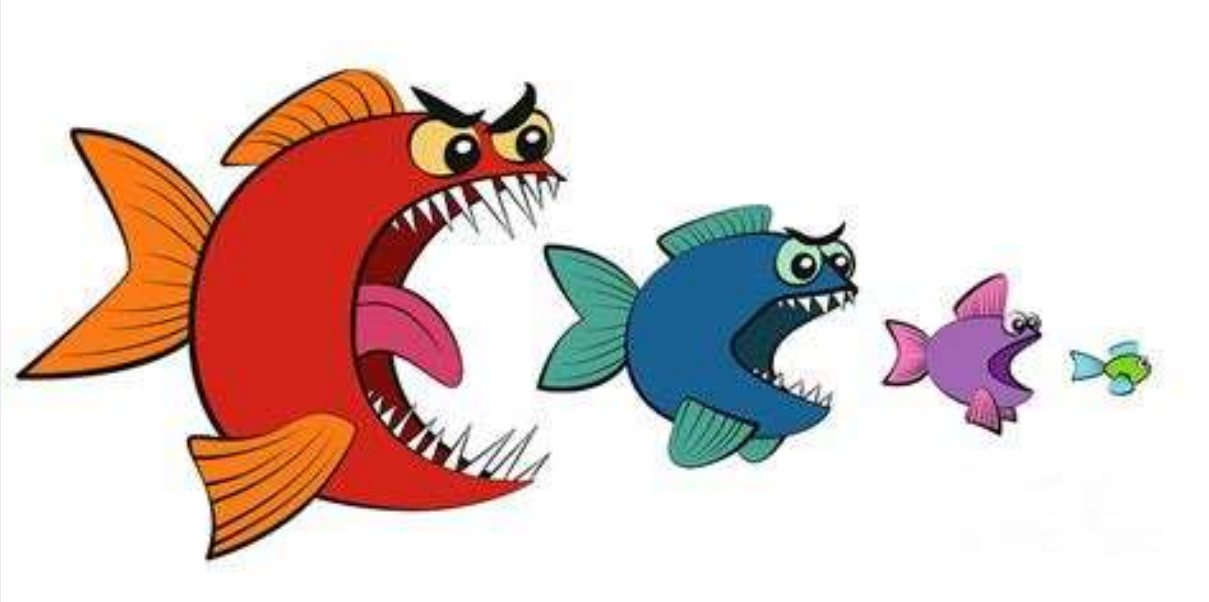
Apex accretors and the partition of metals in the Universe

Based on SM+23 subm.



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Introduction

Provide a coherent & comprehensive explanation for many of the properties of groups and clusters that relate to metals.

In doing so we gained some understanding of the metal content of other key elements in the hierarchical structure of the Universe.

Summary

Clusters

- Bulk of metals is in the ICM not in the stars
- The small scatter in metal abundance arises from the averaging of hundreds of independent enrichment events
- Lack of redshift evolution in cluster outskirt abundance is explained by self-similarity of star formation over a broad redshift range.
- The Fe abundance vs entropy anti-correlation
- The flat abundance profile in outskirts
- Lack of abundance ratio differences between core and circum-core regions
- Fe conundrum

Large scale structure

- Gas not bound to halos must have a metal abundance similar to that of the ICM
- Less than a 1/3 of the Fe in the Universe is locked in stars; a comparable amount is found in gas in groups/clusters and about 3/5 is in a tenuous warm/hot gaseous medium in or between galaxies

Fe Yield in Clusters

Defined as the ratio between the total Fe mass and the gas mass that went into stars

$$\Upsilon_{Fe} = \frac{M_{Fe}^{*} + M_{Fe}^{ICM}}{M_{*}(0)}$$

$$M_{*}(0) = r_{o}\, M_{*}$$

$$M_{Fe}^{*} = Z_{Fe}^{*}\, M_{*}$$

$$M_{Fe}^{ICM} = Z_{Fe}^{ICM}\, M_{ICM}$$

$$\Upsilon_{Fe} = \frac{Z_{Fe}^{*}}{r_{o}}\left(1 + \frac{Z_{Fe}^{ICM}}{Z_{Fe}^{*}}\frac{M_{ICM}}{M_{*}}\right)$$

Fe Yield in Clusters

Defined as the ratio between the total Fe mass and the gas mass that went into stars

Solve it for the ICM abundance

make a few substitutions

$$f_b = \frac{M_b}{M_h}$$ cosmic baryon fraction

$$f_* = \frac{M_*}{M_h}$$ stellar mass fraction

$$f_{gas} = \frac{M_{ICM}}{M_h}$$ gas fraction

$$f_b \approx f_{gas} + f_*$$

$$Z_{Fe}^{ICM} = (r_o \Upsilon_{Fe} - Z_{Fe}^{*})\left(\frac{M_*}{M_{gas}}\right)$$

$$Z_{Fe}^{ICM} = (r_o \Upsilon_{Fe} - Z_{Fe}^{*})\left(\frac{f_*}{f_b}\,\frac{1}{1 - {f_*}/{f_b}}\right)$$

$$\Upsilon_{Fe} = \frac{Z_{Fe}^{*}}{r_o}\left(1 + \frac{Z_{Fe}^{ICM}}{Z_{Fe}^{*}}\frac{M_{ICM}}{M_*}\right)$$

Connecting Fe abundance to stellar forming halo properties

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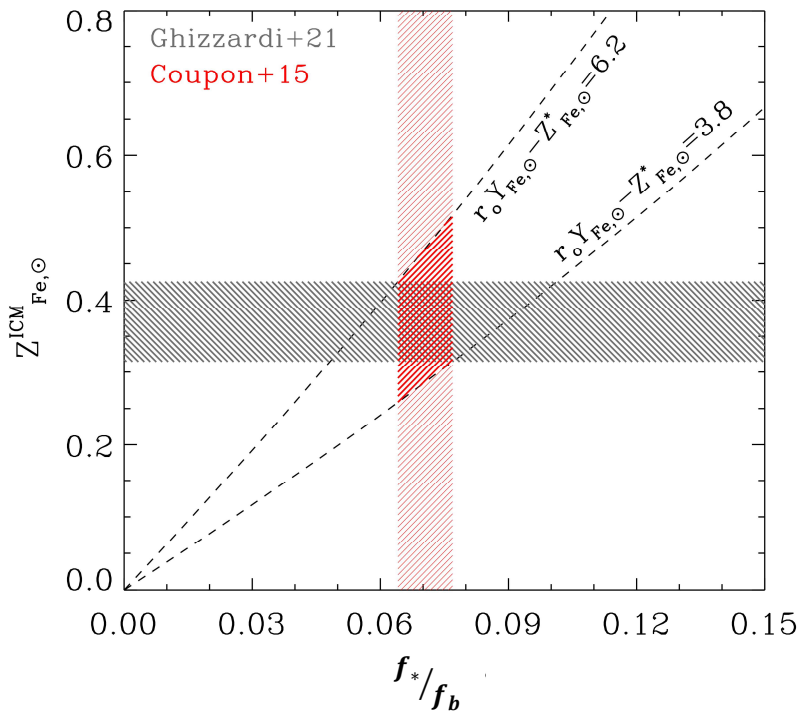
$$Z_{Fe}^{ICM} = \left(r_o \Upsilon_{Fe} - Z_{Fe}^{*}\right)\left(\frac{f_*}{f_b}\,\frac{1}{1 - f_*/f_b}\right)$$

Derive "conversion" factor

$$3.8 < \left(r_o \Upsilon_{Fe,\odot} - Z_{Fe,\odot}^{*}\right) < 6.2$$



Where is the Fe in clusters?

Ratio of Fe locked in stars to total Fe

$$\frac{M_{Fe}^{*}}{M_{Fe}} = \frac{Z_{Fe}^{*}}{r_o \Upsilon_{Fe}}$$

$$3.8 < \left(r_o \Upsilon_{Fe,\odot} - Z_{Fe,\odot}^{*}\right) < 6.2$$

$$1.1 < Z_{Fe,\odot}^{*} < 1.3$$

$$\frac{1}{7} < \frac{M_{Fe}^{*}}{M_{Fe}} < \frac{1}{4}$$

The bulk of metals are in the hot gas, not in the stars the produced them

Going to smaller halo masses (groups)

$$f_b = f_* + f_{gas} + f_M$$

f_b cosmic baryon fraction
f_M missing baryon fraction

In this case the yield equation generalizes to

$$\Upsilon_{Fe} = \frac{M_{Fe}^{*} + M_{Fe}^{gas} + M_{Fe}^{M}}{r_o M_*}$$

where:
M_{Fe}^{*} is Fe mass locked in stars
M_{Fe}^{gas} is the mass in the hot gas (ICM or IGrM)
M_{Fe}^{M} is the mass in the gas not bound to the halo

We rewrite this as

$$\Upsilon_{Fe} = \frac{Z_{Fe}^{*}}{r_o}\left(1 + \frac{Z_{Fe}^{ICM}}{Z_{Fe}^{*}}\frac{M_{gas}}{M_*} + \frac{Z_{Fe}^{M}}{Z_{Fe}^{*}}\frac{M_M}{M_*}\right)$$

And solve it for Z_{Fe}^{gas}

$$Z_{Fe}^{gas} = \left(r_o \Upsilon_{Fe} - Z_{Fe}^{*} - Z_{Fe}^{M}\frac{f_M}{f_*}\right)\frac{f_*}{f_b}\frac{1}{1 - {f_M}/{f_b} - {f_*}/{f_b}}$$

Going to smaller halo masses

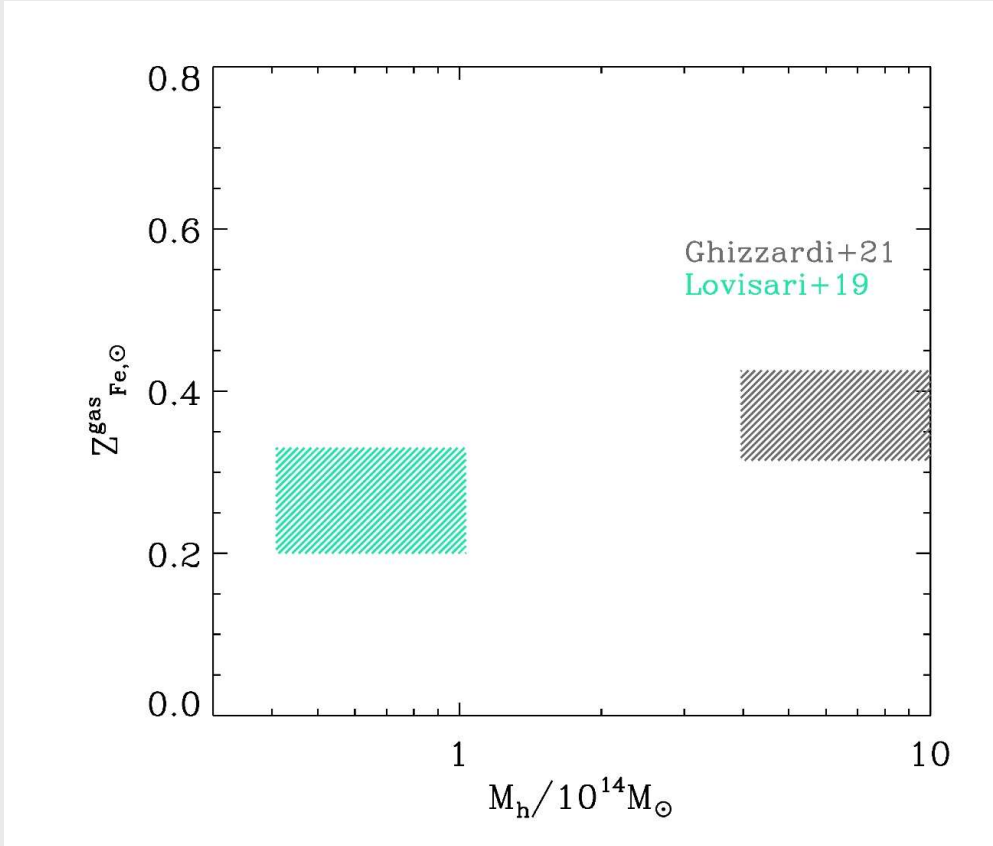
From the equation, an f_{gas} vs M_h relation (Eckert+21), the f_* vs M_h relation (Coupon+15)

$$Z_{Fe}^{gas} = Z_{Fe}^{gas}(M_h)$$

We consider 3 different cases:

1) $Z_{Fe}^{M} = 0$
2) $Z_{Fe}^{M} = 0.37\,(\quad Z_{Fe}^{ICM}@10^{15}\,M_\odot)$
3) $Z_{Fe}^{M} = 0.74\,(\quad 2\,Z_{Fe}^{ICM}@10^{15}\,M_\odot)$

and compare them to measurements of Z_{Fe} for groups and clusters



Going to smaller halo masses

From the equation, an f_{gas} vs M_h relation, the f_* vs M_h relation (C+15)

$$Z_{Fe}^{gas} = Z_{Fe}^{gas}(M_h)$$

We plot curves for 3 different cases:

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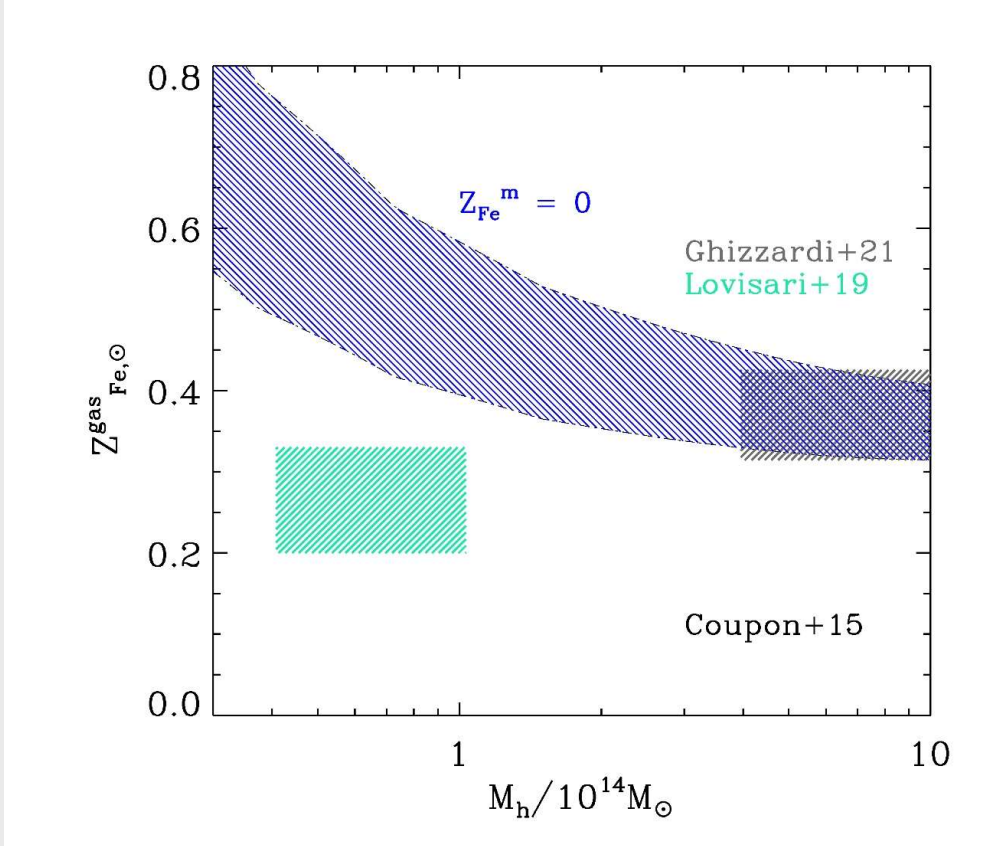

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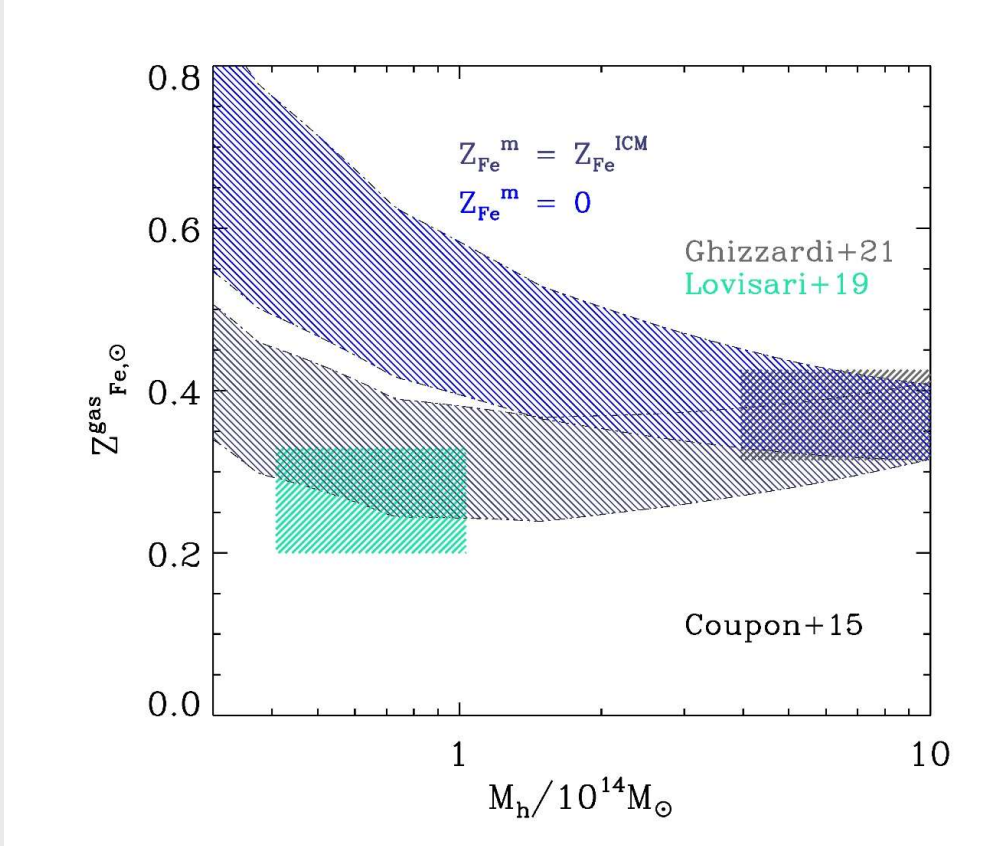

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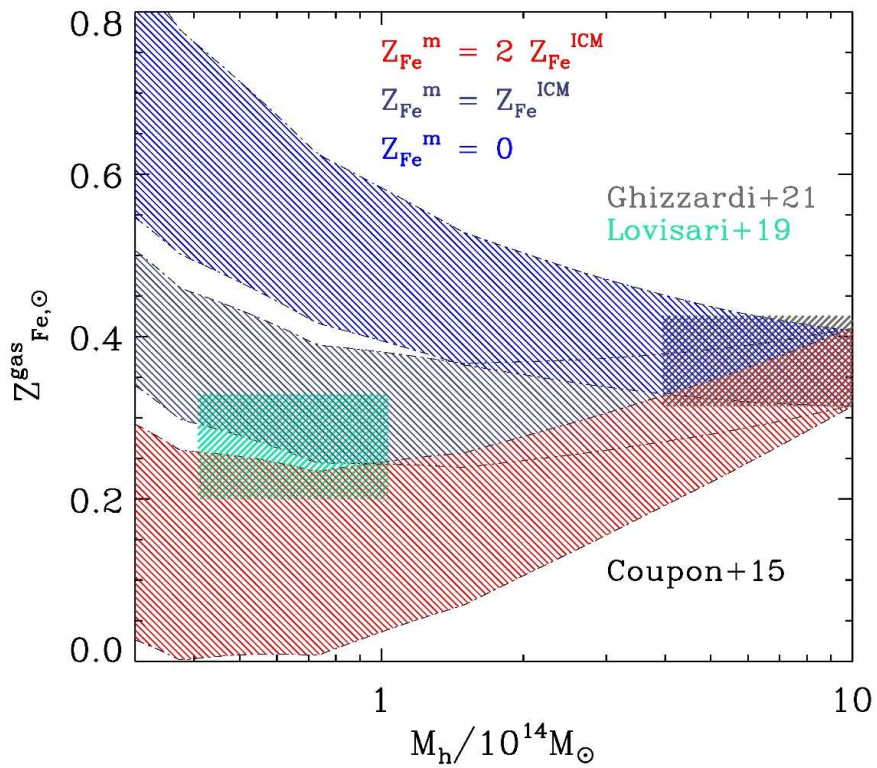
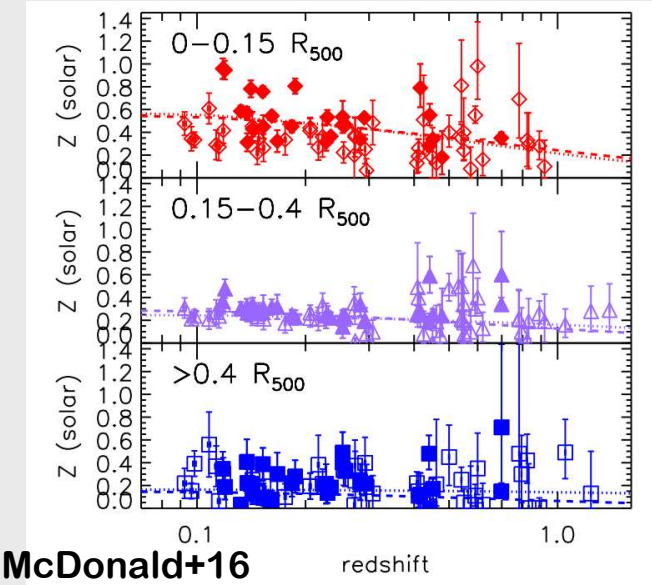


We can exclude the case of pristine gas as this would lead to substantial reduction in Fe abundance when going from groups to clusters

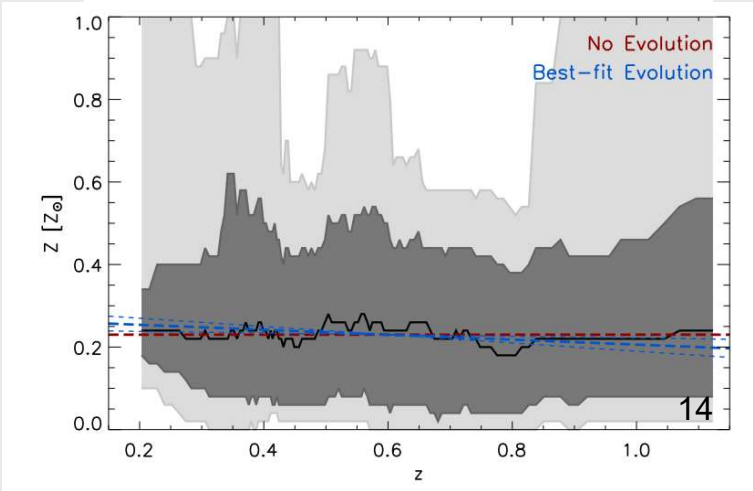
Redshift dependence of metal abundance in clusters

Results, extending to z~ 1.5 (Baldi+12, Ettori+15, McDonald+16, Mantz+17,Liu+20) all consistent with no evolution of metal abundance in core excised clusters.

Ettori+15



McDonald+16



Redshift dependence of metal abundance in clusters

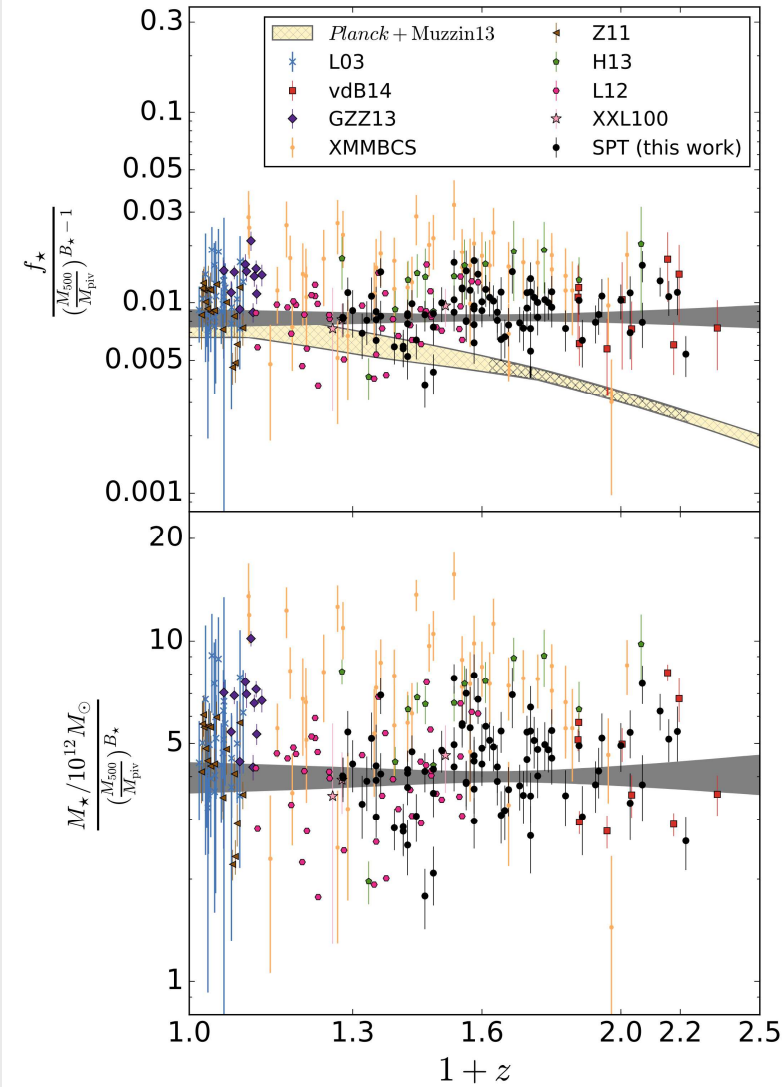
$$Z_{Fe,\odot}^{ICM} = (r_o \Upsilon_{Fe,\odot} - Z_{Fe,\odot}^{*}) \left(\frac{f_*}{f_b} \quad \frac{1}{1 - {}^{f_*}/_{f_b}} \right)$$

$Z_{Fe,\odot}^{ICM}$ scales ~ linearly with f_*

If $Z_{Fe,\odot}^{ICM}$ does not vary with redshift neither should f_*

This is indeed what is observed!

Chiu+18

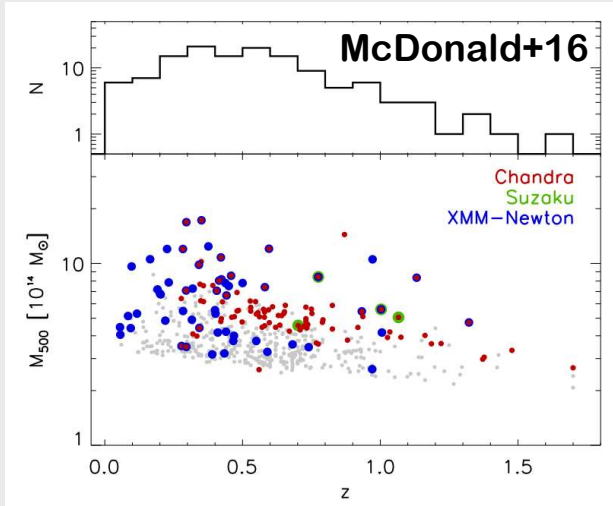


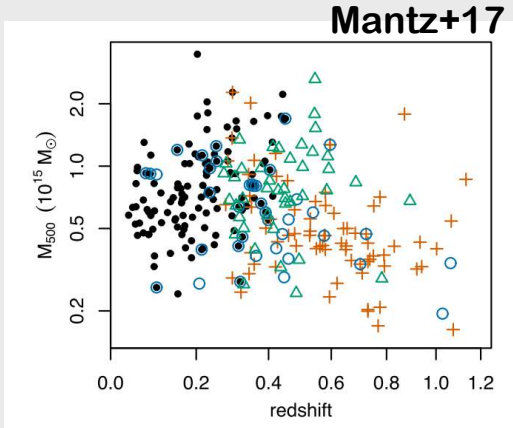
Redshift dependence of metal abundance in clusters

Systems have formed and evolved over different cosmic times

1. Low redshift (z~0) and mass ($M=10^{14}\ M_{\odot}$) systems are relatively young, (~ 1/2 mass accreted since z=1)

2. Massive ($M=10^{15}\ M_{\odot}$) high redshift (z~1) systems formed earlier (~ 1/2 mass before z=2)





The enrichment process is self-similar in a broad redshift range, from z~0 to z~2, when the age of the Universe was ~$\frac{1}{4}$ of what it is today.

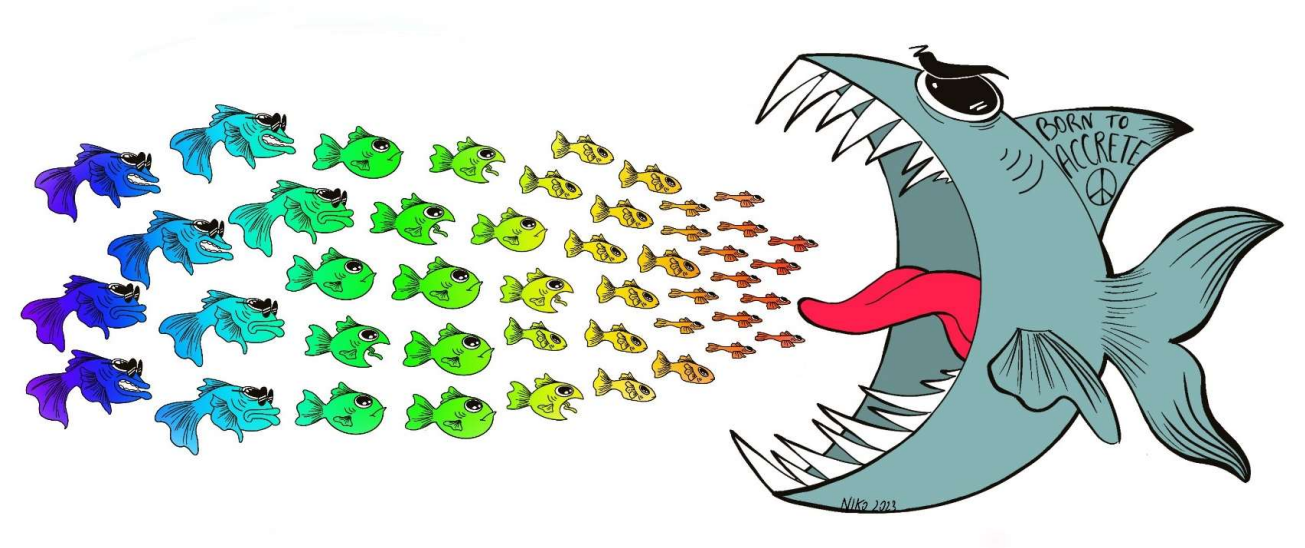
Fe production efficency in less massive systems

$$M_{Fe} = r_o \Upsilon_{Fe} \times M_*$$

$(r_o \Upsilon_{Fe,\odot})$ measured at Cluster scale

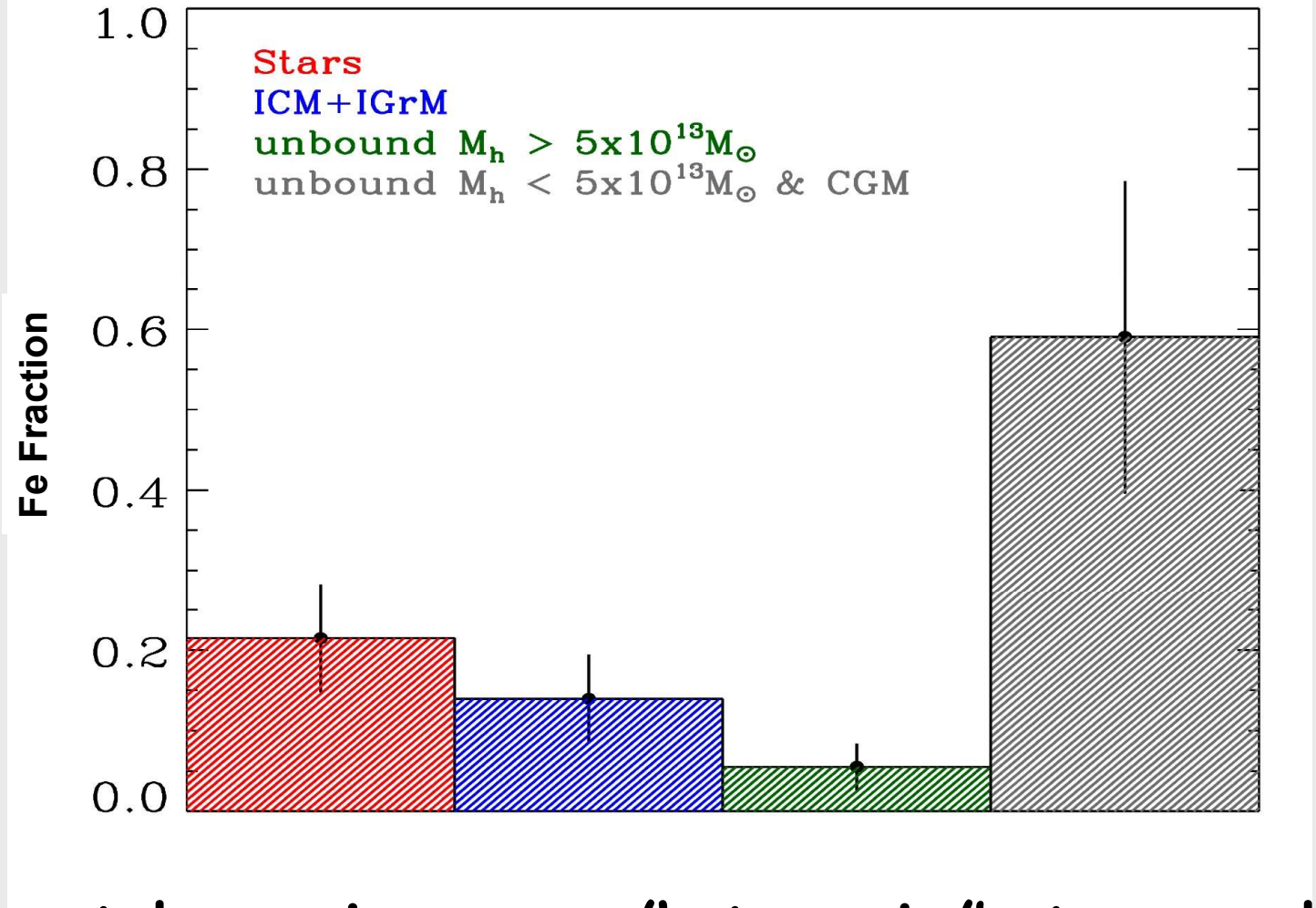
Good reasons to assume that it applies to less maasive halos as well

Stellar mass in clusters synthetized in lower mass halos ($M \sim 10^{12}\ M_\odot$)



With $M_*(M_h)$ and $r_o \Upsilon_{Fe}$ we can produce a metal budget for the Universe

Metal Budget for the Universe



Bulk of metals are in a warm/hot gas in/between galaxies

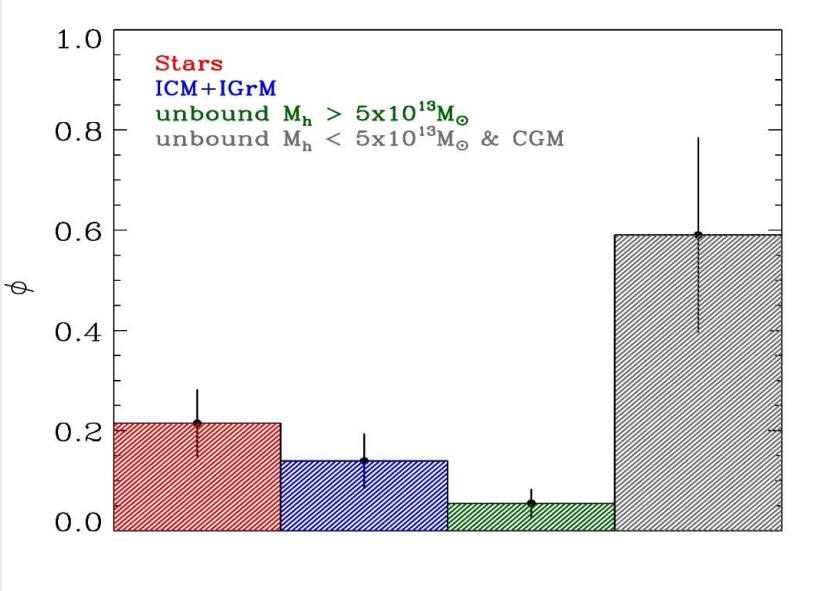
Implications/1

Detection of warm/hot low density baryons in X-rays is based on metal lines.

Detection of these lines has been controversial, one might infer that the lines have not been observed because there are no metals.

The warm/hot gas is enriched ⇒ the lines must be there!

Implications/2

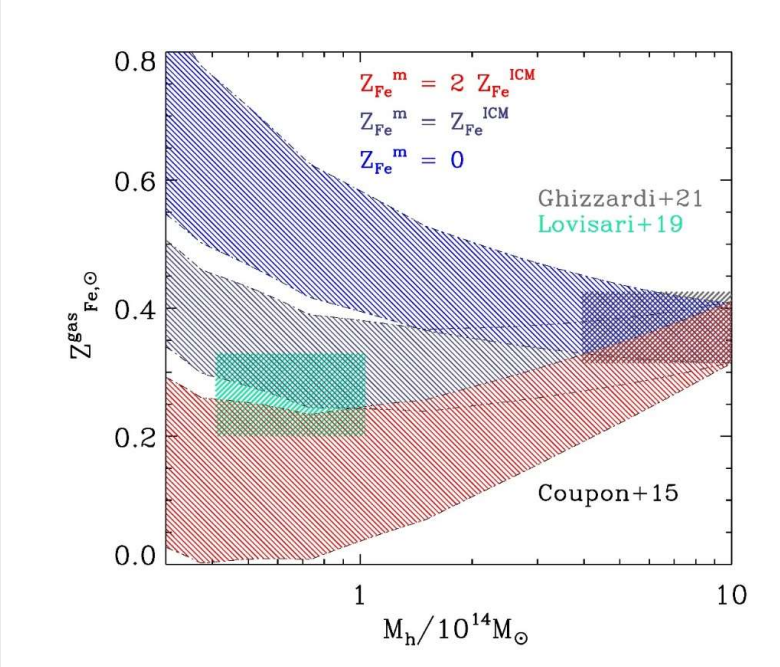


The bulk of the metals in the Universe are in warm/hot gas

The only way to access them is through high resolution X-ray spectroscopy!

The higher the resolution the better

Synergy



Connection between metal content of different components in the Large Scale Structure

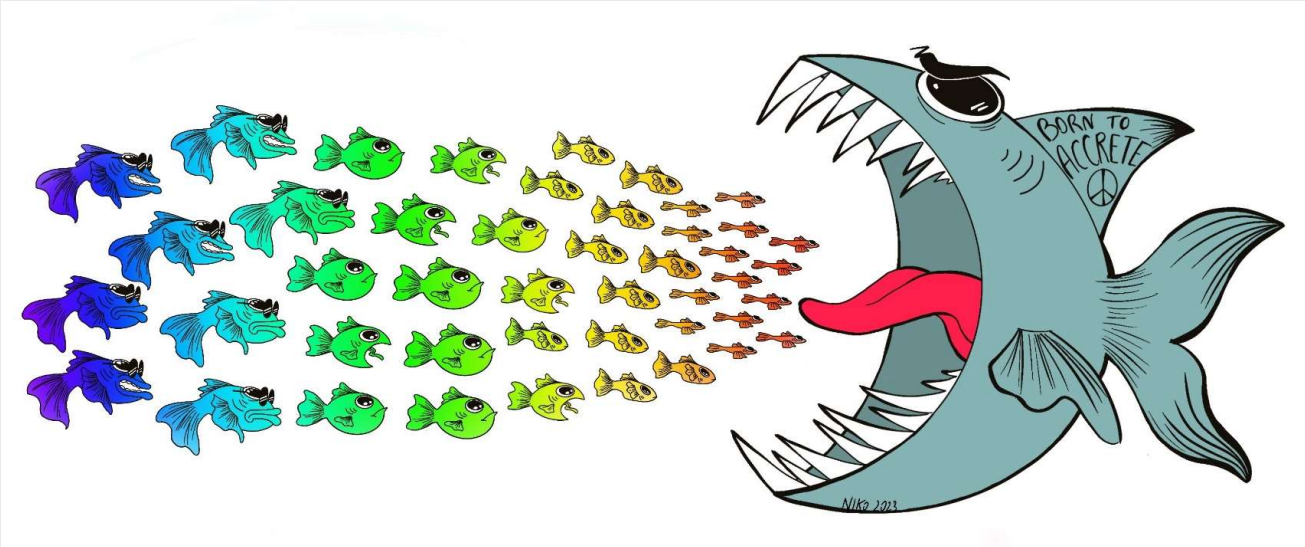
Crude estimate of missing gas metal abundance

$$0.25 < Z_{Fe}^{M} < 0.75$$

Can we do better?

Yes, with a combination of XIFU and WFI observations

Synergy^2



Missing gas comes from 100s independent enrichment events
Estimated abundance is $\langle Z_{Fe}^{M} \rangle$

Combined with direct measurements of WHIM (and CGM) metal abundance on single systems to gain understanding of the distribution

Possible Structure of SPC Presentation (AMC personal view)

- NewAthena science impacts should only be compared to
  - XMM-Newton, Chandra and XRISM
  - Other possible X Ray missions in the mid 2030's
- There should be one overall science "theme", not objective, to give SPC delegates a short form description of the mission purpose.
- The main science objectives as MDSOs:
  - Accretion mechanisms in AGN
  - The Physics of SMBH outflow
  - Black Hole growth and AGN populations
  - Kinematics of hot gas in Clusters of galaxies
  - The connection of clusters to the Cosmic Web
  - Neutron star equation of state via Multi Messenger science
- Examples of the numbers of sources within the sensitivity of NewAthena should be given, i.e. number of AGN's at z=7, etc.

How do hot Baryons assemble in the universe

Summary

You are what you accrete!