# Unraveling the Chemical Evolution of Galaxies Beyond the Milky Way

## Integrated Light Spectroscopy of Globular Clusters


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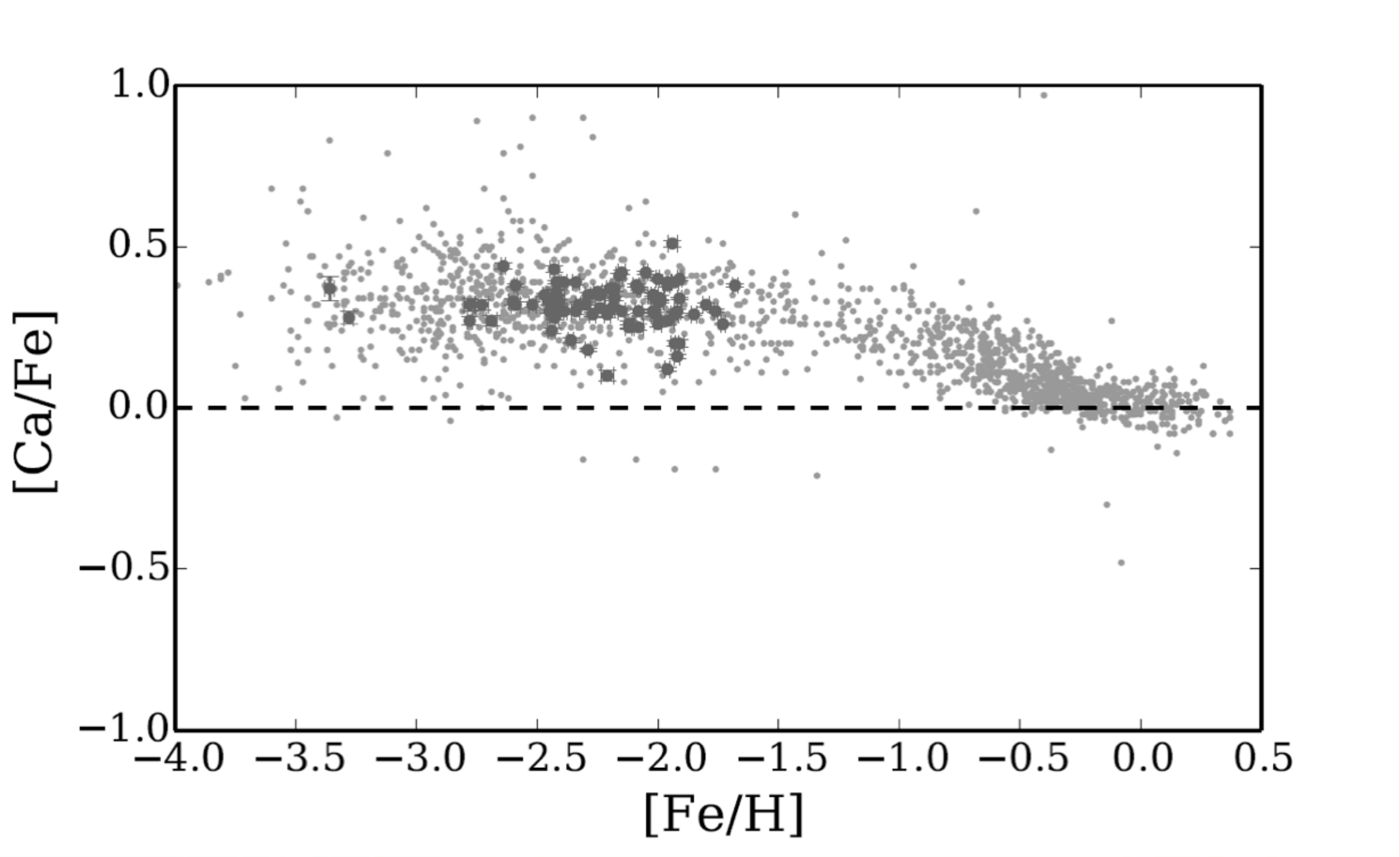
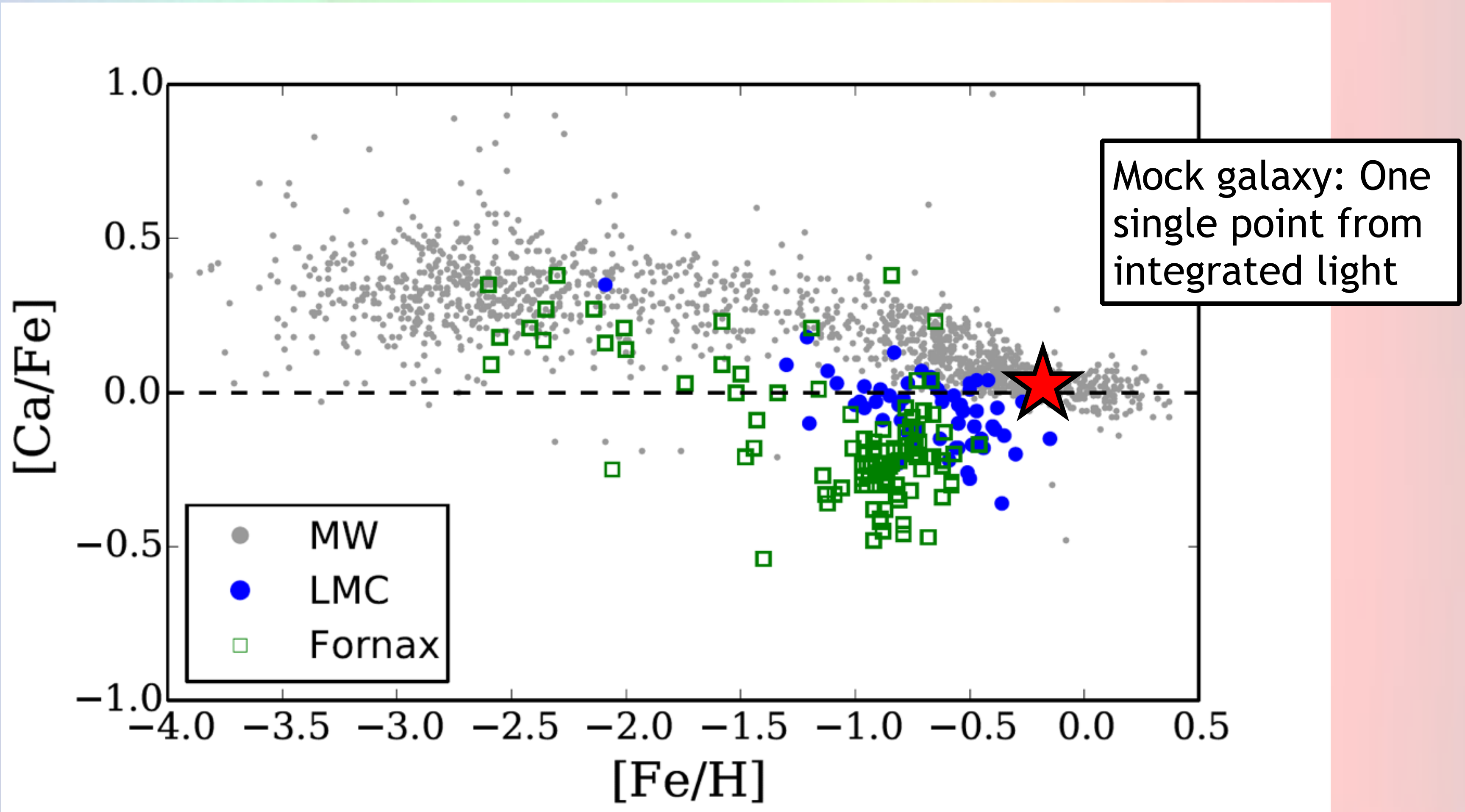
# Chemical Evolution, Nucleosynthesis, Stellar Evolution



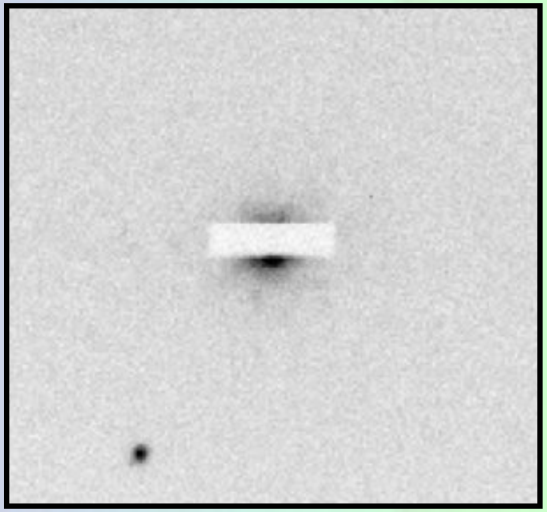

Venn et al. (2004), Frebel et al. (2010), Sakari et al. (2017, in prep.)

# Chemical Evolution, Nucleosynthesis, Stellar Evolution

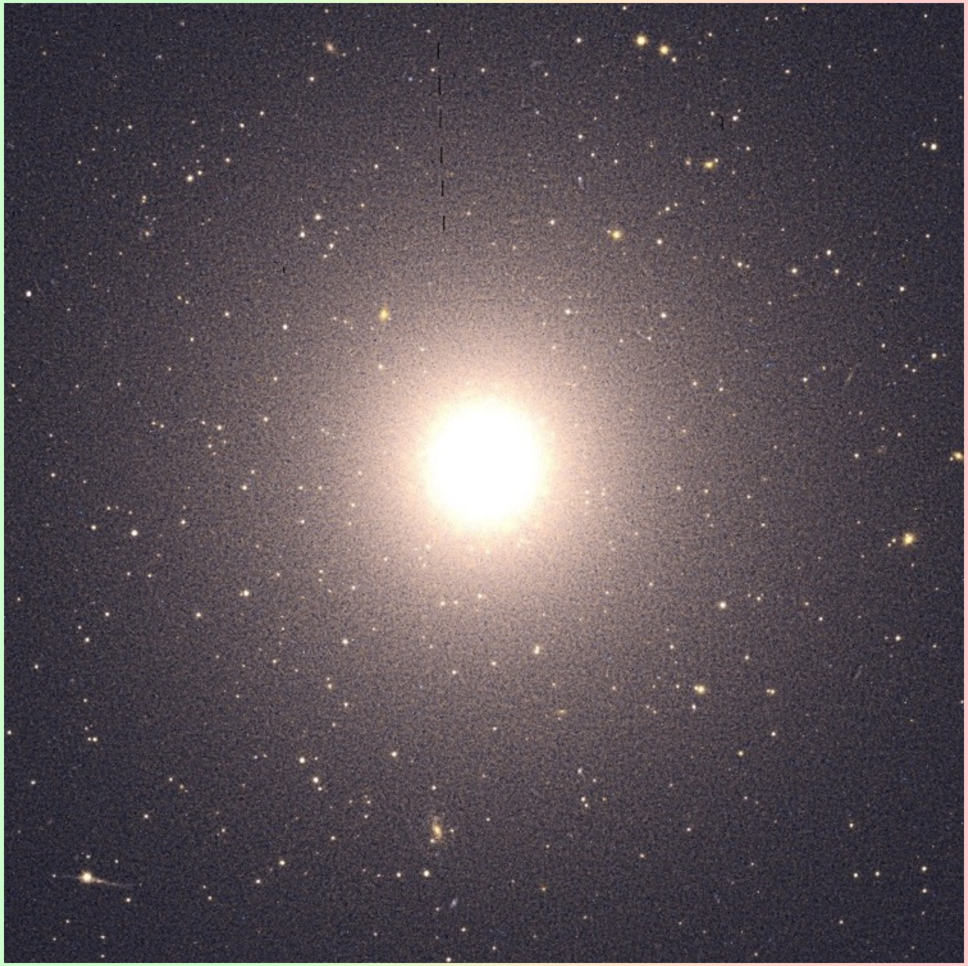



Pompeia et al. (2008), Letarte et al. (2010), Hendricks et al. (2016)

# Integrated Light Spectroscopy

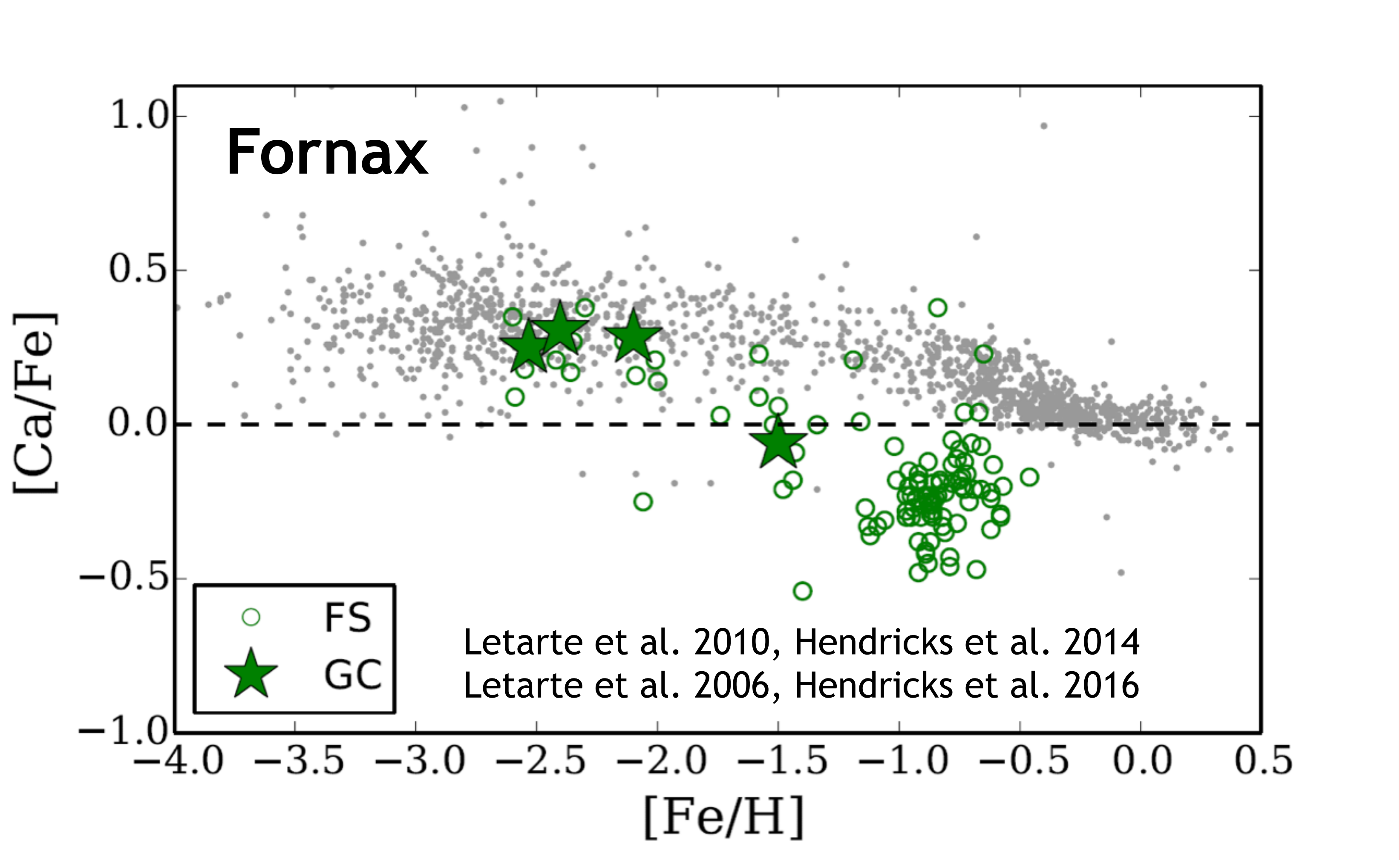


Colucci et al. 2009



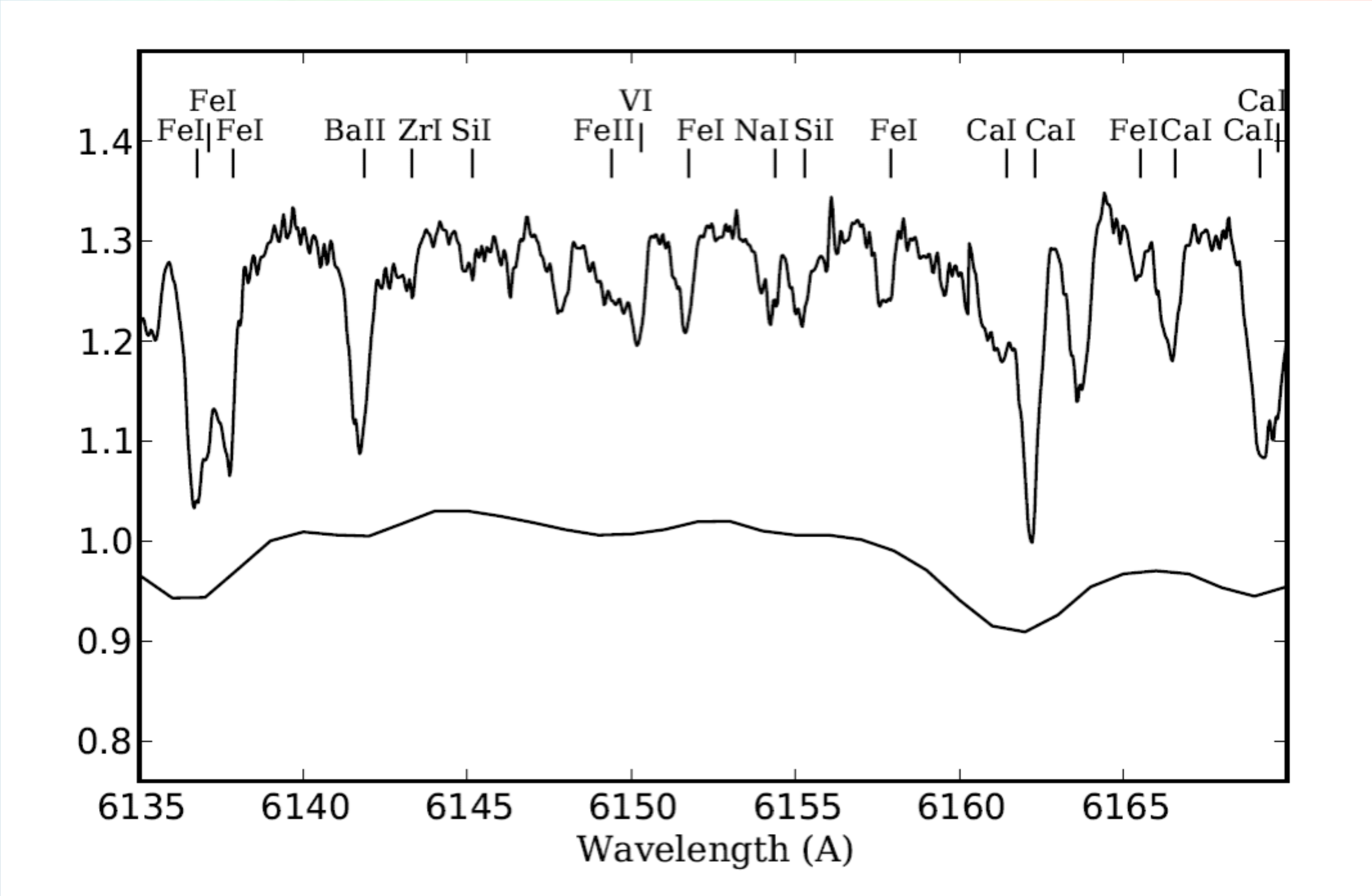
NGC 1407—Image from Harris et al. 2006

# GCs as Field Star Tracers*



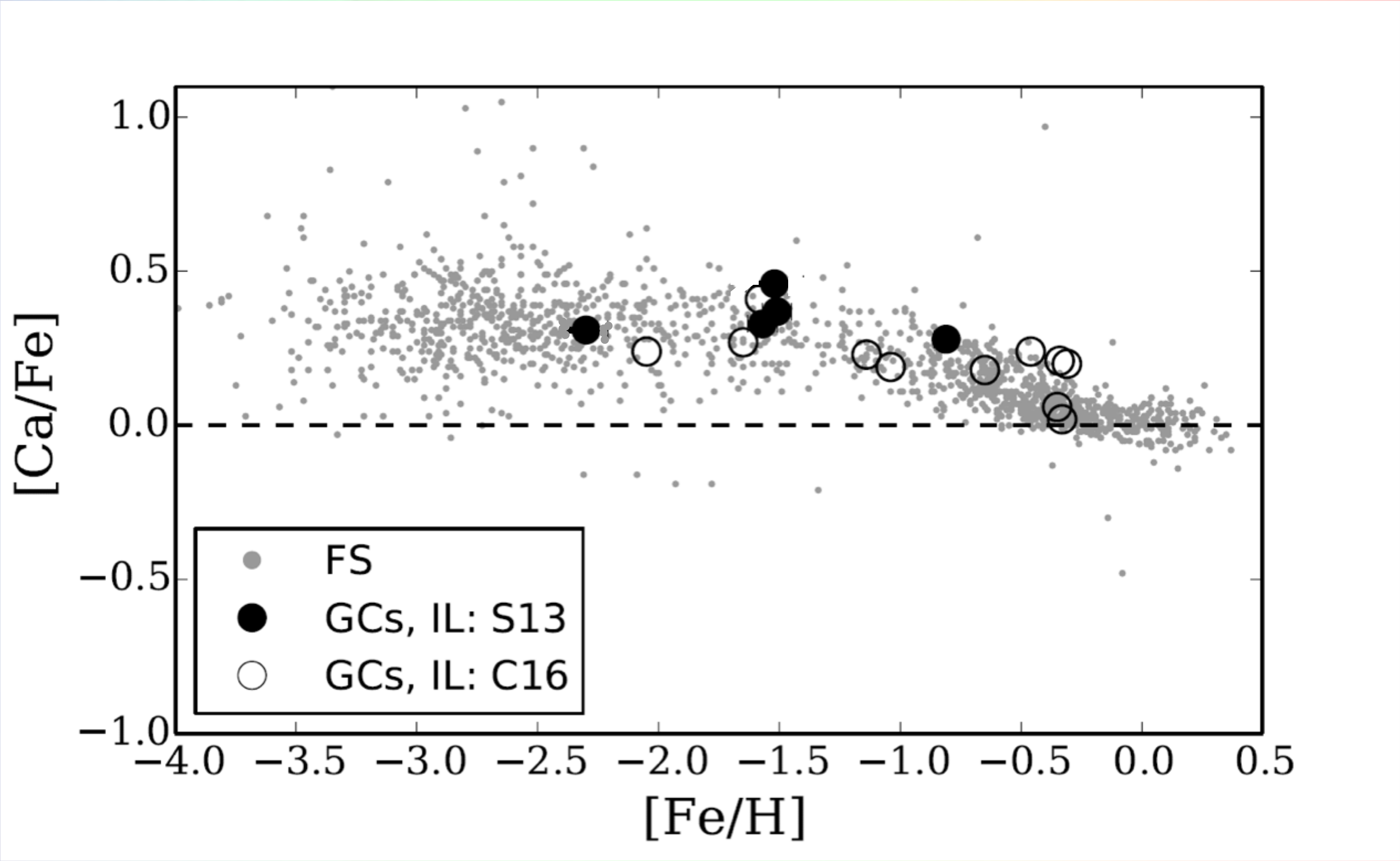

* For most clusters and for certain elements

# High Resolution IL spectroscopy




47 Tuc spectra: McWilliam & Bernstein (2008), Schiavon et al. (2005)

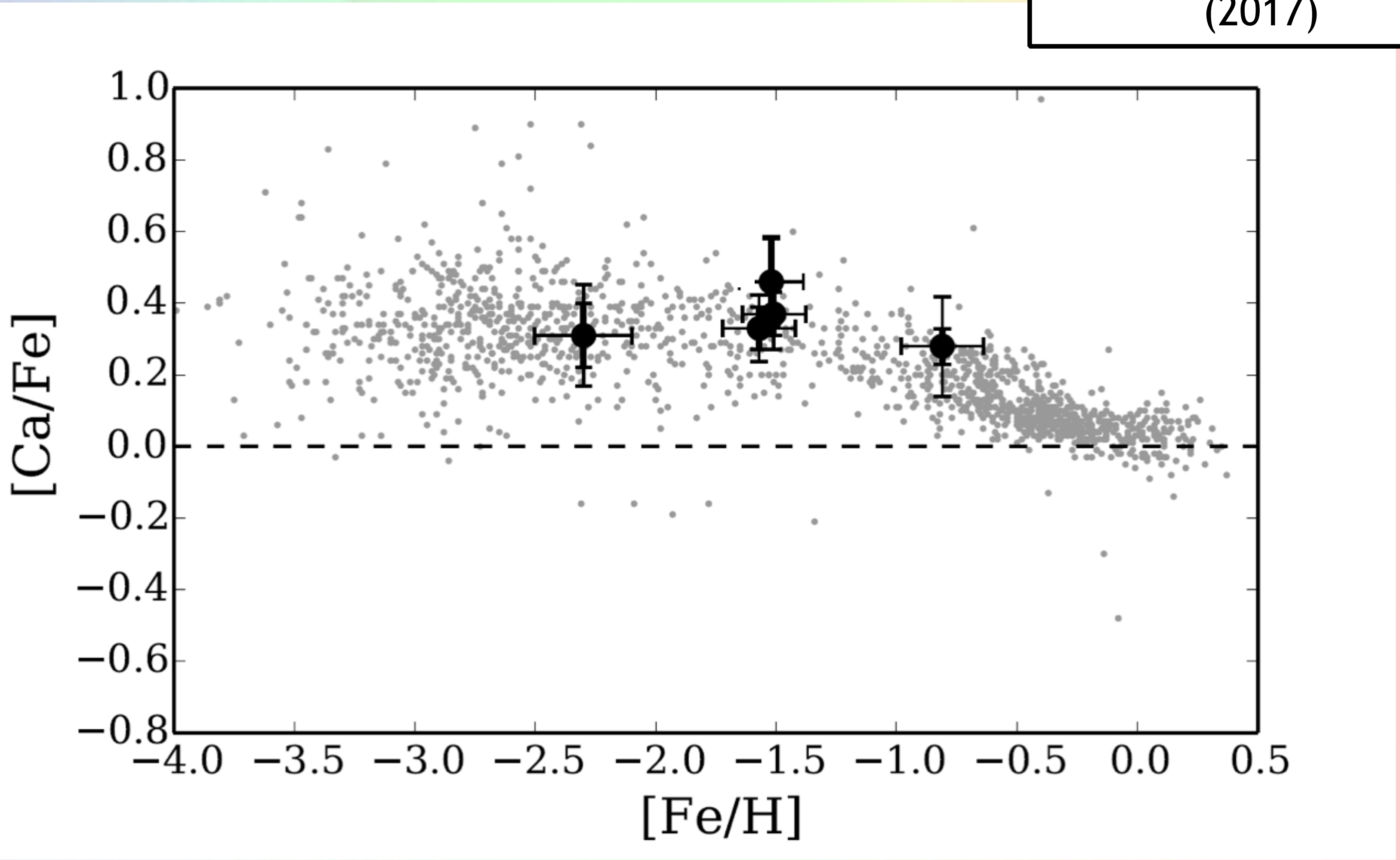
# IL matches values from FSs




Sakari et al. (2013), Colucci et al. (2016)

# Systematic Errors

Also see Colucci et al. (2014), Larsen et al. (2017)




Sakari et al. (2014)

# M31 GCs

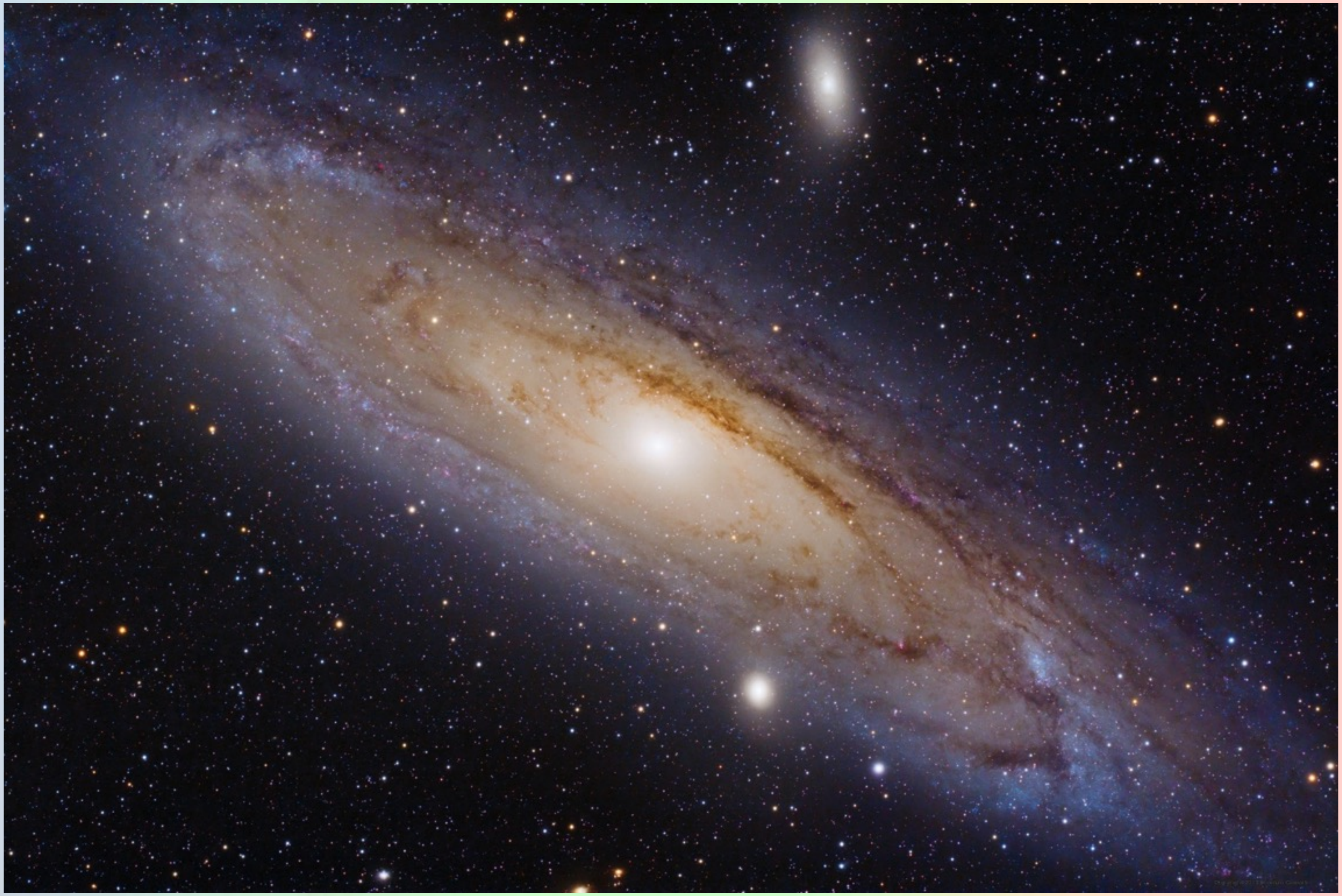
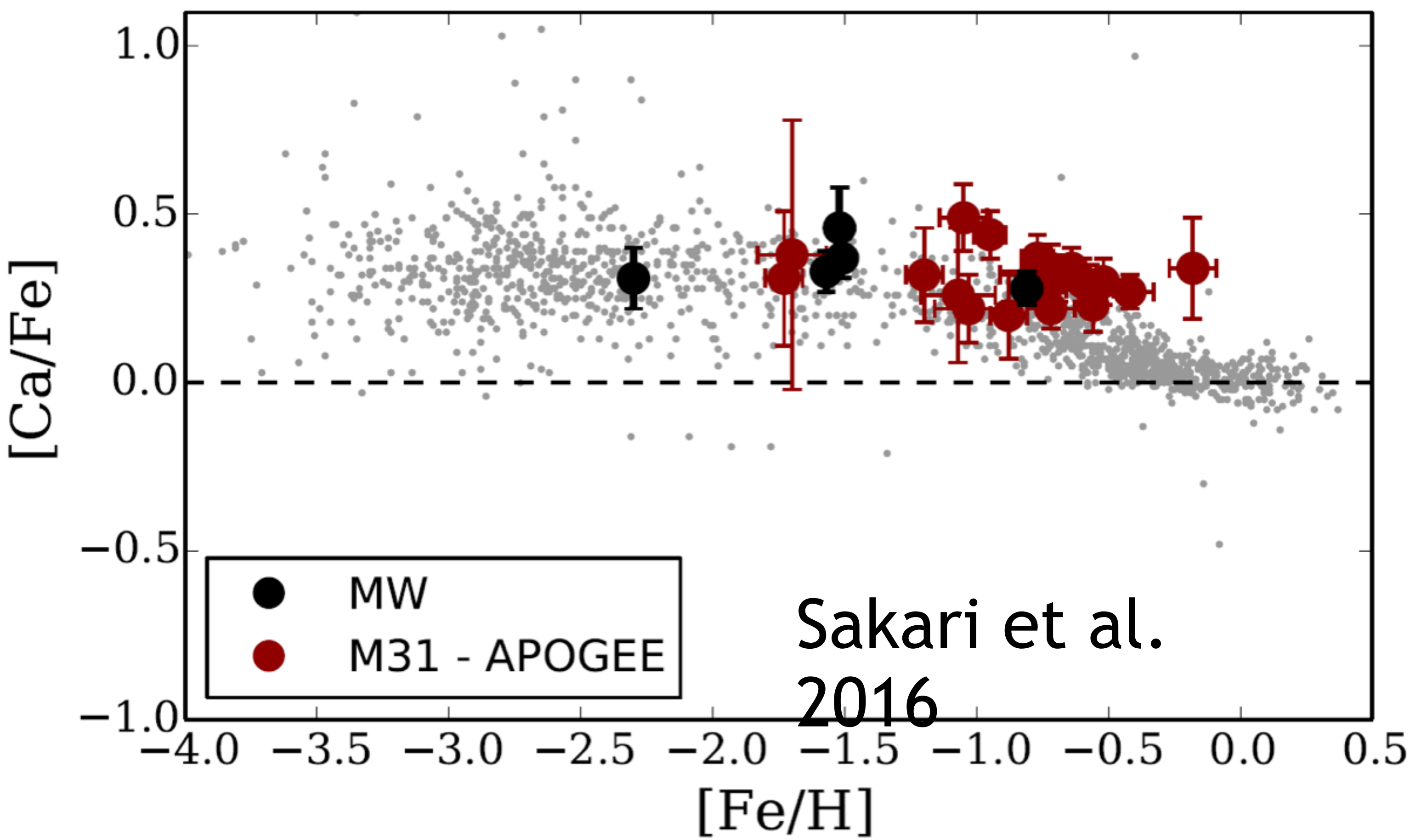


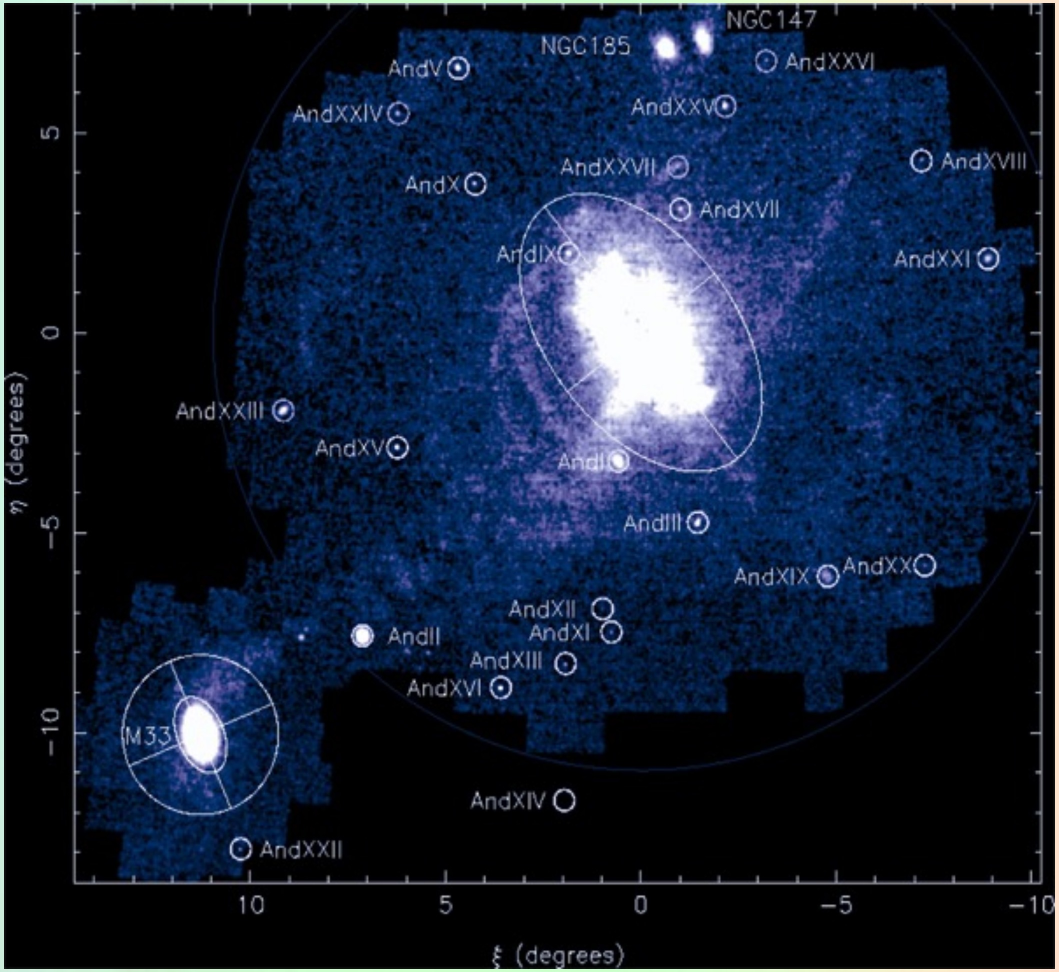
Image from Lorenzo Comolli

# Inner M31 GCs



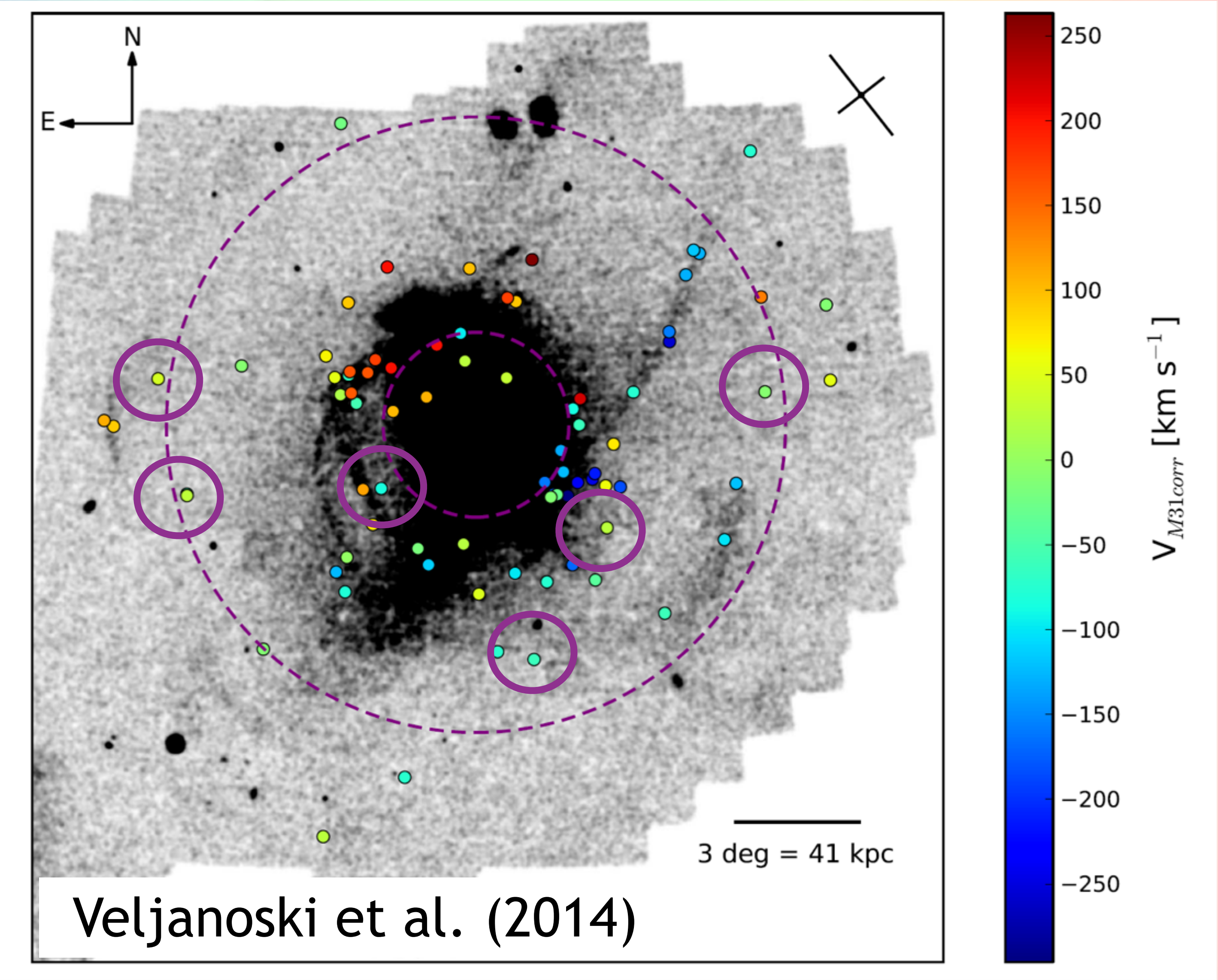

Sakari et al. 2016

# Pan-Andromeda Archaeological Survey

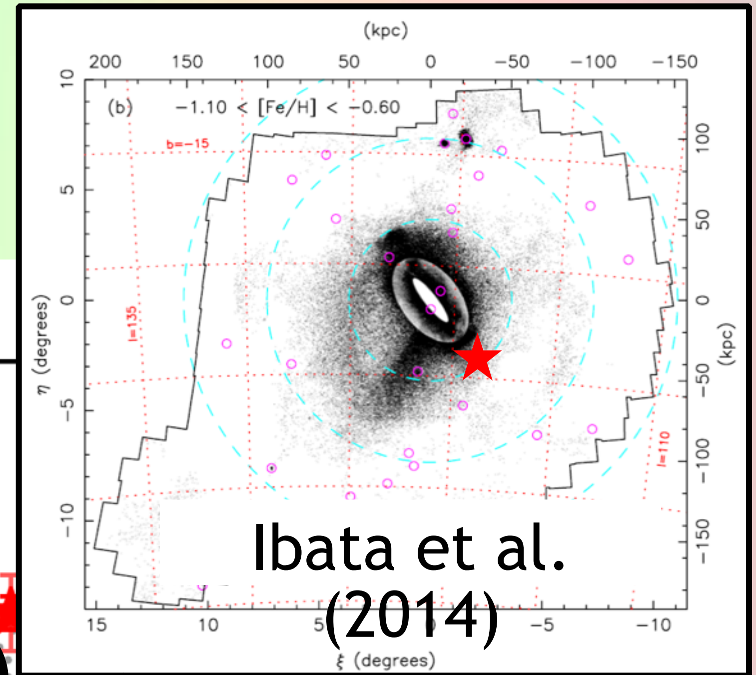


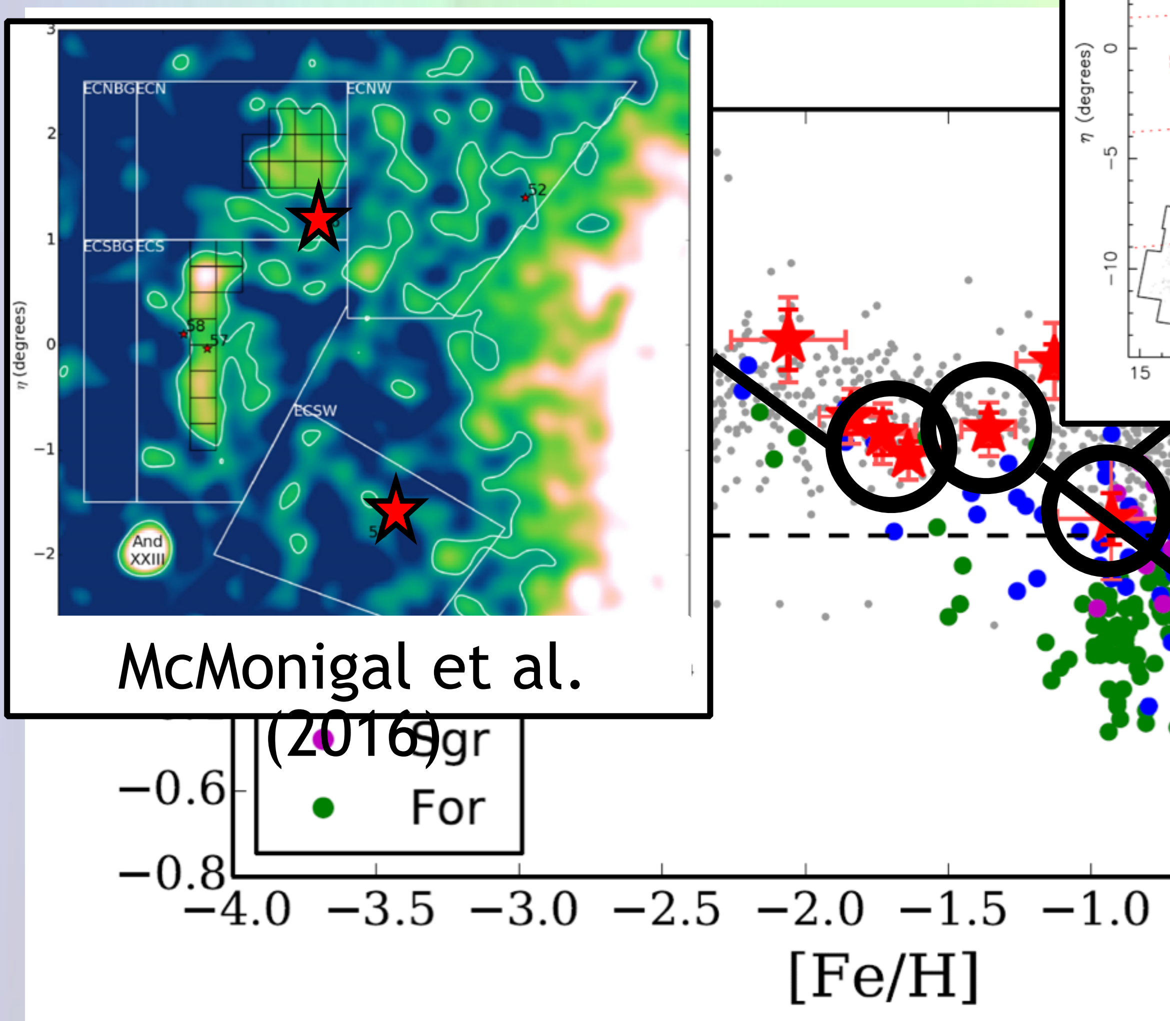

PAndAS image from Geraint Lewis; see McConnachie et al. 2009

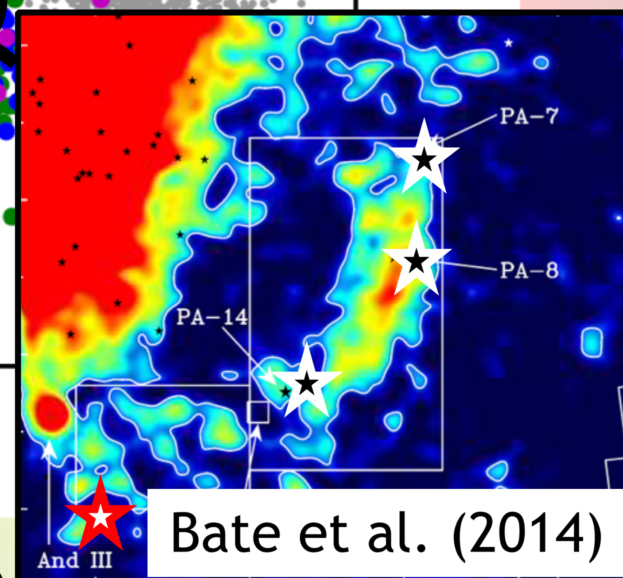
# PAndAS clusters



# PAndAS Clusters

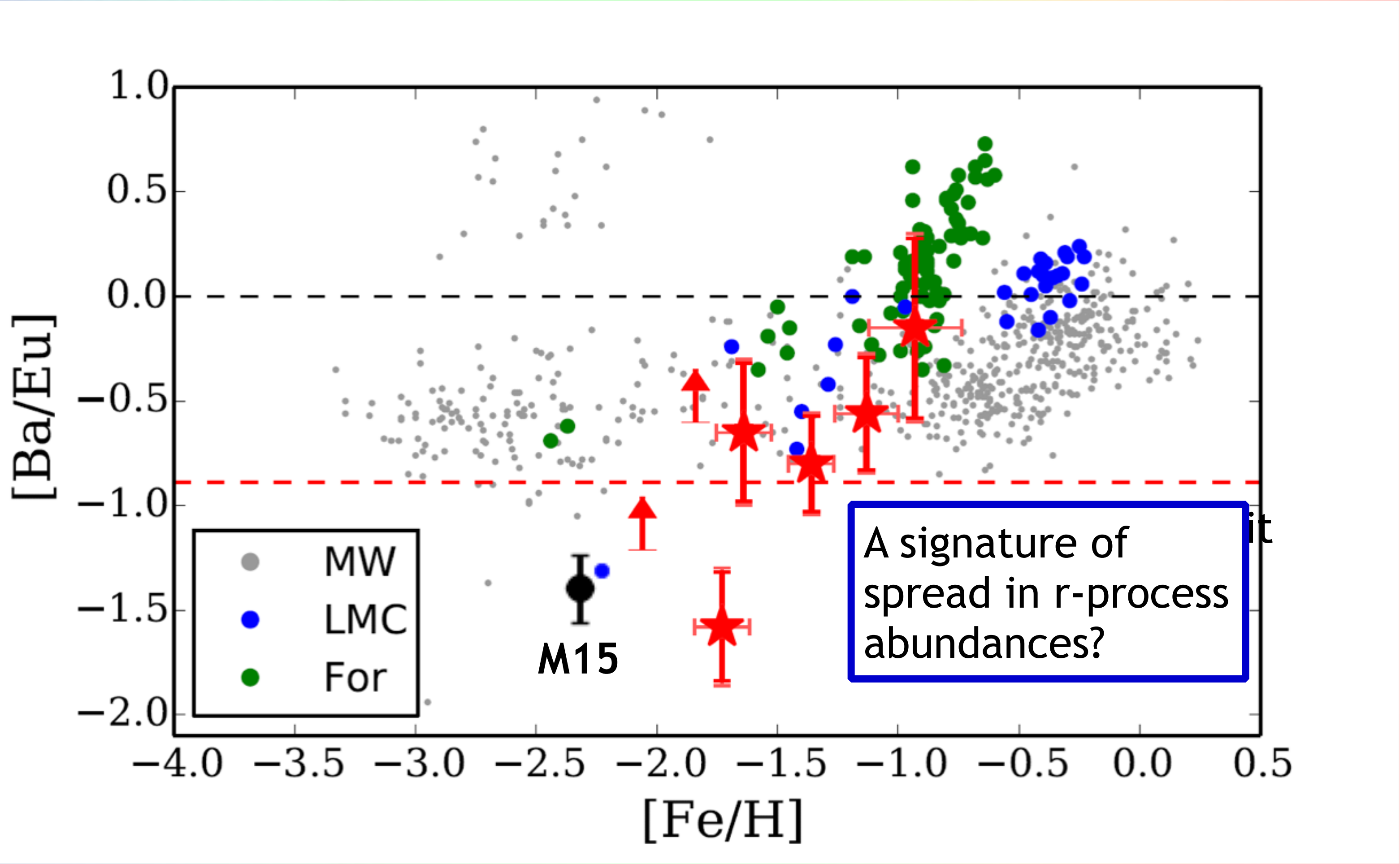



Sakari et al. (2015)

# [Ba/Eu]



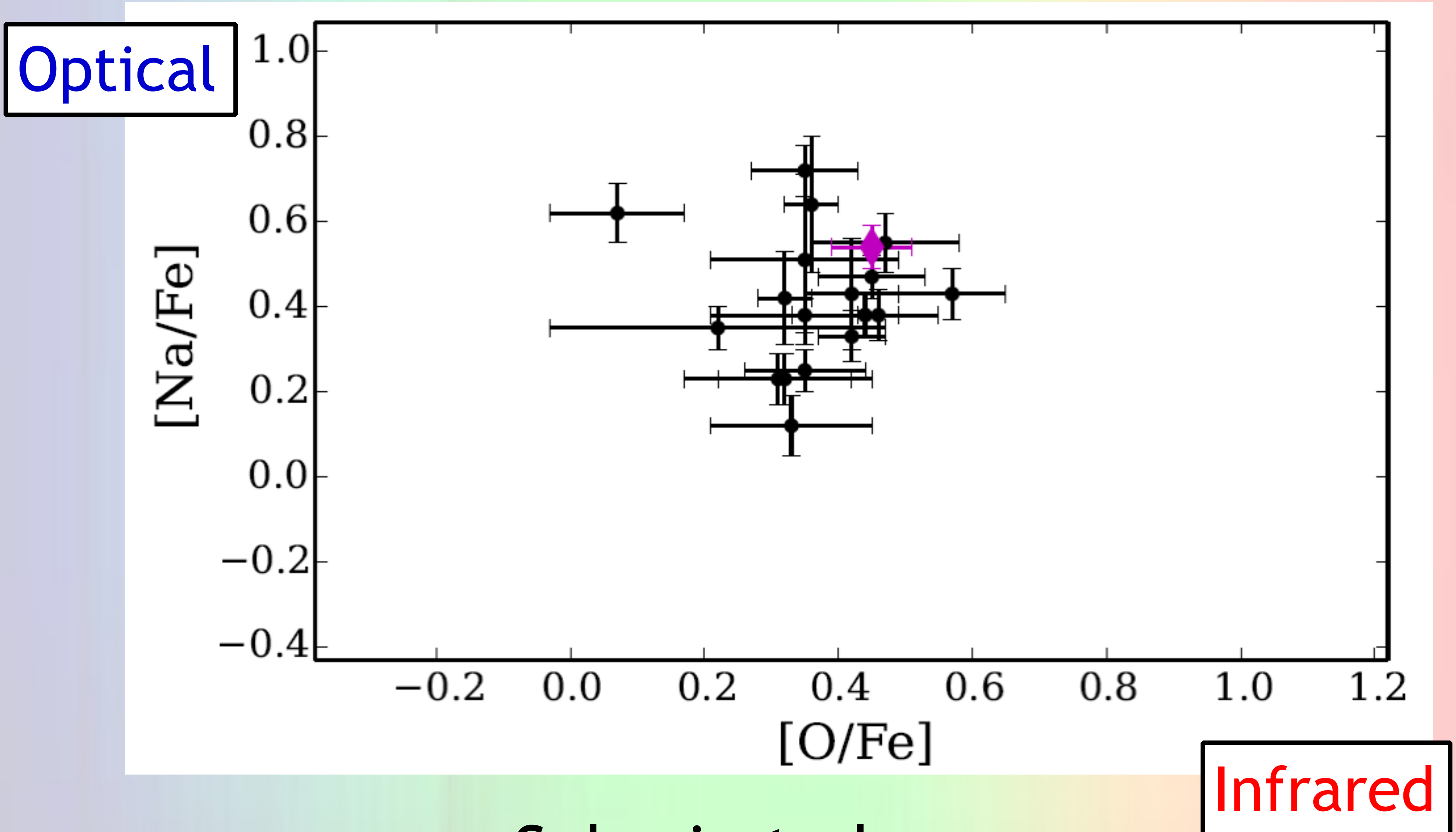

Sakari et al. (2013; 2015)

# From Nuclei to the Cosmic Web

High resolution IL spectroscopy provides information about detailed abundances of stellar populations in galaxy types and environments unlike the Milky Way and its nearest neighbors.

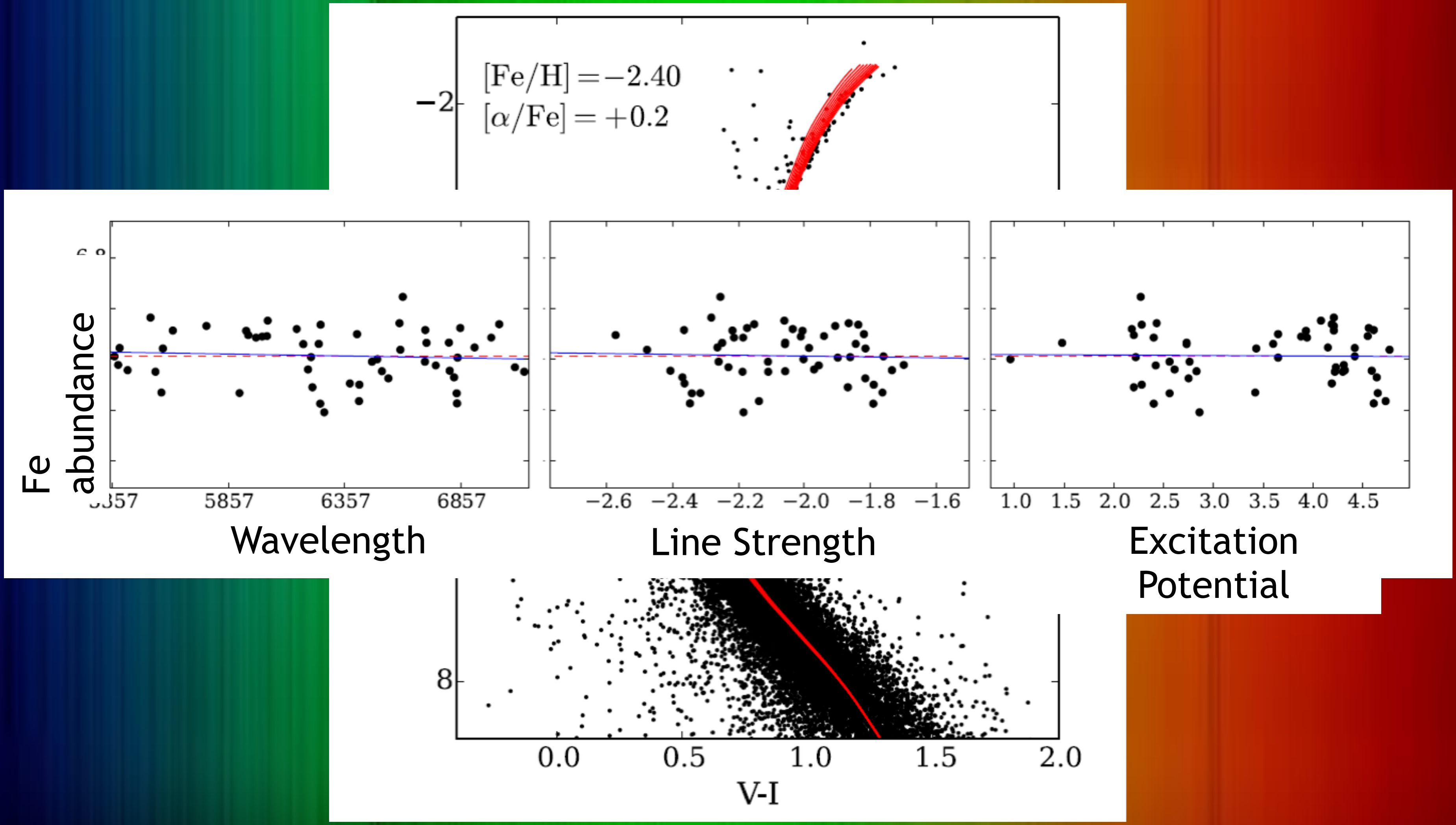
- Chemical evolution in other galaxy types (e.g., massive ellipticals) and environments (e.g., isolation or clusters)
- Metallicity distributions/radial abundance gradients of GCs
- Chemical tagging of globular clusters to host environments (e.g., dwarf galaxies), probing merger and accretion histories
- The detailed information about the Milky Way can be examined in a cosmological context

# Signatures of multiple populations?




Sakari et al. 2016

# Modelling the Underlying Population



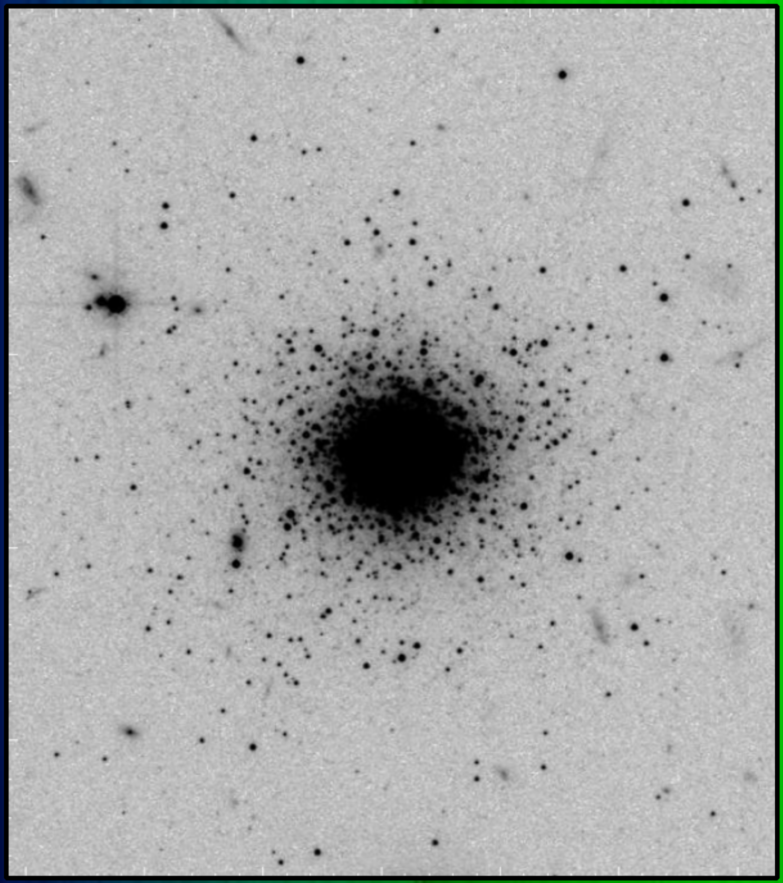
# Systematic Errors

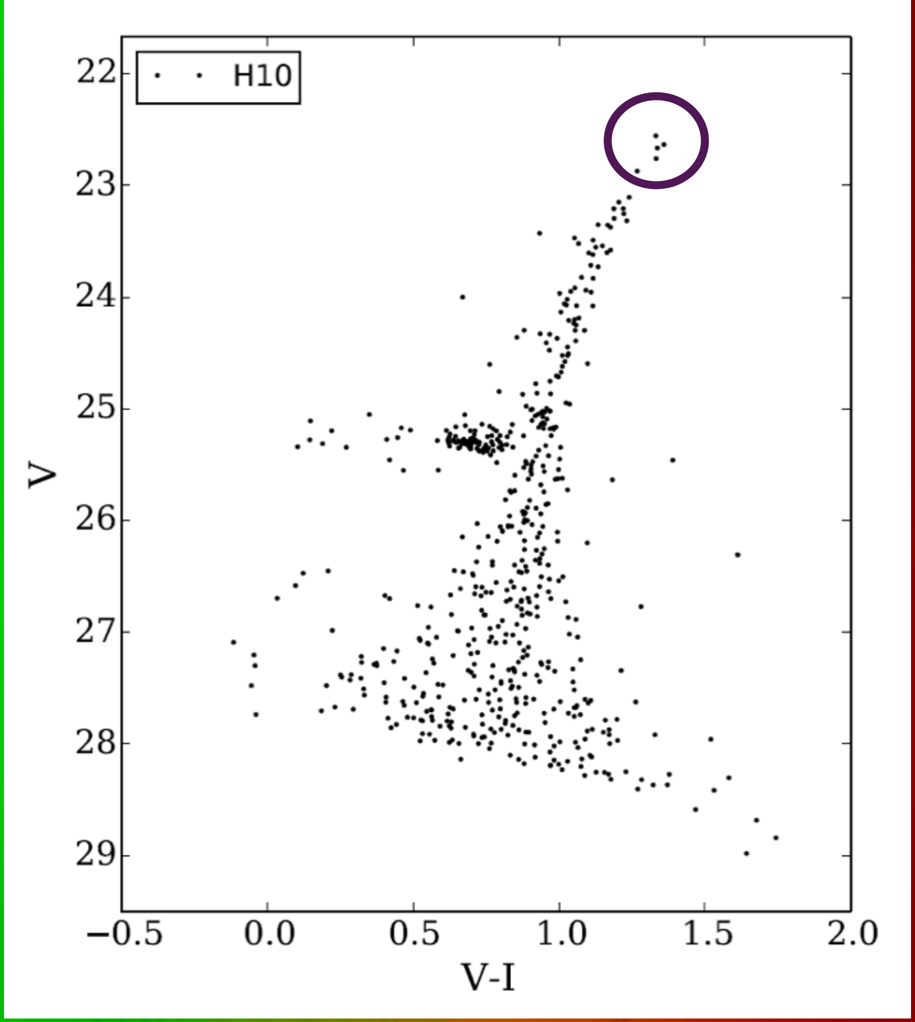
Also see Colucci et al. 2016! arXiv: 1611.02734

| | Δ[Fe I/H] | Δ[Fe II/H] | Δ[Ca I/Fe I] | Δ[Ti I/Fe I] | Δ[Ti II/Fe II] | Δ[Ni I/Fe I] | Δ[Ba II/Fe II] | Δ[Eu II/Fe II] | Δ[Ba II/Eu II] |
|---|---|---|---|---|---|---|---|---|---|
| **CMD-based analyses** | | | | | | | | | |
| Minimum errors[a] | **≤0.12** | **≤0.20** | **≤0.06** | **≤0.09** | **≤0.14** | ≤0.04 | **≤0.22** | **≤0.11** | **≤0.17** |
| CTRs[a, b] | **≤0.07** | ≤0.01 | ≤0.02 | ≤0.03 | ≤0.03 | ≤0.04 | **≤0.06** | ≤0.04 | ≤0.04 |
| Input photometry | ≤0.04 | **≤0.07** | ≤0.02 | ≤0.04 | ≤0.04 | ≤0.01 | **≤0.07** | ≤0.02 | **≤0.06** |
| Incompleteness | **≤0.07** | **≤0.07** | **≤0.05** | **≤0.06** | **≤0.07** | **≤0.04** | **≤0.07** | ≤0.03 | ≤0.04 |
| Sampling[c, d] | **≤0.22** | **≤0.10** | **≤0.09** | – | **≤0.10** | ≤0.03 | **≤0.21** | **≤0.09** | **≤0.14** |
| **HRD-based analyses** | | | | | | | | | |
| HRD versus CMD[a] | **≤0.11** | **≤0.19** | **≤0.05** | **≤0.20** | **≤0.10** | ≤0.04 | **≤0.12** | **≤0.08** | **≤0.10** |
| Age/[Fe/H] errors[a] | **≤0.16** | **≤0.16** | **≤0.07** | **≤0.12** | **≤0.10** | ≤0.04 | **≤0.19** | **≤0.08** | **≤0.10** |
| Diff. isochrones | ≤0.02 | ≤0.04 | ≤0.02 | ≤0.02 | ≤0.01 | 0.0 | ≤0.03 | ≤0.01 | ≤0.02 |
| IMF | ≤0.04 | ≤0.01 | ≤0.02 | **≤0.06** | **≤0.05** | ≤0.02 | **≤0.07** | **≤0.05** | ≤0.02 |
| Cluster $M_V$[e] | **≤0.36** | **≤0.10** | **≤0.10** | **≤0.41** | **≤0.14** | **≤0.10** | **≤0.33** | **≤0.23** | **≤0.10** |
| HB morphology[a, d] | **≤0.13** | **≤0.28** | ≤0.04 | **≤0.17** | **≤0.08** | **≤0.07** | **≤0.14** | **≤0.11** | **≤0.12** |
| AGB prescription | **≤0.19** | **≤0.15** | **≤0.05** | **≤0.23** | **≤0.09** | **≤0.13** | **≤0.19** | **≤0.14** | **≤0.07** |
| Blue stragglers | **≤0.07** | **≤0.07** | ≤0.02 | ≤0.04 | ≤0.04 | ≤0.03 | **≤0.05** | **≤0.06** | ≤0.02 |
| Low mass cut-off[a] | **≤0.13** | **≤0.12** | ≤0.04 | **≤0.24** | **≤0.07** | **≤0.05** | **≤0.11** | **≤0.12** | **≤0.05** |
| **All analyses** | | | | | | | | | |
| CMD/HRD boxes | ≤0.02 | ≤0.01 | ≤0.02 | ≤0.03 | ≤0.04 | ≤0.03 | ≤0.01 | **≤0.07** | ≤0.04 |
| Microturbulence | **≤0.11** | **≤0.05** | ≤0.03 | ≤0.02 | **≤0.08** | **≤0.10** | **≤0.16** | ≤0.04 | **≤0.16** |
| LPVs | ≤0.01 | **≤0.07** | 0.0 | ≤0.03 | ≤0.01 | ≤0.03 | 0.0 | 0.0 | 0.0 |
| CH stars[a, d] | 0.0 | 0.0 | ≤0.01 | 0.0 | 0.0 | ≤0.01 | 0.0 | ≤0.01 | ≤0.01 |
| Hot stars | **≤0.06** | ≤0.04 | ≤0.01 | ≤0.01 | **≤0.07** | ≤0.03 | ≤0.04 | ≤0.04 | **≤0.08** |
| Field stars[d] | **≤0.10** | **≤0.09** | **≤0.09** | ≤0.04 | **≤0.07** | **≤0.06** | **≤0.10** | **≤0.05** | **≤0.09** |
| ODFNEW atms | **≤0.05** | **≤0.12** | ≤0.03 | ≤0.02 | ≤0.03 | ≤0.02 | ≤0.03 | ≤0.03 | ≤0.03 |
| CN-cycled atms | **≤0.05** | **≤0.12** | ≤0.03 | ≤0.02 | ≤0.03 | ≤0.02 | ≤0.03 | ≤0.03 | ≤0.03 |

Sakari et al. (2014)

# Photometry of M31 GCs






Sakari et al. 2015, Mackey et al. in prep