University of Sussex

# The metallicity of the ICM

## Yates, Thomas & Henriques, 2016, 1603.04858

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with
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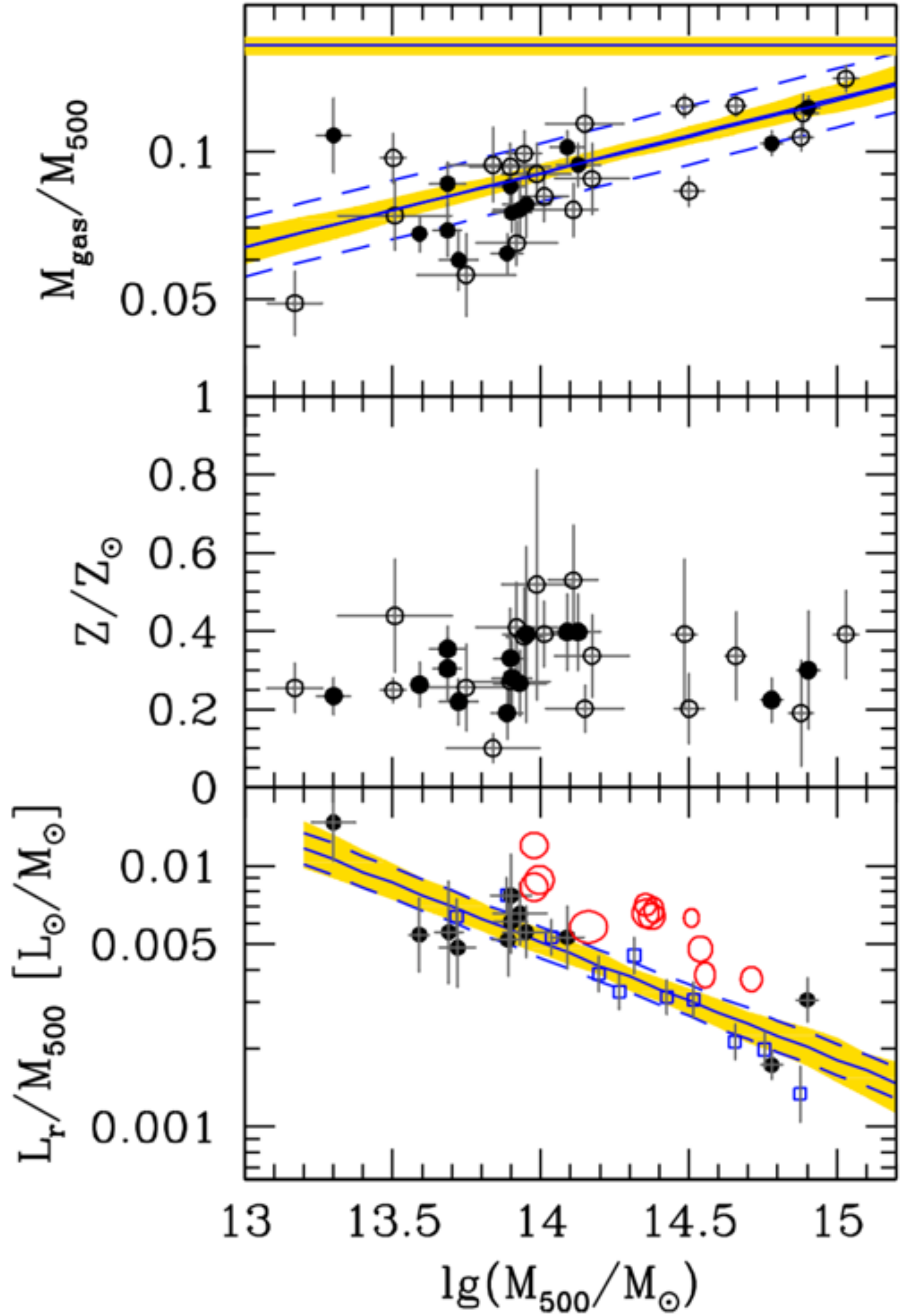
# Outline

- Why bother?
- Observations – compiling a uniform dataset
- The L-Galaxies SAM – metallicity model
- Comparison of observations and SAM
- Future work
- Conclusions

# Why bother?

- Test of galaxy formation / stellar population models – can we produce enough iron?
- Probe of feedback from galaxies into the ICM/IGM.




Renzini & Andreon (2014)

# Observations – data

| Study | Acronym | Observatory | Systems | | | | |
|---|---|---|---|---|---|---|---|
| | | | Groups | Clusters | NCC | CC | Total |
| Fukazawa et al. (1998) | F98 | *ASCA* | 6 | 28 | 9 | 25 | **34** |
| De Grandi & Molendi (2001) | DGM01 | *BeppoSAX* | - | 17 | 8 | 9 | **17** |
| Peterson et al. (2003) | P03 | *XMM Newton* | 1 | 10 | - | 11 | **11** |
| Tamura et al. (2004) | T04 | *XMM Newton* | 1 | 16 | 4 | 13 | **17** |
| de Plaa et al. (2007) | dP07 | *XMM Newton* | - | 21 | 4 | 17 | **21** |
| Matsushita (2011) | M11 | *XMM Newton* | - | 26 | 6 | 20 | **26** |
| Mahdavi et al. (2005) | M05 | *XMM Newton* | 7 | 1 | 1 | 7 | **8** |
| Finoguenov et al. (2006b) | F06 | *XMM Newton* | 6 | - | 1 | 5 | **6** |
| Rasmussen & Ponman (2009) | RP09 | *Chandra* | 14 | 1 | 1 | 14 | **15** |
| Sasaki, Matsushita & Sato (2014) | S14 | *Suzaku* | 4 | - | - | 4 | **4** |
| | | | 39 (25) | 120 (54) | 34 (21) | 125 (58) | **159 (79)** |

**Table 1.** The observational samples we consider in our dataset. The number of usable $T$ and $Z_{\rm Fe}$ measurements from each sample for groups & clusters and NCC & CC are shown. Counts in parenthesis give the total number of *unique* systems considered.

- Group/cluster divide at log($kT_{500}$/keV)=0.1
- CC/NCC divided by central cooling time = 7.6 Gyr, or mass deposition rate consistent with zero, or (for groups) flat slope for central temperature profile.

# Observations – homogenisation procedure

- Hubble parameter, $h_{73}$=1.
- Solar abundances normalised to Grevesse & Sauval (1998).
- All measurements scaled to $R_{500c}$.
- Standard temperature and metallicity profiles

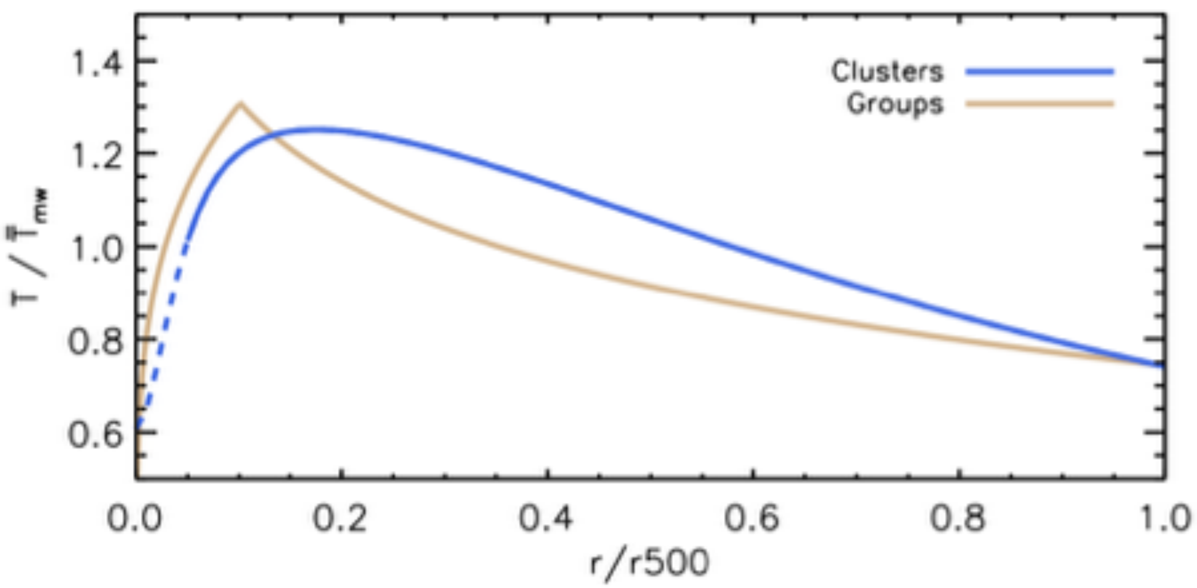



**Figure 1.** The default temperature profiles assumed for clusters and groups, taken from Vikhlinin et al. (2006) and Rasmussen & Ponman (2007), respectively

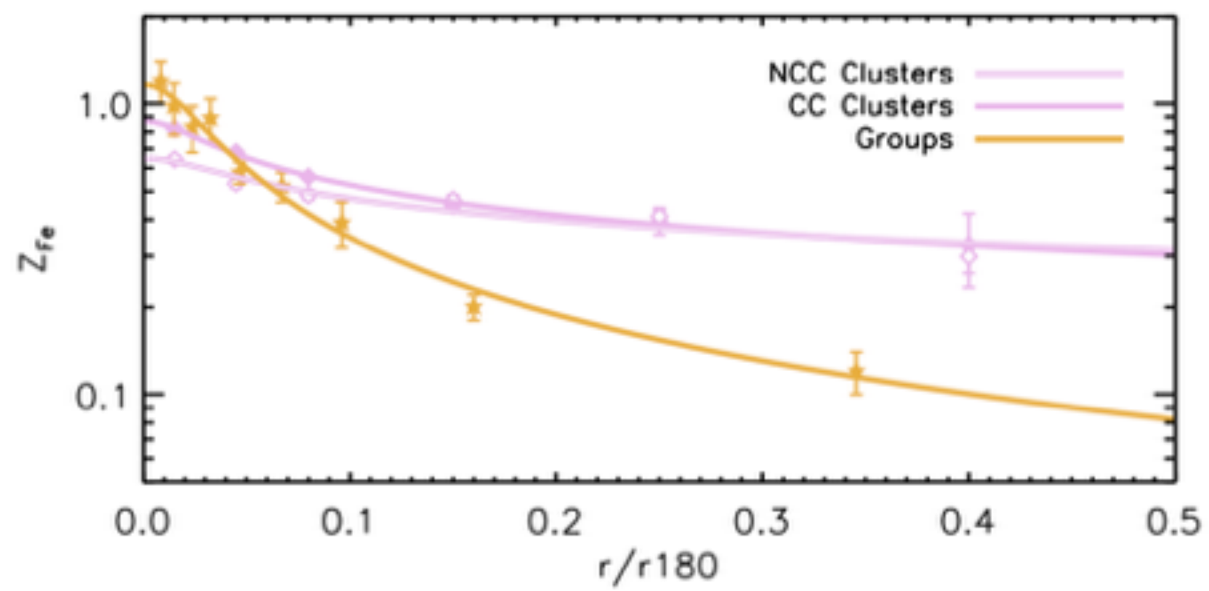



**Figure 2.** The default iron abundance profiles assumed for NCC clusters, CC clusters, and groups

using fits to data from Matsushita (2011)

# Observations – comparison of temperature studies

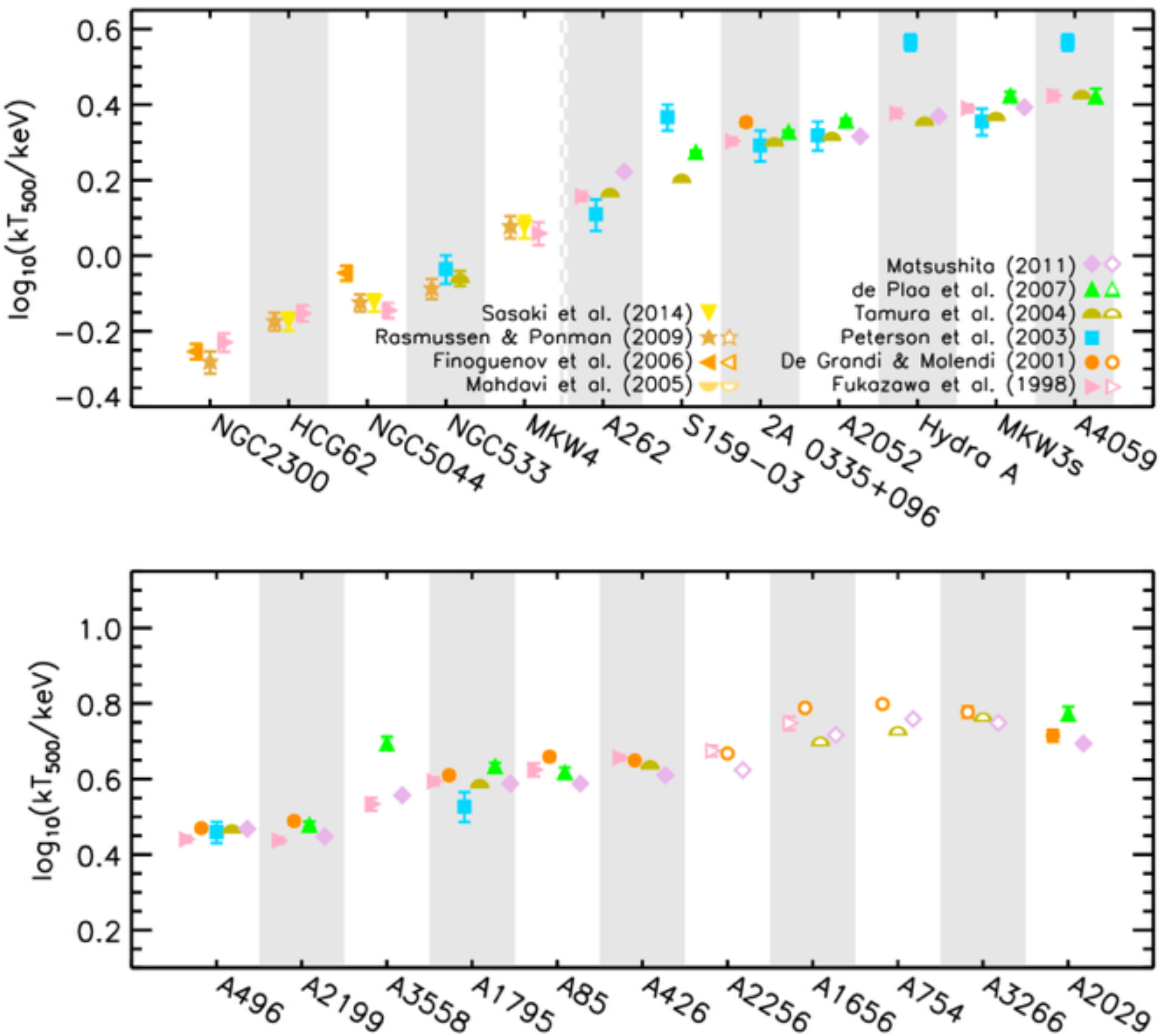



**Figure 4.** A comparison between the values of $kT_{500}$ derived for the same systems from different studies. Only systems with three or more separate estimates of $T_{500}$ and $\bar{Z}_{\mathrm{Fe},500}$ are shown. Objects are ordered from left to right by ICM temperature. The dashed vertical line in the top panel separates groups from clusters, as discussed in §2.1.

# Observations – comparison of metallicity studies

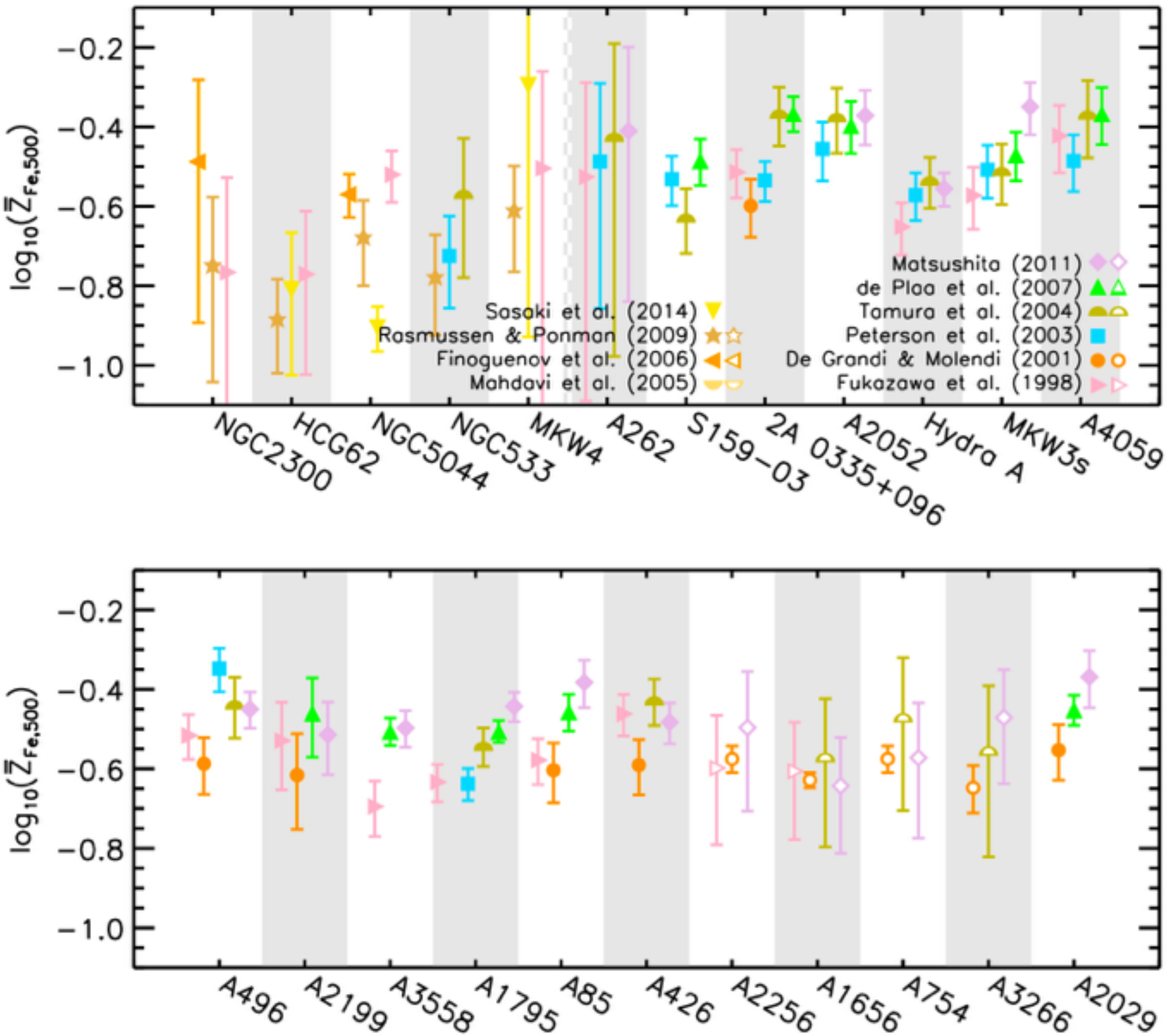



**Figure 5.** A comparison between the values of $\bar{Z}_{\mathrm{Fe},500}$ derived for the same systems from different studies. As in Fig. 4, only systems with three or more separate estimates of $T_{500}$ and $\bar{Z}_{\mathrm{Fe},500}$ are shown. Objects are ordered from left to right by ICM temperature. The dashed vertical line in the top panel separates groups from clusters, as discussed in §2.1.

# Observations – $kT_{500}$ - $Z_{Fe,500}$ relation

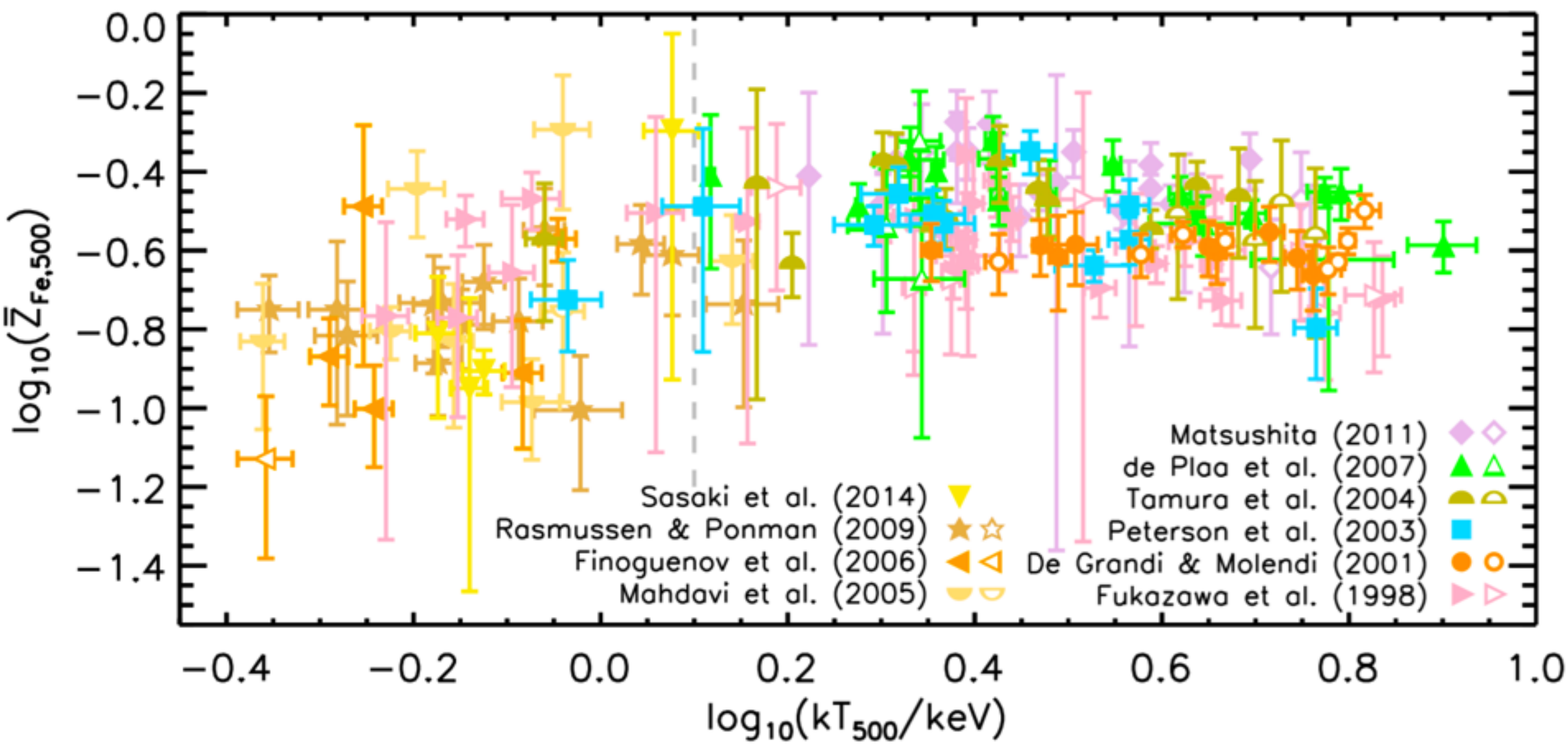



**Figure 3.** The $kT_{500}$-$\bar{Z}_{Fe,500}$ relation for our whole dataset of observed local groups and clusters. Filled symbols indicate CC systems and open symbols indicate NCC systems. The grey vertical line separates groups and clusters at $\log(kT_{500}/\text{keV}) = 0.1$, as discussed in §2.1. There is a strong $T$-$Z_{Fe}$ correlation for groups, albeit with a large scatter, and a weak $T$-$Z_{Fe}$ anti-correlation for clusters, with a small scatter of only 0.10 dex.

# The L-Galaxies SAM

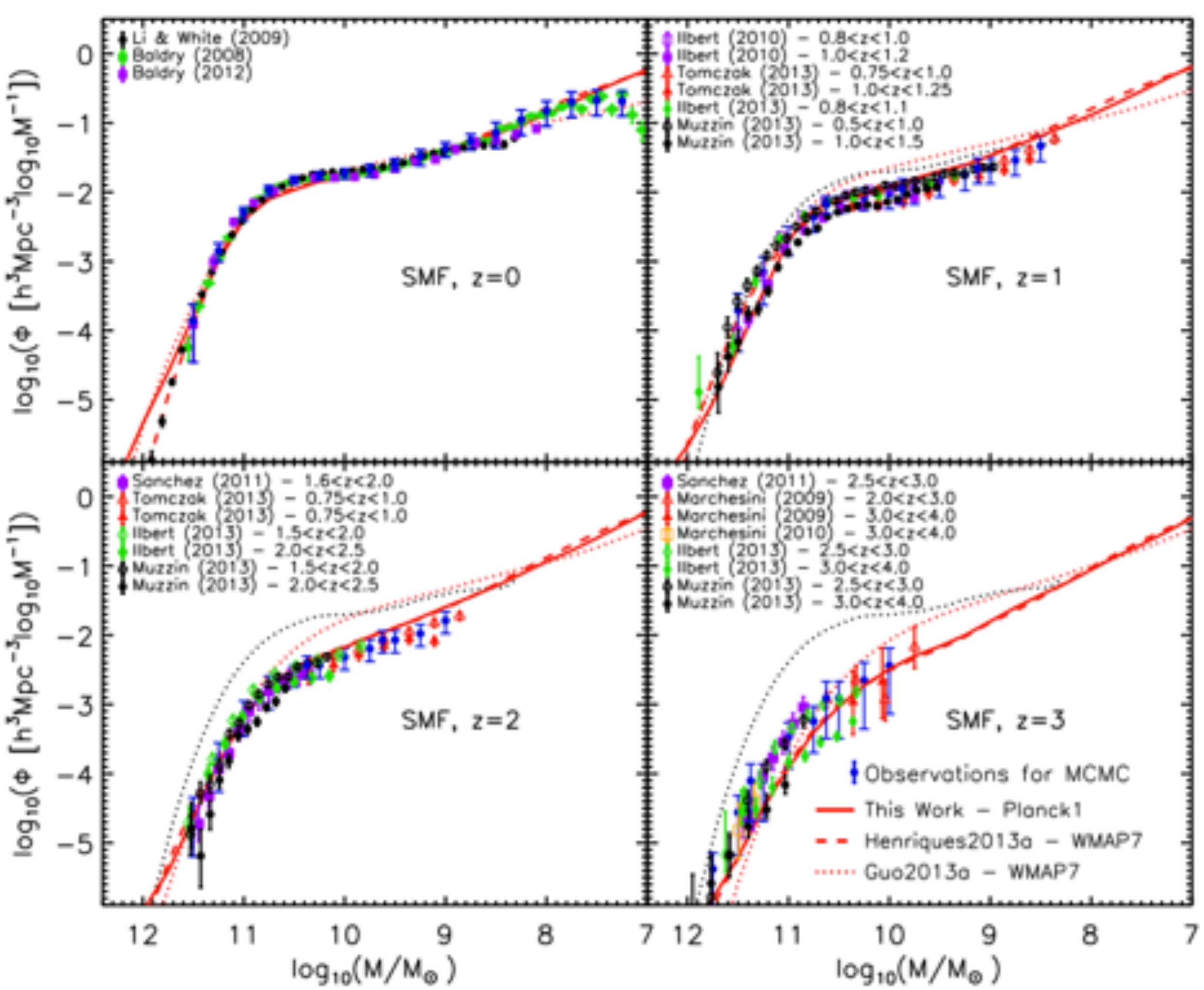
Henriques etal, 2015, MNRAS, 451, 2263

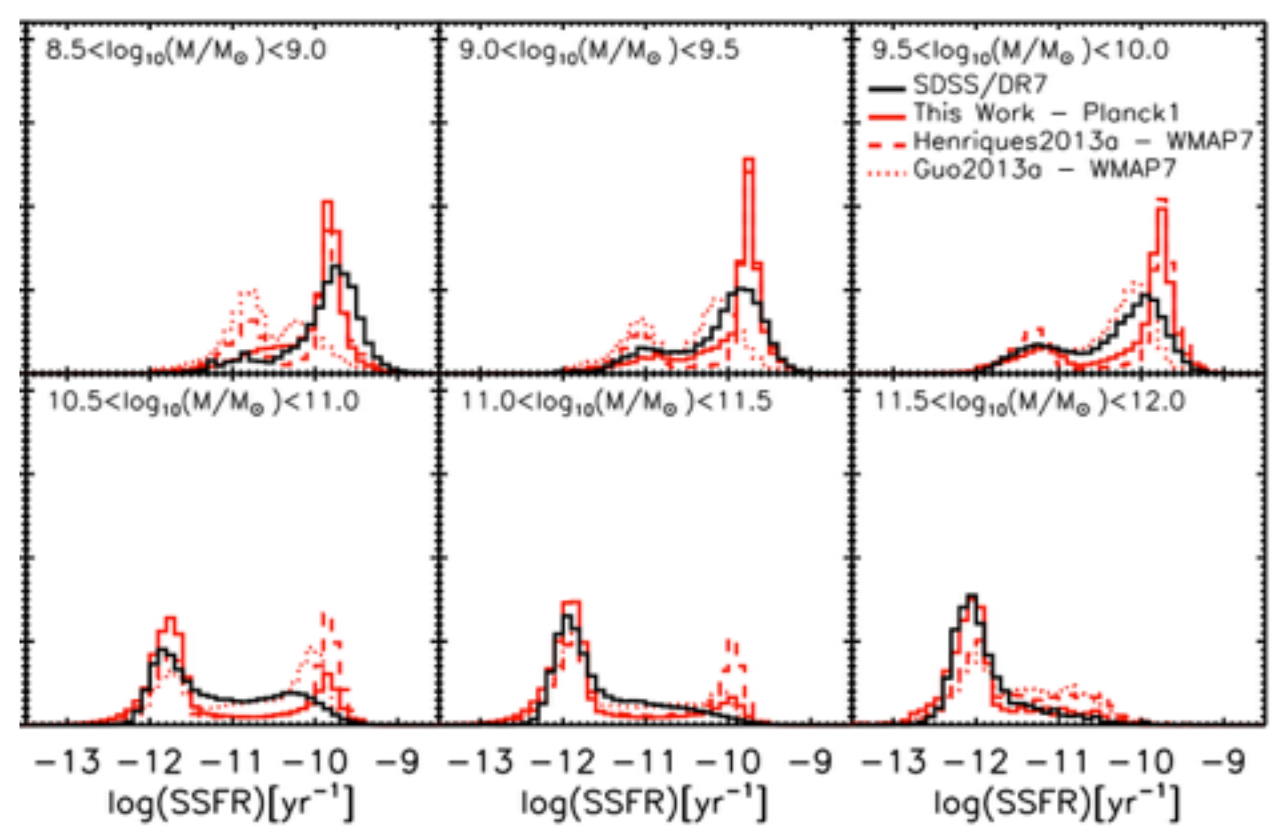
A **self-consistent** model of galaxy formation across cosmic time:

- A semi-analytic model built on a dark matter merger tree
- Merging + astrophysics throughout past history affect the present

Henriques etal, 2015, MNRAS, 451, 2263

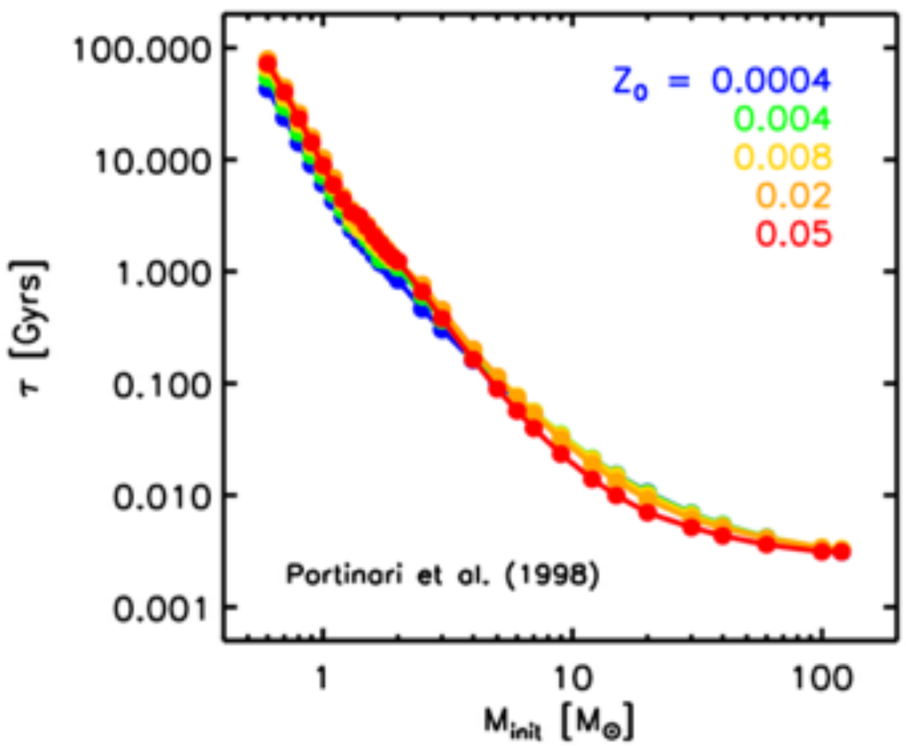
- **Use a minimal set of fundamental quantities as constraints:**
  - mass functions (z=0, 1, 2, 3)
  - red fractions (z=0.1, 0.4, 1, 2, 3)
- **Use MCMC to determine the best-fit parameter set:**
  - parameter correlations/degeneracies can give insight into the astrophysics and help to simplify the model

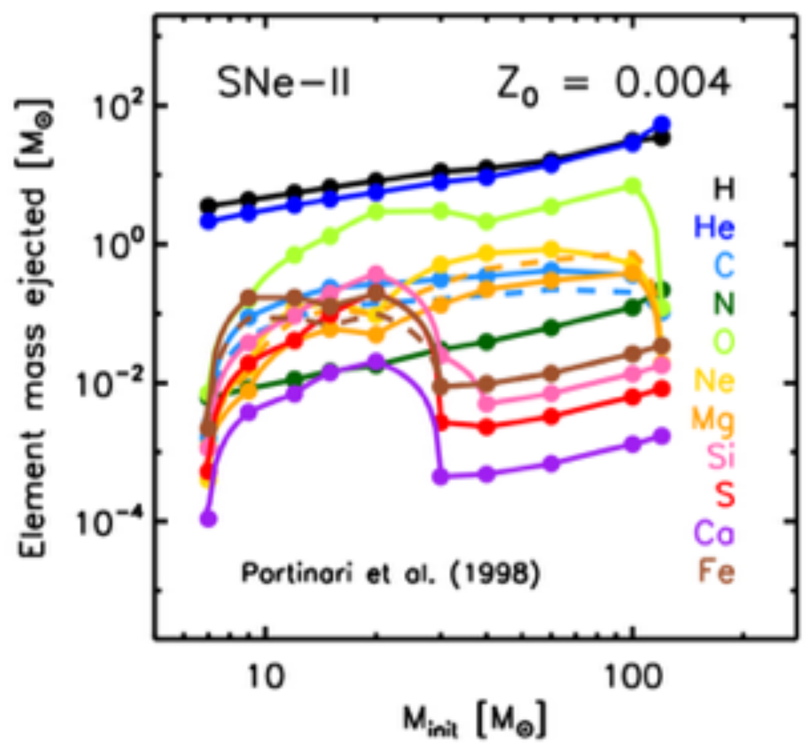


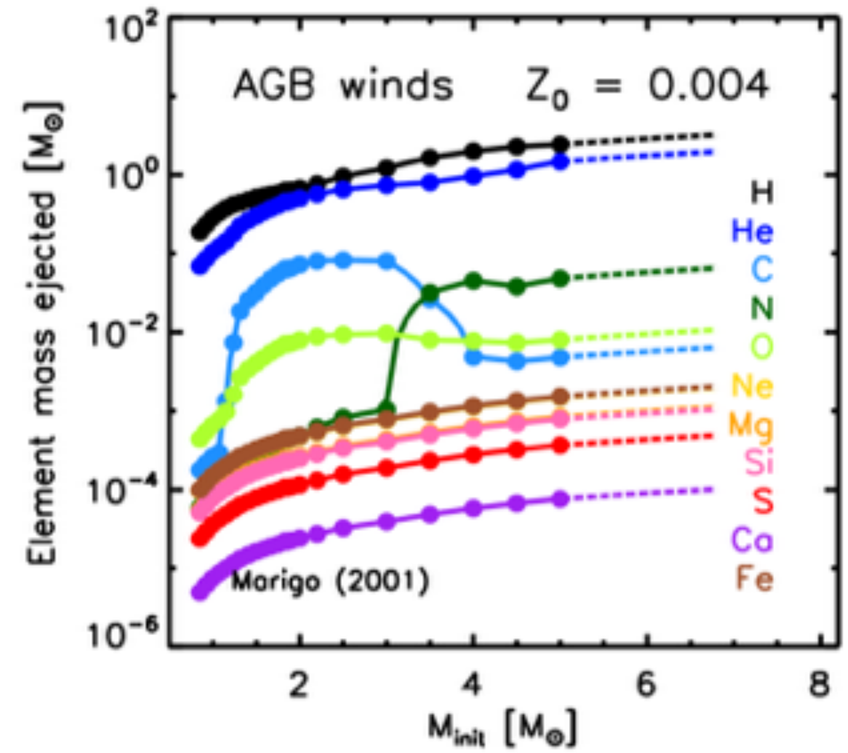



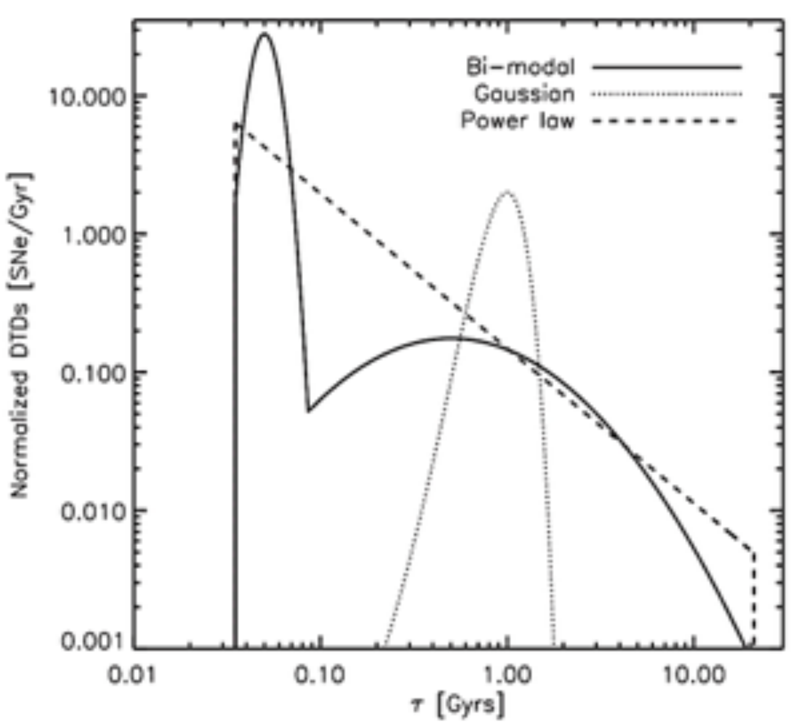
# The L-Galaxies SAM – metallicity

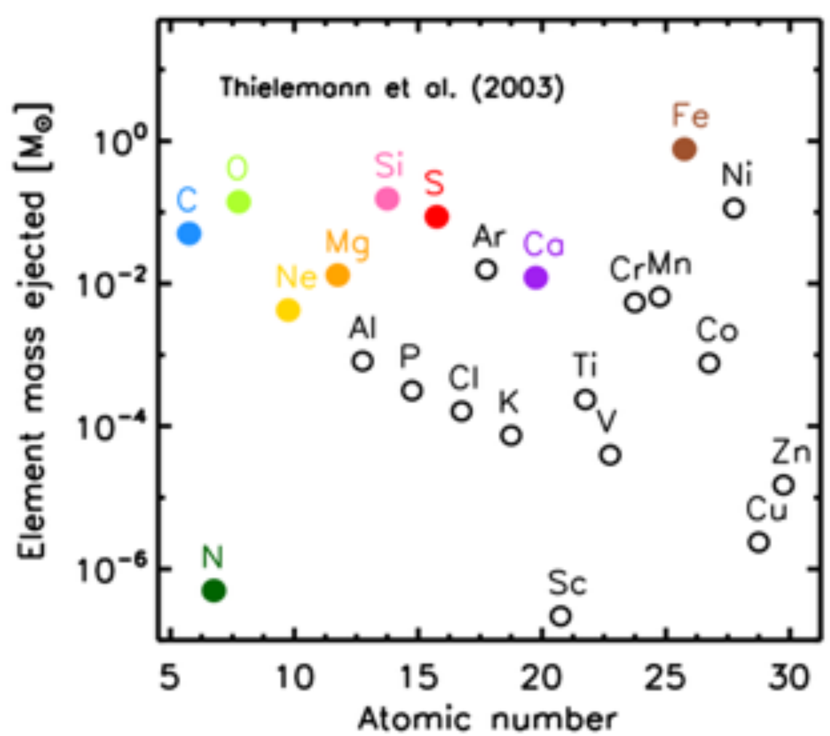
Yates etal, 2013, MNRAS, 435, 3500

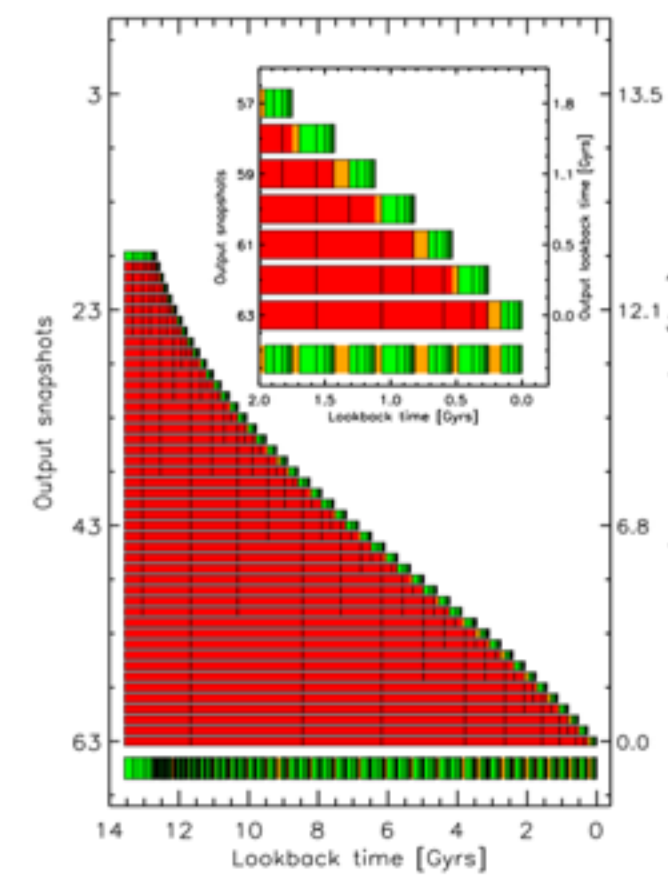


# The L-Galaxies SAM – metallicity results

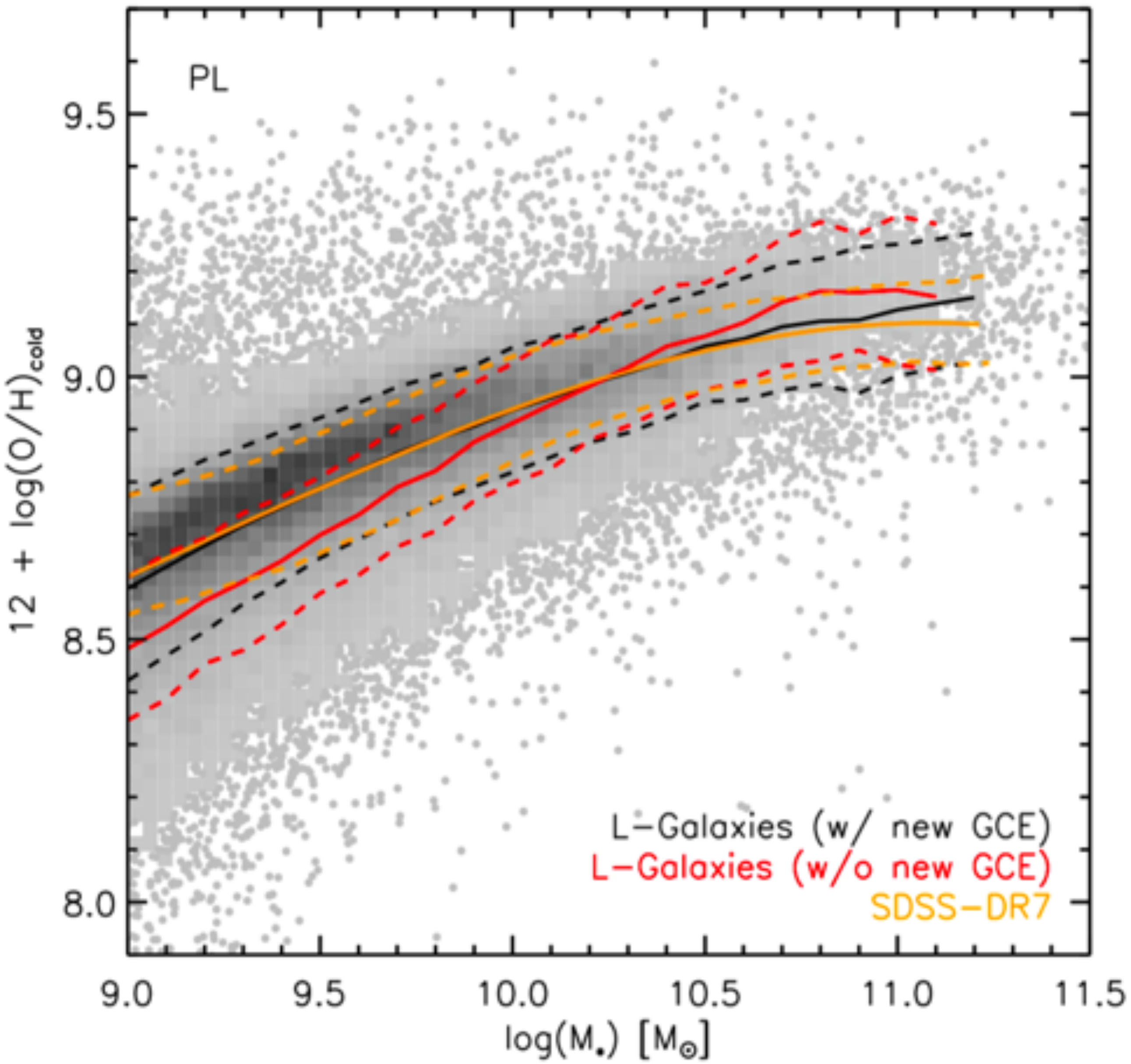



**Figure 7.** The $M_*$–$Z_{\rm cold}$ relation (where $Z_{\rm cold} = 12 + \log(N_{\rm O}/N_{\rm H})$) for L-Galaxies with the new GCE implementation and using a power-law SN-Ia DTD (points and black lines). This relation is compared to that of L-Galaxies prior to the new GCE implementation (red lines), and a fit to the observed $M_*$–$Z_{\rm g}$ relation for emission-line galaxies from the SDSS-DR7 (orange lines) by Yates, Kauffmann & Guo (2012).

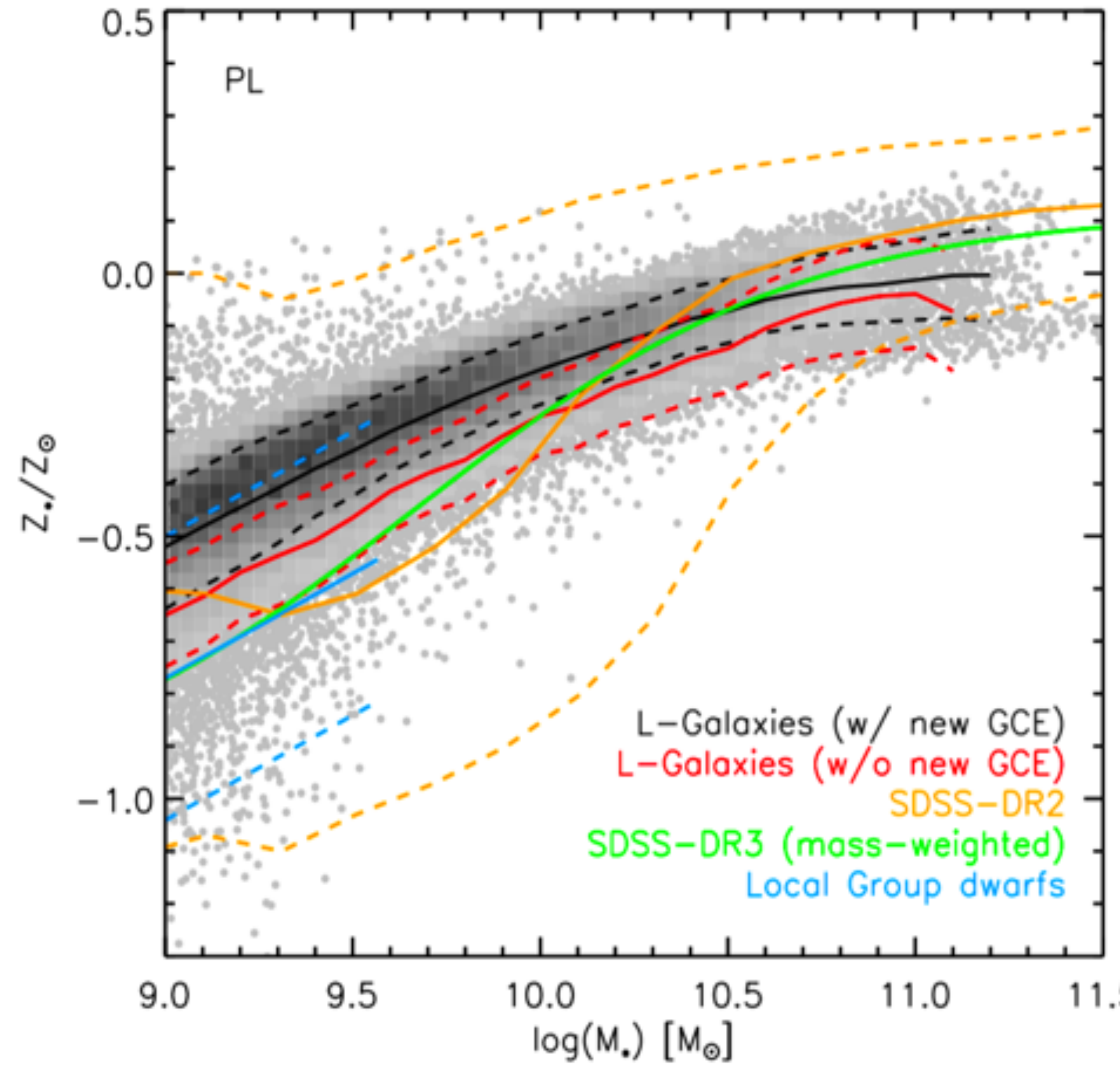
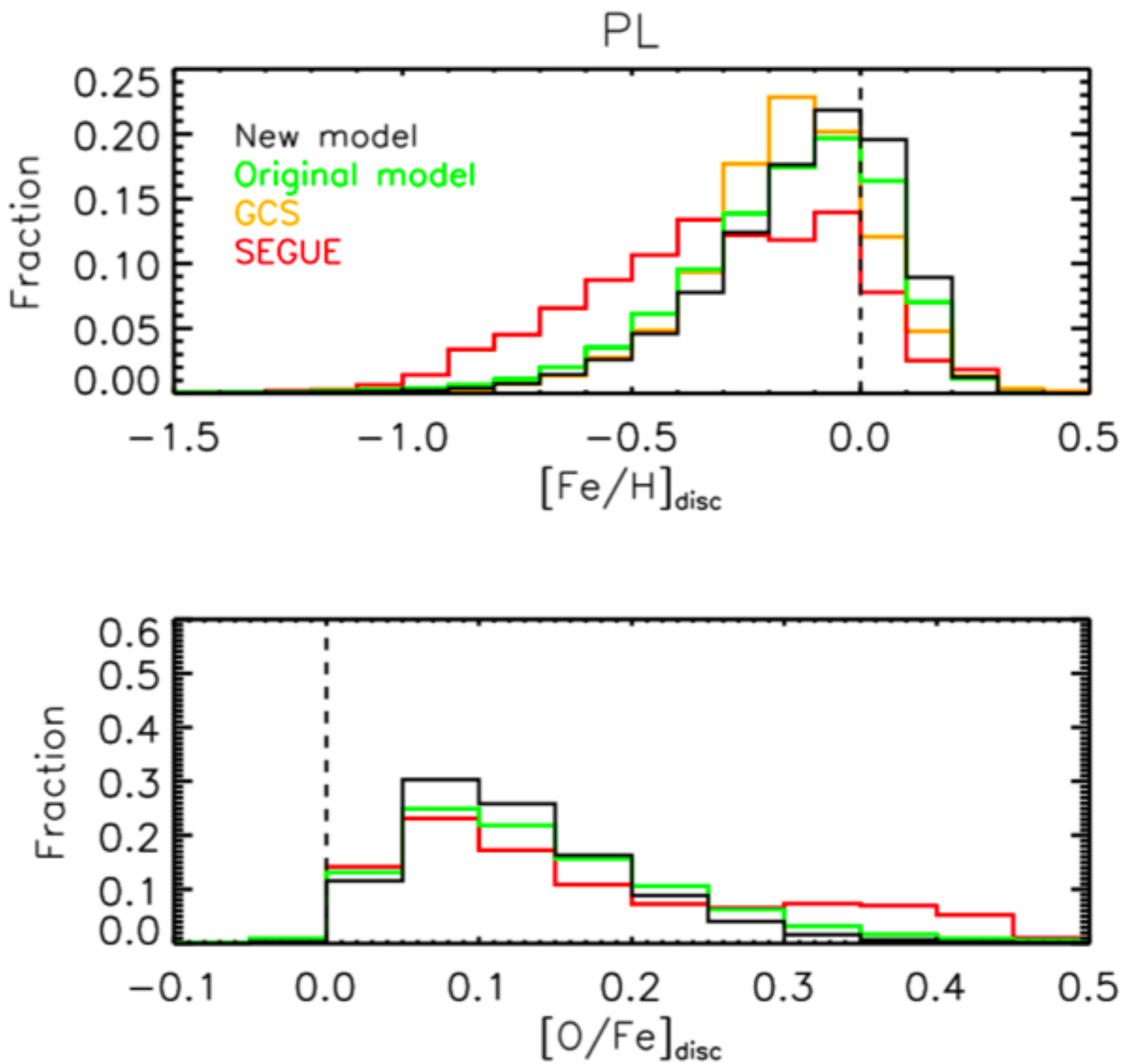



**Figure 8.** The $M_*$–$Z_*$ relation (where $Z_* = \log(M_{*,Z}/M_*/0.02)$) for L-Galaxies with the new GCE implementation and using a power-law SN-Ia DTD (points and black lines). This relation is compared to that of L-Galaxies prior to the new GCE implementation (red lines), the observed relation from the SDSS-DR2 (orange lines) by Gallazzi et al. (2005), a fit to the mass-weighted relation from the SDSS-DR3 (green line) by Panter et al. (2008) and to a set of Local Group dwarf galaxies (blue lines) by Woo, Courteau & Dekel (2008).

# The L-Galaxies SAM – metallicity of Milky Way disks



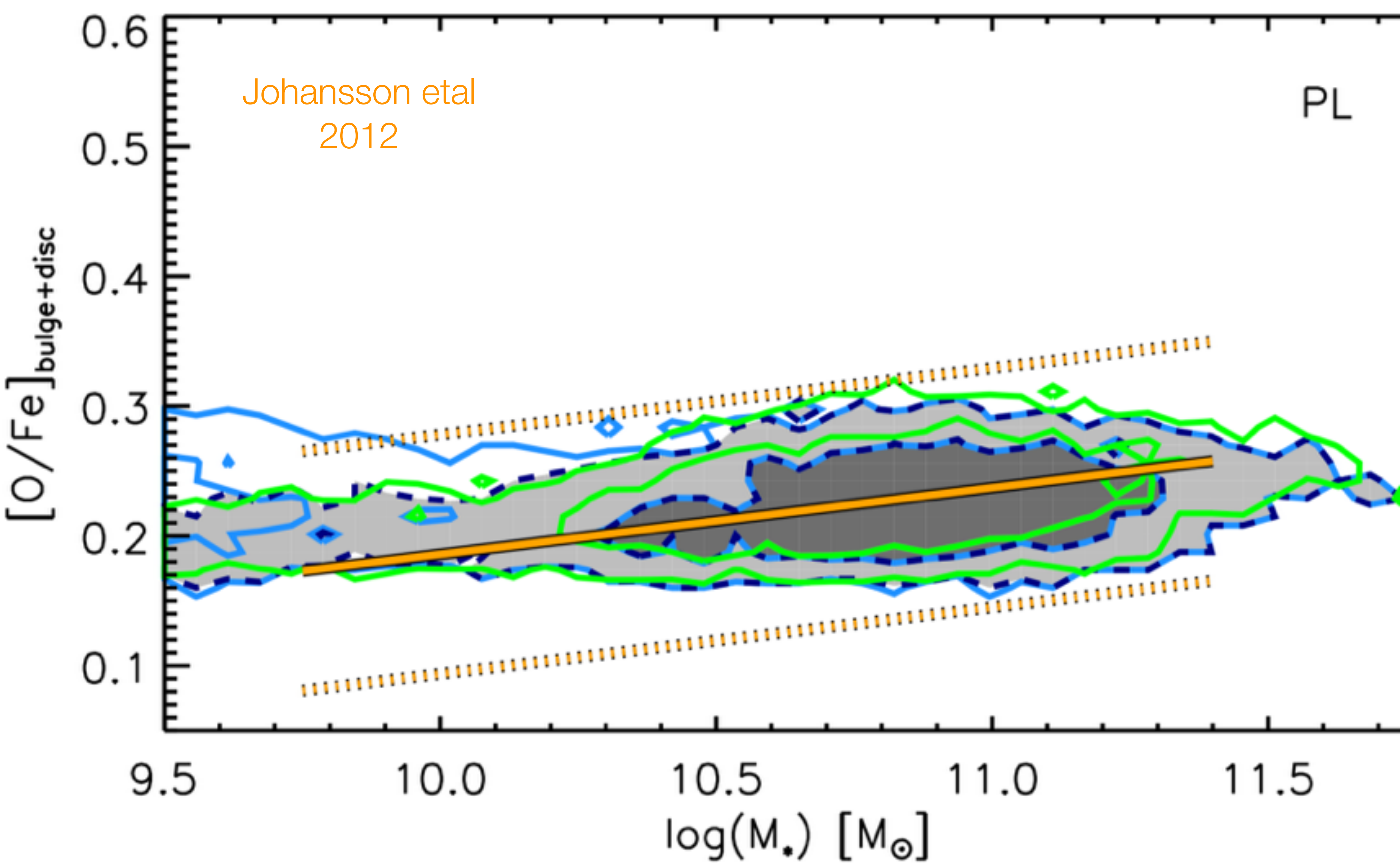

Iron content

GCS - Holmberg etal, 2009

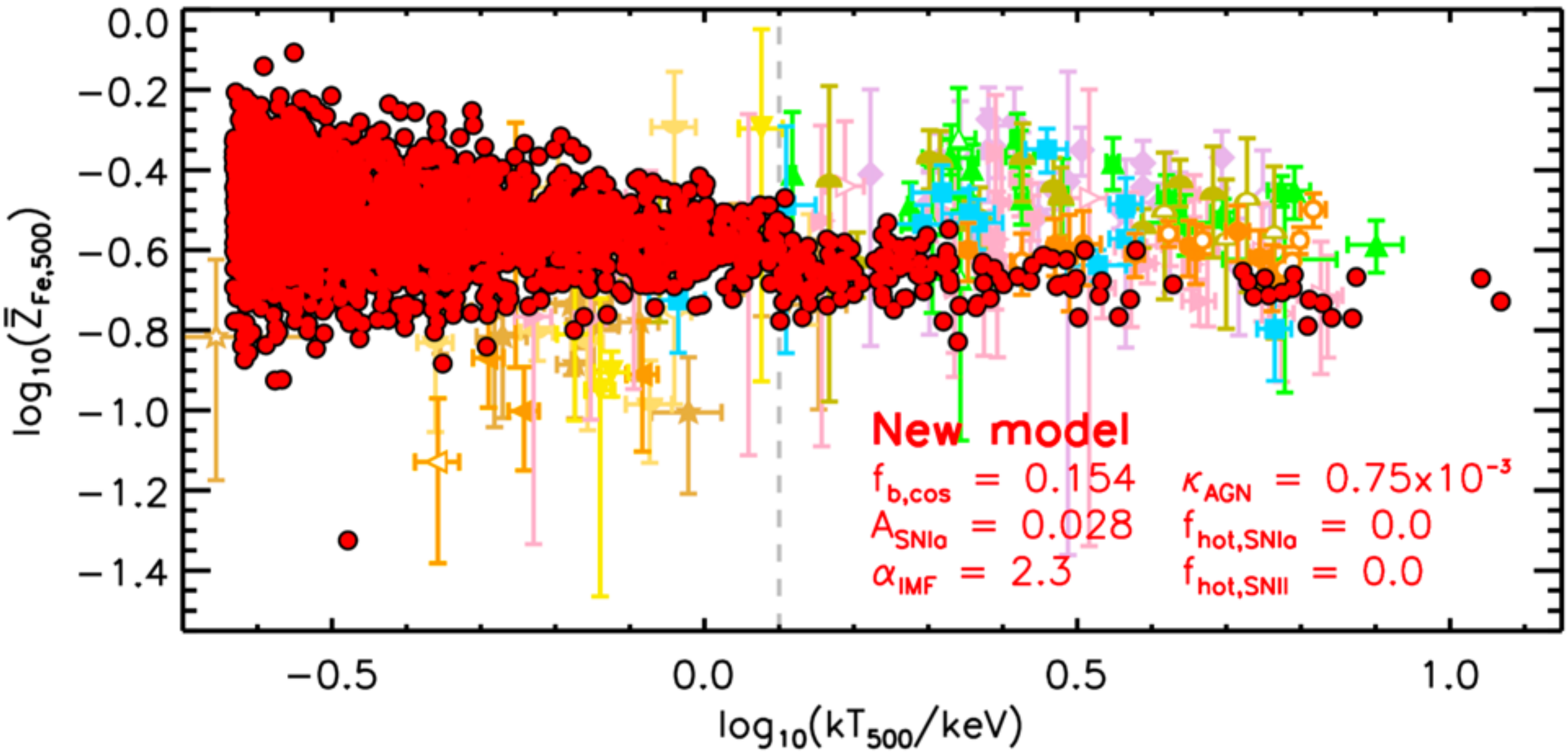
SEGUE - Bovy etal 2012a,b

Alpha-enhancement

# The L-Galaxies SAM – oxygen enhancement of ellipticals

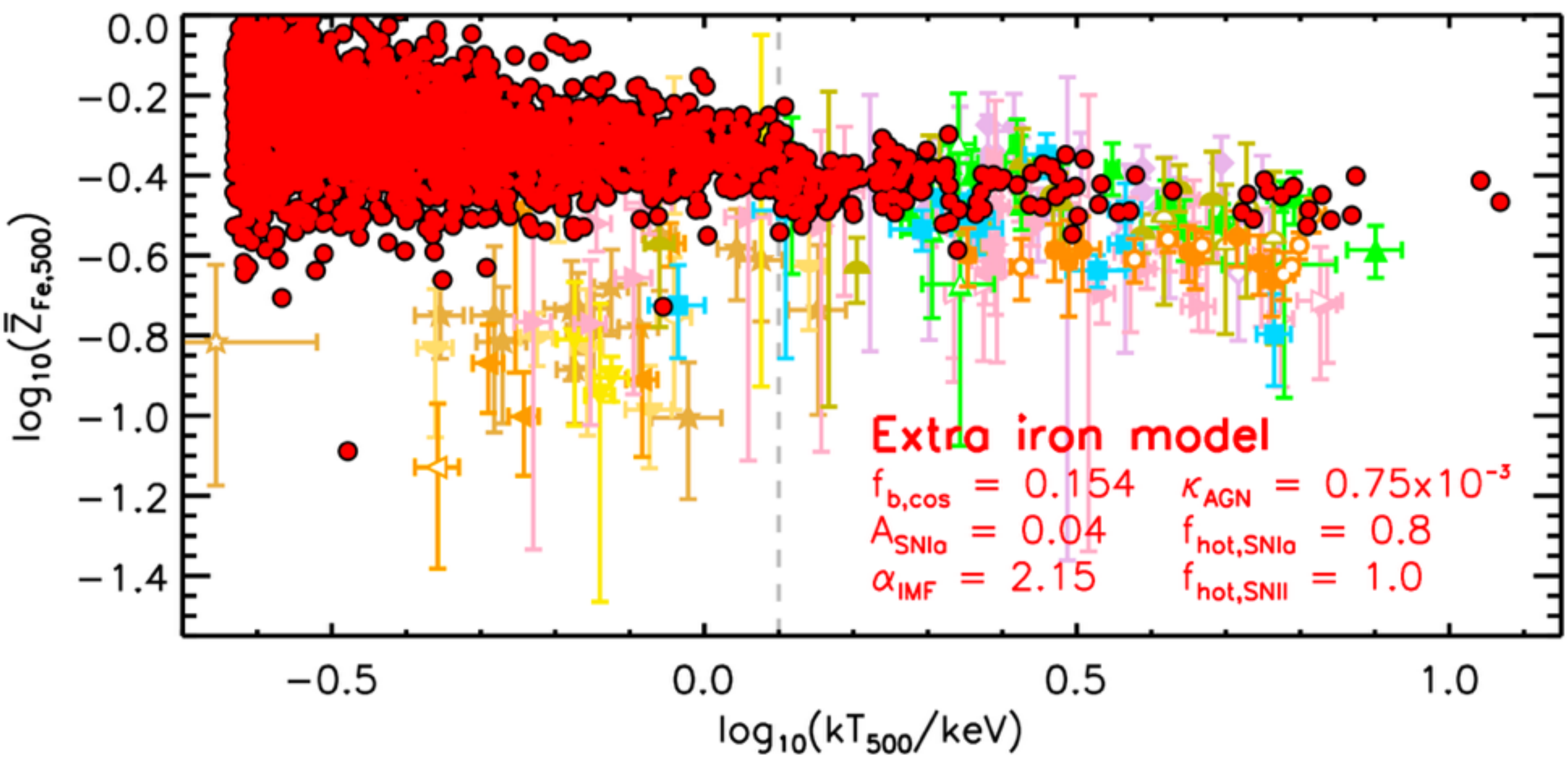


# Obs/SAM comparison – iron fractions

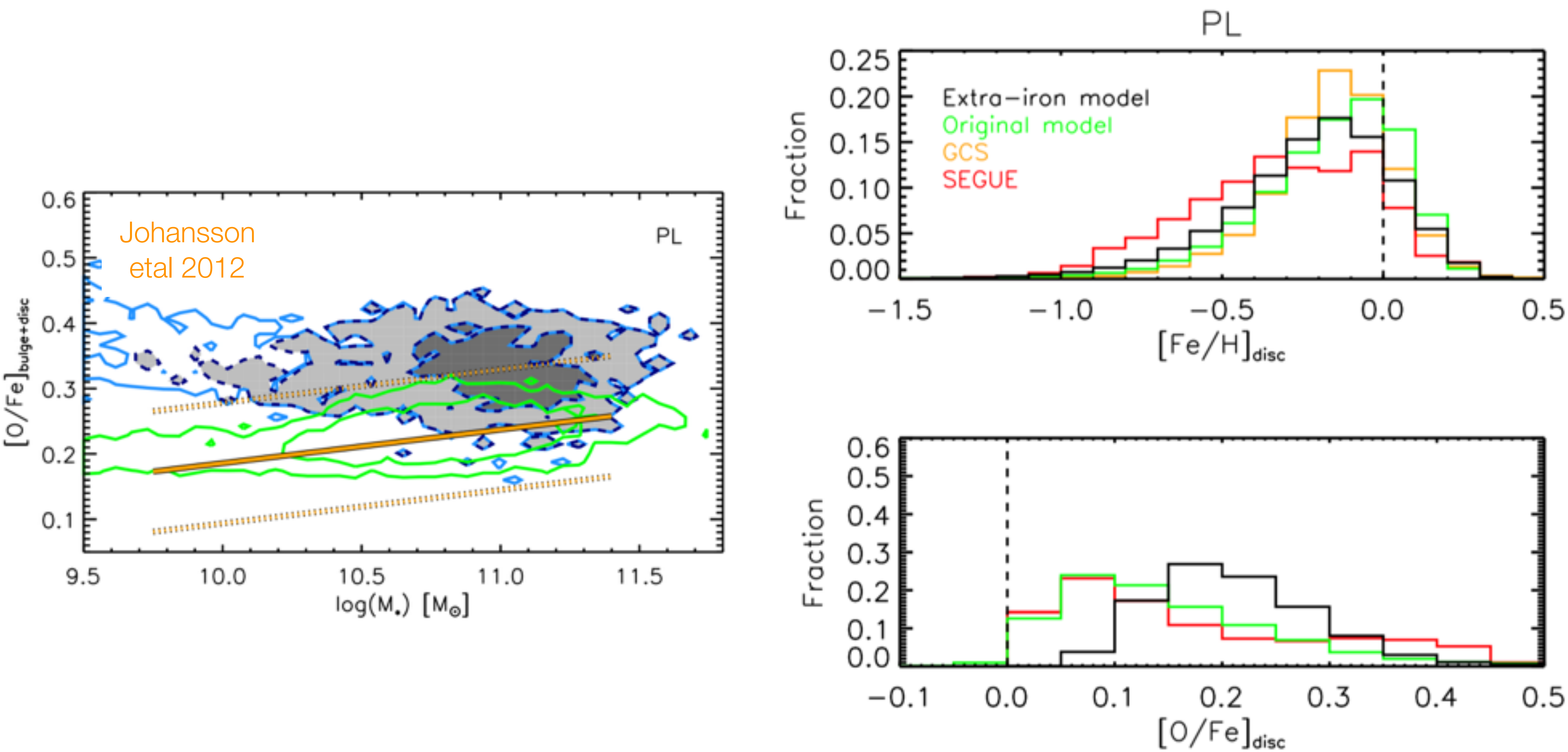


# Obs/SAM comparison – extra iron model

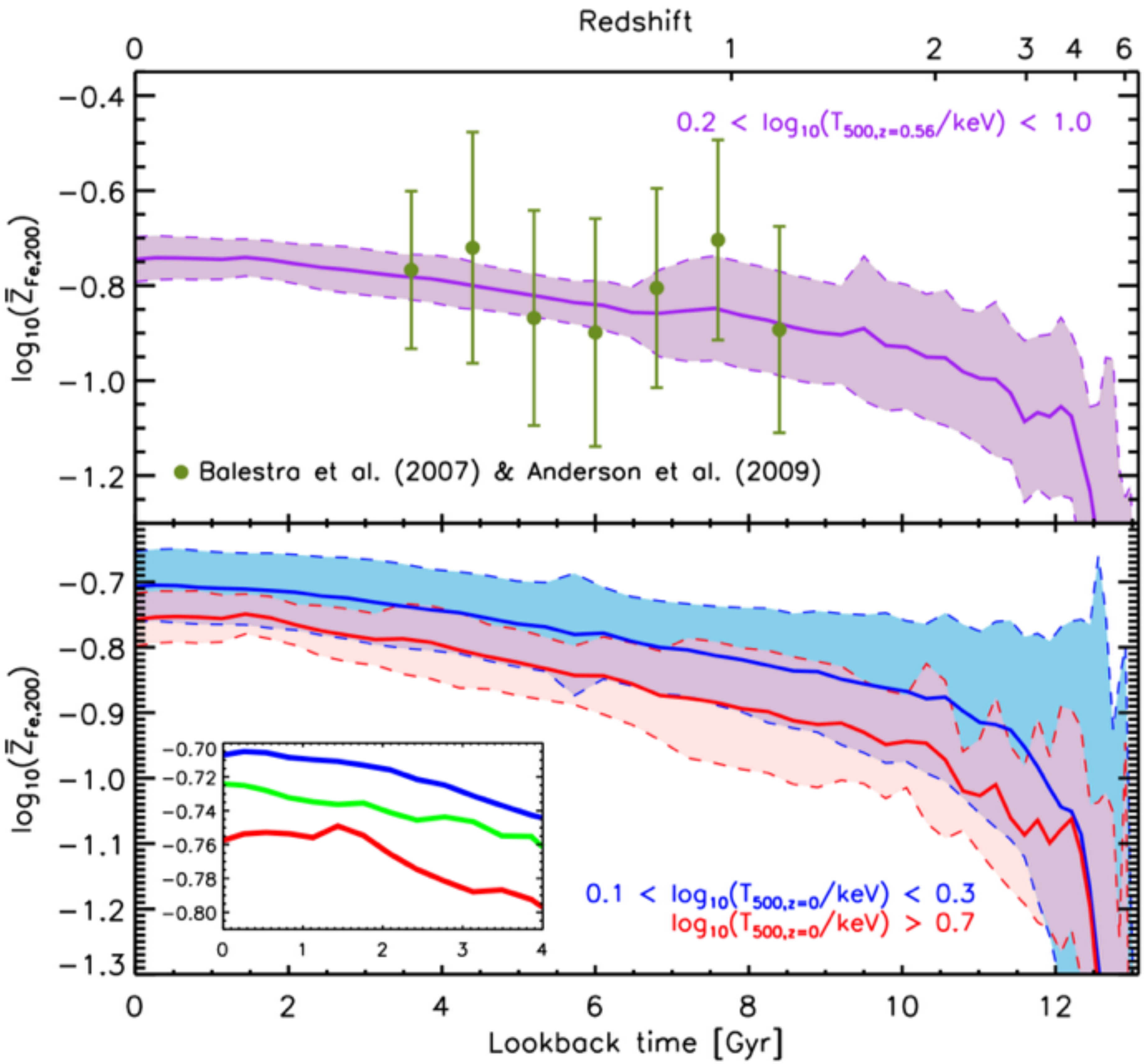
- Flatter IMF slope; greater fraction of binaries: increase Sn1a fraction by 50 per cent.
- 100% of SnIa & 80% SnII pollute ICM directly.



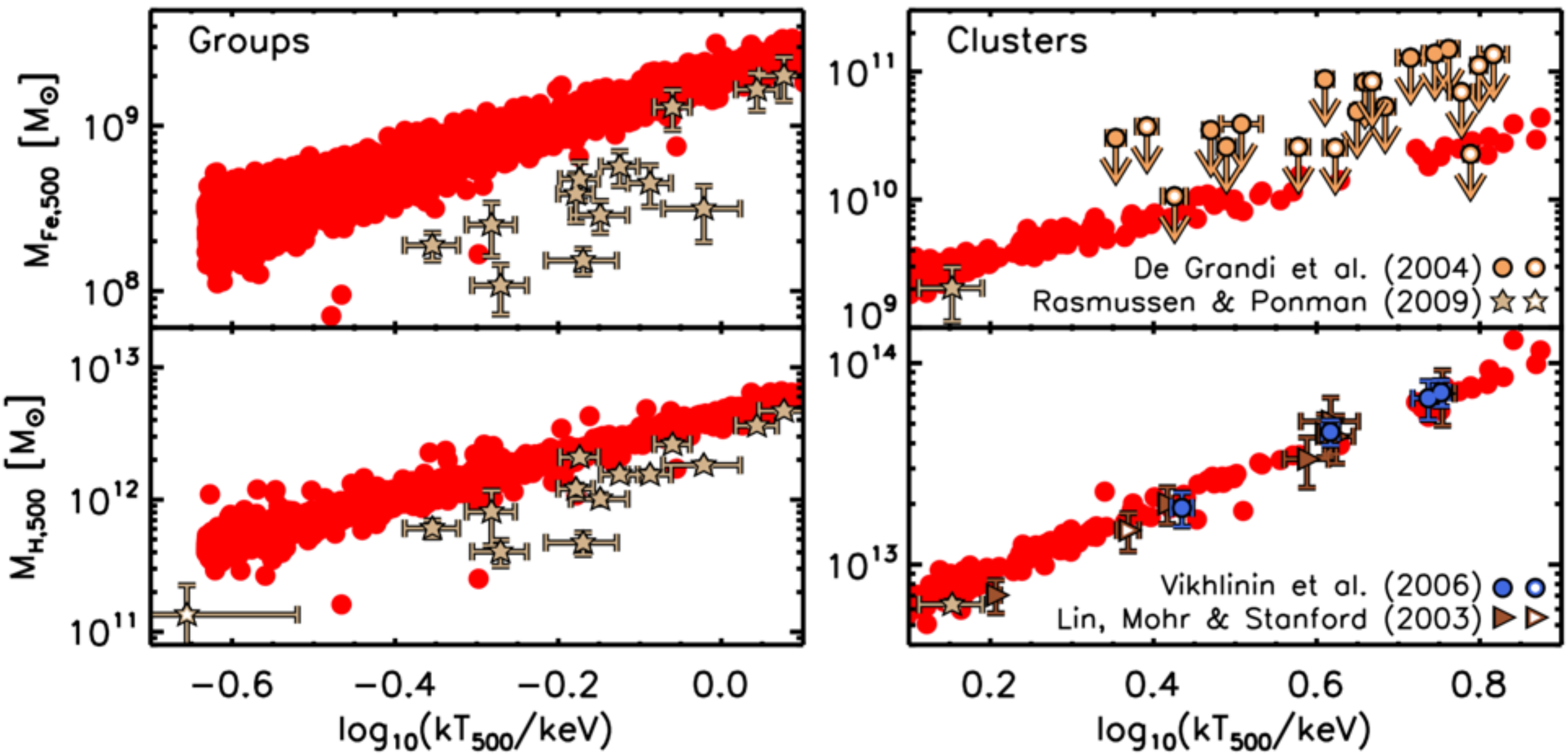
# The L-Galaxies SAM – extra-iron model



# Obs/SAM comparison – iron fraction evolution

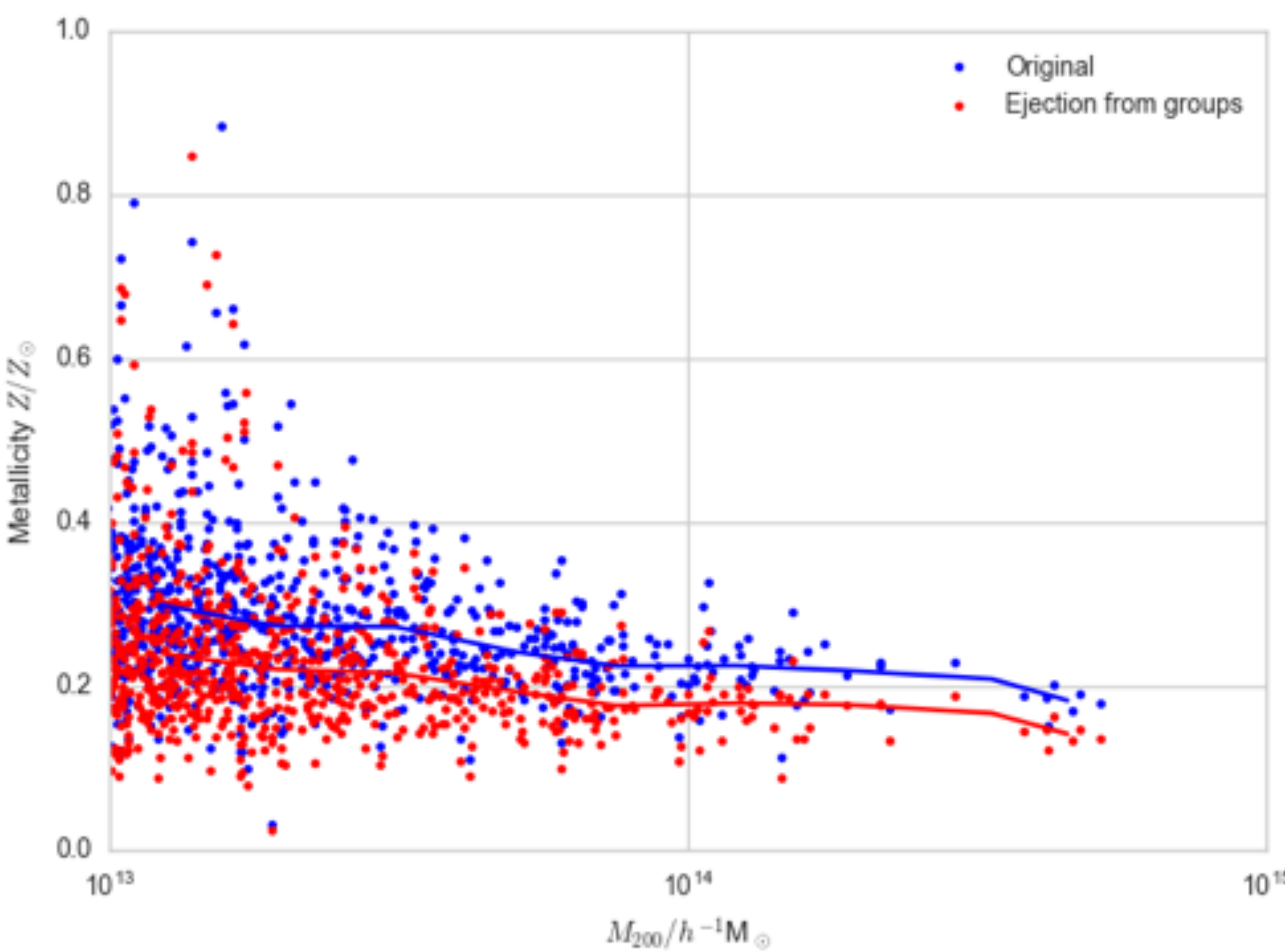


# Obs/SAM comparison – iron masses

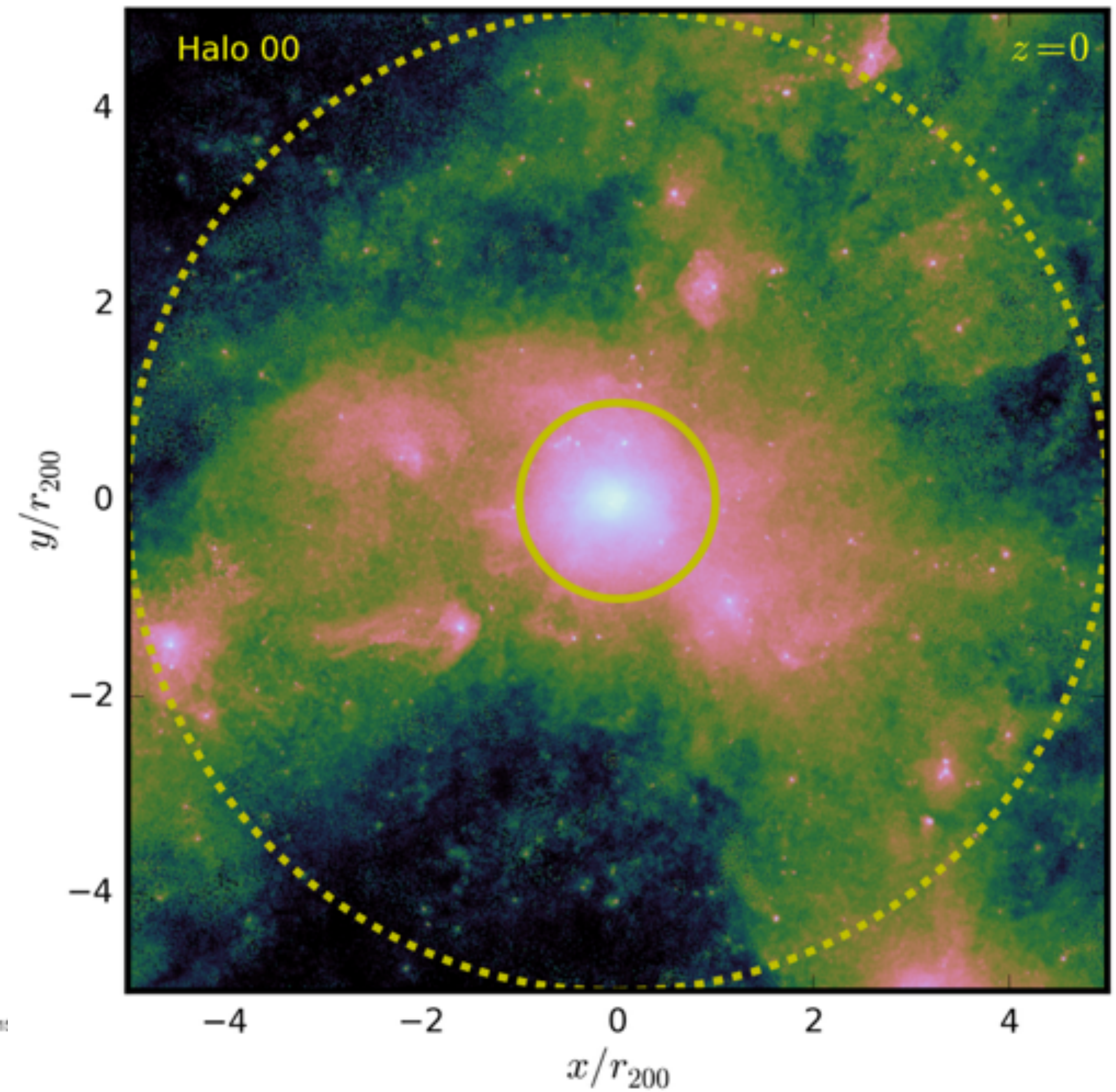


# Future work

Ejection of gas by AGN in the L-Galaxies SAM
Benoit Fournier



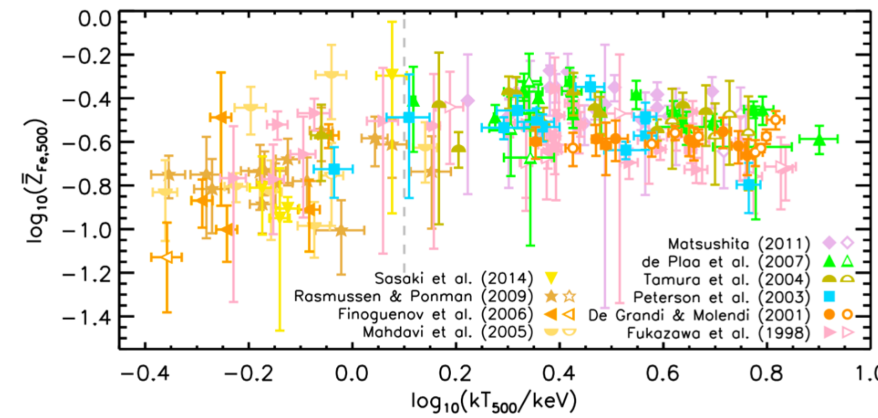

C-Eagle cluster resimulations - David Barnes



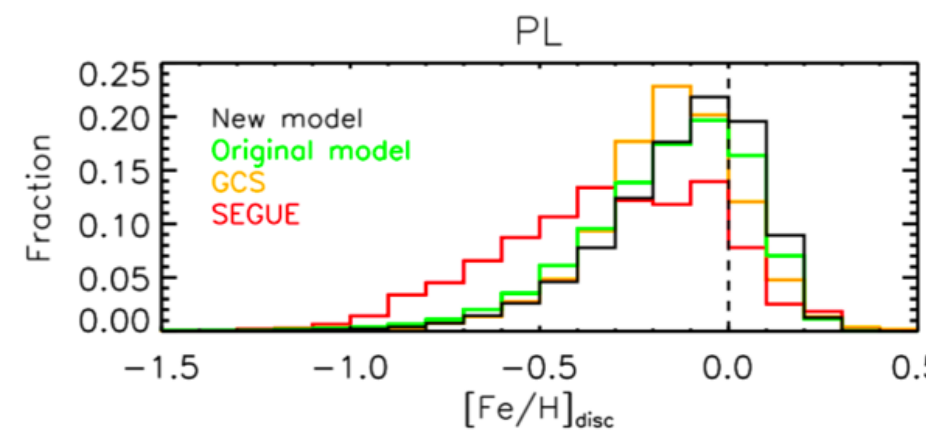
# Conclusions

Paper: Yates, Thomas & Henriques, 2016, submitted to MNRAS, arXiv:1603.04858

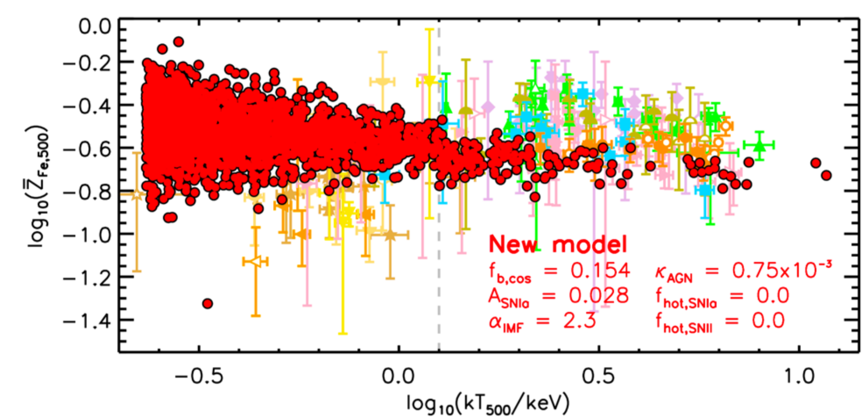
- We have gathered a homogeneous sample of metallicity measurements for groups and clusters, available at robyatesastro.moonfruit.com/data/




- The L-Galaxies semi-analytic model accurately reproduces the metallicity content of low-redshift galaxies…




- …and in the highest and lowest-mass clusters, (but not those of intermediate mass – this is at least partly due to measurement biases in the observations)…




- However, there is a large excess metallicity in galaxy groups – the solution may lie in the need for AGN to expel large quantities of iron from group-sized halos.