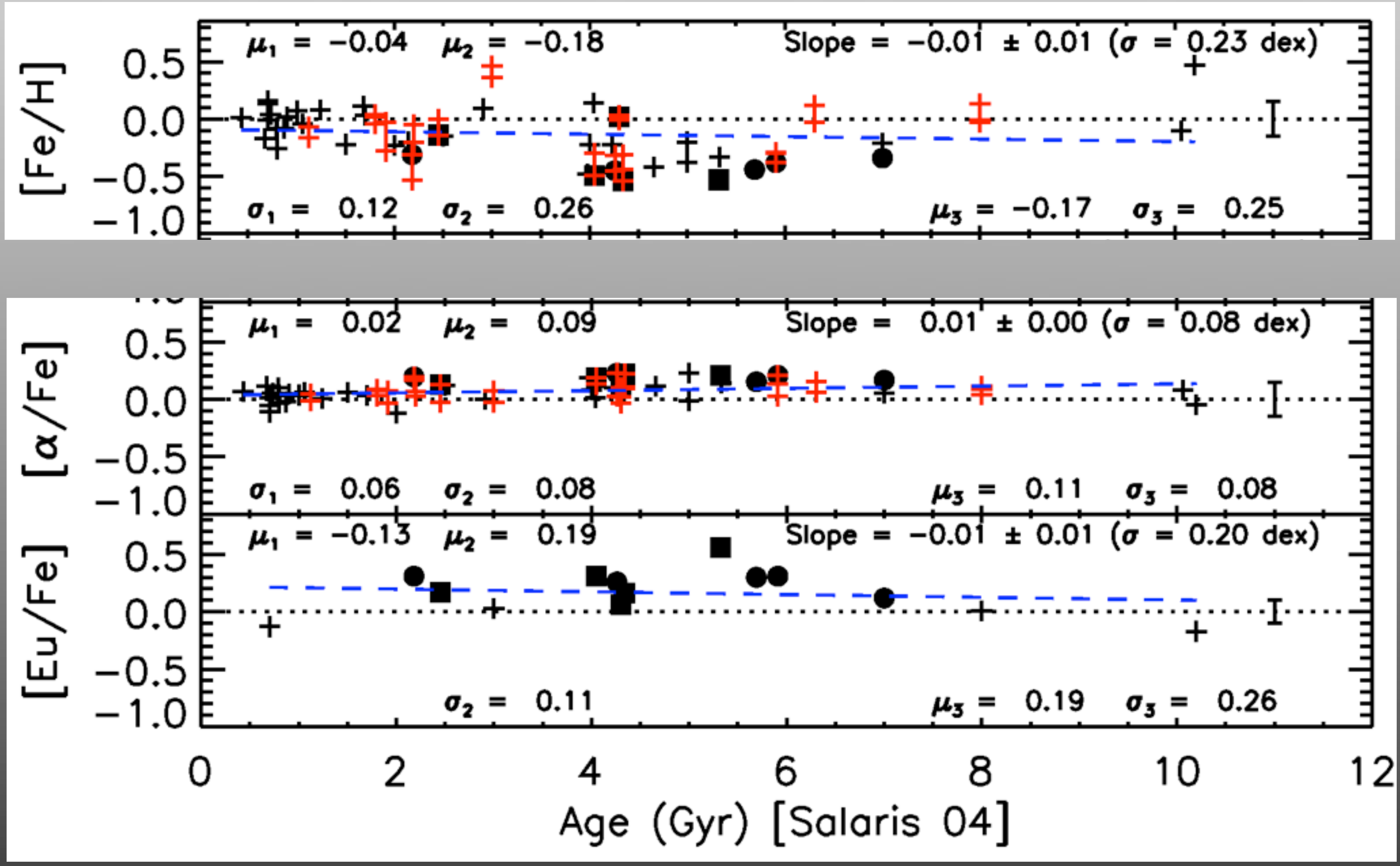
Ba

La

Eu



Abundance vs. age



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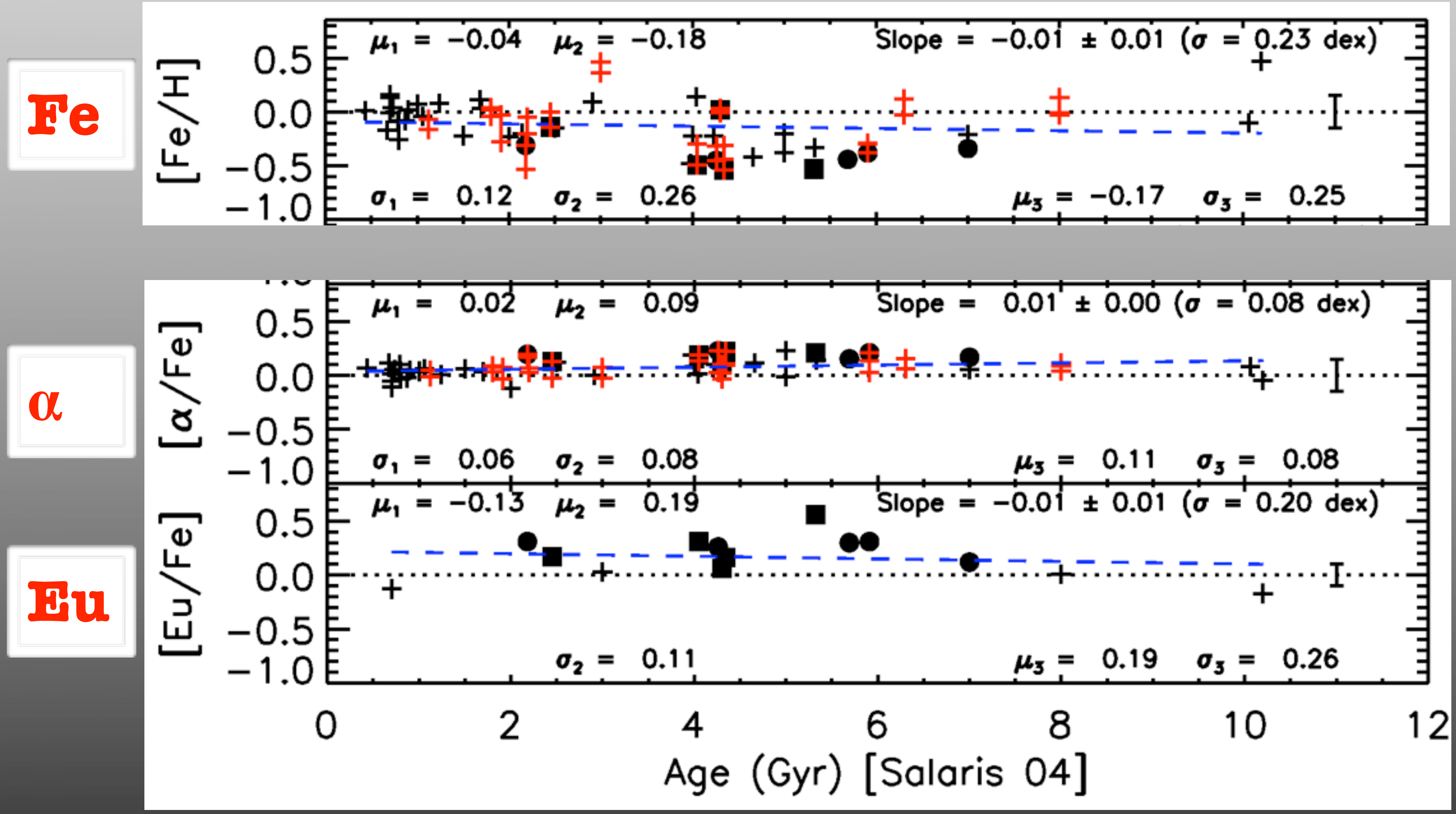
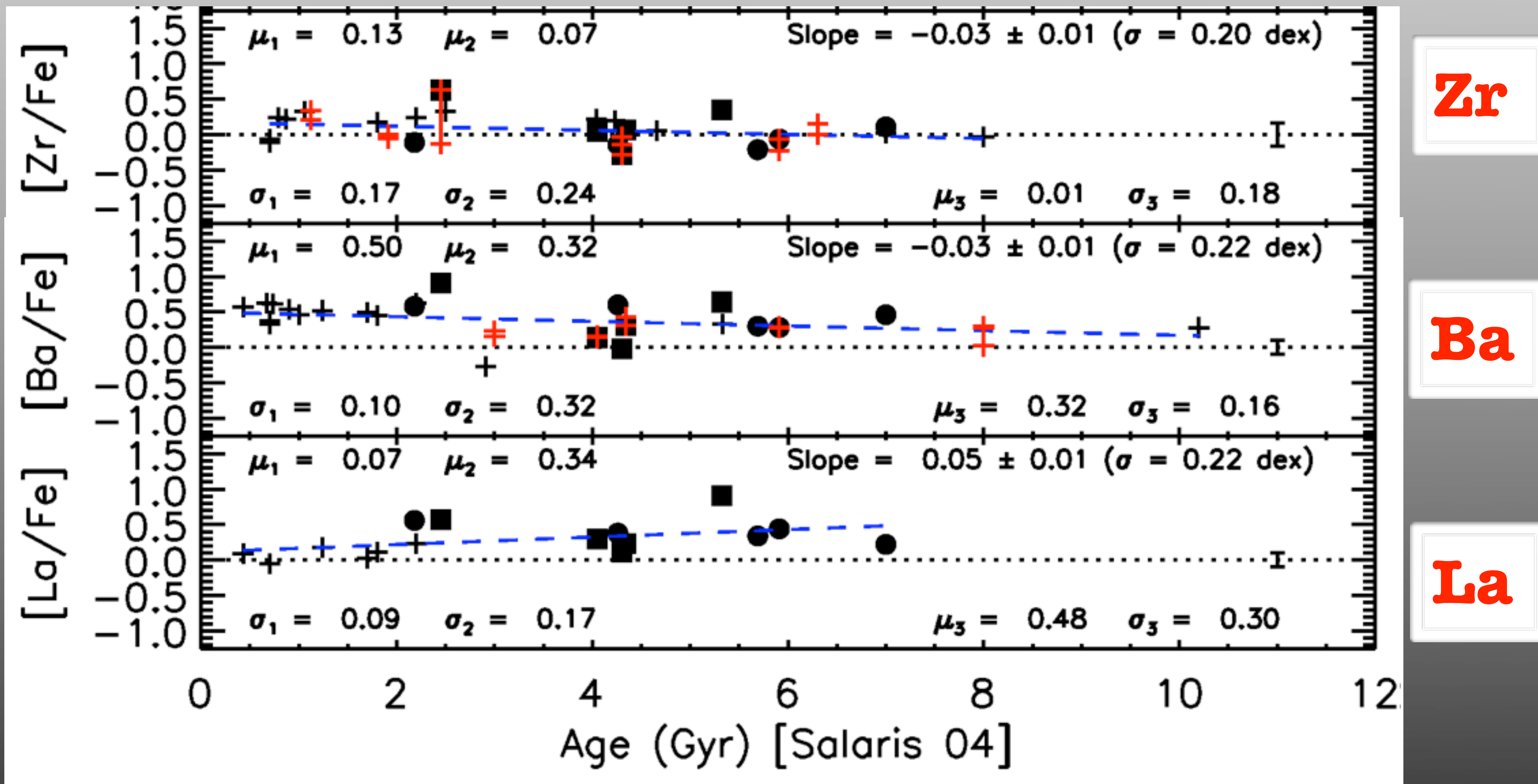
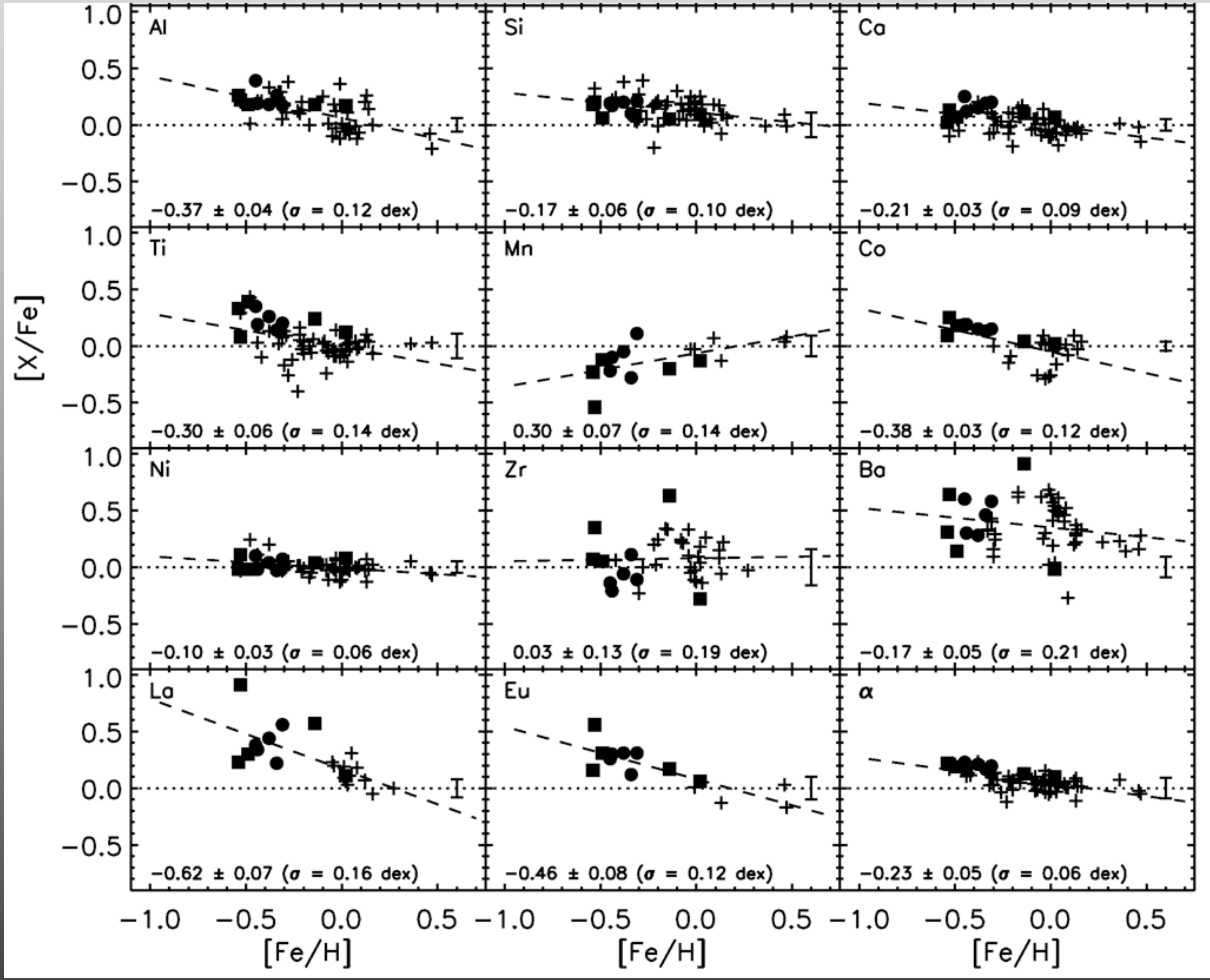


Abundance vs. age

Also see D'Orazi et al. (2009), Maiorca et al. (2011) Jacobson & Friel (2013)

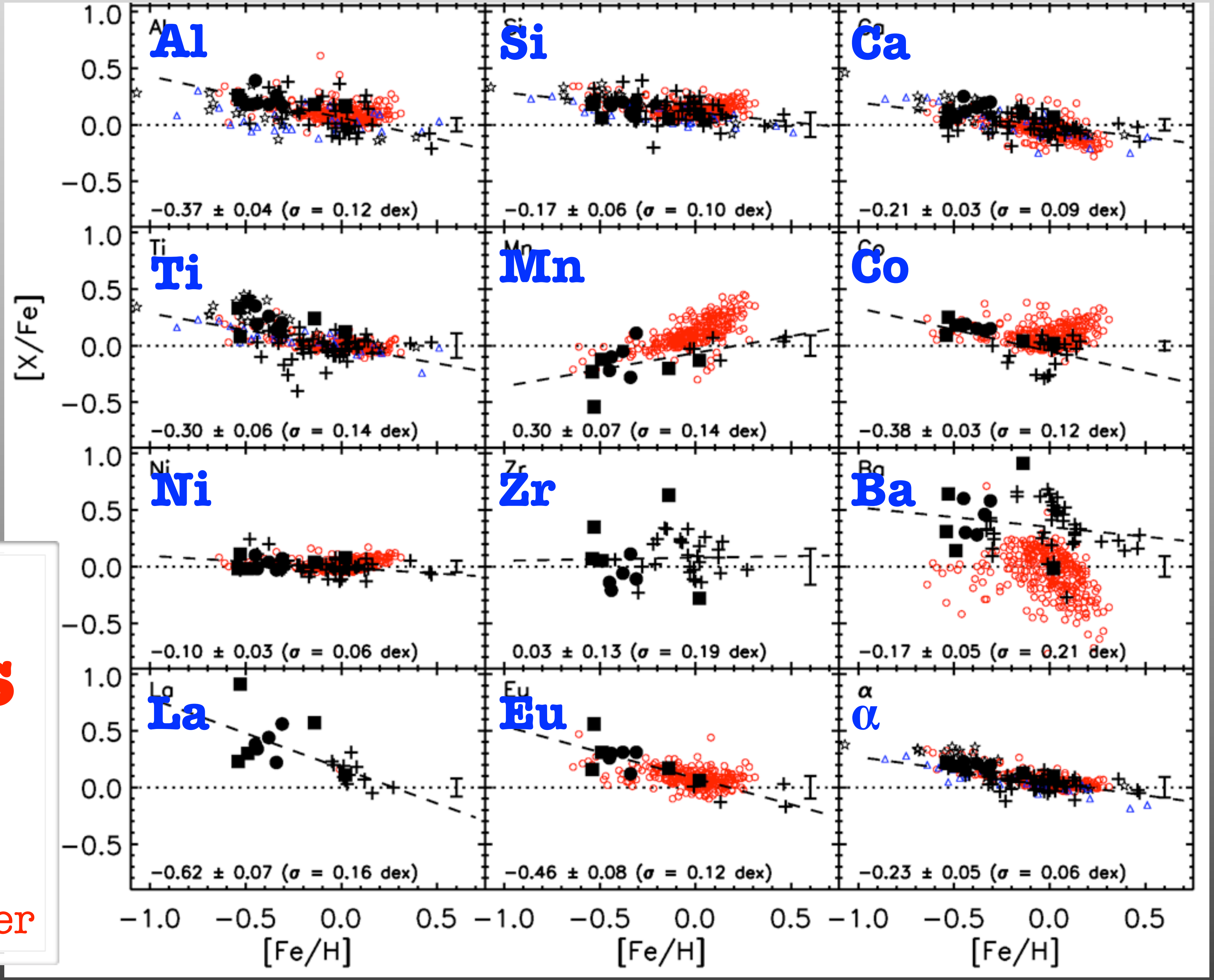


[X/Fe] vs. [Fe/H]



Al
−0.37 ± 0.04 (σ = 0.12 dex)
Si
−0.17 ± 0.06 (σ = 0.10 dex)
Ca
−0.21 ± 0.03 (σ = 0.09 dex)
Ti
−0.30 ± 0.06 (σ = 0.14 dex)
Mn
0.30 ± 0.07 (σ = 0.14 dex)
Co
−0.38 ± 0.03 (σ = 0.12 dex)
Ni
−0.10 ± 0.03 (σ = 0.06 dex)
Zr
0.03 ± 0.13 (σ = 0.19 dex)
Ba
−0.17 ± 0.05 (σ = 0.21 dex)
La
−0.62 ± 0.07 (σ = 0.16 dex)
Eu
−0.46 ± 0.08 (σ = 0.12 dex)
α
−0.23 ± 0.05 (σ = 0.06 dex)
[X/Fe]
[Fe/H]

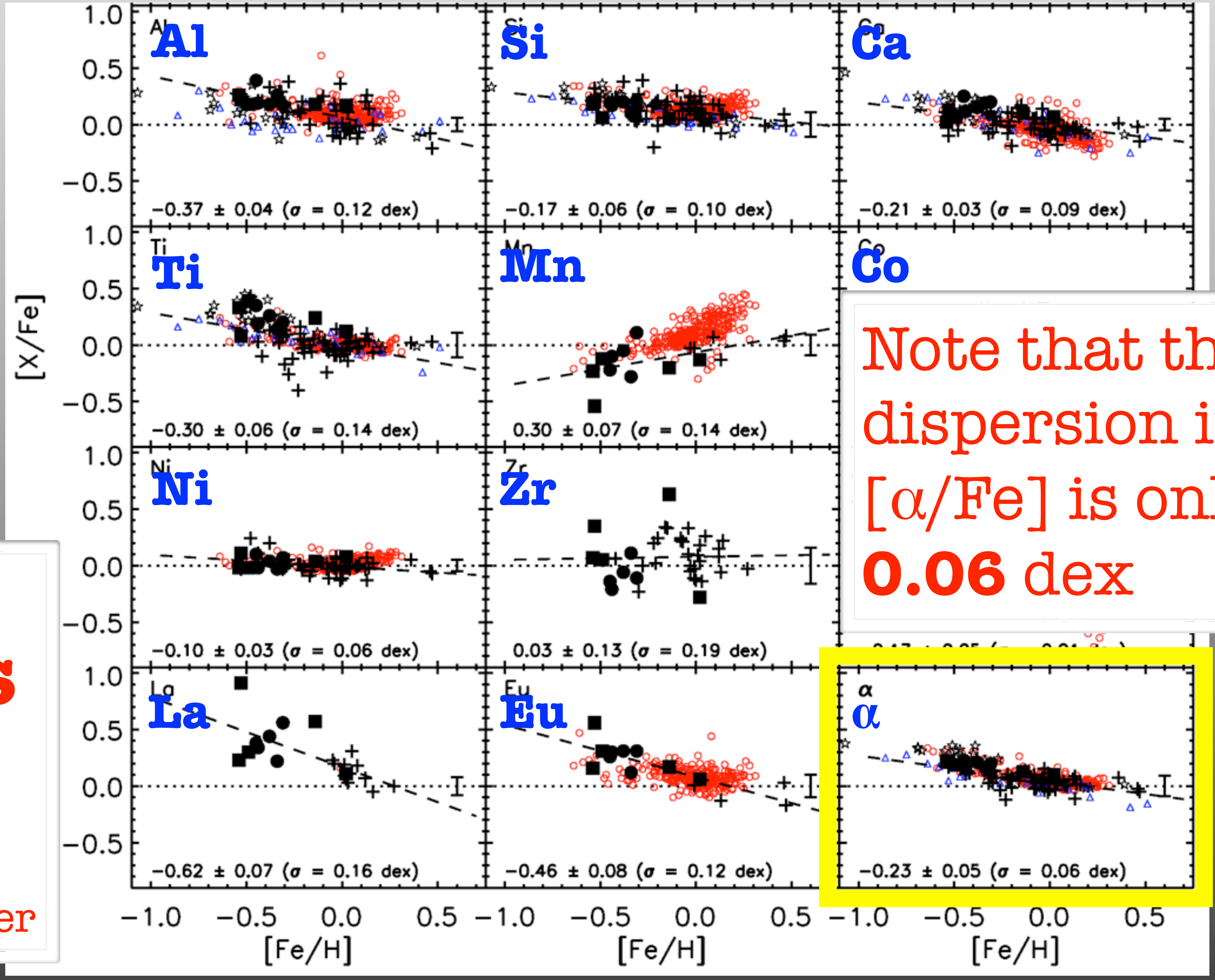
[X/Fe] vs. [Fe/H]



Field giants data from

Alves-Brito
Luck & Heiter

[X/Fe] vs. [Fe/H]



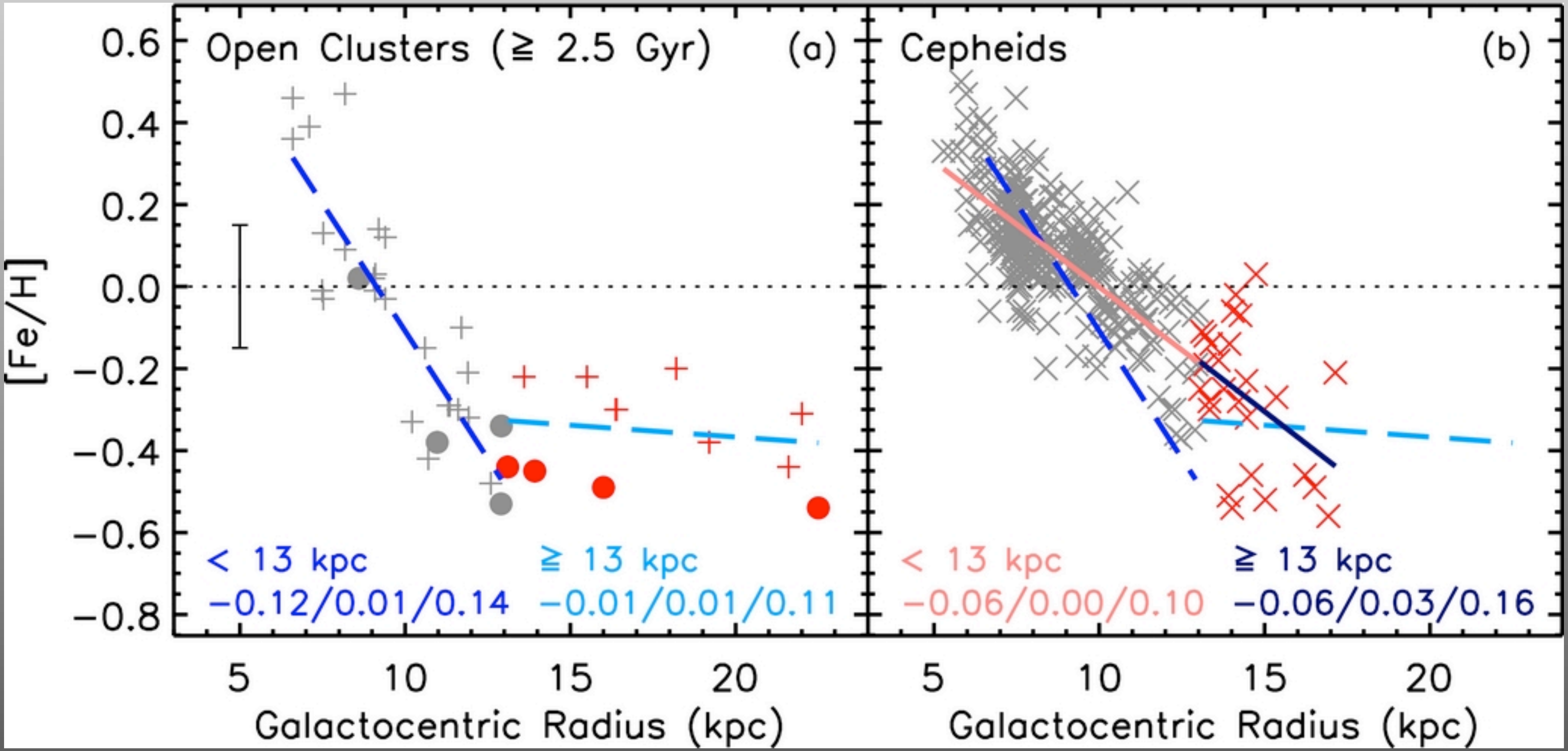
Note that the dispersion in [α/Fe] is only **0.06** dex

Field giants data from

Alves-Brito
Luck & Heiter

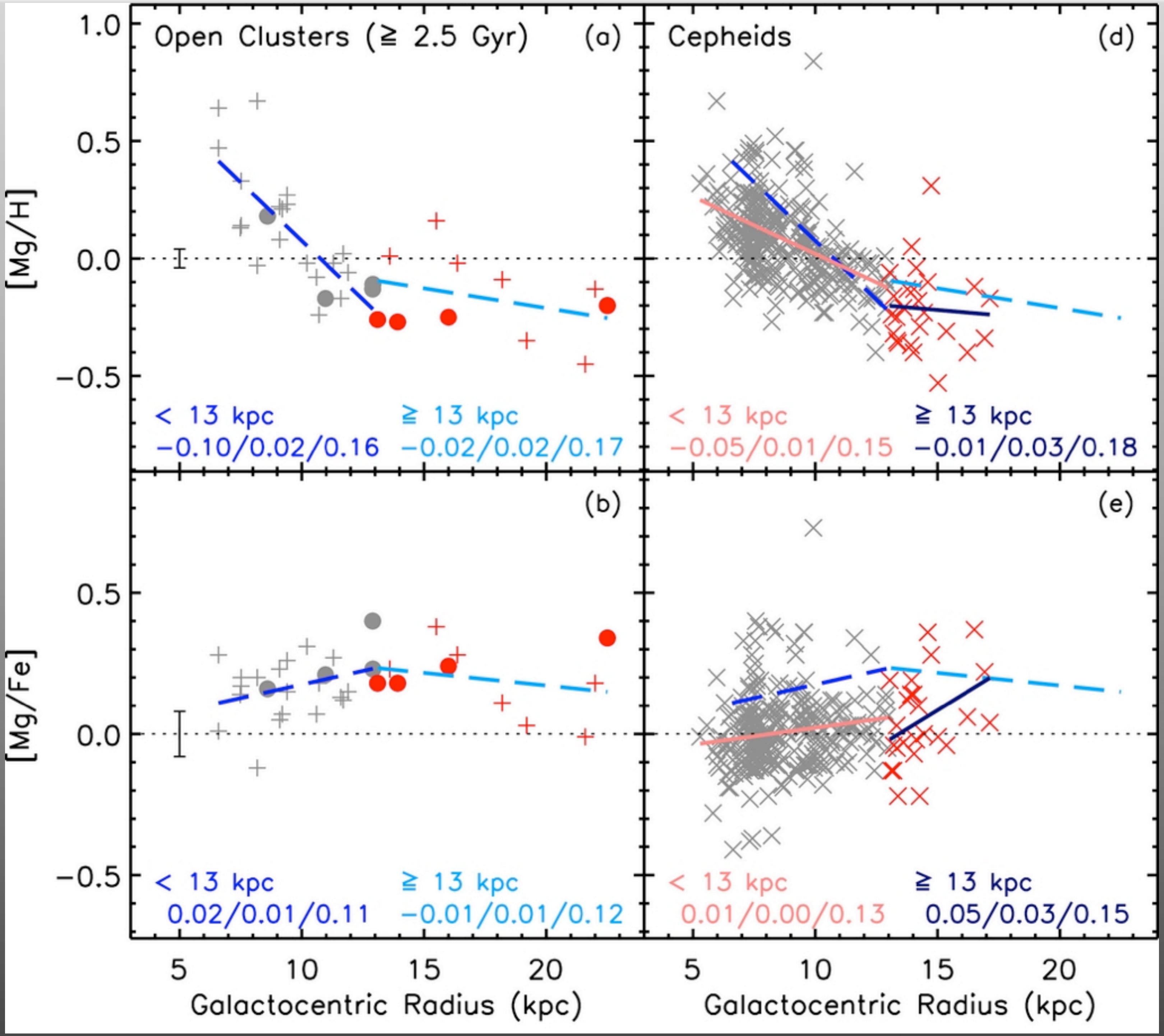
[X/Fe] vs. distance

Old open clusters vs. young Cepheids (Luck & Lambert 2011)



Mg vs. distance

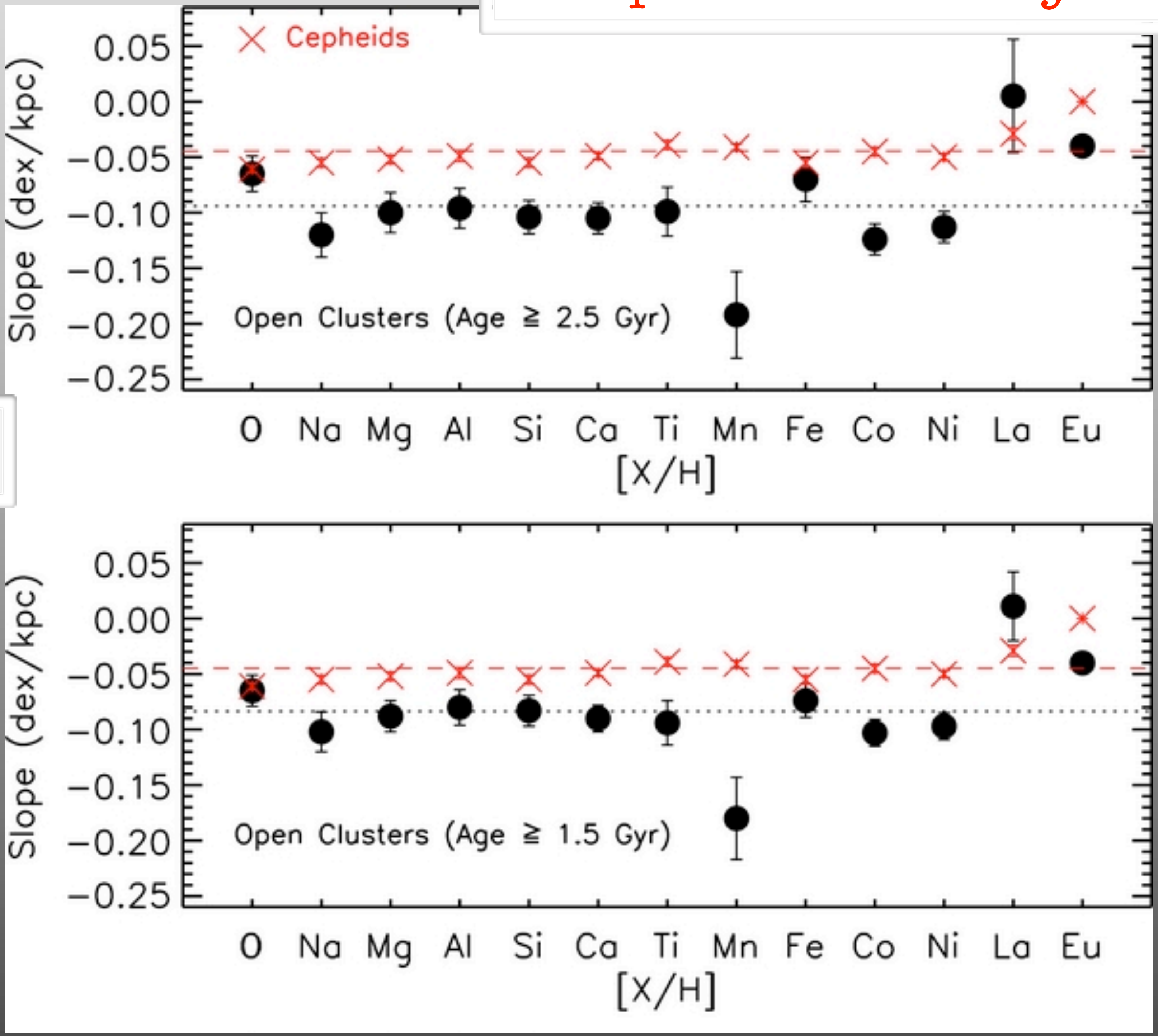
Old open clusters vs. young Cepheids (Luck & Lambert 2011)



[X/H] vs. distance

Old open clusters vs. young Cepheids

RGC < 13 kpc



[X/H] vs. distance

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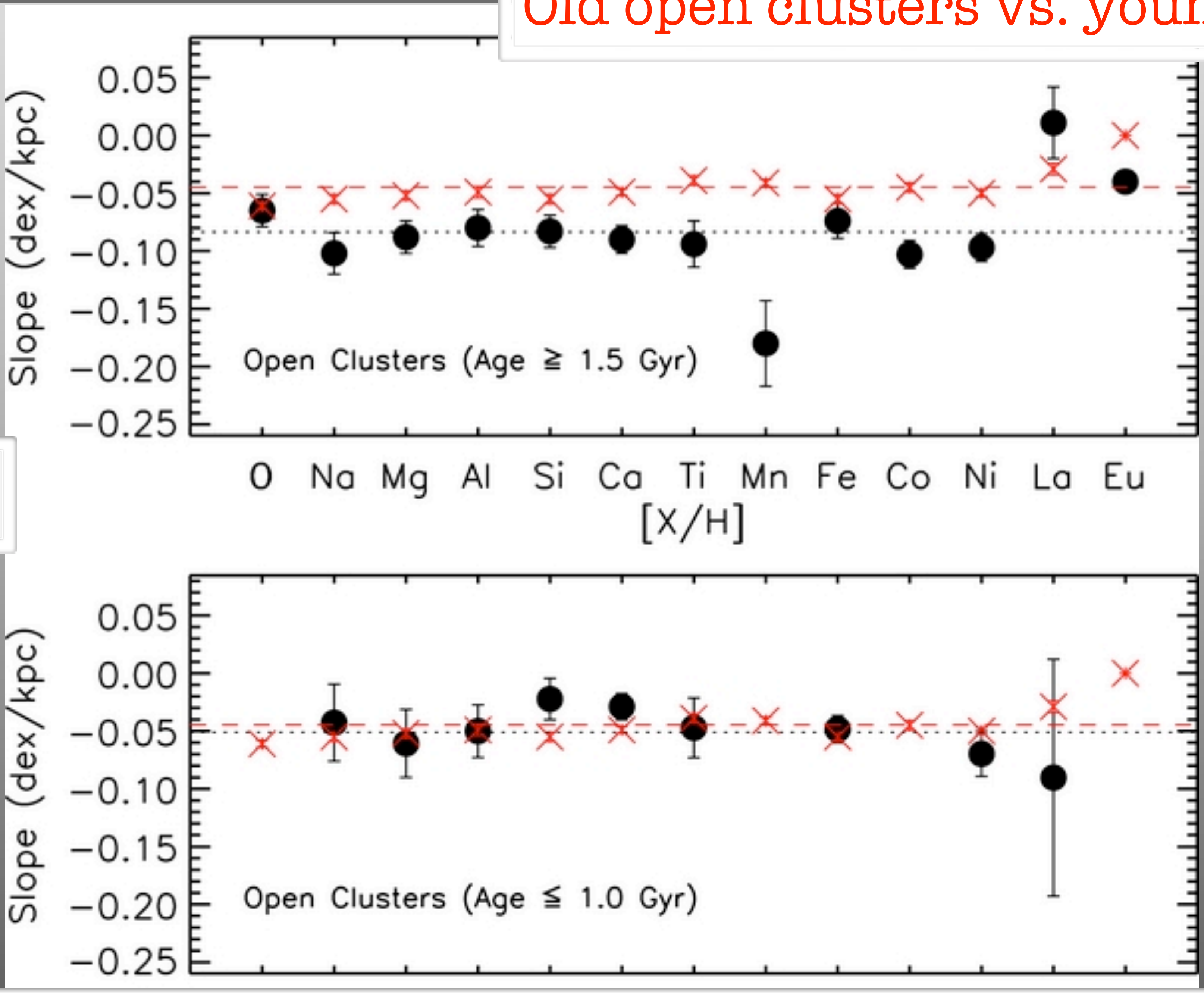


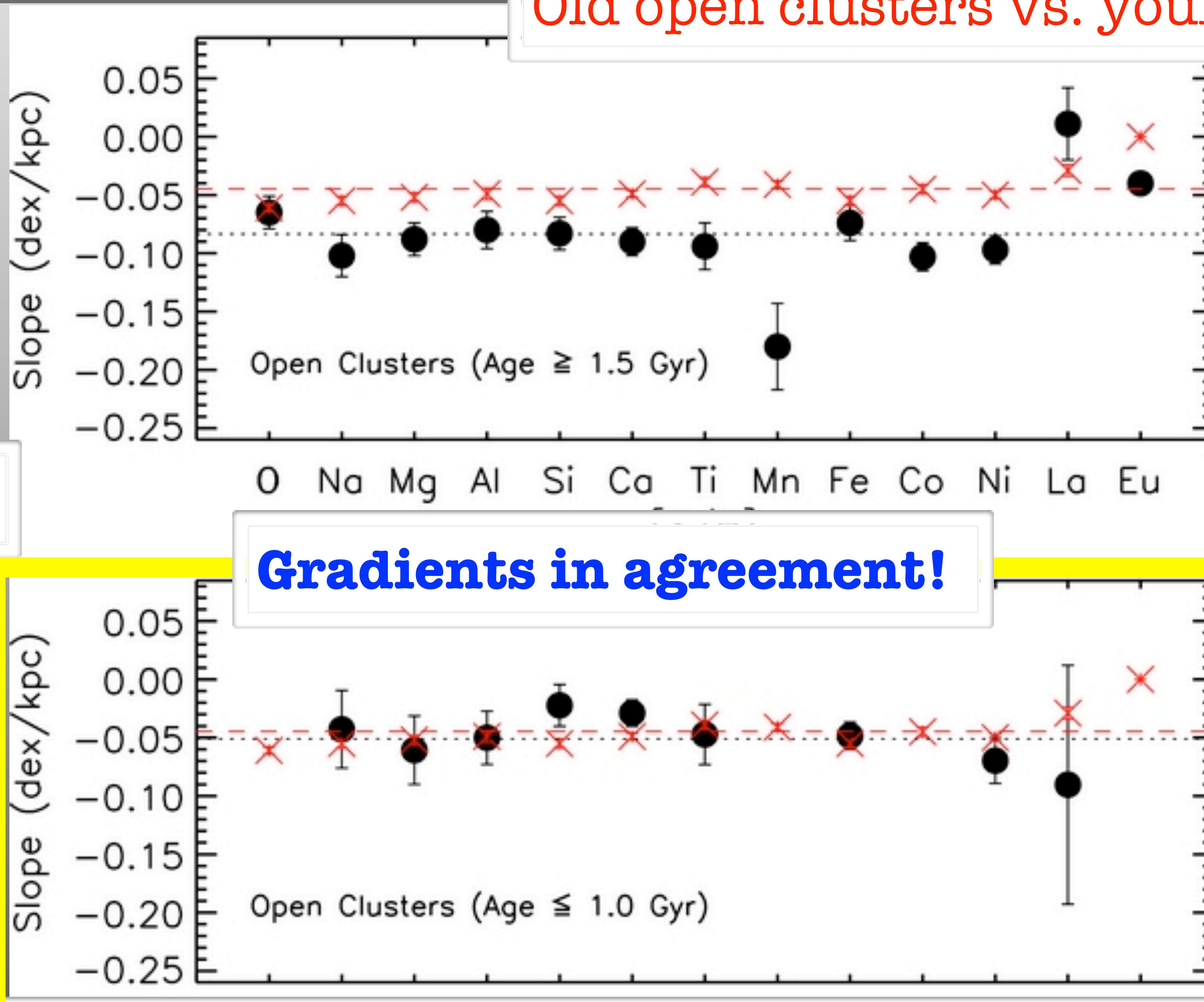
RGC < 13 kpc

Gradients are steeper for the oldest open cluster samples

[X/H] vs. distance

Old open clusters vs. young Cepheids

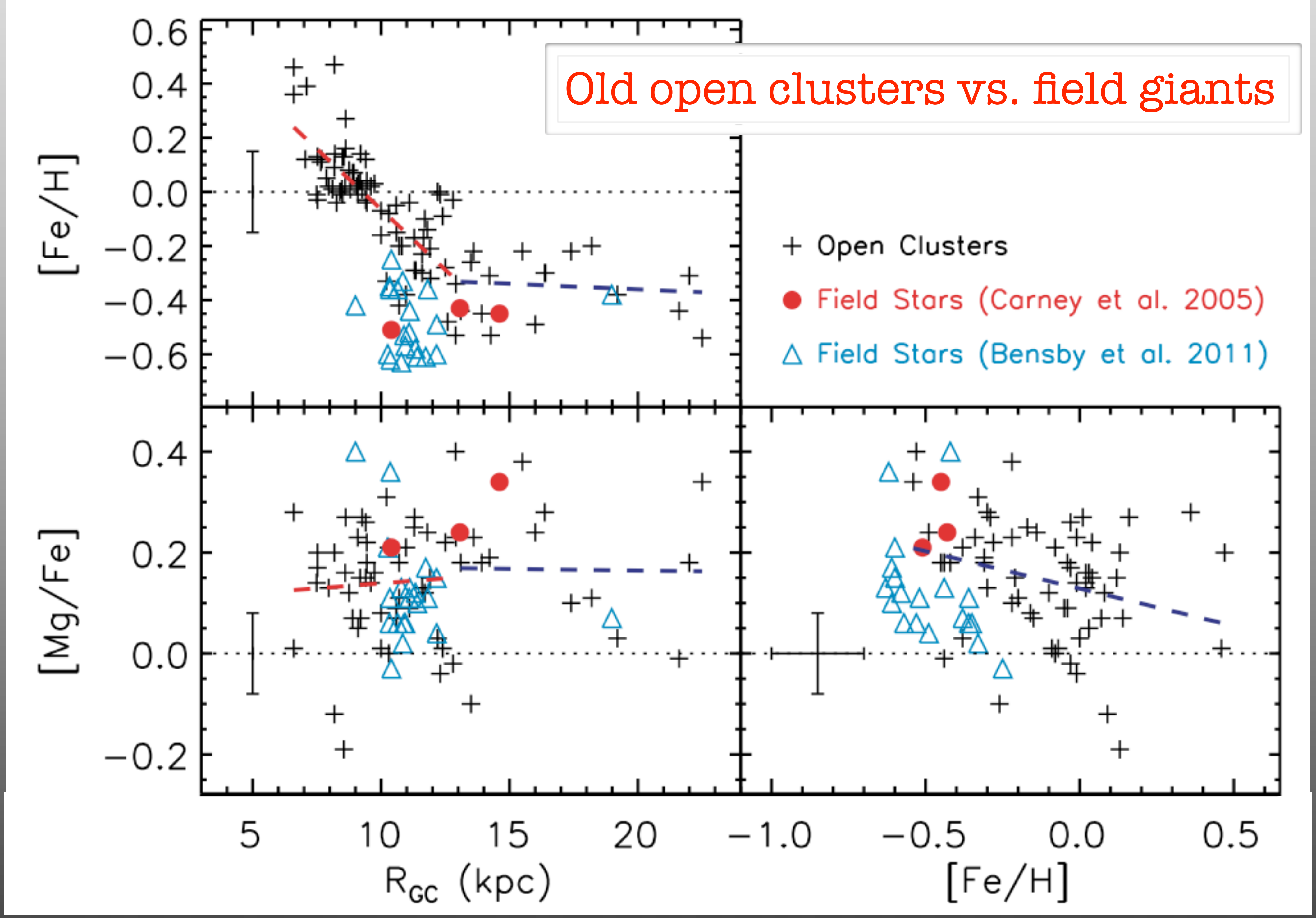
RGC < 13 kpc



Gradients in agreement!

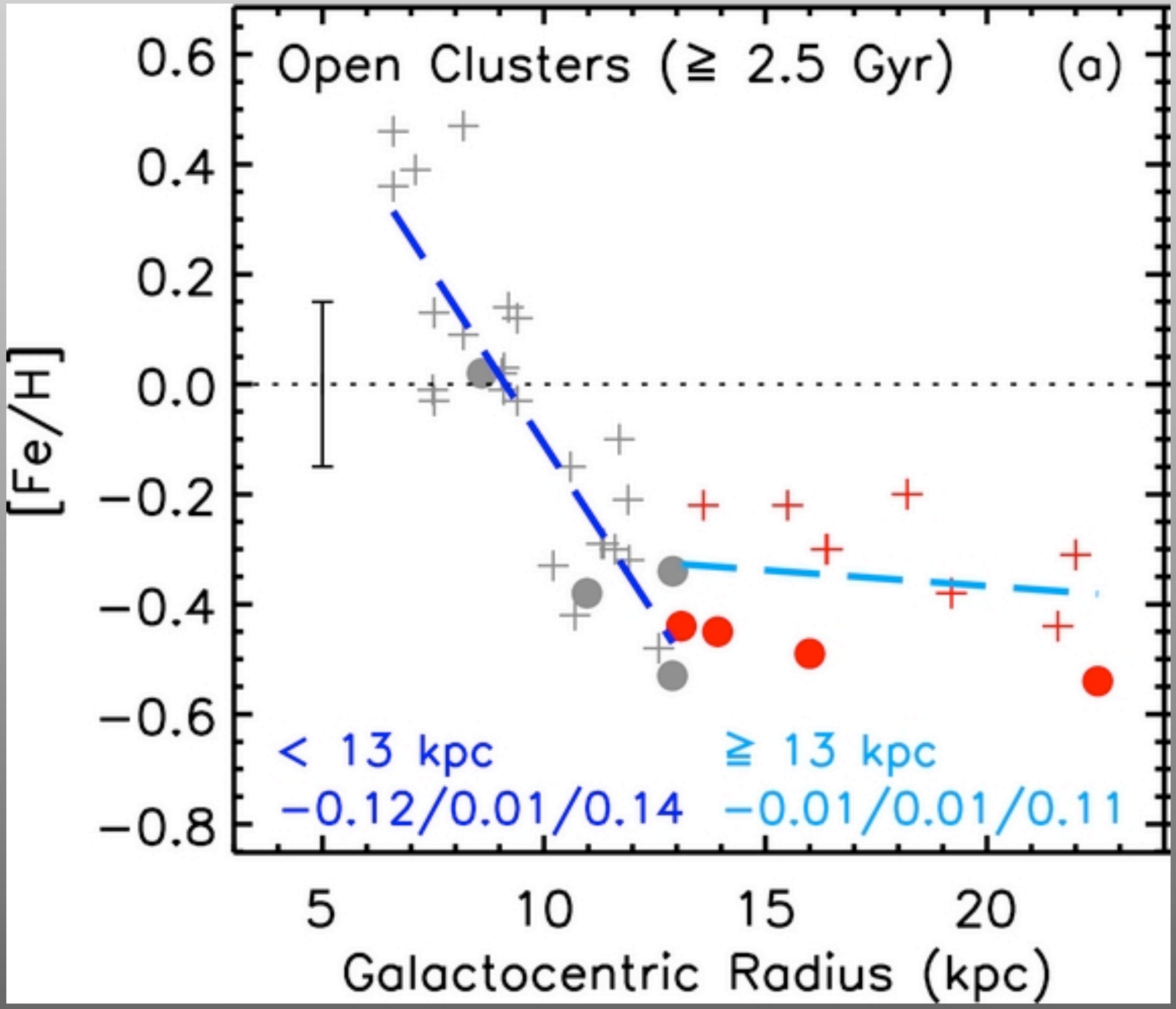
Gradients are steeper for the oldest open cluster samples

Abundance vs. distance



The break radius

RGC = 13 kpc; Arbitrary!



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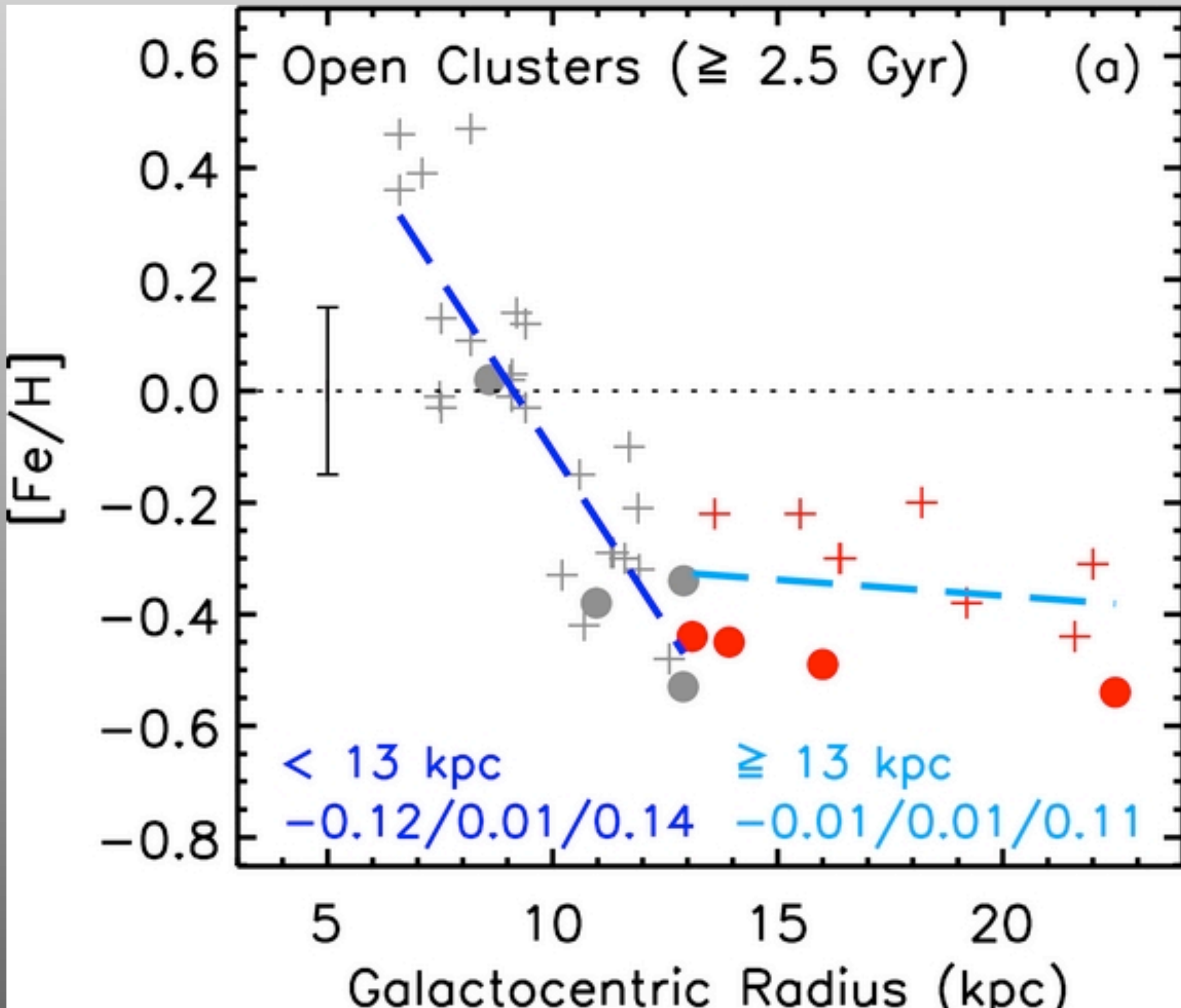
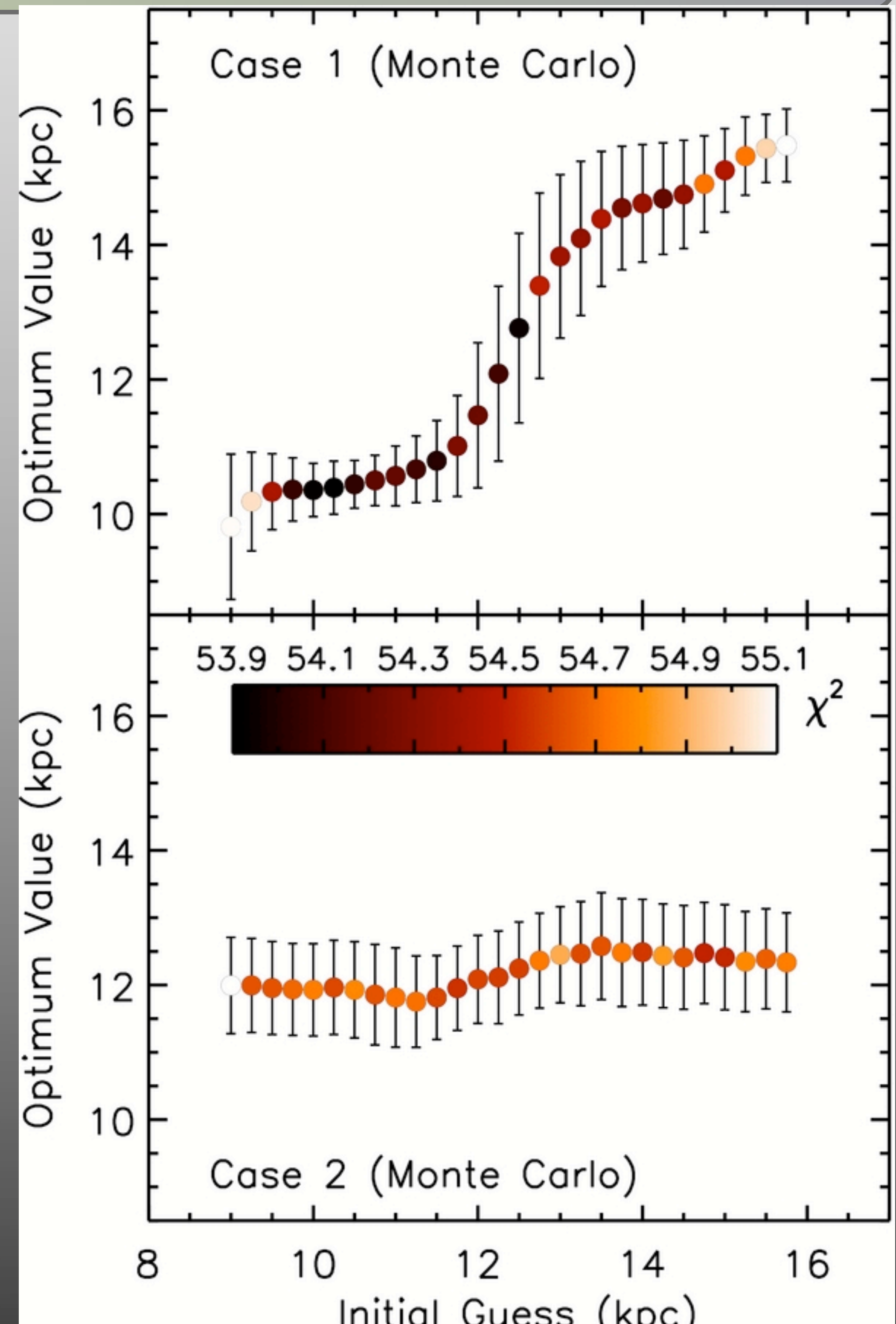
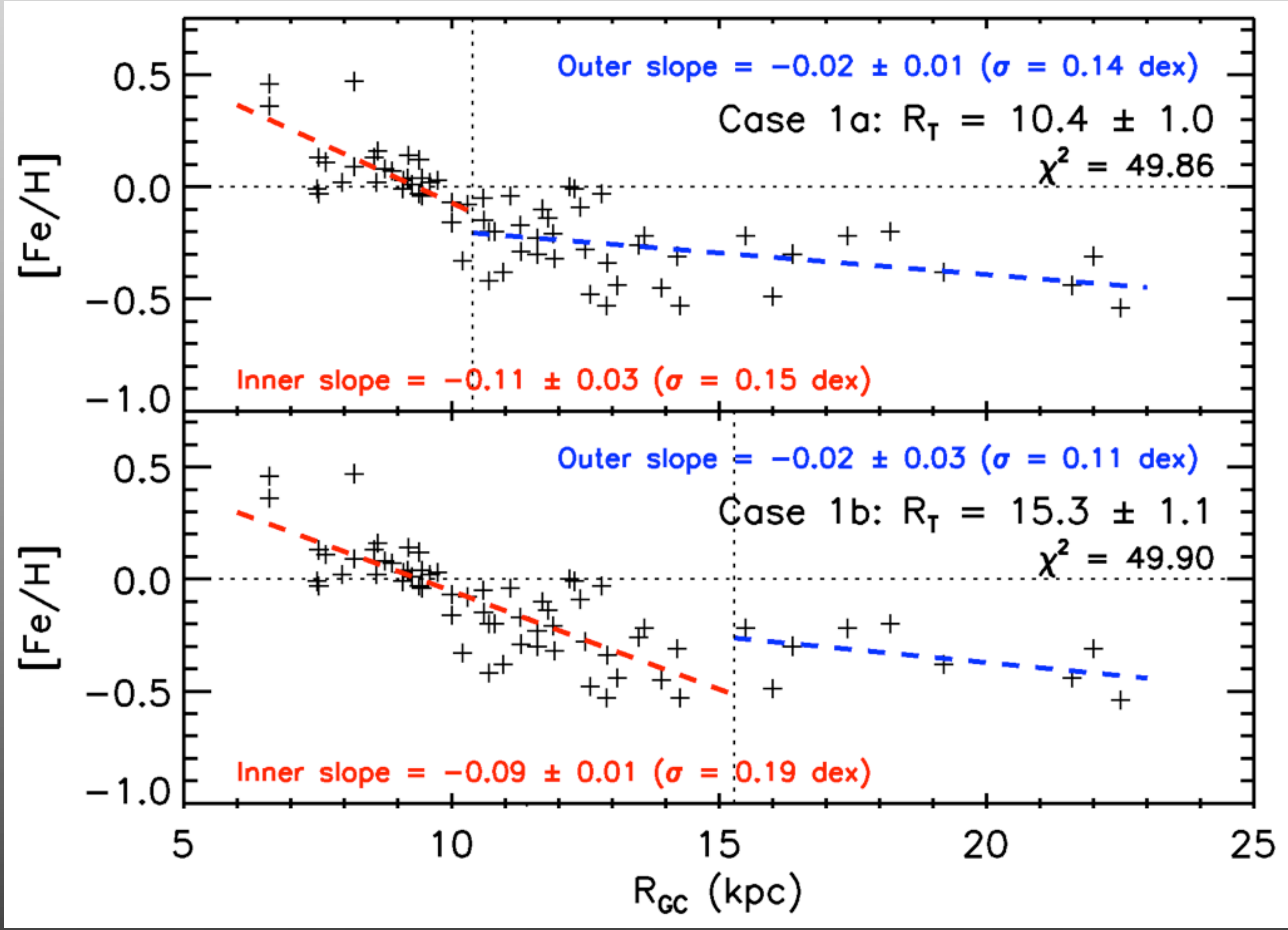




Levenberg–Marquardt technique for least-squares minimization.

The break radius



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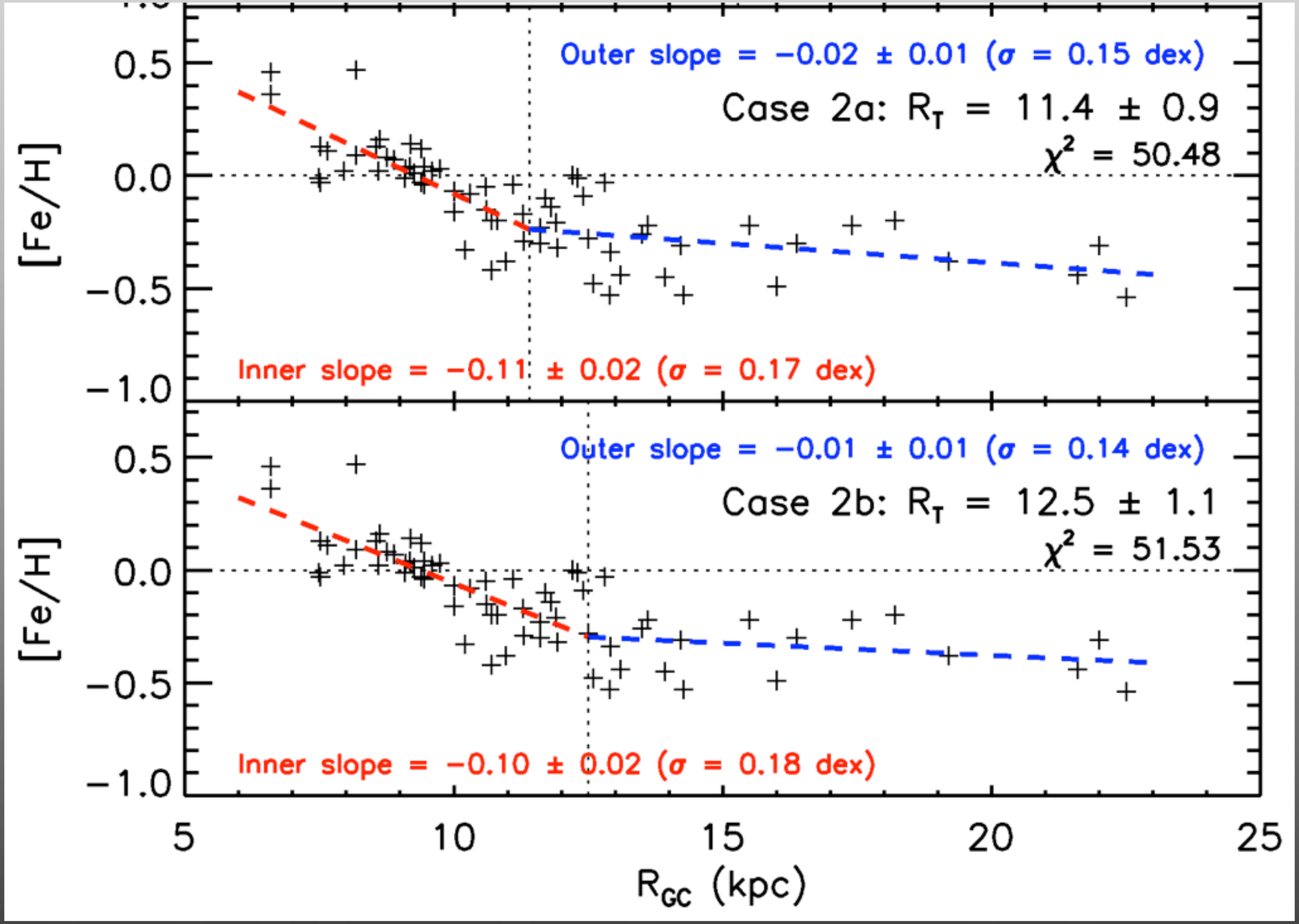
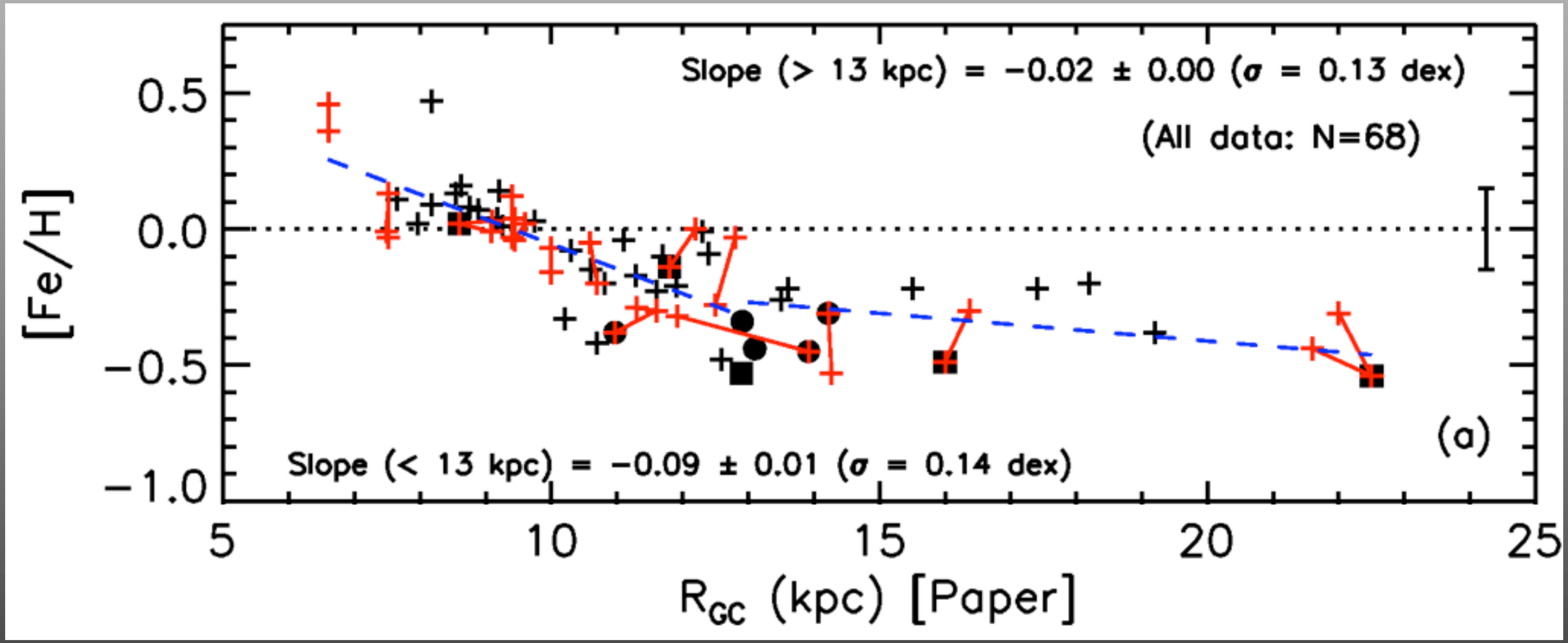
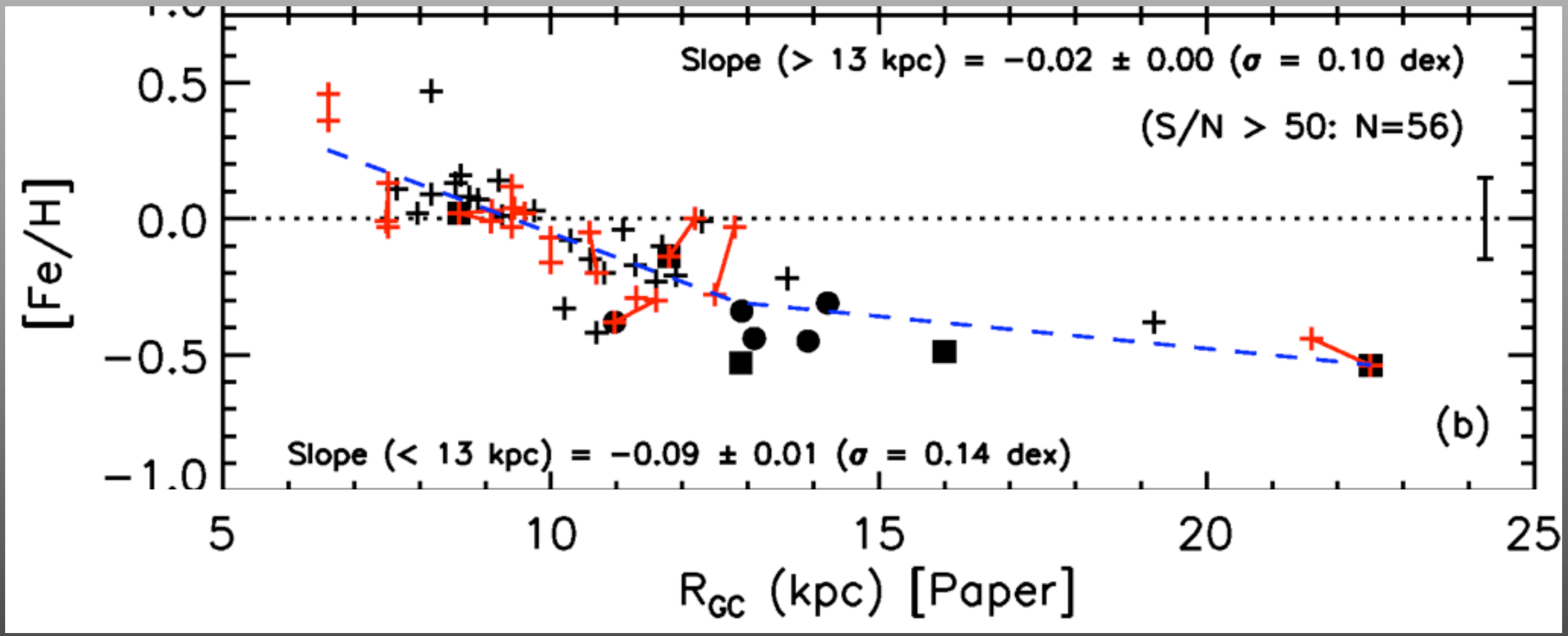


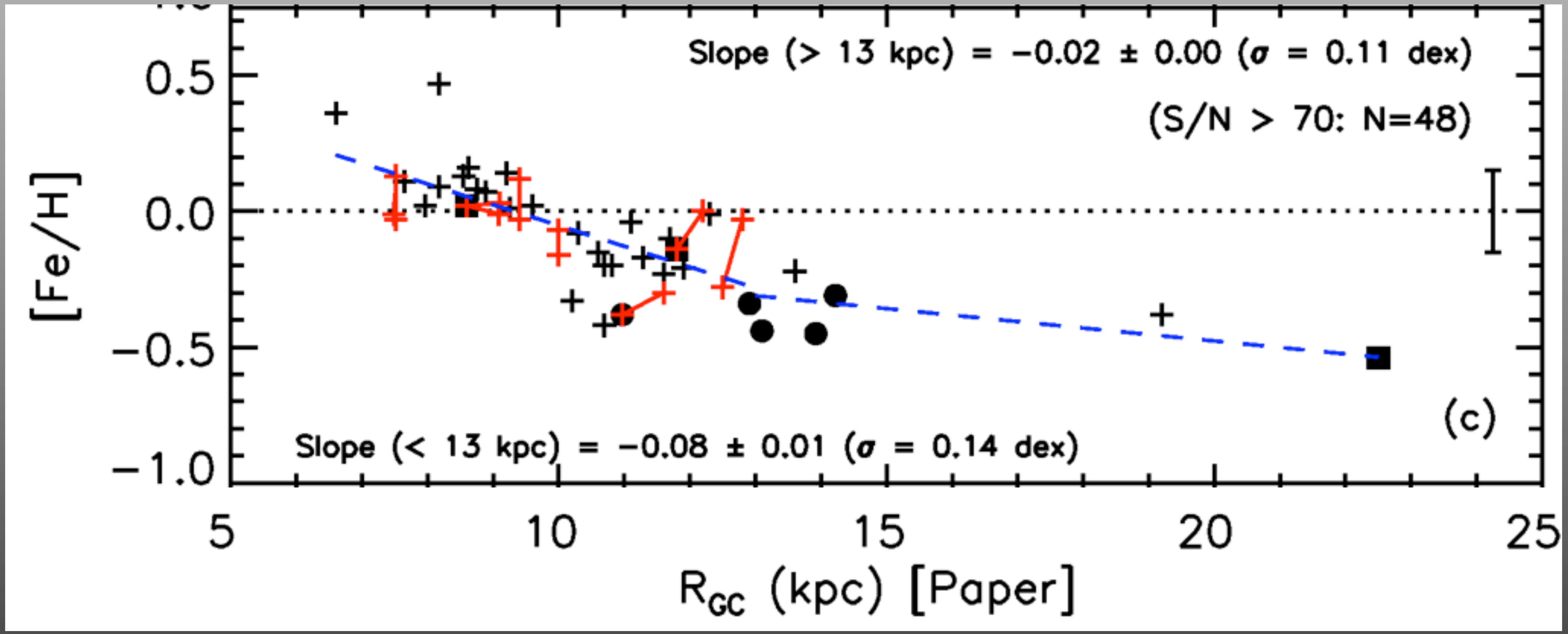
S/N considerations



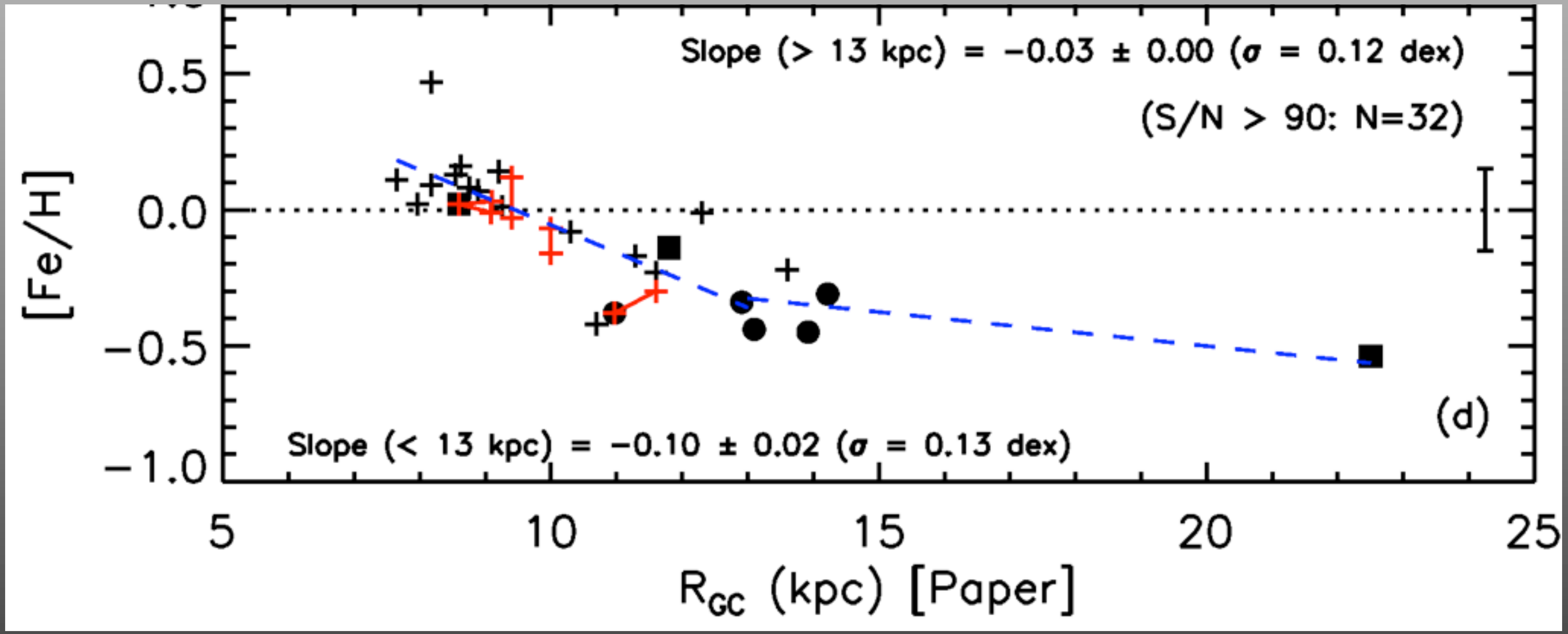
S/N considerations



S/N considerations



S/N considerations



http://www.youtube.com/watch?v=fAADWfJO2qM

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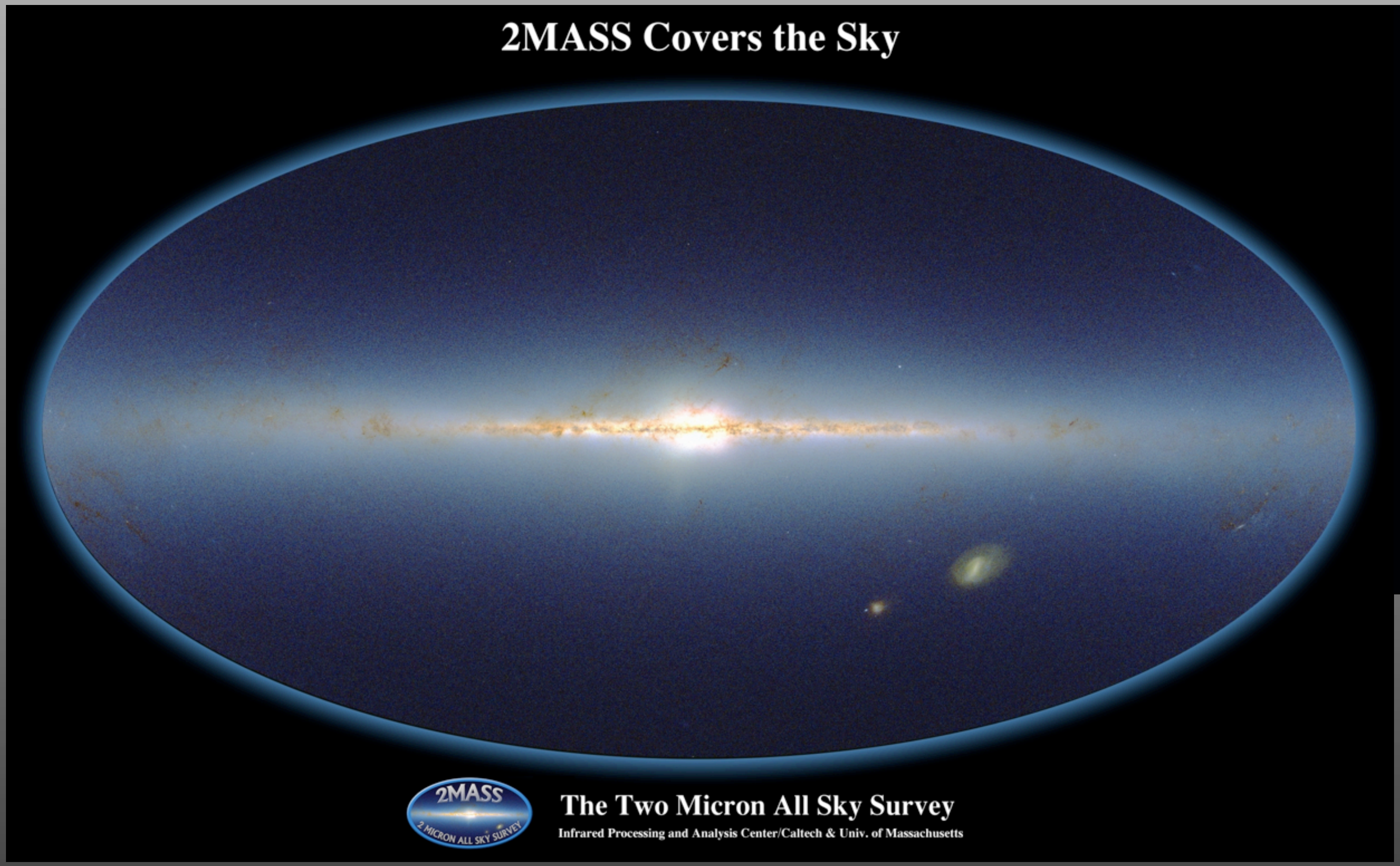
Outline

- Introduction
- New observations and interpretation
- **Future directions**



What have we learned?

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Confirm the metallicity gradient in the outer disk is flatter than in the solar neighbourhood ==> inside-out formation, a constant density distribution and a threshold in the star formation during the halo phase

Outer disk open clusters are metal-poor with enhanced [α/Fe] ==> despite the lower density (and anticipated slower star formation rate) in the outer disk, chemical enrichment proceeded at a similar rate as in the solar neighbourhood

s-process elements exhibit a significant scatter and generally super-solar values ==> AGB stars ([Rb/Zr])

Other factors ==> Radial migration, infall of pristine material, outflows, mergers/accretion events?

Where to from here?

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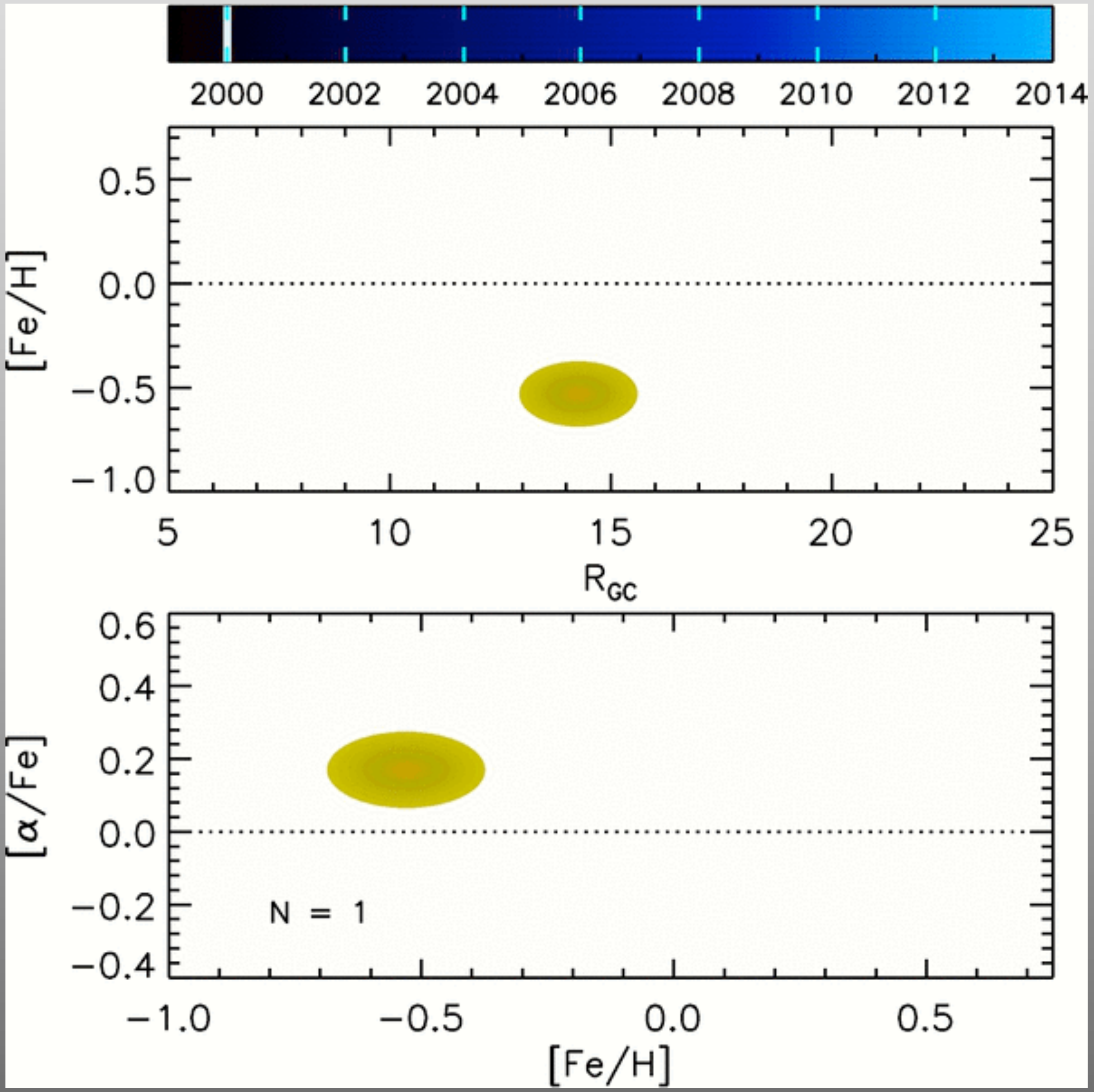
Ultimately, a definitive statement about the origin and evolution of the outer disk requires a

...

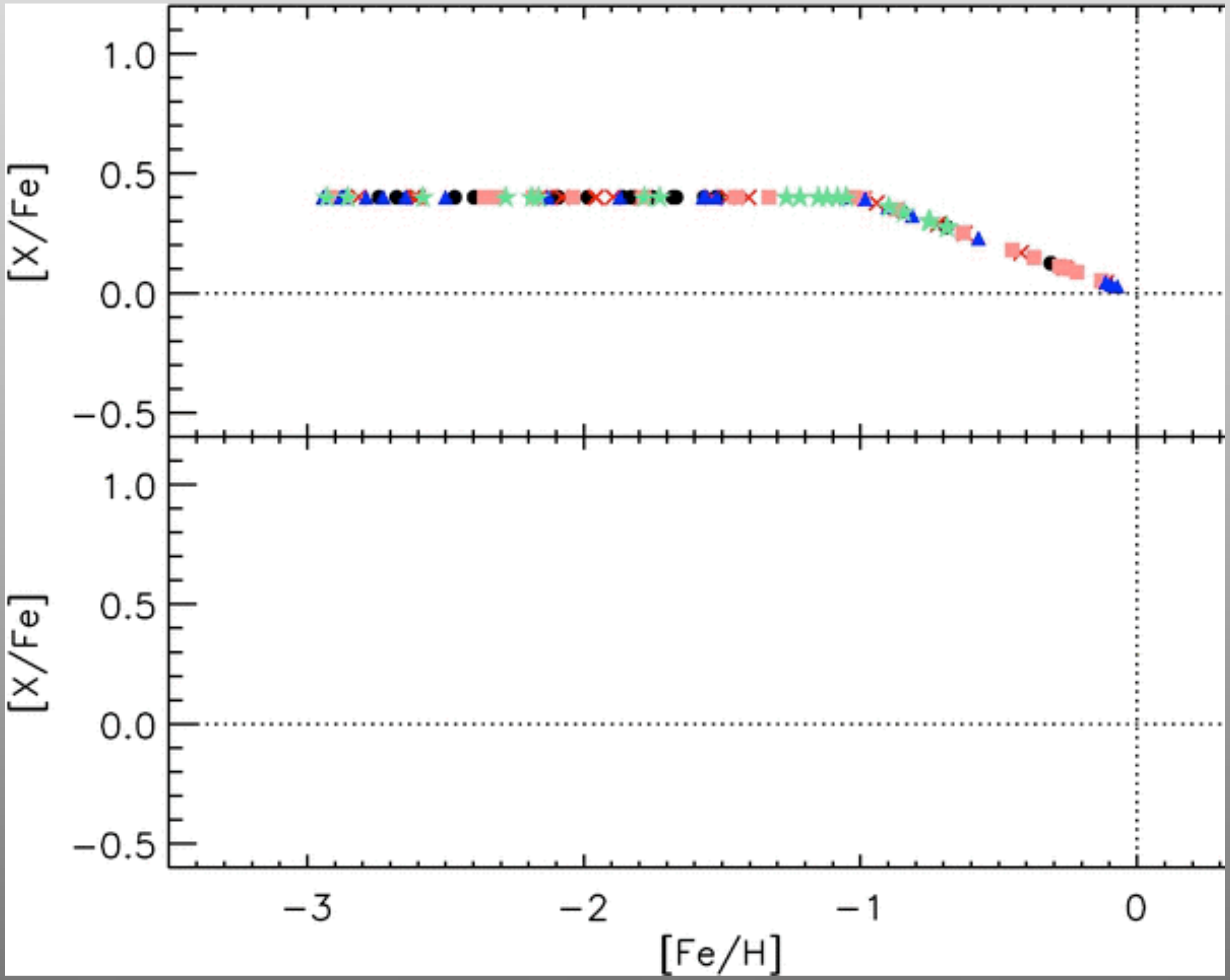
homogeneous analysis of larger samples of stars in larger numbers of clusters based on high quality spectra.

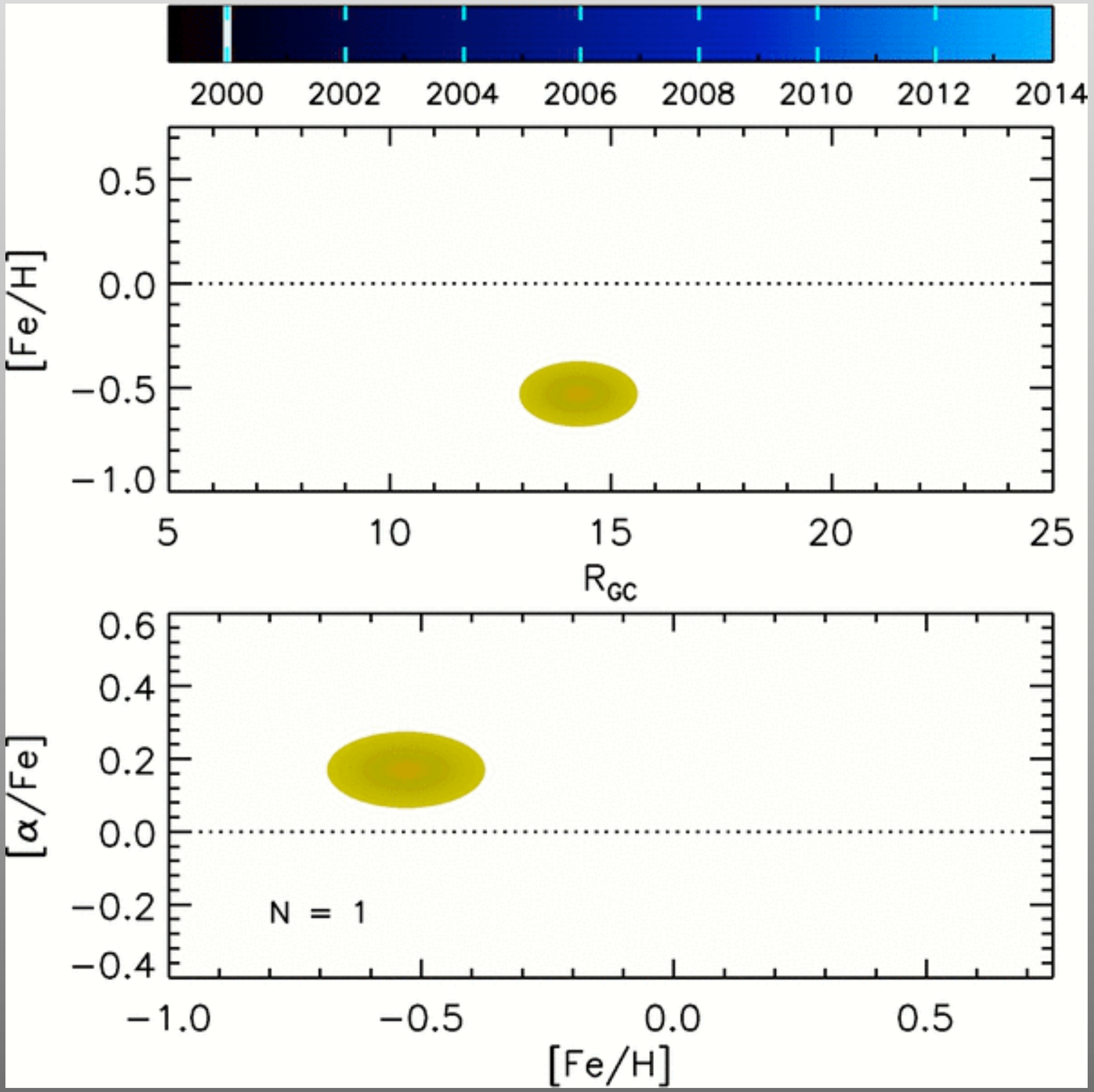
Where to from here?



Improved precision (better data) and **remove systematic uncertainties** (Gaia-ESO, APOGEE, **HERMES**) ==>
Fan Liu: RSAA/ANU PhD student

Where to from here?





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